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Inclusive searches for squarks and gluinos with the ATLAS detector

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Abstract. Despite the absence of experimental evidence, weak scale supersymmetry remains one of the best motivated and studied Standard Model extensions. These proceedings summarise recent ATLAS results utilising the 7-8 TeV LHC datasets, obtained from inclusive searches for supersymmetric squarks and gluinos in events containing jets and missing transverse momentum, together with leptons, photons and b-jets. Limits are set in a range of supersymmetric scenarios including the CMSSM, mGMSB and GGM frameworks.

1 Introduction

Supersymmetry (SUSY) is one of the foremost extensions of the Standard Model (SM) of Particle Physics [1]. Its realisation in Nature would imply heavy "superparticle" (sparticle) counterparts to the fermions and bosons of the SM. The Large Hadron Collider (LHC), which collides protons at energies of 7-8 TeV,[1] is capable of producing supersymmetric particles with masses at or near a TeV, and offers the best chance of directly discovering SUSY or similar novel physics. The ATLAS experiment [2], based at the LHC, is a large general-purpose particle detector, one of whose aims is to test supersymmetric theories by searching for the striking events characteristic of SUSY.

The coloured superparticles, i.e. the squark and gluino, provide particularly important prospects for discovery of SUSY. Searches for squarks and gluinos are hence a critical component of the overall SUSY search strategy. Production cross-sections for gluinos or squarks[2] are large compared to third-generation squark production due to favourable parton distribution functions in the proton-proton initial state, and to electroweak gaugino production because of the strong coupling constant. Furthermore, renormalisation gauge equation evolution from masses determined at a high scale generally produces squarks and gluinos that are on the upper end of the mass spectrum. In such mass hierarchies, the gluinos and squarks may decay in cascades through the lighter sparticles, generating complex event topologies that are easily distinguished from Standard Model backgrounds.

2 Supersymmetric cascade decays

While squarks and gluinos may decay directly to jets and the Lightest Supersymmetric Particle (LSP), the existence of other sparticles intermediate in mass between the heavy parent and LSP permits more intricate decay patterns. For example, low gaugino masses would enable decays to leptons:

$$\tilde{q} \to q\tilde{\chi}_1^{\pm} \to qW^{\pm}\tilde{\chi}_1^0 \to q\tilde{\chi}_1^{\pm} \to q\ell^{\pm}\nu\tilde{\chi}_1^0. \qquad (1)$$

Of special importance are decays producing energetic leptons and isolated photons, which are less common by-products of the QCD processes that dominate LHC physics. A selection of important cascade decay processes is shown in Fig. 1.

An important parameter determining the characteristics of SUSY events is the identity of the LSP. It is commonly assumed to be the lightest neutralino ($\tilde{\chi}_1^0$) and is stable in R-parity conserving (RPC) scenarios, but its mass is not strongly constrained outside the framework of mass unification [3, 4]. Gauge-mediated supersymmetry-breaking (GMSB) models [5], however, contain a gravitino ($\tilde{G}$) LSP that is nearly massless. In these models, a neutralino that is the next-to-lightest supersymmetric particle (NLSP) may decay to a gravitino by one of the following processes, depending on the composition of the neutralino, i.e. Bino (2), Wino (3) or Higgsino (4):

$$\tilde{\chi}_1^0 \to \gamma\tilde{G} \qquad (2)$$

$$\tilde{\chi}_1^0 \to Z\tilde{G} \qquad (3)$$

$$\tilde{\chi}_1^0 \to h\tilde{G} \qquad (4)$$

Based on these possible signatures, ATLAS has carried out multiple searches for SUSY in events containing jets, leptons, photons and missing transverse momentum ($\not{E}_T$). Several inclusive analyses that target a broad range of SUSY signals have reached maturity [6–9]. Further sensitivity to particular signal models is provided by a wide range of searches with more specific analysis requirements. Below, we summarise several recent results from analyses requiring leptons or photons in the final state.

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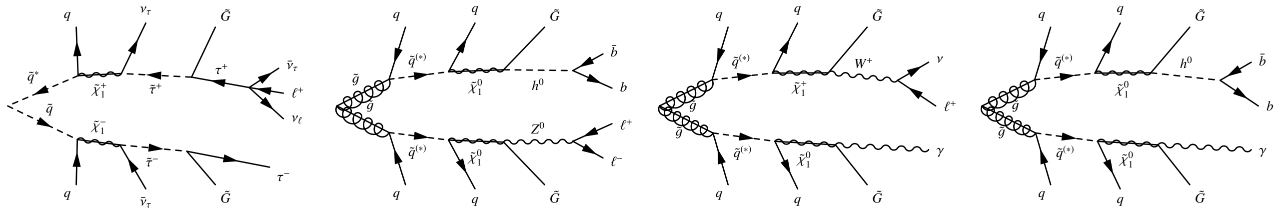
[1] The energy will be raised to 13-14 TeV after the 2013/14 shutdown.
[2] Used throughout these proceedings to represent the superpartners of only the first- and second-generation quarks.



(a) $\tilde{\tau} \to \tau\tilde{G}$ (b) $\tilde{\chi}_1^0 \to Z^0\tilde{G}$ (c) $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ and $\tilde{\chi}_1^\pm \to W^\pm\tilde{G}$ (d) $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ and $\tilde{\chi}_1^0 \to b\bar{b}\tilde{G}$

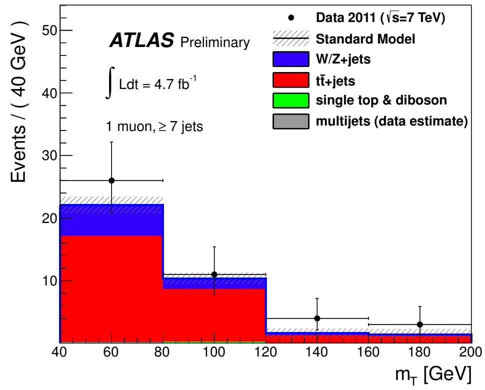
Figure 1: A selection of possible cascade decay processes possible when squarks or gluinos are produced. Allowable decays are determined by the sparticle spectrum, and particularly by the identity of the Lightest Supersymmetric Particle (LSP) and Next-to-Lightest-Supersymmetric Particle (NLSP). The neutralino NLSPs illustrated are predominantly higgsino (b, d) or Wino (c). ATLAS has produced dedicated searches optimised for each of these topologies.

3 Searches with leptons

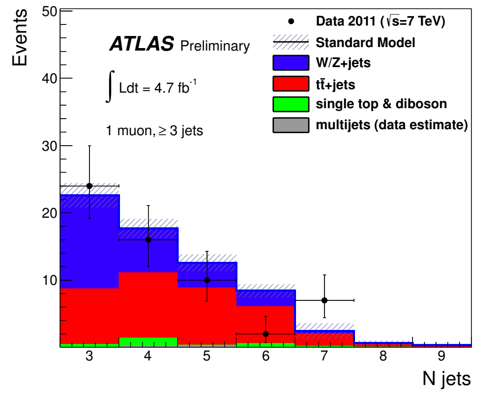
Searches for light leptons offer especially clean signatures in a hadron collider environment. Inclusive searches in ATLAS have historically focused on individual channels defined by lepton multiplicity, selecting only events with 0, 1, or 2 leptons. To probe for extended cascade decays that can produce numerous leptons and jets, ATLAS has implemented a search in the multijet final state, in 7 TeV collision events containing 1 lepton and at least 7 jets [10]. This search applies a hard selection on the $\not{E}_T$, m_T and m_{eff} variables in order to suppress the dominant $t\bar{t}$ and W boson backgrounds, and utilises a background estimation and statistical fitting strategy similar to that of [7]. Excess events are observed over the background predictions, with 4.3 ± 1.2 (2.2 ± 1.1) expected and 7 (7) observed in the electron (muon) channel. However, these appear consistent with background fluctuations, as can be seen in Fig. 2.

An alternative approach to the dedicated single-channel searches is to simultaneously use information from multiple channels, allowing a coherent determination of relative background compositions, and relaxing restrictions on what signatures are admissible to the analysis. An analysis of this nature has been carried out on 7 TeV LHC data from 2011 [11], and utilises the Razor variables defined in [12] and pioneered by CMS [13]. This *multichannel analysis* makes use of 12 exclusive signal region (SR) selections, which take into account lepton multiplicity, flavour and sign, as well as b-tagging information. Background contamination is estimated through the use of appropriately defined control regions (CRs), using a likelihood fit that simultaneously estimates the background normalisation and quantifies the statistical significance of any signal-like excesses. The largest excess observed had a statistical significance of 1.34σ.

Electrons and muons are relatively easy to identify at a hadron collider. However, tau leptons are also important signals of new physics, such as a light stau, which may be relevant to Higgs boson (h) phenomenology [14]. ATLAS has implemented a search for tau leptons and $\not{E}_T$ in 2011 LHC data [15], seeking signatures similar to that shown in Fig. 1a. While two tau leptons are expected in each event, inefficiencies in the identification of hadronically-decaying taus are not negligible, motivating the definition of SRs requiring one or two tau jets. Alternatively, a tau lepton may decay leptonically, so channels with one hadronic tau and one electron or muon are also defined. Data-driven background estimation techniques are used to calibrate the background contamination, including constraints from charge asymmetry in W + jets events. No substantial excesses are observed in the data.



(a) Transverse mass



(b) Jet multiplicity ($p_T > 25$ GeV)

Figure 2: Distributions of transverse mass and jet multiplicity prior to the cuts on the respective variables in the muon signal region of the search for SUSY in events with 1 lepton and multijets [10]. The excess of events with at least 7 jets is balanced by a dearth of events with 6 jets.

Selecting isolated leptons allows elimination of many background processes at the LHC. Further suppression can be achieved by requiring the presence of an on-shell Z boson, which may be produced in SUSY decays such as that shown in Fig. 1b. ATLAS searched for SUSY events containing an on-shell Z boson, together with $\not{E}_T$ from invisible LSPs and additional hard jets from squark or gluino decays, in 5.8 fb^{-1} of 8 TeV LHC data [16]. This analysis used a jet smearing technique [17] to estimate the background contamination from Z + jets events, which enter the SRs when jet mismeasurement produces fake $\not{E}_T$. Additional control region selections are used to constrain other backgrounds, such as $t\bar{t}$ production. Measurements in data are found to be consistent with SM background predictions.

4 Searches with photons

Isolated photons are rarely produced directly in LHC collisions. They may, however, be produced in the decays of a neutralino, e.g. in GMSB models (Fig. 1c). When two such decays occur, a diphoton signature combined with substantial $\not{E}_T$ arises [18]. It is also possible that one of the pair-produced heavy sparticles may decay to a chargino, producing a light lepton, while its partner decays via a neutralino to produce a photon. Such decays would produce an excess of events containing one lepton and one photon. A recent search on 7 TeV LHC data targets precisely this final state [19]. The irreducible backgrounds to this search are W and $t\bar{t}$ production with an accompanying prompt photon, while dileptonic $t\bar{t}$ decays may produce a fake photon if an electron is misidentified. Backgrounds to this search are estimated using Monte Carlo (MC) simulated events, with the predictions validated in a set of CRs. The MC and data event counts are in good agreement.

A light Higgs is required by most SUSY models. If the 125 GeV boson discovered at the LHC in July 2012 [20, 21] is confirmed to be the Higgs, then it could certainly appear as a decay product of squarks or gluinos of $O(100)$ GeV masses. A search for SUSY events with a photon and a b-jet carried out by ATLAS on data from 2011 is sensitive to such decays [22], and is interpreted in terms of the decay topology in Fig. 1d. Data-driven methods are used to estimate the backgrounds arising from misidentification of electrons or jets as photons, with the minor contribution from $Z \to \nu\bar{\nu}$ + jets events estimated from MC. The observed event counts closely matches those predicted from SM contributions only.

5 Constraints on supersymmetric models

Based on the non-observation of signal-like excesses in any of the searches described above, ATLAS set exclusion limits on the SUSY parameter space, ruling out large portions that are inconsistent with the observations. These are set using a profile likelihood method [23], and a signal models are excluded if they produce a CL_s statistic smaller than 5% [24]. A representative summary of the resulting limits is shown below.

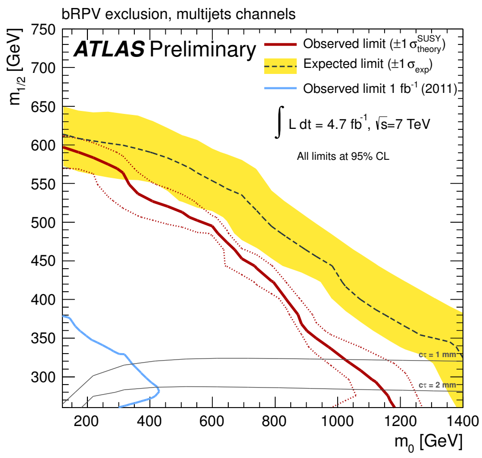


Figure 3: Limits set using a single lepton and multijet analysis [10] on a constrained MSSM (CMSSM) model with bilinear R-parity violating (bRPV) couplings, permitting the $\tilde{\chi}_1^0$ to decay to neutrinos.

The single lepton multijet search produced exclusion limits in a constrained MSSM (CMSSM) model [25–30], in which all scalar (gaugino) sparticles are assumed to have a common mass m_0 ($m_{1/2}$). For this interpretation, the condition of RPC was relaxed to allow bilinear R-parity violating (bRPV) couplings, permitting the neutralino LSP to decay to all-SM final states including neutrinos. Limits on this model are substantially improved by the increase of the dataset from 1 fb^{-1} to 5 fb^{-1}, and are shown in Fig. 3.

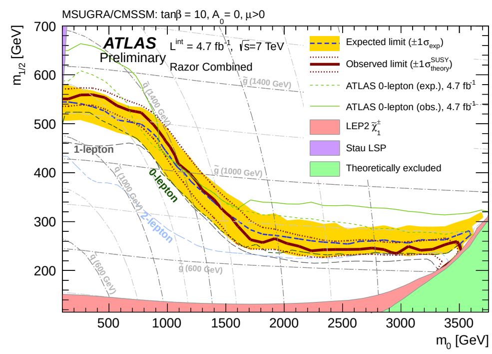


Figure 4: Limits set on a CMSSM model using the ATLAS multichannel analysis [11].

The multichannel analysis results were interpreted in an RPC CMSSM model space, shown in Fig. 4. For comparison, the excluded regions obtained from a number of single-channel searches on the same dataset are also shown. The multichannel analysis result is comparable to, if not fully competitive with the dedicated single-channel searches, particularly the 0 lepton search of [17]. At low m_0 in particular, this reduced sensitivity is explained by the requirement of at least 5 jets in the multichannel SRs, while this region of the parameter space shows a smaller average jet multiplicity. Substantial improvements are expected from further optimisation of the analysis.

The remaining analyses are interpreted in GMSB scenarios in which the LSP is a light gravitino. A minimal GMSB (mGMSB) [5] interpretation was produced using the tau+$\not{E}_T$ search, which in combination with an opposite-sign dilepton search was able to rule out gluinos lighter than 1.2 TeV for all values of the ratio of Higgs vacuum expectation values $\tan\beta$. This implies a limit on the SUSY-breaking scale of 60 TeV. Corresponding exclusion limits are shown in Fig. 5.

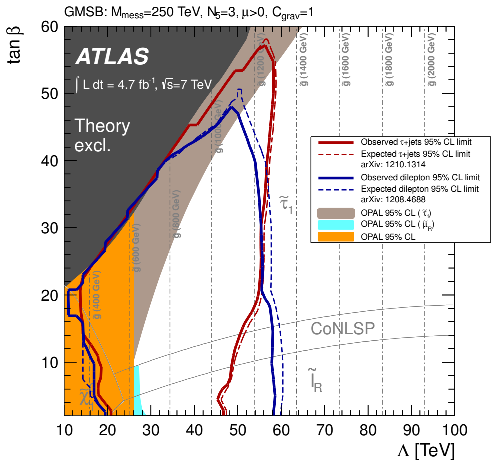
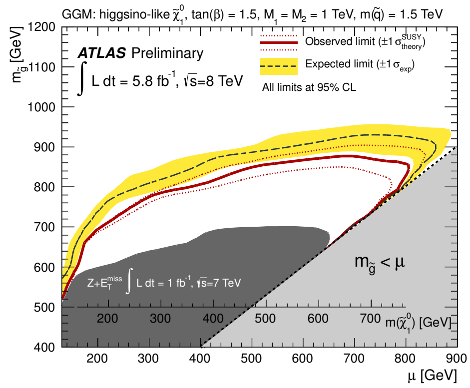


Figure 5: Limits set on a minimal gauge-mediated supersymmetry breaking (mGMSB) model, using a search for tau leptons [15] (blue contours) and opposite-sign dileptons (red contours). The tau search contour extends further in the region marked $\tilde{\tau}_1$, whereas the dilepton search is more powerful in the region marked $\tilde{l}_R$.

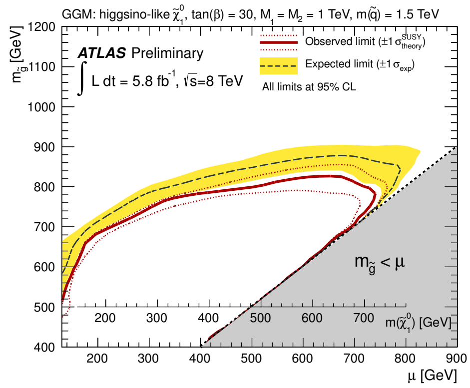
Using the results of the search for a Z boson and $\not{E}_T$, limits are placed on the masses of the gluino and lightest neutralino in a general gauge mediation (GGM) scenario [31], in which it was assumed that the $\tilde{\chi}^0_1$ had a large higgsino component. Figure 6 illustrates the extent of the excluded regions at low and high $\tan\beta$. The addition of the 8 TeV data improves the bound on the gluino mass by roughly 200 GeV for all neutralino masses (Fig.6a). For light neutralinos ($m_{\tilde{\chi}^0_1} \simeq 400$ GeV), the gluino mass is constrained to be larger than 500 GeV, with the constraint improving to 850 GeV for heavier neutralinos. Altering $\tan\beta$ does not substantially affect the position of the limit.

The same model was used for an interpretation of the search for a photon and a b-jet. Limits on the mass of the gluino and squark in this model, for a range of neutralino masses, are shown in Fig. 7. These lie in the neighbourhood of 1 TeV for large neutralino masses ($m_{\tilde{\chi}^0_1} >$ 500 GeV). When the neutralino is light enough to be pair-produced with a high rate (200 GeV $\leq m_{\tilde{\chi}^0_1} \leq$ 350 GeV), all values of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ are ruled out.

Finally, the search for a lepton and a photon with substantial $\not{E}_T$ is used to set limits on a related GGM model, in which the NSLP neutralino is taken to be predominantly Wino in composition (Figure 8). This model assumes also that the charginos are of a similar mass to the neutralino. Gluinos with all masses are ruled out if $m_{\tilde{\chi}^0_1}$ is



(a) $\tan\beta = 1.5$



(b) $\tan\beta = 30$

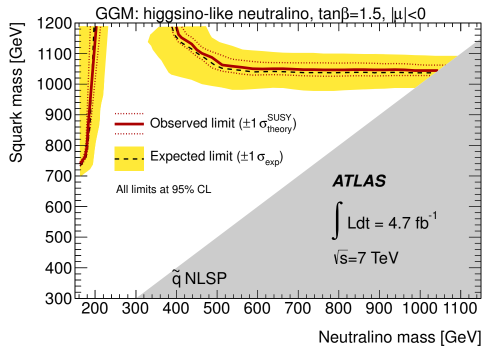
Figure 6: Limits set in the gluino and neutralino mass plane in a general gauge mediation (GGM) model with a higgsino NLSP, using a search for a Z boson, jets and $\not{E}_T$ [16]. Two choices of the ratio of Higgs vacuum expectation values are shown: $\tan\beta = 1.5$ (top) and 30 (bottom). Only results from SR 1 of [16] are shown, as they are everywhere superior to those from SR 2 (which applies a cut on H_T rather than on the p_T of individual jets).

between 100-220 GeV, while if the Wino mass parameter M_2 is higher, the limit on $m_{\tilde{g}}$ is approximately constant at 650 GeV.

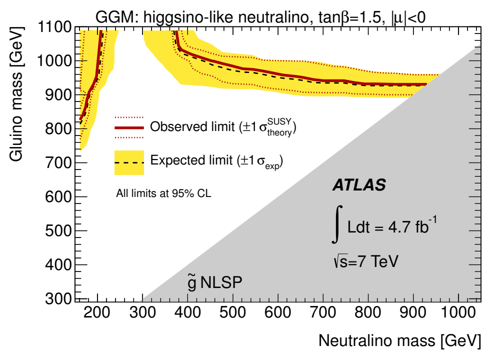
6 Summary and conclusions

While the discovery of SUSY at the LHC has been hotly anticipated since the first collisions at 7 TeV in 2010, no conclusive signs have yet been seen in any direct searches. However, the search program carried out by ATLAS is continually improving its coverage of the wide SUSY parameter space, with an expanding array of searches for both specific and generic signatures. These analyses have begun to make use of the 8 TeV data collected in 2012, but much of the data collected has yet to be analysed.

If SUSY is to be revealed at the LHC, whether before or after the long shutdown of 2013-2014, it may take any one of many guises. Nevertheless, the diverse nature of the ATLAS SUSY program will permit the best prospects for discovery of SUSY, in whatever form it may take.



(a) Squark production



(b) Gluino production

Figure 7: Limits set in the squark (top) or gluino (bottom and neutralino mass plane in a general gauge mediation (GGM) model with a higgsino NLSP, using a search for b-jets, a photon and $\not{E}_T$ [22].

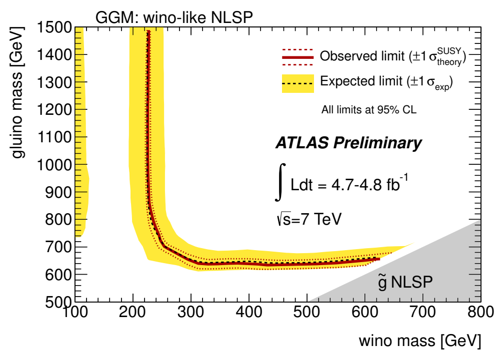


Figure 8: Limits set in the gluino and neutralino mass plane in a general gauge mediation (GGM) model with a bino NLSP and light winos, using a search for a lepton, a photon and $\not{E}_T$ [19].

7 Acknowledgements

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References

[1] S.P. Martin (1997), hep-ph/9709356, and references contained therein.
[2] The ATLAS Collaboration, JINST **3**, S08003 (2008)
[3] The DELPHI Collaboration, Eur.Phys.J. **C31**, 421 (2003)
[4] H.K. Dreiner, S. Heinemeyer, O. Kittel, U. Langenfeld, A.M. Weber et al., Eur.Phys.J. **C62**, 547 (2009), 0901.3485
[5] G. Giudice, R. Rattazzi, Phys.Rept. **322**, 419 (1999), hep-ph/9801271
[6] The ATLAS Collaboration, Tech. Rep. ATLAS-CONF-2012-109, CERN, Geneva (2012)
[7] The ATLAS Collaboration, Tech. Rep. ATLAS-CONF-2012-104, CERN, Geneva (2012)
[8] The ATLAS Collaboration, Tech. Rep. ATLAS-CONF-2012-103, CERN, Geneva (2012)
[9] The ATLAS Collaboration, Tech. Rep. ATLAS-CONF-2012-105, CERN, Geneva (2012)
[10] The ATLAS Collaboration, Tech. Rep. ATLAS-CONF-2012-140, CERN, Geneva (2012)
[11] The ATLAS Collaboration (2012), 1212.6149
[12] C. Rogan (2010), 1006.2727
[13] The CMS Collaboration, Phys.Rev. **D85**, 012004 (2012), 1107.1279
[14] M. Carena, S. Gori, N.R. Shah, C.E. Wagner, JHEP **1203**, 014 (2012), 1112.3336
[15] The ATLAS Collaboration (2012), submitted to EPJC, 1210.1314
[16] The ATLAS Collaboration, Tech. Rep. ATLAS-CONF-2012-152, CERN, Geneva (2012)
[17] The ATLAS Collaboration (2012), accepted by Phys. Rev. D, 1208.0949
[18] The ATLAS Collaboration (2012), submitted to Phys.Lett.B, 1209.0753
[19] The ATLAS Collaboration, Tech. Rep. ATLAS-CONF-2012-144, CERN, Geneva (2012)
[20] The ATLAS Collaboration, Phys.Lett.B (2012), 1207.7214
[21] The CMS Collaboration, Phys.Lett.B (2012), 1207.7235
[22] The ATLAS Collaboration (2012), submitted to Phys.Lett.B, 1211.1167
[23] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Eur. Phys. J. **C71**, 1554 (2011), 1007.1727
[24] A. Read, Journal of Physics G: Nucl. Part. Phys. **28**, 2693 (2002)
[25] A.H. Chamseddine, R.L. Arnowitt, P. Nath, Phys.Rev.Lett. **49**, 970 (1982)
[26] R. Barbieri, S. Ferrara, C.A. Savoy, Phys. Lett. **B119**, 343 (1982)
[27] L.E. Ibanez, Phys.Lett. **B118**, 73 (1982)
[28] L.J. Hall, J.D. Lykken, S. Weinberg, Phys.Rev. **D27**, 2359 (1983)
[29] N. Ohta, Prog.Theor.Phys. **70**, 542 (1983)
[30] G.L. Kane, C.F. Kolda, L. Roszkowski, J.D. Wells, Phys.Rev. **D49**, 6173 (1994), hep-ph/9312272
[31] P. Meade, N. Seiberg, D. Shih, Prog.Theor.Phys.Suppl. **177**, 143 (2009), 0801.3278