Search for Supersymmetry with Vector Boson Fusion-like Topology in Proton-Proton Collisions at CMS

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On behalf of the CMS Collaboration

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Lake Louise 2017
Outline

• Classical SUSY Searches
• Supersymmetry in VBF
• What is VBF and Why?
• 8 TeV Analysis
  ❖ VBF + MET+Dilepton SUS-14-005, JHEP 11 (2015) 189
  ❖ VBF + MET SUS-14-019, PRL 118 (2017) 021802
• Prospect for 13 TeV search:
  ❖ New Approach with Mu+VBF Trigger
• Summary
• Many SUSY searches focused on the colored sector
• Limits of these models probe masses up to $\sim 1.7$ TeV for squark gluinos.
• These type of signatures have final states with MET+multijets (+leptons)(+photons)
• Colored objects expected to be heavy and the production cross-sections are large
• In compressed mass spectra scenarios MET is small and jets (+leptons) (+photons) are soft
• No good sensitivity for compressed spectra scenarios

• DM particles produced in pairs after cascade decay of chargino neutralino
• Signature: Met+leptons and ISR Jet
SUSY Electroweak Searches with VBF

Why VBF?

• VBF tagging useful in tackling some of the interesting physics channels
• VBF topology provides a complementary probe to look for compressed spectra
• Smaller predicted cross sections but lower level of hadronic activity
• Complements the color searches
• EWK’s expected to be light compared to the colored particles
While V+Jets more central with small dijet invariant mass, Signal characterized by non-central Jets with large dijet invariant mass
Main BG’s

- $Z \rightarrow \ell\ell + \text{jets}$:
  1. $Z \rightarrow e\bar{e}/\mu\mu$: fake $E_T^{\text{miss}}$ from mis-measured jets + ISR jets conforming to the VBF topology
  2. $Z \rightarrow \tau\tau$: real $E_T^{\text{miss}}$ from the tau decays + ISR jets.

- $W + \text{jets}$: prompt lepton from the W ($W \rightarrow \mu/e/\tau + \nu$) and recoil jets and ISR jets passing the VBF cuts.

- multijets:
  1. b-jets and leptons from $t\bar{t}$
  2. QCD light quark/gluon
Our general strategy to predict backgrounds across all channels:

1. Scale background estimation before VBF cuts with a control region ‘CF(CR w/o VBF)’ where CF is correction factor data to MC.
2. Determine efficiency of VBF cuts with another (independent) control region ‘$\epsilon_{VBF}$’.
3. A closure test is performed in MC. The difference between the nominal and predicted yields in the closure test, is taken as a systematic error.
• Data: 19.7 fb\(^{-1}\) at 8 TeV with inclusive muon trigger ($p_T^\mu > 24\) GeV\) and di-tau trigger ($p_T^\tau > 35\) GeV\)
• Final states with $e\mu$, $\mu\mu$, $\mu\tau_h$, $\tau_h\tau_h$ plus MET and 2 VBF Jets
• Both Opposite and Same sign charge pair
• $|\eta_{\text{lepton}}|<2.1$, $|\Delta\eta_{\text{jets}}|>4.2$ and $\eta_1\eta_2<0$, $p_T^{\text{jets}}>30/45\) GeV\) $p_T^{\text{miss}}>75/30\) GeV\)
• Main Backgrounds: ttbar, V+Jets, VV
• Analysis performed by looking at shape of $M_{jj}$ as discrimination variable
- All 8 channels combined
- Observed upper bound limit of 170 GeV and an expected limits of 180 GeV set for Compressed scenario where multi lepton search has no sensitivity.
For the average-mass assumption with an uncompressed-mass spectrum the corresponding limit is $\sim 300$ GeV, comparable the multilepton search.
Signature

• 2 high-$p_T$ forward jets and large MET
• Same VBF-like topology strategy as in the EWKino case
• Pair production of the lightest bottom squark and two associated jets where small mass difference between LSP and sbottom give rise to large MET

Selection: Two jets ($p_T > 50$ GeV with $\eta_1 \eta_2 < 0$; large rapidity gap $|\eta_1-\eta_2| > 4.2$ and invariant mass $m_{12} > 750$ GeV; no b-tag); MET > 250 GeV; veto further jets ($p_T > 30$ GeV)

Dominant bgs: ($Z \rightarrow \nu \nu$) + jets & ($W^\pm \rightarrow l^\pm \nu$) + jets estimated from data
Up to 315 GeV (obs.) and ~315 (exp.) for $\Delta M < 10$ GeV for compressed sbottom (& stop) where the monojet analyses by ATLAS and CMS exclude masses below 250 GeV
Prospects of Run II at 13 TeV

- Mu+VBF trigger is commissioned in Run II
  - $p_T^\mu > 8$ GeV, $M_{jj} > 750$, $p_T^j > 40$ GeV, HT (scalar sum of Jet $p_T$) > 600 GeV and MET > 60 GeV.

- Mu+VBF Trigger reaches plateau at low MET while VBF+MET trigger reaches plateau around 200 GeV.

- L1 VBF trigger (L1_Mu6_Mj30j30_360) with L1 seeds including HF → One jet with $|\eta| < 3.0$, one jet with $|\eta| > 3.0$
  - There is a significant difference, Sharp trigger turn-on!
  - improved eff. with L1 VBF

- At least one HF jet at L1
• First VBF topology based search performed successfully with 8 TeV data of CMS
  ❖ SUS-14-005 in dilepton + VBF channels (published in JHEP)
    ➡ A combined observed upper bound limit of 280 GeV and an expected limit on 295 GeV is set, for the large mass gap scenario
    ➡ For the compressed mass spectra scenario we set a combined observed upper bound limit of 170 GeV and an expected limits of 180 GeV
  ❖ SUS-14-019 in MET + VBF channel (published in Phys. Rev. Letter)
    ➡ The stringent limit of 315 GeV obs. and (~315 GeV expected) for squark in compressed mass spectrum scenario ($\Delta M \sim 5$ GeV)
• New Dedicated lepton+VBF trigger for Run II to improve search sensitivity
  ❖ Trigger active for all of 2016, 2017 data taking
• Stay tuned for interesting results!
Back-Up
Standard Model (SM)

- SM includes 12 elementary particles known as fermions and 3 force carriers known gauge bosons + Higgs boson.
- SM Lepton/Quarks → Spin-1/2 particles
  Gauge bosons → Spin 1 particles
- Higgs boson → Spin 0

Standard Model Problems?

- Inability to explain CDM
- Why are there three fermion generations?
- Why are there large differences on the masses of each generation?
- Hierarchy problem in Higgs mass.
- Why do neutrinos have mass?
Supersymmetry (SUSY) introduces a set of new particles by symmetrizing the theory between fermions and bosons.

- Slepton/Squarks → Spin 0 particles
- Gauginos → Spin 1/2 particles
- It has great potential for solving theoretical problems of the SM
- Stable Lightest Supersymmetric particle (LSP) is a leading candidate for dark matter
R-Parity

- \( R = (-1)^{3B + L + 2S} \)
- \( R = 1 \) for SM particles, \( R = -1 \) for SUSY
## Event Yields (SUS-14-005)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mu^+\mu^+jj$</th>
<th>$e^+\mu^+jj$</th>
<th>$\mu^+\tau^+jj$</th>
<th>$\tau^+\tau^+jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY + jets</td>
<td>$4.3 \pm 1.7$</td>
<td>$3.7^{+2.1}_{-1.9}$</td>
<td>$19.9 \pm 2.9$</td>
<td>$12.3 \pm 4.4$</td>
</tr>
<tr>
<td>W + jets</td>
<td>$&lt; 0.01$</td>
<td>$4.2^{+3.3}_{-2.5}$</td>
<td>$17.3 \pm 3.0$</td>
<td>$2.0 \pm 1.7$</td>
</tr>
<tr>
<td>VV</td>
<td>$2.8 \pm 0.5$</td>
<td>$3.1 \pm 0.7$</td>
<td>$2.9 \pm 0.5$</td>
<td>$0.5 \pm 0.2$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$24.0 \pm 1.7$</td>
<td>$19.0^{+2.3}_{-2.4}$</td>
<td>$11.7 \pm 2.8$</td>
<td>$-$</td>
</tr>
<tr>
<td>QCD</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$6.3 \pm 1.8$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$1.0 \pm 0.1$</td>
<td>$1.1 \pm 0.5$</td>
<td>$-$</td>
<td>$1.1 \pm 0.1$</td>
</tr>
<tr>
<td>VBF Z</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$0.7 \pm 0.2$</td>
</tr>
<tr>
<td>Total</td>
<td>$32.2 \pm 2.4$</td>
<td>$31.1^{+4.6}_{-4.1}$</td>
<td>$51.8 \pm 5.1$</td>
<td>$22.9 \pm 5.1$</td>
</tr>
<tr>
<td>Observed</td>
<td>$31$</td>
<td>$22$</td>
<td>$41$</td>
<td>$31$</td>
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</tbody>
</table>

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<tr>
<th>Process</th>
<th>$\mu^+\mu^+jj$</th>
<th>$e^+\mu^+jj$</th>
<th>$\mu^+\tau^+jj$</th>
<th>$\tau^+\tau^+jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY + jets</td>
<td>$&lt; 0.01$</td>
<td>$0^{+1.7}_{-0}$</td>
<td>$0.5 \pm 0.2$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>W + jets</td>
<td>$0.1 \pm 8.2 \times 10^{-4}$</td>
<td>$0^{+3.0}_{-0}$</td>
<td>$9.3 \pm 2.3$</td>
<td>$0.5 \pm 0.1$</td>
</tr>
<tr>
<td>VV</td>
<td>$2.1 \pm 0.3$</td>
<td>$1.9^{+0.4}_{-0.2}$</td>
<td>$1.1 \pm 0.2$</td>
<td>$0.1 \pm 6.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$3.1 \pm 0.1$</td>
<td>$3.5^{+0.7}_{-0.9}$</td>
<td>$6.7 \pm 2.8$</td>
<td>$0.1 \pm 1.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>Single top</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>QCD</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$7.6 \pm 0.9$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>Total</td>
<td>$5.4 \pm 0.3$</td>
<td>$5.4^{+3.5}_{-3.0}$</td>
<td>$17.6 \pm 3.8$</td>
<td>$8.4 \pm 0.9$</td>
</tr>
<tr>
<td>Observed</td>
<td>$4$</td>
<td>$5$</td>
<td>$14$</td>
<td>$9$</td>
</tr>
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</table>
## Event Yields (SUS-14-019)

<table>
<thead>
<tr>
<th>Sample</th>
<th>$L_{\text{Vetos}}$</th>
<th>$L_{\text{Vetos}+2j}$</th>
<th>$L_{bVetos+2j}$</th>
<th>$E_T^{\text{miss}}$</th>
<th>$\mu_\text{VBFcuts}$</th>
<th>$\mu_\text{VBFTriggers}$</th>
<th>$\Delta\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W+\text{Jets}$</td>
<td>$3.702 \cdot 10^8 \pm 1.135 \cdot 10^5$</td>
<td>$2.717 \cdot 10^6 \pm 4433$</td>
<td>$1.972 \cdot 10^6 \pm 3775$</td>
<td>$4015 \pm 99.62$</td>
<td>$43.61 \pm 10.28$</td>
<td>$43.61 \pm 10.28$</td>
<td>$43.61 \pm 10.28$</td>
</tr>
<tr>
<td>$Z_{\nu}+\text{Jets}$</td>
<td>$1.22 \cdot 10^7 \pm 6109$</td>
<td>$7.936 \cdot 10^5 \pm 1209$</td>
<td>$5.58 \cdot 10^5 \pm 1018$</td>
<td>$8401 \pm 99.37$</td>
<td>$96.08 \pm 10.66$</td>
<td>$95.88 \pm 10.65$</td>
<td>$88.17 \pm 9.83$</td>
</tr>
<tr>
<td>$\text{Higgs}_{\text{VBF}}$</td>
<td>$456.9 \pm 21.4$</td>
<td>$66.97 \pm 8.192$</td>
<td>$45.15 \pm 6.727$</td>
<td>$0.3936 \pm 0.6278$</td>
<td>$0.129 \pm 0.3593$</td>
<td>$0.128 \pm 0.3572$</td>
<td>$0.128 \pm 0.3572$</td>
</tr>
<tr>
<td>Z+Jets</td>
<td>$2.555 \cdot 10^8 \pm 4.644 \cdot 10^4$</td>
<td>$9.845 \cdot 10^5 \pm 2436$</td>
<td>$7.849 \cdot 10^5 \pm 2151$</td>
<td>$19.15 \pm 5.389$</td>
<td>$0.02945 \pm 0.1737$</td>
<td>$0.02945 \pm 0.1737$</td>
<td>$0.02945 \pm 0.1737$</td>
</tr>
<tr>
<td>WW</td>
<td>$5.521 \cdot 10^5 \pm 805$</td>
<td>$5.103 \cdot 10^4 \pm 244.9$</td>
<td>$2.967 \cdot 10^4 \pm 186.8$</td>
<td>$42.18 \pm 7.032$</td>
<td>$0.06022 \pm 0.2468$</td>
<td>$0.06022 \pm 0.2468$</td>
<td>$0.06022 \pm 0.2468$</td>
</tr>
<tr>
<td>WZ</td>
<td>$8.497 \cdot 10^4 \pm 303.3$</td>
<td>$6841 \pm 86.26$</td>
<td>$4288 \pm 68.3$</td>
<td>$132.3 \pm 12.03$</td>
<td>$0.3801 \pm 0.6434$</td>
<td>$0.3801 \pm 0.6434$</td>
<td>$0.3801 \pm 0.6434$</td>
</tr>
<tr>
<td>ZZ</td>
<td>$9.144 \cdot 10^4 \pm 320.1$</td>
<td>$6968 \pm 88.45$</td>
<td>$3899 \pm 66.15$</td>
<td>$120.1 \pm 11.61$</td>
<td>$0 \pm 0.1872$</td>
<td>$0 \pm 0.1872$</td>
<td>$0 \pm 0.1872$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$1.808 \cdot 10^6 \pm 1744$</td>
<td>$4.214 \cdot 10^4 \pm 266.3$</td>
<td>$4664 \pm 88.59$</td>
<td>$38.25 \pm 8.032$</td>
<td>$0 \pm 0.6829$</td>
<td>$0 \pm 0.6829$</td>
<td>$0 \pm 0.6829$</td>
</tr>
<tr>
<td>$\Sigma_{\text{MC}}$</td>
<td>$6.405 \cdot 10^8 \pm 1.228 \cdot 10^5$</td>
<td>$4.602 \cdot 10^6 \pm 5215$</td>
<td>$3.357 \cdot 10^6 \pm 4468$</td>
<td>$1.277 \cdot 10^4 \pm 142.2$</td>
<td>$140.3 \pm 14.83$</td>
<td>$140.1 \pm 14.82$</td>
<td>$132.4 \pm 14.24$</td>
</tr>
<tr>
<td>Data</td>
<td>$2.536 \cdot 10^7$</td>
<td>$5.883 \cdot 10^6$</td>
<td>$4.054 \cdot 10^6$</td>
<td>$307$</td>
<td>$120$</td>
<td>$120$</td>
<td>$118$</td>
</tr>
</tbody>
</table>
8 TeV DM and Compressed Mass-Spectra SUSY

![Graph showing the observed and expected cross sections for DM and compressed mass spectra in SUSY](image)

- **Observed**
- **Expected ± 1σ**
- **Expected ± 2σ**

**Observations**:
- **σ(pp → ̃b̃b jj) (NLO)**
- **σ(pp → χχ jj) (LO), Λ = 600 GeV**

**CMS**

**Integration**: 18.5 fb⁻¹ (8 TeV)

**Axes**:
- **σ [fb]**
- **M [GeV]**
VBF Kinematics?

- One jet pair with $m_{jj} > 250$
- Jet $P_T > 50$
- $|\Delta \eta| > 4.2$
- While V+Jets more central with small dijet invariant mass, Signal characterized by non-central Jets with large dijet invariant mass

- MET > 75