Suche nach Elektroweakinos mit dem ATLAS Detektor

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Dissertation

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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 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 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 performed for most signal models sampled. 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 a number of the theory uncertainties in the full analysis.

Although a number of object definitions introduced in section 4.4 are not well-defined at truth-level, they are nonetheless specified in the truth-level implementation as the subsequent truth smearing may depend on them. Additionally, as discussed in section 9.1, the full specification of the original analysis event selection allows for simpler reinterpretations by efforts outside of the ATLAS collaboration that generally do not have access to the full original analysis software.

All observables used in the analysis are computed using truth-level quantities. 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.

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 the *combined performance groups* in 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.

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 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 and end-cap regions. Finally, the transverse energy of the electron is smeared using a random number drawn from a Gaussian distribution with mean corresponding to the truth value and a 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 random number drawn from a Gaussian distribution with mean corresponding to the true transverse momentum, and standard deviation corresponding to the momentum resolution. The momentum resolution of combined truth muons 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 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 truth analysis

11.3.1 Validation at loose preselection

The performance of the truth smearing is illustrated in a loose preselection for a single exemplary benchmark signal point in fig. 11.1. 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 truth-level distributions are compared with the reconstruction-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 general dependence on η, p_{T} 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 tight selections of the signal regions. Additionally, it is worth investigating the agreement across all signal models considered in the original analysis. A comparison of the truth-level and reconstruction-level event rates before and after smearing in the signal regions SR-LM, SR-MM and SR-HM is shown in fig. 11.2 for all signal models considered in the 1-lepton analysis. Only the cumulative m_{CT} bins are shown in each signal region (SR) in fig. 11.2. The agreement in the individual m_{CT} bins in each SR-LM, SR-MM and SR-HM is shown in figs. D.1 to D.3.

It can clearly be seen that 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 simplified likelihood

Using the 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 11.3 compares the expected and observed exclusion contours obtained using the simplified likelihood and smeared truth-level signal inputs with those obtained using the full likelihood and reconstruction-level signal inputs. Even though—with the simplified likelihood and the smeared truth-level inputs—a significant two-fold approximation is made, the agreement is overall quite good and the published exclusion contour can be reproduced to a relatively high degree of precision.

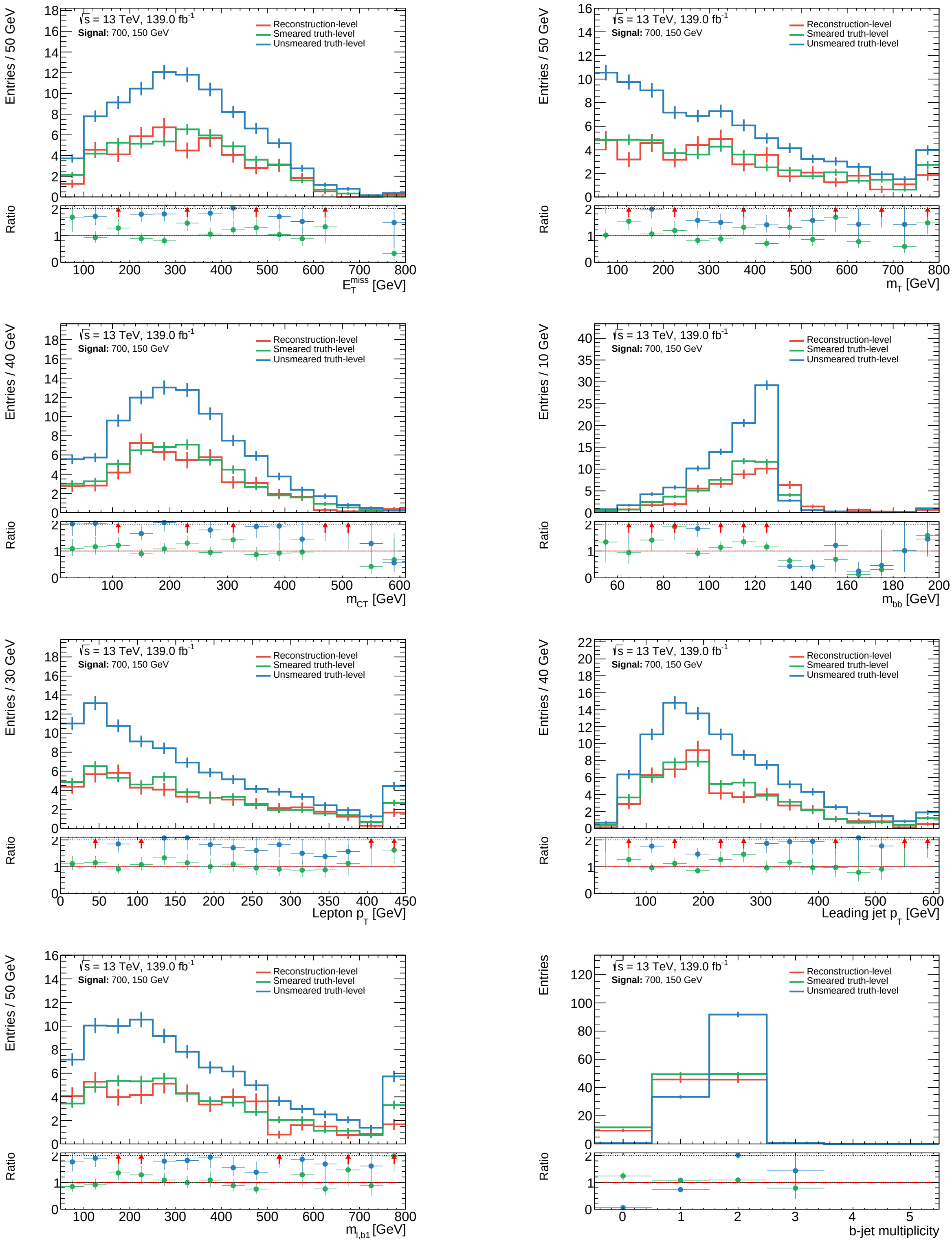

Figure 11.1: Comparisons of the kinematic distributions of key observables at (smeared) truth- and reconstruction-level. The exemplary benchmark signal point with $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 700, 150\,\text{GeV}$ is shown. The ratio pad shows the ratio between smeared and unsmeared truth-level distributions (green and blue) to reconstruction-level distributions (red). 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.

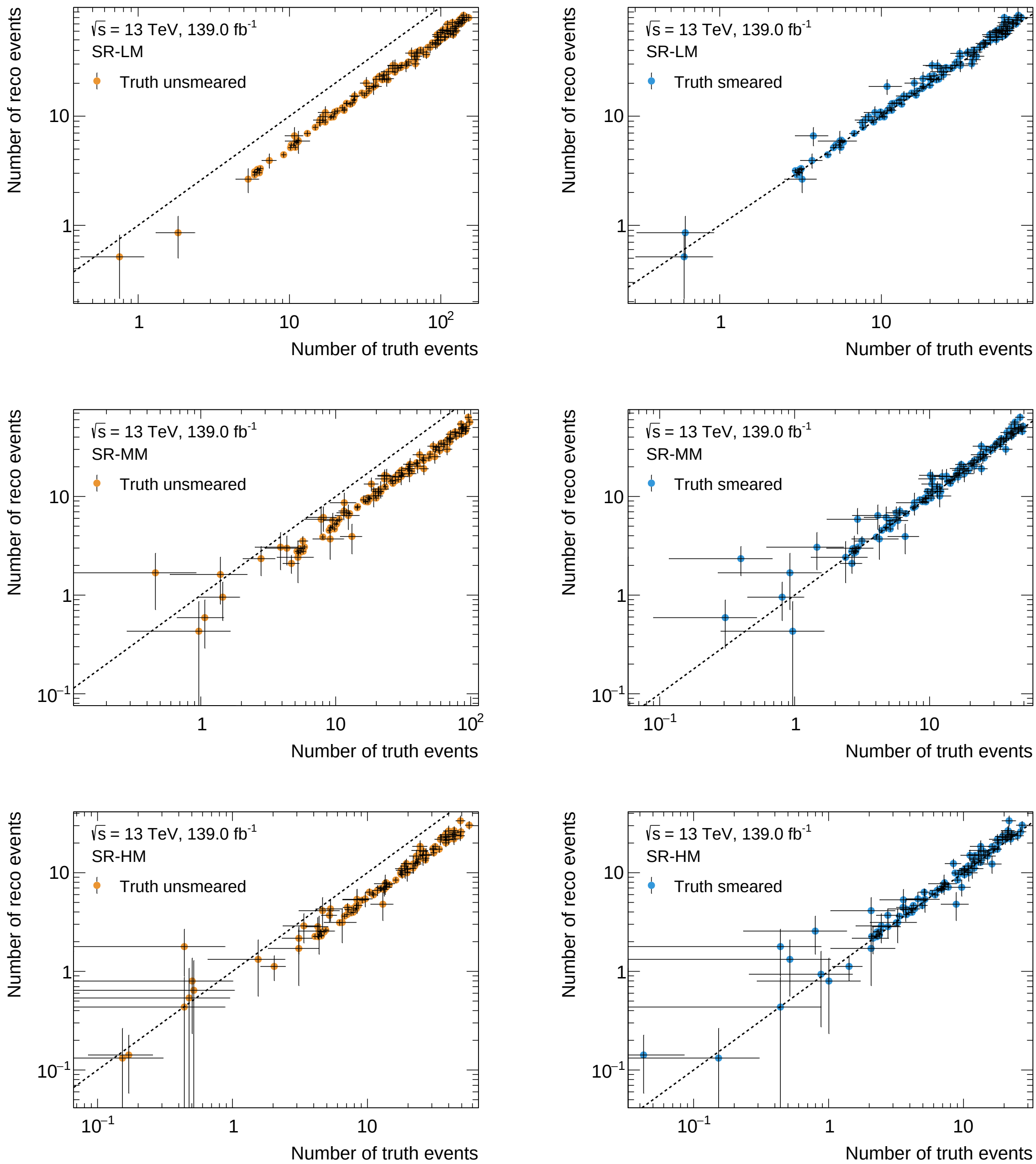

Figure 11.2: Comparison of the event rates at truth- and reconstruction-level before (left) and after (right) truth smearing. From top to bottom, the SR-LM, SR-MM and SR-HM signal regions are shown, with cumulative (integrated) m_{CT} bins. Every single point in the scatter plots represents a single signal model considered in the original 1-lepton analysis. Uncertainties include MC statistical uncertainties.

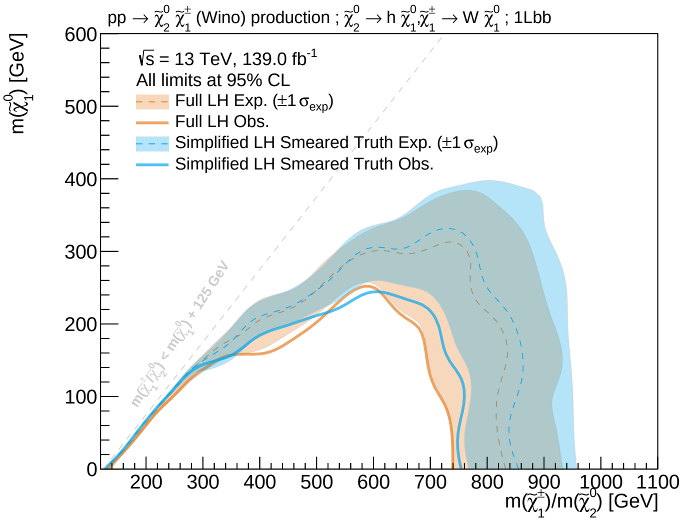

Figure 11.3

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.

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.

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.

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
$\|M_1\|$	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

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

A total of 200,000 unique models are sampled from the pMSSM using the above prescription. After requiring all spectrum generators and properties calculations to finish without errors as well as models to produce a dark matter relic density satisfying $\Omega_c h^2 < 0.12$, a total of 106,854 models survive. The cross section for all 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. Models are also discarded for lack of experimental sensitivity if the $\tilde{\chi}_1^\pm$ is heavier than 1.2 TeV. Next, models are only considered in the following if their lightest supersymmetric particle (LSP) is the $\tilde{\chi}_1^0$. 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.

[†] Not considering the LSP.

Altogether, 90,974 of the pMSSM models sampled satisfy all constraints and are generated at truth-level in a subsequent step.

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. [174, 175] generator. Next, Pythia8.230 [176] with the A14 tune is used for the hadronisation and Parton Shower (PS), together with the NNPDF 2.3 LO [178] Parton Distribution Function (PDF) set.

11.4.4 Truth-level analysis

All models passing event generation are evaluated using the truth-level analysis described in section 11.2.

11.5 Results in the pMSSM

Part IV

Summary and Outlook

Part V

Appendix

Abbreviations

BSM beyond the Standard Model. 143, 149

ID inner detector. 145

JER jet energy resolution. 145

LHC Large Hadron Collider. 149

LSP lightest supersymmetric particle. 150

MC Monte Carlo. 144, 146–148

ME Matrix Element. 151

MS muon spectrometer. 145

NLO next-to-leading order. 150

PDF Parton Distribution Function. 151

pMSSM phenomenological Minimal Supersymmetric Standard Model. 143, 149–151

PS Parton Shower. 151

SR signal region. 146

SUSY Supersymmetry. 143, 144, 149, 150

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