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EXOTIC PHENOMENA SEARCHES AT HADRON COLLIDERS

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This review presents a selection of the final results of searches for various exotic physics phenomena in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV delivered by the LHC and collected with the ATLAS and CMS detectors in 2011 (5 fb^{-1}) and in the first part of 2012 (4 fb^{-1}). Searches for large extra dimensions, gravitons, microscopic black holes, long-lived particles, dark matter, and leptoquarks are presented in this report. No sign of new physics beyond the Standard Model has been observed so far. In the majority of the cases these searches set the most stringent limits to date on the aforementioned new physics phenomena.

1 Introduction

A selection of searches for various exotic physics phenomena beyond the Standard Model (SM) in proton-proton collisions at $\sqrt{s} = 7$ TeV delivered by the LHC and collected with the ATLAS [1] and CMS [2] detectors in 2011 is presented in this paper. The data correspond to an integrated luminosity of 5 fb^{-1}. Searches for large extra dimensions, gravitons, long-lived particles, dark matter, and leptoquarks are presented in this report. A preliminary result of a search for microscopic black holes performed with 3.7 fb^{-1} of proton-proton collisions at $\sqrt{s} = 8$ TeV collected in 2012 by the CMS detector is also shown. Searches for Supersymmetry (SUSY) and other exotic physics phenomena (such as searches for new heavy fermions and bosons) are not discussed in this paper. These results can be found in other proceedings of this conference. The complete set of public results from ATLAS and CMS experiments can be found in references [3,4].

2 Large Extra Dimensions

Compact large extra dimensions (ED) are an intriguing proposed solution to the hierarchy problem of the SM, which refers to the puzzling fact that the fundamental scale of gravity $M_{\text{Planck}} \sim 10^{19}$ GeV is so much higher than the electroweak symmetry breaking scale $\sim 10^3$ GeV. In the ADD model [a], the SM is constrained to the common 3+1 space-time dimensions, while gravity is free to propagate through the entire multidimensional space. The gravitational flux in 3+1 dimensions is effectively diluted by virtue of the multidimensional Gauss's Law. In this framework, the fundamental Planck scale can be lowered to the electroweak scale, thus making

[a] The original proposal to use large extra dimensions to solve the hierarchy problem was presented by Arkani-Hamed, Dimopoulos, and Dvali (ADD).

production of gravitons possible at the LHC. Experimental signatures indicative for the existence of EDs are discussed below.

2.1 Microscopic Black Holes (8 TeV)

One of the exciting predictions of theoretical models with extra dimensions and low-scale quantum gravity is the possibility of copious production of microscopic black holes in particle collisions at the LHC. Events with large total transverse energy are analyzed for the presence of multiple high-energy jets, leptons, and photons, typical of a signal expected from a microscopic black hole. The analysis is performed using the first 3.7 fb^{-1} of data collected by the CMS experiment in 2012 at $\sqrt{s} = 8$ TeV [5]. Figure 1 (left) shows the distribution of the total transverse energy for data, background prediction and various signal samples. Good agreement with the Standard Model backgrounds, dominated by QCD multijet production, is observed for various final-state multiplicities and model-independent limits on new physics in these final states are set. Using a simple semi-classical approximation, new model-specific indicative limits on the minimum black hole mass are derived as well in the range 4.1 – 6.1 TeV, depending on the specific model considered. An example of limits using the BlackMax generator is reported in Fig. 1 (right). The analysis has a substantially increased sensitivity compared to previous searches due to higher collision energy.

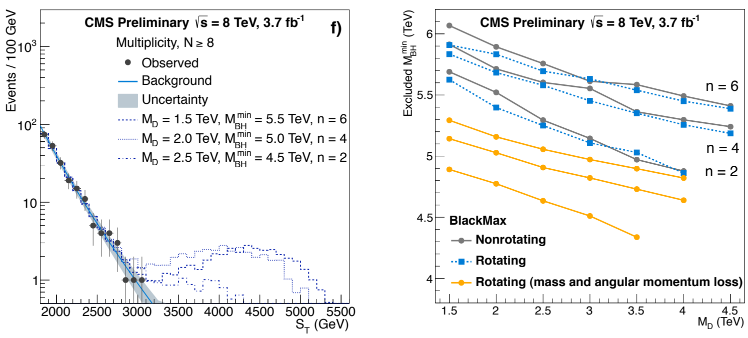

Figure 1. (Left) Total transverse energy (including the missing transverse energy in the sum) for events with at least 8 objects (jets, leptons, and photons) for data, background prediction, and black hole signals for three different parameter sets. (Right) Minimum black hole mass excluded at 95% CL as function of the reduced Planck scale for various BlackMax black hole models without the stable remnant and number of extra dimensions of two, four, and six [5].

2.2 Real Graviton Production and Dark Matter Limits

Searches for production of a real graviton produced in association with either an energetic hadronic jet or a photon have been performed by both ATLAS [6,7] and CMS [8,9] experiments. Since gravitons are free to propagate in the extra dimensions, they escape the detector and can only be inferred from the amount of missing transverse energy ($\not\!\!E_{\mathrm{T}}$). The offline event selection requires large $\not\!\!E_{\mathrm{T}}$, one high p_{T} jet or photon, a veto on the presence of well-identified leptons and isolated tracks, and additional requirements to suppress the cosmics, beam halo, and instrumental backgrounds that can fake the mono-jet+$\not\!\!E_{\mathrm{T}}$ and mono-photon+$\not\!\!E_{\mathrm{T}}$ signatures. Figure 2 (top) shows the $\not\!\!E_{\mathrm{T}}$ distributions in mono-jet and mono-photon events from the CMS and ATLAS analyses, respectively. The number of observed events in data is in good agreement with the SM prediction, and significant improvements are made to the existing limits on the fundamental parameters of the extra dimension model describing real-graviton emission.

These analyses are also sensitive to pair production of weakly interacting dark matter particles (WIMP, denoted as χ) where the χ-χ system recoils against an energetic hadronic jet or photon from initial state radiation. Using an effective field theory, the experimental collider results can be used to derive limits on the WIMP-nucleon cross section as a function of the mass of the dark matter candidate as shown in Fig. 2 (bottom) for the mono-jet analyses. Under the assumptions of this model, the ATLAS and CMS limits are more stringent than the ones from direct and indirect detection experiments for the spin-dependent WIMP-nucleon scattering over the entire WIMP mass (m_χ) range. For the spin-independent scattering the collider limits are the most stringent ones for $m_\chi < 10$ GeV.

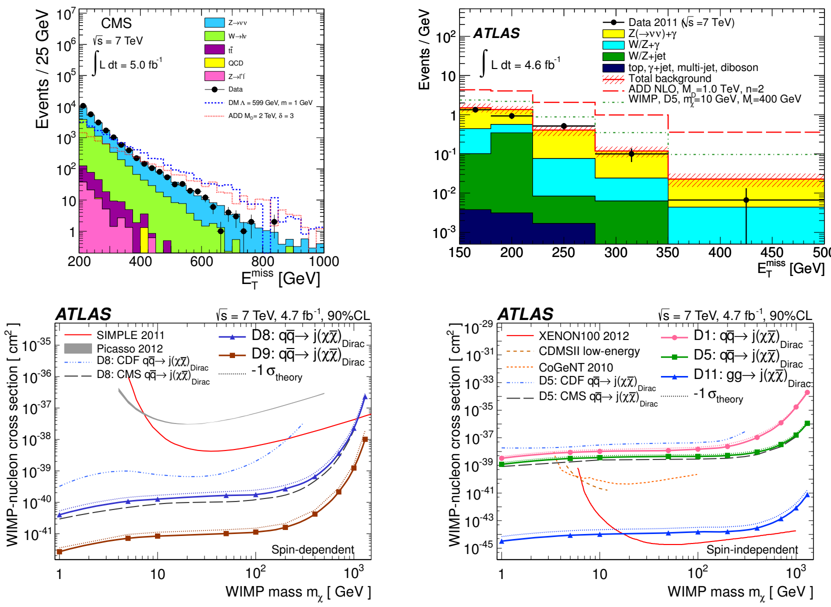

Figure 2. (Top) Distributions of $\not\!\!E_{\mathrm{T}}$ for data and SM background predictions after the CMS mono-jet (top-left) [8] and ATLAS mono-photon (top-right) [7] event selection. Examples of ADD and dark matter (indicated as DM or WIMP) signals are also shown. (Bottom) Limits on spin-dependent (bottom-left) and spin-independent (bottom-right) WIMP-nucleon cross section as a function of WIMP mass from ATLAS and CMS mono-jet searches compared to direct and indirect detection experiments [6]. Limits derived from mono-photon searches are slightly weaker.

3 Warped Extra Dimensions

Another possible solution to the hierarchy problem of the SM is based on the original Randall-Sundrum framework (RS1) with a warped extra dimension [10]. The most distinctive novel feature of this scenario is the existence of spin-2 Kaluza-Klein gravitons whose masses and couplings to the SM are set by the TeV scale. These gravitons would appear in experiments as widely-sephighlyarated-in-mass resonances, in contrast to the very light, closely-spaced-in-mass gravitons predicted in large extra dimension models. In the RS1 scenario, decays of gravitons to pairs of photons, leptons, or light jets provides the most striking experimental signatures for discovery of this new particle. The two model parameters are the graviton mass and the coupling $k/\bar{M}_{\mathrm{Planck}}$, where k is the curvature scale of the warped extra dimension and $\bar{M}_{\mathrm{Planck}}$ is the reduced Planck mass. Upper limits on $k/\bar{M}_{\mathrm{Planck}}$ were derived as a function of the graviton mass more than 10 years ago by using electroweak precision measurements (oblique parameters S, T) [11]. These studies demand that $k/\bar{M}_{\mathrm{Planck}}$ be less than ≈ 0.1.

A well-motivated extension of the original RS1 model (bulk graviton) [12] addresses the flavor structure of the SM through localization of fermions in the warped bulk of the theory. This picture offers a unified geometric explanation of both the hierarchy and the flavor puzzles in the SM. In this case, graviton production and decay via light fermions is highly suppressed and the decay into photons is negligible. On the other hand, production of bulk gravitons from gluon fusion and their decay into longitudinally polarized gauge bosons W/Z can be significant. Depending on the model parameters, production of gravitons via vector boson fusion (VBF) can be sizeable as well. Recent theoretical studies done in the contest of the bulk graviton model show that values of $k/\bar{M}_{\mathrm{Planck}}$ as large as ~ 3 are still within the validity of the model [12]. It should be noted that for values of $k/\bar{M}_{\mathrm{Planck}}$ greater than 2 the bulk graviton width becomes larger than $\sim 20\%$ of its mass, thus introducing experimental issues in the detection of such resonances which are not discussed in this paper.

3.1 Examples of RS1 Graviton Signatures

Both ATLAS and CMS collaborations have searched for narrow resonances in the invariant mass spectrum of dielectron/dimuon [13,14] and diphoton [15,16] final states. The spectra are consistent with the SM expectations in both the bulk and the tails of the aforementioned distributions. Among those searches, the most stringent lower limits on the mass of RS1 gravitons are 0.92 (2.16) TeV for $k/\bar{M}_{\mathrm{Planck}} = 0.01$ (0.1) in the dielectron+dimuon channel, and 1 (2.06) TeV for $k/\bar{M}_{\mathrm{Planck}} = 0.01$ (0.1) in the diphoton channel.

3.2 Examples of Bulk Graviton Signatures

Various searches for heavy, exotic resonances (X) decaying into pairs of vector bosons (W/Z) have been performed by both ATLAS and CMS experiments. The higher the mass of the resonance the larger the boost of its decay products, the W/Z bosons; consequently, their decay products tend to be close in $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

thus requiring special algorithms to define lepton isolation and identification criteria. Jets from hadronic W/Z decays might also merge into a single wide jet (W/Z-jet) thus requiring the use of jet substructure techniques to distinguish W/Z-jets from regular QCD-jets. The transition between boosted and un-boosted event decay topologies (the latter represents the case where all the W/Z decay products are typically reconstructed as well separated objects in the ATLAS and CMS detectors) happens around a mass of 1 TeV for resonances decaying to a pair of W/Z bosons. The analyses of ZZ and WW final states performed by ATLAS and CMS using 2011 data at $\sqrt{s} = 7$ TeV in the contest of exotic phenomena searches (i.e. excluding searches for SM Higgs boson) are:

- $\mathrm{X} \to \mathrm{ZZ} \to (\ell\ell)(\ell\ell)$ [17];
- $\mathrm{X} \to \mathrm{ZZ} \to (\ell\ell)(\mathrm{qq})$ [17,18,19];
- $\mathrm{X} \to \mathrm{ZZ} \to (\nu\nu)(\mathrm{qq})$ [19];
- $\mathrm{X} \to \mathrm{WW} \to (\ell\nu)(\ell'\nu')$ [20] $\star$;
- $\mathrm{X} \to \mathrm{WW/ZZ} \to (\mathrm{qq})(\mathrm{qq}) \to$ dijet [21] $\star$.

Although the results of these searches have not yet been combined, the overall picture suggests that, using 7 TeV data, ATLAS and CMS experiments are able to exclude bulk gravitons with masses below approximately 800-900 GeV assuming $k/\bar{M}_{\mathrm{Planck}} = 1.0$. A selection of these analyses ($\star$) was presented at the conference and is also reported below.

A search for a heavy particle that decays to $\mathrm{WW} \to (\ell\nu)(\ell'\nu')$ final states (ee, $\mu\mu$, eμ) was performed by the ATLAS collaboration [20]. No excess above the SM background prediction is observed in the transverse mass distribution of the WW system ($m_{\mathrm{T}}^{\mathrm{WW}}$) for events with two high p_{T} leptons and large $\not\!\!E_{\mathrm{T}}$, as shown in Fig. 3 (left). Lower limits on the RS1 (bulk) graviton mass are set at 1.23 (0.84) TeV, respectively, for $k/\bar{M}_{\mathrm{Planck}} = 0.1$ (1.0) by combining the three dilepton channels.

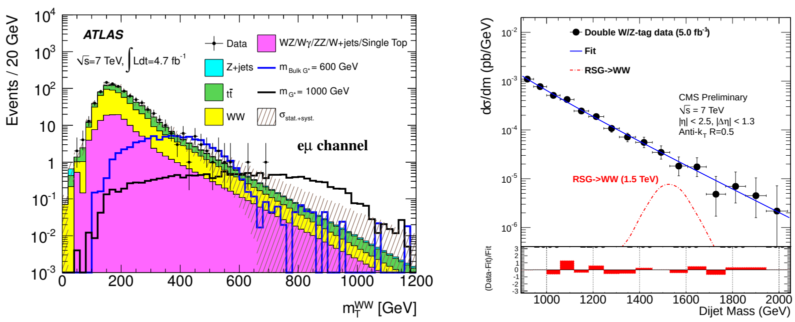

Figure 3. (Left) Observed and predicted $\mathrm{m}_{\mathrm{T}}^{\mathrm{WW}}$ distribution after event selection in the eμ channel. Examples of RS1 and bulk graviton signals are also shown [20]. (Right) Dijet mass spectrum for events in data with two identified W/Z-jets compared to background prediction. A graviton signal shape distribution with arbitrary cross section is also shown [21].

A search for massive resonances decaying into a pair of vector bosons (WW, ZZ, or WZ) or into a quark and a vector boson (qW and qZ), where each vector boson decays in hadrons, has been performed by the CMS experiment [21]. The analysis focus on resonances which are sufficiently heavy to result in boosted vector bosons; the decay products of each vector boson are then merged into a single jet (W/Z-jet), and the event effectively has a dijet topology. The analysis relies on recently developed techniques in the area of jet substructure and uses reconstructed quantities such as the pruned jet mass (m_{jet}) and the mass drop (defined as $\max[m_{\text{subjet1}}, m_{\text{subjet2}}]/m_{jet}$) to identify W/Z-jets and suppress the large QCD dijet background. Figure 3 (right) shows the dijet mass spectrum for events where each of the two jets is identified as a W/Z-jet; a dijet mass spectrum for events with only one identified W/Z-jet is also produced. No significant evidence for new resonance production in both dijet mass spectra is found. The sensitivity of this measurement with the present dataset is not sufficient to extract lower limits on the graviton mass for the models and couplings considered in the previous paragraph. Lower limits on the mass of excited quark resonances decaying into qW (qZ) at 2.32 (2.04) TeV are set instead. These are the most stringent limits in the qW and qZ final states to date.

4 Long-Lived Particles

A wide variety of theories beyond the SM allow for the possibility of new long-lived particles whose passage through the detector or whose decay in flight can be observed by the LHC experiments. For instance, with Supersymmetry being strongly constrained by the experiments, there is growing interest in looking in great detail for SUSY long-lived particles that might have escaped the standard searches which assume prompt decays. These exotic particles may be neutral, charged and/or colored.

4.1 Heavy Stable Charged Particles

Heavy stable (or quasi-stable) charged particles (denoted as HSCP in this paper) appear in various extensions of the SM. These particles have typically masses above 100 GeV thus implying low velocity ($\beta\gamma = p/m <$ or $\ll 1$) given the typical momenta with which they are produced at LHC, where β is the particle velocity in units of the speed of light (c), $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor, p is the particle momentum, and m is the particle mass. They are stable (or quasi-stable) with $c\tau$ greater than the typical dimensions of an LHC detector ($> 1 - 10$ m), where τ is the mean lifetime of the particle. They carry electric charge and therefore they can deposit energy in the detector via ionization (dE/dx signature).

Several searches for these exotic particles have been performed by the ATLAS and CMS experiments in 2011: searches for fractionally-charged HSCPs [22], unit-charge HSCPs [23,24] including HSCPs stopped in the detector volume [25], and multi-charged HSCPs [26] including magnetic monopoles [27]. Overall the analyses rely on a few key elements to distinguish these particles from the quasi-stable SM particles produced in background processes:

1. HSCPs are typically reconstructed as high p_{T} tracks in the inner tracker detector (and can reach the muon detectors in some cases);

2. low value of $\beta\gamma$ implies large dE/dx in the inner tracker detectors for particles with charge ≥ 1. HSCPs with fractional charge can be identified by an anomalous low value of dE/dx in the inner tracker detectors due to the quadratic dependence of the charge in the ionization energy loss;

3. low velocity β also implies late arrival to the detectors from the interaction point, which can be identified by time of flight (TOF) measurements.

A selection of searches for HSCPs was presented at the conference and the results are summarized below.

The CMS experiment has searched for heavy long-lived particles with hadronic nature, such as gluinos or stops, which hadronize in flight, forming meta-stable bound states with quarks and gluons (so called R-Hadrons) [24]. The analysis is also sensitive to lepton-like HSCPs, such as staus in Gauge Mediated Supersymmetry Breaking (GMSB) models. The inner tracking detectors are used to define a sample of events containing tracks with high momentum and high ionization energy loss (dE/dx). A second sample of events with high-momentum and high-ionization tracks satisfying muon identification and long TOF criteria is analyzed independently. In both samples the results are consistent with the data-driven background estimates that exploit the absence of correlation among p_{T}, dE/dx, and TOF measurements (ABCD-like methods). Lower limits are set on the mass of long-lived gluinos, stops, and GMSB staus at 1098, 737, and 223 GeV, respectively. Limits are about 100 GeV weaker for gluinos and stops that hadronize into a neutral bound state before reaching the muon detectors. Similar techniques are also used in the ATLAS analysis [23] bringing to comparable sensitivity of the search.

The ATLAS experiment has performed the first dedicated search at LHC for magnetic monopoles [27]. The Dirac quantization condition leads to a prediction for the minimum unit magnetic charge g: $g/e = 1/2\alpha_e \approx 68.5$, where e is the electric charge and α_e is the fine structure constant. In addition the trajectory of an electrically neutral magnetic monopole in the inner detector is straight in the $r-\phi$ plane and curved in the $r-z$ plane.

Monopoles are identified in the ATLAS detector as high energy clusters in the electromagnetic (EM) calorimeter with an anomalous large ionization energy loss (comparable to that of an ion with electric charge of $68.5e$) in the transition radiation tracker (TRT) along their trajectory. In addition magnetic monopoles give rise to a narrow ionization energy deposit in the EM calorimeter (since bremsstrahlung and e^+e^- pair production are negligible), the size of which provides another powerful discriminator of the monopole signal from backgrounds such as electrons and photons, which induce an EM shower. No event is found in the signal region after the final event selection, which is compatible with the data-driven background expectation.

For relativistic monopoles the magnetic coupling is very large, thus precluding any perturbative calculation of monopole production processes at colliders. Therefore, the main result of this analysis is a cross section upper limit of 2 fb for Dirac monopoles with the minimum unit magnetic charge with mass between 200 GeV and 1500 GeV for the fiducial region defined by i) pseudorapidity $|\eta| < 1.37$ and ii) transverse kinetic energy $600 - 700 < E^{\mathrm{kin}} sin(\theta) < 1400$ GeV, derived without assuming a particular production mechanism. This is the first direct collider search that yields cross section constraints on magnetic monopoles with masses greater than 900 GeV.

4.2 Long-Lived Neutral Particles

ATLAS and CMS experiments have also performed several searches for long-lived neutral particles. These objects can be identified by reconstructing their displaced decay vertex (using tracking and/or timing information). These experimental techniques require that the decay of the neutral long-lived particle happens within the detector volume, thus putting limits on the maximum lifetime that can be probed by these analyses (typically of the order of 1-10 ns). No sign of new physics is found in these searches, which are listed below for reference:

- searches for long-lived neutral particles decaying into a photon and invisible particles [28,29];
- searches for heavy resonances decaying to long-lived massive neutral particles that each decay to pairs of charged fermions [30,31,32];
- search for decay of heavy neutral particles producing a multi-track vertex with a muon and hadrons [33].

5 Leptoquarks

The Standard Model has an intriguing but ad hoc symmetry between quarks and leptons. In some theories beyond the SM, such as SU(5) gran unification, Pati-Salam SU(4), and others, the existence of a new symmetry relates the quarks and leptons in a fundamental way. These models predict the existence of new bosons, called leptoquarks. The leptoquark (LQ) is coloured, has fractional electric charge, and decays to a charged lepton and a quark with unknown branching fraction β, or a neutrino and a quark with branching fraction $(1-\beta)$. Constraints from experiments sensitive to flavour-changing neutral currents, lepton-family-number violation, and other rare processes favour LQs that couple to quarks and leptons within the same SM generation, for LQ masses accessible to current colliders.

Searches for pair-production of first and second generation scalar LQs have been performed in the eejj, eνjj, $\mu\mu$jj, and $\mu\nu$jj channels [34,35,36] by both ATLAS and CMS collaborations. The most stringent lower limits to date on the mass of first and second generation LQs are 830 (640) and 840 (650), respectively, for $\beta = 1$ (0.5).

Searches for pair-production of third generation leptoquarks have been performed by the CMS experiment in two final states: $\nu\nu$bb [37] and $\tau\tau$bb [38]. The $\nu\nu$bb analysis employs data-driven background estimates based on the RAZOR variables, already used extensively in various jets+$\not\!\!E_{\mathrm{T}}$ SUSY searches at CMS. The

$\tau\tau$bb analysis looks at final states with 2 reconstructed τ leptons and two b-tagged jets, where one τ decays in hadrons, while the other decays to either $\mathrm{e}\bar{\nu}_{\mathrm{e}}\nu_{\tau}$ or $\mu\bar{\nu}_{\mu}\nu_{\tau}$. Lower mass limits on third generation leptoquarks are set to 525 (450) GeV assuming $\beta = 1$ (0). In addition both searches are also sensitive to pair production of bottom squarks and top squarks [b] predicted by SUSY scenarios, as shown in Figure 4.

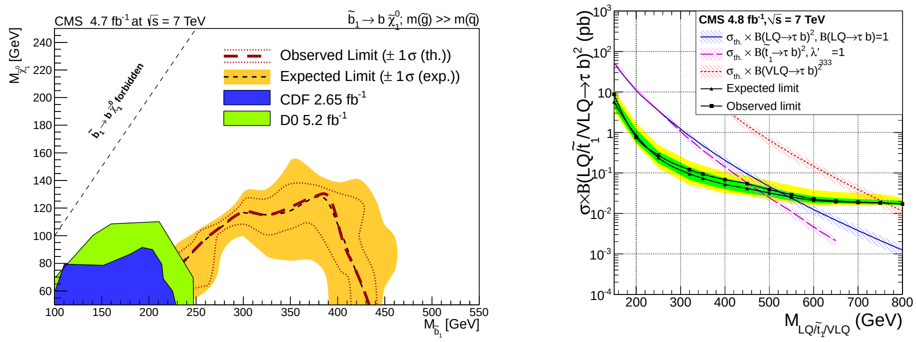

Figure 4. Mass limits from $\nu\nu$bb (left) [37] and $\tau\tau$bb (right) CMS searches [38].

6 Conclusions

No sign of physics beyond the Standard Model has been found so far in many different final states using the 5 fb^{-1} of data collected by ATLAS and CMS detectors in 2011 at $\sqrt{s} = 7$ TeV. Searches for exotic new physics phenomena in 2012 at $\sqrt{s} = 8$ TeV are currently ongoing; only a few preliminary results have been shown in conferences and found to be consistent with the Standard Model predictions. The larger integrated luminosity expected by the end of 2012 (about 20 fb^{-1}) and the higher LHC energy compared to 2011 extend significantly the sensitivity at high mass for most of the searches presented in this review. Experiments are also looking into new final states not previously explored and the results of these analyses will be released in the next months. In conclusion, there is another interesting year ahead of us concerning searches for exotic, new physics phenomena before the long 2013-2014 LHC shutdown!

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[b] Assuming R-Parity violation decays of the stops.

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