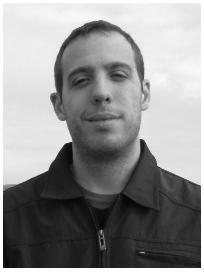
EXOTIC SEARCHES IN THE LARGE HADRON COLLIDER

THIAGO RAFAEL T. FERNANDEZ
FOR THE ATLAS and CMS COLLABORATIONS

Instituto de Física Teórica, Univ. Estadual Paulista,
R. Dr. Bento Teobaldo Ferraz, 271 - Bloco II
01140-070 - São Paulo, SP, Brazil



We present a selection of results of searches for physics beyond the standard model, reported by both the ATLAS and CMS collaborations, based on the data taken in the proton-proton collisions delivered by the LHC during 2012. The studies reported cover generic searches for new phenomena, as well as specific searches for new resonances, excited fermions, leptoquarks and vector-like quarks. In all searches covered in this report, no signs of physics beyond the standard model are observed.

1 Introduction

The standard model of particles and fields is one of the most successful scientific theories ever created, explaining almost all phenomena concerning electromagnetic, weak and strong interactions. However, there is a series of experimental evidences that leads one to expect the existence of a more complete theory of fundamental interactions: the existence of dark matter, the acceleration of the expansion of the universe, the observed baryon asymmetry and the neutrino oscillations rank among those evidences. The CMS [1] and ATLAS [2] collaborations run two independent particle physics experiments at the CERN Large Hadron Collider; one of their scientific goals is the search for direct evidence of physics beyond the standard model in the proton-proton collisions delivered by the LHC. In this review, we present some of their latest results on that front. For results on more specialised aspects of their searches, like those based on supersymmetric scenarios, specific searches for dark matter candidates or exotic Higgs bosons, we invite the reader to the other contributions to these proceedings. For more detailed information, as well as the latest results, we invite the reader to access the web resources provided by both collaborations [3,4,5].

2 General Searches for New Phenomena

One of the most interesting characteristics of both the ATLAS and CMS experiments is their general-purpose particle detection capabilities. Although many searches for physics beyond the standard model have been performed by both collaborations, it is possible that signals of new physics still lie hidden in the data taken during Run I of the LHC. The ATLAS collaboration reports on a new study designed to search for those kinds of signals in a model-independent, comprehensive approach [6]. The study focuses on dividing the full dataset taken by the experiment into exclusive event classes, according to the number and type [a] of reconstructed objects present in the event. For each class, three distributions are calculated: m_{eff}, the scalar sum of p_{T} of all objects; m_{inv}, the invariant mass of all visible objects; and the missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$. An example distribution can be seen in Fig. 1.

The standard model background prediction for all of those categories is taken from simulation, with the exception of background due to single fake leptons, which is taken from data-driven methods. The study reports that a total of 573 event classes are found to contain observed events, while 697 event classes have a standard model expectation greater than 0.1 events. The distributions observed in data are then compared to the predictions and scanned for the regions of higher disagreement. The probabilities of statistical fluctuations in a distribution are modelled by pseudo-experiments, and the region of greatest disagreement (smallest p-value) is computed. The study reports that no event class is found with a local p-value below 10^{-4}; no major disagreement can be found between the standard model prediction and the observed data. An example distribution of the fraction of pseudo-experiments with a p-value above a threshold can be seen in Fig. 2.

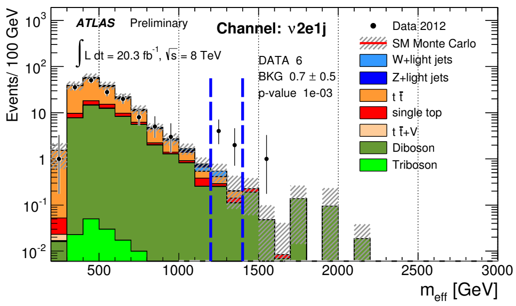


Figure 1: m_{eff} distribution for the event class with three muons. The dashed vertical lines indicate the region of interest which has the smallest p-value (0.0071) for this event class.

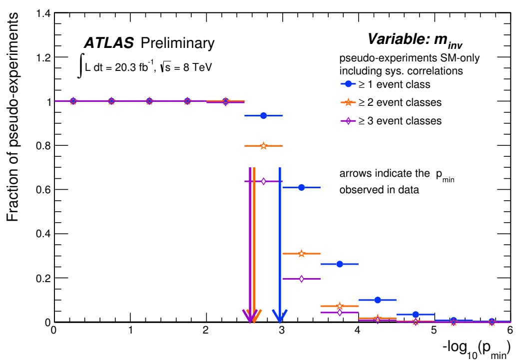


Figure 2: The fraction of pseudo-experiments which have at least one, two and three deviations with a p-value below a given threshold (p_{min}) in the scan of the visible invariant mass distribution. The values observed in data are indicated by arrows.

[a] Object types considered are: electron, muon, photon, hadronic jet, b-tagged hadronic jet and missing transverse energy.

The ATLAS collaboration also reports a different search, done in a similar spirit but focusing on multiple lepton final states, with a minimum of three leptons – electrons, muons or hadronically-decaying taus [7]. Again, the full dataset is classified, according to the following criteria:

- presence/absence of at most one hadronic tau ($3e/\mu$ vs. $2e/\mu + \tau_{\rm had}$);
- presence/absence of a Z boson candidate (on-Z vs. off-Z);
- number of b-tagged jets;
- value of kinematic variables: leptonic $H_{\rm T}$, jet $H_{\rm T}$, $m_{\rm eff}$, $E_{\rm T}^{\rm miss}$.

This search also finds no evidence for new physics, and reports limits in terms of pure visible cross section as function of a given kinematic variable, as shown in Fig. 3. Tables of fiducial efficiencies as function of lepton kinematics are also made available; in this way, theorists can cast the results of this search in terms of different models.

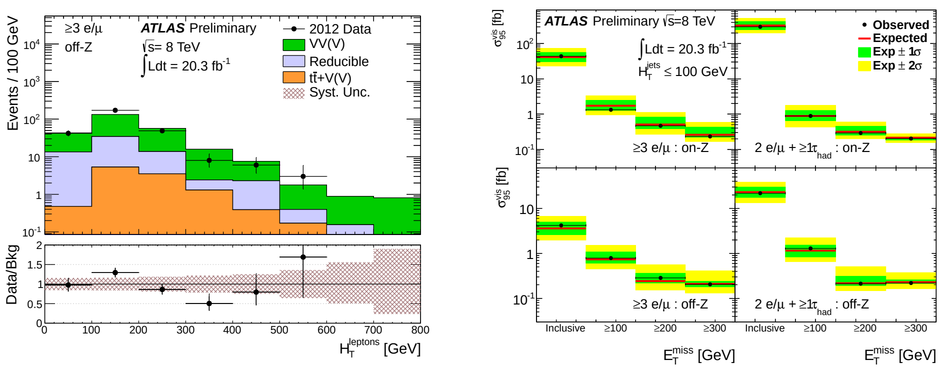


Figure 3: Left: the leptonic $H_{\rm T}$ distribution for the off-Z $3e/\mu$ signal channels. The last bin shows the overflows. Right: The observed- and median-expected 95% CL limit on the visible cross section in the different signal channels, as functions of increasing lower bounds on $E_{\rm T}^{\rm miss}$ in events with jet $H_{\rm T}$ <100 GeV.

3 Resonant Production of HH $\rightarrow$ 4b

The discovery of the Higgs Boson (H) by the ATLAS and CMS collaborations in 2012 opens up a new avenue of searches for physics beyond the standard model: final states with H bosons in the final state [8]. The ATLAS collaboration has recently reported a search for resonant production of pairs of H, focusing on the $H \rightarrow b\bar{b}$ decay ($X \rightarrow HH \rightarrow 4b$). The signature of this process is the presence of at least four resolved, b-tagged hadronic jets in the event, paired in dijet systems of invariant mass M_{JJ} close to the observed mass of the H boson of 125 GeV. As a fully hadronic process, the main standard model background to this search consists of events originating from multijet processes; the requirement of four b-tagged jets leads to a sizeable contribution of $t\bar{t}$ events to the background as well. This study uses the Randall-Sundrum bulk warped extra dimension model as a benchmark, in which the graviton plays the role of the resonant state.

The standard model background prediction is taken from control regions in the dijet invariant mass windows, with one or both of the dijet systems having an invariant mass around that of the Z boson instead of the H boson. This analysis found no evidence for physics beyond the standard model, and set a limit on the cross-section of $\sigma < 7$ fb for a graviton of mass $M_{\rm G*} =$ 1 TeV. The benchmark model, with coupling constant $k/M_{\rm Planck}$=1.0 is excluded for $M_{\rm G*}$ in the 590–710 GeV range. The rising behaviour of the expected limit for $M_{\rm G*} > 1.2$ TeV seen in Fig. 4 is due to the requirement of four resolved jets in the final state; for those masses of the resonance, the "merged jets" topology starts to become dominant and this analysis loses sensitivity.

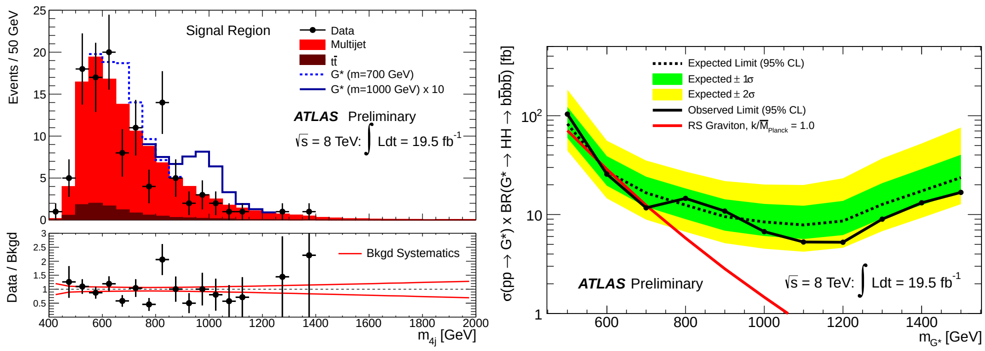


Figure 4: Left: a comparison of the predicted m_{4j} background distribution to that observed in the data in the signal region. The distributions of two G* signal samples are also shown. Right:the expected and observed 95% CL upper limits on $\sigma(G^*) \times BR$ as a function of M_{G*}.

4 Excited Fermions

One of the tenets of the standard model is the fact that the fermions which constitute the main building blocks of matter are fundamental particles, with no internal substructure. The discovery of excited fermionic states would be a clear indication for physics beyond the standard model. In general, excited fermions would couple to standard fermions at energy scales of the order of the compositeness scale Λ. The CMS collaboration reports on a search for excited quarks through the $q^* \to q\gamma$ process [9]. The search is performed by parameterising the shape of the invariant mass of the leading jet and photon found in the data events, and searching for localised structures on top of that shape. The main backgrounds are the standard model process $qg \to q\gamma$ and $q\bar{q} \to g\gamma$, as well as multijet events where one of the hadronic jets is misidentified as a photon. ATLAS presents a similar search, but also interprets their results in terms of a quantum black hole model [10]. Both collaborations find no evidence of new physics, and set limits on the mass of the excited quark of $M_{Q*} > 3.5$ TeV (Fig. 5); ATLAS sets a limit on the mass of quantum black holes $M_{QBH} > 4.9$ TeV. CMS also presents an exclusion region in the (M_{Q*}, f) plane, where f is an universal coupling strength of the excited quark to the standard model ones.

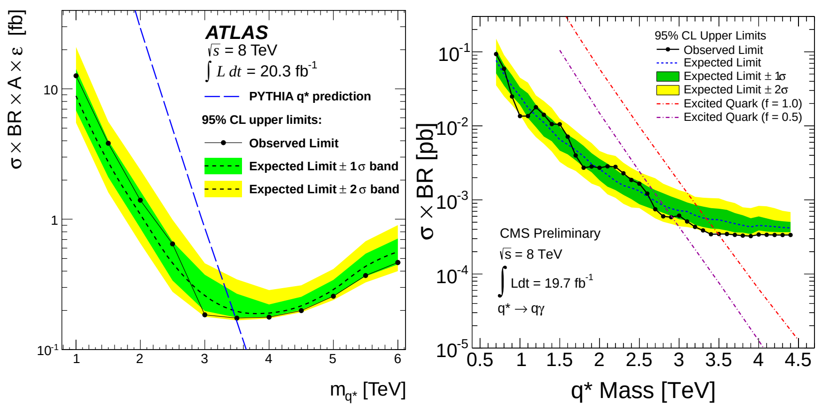


Figure 5: Expected and observed 95% CL upper limits on $\sigma \times BR$ of $pp \to q^* \to q\gamma$ set by the ATLAS collaboration (left) and the CMS collaboration (right).

The ATLAS collaboration has also reported on a search for excited leptons, albeit with only 13/fb of data collected during 2012 [11]. This analysis is based on a signature with two leptons (electrons or muons) and one photon, and the discriminating variable of choice is the three objects' invariant mass $M(\ell\ell\gamma)$. The two main analysis requirements are a veto on Z-peak events, by requesting $M(\ell\ell) > 110$ GeV, and a moving signal window in the $M(\ell\ell\gamma)$ distribution

(Fig. 6). The main standard model background consists of $Z+\gamma$ events. ATLAS reports no evidence for new physics, and sets limits on the cross-section time branching ratio $\sigma \times B$ less than 0.75 fb (for the e^* search) and less than 0.90 fb (for the μ^* search). For the special case where the compositeness scale Λ is equal to the mass of the excited lepton, ATLAS sets a limit on the mass of the excited lepton $M_{\ell^*} > 2.2$ TeV.

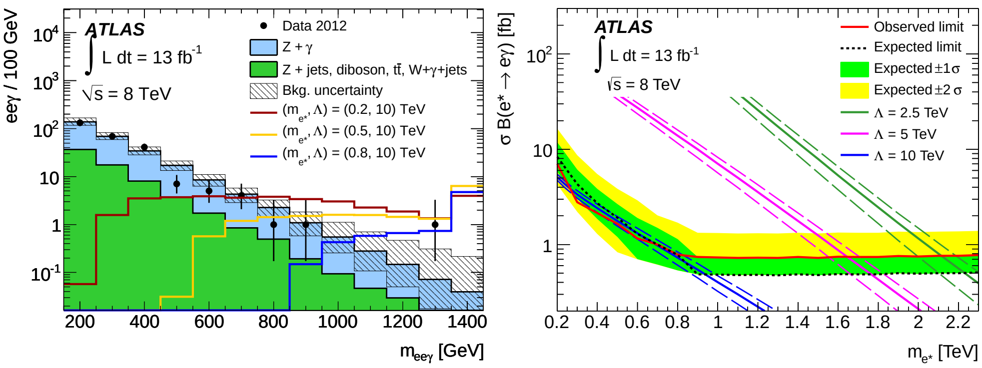


Figure 6: Left: distribution of $M(\ell\ell\gamma)$ for the electron channel after requiring the dilepton mass $M(\ell\ell) > 110$ GeV. The last bin contains the overflows. Right: upper limit at 95% CL on $\sigma \times BR$ as a function of the excited lepton mass M_{ℓ^*} for the electron channel.

On the other hand, CMS presents a new result on search for resonance pairs to t + jet, which uses as benchmark models a spin 3/2 excited top quark and a R-parity-violating bottom squark [12]. This study focuses on signatures with two leptons (electrons or muons) and four jets in the final state, with at least two b-tagged jets. The standard model background estimation is done with control regions in the $p_{\rm T}$ of the second leading light jet; signal regions are defined for $p_{\rm T}^{\rm 2nd\ jet} > 110$ GeV, as shown in Fig. 7. The study does not find evidence for physics beyond the standard model, and limits are set on the mass of the excited top (M_{t*} excluded in the range 300–703 GeV) and of the R-parity-violating bottom squark ($M_{\tilde{b}}$ excluded in the range 250–326 GeV).

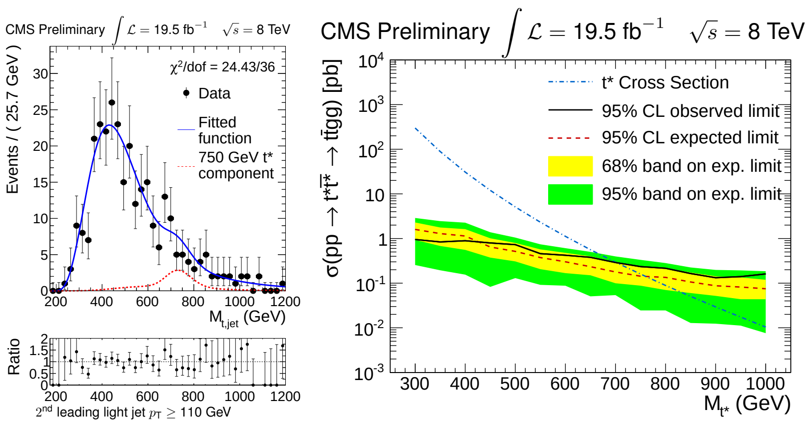


Figure 7: Left: invariant mass distribution in a signal region, after likelihood maximisation with signal cross section set to the calculated upper limit of the 750 GeV t* point. Right: Observed and expected 95% CL upper limits on the production cross section of t* pairs as a function of t* mass using unified intervals.

5 Leptoquarks

A curious property of the standard model is the apparent similarity between quarks and leptons: within a single generation, there are always two quarks and two leptons. Furthermore, the relationship between the pair of quarks resembles a lot that of the pair of leptons, suggesting the possibility of a symmetry between leptons and quarks. Some extensions of the standard model, like technicolour, Pati-Salam and Georgi-Glashow models suggest the existence of leptoquarks (LQ): hypothetical particles that carry both baryon and lepton numbers, which would allow quarks and leptons of the same generation to interact directly. Leptoquarks could be produced at the LHC, decaying into either a charged lepton and a quark (with branching fraction β) or a neutrino and a quark (with branching $1-\beta$). The latter channel is much more challenging, so most searches focus on the lepton + jet signature of the former channel.

A search for the third-generation leptoquark (LQ3), both in the $\tau + t$ and the $\tau + b$ channel, was recently unveiled by the CMS collaboration [13,14]. The $\tau + t$ channel focuses on a signature containing a same-sign pair of μ and hadronically-decaying τ ($\mu\tau_{\text{had}}$ signature), accompanied by two or more hadronic jets and with a high S_{T} (scalar sum of the p_{T} of all objects in the event) > 400 GeV; events are also divided in "central" and "forward" regions. The main background in this search consists of events with fake leptons (essentially, hadronic jets are misidentified as tau leptons), with a subdominant contribution of standard model events of Drell-Yan + jets and $t\bar{t}$ + jets. The $\tau + b$ channel, on the other hand, considers both $e + \tau_{\text{had}}$ and $\mu + \tau_{\text{had}}$ signatures, accompanied by two or more hadronic jets of which at least one is b-tagged. Also, a requirement is set on the invariant mass of the charged lepton and the hadronic tau $M(\ell, \tau_{\text{had}}) > 250$ GeV. No signs of an excess of events above the background prediction were detected in neither channel, and CMS sets the following limits on the mass of the third generation leptoquark: $M_{LQ3}^{t+\tau} >$ 550 GeV, and $M_{LQ3}^{b+\tau} > 740$ GeV, both for the case $\beta = 1$ (Figs. 8 and 9). For the $b + \tau$ channel, CMS also shows an exclusion limit in the (β, M_{LQ3}) plane.

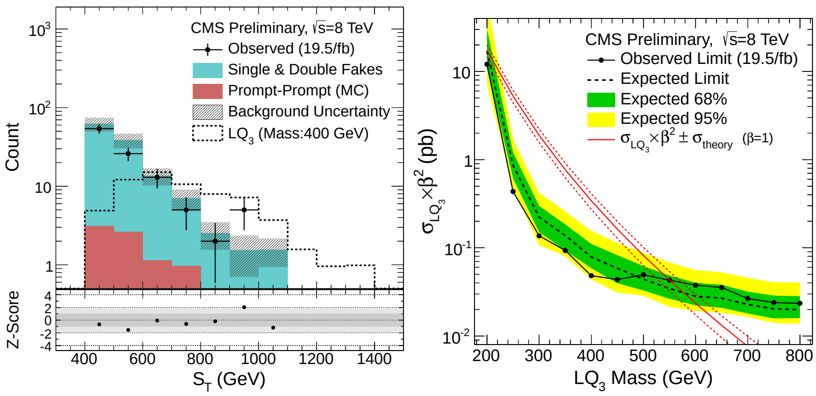


Figure 8: Left: S_{T} distribution in the central channel in the signal region. Right: The expected and observed exclusion limits at 95% CL on the LQ_3 pair-production cross-section times β^2 in the combination channel.

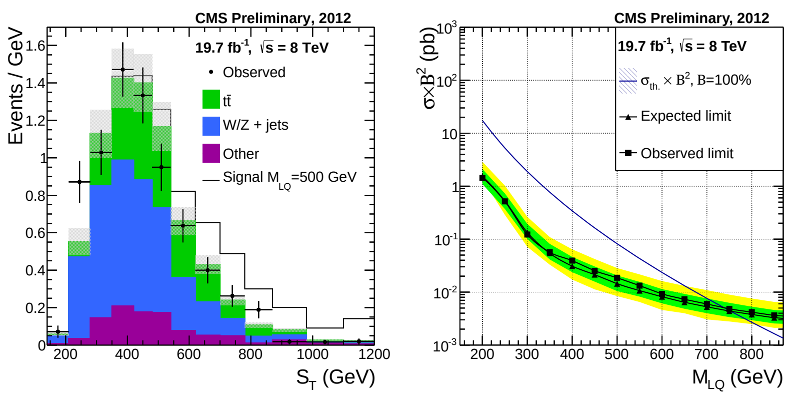


Figure 9: Left: final S_{T} distribution for the LQ search with the $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ channels combined. The last bin contains the overflow events. Right: the expected and observed combined upper limit on the LQ pair production cross section times β^2 at the 95% CL, as a function of the LQ mass.

6 Vector-like Quarks

The last class of models we discuss in this review are those which present vector-like quarks (VLQ). In general, a fermion is defined to be vector-like if both their left-handed and right-handed chiralities transform in the same way the symmetry group of the underlying theory. Vector-like quarks appear in a series of new physics models, including extra dimensions, Little Higgs, Composite Higgs, flavour group gauging and non-minimal SUSY. The CMS collaboration has recently unveiled a search for pair production of vector-like $b' \to bZ, tW, bH$ [15,16]. The experimental signature of the process is the presence of at least three leptons ($e, \mu, \tau_{\text{had}}$). Events are further classified according to:

- number of b-tagged jets (zero vs. one or more);
- multiplicity of opposite-sign, same flavour (OSSF) lepton pairs;
- S_{T} variable.

The main standard model backgrounds for this search are $t\bar{t}$ production for the three leptons channel, and ZZ production for the four lepton channel. The search finds no evidence for physics beyond the standard model, and the b' is excluded for masses smaller than 520–785 GeV, depending on the branching fractions assumed to each of the decay channels, as seen in Fig. 10.

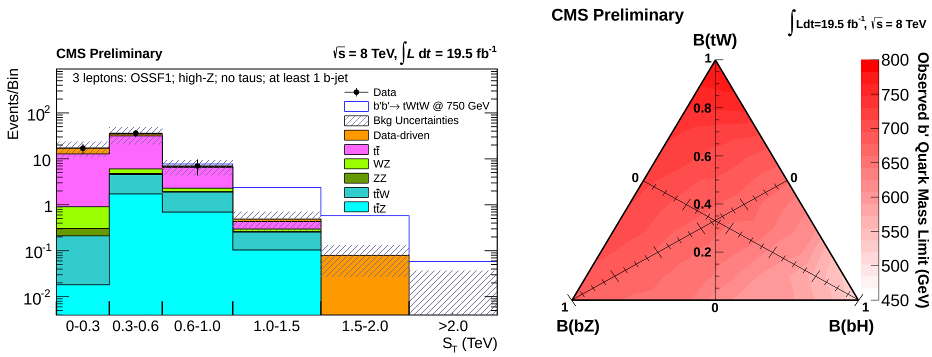


Figure 10: Left: Background breakdown vs S_{T} requiring 3 leptons, OSSF=1, above Z peak, no taus, 1 b-jet. For $b'b' \to tWtW$ as the signal with b' having a mass of 750 GeV. Right: Observed limit results with varied branching ratio of tW, bH, and bZ in steps of 0.1.

Also, a dedicated search for the vector-like b' in the $b' \to Z + X$ final state has been performed by both ATLAS [17,18] and CMS [19]. They have a common strategy of selecting events with a $Z \to ee, \mu\mu$ decay, with p_{T} of the Z boson greater than 150 GeV. However, the ATLAS analysis works with data from single lepton triggers, and further selects events with jet $H_{\text{T}} >$ 600 GeV and at least two b-tagged jets. The CMS analysis, on the other hand, works with data from double lepton triggers and at least one b-tagged jet, with $p_{\text{T}} > 80$ GeV; additionally, they require the invariant mass $M(\ell\ell b)$ to be greater than 375 GeV. Neither of the collaborations see evidence for physics beyond the standard model. The ATLAS results, with 14.3/fb of integrated luminosity, are a lower limit of $M(b') > 645$ GeV for the singlet case ($BR(b' \to Zb) = 1/3$) and $M(b') > 725$ GeV for the doublet case($BR(b' \to Zb) = 2/3$). The CMS results, with 20/fb of integrated luminosity, are a lower limit of $M(b') > 700$ GeV for $BR(b' \to Zb) = 1$, and a mass-dependant limit in the $b' \to Zb$ branching ratio smaller than 0.3–1.0, as function of the b' mass. Both results are shown in Fig. 11.

Many other searches for vector-like quarks were performed by both ATLAS and CMS. Boosted topologies play a prominent role in those studies; for those results, please refer to P. Azzi's review in these proceedings. Summary plots of searches for VLQs are made available by both collaborations in their respective websites.

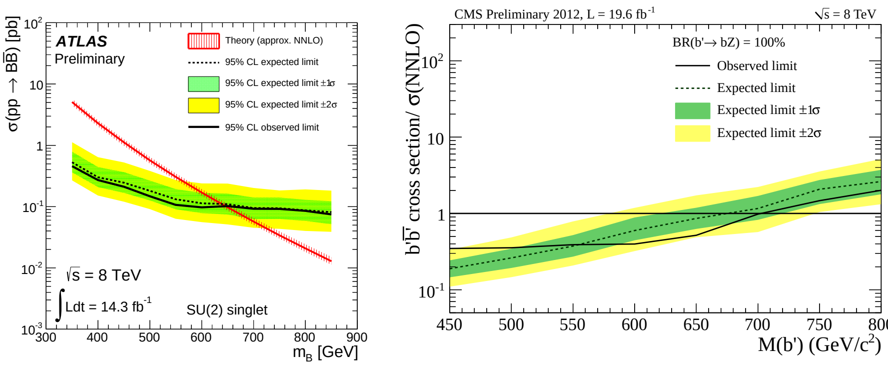


Figure 11: Left: ATLAS result for the 95% CL upper limit on $\sigma(b'b')$ versus b' mass, for a SU(2) singlet vector-like b' quark. Right: CMS result for the 95% CL upper limit on $\sigma(b'b')$/(expected NNLO cross section) versus b' mass, with the assumption of $BR(b' \to bZ) = 100\%$.

7 Conclusions

Searches for physics beyond the standard model are one of the more active areas of both the ATLAS and CMS collaborations. Efforts are being made in order to not only address more benchmark models, but also to do model-independent searches and report model-independent results. The techniques developed for the first run of the LHC are being honed and consolidated, in order to allow a smooth transition into the harsher experimental conditions expected for the second run. It can be expected that, if physics beyond the standard model are accessible at the LHC, both experiments will be thoroughly prepared to uncover it.

Acknowledgements

The author would like to thank Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for the financial support.

References

1. CMS Collaboration, JINST **3**, S08004 (2008)
2. ATLAS Collaboration, JINST **3**, S08003 (2008)
3. `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsCONFnotes`
4. `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO`
5. `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G`
6. ATLAS Collaboration, *ATLAS Note* **ATLAS-CONF-2014-006** (2014).
7. ATLAS Collaboration, *ATLAS Note* **ATLAS-CONF-2013-070** (2013).
8. ATLAS Collaboration, *ATLAS Note* **ATLAS-CONF-2014-005** (2014).
9. CMS Collaboration, *CMS Physics Analysis Summary* **CMS-PAS-EXO-13-003** (2014).
10. ATLAS Collaboration, *Phys. Lett.* B **728C**, 562-578 (2014)
11. ATLAS Collaboration, *New J. Phys.* **15**, 093011 (2013)
12. CMS Collaboration, *CMS Physics Analysis Summary* **CMS-PAS-B2G-12-008** (2014).
13. CMS Collaboration, *CMS Physics Analysis Summary* **CMS-PAS-EXO-12-030** (2014).
14. CMS Collaboration, *CMS Physics Analysis Summary* **CMS-PAS-EXO-12-032** (2014).
15. CMS Collaboration, *CMS Physics Analysis Summary* **CMS-PAS-B2G-12-020** (2014).
16. CMS Collaboration, *CMS Physics Analysis Summary* **CMS-PAS-B2G-13-003** (2014).
17. ATLAS Collaboration, *ATLAS Note* **ATLAS-CONF-2013-051** (2014).
18. ATLAS Collaboration, *ATLAS Note* **ATLAS-CONF-2013-056** (2014).
19. CMS Collaboration, *CMS Physics Analysis Summary* **CMS-PAS-B2G-12-0201** (2014).