Searches for Supersymmetry with the ATLAS Detector at the LHC in Final States with Tau Leptons

Habilitationsbericht für die Fakultät für Physik
an der Ludwig-Maximilians-Universität München

vorgelegt von
Dr. Alexander Mann
aus Göttingen

München, April 2018

The realization that the majority of the matter in the Universe might be non-baryonic is the ultimate Copernican viewpoint; not only are we in no special place in the Universe, but we aren't even made out of the same stuff as dominates the matter density of the Universe.

–Andrew Liddle

Contents

1 Introduction

If the Standard Model of particle physics in its current form already were the final word in this field of research, there would be no need to build new particle colliders at the energy and luminosity frontiers, and detectors capable of recording data from the collision events with ever increasing granularity. However, the Standard Model leaves open some important questions like that about the nature of Dark Matter. And even if the Standard Model has basically passed all experimental tests with flying colours, some cracks have shown in terms of discrepancies between experimental measurements and the theoretical predictions which have no explanation yet within the Standard Model. A famous example is the measured value for the anomalous magnetic dipole moment of the muon, $(g-2)_\mu$, which disagrees with the theoretical prediction by 3.5 standard deviations [42, 43]. Also in flavour physics there are several measurements in tension with the Standard Model predictions. Lepton universality seems to be violated in the decay of B mesons to $D^{(*)}$ mesons by 3.9 standard deviations [44] and in the decay to K^{*0} mesons at the level of 2.1 to 2.5 standard deviations [45]. Combining these with other flavour measurements gives a disagreement of more than 5 standard deviations [46]. In addition, there are a number of open questions that the Standard Model does not offer answers to. And thus particle physics is a very broad and active field of fundamental research, where many theorists and collaborations with sometimes several thousands of experimental physicists from all over the world work on further probing the Standard Model to find out where and how it may need to be improved and extended.

The topic of this thesis is the search for supersymmetry (SUSY), a hypothetical extension of the Standard Model of particle physics, at the ATLAS detector, focusing on final states with tau leptons. The goal is to generate experimental proof for the implementation of supersymmetry in nature by establishing the existence of the new particles that it predicts.

The document is structured as follows. The rest of Chapter 1 introduces the notions and language relevant in the context of this thesis, starting with the basic concepts of supersymmetry and the particle content of the minimal supersymmetric extension of the Standard Model in Section 1.1. Sections 1.2 and 1.3 summarise models of supersymmetry and important aspects when working with tau leptons in collider-detector searches, respectively. Chapter 2 contains two brief sections with a synopsis of the experiment, the LHC and the ATLAS detector, and the datasets and analysis strategy in general. The main part of the document is Chapter 3. It is devoted to the presentation of the various analyses that I have worked on. The overview in Section 3.1 outlines the various analyses described in the rest of this chapter and highlights my contributions to these. Chapter 4 is a recapitulation of the most important findings obtained in this thesis and their meaning for supersymmetry. Chapter 5 describes my related scientific and academic work and my contributions to teaching as part of the thesis. The bibliography in Chapter 6 is divided into three parts, separately listing publications to which I have made important contributions, theses written by students under my supervision, and general references to consult for further information.

1.1 Supersymmetry in a Nutshell

Supersymmetry [47] is a symmetry between fermions and bosons, i. e. between particles with a spin difference of 1/2 (in natural units where $\hbar = 1$). It is the only non-trivial extension of the Poincaré space-time symmetry of the Standard Model, made possible by the introduction of fermionic generators as generators of the new symmetry. In a supersymmetric model, all particles are arranged in supermultiplets, which combine equal numbers of fermionic and bosonic degrees of freedom. A supersymmetry transformation turns a bosonic state into a fermionic state from the same supermultiplet, and vice versa. All other quantum numbers and, in exact supersymmetry, also the mass, are identical for the particles within a supermultiplet.

The introduction of supersymmetry is a very attractive and well-motivated extension of the Standard Model of particle physics. Not only is supersymmetry appealing from a theoretical point of view because the additional symmetry provides a connection between the fermionic and bosonic sectors of elementary particles and is an important ingredient of string theories, but it also offers compelling solutions to a number of shortcomings of the Standard Model: The Standard Model cannot explain Dark Matter, it does not provide unification of the running gauge couplings, and the Higgs-boson mass requires a fine-tuned cancellation of parameters that is felt to be unnatural. The first evidence for the existence of Dark Matter, an additional, non-radiating form of matter, stems from measurements of the rotation curves of galaxies. Independent confirmation comes from gravitational lensing, which allows to map out the amount of gravitationally interacting material in galaxy clusters, a prominent example being the bullet cluster 1E 0657-558. Finally, fitting the power spectrum of temperature fluctuations in the cosmic microwave background radiation in the ΛCDM model allows to deduce that five times more of the energy density of the universe is contained in Dark Matter than in radiating matter. Large-scale simulations of the structure formation in the universe suggest that Dark Matter should be cold, i. e. consist of massive particles that move at non-relativistic velocities. The Standard Model does not contain any weakly-interacting massive particle as candidate for Dark Matter, but in its supersymmetric extension, the lightest supersymmetric particle (LSP) typically is a very good candidate.

The second canonical argument for supersymmetry comes from the unification of gauge couplings. The Standard Model already unifies electromagnetism and the weak interaction. A Grand Unified Theory (GUT) would go one step further and also include the strong interaction. At the corresponding energy scale of about 10^{16} GeV (GUT scale) the running coupling constants of all three forces should then converge. In the Standard Model they do not intersect in one point, but the addition of supersymmetric partner particles to the theory modifies the renormalisation group (RG) equations in such a way that gauge coupling unification appears naturally at the GUT scale.

Another important motivation for the introduction of supersymmetry is the hierarchy or fine-tuning problem of the Higgs mass. The Higgs particle, being an elementary scalar particle, receives large quantum corrections to its mass from loop diagrams. These quantum corrections arise from the self-interaction term in the Higgs potential and diverge quadratically with the cut-off scale, the scale up to which the theory is considered valid. In order to cancel these corrections and arrive at the measured mass value of 125 GeV [48] at the electroweak scale, fine-tuning of the bare mass parameter is required to an extent that is considered unnatural. Supersymmetry does not have this problem, as the quantum corrections from fermion loops and scalar loops have opposite signs and cancel exactly, given that there is an equal number of fermionic and bosonic degrees of freedom in the theory.

The known particle content of the Standard Model cannot be rearranged to obtain complete supermultiplets. Instead, new particles have to be added as the superpartners of Standard Model particles. The model with minimal particle content that includes all Standard Model particles in a supersymmetric way is called Minimal Supersymmetric Standard Model (MSSM). In the MSSM, every known Standard Model particle is complemented by a hypothetical superpartner (except for some subtleties in the Higgs sector), such that the particle content more than doubles with respect to the Standard Model. This is a bold step but very well motivated as explained above.

The nomenclature for the particles in the MSSM is as follows. The symbols for the supersymmetric particles are the same as those for the Standard Model particles but with a tilde on top. The scalar partners of the fermions have a prefix "s-", i. e. the supersymmetric sfermions comprise the squarks ($\widetilde{q}$) and sleptons ($\widetilde{\ell}$, $\widetilde{\nu}$). Each lepton ℓ has two scalar partner sleptons $\widetilde{\ell}_L$ and $\widetilde{\ell}_R$, where the subscript refers to the chirality of the lepton component. In somewhat sloppy notation, they are commonly referred to as left- and right-handed sleptons. The same holds for the squarks. Mixing among scalars from the first and second generation is usually negligible, but due to the larger Yukawa couplings, mixing can be substantial for the third generations. For the tau sleptons, $\widetilde{\tau}_1$ and $\widetilde{\tau}_2$ refer to the lighter and heavier of the two mass eigenstates, which are mixtures of the gauge eigenstates $\widetilde{\tau}_L$ and $\widetilde{\tau}_R$. The lighter state $\widetilde{\tau}_1$ can be significantly lighter than the sleptons from the first and second generation, because of its larger Yukawa and soft couplings in the RG evolution. The situation for the top and bottom squarks is analogous. The names of the spin-1/2 partners of the bosons end in "-ino", i. e. the gauginos are particles with spin 1/2 and the superpartners of the Standard Model gauge bosons, including the bino as an $SU(2)_L$ singlet and the winos as an $SU(2)_L$ triplet. The superpartners of the gluons are the colour-charged gluinos ($\widetilde{g}$). The gravitino $\widetilde{G}$ has spin 3/2 and is the superpartner of the (hypothetical) graviton. It becomes massive through the super-Higgs mechanism when it absorbs the goldstino, the Goldstone fermion from the spontaneous breaking of local supersymmetry, and it also inherits its interactions.

The Higgs sector of the Standard Model needs to be extended from one to two complex Higgs $SU(2)_L$ doublets (2HD) of opposite weak hypercharge in the MSSM. These separately give mass to up- and down-type quarks and charged leptons. After three of the eight degrees of freedom from the two complex doublets have been absorbed to provide longitudinal degrees of freedom, i. e. mass, to the W and Z bosons, five scalar Higgs bosons appear in the MSSM: one CP-odd (A^0) and two CP-even (h^0, H^0) neutral Higgs bosons and two charged Higgs bosons ($H^{\pm}$). The two Higgs doublets are accompanied by two higgsino doublets containing their supersymmetric partner states, that can mix with the bino and the winos. The resulting physical mass eigenstates are referred to as the two charginos $\widetilde{\chi}_i^{\pm}$ and four neutralinos $\widetilde{\chi}_j^0$, indexed in order of increasing mass. The composition of the charginos and neutralinos depends on the MSSM parameters and determines their mass spectrum and couplings to other particles, with important consequences for the electroweak phenomenology. Large mass differences appear more naturally between a bino-like $\widetilde{\chi}_1^0$ and a wino-like $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$ than within a higgsino-like triplet of $\widetilde{\chi}_1^0$, $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$, which tends to be close in mass and yield low energetic (soft) decay products.

At tree-level, the properties of the Higgs sector in the MSSM depend only on two non-Standard-Model parameters, the mass m_{A^0} and $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. In the decoupling limit $m_{A^0} \gg m_Z$ [49], the neutral CP-even Higgs h^0 may be the only light Higgs boson and have properties nearly identical to those predicted by the Standard Model. The particle with a mass of 125 GeV, which was discovered at the LHC in 2012 [50], can therefore have the properties as expected and experimentally confirmed for it to be a Standard Model Higgs, and yet be one of the Higgs bosons of the MSSM (or any 2HD model).

An assumption with important phenomenological consequences that will be used in this thesis is R-parity conservation. The motivation for making this assumption is that the accidental $B-L$ symmetry of the Standard Model (B and L denoting baryon and lepton number, respectively; both are conserved separately in the Standard Model) is not necessarily inherited by its minimal supersymmetric extension. Additional gauge-invariant and renormalisable terms can be introduced in the superpotential which change the baryon number or the total lepton number. These would allow proton decay at a rate that is inconsistent with the experimental lower limit on its lifetime. To forbid these terms and avoid the problem of proton decay, a new multiplicatively conserved quantum number R is introduced, which is $+1$ for Standard Model particles and -1 for their supersymmetric partners. As a consequence, the lightest supersymmetric particle is stable because it cannot decay to Standard Model particles only. Also, supersymmetric particles are then always produced in pairs at collider experiments, yielding two separate decay chains. The decay chains end in the LSP, and at every decay vertex an even number of SUSY particles must be involved, i. e. every SUSY particle can only decay to an odd number of other supersymmetric particles plus any number of additional Standard Model particles. The stable LSP provides a good dark matter candidate and is typically the lightest neutralino $\widetilde{\chi}_1^0$ or the gravitino $\widetilde{G}$. As these only interact weakly, they escape the detector without producing any signal, leading to an imbalance in the vectorial sum of measured momenta. Missing transverse momentum (conventionally denoted by its magnitude $E_{\mathrm{T}}^{\mathrm{miss}} := |\vec{p}_{\mathrm{T}}^{\mathrm{miss}}|$) is thus an important part of the detector signature in many searches for supersymmetric particles. If R-parity is not conserved, the LSP may eventually decay, leading to very high particle multiplicities in the final state. Such signatures are targeted, e. g., in the multi-lepton searches [51].

The existence of scalar electrons with a mass of half an MeV would not have gone unnoticed. The non-observation of these particles, which are predicted by exact supersymmetry, means that either supersymmetry is not realised in the spectrum of elementary particles, or that supersymmetry is a broken symmetry and the supersymmetric partners are heavier than their Standard Model counterparts. It is not known by what mechanism supersymmetry is broken. In order to retain supersymmetry as a solution to the hierarchy problem, the breaking is usually required to be soft, i. e. to not reintroduce quadratic divergences in quantum corrections to scalar masses. In the MSSM, no assumption on the supersymmetry-breaking mechanism is made, but supersymmetry is broken explicitly by introducing new terms in the Lagrangian, adding 105 parameters to the model on top of the 19 free parameters of the Standard Model. Alternatively, there are many, more predictive theories that explain how supersymmetry can be broken spontaneously. In the two main proposals, the breaking of supersymmetry happens in a hidden sector and is mediated to the visible sector, the MSSM, through either interactions of gravitational strength or gauge interactions. This has important consequences for the gravitino and its role in collider phenomenology. In models with gravity-mediated supersymmetry breaking, the gravitino is expected to have a mass of the order of hundreds of GeV and its interactions are of gravitational strength, so that it is not important for phenomenology. Models with gauge-mediated supersymmetry breaking (GMSB) [52], however, usually have a very light gravitino, which then is the LSP. All sparticles will typically follow decay chains that lead to the gravitino through the next-to-lightest supersymmetric particle (NLSP). The goldstino component of the gravitino allows the decays of the NLSP to the LSP to be faster than if it only had gravitational interactions. The nature of the NLSP determines the final-state signatures at collider experiments in this case. The NLSP can, e. g., be the $\widetilde{\tau}_1$, which would decay to a tau lepton and the gravitino as in Section 3.5.

1.2 Supersymmetry at Colliders

The vexing consequence of supersymmetry breaking is that the supersymmetric particles in principle could have any mass, making it unclear where to search for them or whether they lie within the reach of the LHC or any future collider at all. However, there are arguments that suggest that at least those SUSY particles which give the largest loop corrections to the Higgs mass should not be too heavy in order not to reintroduce large fine-tuning. These are the third-generation sparticles, in particular the top squark, the higgsinos, and, when assuming grand unification, also the bino and the winos [53]. In addition, light sleptons are favoured because they can help to obtain a dark-matter relic density consistent with cosmological observations by serving as a coannihilator of the neutralino.

Thus, assuming that at least some of the supersymmetric particles lie within reach, concrete benchmark models are needed to optimise the searches for these particles at a collider detector. The MSSM with its 105 parameters for soft supersymmetry breaking has a prohibitively large parameter space and cannot be scanned exhaustively. On the other hand, large parts of the MSSM parameter space do not yield viable models because in general they have new sources of flavour-changing or CP-violating effects, which are severely restricted by experiment. The phenomenological MSSM (pMSSM) [54, 55] therefore introduces three assumptions, which are motivated by experimental constraints or general features of SUSY breaking mechanisms. The phase factors in the soft-SUSY breaking parameters are set to zero to eliminate sources of CP-violation. The matrices parameterising the sfermion masses and the trilinear couplings are chosen to be diagonal, so that no flavour-changing neutral currents appear at tree level. Furthermore, the first and second generation of squarks and sleptons are assumed to be mass-degenerate. This reduces the number of new parameters to 19. Two approaches are used to cope with this still high number of parameters. Either large quantities of model points are generated by sampling appropriately chosen ranges of values for the 19 parameters (e. g. in [1]), or most of the parameters are fixed based on some further model assumptions, and a remaining small subset of typically two parameters is then varied systematically (e. g. in [2]).

Most of today's searches for supersymmetry by the ATLAS and CMS collaborations, including all that are discussed below, employ simplified models for the optimisation of the signal selection and in the interpretation of the search results. These have largely replaced constrained models such as minimal supergravity (CMSSM/MSUGRA) or non-universal Higgs mass models (NUHM) from the earlier days of the LHC searches (e. g. in [3, 56]) and are conceptually very different. In contrast to complete supersymmetry models, in a simplified model [57] only one specific production mode and a limited number of decay topologies are considered, again often only one. All sparticles that do not appear in the decay chains are assumed to be too heavy to be relevant for the phenomenology. By choosing fixed values for the branching ratios within the decay chain, too, these models are described by a small set of free parameters, which are typically chosen to be two sparticle masses. Simplified models thus aim to capture the behaviour of a small number of kinematically accessible sparticles and to provide results that are simple to interpret and can therefore easily be recast in more complete models. They can be used to directly express the findings of a search in terms of exclusion limits on sparticle masses. However, it should be kept in mind that these limits are only valid under the respective assumptions, and in particular relaxing the assumptions on the branching ratio may significantly reduce the excluded range as demonstrated, e. g., in [58].

In all models discussed here, all supersymmetric particles apart from the stable LSP are assumed to decay promptly. Prompt means that the decay vertex has no measurable displacement with respect to the production vertex, the primary vertex of the pp collision. ATLAS also has a broad programme of dedicated searches for long-lived massive particles.

With increasing size of the available dataset, processes with lower frequency of occurrence can be studied. Therefore, the historical order of the searches follows the same pattern at the beginning of Run 1 and Run 2 of the LHC, mostly dictated by the production cross section for the supersymmetric particles they target but also by the signal acceptance, which folds in branching ratios and kinematic requirements, and detector efficiencies. The production cross section depends on the masses of the initial pair-produced supersymmetric particles and their relevant production modes. At a hadron collider like the LHC, where the interacting particles, the partons inside the protons, carry colour charge, the cross sections for the production of colour-charged particles dominate, because these can be produced through the strong interaction. Particles without colour charge like gauginos can only be produced via the electroweak interaction. At a given mass, the cross section is thus largest for production of gluinos and squarks of the first and second generation, followed by third generation squarks, for which the production cross section is smaller by more than one order of magnitude. Another two orders of magnitude smaller is the cross section for production of gaugino pairs, followed by the even smaller cross section for direct production of slepton pairs. The first analyses in both runs are therefore inclusive analyses targeting strong production, followed by the third-generation squark and electroweak searches, and finally direct slepton production.

Following the same logic, the mass ranges for supersymmetric particles excluded by the ATLAS and CMS collaborations in simplified models [42] are of the order of 2 TeV for gluinos, and 1.5 TeV or 1 TeV for squarks of the first and second or third generation, respectively. The limits on gaugino masses also start to exceed 1 TeV, and those for sleptons of the first and second generation approach 500 GeV. (An overview of the latest results can also be found on the public web pages of the collaborations.) There are also limits from earlier experiments, some of which are still relevant for the searches presented in this thesis: The experiments at the Large Electron-Positron Collider (LEP), the predecessor of the LHC, have published combined limits on chargino and slepton masses [59–65]. They set a lower limit at 95 % confidence level (CL) on the mass of the chargino $\tilde{\chi}_1^{\pm}$ of 103.5 GeV, degrading to 91.9 GeV for small mass splittings $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) < 3\,\text{GeV}$. For tau sleptons $\tilde{\tau}_1$, masses up to a value between 87 GeV and 96 GeV are excluded at 95 % CL depending on the mass of the $\tilde{\chi}_1^0$.

1.3 Tau Leptons in Collider Searches for Supersymmetry

A common feature of all searches discussed in this thesis is the presence of tau leptons in the final state. (Final state refers to the set of collision products or reconstructed physics objects which are characteristic for a given decay topology.) In contrast to electrons and muons, which will be referred to as light leptons in the following, with a mass of 1.777 GeV the tau leptons are heavier than the lightest hadrons. This enables them to decay leptonically (i. e., $\tau \to \ell \, \nu_\ell \, \nu_\tau$, $\ell = e, \mu$) or hadronically (i. e., $\tau \to$ hadrons ν_τ), where the hadronic decay products are mostly pions. Depending to the number of charged products, the tau-lepton decays are called 1- or 3-prong. (Higher numbers may occur but are rare.) The branching ratios for leptonic decays (τ_{lep}) are roughly 1/6 for each of the light leptons and 2/3 for hadronic decays (τ_{had}).

Tau leptons have a proper decay length of $c \cdot \tau_\tau = 87$ µm and decay before they can interact with the detector. At the ATLAS detector, leptonically decaying tau leptons are treated as prompt light leptons. The reconstruction and identification of hadronically decaying tau leptons proceeds in two steps [66–68]. First, tau-lepton candidates are created from energy deposits in the calorimeters reconstructed as jets. A tau-lepton-specific energy correction is applied to calibrate the measured energy to the average visible energy at the generator level, where the visible energy is the energy of the tau-lepton decay products excluding the neutrinos. In a following identification step, multi-variate analysis algorithms based on boosted decision trees are used to discriminate real hadronic tau-lepton decays from the dominant background from jets. Heavy- and light-flavour quark and gluon jets, electrons and, to a lesser degree, muons may be falsely identified as hadronically decaying tau leptons. These are referred to as fake tau leptons. Fakes from electrons and muons can be suppressed by rejecting hadronically decaying tau leptons that overlap geometrically with reconstructed light leptons. Due to their short lifetime, tau leptons cannot be measured directly and have lower reconstruction and identification efficiencies than electrons and muons and higher fake probabilities. Typical identification efficiencies for the medium working point of the ATLAS tau-lepton identification algorithms range from 40 % to 60 % in Run 1, depending on the transverse momentum (p_{T}) and prongness of the tau candidate and detector conditions. The inverse background efficiency varies roughly between 20 to 400, corresponding to fake probabilities of a few percent to per mille. Over the past years, the identification algorithms have been significantly improved, now giving identification efficiencies from 60 % to 70 % and inverse background efficiencies between 50 to 100 in Run 2. This directly translates into a better separation of signal and background in analyses using tau leptons.

The analysis of final states with hadronically decaying tau leptons is a vital part of the physics programme at the LHC. Not only are these final states important for Standard Model measurements and Higgs-boson searches and measurements, but also, of course, for searches for physics beyond the Standard Model (BSM) such as supersymmetry. First of all, they provide complementary information to the search channels with light leptons. Also, if BSM physics is to be found, measurements of the signal strength and the couplings to the known Standard Model particles will provide insight into the nature of the new particles in the same way as this is the case now for the Higgs boson. Furthermore, as the mass spectrum of the supersymmetric particles is unknown, it is not known a priori which of these particles will be seen at the LHC, and it is essential to cover all possibilities. There are many reasons why tau sleptons, the decay of which will yield final states enriched with tau leptons, could be lighter than the other supersymmetric particles. They are therefore of particular interest. In many models, the squarks, especially those of the first and second generation, are heavier than the sleptons. Light sleptons may also be related to the discrepancy between the theoretical prediction and the measured value of the magnetic dipole moment of the muon. For large values of the parameter $\tan\beta$, the lightest of the sleptons will probably be the tau slepton. Neutralinos and charginos will then predominantly decay via tau sleptons. As mentioned above, light tau sleptons can also act as a coannihilator [69] for a bino LSP in the early universe [70, 71], yielding a relic dark-matter density consistent with the observed value. Similarly, light sleptons are consistent with the results from dark-matter searches [72]. And finally, a recent evaluation of the level of fine-tuning of the Higgs-sector parameters needed in the pMSSM to accommodate for the collider constraints on supersymmetry models also favours models with light tau sleptons [73].

In general, there are two possibilities to obtain tau leptons in events with production of supersymmetric particles. First, they can be produced directly in the decay of a supersymmetric particle. Assuming, as usual, conservation of R-parity and lepton number, such a decay will necessarily involve a tau slepton or a tau sneutrino. Tau sleptons can be produced directly in pairs, $pp \to \widetilde{\tau}^+\widetilde{\tau}^-$, and then decay to the LSP as $\widetilde{\tau}^\pm \to \tau^\pm\widetilde{\chi}_1^0$ or $\widetilde{\tau}^\pm \to \tau^\pm\widetilde{G}$. They can also appear in decays of heavier gauginos as $\widetilde{\chi}_1^\pm \to \nu_\tau\widetilde{\tau}^\pm$ or $\widetilde{\chi}_2^0 \to \tau^\pm\widetilde{\tau}^\mp$, where in the first case the following tau-slepton decay yields a tau lepton, and in the second case the tau lepton appears as a decay product of the neutralino. The tau sneutrino gives a tau lepton in decays such as $\widetilde{\chi}_1^\pm \to \tau^\pm\widetilde{\nu}_\tau$. Here, the decay of the second-lightest neutralino $\widetilde{\chi}_2^0$ via a tau sneutrino, $\widetilde{\chi}_2^0 \to \nu_\tau\widetilde{\nu}_\tau$ followed by $\widetilde{\nu}_\tau \to \nu_\tau\widetilde{\chi}_1^0$, however, only contributes to $E_{\mathrm{T}}^{\mathrm{miss}}$. (For completeness, in models with R-parity violation, tau-lepton-rich final states from three-body decays of supersymmetric particles such as $\widetilde{\chi}_1^0 \to \tau^+\tau^-\nu$ are possible. These are also studied in ATLAS [51] but not considered here.)

The second possibility is that tau leptons arise indirectly from the decay of electroweak gauge bosons, which themselves originate from supersymmetric decays, e. g. $\widetilde{\chi}_1^\pm \to W^\pm\widetilde{\chi}_1^0$ or $\widetilde{\chi}_2^0 \to Z\widetilde{\chi}_1^0$. While such a decay is often assumed in light-lepton searches, the branching ratio for W-boson decays to hadronically decaying tau leptons is 3.5 times smaller than that to light leptons (including leptonically decaying tau leptons). This search channel is thus strongly disfavoured and not of interest. The same holds for Z-boson decays. For Higgs bosons, the branching ratio to tau leptons is much larger than that to light leptons due to the larger Yukawa couplings, and also the Standard Model background is smaller, so that the search for supersymmetry with decays through Higgs bosons in tau-lepton final states is more promising. An example will be given in Section 3.6.

2 Experiment, Data and Analysis Strategy

2.1 Experiment and Data

The Large Hadron Collider (LHC) [74] at the European Organization for Nuclear Research (Conseil européen pour la recherche nucléaire, CERN) is the most powerful hadron collider ever built, designed to collide proton bunches at unprecedented centre-of-mass energies $\sqrt{s}$ of up to 14 TeV in the proton–proton (pp) system. In addition to providing proton–proton collisions, the LHC can also be used to collide heavy ions to study properties of the quark–gluon plasma. All searches described below were performed using data from proton–proton collisions taken with the ATLAS detector at the LHC. The ATLAS detector has the conventional layout used for modern multi-purpose detectors at high-energy particle colliders. It is described in full detail in ref. [75]. A brief summary from ref. [4] is reproduced here for the convenience of the reader.

> The ATLAS detector [75] is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.[1] It consists of, starting from the interaction point and moving outwards, an inner tracking detector, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$ and consists of silicon pixel, silicon microstrip, and transition radiation detectors, immersed in a 2 T axial magnetic field provided by a thin superconducting solenoid. The insertable B-layer, the innermost layer of the silicon pixel detector, was added before the $\sqrt{s} = 13$ TeV data-taking and provides high-resolution hits to improve the tracking and b-tagging performance [76, 77]. The calorimeter system covers pseudorapidities $|\eta| < 4.9$. Electromagnetic energy measurements with high granularity are provided by lead/liquid-argon sampling calorimeters in the region $|\eta| < 3.2$. Hadronic calorimetry is provided by sampling calorimeters with scintillator tiles and steel absorbers within $|\eta| < 1.7$ and with copper/liquid-argon for $1.5 < |\eta| < 3.2$. The forward regions are instrumented with sampling calorimeters using liquid-argon as the active medium for both the electromagnetic and hadronic calorimetry. The muon spectrometer features three large superconducting toroid magnets with eight coils each, precision-tracking detectors in the region $|\eta| < 2.7$, and fast, dedicated chambers for triggering in the region $|\eta| < 2.4$. Collision events are selected for recording by a two-stage trigger system, which has been upgraded for the run

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. When the mass of a particle cannot be neglected, the rapidity $y = 0.5\ln\left[(E+p_z)/(E-p_z)\right]$ is used instead of the pseudorapidity η to specify its direction.

at $\sqrt{s} = 13\,\text{TeV}$ [78]. It consists of a hardware-based trigger as the first level, followed by the software-based high-level trigger, which is able to run reconstruction and calibration algorithms similar to those used offline, reducing the event rate to about 1 kHz.

The start-up of the LHC was delayed by an incident in September 2008 [79], when during powering tests of one of the main dipole circuits of the LHC a faulty electrical connection between two magnets produced an electrical arc breaking open the helium enclosure and beam vacuum pipes and a large amount of helium was released into the insulation vacuum of the cryostat, which eventually led to serious damage in several magnets. After the repairs and consolidation works, it was decided to begin operation of the LHC below its design energy of 14 TeV. The first pp collision data used in searches for supersymmetry was taken at 7 TeV in 2010, with a total luminosity of $45\,\text{pb}^{-1}$ recorded by the ATLAS detector in that year, followed by a substantially larger $5.1\,\text{fb}^{-1}$ in 2011, still at 7 TeV. The earliest dataset used in the searches described in this thesis is from 2012, the last year of the first data-taking period (Run 1) of the LHC, in which the centre-of-mass energy was raised to 8 TeV for the first time and $21.3\,\text{fb}^{-1}$ of data were recorded at ATLAS. During the first long shutdown from 2013 to 2015, the LHC was prepared to provide pp collisions at $\sqrt{s} = 13\,\text{TeV}$ in Run 2. The 13 TeV dataset comprises $3.9\,\text{fb}^{-1}$ of luminosity recorded in 2015 and $35.6\,\text{fb}^{-1}$ recorded in 2016. After data-quality assessment, the amount of data considered good for physics is about 10 % less, yielding a total of $36.1\,\text{fb}^{-1}$ which is used in the latest ATLAS publications. Another $47.1\,\text{fb}^{-1}$ of integrated luminosity were recorded in 2017, and up to $60\,\text{fb}^{-1}$ at 13 TeV are expected during 2018, the last year of Run 2, but the analysis of this data is still ongoing or in preparation. The following long shutdown 2 will give three years to thoroughly understand the data and publish results.

From these numbers it becomes clear that both the centre-of-mass energy and the instantaneous luminosity have increased significantly over the years. An interesting quantity is the luminosity-doubling time, the time in which the size of the recorded dataset doubles, because it sets the scale for the lifetime of the results from the data analysis. While in the beginning of the LHC it was of the order of a few months and many analyses received significant updates for every major conferences, it now has surpassed the one-year mark (depending on whether one counts the shutdown phases or not), and the improvement from the addition of the 2017 dataset does no longer warrant a new publication. Instead, many analysis groups plan to publish the next major update only with the full dataset from Run 2.

The peak instantaneous luminosity in 2012 was $8 \cdot 10^{33}\,\text{Hz/cm}^2$. While the performance of the LHC in 2015 after upgrading to $\sqrt{s} = 13\,\text{TeV}$ fell short of that in 2012, in 2016 the instantaneous luminosity reached the design value of the LHC of $10 \cdot 10^{33}\,\text{Hz/cm}^2$ for the first time, later exceeding it by 50 % for most of 2017. The increasing instantaneous luminosity goes along with an increase in the average number of concurrent proton–proton interactions per proton bunch crossing $\langle \mu \rangle$ which are overlaid in the detector signals and referred to as in-time pile-up. The 2012 dataset has $\langle \mu \rangle = 20.7$ and the 2016 dataset $\langle \mu \rangle = 24.9$. This poses significant challenges to the detector and the (offline) reconstruction software and causes a deterioration of the energy and momentum resolution, leading also to higher trigger rates and necessitating higher trigger thresholds in the online selection of events to be stored as will be discussed below.

2.2 General Analysis Strategy and Important Methods

The basic procedure underlying the searches for physics beyond the Standard Model consists of selecting and counting collision events in the recorded dataset which fulfil certain criteria. The observed counts are then compared against corresponding predictions obtained from a Monte-Carlo simulation of collision events in the detector that implements the theory of the Standard Model and potentially additional processes from theories beyond the Standard Model. Statistical tests allow to state the compatibility of the observation with the Standard Model hypothesis. If the observed event yields are incompatible with the Standard Model hypothesis, a discovery can be claimed at a certain statistical confidence level (CL), or else if the observation is incompatible with the hypothesis of the presence of both the background expected from Standard Model processes and a particular new signal from BSM physics, this BSM hypothesis can be excluded.

The criteria for selecting events are based on event-level properties, e. g. the multiplicity of objects of a given type in an event or global quantities such as $E_{\mathrm{T}}^{\mathrm{miss}}$, and object-level properties, e. g. the momentum of a given object. A typical search employs a combination of different types of event selections in parallel. Central element are the signal regions, which are selections defined to cover phase-space regions with a high signal-to-background ratio and which are used to evaluate the hypothesis tests mentioned above. Similarly, control regions are selections designed to be enriched in events from a specific background process, while keeping contributions from other background (and potential signal) processes low to reduce uncertainties from correlations between different control regions. The control regions allow to normalise the estimate of the overall contribution of specific background processes from simulation to the level observed in real data. The extrapolation of the background estimate from the control to the signal regions can be tested by defining additional validation regions in between the control and signal regions and comparing simulation estimates and observed data in these. The control and validation regions are made as similar to the signal regions as possible in order to minimise the uncertainties arising from the extrapolation, while keeping the contamination with signal events at a tolerable level. In general, the selection requirements of the analysis setup are optimised in simulation as a compromise between high purity (tighter requirements) and event counts that are sufficiently large to provide statistical power (looser requirements).

Two types of background processes are distinguished. Irreducible background processes yield events with the same final state as the targeted signal process. Events from reducible background processes, on the other hand, pass the signal selection only due to imperfections in the detector hardware or the reconstruction software, i. e. the algorithms that interpret the detector output in terms of physics objects. Their contribution can potentially be reduced by improving the detector and reconstruction performance. The searches that are the topic of this thesis all consider final states with at least two tau leptons, except for the inclusive search, but also there our contribution focuses on the channel with two tau leptons. The events selected in these analyses may contain real tau leptons, defined as correctly identified hadronically decaying tau leptons, as well as fake tau leptons, which are heavy- or light-flavour quark or gluon jets, electrons or, in rare cases, muons that are falsely identified as a tau lepton. The most important irreducible background processes are the production of top-quark pairs ($t\bar{t}$), two vector bosons (mostly contributing as $WW \rightarrow \tau\nu_\tau\tau\nu_\tau$ or $ZZ \rightarrow \tau\tau\nu\nu$), or a Z boson. All of these may give two real tau leptons. Top-quark processes can be efficiently suppressed by rejecting events with b-jets, i. e. jets that are induced from decays of B hadrons originating from the hadronisation of b-quarks unless these also emerge from the signal decay chain as in the search for production of top squarks. Rejecting events where the invariant mass of the two tau leptons is close to the visible $Z(\rightarrow \tau\tau)$ mass removes most of the background with Z-boson production. The reducible background is dominated by W-boson production with one real and one fake tau lepton and multi-jet events with two fake tau leptons. In addition, production of top-quark pairs may also significantly contribute to the reducible background, if (at least) one of the W bosons decays hadronically and yields a fake tau lepton.

The circumstances which may lead to the misidentification of some physics object as a fake tau lepton are typically more complex and more difficult to capture accurately in the detector simulation than the behaviour and reconstruction of real tau leptons. It is therefore expected that the modelling of fake tau leptons in simulation is less accurate than that of real tau leptons. For processes for which the simulation is considered unreliable, e. g. for fake tau leptons, data-driven methods can be used to improve the estimates of the background from Standard Model processes. These methods try to avoid dependence on the detector simulation as much as possible. Another typical use-case for data-driven methods is the modelling of multi-jet events. Due to its large cross section, a simulation-based estimate of this background process would require prohibitively large numbers of simulated events.

Three data-driven methods appear in several of the searches covered in this thesis. The OS–SS and ABCD methods provide estimates for the multi-jet background and the fake-factor method (FFM) for top-quark production, both in final states with fake tau leptons. The OS–SS method can be employed in selections which require two tau leptons of opposite electric charge. It exploits the fact that there is no charge correlation between the two fake tau leptons in multi-jet background events, i. e. the ratio of the number of same-sign events to the number of opposite-sign events is close to unity. In addition, few Standard Model processes lead to same-sign tau leptons pairs, such that the same-sign selection usually has high purity in multi-jet events with fake tau leptons. Subtracting the simulation-based estimates for all background processes except multi-jet production from the number of events observed in data in the same-sign selection, this number directly provides a reasonable estimate of the number of multi-jet events in the opposite-sign selection. The idea behind the ABCD method is to define three additional, disjoint selections complementing the target selection (D). A transfer factor T computed from the ratio of events in two of these (A and B) is then used to extrapolate the observed event count from the third (C) into the phase-space region of the target selection: $N_D \approx T \cdot N_C := \frac{N_A}{N_B} N_C$. The number N of multi-jet events is obtained as above by subtracting the simulation-based estimates of all processes except multi-jet production from the observed data counts. Two uncorrelated variables from the target selection need to be identified for this method to work, which yield selections with significant contributions from multi-jet events when relaxing the selection requirement in either. Additional selections may be used to validate the extrapolation. The FFM is similar to the ABCD method, but implemented at object level rather than event level. An additional selection based on a loose tau-lepton identification is defined to measure the probability that a tau-lepton that passes the loose identification also passes the tighter nominal identification requirements. This fake factor is used to extrapolate from a region identical to the target selection but with loose tau-lepton identification and thus higher contribution of fake tau leptons to the target region. The object-dependent fake factors need to be measured in a region with a composition of dominant background processes that is similar to that of the target region.

3 Searches for New Physics

3.1 Overview

The following sections summarise the work of the research group consisting of myself and the students I am supervising. The summaries are kept brief and focus on the main features and important results of the analyses, and how these are embedded into the overarching physics programme of the ATLAS collaboration. Details can be found in the accompanying papers and publications that are cited. Due to the complexity of the ATLAS detector and the physics involved, no research group can cover all aspects of the data preparation and analysis. Instead, dedicated physics-performance groups provide recommendations for the entire ATLAS collaboration, and the physics analyses are based on these. For this reason, all qualified ATLAS members sign all ATLAS papers as co-authors.

All of the publications described in this chapter include significant contributions from my research group, and where appropriate these contributions will be mentioned explicitly. The analyses have been performed in collaboration with other research groups. For the search for top-squark production in Section 3.5 in particular, almost all of the analysis work has been done in my research group and under my coordination.

As mentioned above, the central and uniting feature of all analyses discussed in this thesis is the use of final states with hadronically decaying tau leptons. They are distinguished in Sections 3.2 to 3.5 by the respective dominant production mode, which determines the cross section and the event topology. In Section 3.6, two analyses are presented which study prospects for the HL-LHC. Finally, Section 3.7 covers two BSM analyses that go beyond supersymmetry.

3.2 Electroweak Production

In the search for electroweak production of supersymmetric particles, we consider models with associated production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$, where the lightest chargino $\tilde{\chi}_1^\pm$ and second-lightest neutralino $\tilde{\chi}_2^0$ are assumed to be mass-degenerate winos and the $\tilde{\chi}_1^0$ LSP is assumed to be a bino. These assumptions give the largest cross section and allow to have a large mass difference between the mass-degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$ LSP, into which the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay. The production cross sections for other combinations like $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ vanish or are negligibly small. Another possibility would be to assume a higgsino triplet consisting of $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$, but in addition to the smaller production cross section the members of this gaugino triplet would often all be nearly mass-degenerate, leading to decay products which have very small momenta and are thus difficult to detect.

We focus on decays which are mediated by tau sleptons and tau sneutrinos because these yield final states with tau leptons. The tau sleptons and tau sneutrinos are assumed to have the same mass and the branching ratios for the decay of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ through a tau slepton or a tau sneutrino are set to 50 %. Events with $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production then have either three or one tau leptons, depending on whether the $\tilde{\chi}_2^0$ decay proceeds through a tau slepton or sneutrino, and events with $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production have two. All other sparticles, in particular selectrons and smuons, are assumed to be very heavy so that they do not play a role for the phenomenology at the LHC. The excluded parameter space for the simplified models used for the interpretation is reported as a function of two free parameters, the masses of the $\tilde{\chi}_1^{\pm}$ (being identical to the mass of the $\tilde{\chi}_2^0$) and of the $\tilde{\chi}_1^0$. The mass of the intermediate tau slepton and tau sneutrino are set half-way between the masses of the $\tilde{\chi}_1^{\pm}$ and of the $\tilde{\chi}_1^0$.

The searches for electroweak production of supersymmetric particles in tau-lepton final states described below have been performed in close collaboration with other ATLAS groups, in particular with the ATLAS supersymmetry group from Beijing, but also working together, for example, with researchers from the $h \to \tau\tau$ analysis on the modelling of background events with fake tau leptons.

Run-1 Analysis Preliminary results of the first ATLAS search for electroweak production of supersymmetric particles in tau-lepton final states were made public already in spring 2013 [5], only a few months after the last pp-collision data at $\sqrt{s} = 8\,\text{TeV}$ had been taken. Afterwards, a number of refinements were made in the analysis setup, most importantly a reoptimisation of the signal selection and a better background estimation. Together with the improved tau-lepton identification provided by the ATLAS tau performance group this significantly improved the sensitivity. The publication of the final ATLAS Run-1 result for this search followed in 2014 [2, 25]. It is based on $20.3\,\text{fb}^{-1}$ of pp-collision data at $\sqrt{s} = 8\,\text{TeV}$ collected with a two-tau trigger, where the presence of two hadronically decaying tau leptons triggers the recording of an event. Events with at least two hadronically decaying tau leptons with opposite electric charge and large missing transverse momentum from the escaping neutrinos and the LSPs are selected, unless they contain additional light leptons. The latter requirement was introduced to remove any overlap with the event selection of the existing electroweak 3-lepton analysis so that the two results could be combined (see below). Four signal selections are optimised for different mass assumptions and the different production modes.

The dominant background from multi-jet events is estimated using the ABCD method. In order to cross-check the multi-jet estimate from the ABCD method, the reconstruction efficiency for real tau leptons and fake rates for tau leptons were measured in tau-muon events (i. e. events with one hadronically decaying tau lepton and one muon) as inputs to the matrix method [80], which gave consistent results [26]. In the preliminary version of the analysis, the ABCD estimate included a small fraction of $W +$ jets events. However, for the final Run-1 result the fraction of $W +$ jets events in the signal region was no longer negligible due to the improved tau-lepton identification, and a separate, semi-data-driven estimate for $W +$ jets events had to be introduced. A dedicated control region in the tau-muon channel was developed to normalise the $W +$ jets estimate from simulation to the observed data yields, using the OS–SS method to estimate the multi-jet contamination in this region. The extrapolation to the signal region is validated using the tau-electron channel. The third important background source are events with diboson production. Its contribution is validated using a selection of events with one electron and one muon because in the two-tau channel the multi-jet background would dominate, and in channels with a hadronically decaying tau lepton and a light lepton $W +$ jets events would dominate.

As the signal selections are not mutually exclusive, in the interpretation of the analysis results for each mass scenario and production mode the one with the best expected sensitivity is used to derive exclusion limits at 95 % confidence level. In the simplified models with only $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ production, masses $m_{\tilde{\chi}_1^\pm} < 345\,\mathrm{GeV}$ are excluded for a massless $\tilde{\chi}_1^0$ LSP. For the combination of $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$, masses $m_{\tilde{\chi}_1^\pm,\tilde{\chi}_2^0} < 420\,\mathrm{GeV}$ are excluded for a massless $\tilde{\chi}_1^0$ LSP. This improves on the limit obtained by the 3-lepton analysis for this model [81]. The results are also interpreted in the context of the pMSSM with parameters chosen to enhance production of $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$, $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ and tau-slepton pairs and final states with tau leptons. Additionally, upper limits on the signal strength for direct production of pairs of tau sleptons are given, as the analysis is not expected to be sensitive to this production mode with the available dataset.

An important project that we initiated during Run 1 was the development of an analysis setup for the channel with one hadronically decaying tau lepton and one leptonically decaying tau lepton (lep-had channel) to complement the search in events with two hadronically decaying tau leptons (had-had channel) [25, 27]. The motivation for this was manifold: The branching ratio for hadronic decays of tau leptons is about 2/3, and for decays to electrons and muons it is about 1/6 each. The probability that in an event with two tau leptons both decay hadronically is thus the same as the probability that exactly one of them decays leptonically. Including the lep-had channel would therefore double the number of signal events. In addition, the probability of misidentifying a jet as a light lepton is much smaller than that of misidentifying a jet as a hadronically decaying tau lepton and multi-jet events make up most of the inclusive cross section in proton–proton collisions and thereby dictate the trigger thresholds. This leads to high rates for triggers on hadronically decaying tau leptons, which can only be controlled by raising the tau-p_{T} thresholds, resulting in thresholds much higher than for triggers on light leptons. For the same reason, the light-lepton requirement leads to a much lower expected multi-jet background in the lep-had channel. Our studies revealed several problems though. The additional neutrino emerging from a leptonic tau-lepton decay makes the spectrum of the transverse momentum of the light lepton much softer than the reconstructed visible momentum of the decay products from a hadronically decaying tau lepton. This nullifies the gain from the lower light-lepton trigger thresholds to a large part. The additional neutrino also weakens the separation power of the discriminating variables substantially. On the other hand, while the multi-jet background is indeed much smaller, the background from leptonic decays $W \to \ell\nu$ and $W \to \tau_{\mathrm{lep}}\nu$ in the lep-had channel is much larger than that from hadronic decays $W \to \tau_{\mathrm{had}}\nu$ in the had-had channel. Taking all these effects together, the lep-had channel turned out to be significantly less sensitive than the had-had channel, even when multi-variate analysis (MVA) techniques were included to improve the discrimination of signal and background. The difference in sensitivity was so large that even a statistical combination of the lep-had and had-had channel brought a gain so small compared to the had-had channel alone that it would not justify the additional effort to further develop the lep-had analysis. The lep-had channel has not been included in any publication for the electroweak search yet, but it may be interesting to revisit its performance for future publications [28].

pMSSM Run-1 Summary Paper With our analysis we have also participated in the common effort of the ATLAS supersymmetry working group to summarise the results of the most important searches for supersymmetry performed with ATLAS data from the first run for the LHC in the context of the phenomenological MSSM (pMSSM) [1, 25, 29]. This paper provides an extremely valuable assessment of the sensitivity beyond the picture conveyed by the interpretations in simplified models. While these interpretations give the correct picture as long as all assumptions of the simplified models hold, a complete model such as the phenomenological MSSM comprises all possible production modes and considers all possible decays. How much of an excluded mass range from a simplified model is retained when the branching ratios are smaller than assumed due to competing decays is not clear a priori. For this summary paper, a random sample of 500 million model points from the parameter space of the pMSSM was generated. 300.000 of these models fulfil constraints from precision electroweak and flavour results, other collider measurements such as the Higgs-boson mass, and the observed dark matter relic density. These models are then tested by generating event samples at generator level. For this, it was necessary to recast the analysis selections in a framework that allows to evaluate them on event-generator-level information, i. e. without running the simulation of the ATLAS detector and reconstruction of physics objects. Only for a subset of 45.000 models the detector simulation was run. Reasonable correspondence is found between the exclusion limits based on the simplified models and the sensitivity to pMSSM scenarios. Most of the coverage in terms of the fraction of models that are excluded is provided by the inclusive searches, which target production of squarks from the first and second generation and gluinos, whereas searches with more specialised selections such as the electroweak two-tau search provide additional unique sensitivity to specific subsets of models that cannot be covered by the more inclusive searches, in particular to models with long decay chains (with soft decay products) and light tau sleptons. This comes with the caveat that the measure of the fraction of excluded models is arbitrary, as it depends on the scan ranges and density of the sampling of the pMSSM parameter space.

Electroweak Run-1 Summary Paper After the data-taking at $\sqrt{s} = 8\,\text{TeV}$ had ended and the individual ATLAS analyses searching for electroweak production of supersymmetric particles had been finalised, their results were collected in a joint publication [3, 6]. In addition to the summary of existing search results and interpretations, this paper also includes a number of new, previously unpublished results, which target additional, possibly compressed scenarios, or extend the mass reach through the use of lower lepton-p_{T} thresholds and the exploitation of MVA techniques or initial-state radiation, same-sign lepton pairs and vector-boson production modes as signal signatures. For the search for electroweak production of supersymmetric particles in tau final states, two new results were prepared for the summary paper. A statistical combination was done with the electroweak 3-lepton analysis [81], which improves the sensitivity to electroweak $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production with tau-slepton mediated decays. Moreover, the search for direct production of tau sleptons was improved by using boosted decision trees, an MVA technique. Thereby, the sensitivity reaches the theoretically predicted production cross section for the first time at a hadron collider, albeit only for one of the tested mass scenarios with a tau-slepton mass $m_{\tilde{\tau}_R} = 109\,\text{GeV}$, slightly above the LEP exclusion limit, and a massless $\tilde{\chi}_1^0$ LSP.

Run-2 Analysis The first ATLAS paper on the search for electroweak production in final states with tau leptons at $\sqrt{s} = 13\,\text{TeV}$ has been released recently [7]. Our results in this paper are based on the dataset taken in 2015 and 2016 with an integrated luminosity of $36.1\,\text{fb}^{-1}$. They supersede preliminary results from 2017 [8], which are based on the same dataset, and earlier $\sqrt{s} = 13\,\text{TeV}$ results, which are based on a smaller dataset with an integrated luminosity of $14.8\,\text{fb}^{-1}$ and were released in 2016 [9].

In the preparation of the analysis for data-taking at $\sqrt{s} = 13$ TeV, the sensitivity of the $\sqrt{s} = 8$ TeV electroweak analysis was extrapolated using a reweighting of simulated samples using the ratio of the parton density functions at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 8$ TeV [25]. We found that the sensitivity with the 2015 dataset of 3.2 fb^{-1} taken at $\sqrt{s} = 13$ TeV would not be enough to surpass the Run-1 result for electroweak production. This is the reason why we decided to extend our work to the inclusive search for strong production with tau-lepton final states as described in Section 3.4, while additional data was taken in 2016.

The increase in the centre-of-mass energy and the expected higher instantaneous luminosity that the LHC Operations group was planning to achieve in the second run necessitated the development of new triggers. These triggers had to be designed to have the highest possible signal efficiency, while reducing the rate to a manageable level. For the SUSY analyses with final states with two hadronically decaying tau leptons this meant coping with large increases in the trigger thresholds on the tau-lepton p_{T} or moving to more complex triggers with additional requirements e. g. on the missing transverse momentum or a geometrical separation of the tau leptons (topological requirements) [27]. The behaviour of the 2015 two-tau trigger and its performance was studied with the first 3.2 fb^{-1} of $\sqrt{s} = 13$ TeV data [30]. We could show that the efficiency of the combined trigger factorises into a product of the efficiencies of each trigger leg could in simulation. The efficiency of each trigger leg was measured individually with a tag-and-probe method in the tau-muon channel. The knowledge of the trigger turn-on behaviour, i. e. the dependence of its efficiency on the p_{T} of the tau leptons, allows to adjust the analysis selections such that the trigger operates in the regime where its efficiency is nearly constant and systematic uncertainties related to the modelling of the turn-on behaviour of the trigger can be avoided. These studies were also important for the first paper on the search for electroweak production in final states with tau leptons at $\sqrt{s} = 13$ TeV, for which a trigger with high asymmetric thresholds on the p_{T} of two tau leptons as well as a trigger combining requirements on the tau-lepton p_{T} and the $E_{\mathrm{T}}^{\mathrm{miss}}$ are used. For this paper, two new signal selections have been optimised and a setup for the background estimation similar to the Run-1 paper is used. The results are interpreted in the same simplified models with either $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ or associated $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ production, and limits on the masses of the gauginos are derived, which are much stronger than those from the analysis of the $\sqrt{s} = 8$ TeV data for high masses of $\tilde{\chi}_2^{0}$ and $\tilde{\chi}_1^{\pm}$. For a massless $\tilde{\chi}_1^{0}$, masses up to $m_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^{0}} < 760$ GeV for associated $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ production and $m_{\tilde{\chi}_2^{0}} < 630$ GeV for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production are excluded at 95 % confidence level. At low wino masses the limits are weaker because of the higher trigger thresholds, in particular in the $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ model. No interpretation is made for a scenario with direct production of tau slepton pairs, because a dedicated search and publication are in preparation as described below.

A unique new aspect that we study in the Run-2 paper is the impact of the choice of the mass value of the tau slepton and tau sneutrino. As stated above, in the simplified models this value has been chosen to lie half-way between the masses of the $\tilde{\chi}_1^{\pm}$ and of the $\tilde{\chi}_1^{0}$, i. e. $x := (m_{\tilde{\tau}} - m_{\tilde{\chi}_1^0})/(m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0}) = 0.5$. In the Run-2 paper, additional scenarios are considered, where the mass of the two intermediate sfermions is varied within the range $0 < x < 1$ such that the decay chain of the simplified model is still kinematically allowed. Depending on the production mode ($\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ vs. $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$) and the masses of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{0}$, a different behaviour of the exclusion significance ($\mathrm{CL_s}$, [82]) is observed. Two competing effects are at play here. For large mass splitting Δm between the $\tilde{\chi}_1^{\pm}$ and an almost massless $\tilde{\chi}_1^{0}$, the signal acceptance decreases, i. e. the significance decreases, when the mass of the intermediate sfermions moves close to $m_{\widetilde{\chi}_1^\pm}$ (x close to 1) because the p_T of the tau lepton from the wino decay becomes small and more events will fail the selection requirements on the tau-lepton p_T. It is interesting that this does not happen for x close to 0. In this case, the mass of the intermediate sfermions moves close to $m_{\widetilde{\chi}_1^0}$ and the p_T of the tau lepton from the tau-slepton decay becomes smaller but not as sharply peaked at small values as in the first case. Due to the small mass of the $\widetilde{\chi}_1^0$, the p_T is shared differently between the two decay products, the $\widetilde{\chi}_1^0$ and the tau lepton, compared to the first case with a decay to a heavy tau slepton and the tau lepton. The light $\widetilde{\chi}_1^0$ is not as strongly boosted and does not carry away a large fraction of the transverse momentum, leaving more of the p_T for the tau lepton. For compressed scenarios with a small mass splitting Δm (150 GeV in the scenario presented in the paper), the $\mathrm{CL_s}$ significance is found to be smallest for values of x around 0.5, where the event topology most closely matches the assumptions of the scenario the m_{T2} variable is designed for, such that m_{T2} has a sharp cut-off at the value of Δm. For values of x farther away from 0.5, the distribution of m_{T2} develops tails reaching to higher values, allowing more events to pass the m_{T2} requirements of the signal selections. This effect is much less pronounced for $\widetilde{\chi}_1^\pm \widetilde{\chi}_2^0$, where the presence of either three tau leptons or three neutrinos smears out the cut-off of the m_{T2} variables in all cases. This study exemplifies how a rather inconspicuous detail such as the mass of an intermediate particle (in contrast to the more striking assumptions such as those on the branching ratios) in a symmetric decay chain (depending on whether the decay happens through the tau slepton or the tau sneutrino, the tau lepton will be the first Standard Model decay product and the tau neutrino the second or vice versa so that the respective mass splittings appear to be equally important) may lead to significant changes in the findings in non-trivial ways. These changes may go in both directions, leading to either stronger or weaker limits than those obtained for the nominal assumption.

3.3 Direct Production of Tau Sleptons

The cross section for direct production of tau sleptons is very small compared to the production of other sparticles with the same mass. If the tau sleptons decay directly to the LSP, the detector signature for this signal consists of two hadronically decaying tau leptons and missing transverse momentum only. Probing this indistinct signature is experimentally challenging because it is inherently difficult to disentangle from an overwhelmingly large background of events with multi-jet or $W +$ jets production and irreducible processes such as $t\bar{t}$ and diboson production. This makes this search one of the most challenging searches for supersymmetry. Still, if the masses of all other sparticles are much larger or possibly beyond the reach of the LHC, tau-slepton production may be the dominant production mode for sparticles at the LHC and the first or only direct way to discover supersymmetry.

The first comprehensive result on the direct production of tau sleptons from a hadron collider is a highlight still to come. The existing results and current status in the search for direct production of tau sleptons at ATLAS have been touched upon above. All in all, there is virtually no mass limit from ATLAS and CMS as of now. Only two mass scenarios could be excluded by ATLAS with the $\sqrt{s} = 8$ TeV data, one with $m_{\widetilde{\tau}_R} = 91$ GeV and $m_{\widetilde{\tau}_L} = 93$ GeV through a downward fluctuation of the data with respect to the background expectation [2], i. e. where actually no sensitivity was expected, and one with $m_{\widetilde{\tau}_R} = 109$ GeV and $m_{\widetilde{\tau}_L} = 111$ GeV through the use of MVA techniques, where the expected and observed upper limits scrape the cross section predicted by theory [3]. Both scenarios assume a massless LSP and combined production of mass-degenerate left-handed and right-handed tau sleptons. The preliminary results by the CMS collaboration with $\sqrt{s} = 13\,\text{TeV}$ data from 2015 and 2016 show that they are not sensitive yet to production of left-handed nor right-handed tau sleptons [83, 84], even though they benefit from the very competitive thresholds of their trigger on events with two hadronically decaying tau leptons, which allow them to use hadronically decaying tau leptons down to $p_{\mathrm{T}} > 40\,\text{GeV}$ in the offline selection.

In ATLAS, we have not yet made public any results on direct production of tau sleptons based on $\sqrt{s} = 13\,\text{TeV}$ data. The analysis is currently in the research-and-development phase. Our first studies with the dataset from 2015 and 2016 indicate that it should be possible to have sensitivity to tau-slepton masses between 150 and 250 GeV [31, 32] for low LSP masses. With the addition of the 2017 dataset, which more than doubles the available data, and the further improved tau-reconstruction and identification algorithms the prospects are even brighter. Both uncorrelated combinations of selection requirements as well as sophisticated multi-variate analysis techniques based on machine-learning methods have been employed to optimise the signal selections and achieve highest possible sensitivity.

One difficulty in this analysis are the large statistical uncertainties in the background estimate for $W +$ jets events that arise from the limited number of simulated events and the misidentification rate for tau leptons. Second to multi-jet production, events with $W +$ jets production constitute the background with the largest cross section among the relevant background processes. In order to pass the two-tau selection of the analysis, $W +$ jets events in which the W boson yields a hadronically decaying tau lepton need to have at least one jet that is misidentified as the second tau lepton. As the misidentification rate is of the order of a few percent, the fraction of such events in the simulated samples is small, therefore most of the simulated events will be discarded and lost for the background estimate. Still, $W +$ jets events are one of the dominant backgrounds in the analysis and a precise estimate of this background is essential. The contribution of events where the W boson decays to a light lepton is negligible (for the had-had channel) because these need to have two objects misidentified as tau leptons. We have therefore done extensive studies on how to reduce the uncertainties and improve the background modelling by artificially promoting tau-lepton candidates to fake tau leptons in simulated events to make use of the otherwise discarded events. Together with an appropriate reweighting procedure based on the fake probabilities for tau leptons this allows to exploit the full statistical power of the simulated event samples [33–35]. The reduction of the statistical uncertainty on the W boson background achieved with this method provides an important boost of the expected sensitivity [31]. Another crucial component for the success of this search is to establish the robustness of the estimates for the multi-jet background. Several methods for this are being developed in parallel. A conference note with preliminary results is in preparation.

3.4 Strong Production

Together with research groups from Bergen and Bonn we have carried out a search for production of squarks and gluinos in final states with hadronically decaying tau leptons with the $\sqrt{s} = 13\,\text{TeV}$ dataset of $3.2\,\text{fb}^{-1}$ taken in 2015 [10]. The cross section for strong production of supersymmetric particles is larger than for all other production modes. Therefore, the existing limits and consequently the sparticle masses of interest for the $\sqrt{s} = 13\,\text{TeV}$ analysis are also higher. The increase of the production cross sections due to the higher effective parton luminosity also grows strongly with the mass and for the targeted mass range at the higher centre-of-mass energy in Run 2 was significant. The 2015 dataset was thus already enough to surpass the sensitivity of the Run-1 results despite its small integrated luminosity.

For this inclusive search, final states with at least one hadronically decaying tau lepton, jets and large missing transverse momentum are selected. The presence of jets from the decays of squarks and gluinos in the final state targeted in this analysis is one of the fundamental differences with respect to the search for electroweak production, where no jets are expected from the hard scatter process. Two mutually exclusive channels are considered, selecting events with exactly one or at least two hadronically decaying tau leptons. Our contributions focus on the two-tau channel, where we have studied in particular the best choice for a trigger and the background from multi-jet events. In addition, we have developed a signal selection for compressed scenarios, i. e. where the mass difference between the gluino and the gaugino in the simplified model is small [25].

Both analysis channels make use of a trigger which selects events with large $E_{\mathrm{T}}^{\mathrm{miss}}$. Other triggers, in particular the two-tau trigger, were studied for the two-tau channel but not found to give higher signal acceptance in the signal region due to their high thresholds on the p_{T} of the tau leptons. In the one-tau channel, the jet-smearing technique is used to estimate the contribution of multi-jet events to the Standard Model background. For this method, a sample of data events with well-measured jets is selected. These seed events are then smeared using the jet-energy resolution, which is extracted from simulation, to obtain a sample of multi-jet events mirroring the fluctuations arising from mismeasurements found in data. However, this method cannot be used in the two-tau channel, because there are not enough seed events with two fake tau leptons. Instead, a fake-rate method was developed to estimate the contribution of multi-jet events. The estimate is obtained from a sample of multi-jet events taken from data, which is weighted with the p_{T}-dependent probabilities of jets to be misidentified as a tau or light lepton. The fake-rate approach is validated in a multi-jet enriched control region and against an alternative estimate from the OS–SS method. Both methods show good agreement and could thus be used to show that the multi-jet background can be neglected in the signal selections and to quantify its contributions to the other analysis selections, which involve light leptons. It was also shown that the tau-electron channel cannot be used to define control regions for fake tau leptons due to the large contribution of multi-jet background events. In the tau-muon channel this contribution is much smaller due to the lower fake probability for muons, and thus this channel is used for the control regions.

The interpretation of the search results is done in simplified models with gluino pair production and in the context of a complete model with gauge-mediated SUSY breaking, for which the parameters are chosen such that the NLSP is the lightest tau slepton for large $\tan\beta$. For each model point, the signal selection with the highest expected sensitivity is used. At intermediate gluino masses the dedicated two-tau signal selection for compressed scenarios gives the best sensitivity. For the GMSB interpretation, only the two-tau channel is used, as the one-tau channel has very limited acceptance due to the high final-state object multiplicities from the long decay chains in the GMSB model. Values of the GMSB parameter for the SUSY-breaking mass scale in the messenger sector Λ up to values between 92 and 107 TeV are excluded depending on $\tan\beta$, corresponding to an exclusion of gluino masses of up to about 2.3 TeV. In the simplified-model interpretation, gluino masses up to 1.57 TeV and neutralino LSP masses up to 750 GeV are excluded. These limits improve on the ones obtained with the Run-1 dataset by 20 to 30 %.

3.5 Production of Top Squarks

A distinct feature of models with pair production of top squarks with respect to the other two production modes, electroweak and strong production, is the appearance of b-jets in the final state. The production cross section of top squarks is smaller than that of the other squark generations at the same mass [85], but the b-jets give an additional handle in the event selection. Due to the inefficiency of the tagging algorithms that are used to identify b-jets, many signal selections only require at least one of the jets to be tagged as a b-jet rather than the two expected from the signal process. In compressed scenarios, the b-jets also may have too low energy to be reconstructed.

The ATLAS collaboration has a very rich programme of dedicated searches for top-squark pair production. These searches target different lepton and jet multiplicities in the final state, different mass hierarchies, and different topologies of top-squark decays and assumptions on the composition of the LSP. Different decay topologies appear depending on whether the top-squark decay proceeds through a neutralino or a chargino, which are the most important cases studied. Due to the large mass of the top quark, different mass hierarchies are considered separately for the direct decay to a neutralino LSP. The mass difference of the top squark and the LSP in relation to the top-quark, bottom-quark and W-boson mass determines which particles appear on- or off-shell in the decay chain. In general, these searches are expected to have very limited sensitivity to final states with tau leptons because they use signal selections in light-lepton channels. Some analyses even explicitly veto events with hadronically decaying tau leptons to suppress backgrounds arising from semileptonic $t\bar{t}$ decays with fake tau leptons from the hadronic W boson decays [86].

The analysis we have developed and which is described here is designed to fill this gap. It is based on a selection of final states which include tau leptons, b-jets, and large missing transverse momentum. The interpretation assumes a scenario with gauge-mediated supersymmetry breaking, where the LSP is an almost massless gravitino. The decay of the top squarks to the gravitino goes through an off-shell chargino to a tau slepton as an intermediate sparticle. The tau slepton is the NLSP in this model and yields final states enriched in tau leptons from its decay: $\tilde{t} \to b\nu_\tau\tilde{\tau} \to \tau\widetilde{G}$. In models with gauge-mediated supersymmetry breaking, the phenomenology is characterised by the NLSP. All supersymmetric particles will usually promptly decay in cascades that eventually lead to the NLSP, which then decays into the gravitino. Because of the different strengths of the interactions, the direct decay $\tilde{t} \to t\widetilde{G}$ does not dominate over the decay via the tau slepton NLSP. The direct decay $\tilde{t} \to t\widetilde{G}$ yields a detector signature very similar to $\tilde{t} \to t\tilde{\chi}_1^0$ and is covered by other ATLAS searches.

The search for top-squark pair production in final states with tau leptons at $\sqrt{s} = 13\,\text{TeV}$ was developed in my group, with some contributions from the Freiburg ATLAS group. The first public result is based on a dataset with $13.2\,\text{fb}^{-1}$ of integrated luminosity taken in 2015 and the first part of 2016 and was prepared for the ICHEP 2016 conference [11]. For this first iteration of the analysis, the development focused on the lep-had channel with one leptonically and one hadronically decaying tau lepton. This was the most powerful channel in the Run-1 analysis [87], and the trigger strategy was simpler than that developed later for the had-had channel. Several trigger options were compared [36], and single-lepton triggers were found to be the optimal choice. For the simulation of signal events in Run 2, the ATLAS supersymmetry group replaced the Monte-Carlo event generator Herwig++ [88] by a combination of MadGraph5_aMC@NLO [89] for the simulation of hard-scatter process and Pythia 8 [90] for the parton showering and hadronisation. Detailed studies were performed to validate the new simulation setup and to ensure that the spin correlations of the products from the three-body decay of the top squarks are correctly handled, because they have an important impact on the kinematics of the decay products. Afterwards, the new signal samples could be used to optimise the signal selection [36]. The variables that were found to perform best to separate signal from background are m_{T2} [91–93] and $E_{\mathrm{T}}^{\mathrm{miss}}$, which perform so well that the optimised selection requirements on these two are sufficient to obtain very good sensitivity. As b-jets are part of the signal signature, in contrast to the analysis of electroweak production a b-jet veto cannot be used, so that production of top-quark pairs makes up the dominant background process. This background has two components, one where the tau lepton is a real tau lepton, the other where it is a fake. The decay topology of the $t\bar{t}$ background with a fake tau lepton may deviate from the assumptions that underlie the construction of the m_{T2} variable. The cut-off of the m_{T2} variable for these events is thus not as sharp as for events with a real tau lepton, and $t\bar{t}$ events with a fake tau lepton contribute the largest fraction of events passing the signal selection.

The background estimates in the ICHEP analysis are taken from simulation. Separate control and validation regions are used to normalise the $t\bar{t}$ contributions with real and fake tau leptons to data. Owing to the higher centre-of-mass energy and an improved signal selection, the result obtained from $13.2\,\mathrm{fb}^{-1}$ of data at $\sqrt{s} = 13\,\mathrm{TeV}$ already surpasses that from the Run-1 analysis of $20\,\mathrm{fb}^{-1}$ of data at $\sqrt{s} = 8\,\mathrm{TeV}$, excluding top-squark masses up to 870 GeV and tau-slepton masses up to 730 GeV.

Following the conference note for ICHEP 2016, we decided to develop an additional analysis in the had-had channel to join the lep-had channel for the analysis of the full dataset from 2015 and 2016. This required the development of an appropriate trigger and analysis strategy and the design of a signal selection and accompanying control and validation regions [37]. Different trigger options were tested for their performance and efficiency in selecting signal events. Care was taken to design the analyses such that the two channels can be statistically combined, which is facilitated by the fact that for each channel a single signal selection with good sensitivity in most of the targeted parameter space could be found. By rejecting events with additional leptons, the two analyses select disjoint sets of events. The signal selection of the lep-had channel was also reoptimised for the higher luminosity. The ICHEP results had shown that the background from $t\bar{t}$ production with fake tau leptons needed a large scale factor (larger than two) to make the predicted yields in the control region agree with the observed data, an observation confirmed also by the strong-tau analysis. This indicated a problem in the modelling of the $t\bar{t}$ background with a fake tau lepton in simulation and therefore the fake-factor method was developed to replace the simulation-based estimate. The agreement of data and prediction from this method in the validation regions is very convincing.

A preliminary version of the results from $36.1\,\mathrm{fb}^{-1}$ was made public for and presented at the 25th International Conference on Supersymmetry and the Unification of Fundamental Interactions (SUSY17) [12, 38]. The main difference with respect to the final public result [4] is that the latter includes an additional study to evaluate the theory uncertainty on the $V+$jets background modelling. As this background is very small, the main results of the search, the model-independent upper limits on the cross section for physics beyond the Standard Model and the excluded ranges for the masses of the top squark and tau slepton, remain unchanged. With an exclusion of top-squark masses up to 1.16 TeV at 95 % confidence level, this analysis provides the strongest direct limit on the top-squark mass in a simplified model with a massless LSP that has been published so far.

Top-Squark–Tau-Sneutrino Model A simplified model very similar to the one targeted above is obtained by replacing the intermediate tau slepton by a tau sneutrino. This effectively swaps the positions of the neutrino and the tau lepton in the decay chain, i. e. the decays of the supersymmetric particles are now $\tilde{t} \to b\tau\widetilde{\nu}_\tau$ and $\widetilde{\nu}_\tau \to \nu\widetilde{G}$. We have produced signal samples for a few benchmark points that implement this modification in order to test the sensitivity of the existing search to this alternative scenario. Purely left-handed sneutrinos are ruled out as dark-matter candidates but it is not difficult to construct simple viable models beyond the MSSM with admixtures of right-handed sneutrinos to a sneutrino LSP [94]. Good sensitivity is found for large mass differences of the top-squark and tau-sneutrino masses, but the sensitivity in this scenario decreases much faster when the mass difference becomes smaller than in the original model [39]. The reason for this behaviour is that now both products from the decay of the intermediate sparticle, the tau neutrino and the gravitino, are invisible to the detector and are subsumed in the total missing transverse momentum. On the other hand, the visible decay products share the energy from the 3-body decay of the top squark, leading to lower momenta of tau leptons and b-jets for the same mass splitting. This makes this additional model a very interesting alternative interpretation. With two b-jets, two tau leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ it has the same final state as the original model, yet the simple modification of the decay chain leads to a new, challenging signature in some parts of the phase space. This signature deserves more studies and probably a dedicated signal selection in the next iteration of the analysis, which is planned to be published with the full Run-2 dataset.

3.6 Prospects for the HL-LHC

In the third long shutdown, which is scheduled for 2024 to 2026 after the end of the third run of the LHC, the LHC and the detectors will receive significant upgrades in order to permit an increase of the instantaneous luminosity up to $5 \cdot 10^{34}\,\mathrm{Hz/cm^2}$ (potentially $7.5 \cdot 10^{34}\,\mathrm{Hz/cm^2}$). It is expected that a total of up to $3000\,\mathrm{fb}^{-1}$ (potentially $4000\,\mathrm{fb}^{-1}$) of proton–proton collision data will be collected over the full lifetime of the high-luminosity LHC (HL-LHC) before the year 2040 [95]. This huge dataset will allow to push the sensitivity of the analyses for discovery and exclusion significantly beyond the existing limits. In addition, further upgrades and training of the superconducting dipole magnets are planned for the second long shutdown so that the centre-of-mass energy can be raised to its nominal value of 14 TeV, and at some point it could potentially even be increased to 15 TeV.

The aim of the upgrade studies described below is to explore the possibilities for searches for supersymmetry with the HL-LHC dataset. These studies provide vital information about the physics potential and at the same time insights into problems that must be anticipated. They are based on event information at Monte-Carlo-generator level without running the detector simulation. The event samples are corrected for the detector response (energy and momentum resolution, reconstruction efficiencies and misidentification rates) using a parameterisation based on data samples and dedicated simulations of the upgraded ATLAS detector at the high levels of in-time pile-up from the large instantaneous luminosity expected at the HL-LHC. The increased level of pile-up deteriorates the detector performance both in terms of resolution and reconstruction efficiency. For example, the resolution of the missing transverse momentum will become worse with increasing pile-up or isolation requirements on reconstructed objects will become less efficient due to the overall increase of the track multiplicity and calorimeter activity in the detector. The event numbers for signal and backgrounds do therefore not simply scale with integrated luminosity.

We performed a study of the sensitivity to $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production with Wh-mediated decays in a final state with one light lepton, two hadronically decaying tau leptons and large missing transverse momentum for a HL-LHC scenario with $3000\,\text{fb}^{-1}$ of integrated luminosity at a centre-of-mass energy of 14 TeV [13, 40]. In addition to the effects included in the parameterised detector response, the possibility of jets being misidentified as hadronically decaying tau leptons is taken into account. The expected exclusion reach is determined as a function of the gaugino masses and extends up to 550 GeV for a massless $\tilde{\chi}_1^0$. In these very early studies, the sensitivity of the analysis of this final state is found to be substantially lower than that of 3-lepton final states. Yet, the two channels provide excellent complementarity.

The search for direct production of tau sleptons is one of the most challenging searches for supersymmetry for several reasons as explained above. It is therefore interesting to explore the potential of the HL-LHC for this search. This is done in a study assuming again a HL-LHC dataset of $3000\,\text{fb}^{-1}$ at $\sqrt{s} = 14\,\text{TeV}$ [14]. Final states with two hadronically decaying tau leptons, large missing transverse momentum and low jet activity are selected, and the results are interpreted in simplified models with direct production of either left-handed or right-handed tau-slepton pairs or both, and direct decays of the tau sleptons to a $\tilde{\chi}_1^0$ LSP. The cross sections for this process have been computed at next-to-leading order of perturbative QCD matched to resummation at the next-to-leading logarithmic accuracy [96]. The reweighting technique developed to account for fake tau leptons from misidentified jets for the upgrade study above [40] is also employed here. The results indicate that with the HL-LHC dataset, in case no excess is found it should be possible to exclude tau-slepton masses $m_{\tilde{\tau}_L} < 650\,\text{GeV}$ and $m_{\tilde{\tau}_R} < 540\,\text{GeV}$ at 95 % CL, for left- or right-handed tau sleptons, respectively, assuming that the LSP is not too heavy ($m_{\tilde{\chi}_1^0} \lesssim 160\,\text{GeV}$). A 5σ discovery potential up to masses of 430 GeV for left-handed tau sleptons is expected, depending again on the mass of the LSP. Due to the smaller cross section for production of right-handed tau sleptons, the study finds that it would not be possible to claim a 5σ discovery for any mass scenario if only right-handed tau sleptons are produced.

3.7 Beyond Supersymmetry

The focus of this thesis is clearly on supersymmetry. However, even though the final states that are being searched for are inspired by supersymmetric models, and supersymmetric benchmark models are employed in the optimisation of the signal selections, the results of the searches have much broader impact. Two examples of the implications of the searches we have done on other scenarios for physics beyond the Standard Model have been studied in detail and are described in the following. Both reinterpret the results of one of the searches with tau-lepton final states in a different scenario, the first in a model of flavoured dark matter (FDM), the second in a model of scalar third-generation leptoquarks.

The quarks and leptons of the Standard Model both come in three generations, i. e. in three replicas which primarily differ by their mass. Assuming that dark matter is made of elementary particles, it seems natural to consider a similar structure for the particle content of the dark-matter sector. Models of flavoured dark matter pick up this idea. In these models, the dark matter particles are weakly interacting massive particles, which carry flavour quantum numbers, i. e. quark or lepton flavour or possibly a new, internal flavour [97]. In the case of tau-flavoured dark matter χ_τ, the pair production of scalar mediators $\phi^+\phi^-$, with decays $\phi^\pm \to \chi_\tau\tau^\pm$, leads to a detector signature with two tau leptons of opposite electric charge and missing momentum. The production cross section for $\phi^+\phi^-$ is the same as that for pair production of right-handed sleptons with the same mass. In collaboration with the authors of [97], signal samples were developed in order to compare the detector signatures of models with tau-flavoured dark matter to that of models with direct production of supersymmetric tau sleptons. The detector signature of both models and their kinematics were found to be identical, allowing to use the results from the existing search for tau sleptons [2] as a proxy for a search for FDM models and to estimate the luminosity that would be needed to be sensitive to models with tau-flavoured dark matter at the LHC. Both an extrapolation of the $\sqrt{s} = 8\,\text{TeV}$ results in luminosity and an extrapolation in the centre-of-mass energy to $\sqrt{s} = 13\,\text{TeV}$ were studied under the simplifying assumption that the running conditions of the detector stay the same with increasing instantaneous luminosity. The results indicate that a luminosity roughly 10 times larger than the $20\,\text{fb}^{-1}$ used in the tau-slepton search are needed in both cases to reach sensitivity to this model for the masses of the mediator around 100 GeV that were considered [41].

The puzzling question of why there are three generations in both the quark and lepton sector is addressed in models with leptoquarks [98]. Leptoquarks are hypothetical particles that appear in many extensions of the Standard Model, for example in grand unified theories. They can resolve the tension between Standard Model predictions and respective measurements in semi-leptonic B-meson decays mentioned in the introduction [99]. Leptoquarks carry colour and fractional electric charge and have non-zero lepton number as well as non-zero baryon number, and can thus directly decay to a (neutral or charged) lepton and a quark. They provide a connection between the quark and the lepton sector of the Standard Model, and may help to explain the similarities of those. In the minimal Buchmüller-Rückl-Wyler model (mBRW) [100], the assumption is made that leptoquarks come in three generations, and each generation of leptoquarks only decays to the respective generation of quarks and leptons. This avoids constraints from the non-observation of flavour-changing neutral currents at tree level. If we consider pair production of scalar third-generation leptoquarks LQ_3, their decay products yield detector final states which are very similar to that of the search for top-squark pair production with decays mediated by tau sleptons. The cross section for leptoquark pair production is basically identical to that of top-squark pair production with the same mass [101, 102]. This search is thus a perfect candidate for a reinterpretation of its results in a LQ_3 model. There are two types of leptoquarks with different charge, up-type LQ_3^u and down-type LQ_3^d, with decays $\text{LQ}_3^\text{u} \to b\tau$ or $t\nu_\tau$, and $\text{LQ}_3^\text{d} \to t\tau$ or $b\nu_\tau$, respectively. The branching ratio for these competing decays into a charged lepton or a neutrino is determined by the model parameter β. Good sensitivity is found to both models with up-type and with down-type third-generation leptoquarks. In contrast to the original search for supersymmetry, the sensitivity to leptoquark production comes mostly from the lep-had channel, because in the simplified supersymmetric model every event has two tau leptons and events with a light lepton have one additional neutrino with negative impact on the sensitivity, which is not true in the leptoquark model. Furthermore, for events with a decay $\text{LQ}_3^\text{u} \to t\nu_\tau$ and $\text{LQ}_3^\text{d} \to t\tau$, the had-had channel is penalised by the lower probability to have a tau lepton among the top-quark decay products compared to that for a light lepton, and events from these decays with a light lepton have one neutrino less than those with a tau lepton, leading to harder E_T^miss and m_T2 distributions in the lep-had channel. For large β and low leptoquark masses the signal contamination in some control regions was observed to become very large, adversely affecting the reliability of the fit that is used to determine the background normalisation factors. As in a reinterpretation we cannot modify the analysis setup and, e. g., introduce additional requirements to suppress the signal contribution in the control region, these points are omitted from the reinterpretation. Fortunately, this effect is less pronounced in the more important lep-had channel, so that only few mass and branching-ratio scenarios are affected. A paper combining four other ATLAS searches for di-Higgs, top- and bottom-squark production and ours as a reinterpretation in this model is in preparation.

4 Summary and Concluding Remarks

The topic of this thesis is the search for supersymmetry in final states with tau leptons using data taken with the ATLAS detector at the LHC, exploiting the unique opportunities for searches for physics beyond the Standard Model offered by this dataset. The dataset used comprises about $20.3\,\mathrm{fb}^{-1}$ at a centre-of-mass energy of $\sqrt{s} = 8\,\mathrm{TeV}$ and up to $36.1\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13\,\mathrm{TeV}$. Elaborate analyses have been developed covering all relevant production modes of supersymmetric particles: electroweak production [2, 7] and strong (or inclusive) production [10], and production of third-generation squarks [4]. Among the publications listed in Section 6.1, these four publications reflect the central and most significant part of my research and are therefore included in Chapter 7.

All of these searches have found good agreement of the observed data counts with the expected background yields from Standard Model processes, allowing to place stringent upper limits on production cross sections for BSM physics and constraints on masses of supersymmetric particles. Direct production of tau sleptons has also been considered but the data from the first run of the LHC has only limited sensitivity to this signature [2, 3]. A publication using data from the second run of the LHC is in preparation. In addition to the searches for supersymmetry in the current LHC data, studies which go beyond supersymmetry or explore the physics potential of the high-luminosity LHC have been performed.

As high as hopes have been to find unambiguous evidence for BSM physics in the data soon after the LHC would see first collisions in a completely new energy regime, one has to conclude that they have not been fulfilled yet. None of the searches for supersymmetry at the LHC have so far exhibited a significant and persistent excess in the observed number of data events over the Standard Model background prediction as would be expected if a signal from supersymmetry were present in the data. I. e., none of the numerous additional particles predicted by supersymmetric extensions of the Standard Model have been observed yet. These null results do not say that supersymmetry is not realised in nature, but only that if it is, it is not as conspicuous as anticipated initially. As explained in the introduction, there are good reasons to expect interesting new physics beyond the Standard Model to show up at the LHC, and the final word on the results of the second run of the LHC is not yet spoken. A lot of research and development is in progress to cover additional signatures and take advantage of new analysis techniques. It is also not inconceivable that a better understanding of the ATLAS detector and its data output may reveal that some features which at first glance looked like mere mismodelling of the data by simulation turn out to have a pattern that points at so-far hidden discrepancies from the Standard Model. In the end, the dataset employed in the searches described here is only one percent of the full dataset expected to be taken at the HL-LHC. Time will tell whether new physics is to be found at the LHC — or perhaps somewhere else first.

5 Related Scientific and Academic Work

5.1 Contributions as ATLAS Member

As a member of the ATLAS collaboration I have had the privilege to present the latest physics results on behalf of the ATLAS and CMS collaborations at numerous major particle-physics conferences [6, 15–17]. Furthermore, I have been invited to give seminar talks at the Science Week of the Excellence Cluster in Munich in 2013 and 2015, at the Rotary Club Augsburg in 2016, and at the IMAPP Research Institute of the Radboud University Nijmegen (Netherlands) in 2017.

Many searches for BSM physics, including several analyses discussed in this thesis, use a trigger on events with large missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$, both standalone or in combination with other objects, because it is versatile and has high signal acceptance in its efficiency plateau. I have contributed to the publications by the ATLAS $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger group on the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger performance with studies of the rates of the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger and the related triggers on $\sum E_{\mathrm{T}}$ and the $E_{\mathrm{T}}^{\mathrm{miss}}$ significance based on data taken in 2011 at $\sqrt{s} = 7\,\mathrm{TeV}$ [18] and in 2012 at $\sqrt{s} = 8\,\mathrm{TeV}$ [19]. An important observation is that the pile-up dependence of the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger rates is linear for triggers with sufficiently high $E_{\mathrm{T}}^{\mathrm{miss}}$ thresholds, whereas the rate grows exponentially with the number of concurrent interactions for low $E_{\mathrm{T}}^{\mathrm{miss}}$ thresholds. To better understand this behaviour, a phenomenological model of the rate dependence on the level of pile-up was developed, which combines a stochastic and an extreme-event component [20].

In preparation for Run 2 of the LHC, the ATLAS collaboration modernised the format of the event-data model, which comprises the data structures used to describe the collision data. The search for electroweak production of supersymmetry in final states with tau leptons was selected as one of the early adopters by the ATLAS supersymmetry group for this new format. I implemented and evaluated the migration process for this analysis. Furthermore, I developed and tested new samples with simulated events for several different signal models employed in various searches for electroweak production of supersymmetry. From April 2015 until October 2015 I was responsible for the common data formats used by all members of the ATLAS supersymmetry group and the management of the disk space allocated to the ATLAS supersymmetry group in the distributed grid computing.

From October 2015 to September 2016 I convened the ATLAS analysis group which conducts the searches for electroweak production of supersymmetric particles. During this time, our group published two analyses which combine several searches for electroweak production of supersymmetry using data from Run 1 of the LHC. One evaluates the performance of searches with final states with photons or light leptons in models of general gauge mediation and production of mixed wino-higgsino states [21]. The other is similar to the pMSSM summary paper [1] but uses models obtained from a likelihood-driven scan and focuses on a five-dimensional effective model of the electroweak supersymmetry sector and the impact of the electroweak searches on dark-matter observables [22]. For the summer conferences in 2016 two further results were prepared on the search for supersymmetry in final states with

2 and 3 and with 4 and more light leptons [23, 24].

Since October 2016 I have been convening the ATLAS Physics Validation group, leading a team of fifteen physicists who regularly validate the latest developments and improvements of the common software framework which is used for the simulation and reconstruction of collisions events in ATLAS. Given that this framework is the central component of all data-analysis work in ATLAS, the scrutiny of its output is of crucial importance for the reliability of the physics results. This work is done in close collaboration and consultation with experts from the relevant ATLAS physics and computing groups.

5.2 Teaching at LMU

In addition to the supervision of the research of the Bachelor's, Master's and PhD students in my group, I contribute to the physics-education programme at the LMU through the following activities.

- Lectures on supersymmetry as part of the lecture course on "Particle physics at hadron colliders" (summer semesters 2013 and 2014).
- Substitute lecturer for the lecture course on nuclear and particle physics (E5, winter semesters 2016/2017 and 2017/2018) and the lecture course on advanced particle physics (EM2, summer semester 2015).
- Supervision of a tutorial session accompanying the lecture course on nuclear and particle physics (E5), including the marking of exam papers (winter semesters 2012/2013 – 2017/2018).
- Supervision of the tutorial sessions accompanying the lecture course on advanced particle physics (EM2), including the preparation of the exercise sheets, quizzes, the written exams and the solutions for the tutors for all of these (summer semesters 2014 – 2017).
- Preparation and supervision of a seminar course on "Historical discoveries in nuclear and particle physics" (winter semester 2017/2018).
- Supervision of the laboratory course "Analysis of Z boson decays" (as part of the Fortgeschrittenenpraktikum) and marking of reports (both summer and winter semesters, starting winter semester 2012/2013).
- Preparation and organisation of the introductory course for Bachelor's students at our institute (summer semesters 2013 – 2017). I also gave several lectures as part of these one-week introductory courses, which prepare our Bachelor's students with the basics they need to successfully perform the research for their Bachelor's thesis.
- Supervision of student research internships over several months on "Modern Physics" (summer semesters 2013 and 2015 and winter semester 2015/2016). These internships provide Master's students with a real-life experience of the daily work as a researcher in particle physics.
- Organisation of regular meetings on topics relevant to ATLAS physics and supersymmetry for students at our institute.

Beyond the regular academic activities I organise yearly “International Particles Physics Masterclasses” in Munich together with the Max Planck Institute for Physics and the Excellence Cluster of the Technical University of Munich. These events, initiated by the International Particle Physics Outreach Group (IPPOG), give high-school students the opportunity to learn about particle physics and to participate in hands-on sessions with real data analysis and international video conferences. I also coordinate PhD and Master’s students in giving masterclasses on particle physics at high-schools as part of the “Netzwerk Teilchenwelt”.

6 Bibliography

6.1 Publications with Significant Involvement

[1] ATLAS Collaboration, *Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM*, JHEP **10** (2015) 134, arXiv: 1508.06608 [hep-ex].

[2] ATLAS Collaboration, *Search for the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying taus and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, JHEP **10** (2014) 096, arXiv: 1407.0350 [hep-ex].

[3] ATLAS Collaboration, *Search for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, Phys. Rev. D **93** (2016) 052002, arXiv: 1509.07152 [hep-ex].

[4] ATLAS Collaboration, *Search for top squarks decaying to tau sleptons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, CERN-EP-2018-024, submitted to PRD, 2018, arXiv: 1803.10178 [hep-ex].

[5] ATLAS Collaboration, *Search for electroweak production of supersymmetric particles in final states with at least two hadronically decaying taus and missing transverse momentum with the ATLAS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV*, ATLAS-CONF-2013-028, 2013, https://cds.cern.ch/record/1525889.

[6] A. Mann (on behalf of the ATLAS Collaboration), *Search for "Electroweakinos" with the ATLAS Detector at the LHC*, ATL-PHYS-PROC-2015-141, 2015, https://cds.cern.ch/record/2066735.

[7] ATLAS Collaboration, *Search for the direct production of charginos and neutralinos in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Eur. Phys. J. C **78** (2018) 154, arXiv: 1708.07875 [hep-ex].

[8] ATLAS Collaboration, *Search for the direct production of charginos and neutralinos in final states with tau leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, ATLAS-CONF-2017-035, 2017, https://cds.cern.ch/record/2265807.

[9] ATLAS Collaboration, *Search for electroweak production of supersymmetric particles in final states with tau leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, ATLAS-CONF-2016-093, 2016, https://cds.cern.ch/record/2211437.

[10] ATLAS Collaboration, *Search for squarks and gluinos in events with hadronically decaying tau leptons, jets and missing transverse momentum in proton–proton collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector*, Eur. Phys. J. C **76** (2016) 683, arXiv: 1607.05979 [hep-ex].

[11] ATLAS Collaboration,
Search for top-squark pair production in final states with two tau leptons, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, ATLAS-CONF-2016-048, 2016, https://cds.cern.ch/record/2206130.

[12] ATLAS Collaboration, *Search for top squarks decaying to tau sleptons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS-CONF-2017-079, 2017, https://cds.cern.ch/record/2297260.

[13] ATLAS Collaboration,
Search for Supersymmetry at the high luminosity LHC with the ATLAS Detector, ATL-PHYS-PUB-2014-010, 2014, https://cds.cern.ch/record/1735031.

[14] ATLAS Collaboration,
Prospect for a search for direct stau production in events with at least two hadronic taus and missing transverse momentum at the High Luminosity LHC with the ATLAS Detector, ATL-PHYS-PUB-2016-021, 2016, https://cds.cern.ch/record/2220805.

[15] A. Mann (for the ATLAS and CMS collaborations),
SUSY Searches for Inclusive Squark and Gluino Production at the LHC, 2013, arXiv: 1305.3545 [hep-ex], https://cds.cern.ch/record/1547096.

[16] A. Mann (on behalf of the ATLAS Collaboration),
ATLAS High-Level Trigger performance for calorimeter-based algorithms in LHC Run-I, Journal of Physics: Conference Series **513** (2014) 012022, https://cds.cern.ch/record/1621952.

[17] A. Mann (on behalf of the ATLAS Collaboration), *Searches for Gauge-Mediated Supersymmetry Breaking Signatures with the ATLAS Detector at the LHC*, ATL-PHYS-SLIDE-2018-068, 2018, https://cds.cern.ch/record/2302603.

[18] ATLAS Collaboration,
The ATLAS transverse-momentum trigger performance at the LHC in 2011, ATLAS-CONF-2014-002, 2014, https://cds.cern.ch/record/1647616.

[19] ATLAS Collaboration,
Performance of the ATLAS global transverse-momentum triggers at $\sqrt{s} = 8$ TeV, ATL-DAQ-PUB-2018-001, 2018, https://cds.cern.ch/record/2311730.

[20] ATLAS Collaboration, *Analytical description of missing transverse-momentum trigger rates in ATLAS with 7 and 8 TeV data*, ATL-DAQ-PUB-2017-002, 2017, https://cds.cern.ch/record/2292378.

[21] ATLAS Collaboration, *A re-interpretation of $\sqrt{s} = 8$ TeV ATLAS results on electroweak supersymmetry production to explore general gauge mediated models*, ATLAS-CONF-2016-033, 2016, https://cds.cern.ch/record/2198316.

[22] ATLAS Collaboration, *Dark matter interpretations of ATLAS searches for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV proton–proton collisions*, JHEP **09** (2016) 175, arXiv: 1608.00872 [hep-ex].

[23] ATLAS Collaboration, *Search for supersymmetry in events with four or more leptons in $\sqrt{s} = 13$ TeV pp collisions using 13.3 fb^{-1} of ATLAS data.*, ATLAS-CONF-2016-075, 2016, https://cds.cern.ch/record/2206245.

[24] ATLAS Collaboration, *Search for the electroweak production of charginos and neutralinos in multilepton final states at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS-CONF-2016-096, 2016, https://cds.cern.ch/record/2212162.

6.2 Supervised Theses

[25] C. Bock, *Search for Supersymmetry in Final States Containing two Hadronically Decaying Taus with the ATLAS Detector at $\sqrt{s} = 8$ TeV and 13 TeV*, PhD thesis: LMU München, 2016.

[26] Y. Israeli, *Measurement of lepton-identification efficiencies for searches for supersymmetry in events with two taus in the final state*, Master's thesis: LMU München, 2014.

[27] M. Holzbock, *Comparison of tau selections, current triggers and prospective triggers at higher luminosities for the analysis of electroweak production of supersymmetric particles in final states with two taus*, Bachelor's thesis: LMU München, 2013.

[28] C. C. von Wedemeyer, *Sensitivity Study in the Search for Supersymmetry in Events with Two Tau Leptons in the Final States*, Bachelor's thesis: LMU München, 2016.

[29] M. Gulder, *Search for Supersymmetry at ATLAS within the pMSSM*, Bachelor's thesis: LMU München, 2014.

[30] M. Steimle, *Measurement of the trigger efficiencies in the ATLAS detector for searches for supersymmetry in events with tau leptons in the final state*, Master's thesis: LMU München, 2016.

[31] C. Leitgeb, *Search for Direct Production of Supersymmetric Scalar Tau Leptons Using 13 TeV Data Taken with the ATLAS Detector at the LHC*, Master's thesis: LMU München, 2017.

[32] R. Haindl, *Applying Machine-Learning methods on the search for scalar τ-leptons*, Bachelor's thesis: LMU München, 2017.

[33] A. Samara, *Improving the modelling of the associated production of W-bosons and jets in the ATLAS detector*, Master's thesis: LMU München, 2018.

[34] P. M. Schmolz, *Improving Monte-Carlo predictions for the fake-tau background from W-boson events in ATLAS ditau searches*, Bachelor's thesis: LMU München, 2015.

[35] M. N. Dembecki, *Application of the tau-promotion method in tau + light lepton channels*, Bachelor's thesis: LMU München, 2016.

[36] M. Holzbock, *New elements to extend the search for supersymmetric scalar top quarks with the ATLAS detector in LHC Run 2*, Master's thesis: LMU München, 2016.

[37] F. Krieter, *Search for Scalar Top Quarks in Final States with Two Hadronically Decaying Tau Leptons*, Master's thesis: LMU München, 2017.

[38] B. Schachtner, *Search for top-squark pair production with the LHC experiment ATLAS in final states with b-quarks and tau leptons*, PhD thesis: LMU München, 2018.

[39] T. B. Basman, *Search for production of scalar top quarks into final states with tau leptons with the ATLAS detector*, Bachelor's thesis: LMU München, 2017.

[40] B. Schachtner, *Search for electroweak production of supersymmetric particles with the LHC experiment ATLAS at high luminosities*, Master's thesis: LMU München, 2014.

[41] C. Leitgeb, *Reinterpretation of the Run-1 Direct-Stau Search with ATLAS for the Search for τ-Flavoured Dark Matter*, Bachelor's thesis: LMU München, 2015.

6.3 Further Reading

[42] C. Patrignani *et al.* (Particle Data Group), *Review of Particle Physics*, Chin. Phys. C **40** (2016) 100001, and 2017 update.

[43] T. Morishima, T. Futamase, and H. M. Shimizu, *Post-Newtonian effects of Dirac particle in curved spacetime - III : the muon g-2 in the Earth's gravity*, (2018), submitted to PTEP and making an interesting proposal how to resolve the $(g-2)_\mu$ discrepancy, arXiv: 1801.10246 [hep-ph].

[44] Y. Amhis et al., *Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2016*, Eur. Phys. J. C **77** (2017) 895, arXiv: 1612.07233 [hep-ex].

[45] R. Aaij et al., *Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays*, JHEP **08** (2017) 055, arXiv: 1705.05802 [hep-ex].

[46] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, and J. Virto, *Patterns of New Physics in $b \to s\ell^+\ell^-$ transitions in the light of recent data*, JHEP **01** (2018) 093, arXiv: 1704.05340 [hep-ph].

[47] S. P. Martin, *A Supersymmetry Primer*, in "Perspectives on Supersymmetry II", Advanced Series on Directions in High Energy Physics, Volume 21, 2011, arXiv: hep-ph/9709356 [hep-ph].

[48] ATLAS Collaboration and CMS Collaboration, *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments*, Phys. Rev. Lett. **114** (2015) 191803, arXiv: 1503.07589 [hep-ex].

[49] H. E. Haber, „Challenges for nonminimal Higgs searches at future colliders", *Perspectives for electroweak interactions in e+ e- collisions. Proceedings, Ringberg Workshop, Tegernsee, Germany, February 5–8, 1995*, 1996 219, arXiv: hep-ph/9505240 [hep-ph].

[50] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1.

[51] ATLAS Collaboration, *Search for supersymmetry in events with four or more leptons in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, Phys. Rev. D **90** (2014) 052001, arXiv: 1405.5086 [hep-ex].

[52] G. F. Giudice and R. Rattazzi, *Theories with gauge mediated supersymmetry breaking*, Phys. Rept. **322** (1999) 419, arXiv: hep-ph/9801271 [hep-ph].

[53] J. L. Feng, *Naturalness and the Status of Supersymmetry*, Ann. Rev. Nucl. Part. Sci. **63** (2013) 351, arXiv: 1302.6587 [hep-ph].

[54] A. Djouadi et al.,
„The Minimal supersymmetric standard model: Group summary report“,
GDR (Groupement De Recherche) - Supersymétrie Montpellier, France, April 15-17, 1998, 1998, arXiv: hep-ph/9901246 [hep-ph].

[55] A. Djouadi, J.-L. Kneur, and G. Moultaka,
SuSpect: A Fortran code for the supersymmetric and Higgs particle spectrum in the MSSM, Comput. Phys. Commun. **176** (2007) 426, arXiv: hep-ph/0211331 [hep-ph].

[56] ATLAS Collaboration,
Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV proton–proton collisions, Phys. Lett. B **701** (2011) 186, arXiv: 1102.5290 [hep-ex].

[57] D. Alves et al., *Simplified Models for LHC New Physics Searches*, J. Phys. G **39** (2012) 105005, arXiv: 1105.2838 [hep-ph].

[58] ATLAS Collaboration, *ATLAS Run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider*, Eur. Phys. J. C **75** (2015) 510, arXiv: 1506.08616 [hep-ex].

[59] The LEP SUSY Working Group and the ALEPH, DELPHI, L3 and OPAL experiments, notes LEPSUSYWG/01-03.1, 02-04.1, 04-01.1, http://lepsusy.web.cern.ch/lepsusy/Welcome.html.

[60] ALEPH Collaboration, *Absolute mass lower limit for the lightest neutralino of the MSSM from e^+e^- data at $\sqrt{s}$ up to 209 GeV*, Phys. Lett. B **583** (2004) 247.

[61] DELPHI Collaboration, *Searches for supersymmetric particles in e^+e^- collisions up to 208 GeV and interpretation of the results within the MSSM*, Eur. Phys. J. C **31** (2003) 421, arXiv: hep-ex/0311019 [hep-ex].

[62] L3 Collaboration,
Search for charginos and neutralinos in e^+e^- collisions at $\sqrt{s}$ = 189 GeV, Phys. Lett. B **472** (2000) 420, arXiv: hep-ex/9910007 [hep-ex].

[63] OPAL Collaboration,
Search for chargino and neutralino production at $\sqrt{s}$ = 192 GeV to 209 GeV at LEP, Eur. Phys. J. C **35** (2004) 1, arXiv: hep-ex/0401026 [hep-ex].

[64] L3 Collaboration, *Search for scalar leptons and scalar quarks at LEP*, Phys. Lett. B **580** (2004) 37, arXiv: hep-ex/0310007 [hep-ex].

[65] OPAL Collaboration, *Search for anomalous production of di-lepton events with missing transverse momentum in e^+e^--collisions at $\sqrt{s} = 183 - 209$ GeV*, Eur. Phys. J. C **32** (2004) 453, arXiv: hep-ex/0309014 [hep-ex].

[66] ATLAS Collaboration, *Identification and energy calibration of hadronically decaying tau leptons with the ATLAS experiment in pp collisions at $\sqrt{s} = 8$ TeV*, Eur. Phys. J. C **75** (2015) 303, arXiv: 1412.7086 [hep-ex].

[67] ATLAS Collaboration, *Reconstruction, Energy Calibration, and Identification of Hadronically Decaying Tau Leptons in the ATLAS Experiment for Run-2 of the LHC*, ATL-PHYS-PUB-2015-045, 2015, https://cds.cern.ch/record/2064383.

[68] ATLAS Collaboration, *Measurement of the tau lepton reconstruction and identification performance in the ATLAS experiment using pp collisions at $\sqrt{s} = 13\,\text{TeV}$*, ATLAS-CONF-2017-029, 2017, https://cds.cern.ch/record/2261772.

[69] K. Griest and D. Seckel, *Three exceptions in the calculation of relic abundances*, Phys. Rev. D **43** (1991) 3191.

[70] J. R. Ellis, T. Falk, K. A. Olive, and M. Srednicki, *Calculations of neutralino-stau coannihilation channels and the cosmologically relevant region of MSSM parameter space*, Astropart. Phys. **13** (2000) 181, [Erratum: ibid. 15 (2001) 413], arXiv: hep-ph/9905481 [hep-ph].

[71] J. Ellis, T. Falk, and K. A. Olive, *Neutralino-stau coannihilation and the cosmological upper limit on the mass of the lightest supersymmetric particle*, Phys. Lett. B **444** (1998) 367, arXiv: hep-ph/9810360 [hep-ph].

[72] D. Albornoz Vasquez, G. Belanger, and C. Boehm, *Revisiting light neutralino scenarios in the MSSM*, Phys. Rev. D **84** (2011) 095015, arXiv: 1108.1338 [hep-ph].

[73] M. van Beekveld, W. Beenakker, S. Caron, R. Peeters, and R. R. de Austri, *Supersymmetry with dark matter is still natural*, Phys. Rev. D **96** (2017) 035015, arXiv: 1612.06333 [hep-ph].

[74] L. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001.

[75] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[76] ATLAS Collaboration, *ATLAS Insertable B-Layer Technical Design Report*, CERN-LHCC-2010-013, ATLAS-TDR-19, 2010, https://cds.cern.ch/record/1291633.

[77] *ATLAS Insertable B-Layer Technical Design Report Addendum*, Addendum to CERN-LHCC-2010-013, ATLAS-TDR-019, 2012, https://cds.cern.ch/record/1451888.

[78] ATLAS Collaboration, *Performance of the ATLAS trigger system in 2015*, Eur. Phys. J. C **77** (2017) 317, arXiv: 1611.09661 [hep-ex].

[79] M. Bajko et al., *Report of the Task Force on the Incident of 19th September 2008 at the LHC*, LHC-PROJECT-Report-1168, 2009, https://cds.cern.ch/record/1168025.

[80] T. P. S. Gillam and C. G. Lester, *Improving estimates of the number of 'fake' leptons and other mis-reconstructed objects in hadron collider events: BoB's your UNCLE*, JHEP **11** (2014) 031, arXiv: 1407.5624 [hep-ph].

[81] ATLAS Collaboration, *Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, JHEP **04** (2014) 169, arXiv: 1402.7029 [hep-ex].

[82] A. L. Read, *Presentation of search results: the CL_s technique*, J. Phys. G **28** (2002) 2693.

[83] CMS Collaboration, *Search for supersymmetry in events with tau leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$*, CMS-PAS-SUS-17-002, 2017, https://cds.cern.ch/record/2297162.

[84] CMS Collaboration, *Search for pair production of tau sleptons in $\sqrt{s} = 13$ TeV pp collisions in the all-hadronic final state*, CMS-PAS-SUS-17-003, 2017, https://cds.cern.ch/record/2273395.

[85] T. Plehn, *Measuring the MSSM Lagrangean*, Czech. J. Phys. **55** (2005) B213, arXiv: hep-ph/0410063 [hep-ph].

[86] M. Aaboud et al., *Search for top-squark pair production in final states with one lepton, jets, and missing transverse momentum using 36 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data with the ATLAS detector*, (2017), submitted to JHEP, arXiv: 1711.11520 [hep-ex].

[87] ATLAS Collaboration, *Search for direct top squark pair production in final states with two tau leptons in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Eur. Phys. J. C **76** (2016) 81, arXiv: 1509.04976 [hep-ex].

[88] M. Bähr et al., *Herwig++ physics and manual*, Eur. Phys. J. C **58** (2008) 639, arXiv: 0803.0883 [hep-ph].

[89] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP **07** (2014) 079, arXiv: 1405.0301 [hep-ph].

[90] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159, arXiv: 1410.3012 [hep-ph].

[91] C. G. Lester and D. J. Summers, *Measuring masses of semi-invisibly decaying particles pair produced at hadron colliders*, Phys. Lett. B **463** (1999) 99, arXiv: hep-ph/9906349 [hep-ph].

[92] A. Barr, C. Lester, and P. Stephens, *A variable for measuring masses at hadron colliders when missing energy is expected; m_{T2}: the truth behind the glamour*, J. Phys. G **29** (2003) 2343, arXiv: hep-ph/0304226.

[93] C. G. Lester and B. Nachman, *Bisection-based asymmetric M_{T2} computation: a higher precision calculator than existing symmetric methods*, JHEP **03** (2015) 100, arXiv: 1411.4312 [hep-ph].

[94] J. March-Russell, C. McCabe, and M. McCullough, *Neutrino-Flavoured Sneutrino Dark Matter*, JHEP **03** (2010) 108, arXiv: 0911.4489 [hep-ph].

[95] G. Apollinari et al., eds., *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1*, CERN Yellow Reports: Monographs, CERN, 2017, https://cds.cern.ch/record/2284929.

[96] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, *Revisiting slepton pair production at the Large Hadron Collider*, JHEP **01** (2014) 168, arXiv: 1310.2621 [hep-ph].

[97] P. Agrawal, Z. Chacko, S. Blanchet, and C. Kilic, *Flavored dark matter, and its implications for direct detection and colliders*, Phys. Rev. D **86** (2012) 055002, arXiv: 1109.3516 [hep-ph].

[98] I. Doršner, S. Fajfer, A. Greljo, J. Kamenik, and N. Košnik, *Physics of leptoquarks in precision experiments and at particle colliders*, Physics Reports **641** (2016) 1, arXiv: 1603.04993 [hep-ph].

[99] M. Bauer and M. Neubert,
Minimal Leptoquark Explanation for the $R_{D^{(*)}}$, R_K, and $(g-2)_\mu$ Anomalies,
Phys. Rev. Lett. **116** (2016) 141802, arXiv: `1511.01900 [hep-ph]`.

[100] W. Buchmüller, R. Rückl, and D. Wyler, *Leptoquarks in lepton-quark collisions*,
Phys. Lett. B **191** (1987) 442, [Erratum ibid. **448** (1999) 320].

[101] C. Borschensky et al., *Squark and gluino production cross sections in pp collisions at $\sqrt{s}$ = 13, 14, 33 and 100 TeV*, Eur. Phys. J. C **74** (2014) 3174, arXiv: `1407.5066 [hep-ph]`.

[102] M. Krämer, T. Plehn, M. Spira, and P. M. Zerwas,
Pair production of scalar leptoquarks at the CERN LHC, Phys. Rev. D **71** (2005) 057503,
arXiv: `hep-ph/0411038 [hep-ph]`.

7 Selected Publications

The following publications are included in the appendix:

- Electroweak production, Run 1 (reference [2], pages 49 – 100),
"Search for the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying taus and missing transverse momentum in pp collisions at $\sqrt{s} =$ *8 TeV with the ATLAS detector"*

- Electroweak production, Run 2 (reference [7], pages 101 – 133),
"Search for the direct production of charginos and neutralinos in $\sqrt{s} =$ *13 TeV pp collisions with the ATLAS detector"*

- Inclusive production, Run 2 (reference [10], pages 134 – 166),
"Search for squarks and gluinos in events with hadronically decaying tau leptons, jets and missing transverse momentum in proton–proton collisions at $\sqrt{s} =$ *13 TeV recorded with the ATLAS detector"*

- Third-generation-squark production, Run 2 (reference [4], pages 167 – 215),
"Search for top squarks decaying to tau sleptons in pp collisions at $\sqrt{s} =$ *13 TeV with the ATLAS detector"*