Search for "Electroweakinos" with the ATLAS Detector at the LHC

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Abstract. Supersymmetry is one of the most popular extensions of the Standard Model of particle physics, as it offers solutions to several shortcomings of the Standard Model. Natural supersymmetric models favor masses for the new particles which are predicted by supersymmetry in the range of hundreds of GeV, well within the reach of the Large Hadron Collider at CERN. If squarks and gluinos are much heavier, the production of charginos and neutralinos may be the dominant production mode for supersymmetric particles. These proceedings present results from new searches for the production of charginos and neutralinos, focusing on the recent paper by the ATLAS collaboration that summarizes and extends the searches for the electroweak production of supersymmetric particles using data from Run-1 of the LHC.

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INTRODUCTION

Supersymmetry (SUSY) [1–9] is one of the most popular extensions of the Standard Model of particle physics, as it can provide solutions to a number of problems or short-comings of the Standard Model. It introduces a new space-time symmetry between fermions and bosons and predicts essentially a doubling of the number of elementary particles contained in the model. A large number of searches have been designed and carried out in the past to find traces of these particles in collider experiments. These proceedings discuss the search for electroweakinos with the ATLAS detector [10], one of the two large multi-purpose detectors at the Large Hadron Collider (LHC) [11] at CERN. Electroweakinos comprise the supersymmetric charginos $\widetilde{\chi}_i^\pm$ ($i = 1, 2$) and neutralinos $\widetilde{\chi}_j^0$ ($j = 1, \ldots, 4$), which are mixtures of the bino, the wino triplet and the higgsinos, which in turn are the superpartners of the $\mathrm{U}(1)_Y$ and $\mathrm{SU}(2)_L$ gauge bosons and Higgs doublets of supersymmetry.

The primary motivation for the search for electroweakinos comes from its complementarity to the strong-production searches. In fact, electroweak production may be the dominant production mode for supersymmetric particles at the LHC if the squarks and gluinos are sufficiently heavy. Another motivation is naturalness [12, 13]: Natural models of supersymmetry suggest that the masses of the lightest charginos and neutralinos fall into a range that is well accessible at the LHC.

All searches for supersymmetry have produced null results so far, as no significant excess beyond the event yields expected from Standard Model processes has been observed. These null results can be translated into limits on the masses of supersymmetric particles in simplified models, which for strongly produced particles reach beyond 1 TeV, whereas in the case of electroweak production they are of the order of several hundreds of GeV. Recent results from the electroweak analyses carried out by the ATLAS collaboration include a search for exotic decays of the observed 125 GeV Higgs boson into light neutralinos and possibly gravitinos. This yields final states with photons and large missing transverse momentum ($E_\mathrm{T}^\mathrm{miss}$) and is motivated from Gauge-Mediated Supersymmetry Breaking and Next-to-Minimal Supersymmetry extensions of the Standard Model [14]. Then there is another analysis which does somewhat the opposite and looks for the production of a chargino $\widetilde{\chi}_1^\pm$ and a neutralino $\widetilde{\chi}_2^0$ decaying via a W boson and the 125 GeV Higgs boson [15]. The latest result from the ATLAS collaboration on the search for electroweakinos is the electroweak summary paper [16]. This paper will be the focus of these proceedings.

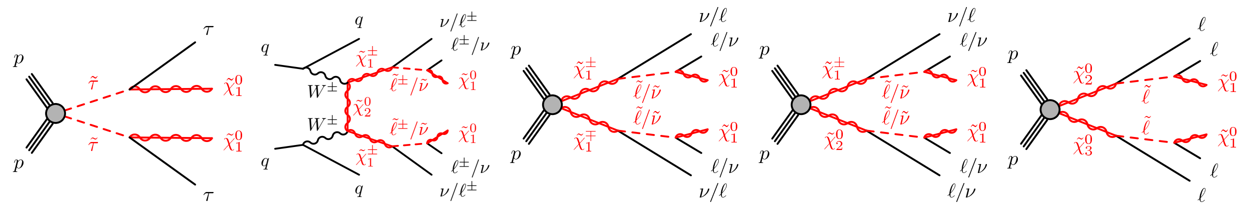

FIGURE 1. Diagrams illustrating the production of supersymmetric particles and their decays modes in the five simplified models that are employed in the interpretation of the results in the electroweak summary paper.

THE SEARCH FOR ELECTROWEAKINOS

The goal of the electroweak summary paper is to summarize and to extend the searches for electroweak supersymmetry with the ATLAS detector using the data taken during the first run (Run-1) of the LHC, corresponding to $20\,\text{fb}^{-1}$ of pp collisions at a center-of-mass energy $\sqrt{s} = 8\,\text{TeV}$. It is not only a summary but also includes five new analyses that have not been published before. These analyses look for two- or three-lepton final states and strive to extend the reach of earlier analyses by lowering the thresholds on the transverse momenta (p_T) of the leptons, by exploiting initial-state radiation (ISR) or vector-boson fusion (VBF) event topologies, or through the application of multi-variate analysis (MVA) techniques. In addition to these five new analyses, statistical combinations of the new and the existing searches are performed to extend the excluded mass ranges, adding also new combinations and reinterpretations of existing searches. Furthermore, the impact of the assumption for the mass of the intermediate slepton in simplified models on the exclusion reach is studied. One particular focus of the new analyses is to improve the sensitivity of the searches for supersymmetry scenarios with compressed mass spectra, where small mass differences between the particles in the supersymmetry decay chains lead to low-energetic decay products. Due to their low energy and momentum, these decay products may fail trigger or offline thresholds and may thus not be reconstructed. This deteriorates the signal acceptances and reduces the sensitivity of the analyses.

The results of the searches described in the electroweak summary paper are interpreted in two classes of models. The first class are simplified models, where only one specific production mode and decay chain for the supersymmetric particles is considered, and the branching ratios for the decays are assumed to be 100 %. Five simplified models are employed in the interpretation of the results in the electroweak summary paper as shown in Fig. 1 (from left to right): Production of stau pairs, production of same-sign chargino pairs in a VBF topology, chargino-pair production, associated production of the lightest chargino ($\tilde{\chi}_1^\pm$) and the second-lightest neutralino ($\tilde{\chi}_2^0$), and production of $\tilde{\chi}_2^0$ together with $\tilde{\chi}_3^0$. In all cases, the decays of the electroweak gauginos may proceed via all three slepton or sneutrino generations. The second class of models are phenomenological models: In the electroweak phenomenological Minimal Supersymmetric extension of the Standard Model (pMSSM), only the direct production of charginos and neutralinos is considered, which results in a small number of only four parameters. The two-parameter Non-Universal Higgs Masses model (NUHM2) is basically a constrained MSSM with two additional parameters that allow to tune the Higgs masses. The third phenomenological model used in the paper is a scenario with Gauge-Mediated Supersymmetry Breaking (GMSB), where the lightest supersymmetric particle (LSP) is the gravitino. This is different from all other models that are considered, where the LSP is always the lightest neutralino $\tilde{\chi}_1^0$. For the GMSB scenario, electroweak production dominates for large values of the parameter Λ, the supersymmetry-breaking mass scale felt by the low-energy sector. In all models discussed in these proceedings, R-parity is assumed to be conserved.

Two of the five new analyses are independent from the others as their selections have little overlap with the other analyses and their results are interpreted in models specific to these analyses. These two analyses are the two-tau analysis using an MVA technique and the search for two same-sign (SS) leptons in a vector-boson fusion topology. They will therefore be discussed, including their results and interpretations, separately from the others.

2τ (MVA) Analysis

The *two-tau (MVA)* analysis is an update of an earlier analysis, which targets the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying tau leptons and missing transverse momentum [17]. In contrast to the simpler, cut-based analysis, the updated version makes use of a boosted-decision tree (BDT) to improve the sensitivity, and the results are interpreted in a simplified model with direct-stau production, where the

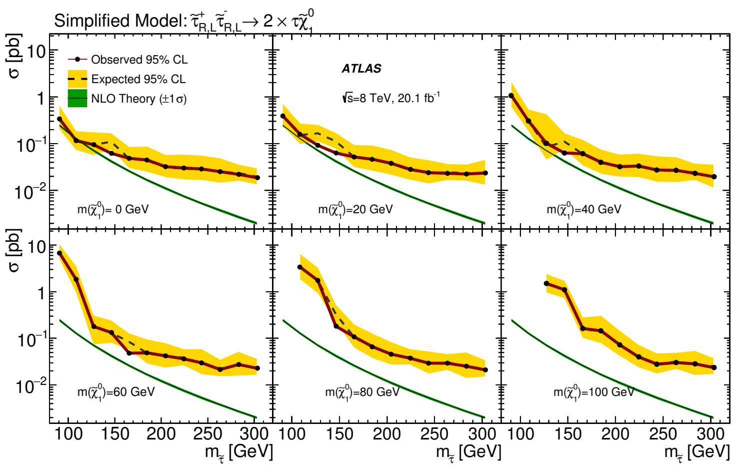

FIGURE 2. For six different masses of the LSP, these plots show the 95 % CL exclusion limits on the cross sections for combined pair production of left- and right-handed staus as a function of the stau mass [16].

cut-based analysis had practically no sensitivity. In the two-tau (MVA) analysis, events with exactly two taus with opposite charge are selected. Events that contain a b-tagged jet or where the two taus have an invariant mass that is compatible with the assumption that the taus are coming from a Z-boson decay are rejected. A boosted decision tree is trained on twelve input variables, which are based on kinematic properties of the two taus and $E_{\mathrm{T}}^{\mathrm{miss}}$ and have good discriminatory power. A cut on the output value of the BDT is then used to define one signal region (SR). Good agreement of the distribution of the BDT output variable in data and its expected distribution from the Standard Model background prediction is found prior to the signal-region cut, and no excess is observed in the signal region. This allows to interpret the analysis in terms of limits on the production cross section for stau pairs as a function of the mass of the stau and the LSP, as shown in Fig. 2. The best limit is found for a stau mass around 110 GeV and a massless LSP.

2 SS ℓ (VBF) Analysis

The second analysis from the summary paper to be presented here looks at final states with two light leptons with the same charge. It specifically targets a scenario where supersymmetric particles are produced via vector-boson fusion (VBF) as shown in the second diagram in Fig. 1. This reduces the production cross section considerably but on the other hand makes it easier to separate signal and background by requiring the presence of the two additional VBF jets. The jets also often cause the chargino to be boosted, yielding energetic decay products even in compressed spectra. In addition to two light leptons with the same charge, events selected in this analysis are required to have two jets and missing transverse momentum above 120 GeV in order to be in the plateau of the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger that is used in this analysis. (This is a unique feature of this analysis. In contrast, all of the other four analyses use combinations of single, double, and triple lepton triggers.) One cut-based signal region is defined, exploiting the VBF topology by requiring that the two jets be well-separated and in opposite hemispheres of the ATLAS detector and have a large invariant mass. Additional cuts suppress the remaining Standard Model backgrounds, mainly diboson and top quark production. No excess is observed in the SR, thus limits are set on the VBF $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}$ production cross section. The limits obtained from the 2012 dataset remain above the theoretical predictions by at least a factor three, i. e. this analysis is not yet sensitive to VBF $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}$ production. Exclusion plots for two different assumptions on the mass of the lighter chargino $\tilde{\chi}_1^{\pm}$ and as function of the mass splitting $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{0})$ can be found in the paper [16]. CMS recently made public a search that is able to set limits on the electroweak production of supersymmetric particles in a VBF scenario [18]. The main differences are that the CMS search does not only consider same-sign chargino production but combines several production modes, assumes larger mass splittings between the chargino and the neutralino, and decays to happen via staus only.

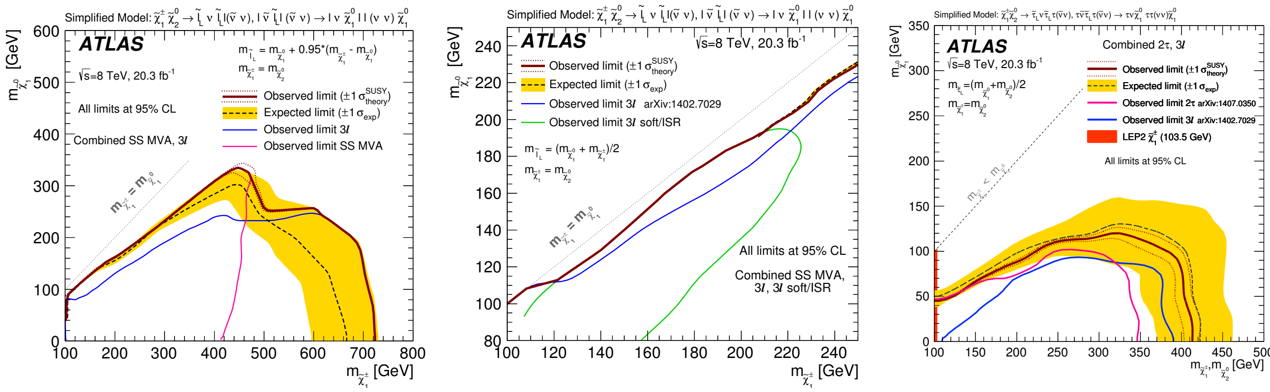

FIGURE 3. The 95 % CL exclusion limits on $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ production from the combinations of several analyses [16]. Left: $\widetilde{\ell}_L$-mediated decays with sleptons close in mass to the $\widetilde{\chi}_2^0$, middle: zoom of the compressed region, $\widetilde{\ell}_L$-mediated decays with sleptons masses halfway between $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$, right: $\widetilde{\tau}_L$-mediated decays with stau mass halfway between $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$.

Compressed Spectra With Two- and Three-Lepton Final States

In the following part, the remaining three of the five new analyses are discussed, before then coming the a joint presentation of their results and interpretations. These three analyses look at final states with two or three light leptons and aim to extend the reach of earlier searches for the production of electroweakinos [19, 20] for compressed supersymmetry scenarios.

The *2 OS ℓ (ISR)* analysis extends the earlier search for supersymmetry in final states with two leptons [19] to small mass splittings $\Delta m(\widetilde{\chi}_1^{\pm},\widetilde{\chi}_1^0)$ between the lightest chargino $\widetilde{\chi}_1^{\pm}$ and neutralino $\widetilde{\chi}_1^0$ by exploiting initial-state radiation jets. The ISR jet boosts the leptons from the supersymmetric decay chain, which otherwise may have too low momentum to pass the trigger or reconstruction thresholds. Events which have exactly two light leptons with opposite charge (OS leptons) and an ISR jet with high transverse momentum are selected, excluding events that contain b-tagged or forward jets, or in which the invariant mass of the two light leptons is close to the Z-boson mass. Two signal regions are defined based on "super-razor variables" [21] with good discriminatory power in compressed spectra and the ratio R_2 of the missing transverse momentum and the sum of missing transverse momentum and the transverse momenta of the leptons. ISR jets are also used in the *3ℓ (ISR)* analysis, which extends the corresponding earlier search [20] to small mass splittings $\Delta m(\widetilde{\chi}_2^0,\widetilde{\chi}_1^0)$ between the second-lightest neutralino $\widetilde{\chi}_2^0$ (or lightest chargino $\widetilde{\chi}_1^{\pm}$) and the lightest neutralino $\widetilde{\chi}_1^0$. Moreover, three-lepton triggers are now included which allow to go lower in lepton p_{T} (*soft leptons*). Events must have exactly three light leptons, including one pair with same flavor but opposite charge (SFOS). After a veto on events with b-tagged jets or where a SFOS lepton pair comes from an Υ meson decay, four signal regions are defined which either veto or require a jet with large p_{T} and differ in the allowed window for the value of the minimum mass of the SFOS pairs. Finally, the *2 SS ℓ (MVA)* analysis complements the search for three-lepton final states in case one of the three leptons is missed, selecting events with exactly two light leptons with the same charge sign. This analysis makes use of eight boosted decision trees which are trained independently to define the same number of signal regions, optimized for four different mass-splitting scenarios $\Delta m(\widetilde{\chi}_2^0,\widetilde{\chi}_1^0)$, each with and without the presence of ISR jets. The output of the BDT is also used to define validation regions that demonstrate that the Standard Model backgrounds are well understood. All three analyses observe good agreement between the event counts in data and their Standard Model predictions and no significant excess in any of the signal regions. These results are interpreted in terms of exclusion limits, combining analyses where they have comparable sensitivity.

INTERPRETATIONS

The exclusion limits on the mass parameters $m(\widetilde{\chi}_1^0)$ and $m(\widetilde{\chi}_1^{\pm}) = m(\widetilde{\chi}_2^0)$ for the simplified model with $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ production are shown in the plots in Fig. 3. Both $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$ are assumed to be pure wino, whereas the $\widetilde{\chi}_1^0$ is pure bino. The resulting observed limits from combinations of both the new analyses and the ones published earlier as indicated in the plots, are given by the thick red lines and compared against the earlier exclusion limits, drawn as thinner lines.

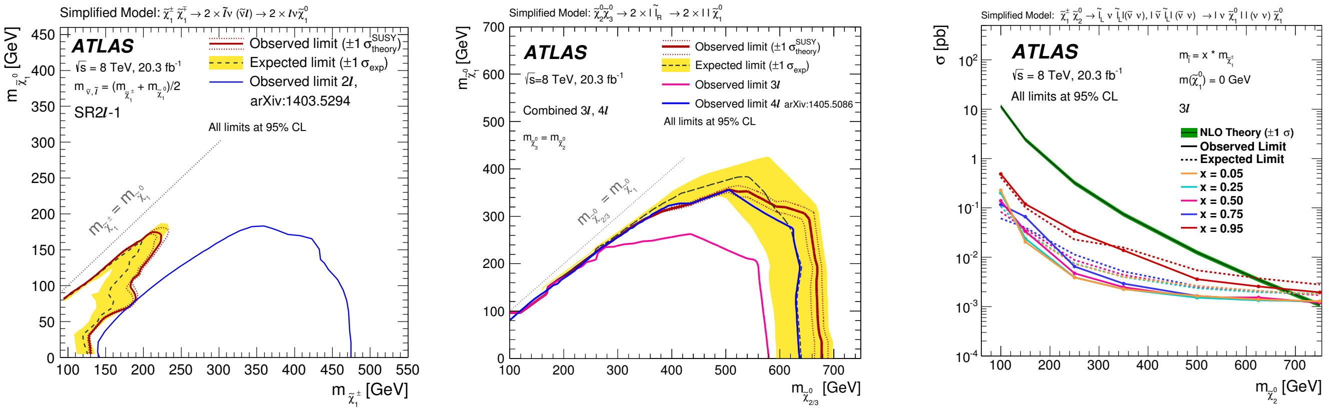

FIGURE 4. The 95 % CL exclusion limits on $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ production (left) and $\widetilde{\chi}_2^0\widetilde{\chi}_3^0$ production (middle) with slepton-mediated decays. The right-hand plot shows the impact of the intermediate slepton mass on the exclusion limit [16].

The left plot in the Figure shows the complementarity of the new 2 SS ℓ (MVA) analysis and the earlier 3ℓ analysis. In the middle, a zoom-in of the compressed region close to the diagonal is shown, which highlights the improvement of the limit in this difficult region that is obtained from the new 3ℓ (ISR / soft-leptons) analysis. Note that the assumption on the mass of the sleptons here is different from the one in the left plot. The 2 SS ℓ (MVA) analysis is also included in the combination but has no sensitivity in this region by itself and thus no exclusion line is shown. The right-hand plot of Fig. 3 shows a new combination of the existing 2τ and 3ℓ analyses in a scenario where the gaugino decays are mediated via staus only.

The left plot in Fig. 4 demonstrates the complementarity of the new 2 OS ℓ (ISR) analysis and the earlier 2ℓ analysis in the exclusion limits for the $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ simplified model with $\widetilde{\ell}_L$-mediated decays, where the new analysis fills the gap between the existing exclusion contour and the diagonal kinematic boundary. Again, the $\widetilde{\chi}_1^{\pm}$ is a pure wino and the $\widetilde{\chi}_1^0$ a pure bino in this simplified model. The plot in the middle shows a new combination of the existing 3- and 4-lepton analyses in the simplified model with $\widetilde{\chi}_2^0\widetilde{\chi}_3^0$ production and decays mediated via $\widetilde{\ell}_R$. Here, the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_3^0$ are assumed to be pure higgsino and mass-degenerate. This combination improves the earlier limits on the mass of the initial supersymmetric particles from the 4-lepton analysis by about 30 GeV. For all three simplified models, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$, and $\widetilde{\chi}_2^0\widetilde{\chi}_3^0$, the impact of the assumption for the intermediate slepton mass on the exclusion reach has been checked for a massless LSP by varying the slepton mass between 5 and 95 % of the mass of the decaying gaugino. The impact is found to be small, as can be seen in the right plot of Fig. 4 for the case of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$.

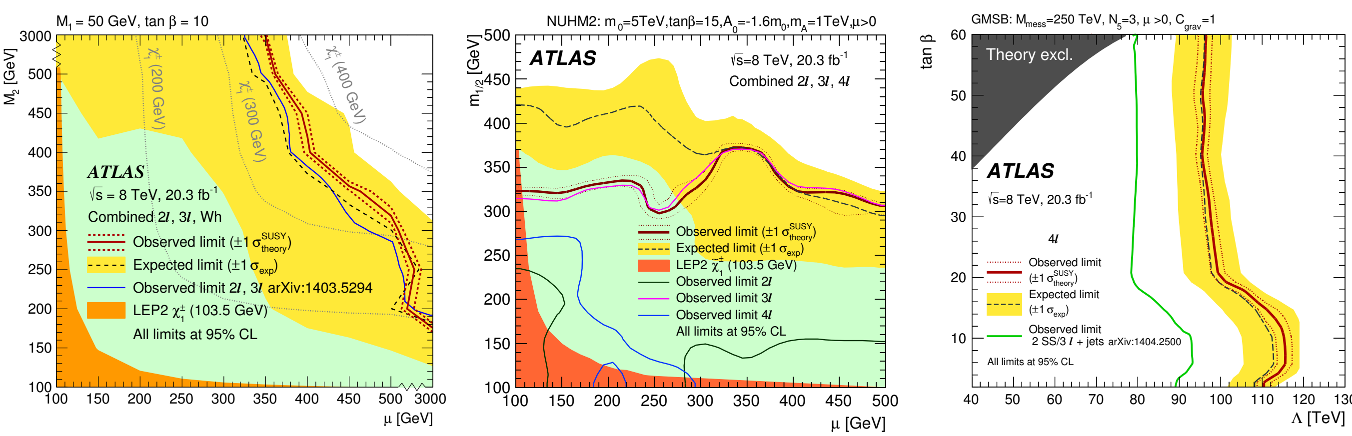

FIGURE 5. 95 % CL exclusion limits from the searches for electroweakinos in phenomenological models: pMSSM (left), NUHM2 (middle), and GMSB (right) [16].

The results of the electroweak analyses have also been interpreted in terms of exclusion limits on parameters of phenomenological models. These limits are shown in Fig. 5. The 95 % CL exclusion limit on the pMSSM parameters μ and M_2 is obtained by combining the Wh analysis [15] with the results from the 2ℓ and 3ℓ analyses [19, 20] and is shown in the left plot. The limits on the NUHM2 parameters μ and $m_{1/2}$ come from a new combination of the existing 2ℓ, 3ℓ, and 4ℓ analyses and are shown in the middle plot in Fig. 5. It can be seen that the 3ℓ analysis drives the exclusion limit in this scenario. The right plot shows that a new reinterpretation of the 4ℓ analysis [22] yields an improvement of 15 to 20 TeV with respect to an earlier combination [23]. The electroweak summary paper also has two plots which compare all earlier and new exclusion contours in the mass-parameter planes of the respective simplified models, providing separate comparisons for slepton- and W / Z / h-boson mediated decays. For the latter decay modes, the sensitivity of the new analyses is small, thus no combination has been attempted.

CONCLUSION

In conclusion, now that the searches for supersymmetry in the data from the first run of the LHC have been wrapped up, no strong signs for physics beyond the Standard Model have emerged from the Run-1 data. Still, a large number of supersymmetry analyses have been made public that constrain the parameter space of supersymmetric models. In these proceedings, the new electroweak summary paper has been discussed, which contains the final ATLAS limits on the electroweak production of supersymmetric particles at a center-of-mass energy of $\sqrt{s} = 8$ TeV. It should be stressed that this paper is not only a summary, but also includes completely new analyses, explores several new analysis techniques, and includes new combinations.

The second run of the LHC has started, and a dataset of around 4 fb^{-1} of integrated luminosity from proton-proton collisions at the increased center-of-mass energy of $\sqrt{s} = 13$ TeV has been collected in 2015. As the cross sections for the production of heavy particles grows stronger than linearly with the center-of-mass energy, the higher the relevant mass ranges, the stronger the benefit from the increased center-of-mass energy for the expected reach of a search. The first results with the new data will thus come from the strong-production searches, which benefit a lot more from the higher center-of-mass energy as the larger cross sections for strong production allow them to go higher in mass than the electroweak searches. Electroweak searches in general need more data to improve upon with the existing Run-1 results. However, they will be able to build upon lots of experience gained during Run-1, and on the long term will also profit from the higher integrated luminosity to be collected in the three years of Run-2, which is expected to exceed the integrated luminosity from Run-1 by a factor around four.

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