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Search for new resonances coupling to third generation quarks at CMS

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Abstract

We present an overview of searches for new physics with top and bottom quarks and top quark-antiquark pairs in the final state, using proton-proton collision data collected with the CMS detector at the CERN LHC at a center-of-mass energy of 13 TeV. The results cover non-SUSY based extensions of the SM, including new heavy gauge bosons, like a W boson replicating the features of its standard model counterpart, or excited third generation quarks. We considered both semileptonic and fully-hadronic scenarios. We explore the use of jet substructure techniques to reconstruct highly boosted objects in events, enhancing the sensitivity of these searches.

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1 Introduction

Nowadays the Standard Model of Particle Physics (SM) is the theory that best explains the fundamental interactions and particles, receiving several experimental confirmations over the years. Despite its extraordinary success, the SM has notable problems and questions still unresolved, for example the origin of neutrino mass, the hierarchy problem, and the mass pattern of the fermions. Several new physics beyond SM (BSM) theories have been consequently formulated, exploring different scenarios in which not yet known phenomena can appear.

In this context, third generation quarks could represent a door between the SM and new exotic physics. For this reason, many efforts have been performed in order to improve the reconstruction of the physics objects that signal their presence in the detector.

Furthermore, to make an analysis as sensitive as possible to processes that does not fit in the SM framework, new algorithms that are specific to the event topology of the considered BSM phenomenon have to be developed.

In this report, we present an overview of the following analyses regarding searches for New Physics with third generation quarks in final states:

- Search for a heavy resonance decaying to a t quark and a top Vector-Like Quark (VLQ) T (cfr Sec. 2) in the lepton+jets final state [18];
- Search for a W' boson decaying to a VLQ and a t or b quark in the all-jets final state [19];
- Search for resonant $t\bar{t}$ production [20].

All these studies are performed using datasets of proton-proton collisions at $\sqrt{s} = 13$ TeV, collected by the CMS Experiment during the Run II of LHC.

First of all, we briefly discuss the theoretical BSM models considered in the presented searches, and then some of the reconstruction techniques implemented in the analyses. Finally we focus on the studies themselves.

2 New Physics scenarios

In the last decades theoretical physicist have been performed several studies to arrange models able to predict physics phenomena outside the SM framework and reply to the unsolved question of the latter.

In general, new physics models predict the existence of some new gauge symmetries that enlarge the one considered in SM, namely $SU(3)_c \times SU(2)_L \times U(1)_Y$. In this report, two main scenario are considered:

- compositeness, in which particles that are fundamental in SM are bound states of new, undiscovered particles [10];
- new extra-dimensions [15, 16].

In this models, new resonances appear, with some of them that can be considered heavy partners of SM vector bosons:

- Z', W' , respectively heavy partners of SM Z, W [14, 17]
- composite spin-1 resonance ρ^0 [12]
- Kaluza-Klein excitations of gluon g_{KK} and graviton G_{KK} [2, 5]

In some cases, especially in composite models, new vector gauge bosons are accompanied with a new fermionic sector, constituted of heavy partners of SM quarks which behave as vectors under transformations of SM symmetry groups. They are called Vector-Like Quarks (VLQs), with B and T the partners of third generation quarks. New heavy bosons could decay in VLQs, that in turn could decay in t and b [1, 3].

In the last years, many searches have been performed for new bosons and VLQs, both separately and in processes where both types of particle were involved.

The new physics models mentioned above try to address, among other issues, the hierarchy problem, namely the naturalness of Higgs boson mass. Introducing new resonances, these cancel the top quark loop contributions to the radiative correction of the aforementioned mass, make it more "natural" [1]. In consequence of that, in many of these models new physics has a preference for third generation quarks, and therefore t and b are considered nowadays a portal to discovery of BSM phenomena.

In order to be more and more sensitive to new physics, experimentalists performed remarkable efforts to push further the ability to reconstruct and identify detected objects produced by third generation quarks and SM massive bosons.

3 Reconstructing physical objects in hadronic environment

3.1 Hadronic jets

Proton-proton collisions at LHC create an environment ideal for strong interactions. Lots of hadrons are consequently produced, and an algorithm that arranges and clusters their final products is needed from an experimental point of view to analyse the detected signals. In CMS collaboration, for this *anti- k_T* algorithm [8] is implemented through the FASTJET software package [7], which clusters reconstructed physical objects in cones, called *jets*, with a fixed angular opening, measured with the R parameter. In general, two values of R are used:

- $R = 0.4$, used for jets coming from the hadronisation of an isolated quark
- $R = 0.8$, used for jets that might stem from the overlapping signatures of multiple collimated quarks, that are typical of hadronic decays of high-momentum H, W, Z, t .

In the first case jets are called *AK4*, in the latter *AK8*.

While AK4 jets are considered the basic unit of hadronic objects, AK8 ones have a complex structure and their use is not straightforward.

Focusing on this type of jets, several corrections can be applied, in order to take account of some effects peculiar of hadronic environment that enter in the reconstruction procedure.

Additional proton-proton interactions within the same or nearby bunch crossings, called *pileup*, could give additional contributions to the jet momentum. To account for both the charged and neutral pileup component, the PileUp PerParticle Identification (PUPPI) algorithm [4] is used, which applies weights that rescale the jet transverse momentum based on the per-particle probability of originating from the primary vertex prior to jet clustering.

When PUPPI algorithm is used both for taking account of both charged and neutral pileup, further correction can be applied with the soft drop (SD) reclustering algorithm [13]. It reclusters the AK8 PUPPI jet j with the Cambridge-Aachen algorithm [11], and then separates it in two subjets, j_1 and j_2 , which must satisfy the SD criterion:

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^\beta$$

where p_{T1} and p_{T2} are the transverse momenta of the two subjets and ΔR_{12} is the distance between them, z_{cut} is the cutoff threshold and R_0 is the characteristic radius of the jet. If the aforementioned criterion is satisfied, the algorithm end with j as resulting jet. Otherwise, the lower- p_T subjet is discard, the procedure is iterated with the remaining one until SD criterion is met.

Applying this algorithm to AK8 jets, it's possible to obtain a jet momentum that is more reliable to be used as estimate of momentum of the particle that generated the jet itself. The corresponding mass, for instance, indicated in the following with m_{SD} , can be constrained to some values compatible with the nominal mass of some known particles, i.e. the top quark.

Once obtained a reasonably stable AK8 jet, it is possible to investigate its substructure in order to exploit its physical and geometric features. For this purpose, it's very useful to define the so-called *N -subjettiness* [22]:

$$\tau_N = \frac{1}{d_0} \sum_i p_{T,i} \min [\Delta R_{1,i}, \Delta R_{2,i}, \dots, \Delta R_{N,i}]$$

where i is a summation over all jet constituents, d_0 is a normalization constant, and ΔR is the distance between a given jet constituent i and a candidate subjet axis N . This quantity measures the consistence of an AK8 PUPPI jet with a substructure of N or fewer subjets. Small values of τ_N indicates greater compatibility.

In order to better exploit the information from this type of variables, several analyses define the following ratio:

$$\tau_{N(N-1)} = \frac{\tau_N}{\tau_{N-1}}$$

By construction, it measures the compatibility with the N -prong substructure, and so it helps to classify jets on the basis of the contained sub-objects. Such variable turns out to be a very powerful tool to determine the origin of an AK8 jet, as its substructure is strictly related to the type and the parent particle of the decay (cfr. Figg. 1)

Figure 1: Left, 2-prong substructure of a jet generated by a W . Right, 3-prong substructure of a jet generated by a t quark

After investigating the substructure of a jet, it is also possible to individuate the origin of its sub-jets. Algorithms that detect the presence of one or more subjets produced by b quarks have been developed [21], and they are implemented in every case b quarks are involved in.

3.2 Tagging techniques overview

Using all the information coming from the quantities introduced in the previous section, it is possible to develop some techniques that recognises the origin of an AK8 jet and discriminates one from another. This procedure is usually referred to as "tagging".

In the studies considered in this report, the following tagging algorithms involving AK8 jets were implemented:

- t tagger:
 - m_{SD} compatible with the nominal value of $m_t = 173$ GeV within a mass window, depending from specific analysis requirements;
 - τ_{32} values compatible with 3-prong substructure;
 - possibly the presence of a b tagged subjet.
- W/Z tagger:
 - m_{SD} compatible with the nominal value of $m_{W(Z)} = 80(91)$ GeV within a mass window, depending from specific analysis requirements;
 - τ_{21} values compatible with 2-prong substructure;
- H tagger:
 - m_{SD} compatible with the nominal value of $m_H = 125$ GeV within a mass window, depending from specific analysis requirements;
 - presence of a one or more b tagged subjets; Higgs boson preferentially decays in b quarks couple, the latter being the heaviest fermionic couple accessible to H .

Final states that are considered in [18–20] receive considerable contributions from SM processes, which therefore act as background to new physics topologies, and such contributions have to be accurately estimated. The tagging techniques described above play a key role to define an event topology capable to significantly enhance the sensitivity to BSM processes.

4 Heavy resonance decaying to a t and a top VLQ in the lepton+jets final state

A search for a heavy spin-1 resonance, generally called Z' decaying to a t and the corresponding VLQ partner T performed in lepton+jets final state is reported in [18]. For this purpose, a data set of proton-proton collisions at $\sqrt{s} = 13$ TeV of an integrated luminosity of 35.9 fb^{-1} , recorded by the CMS experiment at in 2016, has been used.

Figure 2: Feynman diagram associated to the signal searched for in [18]

The considered Z' decay mode is dominant for the mass region in which the decay is kinematically allowed (i.e., $M_t + M_T < M_{Z'}$) and the decay to two VLQ T is kinematically forbidden ($M_{Z'} < 2M_T$).

The search is performed in a model-independent manner by scanning over a large range of possible masses of the Z' and T and couplings of the T to various final states. A mass range of the Z' from 1.5 to 4.0 TeV and of the T from 0.7 to 3.0 TeV is considered.

As shown in 2, the VLQ T coming from the decay $Z' \rightarrow tT$ has three decay channels: $T \rightarrow Ht$, $T \rightarrow Zt$, and $T \rightarrow Wb$. The analysis is optimised for the first two channels, with single lepton + jets in final state, with one of the t quarks semileptonically decaying. The H or Z boson from the T decay likely receives a large Lorentz boost, as there is a large mass difference between parent and child particles. The resulting hadronic decay products will be merged and thus can be reconstructed in a single AK8 jet. The same reasoning can be applied to the t quarks that hadronically decay.

The SM backgrounds considered in this study are Drell-Yan + jets, W + jets, QCD multijet, $t\bar{t}$, and single t quark production. Simulated event samples of first three are produced at Next Leading Order (NLO), the latter at Leading Order.

Event categorisation is based on following taggers developed for the identification of AK8 jets:

- Z/W tagger: $100 < m_{SD} < 150 \text{ GeV}$ and $\tau_{21} < 0.5$;
- H taggers: $100 < m_{SD} < 150 \text{ GeV}$ and presence 1 (H_{1b}) or 2 (H_{2b}) b -tagged subjects;
- t tagger: $150 < m_{SD} < 220 \text{ GeV}$ and $\tau_{32} < 0.57$.

The first two are used to define the main categories, while the latter is used to define additional subcategories for both resolved and merged decays of the hadronically decaying t quark, in order to ensure a high sensitivity over a broad range of the Z' mass.

If one AK8 jet passes the requirements of more than one type of tagging algorithms, priority is given in following order to obtain the best signal sensitivity: H_{2b} , H_{1b} , Z/W . Events are required to contain at least one H_{2b} tagged jet, one H_{1b} tagged jet, or one Z/W tagged jet and are consequently classified. Categories obtained in this way are then divide in two subgroups depending on t tagger output. In all categories, the Z' mass is reconstructed considering various combinations of reconstructed objects, and the final combination is determined with a χ^2 metric.

A binned likelihood combining the reconstructed Z' invariant mass distributions in all categories and channels is constructed to compare the signal and SM backgrounds. The rate of the dominant SM background processes

predicted by simulation, namely $t\bar{t}$ and W +jets, is constrained using the mass spectra in dedicated control regions, and are fit simultaneously with the signal ones.

No significant excess of events in the data over the expected background contributions is found for the ranges of Z' and T masses considered. A Bayesian calculation is used to derive 95% CL upper limits on the product of the cross section and branching fraction, $\sigma(pp \rightarrow Z' \rightarrow tT)\mathcal{B}(T \rightarrow Ht, Zt, Wb)$, for the considered signal.

The results are, then, interpreted in the context of two benchmark models, in which Z' is either a spin-1 Kaluza-Klein excitation of the gluon, G^* , or the resonance ρ^0 . G^* masses are excluded between 1.5 and 2.3 TeV for a T mass of 1.2 TeV, between 2.0 and 2.4 TeV for a T mass of 1.5 TeV, and no exclusion of this model are made for a T mass of 1.5 TeV (cfr. Fig. 3). For what concerns ρ^0 model, the analysis is not able to exclude it yet, as it is quite close to the exclusion for some values of ρ^0 mass.

Figure 3: Upper limits on $\sigma(pp \rightarrow Z' \rightarrow tT)\mathcal{B}(T \rightarrow Ht, Zt, Wb)$ for G^* scenario for $m_T = 1.2(1.5)$ TeV on left (right) [18].

In conclusion, the limits extracted in this study are the most stringent to date for the decay mode $Z' \rightarrow tT \rightarrow tHt$.

5 W' decaying to a VLQ and a t or b in the all-jets final state

A search for a W' boson decaying to a heavy B or T VLQ and a top or b quark is reported in [19]. For the first time a such study is performed. The data sample used corresponds to an integrated luminosity of 35.9 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$, recorded in 2016.

The study considers the decay channel where the B or T VLQ decays into a H and a b or t quark, respectively, in the all-jets final state. Both the B and T VLQ-mediated decays have the same signature (cfr. Fig. 4).

Figure 4: The W' boson production and decays considered in the analysis [19].

The search is performed for W' masses in the range 1.5 to 4.0 TeV with the assumptions that the branching fraction of W' to VLQ is equally distributed between the tB and bT final states. As benchmark, the VLQ branching fractions for each of the decays $B \rightarrow bH$ and $T \rightarrow tH$ are assumed to be 50%. For each W' boson mass ($m_{W'}$) point, three VLQ mass points are generated in a range from 0.8 to 3.0 TeV. These are scaled to $m_{W'}$ in order to have low ($\approx 1/2 m_{W'}$), medium ($\approx 2/3 m_{W'}$), and high ($\approx 3/4 m_{W'}$) mass sample for each W' boson mass point and explore the sensitive phase space of the boosted decay products. The generated W' and VLQ widths are narrow as compared with the detector and reconstruction resolutions.

The SM background is dominated by events of QCD multijet and $t\bar{t}$ production. These backgrounds are evaluated with a combination of Monte Carlo simulation and control regions in data.

Because of the high W' and VLQ masses considered in this analysis, the decay products present a significant Lorentz

boost with respect to the CMS reference frame. The jets from the t quark (t jet) and H boson (H jet) decays tend to be wide and massive, and are reconstructed with AK8 jets, whereas the jet from the b quark (b jet) will tend to be narrow and have a lower mass, and is reconstructed with an AK4 b -tagged jet isolated from the AK8 ones.

These boosted decay products are then reconstructed as single jets with distinct substructure, which is exploited by the following taggers:

- t tagger: $105 < m_{SD}^t < 210$ GeV, $\tau_{32} < 0.8$ and at least one b subjet;
- H tagger: $105 < m_{SD}^H < 135$ GeV and two b subjets.

Such taggers are crucial in distinguishing signal from SM QCD multijet production. Anti-taggers are obtained reverting one or more of the requirements applied in the taggers, and are combined to define control regions (CRs).

QCD multijet contribution is evaluated by extracting pass-to-fail ratio for H -tagged jets in t anti-tagged control regions, used to weight events which are t tagged and H anti-tagged in the signal region. Ratio is validated in dedicated regions defined reverting also the request on the b tag for the AK4 jet.

The $t\bar{t}$ component is estimated, instead, using simulated events.

The invariant mass distribution of the three-jet system, m_{tHb} , is used to perform a binned maximum likelihood fit to data. Since no excess due to the signal has been observed, a Bayesian approach with a flat prior for the signal cross section is used to set the first upper limits on the product of the W' boson production cross section to set the first limits on the W' boson production cross section and decay channel to a B or T VLQ branching fraction, in the considered theoretical scenarios. For the signal, the sum of reconstructed m_{tHb} distributions from the tB and bT decay channels is used (cfr. Fig. 5). Although no signal mass points are excluded by solely analysing the all hadronic $W' \rightarrow T/B \rightarrow tHb$ decay, a W' with a mass below 1.6 TeV is excluded at 95% CL in the case of a 100% bT branching fraction hypothesis.

Figure 5: On left, m_{tHb} distributions in signal region. On right, upper limits on $\sigma(pp \rightarrow W')\mathcal{B}(W' \rightarrow tHb)$ for medium VLQ mass scenario [19].

6 Resonant $t\bar{t}$ production

In [20] a model-independent search for $t\bar{t}$ resonances is performed. It is based on $\sqrt{s} = 13$ TeV proton-proton collision data collected in 2016 by the CMS experiment at the LHC.

The $Z' \rightarrow t\bar{t}$ simulation used in this analysis produces a resonance with the same coupling to fermions as the SM Z boson. In the production, g_{KK} and set of Z' models encompassing a wide range of models are considered. The signal process is simulated at masses between 500 GeV and 7 TeV for resonances with a relative decay width Γ/m of 1% (narrow), 10% (wide), and 30% (extra-wide). For what concerns the g_{KK} resonance, the Γ/m lies between the wide and extra-wide Z' resonances.

The analysis establishes three categories basusersoffice@fnal.gov on dilepton, single-lepton, and fully hadronic decay modes of the $t\bar{t}$ system.

Figure 6: Feynman diagram of $t\bar{t}$ resonant production considered in [19].

In the dilepton final state the large mass of the resonance causes the resulting t quarks to be significantly boosted, which leads to a collimated system consisting of a lepton and a b jet. Only AK4 jets are used to reconstruct the event, then, in order to detect the b quarks coming from t decays. The main SM background is $t\bar{t}$ non-resonant production. Other contributions come from Z boson produced in association with jets (Z +jets), single t quark, and diboson processes. Events that have a large separation between the lepton and b jet populates the control regions, used to validate the modeling of the SM backgrounds.

For the single-lepton final state a t tagging algorithm is used to identify hadronically decaying t quarks ($t \rightarrow qq'b$). The $t\bar{t}$ couple is reconstructed by assigning the reconstructed final-state objects (charged lepton, p_T^{miss} , and jets) to the leptonic or hadronic legs of the decay. For events without an AK8 jet, several hypotheses are investigated based on possible assignments of each AK4 jet. For events with an AK8 jet, that jet is associated with the hadronic t decay, and for the leptonic t decay only AK4 jets that are isolated from the AK8 are considered. In both cases, the combination chosen is the one that minimizes a χ^2 discriminator. In this channel, the largest backgrounds are the $t\bar{t}$ non resonant production and W bosons produced in association with jets (W +jets). The latter background is separated from the signal using a multivariate analysis technique.

In the fully hadronic channel two AK8 jets are required to pass the t tagger. Because of the dijet topology, the largest background arises from QCD interactions between the colliding protons, referred to as QCD multijet production. In order to considerably reduce its contribution, one of the AK4 subjects in each of the two t tagged jets are required to be b jets. As in other scenarios, the other main SM background is $t\bar{t}$ non-resonant production.

The t tagger implemented in single-lepton and fully hadronic channels is described in [6].

QCD multijet in the fully hadronic channel is the only one estimated from data. It is evaluated with the anti-tag and probe technique that, estimating the mistag rate in QCD multijet events, weights its contribution [9].

The sensitive quantity used for fit to data are the reconstructed $t\bar{t}$ invariant mass ($m_{t\bar{t}}$) distribution for the single-lepton and fully hadronic analyses, and the S_T quantity, defined as:

$$S_T = \sum_{i=1}^{N_{jet}} p_{T,i}^{jet} + \sum_{i=1}^2 p_{T,i}^l + p_T^{miss}$$

The shapes of all other SM backgrounds are estimated from simulation. The total normalization of each simulated sample is obtained from a simultaneous binned maximum likelihood background-only fit to the reconstructed $t\bar{t}$ invariant mass ($m_{t\bar{t}}$) distribution for the single-lepton and fully hadronic analyses. After that, a signal+background simultaneous fit is performed.

Data are found to be in agreement with SM expectations in each of the categories considered. Limits on the product of the production cross section and branching fraction, $\sigma(pp \rightarrow X)\mathcal{B}(X \rightarrow t\bar{t})$, are then calculated for heavy resonance decaying to a pair of top quarks (cfr. Fig. 7) for every theoretical scenario investigated. The analysis excludes narrow Z' bosons with masses up to 3.80 TeV, wide Z' bosons with masses up to 5.25 TeV, extra wide Z' bosons with masses up to 6.65 TeV, and the g_{KK} resonance masses up to 4.55 TeV. These results represent a significant improvement on the previous ones in this channel derived from the data collected in 2015 only, due to both for the increase in integrated luminosity and improved reduction and estimation strategies. Such measurement provides the most stringent exclusion limits on a $t\bar{t}$ resonance to date.

Figure 7: Sensitivities for each analysis channel compared. The expected limits at 95% CL are specifically shown for the g_{KK} signal hypothesis [20].

7 Summary

The CMS Collaboration performed several searches for non-SUSY new physics with top and bottom quarks and top quark-antiquark pairs in the final state, using proton-proton collision data collected with the CMS detector at the CERN LHC at a center-of-mass energy of 13 TeV. In order to enhance sensitivity of the analysis to new physics signal as much as possible, new tagging techniques which use jet substructure information have been developed and tested. Thanks to them, the studies we have reported have been able to investigate some new physics processes for the first time and push further previous limits on cross sections of processes already explored at lower luminosities or center-of-mass energies.

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