Zusammenfassung

Obwohl das Standardmodell der Teilchenphysik eine außerordentlich erfolgreiche Theorie darstellt, deuten einige Beobachtungen auf die Existenz neuer Physik jenseits dessen was im Rahmen des Standardmodells erklärt werden kann hin. Supersymmetrie ist der Oberbegriff für eine Klasse von Theorien, die einige der offenen Fragen des Standardmodells erklären könnten. Sie sagt die Existenz von supersymmetrischen Partnern für jedes Teilchen des Standardmodells voraus und könnte, unter anderem, einen Teilchenkandidaten für dunkle Materie liefern.

Diese Arbeit stellt eine Suche nach supersymmetrischen Teilchen, die über die elektroschwache Wechselwirkung paarproduziert werden, vor. Endzustände mit einem Lepton, fehlender Transversalenergie und einem Higgs Boson, welches in zwei b-Quarks zerfällt, werden untersucht. Insgesamt werden $139\,\mathrm{fb}^{-1}$ an Daten aus Proton-Proton Kollisionen berücksichtigt, welche mit dem ATLAS Detektor bei einer Schwerpunktsenergie von $\sqrt{s} = 13\,\mathrm{TeV}$ im Run 2 des Large Hadron Colliders aufgezeichnet wurden. Ein, auf einer Likelihood-Methode basierender, simultaner Fit in allen Suchregionen wird verwendet, um hohe Sensitivität zu möglichst vielen kinematischen Bereichen im untersuchten Parameterraum zu gewährleisten.

Keine signifikante Abweichung von den Standardmodellvorhersagen wird in den Daten beobachtet, weshalb die Ergebnisse in einem vereinfachten Modell für Paarproduktion von Elektroweakinos interpretiert werden. Für leichteste Neutralinos mit Massen von $\lesssim 100\,\mathrm{GeV}$ ($\approx 250\,\mathrm{GeV}$), können leichteste Charginos und zweitleichteste Neutralinos mit Massen bis zu $740\,\mathrm{GeV}$ ($600\,\mathrm{GeV}$) ausgeschlossen werden.

Da heutige Teilchenphysik-Experimente aufgrund ihrer Komplexität und Größenordnung nicht trivial reproduzierbar sind, gleichzeitig aber eine Vielzahl an Modellen für Physik jenseits des Standardmodells existiert, wird ein besonderes Augenmerk auf die technische Durchführbarkeit einer Neuinterpretation der Suche gelegt. Die volle Likelihood-Funktion der Suche wird veröffentlicht und eine vollständig reproduzierbare Umsetzung der Suche anhand Container-Technologie und parametrisierter Job-Vorlagen wird diskutiert. Mit Hinblick auf rechenintensive Neuinterpretationen in hoch-dimensionalen Parameterräumen wird eine Methode eingeführt, um die Likelihood-Funktionen von ATLAS Suchen nach Supersymmetrie zu nähern. Mit Hilfe dieser Methode wird schlussendlich eine Neuinterpretation der Suche in einem Unterraum einer 19-dimensionalen Menge von vollständigeren supersymmetrischen Modellen durchgeführt und deren Ergebnisse diskutiert.

Abstract

Despite the success of the Standard Model of Particle Physics, a number of hints suggest the existence of new physics beyond the scope of phenomena that can be explained in the theoretical framework of the Standard Model. One class of theories that could be able to explain some of the open questions of the Standard Model is Supersymmetry. It introduces supersymmetric partners to each of the Standard Model particles, and could, for example, provide a candidate for Dark Matter.

This thesis presents a search for electroweak production of supersymmetric particles in events with one lepton, missing transverse momentum and a Higgs boson decaying into two b-quarks. The search analyses $139\,\mathrm{fb}^{-1}$ of proton–proton collision data at a centre-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$, recorded by the ATLAS detector at the Large Hadron Collider. A likelihood-based simultaneous fit in all search regions is introduced in order to achieve sensitivity to a large variety of kinematic regimes. No significant deviation from the Standard Model predictions is seen in data in any of the search regions. The results are subsequently interpreted in a simplified model for electroweakino pair-production. Lightest chargino and next-to-lightest neutralino masses of $740\,\mathrm{GeV}$ ($600\,\mathrm{GeV}$) can be excluded for lightest neutralino masses of $\lesssim 100\,\mathrm{GeV}$ ($\approx 250\,\mathrm{GeV}$).

Given that today's particle physics experiments are not easily reproducible and a large number of phenomenologically viable models for physics beyond the Standard Model exist, special focus is put on the reusability and reinterpretability of the search. The full likelihood function of the search is published in a readily available format, and a fully reusable implementation of the search using containerised workflows with parameterised job templates is provided. In light of conceptually interesting but computationally challenging reinterpretations in high-dimensional model spaces, a method for generically approximating the likelihood functions of ATLAS searches for Supersymmetry is introduced and validated. Using this approach, a reinterpretation of the search in a subspace of a 19-dimensional set of more complete supersymmetric models is performed and its results are discussed.

Introduction

Particle physics studies the fundamental constituents and interactions of matter with the ultimate goal of uncovering the laws of nature that govern the most fundamental building blocks of the universe. Over the course of more than a century, fundamental physics has continuously pushed the frontiers of knowledge, reaching ever-smaller length-scales on which the fundamental interactions of the building blocks of matter can be understood. The resulting theoretical framework, the Standard Model of particle physics (SM), provides answers to some of the deepest questions that can be asked about the universe and is the most fundamental, experimentally validated description of nature known to date.

Particle physics finds itself, however, at an interesting crossroad. On the one hand, the SM is very successful in describing nature at its smallest scales and—with the discovery of the Higgs boson in 2012 [1, 2]—has recently been experimentally completed. Through various particle physics experiments, the precision and predictive power of the SM have been tested to an unprecedented level, finding no significant deviations in experimental data so far. On the other hand, however, a number of cosmological observations as well as flavour and precision electroweak measurements are putting increasing pressure on the SM. For example, although the existence of dark matter (DM) is nowadays well-established, it cannot be suitably described within the theoretical framework of the SM. Over the course of the last decades, it has become increasingly clear that the SM is an effective theory, and thus only a low-energy approximation to a more fundamental theory of nature.

A plethora of theories aiming to explain the shortcomings of the SM exist. One class of such theories is Supersymmetry (SUSY), extending the SM by associating supersymmetric partners to the SM particles. SUSY could, for example, be able to provide a candidate particle for DM or explain some of the tensions observed in electroweak precision measurements. Up until the discovery of the Higgs boson, the theory and experimental communities in particle physics were in a state of *symbiosis* with a clear pathway to follow: validating and completing the SM. This is, however, no longer the case and experimental particle physics faces an era where a large number of models for beyond the Standard Model (BSM) physics can be thought of, but no clear indication of where to start looking is available.

Although theoretical arguments suggest that supersymmetric particles could exist at the energies accessible with the Large Hadron Collider (LHC), no such particles have been found so far. Up until recently, searches for SUSY have, however, mostly focused on the production of the supersymmetric partners of quarks and gluons through the strong interaction. With the second run of the LHC recently come to an end, an unprecedented amount of proton–proton collision data has been recorded by the LHC experiments and is available for physics analysis. This allows to search for supersymmetric particles produced through the electroweak interaction that have previously not been accessible due to their low theoretical production rates, compared to those produced through the strong interaction.

Due to their complexity and lifetimes approaching half a century, experiments like the ATLAS detector at the LHC are in general not easily repeatable and thus severely challenge the scientific method. This precarious situation, coupled with the wide landscape of BSM models available to search for, requires efforts to not only preserve searches for BSM physics, but make them fully reusable in the context of new, additional BSM models.

This thesis presents a search for the supersymmetric partners of the SM Higgs and gauge bosons, collectively referred to as *electroweakinos*. The search uses $139\,\mathrm{fb}^{-1}$ of proton–proton collision data recorded at a centre-of-mass energy of $13\,\mathrm{TeV}$ with the ATLAS detector. It is embedded in a larger effort within the ATLAS collaboration, searching for SUSY in the context of a variety of theoretical models. The present work is divided into four main parts. In part I, the fundamental concepts necessary for the remainder of the thesis are presented. This includes a theoretical introduction to the SM and SUSY, followed by a description of the experimental setup, concluding with a discussion of the statistical concepts used. Part II introduces the aforementioned search for electroweakinos and discusses its results using $139\,\mathrm{fb}^{-1}$ of proton–proton collision data recorded by ATLAS. In part III, preservation and reusability efforts are presented, aiming to make the search readily available to reinterpretation efforts inside as well as outside of the ATLAS collaboration. Furthermore, a method for approximating the statistical models of SUSY searches is introduced and validated in chapter 10. These efforts culminate in a reinterpretation of the search in a subspace of a 19-dimensional set of more complete supersymmetric scenarios, the results of which are discussed in chapter 11. Finally, the thesis concludes with a brief summary in part IV.

Chapter 12

Conclusions

This thesis presented a search for direct production of electroweakinos in events with one lepton, missing transverse momentum and a Higgs boson decaying into two b-jets. The full dataset of Run 2 of the LHC, amounting to $139\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, recorded with the ATLAS experiment, was analysed. The search targets a simplified electroweakino ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$) pair-production model with subsequent decays into W and Higgs bosons together with two lightest neutralinos ($\tilde{\chi}_1^0$). The $\tilde{\chi}_1^0$ is the LSP of the model, is electrically neutral and stable, and thus could be a good candidate for DM. It escapes the detector without leaving a trace, resulting, in general, in a significant amount of missing transverse momentum that can be triggered on. The search further targets a W boson decay into a lepton–neutrino pair and a Higgs boson decay into a b-jet pair.

Both the lepton–neutrino and the b-jet pairs offer powerful discriminative handles, exploited through the use of a number of kinematic observables in order to maximise the signal-to-background ratio in the phase space targeted. Using a dedicated optimisation procedure, two sets of signal regions are defined, one targeting generic BSM scenarios (called *discovery* signal regions), and one optimised for the simplified model in question (called *exclusion* signal regions). The exclusion signal regions are designed to be mutually exclusive through their requirements on the transverse mass (m_{T}) and the contransverse mass (m_{CT}). Contributions from SM background processes in the signal regions originate primarily from $t\bar{t}$ and single top production, as well as $W + \mathrm{jets}$ processes. Contributions from SM backgrounds are estimated either with a semi-data-driven technique using dedicated control regions, or directly from MC simulation. A binned likelihood is constructed, statistically combining all exclusion signal regions into a two-dimensional shape-fit that exploits the varying shapes of the m_{T} and m_{CT} distributions of SUSY signal and SM background processes. This approach allows to achieve sensitivity to a wide variety of kinematic regimes.

No significant excess has been observed in any of the signal regions, and thus model-dependent exclusion limits and model-independent upper limits on the visible cross section of BSM processes have been derived. Due to the introduction of the two-dimensional shape-fit and the unprecedented amount of $139\,\mathrm{fb}^{-1}$ of pp collision data analysed, the model-dependent exclusion limits set by previous searches targeting the same simplified model can be significantly extended. For a massless LSP, $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ masses up to $740\,\mathrm{GeV}$ can be excluded at 95% CL. In the case of a heavier LSP with $m(\tilde{\chi}_1^0) \approx 250\,\mathrm{GeV}$, the limits on the $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ masses weaken to about

600 GeV. At the time of writing, the limits obtained by this search represent the most stringent constraints on $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production set by ATLAS in the context of the simplified model considered [256]. The model-independent 95% CL upper limits on the visible cross section of BSM processes vary between 0.26 fb and 0.11 fb, depending on the signal region considered.

The absence of physics beyond the SM in the Run 2 dataset of the LHC in the search presented herein, is in line with the results of other SUSY searches performed by ATLAS and CMS. While the existence of gluinos and squarks at the TeV-scale was already severely challenged by the end of Run 1 of the LHC, the limits on electroweakinos and sleptons were, in general, weaker because of their smaller production cross sections. Due to the large integrated luminosity available through the Run 2 dataset, and the improved analysis techniques and strategies developed over the last years, the limits on electroweakinos and sleptons are also significantly increasing, and in some cases start to approach the 1 TeV mark [256, 258].

Given these constraints, it might be tempting to discard the existence of SUSY at the LHC altogether. Such conclusions would, however, be drawn much too early. On the one hand, 139 fb^{-1} of pp collision data only corresponds to a fraction of the total integrated luminosity the LHC is designed to deliver. By the end of the lifetime of the high-luminosity LHC upgrade, a projected amount of 3000 fb^{-1} [259] will have been delivered to the particle physics experiments. Many supersymmetric models not accessible with the Run 2 dataset using today's analyses, will hence only come into reach in the upcoming runs of the LHC. On the other hand, most limits derived by SUSY searches assume specific simplified models and are thus only valid in the context of the assumptions made in these models. In any realistic SUSY scenario, assumptions like 100% branching ratios or small sets of participating, non-decoupled supersymmetric particles are, however, most likely not exactly fulfilled. Thus, simplified model limits can in general not be trivially interpreted as the true underlying constraints on the respective parameters of a realistic SUSY scenario.

Due to the rapidly changing landscape of models for physics beyond the SM and the limited scope of parameter limits quoted by the experiments, reinterpretations of searches for supersymmetry are highly desirable and see significant interest from both the experimental and theory communities. With this in mind, the search for SUSY presented herein was implemented to be fully reinterpretable in the light of new BSM models. This is achieved by using a cyber-infrastructure called Recast [262], relying on containerised workflows orchestrating parametrised job templates. Additionally, the full likelihood of the search was made publicly available in a readily available format, allowing it to be incorporated in a number of reinterpretation efforts outside of ATLAS [275, 276].

Large-scale reinterpretations in high-dimensional model spaces are especially interesting, but computationally extremely challenging, and thus require suitable approximations. In this thesis, a method to generically approximate the likelihoods of SUSY searches using binned distributions was introduced and validated using a selection of ATLAS searches for SUSY. The search previously presented was reinterpreted in the pMSSM, a 19-dimensional parameter space containing more realistic SUSY scenarios (compared to simplified models). Due to the assumption of 100% branching fractions not being satisfied in many of these more complete SUSY scenarios, the sensitivity of the 1ℓ search was found to be noticeably reduced. A small fraction of models sampled could, however, still be excluded.

The impact of the 1ℓ search on electroweakino masses was investigated, revealing some sensitivity to $\tilde{\chi}_2^{\pm}\tilde{\chi}_2^0$ production with a wino-like LSP, in addition to sensitivity towards models phenomenologically close to the simplified model the search was optimised for. The impact of the 1ℓ search on the DM relic density was also investigated. While no conclusive statement could be made for models with a bino-like $\tilde{\chi}_1^0$ because of the limited number of such models sampled in the relevant parameter space, some models with a wino-like $\tilde{\chi}_1^0$ with cosmological abundance satisfying the Planck constraint could still be excluded.

Although hopes of quickly finding supersymmetric particles with the LHC have not materialised, there is still a possibility of finding hints for physics beyond the SM in the collision data recorded by the LHC experiments. Considerable regions of the parameter space of realistic SUSY scenarios are still largely unconstrained and offer ample space for SUSY to hide in. In order to provide a comprehensive overview of the constrained parameter space, it is not only important to optimise searches to be sensitive to the complex phenomenology of realistic supersymmetric scenarios, but also to design the searches to be systematically reinterpretable, especially in light of more complete and realistic scenarios. After all, searches for BSM physics are the tools that shine a light on the otherwise unilluminated landscapes of the parameter spaces of BSM theories. Allowing these tools to be reusable significantly increases the area of parameter space they can shine a light onto.

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