Erstgutachterin: PD Dr. Jeanette Lorenz
Zweitgutachter: Prof. Dr. Wolfgang Dünnweber

Search for charginos and neutralinos in a signature with a Higgs boson and an isolated lepton with the ATLAS detector and its reinterpretation in the phenomenological MSSM

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Part I

Fundamental concepts

Part II

The 1-lepton analysis

Part III

Reinterpretation

Chapter 11

Reinterpretation in the pMSSM

After having discussed methods and approaches to reinterpret ATLAS searches for Supersymmetry (SUSY), this chapter exploits the analysis approximations previously introduced, and presents a reinterpretation of the 1ℓ search in the phenomenological Minimal Supersymmetric Standard Model (pMSSM).

11.1 Motivation

In today's searches for SUSY, it is common to use simplified models as a way of avoiding the necessity of having to deal with high-dimensional parameter spaces that are extremely challenging to sample and compare to data. As has been discussed in sections 1.2.7 and 8.3, simplified models are however by no means complete SUSY models, but only serve as proxies for more complex and realistic SUSY scenarios. As such, simplified model limits cannot trivially be translated into limits on model parameters of a more complete SUSY model, and large-scale reinterpretations are necessary to understand the constraints current SUSY searches set on realistic SUSY scenarios.

One class of more complete models, focussing on phenomenologically viable models, is the pMSSM, introduced in section 1.2.6. With its 19 parameters it offers much more complex SUSY scenarios, while still being of somewhat manageable dimensionality. Still, large-scale reinterpretations in the pMSSM are computationally challenging and require a set of approximations as those introduced in chapters 9 and 10. In the following, the *simplified analysis* constructed using the smeared truth-level analysis and the simplified likelihood will be used as the sole method to evaluate a set of pMSSM models.

Although the following sections will be restricted to a reinterpretation of the 1ℓ search, efforts are ongoing within the ATLAS collaboration to perform large-scale reinterpretations using a majority of the Run 2 ATLAS searches for SUSY, most likely resulting in one of the most comprehensive sets of ATLAS constraints on SUSY yet.

Table 11.1: Scan ranges used for each of the 19 pMSSM parameters. For parameters written with a modulus sign, both the positive and negative values are allowed. The term 'gen(s)' refers to generation(s). Flat probability distributions are used to sample random values from the given ranges.

Parameter	min	max	Note
$m_{\tilde{L}_1}$ $(= m_{\tilde{L}_2})$	10 TeV	10 TeV	Left-handed slepton (first two gens.) mass
$m_{\tilde{e}_1}$ $(= m_{\tilde{e}_2})$	10 TeV	10 TeV	Right-handed slepton (first two gens.) mass
$m_{\tilde{L}_3}$	10 TeV	10 TeV	Left-handed stau doublet mass
$m_{\tilde{e}_3}$	10 TeV	10 TeV	Right-handed stau mass
$m_{\tilde{Q}_1}$ $(= m_{\tilde{Q}_2})$	10 TeV	10 TeV	Left-handed squark (first two gens.) mass
$m_{\tilde{u}_1}$ $(= m_{\tilde{u}_2})$	10 TeV	10 TeV	Right-handed up-type squark (first two gens.) mass
$m_{\tilde{d}_1}$ $(= m_{\tilde{d}_2})$	10 TeV	10 TeV	Right-handed down-type squark (first two gens.) mass
$m_{\tilde{Q}_3}$	2 TeV	5 TeV	Left-handed squark (third gen.) mass
$m_{\tilde{u}_3}$	2 TeV	5 TeV	Right-handed top squark mass
$m_{\tilde{d}_3}$	2 TeV	5 TeV	Right-handed bottom squark mass
$\|M_1\|$	0 TeV	2 TeV	Bino mass parameter
$\|M_2\|$	0 TeV	2 TeV	Wino mass parameter
$\|\mu\|$	0 TeV	2 TeV	Bilinear Higgs mass parameter
M_3	1 TeV	5 TeV	Gluino mass parameter
$\|A_t\|$	0 TeV	8 TeV	Trilinear top coupling
$\|A_b\|$	0 TeV	2 TeV	Trilinear bottom coupling
$\|A_\tau\|$	0 TeV	2 TeV	Trilinear τ lepton coupling
M_A	0 TeV	5 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

11.2 Model sampling and processing

11.2.1 Sampling

All signal models considered in the following are sampled from the pMSSM using the parameter ranges shown in table 11.1. Flat probability distributions are used to draw random values within the given ranges for each parameter and each unique set of pMSSM parameters generated that way is referred to as an independent pMSSM model.

As this work discusses a search for electroweakinos, the models drawn from the pMSSM are sampled with a special focus on the electroweak sector. This is achieved by setting the mass parameters of the first and second generation squarks to values much higher than those accessible at Large Hadron Collider (LHC) energies, effectively decoupling them. Likewise, sleptons are also effectively decoupled because the 1ℓ search is not expected to be sensitive to slepton pair production or scenarios with sleptons in the decay chains. For naturalness arguments, third generation squarks and the gluino are not strictly decoupled, but set to sufficiently high values such as not to affect the electroweak sector too much. The lower and upper bounds on the 12 scanned parameters are chosen such as to yield a high density of models with electroweakino masses accessible at LHC energies, while allowing the scan to be as general as possible.

Once a value for each of the 19 pMSSM parameters has been chosen, a number of publicly available software packages are executed in order to compute the properties of each model. In a first step, SPheno v4.0.5 [290, 291] is used to calculate the spectrum of the sparticles, which, in turn, serves as input for determining the masses and branching fractions of the Higgs sector using FeynHiggs v2.15.0 [292–294]. An additional SUSY spectrum calculation is performed in parallel with SoftSusy v4.1.8 [295]. Although the spectra obtained from SoftSusy will not be directly used in the following, the program is still required to complete successfully in order to reduce the number of pMSSM models with pathological properties. After the complete model spectrum has been calculated, the dark matter relic abundance of each model is determined with micrOMEGAs v5.0.8 [296, 297].

11.2.2 Selection and processing

In order to avoid models with pathological properties, all spectrum generators and additional programs are required to complete execution without error. The cross sections for surviving models are computed at next-to-leading order (NLO) using Prospino v2.1 [298, 299]. Models with inclusive cross sections for all electroweakino production processes below 0.07 fb are discarded as they would result in less than 10 expected signal events with an integrated luminosity of $139\,\text{fb}^{-1}$, which is not sufficient to be sensitive to with current electroweak SUSY searches. All models are further required to produce a lightest Higgs boson mass compatible within a ± 5 GeV range with the experimentally measured Standard Model (SM) Higgs boson mass[†]. Models where the $\tilde{\chi}_1^0$ is not the lightest supersymmetric particle (LSP) are also rejected.

No constraints on the computed cosmological LSP abundance are applied at this stage in order to give a more general view after the models are evaluated using the 1ℓ search. For the same reason,

[†] The mass range is based on a conservative estimate of the theoretical uncertainties arising from the FeynHiggs calculation.

experimental constraints like the lower limit on the chargino mass from Large Electron Positron (LEP) are also not applied at this stage.

Of the 10,000 unique models sampled from the pMSSM using the above prescription, 5152 models survive the constraints and requirements discussed in this section and are analysed using the simplified 1ℓ search. The majority of the models failing this selection step were rejected due to the cross section constraint.

11.2.3 Event generation

Event generation is performed using the software centrally provided by the ATLAS production system. The initial pair of sparticles with up to one additional parton in the matrix element are generated using the MadGraph5_aMC@NLO v2.6.1. [187, 188] generator. Next, Pythia8.230 [190] with the A14 [191] tune is used for the hadronisation and parton showering, together with the NNPDF 2.3 LO [189] parton distribution function (PDF) set. The number of events N generated for each model is determined by

$$N = \sigma \times \mathcal{L}_{\text{eff}}, \tag{11.1}$$

where $\mathcal{L}_{\text{eff}} = 700\,\text{fb}^{-1}$ is an effective integrated luminosity and σ is the total production cross section of the model. The number of events generated for each model is capped at a minimum number of 10^4 and a maximum number of 10^6 truth-level events.

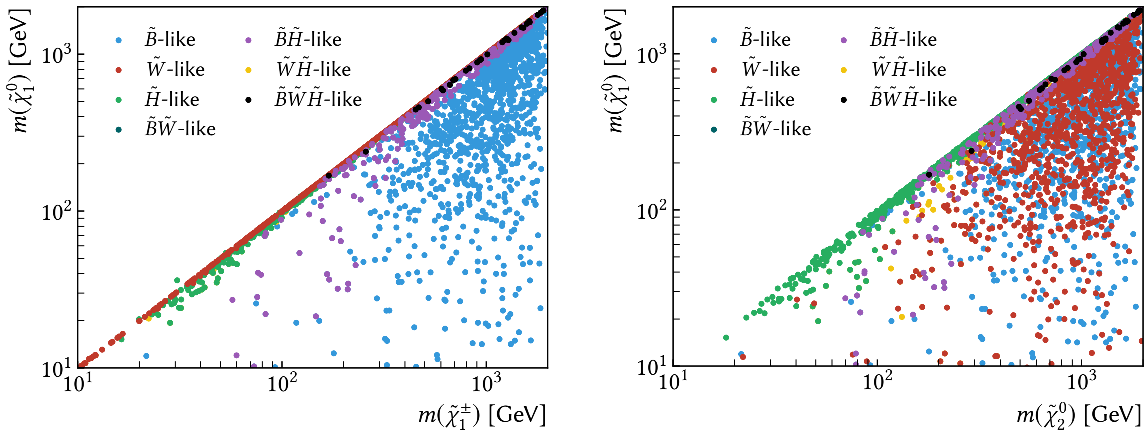
11.2.4 Truth-level analysis

All models passing event generation are evaluated using the simplified analysis comprised of truth-level inputs, four-vector smearing and the simplified likelihood. This is the only evaluation done for the models considered herein. A full scan over the pMSSM including multiple ATLAS searches would additionally include a processing step reverting back to the full analysis available through Recast for model points where (non-)exclusion is uncertain based on the simplified analysis only.

11.3 Phenomenology of the LSP

The composition of the $\tilde{\chi}_1^0$ in each pMSSM model sampled is shown in projections onto the $m(\tilde{\chi}_1^\pm)$–$m(\tilde{\chi}_1^0)$ and $m(\tilde{\chi}_2^0)$–$m(\tilde{\chi}_1^0)$ planes in figs. 11.1(a) and 11.1(b), respectively. The $\tilde{\chi}_1^0$ is considered to be bino-like ($\tilde{B}$-like), wino-like ($\tilde{W}$-like) or higgsino-like ($\tilde{H}$-like) if the corresponding fraction from the neutralino mass mixing matrix is at least 80%. If more than one component has a fraction of more than 20%, then the $\tilde{\chi}_1^0$ is considered to be of mixed nature. For example, a $\tilde{\chi}_1^0$ with more than 20% bino-, wino- and higgsino-components is referred to as $\tilde{B}\tilde{W}\tilde{H}$-like. The nature of the LSP as a function of the bino, wino and higgsino mass parameters (M_1, M_2 and μ) is shown as a reference in fig. C.2.

In the bulk of the $m(\tilde{\chi}_1^\pm)$–$m(\tilde{\chi}_1^0)$ plane, i.e. the parameter space targeted by the 1ℓ search using the simplified model, a large majority of the models produce a bino-like LSP with nearly mass-degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. These models correspond to cases where $M_1 \ll \mu$ and $M_1 < M_2$ and thus produce electroweakino spectra similar to the canonical simplified model considered in the 1ℓ search. Some sensitivity can therefore be expected towards these models in the context of the 1ℓ search, provided



(a) $m(\tilde{\chi}_1^\pm)$–$m(\tilde{\chi}_1^0)$ plane **(b)** $m(\tilde{\chi}_2^0)$–$m(\tilde{\chi}_1^0)$ plane

Figure 11.1: Projections of all models sampled onto the (a) $m(\tilde{\chi}_1^\pm)$–$m(\tilde{\chi}_1^0)$ and (b) $m(\tilde{\chi}_2^0)$–$m(\tilde{\chi}_1^0)$ planes. Each point represents a distinct pMSSM model with a unique combination of pMSSM parameters. The colour encodes the composition of the $\tilde{\chi}_1^0$ in each model. Details on how the LSP type is defined are given in the text.

that the decays $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ have sufficiently large branching fractions and produce on-shell bosons.

Towards the diagonal of the $m(\tilde{\chi}_1^\pm)$–$m(\tilde{\chi}_1^0)$ plane, i.e. for models with nearly mass-degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$, the nature of the LSP shows a larger variation. In a large set of models where M_2 is not too large and much smaller than M_1 and μ, the LSP has a significant wino component and is nearly mass-degenerate with the $\tilde{\chi}_1^\pm$, while the $\tilde{\chi}_2^0$ and other electroweakinos can be more massive. In models where the LSP has a large higgsino component, i.e. μ is much smaller than M_1 and M_2, the three electroweakinos $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ are nearly mass-degenerate and, if promptly decaying, result in very soft decay products, making these models inherently difficult to target.

11.4 Impact of the 1ℓ search on the pMSSM

In the following sections, the impact of the 1ℓ search on the pMSSM is discussed using one-dimensional and two-dimensional projections and distributions. A model is considered to be excluded if the observed CL_s value obtained with the simplified likelihood using the smeared truth-level inputs and the simplified likelihood is below 0.05. Of the 5152 models evaluated, the 1ℓ search excludes a total of 98, or about 1.9%, of the models.

For the one-dimensional distributions shown in the following, the total number of models is compared against the number of models excluded by the 1ℓ search. An additional pad indicates the ratio between models excluded and total models sampled in each bin of the distribution. In the two-dimensional projections, the numbers in the bins indicate the number of pMSSM models sampled in each bin. In these projections, the bin-wise fraction of models excluded with the 1ℓ search is colour-encoded. Bins in which all models are excluded are coloured in black, while bins without any excluded models are left white. Where applicable, the exclusion contour obtained by the 1ℓ search in the simplified model scenario is overlaid.

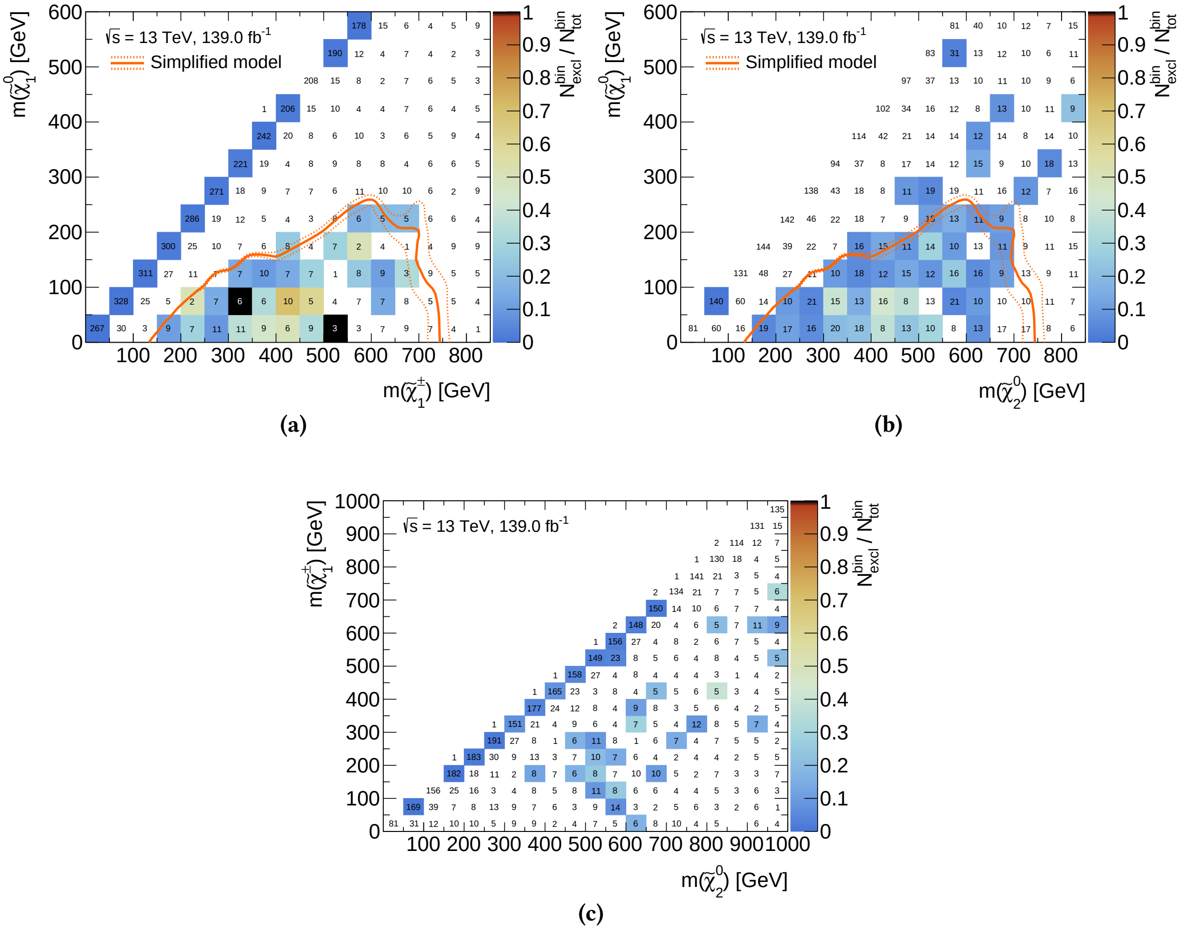


Figure 11.2: Bin-by-bin fraction of excluded models as a function of the relevant sparticle masses. The numbers in the bins correspond to the total number of models sampled in the respective bin. The bin-wise fraction of models excluded by the 1ℓ search is encoded with a colour bar ranging from 0 to 1. Where all models in a given bin are excluded, the bin is coloured in black. Bins without any models excluded are left white. Models are evaluated using the simplified likelihood of the 1ℓ search. Where applicable, the simplified model contour is shown in orange.

11.4.1 Impact on electroweakino masses

Figures 11.2 and 11.3 show the bin-by-bin fractions of models excluded by the 1ℓ search as two- and one-dimensional distributions, respectively. From the $\tilde{\chi}_1^\pm$–$\tilde{\chi}_1^0$ plane in fig. 11.2(a), it can be observed that the 1ℓ search is most sensitive to pMSSM models in electroweakino mass ranges similar to those excluded in the context of the simplified model. Most of the models excluded have $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses ranging from roughly 200 GeV to about 700 GeV, and $\tilde{\chi}_1^0$ masses ranging masses from 0 GeV to about 300 GeV. The proportion of excluded models peaks at $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) \approx 450$ GeV and light LSPs with $\tilde{\chi}_1^0 < 150$ GeV, as visible in fig. 11.3.

The models excluded by the 1ℓ search can be classified in two broad categories: models situated within the parameter range enclosed by the simplified model exclusion contour, and models with nearly mass-degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. As discussed in section 11.3, most models within the simplified model

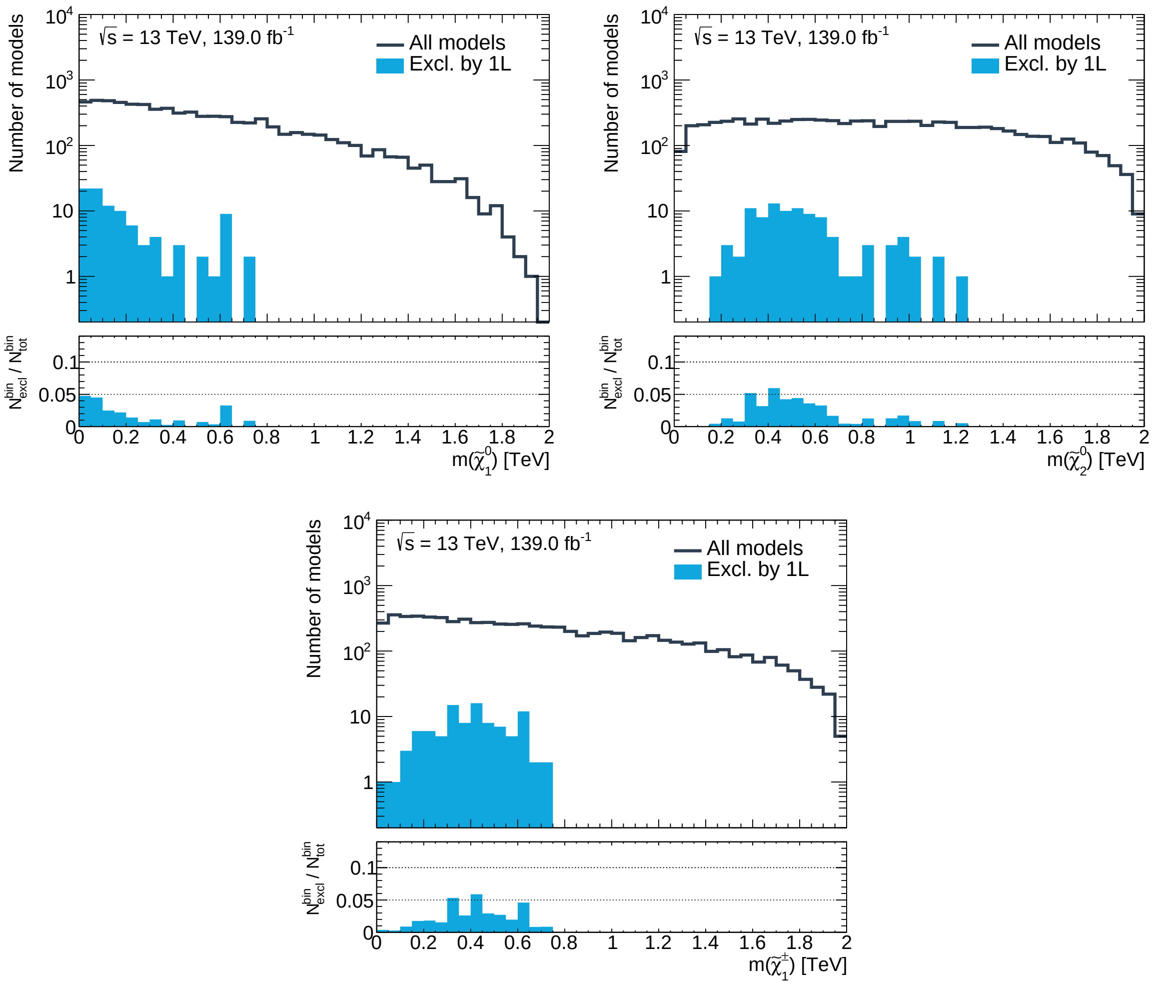
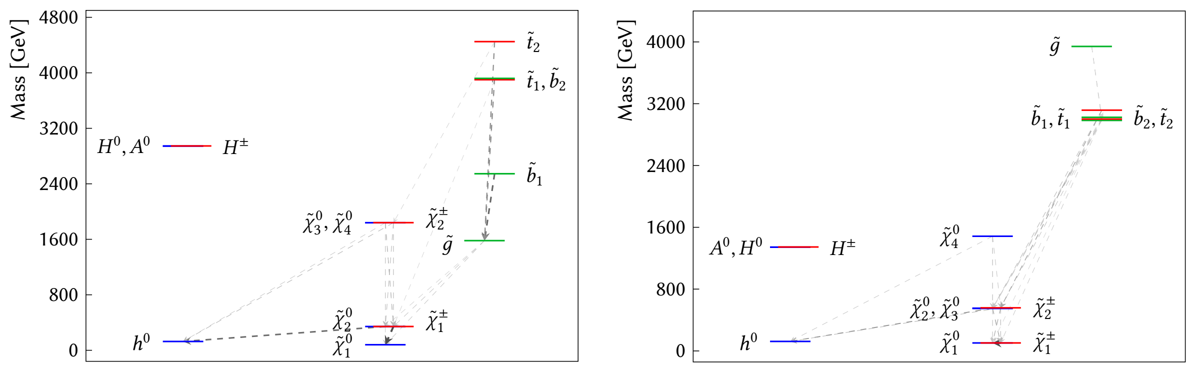


Figure 11.3: Bin-by-bin number of excluded models as a one-dimensional function of the electroweakino masses. The bin-wise fraction of excluded models, $N^{\text{bin}}_{\text{excl}}/N^{\text{bin}}_{\text{total}}$, is shown in the lower pad. All models are evaluated using the simplified likelihood of the 1ℓ search.



(a) Bino-like $\tilde{\chi}_1^0$ model **(b)** Wino-like $\tilde{\chi}_1^0$ model

Figure 11.4: Mass spectra of two exemplary pMSSM models. Both models are excluded by the 1ℓ search. Fig. (a) represents a model with a bino-like LSP and nearly mass-degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. In fig. (b), a model with a wino-like LSP and mass-degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ but relatively light $\tilde{\chi}_2^\pm$ (nearly mass-degenerate with the $\tilde{\chi}_2^0$) is shown. The branching fractions of the different decays are indicated through the width and greyscale colour (pure black being 100% BF, pure white being 0% BF) of the arrows. Branching fractions below 10% are suppressed for the sake of visibility. Figures generated using `pyslha` [92].

exclusion contour produce a bino-like LSP and result in nearly mass-degenerate[†] $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. Expectedly, the 1ℓ search shows sensitivity to $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production in models with wino-like electroweakinos and a bino-like $\tilde{\chi}_1^0$, resulting in spectra close to that of the canonical simplified model originally considered in the search. The mass spectrum of such a model, excluded by the 1ℓ search, is shown in fig. 11.4(a).

The second category of models excluded comprises cases where the LSP is wino-like and nearly mass-degenerate with the chargino. These models correspond to the diagonal of the $m(\tilde{\chi}_1^\pm)$–$m(\tilde{\chi}_1^0)$ plane in fig. 11.2(a). As the mass difference between the LSP and the chargino is typically of the order of only a few 100 MeV, the chargino can become long-lived, and primarily decays to a LSP and an off-shell W boson that, in turn, decays into soft objects not reconstructed in the detector. If the chargino is produced with large momentum, it can live long enough to traverse multiple layers of the ATLAS pixel detector before decaying, leading to a disappearing track signature. Searches targeting prompt electroweakino decays are not expected to be sensitive to these models, and instead dedicated disappearing track searches are developed within the ATLAS Collaboration (cf. Ref. [300]). Even though no sensitivity to these models is expected from the 1ℓ search, a small set of models with a wino-like LSP can still be excluded. In these scenarios the next-to-lightest chargino $\tilde{\chi}_2^\pm$ is comparably light, such that the 1ℓ search is sensitive to $\tilde{\chi}_2^\pm\tilde{\chi}_2^0$ production with cross sections of $\mathcal{O}(1\,\text{fb})$. If the next-to-lightest chargino decays directly into the LSP via $\tilde{\chi}_2^\pm \rightarrow W^\pm\tilde{\chi}_1^0$, enough events with an isolated electron or muon can occur, allowing to exclude the model[§]. An exemplary mass spectrum of such a model, excluded by the 1ℓ search, is shown in fig. 11.4(b).

No sensitivity is observed for pMSSM models with higgsino-like electroweakinos, i.e. compressed mass spectra[‡]. This is expected, as the electroweakino decays in such scenarios typically produce off-shell W, Z and h bosons, resulting in very soft final state objects that the 1ℓ search is not optimised

† Figure C.3 illustrates this behaviour further.

§ Provided that the branching fraction of the $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ decay is also large enough, such that a final state with a lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$ and two b-jets from a Higgs decay can be realised in a sufficient number of events.

‡ The mass spectrum of an exemplary pMSSM model with higgsino-like LSP is shown in fig. C.5, highlighting that all three relevant electroweakinos ($\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$) are nearly mass-degenerate.

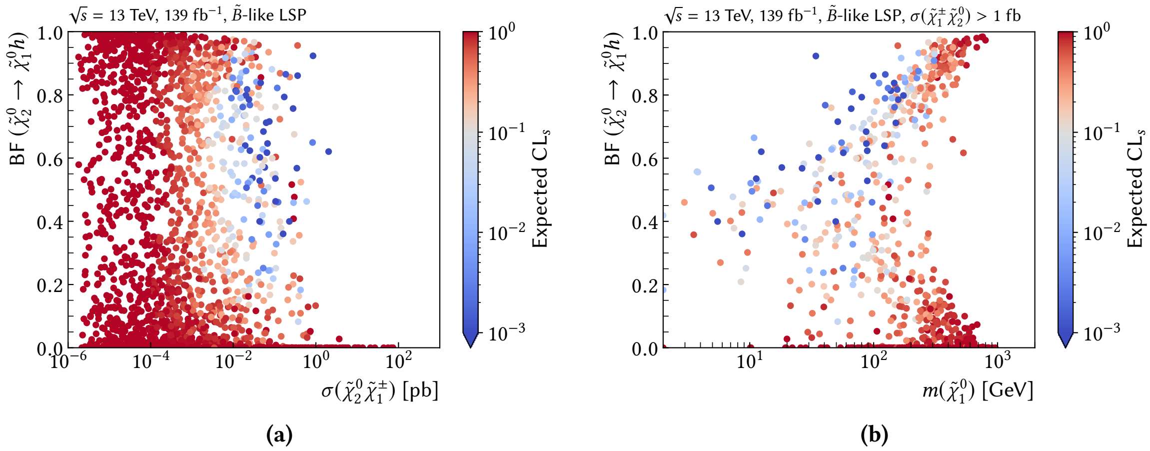


Figure 11.5: Density of the pMSSM models with bino-like $\tilde{\chi}_1^0$ projected onto the plane spanned by (a) the $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair production cross section and BF($\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$), and (b) $m(\tilde{\chi}_1^0)$ and BF($\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$). The expected CL$_s$ value obtained for each model using the 1ℓ search is colour-encoded. While models with a red tint are not expected to be excluded, models with a neutral white tint are on the boundary of expected exclusion, and models with a blue tint are expected to be excluded. Only models with a bino-like LSP are shown in both figures. In fig. (b), models are also required to satisfy $\sigma(\tilde{\chi}_1^\pm\tilde{\chi}_2^0) > 1$ fb.

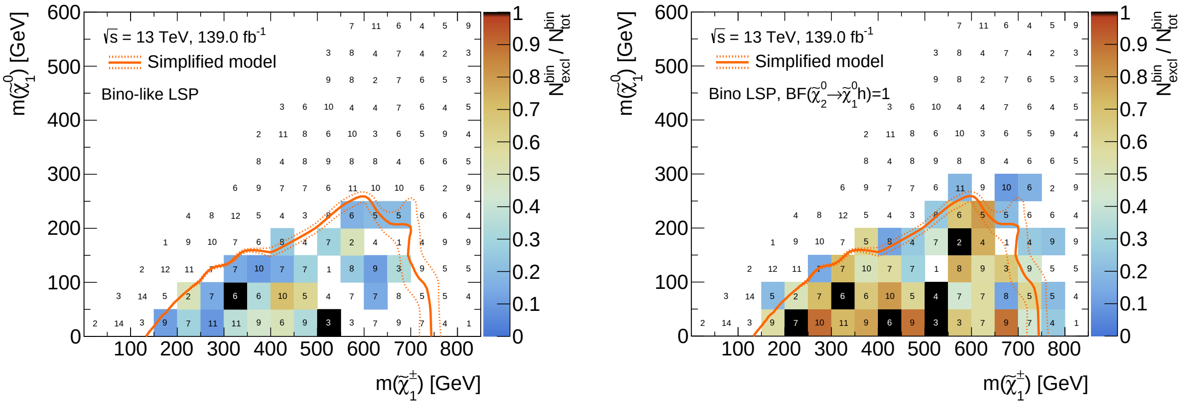
for. Dedicated searches (as for example Ref. [91]) are being performed by the ATLAS Collaboration to target such compressed scenarios. Work is ongoing to include these searches in the large-scale scans of the pMSSM that the efforts discussed herein are embedded in.

In general, the sensitivity of the 1ℓ search to pMSSM models is significantly reduced, compared to the simplified model scenario, even in the electroweakino mass regions covered by the simplified model contour. The loss in sensitivity can be attributed to the fact that the simplified model assumes branching fractions of 100% of the $\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ decays (with on-shell W and h bosons). The decay of the chargino through an on-shell W boson is, in general, a good assumption in R-parity conserving models with $m(\tilde{\chi}_1^\pm) \gtrsim m(\tilde{\chi}_1^0) + m(W)$ and where the sleptons and charged and pseudoscalar Higgs bosons are heavier than the charginos and neutralinos. The decay of the next-to-lightest neutralino through a Higgs boson, however, turns out not to be the most probable decay mode in many models where the competing decay $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$ dominates instead. The couplings of the next-to-lightest neutralino to the Higgs boson are suppressed by powers of $|\mu|/M_2$ in the gaugino-like regions [301], meaning that the branching fraction of the $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ decay takes on reasonably high values only in models with an LSP containing a substantial bino component†.

In the bulk of the $\tilde{\chi}_1^\pm$–$\tilde{\chi}_1^0$ plane (cf. fig. 11.2(a)) that mostly contains models with a bino-like LSP, many models cannot be excluded simply due to their relatively high $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses, and thus low $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair production cross sections. Figure 11.5(a) shows a projection of the pMSSM models in a two-dimensional plane spanned by the $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair production cross section and BF($\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$). The colour of each model point indicates the expected CL$_s$ value§, revealing that the 1ℓ search only starts to become sensitive to models with $\sigma(\tilde{\chi}_1^\pm\tilde{\chi}_2^0)$ larger than $\mathcal{O}(1\,\text{fb})$. This is in line with the sensitivity of the 1ℓ analysis obtained in the simplified model scenario, where model points with electroweakino pair

† The Higgs coupling suppression is illustrated in fig. C.4.

§ The expected CL$_s$ is preferred here over the observed one as it provides a better overview of the sensitivity of the 1ℓ search.



(a) Mixed BFs

(b) BF($\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$) = 1

Figure 11.6: Bin-by-bin fraction of excluded models with a bino-like $\tilde{\chi}_1^0$ as a function of $m(\tilde{\chi}_1^\pm)$ and $m(\tilde{\chi}_1^0)$. In fig. (a) the pMSSM models originally sampled are shown. In fig (b), the branching fraction of the $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ decay is manually set to 100% after which event generation and 1ℓ analysis evaluation are re-exectued. Only models with a bino-like LSP are shown in both figures.

production cross sections as low as 4.1 fb were expected to be excluded. Figure 11.5(a) moreover shows that, for many models with $\sigma(\tilde{\chi}_1^\pm\tilde{\chi}_2^0) \gtrsim 1$ fb, the branching fraction of the next-to-lightest neutralino decay via a Higgs boson is vanishingly small. This ultimately results in a low number of events with Higgs boson candidates, causing a lack of sensitivity in the context of the 1ℓ search.

Even with a sufficiently large electroweakino pair production cross section and at least moderate BF($\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$), a sizeable fraction of models turn out to have a relatively high LSP mass of more than 300 GeV, as shown in fig. 11.5(b). Coupled with an upper bound on the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses due to the pair production cross section requirement, these models thus tend to have comparably small electroweakino mass differences, resulting in signatures with reduced amounts of E_T^{miss} and softer objects that may not always be reconstructed in the 1ℓ search and therefore contribute to a reduced sensitivity[†].

To illustrate the size of the sensitivity loss due to mixed branching fractions, a sizeable fraction of the models with a bino-like LSP have been reprocessed with BF($\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$) fixed to unity, and BF($\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$) consequently set to disappear. The modified models were subsequently reanalysed with the 1ℓ search. Figure 11.6(b) reveals that significantly more pMSSM models can be excluded within the simplified model contour when the branching fraction assumptions of the simplified model are restored. As the $\tilde{\chi}_2^0$ decay into a Z boson and $\tilde{\chi}_1^0$ is the competing decay to $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$, statistically combining searches targeting these decay modes could therefore recover the loss in sensitivity originating from mixed branching fractions in realistic SUSY models. Likewise, the development of searches targeting both decay modes at the same time, would also recover the full sensitivity[§].

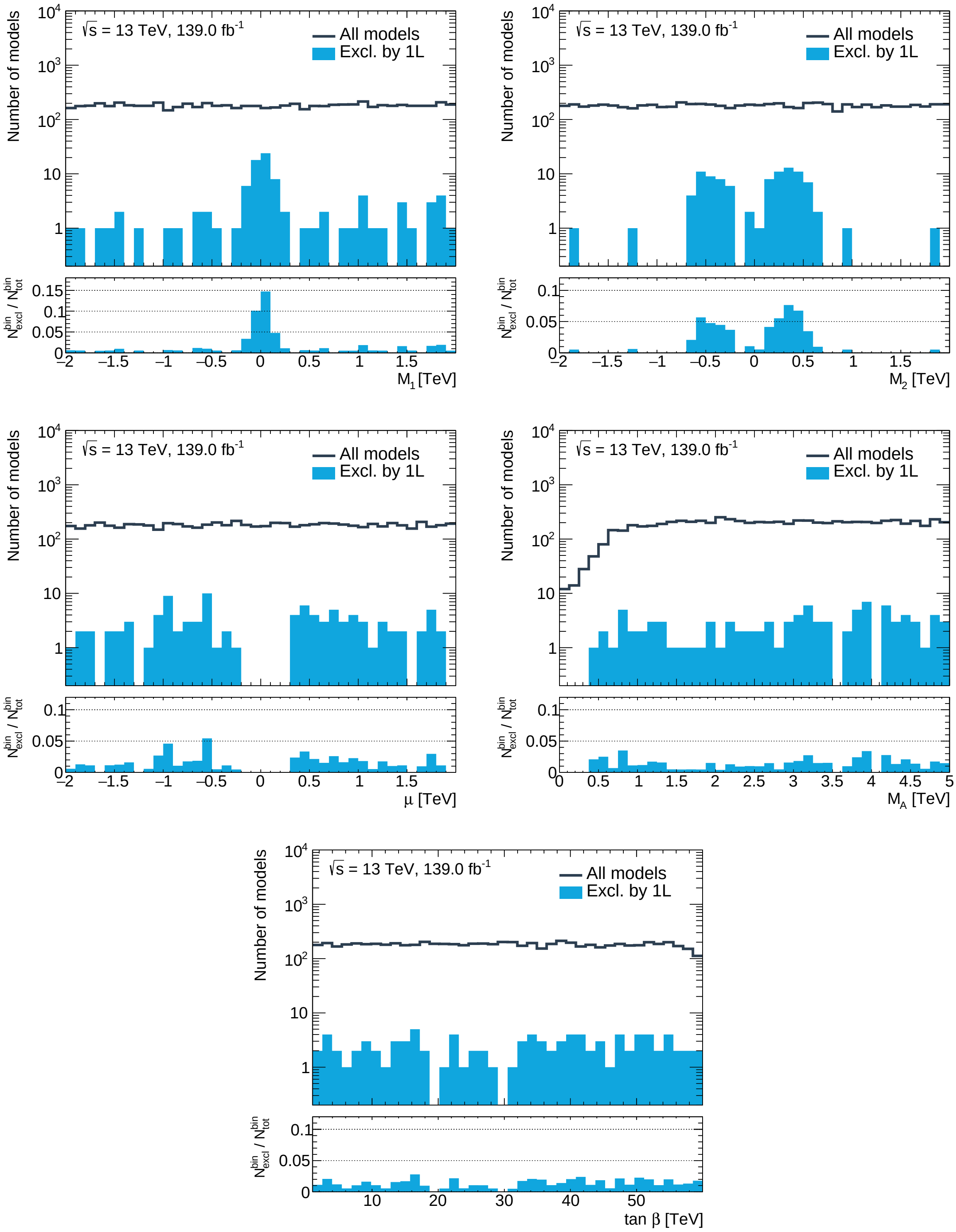


Figure 11.7: Bin-by-bin number of excluded models as a one-dimensional function of the pMSSM parameters relevant to the electroweak sector. The bin-wise fraction of excluded models, $N^{\text{bin}}_{\text{excl}}/N^{\text{bin}}_{\text{total}}$, is shown in the lower pad. All models are evaluated using the simplified likelihood of the 1ℓ search.

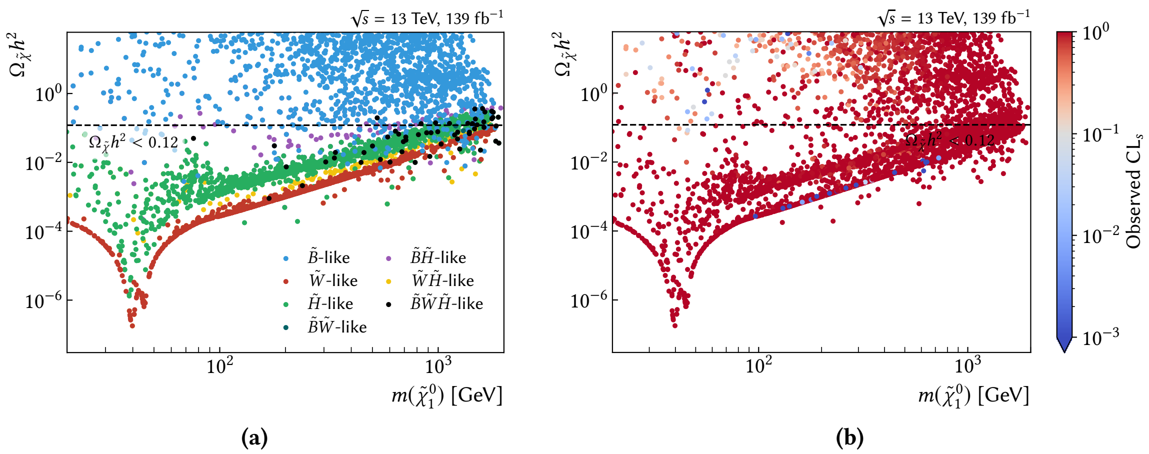


Figure 11.8: Density of the pMSSM model points sampled in the plane spanned by the relic density and mass of the lightest neutralino. The model points are additionally shown as a function of (a) the nature of the LSP and (b) the observed CL$_s$ value obtained for 139 fb^{-1} of data using the 1ℓ search. The horizontal dashed line represents the DM relic density measurement by the Planck Collaboration [47], interpreted as an upper limit, $\Omega_{\tilde{\chi}}h^2 < 0.12$, such that the lightest neutralino can be a sub-dominant DM component.

11.4.2 Impact on pMSSM parameters

The impact of the 1ℓ search on the pMSSM parameters relevant to the electroweak sector are shown in one-dimensional distributions in fig. 11.7. As already discussed in section 11.4.1, the 1ℓ search has the largest impact for small values in the bino mass parameter M_1, leading to models with a bino-like LSP when M_1 is significantly smaller than M_2 and μ. Consequently, the proportion of excluded models peaks at slightly higher values in the distribution of the wino mass parameter, i.e. at around $|M_2| \approx 400$ GeV. As the search is not sensitive to compressed scenarios with a higgsino-like LSP, no models with small values in $|\mu|$ can be excluded.

Since the pseudoscalar Higgs boson does not directly enter the phenomenology of the models targeted by the 1ℓ search, only indirect constraints can be set on m_{A}, excluding models across the full range of the m_{A} distribution sampled. A similar behaviour is observed in $\tan\beta$ where the excluded models have values of $\tan\beta$ spanning the full range from 1 to 60. Likewise, no direct constraints on the trilinear scalar couplings (A_t, A_b, A_τ), and the remaining gluino and third generation squark mass parameters (M_3, $m_{\tilde{Q}_3}$, $m_{\tilde{u}_3}$, $m_{\tilde{d}_3}$) is observed†.

11.4.3 Impact on dark matter relic density

The cosmological abundance of the lightest neutralino $\Omega_{\tilde{\chi}}h^2$ as a function of its type and mass is shown in fig. 11.8(a). The value of the dark matter (DM) relic density measured by the Planck Collaboration is also given [47]. The Planck measurement is interpreted as an upper limit on the DM relic density, thus allowing the $\tilde{\chi}_1^0$ to be a sub-dominant DM component.

† See fig. A.1 for an illustration of this kinematic effect.

§ Provided that they are targeted with statistically independent signal regions such that a combined likelihood can be built.

† Illustrated in fig. C.6.

Some interesting features are worth highlighting in fig. 11.8(a). First, most of the models sampled with a bino-like $\tilde{\chi}_1^0$ overproduce DM and result in a cosmological abundance that is too high. Of the pMSSM models sampled herein, only models with a $\tilde{\chi}_1^0$ containing a considerable wino or higgsino component consistently satisfy $\Omega_{\tilde{\chi}} h^2 < 0.12$ over a large range of the neutralino mass. Models with $m(\tilde{\chi}_1^0) \simeq m(Z)/2$ can produce especially low values in $\Omega_{\tilde{\chi}} h^2$ as the neutralino can resonantly annihilate through s-channel Z exchange. This is the so-called *Z-funnel*, a mechanism that becomes more efficient, the larger the higgsino component of the lightest neutralino is [302]. Likewise, models with a nearly mass-degenerate $\tilde{\chi}_1^{\mp}\tilde{\chi}_1^0$ pair with $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0) \simeq m(W)/2$ can also produce low relic densities because of $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ co-annihilation through s-channel W exchange. A funnel similar to the Z-funnel, but involving s-channel Higgs exchange, exists at $m(\tilde{\chi}_1^0) \simeq m(h)/2$. It requires the $\tilde{\chi}_1^0$ to have a sizeable bino component [302] and is not visible in fig. 11.8(a) because models with a bino-like LSP are underrepresented in the relevant mass range.

In practice, the LEP limits† on the chargino mass of $m(\tilde{\chi}_1^{\pm}) > 92\,\text{GeV}$ [90] rule out models with $|M_2| \lesssim 100\,\text{GeV}$ and $|\mu| \lesssim 100\,\text{GeV}$, leaving only models with a bino-like LSP in the region with $m(\tilde{\chi}_1^0) \lesssim 100\,\text{GeV}$. Although models with a bino-like LSP could theoretically produce low $\tilde{\chi}_1^0$ relic density values through the Z- and h-funnels, in practice, such models are not sampled herein due to the sampling technique employed. To further study the impact of the 1ℓ search on models relevant to the DM phenomenology, i.e. models with a bino-like LSP in the Z- and h-funnels, a different sampling technique would need to be employed, including experimental constraints in the sampling priors in addition to specifically oversampling models with a bino-like LSP in the relevant mass range.

Although of limited use due to the limited number of models in the relevant parameter space, the impact of the 1ℓ search on the DM relic density can still be investigated with the models available. Figure 11.8(b) shows the $\tilde{\chi}_1^0$ cosmological abundance in dependence of the $\tilde{\chi}_1^0$ mass. Instead of encoding the nature of the $\tilde{\chi}_1^0$, the colour now encodes the observed CL_s value obtained by the 1ℓ search. By comparing with fig. 11.8(a), it can be seen that the majority of bino-like models excluded by the 1ℓ search overproduce DM. Through its limited sensitivity to some of the models with a wino-like $\tilde{\chi}_1^0$, the 1ℓ search is, however, still able to exclude some models with a compatible relic density.

11.5 Discussion

Large-scale reinterpretations in high-dimensional SUSY model spaces are crucial in order to assess the sensitivity of SUSY searches in the context of realistic SUSY scenarios. The evaluation of signal models at smeared truth-level, in combination with the simplified likelihoods introduced in chapter 10, offers a computationally efficient and reliable approach for such reinterpretations.

A reinterpretation of the 1ℓ search in a limited number of models sampled from the pMSSM with a focus on the electroweak sector has been discussed. It revealed that the 1ℓ search is sensitive to SUSY scenarios beyond the canonical simplified model originally considered. Although with some caveats, the simplified model phenomenology generally maps reasonably well onto a portion of the pMSSM parameter space. The 1ℓ search is, as expected, found to be most sensitive to pMSSM models with wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production and a bino-like LSP. Interestingly, some sensitivity was found towards $\tilde{\chi}_2^{\pm}\tilde{\chi}_2^0$ pair production in models with a wino-like LSP.

† The limit on the chargino mass of $m(\tilde{\chi}_1^{\pm}) > 92\,\text{GeV}$ considered herein is a conservative lower limit. In a large region of the phase space, the limits on the chargino mass set by LEP reach as high as 103.5 GeV. The impact of the chargino mass limit in the $\Omega_{\tilde{\chi}} h^2$–$m(\tilde{\chi}_1^0)$ projection is shown in fig. C.7.

In general, the sensitivity of the 1ℓ search towards pMSSM models is observed to be negatively impacted by the competing decays $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$, breaking one of the main assumptions of the simplified model. In order to maximise the sensitivity of future searches to $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair production in more complete SUSY scenarios, it is therefore crucial to target both decay modes at the same time. In searches targeting final states with a lepton, multiple jets and missing transverse momentum, both the b-jet multiplicity as well as the invariant mass of the jets originating from the decays $h \to b\bar{b}$ and $Z \to q\bar{q}$ can easily be exploited to develop disjoint† signal regions targeting both decay modes.

Beyond the combination of single decay modes, it could be worth targeting not only $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair production, but also $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ pair production at the same time in a single likelihood function. In the ATLAS Collaboration, work is for example ongoing to perform a search for electroweakinos in the 1ℓ final state using dedicated signal regions simultaneously targeting both $\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to WZ\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \to WW\tilde{\chi}_1^0\tilde{\chi}_1^0$.

Finally, the impact of the 1ℓ search on the DM relic density was discussed. The parameter ranges and sampling technique chosen were used to allow the scan to be as general as possible. For this reason, a large fraction of the models sampled are not directly relevant to the DM phenomenology. Only a small number of models with a bino-like $\tilde{\chi}_1^0$ are sampled from the Z- and h-funnel region where $\Omega_{\tilde{\chi}}h^2 < 0.12$ can be expected to be satisfied for a sizeable fraction of such models. Outside of these two funnels, models with a bino-like $\tilde{\chi}_1^0$ satisfying the relic density constraint tend to have a $\tilde{\chi}_1^0$ mass outside of the range that the 1ℓ search is sensitive to.

In order to be able to further investigate the impact of the 1ℓ search on DM observables, a different sampling technique would need to be adopted, including experimental constraints in the sampling priors and oversampling the relevant regions of the parameter space. The initial sampling of the models, the calculation of their mass spectra and other observables, and the application of experimental constraints is computationally relatively cheap. Therefore, oversampling the relevant parameter space with a brute-force method can be a feasible approach. Machine learning approaches, as for example clustering techniques, can additionally be used to group models into different phenomenological *clusters*, possibly allowing to determine refined parameter ranges to be manually oversampled. Alternatively, active *smart sampling* approaches (as opposed to manually determining and oversampling certain parameter ranges) relying on machine learning methods can be leveraged and are being studied with the aim of improving the sampling efficiency. For example, to dynamically oversample regions of the parameter space with rapidly changing phenomenology and, conversely, undersample regions with low experimental sensitivity or only slowly changing phenomenology§, information geometry methods [304] relying on the Fisher information matrix could be exploited [305].

† Building signal regions that are not orthogonal to each other prevents the construction of a combined likelihood and thus does not allow full statistical combination.

§ The formalisation of this problem is in many aspects directly related to the problem of finding an *inverse map* from the space of LHC signatures to the parameter space of beyond the Standard Model (BSM) models, discussed in Ref. [303].

Part IV

Summary and Outlook

Part V

Appendices

Appendix C

Reinterpretation in the pMSSM

The following sections provide supporting material for the reinterpretation of the 1ℓ search in the pMSSM, discussed in chapter 11.

C.1 Further validation of the simplified likelihood

Figure C.1 compares the observed CL_s values obtained for the pMSSM models sampled using the various likelihoods of the 1ℓ search discussed throughout part III of this thesis. In general, the observed CL_s values from the simplified likelihood are closer to those obtained using the full likelihood, than the ones obtained using the single-bin likelihood (built using the discovery signal regions).

Although revealing a good agreement, the CL_s values naturally do not exactly match. For this reason, the simplified likelihood can only be used for models giving observed CL_s moderately far away from the exclusion boundary at 0.05. Models with a CL_s value too close to 0.05 need to be evaluated using the full likelihood and Recast for full statistical precision. Compared to the single-bin approach using the discovery signal regions, the benefit of the simplified likelihood is that, due to the improved agreement in observed CL_s, the interval around $\mathrm{CL}_s = 0.05$ defining models to be evaluated using the full likelihood can be chosen to be significantly narrower. Ultimately, this approach does allows for more efficient pMSSM scans where a smaller fraction of models needs to be evaluated at full precision.

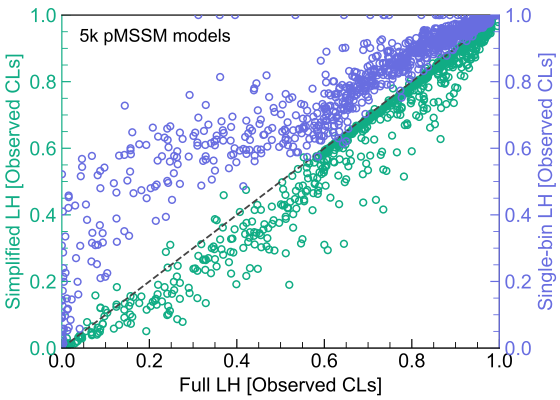


Figure C.1: Observed CL_s values obtained for all pMSSM models sampled for different likelihood configurations of the 1ℓ search. In green, the simplified likelihood discussed in chapter 10 is compared with the full analysis likelihood. In purple, the single-bin likelihood configuration using the discovery signal regions is compared with the full likelihood.

C.2 Phenomenology of the LSP

Figure C.2 shows the LSP type as a function of the pMSSM parameters M_1, M_2, μ and $\tan\beta$. Models with $|M_1| \ll |M_2|, |\mu|$ tend to have an LSP with dominant bino component, while models with $|M_2| \ll |M_1|, |\mu|$, have an LSP that is mostly wino-like. Similarly, models with $|\mu| \ll |M_1|, |M_2|$ have mostly higgsino-like LSPs. The parameter $\tan\beta$ does not have a large impact on the LSP type within the ranges sampled.

Figure C.3 shows the fraction of models excluded by the 1ℓ search in different two-dimensional projections on the electroweakino masses. Models with a bino-like LSP tend to have nearly mass-degenerate $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ and are thus close to the canonical simplified model considered in the search. Models with a wino-like LSP have nearly mass-degenerate $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$. In such models, the 1ℓ search can be sensitive to $\tilde{\chi}_2^{\pm}\tilde{\chi}_2^0$ production.

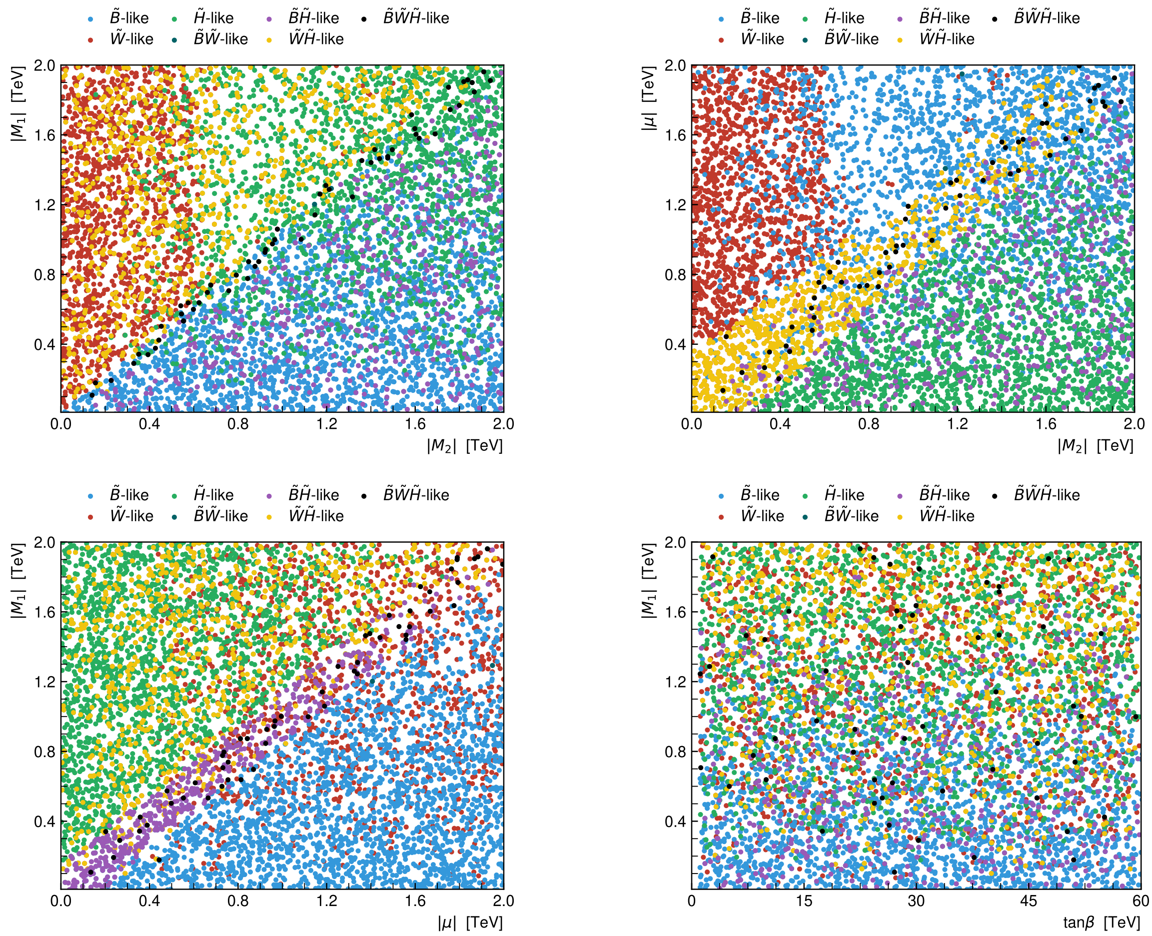


Figure C.2: Phenomenology of the LSP as a function of two-dimensional projections of the pMSSM parameter space. Each point in the plots corresponds to a unique pMSSM model sampled. The colour codes the nature of the LSP using the definitions introduced in section 11.3.

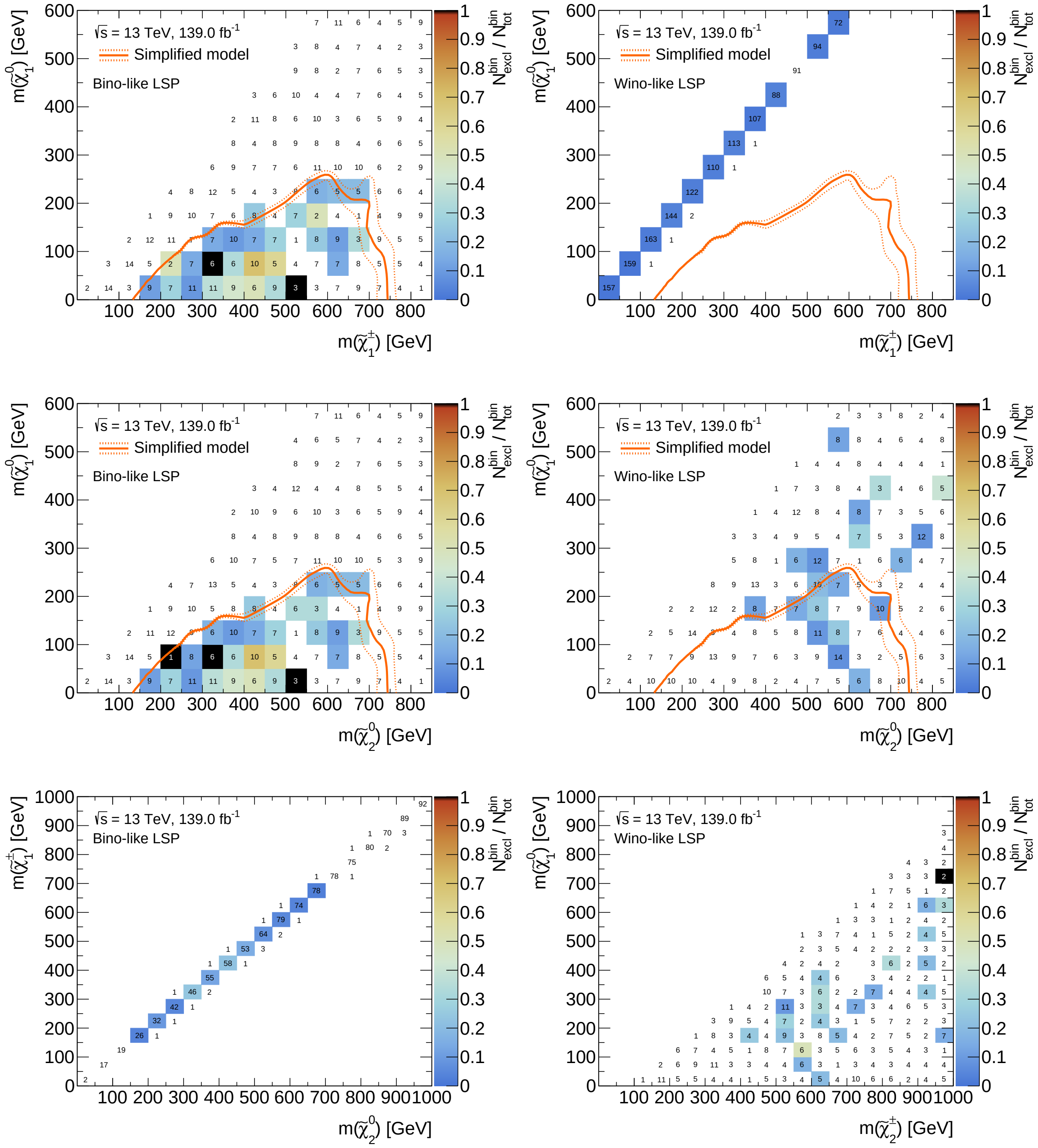
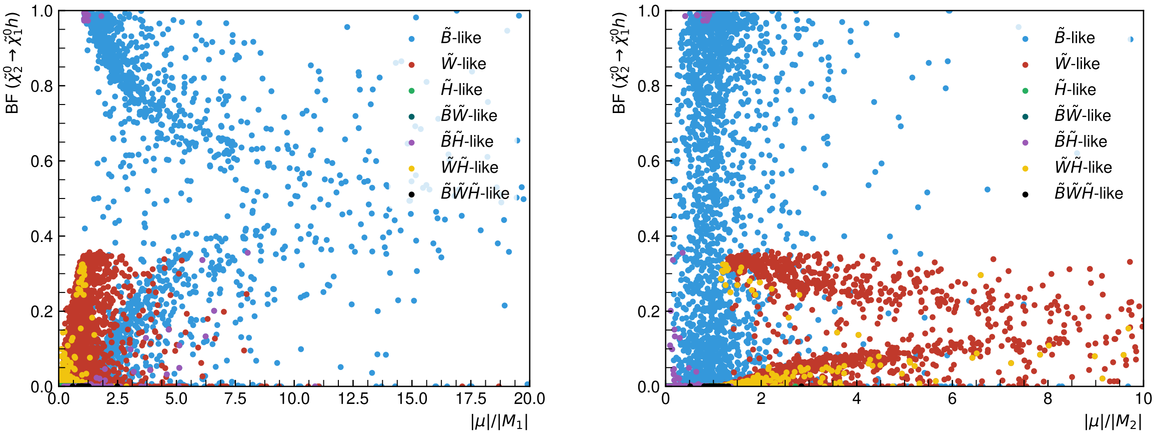


Figure C.3: Bin-by-bin fraction of excluded models as a two-dimensional function of the relevant sparticle masses. Only pMSSM models with a bino-like (wino-like) LSP are shown on the left (right). The numbers in the bins correspond to the total number of models sampled falling into the respective bin. The bin-wise fraction of models excluded by the 1ℓ search is encoded with a colour bar ranging from 0 to 1. Where all models in a given bin are excluded, the bin is coloured in black. Bins without any models excluded are left white. Models are evaluated using the simplified likelihood of the 1ℓ search. If applicable, the simplified model contour is shown in orange.

C.3 Model properties

As illustrated in fig. C.4, the couplings of the $\tilde{\chi}_2^0$ to the Higgs boson are suppressed by powers of $|\mu|/M_2$ in the wino-like and bino-like scenarios [301], meaning that the branching fraction of $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ takes on reasonably high values only in models with an LSP that is nearly pure bino.

Figure C.5 shows the compressed mass spectrum of an exemplary pMSSM model point with higgsino-like $\tilde{\chi}_1^0$, a model that the 1ℓ search is not expected to be sensitive to.



(a) **(b)**

Figure C.4: Density of the pMSSM models projected onto the plane spanned by BF($\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$) and (a) $|\mu|/|M_1|$ or (b) $|\mu|/|M_2|$. Models are shown as a function of their $\tilde{\chi}_1^0$ type.

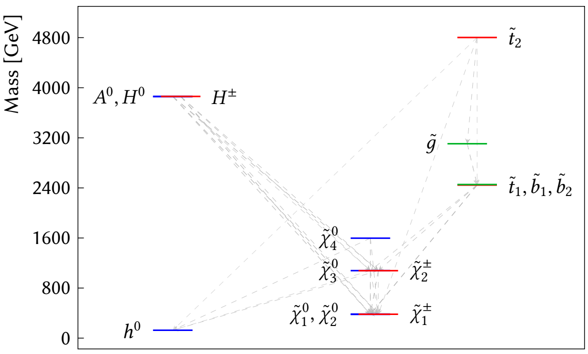


Figure C.5: Mass spectrum of an exemplary pMSSM model with higgsino like lightest electroweakinos. The branching fractions of the different decays are indicated through the width and and greyscale colour (pure black being 100%, pure white being 0%) of the arrows. Branching fractions below 10% are suppressed for the sake of visibility. Figure generated using `pyslha` [92].

C.4 Impact of the 1ℓ search on the pMSSM parameters

In fig. C.6, the impact of the 1ℓ search on the reminaing pMSSM parameters sampled, not already shown in section 11.4.2, are provided. As before, the full set of models evaluated with the 1ℓ search is shown as black line, while the bin-wise number of models excluded by the search are indicated with the blue histogram. An additional pad indicates the bin-wise fraction of models excluded.

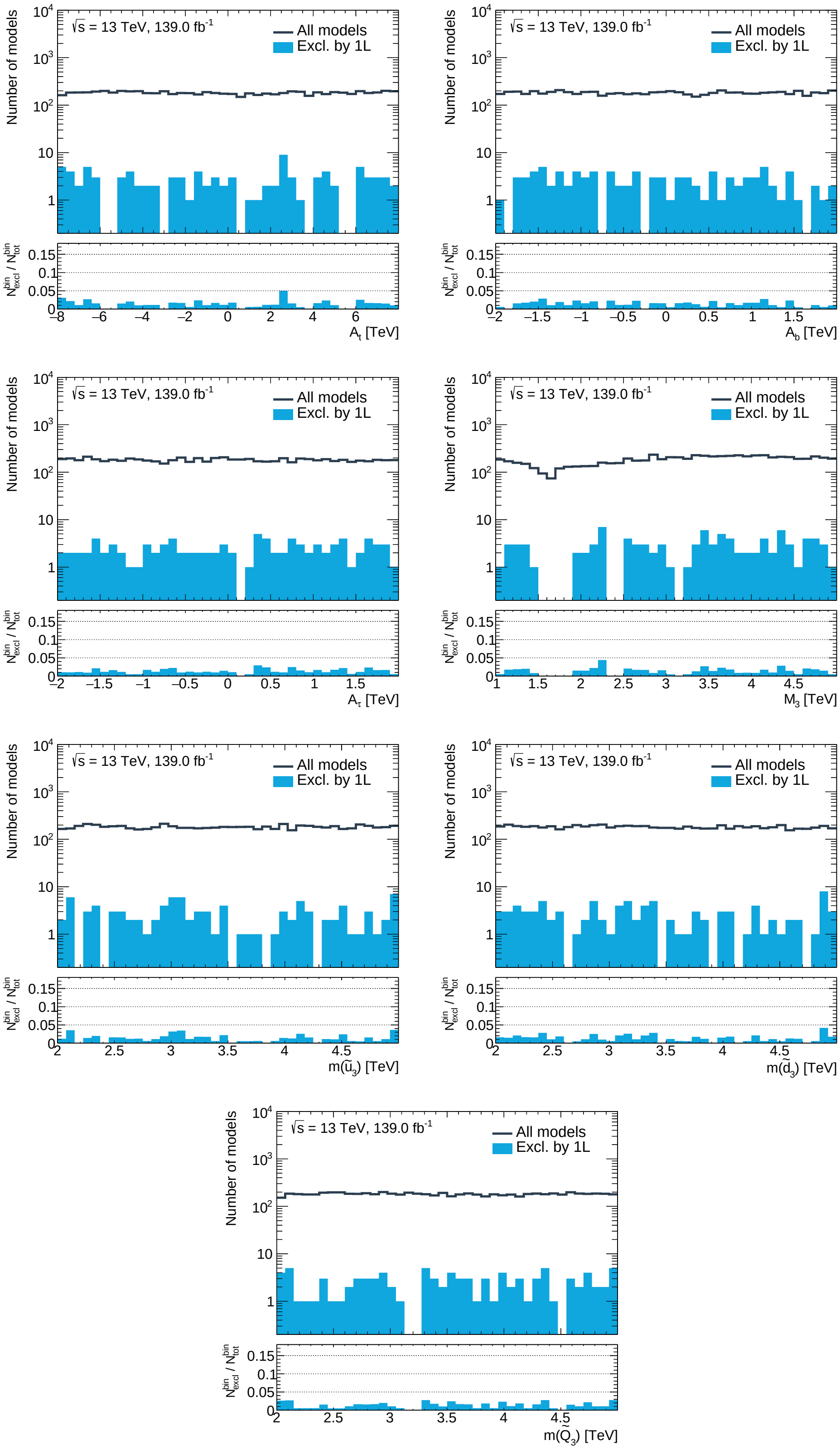
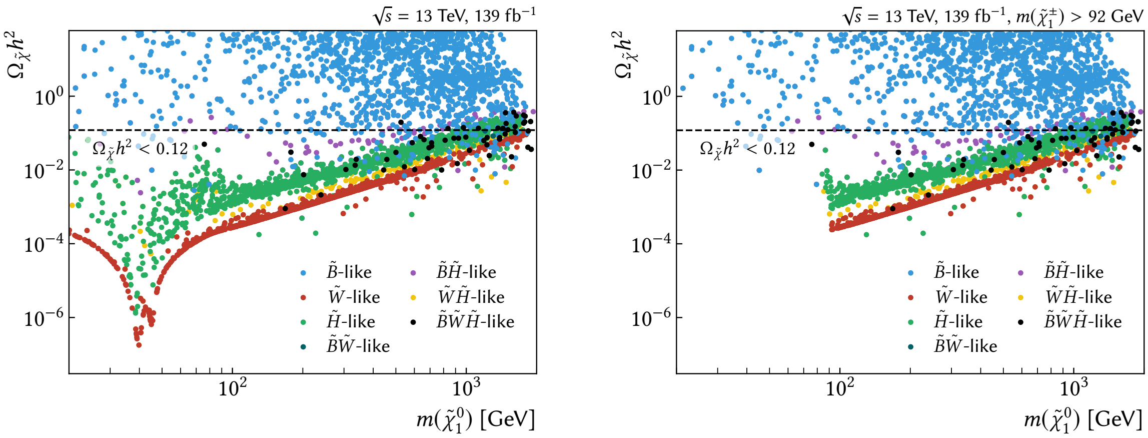


Figure C.6: Bin-by-bin number of excluded models as a one-dimensional function of the remaining pMSSM parameters not already shown in fig. 11.7. The bin-wise fraction of excluded models, $N^{\mathrm{bin}}_{\mathrm{excl}}/N^{\mathrm{bin}}_{\mathrm{total}}$, is shown in the lower pad. All models are evaluated using the simplified likelihood of the 1ℓ search.

C.5 Impact of the 1ℓ search on the dark matter relic density

Figure C.7 compares the density of pMSSM models in a two-dimensional projection on the $\Omega_{\tilde{\chi}}h^2$–$m(\tilde{\chi}_1^0)$ plane before and after the conservative LEP constraint on the chargino mass of $m(\tilde{\chi}_1^\pm) > 92$ GeV [90] is applied. Only models with a bino-like LSP provide a light LSP with mass below 10^2 GeV after the LEP constraint. In order for the Z- and h-funnels to become visible, i.e. for there to be a sizeable number of models with a light bino-like LSP and $\Omega_{\tilde{\chi}}h^2 < 0.12$, the region with $m(\tilde{\chi}_1^0) < 10^2$ GeV would need to be oversampled. Due to the lack thereof within the scope of this thesis, only a small number of such models are sampled and subsequently evaluated using the 1ℓ search.



(a) Without LEP constraint

(b) With LEP constraint

Figure C.7: Density of the pMSSM model points sampled in the plane spanned by the relic density and the $\tilde{\chi}_1^0$ mass. The model points are additionally shown as a function of the nature of their $\tilde{\chi}_1^0$. In fig. (a) all pMSSM models originally sampled and evaluated are shown. In fig. (b), only models satisfying the constraint $m(\tilde{\chi}_1^\pm) > 92$ GeV set by LEP [90] are shown. The horizontal dashed line represents the DM relic density measurement by the Planck Collaboration, interpreted as an upper limit such that the $\tilde{\chi}_1^0$ can be a sub-dominant DM component.

Abbreviations

BSM beyond the Standard Model. 170

DM dark matter. 168–170, 204

LEP Large Electron Positron. 160, 169, 204

LHC Large Hadron Collider. 159, 170

LSP lightest supersymmetric particle. 159–162, 164–166, 168, 169, 200–202, 204

NLO next-to-leading order. 159

PDF parton distribution function. 160

pMSSM phenomenological Minimal Supersymmetric Standard Model. 157, 159–162, 164–170, 199–204

SM Standard Model. 159

SUSY Supersymmetry. 157, 159, 166, 169, 170

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