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Searches for vector-like quarks, $t\bar{t}$ and $t+b$ resonances with ATLAS and CMS

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In many models of physics beyond the Standard Model, the coupling of new physics to third generation quarks is enhanced and signatures are expected that mimic top quark production. Results from searches for new resonances decaying to a top-antitop or a top-b-jet pair are presented. In addition, we report on several search channels for heavy vector-like quarks decaying to a Higgs boson, a W boson, or a Z boson in association with top or b quarks. Many results use novel analysis techniques to reconstruct the highly boosted final states that are created in these topologies. The searches are performed on data collected with the ATLAS and CMS experiments in proton-proton collisions at the LHC at centre-of-mass energies of 7 and 8 TeV.

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1. Introduction

In many extensions of the standard model (SM), new heavy particles with enhanced couplings to quarks of the third generation are predicted. Especially the heavy top quark plays an important role in many new physics models. In such theories, predicted heavy gauge bosons might preferably decay into a top-antitop or, in case of a W-like W′ boson, a top-b quark pair. Also quark-like new particles are often predicted to decay into a top or b quark in association with a W, Z or Higgs boson. The experiments ATLAS [1] and CMS [2] have performed several searches for such heavy particles produced in proton-proton collisions at the Large Hadron Collider (LHC). Their results are presented in the following.

In many of these analyses, top quarks originating from the decay of a heavy new particle are expected to be produced with relatively high momentum. The top quark decays nearly instantaneously and all decay products of the top quark are emerging the interaction region of the initial proton-proton collision within a small angular cone if the top quark has been produced with large boost. This leads to a merging of the decay products and with classical reconstruction tools it becomes difficult to separate them properly based on their detector signals. As an example, a top quark produced with low momentum decaying into a b quark and W boson and the W boson decaying hadronically into two light quarks, normally leads to a signature of three well separated hadronic jets originating from the hadronisation of the three quarks. In case of a highly boosted top quark in the hadronic decay mode, the three jets will merge into one so called *fat* jet. To distinguish such a fat jet from a normal jet, dedicated algorithms have been developed based on the inspection of the jet substructure.

Most so-called *top tagging* algorithms are based on sequential clustering jet algorithms where the last clustering steps are reverted to make the substructure of a jet visible. One specific top tagging algorithm is the CMS Top Tagger [3, 4] which is variation of the Johns Hopkins Tagger [7]. It utilizes Cambridge-Aachen jets [5, 6] with a radius parameter of $R = 0.8$. In the declustering of the jet, at least three subjets are selected that carry at least 10% of the full jet transverse momentum p_{T}. The invariant mass of all three subjets has to be consistent with the top quark mass m_{t}, the invariant mass of a subjet pair has to be consistent with the mass of the W boson m_{W}. Another example is the HEP Top Tagger [8] which is based on Cambridge-Aachen jets with a radius parameter $R = 1.5$. The subjets constructed in the declustering of the entire jet are required to fulfill certain filtering criteria. Reconstructed mass ratios of pairs and triplets of subjets must be consistent with the mass ratio $m_{\mathrm{W}}/m_{\mathrm{t}}$. Due to the larger cone size of 1.5, the HEP Top Tagger is more efficient to detect top quarks with intermediate momenta between 200 GeV and 400 GeV, whereas the CMS Top Tagger has the highest efficiency for top quarks above 400 GeV.

Besides these two algorithms, a variety of other techniques is used in several analyses. Also the tagging of highly boosted W, Z or Higgs bosons is possible when requiring the presence of two instead of three subjets in the declustering step. In these so-called *V tagging* algorithms, the invariant mass of the subjet pair is required to be consistent with a W, Z or Higgs boson mass, respectively.

2. Search for $\mathrm{t\bar{t}}$ resonances

Heavy gauge bosons decaying into a $\mathrm{t\bar{t}}$ pair are predicted by many beyond the SM theories. The ATLAS and CMS collaborations have performed searches for $\mathrm{t\bar{t}}$ resonances in the full hadronic decay channel [9, 10] where both top quarks decay into three quarks, and in the lepton+jets channel where one top quark is assumed to decay into hadrons and the second top quarks into b-quark, charged lepton and neutrino [10, 11]. The ATLAS analysis of the full hadronic channel is based on the full dataset recorded in 2011 at a centre-of-mass energy of 7 TeV, all other measurements use data taken in 2012 at 8 TeV centre-of-mass energy.

In the full hadronic channel, events with two top tagged jets with high transverse momentum are selected. The ATLAS analysis [9] selects events in two categories. In the first category, events with at least two jet fulfilling the criteria of the HEP Top Tagger are selected. For the second event category, jets are identified as top jets using a template tagger. The template tagger quantifies the overlap of the energy flow inside a jet with the expected energy flow of a boosted top quark decay. The template distributions for the expected energy flow are taken from simulated top quark events and only jets with a measured energy flow compatible with one of the simulated templates are selected. In addition, the jet mass has to be compatible with m_{t}. The signal fraction in both event categories is enhanced by combining top tagging with b quark tagging. The CMS analysis [10] utilizes the CMS Top Tagger for the resonance search in the full hadronic decay channel. As in the ATLAS analysis, events with at least two top tags are selected. The main background in both analyses is QCD multi-jet production with misidentified top jets. Its contribution is estimated from control regions with inverted top tagging criteria.

In the lepton+jets decay channel, the event signature of boosted top quarks consist of one merged jet from the hadronic top quark decay, a charged lepton close to a second jet from the leptonic top quark decay and missing transverse energy from the neutrino. Both analysis from ATLAS [11] and CMS [10] consider electrons and muons as charged leptons. Due to the merging of the leptons with the neighboured jet, modified isolation criteria are being applied to select signal events with high efficiency but rejecting misidentified leptons or soft leptons from secondary hadron decays. The ATLAS measurement uses a shrinking isolation cone with increasing lepton momentum, in the CMS analysis combined cuts on the distance and the relative momentum of the lepton with respect to the jet are applied. For the selection of the hadronic top quark candidate, only the ATLAS analysis uses jets with a larger cone size of $R = 1.0$ together with a substructure cut. In the CMS measurement, only standard jets with a small radius parameter of $R = 0.5$ are used to select candidates for the hadronically decaying top quark.

The reconstructed invariant mass of the top-antitop quark pair $m_{\mathrm{t\bar{t}}}$ is used to search for resonances on top of the background. No excess is observed in all analysis channels and limits are set for various models. The most stringent limits are obtained in the combined CMS analysis. As an example, the invariant mass distribution measured in the ATLAS lepton+jets analysis and limits on the cross section of a narrow topcolor $\mathrm{Z'}$ boson [12] obtained in the combined CMS measurement are shown in figure 1. The topcolor $\mathrm{Z'}$ boson with narrow width can be excluded for masses below 2.1 TeV, a topcolor $\mathrm{Z'}$ resonance with 10% width is excluded up to a mass of 2.7 TeV. Kaluza-Klein excitations of the gluon [13] decaying to $\mathrm{t\bar{t}}$ are not allowed if their mass is below 2.5 TeV.

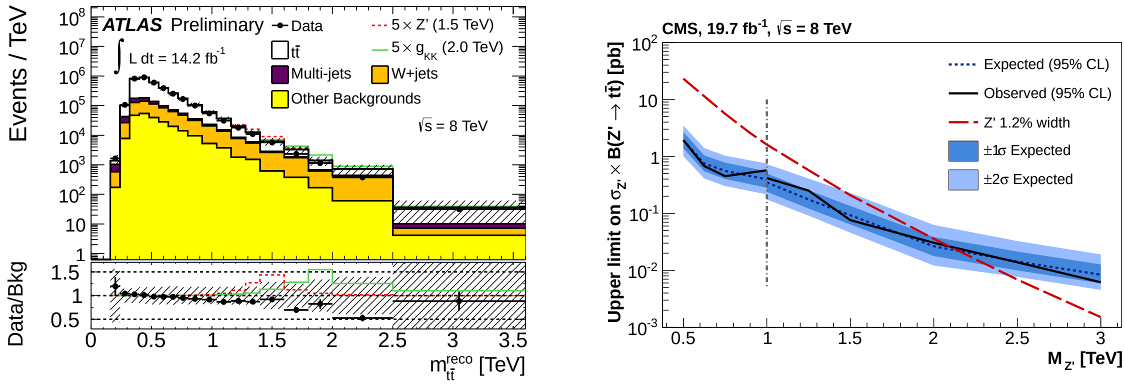

Figure 1: The $t\bar{t}$ invariant mass distribution measured in the lepton+jets channel by the ATLAS experiment [11] (left) and the limits on the production cross section of a narrow topcolor Z' resonance obtained in a combined CMS analysis [10] (right).

3. Search for $t+b$ resonances

Similar to heavy gauge bosons decaying to $t\bar{t}$, also electrically charged W' bosons preferably coupling to third-generation quarks may exist. Both collaborations ATLAS [14] and CMS [15] have preformed searches for a W' boson decaying into a top and b quark using data collected at a centre-of-mass of 8 TeV. The top quark is always assumed to decay leptonically into a charged lepton, a neutrino, and a b quark. Together with the b quark originating directly from the W' decay, this leads to an event signature of two b-tagged jets, one electron or muon, and missing transverse energy. To enhance the signal fraction, events with up to three jets are selected too; in the CMS measurement also events with only one b tag are accepted.

The invariant mass of the t+b system m_{tb} is reconstructed to further discriminate the W' signal from the main SM backgrounds $t\bar{t}$, single top quark, and W+jets production. For the reconstruction of m_{tb}, first the top quark four-momentum is derived from the momenta of one jet, the lepton, and the neutrino that is reconstructed from missing transverse energy. The four momentum of the top quark is then combined with the momentum of one of the remaining jets to reconstruct the momentum of the hypothetical W' boson and its mass. In the CMS analysis, m_{tb} is used directly to search for W' resonances that should appear as enhancements at high values in the m_{tb} distribution. For a better separation of the signal from the background, the ATLAS analysis makes use of Boosted Decision Trees (BDT) that combine the information from several variables including m_{tb} as most important one.

Both measurements do not observe any excess in data over the SM background prediction. Binned likelihood fits of signal and background templates to the m_{tb} and the BDT output distributions, respectively, are performed to derive limits on W' production. Limits on the production cross sections and masses are determined for different combinations of left- and right-handed couplings of the W' boson to fermions. For W' with left-handed couplings, their interference with SM single top quark production in the s-channel has to be considered. This is done by a combined event generation of the W' signal and SM single top quark production in case of the CMS measurement. Assuming the coupling strength parameters of the W' being the same as for the SM W boson, purely left-handed W′ bosons can be excluded up to a mass of 1.84 TeV, the right-handed W′ boson is excluded for masses below 2.05 TeV.

4. Vector-like quarks

Heavy partners of top and b quark emerge from various extensions of the SM. Although a chiral fourth quark generation is basically excluded from the measurement of the Higgs boson branching ratios [16], vector-like quarks are not constrained by the Higgs boson or the electroweak precision measurements. Vector-like quarks are defined as quarks with symmetric couplings for left- and right-handed particles. They may exist as weak-isospin doublets, singlets, or triplets and can occur as down-type quark (B), up-type quark (T), or as a quark with even more exotic electric charges of 4/3 e of 5/3 e. A heavy T quark has the possibility to decay into a W boson and a b quark or via flavour changing neutral currents into top and Z or top and Higgs boson. Similarly, the B quark can decay into top+W, b+Z, or b+Higgs. Depending on further decays of the produced quarks and bosons, a rich variety of different signal signatures can be sought of and has been studied in several analyses by ATLAS [17, 18, 19, 20, 21] and CMS [22, 23, 24, 25, 26]. All analyses perform searches for pair-produced heavy vector-like quarks, because the production of single heavy quarks via the weak interaction is expected to have lower cross sections in the mass region at reach. Searches for singly produced heavy quarks might become more important when searching for quarks with multi-TeV masses in the future.

In all these searches, events with a large number of jets and leptons are selected. In addition, most signal processes predict the presence of b tagged jets originating directly from a heavy quark partner decay or from the decay of a top quark or Higgs boson. Decays of vector-like quarks can also lead to a signature with two leptons with same-sign charges. A selection of same-sign lepton pairs can strongly suppress SM backgrounds. Furthermore, top quarks or bosons originating from the decay of heavy quarks can carry relatively large momenta. This make the application of top and V tagging possible. As an example, V tagging is used in the CMS search for heavy B quarks [24] to identify Higgs, W, or Z bosons from B quark decays. Top an W boson tagging is applied in the study of top quark partners with charge 5/3 e performed by the CMS collaboration [23].

Signal events are expected to have large summed transverse momentum of jets and leptons, and the search regions in the various measurements are chosen accordingly. In all channels, no significant excess over the SM expectation for the background is observed in regions of large summed transverse momentum. Therefore, limits on the allowed mass range are derived for vector-like quarks. B and T quarks can be excluded for masses between 600 to 800 GeV depending on their respective decay mode. Also the searches for quarks with a charge of 5/3 e have not seen any significant deviation from the SM and these top quark partners can be excluded for masses below 770 GeV.

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