The Supersymmetric Electroweak Sector via Vector Boson Fusion at the LHC

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PHENO 2013
Cascade decays of squarks and gluinos

Decay of top squarks

Hints from Higgs physics

Direct probes of the Electroweak sector
SUSY at LHC: Cascade decay probe
SUSY at LHC: Cascade decay probe

\[ \int L \, dt = 5.3 \text{ fb}^{-1}, \quad \sqrt{s} = 8 \text{ TeV} \]

0-lepton combined

- Observed limit (±1\sigma_{\text{SUSY}})
- Expected limit (±1\sigma_{\text{exp}})
- Observed limit (4.7 fb\(^{-1}\), 7 TeV)

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SUSY at LHC: Top Squark Decay

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Electroweak Sector

Can you probe Sleptons, Staus, Charginos, Neutralinos directly?

Is the neutralino a Bino, Wino or Higgsino?

Connection to Dark Matter Physics

Annihilation cross-section mainly depends on colorless particles sleptons, staus, charginos, neutralinos, etc.

Annihilation cross-section of Dark Matter particles generates dark matter content of the universe

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Direct probes of charginos, neutralinos and sleptons

Two high ET forward jets in opposite hemispheres with large dijet invariant mass

VBF studies

1. $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm jj, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp jj, \tilde{\chi}_1^\pm \tilde{\chi}_2^0 jj, \tilde{\chi}_2^0 \tilde{\chi}_2^0 jj$

2. $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj$

3. $pp \rightarrow \tilde{e} \tilde{e} jj, \tilde{\mu} \tilde{\mu} jj, \tilde{\tau} \tilde{\tau} jj, \tilde{\mu} \tilde{\nu} jj, \tilde{\tau} \tilde{\nu} jj$
1. Charginos, Neutralinos via VBF

Vector Boson Fusion Processes as a Probe of Supersymmetric Electroweak Sectors at the LHC

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Vector boson fusion (VBF) processes offer a promising avenue to study the non-colored sectors of supersymmetric extensions of the Standard Model at the LHC. A feasibility study for searching for the chargino/neutralino system in the $R-$parity conserving Minimal Supersymmetric Standard Model is presented. The high $E_T$ forward jets in opposite hemispheres are utilized to trigger VBF events, so that the production of the lightest chargino $\tilde{\chi}_1^\pm$ and the second lightest neutralino $\tilde{\chi}_2^0$ can be probed without a bias by experimental triggers. Kinematic requirements are developed to search for signals of these supersymmetric states above Standard Model backgrounds in both $\tau$ and light lepton ($e$ and $\mu$) final states at $\sqrt{s} = 8$ TeV.

1. **Charginos, Neutralinos via VBF**

1. \( pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm jj, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp jj, \tilde{\chi}_1^\pm \tilde{\chi}_2^0 jj, \tilde{\chi}_2^0 \tilde{\chi}_2^0 jj \)

For: \( m_{\chi_1^\pm}, m_{\chi_2^0} > m_{\tilde{\nu}} > m_{\chi_1^0} \)

Signal: \( \geq 2 j + 2\tau + \text{missing energy} \), \( \geq 2 j + 2\mu + \text{missing energy} \)

For Heavy Sleptons:

Signal: \( 2 j + W W, WZ, ZZ + \text{missing energy} \)

**Background:** \( W^{+} \text{ jets}, Z^{+} \text{ jets}, WW, ZZ, t\bar{t} \text{ etc.} \)
1. Charginos, Neutralinos via VBF

**Backgrounds**

- **Z(νν)+jets**, irreducible background (Data-Driven).

- **W+jets**, when e, μ can’t be identified. (Data-Driven)
  - **W+jets**, $\tau_{\text{hadronic}}$ (MC)

- **QCD** (Data-Driven)
  - TTbar, Single-t, Dibosons (MC)
1. Charginos, Neutralinos via VBF

2 jets with $p_T(j) > 50$ GeV; $p_T(j_1) > 75$ GeV

$|\Delta\eta| > 4.2; \eta_1 \cdot \eta_2 < 0$

$M(j_1, j_2) > 650$ GeV; MET $> 75$ GeV

2 Benchmark Scenarios

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VBF Kinematics

\[ M(j_1, j_2) \]

\[ E_T \]

\[ M(\tilde{\chi}_1^+) \sim M(\tilde{\chi}_2^0) = 180 \text{ GeV} \]

\[ M(\tilde{\chi}_1^0) = 90 \text{ GeV} \]

\[ M(\tilde{\tau}_1^+) - M(\tilde{\chi}_1^0) = 30 \text{ GeV} \]

Large MET, large \( M(jj) \), large \( p_T \) jets


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Signal: \( \geq 2j + 2\tau + \text{missing energy} \)

2 jets each with pT>50 GeV, leading pT>75 GeV
\(|\Delta\eta(j_1, j_2)| > 4.2, \ \eta j_1 \eta j_2 < 0, M_{j1j2} > 650 \ \text{GeV}\)

\[ m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 180 \text{GeV}, \]

\( \sqrt{s} = 8 \ \text{TeV} \)

Lum: 25 fb-1

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Z+jets</th>
<th>W+jets</th>
<th>WW</th>
<th>WZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF cuts</td>
<td>4.61</td>
<td>10.9</td>
<td>3.70 \times 10^3</td>
<td>97.0</td>
<td>19.0</td>
</tr>
<tr>
<td>( E_T &gt; 75, b)-veto</td>
<td>4.33</td>
<td>0.27</td>
<td>5.29 \times 10^2</td>
<td>17.6</td>
<td>3.45</td>
</tr>
<tr>
<td>2( \tau ), inclusive</td>
<td>0.45</td>
<td>0.06</td>
<td>0.23</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>( (S/\sqrt{S+B}) )</td>
<td>0.21</td>
<td>0</td>
<td>0.11</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>( \tau^\pm \tau^\pm )</td>
<td>2.4</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>( (S/\sqrt{S+B}) )</td>
<td>0.24</td>
<td>0.06</td>
<td>0.12</td>
<td>0.07</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Two \( \tau \)'s with pT>20 GeV in \( \eta < 2.1 \), with \( \Delta R(\tau\tau) > 0.3 \). All \( \tau \)'s are hadronic The \( \tau \) ID efficiency is assumed to be 55% and the jet \( \tau \) Mis-identification rate is taken to be 1%,
Signal: $\geq 2j + 2\tau + \text{missing energy}$
Signal: $\geq 2j+2\mu+\text{missing energy}$

2 jets each with $p_T>50$ GeV, leading $p_T>75$ GeV
$|\Delta\eta(j1,j2)|>4.2$, $\eta_{j1}\eta_{j2}<0$, $M_{j1j2}>650$ GeV

$\sqrt{s} = 8$ TeV
Lum: 25 fb-1

<table>
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<tr>
<th></th>
<th>Signal</th>
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<td>0.27</td>
<td>$5.29 \times 10^2$</td>
<td>17.6</td>
<td>3.45</td>
</tr>
<tr>
<td>2 $\mu$, inclusive</td>
<td>1.83</td>
<td>0.15</td>
<td>0</td>
<td>0.12</td>
<td>0.19</td>
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<tr>
<td>$(S/\sqrt{S+B})$</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>$\mu^+\mu^+$</td>
<td>0.87</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
<td>0.05</td>
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<tr>
<td>$(S/\sqrt{S+B})$</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^+$</td>
<td>0.96</td>
<td>0.15</td>
<td>0</td>
<td>0.09</td>
<td>0.14</td>
</tr>
<tr>
<td>$(S/\sqrt{S+B})$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Two isolated $\mu$'s with $p_T>20$ GeV in $\eta<2.1$

For $3\sigma$: $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 330$ GeV

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Signal: $\geq 2j + 2\mu + \text{missing energy}$

$\sqrt{s} = 8\text{ TeV}, L_{\text{int}} = 25\text{ fb}^{-1}$

- $p p \rightarrow \tilde{\chi} \tilde{\chi} jj \rightarrow \mu \mu jj$
- $p p \rightarrow V + \text{jets}$
- $p p \rightarrow VV jj$

Events / 200 GeV

$M(j_1, j_2) [\text{GeV}]$
Probing Dark Matter at the LHC using Vector Boson Fusion Processes

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\textsuperscript{2} Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235, USA
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Vector boson fusion (VBF) processes at the Large Hadron Collider (LHC) provide a unique opportunity to search for new physics with electroweak couplings. A feasibility study for the search of supersymmetric dark matter in the final state of two VBF jets and large missing transverse energy is presented at 14 TeV. Prospects for determining the dark matter relic density are studied for the cases of Wino and Bino-Higgsino dark matter. The LHC could probe Wino dark matter with mass up to approximately 600 GeV with a luminosity of 1000 fb\textsuperscript{-1}.

2. Lightest neutralinos via VBF

\[ pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ jj \]
2. Lightest neutralinos via VBF

\[ pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj \]

\[ |\Delta \eta| > 4.2 \]

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ \sqrt{s} = 14 \text{ TeV} \]

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Wino-DM

2j + MET

2 jets with $p_T(j) > 50$ GeV; $|\Delta\eta| > 4.2$; $\eta_1 \cdot \eta_2 < 0$

$M(j_1, j_2) > 1500$ GeV

Delannoy, Dutta, Gurrola, Johns, Kamon, Luiggi, Melo, Sheldon, Sinha, Wang, Wu
2 jets with $p_T(j) > 50$ GeV; $|\Delta\eta| > 4.2$; $\eta_1 \cdot \eta_2 < 0$

$M(j_1, j_2) > 1500$ GeV

(iii) Events with loosely identified leptons ($l = e, \mu, \tau_h$) and $b$-quark jets are rejected, reducing the $tt$ and $Wjj \rightarrow lvjj$ backgrounds by approximately $10^{-2}$ and $10^{-1}$, respectively, while achieving 99% efficiency for signal events. The $b$-jet tagging efficiency used in this study is 70% with a misidentification probability of 1.5%, following Ref. [22]. Events with a third jet (with $p_T > 50$ GeV) residing between $\eta_{j_1}$ and $\eta_{j_2}$ are also rejected; (iii) The $E_T$ cut is optimized for each dif-
Wino-DM

2 jets with $p_T(j) > 50$ GeV; $|\Delta \eta| > 4.2$; $\eta_1 \cdot \eta_2 < 0$

$M(j_1, j_2) > 1500$ GeV

MET $> 200$ GeV (450 GeV) for $m_{\chi_1^0} = 100$ Gev (1 TeV)

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Wino-DM

O(600) GeV Wino at LHC14

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

S / \sqrt{S + B}

3\sigma  5\sigma

99% Wino, 500 fb^-1, 14 TeV
99% Wino, 100 fb^-1, 14 TeV
DM Mass, Composition, Relic Density

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Conclusion

- Vector Boson Fusion processes provide a direct window to the supersymmetric Electroweak sector

- *Agnostic* about the colored sector

- Complementary to SUSY searches from cascade decays

- Feasibility study shows we can probe Wino mass $\sim 600$ GeV at $5\sigma$ level with 1000 ifb of 14 TeV data

- Best-case scenario $\rightarrow$ need to study large PU environment

- Relic density can be determined up to $\sim 20\% (40\%)$ accuracy at 500 ifb for pure Wino (Higgsino) dark matter
• We are studying production of sleptons, spin of DM particle, bounds on charginos in heavy slepton scenarios, etc. for 14 TeV LHC

• A unique tool at the LHC to directly access the Electroweak sector and dark matter regardless of the fate of new colored physics with an experimentally plausible trigger
Backup
Wino-DM

Wino DM
2j + MET
**Tau-Tagging (at CMS)**

- Tau leptons decay to hadrons ~ 65% of the time
- Tau identification to hadronic decays:

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Resonance</th>
<th>Mass (MeV/c²)</th>
<th>Branching ratio(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow h^- \nu_\tau$</td>
<td>$\rho$</td>
<td>770</td>
<td>26.0 %</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- \pi^0 \nu_\tau$</td>
<td>$a1$</td>
<td>1200</td>
<td>10.8 %</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- h^- \nu_\tau$</td>
<td>$a1$</td>
<td>1200</td>
<td>9.8 %</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- h^- h^- \pi^0 \nu_\tau$</td>
<td></td>
<td></td>
<td>4.8 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>63.0 %</strong></td>
</tr>
<tr>
<td><strong>Other hadronic modes</strong></td>
<td></td>
<td></td>
<td><strong>1.7 %</strong></td>
</tr>
</tbody>
</table>

- Reconstruct decay modes using reconstructed PF particles

  - hadron
  - hadron+strip
  - 3 hadrons

- Cut based: mass of the mesons, rejection against $e/\mu$, and isolation
B-Tagging (at CMS)

- Properties used to identify b-jets
  - Hard fragmentation functions
  - Relatively large mass
  - Long lifetime
  - Semi-leptonic decays

b-Tagging Variables
- 2D and 3D impact parameters (closest approach to primary vertex)
- Flight distance
- Invariant mass of tracks at vertex
- Number of tracks at vertex (~ 5 for b)
- Likelihood variables based on these parameters
- ~70% eff. with light mistag rate ~ 2%
Sleptons via VBF

Figure 2: The total cross section (solid lines) for slepton pair-production at the LHC in association with two forward jets. The cuts of eqns. (1a–1c) have been imposed on the VBF rates. The CTEQ4L parton distributions have been used with the factorization scale set at $m_{\tilde{t}}$. The dashed curves represent the corresponding DY cross section in each case, the upper and lower curves correspond to $\tilde{\ell}_L$ and $\tilde{\ell}_R$ (one flavour) respectively.

slepton mixing\(^2\). Thus the production cross-section is essentially model-independent and is determined solely by the slepton mass $m_{\tilde{t}}$. In Fig. 2, we display this functional dependence. The lowest order DY cross-section (without any cuts) is also shown for an approximate comparison of the relative magnitude. A few points are immediately obvious.

- Formally, our cross-section is suppressed by two powers of $\alpha_{em}(\alpha_{\text{weak}})$ when compared to the DY one. This is reflected in the dominance of the DY rates for small slepton masses.

- The cross-section fall-off with mass is much slower for the VBF process, as compared to the DY mode, as intimated. This can be understood by recognising that the DY cross-section suffers from the presence of an $s$-channel propagator. In contrast, the VBF process could be viewed in terms of an effective $\gamma/Z/W$ approximation, wherein the large logarithms associated with the emission of a “nearly massless” gauge boson compensate for the extra factors of $\alpha_{em}(\alpha_{\text{weak}})$.

\(^2\)However, as we shall see later, $\mu$ plays a significant role in slepton decays and affects then the signal as a whole.