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SEARCHES FOR ELECTROWEAK SIGNATURES OF SUPERSYMMETRY AT ATLAS AND CMS

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Searches for strongly-produced superparticles at the Large Hadron Collider have excluded gluinos and squarks of all generations up to the TeV scale. While limited by statistics, electroweak signatures remain less thoroughly explored, and in particular the Higgsino sector has proven challenging. Conventional searches for leptons associated with missing transverse momentum do not fully cover the phase space, requiring new approaches to extend experimental sensitivity. Dedicated reconstruction techniques address the challenge posed by mass-degenerate spectra. By looking beyond the assumption of leptonic signatures, searches for gauge-mediated supersymmetry have broken new ground.

1 Introduction

Supersymmetry (SUSY)[1–6] at low scales has long been considered a leading candidate for new physics within reach of the Large Hadron Collider[7] (LHC). To date, experimental searches have disfavoured the existence of strongly-produced sparticles up to the TeV scale. Sparticles produced via electroweak (EW) processes are less tightly constrained due to various challenges, not least their generally lower production cross-sections.

With naturalness arguments not having delivered their promised bounty, the present goal of the experimental search programme is to "leave no piste unskied". Therefore, this talk reviews the status of conventional searches for electroweak signatures, and describes the approaches used by the ATLAS[8] and CMS[9] collaborations to extend sensitivity where these searches are limited, such as by mass-degenerate SUSY spectra or by reduced decay rates to leptons. Emphasis is placed on new results showing sensitivity to Higgsino production.

1.1 Phenomenology of the SUSY electroweak sector

EW signatures are primarily defined by the phenomenology of the lightest supersymmetric particle (LSP), and the next-to-lightest supersymmetric particle (NLSP). Assuming R-parity conservation,[10] the LSP (typically the lightest neutralino, $\tilde{\chi}_1^0$) is stable and holds neither electric nor colour charge, and is therefore a dark matter candidate. EW NLSPs include the chargino ($\tilde{\chi}_1^\pm$) and neutralino ($\tilde{\chi}_2^0$), respectively electrically charged or neutral mass eigenstates of mixtures between the superpartners of the Standard Model (SM) gauge bosons and the five Higgs bosons expected from a 2-Higgs-doublet model.[11] Alternatively, the NLSP could be a slepton ($\tilde{\ell}$), partnered with the electron, muon or tau lepton.

For EW sparticle masses of a few hundred GeV, the cross-sections are around $\mathcal{O}(0.1) - \mathcal{O}(10)$ fb, comparable to Higgs production cross-sections, and therefore orders of magnitude below significant background sources such as SM diboson production. The specific example of $M_{\rm NLSP} = 500$ GeV implies cross-sections of 22fb for pair-producing charginos that are pure Wino admixtures, but only 6fb for pure Higgsinos.[12,13] Left- (right-)handed sleptons of the same mass have cross-sections of 0.5fb (0.2fb).

2 Conventional searches: multileptons

The traditional signature of at least two high transverse momentum ($p_{\rm T}$) leptons [b] mitigates the drawbacks of a small production cross-section in comparison with the strong processes dominating proton-proton collisions. This motivates the classic strategy of selecting two or more leptons, in conjunction with missing transverse momentum ($\not\!\!E_{\rm T}$) from the invisible LSPs. The most recent analyses of this nature from ATLAS and CMS have been carried out using 36 fb^{-1} of LHC proton-proton collision data collected at a centre-of-mass energy of 13 TeV.[14–17]

In all cases, these searches deal mainly with irreducible backgrounds from SM diboson production, and implement vetos on hadronic jets to mitigate jetty backgrounds such as top-quark pair-production ($t\bar{t}$), where no jets are expected from the signal decay processes. Searches for ≥ 3 leptons may suffer from a high rate of non-prompt or misidentified leptons.

2.1 Searches for slepton production

Searches for slepton production by ATLAS and CMS highlight various interesting experimental methods.[16,18] Besides selecting events with two opposite-sign, same flavour leptons and no jets, a veto is applied to events whose dilepton mass $M_{\ell\ell}$ falls within the Z mass window. A minimum $M_{\ell\ell}$ cut is also applied to remove dileptons from light hadronic resonances. Further sensitivity is achieved by utilising the "stransverse mass" or $M_{\rm T2}$ variable.[19,20] This observable effectively separates signal from background by assuming that the event arises from the pair-production of two heavy objects that each decay to a visible (lepton) and an invisible (neutrino or neutralino) particle, and uses the $\not\!\!E_{\rm T}$ constraint to place a lower bound on the parent particle mass. The CMS analysis applies a simple cut at 90 GeV to substantially reduce the dominant WW background, as a kinematic endpoint in $M_{\rm T2}$ exists for this process at the W mass, then defines signal regions (SRs) in $\not\!\!E_{\rm T}$. ATLAS, in contrast, uses bins at large $M_{\rm T2}$.

For many of the background processes, background estimation is possible using Monte Carlo simulated events, whose normalisation is constrained by auxiliary measurements of data in control regions. CMS utilises a data-driven "flavour symmetry" method for the two major residual background components of $t\bar{t}$ and WW production. In these processes, the rate of ee and $\mu\mu$ events with the selected kinematics is identical to that of $e\mu$ events, up to corrections for different reconstruction and particle identification efficiencies for the two lepton flavours.

In Figure 1, the flavour symmetry approach is shown to accurately reproduce the data in the signal region, demonstrating the effectiveness of the method, albeit also revealing the lack of any supersymmetric signal. The same figure shows the constraints placed by this search on the masses of sleptons and the LSP, in a simplified model scenario where only production of mass-degenerate left- and right-handed selectrons and smuons is assumed. For light LSPs, the expected (observed) exclusion reach is 500 (450) GeV. Slepton production may be excluded for LSP masses up to 220 GeV. Similar sensitivity is shown by the ATLAS dilepton search channels, which also employ the $M_{\rm T2}$ variable.[16]

Searches for staus occupy a particular niche within the slepton analyses. While many of the same approaches apply to defining the searches, the dominant hadronic tau decay modes are more difficult to differentiate from other hadronic jets, reducing the signal purity. To address

[b] Typically, "lepton" is used to refer only to the electron and muon, with tau leptons being mentioned explicitly.

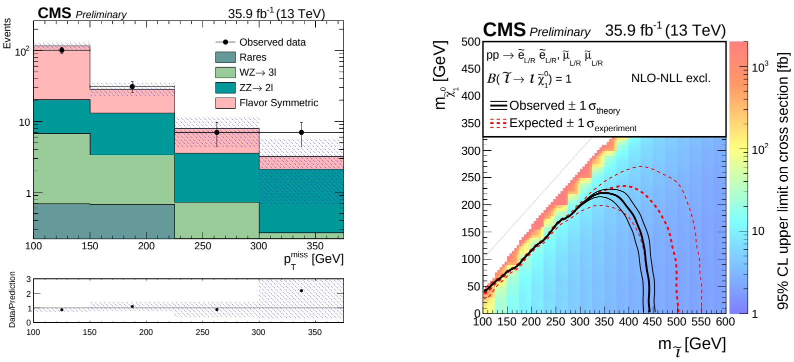

Figure 1 – Left: Signal region $\not{E}_T$ distribution for the CMS slepton search,[18] showing the use of the "flavour symmetry" method to estimate the dominant backgrounds. Right: Limits placed on the slepton and LSP masses, in a simplified model assuming mass-degenerate left- and right-handed selectrons and smuons.

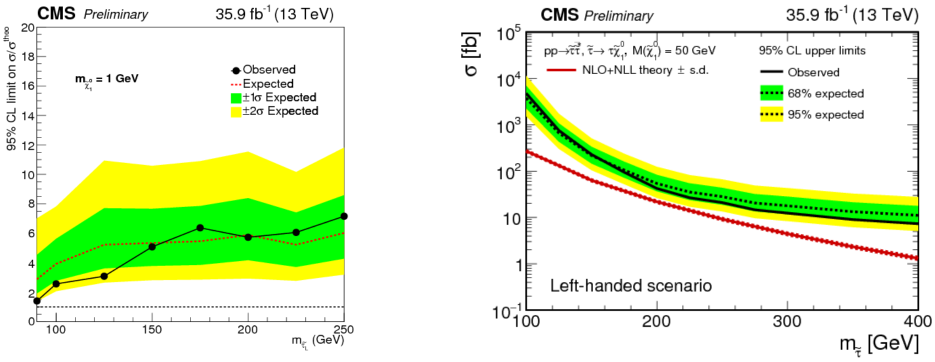

Figure 2 – Limits placed on stau production cross-sections by CMS analyses in channels considering at least one leptonic decay of the taus[23] (left) or doubly hadronic tau decays[24] (right).

this, both ATLAS and CMS have invested significantly in optimising tau reconstruction and identification for LHC Run 2.[21,22] CMS has searched for stau production in channels considering all decay modes of the two taus.[23,24] Due to the low purity, exclusion sensitivity to the nominal stau production cross section has not yet been reached, as shown in Figure 2, but overall, the doubly hadronic decay channel is seen to be more sensitive.

2.2 Searches for charginos and neutralinos

Chargino/neutralino decay modes are less constrained than those of sleptons. Different-flavour dileptons or more than two leptons can be produced. The decay chain may feature on-shell Z bosons, allowing a very clean signature to be identified. However, the rates of purely leptonic final states are diluted due to the propensity of SM bosons to decay to hadrons.

It is possible to carry out searches for chargino pair-production with a very similar approach to the slepton analyses, as exemplified by a recent CMS result.[25] This strategy is effective when assuming 100% chargino decays to leptons via an intermediate slepton or sneutrino, but sensitivity to W-mediated decays is more modest.

Surveying the searches for a wide range of chargino/neutralino decays depicted in Figure 3,[26,27] a few observations are possible. Firstly, for slepton-mediated decays, exclusion sensitivity is achieved for NLSP masses up to nearly 1150 GeV in the limit of massless LSPs. However,the lack of coverage at large LSP masses illustrates how "compression" of the SUSY mass spectrum poses a challenge for experimental sensitivity due to the limited visible final state energy. Constraints are also much weakened when allowing the electroweakino NLSPs to decay via SM bosons. These observations have motivated new analyses that address the challenge of

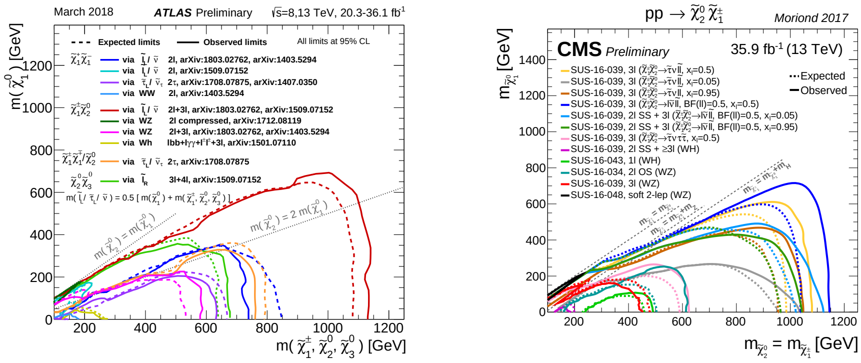

Figure 3 – Overview of current exclusion limits on production of charginos and neutralinos in different search channels using LHC data, shown in the plane of the parent and LSP masses. Left: ATLAS limits on pair-production of charginos or neutralinos, or associated chargino-neutralino production using 8 and 13 TeV data.[26] Right: CMS limits on associated chargino-neutralino production using 13 TeV data.[27]

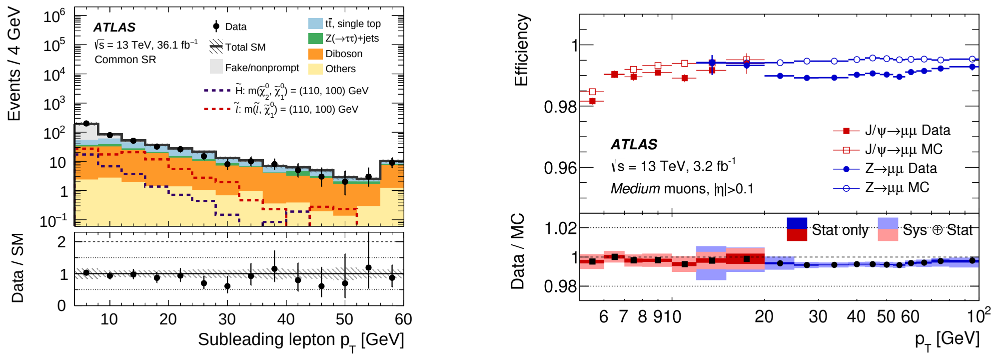

Figure 4 – Left: Subleading lepton transverse momentum spectrum for SM processes and Higgsino or slepton NLSPs with a mass of 110 GeV decaying to a 100 GeV LSP.[32] Right: Efficiency as a function of transverse momentum for reconstructing and identifying muons in ATLAS, measured in simulation and in data using $Z \to \mu\mu$ and $J/\psi \to \mu\mu$ decays.[29]

compressed signal scenarios and challenge the assumption of leptonic signatures.

3 Searches for compressed supersymmetric states

In EW SUSY signal scenarios with compressed mass spectra, leptonic signatures may still be present, but the phase space available to the leptons is severely reduced, as illustrated in Figure 4. This has necessitated special procedures for reconstructing and calibrating soft leptons in both ATLAS and CMS.[28–31]

Searches using soft leptons have been published by both collaborations.[32,33] Leptons with transverse momenta as low as 4-5 GeV can be reconstructed offline, but triggering on these soft leptons is a challenge, although soft dimuon triggers are employed in the CMS search. Due to the large NSLP mass scale, hard ISR jets can be emitted, boosting the entire sparticle system. The heavy LSPs carry away most of the momentum, facilitating a $\not{E}_{\mathrm{T}}$ trigger selection as an alternative to lepton triggers. Other analysis techniques common to ATLAS and CMS include vetos on b-tagged jets, as a major source of soft leptons.

For the final signal-background discriminants, a variety of observables are used: M_{T2} for sleptons, a large ratio of the $\not{E}_{\mathrm{T}}$ to the total visible transverse momentum, or finally structures in the $M_{\ell\ell}$ spectrum, as demonstrated in Figure 5. Analysis of the $M_{\ell\ell}$ spectrum in these signal regions requires vetos on the mass ranges associated with light hadronic resonances such as J/ψ and Υ. Unlike in conventional searches, the signal inhabits ranges well below those

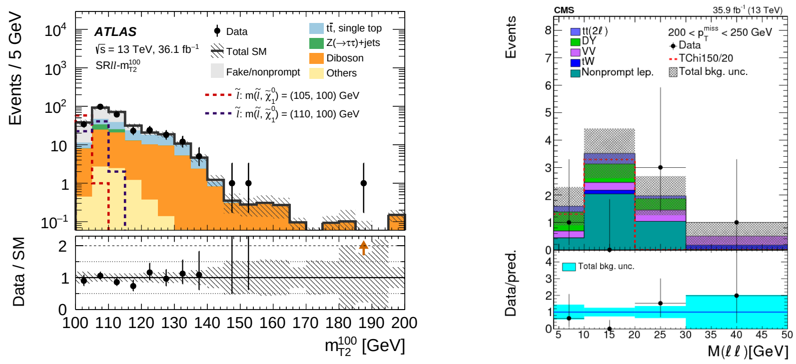

Figure 5 – Discriminating variable distributions used in searches for compressed electroweak SUSY by ATLAS and CMS. Left: Stransverse mass M_{T2} distribution in ATLAS compressed slepton signal regions.[32] Right: Dilepton invariant mass distribution in CMS signal regions in a search with soft leptons.[33]

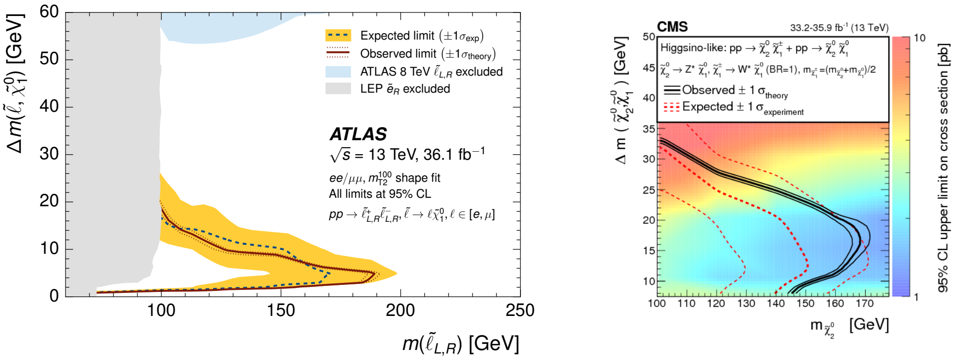

Figure 6 – Limits placed on compressed electroweak SUSY models by using searches with soft leptons, shown in the plane of the NLSP mass and the NLSP-LSP mass splitting.[32,33] Left: ATLAS limits on compressed sleptons. Right: CMS limits on compressed Higgsinos.

typical for the SM background processes. Another important aspect of these analyses is that non-prompt and misidentified leptons make up a major background component, necessitating careful estimation using data-driven methods. These specialised searches extend the limits on slepton, Wino and Higgsino production to NLSP-LSP mass splittings of $\mathcal{O}(10\ \mathrm{GeV})$, for NLSP masses below 150-200 GeV as shown in Figure 6.

Even more unconventional reconstruction is needed for the extremely compressed spectra that can arise in models of Anomaly-Mediated Supersymmetry Breaking (AMSB).[34,35] In such scenarios, a general expectation is that the chargino NLSP is only separated by $\mathcal{O}(100\ \mathrm{MeV})$ from the LSP, and therefore undergoes a non-prompt decay to a soft pion and the LSP, with a typical lifetime of $\mathcal{O}(0.1\mathrm{ns})$, implying that a chargino produced with some boost can travel several centimetres from the interaction point before decaying.[36] Searches have been carried out for this unique “disappearing track” signature by reconstructing “tracklets” with a series of hits in the inner tracking layers but none in the outer layers.[37,38]

These analyses rely on robust data-driven estimates of the rates of fake tracklets, which can originate from genuine hadron or lepton tracks that are bent by nuclear interactions or photon emission, or from random combinations of nearby hits. As in the searches with soft leptons, triggering is accomplished using $\not{E}_{\mathrm{T}}$ triggers benefiting from ISR jet emission. Both ATLAS and CMS produce limits on charginos in the AMSB scenario, featured in Figure 7. Due to different choices in the tracklet reconstruction, the CMS analysis has peak sensitivity for proper lifetimes of a few nanoseconds, while the ATLAS analysis is better tuned for sub-nanosecond lifetimes, successfully excluding pure Higgsinos with masses below 152 GeV.[39]

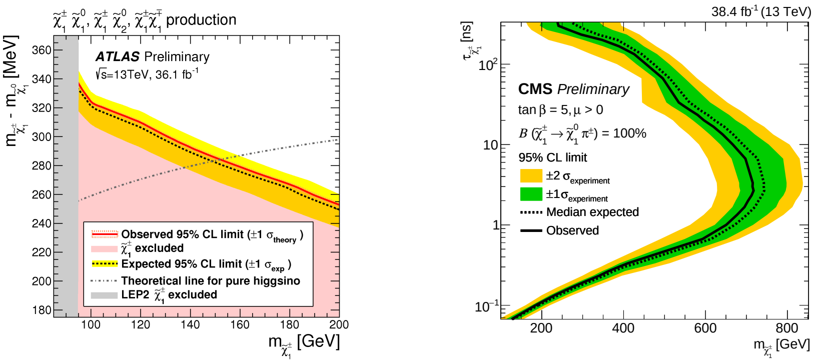

Figure 7 – Exclusion limits on long-lived charginos in AMSB scenarios from searches for disappearing tracks.[37–39] Left: Limits set by ATLAS, shown in the plane of the NLSP-LSP mass splitting versus the chargino mass. Right: CMS limits, shown in the plane of the sparticle lifetime versus the chargino mass.

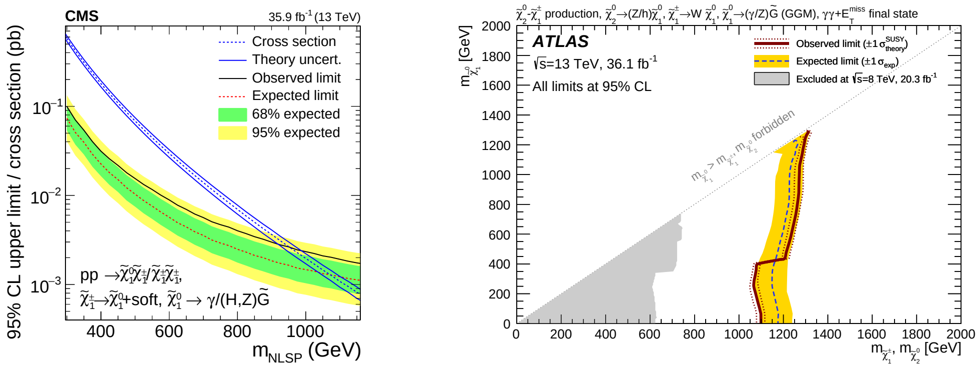

Figure 8 – Exclusion limits on GMSB models from searches in photonic final states, where the lightest neutralino is a pure Bino.[42,43] Left: CMS limits on the cross-section of chargino pair-production or associated chargino-neutralino production with the lightest neutralino and chargino being mass-degenerate. Right: ATLAS limits presented in the mass plane of the lightest neutralino versus the mass-degenerate lightest chargino and second-lightest neutralino.

4 Searches without leptons

New search channels have been realised by stepping beyond the boundaries of leptonic signatures. Gauge-Mediated Supersymmetry Breaking (GMSB) models in particular motivate the investigation of photonic or purely hadronic final states.[40,41] A characteristic feature of GMSB is a keV-scale gravitino LSP, which eliminates the possibility of a compressed mass spectrum. The lightest neutralino can then be the LSP, its mixings determining the precise signature.

Pure Bino NLSPs typically decay producing a high p_T photon, the subject of searches by CMS and ATLAS.[42,43] Because both of the Bino decay products are massless, the combination of one or two energetic photons and large $\not{E}_T$ suffices to extract a signal. This can be seen from the ATLAS and CMS limits in Figure 8, in which it is assumed that the production process features the heavier $\tilde{\chi}_1^{\pm}$ and/or $\tilde{\chi}_2^0$ due to the low rate of Bino direct production. The limits from both experiments are seen to be consistent, and are sensitive only to the production cross-section, but not to other mass scales that would affect the kinematics of additional jets and leptons in the final state.

Finally, all-hadronic final states have become of interest particularly in the context of Higgsino production. Both CMS and ATLAS have exploited the multi-b topology in searches that reconstruct two Higgs bosons accompanied by large $\not{E}_T$ from the light gravitino LSP.[44,45] Reconstruction of Higgs candidates from high-mass Higgsinos in the ATLAS analysis is done by pairing nearby b-tagged jets, based on the expectation that the Higgs bosons will be somewhat

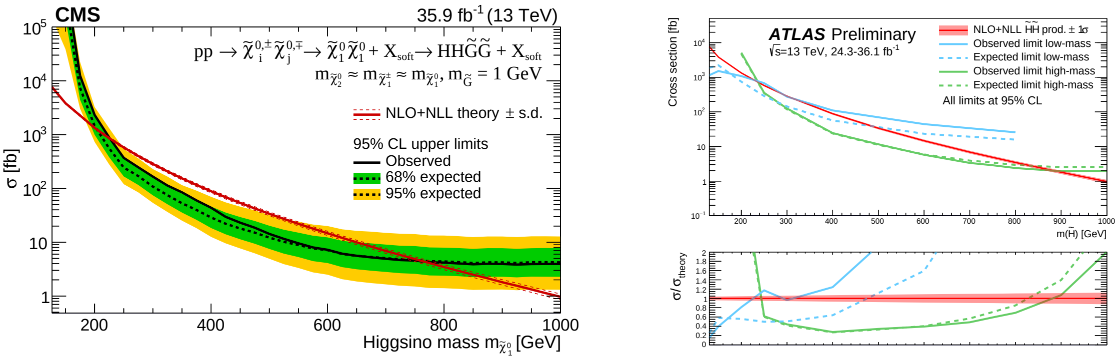

Figure 9 – Exclusion limits on Gauge-Mediated Supersymetry Breaking models from searches in fully hadronic final states, where the lightest neutralino is a pure Higgsino, using data from CMS[44] (left) and ATLAS[45] (right). Limits on the production cross-section are displayed, with the ATLAS plot showing the contributions of selections optimised for low and high Higgsino masses separately.

boosted, and hence their decay products will be collimated. In the CMS analysis, as well as in the ATLAS dedicated low-mass selection, the Higgs candidates are instead identified by minimising the mass difference between the candidate jet pairs. The ATLAS low-mass analysis further accounts for possible biases in the mass peak position. Top pair-production being the dominant source of background with multiple b-tagged jets, an explicit reconstruction of and veto on top pairs is executed in both searches. Remaining background contributions are assessed using side bands and control regions, with the ATLAS low-mass estimate employing a BDT reweighting of 2-b-tag data to the 4-b-tag signal region.

Figure 9 shows the resulting exclusion limits. Higgsinos with masses up to 890 GeV are excluded, with the ATLAS low-mass optimisation proving crucial for closing the gap at Higgsino masses below 200 GeV.

5 Conclusions

Having analysed up to 36 fb^{-1} of LHC Run 2 data, the ATLAS and CMS collaborations have made substantial inroads in the search for electroweak signatures of supersymmetry. Conventional searches for multilepton signatures are well developed and provide some of the strongest bounds on chargino and neutralino production. More challenging searches for compressed mass spectra have been implemented thanks to refinements in soft electron and muon reconstruction, and more exotic methods have been employed to achieve sensitivity to sparticles with $\mathcal{O}$(100 MeV) degeneracies. Sensitivity to pure Higgsino production is beginning to be achieved, aided by the use of non-leptonic and in particular fully hadronic final states. Yet, weak-scale SUSY might still be hiding in the form of the stau.

Acknowledgments

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