Search for Exotic Top Partners at $\sqrt{s} = 8$ TeV

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We present searches for heavy top and bottom quark partners at CMS using data collected at $\sqrt{s} = 8$ TeV. Such partners, if vector-like, occur in models such as the Little Higgs and Large Extra Dimensions. Fermionic top partners could also occur in composite Higgs models. The searches presented here span a wide range of final states, from lepton plus jets to multi-leptonic, and exclusion limits are set on mass and production cross sections as a function of branching ratios of the heavy quarks to their decay products.

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1 Introduction

Many theoretical extensions that predict physics beyond the standard model (BSM) propose the existence of fermionic partners of the top-quark. These quarks could either be vector-like or could occur in composite-Higgs models ($T_{5/3}$). The search for vector-like $T$ quarks includes $T$ decaying to $bW$, $tZ$ and $tH$. These final states are interesting since the newly discovered Higgs boson is used as a probe for new physics (Sec. 2). Composite Higgs models that posit the existence of $T_{5/3}$ are not ruled out by the presence of a SM Higgs at 125 GeV, since $T_{5/3}$ pair production does not contribute significantly to the Higgs cross section (Sec. 3). Searches for models with bottom quark partners, $b'$, have also been carried out at CMS [1]. The reinterpretation of an R-parity violating (RPV) SUSY search as a $b'$ search is presented in Sec. 4.

2 Search for vector-like top partners [3]

Vector-like quarks appear in many BSM scenarios such as the Little Higgs models or models with Extra Dimensions or MSSM. A vector-like quark, $T$ is pair produced via gluon fusion and quark-anti-quark annihilation and decays to $bW$, $tH$ and $tZ$. This leads to busy final states with multiple bosons and $b$-jets.

2.1 The Single Lepton Channel

The single lepton channel requires an isolated lepton with $p_T > 32$ GeV and $|\eta| < 2.1$. The event selection requires a minimum transverse momentum ($p_T$) threshold (35 GeV) on the first four leading (anti-$k_T$ with radius parameter, $R$, 0.5 (AK5)) jets [2]. Jet substructure variables are used to tag top and $W$ jets. $W$-tagging uses a jet-pruning algorithm which takes Cambridge-Aachen (CA) jets of distance parameter, $R$, of 0.8 as inputs. The jets from highly boosted top quarks are merged into one jet using a top-tagging algorithm.

A boosted decision tree (BDT) is used to obtain optimal separation between signal and SM background ($t\bar{t}$, $W$ and $Z$ boson production processes constitute 96% of the total background). Two separate event categories are constructed based on the presence (or absence) of a $W$ tagged jet. The input variables to the BDT are the following kinematic variables: jet multiplicity, $b$-jet multiplicity, the sum of the transverse momenta of the selected jets ($H_T$), missing transverse momenta ($E_T$), $p_T$ of the leading lepton, $p_T$ of the 3rd and the 4th jets. In the $W$ tagged events, the $p_T$ of the $W$-jets and the number of top-tagged jets are used. The BDT discriminants obtained are shown in Fig. 1, 2. The event yields are quoted in Table 1.

2.2 The Multilepton Channels

In the multilepton channel, various event categories are constructed to be sensitive to a variety of leptonic final states. To this end, we create three broad categories:

- Opposite sign (OS) lepton final state: In this category, we require two isolated leptons with opposite charge. The major irreducible backgrounds in this category are $t\bar{t}$ and Drell-Yan. While the Drell-Yan background can be minimized with the requirement of $b$-jets, $t\bar{t}$ completely mimics the $T \rightarrow bWbW$ signal. Hence, we further subdivide the OS category based on requirements on the number of AK5 jets, $b$-jets, the minimum invariant mass of the lepton and $b$-jet ($\text{min}M_{lb}$, shown in Fig. 3), the sum of the transverse momenta of all jets ($H_T$) and the sum of the transverse momenta of all jets, leptons and missing $E_T$ ($S_T$, shown in Fig. 3).
Table 1: The total number of expected and observed events in the single-lepton channel.

| lepton flavor | muon       | electron   |
|--------------|------------|------------|
| t\bar{t}     | 36700±5500 | 35900±5400 |
| single top   | 2190±1101  | 2100±1000  |
| W            | 19200±9700 | 18200±9200 |
| Z            | 2170±1100  | 2000±1000  |
| multijets    | 0          | 1680±620   |
| t\bar{t} W   | 144±72     | 137±68     |
| t\bar{t} Z   | 109±54     | 108±54     |
| t\bar{t} H   | 570±280    | 570±285    |
| WW/WZ/ZZ     | 410±205    | 400±200    |
| total background | 61500±13700 | 61100±13500 |
| data         | 58478      | 57743      |

Figure 1: BDT distributions in events with 1 W-jet and at least 3 AK5 jets.

Figure 2: BDT distributions in events with 1 W-jet and at least 4 AK5 jets with p_{T} > 35 GeV.
– OS23: This category is constructed to be sensitive to the TT → bWbW signal. We require 2 or 3 jets, a Z-veto (since there are no real Z's in the signal), 1 b-jet, missing $E_T > 30$ GeV, $H_T > 300$ GeV, $S_T > 900$ GeV and minMlb > 170 GeV. Since minMlb is directly proportional to the mass of the T quark, the last selection facilitates in the reduction of the $t\bar{t}$ background.

– OS5+: This category is sensitive to final states where the T quark decays to tH and tZ. We require at least 5 jets, 2 b-jets, missing $E_T > 30$ GeV, $H_T > 500$ GeV and $S_T > 1000$ GeV.

• Same signed (SS) lepton final state: The backgrounds in this relatively clean channel are from SM processes like diboson and triboson decays. In addition to these backgrounds, there is a non-trivial contribution from fake leptons, either from events where both leptons are fake (from jets faking as leptons from multijet processes) or from events where one lepton is fake and the other prompt (from $t\bar{t}$). In the SS category, we find that fake leptons constitute 50% of the total background. The final selection criteria involves requirements on the number of jets ($\geq 3$ jets, 1 b-jet), missing $E_T (> 30$ GeV), $H_T (> 500$ GeV) and $S_T (> 700$ GeV).

• Trilepton final state: The backgrounds are SM processes like diboson and triboson decays. The fraction of fake leptons contributing to the total background is about 33% in this category. A requirement on the number of jet (require $\geq 3$ jets, 1 b-jet), missing $E_T (> 30$ GeV), $H_T (> 500$ GeV) and $S_T (> 700$ GeV) is made.

In both SS and trilepton categories, the instrumental backgrounds (fake leptons in both SS and trilepton category and charge misidentification in the SS category) are estimated directly from data. The final yields after the application of all event selection requirements are in Table 2.

| channel                  | OS1  | OS2  | SS  | trileptons |
|--------------------------|------|------|-----|------------|
| $t\bar{t}$               | 5.2±1.9 | 80 ±12 | -   | -          |
| single top               | 2.5±1.3 | 2.0±1.0 | -   | -          |
| Z                        | 9.7±2.9 | 2.5±1.9 | -   | -          |
| $t\bar{t}W$              | -    | -    | 5.8 ±1.9 | 0.25±0.11 |
| $t\bar{t}Z$              | -    | -    | 1.83±0.93 | 1.84±0.94 |
| WW                       | -    | -    | 0.53±0.29 | -          |
| WZ                       | -    | -    | 0.34±0.08 | 0.40±0.21 |
| ZZ                       | -    | -    | 0.03±0.00 | 0.07±0.01 |
| WWW/WWZ/ZZZ/WZZ          | -    | -    | 0.13±0.07 | 0.08±0.04 |
| $t\bar{t}WW$             | -    | -    | -    | 0.05±0.03 |
| charge mis-ID            | -    | -    | 0.01±0.00 | -          |
| non-prompt               | -    | -    | 7.9 ±4.3 | 0.99±0.90 |
| total background          | 17.4±3.7 | 84 ±12 | 16.5 ±4.8 | 3.7 ±1.3  |
| data                     | 20   | 86   | 18  | 2          |

### 2.3 Results

In the single lepton final state (Sec. 2.1), the shape of the BDT distributions is used to obtain the final likelihood using a Bayesian approach [7]. In the multi-lepton channel (Sec. 2.2), the event...
yields in 12 bins (corresponding to three dilepton channels, ee, e\(\mu\) and \(\mu\mu\) and eee, e\(\mu\mu\) or ee\(\mu\) and \(\mu\mu\mu\) in the trilepton case) is used to compute the final likelihood to obtain an exclusion limit. These two channels are then combined to obtain exclusion limits at 95% C.L. as shown in Fig. 5 and 6. Further, we scan across 22 branching fraction scenarios as shown in Fig. 7. Each point on this plot shows the mass exclusion at 95% C.L. for a given combination of branching ratios. These results represent an inclusive search for the T quark with minimal model dependence.
Figure 5: Expected and observed limit at 95% C.L. for T pair production to bW, tH and tZ final states in the nominal (50% bW, 25%tZ and 25%tH) branching ratio scenario (left) and exclusively to bW final state (right).

Figure 6: Expected and observed limit at 95% C.L. for T pair production to either exclusively tZ final states (left) or tH final states (right).

Figure 7: Expected and observed limit at 95% C.L. for T pair production to either exclusively tZ final states (left) or tH final states (right).
3 Search for top partners with charge 5/3 in the same sign dileptonic final state [4]

A search is carried out for an exotic heavy quark of charge 5/3. The production mechanism along with the decay products is shown in Figure 8. The $T_{5/3} \rightarrow bW$ branching ratio is assumed to be 100%. The smoking gun signature of these exotic top partners is same-signed dileptons that, should be noted, arise from only one leg of the Feynman diagram. The hadronic W decays can, hence, be utilized to reconstruct the mass of the $T_{5/3}$. Among the various backgrounds, there are SM processes such as diboson and triboson decays. The contribution of these processes to the total background is obtained directly from simulations, since the rate of production of these processes is extremely low and hence are rarely produced in the detector. The instrumental backgrounds such as charge mis-identification are estimated in a data driven way by estimating the frequency with which one obtains same signed leptonic events within the Z-boson mass window. The backgrounds from fake leptons are obtained from data as described in Section 2.2.

The center of mass energy of the LHC allows one to probe $T_{5/3}$ masses where jets from the decay of the heavy quark start merging due to the Lorentz boost experienced by the system of particles. Jet substructure techniques are utilized by constructing the “jet-constituent” variable. This variable represents the number of AK5 jets, W-tagged jets weighted by a factor of 2 and top-tagged jets weighted by a factor of 3. The weighting factors are based on the number of hadronic components in W or top-tagged jets. To obtain the final yields (Table 3), events that have an invariant mass of the dilepton system within 15 GeV of the Z boson mass window are vetoed, a minimum of five jet constituents are required and $H_T$ (shown in Fig 9 and computed as the scalar sum of the $p_T$ of the jets and the leptons) of the event should be at least 900 GeV. A candidate $T_{5/3}$ pair production event that passes the event selection requirements is shown in Fig 8.

![Feynman diagram](image)

Figure 8: Feynman diagram of the process under consideration (left). Candidate event of $T_{5/3}$ pair production (right).

The final exclusion limits are computed with a frequentist approach, shown in Fig 9.

3.1 Mass reconstruction

The reconstruction of the $T_{5/3}$ mass in essential in determining the nature of new physics, if a statistically significant excess is observed in the same-sign dileptonic final state. The mass of the $T_{5/3}$ is reconstructed in the following way:
Table 3: The total number of expected and observed events after all event selection requirement. The backgrounds include contribution from Monte Carlo driven estimates, the contribution due to fake leptons and from charge mis-identification. The errors indicate systematic as well as statistical errors.

|     | MC    | Fake leptons | Charge Mis-ID | Total Expected | Observed |
|-----|-------|--------------|--------------|----------------|----------|
| ee  | 0.7 ± 0.2 | 1.9 ± 1.2    | 0.06 ± 0.02  | 2.6 ± 1.3     | 0        |
| eμ  | 1.9 ± 0.4 | 0.6 ± 0.9    | 0.05 ± 0.01  | 2.5 ± 1.0     | 6        |
| μμ  | 1.3 ± 0.3 | 0.2 ± 0.6    | -            | 1.5 ± 0.7     | 5        |
| All | 3.9 ± 0.8 | 2.6 ± 1.8    | 0.1 ± 0.02   | 6.6 ± 2.0     | 11       |

Figure 9: $H_T$ distribution in the same sign dilepton final state (left). Exclusion limit obtained at 95% C.L. (right)

- If there exists a CA jet (in 22% signal events), then is it combined with the hadronically decaying “W” tagged jet or two AK5 jets with an invariant mass within 20 GeV of $m_W$.
- In the absence of CA jets, two Ws are reconstructed (from CA jets in 80% signal events or AK5 jets with an invariant mass within 20 GeV of $m_W$) and combined with a jet. The invariant mass of the top jet is required to be within 30 GeV of the top-quark mass.

The reconstructed $T_{5/3}$ mass is shown in Fig. 10.

Figure 10: Reconstruted $T_{5/3}$ mass.
4 Reinterpretations from RPV SUSY search for \( b' \) searches

Dedicated searches for \( b' \) to tW, bZ and bH have been carried out in CMS. This analysis reinterprets an RPV SUSY search into multilepton final states as a search for \( b' \). The main discriminating variable under consideration is \( S_T \). Two distinct event categories are constructed based on the presence of three or four leptons. The final yields are computed in bins of \( S_T \) as shown in Fig. 11 and the final exclusion limit as a function of branching ratio is shown in Fig. 12.

![Figure 11](image1.png)

Figure 11: \( S_T \) distribution in the three (left) and four lepton (right) category with requirements on opposite-sign same flavor (OSSF) leptons.

![Figure 12](image2.png)

Figure 12: Exclusion limit on mass and cross section as a function of the branching ratio (left). The exclusion limit at 95% C.L. for 50% branching ratio of \( b' \rightarrow tW \) and \( b' \rightarrow bZ \).
5 Conclusion

In the searches quoted above, we do not observe an excess and our findings are consistent with SM predictions. Hence we compute exclusion limits at 95% C.L. These results are summarized in Table 4.

| Model considered | Branching ratio scenario | Exclusion Limit |
|------------------|--------------------------|-----------------|
| Vector-like T quark | 50% bW, 25% tH and 25% tZ | 696 GeV |
| Vector-like T quark | 100% bW | 700 GeV |
| Vector-like T quark | 100% tH | 706 GeV |
| Vector-like T quark | 100% tZ | 782 GeV |
| $T_{5/3}$ | 100% tW | 770 GeV |
| $b'$ | 50% tW and 50% bZ | 715 GeV |

Table 4: Summary table of current limits as a function of the branching ratio scenario.

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