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Search for electroweakinos with the ATLAS detector

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Chapter 9

Preservation and reusability

Particle physics experiments such as the Large Hadron Collider (LHC) experiments are designed to collect physics data over several decades, and operate at scales and complexities that make an independent and complete replication unfeasible [261]. Due to their uniqueness, the data taken at these experiments and the physics results derived are highly valuable and challenge the scientific method from a reproducibility and reusability point of view [261].

In the following, reusability problems directly related to the computational analysis of a given dataset[†] are discussed, and approaches taken in view of analysis preservation and reusability are presented. This chapter starts with a brief motivation for *reinterpretations*, i.e. reusing an analysis in light of additional signal models, followed by a description of the main ingredients required. The remaining sections discuss three separate efforts aiming to improve the reusability of the 1ℓ analysis. All three efforts are not only relevant in the scope this thesis, but also for reinterpretation activities currently ongoing within ATLAS.

9.1 The case for reinterpretations

9.1.1 Motivation

Designing and performing searches for beyond the Standard Model (BSM) physics requires a substantial amount of person-power and computing resources. As laid out in detail in part II of this thesis, an analysis generally aims to design signal regions in which a given BSM signal can be efficiently discriminated against Standard Model of particle physics (SM) background. Although the careful design of such regions already requires a significant amount of resources, it constitutes only a fraction of the work necessary for concluding the search. Contributions in the signal regions from SM processes need to be estimated, usually requiring expensive Monte Carlo (MC) simulations and the development of background estimation strategies. Systematic uncertainties arising from numerous sources need to be considered and their impact estimated. For the BSM signal, a similar processing pipeline involving MC simulation, event reconstruction and event selection including uncertainties needs to be executed. Furthermore, recorded data also has to be reconstructed and processed through the analysis-specific

[†] This is in contrast to also considering the actual collection of data. As such, the implementation of a computational analysis of a dataset can, in the following, be seen as an experimental setup that needs to be preserved and reusable.

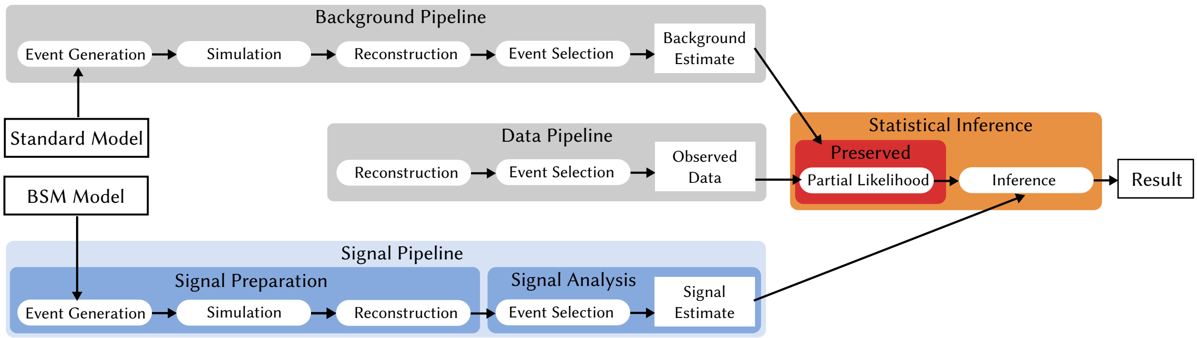

Figure 9.1: Full analysis workflow including the three main processing pipelines for deriving background and signal estimates as well as observed data counts. The outputs of the three processing pipelines are combined into a likelihood forming the basis for the statistical inference. In a Recast setup (details in the text), the estimated background rates and observed data counts are archived, and the signal pipeline is fully preserved, such that it can be re-executed with different inputs at any time. Figure created by the author but based on Ref. [263].

event selection. Only after the expected and observed event rates in all regions are known, the statistical evaluation can be performed, and the final analysis results, like quantifying excesses in data or setting limits on model parameters, can be determined. Figure 9.1 illustrates the formal structure of such an analysis, consisting of three main processing pipelines; a *background pipeline*, a *signal pipeline* and a *data pipeline*; followed by the *statistical inference*.

Due to the substantial amount of resources necessary for developing and performing an analysis, it is not feasible to develop dedicated searches for every possible BSM scenario. Instead, analyses are typically only interpreted in a finite set of models with a small number of free parameters that need to be varied. Still, it is likely that a given analysis is sensitive to a variety of different BSM scenarios not considered in the original publication.

Consequently, it is not surprising that there is significant interest in the high energy physics (HEP) community to reinterpret BSM searches in different signal models. Reinterpretations of ATLAS searches for Supersymmetry (SUSY) are routinely performed by various reinterpretation efforts. In the context of direct constraints on BSM physics†, the search results published by the experimental collaborations represent the only windows into the LHC data that are available to the wider HEP community. Reinterpretations of BSM searches are thus the only possibility to determine the implications of LHC data for a broad range of models [262].

As will be discussed in detail in chapter 11, reinterpretations are not only of interest for the wider HEP community, but also for the experimental collaborations themselves. Within ATLAS, reinterpretations of SUSY searches in complete SUSY models can, for example, serve as powerful tools to state a comprehensive summary of the overall sensitivity to more realistic supersymmetric models. As such, the efforts discussed in the remainder of this chapter, as well as in chapters 10 and 11, are not only relevant for the work presented in this thesis, but also reinterpretation efforts currently ongoing within ATLAS.

† As discussed to some extent in ??, indirect constraints on BSM models can also come from SM precision measurements.

9.1.2 Approaches for reinterpretations

As the event selection of an analysis is fixed, the *pre-fit* background estimates (i.e. the estimated background rates before the background-only fit described in section 8.1) and observed data counts in the regions of interest of the analysis do not change. Hence, the data and background pipelines shown in fig. 9.1, entering the statistical inference of the analysis by means of event rates, can be archived in a format significantly smaller than the original input data. In consequence, reinterpreting a search in the light of a new signal model requires the re-execution of two main analysis ingredients with (partially) new inputs; the signal pipeline and the statistical inference.

Recently, it has become possible to preserve, in a pure-text format [161], the partial analysis likelihood[†] built from the background estimates and observed data, including all auxiliary data and details of the statistical model used for inference. In fig. 9.1, this is indicated through a red rectangle. Once the signal estimates are known, a new full analysis likelihood can be built, and the viability of the new signal model can be tested with respect to the analysis in question. The publication of the likelihood of the 1ℓ search will be discussed further in section 9.2.

Different approaches can be taken for rendering the signal pipeline reusable to the extent that signal estimates for a new BSM scenarios of interest can be derived. Manifestly the most precise approach involves executing the original analysis software, but using a different BSM model as input. As this requires the preservation of the entirety of the original software environment, including the workflows used in the analysis, this is arguably the most involved approach, especially since it involves executing the computationally expensive detector simulation. A framework designed to facilitate such an effort, called Recast and originally proposed in Ref. [264], is under development and aims to provide the cyber-infrastructure needed for offering *reinterpretations as a service*. Through a web interface, physicists wishing to reinterpret a search with Recast, would provide an alternative BSM model and trigger a computational workflow that would re-execute the original analysis using the new signal inputs and ultimately deliver the *recasted* results. An attempt to fully preserve the 1ℓ search using the Recast paradigm is discussed in section 9.3.

As the details of the existing Recast implementations of ATLAS searches for SUSY are not publicly available, but only meant to be interacted with through a Recast request, the exact implementation of the analysis selection is in general not available outside the ATLAS Collaboration. For this reason, a number of public tools aiming to reimplement an approximated version of the event selections of a number of BSM searches at the LHC are available. Prominent examples include CheckMate [265, 266] and MadAnalysis5 [267]. ATLAS has internally maintained a similar catalogue of its SUSY analyses and is publishing event selection snippets in C++ for many SUSY searches on HEPData [268], a repository for high energy physics data. Recently, this package maintained by ATLAS, called SimpleAnalysis [269], has been made publicly available, allowing the C++ snippets published to be executed outside the collaboration.

A crucial step, necessary for achieving a reliable reimplementation of the signal pipeline, is the detector simulation. Executing the full detector simulation requires access to the collaborations's detector description and is computationally expensive, disfavouring[§] its usage in the context of large-scale reinterpretations over a large set of models. For this reason, it is often approximated using simplified detector geometries and granularities. The most commonly used package for a fast detector

[†] As before, this only refers to likelihoods built using the HistFactory template.

[§] This is especially true for reinterpretation efforts outside the ATLAS Collaboration, which, for reasons not discussed herein, cannot make use of the collaboration's detector description.

simulation outside of the ATLAS Collaboration is Delphes [270], which is used in, e.g., CheckMate and MadAnalysis5. Other packages like, e.g., Rivet [271, 272] approximate the detector response using dedicated four-vector smearing techniques, assuming that the detector response roughly factorises into the responses of single particles. Internally, ATLAS also maintains a dedicated framework for four-vector smearing, used in scenarios where other fast simulation techniques are still too expensive. Section 9.4.2 discusses these dedicated smearing functions further.

Finally, instead of trying to estimate the signal rates of a new model using MC simulation and (reimplemented) analysis event selections, some reinterpretation efforts like, e.g., SModelS [273, 274], use *efficiency maps* encoding the selection and acceptance efficiencies of the analysis as a function of the model parameters (typically the sparticle masses in the case of SUSY searches) and analysis selections. Such efficiency maps are routinely published on HEPData by ATLAS searches for SUSY, and allow for efficient reinterpretations, as long as the signal efficiencies mostly depend on the signal kinematics and are largely independent from the specific details of the signal model [273]. For the 1ℓ search presented herein, the efficiency maps, including additional analysis data products, are available at Ref. [275].

9.2 Public full likelihood

The likelihood is arguably one of the most information-dense and important data products of an analysis. If the exact likelihood function of the original analysis is not known in reinterpretation efforts[†], approximations need to be made for the statistical inference, e.g. in terms of the correlations between event rate estimates as well as the treatment of uncertainties. Recently, ATLAS has started to publish full analysis likelihoods built using the HistFactory probability density function (pdf) template [161]. This effort has been facilitated by the development of `pyhf` [169, 170] (cf. section 3.1), in conjunction with the introduction of a `JSON` specification fully describing the HistFactory template. As a pure-text format, the `JSON` likelihoods are human- and machine-readable, highly compressible and can easily be put under version control, all of which are properties that make them suitable for long-term preservation, which is a crucial condition for reinterpretations.

The full likelihood of the 1ℓ search is publicly available at Ref. [276] and is not only heavily used in the following chapters, but also in various analysis reinterpretation and combination efforts currently ongoing in ATLAS. Several efforts outside of the ATLAS Collaboration have already included the analysis likelihood into their reinterpretations, and the SModelS and MadAnalysis5 Collaborations have both reported significant precision improvements through its use [277–279]. Furthermore, the full likelihood of the search presented herein has recently been used to demonstrate the concept of scalable distributed statistical inference on high-performance computers (HPCs) [280]. Through the `funcX` package [281], `pyhf` is used as a highly scalable *function as a service* to fit the entire 1ℓ signal grid of 125 signal points with a wall time of 156 s using 85 available worker nodes[§].

[†] Up until recently, the exact likelihood function was not part of the data products published by ATLAS searches for SUSY, hence approximations of the statistical models were a crucial part of most reinterpreation efforts.

[§] Theses benchmarks use `pyhf`'s NumPy backend and SciPy optimiser, a combination that has a slower log-likelihood minimisation time than e.g. PyTorch coupled with SciPy, as will be shown in section 10.3.

9.3 Full analysis preservation using containerised workflows

For an analysis to be fully reusable under the Recast paradigm, the signal pipeline of the original analysis (cf. fig. 9.1) needs to be preserved such that it can be re-executed on new inputs. As typically only the processing steps after the event reconstruction are analysis-specific, it is sufficient to preserve this part of the signal pipeline. Processing steps including and preceding the event reconstruction only involve the central ATLAS production system, introduced in section 2.2.8, and result in an ATLAS-internal data format serving as input for physics analyses. These processing steps are preserved using centrally provided ATLAS infrastructure and thus do not need to be within the scope of the preservation discussed in the following.

In the following, the term *signal analysis* (cf. fig. 9.1) will refer to the analysis-specific processing steps that are not handled by the central ATLAS production system, typically starting with the selection of events that have passed the reconstruction step in fig. 9.1, provided in the aforementioned internal data format. Preserving the signal analysis not only needs preservation of the full software environment required for the different processing steps, but also knowledge of the correct usage of the software through parameterised job templates together with a workflow graph connecting the different processing steps. A graph representation of the entire analysis, implemented in Recast, is shown in fig. 9.2.

9.3.1 Software preservation

As much of the software is only tested, validated and deployed on a narrow set of architectures and platforms, the full software environment defining an analysis pipeline not only includes the original analysis-specific code used for object definitions, calibrations, event selection and statistical inference, but also the operating system used, and a number of low-level system libraries that the applications depend upon. Preserving the full software environment can be achieved through the use of *Docker containers* [282, 283], a technology that—except for the operating system kernel—packages the full software environment into a portable data format, including a layered file system, the operating system as well as the actual application and all of its dependencies. As opposed to full virtualisation, Docker containers do not rely on actual hardware virtualisation but share the operating system kernel with the host, i.e. the computing system that the containers are run on. As such, they only interact with the host through system calls to the Linux kernel [283], offering a highly stable interface. This makes Docker containers a well-suited solution for deploying isolated applications on a heterogeneous computing infrastructure.

Due to the specific software structure of the 1ℓ search, a containerisation requires a total of three container images. Two images contain the software necessary for performing the physics object calibrations and event selection, as well as the conversion of the information in a format that can be used by the downstream steps. The third image contains the software necessary for the statistical inference, relying on the `pyhf`-implementation of the HistFactory models in order to benefit from the possibility of using a partial `JSON` likelihood to preserve background and data rates.

The Docker images are built from suitable base images containing the software environment used for deriving the published 1ℓ search results, expanded with the relevant analysis software. All docker images are subject to version control and continuous integration, such that changes to the underlying software environment can be automatically tracked and tagged. This enables a consistent preservation of multiple versions of the analysis pipeline.

9.3.2 Processing steps preservation

Preserving the software environment is not sufficient, as detailed instructions on how to use it have to be given. This is achieved through parameterised job templates that specify the precise commands and arguments required to re-execute the analysis code for specific processing steps. As re-executing the analysis pipeline using different signal models involves varying input parameters, all job template parameters are exposed to the user. In fig. 9.2, the parameterised job templates are shown as blue rectangles, while their input arguments and outputs are illustrated as red oval nodes. In the following, a brief overview of the user-specifiable arguments and inputs to the job templates is given.

The event selection and physics object calibration step require the actual reconstructed MC events in the aforementioned ATLAS-internal format as input (`input_mc16(a,d,e)`), obtained through the central ATLAS production system, as well as corresponding files necessary for the pile-up correction in MC (`prwfile_mc16(a,d,e)`). For each new signal model to be tested, three MC samples need to be provided, generated with specific pile-up profiles close to the pile-up profile in data during the 2015–2016, 2017 and 2018 data-taking periods, respectively[†]. In all three jobs, the events processed are weighted according to the integrated luminosity of the data-taking period they represent within the full Run 2 dataset. For the correct normalisation of the estimated signal rates to the integrated luminosity of the full Run 2 dataset, the signal process cross section (`xsec`), as well as MC generator-level efficiencies (`filer_eff`) need to be given. A subsequent *merging* step relies on the same docker image as the previous processing step, and serves to merge the three produced outputs into a single ROOT file containing bin-wise expected signal rates and experimental uncertainties.

In addition, a `JSON` file containing theory uncertainties on the expected signal rates can be provided (`signal_theory_uncertainties`). These are optional and do not have to be specified if deemed to be negligible for the signal model under consideration.

The statistical inference step requires, as external input, the archived partial likelihood containing observed data as well as expected background rates including systematic variations thereof (`partial_likelihood`). This step generates a new full analysis likelihood and performs the necessary hypothesis tests.

9.3.3 Workflow preservation

Finally, the preserved processing steps need to be linked together, creating a parameterised workflow completely defining the analysis pipeline, starting from centrally produced MC datasets up to the statistical inference results. Within Recast, this is achieved using the workflow description language `yadage` [284], capturing the full workflow in `YAML` format. The workflow connects the job templates and defines their processing order and dependencies.

The Recast implementation of the analysis presented in this work has been validated against original analysis inputs. The expected and observed CL_s values derived in the original analysis were successfully re-derived using the containerised workflow implementation. On a non-isolated CPU, the full preserved

[†] This allows to have pile-up weights relatively close to unity, avoiding unnecessary statistical dilution.

analysis pipeline for a single signal model can be executed with a wall time of about 50 min. Due to the highly portable nature of the containerised workflow, the pipeline can easily be run in a distributed setup, allowing scalable reinterpretations at full analysis precision. Although not explicitly used in the remainder of this thesis, the RECAST implementation of the 1ℓ search is crucial for the large-scale reinterpretation efforts in the phenomenological Minimal Supersymmetric Standard Model (pMSSM) currently ongoing in ATLAS (and discussed to some extent in chapter 11). In these efforts, the RECAST implementation allows the systematic reinterpretation of the 1ℓ search in any pMSSM model of interest using the full analysis precision.

9.4 Truth-level analysis

A full preservation of the entire analysis pipeline, as presented in the previous section, is highly desirable as it allows for a maximum precision reinterpretation of the original analysis using a new BSM model. As the full detector simulation needs a significant amount of computing resources in addition to the non-negligible wall time of the actual preserved analysis pipeline, this approach can only be used on a limited set of models. In large-scale reinterpretations over high-dimensional parameter spaces, the amount of models that need to be sampled and investigated using the analysis is too high to employ the fully preserved analysis pipeline in every case. In order to significantly reduce the number of models that need to be passed through the full analysis pipeline, a pre-sorting of the models needs to be performed, filtering models for which (non-)exclusion based on a simplified analysis implementation is uncertain.

In the following, two major, complementary approaches to analysis simplifications are discussed, targeting both the *signal pipeline* as well as the *statistical inference* blocks in fig. 9.1. This section discusses the SIMPLEANALYSIS implementation of the analysis, an approach implementing the signal pipeline at *truth-level*, i.e. using the generator-level objects without running a dedicated detector simulation. An approximation of the detector response using four-vector smearing techniques is discussed.

The second simplification is discussed in chapter 10, introducing a procedure for building simplified likelihoods from the full likelihoods of ATLAS SUSY searches in order to significantly lower the wall time needed for the statistical inference. In chapter 11, both approximations are combined and applied on a set of SUSY models sampled from the pMSSM.

9.4.1 Truth-level selection

All signal and control regions considered in the original 1ℓ search are implemented at truth-level using the publicly available framework SIMPLEANALYSIS. The exact implementation has been published, together with the previously discussed efficiency maps and analysis likelihod, as part of the auxiliary analysis data at Ref. [275]. In fact, the SIMPLEANALYSIS implementation of the search was already used in chapter 7 for the derivation of some of the theory uncertainties.

The truth-level implementation explicitly specifies all object definitions introduced in section 4.4, even though some of them, like the lepton isolation, are technically not well-defined at truth-level. The four-vector smearing subsequently described is, however, in many cases implemented as a function of said object definitions and hence still allows to consider them to some extent. Additionally, as discussed in section 9.1, the full specification of the original analysis event selection including all

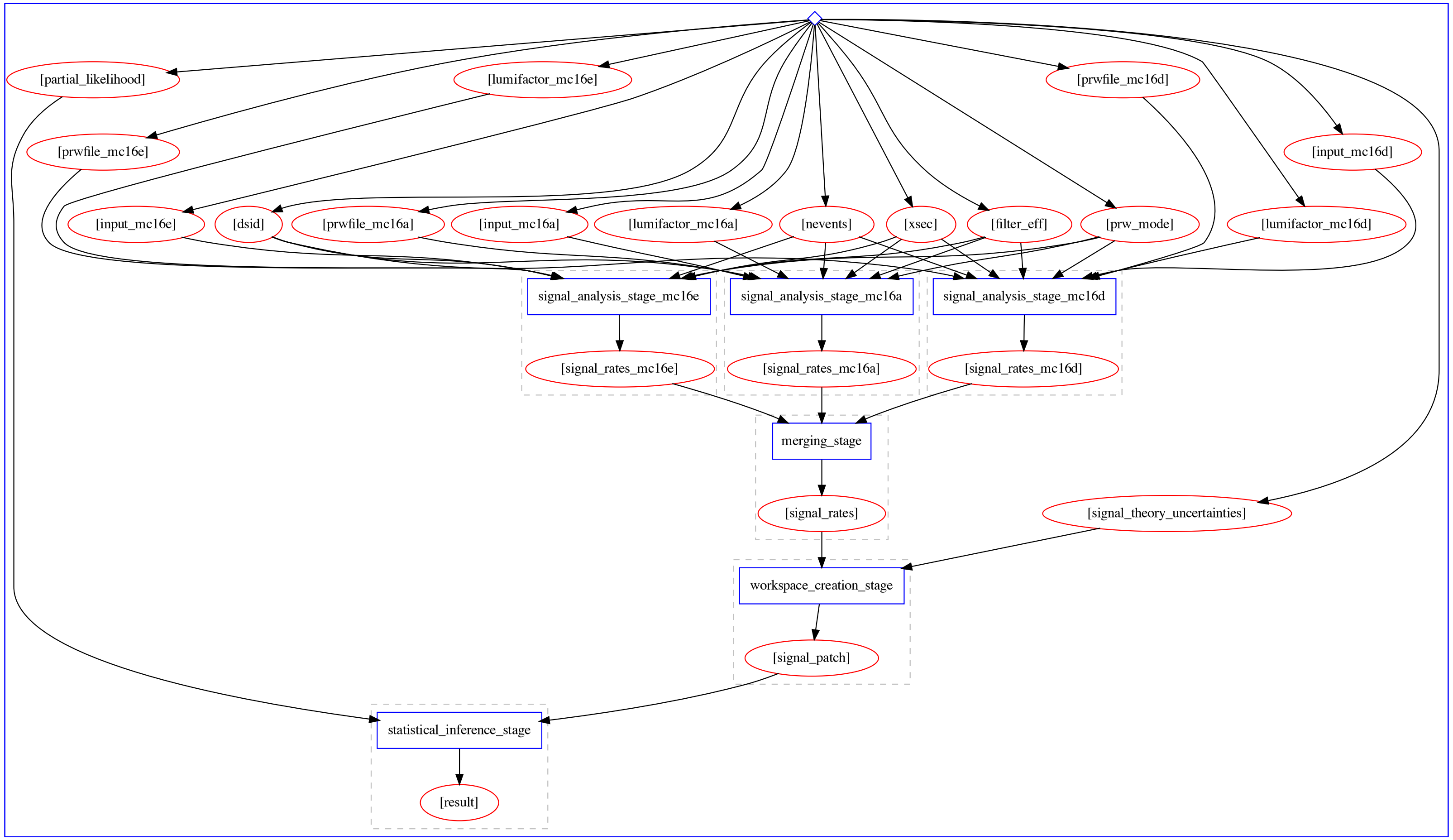

Figure 9.2: Graph of the workflow as specified for the analysis pipeline. The containerised processing steps are represented as blue rectangular nodes, while input parameters, input files and outputs are shown as red oval nodes. The workflow is comprised of four processing steps: `signal_analysis_stage_mc16(a,d,e)`, `merging_stage`, `workspace_creation_stage` and `statistical_inference_stage`. The first two steps perform the object calibration, event selection and merging of the three MC datasets representing the three data-taking periods 2015–2016, 2017 and 2018. The latter two steps implement the patching of the partial likelihood with the expected signal rates, as well as the final statistical inference. Compared to fig. 9.1 the first two steps implement the *signal analysis* part, while the latter two steps implement the *statistical inference* deriving the final results. Figured created using GraphViz [285, 286].

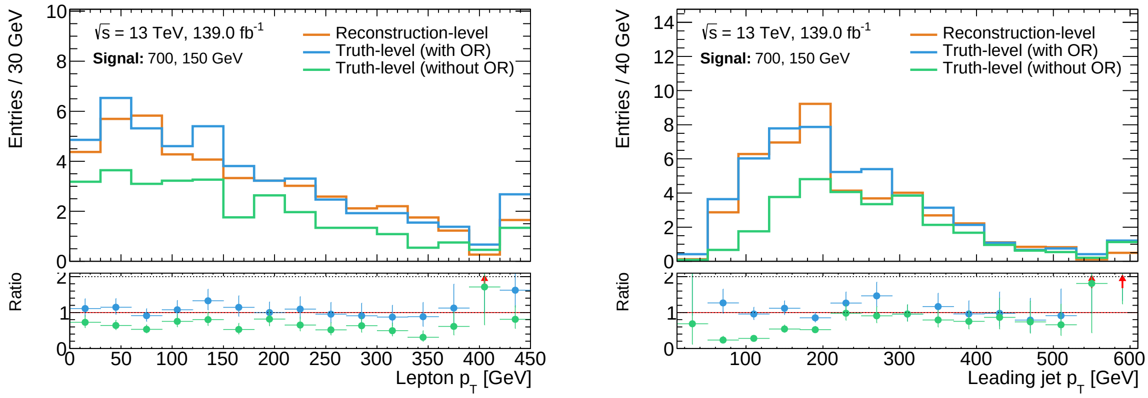

Figure 9.3: Impact of the overlap removal (OR) procedure at truth-level illustrated in the lepton and leading jet transverse momenta distributions. The truth-distributions with (blue) and without (green) overlap removal (green) are compared with a reconstruction-level (orange) distribution. The exemplary benchmark signal point with $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 700, 150\,\text{GeV}$ is shown in both plots. Both truth-level distributions are shown after smearing. All distributions are shown in a loose preselection requiring an electron or a muon, $E_{\text{T}}^{\text{miss}} > 50\,\text{GeV}$, $m_{\text{T}} > 50\,\text{GeV}$, and 2–3 jets, two of which need to be b-tagged.

object definitions allows for more straightforward 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 in section 4.5 for the reconstruction-level analysis is performed, i.e. especially also using the same shrinking cone definitions. Since tracking information is not available at truth-level, the 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 crucial to reproduce the signal estimates of the original analysis. Figure 9.3 illustrates this by showing exemplary kinematic distributions of an exemplary signal point in configurations with and without overlap removal at truth-level, and comparing it with the distributions obtained at reconstruction-level[§]. Not implementing the overlap removal procedure of the original 1ℓ search, results in many truth-level events not passing the analysis selections because of additional objects in the final state that would otherwise have been removed through the overlap removal.

Finally, the exact implementation of all analysis observables is explicitly given, followed by the definition of all control and signal regions.

9.4.2 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 the ATLAS detector

† 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.

§ The term *reconstruction-level* here refers to distributions obtained with MC simulated datasets for which either the full detector simulation using GEANT4, or the ATLFAST-II fast simulation have been run with subsequent object re-construction.

performance results 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 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 four-vector components of electrons, muons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ are smeared.

In the case of truth electrons, the identification efficiencies considered are parameterised in η and p_{T} [220]. Different efficiency maps exist for the different working points of the likelihood-based identification discriminant introduced in section 4.4.2 [220]. In η, nine fixed-width bins are used to parameterise the identification efficiency. In p_{T}, six bins are implemented and a linear interpolation between two adjacent p_{T}-bins is employed to get the efficiency for the 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, covering the majority of all electrons in the analysis. If the truth p_{T} of the electron is outside of this range, the identification efficiency and fake rate from the respective bound of the corresponding η-bin are taken. The probability for misidentifying an electron as a photon is estimated with different fixed values for the barrel and end-cap regions [219]. Finally, the transverse energy of the electron is smeared with a random number drawn from a Gaussian distribution with standard deviation corresponding to the η- and p_{T}-dependent energy resolution, measured in $Z \to ee$ and $J/\Psi \to ee$ events [287].

For truth muons, the identification efficiencies are also parameterised in η and p_{T} [222]. Different efficiency maps exist again for the different identification working points (cf. ??) [222]. 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 resolutions in the inner detector (ID), σ_{ID}, and muon spectrometer (MS), σ_{MS}, as

$$\sigma_{\mathrm{CB}} = \frac{\sigma_{\mathrm{ID}}\sigma_{\mathrm{MS}}}{\sqrt{\sigma_{\mathrm{ID}}^2 + \sigma_{\mathrm{MS}}^2}}, \tag{9.1}$$

where σ_{ID} and σ_{MS} are parameterised in η and p_{T} and measured in $Z \to \mu\mu$ and $J/\Psi \to \mu\mu$ events [221].

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 $|\eta|$, ranging from $|\eta| = 0$ to $|\eta| = 4.5$. The jet energy resolutions are measured in dijet events [226] and provided as 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

$$\frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}} = \frac{N}{p_{\mathrm{T}}} \oplus \frac{S}{\sqrt{p_{\mathrm{T}}}} \oplus C. \tag{9.2}$$

Only truth jets with 10 GeV $< p_{\mathrm{T}} <$ 1.5 TeV are smeared. For truth jets with $p_{\mathrm{T}} >$ 20 GeV, the flavour tagging efficiency is considered through efficiencies parameterised in η, p_{T}. Different flavour tagging efficiency maps are available for the different MV2c10 efficiency working points (introduced in section 4.4). All flavour tagging efficiencies are measured in fully reconstructed simulated $t\bar{t}$ events [232].

Finally, the smeared missing transverse energy is computed by considering the transverse momenta of all smeared truth objects in the event, including an approximation for the track soft term. The latter is approximated using resolution measurements from $Z \to \ell\ell$ events [235], 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.

9.5 Validation of the truth-level analysis

9.5.1 Validation in loose preselection

The performance of the truth smearing is illustrated in fig. 9.4 in a loose preselection for an exemplary benchmark signal point. The loose preselection applied requires a final state with 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 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} and individual working points—crucial for the overall agreement in shape, especially at low p_{T}, the inclusion of flavour-tagging efficiencies significantly improves the overall agreement in normalisation.

Although some minor differences remain, a good agreement is observed overall across the relevant kinematic distributions at loose preselection level. Most of the differences remaining 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.

9.5.2 Validation in signal regions

As the expected signal rates in the signal regions are ultimately what is entering the statistical inference, 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 for all signal models considered in the 1ℓ search is shown in fig. 9.5. For the sake of conciseness, only the cumulative m_{CT} bins are shown in each signal region in fig. 9.5. The agreement in the individual m_{CT} bins in each SR-LM, SR-MM and SR-HM is provided in figs. B.1 to B.3.

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

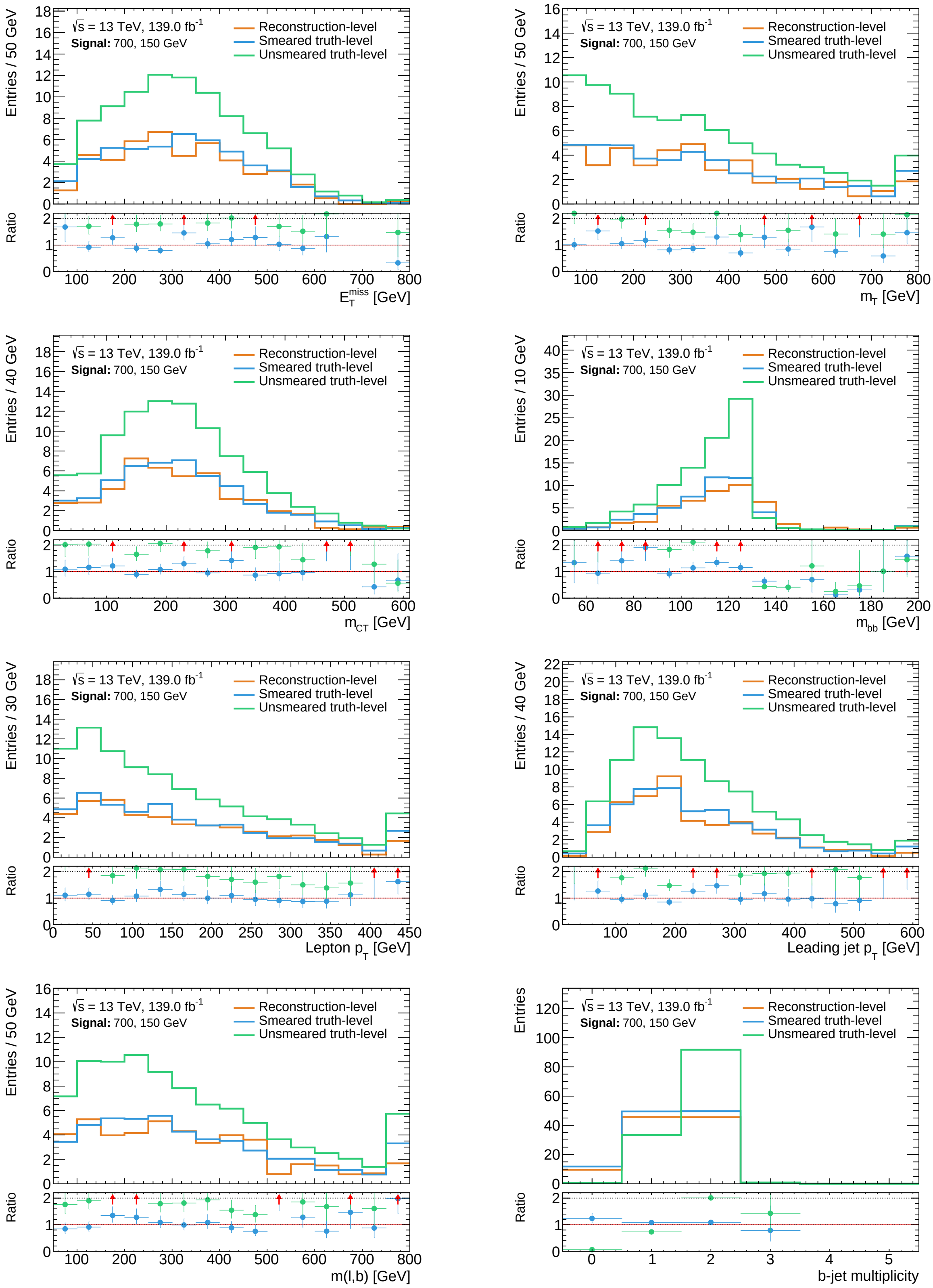

Figure 9.4: Comparisons of the kinematic distributions of key observables at (smeared) truth- and reconstruction-level. The exemplary benchmark signal point with mass parameters $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 700, 150$ GeV is shown. The ratio pad shows the ratio of smeared 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, $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV, $m_{\mathrm{T}} > 50$ GeV, and 2–3 jets, two of which need to be b-tagged. The latter requirement is dropped for the b-jet multiplicity distribution.

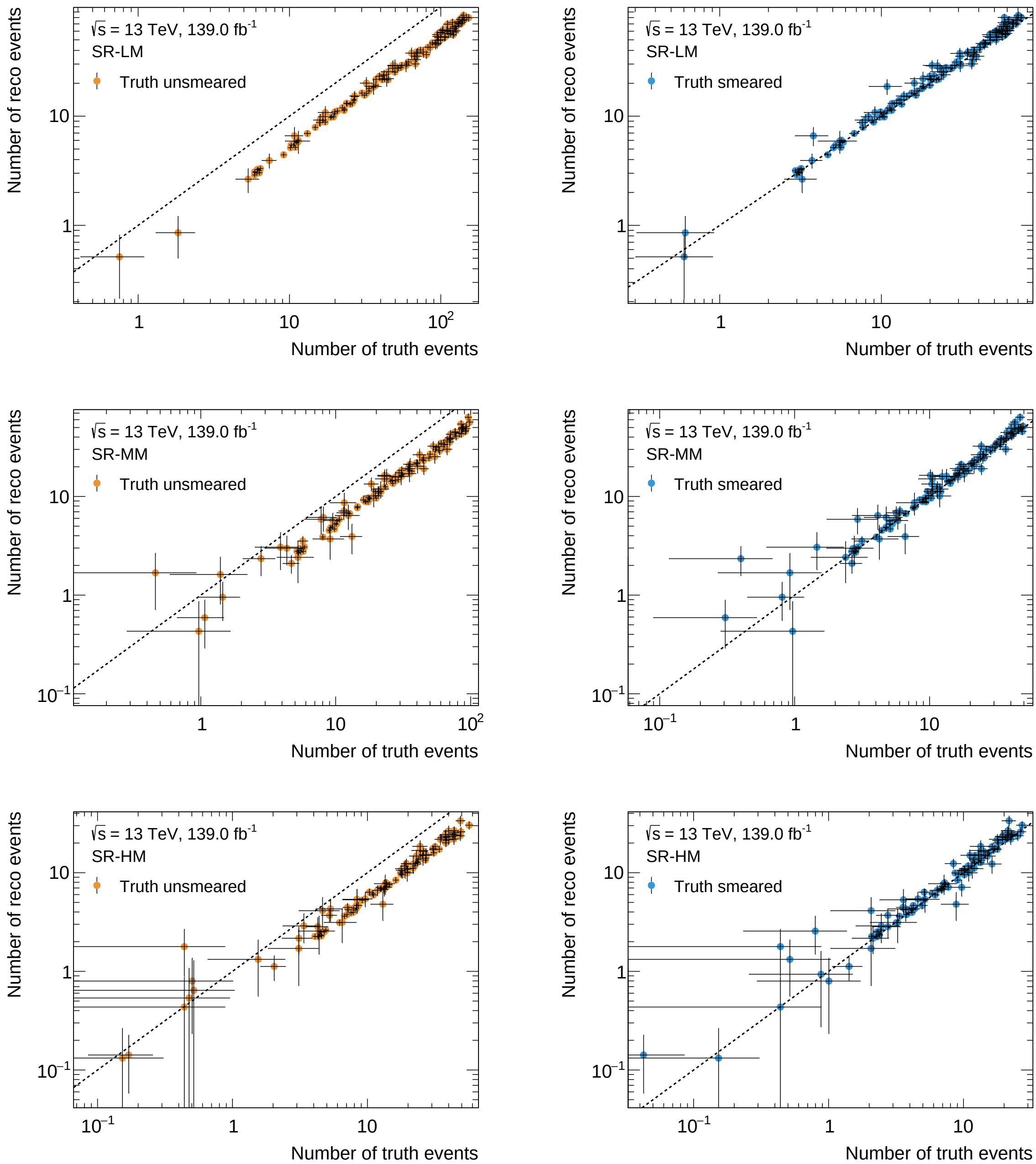

Figure 9.5: Comparison of the event rates at truth- and reconstruction-level before (left) and after (right) truth smearing. From top to bottom, the SR-LM, SR-MM and SR-HM signal regions are shown, with cumulative (integrated) m_{CT} bins. Every single point in the scatter plots represents a single signal model considered in the 1ℓ search. Uncertainty bars include MC statistical uncertainties.

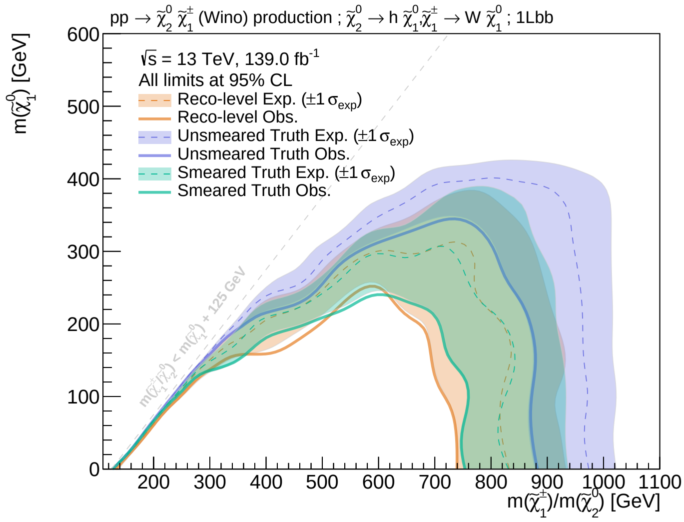

Figure 9.6: Expected and observed exclusion contours obtained with the full likelihood using reconstruction-level inputs (orange) as well as truth-level inputs before (purple) and after (green) smearing. Uncertainties include all statistical and systematic uncertainties on the background and signal for the reconstruction-level contours, but only statistical and systematic uncertainties on the background for truth-level signal inputs.

9.5.3 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 1ℓ search, expected and observed CL_s values can be computed and exclusion contours can be derived. Figure 9.6 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 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.

In summary, the validation process performed at multiple selection levels of the analysis shows that the signal pipeline can be approximated reasonably well using a truth-level analysis and dedicated smearing functions. For signal models producing final states with kinematics close to those of the scenarios validated in the previous sections, this approach allows to determine the event rate estimates with high computational efficiency. In large-scale reinterpretations, the smeared truth-level analysis can be used as a basis for an efficient classification of models into two categories: models that are safely excluded or not excluded based on truth-level analysis only, and models where exclusion is in doubt and instead the precision of the full analysis pipeline using Recast is required.

Part IV

Summary and Outlook

Part V

Appendices

Abbreviations

BSM beyond the Standard Model. 131–133, 137

HEP high energy physics. 132

HPC high-performance computer. 134

ID inner detector. 140

JER jet energy resolution. 140

LHC Large Hadron Collider. 131–133

MC Monte Carlo. 131, 134, 136, 138–143

MS muon spectrometer. 140

pdf probability density function. 134

pMSSM phenomenological Minimal Supersymmetric Standard Model. 137

SM Standard Model of particle physics. 131, 132

SR signal region. 141

SUSY Supersymmetry. 132–134, 137, 139

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