Electroweak production
SUSY searches in CMS

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On behalf of the CMS Collaboration

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Motivation

- Still no direct hints of BSM physics in the LHC... but we are not done yet!

- Strongly charged SUSY partners are preferred when they have similar masses to electroweak ones but current limits have pushed them beyond the TeV scale.

- The electroweak sector could be the key in finding SUSY.

- Spectacular effort during 2016 and 2017.

- Started to reach sensitivity to the TeV scale

Light slepton models

→ Models where the sleptons are amongst the lightest SUSY partners.

Direct slepton pair production

SUS-17-002 (CDS)
- taup pair (leptonic) + $p_T^{\text{miss}}$

SUS-17-003 (CDS)
- Hadronic taup pairs + $p_T^{\text{miss}}$

SUS-17-009 (CDS)
- Jetless, off-Z double lepton final states (same flavor, opposite sign) + $p_T^{\text{miss}}$

Slepton-mediated chargino/neutralino decay

SUS-17-010 (CDS)
- Jet inclusive off-Z double lepton final states (opposite sign) + $p_T^{\text{miss}}$

JHEP 03 (2018) 166
- Multileptonic final states (including light leptons and hadronic taup) + $p_T^{\text{miss}}$

Remember: neutralinos and charginos are mixings of the Higgsinos and the electroweak boson’s partners
**Heavy slepton models**

- Models where the sleptons are too heavy. Charginos and neutralinos decay to SM bosons.
- Include Gauge Mediated Supersymmetry Breaking (GMSB) scenarios with near massless gravitinos.

**Combined result** JHEP 03 (2018) 160

JHEP 03 (2018) 166  Multileptons + $p_T^{\text{miss}}$
JHEP 03 (2018) 076  Two leptons on-Z + $p_T^{\text{miss}}$
JHEP 11 (2017) 029  Lepton + two b-jets + $p_T^{\text{miss}}$
Submitted to Phys. Lett. B  Soft two leptons

**SUS-17-010 (CDS)**

- Jet inclusive off-Z double lepton final states (same flavor, opposite sign) + $p_T^{\text{miss}}$
Jetless off-Z double lepton

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

Stransverse mass variable:

\[ M_{T2}(\ell\ell) = \min_{p_{T\text{miss}}^{\text{lep}1} + p_{T\text{miss}}^{\text{lep}2} = p_{T\text{miss}}} \left( \max \left[ M_T(p_{T\text{lep}1}^{\text{lep}}, p_{T\text{miss}}^{\text{lep}1}), M_T(p_{T\text{lep}2}^{\text{lep}}, p_{T\text{miss}}^{\text{lep}2}) \right] \right) \]

Kinematical endpoint at \( m_W \) for \( tt, WW \) backgrounds

\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Source of uncertainty} & \textbf{Uncertainty (\%)} \\
\hline
Jet energy scale & 1-15 \\
Fast simulation \( p_T^{\text{miss}} \) modeling & 0-20 \\
Unclustered energy shifted \( p_T^{\text{miss}} \) & 0-8 \\
Muon energy scale shifted \( p_T^{\text{miss}} \) & 0-20 \\
Electron energy scale shifted \( p_T^{\text{miss}} \) & 0-4 \\
\hline
\end{tabular}
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>$\geq 20 \text{ GeV}$</td>
</tr>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
</tr>
<tr>
<td>$p_T^{\miss}$</td>
<td>$\geq 140 \text{ GeV}$</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 $M_{T2}(ll)$ variable (multiple bins).

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

<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.

SUS-17-009 (Jetless)

SUS-17-010 (Jet inclusive)
Hadronic τ pair final state

→ Requiring exactly two reconstructed high-p_T OC hadronic τ with no b-tagged jets in the event.
→ Define three dedicated signal regions:

<table>
<thead>
<tr>
<th>Region</th>
<th>Conditions</th>
<th>Description</th>
</tr>
</thead>
</table>
| SR1 | \(M_{T2} > 90 \text{ GeV} \)  
\( |\Delta\phi(l_1,l_2)| > 1.5 \) | Targets high stau masses |
| SR2 | \(40 \text{ GeV} < M_{T2} < 90 \text{ GeV} \)  
\(\Sigma M_T > 350 \text{ GeV} \)  
\(E_T^{\text{miss}} > 50 \text{ GeV} \)  
\( |\Delta\phi(l_1,l_2)| > 1.5 \) | Targets compressed scenarios |
| SR3 | \(40 \text{ GeV} < M_{T2} < 90 \text{ GeV} \)  
\(300 \text{ GeV} < \Sigma M_T < 350 \text{ GeV} \)  
\(E_T^{\text{miss}} > 50 \text{ GeV} \)  
\( |\Delta\phi(l_1,l_2)| > 1.5 \) | Targets compressed scenarios |

→ Relevant Background sources:
1) QCD or W+jets (“fake” τ): estimated from sideband region of loosely isolated τ.
2) Drell-Yan: simulation is corrected by scale factors derived in \(Z \rightarrow \mu \mu\) data control region.

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τ pair production (semileptonic/dileptonic)

→ Events with either an eμ OC pair or an hadronically decaying τ and a light lepton forming an OC pair.
→ Veto b-tagged jets. Allow only up to one jet.

ζ = bisector between the two leptons. Discriminant variables:

\[ P_{\zeta,\text{miss}} = \vec{p}_T^{\text{miss}} \cdot \vec{\zeta} \]
\[ P_{\zeta,\text{vis}} = (\vec{p}_T(\ell_1) + \vec{p}_T(\ell_2)) \cdot \vec{\zeta} \]
\[ D\zeta = P_{\zeta,\text{miss}} - 0.85P_{\zeta,\text{vis}} \]

→ Search strategy: 3D-bins of Dζ, \( p_T^{\text{miss}} \) and \( M_{T^2} + \) jet categories.
Tau pair production interpretations

→ Stau pair production model. Special interest in the compressed scenarios.

→ $\tilde{\tau} \chi_1^0$ mechanism could explain the current observed relic density of dark matter in the universe.
Chargino/neutralino pair production combination

→ Statistical combination of all CMS analysis targeting direct decays of neutralino/chargino pairs to SM bosons (heavy sleptons electroweak SUSY scenarios). 6 main publications of CMS.

<table>
<thead>
<tr>
<th>Search</th>
<th>WZ</th>
<th>WH</th>
<th>ZZ</th>
<th>ZH</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(\ell) 2b</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4b</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2(\ell) on-Z</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2(\ell) soft</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\geq3\ell)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(H(\gamma\gamma))</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

GMSB models

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Combined results

→ Setting even higher limits in the electroweak SUSY energy scale.

CMS

pp → \tilde{\chi}_1^\pm \tilde{\chi}_2^0

35.9 fb⁻¹ (13 TeV)

CMS

35.9 fb⁻¹ (13 TeV)

m_{\tilde{\chi}^0_1} = m_{\tilde{\chi}_2^0} (GeV)

m_{\tilde{\chi}^0_1} = m_{\tilde{\chi}^0_1} (GeV)

m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_1^0} (GeV)

m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_1^0} (GeV)

Higgsino mass m_{\tilde{\chi}_1^0} [GeV]
Conclusions

→ Great quantity of new high quality results in SUSY searches during the last year.

→ Constantly increasing our sensitivity, reaching new limits in our search for BSM physics.

→ Expect the new data, both from 2017 and 2018, to provide further insight in our searches.

→ What could be hiding close to the TeV scale?

→ It’s the time to study electroweak SUSY!
Back-Up
Multilepton final states

→ Recent results (Moriond 2017) in slepton mediated chargino-neutralino decays.

→ Events with 3 or more leptons (including taus) or a SC pair.

<table>
<thead>
<tr>
<th>Category</th>
<th>Selection</th>
<th>Categorization</th>
</tr>
</thead>
<tbody>
<tr>
<td>2l SC</td>
<td>$p_T^{\text{miss}} &gt; 60\text{GeV}$, $m_{ll} &gt; 12\text{GeV}$, $</td>
<td>m_{\ell\ell} - m_Z</td>
</tr>
<tr>
<td>3 (l+τ)</td>
<td>$p_T^{\text{miss}} &gt; 50\text{GeV}$, $m_{ll} &gt; 12\text{GeV}$, $</td>
<td>m_{3l} - m_Z</td>
</tr>
</tbody>
</table>

High multiplicity of signal regions
Designed for increased sensitivity to a broad range of SUSY models

→ Specific treatments for background:

1) WZ: normalized to data in a dedicated control region. Dedicated studies on its uncertainty per signal region.

2) Non-prompt leptons: extrapolated from selection with looser lepton requirements. Lepton ID specifically designed for great reductions of the non-prompt presence.
Multilepton interpretations

→ Multiple interpretations in the slepton mediated chargino-neutralino pair decay scenario based on the mass splitting of the particles and the preferred flavor and chirality of the mediating slepton.

![Diagrams showing different slepton mediated processes](image-url)
→ Statistical combination of all CMS analysis targeting direct decays of neutralino/chargino pairs to SM bosons (heavy sleptons electroweak SUSY scenarios). Results from 6 main publications of CMS as well as a new optimization.

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<tr>
<td>1ℓ 2b</td>
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<td>✓</td>
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<tr>
<td>2ℓ soft</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>H(γγ) ≥3ℓ</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

(Very) Short summaries:
1) 1ℓ + 2b: require additional high $p_T^{miss}$, includes a $M_T$ cut (to decrease tt) and requires $m_{bb} \in [90,150]$ GeV. $p_T^{miss}$ bins for signal extraction.
2) 4b: reconstructs the two $H\rightarrow bb$ masses and requires consistency between them. Categorizes in number of tightly b-tagged jets and mean measured Higgs’ boson mass for signal extraction.
3) $H\rightarrow γγ$: specific $γbb$ category sensitive to HH and HZ. Using razor variables as discriminant. Fit to the $m_γ$ spectrum.
4) On-Z 2l: multiple categories (llqq and llbb) targeting different final state topologies. Uses $p_T^{miss}$ bins for signal extraction.

- ≥3l and soft 2l: more on the compressed SUSY talk.
An additional reinterpretation of multiple analysis in terms of the mixed model between the two cases was also performed.
GMSB models interpretation

→ Clear improvement from the combination is seen for the more Z-like neutralinos.
→ Further reach in this specific channel is to be expected mostly from the 4b and on-Z 2l targeted searches.