Search for vector-like quarks with oppositely-charged dilepton pairs, jets, and missing transverse energy in proton-proton collisions at centre-of-mass energy of 13 TeV

Rachitha Mendis
Kansas State University
On behalf of the CMS Collaboration
Introduction – Vector Like Quarks

- Candidates that could solve the hierarchy problem by stabilizing quantum corrections to the Higgs mass

\[ m_h^2 = m_{bare}^2 + \delta m_h^2 \]

Where \( \delta m_h^2 \) =

- Their contributions to the Higgs mass would cancel the corrections due to the top quark loop naturally
- Spin ½, non chiral, colored charged particles, heavier than t quark

QCD Pair production
- Model-independent cross section

<table>
<thead>
<tr>
<th>SM</th>
<th>Singlets</th>
<th>Doublets</th>
<th>Triplets</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u) (c) (s) (t)</td>
<td>( t' )</td>
<td>( t' ) ( t' ) ( b' )</td>
<td>( t' ) ( t' ) ( b' ) ( Y' )</td>
</tr>
</tbody>
</table>

2 and 1

- 1
- 2
- 3

- \( q_L = 1/6 \)
- \( u_R = 2/3 \)
- \( d_R = -1/3 \)
Introduction

• Search for VLQ TT Pairs with two leptons from Z boson decay
  • TT → tZ + X
    Where X = tZ, tH, bW

Pre-Event Selection
  • Opposite sign dilepton pair from Z
  • Jets
    • ≥ 3 Ak4 jets
    • ≥ 1 b-tagged jets

Pair Produced TT decays into tZtZ, where one Z decays into $l^+l^-$
• **Signal cross-sections**: Pair-production cross-section at QCD NNLO
• **Background cross-sections**: NNLO, NLO, or measured (when available)
• **Data**: Collected in 2016 with at least a single lepton (35.9 fb⁻¹)

### Pair-production TT cross section

<table>
<thead>
<tr>
<th>M (GeV)</th>
<th>σ(pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>0.455</td>
</tr>
<tr>
<td>800</td>
<td>0.196</td>
</tr>
<tr>
<td>900</td>
<td>0.0903</td>
</tr>
<tr>
<td>1000</td>
<td>0.0440</td>
</tr>
<tr>
<td>1100</td>
<td>0.0224</td>
</tr>
<tr>
<td>1200</td>
<td>0.0118</td>
</tr>
<tr>
<td>1300</td>
<td>0.00639</td>
</tr>
<tr>
<td>1400</td>
<td>0.00354</td>
</tr>
<tr>
<td>1500</td>
<td>0.00200</td>
</tr>
</tbody>
</table>
**Event Selection**

**Muon Channel**

- Work in progress
- $\mu^+\mu^-+jets$
- $35.9 \text{ fb}^{-1} (13 \text{ TeV})$
- **Data / Bkg**
- **Events / Bin**
- **$Z$ boson mass**
- $75 < M(Z) < 105 \text{ GeV}$
- **$N (Z \rightarrow l^+l^-)$**
- $=1$
- **$p_T (Z \rightarrow l^+l^-)$**
- $> 100 \text{ GeV}$
- **$N (AK4)$**
- $\geq 3$
- **$H_T$**
- $\geq 200 \text{ GeV}$

**AK4 Jet**

- A Jet clustered with the anti-kT algorithm
- with distance parameter $R=0.4$

**$H_T$**

- $\sum_{\text{all jets}} P_T$

**$S_T$**

- $\sum_{\text{all jets+leptons}} P_T$

**MET**

- Missing Transverse Energy

**Electron Channel**

- Work in progress
- $e^+e^-+jets$
- $35.9 \text{ fb}^{-1} (13 \text{ TeV})$
- **Data / Bkg**
- **Events / Bin**
- **$Z$ boson mass**
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- **$N (AK4)$**
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- **$H_T$**
- $\geq 200 \text{ GeV}$

**Pre Selection Region**

**Control region selection**

- **Leading AK4 jet $p_T$**
  - $> 100 \text{ GeV}$
  - $> 50 \text{ GeV}$
  - $\geq 1$
  - $S_T \leq 1000 \text{ GeV}$

**Signal region selection**

- **Leading AK4 jet $p_T$**
  - $> 100 \text{ GeV}$
  - $> 50 \text{ GeV}$
  - $\geq 1$
  - $S_T \geq 1000 \text{ GeV}$
Signal Region

<table>
<thead>
<tr>
<th>Sample</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Integrated Lumi. = 35.9 fb⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DY</td>
<td>268.8 ± 2.1</td>
<td>532.8 ± 3.3</td>
</tr>
<tr>
<td>Top</td>
<td>29.9 ± 2.4</td>
<td>86.7 ± 4.2</td>
</tr>
<tr>
<td>Diboson</td>
<td>9.4 ± 2.1</td>
<td>9.7 ± 2.1</td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>308.1 ± 3.8</td>
<td>629.2 ± 5.7</td>
</tr>
<tr>
<td>$TT\rightarrow t\bar{t}Zt\bar{Z}$-M1000</td>
<td>35.2 ± 0.8</td>
<td>44.4 ± 0.9</td>
</tr>
<tr>
<td>$TT\rightarrow t\bar{t}ZbW$-M1000</td>
<td>16.8 ± 0.4</td>
<td>22.1 ± 0.5</td>
</tr>
<tr>
<td>$TT\rightarrow t\bar{t}ZtH$-M1000</td>
<td>18.3 ± 0.4</td>
<td>25.6 ± 0.5</td>
</tr>
</tbody>
</table>

* Signal is normalized to 1 pb cross section for visualization

**S_T in Signal region (Electron)**

Work in progress

**S_T in Signal region (Muon)**

Work in progress

Sample

(DIagram with histograms for electron and muon channels, showing events/bin distribution and legend for different processes such as DY, Top, Diboson, and various $TT\rightarrow t\bar{t}Z$ processes.)

*Integrated Lumi. = 35.9 fb⁻¹*
Analysis Strategy

- Search for hadronic top, Z, H candidates in events
- See how categorizing events according to n-tops, n-Z, n-H and n-b reduces the SM Bkg
- The hadronically decaying objects are reconstructed using,
  - AK8 jets for Partially merged or Fully merged categories
  - AK4 jets for Resolved categories
- AK8 Jet ≡ A Jet clustered with the anti-kT algorithm with distance parameter R=0.8

Resolved, Partially merged, Fully merged Categories

Resolved

Resolved

Partially Merged

Fully Merged
## Analysis Strategy (n-top, n-Z, n-H & n-b)

<table>
<thead>
<tr>
<th>Category</th>
<th>top</th>
<th>Z</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolved</td>
<td>( \sum_{3 \text{jets}} \vec{p}<em>T &gt; 100 \text{ GeV} ) [120 &lt; \sum</em>{3 \text{jets}} M &lt; 240 \text{ GeV} ]</td>
<td>( \sum_{2 \text{jets}} \vec{p}<em>T &gt; 100 \text{ GeV} ) [70 &lt; \sum</em>{2 \text{jets}} M &lt; 120 \text{ GeV} ]</td>
<td>( \sum_{2 \text{jets}} \vec{p}<em>T &gt; 100 \text{ GeV} ) [80 &lt; \sum</em>{2 \text{jets}} M &lt; 160 \text{ GeV} ]</td>
</tr>
<tr>
<td>Partially Merged</td>
<td>W Tagged AK8 Jet</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \sum_{2 \text{jets}} \vec{p}<em>T &gt; 150 \text{ GeV} ) [120 &lt; \sum</em>{2 \text{jets}} M &lt; 240 \text{ GeV} ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fully Merged</td>
<td>top Tagged AK8 Jet</td>
<td>Z Tagged AK8 Jet</td>
<td>H Tagged AK8 Jet</td>
</tr>
</tbody>
</table>

### Top Jets
- JetPt < 400
- 105 < SoftDropMass < 220
- \( 0 < \tau_3/\tau_2 < 0.81 \)

### Z/W Jets
- JetPt < 200
- 65 < PrunedMass < 105
- \( 0 < \tau_2/\tau_1 < 1 \)

### H Jets
- JetPt < 300
- 105 < PrunedMass < 135
- \( 0 < \tau_2/\tau_1 < 1 \)
- \( \text{subjjetCSV} < 0.5426 \)
Optimization of the Analysis

- signal - fitting the observed $S_T$ spectrum to the combination of the SM backgrounds + a new physics signal

- The 95% limits are computed using Bayesian technique

- The categories are sorted in descending order of significance ($S / \sqrt{B}$)

- Select only categories with highest significances

- Combine categories with similar significances

- 4 such combined categories have been identified

<table>
<thead>
<tr>
<th>Category</th>
<th>$TT \rightarrow tZtZ$, $M_T = 1000$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp. Signal</td>
</tr>
<tr>
<td>1 t1Z1H1b1</td>
<td>12.6 ± 0.7</td>
</tr>
<tr>
<td>2 t1Z1H1b2</td>
<td>17.0 ± 0.8</td>
</tr>
<tr>
<td>3 t1Z1H0b1</td>
<td>18.0 ± 0.8</td>
</tr>
<tr>
<td>4 t1Z1H0b2</td>
<td>9.0 ± 0.6</td>
</tr>
<tr>
<td>5 t0Z1H1b1</td>
<td>2.2 ± 0.3</td>
</tr>
<tr>
<td>6 t0Z1H1b2</td>
<td>2.4 ± 0.3</td>
</tr>
<tr>
<td>7 t0Z1H0b1</td>
<td>3.7 ± 0.4</td>
</tr>
<tr>
<td>8 t0Z1H0b2</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td>9 t1Z0H1b1</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>10 t1Z0H1b2</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>11 t1Z0H0b1</td>
<td>4.8 ± 0.4</td>
</tr>
<tr>
<td>12 t1Z0H0b2</td>
<td>2.6 ± 0.3</td>
</tr>
<tr>
<td>13 t0Z0H1b1</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>14 t0Z0H1b2</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>15 t0Z0H0b1</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
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<td>0.7 ± 0.2</td>
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Optimization of the Analysis

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S_T distribution for Final Categories in Control Region (Muon Channel)

- Data/MC modelling in Control region

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**S_T dist^n of Cat A**

- Work in progress
- $\mu^+\mu^-$+jets
- 35.9 fb$^{-1}$ (13 TeV)

**S_T dist^n of Cat B**

- Work in progress
- $\mu^+\mu^-$+jets
- 35.9 fb$^{-1}$ (13 TeV)

**S_T dist^n of Cat C**

- Work in progress
- $\mu^+\mu^-$+jets
- 35.9 fb$^{-1}$ (13 TeV)

**S_T dist^n of Cat D**

- Work in progress
- $\mu^+\mu^-$+jets
- 35.9 fb$^{-1}$ (13 TeV)
The $S_T$ distribution for Final Categories in Signal Region (Muon Channel) is shown below. The signal is normalized to 1 pb cross section for visualization.

- **Cat A**: $\mu^+\mu^-+jets$
- **Cat B**: $\mu^+\mu^-+jets$
- **Cat C**: $\mu^+\mu^-+jets$
- **Cat D**: $\mu^+\mu^-+jets$

The $S_T$ distribution is shown for each category, with the number of events/bin indicated. The data is preliminary and work in progress.
• Devised an efficient method for calculating expected limits with event categorization using hadronically decaying objects

• Full unblinded results will be available later this year along with limit plots
BackUp
Electroweak Corrections

• AN2015_186_v9
• Corrections due to NLO electroweak contributions
• Applied to the event weight per event
• Increasingly important at high pt
Categorization using $n$-top, $n$-Z, $n$-H & $n$-b

<table>
<thead>
<tr>
<th>N-Top/ Z/ H candidates and N-btags</th>
<th>$t_1Z_1H_1b_1$</th>
<th>$ntop \geq 1$  $nZ \geq 1$  $nH = 1$  $nb = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1Z_1H_1b_2$</td>
<td>$ntop \geq 1$  $nZ \geq 1$  $nH = 1$  $nb \geq 2$</td>
<td></td>
</tr>
<tr>
<td>$t_1Z_1H_0b_1$</td>
<td>$ntop \geq 1$  $nZ \geq 1$  $nH = 0$  $nb = 1$</td>
<td></td>
</tr>
<tr>
<td>$t_1Z_1H_0b_2$</td>
<td>$ntop \geq 1$  $nZ \geq 1$  $nH = 0$  $nb \geq 2$</td>
<td></td>
</tr>
<tr>
<td>$t_0Z_1H_1b_1$</td>
<td>$ntop = 0$  $nZ \geq 1$  $nH = 1$  $nb = 1$</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>$t_0Z_1H_0b_2$</td>
<td>$ntop = 0$  $nZ \geq 1$  $nH = 0$  $nb \geq 2$</td>
<td></td>
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<td>$t_1Z_0H_1b_1$</td>
<td>$ntop \geq 1$  $nZ = 0$  $nH = 1$  $nb = 1$</td>
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<td>$t_1Z_0H_1b_2$</td>
<td>$ntop \geq 1$  $nZ = 0$  $nH = 1$  $nb \geq 2$</td>
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<td>$t_1Z_0H_0b_2$</td>
<td>$ntop \geq 1$  $nZ = 0$  $nH = 0$  $nb \geq 2$</td>
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<tr>
<td>$t_0Z_0H_0b_2$</td>
<td>$ntop = 0$  $nZ = 0$  $nH = 0$  $nb \geq 2$</td>
<td></td>
</tr>
</tbody>
</table>

Sorting the events into 16 mutually exclusive categories
$S_T$ distribution for Final Categories in Control Region (Electron Channel)

- Data/MC modelling in Control region
**ST distribution for Final Categories in Signal Region (Electron Channel)**

* Signal is normalized to 1 pb cross section for visualization

**Fig : ST dist^n of Cat A**

Work in progress

![Graph A](image1.png)

**Fig : ST dist^n of Cat B**

Work in progress

![Graph B](image2.png)

**Fig : ST dist^n of Cat C**

Work in progress

![Graph C](image3.png)

**Fig : ST dist^n of Cat D**

Work in progress

![Graph D](image4.png)

* Signal is normalized to 1 pb cross section for visualization
## Systematics

### Normalization Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ + jets</td>
<td>15</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>15</td>
</tr>
<tr>
<td>Diboson</td>
<td>15</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>2.6</td>
</tr>
<tr>
<td>Lepton ID + Isolation</td>
<td>3</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>1</td>
</tr>
</tbody>
</table>

### Shape Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>Jet Energy Resolution</td>
</tr>
<tr>
<td>Pileup</td>
<td>b tagging scale factor</td>
</tr>
<tr>
<td>$W/Z/H$-tagging</td>
<td>DY- Scale factor</td>
</tr>
<tr>
<td>Top tagging $\tau_3/\tau_2$</td>
<td>subject b-tagging for H-tag</td>
</tr>
<tr>
<td>PDF</td>
<td>QCD scale</td>
</tr>
</tbody>
</table>
Expected Limits

- Expected limits are computed using Bayesian likelihood-based technique.
- If data is consistent with SM Bkg T quark can be excluded with masses below,
  1. $1245 \text{ GeV (TT} \to tZtZ)$
  2. $1165 \text{ GeV (TT} \to tZtH)$
  3. $1065 \text{ GeV (TT} \to tZbW)$
What is a jet?

- From a list of particles one can form jets, an object to reconstruct the shower of particles produced from a quark or gluon.

- Each particle belonging to a jet is known as a constituent.
  - Each has a 4-vector that can be used for further studies.

\[
\begin{align*}
    d_{ij} &= \min (p_{t_i}^{2p}, p_{t_j}^{2p}) \Delta R_{ij}^2 / R^2 \\
    d_{iB} &= p_{t_i}^{2p}.
\end{align*}
\]

- \(p = 1\) → kt algorithm (KT)
- \(p = 0\) → Cambridge Aachen algorithm (CA)
- \(p = -1\) → anti-kt algorithm (AK)

- Need a jet algorithm to collect the particles in this shower.

- “Clustering Algorithm”
  - Iteratively find the two particles in the event which are closest in some distance measure and combine them.
  - Combine two particles if \(d_{ij} < d_{iB}\)
    - Stop when \(d_{ij} > d_{iB}\)
Jet properties

- Jet 4-vector = sum of all constituent particle 4-vectors
  - energy, $p_T$, $\eta$, $\phi$
  - Jet mass $m = \sqrt{E^2 - p^2}$
  - Jet constituent multiplicities (PF)
    - ex. charged multiplicity
  - Jet constituent fractions
    - ex. charged hadron energy fraction
  - Jet area = area in $\eta$-$\phi$ plane in which an infinitely soft particle will be clustered with the jet
Jet substructure

- The internal structure of the jet constituents give us handles to discriminate between:
  - Noise jets
  - Quark jets
  - Gluon jets
  - b-jets
  - W-jets
  - Z-jets
  - t-jets
  - H-jets
  - PU jets
Topological Algorithms

- We know how many final state objects to expect from these decays
  - Can look inside the jet for the expected substructure
    - Top decays $\rightarrow$ 3 subjets
    - W/Z/H decays $\rightarrow$ 2 subjets

- A quantity called N-subjettiness is a measure of how consistent a jet is with a hypothesized number of subjets
  - Low $\tau_N \rightarrow$ consistent with N (or fewer) subjets
  - Ratios used for additional discrimination

$$\tau_N = \frac{1}{\sum_i p_{T,i} \cdot R} \sum_i p_{T,i} \cdot \min(\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i})$$
at hadron colliders (LHC)

**B-hadrons** are produced inside of **jets**

(b-quarks hadronize into $B^+, B^-, B^0, B_s, \Lambda_B$)

their **lifetime** (1.5ps) and the Lorentz boost lead to displaced **decay vertices**

**b-tagging:**
look for displaced tracks and vertices (**secondary**) within jets

**why?** for example $Higgs \rightarrow b\bar{b}$ and many “new physics” scenarios
b-tagging algorithms

- **Impact Parameter** based b-tagging:
  IP of one track in the jet ("track counting" TC algorithms, based on the IP significance of the 2nd most displaced track)
  or combination of all tracks in the jet ("jet probability")

- **Secondary Vertex** algorithms:
  SSV discriminators, based on the 3D SV flight distance

- **combined** methods using multivariate techniques (e.g. neural networks) to calculate one discriminator from many variables: CSVv2, cMVA
  $$\text{CSVv2M} = 0.8484$$

- **soft lepton** tagging, exploiting B→lepton decays: limited BR to leptons, used for calibration purposes or combined with other variables