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Beyond two generations

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Abstract. A review is presented of searches performed by CMS experiment for new particles produced in association with or decaying to top quarks, as well as heavy top partners. The analysis presented use data collected with CMS experiment during 2012, in proton-proton collisions at a centre-of-mass energy of 8 TeV.

1 Introduction

After the discovery of a SM-like Higgs boson [1, 2], an explanation for the scale of its mass became of great importance. New particles, such as heavy top partners, could improve our understanding of the problem, through cancelations in the radiative corrections of the Higgs boson mass.

Many searches have been performed by CMS experiment [3] for new particles produced in association with or decaying to top quarks, as well as heavy top partners [4]. In this high energy regime, the top quarks become boosted and their decay products are oftenly collimated. Sophisticated algorithms have been developed for tagging top quarks and estimating the mass of their hadronic decays [5–7]. These techniques allow the reconstruction of invariant mass observables in many final states, a powerful tool to discrimimate possible new resonances from their background processes. Mass reconstruction methods are also developed for leptonic final states including one or two invisible particles [8–10].

This report summarizes many of the searches performed by the CMS for heavy top partners as well as new particles produced in association with or decaying to top quarks [8–18]: top quarks associated with possible dark matter particles (section 2) and resonances decaying to top quarks (sections 3, 4, 5). Finally, searches for heavy top partners are presented in sections 6, 7.

2 Dark matter searches

Theories that attempt to extend the Standard Model like supersymmetry or extra dimensions, predict the existence of neutral weakly interacting particles which escape detection in collider experiments. Final states with a single jet [19, 20] or photon [21, 22] associated with large missing energy have been searched by both ATLAS and CMS without any evidence for new physics. This result can be accomodated by models where the new particle converts a light quark to a top quark, predicting "monotop" candidates, that is an invisible particle in association with a top quark [23, 24]. The CMS search [11] is focused on the hadronic final state, in which top decays to a bottom quark and a W

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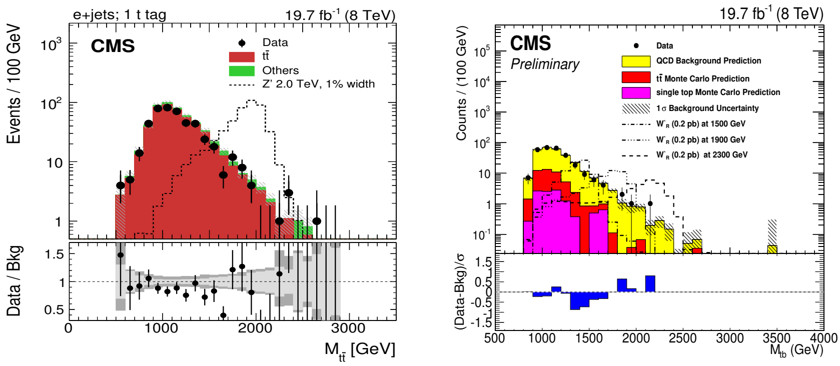

Figure 1. Invariant mass of the reconstructed $t\bar{t}$ pair in the electron+jet channel for events with 1 t-tagged jet (left) [13], and the reconstructed M_{tb} invariant mass in the all-hadronic $W' \rightarrow t\bar{b}$ search (right) [15].

boson, which further decays into a pair of quarks. Events with large missing energy and three jets are selected and one of them must be identified as originating from a b quark. The signal events as well as the number of multijet background events, are measured simulatenously using a likelihood approach. The observed lower limits for the invisible particle are 330 GeV for a scalar and 650 GeV for a vector particle respectively.

Another scenario predicts a new fermion interacting with quarks via a four-fermion contact interaction [25, 26]. The exclusion limit for the scalar case is the least stringent among all types that have been searched. In addition, the interaction coupling strength is proportional to the mass of the quark, predicting better sensitivity in final states with third-generation quarks [27]. The CMS search is focused on the scalar case, in the final state originating from the semi-leptonic top pair decay. The selection requires events with a single isolated lepton, at least three jets of which one must be identified as originating from b quark fragmentation and large missing transverse energy [12]. Further selection criteria are based on the transverse mass of the lepton and missing energy, as well as M_{T2}^{W} variable [28], in order to suppress W+jets and top pair backgrounds. The upper limits on the $pp \rightarrow t\bar{t} + X\bar{X}$ production cross section depend on the mass hypothesis of the DM particle: cross sections larger than 20 to 55 fb are excluded for DM particles ranging from 1 to 1000 GeV.

3 Resonances decaying to top pairs

A resonance decaying to top pairs is predicted by many BSM theories like leptophobic Z′ [29], extended gauge theories [30] or extensions of the Randal-Sundrum model with Kaluza-Klein (KK) excitations [31]. The CMS search for resonances decaying to top quarks [13] is performed in final states with two, one or zero leptons refered to as dilepton, lepton+jet and all hadronic channels respectively.

The dilepton final states requires two non-isolated leptons (electrons or muons) of opposite charge, at least two jets, as well as large transverse missing energy. The final observable is a mass variable constructed from the vectorial sum of the above. The lepton+jet final state selects one electron or muon, at least two jets and large missing energy. The CMS top tagging algorithm is applied to identify the fully hadronic top decays merged into a single jet, using Cambridge-Aachen jets with a distance parameter of R=0.8 (CA8 jets) [5, 6]. Events are categorized based on the lepton flavour and the number of CA8 t-tagged jets, from which no more than one is allowed to avoid overlap with the all-hadronic channel. The invariant mass of the $t\bar{t}$ system is reconstructed (Figure 1, left), by minimizing a χ^2 function based on the masses of the possible $t\bar{t}$ candidates.

The all-hadronic final state requires a di-jet topology in which each jet is consistent with the decay of a top quark. The search is performed in two different Z′ mass regions: in the $M_{Z'}$ region below 1 TeV the Cambridge-Aachen (CA) jet reconstruction is applied with a distance parameter of R=1.5 and HEPTopTagger algorithm [7], whereas in the high mass region the top jets are reconstructed using an R=0.8 and CMS t-tagging algorithm [5, 6]. In order to reduce the dominant multijet production, b-tagging is applied to the subjets of top, requiring one of them to originate from the fragmentation of a b quark. The combination of the above channels for resonances decaying to top pairs gives an exclusion range up to 2.4 TeV for the narrow Z′ hypothesis. For wide resonances (width 10% of its mass) the exclusion range is up to 2.9 TeV. Randall-Sundrum KK gluons decaying to top pairs are excluded for masses below 2.8 TeV.

4 Excited top quark

The proposal that the top quark might have a composite structure [32], can be directly tested by searching for an excited top quark. The CMS search [8] adopts a model in which pair produced t^* quark decays predominantly to a top quark and a gluon [33]. The analysis is targeting the lepton+jets final state ($t^*t^* \rightarrow t\bar{t}gg \rightarrow l^+\nu_l b\bar{q}q'\bar{b}gg$), requiring an isolated lepton and at least six jets, of which one must be combatible with originating from b quark fragmentation. A kinematic fit is performed to final state objects in order to reconstruct t^* candidates in each event. The fit is subject to the six mass constraints from excited top t^*, top quark and W boson decays in both brances of the pair production. The analysis estimates a lower limit for m_{t^*} of 803 GeV for the combined electron and muon channels.

A search for pair produced resonances decaying to a top quark and another parton is also performed by CMS in the dilepton final state [9]. The experimental signature constists of two isolated leptons (electrons or muons), two jets coming from the decays of b quarks and two jets originating from light flavour quarks or gluons. The interpretation is based on a spin-3/2 top quark excitation model, as in the lepton+jets final state [34]. An additional interpretation is also used, based on an R-parity violating MSSM model with the LSP bottom squark decaying into a top quark and a strange quark [35]. The invariant mass of the t^* or $\tilde{b}$ resonance can be reconstructed: given the masses of the top quark and the W boson, the $t\bar{t}$ system can be solved analytically [36, 37]. The quadric equation can be solved for the two leptons and b-tagged jets combinations to form $t\bar{t}$ candidates which can further be combined with the selected light jets to form pairs of t^* or $\tilde{b}$ candidates. The pair with the closest $M_{t,jet}$ values is chosen and the average value of the pair is used as the final reconstructed mass. The observed upper limit for t^* and $\tilde{b}$ resonances is 703 GeV and 326 GeV respectively.

5 t+b resonances

A new massive charged gauge boson W′ is predicted by many extensions of the SM [38, 39] and has been searched in the lepton-neutrino, diboson and light quark final states [40–42]. The most important experimental constraints imposed by the leptonic final state, do not apply for the case of W′ bosons with purely right-handed couplings and a hypothetical right-handed neutrino mass larger than a few GeV [43]. CMS has performed further searches for a $W'^+ \rightarrow t\bar{b}$ (or charge conjugate) in the lepton+jets and all-hadronic final state [14, 15].

The lepton+jets search [14] selects events with an isolated lepton (electron or muon), at least two jets of which one must originate from b-quark fragmentation. The topology $W' \rightarrow tb, t \rightarrow bW \rightarrow bl\nu$ is fully reconstructable: The z component of the neutrino momentum is calculated using the W-boson

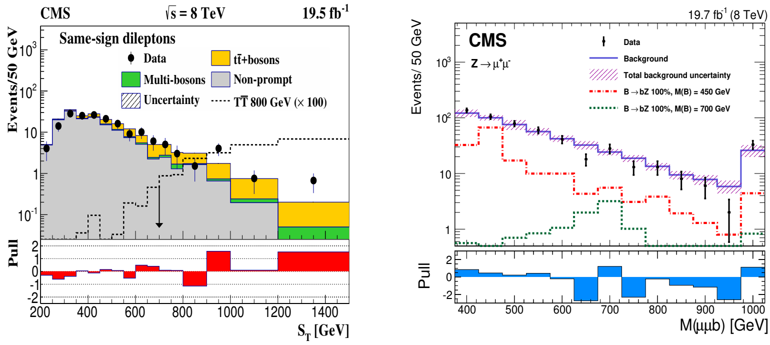

Figure 2. Observed and excpected S_T distribution (same-sign dilepton sample) in the vector-like T quark search (left) [17], and the invariant mass of reconstructed B quark candidates in the opposite-sign dimuon channel (right) [18].

mass constraint. Each W-candidate is combined with all selected jets to form top-quark candidates. The candidate with invariant mass closest to top-quark mass is chosen and is further combined with the highest -in P_T- of the remaining jets to form a W′ candidate. The observed limit for purely right-handed W′ bosons is 2.05 TeV. For a W′ boson with purely left-handed couplings including interefence effects, the observed limit is 1.84 TeV.

In the all-hadronic $W' \to t\bar{b}$ search [15], the Cambridge-Aachen algorithm is used for jet reconstruction (CA8 jets) and the CMS top-tagger for top jet identification. The selection requires a back-to-back dijet topology composed of a t-tagged jet and a low mass b-tagged jet which further allow the reconstruction of the W′ candidate mass (Figure 1, right). The production of a right-handed W′ boson in the all-hadronic search is excluded for masses up to 2.02 TeV. The combination of both lepton+jets and all-hadronic channels increase the exclusion range up to 2.15 TeV.

6 Vector-like quarks

Vector-like quarks are hypothetical new quarks for which both left and right-handed fields have the same transformation properties under the electroweak gauge group [45]. They do not need to receive their masses from Yuakawa couplings to Higgs doublet, as their bare mass terms are invariant under the symmetry of the theory. So these models are constistent with existing Higgs data, in contrast with models predicting extra quarks with chiral couplings such as fourth generation quarks [46].

The CMS search for top-quark partners with an exotic charge [16] is looking for pair produced new particles $T_{5/3}$ with charge 5e/3 and decay via $T_{5/3} \to tW^+$, followed by $t \to W^+b$ (and charge conjugates). The analysis is performed in the same-sign final state: it has less $t\bar{t}$ background but also instrumental effects from charge misidentification and fake leptons which are estimated from control regions. In addition to the CMS top-tagging, a W-tagging algorithm is applied to the CA8 jets, requiring exactly two subjets and their mass to be consistent with a W boson mass [44]. The selection requires two isolated same-sign leptons, large scalar sum of the P_T of all leptons/jets and the number of CA8 subjets, leptons and anti-kt jets to be greater than six. The observed limit on the mass of $T_{5/3}$ is 800 GeV.

CMS has performed an inclusive search for a vector-like T quark with charge 2/3, which further decays to bW, tZ or tH, in single-lepton and mulitlepton final states [17]. The single lepton channel requires at least four jets and uses a BDT to further separate T-quark signal from SM background. The multilepton channel requires at least two leptons and is further divided into four mutually exclusive subchannels. The opposite-sign dilepton sample targets the bWbW final state and exploits the smallest invariant mass combination of leptons and b-jets M_{lb}^{min}, in order to suppress the $t\bar{t}$ background. A second opposite-sign dilepton channel targets events in which both leptons originate from a Z boson decay and has further selection criteria based on the increased jet activity. A same-sign dilepton sample accepts events in which at least one T quark decays to tZ or tH and uses control regions to estimate charge misidentification and non-promt lepton backgrounds (Figure 2, left). Finally, a trilepton channel also accepts events in which at least one T quark decays to tZ or tH. The non-prompt backgrounds are determined from data, as in the dilepton case. All the subchannels are using observables like H_T and S_T, in order to exploit the increased jet activity and the invisible particles included. The lower limits for a vector-like T-quark ranges between 687 and 782 GeV, depending on the possible branching ratios of the three decay modes.

CMS has also searched for a vector-like heavy B quark having an electric charge $-1/3$ [18]. The B quarks are assumed to be pair produced and decay via $B \to tW$, $B \to bZ$ or $B \to bH$. Several different mutually exclusive final states are searched in order to be sensitive to the different decay modes, based on the number of selected leptons: single leptons, dileptons with opposite or identical charges, multileptons or all-hadronic without any identified leptons. The first two final states (single lepton and same-sign dilepton) target the tW decay and use as final observable the S_T variable. The same observable is also used in the multilepton final state which is sensitive to both tW and bZ decay modes. The all-hadronic channel is designed for Higgs bosons decaying to a pair of b quarks. The Higgs boson is identified using CA8 jets that are composed of two b-tagged subjets with an invariant mass constistent with m_H. At least one CA8 jet is required to satisfy these criteria known as Higgs tagging (H-tagging). Finally, in the opposite sign lepton pair channel, the B quark candidate is fully reconstructed from its decay products ($B \to Zb, Z \to ll$), by requiring an M_{ll} close to Z boson mass and an additional b-tagged jet (Figure 2, right). The observed exclusion limit for a vector-like B quark ranges from 740 GeV to 900 GeV depending on the possible branching ratios of the different decay modes.

7 Search in the 2-dimensional mass plane

Many BSM models predict final states with two invisible particles [47–49]. The experimental searches are often based on missing energy related observables where the new physics appears in the tail of the distribution. In this case, the establishment of a possible discovery and the model constraining (e.g particle masses) are challenging problems. The suggestion to search in 2-dimensional mass space, for final states with two invisible particles is described in [50]. The reconstruction of mass peaks concentrates signal events in a small region of the two-dimensional mass space whereas background events have no reason to do the same. The reconstructed masses also give valuable information about the particle content and thus the parameters of the model.

CMS has performed a search for anything decaying like top pairs, in their dilepton final state [10]. The analysis is searching simultaneously for both a new heavy top partner T′ and a new heavy charged gauge boson W′ as predicted by the littlest higgs model [47, 48]. The selection requires two leptons, two jets and large missing energy with the same energy requirements for all reconstructed objects. The analysis is based on a two-dimensional mass reconstruction of both unknown particles in the $[M_{T'}, M_{W'}]$ plane (Figure 3). The analytic solutions [36, 37] together with constraints from the parton distribution functions (PDFs) [51–53] are used to reconstruct the masses of two unknown particles simultaneously. The region of $M_{T'}$ excluded is in the range 800-920 GeV, depending on $M_{W'}$.

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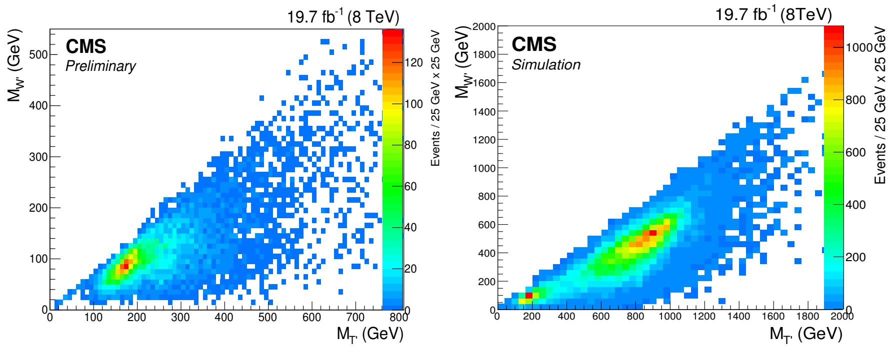

Figure 3. Mass reconstruction in two-dimensional mass space using the 2012 dataset (left) as well as simulated events for the same luminosity of both signal [$M_{T'}$ = 1000 GeV, $M_{W'}$ = 600 GeV] and background processes (right) [10].

8 Conclusions

A summary of many CMS searches with final states involving top quarks or heavy top partners is presented. Sophisticed alogorithms are developed for top tagging/mass reconstruction in final states with/without missing energy. No evidence for new physics was found for top quarks associated with possible dark matter particles, resonances decaying to top quarks as well as heavy top-partners. The analysis methods developed in Run1 will facilitate the searches for BSM physics in the new energy regime of Run2.

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