Searches for charginos and neutrinos at CMS

LHCP 2019, Puebla, Mexico
Sam Bein, on behalf of CMS

May 22, 2019
EWKino direct production

- Direct chargino and neutralino production is challenging due to small cross sections/leptonic branching fractions
  - However, more interesting as tighter bounds on strongly charged particles are established

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\begin{align*}
\tilde{\chi}_1^\pm, \chi_0^2, \tilde{\chi}_0^0, \chi_0^0, W, \gamma, Z, h
\end{align*}
```
Processes

Outline

- Signatures
  - MET, MT, MT2, MLL, Razor
- Searches for WZ model
- WZ Combination
- Searches for WH model
- WH Combination
- New results from WH
- Summary

Chargino/neutralino production has the largest cross section

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Signatures (i)

“MET”

Missing transverse energy/momentum

\[ E_T^{\text{miss}} = p_T^{\text{miss}} = | - \sum_{\text{particles}} \vec{p}_T | \]

“M(\text{LL})”

Invariant mass

\[ M_{\text{ll}} = \sqrt{ (| p_{L1} | + | p_{L2} |)^2 - (| \vec{p}_{L1} + \vec{p}_{L2} |)^2 } \]

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Signatures (ii)

“MT”
Transverse mass

\[
M_T = \sqrt{2 p_T(l) \not{p}_T \text{miss} (1 - \cos[\Delta \phi(\text{lep}, \not{p}_T \text{miss})])}
\]

“MT2”
Stransverse mass

\[
M_{T2}(L1, L2) = \min_{\not{p}_T^1 + \not{p}_T^2 = \not{p}_T \text{miss}} \left[ \max(M_T^{L1} + M_T^{L2}) \right]
\]

arXiv:1709.05406
### Razor variables

\[ M_R = \sqrt{(|\vec{p}^{j1}| + |\vec{p}^{j2}|)^2 - (p_z^{j1} + p_z^{j2})} \]

\[ M_T^R = \frac{1}{\sqrt{2}} \sqrt{p_T^{\text{miss}}(p_T^{j1} + p_T^{j2}) - \vec{p}_T^{\text{miss}} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})} \]

\[ R = \frac{M_T^R}{M_R} \]

- Event objects clustered into “megajets”, used as j1 and j2
- MR gives mass scale
- R provides discrimination like MET

From discriminant study [Cohen et al., 2016]
Opposite-sign dilepton (on-Z)

- Target leptonically-decaying Z boson with hadronic decay of the W
- Events collected with di-lepton triggers, with and without isolation
- OSSF lepton pair selected with invariant mass $m(LL) \in [86, 96]$
- Require at least 2 jets, $m(JJ)<110$, 0 b-tagged jets
- Require MET>100, $MT_2(LL)>80$, $MT_2(LL)>80$ GeV
- Categorize in MET regions: 100–150, 150–250, 250–350, and > 350 GeV

Main background in high MET tail arises from standard model WZ events, estimated with data-validated simulation
OSSF dilepton compressed

- Events triggered with MET $>120$ or $80$ GeV
- Lepton selected with $p_T \in [5, 30]$ GeV
- OSSF loose lepton pair selected with invariant mass
  - $m(LL) \in [4, 9], [10.5, 50]$ GeV
- 0 b-tagged jets, other kinematic cuts
- Require MET $>200$ for $ee$ (125 for $\mu\mu$) GeV
- Categorize in MET regions: 125–200, 200–250, and $>250$ GeV

Main background: events with 1 prompt+ 1fake lepton in W+jets events. A tight-to-loose ratio is applied in a loose application region
**Results (OSSF lepton)**

Red/black contours show 95% exclusion for wino-like cross sections

Good complementarity between search strategies
Three or more leptons

- Select event with three leptons (at most 2 $\tau$s)
  - $p_T > 25$ (20) GeV for leading e ($\mu$)
  - $p_T > 15$ (10) GeV for sub-leading e ($\mu$)

Many categories, each optimised:

- 3 light-flavor leptons (e or $\mu$)
- 2 light-flavor leptons and a $\tau$
- 1 light-flavor lepton and 2 $\tau$s
- >3 light-flavor leptons and 0 $\tau$
- >2 light-flavor leptons and 1 $\tau$
- >1 light-flavor leptons and 2 $\tau$

Further split by presence of OSSF pair, $M(\text{LL})$ regions $[0,75]$, $[75,105]$, $[105,\infty]$ GeV
Results multi-lepton

M(LL) regions [0,75], [75, 105], [105,∞]

Red/black contours show 95% exclusion for wino-like cross sections
Combination of OSSF and multi-lepton searches

Red/black contours show 95% exclusion for wino-like cross sections.
Higgs+MET (h->bb)

- Data samples collected with single-electron and single-muon triggers
- Require
  - exactly 1 lepton with \( p_T > 30 \) (25) GeV for central e (\( \mu \))
  - exactly 2 jets with \( p_T > 30 \) GeV, b-tagged
- Require
  - MET>125, MT>50 GeV
  - MCT(bb)>170 GeV
  - Require \( m(bb) \in [90,150] \) GeV
  - Categorize events in MET slices

\[ \text{arXiv:1706.09933} \]

<table>
<thead>
<tr>
<th>( 125 \leq E_T^{\text{miss}} &lt; 200 \text{ GeV} )</th>
<th>( E_T^{\text{miss}} \geq 200 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total SM background</td>
<td>7.5 \pm 2.5</td>
</tr>
<tr>
<td>Data</td>
<td>11</td>
</tr>
<tr>
<td>( \tilde{\chi}_1^\pm \tilde{\chi}_1^0 ) (225,75)</td>
<td>2.4 \pm 0.4</td>
</tr>
</tbody>
</table>
Higgs+Met (h->γγ)

- Data samples collected with diphoton trigger
- Require exactly 2 barrel photons with \( p_T > 40 \) (20) GeV for leading (sub-leading), \( |\eta| < 1.44 \)
- \( m(\gamma\gamma) \in [103, 160] \) GeV
- At least one additional jet with \( p_T > 30 \) \( |\eta| < 3 \)
- Selection with Razor variables and binning in terms of photon resolution

Background determined by global fit to model of non-resonant \( \gamma\gamma \) events + SM Higgs MC
Results Higgs+MET (h->bb and h->γγ)

Red/black contours show 95% exclusion for wino-like cross sections

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Combination Higgs+MET (h->bb and h->γγ)

Red/black contours show 95% exclusion for wino-like cross sections

Combination arXiv:1801.03957

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Updated analysis targeting h→γγ SUSY

- 2016+2017 dataset used
- Additional categories based on lepton multiplicity and re-optimised selection
- Improved exclusion limit by 50 GeV on the heavier EWKinos

**Graphs:**

**CMS 35.9 fb⁻¹ (13 TeV)**

- $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow H \tilde{\chi}_1^0$

  - **Observed ± 1 $\sigma_{\text{theory}}$**
  - **Expected ± 1 $\sigma_{\text{experiment}}$**

- NLO+NLL exclusion

**CMS Preliminary 77.5 fb⁻¹ (13 TeV)**

- $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow H \tilde{\chi}_1^0$

  - **Observed ± 1 $\sigma_{\text{theory}}$**
  - **Expected ± 1 $\sigma_{\text{experiment}}$**

**SUS-18-007 h→γγ**

- $arXiv:1709.00384$

- 95% CL upper limit on cross section [pb]
Summary

- Run 2 searches have made significant progress in constraining pure EWKinos models
- Most stringent limits on the EWKino masses for 100 GeV LSP is \(~600\) GeV
- Statistical combinations of final states allow for more stringent, global constraints on WZ, WH
- Naturalness is being tested, but low-mass EWKinos cannot be ruled out
Backup
Overview of SUSY results: electroweak production

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

\[ PP \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow \ell\nu\bar{\ell}\ell \rightarrow \ell\nu\ell\ell\tilde{\chi}_1^0 \]

3\ell: arXiv:1709.05406
flavour democratic, \(x = 0.5\)

3\ell/2\ell same-sign: arXiv:1709.05406
flavour democratic, \(x = 0.05\)

3\ell/2\ell same-sign: arXiv:1709.05406
flavour democratic, \(x = 0.95\)

3\ell/\ell: arXiv:1709.05406
\(\tau\) enriched, \(x = 0.5\)

3\ell/\ell: arXiv:1709.05406
\(\tau\) enriched, \(x = 0.05\)

3\ell/\ell: arXiv:1709.05406
\(\tau\) enriched, \(x = 0.95\)

\[ PP \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\mp \rightarrow \ell\nu\bar{\ell}\ell \rightarrow \ell\nu\ell\ell\tilde{\chi}_1^0 \]

\[ PP \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\mp \rightarrow \ell\nu\bar{\ell}\ell \rightarrow \ell\nu\ell\ell\tilde{\chi}_1^0 \]

\[ PP \rightarrow WH \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_2^\pm \tilde{\chi}_1^\mp \rightarrow \ell\nu\bar{\ell}\ell \rightarrow \ell\nu\ell\ell\tilde{\chi}_1^0 \]


\[ PP \rightarrow WH \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_2^\pm \tilde{\chi}_1^\mp \rightarrow \ell\nu\bar{\ell}\ell \rightarrow \ell\nu\ell\ell\tilde{\chi}_1^0 \]

2\ell opposite-sign: arXiv:1709.08908

3\ell: arXiv:1709.05406

2\ell soft: arXiv:1801.01846 \(\Delta M = 20\) GeV

combined: arXiv:1801.03957
BF = 50%

combined: arXiv:1801.03957
BF = 50%, \(x = 0.5\)

PP \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp

2\ell opposite-sign: arXiv:1807.07799 \(M_{\chi}\) = 1 GeV

PP \rightarrow \tilde{\ell}_{L/R} \ell_{L/R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0

PP \rightarrow \tilde{\ell}_{L/R} \ell_{L/R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0

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 divergence between the intermediate sparticle and the LSP relative to \(\Delta M\), respectively, unless indicated otherwise.
A word on decay modes

- The presence of a low-mass slepton can change the chargino branching fraction
  - Generation of slepton influences final states
    - Light staus enhance $\tau$ lepton final states
  - Chirality of slepton influences final state
    - Right-handed light sleptons enhance $\tau$ lepton final states

- The mixing of the EWKinos and mass differences impact the neutrino decays
  - Large mass differences can allow on-shell Higgs boson decays of the neutrinoChirality

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“MCT”

Contransverse mass

\[ M_{CT} = \sqrt{2 p_{T1} p_{T2} (1 + \cos[\Delta \varphi(\vec{p}_1, \vec{p}_2)])} \]

Exhibits endpoint at mass of semi-invisibly decaying pair-produced particles, without knowing about the MET
Same-sign dilepton

- Require exactly 2 tight same-charge leptons
  - $p_T > 25, 20$ GeV ($e, \mu$) for leading
- Veto events with OSSF pair found among all loose leptons ($p_T > 20, 10, 20$ GeV ($e, \mu, \tau$)) with
  - $|m_{LL} - m_Z| < 15$ GeV or $m_{LL} < 12$ GeV
- Require MET $> 60$ GeV
- Sub-divide by $n(\text{jets})$
- Further categories in di-lepton $p_T$, MET, and MLL
- Target left-handed sleptons with masses between the EWKinos states

\textbf{arXiv:1709.05406}

<table>
<thead>
<tr>
<th>$N_{\text{jets}}$</th>
<th>$100 \leq p_T^{\text{miss}} &lt; 150$ GeV</th>
<th>$150 \leq p_T^{\text{miss}} &lt; 200$ GeV</th>
<th>$p_T^{\text{miss}} \geq 200$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>SS02 (++) SS03 (--)</td>
<td>SS04</td>
<td>SS05</td>
</tr>
<tr>
<td></td>
<td>SS07 (++) SS08 (--)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SS12 (++) SS13 (--)</td>
<td>SS14</td>
<td>SS15</td>
</tr>
<tr>
<td>1</td>
<td>SS17 (++) SS18 (--)</td>
<td>SS19</td>
<td>SS20</td>
</tr>
<tr>
<td></td>
<td>SS22 (++) SS23 (--)</td>
<td>SS24</td>
<td>SS25</td>
</tr>
<tr>
<td></td>
<td>SS27 (++) SS28 (--)</td>
<td>SS29</td>
<td>SS30</td>
</tr>
</tbody>
</table>

\textit{arXiv:1709.05406}
Three or more light leptons

- Require exactly 2 tight same-charge leptons
  - $p_T > 25, 20$ GeV (e,μ) for leading

Many categories, each optimised:

- 3 light-flavor leptons (e or μ)
- 2 light-flavor leptons and a $\tau$
- 1 light-flavor lepton and 2 $\tau$s
- >3 light-flavor leptons and 0 $\tau$
- >2 light-flavor leptons and 1 $\tau$
- >1 light-flavor leptons and 2 $\tau$

Further split by presence of OSSF pair, regions of invariant mass MLL

<table>
<thead>
<tr>
<th>$p_T^{\text{miss}}$ (GeV)</th>
<th>0$\tau_h$</th>
<th>1$\tau_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nOSSF ≥ 2</td>
<td>nOSSF &lt; 2</td>
</tr>
<tr>
<td>0 – 50</td>
<td>G01</td>
<td>H01</td>
</tr>
<tr>
<td>50 – 100</td>
<td>G02</td>
<td>H02</td>
</tr>
<tr>
<td>100 – 150</td>
<td>G03</td>
<td>H03</td>
</tr>
<tr>
<td>150 – 200</td>
<td>G04</td>
<td>H04</td>
</tr>
<tr>
<td>≥200</td>
<td>G05</td>
<td>H04</td>
</tr>
</tbody>
</table>

arXiv:1709.05406

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“MET”

\[ E_{T}^{\text{miss}} = p_{T}^{\text{miss}} = - \sum_{\text{particles}} \vec{p}_{T} \]

Missing transverse energy/momentum

Undetected particles in the final state can carry large momentum
“MT”

Transverse mass

\[ M_T = \sqrt{2 p_T(l) p_T^{\text{miss}} (1 - \cos[\Delta \phi(\text{lep}, p_T^{\text{miss}})])} \]

Background exhibits a smeared endpoint near the W mass
“MLL”

\[ M_{ll} = \sqrt{\left( |p_{L1}| + |p_{L2}| \right)^2 - \left( |\vec{p}_{L1} + \vec{p}_{L2}| \right)^2} \]

Invariant mass

Signal exhibits endpoint structure, background has Z boson pole mass

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"MT2"

\[ M_{T2}(L1, L2) = \min_{\frac{1}{p_T^v} + \frac{1}{p_T^v} = p_T^{miss}} [\max(p_{T1}^{L1} + p_{T2}^{L2})] \]

Stransverse mass

Background exhibits a steep shoulder near the W mass

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