Searching for SUSY with Vector Boson Fusion

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
Colored objects heavy and the cross-section is small

\[ \sigma_{\text{tot}}[\text{pb}]: pp \rightarrow \text{SUSY} \]
\[ \sqrt{S} = 8 \text{ TeV} \]

Strong production

EWK production

\[ \tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^- \]

\[ \tilde{\chi}_1^0, \tilde{\chi}_1^- \]

\[ \tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^- \]

\[ \nu \]

\[ p_1, p_2 \]

Started to look at direct production of EWKinos & 3\textsuperscript{rd} generation
Classic SUSY DM Searches

No sensitivity in cases with 3rd gen and compressed spectra

VERY important for cosmology

Tackling these scenarios is a very tall task at the LHC
LSP has large Wino/Higgsino component
- LSP annihilation cross section is too large to fit observed DM relic density
- LSP is mostly Bino
- LSP annihilation cross section is too small to fit observed DM relic density

Some problems can be solved if the DM is non-thermal. For thermal DM, some problems can be solved by adding coannihilation, resonance effects, etc.

Determining the composition of the LSP for a given mass is very important to understand early universe cosmology
Classic SUSY DM Searches

No sensitivity in cases with 3rd gen and compressed spectra

VERY important for cosmology

Tackling these scenarios is a very tall task at the LHC

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

T1: $\tilde{g} \rightarrow q\tilde{q}^0$
T1bbbbb: $\tilde{g} \rightarrow M\tilde{q}^0$
T1tttt: $\tilde{g} \rightarrow t\tilde{q}^0$
T2: $\tilde{g} \rightarrow q\tilde{q}^0$
T2bb: $\tilde{t} \rightarrow \tilde{q}^0$
T2ttt: $\tilde{t} \rightarrow t\tilde{q}^0$
T3h: $\tilde{g} \rightarrow q\tilde{q}^0 \rightarrow t\tilde{t}^+\tilde{t}^-$
T3w: $\tilde{g} \rightarrow q\tilde{q}^0 \rightarrow W^+\tilde{t}^0$
T5l: $\tilde{g} \rightarrow q\tilde{q}^0 \rightarrow \nu\tilde{q}^0$
T5zz: $\tilde{g} \rightarrow q\tilde{q}^0 \rightarrow Z\tilde{t}^0$
TChis: $\tilde{g} \rightarrow q\tilde{q}^0 \rightarrow W^+\tilde{Z}^0$
TChiz: $\tilde{g} \rightarrow q\tilde{q}^0 \rightarrow W^+\tilde{Z}^0$

$\rightarrow$ T2tt: stop $\rightarrow t + \chi^0$

Events / 3 GeV

7 TeV, $\lesssim 4.98$ fb$^{-1}$
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 & EWK sector using "standard" searches (e.g. how to trigger?)
Monojet searches probing QCD production of WIMPs \(\rightarrow\) limits what one can say about its Wino, Bino, or Higgsino composition in the case of SUSY.
Probing SUSY DM with VBF

Cold dark matter candidate

Forward tagging jets

MET + jj
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 EWK SUSY with VBF

Cold dark matter candidate

Forward tagging jets

\( \phi \quad \text{MET} + jj + \text{leptons} \)
Vector Boson Fusion Processes as a Probe of Supersymmetric Electroweak Sectors at the LHC

Bhaskar Dutta¹, Alfredo Gurrola², Will Johns², Teruki Kamon¹,³, Paul Sheldon², and Kuver Sinha¹

¹ Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics, Texas A&M University, College Station, TX 77843-4242, USA
² Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235
³ Department of Physics, Kyungpook National University, Daegu 702-701, South Korea

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.

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}.

Probing DM with VBF


**MET + jj + leptons**

**MET + jj**
VBF SUSY Kinematics

Events (scaled to one)

$t\bar{t}\rightarrow llbb$
$t\bar{t}\rightarrow lqqbb$
$V+Jets$
$\chi\chi jj$ (100)

$p_T [j_1]$ (GeV)

Events (scaled to one)

$p_T [j_2]$ (GeV)

Events (scaled to one)

$M [j_1, j_2]$ (GeV)

Events (scaled to one)

$P_T$ (GeV)
VBF SUSY Phenomenology

**Benchmark Point:**

\[ M(\tilde{\chi}_1^+ - M(\tilde{\chi}_2^0) = 180 \text{ GeV} \]
\[ M(\tilde{\chi}_1^0) = 90 \text{ GeV} \]
\[ M(\tilde{\tau}_1^+) - M(\tilde{\chi}_1^0) = 30 \text{ GeV} \]

\[ \Delta M = 30 \text{ GeV} \]

\[ \tilde{\chi}_1^0 \rightarrow \tilde{\tau}_1 \rightarrow \tau \]

\[ \tilde{\chi}_2^0 \rightarrow \mu \]

\[ \mu \rightarrow \tilde{\mu}_1 \]

\[ \Delta M = 30 \text{ GeV} \]

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**Graph:**

- Events per 200 GeV
- \( \sqrt{s} = 8 \text{ TeV}, L_{\text{int}} = 25 \text{ fb}^{-1} \)

- \( p p \rightarrow \tilde{\chi}_1 \tilde{\chi}_2 j j \rightarrow \tau \tau j j \)
- \( p p \rightarrow V + \text{jets} \)
- \( p p \rightarrow VV j j \)

- **2.4\sigma**

- **6.0\sigma**

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**Reference:**

VBF SUSY Phenomenology


- Jets with $p_T > 50$, $|\eta| < 5$
- $|\Delta\eta(j,j)| > 4.2$
- $M(j,j) > 700$
- Veto on events with $b$-jets
- Select at least two leptons
- $MET > 75$ GeV

Events / 200 GeV

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

$pp \rightarrow \tilde{\chi} \tilde{\chi} jj \rightarrow \tau \tau jj$

2.4$\sigma$

$pp \rightarrow V +$ jets

$pp \rightarrow V V jj$

6.0$\sigma$
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


Real sensitivity is at 14 TeV

8 TeV reach is $\sim < 100$ GeV

@ 1000 fb$^{-1}$, 5$\sigma$ obtained up to a Wino mass of $\sim 600$
Simultaneously fit the MET shape and observed rate in data to extract the mass and composition of the LSP

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

\[ \Omega_{\text{LSP}} h^2 = f[F\%, m(\text{LSP})] \]
Use Delphes samples to study MET degradation with pileup

Select Z + jets events and study the perpendicular and parallel components of the hadronic recoil

\[ E_T \text{ energy scale } = -\langle u_\parallel \rangle / q_T \]
MET Performance w/ Pileup

Preliminary: ~ 10% effect on energy scale and 50 GeV on resolution (PU=140)

Minimal effect on mass reach (e.g. 20% energy scale $\rightarrow$ 4% in signal significance)

Ongoing study: effect on the mass reach due to MET resolution
VBF for Colored SUSY Sector

Same authors/group developed a way to probe stops with VBF

*See Kuver Sinha’s talk on Monday (Top session)*
Summary

- VBF offers a powerful way to “directly” probe EWK SUSY at the LHC
- **Compliments** current SUSY searches and has some 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*
- Pheno 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* ("best" case scenario)
- **Relic density can be determined to ~20% (40%) accuracy at 500 fb⁻¹** for the pure Wino (Higgsino) dark matter scenario
- Ongoing MET performance studies w/ Delphes shows ~10% energy scale degradation with a 50 GeV effect on resolution
  - Linearity has small effect on mass reach (linearity can also be corrected), while the effect on the reach due to resolution is ongoing …