Suche nach Elektroweakinos mit dem ATLAS Detektor

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Dissertation

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March 2021

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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 to some extent efforts and methods to reinterpret ATLAS searches for Supersymmetry (SUSY), this chapter presents a reinterpretation of the 1-lepton analysis in the phenomenological Minimal Supersymmetric Standard Model (pMSSM). The truth analysis and simplified likelihoods discussed in chapters 9 and 10, respectively, are instrumental for the following sections.

11.1 Motivation

In today's searches for beyond the Standard Model (BSM) physics, it is common to use simplified models as a way of avoiding to necessity to deal with high-dimensional parameter spaces that are extremely challenging to sample and compare to data in an exhaustive way. The simplified model approach has also been used in the second part of this work, where results of the interpretation of the 1-lepton analysis in the $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to Wh\tilde{\chi}_1^0\tilde{\chi}_1^0$ model have been presented. As has been discussed in section 1.2.7, simplified models are however by no means complete SUSY models and 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. Large-scale reinterpretations are necessary to understand the constraints today's 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 approximation as those introduced in chapters 9 and 10.

Large-scale reinterpretations in the pMSSM using a collection of relevant ATLAS SUSY searches not only allow to assess the sensitivity of the ATLAS SUSY search program towards more realistic SUSY scenarios, but can also potentially reveal interesting regions of the parameter space not yet covered by the current search programme. Moreover, such reinterpretations allow to demonstrate the sensitivity of simplified model searches beyond the simplified models they are originally interpreted in, thereby justifying the use of simplified models as proxies for more complete SUSY scenarios. In addition, reinterpretations in the pMSSM can be used to connect

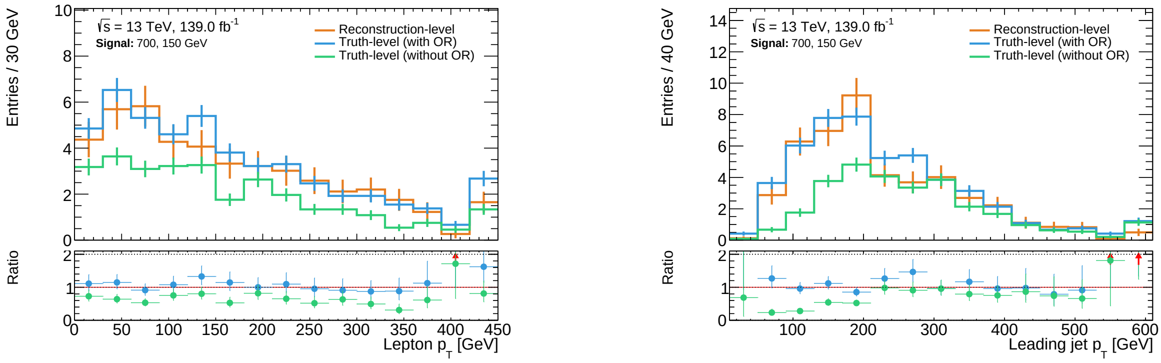


Figure 11.1: Impact of the overlap removal procedure at truth-level illustrated in the lepton and leading jet transverse momenta distributions. The truth-distribution without overlap removal (green) generally underestimates the number of signal events at reconstruction-level (orange). Correct overlap removal procedure at truth-level (blue) improves the agreement. The exemplary benchmark signal point with $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 700, 150\,\mathrm{GeV}$ is shown in both plots (at truth- and reconstruction-level). All distributions are shown in a loose preselection requiring exactly one lepton, $E_\mathrm{T}^\mathrm{miss} > 50\,\mathrm{GeV}$, $m_\mathrm{T} > 50\,\mathrm{GeV}$, and 2–3 jets, two of which need to be b-tagged.

the ATLAS SUSY searches with dark matter constraints from non-collider experiments, as well as Higgs and flavour measurements.

Although the following sections will be restricted to a reinterpretation of the 1-lepton search presented in the second part of this thesis, efforts are ongoing in ATLAS to perform large-scale reinterpretations using a majority of the full Run 2 ATLAS SUSY searches. These efforts will most likely result in one of the most comprehensive set of ATLAS constraints on SUSY yetope.

11.2 Truth-level analysis

As discussed in chapter 9, the reinterpretation of an analysis involves re-executing the analysis pipeline in order to derived signal rate estimates in all regions. In large-scale reinterpretations, running a Recast implementation on all signal models considered is not computationally feasible and instead a *truth-level* analysis is first performed for all signal models sampled. Only models with uncertain exclusion at truth-level are processed through the computationally expensive full analysis chain implemented in Recast. The truth-level analysis skips the detector simulation and uses generator-level objects instead. Any detector-level effects and inefficiencies will thus not be reflected in truth-level observables. In order to reproduce the kinematic distributions observed in the full analysis (using reconstruction-level objects), a dedicated *truth smearing*—discussed in detail in section 11.2.2—is applied.

11.2.1 Truth selection

All signal and control regions considered in the original 1-lepton search are implemented at truth-level using SimpleAnalysis. The exact implementation is publicly available at Ref. [258]

and was already used in chapter 7 for the derivation of some of the theory uncertainties in the full analysis.

The truth-level implementation full specifies all object definitions introduced in section 4.4 even though some of them, like e.g. lepton isolation, are technically not well-defined at truth-level The subsequent smearing is in many cases implemented as a function of said object definitions and thus allows to consider them nonetheless. Additionally, as discussed in section 9.1, the full specification of the original analysis event selection including all object definitions allows for simpler reinterpretations by efforts outside of the ATLAS collaboration that generally do not have access to the original analysis software.

Following the object definitions, an overlap removal procedure following the same prescription as described for the reconstruction-level analysis is performed, i.e. especially also using the same shrinking cone definitions introduced in section 4.5. Overlap removal step removing electrons sharing a track with a muon is approximated by using a distance parameter of $\Delta R = 0.01$ between the objects. Although often neglected† in reinterpretation efforts outside of the collaboration, the correct implementation of the overlap removal procedure employed in the original analysis is typically crucial to reproduce the signal estimates of the original analysis, as illustrated in fig. 11.1. Furthermore, the exact implementation of all analysis observables is explicitly given in the SimpleAnalysis implementation, followed by the full definition of all control and signal regions.

11.2.2 Truth smearing

The general assumption of the truth smearing applied in the following is that the detector response roughly factorises into the responses of single particles. This allows to use detector performance results provided by ATLAS in order to construct detector response maps parameterised in different observables for each physics object. Detector response maps include object reconstruction and identification efficiencies as well as scale factors to correct for differences between Monte Carlo (MC) and observed data. Likewise, effects from the finite resolution of energy measurements in the detector are modelled through energy resolution maps. In the following, the 4-vector components of electrons, muons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ are smeared. The implementation of the smearing functions is internal to ATLAS and originates predominantly from various upgrade studies.

In the case of truth electrons, the identifications efficiencies considered are parameterised in η and p_{T} as well as the identification working point used. In η, nine fixed-width bins are used. In p_{T}, six bins are implemented and a linear interpolation between two adjacent p_{T}-bins is used to get the efficiency for the given p_{T} of each truth electron. The probability of finding a fake electron in a truth jet is estimated through a similar two-dimensional map depending on the truth jet η and p_{T}, again using fixed-width bins in η and a linear interpolation in p_{T}. The range of the p_{T} interpolation for identification efficiencies and fake rates extends from 7 GeV to 120 GeV. If the truth p_{T} of the electron is outside of that range, the identification efficiency and fake rate from the respective bound of the corresponding η-bin are used. The probability for misidentifying an electron as a photon is estimated using different fixed values for the barrel

† The overlap removal procedures in ATLAS SUSY searches tend to be quite intricate, making them non-trivial to re-implement without ATLAS and analysis-specific knowledge.

and end-cap regions. Finally, the transverse energy of the electron is smeared using a random number drawn from a Gaussian distribution with standard deviation corresponding to the η- and p_{T}-dependent energy resolution.

For truth muons, the identification efficiencies are also parameterised in η and p_{T} as well as the identification working point used. Similar to truth electrons, the p_{T} of the muon is smeared using a Gaussian distribution with standard deviation corresponding to the momentum resolution. The momentum resolution of combined truth muons, σ_{CB}, is computed from the measured resolutions in the inner detector (ID),σ_{ID}, and muon spectrometer (MS), σ_{MS}, as

$$\sigma_{\mathrm{CB}} = \frac{\sigma_{\mathrm{ID}}\sigma_{\mathrm{MS}}}{\sqrt{\sigma_{\mathrm{ID}}^2 + \sigma_{\mathrm{MS}}^2}}, \tag{11.1}$$

where σ_{ID} and σ_{MS} are parameterised in η and p_{T}.

The transverse momentum of truth jets is smeared using a Gaussian with standard deviation equal to the jet energy resolution (JER), provided in a map parameterised in five bins in η ranging from $|\eta| = 0$ to $|\eta| = 4.5$. Following [216], jet energy resolutions are provided using parameterisations of a noise N, stochastic S and constant C term for each of the seven bins in $|\eta|$, such that the resolution can be computed as

$$\frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}} = \frac{N}{p_{\mathrm{T}}} \oplus \frac{S}{\sqrt{p_{\mathrm{T}}}} \oplus C. \tag{11.2}$$

Only truth jets with $10\,\mathrm{GeV} < p_{\mathrm{T}} < 1.5\,\mathrm{TeV}$ are smeared. For truth jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, the flavour tagging efficiency is considered using efficiencies parameterised in η, p_{T} and the MV2c10 working point (introduced in section 4.4) used, measured in fully reconstructed simulated $t\bar{t}$ events [222].

Finally, the smeared missing transverse energy is computed using the transverse momenta of all smeared truth objects in the event, including an approximation for the track soft term. The latter is approximated using results from $Z \to e^+e^-$ events, allowing to infer a distribution of the mean soft term projected in the direction longitudinal to the total transverse momentum of all hard objects in an event, $\boldsymbol{p}_{\mathrm{T}}^{\mathrm{hard}}$. The measured resolution parallel and perpendicular to $\boldsymbol{p}_{\mathrm{T}}^{\mathrm{hard}}$ is then used to smear the nominal soft track value.

11.3 Validation of the truth-level analysis

11.3.1 Validation in loose preselection

The performance of the truth smearing is illustrated in a loose preselection for a single exemplary benchmark signal point in fig. 11.2. The loose preselection applied requires exactly one lepton, $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$, $m_{\mathrm{T}} > 50\,\mathrm{GeV}$, and 2–3 jets, two of which need to be b-tagged. The reconstruction-level distributions are compared with the truth-level distributions before and after truth smearing. It can clearly be observed that the truth smearing noticeably improves the agreement between the truth- and reconstruction-level distributions. While the lepton and jet reconstruction and identification efficiencies are—due to their dependence on η, p_{T}

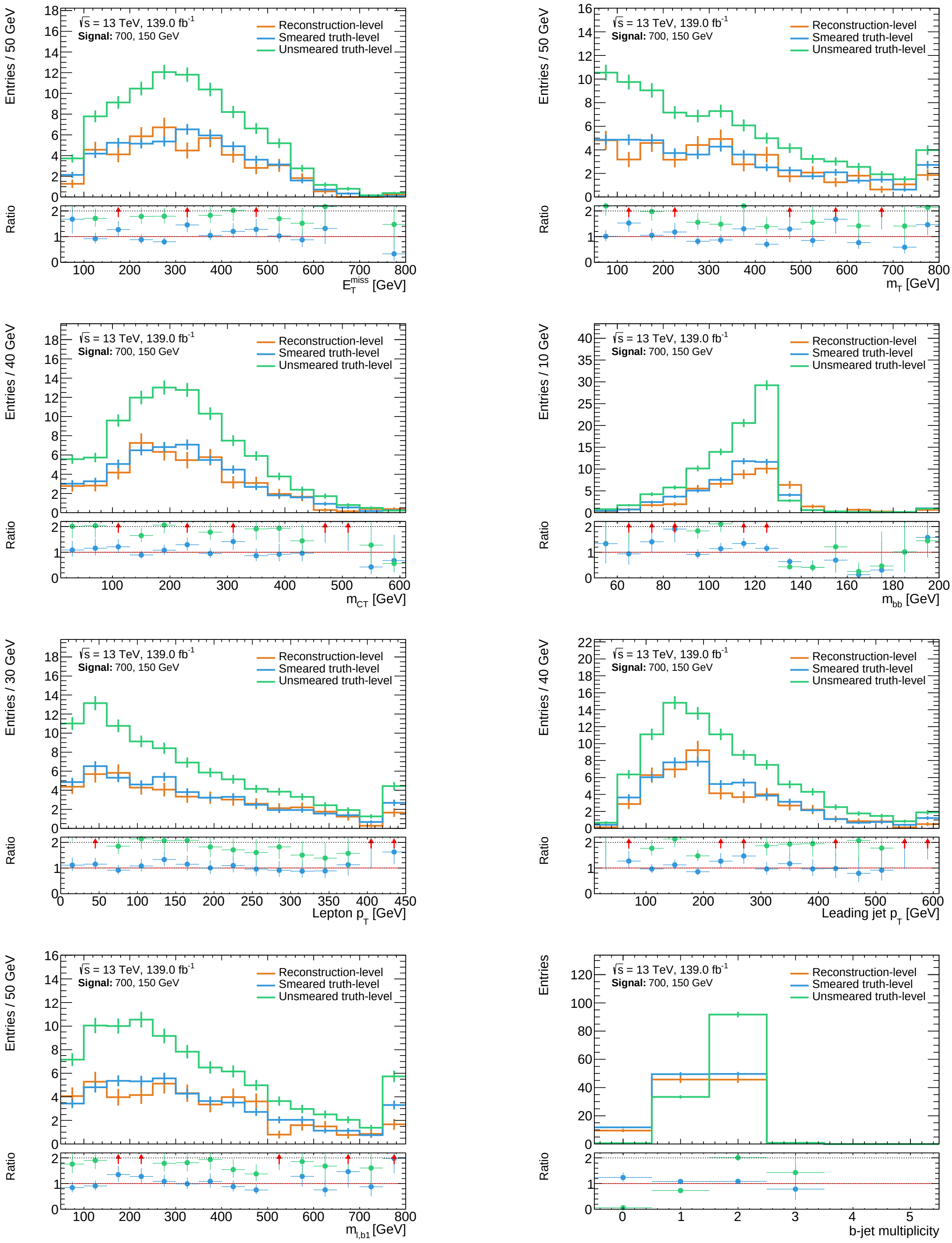


Figure 11.2: Comparisons of the kinematic distributions of key observables at (smeared) truth- and reconstruction-level. The exemplary benchmark signal point with $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 700, 150\,\text{GeV}$ is shown. The ratio pad shows the ratio between smeared and unsmeared truth-level distributions (blue and green) to reconstruction-level distributions (orange). Only MC statistical uncertainty is included in the error bars. All distributions are shown in a loose preselection requiring exactly one lepton, $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\text{GeV}$, $m_{\mathrm{T}} > 50\,\text{GeV}$, and 2–3 jets, two of which need to be b-tagged. The latter requirement is dropped for the b-jet multiplicity distribution.

and individual working points—crucial for the overall agreement in shape, the inclusion of flavour-tagging efficiencies significantly improves the overall agreement in normalisation.

Although some minor differences remain, overall a good agreement is observed across all relevant kinematic distributions at loose preselection level. Most of the differences between smeared truth-level and reconstruction-level distributions in individual bins are well within the MC statistical uncertainties arising from the relatively limited MC statistics available.

11.3.2 Validation in signal regions

As the expected signal rates in the signal regions are ultimately what is entering the (simplified) likelihood, it is important that the good agreement observed at preselection is still present in the kinematically tighter selections of the signal regions. Additionally, it is worth investigating the agreement across all signal models considered in the original analysis, as opposed to only validating specific benchmark points. A comparison of the reconstruction-level and truth-level event rates before and after smearing in the signal regions SR-LM, SR-MM and SR-HM is shown in fig. 11.4 for all signal models considered in the 1-lepton analysis. For the sake of conciseness, only the cumulative m_{CT} bins are shown in each signal region (SR) in fig. 11.4. The agreement in the individual m_{CT} bins in each SR-LM, SR-MM and SR-HM is provided in figs. C.1 to C.3.

The truth smearing drastically improves the agreement in event rate estimates at truth- and reconstruction-level across all SR bins considered. While the event rates are generally overestimated at truth-level before smearing, compared to reconstruction-level, both tend to agree well within statistical uncertainties after smearing.

11.3.3 Validation using likelihood

Using the nominal expected event rates at smeared truth-level for every signal model in the original signal grid considered in the 1-lepton analysis, expected and observed CL_s values can be computed and exclusion contours can be derived. Figure 11.4(a) compares the expected and observed exclusion contours obtained using the full likelihood and reconstruction-level signal inputs with those obtained using the full likelihood and truth-level signal inputs before and after truth smearing. While all theory and systematic uncertainties on the signal are included in the reconstruction-level contours, no signal uncertainties are considered when obtaining both the smeared and unsmeared truth-level contours. As expected from the previous validation steps in the signal regions, the sensitivity using unsmeared truth-level signal inputs is significantly overestimated compared to the published analysis exclusion limit using reconstruction-level inputs. The smeared truth-level inputs, however, yield exclusion contours with an acceptable match compared to the reconstruction-level results.

With the truth smearing validated at multiple selection levels of the analysis, the full two-fold approximation of signal pipeline and statistical inference can be constructed. Figure 11.4(b) compares the exclusion contours of the original analysis results with those obtained using smeared truth-level signal inputs as well as the simplified likelihood. Even with the approximations made, overall a good agreement is found and the original analysis results can be reproduced to a relatively high degree of precision.

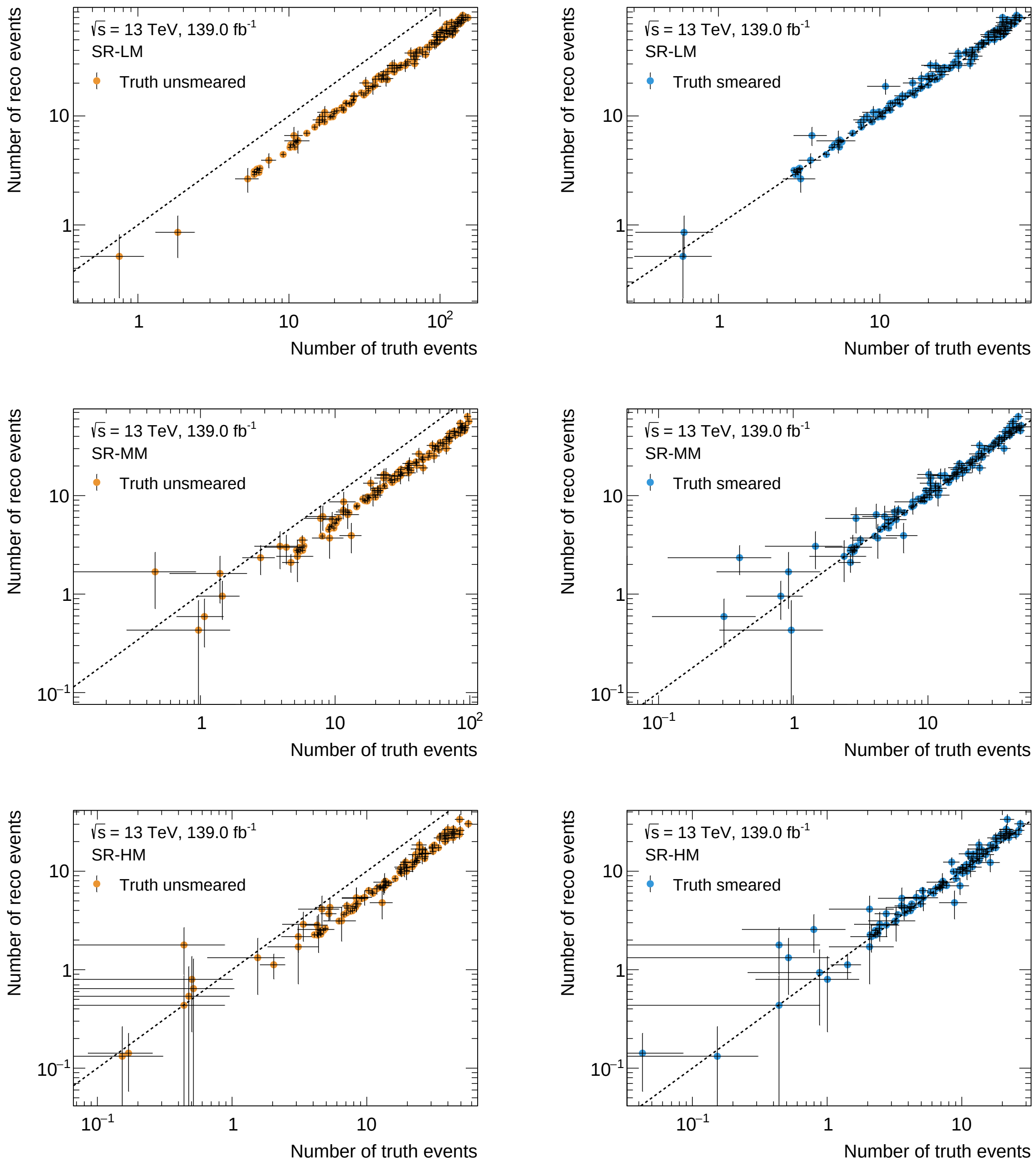
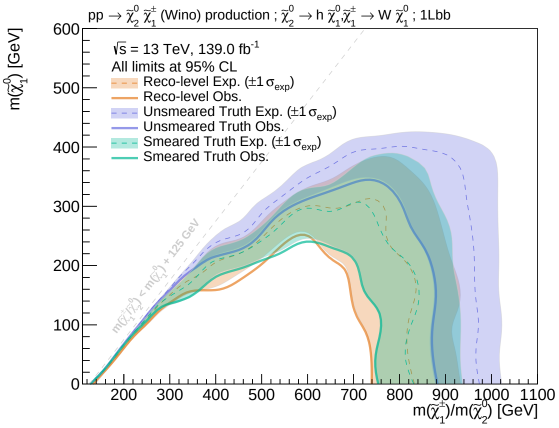
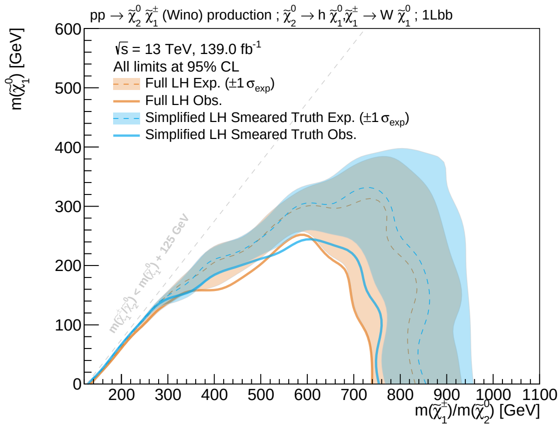


Figure 11.3: Comparison of the event rates at truth- and reconstruction-level before (left) and after (right) truth smearing. From top to bottom, the SR-LM, SR-MM and SR-HM signal regions are shown, with cumulative (integrated) m_{CT} bins. Every single point in the scatter plots represents a single signal model considered in the original 1-lepton analysis. Uncertainties include MC statistical uncertainties.



(a)



(b)

Figure 11.4: Expected and observed exclusion contours obtained with the full and simplified likelihoods. Fig. (a) compares the full likelihood contours obtained with the reconstruction-level inputs (orange) to results obtained with truth inputs before (purple) and after (green) smearing. Fig. (b) compares the full likelihood reconstruction-level contours (orange) with those obtained using the simplified likelihood and smeared truth-level inputs (blue). Uncertainties include all statistical and systematic uncertainties on the background and signal for the reconstruction-level contours, but only statistical and systematic uncertainties on the background for truth-level signal inputs.

In summary, this validation process shows that the signal pipeline in fig. 9.1 can be efficiently approximated using truth-level analysis and a simplified treatment of the statistical model, allowing a considerably faster evaluation of BSM models while still offering reliable results. In large-scale reinterpretations, this approach thus enables an efficient classification of models into safely excluded and non-excluded models as well as models where exclusion is in doubt and where the full analysis pipeline using RECAST is needed.

11.4 Model sampling and processing

11.4.1 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 SUSY model.

As this work discusses a search for electroweakinos, the SUSY models drawn from the pMSSM are sampled with a special focus on said supersymmetric particles. This is achieved by setting the mass parameters of the first and second generation squarks as well as those of the sleptons to values much higher than those accessible at Large Hadron Collider (LHC) energies, effectively decoupling them. 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 to yield a high density of models with electroweakino masses accessible at LHC energies.

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).

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
$\lvert M_1\rvert$	0 TeV	2 TeV	Bino mass parameter
$\lvert M_2\rvert$	0 TeV	2 TeV	Wino mass parameter
$\lvert\mu\rvert$	0 TeV	2 TeV	Bilinear Higgs mass parameter
M_3	1 TeV	5 TeV	Gluino mass parameter
$\lvert A_t\rvert$	0 TeV	8 TeV	Trilinear top coupling
$\lvert A_b\rvert$	0 TeV	2 TeV	Trilinear bottom coupling
$\lvert A_\tau\rvert$	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

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 point. In a first step, SPheno v4.0.5 [274, 275] is used to calculate the spectrum of the sparticles. The result of SPheno is used to determine the masses and mixings of the Higgs bosons using FeynHiggs v2.16.0 [276–278], after which SPheno is re-executed in order to update the rest of the sparticle spectrum. An additional SUSY spectrum calculation is performed with SoftSusy v4.1.10 [279]. Although the masses, mixings and branching fractions from SoftSusy will not directly be 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 calculated, additional properties are determined. The dark matter relic abundance of each model is calculated with micrOMEGAs v5.2.1 [280, 281]. Finally, flavour physics and precision electroweak observables like $\Delta\rho$, $\Delta(g-2)_\mu$, $\mathrm{BR}(b \to s\gamma)$ and $\mathrm{BR}(B_s \to \mu^+\mu^-)$ are determined using GM2Calc v1.7.1 [282] and SuperIso v4.0 [283].

11.4.2 Selection and processing

In order to avoid models with pathological properties, all spectrum generators are required to finish execution without error. The cross section for surviving models is computed at next-to-leading order (NLO) using Prospino v2.1 [284, 285]. Models with an inclusive cross sections for all electroweak 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 fb^{-1}, not enough to be sensitive to with current electroweak SUSY searches. For the sake of experimental sensitivity, models are also required to have a lightest chargino with mass below 1.2 TeV and produce a neutralino lightest supersymmetric particle (LSP). Finally, models with long-lived or even stable (on the time scale needed for traversing the ATLAS detector) sparticles† are discarded as SUSY searches targeting prompt electroweakino decays (like the 1-lepton search), are not expected to be sensitive to these models.

Furthermore, as only R-parity conserving models are considered, the LSP is stable and thus has a non-vanishing cosmological abundance. The resulting LSP abundance is required to be below the experimentally observed value of the cold dark matter relic density of $\Omega_c h^2 = 0.12$, thus not making a statement about whether or not the LSP is the only dark matter (DM) particle. No constraints on the computed precision electroweak and flavour observables are applied. Experimental constraints from e.g. Large Electron Positron (LEP) are also not applied at this stage.

Of the 200,000 unique models sampled from the pMSSM using the above prescription, 90,974 models survive the constraints and requirements discussed in this section. The majority of the models rejected are SUSY scenarios that do not satisfy the DM relic density constraint.

11.4.3 Event generation

Event generation is performed using the software centrally provided by the ATLAS production system. The initial pair of sparticles with two one parton in the matrix element (ME) are generated using the MadGraph5_aMC@NLO v2.6.1. [175, 176] generator. Next, Pythia8.230 [177] with the A14 tune is used for the hadronisation and parton shower (PS), together with the NNPDF 2.3 LO [179] parton distribution function (PDF) set. The number of events generated scales with the cross section of the model, starting at 10^4 and capping out at 10^6 truth-level events.

11.4.4 Truth-level analysis

All models passing event generation are evaluated using the truth-level analysis described in section 11.2. This is the only evaluation done for the models considered in this work. A full scan over the pMSSM including multiple ATLAS SUSY searches would most likely include an additional processing step reverting to reconstruction-level analysis including the original analysis pipelines and full detector reconstruction for model points where (non-)exclusion is uncertain based on truth-level analysis only.

11.5 Impact of the 1-lepton search on the pMSSM

The impact of the 1-lepton search on the pMSSM is discussed using one-dimensional and two-dimensional distributions in the following sections. As usual, a model is considered to be excluded if the observed CL_s value obtained from the simplified likelihood using the smeared truth-level inputs is below 0.05. Of the 7264 models evaluated, the 1ℓ search excludes a total of 98, or about 1.3%, of the models.

† Not considering the LSP.

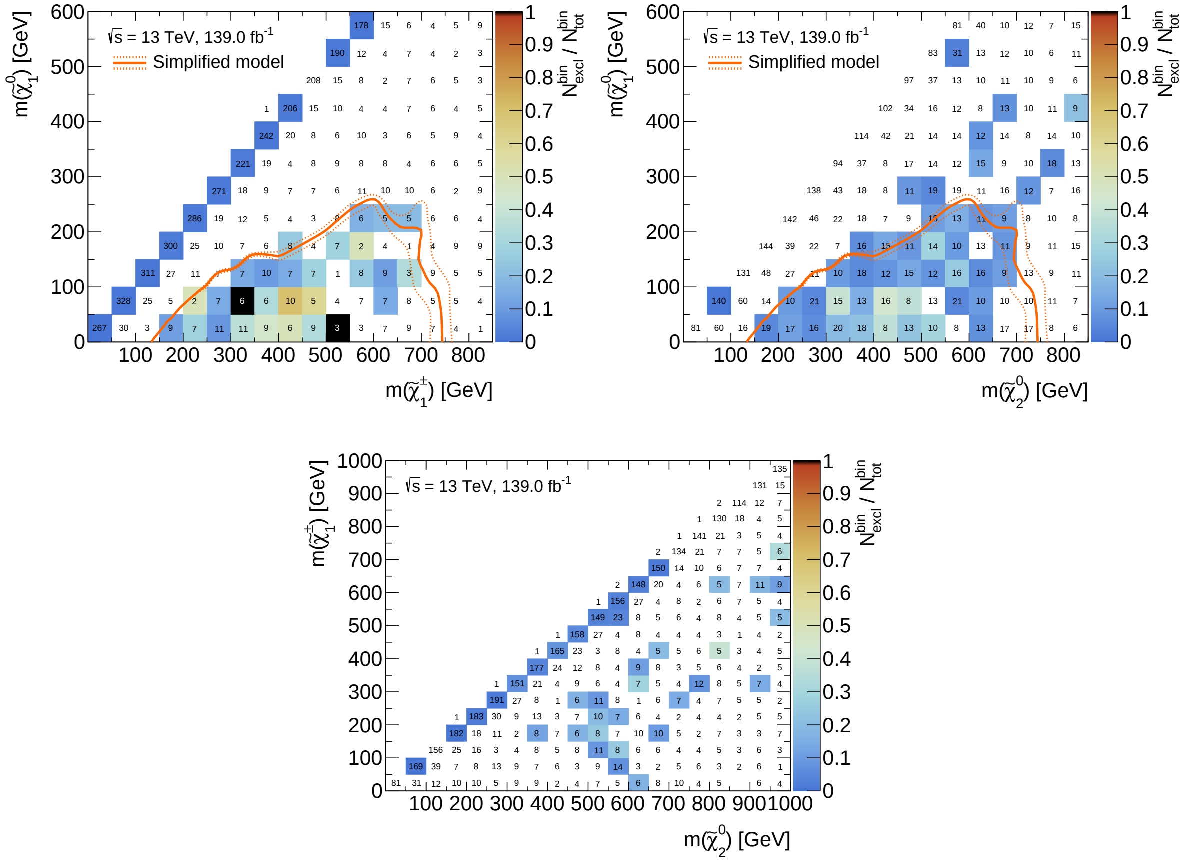


Figure 11.5: Bin-by-bin fraction of excluded models as a function of the relevant sparticle masses. The numbers in the bins correspond to the total number of models sampled falling into the respective bin. The number of models excluded by the 1-lepton analysis is encoded with a colour bar ranging from 0 to 1. Where all models in a given bin are excluded, the bin is coloured in black. Bins without a models excluded are left white. Models are evaluated using the simplified likelihood of the 1-lepton analysis.

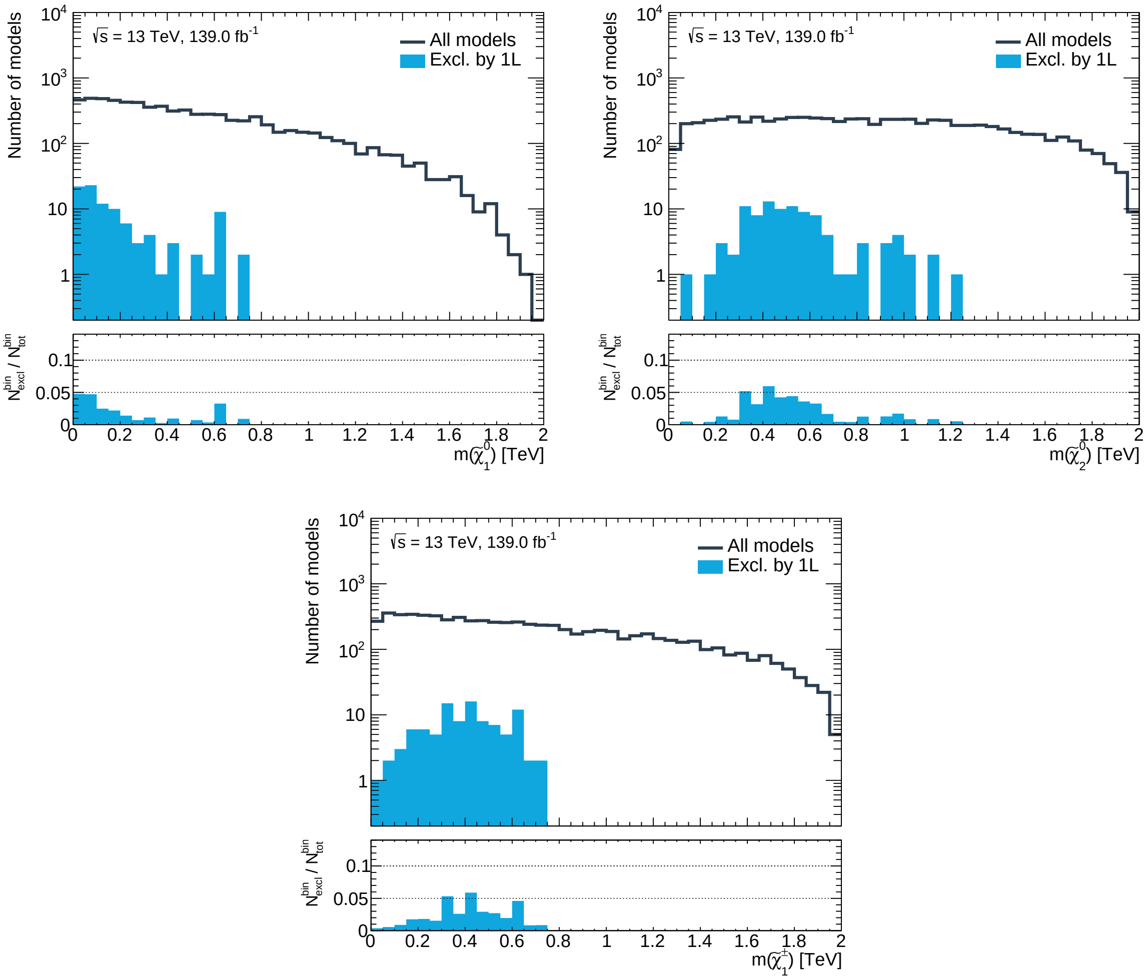
For the one-dimensional distributions shown in the following, the total number of models is compared against the number of models excluded by the 1ℓ search. An additional pad indicates the ratio between models excluded and total models sampled in each bin of the distribution. In the two-dimensional distributions, the numbers in the bins indicate the number of pMSSM models falling into each respective bin. In these distributions, the fraction of models excluded with the 1ℓ search is encoded using the z-axis, represented by a colour bar.

11.5.1 Impact on electroweakino masses

Figure 11.5

11.5.2 Impact on pMSSM model parameters

11.5.3 Impact on dark matter



Number of models
$\sqrt{s}$ = 13 TeV, 139.0 fb^{-1}
All models
Excl. by 1L
$N^{bin}_{excl} / N^{bin}_{tot}$
m($\tilde{\chi}^0_1$) [TeV]
m($\tilde{\chi}^0_2$) [TeV]
m($\tilde{\chi}^{\pm}_1$) [TeV]

Figure 11.6

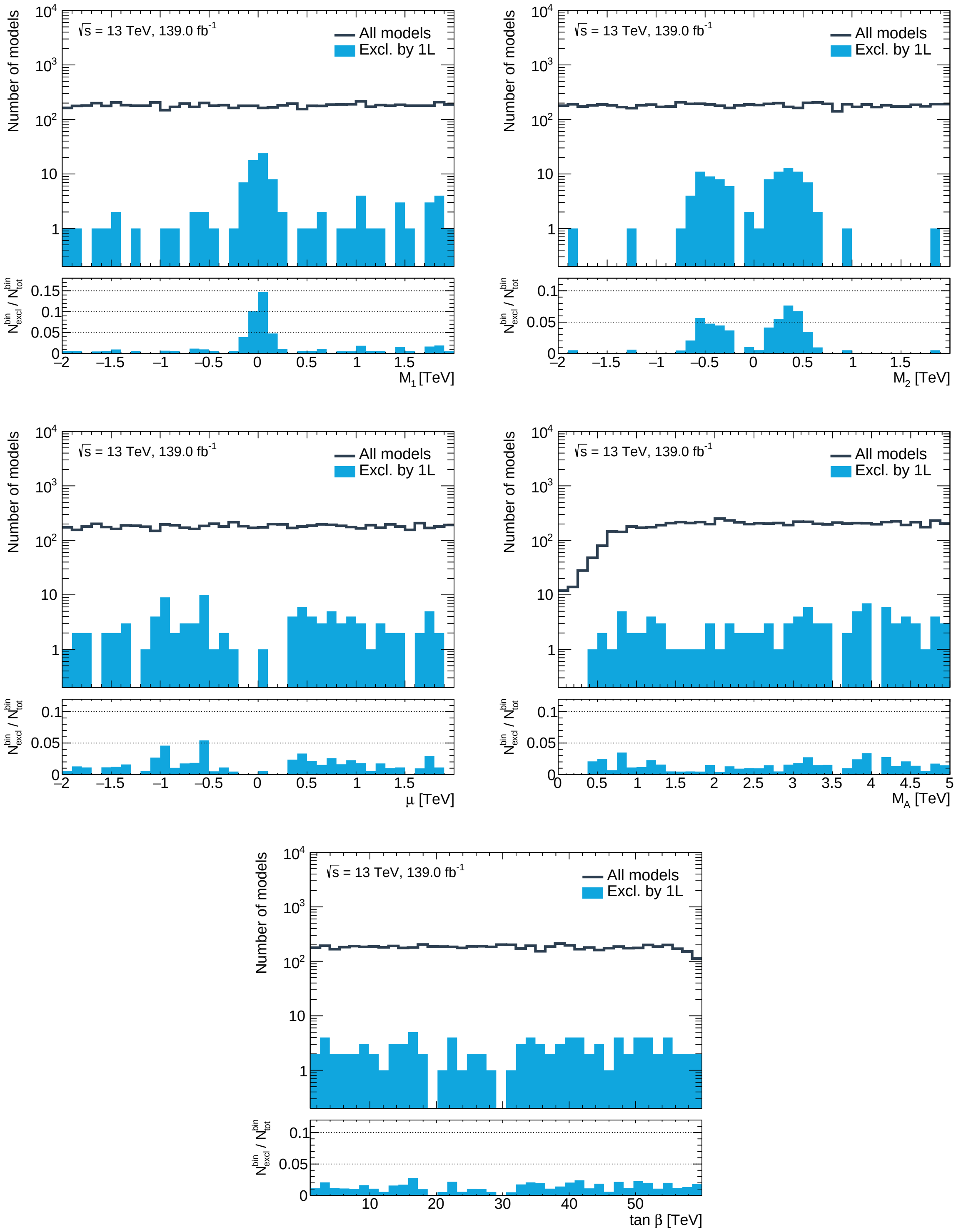

√s = 13 TeV, 139.0 fb⁻¹
All models
Excl. by 1L
Number of models
$N^{bin}_{excl} / N^{bin}_{tot}$
M_1 [TeV]
M_2 [TeV]
μ [TeV]
M_A [TeV]
tan β [TeV]

Figure 11.7

Part IV

Summary and Outlook

Part V

Appendix

Abbreviations

BSM beyond the Standard Model. 147, 154

DM dark matter. 156

ID inner detector. 150

JER jet energy resolution. 150

LEP Large Electron Positron. 156

LHC Large Hadron Collider. 154

LSP lightest supersymmetric particle. 156

MC Monte Carlo. 149, 151–153

ME matrix element. 156

MS muon spectrometer. 150

NLO next-to-leading order. 155

PDF parton distribution function. 156

pMSSM phenomenological Minimal Supersymmetric Standard Model. 147, 154–157

PS parton shower. 156

SR signal region. 152

SUSY Supersymmetry. 147–149, 154–156

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