Searches for $t\bar{t}$ Resonances at CMS

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We present a search for new massive particles decaying to a pair of top quarks with the CMS detector at the LHC. Proton-proton collision data recorded at a center-of-mass energy of 13 TeV is used. The search is performed by measuring the invariant mass distribution of the top-quark pair and testing for deviations from the expected Standard Model background. Final states with 0 or 1 leptons are considered, and the selection is optimized accordingly. In the high mass ranges accessible by the LHC at these energies, the top quarks are produced with high transverse momenta: the products of hadronically decaying top quarks emerge as a single jet, whereas the products of the semileptonic decay mode are characterized by the overlap of the lepton and the b jet. Specific reconstruction algorithms and selections are employed to address the identification of boosted top quark signatures. The results are presented in terms of upper limits on the model cross section. Models of Randall-Sundrum Kaluza-Klein gluon production as well as narrow, wide, and extra-wide Z' boson models are considered.

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1. Introduction

This note focuses on the search for heavy "Beyond-the-Standard-Model" (BSM) resonances that decay preferentially to top quarks [1, 2], using data recorded by the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) during the 2015 proton-proton run, with a collision energy of $\sqrt{s}$ = 13 TeV [3]. We consider a leptophobic topcolor Z' model, in which the Z' width is either 1%, 10%, or 30% of its mass. Randall-Sundrum Kaluza-Klein (RS KK) gluon production is also considered. Two decay channels are studied: the all-hadronic channel, in which both tops decay hadronically, and the semileptonic channel, in which one top decays hadronically and the other decays leptonically. At the high energies reached by the Run II LHC, each top quark is expected to be highly Lorentz-boosted, with the subsequent decay products merged into a single jet. The latest reconstruction techniques are used, namely b-tagging and top-tagging. To identify hadronically-decaying top quarks, we make use of the CMS Top Tagger Version 2 (CMSTTv2) algorithm [4]. We identify b jets using the Combined Secondary Vertex v2 (CSVv2) algorithm [5, 6]. We then use the $t\bar{t}$ invariant mass spectrum to search for a signal peaking over the falling Standard Model (SM) background.

2. Event Selection

Due to the high mass of the Z', events are described by a dijet topology in which each top is boosted and its decay products are merged into a single jet. The dijet event selection requires two back-to-back high p_T jets, in the case of the all hadronic decay mode. The semileptonic selection requires an energetic lepton (electron or muon), missing energy, a large-radius high p_T jet, and a smaller radius jet. In order to increase sensitivity, each analysis separates its events into six categories. The all-hadronic channel requires two top-tagged jets that are separated into event categories based on the rapidity (y) separation between the two jets ($|\Delta y| < 1.0$ or $|\Delta y| > 1.0$) and the number of top jets with subjet b-tags (0, 1, or 2). The semileptonic selection separates events into electron and muon channels. Then, each channel is separated into events with either 1 top-tag, 0 top-tags and 1 b-tagged jet, or 0 top-tags and 0 b-tags.

For the all-hadronic channel, the SM backgrounds consist of $t\bar{t}$, which is estimated from simulation, and QCD, which is estimated from data. The semileptonic SM background consists of $t\bar{t}$, W + jets, single top, Drell-Yan + jets, VV, and QCD, all of which are estimated from simulation. The kinematics of the boosted event topology are utilized to determine additional selection criteria to remove background from the semileptonic channel. In a lower energy regime, an isolation requirement would be placed on the lepton, but in the boosted regime the lepton can overlap with the b-jet. Therefore, a 2D requirement is made: $\Delta R(l, j) > 0.4$ or $p_T^{\rm rel}(l, j) > 20$ GeV, where j indicates the small-radius jet with minimum angular separation to the lepton (electron or muon) l, and $p_T^{\rm rel}(l, j)$ is defined as the magnitude of the lepton momentum orthogonal to the axis of jet j. The left plot in Fig. 1 shows the high QCD background rejection power of the 2D cut, as compared to a simple isolation requirement. Additionally, a $\chi^2 < 30$ cut is made, where χ^2 is defined as

$$\chi^2 = \left(\frac{M_{lep} - \overline{M}_{lep}}{\sigma_{M_{lep}}}\right)^2 + \left(\frac{M_{had} - \overline{M}_{had}}{\sigma_{M_{had}}}\right)^2,$$

(2.1)

where M_{lep} and M_{had} are the invariant masses of the reconstructed leptonic and hadronic top quark, respectively. The right plot in figure 1 shows the distribution of the χ^2 variable.
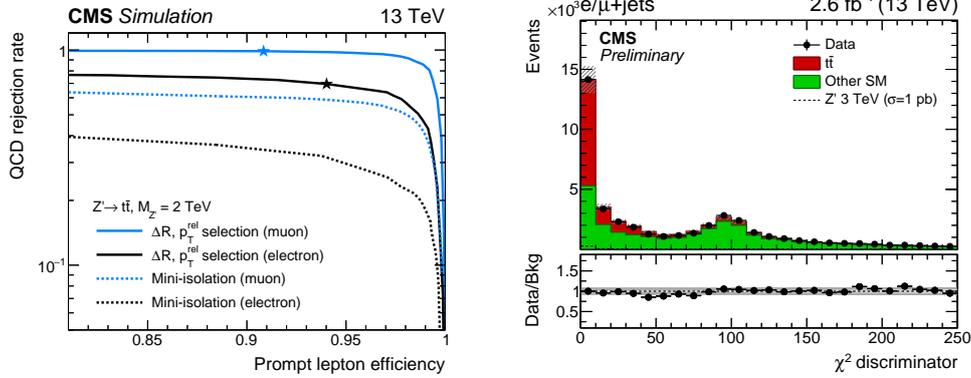
Figure 1: Kinematic variables used in the semileptonic event selection. Left: QCD rejection rate as a function of the reconstruction efficiency of prompt leptons from W decays in signal events. It is evident that using a 2D cut (solid curves) instead of an isolation requirement (dashed curves) results in a large gain in QCD rejection. The stars indicate the muon (blue) and electron (black) channel working points. Right: The distribution of the χ^2 variable, where the red histogram shows SM $t\bar{t}$, the green is other SM background, the dotted curve is the signal, and the black points are data. The $\chi^2 < 30$ cut keeps most of the $t\bar{t}$ events and rejects most of the other SM background.

3. Top-tagging

Top-tagging is done using CMSTTv2 - the latest top-tagger developed for CMS in Run II of the LHC. It uses the softdrop grooming algorithm, which removes soft and collinear radiation from a jet, to determine the softdrop mass (M_{SD}) of the top jet [7]. It also places an N-subjettiness (τ_{32}) requirement on the jet. N-subjettiness distinguishes 3-pronged jet substructure, indicative of a top jet, from non-top jets and is useful for distinguishing signal from QCD background [8]. The top-tagging working point requires the top jets to have 110 GeV $< M_{\mathrm{SD}} < 210$ GeV and $\tau_{32} <$ 0.69, which corresponds to a 3% QCD mistag rate in simulation. Figure 2 shows "N-1" plots for these two cuts after the semileptonic selection. A nice top peak can be seen in the softdrop mass distribution, and very good data/MC agreement is observed in both plots.

4. Results

The sensitive variable in this analysis is the $t\bar{t}$ invariant mass - we look for a signal peaking over the falling background spectrum. Figure 3 shows the mass distributions for the $|\Delta y| < 1$, one subjet b-tag category in the all-hadronic channel and the combined e/μ, one top-tag category in the semileptonic channel. After the event selection, the invariant mass spectrum shows reasonable signal/background discrimination, though no excess can be seen in the data. Limits on the production cross section times branching ratio are set as a function of mass for the four signal hypotheses, combining all six event categories for both the all-hadronic and semileptonic analyses. Figure 4
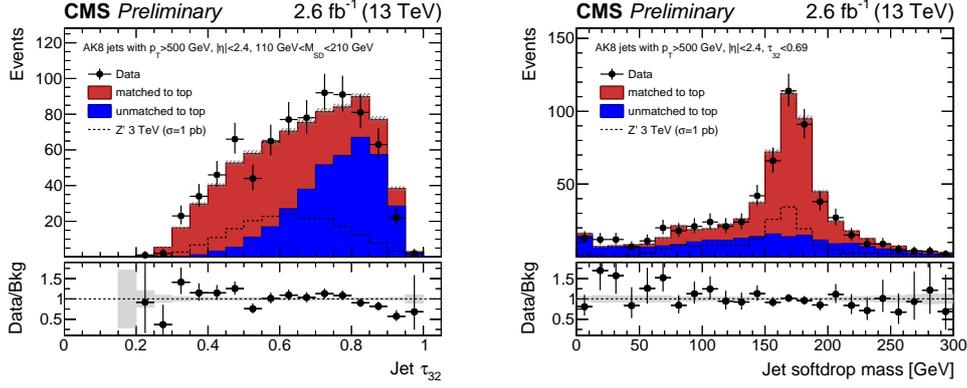
Figure 2: Distributions of the N-subjettiness ratio τ_{32} (left) and the softdrop mass M_{SD} (right) in data and simulation after the semileptonic signal selection. The distribution of τ_{32} is shown after the selection $110 < M_{SD} < 210$ GeV and the distribution of M_{SD} is shown after the selection on $\tau_{32} < 0.69$.

Decay Channel	Observed Limit			
	Narrow Z′	Wide Z′	Extra Wide Z′	RS KK Gluon
Semileptonic	0.6 − 2.3	0.5 − 3.4	0.5 − 4.0	0.5 − 2.9
All-Hadronic	1.4 − 1.6	1.0 − 3.3	1.0 − 3.8	1.0 − 2.4

Table 1: Comparison of the observed mass exclusion results for the semileptonic and all-hadronic analyses.

shows the limits set by both analyses for a narrow Z', while Table 1 shows the observed limits for all four signal hypotheses.
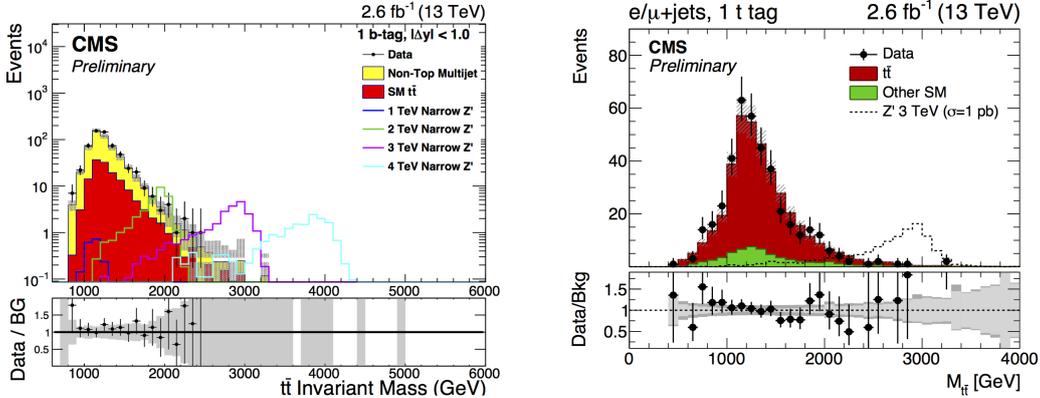
Figure 3: Distributions of the $t\bar{t}$ invariant mass after the $|\Delta y| < 1.0$, one b-tag all-hadronic (left) and combined e/μ, one top-tag semileptonic (right) event selection. The solid histograms show the background, the curves show the expected signal, and the black points show the data. Although good signal to background discrimination is seen, no excess is observed.

5. Summary

The first 13 TeV searches for high-mass top quark pair resonances in the all-hadronic and semileptonic channels were performed, using 2.6 fb^{-1} of CMS data. The latest reconstruction
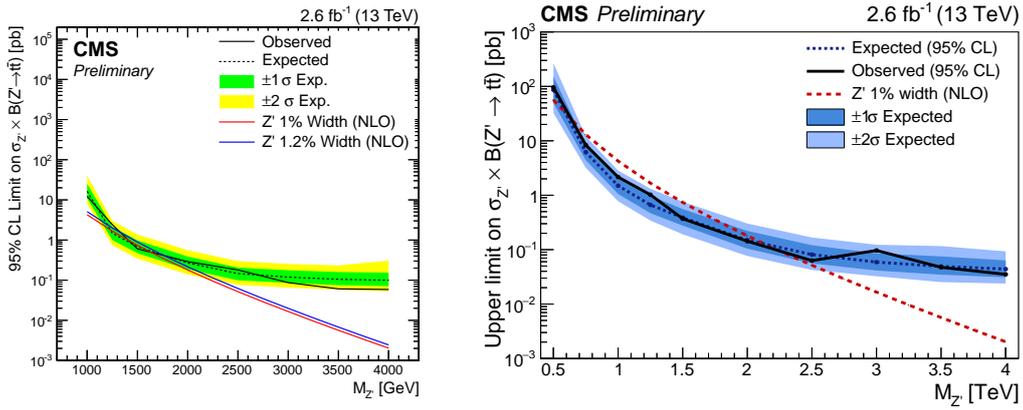
Figure 4: 95% Confidence Level (CL) limits on the cross section times branching ratio of the narrow Z' boson as a function of mass. The dashed black line shows the median expected limits, while the solid black line gives the observed limit. The one sigma expected limit band is shown in green (dark blue) for the all-hadronic (semileptonic) channel, while the two sigma band is shown in yellow (light blue). The red and blue lines give the theoretical cross section predictions.

techniques were used, including the Run II CMS top tagger. No signs of new physics were observed, and upper limits were set for Z' bosons of various widths and RS KK gluons. Improvements were seen with respect to the 8 TeV results. For instance, a wide Z' boson (10% width relative to its mass) was previously excluded up to a mass of 2.8 TeV [9], whereas the 13 TeV all-hadronic (semileptonic) search extends this limit up to 3.3 (3.4) TeV. Further increases in sensitivity are expected with the inclusion of 2016 data and the combination of the all-hadronic and semileptonic channels.

References

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