New physics in top pair production

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-02/32

We present the latest results about the searches for a new physics in top quark pair production. The ATLAS and CMS collaborations results are presented using the data collected at LHC in 2012 at the energy of interactions of 8 TeV. The most of such searches look for vector-like quarks. No presence of excess is found and the 95% C.L. lower limits on vector-like quark masses are set between about 600 – 850 GeV depending on quark type and its decay mode. The searches for an excited top quark and a baryon number violation in $t\bar{t}$ process are also presented.

1 Introduction

The Standard Model (SM) of the particle physics is extremely successful in describing the experimental data. However, we know that it is incomplete, e.g. it does not include the gravitational interaction. We want to find a more general theory of which the SM is just a low-energy approximation. Since the top quark is the heaviest elementary particle known, the processes which involve the top quark production are therefore the natural place to look for a manifestation of a new physics.

This article presents the searches which either involve the production of $t\bar{t}$ pair or the final state mimics the $t\bar{t}$ pair signature. Specifically, there are covered searches for the pair production of vector-like quarks, the 4th generation chiral quarks, the sgluons, and the Kaluza-Klein excitations (Sec. 2) followed by the excited top quark search (Sec. 3) and the search for baryon number violation in $t\bar{t}$ process (Sec. 4). The searches for the flavor changing neutral currents and the searches involving the single top final states are presented in the other articles of these proceedings, see [1, 2].

The results from ATLAS [3] and CMS [4] experiments are presented. In all searches, ATLAS used the data collected at CERN Large Hadron Collider (LHC) in 2012 at the energy of interactions of 8 TeV corresponding to 14.3 fb^{-1} of integrated luminosity while CMS used 19.6 fb^{-1} (except in the vector-like bottom quark search presented in Sec. 2.2.1 where the luminosity of 19.8 fb^{-1} was analysed). All the limits mentioned below correspond to either 95% credibility or confidence level (C.L.) depending whether Bayesian (CMS, except for search in Sec. 4) or frequentist (ATLAS) approach was applied.

2 Vector-like quark searches

The discovery of the Higgs particle raised the questions for a mechanism to stabilize its mass since the loop corrections to the mass of a scalar particle diverge. There should be other new particles which cancel these contributions. There are several models (e.g. the little Higgs models, the composite Higgs model, the grand unification models) predicting such heavy quarks which are assumed to have only the vector couplings to the gauge bosons (therefore called the 'vector-like' quark) and the masses independent of their coupling to the Higgs boson thus evading many constraints from the electroweak measurements and from the discovery of the Higgs particle.

The vector-like quarks (VLQ) could be a singlet or a doublet under the electroweak SU(2) x U(1) transformation. It is assumed the dominant decay modes are to the 3rd generation quark and W/Z/H boson, see Fig. 1. It is possible that such vector-like quarks can have also the exotic electric charge of $5/3e$ or $-4/3e$.

The mass dependence of the branching ratios (BR) for various scenarios and decay modes is shown in Fig. 2 for both the vector-like top (T, left) and the vector-like bottom quarks (B, right). The branching ratios corresponding to a singlet model in the limit of a large mass are 50%, 25%, 25% for the decay modes $T/B \to b/t+W$, $T/B \to t/b+Z$, $T/B \to t/b+H$, respectively.

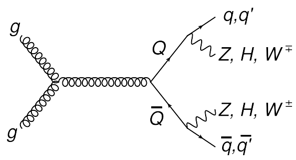

Figure 1: The VLQ decays.

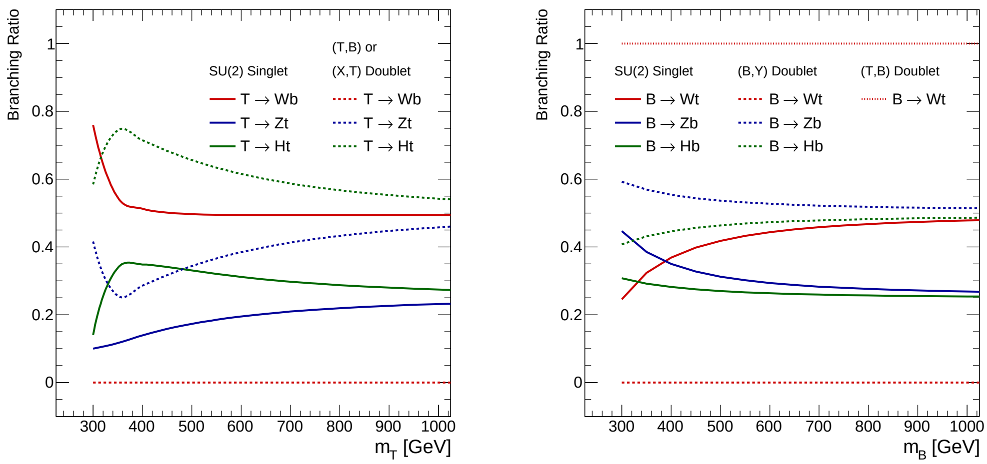

Figure 2: The branching fractions mass dependence for the vector-like top (left) and bottom quark (right) in the different scenarios [6].

The analysis strategy for VLQ search from the ATLAS and CMS experiment is different. The ATLAS analyses exploit the topologies of specific decay modes of the VLQ, while still estimating the limits for all possible BR combinations. On the other hand, CMS performs more general searches that attempt to cover all decay modes at once.

Although the 4th chiral quark generation is highly disfavored after the Higgs discovery, the searches for such quarks have been performed as a part of the analyses considering also the other models. When it is the case, such analyses will be also mentioned below.

2.1 ATLAS searches

2.1.1 Search for $T \to tH$ decays

In this analysis [5], the search for the pair of vector-like top (VLT) quark is performed assuming a significant branching ratio for the subsequent T decay into the top quark and the Higgs boson.

The data are analyzed in the sample where it is required one lepton (electron or muon), the large missing E_T ($E_T^{miss} > 20$ GeV and $E_T^{miss} + m_T > 60$ GeV where m_T is the transverse mass of the lepton and E_T^{miss}) and at least 6 jets where at least two of them are identified as coming from the hadronization of a b-quark (b-tagged).

The analysis exploits the expected large scalar sum of the p_T of a charged lepton, E_T^{miss} and the p_T of the jets (H_T) and the number of b-tagged jets in the signal events to discriminate against the background, see Fig. 3. There are three sub-channels defined according to the number of b-tags (2,3,≥ 4) in order to optimize the sensitivity.

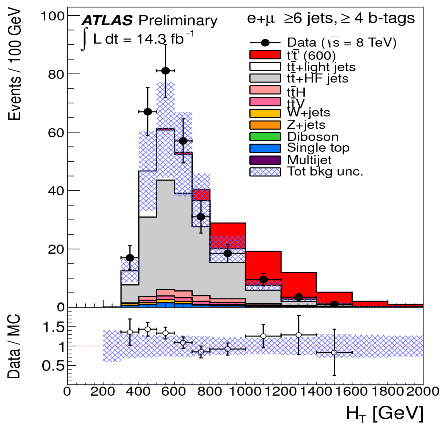

Figure 3: The H_T distribution. The expected signal in the T doublet scenario for $M_T = 600$ GeV is shown [5].

There is no signal found and the mass limits are placed in the general 2D plane of $BR(T \to tH)$ vs. $BR(T \to bW)$ ($BR(T \to tZ)$ is subsequently determined by the unitary condition), see Fig. 11 where the label 'Ht+X' corresponds to this analysis. The limits on different scenarios (a singlet or a doublet) correspond to the particular points in this plane.

2.1.2 Search for $T/B \to t/bZ$ decays

ATLAS also searches for the VLQ pair assuming such VLQ to have a significant branching fraction into its corresponding 3rd generation partner and the Z boson which decays leptonically [6].

The events in the sample are required to have at least 2 leptons of the same flavor with the opposite electric charge and at least 2 b-tagged jets. It is expected that in the VLQ decays there will be a quite high activity in the transverse plane and the Z boson will be boosted. Therefore, the high cuts on the scalar sum of p_T of jets, $H_T(jets) > 600$ GeV and $p_T(Z) > 150$ GeV are applied in the final selection.

The discriminant used to separate the signal from the background is the invariant mass of the reconstructed Z boson and the b-tagged jet, see Fig. 4. Since no signal is found, the limits are placed in the general 2D plane of $BR(T \to tH)$ vs. $BR(T \to bW)$, see Fig. 11 and Fig. 12 for the 'Zb/t+X' analysis.

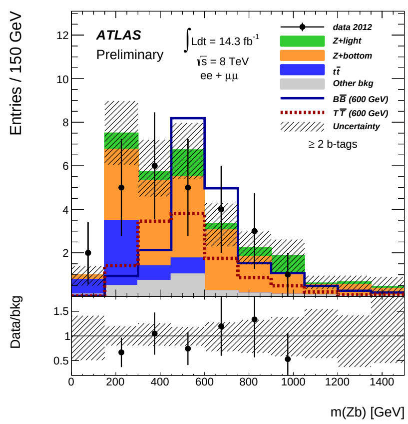

Figure 4: The invariant mass of Z boson and the b-tagged jet [6].

2.1.3 Search for $T \to bW$ decay

Finally, ATLAS searches for the vector-like top quark pair assuming VLT to have a significant decay branching fraction into b quark and W boson [7].

The events in the sample are required to have one lepton, the large missing E_T and at least 4 jets where at least one of them is b-tagged.

The W bosons and b jets from T decays are expected to be highly energetic with large angular separation between them while the decay products from the W bosons have small angular separation. This is taken into account when defining two types of W_{had} candidates depending on whether the decaying quarks are reconstructed as one or two jets.

The reconstructed heavy quark mass m_{reco} built from the W_{had} candidate and one of the two b-jet candidates is used as a discriminant, see Fig. 5. Among all possible combinations, the one with the smallest absolute difference between two reconstructed heavy quark masses is chosen.

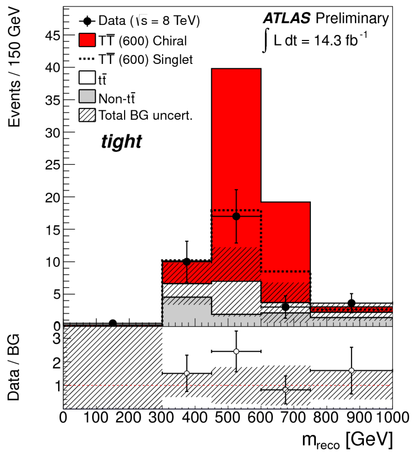

Figure 5: The reconstructed invariant mass of the W boson and the b-jet [7].

There is no signal over expected background observed and the lower limits are again placed in the general 2D plane of $BR(T \to tH)$ vs. $BR(T \to bW)$, see Fig. 11 where the label 'Wb+X' corresponds to this analysis.

This analysis also places the lower limit on the mass of the chiral fourth generation top quark partner of 740 GeV while the expected limit is 770 GeV. This result is also applicable to the vector-like quark with the electric charge of $-4/3e$.

2.1.4 Search for same-sign leptons

The ATLAS experiment also performs a search for a new physics in the events with a same-sign dilepton pair, a b-tagged jet, and significant additional jet activity [8]. Such final state signature is predicted in various models, which are considered here: the pair production of 4th chiral generation b' quarks, the pair production of VLQ, the sgluon (color-adjoint scalars) pair production and the model with two universal extra dimensions both leading to four top quark production.

The events in the sample are required to have two leptons (electrons or muons) where the invariant mass of the same flavor leptons is inconsistent with Z boson mass, the large missing $E_T > 40$, the large scalar sum of p_T of leptons and jets $H_T > 550$ GeV and at least 2 jets where at least one of them is b-tagged. The additional criteria on H_T, the number of b-jets and the charge of leptons are optimized for the various models in question.

There is no excess of events over predicted background observed and the observed yields are used to place the limits. The 4th generation chiral b-quark has lower mass limit $m_{b'} > 720$ GeV (assuming $BR(b' \to Wt) = 100\%$). The vector like top (bottom) quark is limited to the mass $m_{T(B)} > 540$ (590) GeV (assuming BR consistent with T/B being a singlet), for the limits in the general BR plane, see Fig. 11 and Fig. 12. The s-gluon lower mass limit is 800 GeV and the lower limit on the Kaluza-Klein mass is 900 GeV.

2.2 CMS searches

2.2.1 Inclusive searches for vector-like top and bottom quark

CMS performs inclusive search for both the VLT and the vector-like bottom (VLB) quark that are pair-produced together with their antiparticles and decay into three different finale states, $T \to tZ/bW/tH$, $B \to bZ/tW/bH$ [9, 10]. In the T decays, all decay channels produce the final states with the b quarks and the W bosons where at least one W boson is considered to decay leptonically. In the B decays, exactly one lepton is selected from the W decay where the W may come directly from the B quark or from its decay products, such as $t \to Wb$ or $H \to WW$.

For the large masses of VLT or VLB, it is expected that their decay products will be highly boosted and could be merged into one single jet. Therefore, the additional jet reconstruction (independent of the standard jet reconstruction using the anti-k_t algorithm) is performed using the Cambridge-Aachen (CA) algorithm with a distance parameter of 0.8. The jets are required to have $p_T > 200$ GeV. In the VLT analysis, the W-jets are identified if their mass is between 60 and 130 GeV and they contain at least two sub-jets. Similarly, the top-jets are identified if the decay products of hadronically decaying top quark are merged in one jet and have the mass between 140 and 250 GeV and at least three sub-jets with a minimum pairwise mass above 50 GeV. In the VLB analysis, the V-jets are identified if the mass of two sub-jets is between 50 and 150 GeV and the ratio of the most massive sub-jet mass to the mass of the jet is below 0.4.

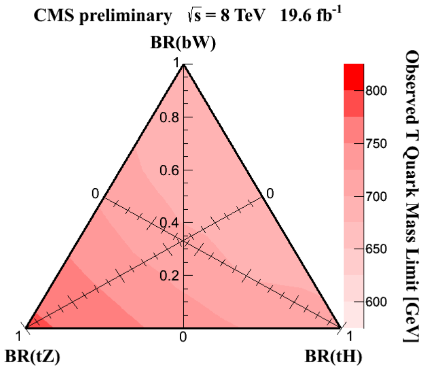

Figure 6: The BR triangle with the observed limits for the T quark mass. Every point in the triangle corresponds to a particular set of branching fraction values subject to the constraint that all three add up to one [9].

The VLT analysis is split into the single-lepton and the multilepton channel. In the single-lepton channel, the boosted decision trees (BDT) are used to separate the signal from the backgrounds while the multilepton analysis simply uses the yields as the discriminant in the limit calculation. The VLB analysis is performed in the single-lepton channel where the data fit is performed to the 2-dimensional distribution of the scalar sum of the jets transverse energies, the lepton p_T and the missing E_T vs. the V-tag multiplicity.

The full BR space is explored and no excess of the signal over the background is found. The lower limits between 687 and 782 GeV are placed for the VLT quark mass for all possible BR combinations, see Fig. 6. For the VLB quark, the lower B mass limits between 582 and 732 GeV are placed depending on the BR, see Fig. 7. The shaded regions in Fig. 7 represent regions with small expected sensitivity, precisely that the ex-

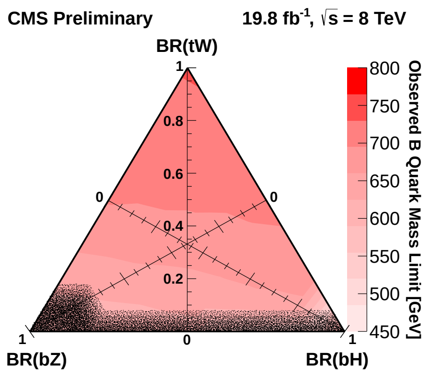

Figure 7: The BR triangle with the B quark mass observed limits [10].

pected limit is less than 500 GeV.

2.2.2 Vector-like bottom $B \to bZ$ search

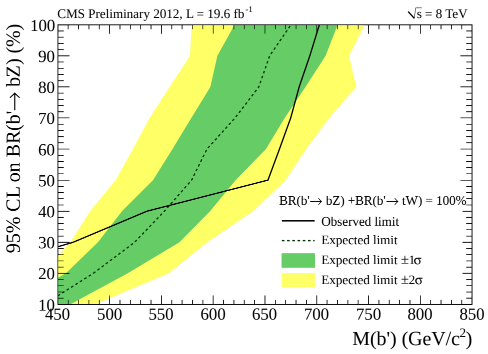

Figure 8: The mass exclusion limits on $BR(B \to bZ)$ [11].

CMS searches for the VLB quarks assuming one of the pair produced VLB decays into $B \to bZ$ [11]. Only two decay modes of VLB $B \to bZ$ and $B \to tW$ are assumed in this analysis.

Two leptons and at least one b-tagged jet are required in the final state. The dilepton invariant mass is required to be consistent with Z boson mass while the transverse momentum criteria on the lepton pair $p_T(\ell\ell) > 150$ GeV is also applied.

The data-driven estimate of $Z + b$ jet background was performed by considering the different regions of the two-dimensional plane of the number of jets and the b-tagging discriminant variables for the signal and the control regions.

The kinematics of B quark is reconstructed from two leptons and the highest-p_T b-jet. The invariant mass of B is used as a discriminant. No excess of the events is found and the limits on $BR(B \to bZ)$ from 30% to 100% as a function of VLB mass are determined, see Fig. 8. The observed (expected) lower limit on the mass of the B quark is 700 (680) GeV assuming $BR(B \to bZ) = 100\%$ which could be compared to the observed (expected) limit of ~ 750 (750) GeV from a similar analysis in ATLAS, see Fig. 12.

2.3 Search for vector-like top quark with charge 5/3e

The CMS experiment searches for the vector-like quarks with the exotic charge of $5/3e$ assuming their pair production and the decay to the top quark and the W boson of the same-sign charge, see Fig. 9 [12]. As a consequence, two same-sign leptons are possible in the final state which is quite rare signature within the SM processes.

Since both the top quark and the W boson from $T_{5/3}$ decay are expected to be highly boosted, the top/W boosted tagging techniques are used to identify these objects. The jets corresponding to highly boosted top quarks ('CA top jets') are clustered using the CA clustering algorithm with a distance parameter of 0.8. The main conditions applied are the jet $p_T > 200$ GeV, at least three sub-jets and the mass of jet being in between 140 and 250 GeV. The jets corresponding to highly boosted W bosons ('CA W jets') are also clustered using the CA algorithm with a distance parameter of 0.8 and are required to have $p_T > 200$ GeV, exactly two sub-jets

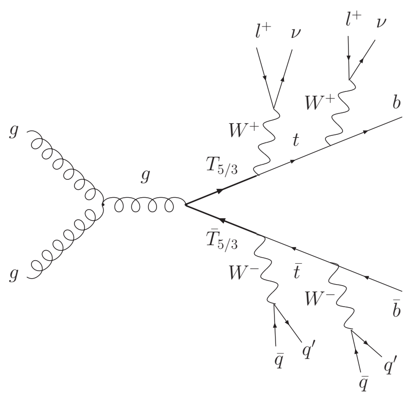

Figure 9: The pair production of $T_{5/3}$ quarks and the decay to same-sign dilepton final state [12].

and the mass of jet in between 60 and 130 GeV. All other jets are identified as anti-k_t jets with radius parameter of $R = 0.5$ (AK5 jets).

Since lots of final state high-p_T particles are expected to be produced in decays of $T_{5/3}$, two strong cuts are applied as part of the event selection. The very high cut on $H_T > 900$ GeV is applied where H_T is the scalar sum of the p_T of all the jets and leptons in the event. Another cut is applied on the number of constituents $N(con) > 5$ where each AK5 jet and each lepton not used for the same-sign lepton requirement counts as one constituent while 'CA W jet' counts as two and 'CA top jet' as three constituents.

There is no excess of events above the background observed, see Fig. 10. The event yields from all channels (ee,$e\mu$,$\mu\mu$) are combined when setting the limits. The lower limit is placed on mass of $T_{5/3}$: $m > 770$ GeV, while the expected limit is 830 GeV.

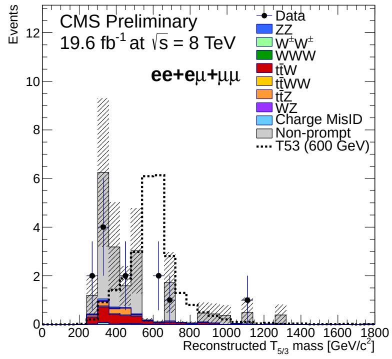

Figure 10: The reconstructed mass of $T_{5/3}$ [12].

2.4 Summary of VLQ searches

The ATLAS searches for vector-like quarks are summarized in Fig. 11 and Fig. 12. It can be seen that the full BR space is excluded up to about 550 (450) GeV for the vector-like $T(B)$ quark while for the specific decay mode, the limit goes up to about 850 GeV (assuming $BR(T \to tH) = 100\%$).

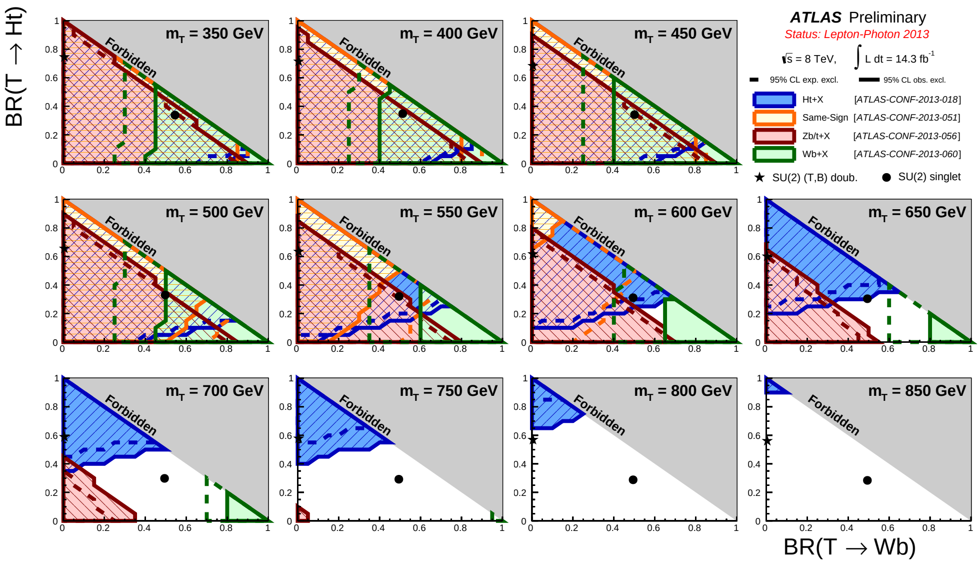

Figure 11: Summary of ATLAS searches for vector-like top quarks [13].

Since the ATLAS and CMS experiments applied different strategies for their searches and CMS used larger statistics, the obtained results mostly reflect this. While CMS has the higher

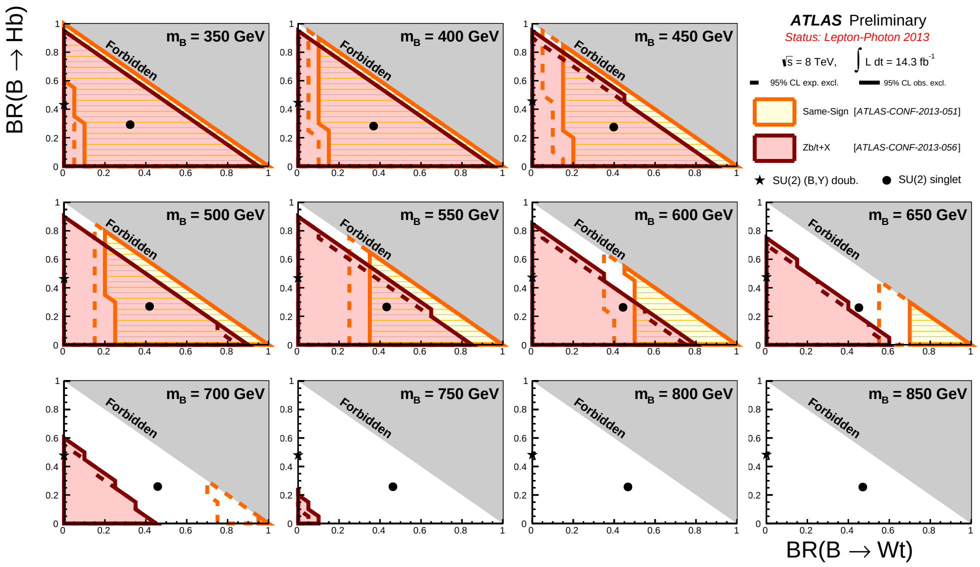

Figure 12: Summary of ATLAS searches for vector-like bottom quarks [13].

limit for the full BR plane (687 GeV comparing to $\sim 500-600$ GeV from ATLAS), the limit for the branching ratio being 1.0 for a certain decay mode is sometimes higher for ATLAS, e.g. for $BR(T \to tH) = 1.0$. The limits for the vector-like B quarks are usually stronger for CMS since ATLAS did not yet obtain the result optimized for the $B \to bH$ decay mode. It should be also noted that the ATLAS limits could be improved in the future by combining all the different analyses.

3 Search for excited top quark

Many theories beyond the SM surmise the top quark may be a composite rather than an elementary particle. An experimental test of such a prediction would be to search for the existence of an excited top quark (t^*).

CMS performs such search for the pair produced excited top quark assuming a model in which t^* has spin 3/2 and decays 100% of time to the top quark via the emission of a gluon [14]. The analysis is performed in the lepton+jets channel requiring the presence of one lepton (electron or muon) and at least six jets with at least one of them being b-tagged in the final state.

The t^* mass reconstruction is performed by the minimization of the χ^2 where the invariant mass of the top quark and the gluon m_{t+g} is a free param-

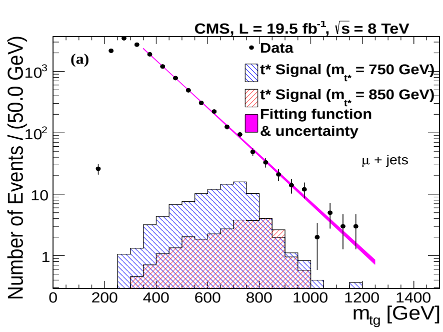

Figure 13: The reconstructed mass of the top quark and the gluon, the background fit and the expectation for the signal [14].

eter. The data driven method is used to estimate the background contribution in the signal region by fitting the invariant mass of the top quark and the gluon with a Fermi-like function.

As seen in Fig. 13, no significant excess of the events over the predicted background is observed and the lower observed (expected) limit is placed on the mass of excited top $m > 803$ (739) GeV.

4 Baryon number violation search

In the SM, the baryon number is conserved while it can be violated in many theories, such as the supersymmetry and the grand unified theories. It was recently suggested that the baryon number violation (BNV) can proceed in the processes involving the top quark where it would undergo the decay of the type $t \to \bar{b}\bar{c}\mu^+(\bar{t} \to bc\mu^-)$ and $t \to \bar{b}\bar{u}e^+(\bar{t} \to bue^-)$ involving an electron or a muon in final state.

The CMS experiment searches for such violation in the $t\bar{t}$ process where one SM top quark decays hadronically into three jets and one top quark decays through the BNV mode [15]. Such a final state includes an isolated lepton and five jets but no significant missing transverse momentum. Only one relatively loosely b-tagged jet is required in order to maintain the sensitivity of the search to other possible BNV decays involving only the light-quark jets. This so-called 'basic selection' is used for the normalization of SM $t\bar{t}$ and $t + W$ processes. As a result of the normalization, the impact of the systematic uncertainties is largely reduced.

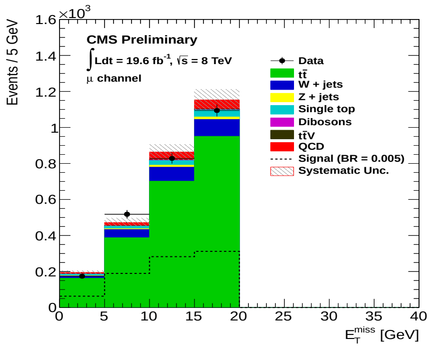

Figure 14: The missing E_T distribution after the final selection. The signal contribution for $t\bar{t}$ with the baryon number violation decays at the level of 0.5% is also shown [15].

The final ('tight') selection involves two additional cuts to enhance the presence of the signal. The first requirement is on the missing energy $E_T^{miss} < 20$ GeV (Fig. 14). The second requirement is on the compatibility of the event with the kinematics expected in the $t\bar{t}$ event having SM-BNV decays. The compatibility is tested using the χ^2 which includes the terms of the reconstructed masses of the W boson and the hadronically decaying top quark and the top quark with the BNV decay. The best combination for a given event must pass the cut $\chi^2 < 20$.

The branching-ratio for the BNV decay mode is estimated from the likelihood fit to the yield in data for the tight selection where the expected number of the events is a function of the $t\bar{t}$ and tW efficiencies of passing the tight selection which themselves are the function of BR for BNV decay.

There is no excess of events observed and the upper limit of 0.15% is placed on the branching ratio for the baryon number violating decay for the combined electron and muon analysis while the expected upper limit was estimated to be 0.29%.

5 Conclusion

There are plenty of searches for a new physics in $t\bar{t}$ pair production from the ATLAS and CMS experiments performed using the LHC data delivered in 2012 at the energy of the interaction of 8 TeV.

The significant mass ranges of the top quark partners are excluded for various models. The vector-like quark masses are excluded at 95% C.L. below the range of about 600 – 850 GeV depending on the quark type and its decay mode. The lower limit on the mass of the excited top quark of 790 GeV is set at 95% C.L. The baryon number violation mode of top quark is excluded for the branching ratio above 0.15% at 95% C.L.

Although there are no hints of the new physics yet, there are still many analyses in the preparation.

The next round of LHC running is supposed to start at the beginning of 2015 with the much higher energy of interaction (13 TeV or 14 TeV). We can hope some new physics will be revealed. If that will happen, there is a high chance it will be in the top quark sector.

6 Acknowledgments

The author would like to thank the colleagues from the experiments who contributed to this article with their comments.

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