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Searches for new resonances with couplings to third generation quarks with the CMS detector

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Many models of physics beyond the Standard Model (SM) feature the existence of new particle states with enhanced couplings to quarks of the third generation. In run-2 of the LHC, the high centre-of-mass energy ($\sqrt{s}$) of pp collisions enables searches for theses new states up to mass regions not accessible before. For the identification of the boosted decay products powerful new reconstruction tools have been developed using e.g. the substructure of hadronic jets or dedicated lepton-isolation requirements.

In this article an overview is presented of searches for new resonances decaying to top quarks as performed by the CMS collaboration in data collected during the years 2015 and 2016 at $\sqrt{s} = 13\,\text{TeV}$. This includes searches for $t\bar{t}$ and tb resonances, resonances with decays to a SM top quark and a vector-like T quark, as well as excited top quarks.

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1. Introduction

The discovery of a Higgs boson by the ATLAS and CMS collaborations [1, 2] with properties in agreement with those predicted by the Standard Model (SM) and with a mass of $M_H \simeq 125\,\text{GeV}$, consistent with electroweak precision data [3, 4], marks a great success of the SM. However, the SM is known to be an incomplete theory since gravity is not included in the mathematical description and it leaves many questions unanswered – among them is the reason for the stability of M_H at the electroweak scale despite large quantum loop corrections. The largest contribution results from the SM top quark due to its large mass. Many models of physics beyond the SM introduce new particles which either couple to the SM top quark or feature similar properties as the SM top quark to cancel these divergent loop corrections.

During the last years, the ATLAS and CMS collaborations have started an enormous effort to search for all kinds of these new particles. The high centre-of-mass energy available in the pp collisions at the LHC provides sensitivity in mass ranges not accessible before. For this mass regime new reconstruction tools have been developed to identify the boosted decay products using e.g. special lepton isolation criteria or new techniques to separate the hadronic decays of signal events from the background of QCD multijet production based on the substructure of hadronic jets.

In this article, recent results of searches for new resonances with decays to top quarks using data recorded in 2015 and 2016 by the CMS experiment [5] are summarized. The data-sets have been taken at a centre-of-mass energy of $\sqrt{s}$=13 TeV and correspond to integrated luminosities of $2.6\,\text{fb}^{-1}$ and $35.9\,\text{fb}^{-1}$, respectively. Results are shown for CMS searches for $t\bar{t}$ and tb resonances, searches for resonances with decays to a SM top quark and a vector-like T quark, as well as searches for excited top quarks. Similar results of the ATLAS collaboration are discussed in [6]. The results of CMS searches for third generation leptoquarks can be found in [7]. The results of CMS searches for the production of vector-like quarks (VLQ) using similar experimental techniques are discussed elsewhere [8, 9].

2. Important reconstruction tools

Searches for high mass resonances with decays to SM top quarks require dedicated techniques for the reconstruction and identification of the decay products of the top quark since the large Lorentz boost leads to collimated objects in the final state.

In case of leptonic decays of the top quark ($t \to b\nu_{e/\mu}e/\mu$) the large Lorentz boost leads to leptons (e or μ) in close angular vicinity to a b-quark jet and the usual identification criterion of lepton isolation leads to a signal efficiency loss at both the trigger and offline level. For this reason special requirements have been developed to select lepton candidates from the boosted top decay and separate them from fake or true lepton candidates of the QCD background. Most CMS analyses in this area make use of a two-dimensional criterion requiring either a minimum angular separation between the lepton and the closest jet or an analysis-dependent minimum value for the lepton transverse momentum orthogonal to the jet axis: $\Delta R(l,j) > 0.4$ or $p_T^{\text{rel}}(l,j) > 20(50,60)$ GeV. In Fig. 1 (left) the performance of this '2d-cut' is compared to a 'mini-isolation' criterion based on a p_T dependent isolation cone around the lepton candidate ($R_{\text{mini}} \sim 1/p_T$). The two-dimensional requirement shows better background rejection over the full range in efficiencies for both electrons

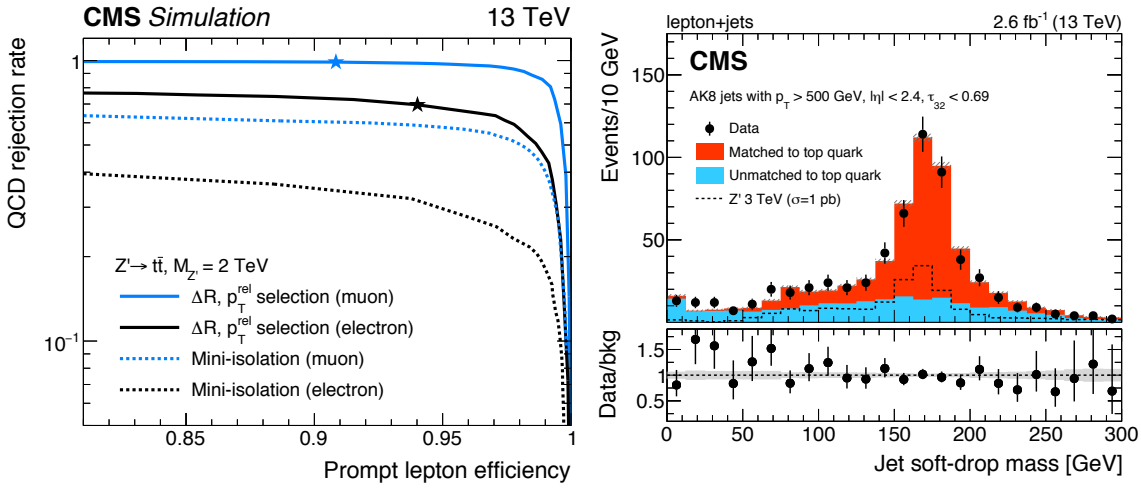

Figure 1: Performance studies of reconstruction tools for boosted decays: (left) comparison of the QCD rejection rate vs. prompt lepton efficiency in Z' signal events using the '2D-cut' and the 'mini-isolation' [10]; (right) distribution of the soft drop mass of jets identified with the anti-k_T algorithm with $R = 0.8$ after the kinematic selection indicated in the figure [14].

and muons [10]. After the identification of the lepton the four-momentum of the neutrino of the leptonic top quark decay can be reconstructed in l+jets events using the two components of the missing transverse energy E_T^{miss}, the negligible neutrino mass and the kinematic constraint from the mass of the decaying W. In this way, invariant masses of resonances decaying to top quarks can be calculated for events in the l+jets event category.

In case of hadronic decays of the top quark ($t \to bqq'$,) the large Lorentz boost leads to overlapping hadronic jets which can be identified using novel substructure techniques. Large progress has been made in the development, study and usage of these techniques in measurements and searches in run-1 of the LHC. An interesting new analysis in this area is the first measurement of the distribution of the jet mass in highly boosted $t\bar{t}$ events by the CMS collaboration [11]. For the identification of boosted hadronic top quark decays most searches in CMS make use of the 'CMS top tagger v2' algorithm [12] in which the constituents of jets identified with the anti-k_T algorithm using R=0.8 are reclustered with the Cambridge-Aachen algorithm. The 'soft drop' (SD) algorithm is then used to discard soft and wide-angle radiation jet components leading to an improved jet mass resolution of this algorithm as demonstrated in Fig. 1 (right) where the mass distribution is shown after the event selection as indicated in the figure. Furthermore, requirements on the N-subjettiness variables are used to increase the ratio of events with three subjets. Finally, the searches take advantage of b-tagging techniques applied on subjets to enhance the signal of hadronic top quark decays.

3. Searches for resonances decaying into top quark-antiquark pairs

Numerous SM extensions predict new particles which could be observable at the LHC as a resonance in the reconstructed invariant mass spectrum of a top quark-antiquark pair, $M_{t\bar{t}}$. Examples are massive colour-singlet Z-like bosons in extended gauge theories (Z') or Kaluza-Klein (KK) excitations of gluons (g_{KK}). Respective searches had been performed at the Tevatron and by the

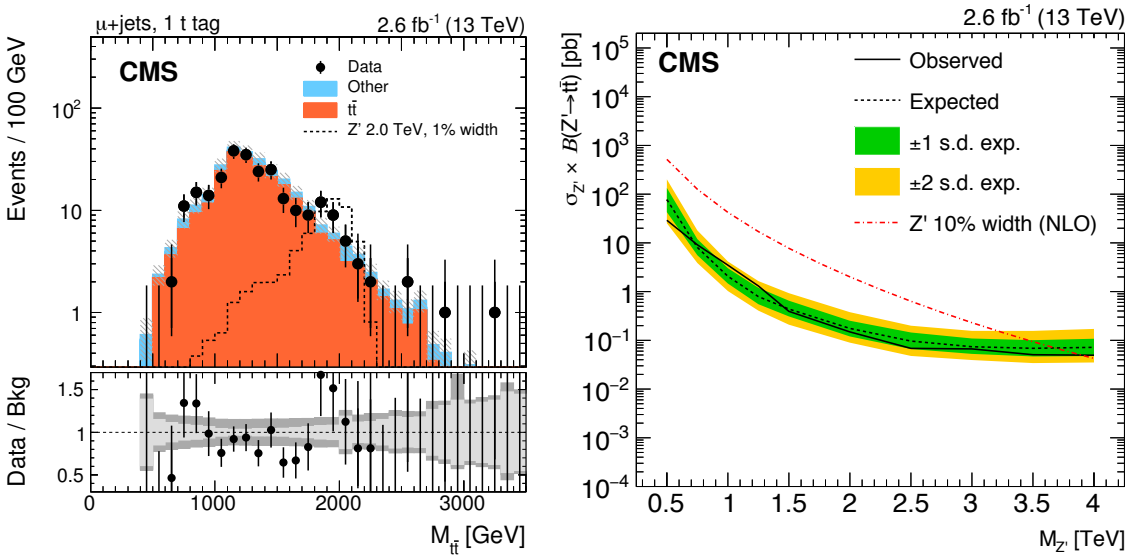

Figure 2: Searches for $t\bar{t}$ resonances in the 2015 CMS data set [14]: (left) distribution of the invariant mass of the $t\bar{t}$ system in data, expected background and Z' signal events in the (μ+jets, 1 t-tag) category; (right) observed and expected upper 95% CL limit on the production cross section times branching fraction as a function of the resonance mass as obtained for the full combination (fully hadronic and highly boosted e/μ+jets final states) compared to the theory prediction for a Z' boson with Γ/M of 10%.

ATLAS and CMS collaborations using LHC run-1 data. The most stringent run-1 limits have been obtained in the CMS 8 TeV analysis [13] which combines searches in the fully hadronic, l+jets and dilepton+jets channels and exclude Z' masses up to 2.9 TeV.

The data recorded during the year 2015 by the CMS detector with a centre-of-mass-energy of $\sqrt{s} = 13$ TeV have been analysed in the l+jets and the fully hadronic channels [14] using the reconstruction tools mentioned in Sect. 2. In the l+jets channel, selected events are classified in six exclusive categories based on the lepton flavour (e or μ) and the number of observed b- and t-tags. In these categories the invariant mass distribution in data has been compared to the SM background expectation. As an example the $M_{t\bar{t}}$ distribution in the μ+jets channel with 1 t-tag are shown in Fig. 2 (left) for data and expected background after a template fit. No deviation from the SM background expectation has been observed in any of the categories, which is also true for the fully hadronic channel where again six exclusive categories have been exploited.

From these results 95 % CL exclusion limits on the cross section times branching fraction are determined as a function of the resonance mass for the combination of the l+jets channel and the fully hadronic channel in four benchmark models with different resonance types (Z' or g_{KK}) and different relative resonance widths (Γ/M). Example limits for a Z' with $\Gamma/M = 10\,\%$ are shown in Fig. 2 (right). The exclusion limits for resonances with masses above 2 TeV are significantly improved compared to those of previous analyses at $\sqrt{s} = 8$ TeV. The comparison with the theory prediction yields mass limits in the region of 4 TeV thereby approaching the kinematic region where parton luminosities enhance the off-shell contribution of the cross section leading to non-resonant behaviour which will gain importance and requires a dedicated treatment in future analyses of larger LHC data-sets.

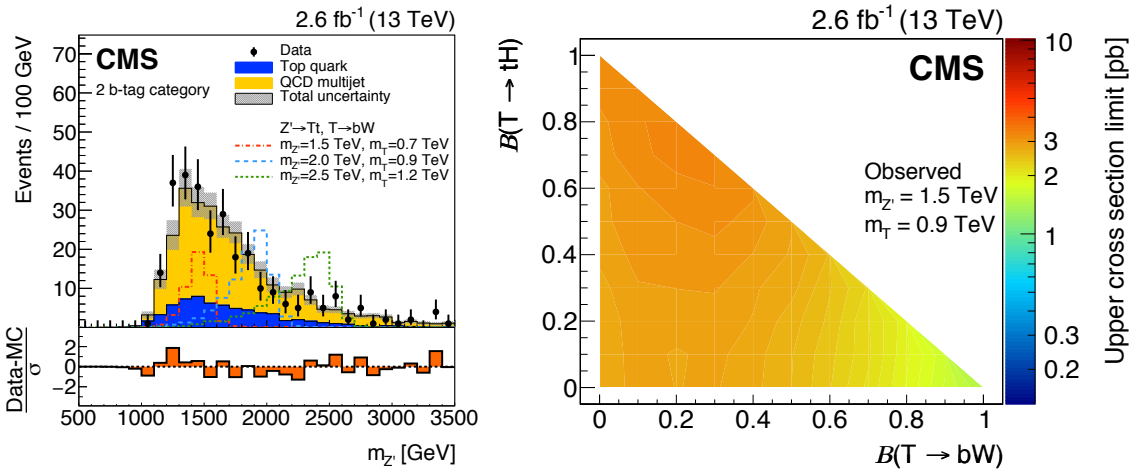

Figure 3: Searches for resonances with decays to a top quark and a vector-like T quark using the boosted fully hadronic channel in the 2015 CMS data-set [15]: (left) distribution of the invariant mass of the tT system for data, expected background and Z' signal events in the (2 b-tag) category; (right) observed 95% CL limits on the $Z' \to Tt$ production cross section for different branching fraction of the T quark decay into the bW and tH channels with $B(T \to tZ) = 1 - B(T \to bW) - B(T \to tH)$ for a particular (Z', T) mass configuration.

4. Searches for resonances decaying to a top and a vector-like T quark

As detailed in Sec. 3, the ATLAS and CMS collaborations have performed several searches for $t\bar{t}$ resonances and obtained very stringent limits. However, in certain new physics models including resonances with couplings to third-generation SM quarks an additional fermionic sector may be realised as a vector-like fourth generation of quarks. For this reason, the CMS collaboration performed a first search for resonances (Z') decaying into a SM top-quark and a heavy vector-like T quark: $Z' \to tT$ [15]. Indeed this decay mode is dominant for the intermediate mass configurations ($m_t + m_T < M_{Z'} < 2m_T$). The search in the 2015 CMS data-set makes use of the boosted fully hadronic event topology and is optimized for the decay channel $T \to bW$. In a 3-jet selection (t, b, W), the techniques of W-tagging, t-tagging, b-tagging and subjet b-tagging are exploited and events are classified in two categories based on the number of b-tags observed. As an example, the invariant mass distribution of the 2-b-tag category is shown in Fig. 3 (left) together with the expected SM background and the expected signal for various (Z', T)-mass combinations. No significant deviation from the SM expectation has been observed. For fixed values of the T branching fractions and of the T mass, upper cross sections limits in the order of 1 pb have been obtained as a function of the Z' mass. Furthermore a scan of the T branching fractions $BR(T \to bW, tH, tZ)$ has been performed for fixed values of the Z' and T masses. In Fig. 3 (right) one example scan result is shown. More data are needed for an exclusion of the theory benchmark models considered in the study.

5. Searches for resonances decaying to a top and a bottom quark

In addition, CMS has performed searches for heavy gauge bosons decaying into a top and a

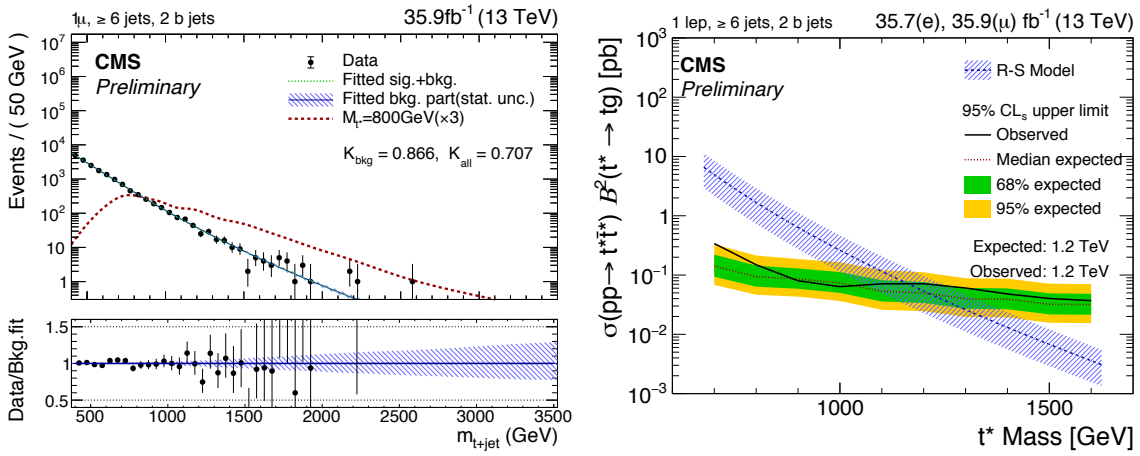

Figure 4: Searches for excited top quarks decaying to a top quark and a gluon using the l+jets channel in the 2016 CMS data set [19]: (left) data distribution of the invariant mass of the t+jet system in the μ+jets channel compared to the fitted background expectation and a hypothetical t^*-signal; (right) observed and expected upper 95% CL limit on the production cross section times branching fraction as a function of the t^* mass for the combined l+jets channel compared to the theory prediction in an extension of the Randall-Sundrum model.

bottom quark ($W' \to tb$). The 2015 data-set has been analysed [16] in the l+jets and in the fully hadronic channel. No significant deviation from the SM expectation has been observed and combined upper limits on the cross section times branching fraction have been obtained as a function of the mass of right-handed W' bosons leading to W'_R mass exclusion limits up to 2.6 TeV.

An update of the l+jets channel using the full 2016 data-set has been available as preliminary result at the time of the conference [17]. In the meantime, the result has been finalized and submitted to the scientific journal [18]. In this analysis, final states with a single lepton (e, μ), multiple jets and missing transverse momentum have been selected and classified in eight exclusive event categories with different signal and background sensitivities. No significant deviation from the SM background expectation has been observed in any category. Limits on the W'_R mass up to 3.6 TeV are derived. The exclusion limits are also presented as a function of their coupling strength to left- and right-handed fermions. These limits represent the most stringent limits for resonances decaying to top and bottom quarks published to date.

6. Searches for excited top quarks

A new result using the 2016 data-set is the CMS search for the pair production of spin-3/2 excited top quarks decaying in the decay channel $t^* \to tg$. The resolved analysis [19] in the l+jets channel requires the presence of an isolated lepton (e/μ), missing transverse momentum and at least six hadronic jets. The reconstruction of the t^* mass makes use of a χ^2 based method for the identification of the correct jet assignment. The resulting mass spectrum in the μ-channel is shown in Fig. 4 (left). No significant deviation from the background fit is observed. The 95% CL exclusion limit on the cross section times squared branching fraction as a function of the t^* mass is shown in Fig. 4 (right). For a branching fraction of 100% for its decay into top quark and gluon,

the analysis provides a lower limit of 1.2 TeV on the mass of the spin-3/2 excited top quark in an extension of the Randall-Sundrum model.

7. Conclusion

With the high centre-of-mass energy available in pp collisions of run-2 at the LHC, the importance of processes with boosted decays is highly increased. The ATLAS and CMS collaboration have started an enormous effort to identify these decays using dedicated reconstruction tools and to search for hints of new physics in boosted final states. In this article a review is given of the searches for resonances decaying to top quarks as performed by the CMS collaboration in the data-sets of the years 2015 and 2016. So far, no deviation from the SM background expectation has been observed and limits on the production cross section times branching fraction have been obtained for various final states. Most results represent the most stringent exclusion limits on the resonance masses to date. While the approach of conventional searches for resonant deviations in the invariant mass spectrum will still hold in future analyses for most final states, some analyses have reached mass limits up to 4 TeV and are approaching the kinematic region where parton luminosities enhance the off-shell contribution of the cross section leading to non-resonant behaviour which will require a dedicated treatment in future analyses of larger LHC data-sets, as already performed in recent searches for e.g. leptonic resonances ($Z' \to ll$) in CMS.

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