Dark Matter SUSY search at the LHC

Zhenbin Wu
(University of Illinois at Chicago)
-- On behalf of the ATLAS and CMS Collaboration
Supersymmetry (SUSY) is a spacetime symmetry that adds a fermionic partner to each SM boson and a bosonic partner to each SM fermion.

- SUSY provides the cancellation of the Higgs boson quadratic mass renormalization between top and top squark (stop)
• SUSY also provide gauge unification at GUT scale
Dark Matter Candidate

- With R-parity conservation, the lightest supersymmetric particle (LSP) is a dark matter candidate.
- Use **Simplified Model Spectra** as guideline, consider $\tilde{\chi}^0_1$ as LSP:
  - Simple decay chain, assuming 100% branch ratio.
  - Unknown LSP mass, limited are set in two dimensions.

Common search strategies:
- **Gluinos, Squarks:**
  - "Inclusive" searches based on topologies, sensitive to broad SUSY(−like) signal.
- **Stop/Sbottom, electroweakinos:**
  - "Targeted" searches, dedicated to corresponding SUSY signals.
Gluinos and Squarks

- Classic inclusive Jet and MET searches:
- Binning in $H_T$, $H_T^{\text{miss}}$, #jets, #b-jets

Main backgrounds:
- $tt\bar{t}$ and $W + \text{jets}$ where a lepton was lost, predict from single lepton control region in data
- $Z$ invisible (genuine MET), predict from gamma + jet and $Z \rightarrow \ell\ell$ control region in data
- QCD multijets (mismeasured jets leading to fake MET), predict from smeared events in data

CMS-PAS-SUS-19-006
Gluinos and Squarks

• Classic Multi-bin analysis

<table>
<thead>
<tr>
<th></th>
<th>MB-SSd</th>
<th>MB-GGd</th>
<th>MB-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_i$</td>
<td>$\geq 2$</td>
<td>$\geq 4$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$p_T(j_1)$ [GeV]</td>
<td>$&gt; 200$</td>
<td>$&gt; 200$</td>
<td>$&gt; 600$</td>
</tr>
<tr>
<td>$p_T(j_{i=2,\ldots,N_{j\min}})$ [GeV]</td>
<td>$&gt; 100$</td>
<td>$&gt; 100$</td>
<td>$&gt; 50$</td>
</tr>
<tr>
<td>$</td>
<td>\eta(j_{i=1,\ldots,N_{j\min}})</td>
<td>$</td>
<td>$&lt; 2.0$</td>
</tr>
<tr>
<td>$\Delta \phi(j_{1,2,(3)}, p_T^{miss})_{\min}$</td>
<td>$&gt; 0.8$</td>
<td>$&gt; 0.4$</td>
<td>$&gt; 0.4$</td>
</tr>
<tr>
<td>$\Delta \phi(j_{i&gt;3}, p_T^{miss})_{\min}$</td>
<td>$&gt; 0.4$</td>
<td>$&gt; 0.2$</td>
<td>$&gt; 0.2$</td>
</tr>
<tr>
<td>Aplanarity</td>
<td>-</td>
<td>$&gt; 0.04$</td>
<td>-</td>
</tr>
<tr>
<td>$E_T^{miss} / \sqrt{H_T}$ [GeV$^{1/2}$]</td>
<td>$&gt; 10$</td>
<td>$&gt; 10$</td>
<td>$&gt; 10$</td>
</tr>
<tr>
<td>$m_{\text{eff}}$ [GeV]</td>
<td>$&gt; 1000$</td>
<td>$&gt; 1000$</td>
<td>$&gt; 1600$</td>
</tr>
</tbody>
</table>

• 8 BDT trained in kinematic regions of interest, for different signal points

<table>
<thead>
<tr>
<th></th>
<th>BDT-GGd1</th>
<th>BDT-GGd2</th>
<th>BDT-GGd3</th>
<th>BDT-GGd4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_i$</td>
<td></td>
<td></td>
<td>$\geq 4$</td>
<td></td>
</tr>
<tr>
<td>$\Delta \phi(j_{1,2,(3)}, p_T^{miss})_{\min}$</td>
<td></td>
<td></td>
<td></td>
<td>$\geq 0.4$</td>
</tr>
<tr>
<td>$\Delta \phi(j_{i&gt;3}, p_T^{miss})_{\min}$</td>
<td></td>
<td></td>
<td></td>
<td>$\geq 0.4$</td>
</tr>
<tr>
<td>$E_T^{miss} / m_{\text{eff}}(Nj)$</td>
<td></td>
<td></td>
<td></td>
<td>$\geq 0.2$</td>
</tr>
<tr>
<td>$m_{\text{eff}}$ [GeV]</td>
<td></td>
<td></td>
<td>$\geq 1400$</td>
<td>$\geq 800$</td>
</tr>
<tr>
<td>BDT score</td>
<td>$\geq 0.97$</td>
<td>$\geq 0.94$</td>
<td>$\geq 0.94$</td>
<td>$\geq 0.87$</td>
</tr>
<tr>
<td>$\Delta m(\tilde{g}, X_1)$ [GeV]</td>
<td>$1600 - 1900$</td>
<td>$1000 - 1400$</td>
<td>$600 - 1000$</td>
<td>$200 - 600$</td>
</tr>
</tbody>
</table>

ATLAS-CONF-2019-040
Gluino Limits

CMS Preliminary 137 fb⁻¹ (13 TeV)

\(pp \rightarrow \tilde{g} \tilde{g}, \tilde{g} \rightarrow b \bar{b} \chi_1^0\) Approx NNLO+NNLL exclusion

- Observed \(\pm 1 \sigma_{\text{theory}}\)
- Expected \(\pm 1, \pm 2 \sigma_{\text{experiment}}\)

\[m_{\tilde{g}} \text{ [GeV]} \quad m_{\chi_1^0} \text{ [GeV]} \]

95% CL upper limit on cross section [pb]

ATLAS Preliminary \(\sqrt{s}=13 \text{ TeV}, 139 \text{ fb}^{-1}\)

- 0-leptons, 2-6 jets
- All limits at 95% CL

\[m(\tilde{g}) \text{ [GeV]} \]

Exp. limit \((\pm 1 \sigma_{\exp})\)
Obs. limit \((\pm 1 \sigma_{\text{theory}})\)
Exp. limits MB
Exp. limits BDT
0L obs. 36 fb⁻¹

[arXiv:1712.02332]
Squarks

Mass limits have reached $\sim 1.2$ TeV on individual squarks for low LSP masses and $\sim 1.9$ TeV for 8-fold degenerate squarks.
Single Lepton Search

Single lepton search using sum of large-R jet masses ($M_J$)

$$M_J = \sum_{j_i = \text{large-R jets}} m(j_i).$$

Single lepton + $p_T^{\text{miss}}$, $S_T$, #jets, #b-jets, $M_J$
Multi Lepton Search

ATLAS-CONF-2019-015

CMS-SUS-19-008

Same-sign 2l & > 3l search

Signal selection:
Binning in $H_T$, $p_T^{miss}$, $m_T$, #jets, #b-jets

<table>
<thead>
<tr>
<th>SR</th>
<th>$n_e$</th>
<th>$n_b$</th>
<th>$n_l$</th>
<th>$E_T^{miss}$ [GeV]</th>
<th>$m_{eff}$ [GeV]</th>
<th>$E_T^{miss}/m_{eff}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rpv2L</td>
<td>≥ 2 ($\ell^+\ell^-$)</td>
<td>≥ 0</td>
<td>≥ 6 ($p_T &gt; 40$ GeV)</td>
<td>-</td>
<td>&gt; 2600</td>
<td>-</td>
</tr>
<tr>
<td>Rpv2L0b</td>
<td>≥ 2 ($\ell^+\ell^-$)</td>
<td>= 0</td>
<td>≥ 6 ($p_T &gt; 40$ GeV)</td>
<td>&gt; 200</td>
<td>&gt; 1000</td>
<td>&gt; 0.2</td>
</tr>
<tr>
<td>Rpv2L1b</td>
<td>≥ 2 ($\ell^+\ell^-$)</td>
<td>≥ 1</td>
<td>≥ 6 ($p_T &gt; 40$ GeV)</td>
<td>-</td>
<td>-</td>
<td>&gt; 0.25</td>
</tr>
<tr>
<td>Rpv2L2b</td>
<td>≥ 2 ($\ell^+\ell^-$)</td>
<td>≥ 2</td>
<td>≥ 6 ($p_T &gt; 25$ GeV)</td>
<td>&gt; 300</td>
<td>&gt; 1400</td>
<td>&gt; 0.14</td>
</tr>
<tr>
<td>Rpv3LSS1b</td>
<td>≥ 3 ($\ell^+\ell^+\ell^-$)</td>
<td>≥ 1</td>
<td>no cut but veto 81 GeV $&lt;$ $m_{\ell^+\ell^-} &lt;$ 101 GeV</td>
<td>-</td>
<td>-</td>
<td>&gt; 0.14</td>
</tr>
</tbody>
</table>

8/14/19

DM@LHC 2019

10
Interpretations

**ATLAS-CONF-2019-015**

**CMS-SUS-19-008**

\[ m_{\tilde{\chi}_1^\pm} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_0^0}) \]

\[ \tilde{g} \tilde{g} \text{ production, } \tilde{g} \rightarrow q\bar{q}'WZ_1^0; \quad m(\tilde{g}) = (m(\tilde{q})) + m(\tilde{W})/2, \quad m(\tilde{q}) = (m(\tilde{W}) + m(\tilde{q}))/2 \]

**ATLAS Preliminary**

\[ s=13 \text{ TeV, 139 fb}^{-1} \]

All limits at 95% CL

**Expected Limit (± 1 \sigma_{\exp})**

**Observed Limit (± 1 \sigma_{\text{SUSY}})**

**SS/3L obs. 36 fb}^{-1} [arXiv:1706.03731]**

**CMS Preliminary**

137 fb}^{-1} (13 TeV)

pp → \tilde{g}\tilde{g}, \tilde{g} → q\bar{q}'V\tilde{\chi}_1^0

NNLO+NNLL exclusion

95% CL upper limit on cross section (pb)

\[ m_{\tilde{\chi}_1^0} \text{ vs. } m_{\tilde{g}} \text{ (GeV)} \]

\[ m_{\tilde{\chi}_1^0} \text{ vs. } m_{\tilde{g}} \text{ (GeV)} \]

\[ m_{\tilde{g}} \text{ vs. } m_{\tilde{\chi}_1^0} \text{ (GeV)} \]
Bottom Squark

- Inclusive searches in all hadronic final state, binned in $H_T$, $N_j$, $N_b$, $M_{T2}$
- Extend reach by $\sim 100$GeV on sbottom mass compared to 36fb$^{-1}$ result

**CMS Preliminary** 137 fb$^{-1}$ (13 TeV)

$pp \rightarrow \tilde{b}_1 \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$ Approx. NNLO+NNLL exclusion

| Expected $\pm 1$, 2 $\sigma$ | Observed $\pm 1 \sigma_{\text{theory}}$ |

**CMS-PAS-SUS-19-005**
Top Squark

Enriched final states for top squark searches

$\Delta m = m(\tilde{t}_1) - m(\tilde{\chi}^0_1)$

$m(\tilde{\chi}^0_1)$ [GeV]

$m(\tilde{t}_1) < m(\tilde{\chi}^0_1)$

$m(W)+m(b)$

$m(t)$

$m(\tilde{t}_1)$ [GeV]
Top Squark with $M_{T2}$

- Inclusive searches in all hadronic final state, binned in $H_T$, $N_J$, $N_b$, $M_{T2}$
- Extend reach by $\sim 130$ GeV on stop mass compared to $36 \text{fb}^{-1}$ result
- Blinded top corridor due to finite granularity of the fastsim MC samples
Stop Single Lepton

Classic single lepton stop search

Signal selection:
Binning in $H_T$, $H_T^{\text{miss}}$, #jets, #b-jets
  + resolved and boosted top-tagging

Main backgrounds:
• ttbar and single top with 1 lost lepton, predicted from dilepton control region in data
• $W$+jets, taken from 0b control region in data

CMS Preliminary 137 fb$^{-1}$ (13 TeV)

$pp \rightarrow \tilde{t} \tilde{\tau}, \tilde{t} \rightarrow t \tilde{\chi}_1^0$ Approx. NNLO+NNLL exclusion

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

95% CL upper limit on cross section [pb]
Compressed Stop

- stop decay via the 3-body mode,
- Dedicated recurrent neural network
Stop to Tau

- Stop search in decays to tau leptons

Signal selection:
- Binning in $H_T$, $P_T^{\text{miss}}$, MT2

Main backgrounds:
- ttbar with two genuine taus
- mis-identified taus
Search for stop decaying to Z-boson (decaying to a lepton pair)
Chargino/neutralino pair production assuming decays to W/Z/h bosons
Compressed ewkinos

Soft opposite sign dileptons, with ISR boost

**Higgsino scenario**

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

- **ATLAS Preliminary**
  \( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
  - \( ee/\mu\mu, m_t \) shape fit
  - All limits at 95% CL
  - \( pp \rightarrow Z^0 \tilde{\chi}_2^0 \tilde{\chi}_1^+ \rightarrow W^+ \tilde{\chi}_1^0 \)
  - \( m(\tilde{\chi}_1^0) = [m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)]/2 \)

**Wino scenario**

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

- **ATLAS Preliminary**
  \( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
  - \( ee/\mu\mu, m_t \) shape fit
  - All limits at 95% CL
  - \( pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \) (Wino)
  - \( \tilde{\chi}_2^0 \rightarrow Z^0 \tilde{\chi}_2^0 \rightarrow W^+ \tilde{\chi}_1^0 \)
  - \( m(\tilde{\chi}_2^0) \times m(\tilde{\chi}_1^0) > 0 \)
Summary

• Broad SUSY signal and decay modes leads to broad coverage of topologies from SUSY searches

• Robust performance of LHC during Run 2, ATLAS and CMS collected ~137/fb integrated luminosity

• Early searches with full Run 2 exclude gluino mass up to ~2.2TeV, sbottom and stop up to ~1.2TeV

• Many more to come. Stay tune

• SUSY searches with long live signatures will covered in the Long-lived particles session tomorrow afternoon

CMS Public SUSY Result: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS)

ATLAS SUSY Result: [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults)
BACKUP
Relic Density Model

- Motivated by naturalness arguments and provides a dark matter candidate with the right relic density.
- The lightest neutralinos and charginos are an admixture of bino and higgsino.
- Corresponding branching ratios vary mostly as a function of the stop left-right mixing, and the sum of the branching ratios is bound to unity.

**ATLAS Preliminary**

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

All limits at 95% CL

\[
\begin{align*}
\tilde{t}_1 &\rightarrow b \tilde{\chi}_1^{0}, t \tilde{\chi}_{1,2,3}^{0} \\
\tilde{b}_1 &\rightarrow t \tilde{\chi}_1^{0}, b \tilde{\chi}_{1,2,3}^{0} \\
\tilde{\chi}_1^{0} &\rightarrow W^+ \tilde{\chi}_{1,2}^{0} \\
\tilde{\chi}_3^{0} &\rightarrow W^+ \tilde{\chi}_1^{+}, Z/h^+ \tilde{\chi}_{1,2}^{0} \\
\tilde{\chi}_2^{0} &\rightarrow Z/h^+ \tilde{\chi}_1^{0}
\end{align*}
\]