Suche nach Elektroweakinos mit dem ATLAS Detektor

Ludwig-Maximilians-Universität München
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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 9

Analysis preservation

Today's particle physics experiments operate are designed to collect physics data over a span over several decades. They thus operate at scales that makes it impossible for the experiments to be repeated in the foreseeable future. The data taken at these experiments and physics results derived are thus extremely valuable and major problems arise from a scientific reproducibility point of view. In this chapter, the reproducibility problems directly connected to an individual analysis are discussed, and approaches taken in view of analysis preservation are presented.

9.1 The case for reinterpretations

9.1.1 Motivation

Designing and executing searches for beyond the Standard Model (BSM) physics requires a large amount of human and computational resources. As laid out in the previous part of this work, an analysis generally aims to define a phase space region where a given signal model can be efficiently discriminated against Standard Model of Particle Physics (SM) background. Although the careful design of such regions already requires significant amount of resources, it constitutes only a fraction of the work necessary for concluding the search. Contributions from SM processes need to be estimated, usually requiring expensive Monte Carlo (MC) simulation and the development of background estimation strategies. Systematic uncertainties arising from numerous sources need to be considered and estimated. Furthermore, simulated signal events also need to be generated, reconstructed and processed through the event selection. Recorded data also needs to be reconstructed and processed through the event selection. Only after all three processing pipelines are concluded can the likelihood be built and statistical inference can be performed, produced the results like e.g. limits on model parameters can be obtained. Figure 9.1 illustrates the main data pipelines in an analysis, including their most important processing steps.

Due to the substantial amount of resources necessary for each analysis, it is not feasible to develop dedicated searches optimised for every possible signal model. Instead, analyses are typically interpreted in a finite set of BSM models. Still, it is very likely that any given analysis is sensitive to a variety of different BSM models not considered in the original publication. There is a real possibility that Supersymmetry (SUSY) is accessible at the energies of the Large

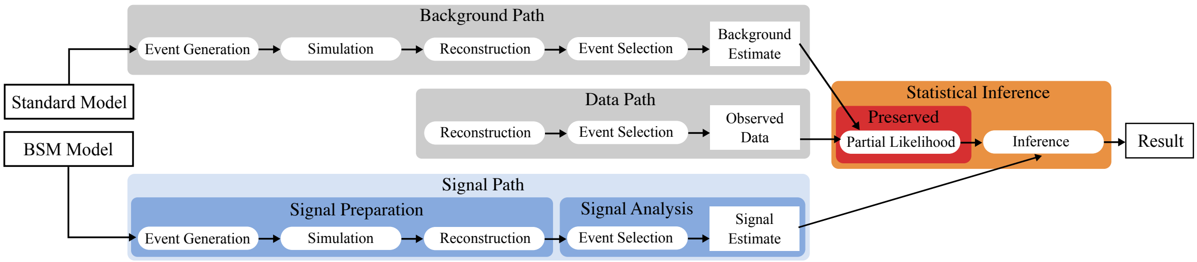

Figure 9.1: Full analysis workflow including the three main processing pipelines for deriving background and signal estimates as well as observed data rates. The outputs of the three processing pipelines are combined into a likelihood forming the basis for statistical inference. Figure recreated from Ref. [246].

Hadron Collider (LHC) but is still hiding in unexpected places or the complex topologies arising from complete SUSY models.

Consequently, it is not surprising that there is significant interest in the high energy physics community in reinterpreting BSM searches in different signal models. Reinterpretations of published BSM searches routinely happen both within as well as outside of the ATLAS collaboration. For theorists, the analyses performed by the collaboration represent the only available windows into the dataset recorded. Reinterpretations of reproducible analyses are thus the only possibility to determine the implications of LHC data for a variety of models [245]. Likewise, within the experimental collaborations, reinterpretations can additionally serve as powerful guides for designing the search program. Reinterpretations of ATLAS SUSY searches in more complete SUSY models like the phenomenological Minimal Supersymmetric Standard Model (pMSSM)(as was done after Run 1 of the LHC, see Ref. [76]) not only allow to state a combined sensitivity of ATLAS to more realistic SUSY models, but also enables the collaboration to identify potential blind spots and parameter regions still uncovered by existing analyses. Reinterpretations of existing analyses are thus highly desirable and vital for designing future searches with a maximal scientific relevance.

9.1.2 Necessary ingredients

As the event selection of an analysis is fixed, the background estimates and observed data in the targeted regions of interest do not change and can be archived in a suitable format. Reinterpreting a search in the light of a new signal model consequently only requires the signal pipeline in fig. 9.1 to be run again, in order to derive the signal estimates that serve as input for the statistical inference. As the data and background processing pipelines shown in fig. 9.1 only enter the statistical inference as estimated event rates, the volume of data that needs to be archived is significantly smaller than the original input data. As will be discussed in section 9.2, it has recently become technically possible to directly preserve the partial analysis likelihood built from the background estimates and observed data and including all details of the statistical model used for inference. 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.

Different approaches exist for deriving signal estimates. Manifestly the most precise approach involves running the original analysis using a different BSM model. As this requires to preserve the entirety of the original software and workflows used in the analysis, this is arguably the most involved approach. A framework designed to facilitate such an effort, called Recast, has originally been proposed in Ref. [247] and aims to provide reintepretations as a service. Through a web interface, physicists would request a reinterpretation of a search, providing an alternative model, triggering a computational workflow executing the original analysis and delivering the recasted results. Section 9.3 discusses an attempt at fully preserving the search for electroweakinos presented in this work in the context of Recast.

In many cases, the full precision of the original analysis pipeline is either not needed, or not accessible. As the full detector simulation requires access to the collaborations's detector description and is the most computationally expensive step in the signal pipeline, even when using fast simulations like ATLFAST-II, it is often approximated using simplified detector geometries and granularities. The most commonly used package for fast detector simulation outside of the collaboration is Delphes [248]. Other packages like e.g. Rivet [249, 250] approximate the detector response using dedicated 4-vector smearing techniques, assuming that the detector response roughly factorises into the responses of single particles. Internally, ATLAS also uses a dedicated framework for 4-vector smearing techniques, used in scenarios where other fast simulation techniques are still too expensive. Section 11.1 discusses these dedicated smearing functions further.

Similarly to the detector simulation, the analysis-specific event selection is also routinely approximated using different approaches. A number of public tools aiming to reimplement approximations of the event selections of various BSM searches are available. Prominent examples include CheckMate [251, 252] and MadAnalysis [253]. ATLAS has internally maintained a similar catalogue of its SUSY analyses and has published event selection snippets in C++ on HEPData [254]. Recently, this package maintained by ATLAS, called SimpleAnalysis [255], has been made publicly available, allowing the C++ snippets published to be run outside the collaboration.

Instead of trying to estimate the signal rates of a new signal model using MC simulation and (reimplemented) analysis event selections, some reinterpretation efforts like e.g. SModelS [256, 257] use *efficiency maps* encoding the selection efficiency of the analysis as a function of some of the analysis observables (typically the sparticle masses). Such efficiency maps are routinely published by the ATLAS SUSY searches on HEPData, and allows 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 [256]. For the analysis presented in the previous part of this work, the efficiency maps and further analysis data products are available at Ref. [258].

9.2 Public full likelihood

The likelihood is arguably one of the most information-dense and thus valuable data products of an analysis. Without precise knowledge of the exact likelihood of the original analysis, approximations need to be made for the statistical inference e.g. in terms of 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 introduced in chapter 3 [147]. This extraordinary step towards more open and reproducible science has been praised by the theory community [259] as it allows for

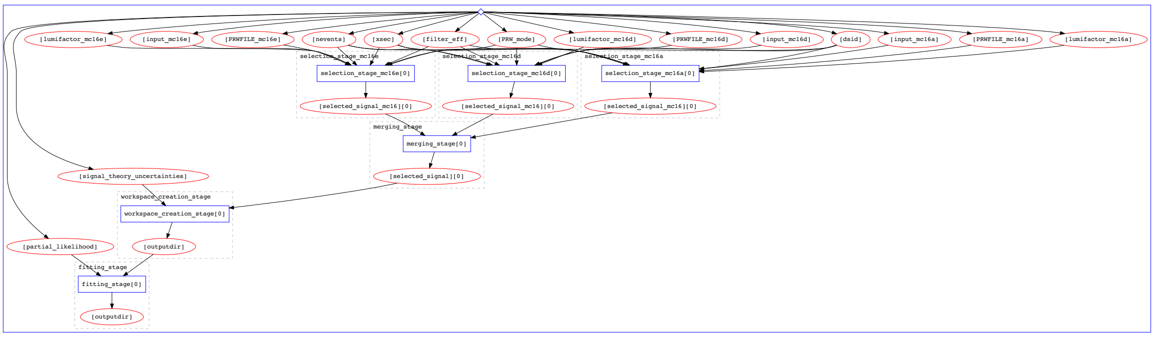

Figure 9.2: Workflow

considerably more trustful reinterpretations. This effort has been facilitated by the development of `pyhf` 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 ideal for long-term preservation.

The full likelihood (in `JSON` format) of the search for electroweakinos presented in the previous part of this work has been published [260] 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, e.g. SModelS [261] and MadAnalysis [262, 263] both reporting significant precision improvements through the use of the full likelihood (as opposed to approximating the statistical model). 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) [264]. Through the `funcX` package [265], `pyhf` is used as a highly scalable function as a service to fit the entire signal grid of 125 signal points with a wall time of 156 s using 85 available worker nodes[†].

9.3 Analysis preservation using containerised workflows

In order to re-run the original analysis pipeline, the full software environment used for deriving the public analysis results needs to be archived and available. This not only includes the original analysis-specific code used for object definitions, calibrations, event selection and statistical inference, but also the full software necessary for event generation, simulation and reconstruction. Much of the software depends on the operating system used and a number of low-level system libraries, which also need to be conserved. From a technical point of view, this can be achieved using *Linux containers*

Recast, originally proposed in Ref. [247] and recently used within ATLAS in e.g. Ref. [246]

[†] Theses benchmarks use `pyhf`'s NumPy backend and SciPy optimiser, which does have a slower log-likelihood minimisation time than e.g. PyTorch coupled with SciPy.

Part IV

Summary and Outlook

Part V

Appendix

Abbreviations

BSM beyond the Standard Model. 127–129

HPC high-performance computer. 130

LHC Large Hadron Collider. 127, 128

MC Monte Carlo. 127, 129

pdf Probability Density Function. 129

pMSSM phenomenological Minimal Supersymmetric Standard Model. 128

SM Standard Model of Particle Physics. 127

SUSY Supersymmetry. 127–129

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