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Search for vector-like quarks and heavy resonances decaying to top quarks in ATLAS

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This document presents the recent results of the ATLAS experiment at the LHC concerning the $t\bar{t}$ resonance and vector-like quark searches. A search for $t\bar{t}$ resonances at 13 TeV in proton-proton collisions data is performed in the lepton+jet final state and for boosted top topologies. A re-interpretation of the analysis performed with the data recorded at the center of mass energy of 8 TeV, is also presented, for a scalar resonant signal. A vector-like top pair production is also searched for, through three analyses where the vector-like quark decay to Zt, Ht or Wb. A comparison of those analyses is presented. In addition, vector-like quarks are searched via the same sign lepton topology. The results are presented as mass limits on the vector-like top branching ratio plane and as the cross section limit on the $T_{5/3}$ pair production.

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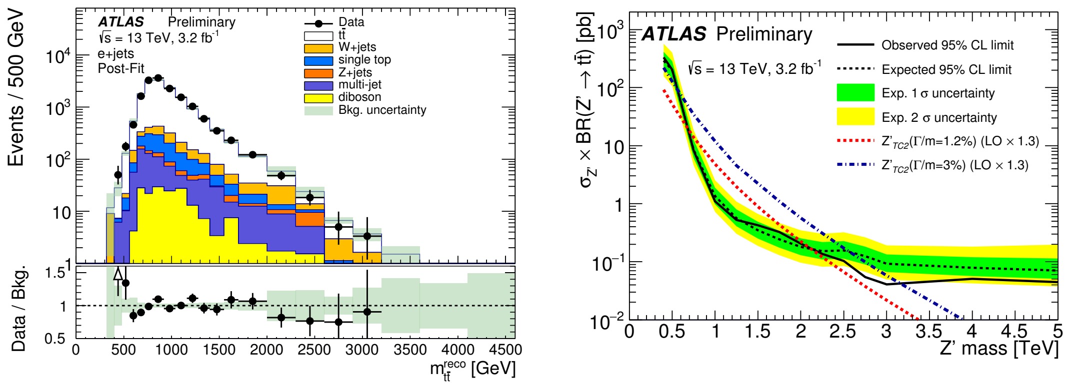
The top quark is currently the fundamental particle with the highest mass, implying that this particle has the highest coupling to the Higgs boson. Therefore in the loop corrections of the Higgs boson mass, the top quark contribution is dominant. Many beyond standard model theories predict a top partner and others predict new couplings between the top and the particles of new physics. To probe those models, a variety of analyses have been carried out by the ATLAS collaboration [1] using data recorded from proton-proton collisions at the center of mass energy of 13 TeV. The recent searches for resonances in the top-antitop invariant mass spectrum are detailed in the following, as well as the searches for vector-like quarks.

1. Searches for $t\bar{t}$ resonances

The $t\bar{t}$ resonance search in ATLAS has been carried out in the lepton + jet channel [2], where one top decays hadronically while the other decays with an electron or a muon. This study is intended to be as model independent as possible. First are select the events for which the measured particle candidates are compatible with a lepton+jet top pair decay. Then an optimization is done to assign each object to the correct top quark. The reconstructed invariant mass distribution is scanned to search for deviations with respect to the standard model predictions. In absence of significant deviation from the standard model exectation, limits on benchmark models are derived.

1.1 Lepton + jets boosted channel



(a) (b)

Figure 1: (a) Reconstructed $t\bar{t}$ invariant mass for the electron +jet selection. (b) Limit on the cross section times branching ratio as a function of the mass of a narrow width Z' ($\Gamma/m = 1.2\%$) [2].

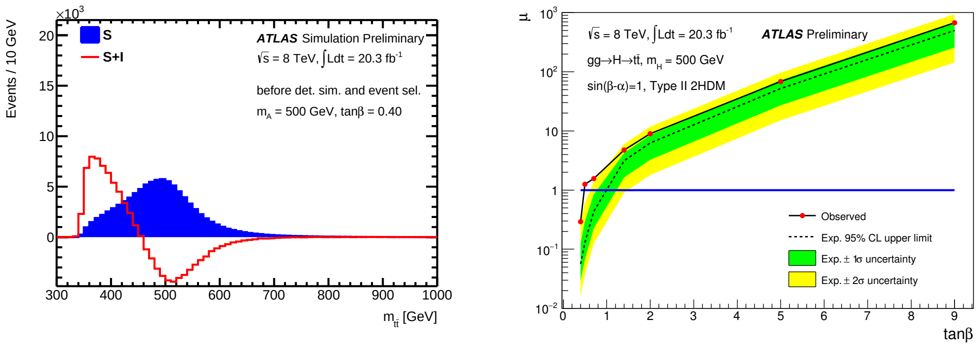
This analysis used the first 3.2 fb^{-1} LHC Run-2 data and consideres only the boosted topologies. In this context, the assignment of the objects to each top quark is straightforward. The selection requires one fat jet from the hadronic top that has to be top-tagged. For the leptonic top, exactly one lepton (electron or muon) is required. The neutrino transverse component is estimated using the transverse missing momentum, and its longitudinal component is derived by constraining the system with the on-shell W boson mass. Finally the leptonic b-jet is selected as being the highest p_{T} jet within $\Delta R = 1.5$ around the lepton.

The main background of this analysis is the standard model $t\bar{t}$ pair production which has a very close topology to the signal.

The resulting invariant mass distribution is shown in Figure 1a for the electron selection. As no significant deviation has been found, a limit is derived for a narrow Z' resonance with a width of $\Gamma/m = 1.2\%$. Figure 1b shows that this analysis excludes such type of signal for a mass between 0.7 and 2 TeV.

1.2 Scalar resonance search

The $t\bar{t}$ resonance search using 8 TeV data [3] has been re-interpreted for scalar and pseudo-scalar resonances [4]. Such a signal strongly interferes with the standard model $t\bar{t}$ background. Hence, the analysis requires a modelling of the background, the interference and the signal for each point of the parameter space. This is too demanding in terms of computing, thus another approach was used. The generator was modified at the matrix element level to produce only the signal + interference part. The comparison between the signal only and the signal + interference distribution is shown in Figure 2a. To validate this procedure, the background + interference + signal terms have been simulated for few a samples. The small differences observed between the two methods have been treated as systematic uncertainties. This study was done in the channel, where all the top decay products are well separated. No strong deviation from the standard model was observed and limits on the signal strength μ (scaling factor to apply on the signal to observe it with a 95% confidence level) as a function of $\tan\beta$ for a scalar and a pseudo-scalar signal of a two Higgs doublet model have been derived. Such a limit is presented as an example in Figure 2b for a scalar signal with a mass of 500 GeV.



(a) (b)

Figure 2: (a) Scalar signal shape with and without taking into account the interference term. (b) Limits on the signal strength of a 500 GeV scalar as a function of $\tan\beta$ [4].

2. Searches for vector-like quarks

Models with vector-like quarks are interesting as these particles don't get their mass through the Brout-Englert-Higgs mechanism, and would compensate the divergences induced by the top quark on the loop corrections to the Higgs boson mass. In ATLAS, three analyses have been developed to probe the vector-like top pair production. A fourth analysis uses the same sign leptons topology and is also sensitive to vector-like bottom and $T_{5/3}$ pair production.

2.1 Vector-like tops

The Feynman diagram of the vector-like top pair production and decay is presented in Figure 3. Three different analyses have been optimised, each focusing on one of the decay channels: Zt+X [5], Ht+X [6], Wb+X [7] where X stands for any other kind of decay.

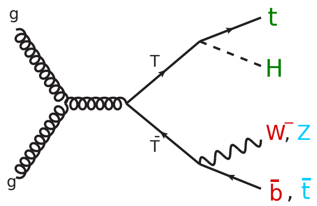


Figure 3: Feynman diagram of the vector-like top production and decay.

The three analyses require similar preselections. One lepton signs the presence of a W either from the top or directly from the decay of the vector-like top. In the case of the zero lepton search, a high missing transverse energy is required and would sign the presence of a Z decaying in two neutrinos. At least one b-jet and several jets are also required.

Although those analyses are similar, they have some specificities which are presented in the following:

Zt+X [5]: This analysis requires exactly one lepton. An optimization is done with more complex variables such as am_{T2} and m_T^W. The former variable has a cut-off at the mass of the top for a $t\bar{t}$ event and the later has a cut-off at the mass of the W. The main backgrounds are $t\bar{t}$ and W+jets which are normalized by a simultaneous fit in background enriched (control) regions.

Ht+X [6]: In this analysis, the parameter space is split with respect to the number of leptons (0 or 1), the number of b-jet, the number of mass-tagged jet and the high or low mass tag region. A jet is mass-tagged if its mass is higher than 100 GeV. Then on each of the defined regions, a scan is done over the $m_{eff} = p_{\mathrm{T}}^{lep} + p_{\mathrm{T}}^{jets} + E_{\mathrm{T}}^{miss}$ distribution, searching for a bump above the standard model expected background.

Wb+X [7]: In this case exactly one lepton is required. A resolved and a boosted region have been designed based on the topology of the event. Here also a scan is done on the reconstructed mass of the leptonically decaying vector-like top. The background is constrained via two control regions.

No deviation with respect to the standard model have been observed and limits were derived in the three branching ratio planes presented in Figure 4. Each analysis probes well the corner to which it is sensitive, up to a mass of at least 1 TeV.

2.2 Same-sign lepton search

Another type of vector-like quarks analysis consists in selecting events containing same sign leptons [8]. In the standard model, very few processes produce such a signature. This analysis

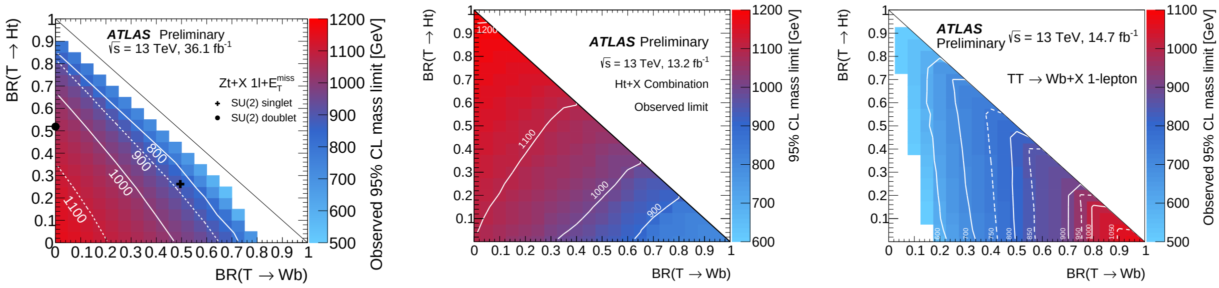
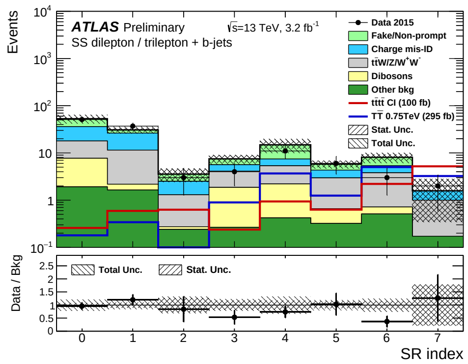


Figure 4: Observed limits in the branching ratio plane (a) for the Zt+X [5] (b) for the Ht+X [6] and (c) for the Wb+X [7] analysis.

requests therefore at least two leptons with the same sign, an important missing transverse energy and at least one b-tagged jet. The main backgrounds come from charge mis-identified lepton or from hadrons faking leptons. To estimate these backgrounds, data driven approaches have been used. The charge mis-identification rate has been estimated in the Z boson resonance region. The rate is then propagated into the signal regions. The QCD background has been estimated with the so called "matrix method", which extrapolates in the signal regions, a fake lepton selection efficiency which is measured in a dedicated region enriched with background. A closure test ensures that the propagation of those efficiencies in the signal region is valid. The parameter space is split in seven regions based on the scalar sum of the jets p_{T} ($\mathrm{H_T}$), the missing transverse momentum $\mathrm{E_T^{miss}}$ and the number of b-tagged jets as it is detailed in Figure 5a. The event yield as well as two examples of signal contributions are presented in Figure 5b.

Definition			Name
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_{\text{jets}} \geq 2$			
$400 < H_{\mathrm{T}} < 700 GeV$	$N_b = 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SR0
	$N_b = 2$		SR1
	$N_b \geq 3$		SR2
$H_{\mathrm{T}} \geq 700$ GeV	$N_b = 1$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100 GeV$	SR3
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100$ GeV	SR4
	$N_b = 2$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100 GeV$	SR5
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100$ GeV	SR6
	$N_b \geq 3$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SR7

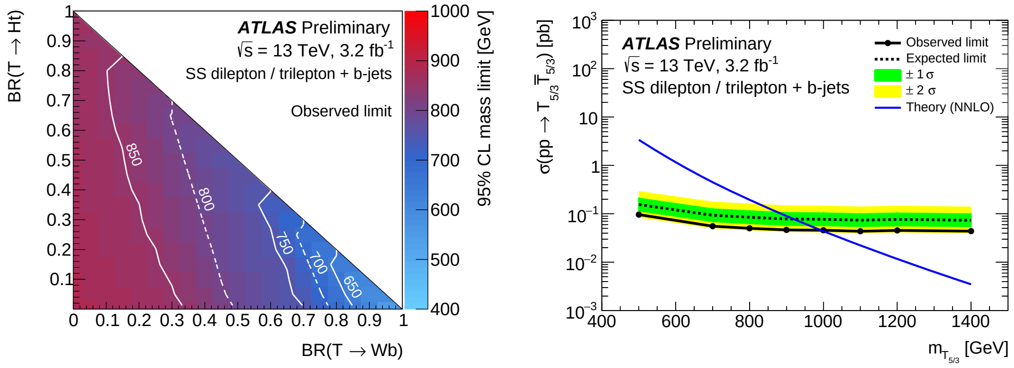
(a)



(b)

Figure 5: (a) Definition of the seven signal regions and (b) yield of events in these regions. The estimated standard model background (histograms) and the signal contributions (colored lines) are also displayed [8].

No deviation with respect to the standard model have been observed. Therefore limits were derived on the vector-like top branching ratio plane. The sensitivity is complementary to the previous analysis. More exotic models where the charge of the new particle is equal to 5/3 have also been tested. Exclusions on the production of a pair of $T_{5/3}$ is shown in Figure 6.



(a) (b)

Figure 6: Limits derived as interpretation of the same sign lepton search (a) in the vector-like top branching ratio plane, and (b) limits derived on the production cross section of a pair of $T_{5/3}$ vector-like quarks [8].

3. Conclusion

The search for new physics in the top quark pair invariant mass has excluded a narrow width Z' with a mass between 0.7 and 2 TeV with the 13 TeV data. In addition, an interpretation on scalar signal in the context of two Higgs doublet model, with interfering terms has also been done. The limits for scalar and pseudo scalars have been processed for masses of 500 and 750 GeV.

Searches for pair production of vector-like top decaying to Ht, Zt or Wb have also been carried out. Such production is excluded for vector-like top mass below 1 TeV in most of the regions of the branching ratio plane. A complementary search for vector-like top uses a same sign lepton signature. This analysis is also sensitive to signals like $T_{5/3}$ pair production, which is excluded for a mass below 1 TeV.

For most of these analyses, less than 10% of the complete 13 TeV dataset have been so far analysed. In addition, for the $t\bar{t}$ resonance search, the resolved topology has still to be studied. This topology has the advantage of higher statistic, but the drawback is the presence of a higher background. To improve the vector-like quarks analyses, a combination may also be expected soon.

References

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