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SUSY searches in ATLAS and CMS

Pablo Matorras Cuevas for the ATLAS, CMS and SUSY collaborations.

Abstract

A selected summary of the most recent searches for signals of supersymmetry performed at the ATLAS and CMS Collaborations is presented. This presentation was given at the School and Workshops on Elementary Particle Physics and Gravity in Corfu, Greece, and in addition to a brief introduction to supersymmetry and its motivations, a selection of analyses was presented, including searches for gluino/squark, top and bottom squarks, chargino-neutralino pair productions, sleptons, and R-parity violation long lived particles, finishing up with a short conclusion and outlook.

Presented at *Corfu2021 Corfu Workshop on the Standard Model and Beyond*

PROCEEDINGS OF SCIENCE

Supersymmetry searches in ATLAS and CMS

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A selected summary of the most recent searches for signals of supersymmetry performed at the ATLAS and CMS Collaborations is presented. This presentation was given at the School and Workshops on Elementary Particle Physics and Gravity in Corfu, Greece, and in addition to a brief introduction to supersymmetry and its motivations, a selection of analyses was presented, including searches for gluino/squark, top and bottom squarks, chargino-neutralino pair productions, sleptons, and R-parity violation long lived particles, finishing up with a short conclusion and outlook.

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Contents

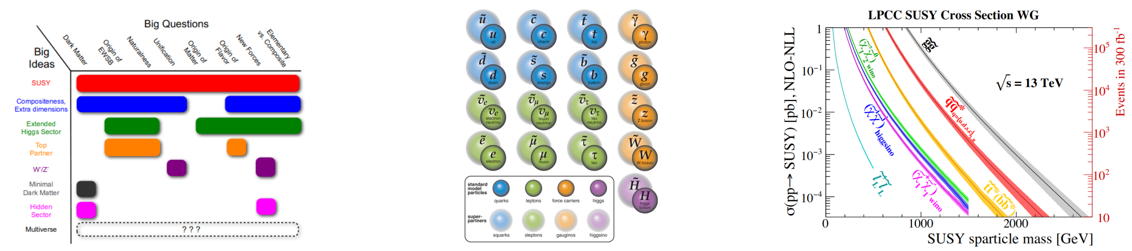
1. Introduction to Supersymmetry

Among the multiple beyond standard model theories, supersymmetry (SUSY) has been amongst the most promising, since it can solve multiple open questions both theoretical (i.e, helping towards a great unification theory) or experimental (some of the particles predicted by SUSY are thought to be good dark matter candidates) at the same time. A list of the different questions addressed by SUSY as well as other theories is shown in Figure 1a.

Making an in depth description of how SUSY is constructed would require the use of complex mathematics that are outside of the aim of this text. Thus, it suffices to remember that this theory introduces a new space-time symmetry to the standard model (SM), so that per each SM particle, one superpartner companion is retrieved, as shown in Figure 1b. Also, if the R parity is assumed to be conserved[1], then particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. Finally, if naturalness is assumed, then the gluinos, top squark (stop), charginos and neutralinos should have a mass at the TeV scale.

After finishing in 2018 the Run-2 data taking period, up to approximately 150 fb^{-1} of data were collected in ATLAS and CMS detectors. According to the expected cross sections per particle and mass, shown in Fig 1c, a large amount of particles should have been produced, albeit no statistically significant deviations have been found so far. Therefore, current searches are being done in more challenging regions of the parameter space. These can be separated in three search types :

Figure 1



(a) Diagram showing each theoretical/experimental questions adressed per each BSM theory [1].

(b) List of SUSY particles per each SM counterpart.

(c) Production cross section for several SUSY productions in terms of their mass.

- Gluino/squark searches: Favoured due to their high cross sections (as shown in Fig. 1c), which produces a high mass sensitivity.
- Third generation quarks (stop, sbottom): Lower cross section than the gluinos or the other quarks, but of interest since they are favoured by naturalness.
- Electroweak production (charginos/neutralinos and sleptons): Lower cross sections, but with a higher branching fraction to leptons.

Whereas from an experimental perspective, searches can be focused on:

- Looking for SUSY production with either a heavier mass or a smaller cross section to what's been already probed. These analyses are characterised by probing phase spaces with a very high p_T^{miss} coming form the LSPs.
- Searching for "soft" signatures (i.e. less energetic). This is the case of searches for models with compressed phase spaces.
- Assuming that R-parity is not conserved. These models are known as R-Parity Violating (RPV) SUSY.
- Assuming that the new particles have slightly longer lifetimes, which is the topic studied by long lived particles (LLP) SUSY searches.

Since the number of analyses surpasses what was explainable in the length of the talk, a selection of different analyses was made, trying to englobe both the most recent analyses at the

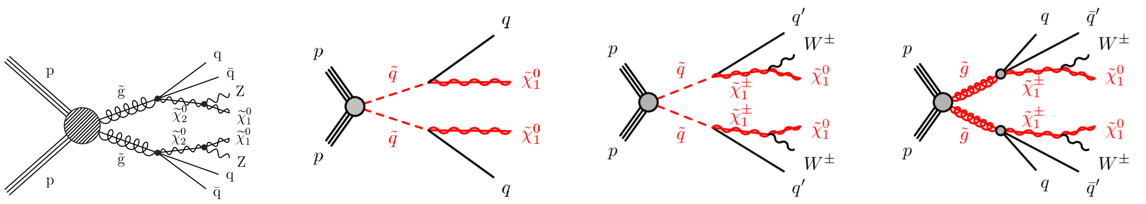
[1] Some theories do not take this assumption, as explained in the Section 7

time, as well as covering all the different search types. A complete and updated list of the public SUSY results can be found at [2] and [3] for the ATLAS and CMS collaborations, respectively.

2. Gluino/squark searches

These kind of analyses study gluino and light squark production in topologies with presence of jets. Most searches exploit fully hadronic final states with a large p_T^{miss}, in final states with decay chains involving light quarks, b quarks or top quarks, where lower p_T^{miss} backgrounds make a large sensitivity possible. Examples of gluino and squark hadronic decays are shown in Figures 2a and 2b respectively. Other final states can be considered, including leptons from the decays from the next to LSP (NLSP). One example of this latter type of analysis is the search for a single lepton signature where the charginos decays to W bosons [4], as in the models shown in Figs. 2c and 2d respectively. Current analyses are sensitive to very high mass particle production due to these particles being produced via the strong interaction. The main challenge in this case is to reconstruct large-cone jets from boosted object decays, since very energetic jets whose products are emitted collimated, making them difficult to resolve from each other.

Figure 2: Feynman Diagram for gluino/squark production for:



(a) Gluino pair production decaying hadronically [5].

(b) Squark pair production decaying hadronically [6, 7].

(c) Squark pair production with a W boson [4, 6] in the final state.

(d) Gluino pair production with a W boson [4, 6] in the final state.

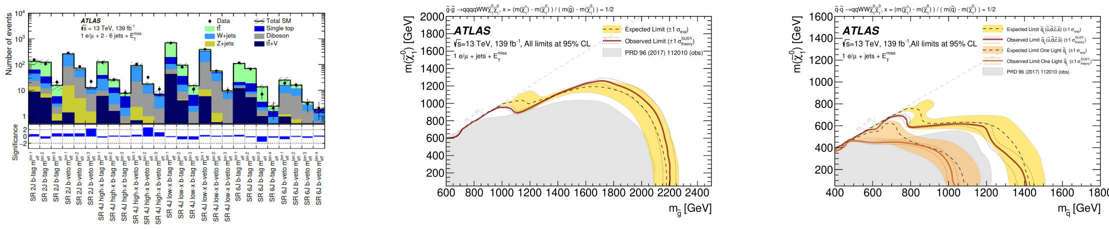
2.1 Gluino/squark searches with one lepton

In this analysis, performed by ATLAS [4], gluino (Fig. 2d) and squark (Fig. 2c) production decaying to two W bosons LSPs and quarks, with the chargino assumed to be wino like, and the LSP bino like [4] is searched. For doing so, several signal regions (SRs) are defined in terms of the number of jets and variables such as the transverse mass from the lepton transverse momentum and the p_T^{miss}, m_T,(ℓ, p_T^{miss}), whose yields are shown in Fig. 3a. Control and validation regions are defined in the same space but with lower m_T(ℓ, p_T^{miss}). Limits are set up to 2200 GeV for the mass of the gluino as shown in Fig. 3b, whereas for the squarks, limits were set at 1400 GeV if the first two generations are mass degenerate and 1000 GeV if only one quark mass is accessible, as shown in Figure 3c in yellow and orange respectively.

2.2 Conclusions

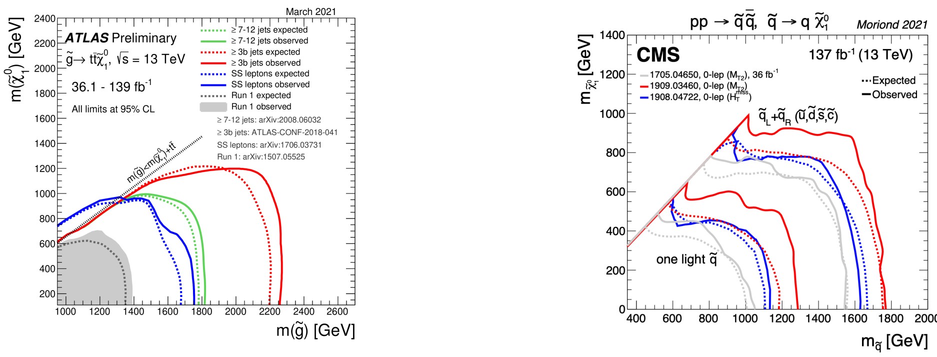
No significant deviation from the SM has been found, and limits are set both from ATLAS and CMS at 2100-2300 GeV for the mass of the gluino decaying to a quark pair and an LSP, as shown in Fig 4a for the ATLAS collaboration; at 2200 GeV if the gluino is decaying to a top pair and the LSP, and at 1800-1900 GeV for the squark mass, shown in CMS's Fig. 4b.

Figure 3



(a) Event yields per SR. **(b)** Expected and observed limits for the gluino mass with respect to the LSP. **(c)** Expected and observed limits for the squark mass with respect to the LSP.

Figure 4: Summary of limits for the mass with respect to the LSP's mass for:



(a) Gluino (ATLAS). **(b)** Squarks (CMS).

3. Searches for the top squark

As mentioned in the introduction, thanks to the constrains imposed on different SUSY models to satisfy naturalness, the top squark is often expected to be the lightest squark. Stop searches where the stop decays to the top quark and the LSP are typically classified by the mass splitting Δm between the stop and the LSP, since they will produce different kinematics, as shown in Figure 5:

- Searches with high mass splitting ($\Delta m > m_t$): characterised by having a high p_T^{miss}.
- Searches in an intermediate mass region ($m_W + m_b < \Delta m < m_t$): typically three body decays.
- Searches in the compressed region ($\Delta m < m_W + m_b$): four body decays.

Among the different analyses published, two are specifically mentioned here:

- $\tilde{t}$ in all hadronic final states: traditionally the most sensible at high Δm, due to customised boosted object reconstructions [8].
- $\tilde{t}$ with other signatures: stop decaying to the $\tilde{\tau}$ lepton [9].

3.1 Search for the top squark in the hadronic final state

This CMS analysis [8] targets events with multiple jets, high p_T^{miss} and a veto on leptons. Two different object reconstructions are used depending on the Δm. For low Δm, a soft b-tagged jet and

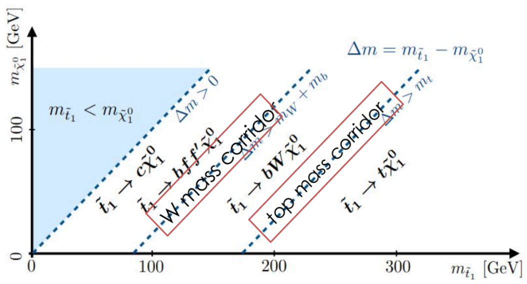
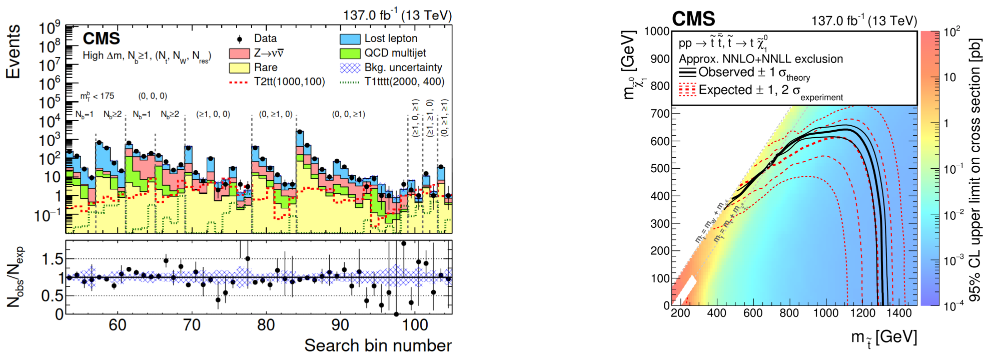


Figure 5: Stop different search regions by mass splitting, with each boundary region shown.

another jet coming from initial state radiation (ISR) are required, whereas a neural network (NN) was used to reconstruct boosted top quarks or W bosons in the high Δm case. Signal regions are thus defined in terms of several event kinematic variables and multiplicity of dedicated objects (i.e. number of top quarks), giving the yields shown in Fig. 6a. Exclusion limits are set up for the $\tilde{t}$mass, reaching up to 1300 GeV for low LSP mass, as shown in Fig. 6b.

Figure 6: $\tilde{t}$ in the hadronic final state



(a) Yields per search bin number. **(b)** Observed (black) and expected (red) exclusion limits.

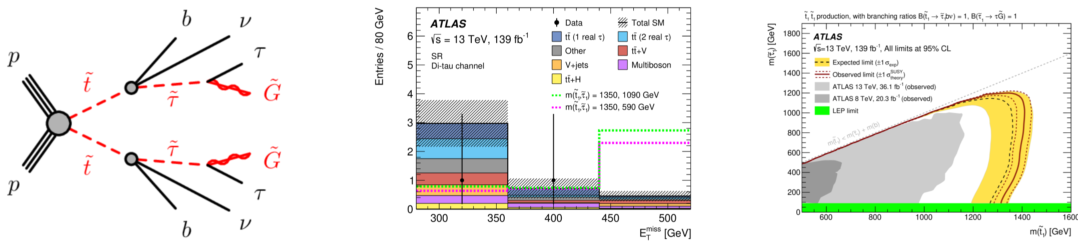
3.2 Search for the top squark in decays involving $\tilde{\tau}$.

This analysis, performed by ATLAS [9], focuses on the top squark decaying to staus, as shown in Fig 7a. It targets events with p_T^{miss}>250 GeV, 2 jets, with at least one of which b-tagged, and with no electrons or muons. Two SRs are set in place, one requiring 1 tau lepton decaying hadronically (τ_h) and at least 2 b-jets; and another with two τ_h, from which the number of simulated and observed events is shown in Fig 7b, for several signal models. Exclusion limits are obtained, excluding $\tilde{t}$ masses up to 1300 GeV, reaching 1400 GeV for $\tilde{\tau}$ masses between 400 and 1000 GeV, as shown in Fig 7c.

3.3 Summary

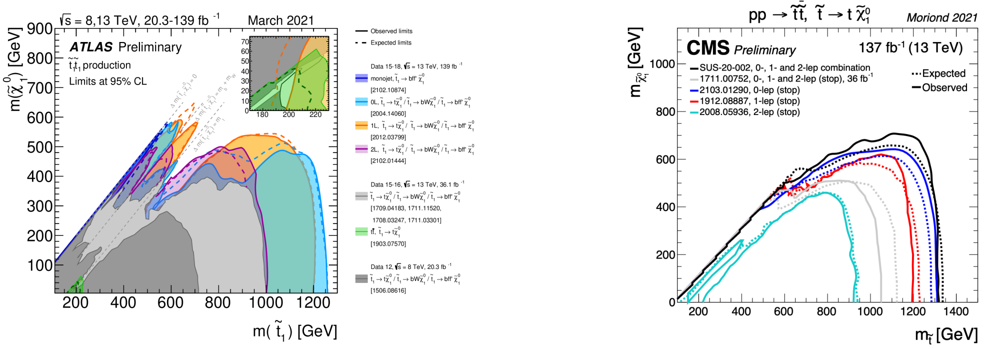
No statistically significant deviations from the SM have been found, stop masses up to 1300 GeV are excluded for low LSP masses, as shown in Figs 8a and 8b. Compressed searches are also excluded by both experiments for stop masses up to 600 GeV. Finally, the Δm~m_t is also now excluded by both experiments up until 295 GeV.

Figure 7: $\tilde{t}$ in decays involving $\tilde{\tau}$



(a) Feynman diagram. **(b)** p_T^{miss}distribution in the $\tau\tau$ signal region. **(c)** Expected (Black) and observed (red) limits, and previous analyses.

Figure 8: Summary of limits for the $\tilde{t}$ mass with respect to the LSP's mass for:



(a) Gluino (ATLAS). **(b)** Squarks (CMS).

4. Other squark searches: sbottom

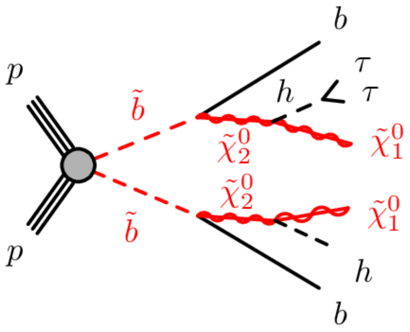
One example of search for the bottom squark is the analysis performed by ATLAS [10], in which bottom squarks are searched in events with $2\tau_h$, 2 b-jets, and a large p_T^{miss}, as can be understood from Fig. 9a. This analysis is specially characterised by the use of the Θ_{min}, defined as the smallest 3D angle between all possible τ_h-b jets pairs, as shown in Fig 9b. One single bin is defined, as well as three multi bin SRs, defined in terms of Θ_{min}, obtaining the yields shown in Fig. 9c. No significant excesses are found, and sbottom masses up to 850 GeV are excluded, assuming a mass difference between the LSP and the NLSP of 130 GeV, as shown in Fig. 9d.

5. Electroweakino searches

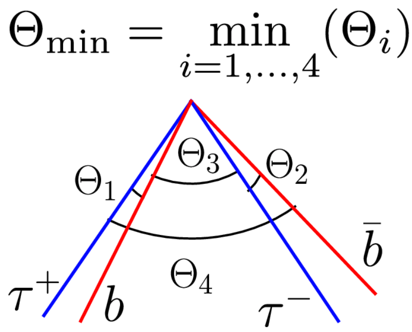
Electroweakino searches consist of probing for pair production of charginos and/or neutralinos decaying into the LSP, where the decay chain can involve W, Z or Higgs bosons as well as sleptons. Among the many analyses in the topic, the following are considered here:

- Multilepton searches, where two or more leptons are found in the final state, a signature that helps reduce the SM backgrounds [11, 12].
- All hadronic searches, with the advantage of a higher branching ratio, and that are performed using boosted reconstruction objects [13, 14].

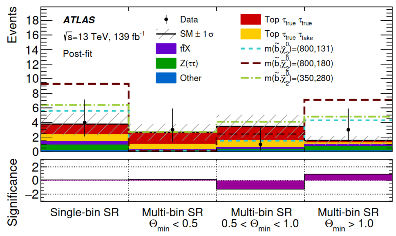
Figure 9: Sbottom search



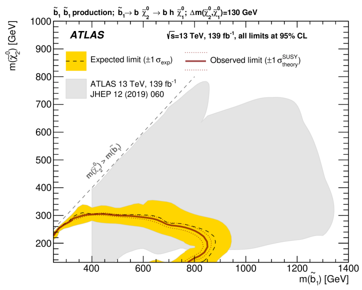
(a) Feynman diagram.



(b) Squarks (CMS).



(c) Yields obtaine for the single bin SR as well as the three multi-bin SR.



(d) Gluino (ATLAS).

- Other novel signatures, such as final states involving the $H \to b\bar{b}$ decay, which uses boosted b-tagging techniques [15].

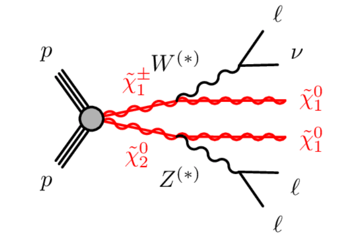
5.1 Electroweakino multileptonic searches

Two analyses performed independently by ATLAS [11] and CMS [12] were made public targeting very similar final states. ATLAS' one targets bino/wino and higgsino states decaying to W/Z/H bosons, as shown in Fig. 10a for the WZ case, being the WH a similar final state, as the Higgs boson is required to decay via ZZ, WW or $\tau\tau$. Events with exactly three leptons are considered, defining different SRs per each mode, in terms of m_T and p_T^{miss}.

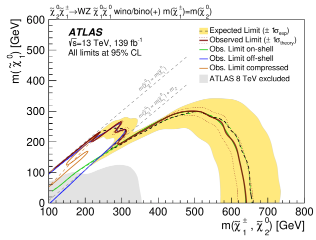
The same final state is considered by the CMS search, including also decays involving intermediate slepton decays, as shown in Fig. 10d. Events are therefore required to have either three or four leptons, with up to $2\tau_h$, also categorised in terms of lepton flavours and charges. A NN is used to discriminate signal from background, after training it with variables such as $m_{\ell\ell}$, m_T, $m_T^{3\ell}$ or p_T^{miss}.

Limits are set up to 650 GeV for the WZ decay scenario for low LSP mass both at ATLAS and CMS, as shown in Figs. 10b and 10e, respectively. In this model, a higher exclusion limit of up to 300 GeV is obtained by ATLAS in the compressed area. As for the WH decay scenario, observed and expected limits are slightly higher for the CMS analysis, being able to exclude up to 250 GeV for a low m_{LSP} values. Both exclusion limits are shown in Figs. 10c and 10f for ATLAS and CMS analyses, respectively.

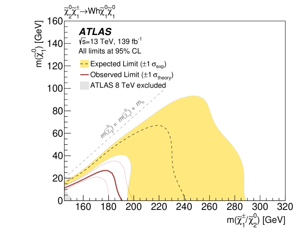
Figure 10: Electroweakino searches in the multileptonic channel



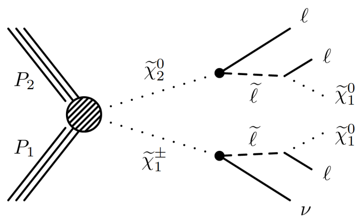
(a) Feynman diagram for both ATLAS and CMS.



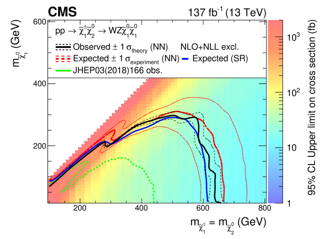
(b) WZ ATLAS Expected (black) and observed (red) limits.



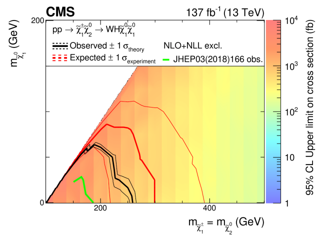
(c) WH ATLAS Expected (black) and observed (red) limits.



(d) Feynman diagram.



(e) WZ CMS Expected (black) and observed (red) limits.



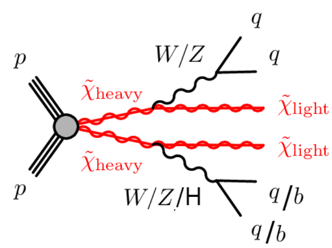
(f) WH CMS Expected (black) and observed (red) limits..

5.2 Electroweakino all hadronic searches.

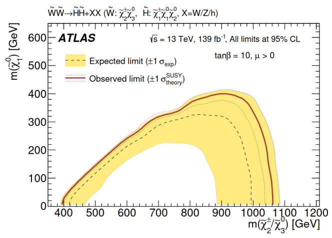
Two analyses were published by ATLAS [13] and CMS [14], targeting final states with hadronic topologies, exploiting their high branching ratio, and the possibility of using boosted reconstructions, advantageous for high mass splittings. In both cases, a pair of electroweakinos is searched in signal regions with a p_T^{miss}>200 GeV, reconstructing boosted W/Z/H, coming from the bino/wino or higgsino decays, as shown in Fig 11a.

The limits obtained by both searches are competitive with previous leptonic analyses, especially in the high Δm splitting regime. For instance, for the wino-higgsino model, expected exclusion limits are found to be at 1025 GeV for ATLAS and 1100 GeV for CMS for low m_{LSP}, with observed limits at 1075 GeV for the former and 975 GeV for the latter, as it can be seen in Figs 11b and 11c, respectively.

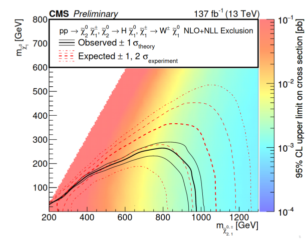
Figure 11: Electroweakino searches in the all hadronic channel



(a) Feynman diagram for both ATLAS and CMS searches.



(b) ATLAS 95% CL exclusion limits for the $(\tilde{W}, \tilde{H})$ models.

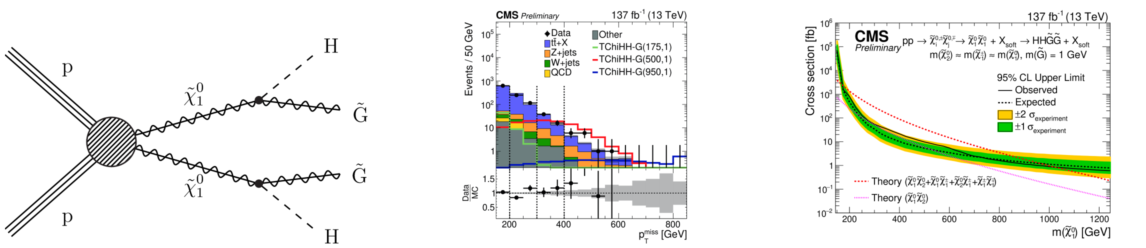


(c) CMS expected and observed 95% limits on the electroweakino pair production decaying to WH bosons.

5.3 Electroweakino searches in the HH final state

In this CMS analysis [15], final states with two Higgs bosons as shown in Fig. 12a are targeted, with each Higgs boson decaying to a pair of b quarks. Two different SRs are considered. A first so called "resolved" SR, where jets can be reconstructed separately. In this case, p_T^{miss}>150 GeV, and four or five jets among which two b tagged jets, forming an invariant>100 GeV are required. The p_T^{miss} distribution for this SR is shown in Fig. 12b. The other region, labeled as the "boosted" SR, requires p_T^{miss}>300 GeV, at least two AK8 jets, with each jet's p_T being at least 300 GeV, and its invariant mass between 95 and 145 GeV. Several models are considered, excluding, for instance, masses from 175 to 1025 GeV are excluded for the model shown in Fig. 12a, as shown in Fig 12c.

Figure 12: Electroweakino searches in the HH final state



(a) Feynman diagram.

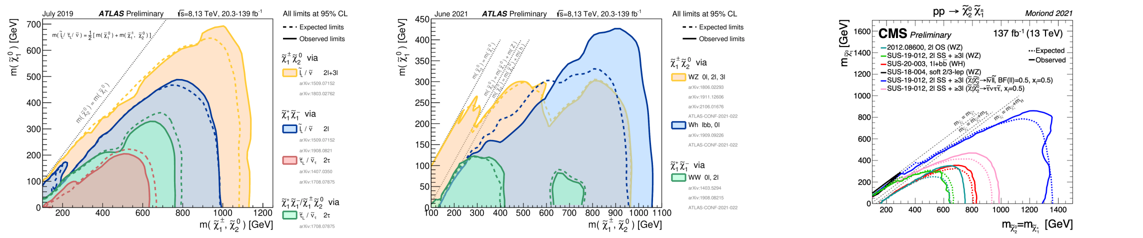
(b) Number of data and simulations, as well as different signal types in terms of the p_T^{miss}.

(c) CMS expected and observed 95% CL upper limits for the HH$\tilde{G}\tilde{G}$ model.

5.4 Summary

No significant deviations from the SM have been found. Limits on the electroweakino mass over 1 TeV have been probed by both ATLAS and CMS. Newer signatures (mostly hadronic), that are being used to further constrain the electroweakino production are being explored by both collaborations. A full summary of ATLAS and CMS' results is shown in Fig. 13.

Figure 13: Summary of the electroweakino searches



(a) Leptonic decays at ATLAS.

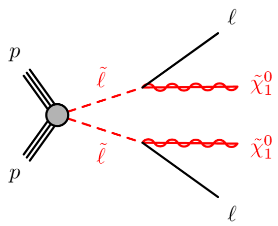
(b) Decays involving W or Z bosons at ATLAS.

(c) Leptonic and bosonic decays at CMS.

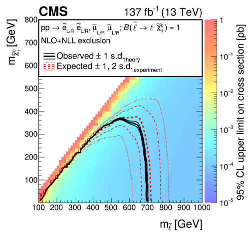
6. Slepton searches

Slepton searches are studied in decays involving a lepton and the LSP, as shown in Fig. 14a. Thus, there are two possible search types, leptonically or hadronically (via τ_h). In the leptonic searches, the slepton is assumed to decay to a lepton pair (ee or $\mu\mu$) pair. Therefore, two leptons with opposite charge and same flavour are required, in addition to high p_T^{miss}. Analyses at ATLAS [16] and CMS [17] exclude up to 700 GeV for low LSP masses, as shown in Fig. 14b for CMS, and 14d (yellow area) for ATLAS, respectively. In the hadronic case, a tau slepton is expected, decaying to a τ_h, probing therefore for $2\tau_h$ jets and a high p_T^{miss}. These analyses exclude masses of approximately 400 GeV for low m_{LSP}, in both ATLAS [18] and CMS [19], as shown in Figs. 14c for the CMS analysis and 14d (green area) for ATLAS.

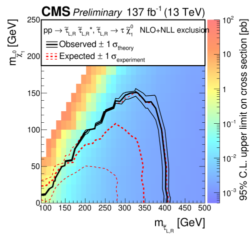
Figure 14



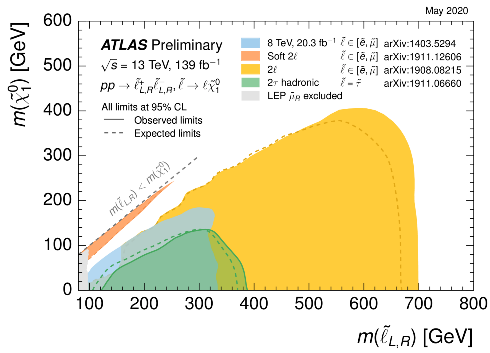
(a) Slepton decay, where ℓ can be eμ or τ.



(b) Expected (red) and observed (black) limits for the slepton search decaying leptonically [17].



(c) Expected (red) and observed (black) limits for the slepton search decaying hardonically [19].



(d) Summary of slepton searches in the ATLAS collaboration.

7. Searches for RPV Stealth and LLP SUSY

As mentioned in Section 1, there is no compelling reason as to be certain that our BSM model has to have the properties mentioned in previous analysis. Thus, three different types of SUSY were considered, RPV, Stealth and LLP SUSY.

In the model with R-parity violation, the LSP is unstable, which causes it to decay into SM particles, resulting in final states with no SUSY particles contributing to the p_T^{miss}. Two analyses, one from ATLAS [20] and one from CMS [20] are considered for this scenario.

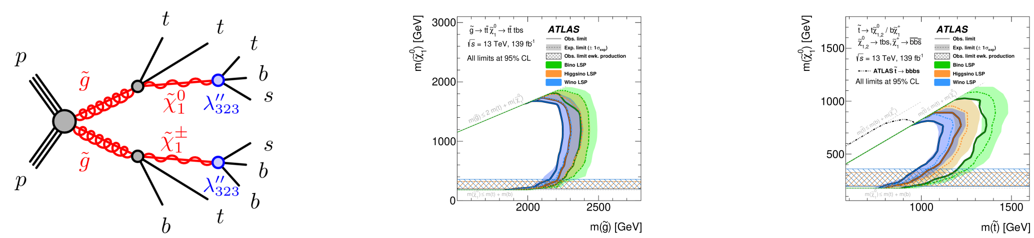
Stealth SUSY assumes that the stop decays through a hidden SUSY sector. This was explored by the same CMS RPV analysis [20].

Long lived particles: These analyses are particularly challenging in terms of reconstruction and analysis, due to the formation of displaced vertices and the LLPs' small couplings. One analysis from ATLAS [21] and one from CMS [22] are considered for this scenario.

7.1 RPV searches

As mentioned earlier, two analyses, performed by ATLAS and CMS, are considered. For the case of the ATLAS search [23], a final state with many jets is expected, so that a jet counting is applied, utilising several lepton and b-jet multiplicity bins, as it can be seen in the Fig. 15a. Exclusions up to 2.4 TeV for the gluino mass, as shown in the Fig. 15b, and 1.35 TeV for the stop, represented in Fig. 15c are achieved for the bino model, obtaining slightly lower values for the other wino/higgsino models.

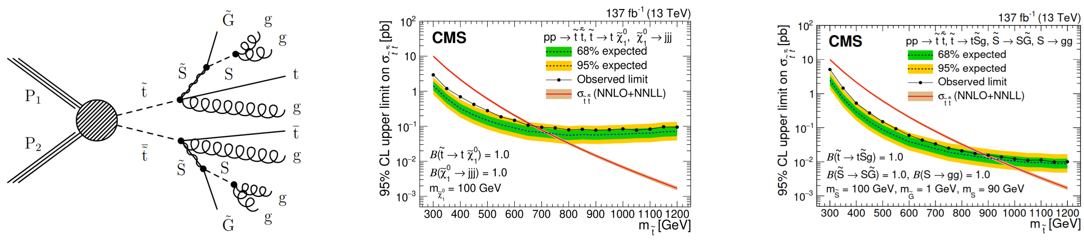
Figure 15: RPV search at ATLAS



(a) Feynman diagram for the gluino production. **(b)** Exclusion limits for the gluino mass for the Bino/Higgsino/Wino models. **(c)** Exclusion limits for the stop mass for the Bino/Higgsino/Wino models.

As for the CMS analysis [20], it studies stop production in both the RPV and Stealth models, being the latter shown in Fig. 16a, with the former similar in terms of jet multiplicity. Thus, a selection is made, with 2 top quarks, at least 7 jets and 1 b-jet, H_T>300 GeV, and one lepton. A NN is then used with the information of the 7 jets and lepton as input. This leads to exclusions of the stop mass up to around 670 GeV for RPV (Fig. 16b) and 870 GeV for the Stealth model (Fig. 16c).

Figure 16: RPV and stealth search at CMS.



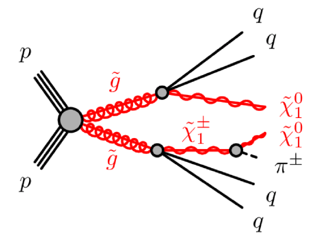
(a) Feynman diagram for the gluino production. **(b)** 68 and 95 % expected and observed limits for the RPV model. **(c)** 68 and 95 % expected and observed limits for the stealth model.

7.2 Long lived particle searches

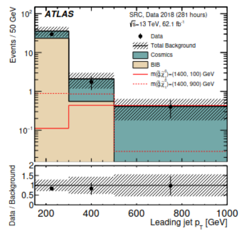
Just like for the RPV case, two analyses, one by ATLAS and one by CMS, are considered. The ATLAS analysis [21] looks for events with high $p_T$in data from empty bunch crossings, obtaining distributions such as Fig 17b for the jet p_T. Limits are set, as shown in Fig. 17c, from where gluino masses under 1400 GeV are excluded for gluino lifetimes between 10^{-5} and 10^{-3} seconds.

As for the CMS analysis [22], it must be noted that the analysis was designed to be as broad as possible, being sensitive to any model whose signature includes two displaced leptons (ee, $\mu\mu$,

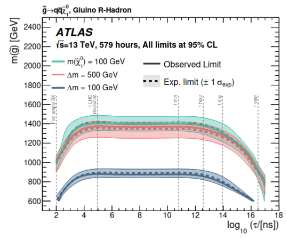
Figure 17: LLP searches at ATLAS.



(a) Feynman diagram for the gluino production and possible final states.



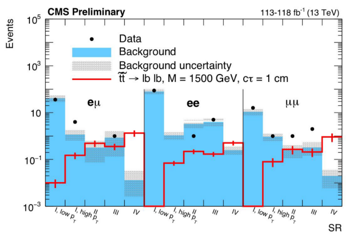
(b) Leading jet p_T distribution.



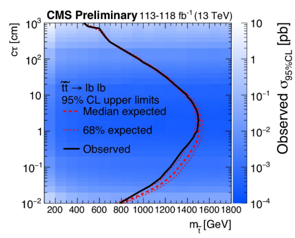
(c) Gluino lifetime exclusion limits in terms of its mass, for several $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ splitting.

eμ). Two SUSY models are considered, $\tilde{t} \rightarrow b\ell$, from which the yields per SR is presented in Fig 18a, and a $\tilde{\ell} \rightarrow b\ell$ model. the transverse impact parameter (d_0) is used as the discriminant variable, with 10μm<$|d_0|$ <10 cm. Limits were set, excluding decay lengths from 0.1 to 30 cm for a stop mass of TeV (Fig. 18b), whereas masses up to 600 GeV were excluded for the selectron and smuon cases, for decay lenghts of around 1 cm (Fig 18c).

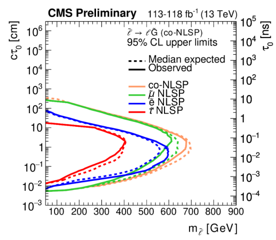
Figure 18: LLP searches at CMS.



(a) Yields found per SR.



(b) Limits on the stop mass in terms of the decay length.



(c) Limits in the slepton mas in terms of the decay length.

8. Summary and outlook

Plenty of analyses have been made public recently, both from ATLAS and CMS collaborations, both tackling challenging space regions, such as boosted or compressed scenarios, and also in terms of non classical signatures, as it is the case of long lived or RPV SUSY, improving the exclusion limits on both squarks, sleptons or electroweakinos. As for the future prospects, LHC's Run-3 is about to start, with higher luminosity and improved detectors, so that, together with refinements on the analysis techniques will help us probing for SUSY with even greater sensitivity.

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