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PROJEKTARBEIT

Estimating the Conservatism of Experimental Results from ATLAS and CMS Searches

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Abstract

The search for physics beyond the standard model (BSM) has been one of the biggest tasks tackled by modern particle physics with supersymmetry (SUSY) trying to explain the shortcomings of the SM. Experimental searches at the Large Hadron Collider (LHC) have accumulated a large number of data over the past years with energy boundaries being pushed higher and higher. With the two biggest experiments ATLAS and CMS adopting a simplified models approach tools to validate new kinds of BSM models have become increasingly important. SModelS accomplishes just that by decomposing full models into simplified topologies and featuring a database of experimental results. These results contain a number of unknown parameters which is why experimentalists have to be conservative when giving error estimations for them. This thesis gives an introduction to the theoretical and experimental background as well as trying to evaluate the conservatism of the experimentalists by analysing data provided by the SModelS database.

Abstract

Die Suche nach Physik jenseits des Standardmodells (SM) ist eine der größten Herausforderungen der modernen Teilchenphysik. Supersymmetrie zählt dabei zu den am weitesten verbreiteten Theorien, welche offene Fragen des SM zu erklären versuchen. Mit immer höher erreichbaren Kollisionsenergien am LHC nimmt auch die Anzahl der zur Verfügung stehenden Daten zu. Eine effiziente Methode zum Vergleich von Theorie mit experimentellen Daten bieten simplified model spectra (SMS). Das Tool SModelS implementiert einen Algorithmus zum Zerlegen beliebiger BSM Modelle in vereinfachte Topologien, welche leichter validiert werden können und beinhaltet außerdem eine Datenbank mit experimentellen Ergebnissen. Die Daten, welche von Seiten der Experimente ATLAS und CMS zur Verfügung stehen unterliegen Unsicherheiten, eine konservative Abschätzung von Fehlern ist erforderlich. Diese Arbeit gibt eine Einführung in den theoretische und experimentellen Hintergrund und versucht den Konservatismus der aus der SModelS Datenbank stammenden Daten abzuschätzen.

Contents

1 Introduction

In modern particle physics the Standard model (SM) has been the predominant theory for the last 50 years since its introduction in the 1970s. During this time it has been tested in numerous experiments all around the world and many of its predictions have since been confirmed, such as the existence of the Higgs boson in 2012. Though experimental results which contradict the Standard Model with high significance (discrepancies of 5σ and above) are yet to be found this seems to be only a matter of time. There are also a number of urging questions not answered at all by the SM such as the asymmetry between matter and antimatter as well as the nature of dark matter, which seems to be much more common than regular types of matter in the universe.

New theories have been formulated to explain the physics beyond the Standart Model (BSM) and explain some of these deficiencies of the SM. The most widespread one being the supersymmetry (SUSY), which is an extension of the SM where each fermionic and bosonic particle is associated with a partner particle of the other group respectively, with the only differing property being the spin.
The Minimal Supersymmetric Standard Model (MSSM) gives rise to more than 100 new parameters in addition to the 19 imposed by the SM. This makes phenomenological analysis of MSSM highly impractical because finding regions in the parameter space which are consistent with experimental results becomes increasingly difficult. By making use of some assumptions such as prohibiting new sources of charge-parity (CP) violations the number of free parameters can again be reduced to 19 and the resulting theory is the phenomenological Minimal Supersymmetric Model (pMSSM).
In the energy regions which are accessible to us so far by these experiments no evidence of SUSY has been found so far, which might be an indication for broken symmetry.

The worlds largest facility to detect physics beyond the SM is the Large Hadron Collider (LHC) which is located near Geneva where tremendous energies are achieved by collisions of fast protons. During these impacts a large quantity of particles are produced which on their part decay very quickly and in characteristic decay topologies. By detecting these secondary particles as well as taking into consideration not detected particles (most notably neutrinos) which are confined by conservation

of energy and momentum and result in missing transverse energy (MET), information about the initially produced particles can be obtained.
The evaluation of these results in terms of BSM models is however extremely demanding and is only getting increasingly difficult the more SUSY models emerge, which is why researchers have adopted a simplified model approach resulting in simplified model spectra (SMS). SMS offer a new perspective by reducing the number of considered BSM particles and can be used to group together different BSM models by tracing them back to similar shared topologies.
A useful tool related to this is SModelS, which makes it possible to decompose specific BSM models into their simplified topologies and make statements about their validity by testing them against the experimental database.

For this thesis the experimental results from past years of the ATLAS and CMS experiments, located at the LHC have been analysed. When working with this data one must also consider nuisance parameters which are not available to the theorist. The errors provided for these results are typically also overestimated. By calculating the p-values for the experimental results from the database it is possible to gain insight on this conservatism by researchers of the LHC.
If a theory with perfect knowledge about the underlying processes is implied the p-values would be expected to be uniformly distributed across $[0, 1]$. By overestimating the errors extreme events from both sides of the interval will be shifted towards the center.

2 Theoretical Background

2.1 Standard Model of particle physics

The Standard Model was finalized during the 1970s and is one of the most thoroughly tested theories in physics. It is a renormalizable and mathematically self-consistent field theory containing the fermion fields, accounting for all matter particles as well as gauge fields (electroweak, gluon, Higgs). The gauge fields ensure invariance of the Lagrangian under certain local transformations and therefore induce symmetries in the form of gauge groups.
The Lagrangian is constructed by coupling the gauge fields to the fermions thus allowing interactions and can then also be used to describe the temporal evolution of a physical system.
There are 19 free parameters needed to fully formalize this, which have to be evaluated experimentally. They are the masses of the fundamental particle as well as coupling constants.

Figure 2.1 shows a table of all particles which make up the SM:

- Fermions (Quarks and Leptons) with spin $\frac{1}{2}$ in purple and green which subsequently form all matter.
- Gauge bosons with spin 1 in red, responsible for the fundamental forces (excluding gravity).
- The Higgs boson with spin 0 which gives rise to all other particle masses via the Higgs mechanism.

The most prominent prediction of the SM has to be the Higgs boson which was discovered at the LHC in 2012 but it has also played a role in successfully predicting the top quark as well as the tau neutrino. It is also responsible for some tremendously accurate calculations such as the magnetic moment of the electron which matches the experimental results to an accuracy of one in a trillion.
Yet there are still shortcomings of the SM which show the need for extensions of the theory:

- *Neutrino Oscillation*:
  Neutrinos come in three different lepton flavours (electronm, muon, tau). In

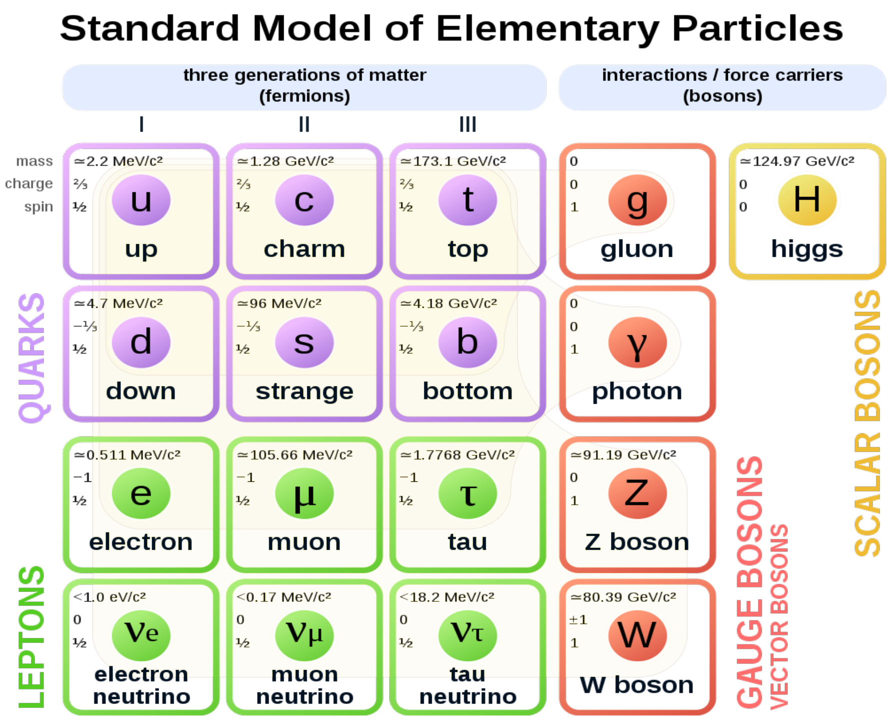

Figure 2.1: SM of particle physics [1]

the SM neutrinos are massless particles, but neutrino oscillation experiments, where neutrinos are shown to be able to change lepton flavour over time imply a non zero neutrino mass which contradicts the SM.

- *Anomalous magnetic moment of the muon*:
  Experiments conducted at Fermilab have suggested that the anomalous magnetic moment of the muon to be more than 4 standard deviations higher than predicted by the SM. While the experiment has not yet fully been concluded it seems to be a strong hint at least.

In addition to these experimental results which seem to contradict the SM there are also some phenomena which have no explanation at all in terms of the SM, implying the SM is at least an incomplete theory, specifically:

- *Hierarchy Problem*:
  This relates to large discrepancies between weak force and gravity notably the weak force being 10^{24} times stronger than gravity.

- *Gravity*:
  Einstein's general relativity is also one of the most profoundly tested physical theories, making some amazingly accurate predictions, yet there seems to be no way to combine SM with GR so far as gravity is not included in the SM at all.
- *Asymmetry between antimatter and matter*:
  As far as we know the universe is made out of mostly matter. There is no mechanism contained in the SM which explains matter being so vastly dominant over antimatter if both were created equally during the Big Bang which seems to be a reasonable assumption.
- *Dark matter*:
  Dark matter is much more prominent than matter but interacts not at all (or at least very weakly) with the fields described by the SM and only its gravitational effect can be observed. The SM does not contain any particles which could explain such behaviour.
- *Dark energy*:
  Most of the universes energy exists in the form of dark energy. If calculated in terms of vacuum energy using the SM the results do not match our observations by orders of magnitude.

Though the SM is to this date still our best explanation of particle physics many of its problems have been apparent since its initial formulations which is why many theories have since emerged to explain the shortcomings of the SM with the most prominent and widespread example being supersymmetry (SUSY).

2.2 Supersymmetry

Supersymmetry has been a staple in particle physics and contender to explain BSM physics for the past decades. It is an extension of the SM and tries to overcome its problems by introducing a new type of symmetry. It combines fermionic fields, which anticommute with bosonic fields, which commute, by introducing a $\mathbb{Z}_2$ graded algebra. The result is the existence of a bosonic superpartner for every fermion of the SM and vice versa (Fig. 2.2). Gauginos and higgsino, the partner particles of the gauge bosons and the Higgs boson mix under electroweak symmetry breaking to neutralinos and charginos. Under normal circumstances the prediction would be that the only differing property of these superpartners is their spin with their masses being the same. However the fact that no new particles have been observed in these energy ranges suggests the symmetry to be broken.

The introduction of these new particles also requires a new large set of parameters describing particle properties and coupling constants due to the number of new available interactions. In MSSM which is the smallest supersymmetrical extension of the SM over 100 new free parameters are introduced in addition to the already existing 19. The price to be paid is that phenomenological analysis becomes exceedingly difficult. To counteract this problem a number of assumptions can be asserted to impose dependencies and restrictions on these parameters and bring their number back down to 19. The result is the phenomenological minimal supersymetric model (pMSSM) and the reduction in phase space is also accompanied by making phenomenological analysis easier.

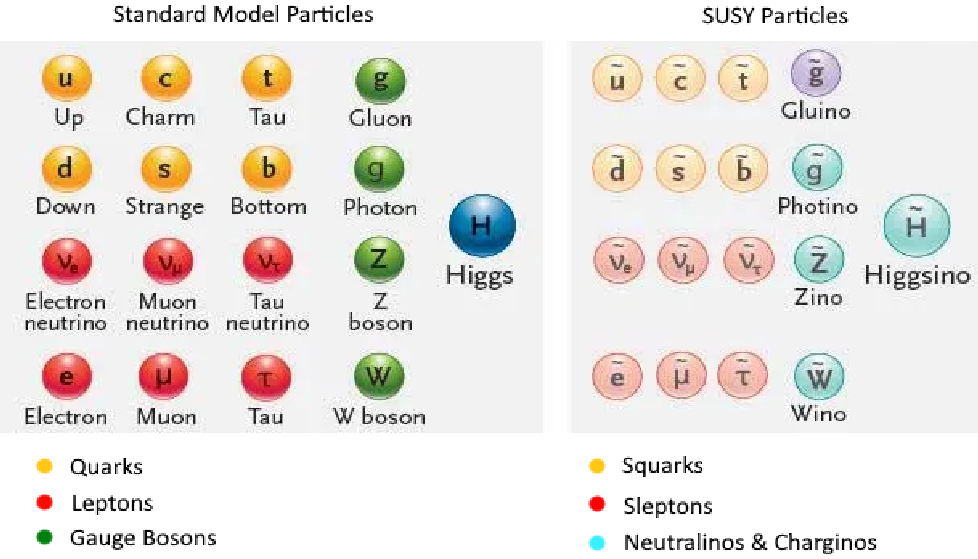

Figure 2.2: SM and SUSY particles [2]

2.3 Problems solved by SUSY

Not only might the introduction of a new symmetry between fermionic and bosonic particles seem mathematically quite aesthetic, there are also a number of open questions which could get answered by SUSY:

- *Gauge coupling unification*:
  The idea is that at large energies the three gauge interactions unify to just one type of interaction. In the SM this does not happen however under SUSY this is expected to happen.

- *Hierarchy Problem*:
  A hierarchy problem occurs due to renormalization in QFT which applies corrections to coupling constants or masses and results in seemingly arbitrary fine-tuning. In the case of the Higgs boson its observed mass is much lighter than expected. Extreme fine tuning is required to cancel quadratic corrections. In SUSY this is no longer a problem because the coupling of the superpartners to the Higgs field would just cancel out these contributions.

- *Dark Matter*:
  In the SM there is no particle which behaves the way dark matter does. Baryon number and lepton number are conserved quantities in the SM however for SUSY this is no longer the case. Instead there is a new concept called R-parity consisting of a combination of baryon and lepton numbers. SM particles would have an R-parity of $+1$ and their supersymmetric partners a value of -1. If R-parity is assumed to be conserved then the lightest supersymmetric particle (LSP) is stable and a weakly interacting massive particle therefore making it a good candidate for dark matter.

Supersymmetry is also a requirement for many other ambitious theories trying to unify the SM with gravity such as superstring theory.

3 Experimental Background

3.1 LHC

The Large Hadron Collider (LHC) is the largest and most potent particle accelerator in the world and was built by the European Organization for Nuclear Research (CERN-Conseil européen pour la recherche nucléaire). Its construction took place between 1998 and 2008 with participation of more than 100 countries from all over the world. The accelerator has a circumference of 27 km and lies between the boarder of France and Switzerland near Geneva in a depth of up to 175 m. Negative hydrogen ions are first accelerated in a linear particle accelerator and synchrotron boosters before being stripped of their electrons leaving only the protons to be injected into the main ring. A system of 1232 superconducting dipole magnets is used to keep the particles on their trajectory while 392 quadrupole magnets focus the beams. At four interaction points the protons of two opposing beams collide releasing huge amounts of energy and secondary particles which are measured by the eight detector experiments namely ATLAS, ALICE, CMS, LHCb, LHCf, MoEDAL, TOTEM and FASER. When the accelerator is operating more than 100 terabyte of data is collected every day which is used to reconstruct the events and look for possible new physics.
The first operational started in 2009 with protons of each beam being accelerated to up to 4 TeV thus resulting in collision energies of 8 TeV. It concluded in 2013, with the discovery of the higgs boson being one of the most prestigious revelations of recent times. After upgrading the collider for the second operation run from 2015-2018 collision energies of 13 TeV were achieved and a third run is expected to start in late 2021.
ATLAS and CMS are the two of the eight detectors charged to search for SUSY which makes their data relevant for this thesis.

3.2 ATLAS

ATLAS (A Toroidal LHC ApparatuS) is the largest particle experiment at the LHC, weighing 7000 tonnes and being 46 m in length and 25 m in diameter. It features a layered design with each layer being made up of different detectors specialised to observe different types of particles.

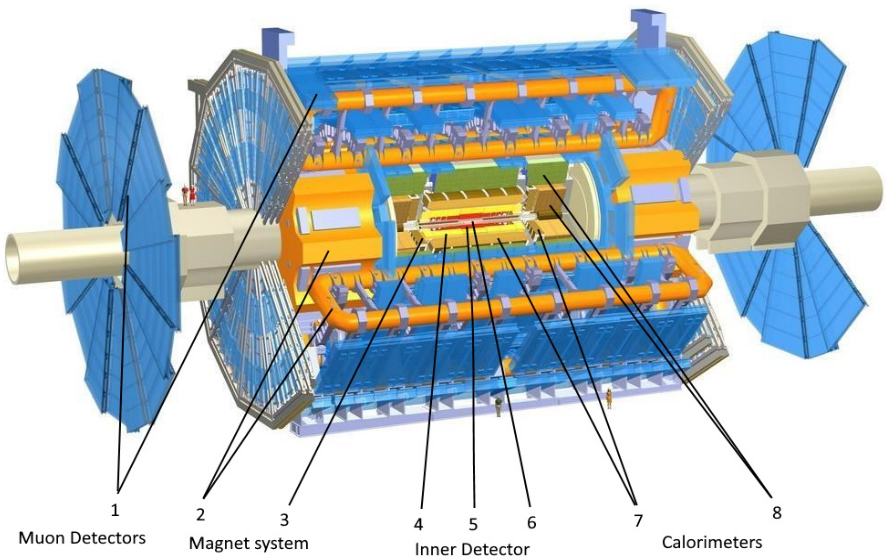

Figure 3.1: Illustration of the ATLAS detector [3]

Figure 3.1 shows the structure of the ATLAS detector.
The inner detector features the innermost Pixel Detector (6) allowing precise tracking very close to the interaction point, the Semi-Conductor Tracker (5), measuring particles over a much larger area and the Transition Radiation Tracker (4) which allows for continued particle tracking.
Calorimeters (7 and 8) measure energies of secondary particles. Both electromagnetic and hadronic calorimeters are used which measure energy absorption by electromagnetic and strong force interaction.
Solenoid (3) and toroid (2) superconducting magnet systems are used to bend charged secondary particles in order to measure their momenta.
The largest tracking system is the muon spectrometer (1) which is able to measure the momenta of 100 GeV muons with 3% accuracy and those of 1 TeV muons with 10% accuracy.

3.3 CMS

The Compact Muon Solenoid (CMS) is a general purpose detector and although smaller than ATLAS, being 21m long and 15 m in diameter it is also much heavier weighing around 14000 t. In some ways it is similar in structure to ATLAS (Fig.3.2) but its design allows for especially sensitive detection of muons and offering high momentum tracking. Like ATLAS it also features a layered design with a magnet system to bend secondary particles, calorimeters and a thick muon detector on the outside. The CMS detector is not only used to study standard proton-proton collisions but also studies aspects of heavy ion collisions.

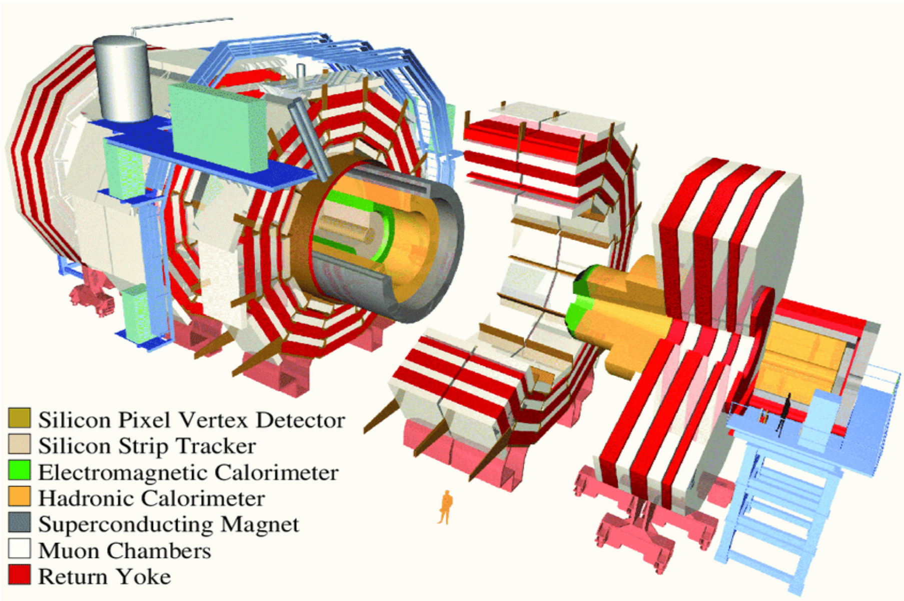

Figure 3.2: CMS detector with its most important components [4]

4 Processing the data

The pictures obtained from the collisions inside the particle tube are called events (4.1). When looking for events correlating to new particles beyond the SM the expected decay chains usually consist of leptons, jets produced by hadronization of quarks and gluons as well as missing transverse energy (MET) which is a part of the total missing energy transverse to the beam. Unfortunately many SM processes such as the decays of the W and Z bosons containing neutrinos yield similar results and are much more common therefore contributing to a very large undesirable background. Consequently advanced strategies are needed to distinguish BSM signals from those caused by SM physics.

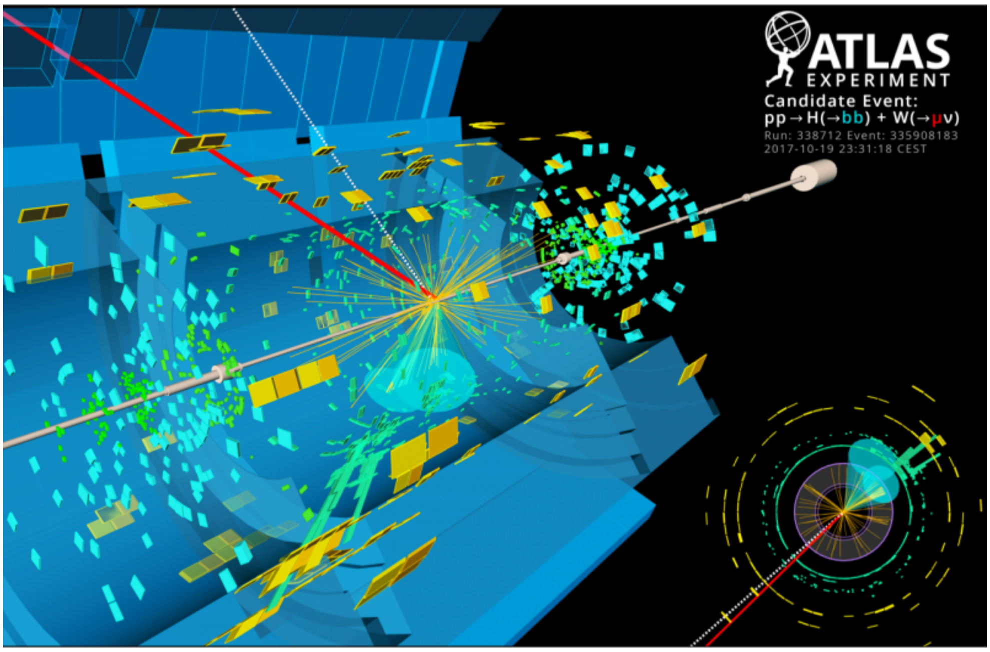

Figure 4.1: Example event at ATLAS [5]

4.1 Simplified Models

BSM models make predictions about SUSY particles, their masses and characteristic decay patterns. By looking at experimental results regions the parameter space of these models can be excluded which is however computationally expensive. In the presence of BSM physics the number of observed events is composed of BSM processes as well as the SM background therefore the number of signal events corresponding to new physics can be described by

$$N_{signal} = N_{obs} - N_{SM} \tag{4.1}$$

and also in terms of physical quantities by

$$N_{signal} = L \times (\mathcal{A} \times \varepsilon) \times (\sigma \times BR) \tag{4.2}$$

with:

L: the integrated luminosity which is known from the measurement
$\mathcal{A}$: the acceptance rate, represents the fraction of events which reach the detector
ε: the efficiency, total number of events impinging on the detector, constrained by certain analysis criteria
σ: the production cross section of the involved BSM primary particles
BR: the branching ratios for the decays of the BSM particles

The fact that many BSM models make similar phenomenological predictions can be used in a simplified model approach. Topologies which share common features, such as decaying branches and final states are grouped together. The observed number of events N_{obs} is the result of many different decay modes but complexity can be reduced by setting all branching ratios to 0 except the simplest one which is consequently 100%. In addition to that only a few number of BSM particles are assumed to have masses within reach of the collision energies.
By making these assumptions and restricting yourself to a specific model

$$(\sigma \times BR)_{SMS} \simeq \frac{N_{signal}}{(\mathcal{A} \times \varepsilon) \times L} \tag{4.3}$$

can be obtained from eq.(4.2).
$(\mathcal{A} \times \varepsilon)$ is a function of the masses of the primary BSM particle created in the collision as well as the lightest supersymmetric particle (LSP) which is always the end product of the decay process. By utilizing Monte Carlo simulations it can be calculated for a range of both particle masses which is used to create an **efficiency map** (EM). (Fig. 4.2)

These results can then be used in conjunction with eq.(4.3) to construct an **upper limit** (UL) map specifying the 95% confidence level (CL) upper limit of the production cross section σ_{UL}. (Fig. 4.2) This is done by calculating the likelihood for the observed number of events given the number of expected background and signal events.

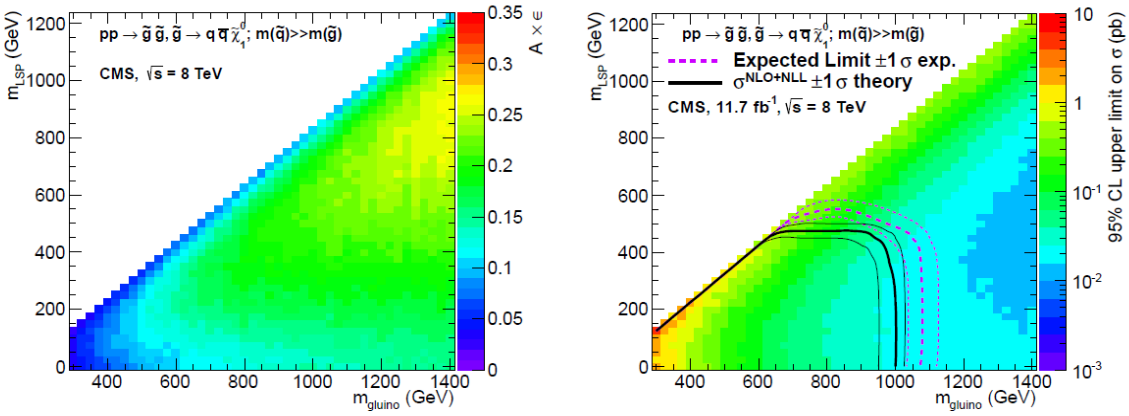

Figure 4.2: example of a simplified model (left: efficiency map, right: upper limit map) for gluino decay $\tilde{g} \to q\tilde{q}\tilde{\chi}^0_1$ excluded up to a gluino mass of 1000 GeV with 95% CL. [6]

In short simplified models include only a small amount of new particles and interactions, they are limits of more complicated scenarios reducing complexity of decay topologies and can still be described by a small number of physical parameters such as particles masses, production cross sections and branching ratios. They can offer a natural starting point for characterizing new physics signals and are also useful to derive limits of more general models.

4.2 SModelS

SModelS is a public tool for interpreting the simplified model results from both the ATLAS and CMS experiment which was published first in 2014 with the current version being v2.0 as of May 2021.
When testing for a BSM model the number of expected signal events is proportional to the signal efficiency which relies on the specifics of the BSM model however model independence would be preferred for experimental analysis.
The underlying assumption used by SModelS is that signal efficiencies for most experiments searching for new physics are only slightly affected by the specifics of a BSM model and depend mostly on the event kinematics.

SModelS is able to decompose any BSM model with a $\mathbb{Z}_2$ symmetry into its signal topologies, their weights consisting of production cross sections and branching ratios as well as the relevant BSM masses. $\mathbb{Z}_2$ symmetries are a very easy way to include dark matter in a new model because they allow for the LSP to be stable. Either SLHA or LHE input files can be used and depending on the input decomposition is done either Monte Carlo based or SLHA based (Fig.4.3). The obtained topologies can then be tested against the database containing experimental results which are stored in two different categories:

- **Efficiency Map (EM)** results: these correspond to the product of acceptance $\times$ efficiency ($\mathcal{A} \times \varepsilon$) as a function of BSM particle masses for the signal regions of the experiment. The number of observed events n_{obs} and expected events by the SM n_{bg} as well as their uncertainties are also included.

- **Upper Limit (UL)** results: these correspond to the 95% confidence level (CL) limits of the production cross section as a function BSM particle masses for the signal regions of the experiment. For some results also expected upper limits are provided.

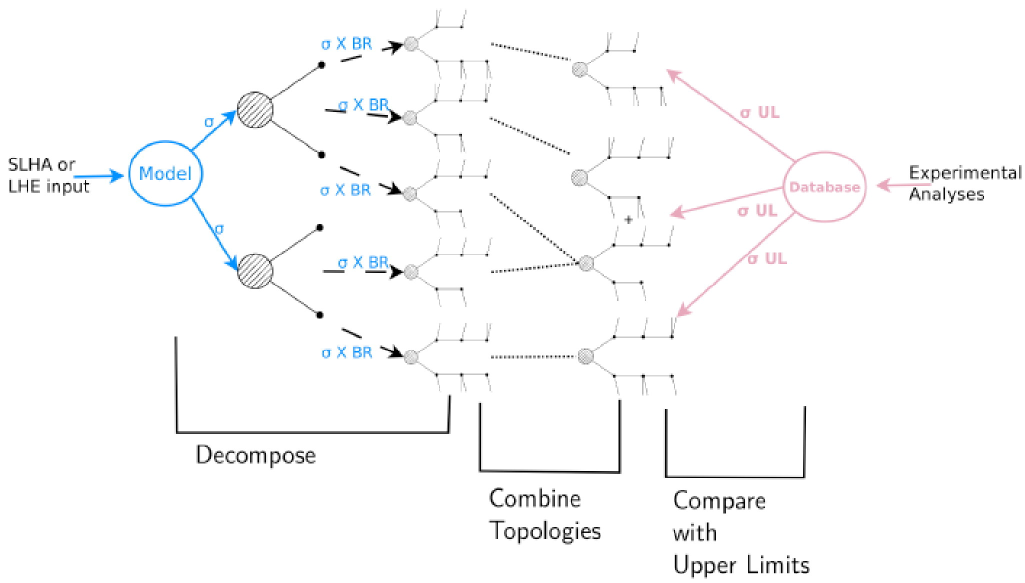

Figure 4.3: Schematic concept of SModelS: decomposition → signal topologies → validation [7]

5 Implementation

The first step is to obtain all the experimental results. The data which was used in this thesis comes from the SModelS database which as discussed previously contains EM resuts aswell as UL map results. EM maps include more information which makes it possible to compute a proper likelihood function from them. The information given by UL events are restricted to 95% CL limits on the cross section making it not possible to create a likelihood without a number of assumptions. The data used in this thesis contains 148 ATLAS and 199 CMS MET searches. 265 of those 347 results are EM results with the remaining 82 being UL results. Results from the first run of LHC (2013 and before) have a collision energy of 8 TeV while in the second run energies of 13 TeV were achieved. Only EM results were considered, amounting to 265 signal regions. The variables extracted from the database which are used are:

- nobs: the number of observed events in the experiment
- expectedbg: the number of expected background events as predicted by the SM
- bgerr: the estimated error on these background events
- newObs: generated fake number of observations

The way how the number of background events as well as their error are calculated is the following: Control regions in phase space with large sample sizes where the SM is assumed to be predominant yield the necessary results which can be used to infer the number of SM background events as well as giving an estimation on their error in the signal region. When trying to construct a likelihood from the results one must consider that there are nuisance parameters involved which are elusive to the theorist.
If the vector parameter δ can be written as $\delta = (\mu, \theta)$ with μ including the parameters of interest and nuisance parameter θ, then the likelihood function can be written as $\mathcal{L}(\delta|D) = \mathcal{L}(\mu, \theta|D)$ and the nuisance parameter can be eliminated by either marginalization:

$$\mathcal{L}(\mu|D) = \int_\theta p(D|\mu, \theta)p(\theta|\mu)\, d\theta \tag{5.1}$$

where it is removed by integrating over it or profiling:

$$\mathcal{L}(\mu|D) = \sup_{\theta} \mathcal{L}(\mu, \theta|D) \tag{5.2}$$

where the nuisance parameter is chosen which maximizes the likelihood function. In our case we can construct a simplified likelihood:

$$\mathcal{L}(\mu|D) = \frac{(\mu s + b + \theta)^{n_{obs}} e^{(\mu s + b + \theta)}}{n_{obs}!} exp(-\frac{\theta^2}{2\delta^2}) \tag{5.3}$$

with:
μ: the number of signal events
s: the relative signal strength
b: the number of background events as predicted by the SM
n_{obs}: the number of observed events in the signal region
θ: the nuisance parameter
and $\delta^2 = \delta_b^2 + \delta_s^2$ containing the signal and background uncertainty.

We assume the background events to be from a normal or a lognormal distribution with the mean and standard deviation being the number of expected background events and their estimated error taken from the database. The signal uncertainty δ_s is assumed to be 20%.
We first calculate the p-values for each signal region by sampling over this distribution and using the results as the parameter of a lambda distribution which corresponds to the number of observed events. These obtained fake observations can then be used to calculate the p-values by integration.

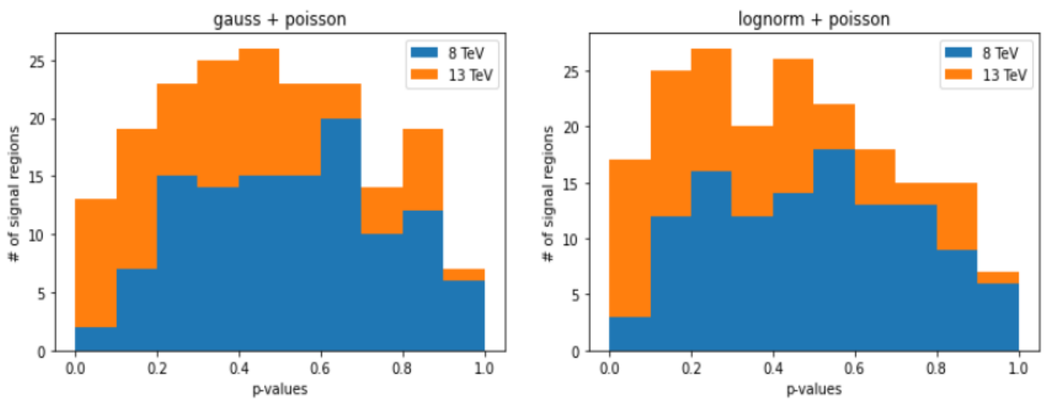

Figure 5.1: Histogram of the p-values of all signal region for both 8 TeV and 13 TeV results.

Because low numbers of observed events are prone to being statistical outliers we only consider signal regions with at least 3.5 expected events. Figure 5.1 shows these results for both the 8 TeV and 13 TeV experiments. From this graph we can already obtain some information. P-values below 0.5 which correspond to the number of observed events being too small in regard to what would be expected are overrepresented with a much smaller amount of signal regions where more events than expected are measured. Also p-values near the extremes 0 and 1 are much rarer than ones near the center. This can be explained by taking the following into consideration: The errors on the number of expected background events can of course always only be an estimation with too many uncertainties playing a role. The experimentalists which provide these results will therefore always be leaning to the conservative side. Indeed if one would assume perfect understanding of the underlying model the p-values would be expected to be approximately uniformly distributed among [0,1]. We can demonstrate this by calculating the p-values from the database of fake observations which are generated under the SM hypothesis. This is shown in Figure 5.2.

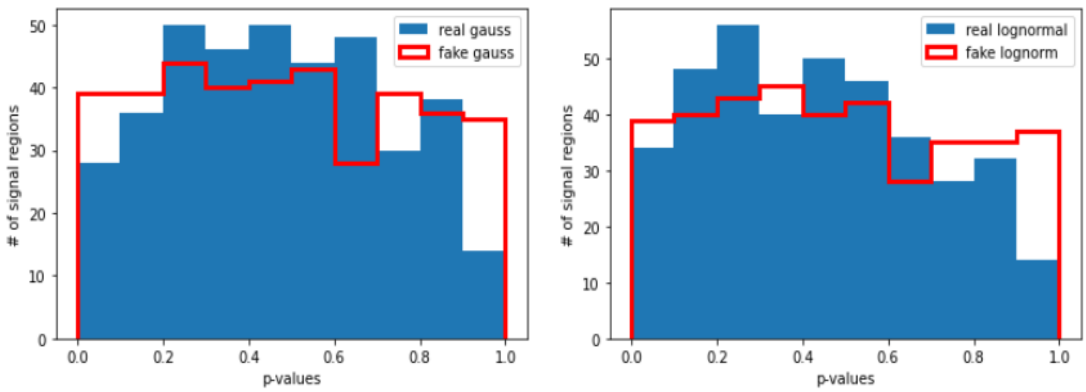

Figure 5.2: Comparison between real p-values obtained by real results and created by a fake dataset which assumes complete knowledge about the underlying model.

The next step is then to quantify this overestimation of the SM background error. To do this we perform a chi-squared test for binned uniform distribution. The test statistic which we use to perform this is:

$$T = \sum_{j=1}^{k} \frac{(Y_j - np_j)^2}{np_j} \tag{5.4}$$

where the number of observed frequencies Y_i are compared to their expected values. The background error of all signal regions is then multiplied by a varying fudge factor less than 1 and p-values are again calculated from this modified set of data. We first minimize the test statistic T from equation(5.4) across the whole interval [0,1] which allows the fudge factor yielding the most uniformly distributed p-values to be found. This is shown in figure(5.3) and was done not only for the combination of 8 TeV and 13 TeV results but also for both individually.

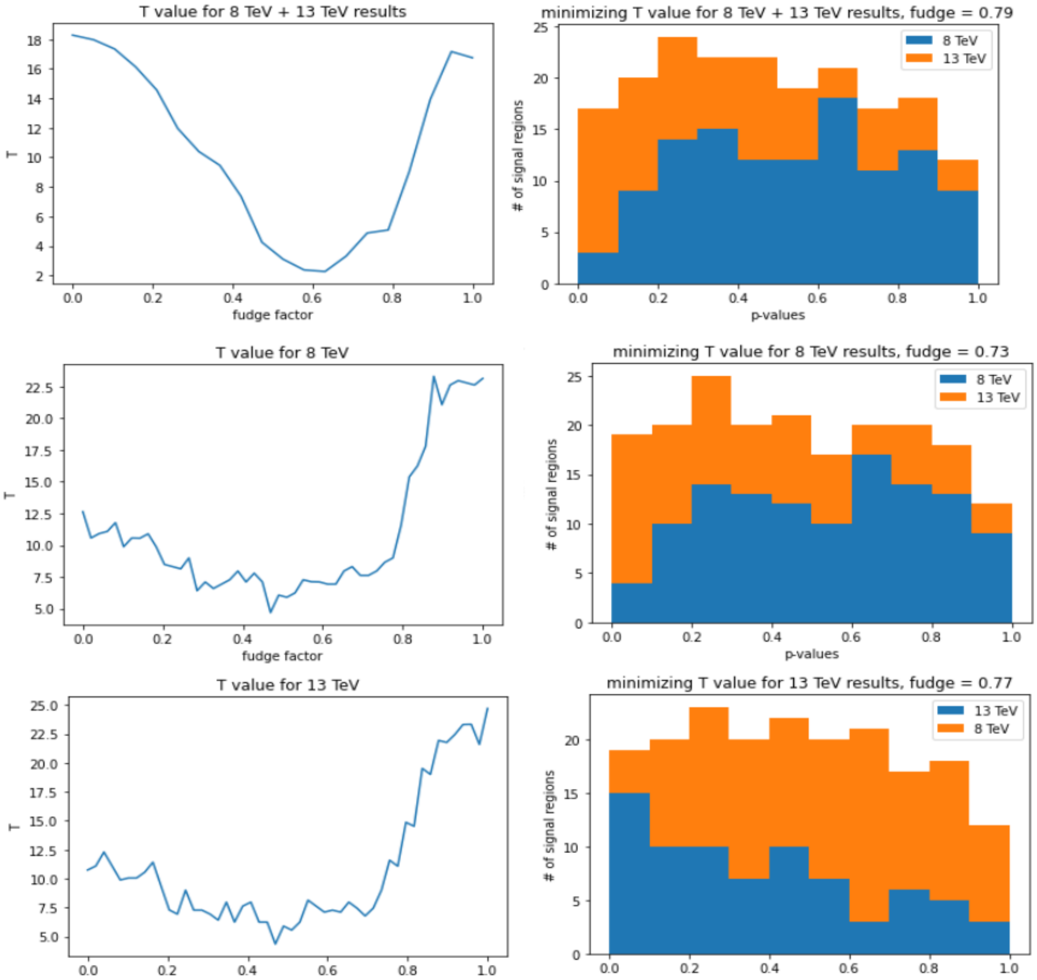

Figure 5.3: Plots of the test statistic T as a function of the fudge factor in combination with the p-value histogram obtained by considering the fudge factor where the test statistic is at its turning point or first local minimum below 1.

P-values above 0.5 are of special importance since they correspond to an over fluctuation of events and new physics is assumed to only result in an additional number of events and never a reduced number of events. In this next step the analysis is done again utilizing the same test statistic but restricting it to the interval [0.5,1]. In this manner the fudge factor which yields the most uniform distribution of p-values above 0.5 is calculated. This analysis was again done for the combination of all experimental data as well as 8 TeV and 13 TeV results individually.(5.4)

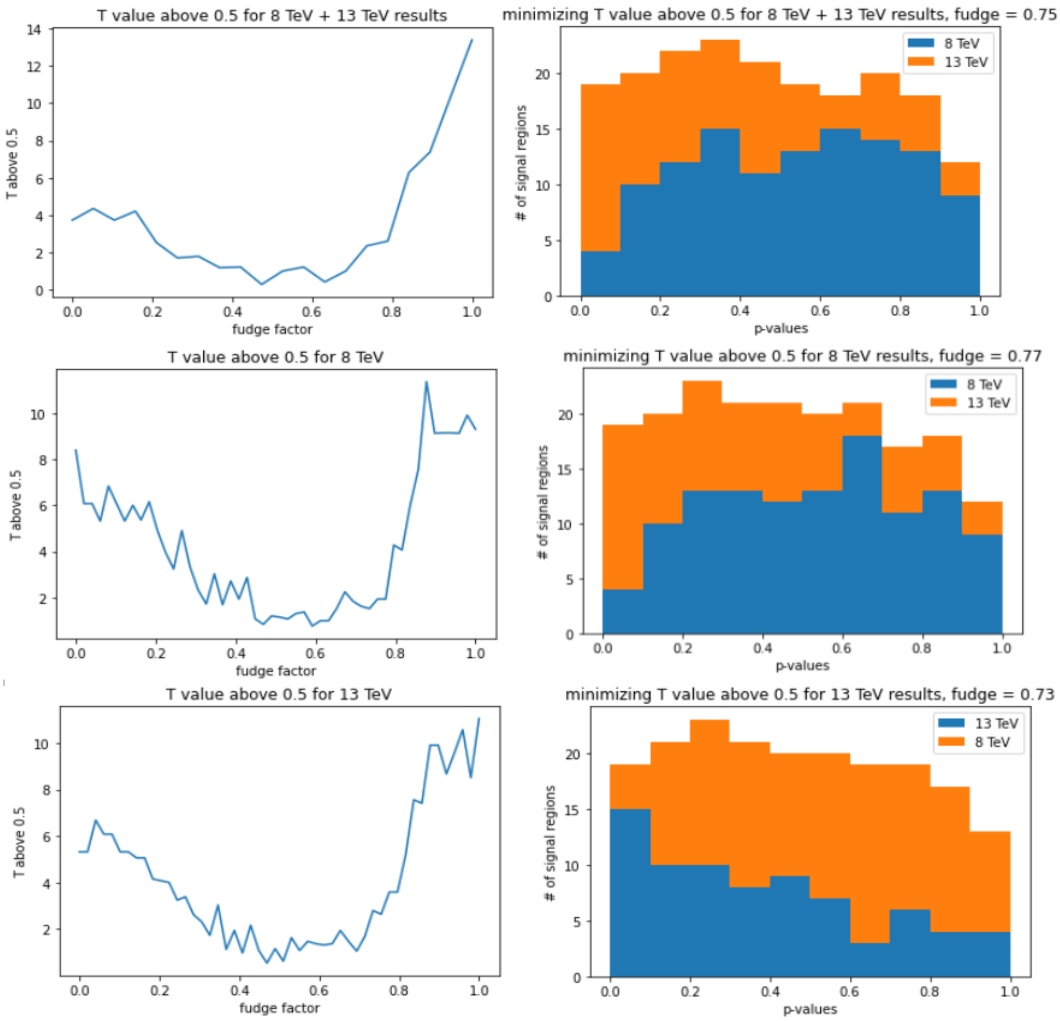

Figure 5.4: Plots of the test statistic T as a function of the fudge factor when only considering the interval [0.5,1] as well as histograms of the p-values at the fudge factor obtained by the same metric as in fig. 5.3

As seen in the previous figures the obtained fudge factor and trends of the test statistic are consistent across all the results, when considering the full dataset as well as 8 TeV and 13 TeV experimental results individually.
These results let us make an approximation on the conservatism of the error estimation in the provided data and it is concluded that these errors are overestimated roughly by an amount of 25-30%.

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