



*Strong Supersymmetry. A Search for Squarks and Gluinos in Hadronic Channels
Using the ATLAS Detector*

R.H.L. van der Leeuw

Summary

Ever since I started studying physics, I have heard the sentence ‘as a high school student I always thought physics was fascinating, but I just don’t understand any of it’ more often than I can count. During my years working as a PhD student in particle physics the interest but also the incomprehension only increased among my friends and family. Therefore in the first pages of this summary I will attempt to shortly explain the concepts behind particle physics.

My contributions to particle physics are in the field of supersymmetry. This theory is introduced to solve several issues with the current theory of particle physics, called the *Standard Model*. I have searched for signs of supersymmetry in particle collisions in the ATLAS detector at CERN. The second part of this summary will elaborate on the experimental analysis performed and documented in this thesis.

Particle physics and the Standard Model

The subject of particle physics attempts to explain how nature works on the smallest currently testable length scales. This basically comes down to answering the questions ‘what are we (and everything around us) made of?’ and ‘how do the smallest building blocks interact with each other’?

All matter on earth is made of molecules composed of atoms. For example, water molecules consist of two hydrogen atoms and one oxygen atom. Since the beginning of the 20th century it is known that atoms are not ‘indivisible’, as their Greek name suggests, but consist of a nucleus made from protons and neutrons with electrons surrounding it. In the 1960s it was discovered that even protons and neutrons are composite particles: they are composed of a combination of *quarks*. These quarks, together with several other particles such as the electron, are finally currently considered to be the most fundamental particles. The theoretical model describing all fundamental particles is known as the Standard Model of particle physics. It also describes three of the four fundamental forces between particles: electromagnetism, the strong and the weak nuclear force. Electromagnetism is well known from daily life, for instance from electromagnetic radiation (e.g. light) and is the driving force behind most chemistry processes. The other two are less well known, since they only act such short length scales that we do not experience them consciously. The strong nuclear force binds protons and neutrons together in the atomic nucleus. The weak nuclear force is the only force which can change the flavour of quarks, and is thus responsible for radioactive decay of subatomic particles. Gravity is not incorporated in the theory, since the large scales on which it acts cannot be united with the underlying quantum

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	

Figure S.1: Graphical representation of the particles in the Standard Model. Figure taken from [1].

mechanics of the Standard Model.

To make sense of the big jumble of particles in the Standard Model, they are categorised according to their properties, as illustrated in figure S.1. Particles with a half-integer *spin*, a quantum-mechanical form of angular momentum, are called *fermions*. Among the fermions are six flavours of *quarks*, while the electron is an example of one of the six *leptons*. Fermions are generally considered to be matter particles. Everything we know is built up of only the lightest family of fermions (up and down quarks, electrons and electron neutrinos), since heavier fermions are unstable: when produced, they decay after a very short time into the lighter stable particles.

Interactions between the fermions are mediated by particles with an integer spin, called *bosons*. For example, the electromagnetic force is mediated by photons, particles which we perceive as light. The decay of heavy particles often involves gluons, W and Z bosons. The former mediate the strong force, while the latter two mediate the weak force. The Higgs boson, recently found at CERN, is a special particle, since it does not really mediate a force, but is a 'collateral' particle coming from the Brout-Englert-Higgs mechanism through which particles obtain mass.

Shortcomings of the Standard Model

Throughout the 20th century, the Standard Model described above has been tested to incredible precision. However, for all its success, there are several shortcomings to the model causing the physics community to doubt that it is the final theory of fundamental particles.

One of these shortcomings has to do with cosmological observations of additional

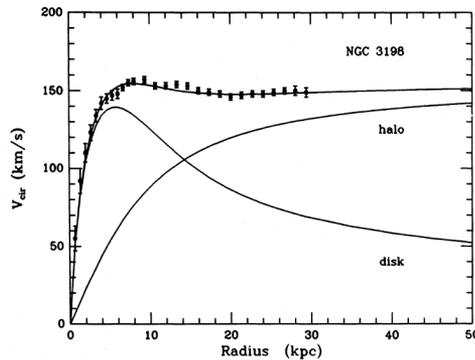


Figure S.2: Measured stellar orbital velocity of stars in spiral galaxy NGC 3198, given as a function of distance to the galactic centre is shown by the black blocks. The lower curve shows the expected rotational curve assuming no dark matter, with all visible matter in a disk, while the middle curve shows the dark matter contribution to fit the data [2].

matter of unknown origin in the universe. The first sign of such matter was observed in the 1930s from measurements of the orbital velocity of stars in spiral galaxies. Considering the assumed particle content in the galaxy and Newtonian laws of gravity, it is expected that the orbital velocity for stars decreases as the square root of the distance to the galactic centre, as illustrated by the lower line in figure S.2. However, observations show that the orbital velocity remains nearly constant. The most popular explanation is that there exists a halo of unknown matter around galaxies. This *dark matter* does not (or only very weakly) interact with the 'normal' matter inside the galaxy in any other way than via gravity. Without interactions the matter does not heat up and is not visible to us. Because the effect is not consistent with any known particles, dark matter should consist of some unknown particle(s). Since this observation the evidence for the dark matter hypothesis has increased enormously, for instance via measurements of the cosmic microwave background radiation. It is estimated that only 15% of all matter in the universe is in the form of ordinary Standard Model matter, while the remaining 85% is of the form of dark matter.

Besides dark matter, there are several theoretically reasons to believe something is missing in the Standard Model, one of which is called the *hierarchy problem*. It states that there is a conflict between energy scales in particle physics: on the one hand the mass of the Higgs boson is required to be low for the Brout-Englert-Higgs mechanism to do its job, while on the other hand quantum-mechanical effects in its theoretical calculation allow the Higgs mass to be enormous. To counter the effect, bringing the calculated Higgs mass back to the preferred lower mass scale, involves fine-tuning of the calculation by a factor of 10^{17} , which does not feel right - it would mean the reason this universe works as it does is just because two gigantic numbers nearly cancel each other by chance.

Supersymmetry

Since the Standard Model has been so successful in its predictions, one way to deal with the above issues is to use the Standard Model as a foundation for a more complete model, instead of moving to a new theory entirely. This new model should describe the Standard Model as well as 'new physics', allowing for solutions to the shortcomings listed above. One such theory introducing new physics is called *supersymmetry* (SUSY). As the name suggests, it is based on a fundamental symmetry in nature. In particle physics a symmetry should be understood as a transformation under which the physical laws remain unchanged.

The Standard Model incorporates many such symmetries, however it is still possible to add one: we can require that bosons and fermions can be interchanged without changing the physics of particle interactions. Including this symmetry requirement in the Standard Model leads to supersymmetry: the hypothesis that for each boson there is a fermion with the exact same properties except for its spin, and likewise for each fermion there is such a boson. Since these (supersymmetric) partner particles have not yet been observed in nature they should be heavier than their Standard Model partners, which is possible by breaking the symmetry at a high energy. One of these additional particles is a perfect dark matter candidate: the neutralino $\tilde{\chi}_1^0$. Supersymmetry also allows for a solution to the hierarchy problem. However, since there are many ways of breaking the symmetry, and since the masses of the SUSY particles are unknown, we do not have one single SUSY theory, but are left with a vast landscape of possible SUSY scenarios.

Goal of this thesis

With the introduction of supersymmetry, we have arrived at the goal of this thesis. Since we know the Standard Model is not the final theory of particle physics, we want to detect hints of physics beyond the Standard Model. To this end, together with a large group of physicists at CERN, I have searched in proton-proton collisions for deviations from the Standard Model expectations consistent with supersymmetry. If large deviations are observed it can lead to the discovery of SUSY, giving a whole new view on physics in the early universe and raising many new tantalising questions. On the other hand, even though we cannot disprove supersymmetry completely, observing no significant deviations is very useful as well. In this case, we can set exclusion limits. These give the upper limit on masses of SUSY particles for which SUSY is excluded, while above these limits we cannot rule it out. It will give us a lot of information on the remaining possibilities for SUSY to exist, and will guide future physicists in their search for new physics.

Detecting particles

To search for supersymmetric particles, one needs to create an environment to both create them and (indirectly) detect them. Since most SUSY particles are unstable, they do not exist in ordinary matter. To study or discover them, they first need to

be produced by colliding protons at very high energy at the Large Hadron Collider (LHC) at CERN in Geneva. Einstein's famous $E = mc^2$ tells us that energy can be transformed into mass and vice versa. Therefore, when two particles with high energies collide, one or more heavier particles can be produced. The LHC is currently the world's largest and most powerful particle accelerator, colliding protons at a centre-of-mass energy of 8 TeV, where 1 TeV is equivalent to the energy of a flying mosquito, which consists of the order of 10^{23} atoms.

After the production of supersymmetric or other heavy particles (such as top-quarks), these will decay immediately into lighter quarks and leptons. Although these particles themselves are too small to be perceived directly, they can be indirectly detected using the ATLAS particle detector, situated around a collision point of the LHC. Particles travelling through the detector ionise certain material and are slowed down and stopped in calorimeters, via which the particles can be reconstructed and their momentum measured.

Searching for supersymmetry

Using data recorded from proton-proton collisions, or *events*, by the various detector elements of ATLAS I searched for signs of supersymmetric particles in proton-proton collisions. To this end I used a 'counting experiment'. Each event is categorised as being either Standard Model-like or SUSY-like. The observed number of SUSY-like events is compared to the number expected from collisions involving only Standard Model particles.

However, each event comes with a calculable probability of producing certain particles, which depends on the mass of the involved particles. Since SUSY particles are expected to be heavier than their Standard Model counterparts, in each event there is a smaller probability of producing SUSY particles than 'normal' Standard Model particles. In the 20 million events occurring per second many more Standard Model particles are produced than (hypothetical) SUSY particles. The selection of SUSY-like events therefore needs to be carefully optimised.

Selection of the hadronic channels

To differentiate between SUSY and Standard Model events it is essential to accurately know the signature which either type of event leaves in the detector. In large portions of the possible SUSY scenarios the majority of events lead to 2 strongly interacting SUSY particles being produced that decay into high-momentum quarks and two neutralinos. Solitary quarks are not allowed in the Standard Model, causing the outgoing quarks to hadronise into a shower or *jet* of particles. Neutralinos are stable particles which do not interact with the detector and are therefore invisible to us. However, due to momentum conservation, we do observe a net loss of momentum in the transverse plane: since the two incoming protons have no transverse momentum, the outgoing particles should have zero net transverse momentum as well. If any particle, such as a neutralino, escapes detection, it will show up as a momentum imbalance, measured as missing transverse energy \cancel{E}_T .

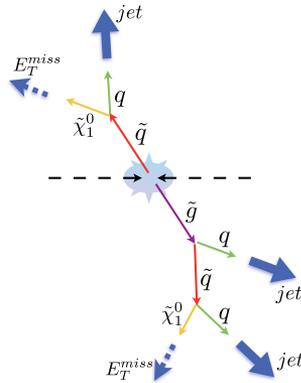


Figure S.3: Illustration of the production and immediate decay of a squark and a gluino into quarks and the lightest supersymmetric particles, neutralinos ($\tilde{\chi}_1^0$), leading to a signature of jets and missing transverse energy.

Such SUSY scenarios thus have a *hadronic* signature of two or more jets and high missing transverse momentum, while leptons are less likely in the decays. Such a decay is illustrated in figure S.3. To reduce the Standard Model backgrounds to our search, we select events with high \cancel{E}_T and high momentum jets. Since the decay of most Standard Model particles involves leptons, requiring no leptons in our search reduces the backgrounds even further. Finally, the selections are optimised for different types of SUSY using information on \cancel{E}_T , the number of jets and their momentum. All in all 12 such signal selections are defined, which all have a final requirement on the *effective mass* m_{eff} of the event. This is defined as the sum of \cancel{E}_T and the transverse momenta of the jets in the event. The effective mass is correlated to the mass of the SUSY particles, and will thus be higher on average in SUSY events than in Standard Model events.

Background estimation

Once the signal selection criteria have been established, we need to know how many data events are selected if SUSY does not exist. This Standard Model background is estimated using a combination of simulations of the data and extrapolations from Standard Model rich selections to our SUSY rich selection. The simulations are performed by Monte Carlo event generators. These simulate events from theoretical principles, including the production of particles in a collision, as well as their decay and the interaction of the decay particles with the detector. It is essential to know and reduce the uncertainties on the background estimates. The uncertainties have both a theoretical origin, due to the used simulations, and an experimental origin, due to detector calibrations.

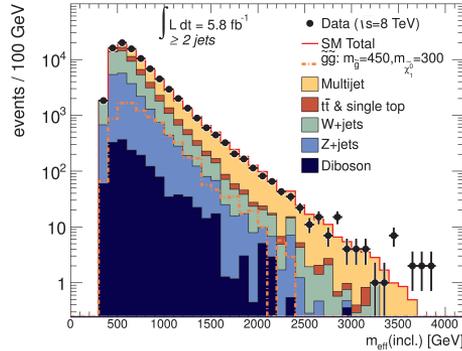


Figure S.4: Observed m_{eff} distribution with the final selection requirement indicated by the red arrow. Data is given by black dots, while the Standard Model backgrounds are illustrated by the stacked coloured histograms. The dashed histogram represent a SUSY model.

Supersymmetric particle production

Besides these background estimates, the number of SUSY signal events in the selection also needs to be estimated. To this end, events are simulated with supersymmetric particle production. Knowledge of the number of hypothetically produced SUSY particles is essential. The production rate of any fundamental particle can be calculated using its *cross section*. The calculation of the cross section depends on several theoretical and experimental inputs, of which *parton distribution functions* (PDFs) are the most important. They are used to estimate the momentum-dependent probability that for instance a quark in one incoming proton collides with a gluon in the other proton. However, since PDFs are difficult to measure, they carry large uncertainties which propagate into an uncertainty on the value of the calculated cross section. Using methods I have developed it is determined that this propagation leads to uncertainties on the production rate of *squark* and *gluino* pairs, the SUSY partners of quarks and gluons of between 10% for low mass particles and 70% for very massive particles. Since these theoretical uncertainties only affect the signal, their effect is shown separately from the background uncertainties in the following results

Results

Only once all the above-mentioned groundwork has been done, the data taken in the first half of 2012 is tested against our selections. In figure S.4 the number of selected events is plotted against their observed m_{eff} for a signal selection where at least two jets are selected. The black dots represent the data points, while the stacked coloured histograms represent the various estimated backgrounds. The dashed line represents a m_{eff} distribution for a SUSY model. If SUSY exists with squarks and gluinos with such masses, large discrepancies would be seen between data and expectations at high values of m_{eff} , to the right of the red arrow. However, no significant deviation is seen

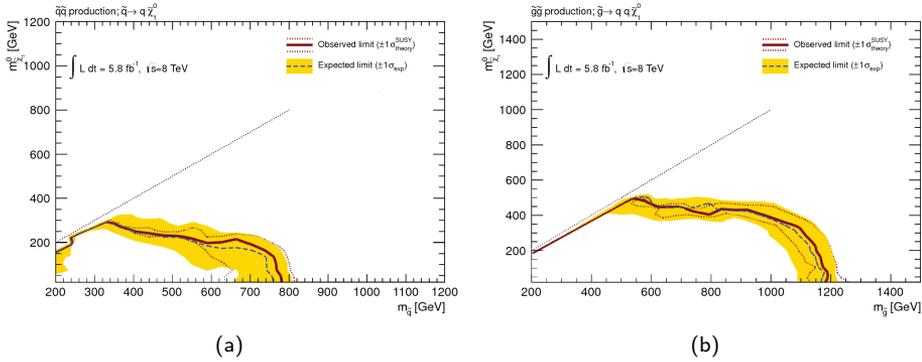


Figure S.5: Exclusion limits for producing two squarks (a) or two gluinos (b). SUSY models are excluded if the squark or gluino mass and neutralino mass fall inside the excluded area. The red line indicates the observed limit, while the blue line indicates the expected limit if data would follow the background estimates exactly. The yellow band gives the uncertainty on the expected limit.

in this or any other selection. With no large observed discrepancies, the number of possible supersymmetric signal events hiding in the data is calculated using a statistical framework, based on the theoretical and experimental uncertainties on the background estimates. This number can tell us if certain supersymmetric scenarios can be ruled out. As mentioned before, more massive particles are less frequently produced, thus for very high masses we will not be able to draw any conclusions.

Since there are many possible SUSY scenarios, we need to choose in which we interpret our results. To be fairly model independent, the excluded masses are given for two hypothetical *simplified* SUSY scenarios where a restriction is set on which particles may be produced. On the left hand side in figure S.5 a the limit is shown in a model shown in which only squarks are produced, while the right figure shows a model with only gluino production. Although these simplified models cannot be the real manifestation of SUSY, if combined limits set in these can be used to configure a limit in any type of SUSY model. The limits are given as function of either the squark or gluino mass (x -axis) and neutralino mass (y -axis). The red line indicates the observed limit: SUSY models with squark or gluino masses below this limit are ruled out. The dotted red lines indicate this same limit when the cross sections for SUSY production are taken to be consistent with their (up- or downward) uncertainty discussed previously. In SUSY with massless neutralinos, squarks are limited to be heavier than $\sim 780 \text{ GeV}$ ¹, while gluinos should be heavier than $\sim 1175 \text{ GeV}$. However, the limits depend greatly on the neutralino mass, into which squarks and gluinos decay. For very heavy neutralinos, with masses close to the squarks and gluinos, SUSY cannot be excluded.

¹if all partners of the five lightest quarks are of equal mass

Conclusions and outlook

Although unfortunately no indications of supersymmetry have yet been found the analysis in this thesis only scratches the surface of the SUSY landscape, leaving many possibilities for SUSY to still exist. One such possibility is for it having neutralino masses close to that of squarks and gluinos. However, it is being hunted down and slowly cornered² due to the relentless and ongoing efforts of many physicists around the world. These efforts will only increase in the coming years, when the LHC will reach higher collision energies and record up to one hundred times more data. Even if no evidence for SUSY is found, I am hopeful that such searches at the LHC will expose anomalies in the Standard Model.

²At least the most interesting SUSY models with not too heavy particles.

Bibliography

- [1] American Association for the Advancement of Science.
- [2] T. S. van Albada, J. N. Bahcall, K. Begeman and R. Sancisi. *Distribution of dark matter in the spiral galaxy NGC 3198*. *Astrophys. J.* **295** (1985).