SUSY Searches: Recent Results from ATLAS and CMS

Michael Rammensee on behalf of the ATLAS and CMS Collaborations
CERN
E-mail: mrammens@cern.ch

Abstract. Despite the absence of experimental evidence, weak scale supersymmetry remains one of the best motivated and studied Standard Model extensions. Recent results from ATLAS and CMS searches for supersymmetric particles are summarized here. Weak and strong production in both R-Parity conserving and R-Parity violating supersymmetric scenarios are considered. In particular, a selection is presented of the most recent searches for squarks and gluinos, third generations squarks, direct production of charginos, neutralinos and sleptons and long-lived particles. These searches involve final states including jets, missing transverse momentum, electron or muons, taus or photons, as well as long-lived particle signatures. The data in these searches was found to be compatible with the estimated Standard Model backgrounds. Therefore, limits have been set on the masses of supersymmetric particles in various models.

1. Introduction

Supersymmetry (SUSY) [1, 2, 3, 4, 5, 6, 7, 8, 9] is one of the most studied extensions to the Standard Model (SM). Many models predicting supersymmetric particles observable at the LHC have been developed. They extend from easy-to-observe models with clear signatures and large cross sections to models with very low signal cross sections that are hard to distinguish from the relevant SM backgrounds.

The ATLAS [10] and CMS [11] detectors have analyzed data from proton-proton collisions recorded in 2012 at the Large Hadron Collider (LHC) [12] at 8 TeV center of mass energy, corresponding to an integrated luminosity of ~ 20 fb^{-1}.

SM processes have been measured with high precision at the LHC in proton-proton collisions. Figure 1 and Fig. 2 show summaries of SM cross section measurements of the ATLAS and CMS collaborations, respectively, and demonstrate the broad range of SM measurements that have been carried out.

However, the phase spaces, in which searches for supersymmetric particles are carried out, cover most often much smaller regions than these measurements, because of strict requirements on e.g. large transverse momentum of the objects in the final states or of large missing transverse momentum. Dedicated techniques have been developed therefore to estimate the irreducible backgrounds to potential SUSY signals. These are usually estimated via partially data-driven techniques, where the normalization between data and predictions is performed in control regions, as pure as possible in the SM process of interest. Also the influence of signal contamination in the control regions is investigated and controlled. The residual reducible backgrounds after

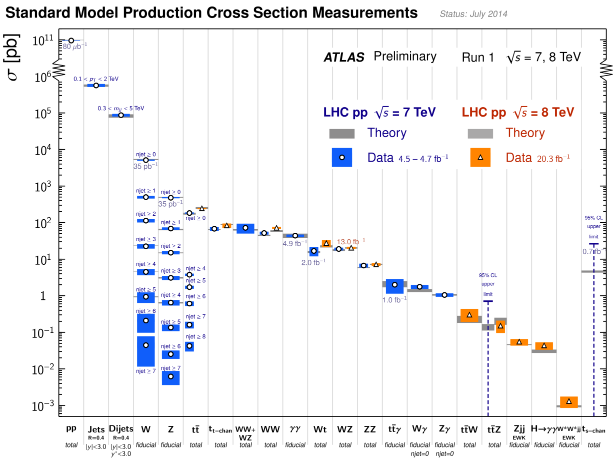

Figure 1. Standard model cross section measurements at ATLAS [13].

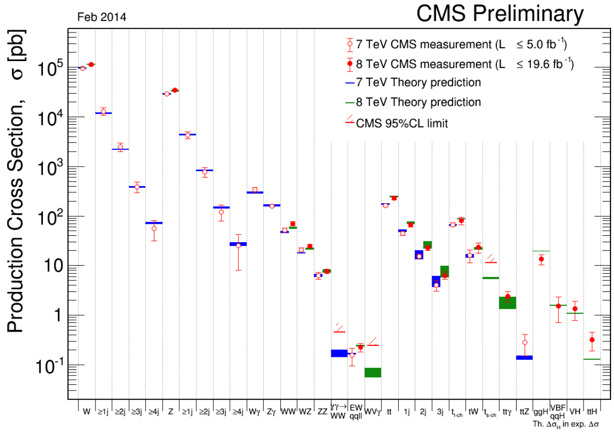

Figure 2. Standard model cross section measurements at CMS [14].

the full event selection are estimated via fully data-driven methods. All background estimates are validated in additional phase-space regions, as close as possible to the search region, prior to carrying out hypothesis tests in the signal regions.

A selection of most recent searches for supersymmetry are presented in the following. In Sec. 2 searches for squarks and gluinos are discussed, in Sec. 3 dedicated searches for third generations squarks are presented. Searches for weak production processes are presented in Sec. 4, followed by searches for long-lived supersymmetric particles in Sec. 5.

2. Searches for squarks and gluinos

The potential production of supersymmetric particles at the LHC is dominated by squark-gluino ($\tilde{q}\ \tilde{g}$), gluino-gluino ($\tilde{g}\ \tilde{g}$) and squark-squark ($\tilde{q}\ \tilde{q}$) pair production. Assuming R-parity conservation, the decay chains of these particles contain the Lightest Supersymmetric Particle (LSP). The LSP escapes the detector unseen, thus leading to final states with jets and missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$). Additional objects, such as electrons, muons, taus or photons may also be observed in the detector, depending on the exact decay chain considered. If a LSP exists, e.g. the lightest stable neutralino ($\tilde{\chi}_1^0$), the primarily produced squarks and gluinos will decay subsequently to the LSP. The most general signal in a detector in this case would be jets and missing transverse momentum originating from e.g. $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ or $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$. Previous searches, investigating final states with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ e.g. [15, 16, 17], of the ATLAS and CMS collaborations showed no deviation from the standard model.

Final states targeting more complex decay chains have been investigated. In models with general gauge mediated SUSY breaking, any supersymmetric particle of the Minimal Supersymmetric Standard Model (MSSM) can be the Next to Lightest Supersymmetric Particle (NLSP). Assuming the NLSP is a neutralino and the LSP is a gravitino, photons with large transverse momentum (p_{T}) can appear in the decay chain. A search requiring photons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ has been carried out in Ref. [18]. One or more photons with a p_{T} of at least 110 GeV at least two jets with a p_{T} larger than 30 GeV and $E_{\mathrm{T}}^{\mathrm{miss}}$ larger than 150 GeVare required. The dominant background comes from the mis-measurement of $E_{\mathrm{T}}^{\mathrm{miss}}$ in QCD processes such as direct di-photon, photon plus jets, and multi-jet production, with jets mimicking photons. Additional backgrounds are events with W-bosons, that decay into a neutrino and an electron if the electron

is misidentified as a photon and initial and final state radiation of photons.
A search requiring at least two photons is carried out in Ref. [19]. The leading photon is required to have a p_{T} of at least 30 GeV, while the sub-leading one is required to have a p_{T} larger than 22 GeV. Furthermore at least one jet with a p_{T} larger than 40 GeVand $E_{\mathrm{T}}^{\mathrm{miss}}$ to be larger than 150 GeV are required. The analysis makes use of the razor approach, see references in Ref.[19], in a purely data-driven way. The main uncertainty in the search comes from the interpolation from the control region to the search region, which is determined via a control sample of events with calorimetric deposits from hadrons, misidentified as photons
No excess above the standard model background estimate has been found in these searches with photons in the final state, similar to previous searches Ref. [20].
If charm quarks are produced in decay chains, requiring c-tagged jets adds sensitivity to the search. The analysis in Ref.[21] is performed requiring at least 2 c-tagged jets identified as originating from the fragmentation of a c-quark and large missing transverse momentum. Selected events must have $E_{\mathrm{T}}^{\mathrm{miss}}$ larger than 150 GeV and at least two c-tagged jets, of which the leading one is required to have p_{T} larger than 130 GeVand the sub leading one a p_{T} of larger than 110 GeV. The main background in this search is originating from $t\bar{t}$, associated W-boson and jets and associated Z-boson and jets production. No excess is observed with respect to the SM predictions. The results are interpreted in the context of a simplified scenario, where two superpartners of the charm quark (scharm) are produced each decaying into a c-jet and a neutralino, see Fig. 3. In this specific scenario scharm quark masses below 550 GeVare excluded.

Stealth SUSY, see references in Ref. [22], predicts a hidden sector at the electroweak energy

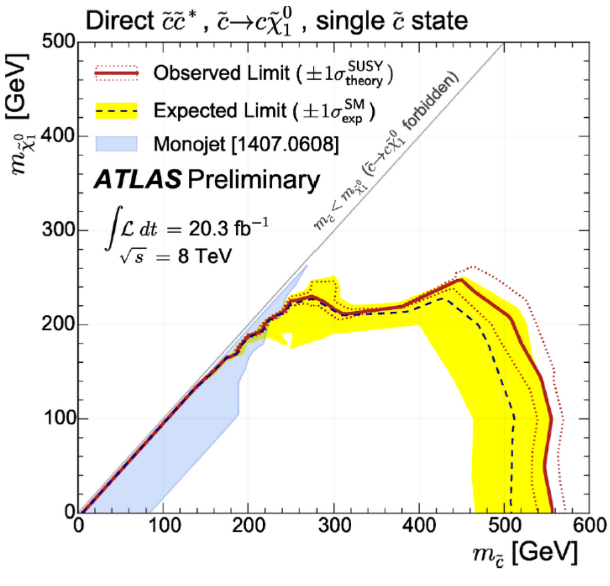

Figure 3. Limit on scharm production [21].

scale in which SUSY is approximately conserved. The model predicts cases where the gravitino as LSP carries away only a small amount of p_{T}. Thus the signal would evade the $E_{\mathrm{T}}^{\mathrm{miss}}$-based searches. In Ref. [22], two categories of final states have been investigated, one requiring photons and one requiring opposite-sign same-flavor pairs of electron or muons. At least two photons with a p_{T} of more than 25 GeVare required in the first category. The leading photon is required to have a p_{T} of at least 40 GeV. At least four jets with a p_{T} of more than 40 GeVare required, and the sum of the transverse momenta of all identified objects (S_T), must be larger than 1.2 TeV. In Fig. 4 the S_T distribution in the signal region with four jets is shown. The dominant background

is SM production of events with two photons, and with a photon and a jet misidentified as a photon. This background is directly estimated form data.
In the second category opposite sign same flavor pairs of electron or muons are are required to be in the event. Electrons must have a p_{T} of more than 15 GeVand to ensure optimal trigger efficiency, the muon is required to have a p_{T} of more than 30 GeV. No b-tagged jets are allowed to suppress $t\bar{t}$ background. The main background in this category comes from $t\bar{t}$ and single top production.
No excess above the SM background estimation was observed and limits have been placed in a simplified scenario, where two squarks are produced, each decaying into a jet and a neutralino. The neutralino then decays via the hidden sector to jets and the gravitino. Squark masses below 1.1 TeV are excluded in this scenario for next-to-lightest neutralino masses of above 300 GeV, as depicted in Fig.5.

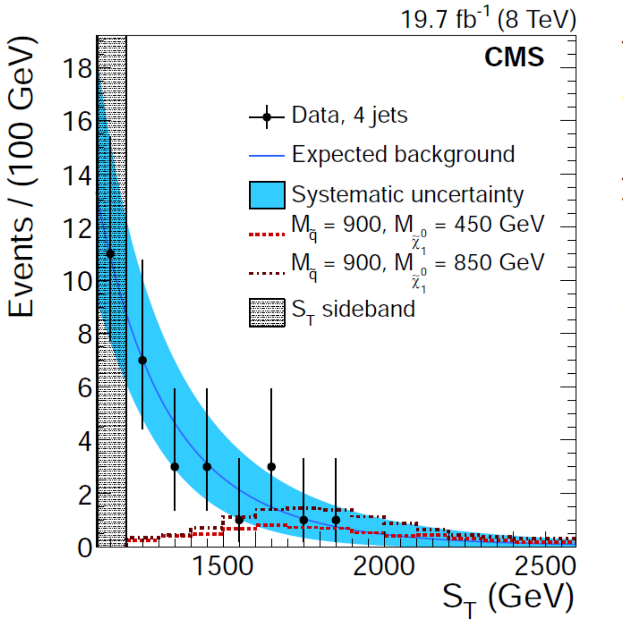

Figure 4. Stealth SUSY search, signal region distribution of S_T [22].

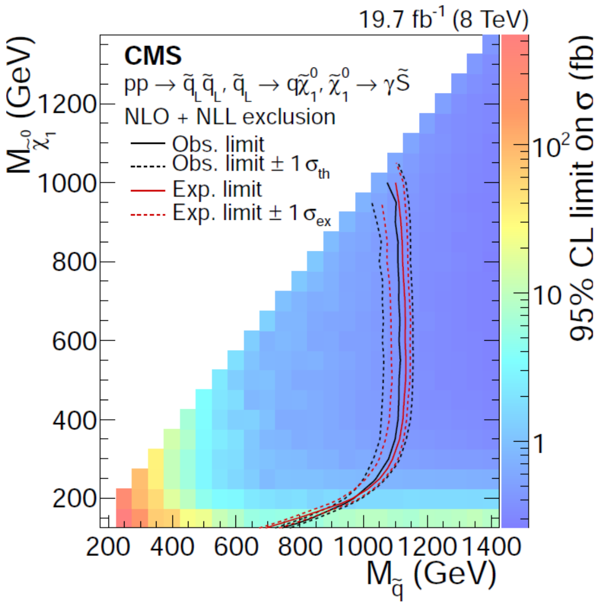

Figure 5. Stealth SUSY search, limit on squark mass [22].

3. Searches for third generation squarks

In natural SUSY theory, models with a low-level of fine-tuning are considered. This is achieved with light SUSY partners of the Higgs bosons (higgsinos), top and bottom quarks (stop and sbottom, respectively) and not-too-heavy gluinos. In Ref. [23] several analyses targeting gluino-mediated stop production are combined. These require four W-bosons and several b-jets in the final state. The combination of the analyses yields a limit on the gluino mass of 1.35 TeV in a simplified scenario where gluinos are produced in pairs and each gluino is decaying into a stop, a top quark and a neutralino.
Dedicated searches for stop pair production have been carried out in Refs.[24, 25, 26, 27, 28, 29, 30, 31] and summary plots of both ATLAS and CMS are shown in Fig. 6 and Fig. 7, respectively. Assuming the stop is the next-to-lightest SUSY particle, it may decay via several mechanisms. The stop can decay to a top quark and a neutralino, to a bottom quark, a W boson, and a neutralino or to a bottom quark, an on-shell W boson, and a neutralino, and finally via loop-

suppressed diagrams to a charm quark and a neutralino.
A stop mass is excluded below 700 GeV for neutralino masses of up to 250 GeV, with the following exceptions, which are indicated by the diagonal lines in both figures:

- The masses states of the stop and of the neutralino are almost degenerate, and thus the decay spectrum is very soft.
- The stop mass is close to the sum of the top quark mass and the neutralino masses, and thus the signature looks like $t\bar{t}$ production.
- The stop mass is close to the sum of the W-boson mass and the neutralino masses, and thus signature looks like W-boson pair production.

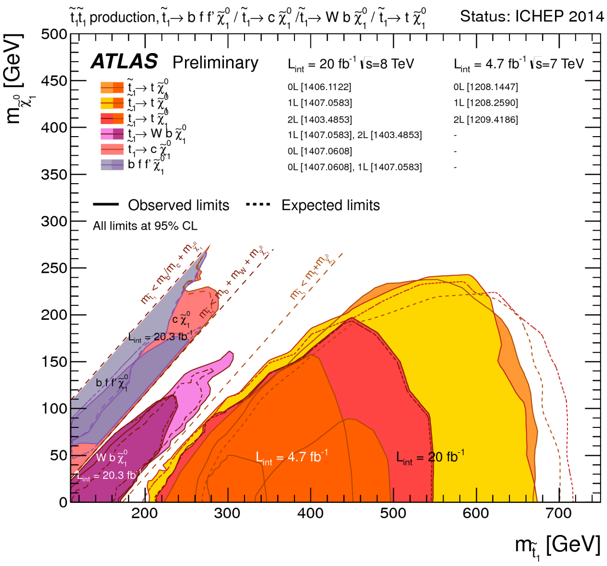

Figure 6. Summary of stop searches in ATLAS [32].

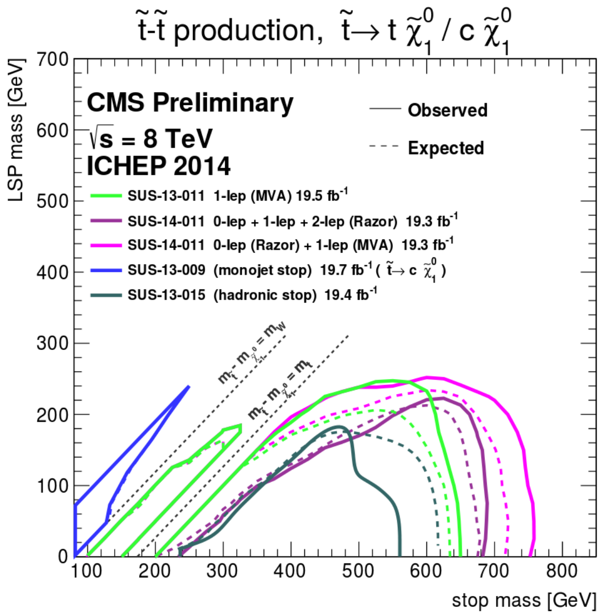

Figure 7. Summary of stop searches in CMS [33].

The measurement of spin correlations in $t\bar{t}$ events adds sensitivity in the case where the stop mass is close to the mass of the top quark and the neutralino. In Ref.[34], an analysis is presented using di-leptonic $t\bar{t}$ events. The selection is based on events with two leptons and requires at least two jets with at least one b-tagged jet and moderate missing transverse momentum. Figure 8 shows the distribution of the azimuthal angle between the two leptons in di-leptonic $t\bar{t}$ events. Figure 9 shows the resulting exclusion limit as a function of the stop mass, excluding stop masses between 177 and 191 GeV for a neutralino mass of 1 GeV.

4. Searches for direct production of charginos, neutralinos and sleptons

Direct pair production of charginos and neutralinos may be the dominant production of supersymmetric particles if the supersymmetric partners of the gluon and quarks are heavier than a few TeV. Some of the recent searches of ATLAS and CMS use signatures involving the recently discovered Higgs boson. Neutralinos and charginos are predicted to decay to a Higgs boson or to vector bosons over large regions of SUSY phase space.
In Ref.[35], several decay chains have been investigated. Assuming pair production of the NLSP two Higgs bosons may be produced, each of which decays to $b\bar{b}$, thus requiring four b-tagged jets in the analysis. Other branches of the analysis make use of the decay products of Higgs and

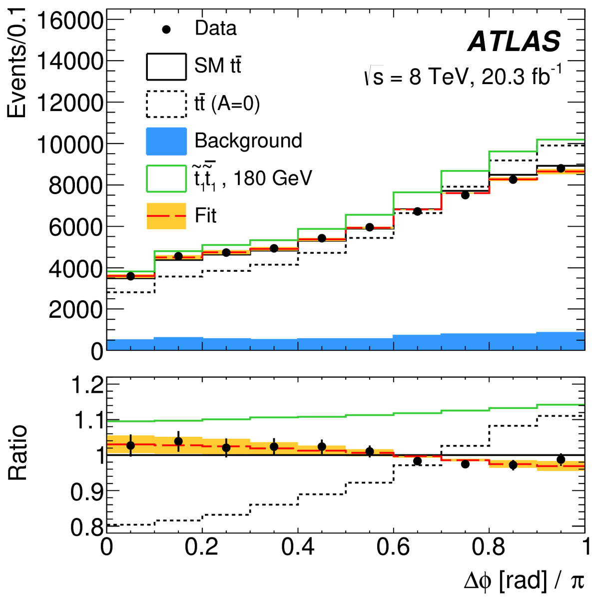

Figure 8. Azimuthal angle between the two leptons in di-leptonic $t\bar{t}$ events [34].

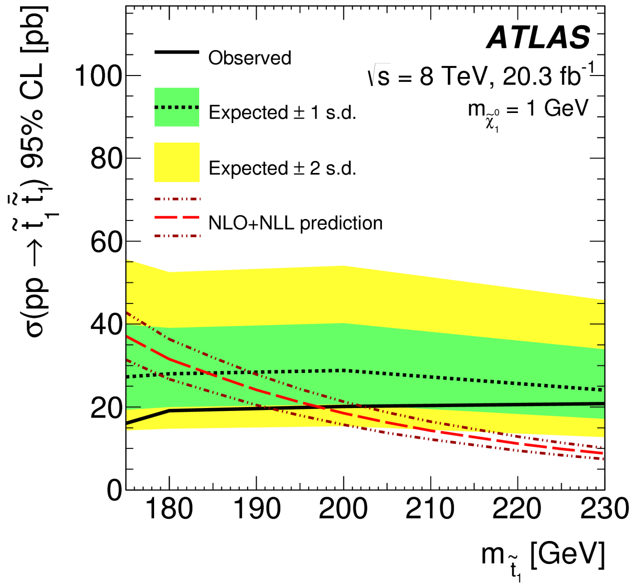

Figure 9. Stop mass limit from $t\bar{t}$ spin correlation measurement [34].

Z-bosons, investigating final states with photons, b-jets and leptons.
In Ref.[36], final states have been investigated with one electron or muon and two b-tagged jets, one electron or muon and two photons or two same-sign electron or muons.
None of the referenced searches showed a deviation from the SM expectations. In Fig. 10 and Fig. 11, summaries of the limits on direct chargino and neutralino production are shown. Depending on the decay chain considered and the assumption of equal neutralino and chargino mass, masses of up to 700 GeV for LSP masses of up to 300 GeV are excluded. However, these figures also show that these limits can be much weaker for specific decay chains.

5. Searches for long-lived particles

If mass states are almost degenerate or in R-Parity violating (RPV) models long-lived supersymmetric particles may exist. Heavy long-lived particles are predicted by several groups of models, i.e. split SUSY and gauge mediated SUSY breaking. In Ref.[37], a search was carried out for muon-like particles that move slower than the speed of light. Independent measurements in the inner detector and the muon spectrometer have been carried out. Events have been selected by $E_{\mathrm{T}}^{\mathrm{miss}}$ and muon triggers. The dominant backgrounds are high p_{T} mis-measured muons. As a result an upper limit of ~ 1 fb on the cross section of the produced charged SUSY particle was measured in the phase space considered.
In Ref.[38], a search for long-lived particles decaying to electrons or muons was carried out. This analysis is sensitive to non-prompt electron or muon final states and is based on the transverse impact parameter, which measures the distance between the interaction point and reconstructed tracks. The sensitivity to stops decaying via RPV interactions is shown in Fig. 12. Stops of up to 800 GeV for stop decay length of $\sim$ 2 cm are excluded by this analysis. The limit degrades for longer or smaller decay lengths.
In Ref.[39], an analysis for delayed and non pointing photons is carried out using timing information in the calorimeter. Non pointing means in this context that the electro-magnetic shower does not point back to the primary vertex. The analysis requires two photons and $E_{\mathrm{T}}^{\mathrm{miss}}$

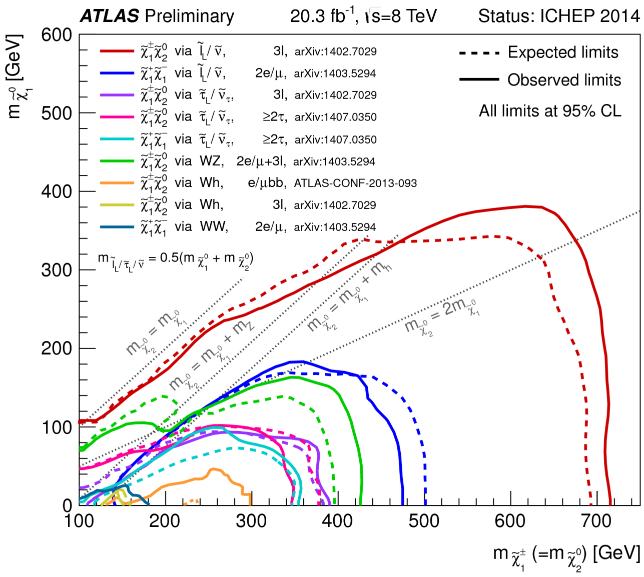

Figure 10. Summary of searches for electroweak SUSY partners in ATLAS [32].

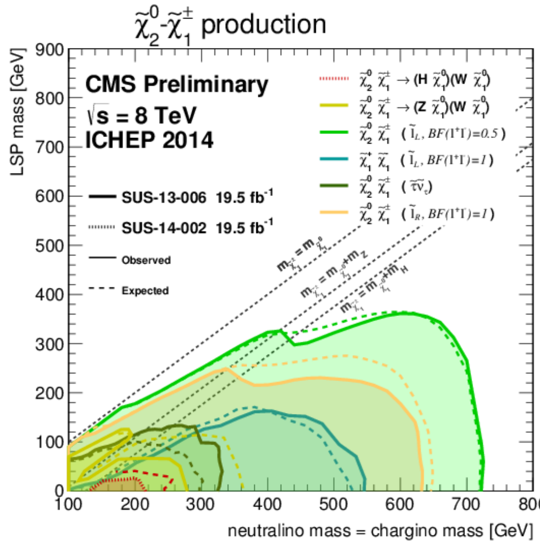

Figure 11. Summary of searches for electroweak SUSY partners in CMS [33].

and is thus sensitive to pair-production of long-lived particles decaying to photons and $E_{\mathrm{T}}^{\mathrm{miss}}$. In Fig. 13 the limits on the chargino mass, neutralino mass and the effective scale of SUSY breaking Λ, in a specific GMSB model in dependence of the neutralino life time τ are shown. Effective SUSY scales of up to 300 TeV are excluded for lifetimes of the neutralino of ~ 2 ns, degrading with smaller or longer lifetimes.

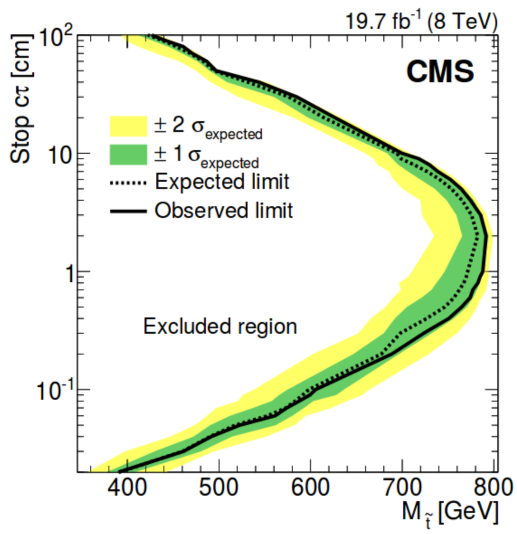

Figure 12. CMS limits for stops decaying via RPV interactions [38].

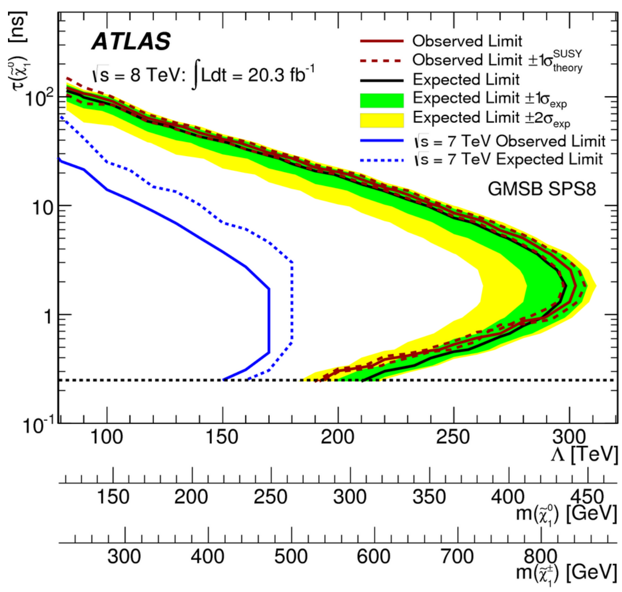

Figure 13. ATLAS limits in a specific GMSB model [39].

6. Summary

Recent results of the ATLAS and CMS collaborations in searches for supersymmetric particles, using data recorded in 2012 in $\sqrt{s} = 8$ TeV proton-proton collisions, have been highlighted. In particular I showed progress in the searches for quarks and gluinos, third generations squarks, direct production of charginos, neutralinos and sleptons and long-lived particles. None of the searches have shown a statistical significant deviation from the Standard Model of particle physics. In Fig. 14 an overview on searches carried out by the ATLAS experiment is shown, yielding an overview on the mass scales for various models the LHC is sensitive to.

At 13 TeV center of mass energy of proton-proton collisions which will be provided by the Large Hadron Collider in 2015, the production cross section for squarks and gluinos is significantly enhanced. In Fig. 15 the prospect of CMS to discover weak production of charginos and neutralinos and strong production of gluinos are shown. The prospects for weak production reach up to $\sim$ 1 TeV in mass and up to $\sim$ 2.2 TeV in mass for gluinos for 3000 fb^{-1}of integrated luminosity. Thus the upcoming data taking period provides the hope of discovering supersymmetric particles, if they exist at the TeV scale.

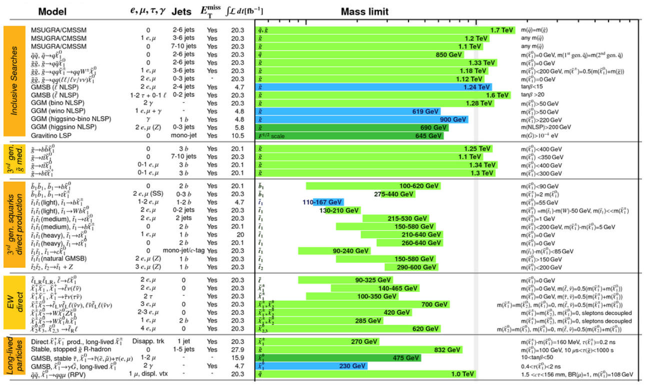

Figure 14. ATLAS limit summary [32].

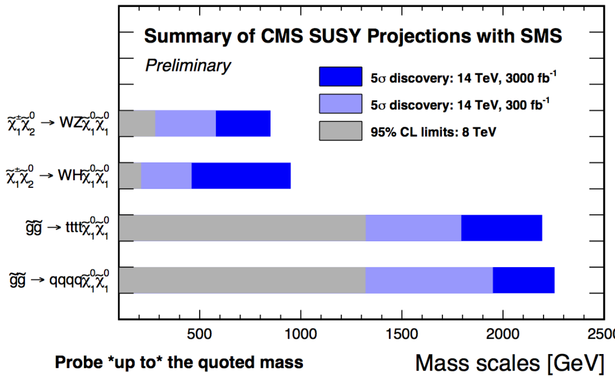

Figure 15. CMS SUSY prospects [33].

References

[1] H. Miyazawa, Prog. Theor. Phys. **36** (6), 1266 (1966).
[2] P. Ramond, Phys. Rev. D **3** 2415 (1971).
[3] Y. A. Golfand and E. P. Likhtman, JETP Lett. **13** 323 (1971) [Pisma Zh. Eksp. Teor. Fiz. **13** 452-455 (1971)].
[4] A. Neveu and J. H. Schwarz, Nucl. Phys. B **31** 86 (1971).
[5] A. Neveu and J. H. Schwarz, Phys. Rev. D **4** 1109 (1971).
[6] J. Gervais and B. Sakita, Nucl. Phys. B **34** 632 (1971).
[7] D. V. Volkov and V. P. Akulov, Phys. Lett. B **46** 109 (1973).
[8] J. Wess and B. Zumino, Phys.Lett. B **49** 52 (1974).
[9] J. Wess and B. Zumino, Nucl. Phys. B **70** 39 (1974).
[10] ATLAS Collaboration, JINST **3**, S08003 (2008).
[11] CMS Collaboration, JINST **3**, S08004 (2008).
[12] L. Evans and P. Bryant (editors), JINST **3**, S08001 (2008).
[13] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
[14] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
[15] CMS Collaboration, arXiv:1502.04358, to appear in JHEP.
[16] ATLAS Collaboration , ATLAS-CONF-2013-047, http://cds.cern.ch/record/1547563.
[17] ATLAS Collaboration , JHEP **10** 130 (2013).
[18] CMS Collaboration, CMS-PAS-SUS-14-004, http://cds.cern.ch/record/1754939.
[19] CMS Collaboration, CMS-PAS-SUS-14-008, http://cds.cern.ch/record/1749154.

[20] ATLAS Collaboration, ATLAS-CONF-2014-001, http://cds.cern.ch/record/1641169.
[21] ATLAS Collaboration, http://arxiv.org/abs/1501.01325, to appear in Phys. Rev. Lett..
[22] CMS Collaboration, Phys. Lett. B **743**, 503 (2015).
[23] CMS Collaboration, arXiv:1412.4109, Submitted to Phys. Lett. B.
[24] CMS Collaboration, CMS-PAS-SUS-13-015, http://cds.cern.ch/record/1635353.
[25] ATLAS Collaboration, JHEP **09**, 015 (2014).
[26] ATLAS Collaboration, JHEP **11**, 118 (2014).
[27] ATLAS Collaboration, JHEP **06**, 124 (2014).
[28] ATLAS Collaboration, Phys. Rev. D **90**, 052008 (2014).
[29] CMS Collaboration, Eur. Phys. J. C **73**, 2677 (2013).
[30] CMS Collaboration, CMS-PAS-SUS-14-011, https://cds.cern.ch/record/1745586.
[31] CMS Collaboration, CMS-PAS-SUS-13-009, https://cds.cern.ch/record/1644584.
[32] *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults*
[33] *https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS*
[34] ATLAS Collaboration, Phys. Rev. Lett. **114**, 142001 (2015)
[35] CMS Collaboration, Phys. Rev. D **90**, 092007 (2014).
[36] ATLAS Collaboration, arXiv:1501.07110, Submitted to Eur. Phys. J. C.
[37] ATLAS Collaboration, JHEP **01**, 068 (2015).
[38] CMS Collaboration, Phys. Rev. Lett. **114**, 061801 (2015).
[39] ATLAS Collaboration, Phys. Rev. D **90**, 112005 (2014).