Probing SUSY Dark Matter with Vector Boson Fusion at the LHC

Alfredo Gurrola (Vanderbilt University)
The identity of dark matter is one of the most profound questions at the interface of particle physics and cosmology.
It is important to “directly” probe the EWK SUSY sector in order to determine their DM connection.
Current Dark Matter Searches

- Cascade decay of heavier particles to the DM particle
  - Signature: Large MET + jets (+ leptons) (+ photons)

- DM particles directly produced in pairs after ISR
  - Signature: Large MET + mono-jet (mono-Z, etc.)
Determining the mass and content of the LSP requires model dependent correlations between colored and non-colored sector (e.g. grand unification in mSUGRA)

### ATLAS and CMS pushing limits on 1st / 2nd squarks and gluinos to ~ 1.5 TeV

**CMS preliminary**

<table>
<thead>
<tr>
<th></th>
<th>m(LSP) = 200 GeV</th>
<th>m(LSP) = 0 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1: $\tilde{g} \rightarrow \tilde{\chi}_1^0$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T1bbbe: $\tilde{g} \rightarrow \tilde{\chi}_1^0 t \bar{t}$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T1s: $\tilde{g} \rightarrow \tilde{\chi}_1^0 s \bar{t}$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T2: $\tilde{g} \rightarrow \tilde{\tau}$</td>
<td>squark</td>
<td></td>
</tr>
<tr>
<td>T2bb: $\tilde{g} \rightarrow \tilde{\tau} b \bar{b}$</td>
<td>sbottom</td>
<td></td>
</tr>
<tr>
<td>T2tt: $\tilde{g} \rightarrow \tilde{\tau} t \bar{t}$</td>
<td>stop</td>
<td></td>
</tr>
<tr>
<td>T3: $\tilde{g} \rightarrow \tilde{\chi}_2^0 \tilde{\tau}$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T3ww: $\tilde{g} \rightarrow \tilde{\chi}_2^0 W^+ W^-$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T3ln: $\tilde{g} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T3zn: $\tilde{g} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>TChSlept: $\tilde{g} \rightarrow \tilde{\chi}_2^0 \tilde{\mu}^\pm \tilde{\mu}^\mp$</td>
<td>neutralino/chargino</td>
<td></td>
</tr>
<tr>
<td>TChw: $\tilde{g} \rightarrow \tilde{\chi}_2^0 \tilde{\tau} \bar{\tau}$</td>
<td>neutralino/chargino</td>
<td></td>
</tr>
</tbody>
</table>

**T2tt:** stop $\rightarrow t + \tilde{\chi}_1^0$
What do we know so far?

Key points: No SUSY yet & 126 GeV Higgs

M(mother) - m(LSP) = 200 GeV | m(LSP) = 0 GeV

CMS preliminary

- $\tilde{g} \rightarrow g\tilde{g}$
- $\tilde{g} \rightarrow M_{Z^0}$
- $\tilde{g} \rightarrow M_{Z^0}$
- $\tilde{g} \rightarrow M_{Z^0}$
- $\tilde{t}_2 \rightarrow t\chi^0_1$
- $\tilde{b}_1 \rightarrow b\chi^0_1$
- $\tilde{t}_2 \rightarrow t\chi^0_1$
- $\tilde{t}_3 \rightarrow q\chi^0_1$
- $\tilde{t}_3 \rightarrow q\chi^0_1$
- $\tilde{t}_4 \rightarrow t\chi^0_1$
- $\tilde{t}_4 \rightarrow t\chi^0_1$
- $\tilde{t}_5 \rightarrow t\chi^0_1$
- $\tilde{t}_5 \rightarrow t\chi^0_1$
- $\tilde{t}_6 \rightarrow t\chi^0_1$
- $\tilde{t}_6 \rightarrow t\chi^0_1$
- $\tilde{t}_7 \rightarrow t\chi^0_1$
- $\tilde{t}_7 \rightarrow t\chi^0_1$
- $\tilde{t}_8 \rightarrow t\chi^0_1$
- $\tilde{t}_8 \rightarrow t\chi^0_1$

$\tilde{g} \rightarrow g\tilde{g}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{t}_2 \rightarrow t\chi^0_1$
$\tilde{b}_1 \rightarrow b\chi^0_1$
$\tilde{t}_2 \rightarrow t\chi^0_1$
$\tilde{t}_3 \rightarrow q\chi^0_1$
$\tilde{t}_3 \rightarrow q\chi^0_1$
$\tilde{t}_4 \rightarrow t\chi^0_1$
$\tilde{t}_4 \rightarrow t\chi^0_1$
$\tilde{t}_5 \rightarrow t\chi^0_1$
$\tilde{t}_5 \rightarrow t\chi^0_1$
$\tilde{t}_6 \rightarrow t\chi^0_1$
$\tilde{t}_6 \rightarrow t\chi^0_1$
$\tilde{t}_7 \rightarrow t\chi^0_1$
$\tilde{t}_7 \rightarrow t\chi^0_1$
$\tilde{t}_8 \rightarrow t\chi^0_1$
$\tilde{t}_8 \rightarrow t\chi^0_1$

$\tilde{g} \rightarrow g\tilde{g}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{t}_2 \rightarrow t\chi^0_1$
$\tilde{b}_1 \rightarrow b\chi^0_1$
$\tilde{t}_2 \rightarrow t\chi^0_1$
$\tilde{t}_3 \rightarrow q\chi^0_1$
$\tilde{t}_3 \rightarrow q\chi^0_1$
$\tilde{t}_4 \rightarrow t\chi^0_1$
$\tilde{t}_4 \rightarrow t\chi^0_1$
$\tilde{t}_5 \rightarrow t\chi^0_1$
$\tilde{t}_5 \rightarrow t\chi^0_1$
$\tilde{t}_6 \rightarrow t\chi^0_1$
$\tilde{t}_6 \rightarrow t\chi^0_1$
$\tilde{t}_7 \rightarrow t\chi^0_1$
$\tilde{t}_7 \rightarrow t\chi^0_1$
$\tilde{t}_8 \rightarrow t\chi^0_1$
$\tilde{t}_8 \rightarrow t\chi^0_1$

$\tilde{g} \rightarrow g\tilde{g}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{t}_2 \rightarrow t\chi^0_1$
$\tilde{b}_1 \rightarrow b\chi^0_1$
$\tilde{t}_2 \rightarrow t\chi^0_1$
$\tilde{t}_3 \rightarrow q\chi^0_1$
$\tilde{t}_3 \rightarrow q\chi^0_1$
$\tilde{t}_4 \rightarrow t\chi^0_1$
$\tilde{t}_4 \rightarrow t\chi^0_1$
$\tilde{t}_5 \rightarrow t\chi^0_1$
$\tilde{t}_5 \rightarrow t\chi^0_1$
$\tilde{t}_6 \rightarrow t\chi^0_1$
$\tilde{t}_6 \rightarrow t\chi^0_1$
$\tilde{t}_7 \rightarrow t\chi^0_1$
$\tilde{t}_7 \rightarrow t\chi^0_1$
$\tilde{t}_8 \rightarrow t\chi^0_1$
$\tilde{t}_8 \rightarrow t\chi^0_1$

$\tilde{g} \rightarrow g\tilde{g}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{g} \rightarrow M_{Z^0}$
$\tilde{t}_2 \rightarrow t\chi^0_1$
$\tilde{b}_1 \rightarrow b\chi^0_1$
$\tilde{t}_2 \rightarrow t\chi^0_1$
$\tilde{t}_3 \rightarrow q\chi^0_1$
$\tilde{t}_3 \rightarrow q\chi^0_1$
$\tilde{t}_4 \rightarrow t\chi^0_1$
$\tilde{t}_4 \rightarrow t\chi^0_1$
$\tilde{t}_5 \rightarrow t\chi^0_1$
$\tilde{t}_5 \rightarrow t\chi^0_1$
$\tilde{t}_6 \rightarrow t\chi^0_1$
$\tilde{t}_6 \rightarrow t\chi^0_1$
$\tilde{t}_7 \rightarrow t\chi^0_1$
$\tilde{t}_7 \rightarrow t\chi^0_1$
$\tilde{t}_8 \rightarrow t\chi^0_1$
$\tilde{t}_8 \rightarrow t\chi^0_1$
What do we know so far?

“Nightmare compressed scenario” is starting to look like the actual scenario

Becoming EXPERIMENTALLY difficult to search for dark matter through cascade decays (e.g. how to trigger?)

From Michael Peskin’s talk (Craig et al arXiv: 1203.1622)
Probing DM with VBF

Cold dark matter candidate

Forward tagging jets

MET + jj
Probing Dark Matter at the LHC using Vector Boson Fusion Processes

Andres G. Delannoy\textsuperscript{2}, Bhaskar Dutta\textsuperscript{1}, Alfredo Gurrola\textsuperscript{2}, Will Johns\textsuperscript{2}, Teruki Kamon\textsuperscript{1,3}, Eduardo Luiggi\textsuperscript{4}, Andrew Melo\textsuperscript{2}, Paul Sheldon\textsuperscript{2}, Kuver Sinha\textsuperscript{1}, Kechen Wang\textsuperscript{1}, and Sean Wu\textsuperscript{1}

\textsuperscript{1} Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A\&M University, College Station, TX 77843-4242, USA
\textsuperscript{2} Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235, USA
\textsuperscript{3} Department of Physics, Kyungpook National University, Daegu 702-701, South Korea
\textsuperscript{4} Department of Physics, University of Colorado, Boulder, CO 80309-0390, USA

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}.

\url{http://arxiv.org/pdf/1304.7779v1.pdf}
1. Bino Dark Matter
   - $N_1 \sim \text{Bino and } C_1 \sim \text{Wino}$.

2. Wino Dark Matter
   - $N_1 \text{ and } C_1 \text{ are Wino } \Rightarrow M(N_1) \sim M(C_1)$

3. Higgsino Dark Matter
   - $N_1 \sim C_1 \sim \text{Higgsino } \Rightarrow M(N_1) \sim M(C_1)$

4. Bino-Higgsino Dark Matter
   - $N_1 \sim \text{Bino+Higgsino; } C_1 \sim \text{Higgsino}$
Depending on whether CDM is Bino, Wino, Higgsino (and C1 Wino/Higgsino), or mixture will enhance/suppress these diagrams to dominate the cross-section.

e.g. CDM=Wino, C1=Wino $\rightarrow$ WW diagrams dominate

W luminosity is largest $\rightarrow$ expect Wino+Wino case to give us largest x-section
Pure Wino/Higgsino dark matter scenarios are special

\[ \Delta M = M(\tilde{\chi}_1^\pm) - M(\tilde{\chi}_1^0) \sim 100 \text{ MeV} \]

\[ \Rightarrow Br(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm) \sim 100\% \]

\[ P_T(\pi^\pm) \sim \Delta M \sim 100 \text{ MeV} \]

\[ \Rightarrow \text{Final state once again } jj + \text{MET!} \]

\[ \tilde{\chi}_1^\pm \tilde{\chi}_1^0 jj, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp jj \text{ also contribute!} \]
Probing DM with VBF

\[ \sigma (\text{fb}) \]

- 100% Wino (inclusive)
- 100% Higgsino (inclusive)
- 20% Bino, 80% Higgsino
- 40% Bino, 60% Higgsino
- 60% Bino, 40% Higgsino
- 80% Bino, 20% Higgsino

\[ \text{pp} \rightarrow jj \tilde{\chi}_1^0 \tilde{\chi}_1^0, |\Delta \eta_{jj}| > 4.2 \]

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

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

MADGRAPH5
Backgrounds

Z\rightarrow \nu\nu + jets, irreducible background

Large MET from the neutrinos
Rely heavily on VBF to reduce this BG

W\rightarrow \mu \nu + jets, “lost” leptons

e,\mu,\tau fall outside detector acceptance
e,\mu,\tau fail identification criteria
Suppressed by l vetoes, VBF, and MET cuts

Top pair

Suppressed by l vetoes, central jet veto, VBF cuts, and MET cut
VBF DM Kinematics

MADGRAPH5 + PGS4

Snowmass Meeting

15
Forward tagging jets

- Two lead jets with $p_T > 50$, $|\eta| < 5$
- $|\Delta\eta(j,j)| > 4.2$ & $M(j,j) > 1500$
- Veto on leptons ($e, \mu, \tau$) & b-jets
- Central jet veto: no 3rd jet with $\eta_1 < \eta_3 < \eta_2$
- MET > X optimized for each mass

@ 1000 fb$^{-1}$, 5\sigma obtained up to a Wino mass of ~ 600

NOTE: represents “best” case scenario
Final performance to depend on the planned upgrades for ATLAS & CMS (e.g. large PU studies)
Determining the composition of the LSP for a given mass is very important to understand early universe cosmology.
Simultaneously fit the MET shape and observed rate in data to extract the mass and composition of the LSP

\[ \Omega_{LSP} h^2 = f[F\%, m(LSP)] \]

Mass and composition of the LSP used to determine the LSP relic density
Summary

- Vector boson fusion offers a powerful way to “directly” probe SUSY dark matter at the LHC
- **Compliments** current mono-X searches as well as “classic” SUSY searches
- Many advantages:
  - largely *agnostic about the colored sector*
  - Direct window to determination the composition of the LSP
  - Unique tool at the LHC to directly access DM and compressed spectra with an *experimentally plausible trigger*
- Feasibility study shows that we can *probe e.g. Wino masses up to ~ 600 GeV at the 5σ level with 1000 fb⁻¹ of 14 TeV data*
  - Represents “best” case scenario → e.g need to study large PU environment
- **Relic density can be determined to ~20% (40%) accuracy at 500 fb⁻¹** for the pure Wino (Higgsino) dark matter scenario
- Hope to use this study to push detector upgrade studies in the right direction