Searches for new physics in final states with third-generation quarks at 13 TeV

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A wide variety of new physics models gives rise to final states with third-generation quarks. This note presents new results for some of these models using 13 TeV proton-proton collisions at the CERN LHC. Direct production of third-generation supersymmetric superpartners and vector-like quarks are discussed. Also the searches looking for resonances with third-generation quarks are covered. None of the searches discussed here shows an indication of new physics and the new exclusion limits are presented.

1 Introduction

One of the problems in the Standard Model is the quadratic divergence of the top quark radiative corrections to the Higgs boson mass calculation. These terms can be canceled by similar terms from new beyond-the-standard model particles. In supersymmetry (SUSY) the top squark is the superpartner of the top quark and it takes care of this cancellation. In Composite Higgs and Little Higgs models vector-like quarks (VLQ) play the same role. Standard Model (SM) top and bottom quarks are produced in the decay of both top squarks and vector-like quarks. New gauge interactions can preferably couple to third-generation quarks, e.g. a leptophobic Z'. Those can be discovered by looking at the invariant mass of the tb, $\mathrm{t\bar{t}}$ or $\mathrm{b\bar{b}}$ pair.

This note focuses on new results for these searches from the ATLAS [1] and CMS [2] collaborations using 13 TeV proton-proton collisions from the CERN LHC. Moving to a higher energy led to further improvements to the different analyses. The sensitivity at 13 TeV is higher for heavy new particles. The decay of these particles leads to a larger boost for its decay products. To keep a high signal efficiency and strong background rejection, new tools are deployed to identify these boosted objects. For example, the leptons from a top decay are in such a boosted topology not isolated in the standard cones of 0.3. Therefore the isolation definition is changed by using smaller isolation cones for high-p_T objects or by using the relative momentum of the lepton with respect to the closest jet. The hadronic decays of boosted bosons and top quarks are targeted by further exploring the use of large radius jets and using the new W-,top- and Higgs-tagging algorithms.

By changing the selection at 13 TeV, also the background composition is altered. Some of the background sources become more important in the new selection. Therefore it becomes important to lower the systematic uncertainties on the background estimation technique and new, more sophisticated techniques are used to target these rare SM backgrounds. For example, the ATLAS single-lepton stop search [5] uses a $\mathrm{t\bar{t}}\gamma$ control region to predict the $\mathrm{t\bar{t}Z}$ ($\mathrm{Z} \rightarrow \nu\nu$) background, exploiting the fact that the photon momentum can be used to estimate the Z boson momentum. Also single-top production in association with a W boson becomes a more important background at 13 TeV and dedicated control regions are added for that background.

Finally more dedicated search regions are added to make sure we are sensitive to top squarks and vector-like quarks over the full mass parameter space.

2 Supersymmetry

First we are discussing the searches for supersymmetric particles. This note focuses on the direct production of top and bottom squarks. Top squarks can decay into a top quark and the lightest supersymmetric particle (LSP), a neutralino, or to a bottom quark and a chargino. This chargino can then decay further to a W boson and an LSP. If the mass splittings between the SUSY particles are small, then the top quark and the W boson can be off-shell. Figure 1 shows the different options for top squark pair production. Depending on the branching fraction of the possible decays the two top squarks can always decay to a top quark and a LSP (left), or always to a bottom quark and a chargino (middle). The right diagram only happens if the branching fraction is not 100% or 0%. Then both top squarks can decay in different ways. The CMS single-lepton stop paper [6] shows the sensitivity to top squark pair production as a function for the branching fraction under the assumption that the chargino is nearly mass-degenerate with the LSP. For bottom squark pair production only the option that the bottom squarks decays to a bottom quark and an LSP is considered. At that moment the final state has two energetic b jets and a considerable amount of missing transverse momentum (E_T^{miss}) coming from the LSPs.

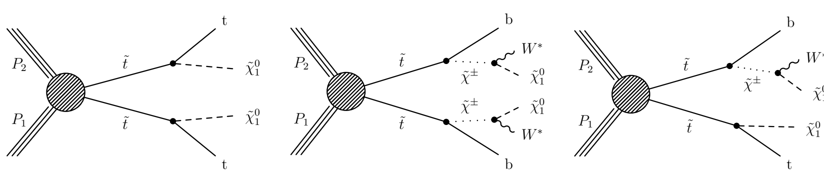

Figure 1 – Feynman diagrams for the pair production of top squarks with the different decay modes considered in this paper. The top squarks can always decay to a top quark and a LSP (left), always to a bottom quark and a chargino (middle), or each top squark can decay in a different way (right).

2.1 Bottom squark pair production

The search for bottom squarks looks for exactly two jets, large E_T^{miss} (> 250 GeV) and no leptons in the events [3]. It also vetoes events with four or more jets. The search has two dedicated search regions. The first one targets the bulk of the mass parameter space, where the mass difference between the bottom squark and the LSP is large. The two leading jets have to be b-tagged in this case and the mass of the $b\bar{b}$ pair is required to be larger than 200 GeV. The final discrimination is done by the m_{CT} variable, a kinematic variable that has an endpoint for Standard Model Processes with two decay chains that each yield a neutrino, as can be seen from Fig. 2 (left). The second search region targets the compressed spectra, when the mass difference between the bottom squark mass and the LSP mass is small. In this case an initial-state-radiation jet is needed to give the system a significant boost. This increases the transverse momentum of the b-jets and allows them to be detected. Since the initial-state-radiation jet is unlikely to originate from a b quark, the leading jet is required to be a high-p_T (> 300 GeV), non-b-tagged jet. In this case the E_T^{miss} cut is also tightened and the E_T^{miss} has to be back-to-back with the leading jet.

The main backgrounds are estimated by renormalizing them to dedicated control regions. For the Z+jets background a dilepton control region with a mass requirement on the dilepton mass ($76 < M(l^+, l^-) < 106\,GeV$) is used, while $t\bar{t}$ pair production is estimated from a single-lepton control region. For the region with large mass splittings, also dedicated search regions for single-top and W+jets production are added. The search did not find any significant excess and the 95% exclusion limits on the bottom squark pair production are shown in Fig. 2 (right). At 13 TeV we are already probing 200 GeV higher masses than at 8 TeV.

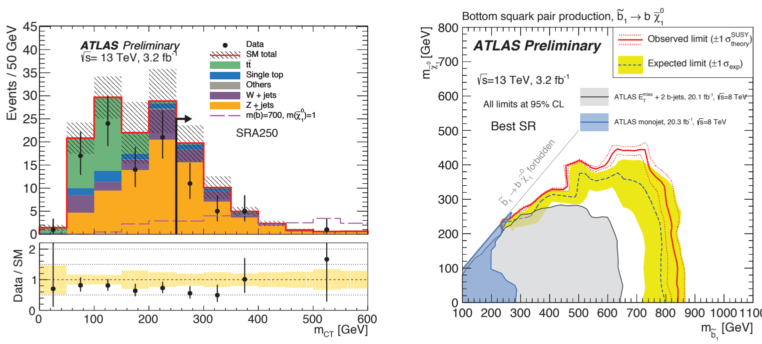

Figure 2 – (left) m_{CT} distribution in the non-compressed search regions with all the selection criteria applied except the m_{CT} threshold[3]. (right) Expected and observed exclusion limits at 95 % CL, as well as $\pm 1\ \sigma$ variation on the expected limit, in the $\tilde{b}$-LSP mass plane. The yellow band around the expected limits show the impact of the experimental and SM background theoretical uncertainties[3]. The exclusion limits from the Run-1 ATLAS searches are also superimposed.

2.2 Top squark pair production

All-hadronic search

The all-hadronic search[4] for top squark pair production focuses on the all-hadronic decays of $t\bar{t}$ system with extra E_T^{miss} coming from the LSPs. To disentangle this from $t\bar{t}$ pair production and Z boson production in association with jets, a range of variables are exploited: jet multiplicity, number of b-tagged jets, the angle between the E_T^{miss} and the leading jets, the E_T^{miss} spectrum, the number of top-tagged jets in the event. There are two searches with slightly different final discriminating variables but similar performance. One of them uses the transverse mass variable calculated with the b-jet and the E_T^{miss}, while the other analysis uses the stransverse mass (M_{T2}).

The lost lepton background, which consists primarily of W boson $t\bar{t}$ pair production is estimated from a single-lepton control region, taking into account the acceptance and efficiency of the leptons. The normalization of the background coming from Z boson production in association with jets, where the Z decays to two neutrinos is estimated from a dilepton control region. The distribution in the different discriminating variables are estimated in two different ways: from a photon control sample or from a dilepton control sample, where every requirement is checked individually and the correlations are assumed to be well-modeled in simulation. A control region to normalize the multijet background is obtained by inverting the cut on the angle between the leading jets and the E_T^{miss}. Other backgrounds are estimated from simulation.

Single-lepton search

The second search for top squark pair production requires at least one high-p_T, well-identified and isolated electron or muon to be present in the event and at least one b-tagged jet, in order to suppress electroweak backgrounds[5,6]. Single-lepton backgrounds, like W boson and $t\bar{t}$ pair production, are suppressed by requiring a large transverse mass (M_T), calculated with the lepton and the E_T^{miss}, in the event. After these requirements mainly the the dilepton background, predominantly $t\bar{t} \rightarrow 2l$, survive. An explicit veto on additional electrons, muons, tracks or hadronic tau leptons is applied to further reduce these. Then both collaborations use some specific kinematic variables (M_{T2}^{W} topness, asymmetric M_{T2},...) to further reduce the $t\bar{t} \rightarrow 2l$ background. Finally, the baseline selections require at least four jets in the events, this also lowers the dilepton backgrounds since $t\bar{t} \rightarrow 2l$ only has two jets without any additional initial-state-radiation jets or hadronic tau leptons that are misidentified as leptons. The CMS and ATLAS collaborations target boosted scenarios in a slightly different way. The ATLAS collaboration uses large-radius jets and more stringent E_T^{miss} requirements [5]. The CMS collaboration applies uses exclusive E_T^{miss} bins everywhere and lowers the jet multiplicity requirement for boosted scenarios, to allow for merged jets [6].

The background methods are slightly different between both collaborations. The ATLAS collaboration predicts the main backgrounds from low-M_T regions with different b-tagged jet multiplicity: 0 b-tagged jets for W boson production, 1 b-tagged jet for $t\bar{t}$ pair production and 2 b-tagged jets and additional angular and kinematic cuts for single-top production in association with a W boson. The estimates are verified in control regions with larger M_T, that are still disjoint from the signal regions. Specific effects such as the jet multiplicity are verified in dedicated control regions. An extra control region looking at $t\bar{t}$ pair production in association with a photon is added to estimate the background due to $t\bar{t}$ pair production in association with a Z boson.

The CMS collaboration considers $t\bar{t}$ pair production and single-top production in association with a W boson predominantly as a lost lepton background. The yields are estimated by using a dilepton control region with otherwise identical requirements as the signal region, taking into account the kinematic acceptance and the selection efficiency of the leptons. W boson production is estimated from a control region without any b-tagged jets and with the same M_T-requirement as the signal region. The other backgrounds are estimated from next-to-leading order simulations. The predicted yields in the single lepton searches agree quite well with the predicted ones, as can be seen in Fig. 3 for the CMS (left) and ATLAS (right). Only the low E_T^{miss} regions have a small excess, in the ATLAS results the excess has a local significance of 2.3σ.

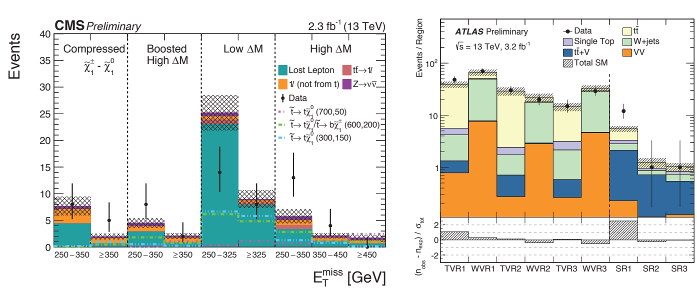

Figure 3 – (left) Data- and simulation-driven background estimates together with the observed data yields in the signal regions for the single lepton top squark search of the CMS experiment [6]. The uncertainties, which are the quadratic sums of statistical and systematic uncertainties, are shown as shaded band. (right) Comparison of the observed data with the predicted background in the validation and signal regions for the ATLAS single lepton search [5]. The background predictions are obtained using the background-only fit configuration. The bottom panel shows the significance of the difference between data and predicted background, where the significance is based on the total uncertainty.

Dilepton search

Looking for top squar pair production in the dilepton final state gives a very clean sample with a modest signal acceptance. Therefore it is well-suited to target specific regions of the mass parameter space that are hard to probe with the all-hadronic and single-lepton search. The dilepton search [7] presented here focuses on a model where the top squark always decays to a bottom quark and a chargino. The chargino then decays to a W boson and an LSP. If the mass of the chargino is very close to the mass of the top squark but far away from the LSP mass, then the b-quarks are very soft but the W bosons and their decay products are highly energetic. To target this specific area of mass parameter space, a search is designed in the dilepton final state without any requirement on the number of b-tagged jets. A M_{T2} cut is applied to reduce most standard model backgrounds and an extra kinematic cut, looking at how much of the activity in the event is due to the E_T^{miss} is added to further reduce the background due to Z boson production. The sample is split in two depending on whether the two leptons have the same or different flavor. In case the two leptons have the same flavor, the mass of the dilepton pair is required not to be consistent with the Z boson hypothesis to further reduce Z boson events.

The background is estimated by using a simultaneous fit of the signal region, a $t\bar{t}$ control region at lower M_{T2}, and a diboson control region. The non-prompt and misidentified leptons are estimated from a tight-loose method. The background predictions are checked in dedicated validation regions.

Interpretation

The interpretation of the top squark searches from the CMS collaboration are summarized in Fig. 4 (left) in the model where both top squarks decay to a top quark and a LSP for the all-hadronic and single-lepton final state. Most sensitivity comes from the all-hadronic searches and the sensitivity for these searches is comparable to the best 8 TeV result, which used a highly optimized selection with multivariate techniques. The region where the mass splitting between the top squark and the LSP is close to top quark mass is subject to further study and has therefore been removed from this plot. The results of the ATLAS collaboration in the single-lepton search for the same signal model are shown in Fig. 4 (middle). The expected reach is slightly further than the CMS reach due to the larger dataset. Due to a small 2.3σ excess in the signal region optimized for high neutralino masses, the observed exclusion reaches less far. The best signal region for each mass point based on the expected upper limits is used and since in one of the regions the observed exclusion is worse than the expected one due to the excess observed in data, the transition between two signal regions is not smooth anymore, but there is a region that is not excluded. The expected reach at 13 TeV already surpasses the one at 8 TeV. Finally we show the results of the dilepton search for a model where both top squarks decay to a bottom quark and a chargino and the chargino decays to a W boson and the LSP. The chargino mass is fixed to be twice the mass of the LSP. Figure 4 (right) shows the analysis is mainly sensitive for high LSP masses, which leads to high chargino masses using mass relation in this model. At that model the chargino mass is very close to the top squark mass and the bottom quarks are very soft and hard to detect. This is exactly the scenario the search is designed for.

3 Vector-like quarks

Several beyond-the-standard models, e.g. little Higgs models and extra dimensions, predict the existence of vector-like quarks (VLQ) that can stabilize the Higgs boson mass calculation. Vector-like T quarks can be strongly pair-produced or weakly produced in association with a vector boson. Here we focus on the strong production mechanism. The T quark that has a charge of 2/3e can decay in three distinct ways: bW, tH and tZ. Some of the models predicting vector-like quarks also predict more exotic top partners like $X^{5/3}$, that can decay to a top quark

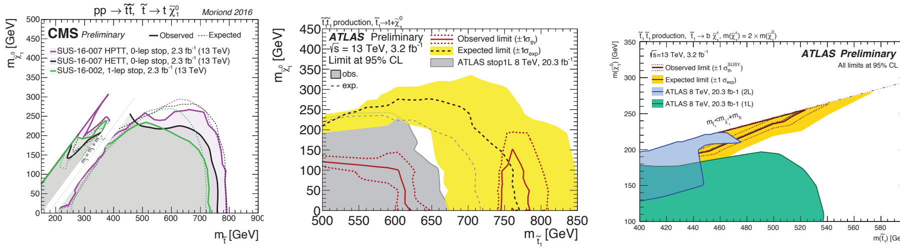

Figure 4 – (left) Observed and expected result for direct top squark production, with the top squark decaying 100% to a top quark and a LSP, for the all-hadronic [4] and single lepton [6] searches in CMS. (middle) Expected (black dashed) and observed (red solid) 95% excluded regions for the ATLAS single-lepton search [5] in the plane of and in the plane of stop mass versus LSP mass for direct stop pair production, again for the scenario where all top squarks decay to a top quark and a LSP. The gray filled area and gray dashed line shows the observed and expected exclusion limits, respectively, from ATLAS Run 1 search. (right) Exclusion limits from the ATLAS dilepton search [7] at 95% CL on direct top squark pair production, assuming that all top squarks decay to a bottom quark and a chargino and that the chargino mass is twice the LSP mass. The shaded azure and blue areas show respectively the observed exclusion from the ATLAS 8 TeV analyses performed in the one-lepton (1L) and two-lepton (2L) channels.

and a W^+ boson, which leads to two same-sign W bosons and a bottom quark in the final state.

3.1 Pair-production T quark

A search is performed in the single-lepton final state for the pair production of vector-like T quarks with at least one of the T quarks decaying to a top quark and a Higgs boson [8]. The Higgs boson decays predominantly to a $b\bar{b}$ pair. The search focuses on this final state with two top quarks and at least two bottom quarks. The same analysis can also be used to put an upper limit on four-top production.

The analysis uses mass-tagged jets, large radius jets with a mass above 100 GeV, as a proxy for hadronically decaying top quarks and Higgs bosons. At least six jets are required, of which two have to be b-tagged. The final state is binned exclusively in the number of mass-tagged jets, the number of b-tagged jets and the invariant mass of the $b\bar{b}$ pair with the smallest angular separation. The number of mass-tagged jets is a very strong discriminator between signal and background as can be seen from Fig. 5 (left).

The main backgrounds are estimated from simulation except for the multijet background. The multijet background is estimated using a matrix element method that exploits the differences between prompt leptons and leptons that are non-isolated or result from the misidentification of photons or jets. The background estimates are validated in lower jet multiplicity bins and good agreement between data and prediction is seen. The scalar sum of the E_T^{miss}, lepton p_T and the p_T of the jets in the event, referred to as the effective mass m_{eff}, is used as the final discriminator to further reduce the background.

Figure 5 (right) shows the expected and observed upper limit on T quark pair production. We exclude T quarks with masses up to 750 GeV, which is around 50 GeV further than at 8 TeV. The top squark search in the single lepton final state (Sec. 2.2) is also reinterpreted as a T quark search focusing on the tZ final state with the Z decaying to neutrinos.

3.2 Top partners with charge 5/3e

Pair production of exotic top partners with charge 5/3e ($X^{5/3}$) is also been searched for at the LHC [9]. Top partners with charge 5/3 decay to a W boson and a top quark. Such a decay can lead to two same-sign leptons. The search in the same-sign dilepton final state is discussed in these proceedings in detail in [10]. In the single-lepton final state at least one lepton and four

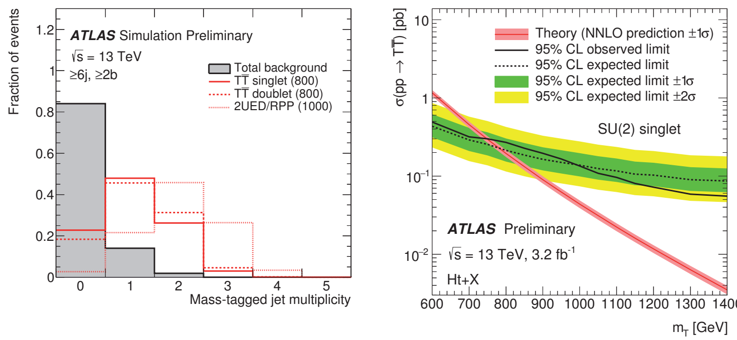

Figure 5 – (left) Comparison of the shape of the mass-tagged jet multiplicity distribution, between the total background (shaded histogram) and different signal scenarios [8]. (right) Observed (solid line) and expected (dashed line) 95% CL upper limits on the TT cross section as a function of the T quark mass (for a weak-isospin singlet. The surrounding shaded bands correspond to ±1 and ±2 standard deviations around the expected limit [8]. The thin red line and band show the theoretical prediction and its ±1 standard deviation uncertainty.

jets are required. Requiring at least 100 GeV E_T^{miss} and large distance between the second highest-p_T jet and the lepton ($\Delta R(\ell$,2nd jet$)>2$) reduces the SM backgrounds further, as shown in Fig. 6 (left). The search is binned in the number of b-tagged jets (1, $\geq$2) and the number of boosted W-tagged jets. The identification of boosted W candidates is done using the pruned mass and n-subjettiness of the large radius jet. Finally the minimum mass of the lepton with one of the b-tagged jets is used as a final discriminating variable. Figure 6 (middle) shows that no significant excess can be seen in this mass distribution.

The background modeling is checked in a sideband with small distance between the second highest-p_T jet and the lepton ($\Delta R(\ell$,2nd jet$)<1$). The background originating from vector-boson production and from top pair production are verified separately by splitting the control region in b-jet multiplicity. Figure 6 (right) shows the exclusion plot for right-handed $X^{5/3}$ quarks. $X^{5/3}$ with a mass less than 950 GeV are excluded by combining the single-lepton and same-sign dilepton final state. The exclusion is driven by the same-sign analysis, but the single-lepton search provides an important cross-check.

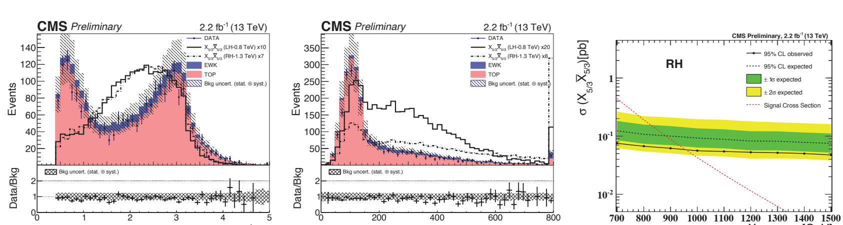

Figure 6 – Distributions of $\Delta R(\ell$, sub-leading jet) (left) min[M(ℓ, b)] (middle) in data and MC for selected events with at least four jets and lepton $p_T > 80$ GeV [9]. Uncertainties include statistical and all systematic uncertainties. (right) 95% CL expected and observed upper limits (Bayesian) after combining the same-sign dileptons, and the lepton+jets signatures for right-handed $X^{5/3}$ signals [9]. The same-sign analysis has the largest sensitivity to these signals.

4 Resonances

Resonances with third generation quarks can occur in case of the production of W′ and Z′ bosons, axigluons, pseudoscalar Higgs bosons, etc. The $W' \to tb$ search from CMS [11] and the search for $b\bar{b}$ resonances from ATLAS [12] are not covered in these proceedings, but we focus on the results for $t\bar{t}$ resonances at 13 TeV from CMS [13] and ATLAS [14].

4.1 Top quark resonances

To search for top quark resonances in the single-lepton final state, dedicated lepton isolation variables are used that are developed for such boosted topologies, as discussed in Sec. 1. The CMS search [13] treats the electron and muon channel separately and applies tighter cuts on the E_T^{miss} and the reconstructed jets in the electron channel to reduce the larger SM background. Three different search regions are used: one with a hadronic top-tagged jet present in the event, one with a b-tagged jet present and one without any top-tagged or b-tagged jets in the event. To reduce the background due to vector-boson production, a kinematic variable is used to describe how top-like the event is:

$$\chi^2 = \left(\frac{M_{lep} - \overline{M}_{lep}}{\sigma_{M_{lep}}} \right)^2 + \left(\frac{M_{had} - \overline{M}_{had}}{\sigma_{M_{had}}} \right)^2, \tag{1}$$

The background is estimated by simultaneously fitting the M(t,$\bar{t}$) spectrum in the control region enriched in single vector-boson production, created by inverting the cut on the top system χ^2, the M(ℓ,ℓ) spectrum in Drell-Yan enriched dilepton control region, and the M(t,$\bar{t}$) spectrum at low M(t,$\bar{t}$) masses, where it is enriched in t$\bar{t}$ background.

The ATLAS experiment also focuses on the single-lepton final state [14]. Again, dedicated isolation variables are used to maintain high selection efficiency. The presence of at least one b-tagged jet and one hadronic top candidate is required. A hadronic top candidate is a large radius jet that passes further requirements on the jet mass and the n-subjettiness. The top candidate also has to be back-to-back with the lepton. A leptonic top candidate is formed from the lepton and the b-tagged jet. The W+jets background is estimated by comparing the W charge asymmetry distribution in data and simulation. For the multijet background, an extrapolation is done from a sample with loosely-identified leptons to a sample with leptons passing tighter identification criteria. The other backgrounds are estimated from simulation. The invariant mass of the t$\bar{t}$ is then investigated for excesses using a specialized algorithm looking for deviations and no indication for new physics is found.

4.2 Results

None of the resonance searches show a significant excess over the SM background. The t$\bar{t}$ resonance searches are interpreted in the context of a narrow-width top-color Z. The results of ATLAS (Fig. 7 (left)) and CMS (Fig. 7 (right)) cannot be compared directly since a slightly different width (1.2% in ATLAS vs. 1% in CMS) is used for the signal models. The results outperform the single-lepton results at 8 TeV but do not yet improve upon the full combination of the 0ℓ, 1ℓ and 2ℓ final states at 8 TeV.

5 Conclusions

A variety of searches with top and bottom quarks in the final state have been explored in CMS and ATLAS at 13 TeV: supersymmetry, heavy top partners, resonances,... These analyses are already starting to surpass the 8 TeV sensitivity despite the much smaller dataset. The analyses were also adapted to the new running conditions. The new lepton and jet selections have been modified to maintain a high efficiency for boosted objects. Also the background composition

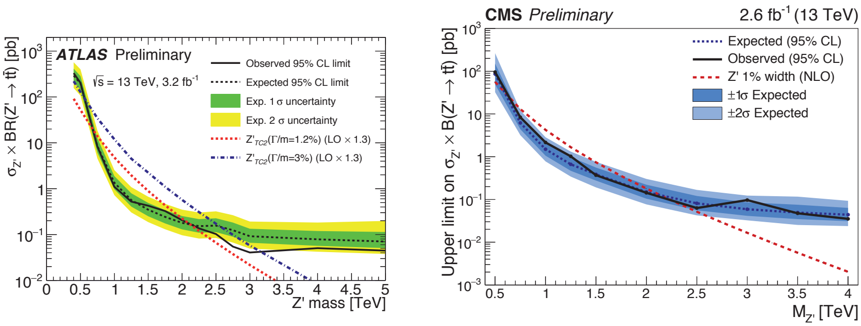

Figure 7 – (left) The observed and expected cross section 95% CL upper limits on the Z' signal for two width hypotheses from the ATLAS experiment [14]. The theoretical predictions for the production cross section times branching ratio at the corresponding masses are also shown. (right) 95% CL upper limits from the CMS experiment [13] on the production cross section times branching ratio for a resonance decaying to $t\bar{t}$, shown as function of the resonance's mass for a Z' boson with relative width of 1%.

changes uses the new selection and new techniques have been developed to predict some of the rare SM backgrounds that become more important at this new energy. Using these new tools we are eagerly awaiting the larger 2016 dataset to hopefully discover the first hints of new physics.

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