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A statistical combination of ATLAS Run 2 searches for charginos and neutralinos at the LHC

The ATLAS Collaboration

Statistical combinations of searches for charginos and neutralinos using various decay channels are performed using 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector at the Large Hadron Collider. Searches targeting pure-wino chargino pair production, pure-wino chargino-neutralino production, or higgsino production decaying via Standard Model W, Z, or h bosons are combined to extend the mass reach to the produced SUSY particles by 30–100 GeV. The depth of the sensitivity of the original searches is also improved by the combinations, lowering the 95% CL cross-section upper limits by 15%–40%.

Supersymmetry [1–6] (SUSY) proposes a superpartner for every Standard Model (SM) particle, where the spin differs by one-half. It remains one of the more popular beyond the SM theories as it can provide solutions for the hierarchy problem, dark matter, and unification of the fundamental forces [7–10]. Naturalness arguments motivate some SUSY particles to be within reach of the LHC, namely the fermionic superpartners of the gauge and Higgs fields: the charginos $\tilde{\chi}^{\pm}_{1,2}$ and neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$ [11, 12]. The lightest neutralino $\tilde{\chi}^{0}_{1}$ (or the gravitino $\tilde{G}$ in general gauge mediated (GGM) SUSY [13, 14]) is stable in the R-Parity [15] conserving scenarios considered here and is an excellent dark matter candidate [16, 17]. In these scenarios, charginos and neutralinos are produced in pairs at the LHC and decay into the $\tilde{\chi}^{0}_{1}$ or $\tilde{G}$ via SM bosons (where the SM boson decays follow SM branching fractions), assuming other SUSY particles are too heavy to play a role. With the limits on strongly produced SUSY particle masses exceeding ~2 TeV [18], electroweakly produced SUSY particles may dominate LHC SUSY production. Small production cross-sections and decay modes with similar experimental signatures to SM processes make these some of the more challenging searches at the LHC.

The investigation of electroweakly produced SUSY particles by the ATLAS Collaboration [19–22] comprises searches with multiple final states targeting different production and intermediate decay modes. These searches are harmonized to allow for the statistical combination of the results, increasing the sensitivity to SUSY by broadening the mass reach and improving the cross-section reach. Combining results can be particularly powerful when the searches have different, but complementary, sensitivity to the same SUSY models. This letter focuses on the pair production of pure-wino or pure-higgsino next-to-lightest SUSY particles (NLSP) decaying into the lightest SUSY particle (LSP) via a SM boson. The Run 2 electroweak SUSY searches at ATLAS, corresponding to 139 fb^{-1} of pp LHC collision data at a center-of-mass energy of $\sqrt{s}$ = 13 TeV, are statistically combined for each SUSY scenario considered, as reported in Table 1. The CMS Collabration have also performed statistical combinations of their electroweak SUSY searches, found in Ref. [23].

Table 1: The electroweak SUSY production modes considered, along with the multiple decay modes and final states used for the statistical combination.

Production mode	Wino $\tilde{\chi}^{+}_{1}\tilde{\chi}^{-}_{1}$	Wino $\tilde{\chi}^{\pm}_{1}\tilde{\chi}^{0}_{2}$	Wino $\tilde{\chi}^{\pm}_{1}\tilde{\chi}^{0}_{2}$	Higgsino GGM $\tilde{\chi}^{+}_{1}\tilde{\chi}^{-}_{1}, \tilde{\chi}^{\pm}_{1}\tilde{\chi}^{0}_{1,2}, \tilde{\chi}^{0}_{1}\tilde{\chi}^{0}_{2}$
Decay mode	$\tilde{\chi}^{\pm}_{1} \to W^{\pm}\tilde{\chi}^{0}_{1}$	$\tilde{\chi}^{\pm}_{1} \to W^{\pm}\tilde{\chi}^{0}_{1}$ $\tilde{\chi}^{0}_{2} \to Z\tilde{\chi}^{0}_{1}$	$\tilde{\chi}^{\pm}_{1} \to W^{\pm}\tilde{\chi}^{0}_{1}$ $\tilde{\chi}^{0}_{2} \to h\tilde{\chi}^{0}_{1}$	$\tilde{\chi}^{0}_{1} \to Z/h\tilde{G}$
Searches				
All Hadronic [24]	✓	✓	✓	✓
1L [25]	✓	✓		
1Lbb [26]			✓	
2L Compressed [27]		✓		
2L0J $\Delta m > m(W)$ [28]	✓			
2L0J $\Delta m \sim m(W)$ [29]	✓			
2L2J [30]		✓		✓
2τ [31]			✓	
3L [32]		✓	✓	
SS/3L [33]		✓	✓	
4L [34]				✓
Multi-b [35]				✓

To obtain the best sensitivity to a new physics signal through a statistical combination of the individual results, the searches used should be statistically independent and not overlap in their event selection for signal regions (SR) or control regions (CR). Overlap is avoided for the most part by requiring exclusive lepton multiplicity in any search selection, so that 0ℓ, 1ℓ, 2ℓ, 3ℓ, and 4ℓ searches (where $\ell = e, \mu$) are statistically independent. To achieve this, the searches adopted common loose selection criteria[1] at the very start of each analysis, allowing the free use of any further criteria without overlapping with other lepton multiplicities. The *All Hadronic*, *Multi-b*, and *1L* searches found the veto of loose and low-p_T leptons detrimental to signal acceptance. To avoid this, a less stringent veto was adopted,[2] designed to reject events selected by 2ℓ or 3ℓ searches. The *2L Compressed* search used an even looser muon definition, however, the search selection is unique enough to result in orthogonality to the others used in a combination. The harmonization procedure was adopted early in the ATLAS Run 2 search programme and proved to be a keystone of this final combination effort.

The statistical independence of the searches is verified by inspecting the events selected by SRs and CRs in the data and in high statistics simulation of SUSY signals. Significant overlaps are observed between those with equal lepton multiplicity selections, e.g. the *All Hadronic* and *Multi-b* searches, and statistical combinations are not performed for those with $> 10\%$ overlap. In these cases, the search with the best expected sensitivity is used and each instance is discussed for the SUSY models in the following. Otherwise, all SRs used in the combination have zero overlap with other SRs and CRs, while a few CRs have a small $\sim$1%–2% overlap with one another.

Limits are set in SUSY simplified models [38–40] using a combined profile likelihood fit to the observed yields, the estimate of SM background yields, and the expected SUSY yields in the CRs and SRs. Systematic uncertainties are included as Gaussian-distributed nuisance parameters in the likelihood fit and can be correlated between CRs and SRs with common nuisance parameters. The fit parameters are determined by maximizing the product of the Poisson probability functions and the constraints for the nuisance parameters. The compatibility of a signal scenario with the data observation is assessed by accounting for the SUSY signal in all CRs and SRs scaled by a floating signal normalization factor. A signal scenario is excluded if the upper limit at 95% confidence level (CL) of the signal normalization factor obtained in the fit is smaller than that predicted by the cross-section of the scenario [41]. Signal cross-sections are calculated to next-to-leading order in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [42–46]. The nominal cross-section and the uncertainty are taken from an envelope of cross-section predictions using different parton distribution function sets and factorization and renormalization scales, as described in Ref. [47].

The statistical combination for each signal scenario is performed with the PYHF package [48], using inputs produced by the original search (typically using HistFitter [49]), or via the RECAST implementation of the search [50]. The inputs contain information about the yields and uncertainties in the SM background and signal in each CR and SR, as well as the observed data yields. Systematic uncertainties can be set as correlated between searches, where appropriate, by modifying the inputs to share nuisance parameters in the likelihood fit. Theory systematic uncertainties in the SM backgrounds and signal are treated as uncorrelated between searches since each search targets a different final state and parameter space. Experimental systematic uncertainties might be correlated if compatible uncertainty schemes are used by each search to be combined. However, this is not always possible because the searches to be combined span significant updates in particle reconstruction and identification methods, and the related calibrations, preventing the correlation of multiple sources between searches. Additionally, incompatible choices for jet systematic schemes were used in individual searches, preventing the correlation of jet energy scale and resolution uncertainties. Correlating only the allowed sources of experimental systematic uncertainties between

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[1] Electrons must satisfy $p_T > 4.5$ GeV, $|\eta| < 2.47$, $|z_0 \sin\theta| < 0.5$ mm, and “LooseAndBLayerLLH” requirements [36]. Muons must satisfy $p_T > 3$ GeV, $|\eta| < 2.7$, $|z_0 \sin\theta| < 0.5$ mm, and “Medium” identification requirements [37].

[2] Events selected by 0ℓ and 1ℓ searches must have fewer than three leptons passing the common loose selection, and fewer than two satisfying $p_T > 8$ GeV.

searches is found to have a negligible impact on the results. In this letter, statistical combinations are performed with theory and experimental uncertainties uncorrelated between searches.

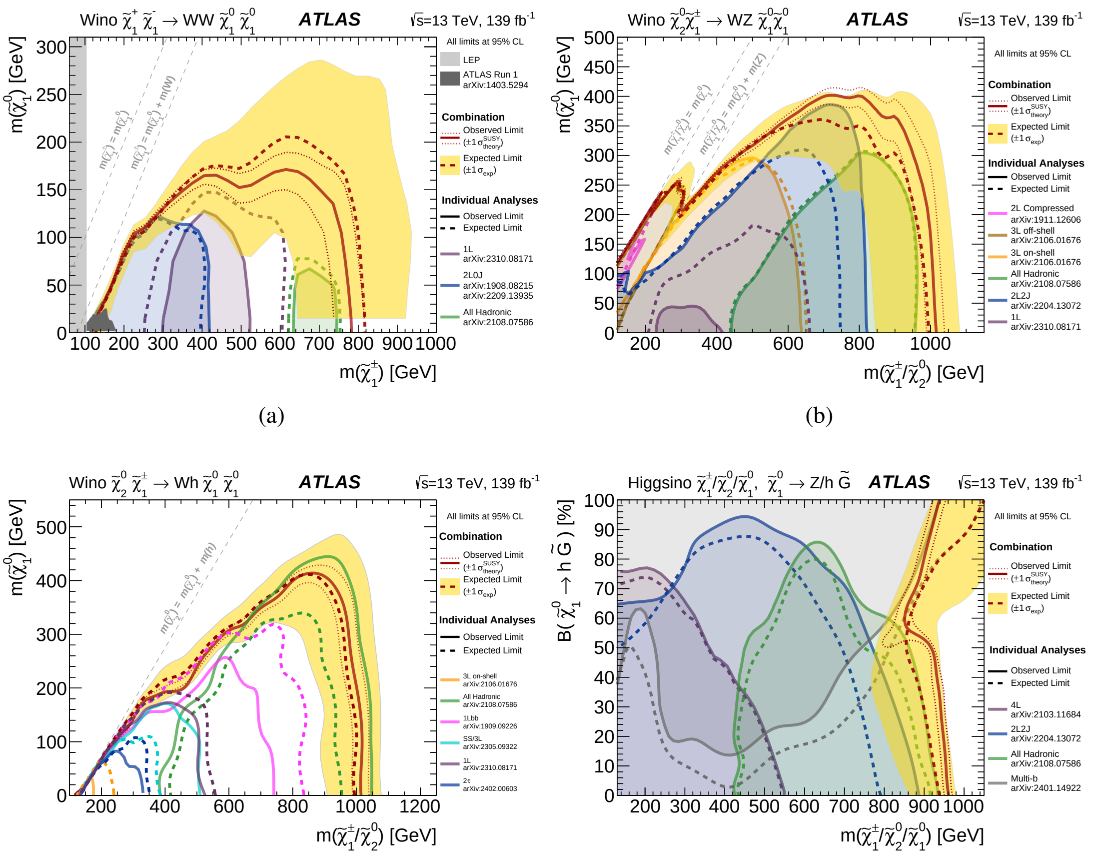
A simplified model of pure-wino chargino-pair production decaying into W bosons and the LSP 100% of the time ($\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^\pm \rightarrow W^\pm\tilde{\chi}_1^0$) can produce final states of $\ell\nu\ell\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\ell\nu qq\tilde{\chi}_1^0\tilde{\chi}_1^0$, or $qqqq\tilde{\chi}_1^0\tilde{\chi}_1^0$. The fully leptonic final state was targeted in two searches: *2L0J* $\Delta m > m(W)$ for moderate NLSP-LSP mass splittings and *2L0J* $\Delta m \sim m(W)$ for smaller mass splittings. The two *2L0J* searches overlap in their selection, so the search with the lowest expected CL value is used in the statistical combination for each signal scenario. The semileptonic and fully hadronic final states were targeted by the *1L* and *All Hadronic* searches, respectively, both of which are statistically independent of one another and the *2L0J* searches. The original exclusion contours in the $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$ parameter space are shown in Figure 1(a), along with that obtained by the statistical combination of the searches. The combination of the search results closes the gaps left by the individual searches, and increases the sensitivity to high $\tilde{\chi}_1^0$ masses, where $\tilde{\chi}_1^0$ masses are excluded up to 150 GeV for a $\tilde{\chi}_1^\pm$ mass of 400–700 GeV. The combination is used to calculate the upper limit on the cross-section for these $\tilde{\chi}_1^+\tilde{\chi}_1^-$ simplified models, where the limits are improved by 20%–30% for $\tilde{\chi}_1^\pm$ masses of 400–800 GeV, compared to the individual searches. Improvements in the upper limit on the cross-section are particularly important for non-simplified SUSY models where the production cross-section and decay branching fractions may be lower than those in simplified models.[3]

A second simplified model is considered consisting of pure-wino, mass-degenerate chargino–neutralino pair production decaying into W or Z bosons and the LSP 100% of the time ($\tilde{\chi}_1^\pm\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm \rightarrow W^\pm\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$). Searches targeting the fully hadronic, semileptonic, and fully leptonic decays of the SM bosons are considered for a statistical combination, as listed in Table 1, where all searches are statistically independent and can be combined. The original exclusion contours in the $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0)$-$m(\tilde{\chi}_1^0)$ parameter space are shown in Figure 1(b), along with that obtained by the statistical combination of the searches. The combination has little impact for small NLSP-LSP mass splittings, where the *2L Compressed* search is uniquely sensitive. However, at larger mass splittings, multiple searches have common sensitivity and the combination is more effective. The exclusion contour is extended for high $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0)$ by around 50 GeV, while the reach to $m(\tilde{\chi}_1^0)$ masses is extended by 40–100 GeV at $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses around 550 GeV and 800 GeV. The upper limit on the cross-section for these simplified models is improved by 20%–40% for $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses of 600–1000 GeV relative to respect to the individual searches alone.

A third simplified model is considered of pure-wino, mass-degenerate chargino–neutralino pair production decaying into W or Higgs bosons h and the LSP 100% of the time ($\tilde{\chi}_1^\pm\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm \rightarrow W^\pm\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$). The *All Hadronic* and *1Lbb* searches target the $h \rightarrow bb$ decay and dominate the sensitivity to these models, while h decays resulting in leptons are targeted using the *SS/3L*, *3L*, and 2τ searches and are sensitive to low mass NLSP production. The *SS/3L* and *3L* searches overlap in their selection, so the search with the lowest expected CL is considered for statistical combination with the other searches for each signal scenario. The original exclusion contours in the $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0)$-$m(\tilde{\chi}_1^0)$ parameter space are shown in Figure 1(c), along with that obtained by the statistical combination of the searches. The combination smooths out the effects of the small observed deficit seen in the *All Hadronic* search and a small observed excess in the *1Lbb* search, with a stronger expected limit for the combination, but a weaker observed limit than the *All Hadronic* search. The exclusion contour is extended up to 30 GeV in $\tilde{\chi}_1^0$ masses for $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses of 300–600 GeV. The combination improves the upper limit on the cross-section for these simplified models by 20%–30% for $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses below 600 GeV compared to the individual searches alone.

[3] Non-simplified SUSY models typically describe mixed wino/higgsino/bino charginos and neutralinos.

A fourth simplified model of almost mass-degenerate,[4] pure-higgsino production is considered ($\tilde{\chi}_1^+\tilde{\chi}_1^-$ / $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ / $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ / $\tilde{\chi}_1^0\tilde{\chi}_2^0$), the higgsino GGM scenarios. The $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ decay into $\tilde{\chi}_1^0$ via off-shell W or Z bosons, which in turn decay into unimportant, low momentum (< 1 GeV) final states. The $\tilde{\chi}_1^0$ decays into an LSP $\tilde{G}$, either with a Z boson or a h boson. The higgsino GGM scenarios are parameterized by the mass of the higgsinos and the branching fraction of the $\tilde{\chi}_1^0$ decay. These signal scenarios are targeted by the *4L*, *2L2J*, and *All Hadronic* searches selecting leptonic or hadronic decays of the Z boson, and by the *Multi-b* search selecting $h \to bb$ decays. The *All Hadronic* and *Multi-b* searches overlap in their selection, so the search with the lowest expected CL is used in the statistical combination. The original exclusion contours in the $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0)$-$\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G})$ parameter space are shown in Figure 1(d), along with that obtained by the statistical combination of the searches. Full coverage of the $\tilde{\chi}_1^0$ branching ratio possibilities is obtained by the individual searches and the combination extends the exclusion by around 60 GeV for high mass higgsino production. The upper limit on the cross-section for these simplified models is improved by 15%–40% for $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G}) < 80\%$ compared to the individual searches alone.



(a) (b)

(c) (d)

Figure 1: The expected (dashed) and observed (solid) 95% CL exclusion limits on (a) chargino-pair production decaying via W bosons, (b) chargino–neutralino production decaying via W and Z bosons, (c) chargino–neutralino production decaying via W and h bosons, (d) higgsino GGM scenarios. The limits are set using a statistical combination of searches targeting each SUSY scenario. Limits obtained by individual searches are overlaid.

[4] In practise, the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are set 1 GeV above the $\tilde{\chi}_1^0$ mass to ensure prompt decays.

Statistical combinations of the Run 2 ATLAS electroweak SUSY searches targeting chargino/neutralino production are performed. Four simplified SUSY models are studied: pure-wino $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production decaying via W bosons, pure-wino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production decaying via W and Z bosons, pure-wino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production decaying via W and h bosons, and higgsino GGM scenarios. The combinations extend the sensitivity to SUSY production up to 100 GeV in NLSP or LSP masses, and the sensitivity to SUSY production cross-sections is increased by up to 40%.

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