Searches for heavy BSM particles coupling to third generation quarks at CMS

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“Heavy BSM particles coupling to third generation quarks”

Signatures which fall into this category:

**Vector-like Quarks**

- $T \rightarrow bW$
- $T \rightarrow tZ$
- $T \rightarrow tH$

- $B \rightarrow tW$
- $B \rightarrow bZ$
- $B \rightarrow bH$

Single production
(ex. T in association with t and b)

Pair production
(ex. TT, BB, etc.)

**Resonances**

- Heavy resonance → standard model
  (ex. $Z' \rightarrow tt$, $W' \rightarrow tb$)

- Heavy resonance → vector-like quarks
  (ex. $Z' \rightarrow tT$, $Z' \rightarrow TT$, $W' \rightarrow bT$)

- Excited quark
  (ex. $b^* \rightarrow tW$, $t^* \rightarrow tg$)

- Leptoquark
  (ex. $LQ \rightarrow \tau\nu$, $LQ \rightarrow t\mu$)
Signatures which fall into this category:

**Vector-like Quarks**
- \( T \to bW \)
- \( T \to tZ \)
- \( T \to tH \)
- \( B \to tw \)
- \( B \to bZ \)
- \( B \to bH \)

**Resonances**
- Heavy resonance \( \to \) standard model
  - (ex. \( Z' \to tt, W' \to tb \))
- Heavy resonance \( \to \) vector-like quarks
  - (ex. \( Z' \to tT, Z' \to TT, W' \to bT \))
- Excited quark
  - (ex. \( b^* \to tW, t^* \to tg \))
- Leptoquark
  - (ex. \( LQ \to t\tau, LQ \to t\mu \))

Today: Highlight three of the most recent searches using 2016 CMS data
Jet-tagging Menu
Utilize jet substructure to tag partially or fully merged jets

- **W-jet**: 
  - $W$ to $q$, $\bar{q}$

- **Z-jet**: 
  - $Z$ to $q$, $\bar{q}$

- **H-jet**: 
  - $H$ to $b$, $\bar{b}$

- **Unmerged hadronic top**
  - $t$, $w$, $q$, $\bar{q}$

- **Partially merged hadronic top**
  - $(W \text{ jet} + b \text{ jet})$

- **Fully merged hadronic top jet**
  - $t$, $w$, $q$, $\bar{q}$

- **Leptonic top with non-isolated lepton**
  - $t$, $w$, $\mu$, $\nu$
Jet Tagging Tools

- **Jet grooming**
  - Pruning, soft drop

- **N-subjettiness**
  - Determines how consistent a jet is with having N or fewer subjets
  - Better discrimination by using ratios (ex. $\tau_3/\tau_2$)

- **Subjet b-tagging**

- **Boosted Event Shape Tagger (BEST)**
  - Neural network approach: When boosting to ‘correct’ reference frame, jet constituents should be isotropic and show the N-prong structure
Search for vector-like $T$ quark

- Vector-like top quark partner $T$ with charge 2/3
- Electroweek production (either charged current or neutral current)
- Hadronic final states

Search for vector-like T quark

- **T → tH or T → tZ**
- **All-hadronic channel → principal backgrounds QCD and ttbar**
- **Low mass search** - resolved jets from decays of t, H, Z
  - Five jet final state
  - Chi-squared sorting algorithm used to associate jets with t/W/Z/H
  - Further signal discrimination using relative HT (majority of transverse momentum in the event should originate from t and H/Z candidates) and angular variables
- **High mass search** - merged jets from decays of t, H, Z
  - At least 1 t-tag and 1 H/Z tag
Search for vector-like $T$ quark

- **Low mass search**
  - Three signal regions based on b-tagging
  - 3 tight working point b-tagged jets, 3 medium working point b-tagged jets, 2 medium 1 loose working point b-tagged jets

- **High mass search**
  - Six mutually exclusive control regions used to predict the shape of the QCD background

- No significant excess above the SM found
  - Limits set for T-singlet model
  - Four fractional widths considered
Search for TT in the fully hadronic state

- Search for pair produced vector-like quarks (optimized for TT but BB also so considered)
- Decay products of T are highly boosted → merged within one jet
- Two analyses
  - Cut-Based approach
    - targets $T \rightarrow bW$
    - Utilize W-tagging and b-tagging
  - Neural Net Multiclassification approach
    - Broad search for TT or BB
    - Utilize Boosted Event Shape Tagger (BEST) to identify $t$, $W$, $H$, $Z$

Search for $TT$ in the fully hadronic state

- **Cut-based analysis**
  - Require two Anti-KT $R=0.8$ jets and two Anti-KT $R=0.4$ jets
  - Two possible combinations of $b$ and $W$ jet. Assignment of jets to $T$ candidate is made such that $T$ candidate mass difference is minimized.
  - Categorize based on the number of $W$-tags and $b$-tags - 9 regions

- **Neural Net analysis**
  - BEST algorithm used to classify jets into 6 categories: $t$, $b$, $W$, $Z$, $H$, light
  - Require exactly 4 jets
  - Categorize based on number of classified jets: 126 independent signal regions
Search for $TT$ in the fully hadronic state
Search for $TT$ in the fully hadronic state

- No significant deviation found
- Limits set
Search for resonant $tT$ production

- Heavy spin-1 resonance $Z'$
- Decaying to a top quark and a vector-like top quark partner $T$
- Benchmark model - Kaluza-Klein Gluon


Search for resonant $tT$ production

- Optimized for $T \rightarrow tZ$ or $T \rightarrow tH$
- Two principal decay channels:
  - $Z' \rightarrow tT \rightarrow tZt$
  - $Z' \rightarrow tT \rightarrow tHt$
- Require one top to decay leptonically and other top hadronically
  - Search channel: lepton+jets
  - Leptonic top - non-isolated lepton
  - Hadronic top may be merged within a single jet
- $H$ or $Z$ is typically produced with large momentum $\rightarrow$ collimated decay products $\rightarrow$ utilize jet substructure
Search for resonant $t\bar{t}$ production

- Categorize events using jet substructure and subjet b-tagging
- Search for an excess in the reconstructed $Z'$ mass distribution

$H_{2b}$ tag + $t$ tag
$H_{2b}$ tag + no $t$ tag
$H_{1b}$ tag + $t$ tag
$H_{1b}$ tag + no $t$ tag
$Z$/W tag + $t$ tag
$Z$/W tag + no $t$ tag
Search for resonant $tT$ production

- No significant excess observed
- Observed limits depend on mass of $Z'$, mass of $T$, and branching ratio

Kinematically forbidden

No signal samples

Suppressed by the preferred $Z \rightarrow TT$ mode
Conclusion

- Broad search program at CMS for heavy BSM particles decaying to third generation quarks
- Motivated models
- No significant excess found in 2016 data
  - Analysis of much more data to come!

**Vector-like Quarks**
- $T \rightarrow bW$
- $B \rightarrow tW$
- $T \rightarrow tZ$
- $B \rightarrow bZ$
- $T \rightarrow tH$
- $B \rightarrow bH$

**Resonances**
- Heavy resonance $\rightarrow$ standard model (ex. $Z \rightarrow tt, W \rightarrow tb$)
- Heavy resonance $\rightarrow$ vector-like quarks (ex. $Z \rightarrow tT, Z \rightarrow Tt, W \rightarrow bT$)
  - Excited quark (ex. $b^* \rightarrow tW, t^* \rightarrow tg$)
  - Leptoquark (ex. $LQ \rightarrow tt, LQ \rightarrow t\mu$)
Additional Slides
CMS Data 2016

- $\sqrt{s} = 13$ TeV
- $35.9$ fb$^{-1}$
- Average pileup = 27
**Top and W jet validation in data**

- **Semileptonic ttbar selection** → very pure sample of boosted Ws

  - Muon + one b-tag

  - Data-MC scale factors measured

  ![Diagram of top and W jet validation](image)

  ![Histograms and plots showing data vs. MC for W-subject mass and P_T](image)

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Double $b$-tagged $H$-jet

CMS DP 2017/032

CMS Experiment at LHC, CERN
Data recorded: Wed Dec 31 19:00:00 1969 EDT
Run/Event: 1 / 363
Lumi section: 2
Orbit/Crossing: -1 / -1
Jet grooming

Algorithmic jet substructure techniques designed to remove isolated soft radiation in jets (contamination from ISR, UE, pileup)

**Trimming, Filtering** - Reclassify jets with smaller distance parameter. Condition based subjet removal.
- Reclassify small R
- Trimming: Remove soft subjets
- Filtering: Keep N hardest

**Pruning** - Reclassify jet. Remove soft large angle particles.
- Redo clustering remove soft large angle constituents

**BDRS, MMDT, Soft Drop, JHU top tagger, CMSTT** - Recursively decluster jet. Remove sub-clusters not satisfying algorithm condition. Stop declustering when both subjets satisfy condition.
- Decluster iteratively
- Remove sub-clusters not satisfying some criterion
- Stop when both subjets satisfy criterion

Reduces jet mass dependence on pileup
Reduces measured QCD jet mass (improves discrimination)
Improved jet mass resolution for boosted heavy object

Boosted W jet mass before grooming
Boosted W jet mass after grooming

QCD jet mass before grooming
QCD jet mass after grooming

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CMS Simulation

CMS HIG-13-008
H → WW → lνqq

Boosted W jet mass
QCD jet mass

Improved jet mass resolution for boosted heavy object