Probing SUSY Dark Matter at the LHC

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OUTLINE

Supersymmetry dark matter (DM)
- Relic density & DM composition
- LHC search status

DM search using Stop decay
- Stop decay & DM composition
- Light slepton case
- Heavy slepton case

DM search using Vector Boson Fusing (VBF) processes
- VBF signature
- Search strategy
- Results

Conclusion
Supersymmetric Dark Matter

(a) Fermion ↔ Boson
(b) R parity conserving SUSY, lightest neutralino $\tilde{\chi}_1^0 \rightarrow$ cold dark matter candidate

After EW symmetry breaking,

$$\tilde{\chi}_1^0 \sim (\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u) \quad \tilde{\chi}_1^+ \sim (\tilde{W}^+, \tilde{H}_u^+) \quad \tilde{\chi}_1^- \sim (\tilde{W}^-, \tilde{H}_d^-)$$

(Planck, 2013)
DM thermal relic density

After EW symmetry breaking, $\tilde{\chi}_1^0 \sim (\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u)$, $\tilde{\chi}_1^+ \sim (\tilde{W}^+, \tilde{H}_u^+)$, $\tilde{\chi}_1^- \sim (\tilde{W}^-, \tilde{H}_d^-)$

### Composition

<table>
<thead>
<tr>
<th>Composition</th>
<th>To satisfy relic density</th>
<th>Generic case</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bino</td>
<td>20 - 100 GeV, depending on a slepton mass</td>
<td>small</td>
<td>large</td>
</tr>
<tr>
<td>Wino</td>
<td>$\sim 2.4$ TeV</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>Higgsino</td>
<td>$\sim 1$ TeV</td>
<td>large</td>
<td>small</td>
</tr>
</tbody>
</table>

Stop search: $\tilde{\chi}_1^0 \sim (\tilde{B}, \tilde{H})$

VBF DM search: $\tilde{\chi}_1^0 \sim \tilde{W}, \tilde{H}, (\tilde{B} + \tilde{H})$
LHC status of SUSY DM searches

Challenge: small production cross section of EW sector.

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DM search using Stop decay

Goal:
\[ \tilde{t} \] decay → dark matter sector
in a scenario:
\[ \tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H}) \]

Motivation:
\[ \tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H}) \]
Light \[ \tilde{t} \] → Correct relic density
Naturalness

Why Stop can be light?

Hierarchy Problem, naturalness

\[ \Delta m^2_H \sim |y_t|^2 \left[ -\Lambda_{\text{UV}}^2 + \frac{3}{2} m_t^2 \log \left( \frac{\Lambda_{\text{UV}}^2}{m_t^2} \right) + \Lambda_{\text{EW}}^2 \right] \]

- In SM enormous corrections to \( m_h \): \( \Delta m^2 \propto \Lambda_{\text{UV}}^2 \) from top quark.
- In SUSY Stop loop cancels \( \Lambda_{\text{UV}}^2 \) term, and give a finite correction.
- Light stops (~TeV) needed for “natural” (not fine-tuned) solution to hierarchy problem.
Stop mixing

Tree level contribution

\[ m_h^2 \sim m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left( \frac{\bar{X}_t}{2} + \log \frac{M^2_{\text{Susy}}}{m_t^2} \right) \]

Stop loop contributions

Valid in the approximation \( m_{\tilde{q}_3} \sim m_{\tilde{u}_3} \)

They have to lift the mass of the Higgs by \( \sim 35 \text{ GeV}! \)

- Obtain mass matrix eigenstates \( \tilde{t}_1 \) and \( \tilde{t}_2 \)

\[
\begin{pmatrix}
\tilde{t}_1 \\
\tilde{t}_2
\end{pmatrix} = U_t
\begin{pmatrix}
\tilde{t}_L \\
\tilde{t}_R
\end{pmatrix} =
\begin{pmatrix}
\cos \theta_t & \sin \theta_t e^{-i\phi_t} \\
-\sin \theta_t e^{i\phi_t} & \cos \theta_t
\end{pmatrix}
\begin{pmatrix}
\tilde{t}_L \\
\tilde{t}_R
\end{pmatrix}
\]

- For \( m_h \approx 125 \text{ GeV} \) requires:
  - Small mixing \( \rightarrow \) both stops in the multi-TeV scale
  - OR
  - Large mixing \( \rightarrow \) two stops close in mass, in the several hundred GeV scale.
  - \( \rightarrow \) very large splitting between the two stops: one is very light (100-200 GeV)

\[ \bar{X}_t = \frac{2X_t^2}{M^2_{\text{Susy}}} \left( 1 - \frac{X_t^2}{12M^2_{\text{Susy}}} \right) \]

\[ X_t = A_t - \frac{\mu}{\tan \beta} \]

\[ M^2_{\text{stop}} = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L & m_t X_t \\
m_t X_t & m_{\tilde{u}_3}^2 + m_t^2 + D_R \end{pmatrix} \]
Stop decay

Stop decay $\leftrightarrow$ Stop mixing & neutralino/chargino composition

<table>
<thead>
<tr>
<th>LSP</th>
<th>Allowed stop decays</th>
<th>Why</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}^0_1 = \tilde{B}_3$</td>
<td>$\tilde{t}_L \rightarrow t_L \tilde{\chi}^0_1$, $\tilde{t}_R \rightarrow t_R \tilde{\chi}^0_1$</td>
<td>U(1) couples L to L and R to R</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1 = \tilde{W}_3$</td>
<td>$\tilde{t}_L \rightarrow t_L \tilde{\chi}^0_1$</td>
<td>SU(2) only acts on L</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1 = \tilde{H}^0_d$</td>
<td>none</td>
<td>Only couples to down-type</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1 = \tilde{H}^0_u$</td>
<td>$\tilde{t}_L \rightarrow t_R \tilde{\chi}^0_1$, $\tilde{t}_R \rightarrow t_L \tilde{\chi}^0_1$</td>
<td>Higgs couple L to R (mass term)</td>
</tr>
</tbody>
</table>

(From Claudio Campagnari’s talk)

**Composition of $\tilde{\chi}^0_1$ in our light slepton case**

- 28% Higgsino
- 72% Bino

**Classic scenario** $\tilde{\chi}^0_1 \sim \tilde{B}$, $\tilde{\chi}^0_2 \sim \tilde{W}$; $\tilde{t}_L \sim \tilde{t}_R$

$\tilde{t}_1 \rightarrow \tilde{\chi}^0_1 + t$ (100%)

**Our scenario** $\tilde{\chi}^0_1 \sim (\tilde{B} + \tilde{H})$, $\tilde{\chi}^0_{2,3} \sim \tilde{H}$; $\tilde{t}_L \sim \tilde{t}_R$

$\tilde{t}_1 \rightarrow \tilde{\chi}^0_{3,2} + t$ (39%); $\tilde{\chi}^0_{3,2} \rightarrow \tilde{\chi}^0_1 + l^+ + l^-$ (via $\tilde{t}$ or $Z$)
Light slepton case

\[ \tilde{\chi}_{2,3}^0 \sim \tilde{H} \text{ almost degenerate.} \]

\[ \bar{t} \rightarrow \tilde{\chi}_{3,2}^0 + t \text{ (39\%)} \]

\[ \tilde{\chi}_{3,2}^0 \rightarrow \tilde{\chi}_1^0 + l^+ + l^\mp \text{ (100\%, via } \tilde{e}^\pm \text{ or } \tilde{\mu}^\pm) \]

\[ M_{\text{edge}}^\text{edge} \sim \Delta M = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \]
Dilepton mass distribution

Final State:
2 l + 2 j + 1 b + large MET
MET > 150 GeV
H_T > 100 GeV

30 fb^{-1} luminosity, 8 TeV

Dominant SM BG: \( \bar{t}t + \text{jets} \)

BG data simulation:
MadGraph + PYTHIA + PGS4

Signal data simulation:
ISAJET + PYTHIA + PGS4

OSSF \( (e^\pm e^\mp + \mu^\pm \mu^\mp) \)
\( \bar{t}t^* \) and \( \bar{t}t + (0-4) \) jets

OSDF \( (e^\pm \mu^\mp + \mu^\pm e^\mp) \)
\( \bar{t}t^* \) and \( \bar{t}t + (0-4) \) jets

OSSF – OSDF

\[ \Delta M = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 63 \text{ GeV} \]
Dilepton mass distribution

The edge shifts with \( \Delta M = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \)

30 fb\(^{-1}\) luminosity, 8 TeV

\( \tilde{\chi}^0_{3,2} \rightarrow \tilde{\chi}^0_1 + l^\pm + l^{\mp} \) (100\%, via \( \tilde{e}^\pm \) or \( \tilde{\mu}^\pm \))
Significance

30 fb⁻¹ luminosity, 8 TeV

\[ s = \frac{N_S}{\sqrt{N_S + N_B}} \]

<table>
<thead>
<tr>
<th>( m_\tilde{t} ) (GeV)</th>
<th>Signal, ( N_S )</th>
<th>Background, ( N_B )</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>390</td>
<td>212</td>
<td>1392</td>
<td>5.3</td>
</tr>
<tr>
<td>440</td>
<td>180</td>
<td>1368</td>
<td>4.6</td>
</tr>
<tr>
<td>500</td>
<td>117</td>
<td>1354</td>
<td>3.1</td>
</tr>
<tr>
<td>550</td>
<td>78</td>
<td>1348</td>
<td>2.1</td>
</tr>
<tr>
<td>600</td>
<td>51</td>
<td>1345</td>
<td>1.4</td>
</tr>
</tbody>
</table>

\( \Delta M = 63 \)

\( 20 \text{ GeV} < M_{ll} < 70 \text{ GeV} \)

distinguishable edge, for \( m_\tilde{t} \leq 550 \text{ GeV} \).

significance \( \sim 3\sigma \), for \( m_\tilde{t} = 500 \text{ GeV} \).
Heavy slepton case

\[ \tilde{q}, \tilde{g} \rightarrow t \rightarrow \tilde{\chi}_{3,2}^0 + t (31\%) \]
\[ \tilde{\chi}_{3,2}^0 \rightarrow \tilde{\chi}_1^0 + l^\pm + l^\mp (7\%, \text{via Z boson}) \]

30 fb\(^{-1}\) luminosity, 8 TeV

\[ s = \frac{N_S}{\sqrt{N_S + N_B}} \]

20 GeV < \(M_{ll}\) < 70 GeV

<table>
<thead>
<tr>
<th>(m_{\tilde{t}}) (GeV)</th>
<th>Signal (N_S)</th>
<th>Background (N_B)</th>
<th>significance (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>393</td>
<td>22</td>
<td>395</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Small value of \(Z \rightarrow ll\) branch ratio causes smaller significance.
**(\(\tilde{B} + \tilde{H}\)) Dark Matter**

\[
\begin{align*}
\tilde{m}_{\tilde{\chi}_1^0} &= 113 \text{ GeV} \\
\Delta M &= m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Masses</th>
<th>(\tilde{B})</th>
<th>(\tilde{H})</th>
<th>(\Omega h^2)</th>
<th>s</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(GeV)</td>
<td>(%)</td>
<td>(%)</td>
<td>(30 fb(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta M=160)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mainly Bino DM</td>
</tr>
<tr>
<td>(m_l=123)</td>
<td>96</td>
<td>4</td>
<td>0.11</td>
<td>0.44</td>
<td>(Coannihilation)</td>
</tr>
<tr>
<td>(m_l=500)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta M=63)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bino-Higgsino DM</td>
</tr>
<tr>
<td>(m_l=144)</td>
<td>72</td>
<td>28</td>
<td>0.11</td>
<td>3.1</td>
<td>(Light slepton scenario)</td>
</tr>
<tr>
<td>(m_l=500)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta M=62)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bino-Higgsino DM</td>
</tr>
<tr>
<td>(m_l=4000)</td>
<td>67</td>
<td>33</td>
<td>0.11</td>
<td>1.1</td>
<td>(Heavy slepton scenario)</td>
</tr>
<tr>
<td>(m_l=390)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) \(\tilde{\chi}_1^0 \sim \tilde{B}\), need \(\tilde{\chi}_1^0 - \tilde{l}\) coannihilation. a low \(p_T\) lepton \(\rightarrow\) small significance.

(b) \(\tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H})\) and light \(\tilde{l}\), \(\rightarrow\) edge around \(\Delta M\).

(c) \(\tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H})\) and heavy \(\tilde{l}\), \(Z \rightarrow ll\) \(\rightarrow\) small significance.
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VBF DM search

Cross section \( \sim \frac{m}{\tilde{\chi}_1^0} \) & composition of \( \tilde{\chi}_1^0 \) and \( \tilde{\chi}_1^\pm \).

Depending on whether \( \tilde{\chi}_1^0 \) is Bino, Wino, Higgsino (and \( \tilde{\chi}_1^\pm \) Wino/Higgsino), or mixture, it will enhance/suppress these diagrams to dominate the cross-section.

For example, \( \tilde{\chi}_1^0 = \text{Wino}, \tilde{\chi}_1^\pm = \text{Wino} \rightarrow WW \) diagrams dominate

W luminosity is largest \( \rightarrow \) expect Wino + Wino case to give us largest x-section
VBF signature

Advantages of VBF DM search:
(a) VBF tagging jets
(b) Broad enhancements in MET
(c) Compressed scenarios
(d) Free from trigger bias
(e) Direct probing EW sector, complementary
   ← agnostic about colored sector

VBF tagged jets (2 energetic jets: large $m_{jj}$, forward region, opposite hemispheres)

VBF DM production topology
Transverse plane
Search strategy

\[ pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj, \ 2j + E_T \]

BG:
1. \( Zjj \rightarrow \nu \nu jj \): irreducible, mimic topology
2. \( Wjj \rightarrow l \nu jj \): veto leptons
3. \( t \bar{t} + jets \): veto b jet, leptons, veto central jets

Pre-selection:
(a) MET > 50 GeV
(b) \( p_T (j_1, j_2) > 30 \) GeV
(c) \( |\Delta \eta(j_1, j_2)| < 4.2, \ \eta_1 \eta_2 < 0 \)

Final selection:
(d) \( p_T (j_1, j_2) > 50 \) GeV
(e) \( m(j_1, j_2) > 1500 \) GeV
(f) veto leptons (e, mu, tau)
(g) veto b jets (70% efficiency, 1.5% fake rate)
(h) veto central jet with \( p_T > 50 \) GeV
(i) MET > 200 GeV (450 GeV) for \( m_{\tilde{\chi}_1^0} = 100 \) GeV (1 TeV)

Data simulation: MadGraph + PYTHIA + PGS4
VBF production cross section

\[ \tilde{\chi}_1^0 \sim \tilde{W} \text{ or } \tilde{H} : \text{pp} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj, \tilde{\chi}_1^- \tilde{\chi}_1^+ jj, \tilde{\chi}_1^+ \tilde{\chi}_1^- jj, \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj \text{ (inclusive), since } m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_1^0} \]

\[ \tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H}) : \text{pp} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj \]

After \( |\Delta \eta(j_1, j_2)| > 4.2 \)
Invariant mass distribution of VBF tagged jets

After pre-selection cuts & $p_T(j_1, 2) > 50$ GeV
MET distribution

After all selection cuts, except $E_T$ cut.
Significance curve

\[ \frac{S}{\sqrt{S+B}} \]

- 99% Wino, 1000 fb^{-1}, 14 TeV
- 99% Wino, 500 fb^{-1}, 14 TeV
- 99% Wino, 100 fb^{-1}, 14 TeV

\[ m(\tilde{\chi}_1^0) \text{ [GeV]} \]
DM mass & relic density

VBF cross section, MET shape → neutralino1 mass, composition → DM relic density

benchmark: $m_{\tilde{\chi}_1} = 100 \text{ GeV}$
Conclusion

DM using $\tilde{t}$ decay: $(\tilde{B} + \tilde{H})$
- $2l$ (OSSF) + $2j + 1b + \not{E}_T$
- Two Cases:
  - Light $\tilde{t}$: Sensitivity up to 600 GeV $\tilde{t}$ @ 30 fb$^{-1}$, 8 TeV.
  - Heavy $\tilde{t}$: Small significance.
- Relic density

DM using VBF: $\tilde{W}, \tilde{H}, (\tilde{B} + \tilde{H})$
- $2j + \not{E}_T$
- Signature
  - VBF tagging jets (large $m_{jj}$, big rapidity gap)
  - Broad enhancements in MET
- Expected reach
  - For $\tilde{W}$, 600 GeV 5$\sigma$ reach @ 1000 fb$^{-1}$, 14 TeV.
  - Relic density uncertainty: 20% (40%) for 100 GeV $\tilde{W}$ ($\tilde{H}$) @ 500 fb$^{-1}$, 14 TeV.

Further work:
- $\tilde{t}$ decay @14 TeV
  - Heavier stop: small cross section, threshold (jet, lepton), pile up $\leftrightarrow$ large luminosity
  - $\rightarrow$ neutralino mass and composition $\rightarrow$ DM relic density
- VBF DM
  - Optimization, other kinematic distributions $\rightarrow$ best significance
Backup Slide

Status of Stop searches

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\[ \widetilde{t} \rightarrow c \ell^+ / \ell^- \rightarrow W b \tilde{\chi}^0_1 \]