Electroweak SUSY production searches at ATLAS and CMS

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The discovery of weak-scale supersymmetric (SUSY) particles is one of the primary goals of the Large Hadron Collider experiments. Depending on the mechanism of SUSY breaking, it could be that strongly interacting squarks and gluinos are too massive to produce at the LHC. In this case, the primary SUSY production mode is of charginos, neutralinos and sleptons, mediated by electroweak interactions. However, the experimental signatures for discovery vary widely, depending on the mass hierarchy, SUSY particle mixing parameters and conservation/violation of R-parity, necessitating a large and complex suite of experimental search strategies. These strategies include searching for events with multiple charged leptons, photons, reconstructed higgs bosons or new long-lived particles. In this presentation, the latest ATLAS and CMS search results in these channels are presented, based mainly on 20 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV collected in 2012. The resulting constraints on the parameter spaces of various SUSY models are shown.

1 Introduction

The apparent shortcomings of the Standard Model (SM) as a final theory of nature have prompted many searches for the production of non-SM particles in high-energy particle collisions. A great number of these have been inspired by the invention of supersymmetry (SUSY), which, if realised at the TeV scale, would allow a vast range of new particles to be produced and discovered at the LHC. To date, no such discovery has been made, resulting in very powerful constraints on the production of strongly interacting SUSY particles (the squarks and gluino) in particular. This motivates the separate consideration of electroweak (EW) SUSY particle production, that is, direct production of particles that have no colour charge. These comprise the charged sleptons ($\tilde{\ell}$) and sneutrinos ($\tilde{\nu}$), partners of the SM leptons, together with the partners of the electroweak gauge bosons (bino $\tilde{B}$ and winos $\tilde{W}$) and Higgs bosons (higgsinos $\tilde{H}$). The mixing between bino, wino and higgsino states produces in total four neutralinos $\tilde{\chi}^0_{1..4}$ and two

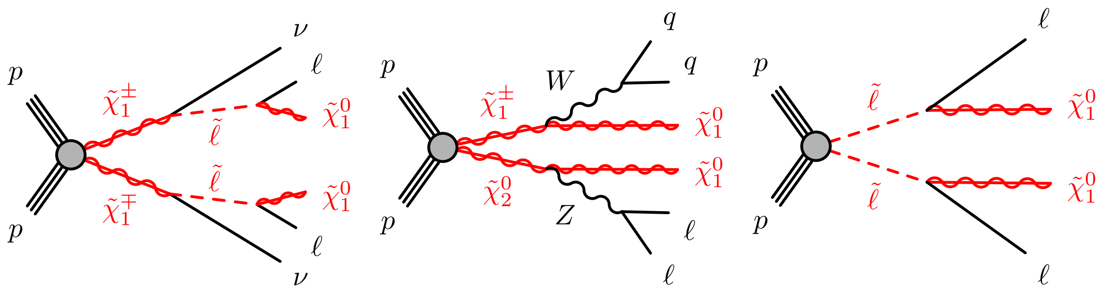

Figure 1: Example two-lepton signatures arising from chargino, neutralino and slepton production.

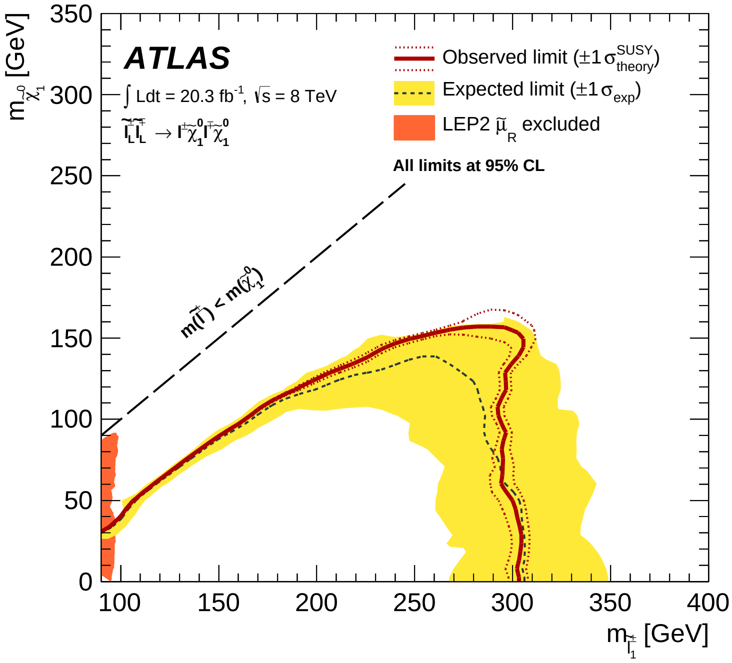

Figure 2: Limits on the direct production of the SUSY partners of left-handed leptons (see Fig. 1 (right)) from the ATLAS two-lepton search [3]. The parameter space below the thick solid line is excluded at the 95% confidence level (CL). The dashed line shows the median expected exclusion reach, while the shaded band indicates the expected $\pm 1\sigma$ variation. The constraint on $\tilde{\mu}_{\rm R}$ production from LEP is also indicated.

charginos $\tilde{\chi}^{\pm}_{1,2}$ as physical mass eigenstates.

Most searches for SUSY at the LHC additionally assume R-parity conservation. This implies that EW SUSY particles are produced in pairs and decay, either directly or via a cascade, to the stable lightest SUSY particle, or LSP. In all of the models described here, the LSP is either the least massive neutralino ($\tilde{\chi}^0_1$) or the gravitino ($\tilde{G}$), the SUSY partner of the graviton. The LSPs escape the detector unseen, producing missing transverse momentum ($E_{\rm T}^{\rm miss}$), while the decays to the LSP produce visible SM particles that can be used to trigger and select SUSY events. Depending on the SUSY model parameters, SM fermions, gauge bosons and Higgs bosons can all be produced in EW SUSY particle cascades, producing a wide variety of potential experimental signatures.

This note presents a selection of the most recent searches for EW SUSY particle production at the LHC by the ATLAS [1] and CMS [2] collaborations. All of the searches use the full dataset collected in pp collisions in 2012, amounting to about 20 fb^{-1} per experiment. The searches are presented in three sections. The first two differ mainly in the assumed nature of the LSP: neutralino (usually bino-like) or gravitino. In the final section, searches for stable or metastable SUSY particles are considered, which yield distinct experimental signatures that demand dedicated techniques for their discovery.

2 Searches assuming a neutralino LSP

One of the most promising ways to discover EW SUSY production at the LHC is through the detection of events with multiple charged leptons. The leptons could be produced in a number of ways. For example, charginos and neutralinos may produce sleptons or gauge bosons in their decays, and charged sleptons may also be produced directly if they are sufficiently light. Examples of these processes yielding two charged leptons are shown in Fig. 1.

These topologies are the target of a recent ATLAS search for events with two electrons or muons and anomalously large $E_{\rm T}^{\rm miss}$ [3]. Direct slepton production results in two leptons of the

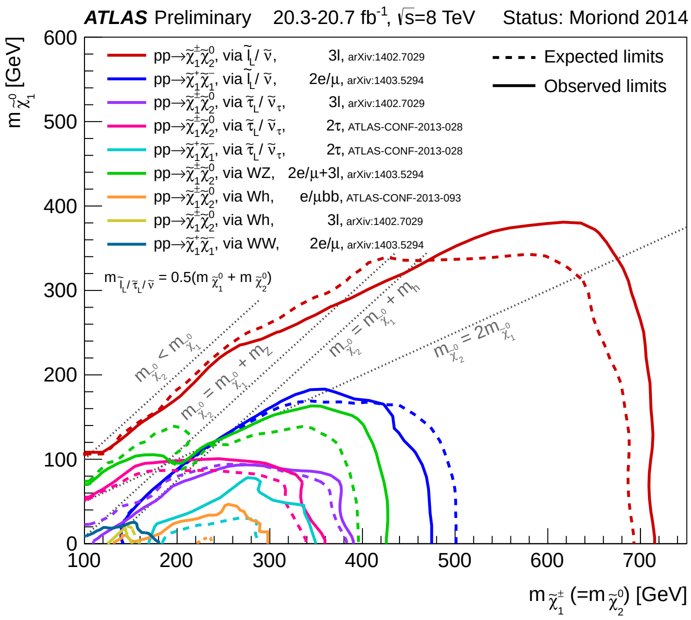

Figure 3: Summary of ATLAS searches for chargino and neutralino production in multiple channels [4]. The areas below the solid curves are excluded at the 95% CL, while the corresponding dashed lines show the median expected exclusion limits.

same flavour (e^+e^- or $\mu^+\mu^-$) and two LSPs. To detect these, the stransverse mass variable m_{T2} is used to reject SM WW diboson production and $t\bar{t}$ events, as it has a kinematic edge at the W mass for these processes. With no significant excess of events observed, constraints are placed on the allowed slepton and LSP masses, shown in Fig. 2 in the case of mass-degenerate $\tilde{e}_{\mathrm{L}}$ and $\tilde{\mu}_{\mathrm{L}}$. Slepton masses of up to 325 GeV are excluded in this scenario.

The same analysis also constrains chargino pair production, where the charginos may decay either via sleptons (Fig. 1 (left)) or via $\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0 \to \ell^{\pm}\nu\tilde{\chi}_1^0$. The latter is targeted using dedicated selections, optimised for a $W^{\pm}W^{\mp}$-like event topology. Finally, a two-lepton region requiring leptons consistent with a $Z \to \ell\ell$ decay targets the signature shown in Fig. 1 (middle).

ATLAS has also published a complimentary search in the three-lepton channel, which improves on earlier preliminary results on the same dataset [5]. A binned signal region increases the sensitivity of the analysis to lepton-rich final states across a wide range of SUSY models. Additionally, selected events may contain up to two hadronically decaying τ leptons, improving sensitivity to models where the $\tilde{\tau}_1$ is light and events with Higgs bosons in the final state.

Constraints on chargino and neutralino production from both of these analyses, and several others, are summarised in Fig. 3. Considering only direct (wino-like) $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production, the strongest constraints are set by the three-lepton analysis if they decay flavour-democratically via sleptons. Chargino and neutralino masses of up to 700 GeV can be excluded in the best cases. This limit is weaker, but still significant ($m \lesssim 380$ GeV) if decays proceed mainly via tau sleptons. Both the two- and three-lepton searches are sensitive to the process $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to WZ\tilde{\chi}_1^0\tilde{\chi}_1^0$, and the results are statistically combined to exclude chargino and neutralino masses of up to 420 GeV if this is the only available decay channel. Comparable constraints on all of these models are reported in preliminary multi-lepton searches from the CMS collaboration [6].

If the $\tilde{\chi}_2^0$ decays mostly into $h\tilde{\chi}_1^0$, the signal-to-background ratio is reduced with respect to the other channels. In both ATLAS and CMS, the three-lepton final state (with, *e.g.* $h \to \tau\tau$) has some sensitivity at low chargino and neutralino masses, but the strongest constraint comes from the $eb\bar{b}/\mu b\bar{b}$ channel[7,8]. Figure 4 (left) shows how the $b\bar{b}$ invariant mass can be used to select SUSY events with a Higgs boson, with a yield nearly independent of $m_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0}$ for an assumed LSP mass of 1 GeV. The resulting constraints on the chargino and neutralino masses are shown

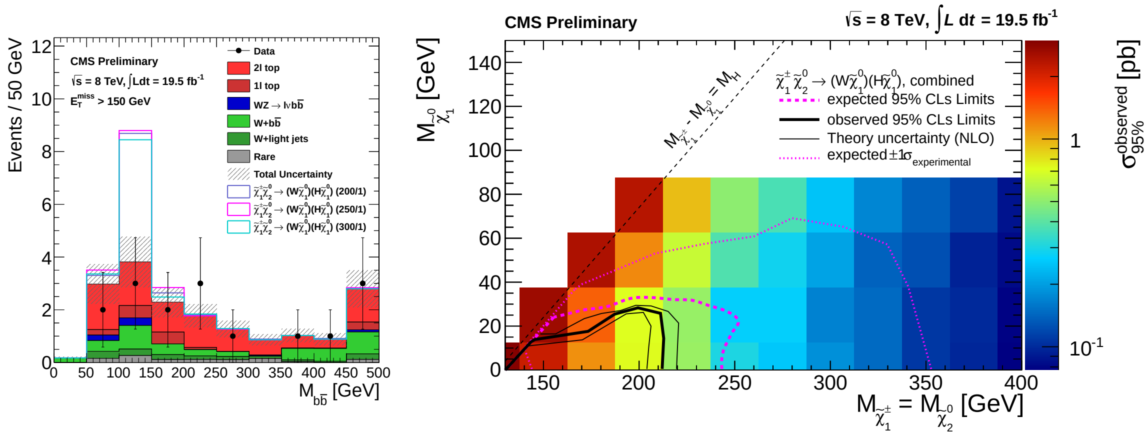

Figure 4: Results for the CMS search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow Wh\tilde{\chi}_1^0\tilde{\chi}_1^0$ production [7]. Left: $b\bar{b}$ pair mass distribution, showing data points compared to the background prediction (shaded, stacked histograms) and three signal models (unshaded histograms). Right: 95% CL limits on the production cross-section as a function of the SUSY particle masses. The observed and expected exclusion limits as a function of mass, assuming wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production is also shown.

in Fig. 4 (right) for CMS and in Fig. 3 for ATLAS.

3 Searches assuming a gravitino LSP

Even restricting attention to SUSY models where R-parity is conserved, the LSP need not be a neutralino. It may instead be the gravitino, which in theories with gauge-mediated SUSY breaking is predicted to very light, essentially massless relative to LHC kinematic scales. As couplings to the gravitino are very weak, SUSY particles generally cascade to the next-to-lightest SUSY particle, or the NLSP. The NLSP then decays to its SM partner and a gravitino, and thus the nature of the NLSP largely defines the observable signature in pp collisions. Sometimes the signatures covered in Sec. 2 are still produced, for example $\tilde{\ell} \rightarrow \ell\tilde{G}$ can mimic $\tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$ when the $\tilde{\chi}_1^0$ is massless, but in other cases alternative signatures can be enhanced.

The neutralinos are mixtures of bino, wino and higgsino states, and therefore a neutralino NLSP will produce a photon, Z boson or a Higgs boson when it decays. If the NLSP is bino-like, there will be a significant branching fraction to photons, a fact exploited by an ATLAS search in the diphoton final state [9]. Separate search regions are defined for strong and EW SUSY production. For EW production, additional leptons and/or jets are not required, but neither are they vetoed, ensuring sensitivity to a variety of production processes and SUSY cascade decays. The scalar p_{T} sum of photons, leptons and jets (called H_{T}) is used to suppress SM background processes, together with the $E_{\mathrm{T}}^{\mathrm{miss}}$ and various angular requirements on reconstructed objects. Using data-driven techniques to estimate the main backgrounds, wino-like $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ particles that decay directly to the NLSP are excluded for massess less than 570 GeV.

Another limiting case occurs when the NLSP is higgsino-like. If the wino and bino mass parameters are sufficiently high, the $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ are nearly degenerate in mass, and the $\tilde{\chi}_1^0$ decays to a Higgs boson and a gravitino, illustrated in Fig. 5 (left). The Higgs boson decays primarily to $b\bar{b}$, and so the dominant final state is $4b + E_{\mathrm{T}}^{\mathrm{miss}}$. This is probed by a CMS search looking for 4-jet events with multiple b-tagged jets and significant $E_{\mathrm{T}}^{\mathrm{miss}}$ [10]. Higgs boson candidates are constructed by forming two pairs of jets with the smallest absolute difference in dijet mass (m_{jj}), with no explicit mass constraint to avoid biasing the background shape. After construction of the candidates, the average mass of the two jet pairs is required to lie between 100 and 140 GeV. The dominant semileptonic $t\bar{t}$ background is estimated using an ABCD-like method. A slight excess in the data ($< 2\sigma$) prevents exclusion of a higgsino-like NLSP for any mass, as shown in Fig. 5 (right).

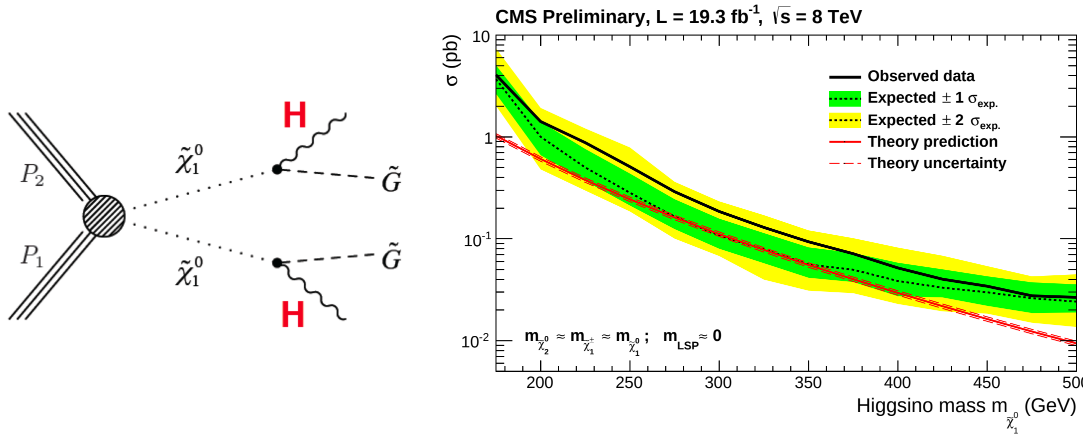

Figure 5: Left: Illustration of di-Higgs boson production in SUSY models with a gravitino LSP. Right: 95% CL cross-section limits on this process from a search by CMS for events with at least 2-4 b-jets [10]. The solid line indicates the observed exclusion limit, while the thin dashed line shows the median expected limit, surrounded by $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands. The theoretically predicted cross-section for higgsino-like chargino and neutralino production is shown for comparison.

If the NLSP is a slepton, events with large numbers of charged leptons in the final state will be common. For example, charginos and neutralinos production could lead to the following cascade: $\tilde{\chi}_1^0 \to \ell\tilde{\ell}_{\rm R} \to \ell\ell\tilde{G}$. Additionally, mixing in the stau sector suggests that the $\tilde{\tau}_1$ may be less massive than the other sleptons, opening up the possibility for a lepton-rich cascade such as $\tilde{\ell}_{\rm R} \to \ell\tau\tilde{\tau}_{\rm R} \to \ell\tau\tau\tilde{G}$. CMS has placed constraints on these models by searching for events with at least three charged leptons, including up to one hadronic τ decay [11]. Candidate events are separated into a large number of exclusive channels depending, amongst other things, on $E_{\rm T}^{\rm miss}$, the presence of a Z boson candidate, and the number of identified b-jets. In the case of charginos and neutralinos decaying to degenerate $\tilde{e}_{\rm R}$, $\tilde{\mu}_{\rm R}$ and $\tilde{\tau}_{\rm R}$ co-NLSPs, chargino masses below about 850 GeV are excluded at the 95% confidence level (CL). When first- and second-generation sleptons decaying to a $\tilde{\tau}_1$ NLSP are considered, a 3σ excess is observed in data, weakening the observed limit compared to expectation. However, this excess is not statistically significant when the large number of search channels is taken into account.

4 Searches for metastable or stable SUSY particles

The searches described so far assume that all SUSY particles except the LSP decay promptly at the primary interaction vertex, with decay lengths $\lesssim \mathcal{O}(1\ \mathrm{mm})$. This assumption may not be correct, as, for example, extremely degenerate SUSY spectra could lead to metastable particles with phase-space-suppressed decays. Alternatively, a SUSY particle that can only decay via extremely weak couplings may also travel a macroscopic distance before decaying. Such interactions could be gravitational (*i.e.* decays to a $\tilde{G}$ LSP) or an R-parity-violating decay of the LSP, to give two examples. Events with stable charged particles or SUSY particles decaying within the detector volume will typically be mis-reconstructed or explicitly vetoed by conventional analyses; special reconstruction and identification techniques are usually required to detect these signatures.

The CMS search for heavy stable charged particles (HSCPs) [12] reconstructs detector-stable charged particles as massive muons, combining information from both the inner tracker and the muon system. These tracks are selected using three main variables: the track $p_{\rm T}$, the time-of-flight measurement in the muon system, and the anomalously large ionisation charge deposited in the inner tracker. The ionisation measurement is also used to estimate the particle's mass. In models with gauge-mediated SUSY breaking, a $\tilde{\tau}_1$ NLSP can be long-lived. Using this search, detector-stable $\tilde{\tau}_1$ particles with masses below 339 GeV are excluded at the 95% CL, assuming

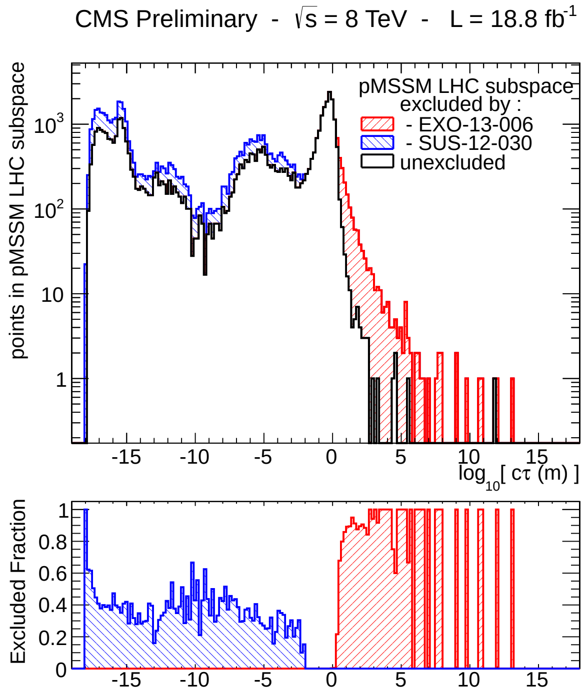

Figure 6: Constraints from multiple CMS searches on pMSSM models, displayed as a function of the decay length of the lightest chargino [13]. The number (top) and fraction (bottom) of excluded models are shown by shaded regions, with the red region corresponding to the search for heavy stable charged particles [12].

only their direct pair production.

The HSCP analysis has also been used to constrain the parameter space of the phenominological minimal supersymmetric SM (pMSSM) with a $\tilde{\chi}_1^0$ LSP [13]. In a significant portion of the parameter space, the lightest chargino is nearly degenerate with the LSP and therefore detector-stable. Figure 6 shows the distribution of the $\tilde{\chi}_1^\pm$ decay length within the models considered, together with the fraction excluded by the HSCP search and more conventional prompt SUSY searches. The latter were only considered when $c\tau < 10$ mm, the HSCP search extends this by excluding a large fraction of models with $c\tau > 1$ m.

Intermediate chargino lifetimes are probed by an ATLAS search for "disappearing" tracks [14]. If the $\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ mass difference is $\mathcal{O}(160$ MeV), the chargino lifetime will be of the order of a nanosecond, *i.e.* decay lengths $\mathcal{O}(30$ cm). In this regime, the dominant chargino decay mode is $\tilde{\chi}_1^\pm \rightarrow \pi^\pm\tilde{\chi}_1^0$. The small mass splitting makes the pion too soft to reconstruct, and thus the track from the $\tilde{\chi}_1^\pm$ appears to end abruptly where it decays. Events are triggered using one or more jets radiated from the initial state partons, together with the $E_{\mathrm{T}}^{\mathrm{miss}}$ associated with the SUSY LSPs. A modified track reconstruction algorithm optimised for short tracks is used to increase the efficiency of SUSY signal events, which can be seen in Fig. 7 (left) as a function of the $\tilde{\chi}_1^\pm$ decay position. Charginos which decay less than 300 mm from the beam pipe are not reconstructed, as there are too few measurements to sufficiently constrain the transverse momentum measurement. Tracks from charginos which decay at radii greater than about 700 mm are difficult to differentiate from hadron tracks, which leads to a falling efficiency in this region. The observed data are consistent with the data-driven background model, and Figure 7 (right) shows the resulting constraints from this analysis on the mass of a long-lived chargino, as a function of its lifetime within the range where the $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0\pi^\pm$ decay is kinematically accessible. The analysis is most sensitive to $\tilde{\chi}_1^\pm$ lifetimes between 1 and 10 ns, where chargino masses of up to approximately 500 GeV are excluded.

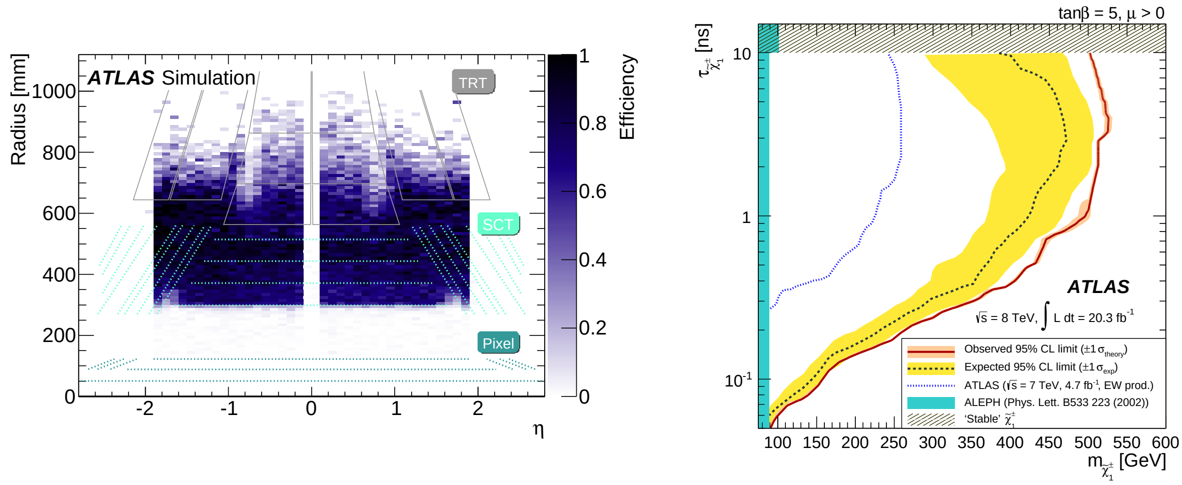

Figure 7: Left: Efficiency for reconstruction in ATLAS of "disappearing" tracks as a function of pseudorapidity and the radius at which the track disappears [14]. The tracking detectors (Pixel, SCT and TRT) are also shown. Right: Observed (solid line) and expected (dotted line) constraints on the mass and lifetime of the lightest chargino from this search. The shaded band around the expected limit shows the expected $\pm 1\sigma$ variation.

5 Conclusions

The EW SUSY searches performed by ATLAS and CMS are now mature, in particular including signatures where a Higgs boson is produced and scenarios with metastable charged particles. Many of the remaining loopholes in previous searches are now being closed, and further gains in sensitivity are anticipated in Run 2.

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