Dark Matter Searches with ATLAS and Fermi

By: Knut Dundas Morå
Supervisor: Heidi Sandaker

June 3, 2013
Thanks

Thanks, Heidi, for always taking time to talk with me, and ask me the questions I needed.
Thanks, Anna, Bjarne, Gerhaldt and Per, for friendly advice and assistance.
Thanks, everyone in the corridor, Alex, Jan, Justas, Maren, Nils, Therese, Thomas, Trygve
and Ørjan, for two fun years
Thanks, Agnethe, Helge, Steffen and Zhuo, for the company and talk
Thanks, Olga, Jan and Torsten, for helping me along.
Abstract

This thesis presents Dark matter inspired searches for supersymmetry with a one-tau analysis at ATLAS, which excludes a region close to that of allowed dark matter densities at $m_0 \sim 400$ GeV, $m_{1/2} \sim 600$ GeV, $\tan \beta = 30$, $A_0 = -1200$ GeV in a "Higgs aware grid". The one tau analysis was among the first groups to constrain regions of this grid at ATLAS.

In addition, this thesis presents a computation of variables and limits in the mSUGRA parameter space, both by astrophysical experiments and other observables. The new Higgs mass and the LHCb measurement of $BR(B_s \to \mu^+ \mu^-)$ impose constraints on large areas of the parameter space. However, some regions of interest are still there; the Higgs-aware grid was a good example. Also, in the region $\tan \beta = 30, A_0 = -2300$ GeV some promise may be found for both astro- and high-energy physics.

Last; This thesis presents an exploration of the Fermi-LAT photon data in support of an ongoing effort to investigate the planned CTAs potential. Last spring, a paper presenting a line feature at 130 GeV [70] in the Fermi-LAT spectrum was published, which has engendered an appropriately cautious response; both in view of the lack, for now, of a second experiment, as well as the importance a discovery would have.
Contents

Preface ......................................................... i
Abstract ....................................................... iii

1 Introduction ............................................. 1

2 Theory ..................................................... 3
  2.1 The Standard Model .................................... 3
    2.1.1 The matter particles .......................... 3
    2.1.2 The three forces ............................. 4
    2.1.3 Gravity ....................................... 5
    2.1.4 The formulation of the Standard Model .... 5
    2.1.5 The Higgs boson .............................. 5
    2.1.6 Computing processes .......................... 6
  2.2 Supersymmetry ....................................... 7
    2.2.1 Problems that SUSY solves ................. 7
    2.2.2 Particles ..................................... 8
  2.3 Computing processes in SUSY ...................... 8
    2.3.1 Dark matter candidates ..................... 9
    2.3.2 supergravity ................................ 9
    2.3.3 Dark Matter Candidates .................... 10
  2.4 Cosmology .......................................... 11
  2.5 Dark Matter ........................................ 13
    2.5.1 Rotation curves of large structures ....... 13
    2.5.2 Gravitational Lensing ........................ 16
    2.5.3 Structure formation in the early universe 18
3 Experiments

3.1 The Fermi Experiment

3.1.1 Rejecting charged particles

3.1.2 Good Time Intervals

3.1.3 Energy Resolution

3.1.4 Angular Resolution

3.1.5 Effective Area and Exposure

3.2 Dark Matter limits

3.3 Dark matter

3.4 The ATLAS experiment

3.4.1 The LHC accelerator

3.4.2 The structure of ATLAS

3.4.2.1 Inner Detector

3.4.2.2 Calorimeters

3.4.2.3 Muon Systems

3.5 Experiments and bounds

3.5.1 LEP

3.5.2 IceCube

3.5.3 XENON100

3.5.4 CTA

3.5.5 LHCb

4 Analyses

4.1 Likelihood analysis of Fermi

4.1.1 The maximum likelihood method

4.1.2 Model of spectrum

4.1.3 Data utilized

4.1.4 Analysis

4.1.5 Limits on Cross-Sections

4.2 Computation of supersymmetric parameters

4.2.1 Program packages used

4.2.1.1 ISAJET

4.2.1.2 DarkSusy

4.2.1.3 FeynHiggs and HiggsBounds
\[ \tan \beta = 30A_0 = -2300 \text{ GeV} \]

5.2.2 \[ \tan \beta = 30A_0 = -2m_0 \] ................................. 60

\section*{Accelerator bounds} ................................................. 62

\section*{Astrophysical bounds} .................................................. 62

\section*{Summary} ................................................................. 63

5.3 Results from ALTAS search ............................................. 67

5.3.1 Observed events ......................................................... 67

5.3.2 Setting a limit ............................................................. 68

\section*{6 Conclusions} .............................................................. 71

\section*{A Computer Programs} .................................................. 80

\section*{A.1 Software Acknowledgments} ..................................... 80

\section*{B ATLAS supporting material} ....................................... 82

\section*{B.1 Signal Samples} ......................................................... 82
List of Figures

2.1 NGC3198 rotation curve ......................................................... 15
2.2 The Bullet Cluster ................................................................. 17

3.1 A Fermi-LAT piece ................................................................. 21
3.2 Integrated livetime ................................................................. 22
3.3 Energy Resolution ................................................................. 23
3.4 Fermi Effective Area ............................................................... 24
3.5 The ATLAS detector ............................................................... 26
3.6 XENON100 90% exclusion from [14]. ..................................... 29

4.1 The Galactic Center ............................................................... 33
4.2 Higgs mass vs top ................................................................. 37
4.3 $\tan \beta = 3, A_0 = 0$ GeV, $\mu > 0$ ........................................ 38
4.4 $\tan \beta = 3 \sigma_{\text{independent}}$ ............................................... 39
4.5 Asimov significance, $H_T$ cut ................................................. 50
4.6 $m_T$ for signal, background and data ..................................... 51
4.7 $p_{T_T}$ for signal, background and data .................................... 51
4.8 $H_T$ for signal, background and data ..................................... 52
4.9 Expected Events ................................................................. 53
4.10 Total cross-section ............................................................. 54
4.11 Uncertainty cross-section .................................................... 54

5.1 The 95% confidence limit for a line signal ............................... 56
5.2 $2(\log \mathcal{L}_{s+b} - \log \mathcal{L}_b)$ for the tested masses. ............... 56
5.3 Best Fit ................................................................. 57
5.4 $\tan \beta = 3$ exclusion ....................................................... 58
5.5 $\tan \beta = 10$ exclusion ....................................................... 59
5.6 $\tan \beta = 40$ exclusion
5.7 $\tan \beta = 3$ exclusion
5.8 $m_H$
5.9 $m_\tau$ and $m_{Neutralino}$
5.10 $B_s \to \mu^+ \mu^-$
5.11 caption
5.12 $\langle \sigma v \rangle_{\gamma \gamma}$
5.13 $\langle \sigma v \rangle$
5.14 $m_\tau$ and $m_{Neutralino}$
5.15 $m_\tau$ and $m_{Neutralino}$
5.16 Exclusion contours for the Higgs aware grid
5.17 The same as Figure 5.16, but with a higher $m_0$ resolution.
5.18 $H_T$
5.19 ATLAS exclusion contour
5.20 exclusion in grid
List of Tables

2.1 The leptons, with masses\[60\] and charges ................................. 4
2.2 The quarks, with masses\[22\] and charges. Note that light quarks are estimates, ......................................................... 4
2.3 caption here .................................................................... 4
2.4 Supersymmetric partners of standard model particles ............... 8
2.5 The balance of energy densities in the current universe ............... 13

4.1 Cut-flow for the kinematic cuts defining the SR after the baseline event selection. All numbers are from MC scaled to an expected data luminosity of \(20.7\text{fb}^{-1}\) with scale factors applied to top, W+jets and Z+jets, except for the final estimate of QCD events. The errors are statistical only. .............. 52
4.2 Number of expected events at \(20.7\text{fb}^{-1}\) that are expected to pass the analysis cuts. .......................................................... 53

5.1 Cut-flow for background, data and some signal points. The expected numbers of events for all standard model backgrounds and for the example of one GMSB and two mSUGRA parameter space points correspond to an integrated luminosity of \(20.7\text{fb}^{-1}\). .............................................................. 67

B.1 List of MC samples for the SUSY signal in the mSUGRA Higgs boson-aware grid. Masses are quoted in GeV. Another 105 samples with \(m_0 > 2000\text{GeV}\) have been generated, but they are far away from the region where the \(\tilde{\tau}\) is the NLSP. .............................................................. 83
B.2 List of nine additional MC samples close to the coannihilation region for the SUSY signal in the mSUGRA Higgs boson-aware grid. Masses are quoted in GeV. .............................................................. 84
1

Introduction

Dark matter is currently in the exiting position of being a mystery that might soon be revealed. Any confirmation would raise the impetus to produce and study the particle in a particle accelerator. Part of my work has therefore been to examine the possibility or degree of overlap between the reach of accelerators and astrophysical dark matter detection experiments.

To relate the two, I have focused on the mSUGRA supersymmetric models. Computing cross-sections and masses provide a glue between the different experiments by relating them all to the same space.

The main effort in my thesis is divided into three parts, all dealing with dark matter

- I have studied data from the Fermi-LAT telescope, that last year reported a line in their photon spectrum to support work done on the planned CTA telescope. If the line turns out to be confirmed by other experiments, this will be of major importance.

- I have computed properties of slices of the mSUGRA parameter space,

- And I participated in an ATLAS search for supersymmetry, in which an mSUGRA slice was among the grids considered, and the limit excluded regions of acceptable relic
density.

In the following text, I will start with a very short introduction to the standard model and supersymmetry, before reviewing some of the evidence for dark matter. After this, I will go through the work I have done, and afterwards the results.
Theory

2.1 The Standard Model

The current understanding of particle physics is gathered in the Standard Model. It has withstood experimental scrutiny for around 30 years, and recently the last particle in the standard model- the Higgs boson- was discovered at CERN[62].

2.1.1 The matter particles

Matter particles are all spin 1/2-particles in the standard model. They are split in two families; the leptons and the quarks. As matter particles, they have an intrinsic angular momentum that will be observed to be $\pm 1/2$, whatever the direction of the measurement. Spin 1/2 particles, fermions, follow Fermi-Dirac statistics; two identical particles cannot have the same quantum numbers. All the particles have an antiparticle- a mirror image with the same mass, but opposite helicity and charges.

The leptons interact with the electroweak forces. There is the electron $e$, muon $\mu$ and tau $\tau$, all of which interact similarly, only with different masses. In addition, each of them has a corresponding neutrino; a light, neutral particle that only interacts with the weak force.
Table 2.1: The leptons, with masses[60] and charges

<table>
<thead>
<tr>
<th>1st gen</th>
<th>2nd gen</th>
<th>3rd gen</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron, $e$</td>
<td>muon, $\mu$</td>
<td>tau, $\tau$</td>
</tr>
<tr>
<td>0.511MeV, +1</td>
<td>105.7MeV, +1</td>
<td>$1.78 \times 10^3$MeV, +1</td>
</tr>
<tr>
<td>$e$ neutrino, $\nu_e$</td>
<td>$\mu$ neutrino, $\nu_\mu$</td>
<td>$\tau$ neutrino, $\nu_\tau$</td>
</tr>
<tr>
<td>$\sim 0$, 0</td>
<td>$\sim 0$, 0</td>
<td>$\sim 0$, 0</td>
</tr>
</tbody>
</table>

Table 2.2: The quarks, with masses[22] and charges. Note that light quarks are estimates,

<table>
<thead>
<tr>
<th>1st gen</th>
<th>2nd gen</th>
<th>3rd gen</th>
</tr>
</thead>
<tbody>
<tr>
<td>up, $u$</td>
<td>charm, $c$</td>
<td>top, $t$</td>
</tr>
<tr>
<td>$2.3^{+0.7}_{-0.5}$ MeV, +2/3</td>
<td>$1.275 \pm 0.025$GeV, +2/3</td>
<td>$173.5 \pm 0.6 \pm 0.8$ GeV, +2/3</td>
</tr>
<tr>
<td>down, $d$</td>
<td>strange, $s$</td>
<td>bottom, $b$</td>
</tr>
<tr>
<td>$2.8^{+0.7}_{-0.3}$ MeV, −1/3</td>
<td>$95 \pm 5$MeV, −1/3</td>
<td>$4.18 \pm 0.03$GeV, −1/3</td>
</tr>
</tbody>
</table>

Quarks

2.1.2 The three forces

In the Standard Model, forces are mediated by particles. The three forces of the standard model are the electromagnetic, weak and strong force. The electromagnetic force couples to electric charge, and is mediated by photons. The Weak force is carried by the $W^\pm$ and $Z$ bosons, and is confined to short ranges due to their large masses[64, p.13]. In the end comes the gluons that interact with color charge, which only quarks and gluons carry.

<table>
<thead>
<tr>
<th>Force Boson</th>
<th>Electromagnetic</th>
<th>Weak</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass[22]</td>
<td>$\gamma$</td>
<td>$Z^0,W^\pm$</td>
<td>$g \times 8$</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>91.1876 GeV, 80.385 GeV,0</td>
<td></td>
</tr>
</tbody>
</table>
2.1.3 Gravity

The fourth force we observe in nature is gravity. No attempts to combine gravity and the other forces in one framework has so far succeeded. The strength of gravity is vastly smaller than the other forces; $G_N = 6.7 \times 10^{-11} \text{ N m}^2 \text{kg}^{-2}$, or $G_N = 6.7 \times 10^{-45} \text{ MeV}^{-2}$, and ignoring it for processes below these massive scales is an excellent approximation.

2.1.4 The formulation of the Standard Model

The Standard model is formulated in terms of field theory, with a Lagrangian that governs the equations of motion of the fields. It turns out that there are operations you can do to the fields which leave the Lagrangian and the equations of motion unchanged. This is termed a symmetry of the Lagrangian, and an example is the freedom to choose a complex phase for a field that is always multiplied with its conjugate. If one further requires that the phase should be able to change as a function of space, derivatives acting on the fields will act on the phase transformation, adding a term to the Lagrangian. It turns out that to balance this out, a vector field is needed that will transform to keep the Lagrangian invariant. Different symmetries lead to different physics. The standard model is built on three symmetries; $U(1)_Y \times SU(2)_L \times SU(3)$. The first is akin to the photon, the $SU(2)_L$ transforms in isospin and acts only on left-handed particles, and $SU(3)$. The number of vector fields needed is related to the symmetry; so a $U(1)$ will lead to one vector boson field $B$, the $SU(3)$ has three: $W^+, W^-, W^0$ and a $SU(3)$ has eight $g$. The $B$ and $W^0$ bosons mix, and the result is a $\gamma$ and the $Z_0$.

2.1.5 The Higgs boson

Simple mass terms for the weak bosons will not be invariant under $SU(2)$ transformations, which only acts on the left handed spinors. Fermion masses are similarly compromised. What is needed is a mass term that will combine left-handed isospin doublets with right-[1]

---

[1] sorry
handed isospin singlets, as well as provide a mass to the heavy vector bosons. The Higgs mechanism provides such an object- it introduces a scalar isospin doublet $\phi$ that interacts with the vector bosons. Adding a potential $V = \mu^2 |\phi|^2 + \lambda |\phi|^4$, with $\mu^2 < 0$ means that the state of lowest energy is when $|\phi| = \sqrt{-\mu^2/(2\lambda)}$. This is the famous Mexican hat potential; as the field may have any complex phase, the minimum lies in the rim of the hat. Perturbations to the field may be either in the phase, which does not change the potential, or it may be a perturbation in the absolute value of the field. When the Higgs field interacts with the vector bosons, the Lagrangian will include a term where the vacuum expectation value of the Higgs field is multiplied by a mass term. From a isospin scalar field and massless vector fields, the Higgs field condenses into the rim of the hat. At the outset, the Higgs field has four degrees of freedom- a complex field up and down. Using the freedom to choose a gauge, it may be seen that the three vector bosons gain a mass, and thereby gaining one degree of freedom each, since massive spin-1 bosons may have a longitudinal spin. In addition, a field corresponding to an oscillation to and fro in $|\phi|$ represents a massive scalar particle- the Higgs boson. The condensation of a Higgs field, where an arbitrary but fixed direction in isospin and phase is chosen is referred to as spontaneous symmetry breaking [55, p.410].

The matter particle masses may be included by Youkawa couplings; $\propto m\psi\theta\psi$. In addition to the mass term, the Higgs particle, the oscillations in $\phi$, will have interactions with the matter particles proportional to their mass. Finally, the Higgs may interact with itself by threes and fours.

On the fourth of June 2012, the ATLAS and CMS experiments announced the discovery of a Higgs boson with mass 126.5 GeV[62]. The current ATLAS combined measurement of the mass is $125.5 \pm 0.2(\text{stat})^{0.5}_{-0.5}(\text{say's})$ GeV[1].

### 2.1.6 Computing processes

When one wishes to calculate the probability of a quantum mechanical process, it turns out to be an infinite sum of powers of the interaction Hamiltonian[55, p.92]. Electromagnetic interactions, for example, are dampened by a factor $\alpha \approx 1/137$ for each power. \footnote{$\lambda$ must be positive lest the lowest energy state should be at $|\phi| = \infty$}
Perturbation theory is then to truncate this infinite series as higher order terms become small. Furthermore, the results of the series may be formulated more intuitively in terms of Feynman diagrams, where lines represent particles, and vertices correspond to the couplings. All possible diagrams with one vertex that incorporates the in- and out-going particles will together represent the first order term in perturbation theory. An intuitive way of putting together the different levels is through Feynman diagrams. The Feynman rules incorporate propagators- they are inserted on all internal lines.

For spin 0, for example, the propagator is simple: \( \frac{i}{q^2 - m^2} \) Where \( q \) is the momentum along the internal line, and \( m \) the mass. For spin 1/2 particles, the propagator is somewhat: \( \frac{i(q+im)}{q^2 - m^2} \).

However, Feynman graphs are only an approximation to nature. There are an almost infinite number of paths from any given input state to the output. The effects of all this activity is observable- the strength of the electromagnetic force changes at very high momentum transfers, as does the other couplings. The couplings converge and almost meet at some hard energy scale, leading to speculation if this could mean that at the very highest energy level, all forces are one and the same.[64, p.99]

### 2.2 Supersymmetry

Supersymmetry is one of the best-studied models of new physics. It introduces operators that will transform a fermion into a boson, and the other way around, doubling the number of particles. No superpartner has been observed, and therefore they must, if they exist be heavy, and supersymmetry somehow broken.

#### 2.2.1 Problems that SUSY solves

Supersymmetry solves some of the less photogenic sides of the standard model:

- Most SUSY models will have a dark matter candidate
• A unification of the forces at the GUT scale is possible due to changes in the running couplings[22, p. 1420]

• The Higgs mass would be affected if there were heavier particles it could couple to. Supersymmetry gives each fermion its bosons and vice versa. In this case, the loops will cancel out, and the Higgs not be [44, p412].

### 2.2.2 Particles

Each standard model particle has a supersymmetric partner, sparticle, with opposite statistics. Superpartners of fermions get an s, while those of the bosons get an -ino.

<table>
<thead>
<tr>
<th>quarks</th>
<th>$u$</th>
<th>$c$</th>
<th>$t$</th>
<th>$d$</th>
<th>$s$</th>
<th>$b$</th>
<th>spin 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>leptons</td>
<td>$e$</td>
<td>$\mu$</td>
<td>$\tau$</td>
<td>$\nu_s$</td>
<td>$\nu_s$</td>
<td>$\nu_s$</td>
<td>spin 1/2</td>
</tr>
<tr>
<td>gauge bosons</td>
<td>$\gamma$, $W$, $Z$</td>
<td>$g$</td>
<td>$h$</td>
<td>$H$</td>
<td>$H$</td>
<td>spin 1</td>
<td></td>
</tr>
<tr>
<td>scalar bosons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gauginos</td>
<td>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$, $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$</td>
<td>$\tilde{g}$</td>
<td>$\tilde{g}$</td>
<td>$\tilde{s}$</td>
<td>$\tilde{s}$</td>
<td>spin 1/2</td>
<td></td>
</tr>
<tr>
<td>sleptons</td>
<td>$\tilde{e}$</td>
<td>$\tilde{\mu}$</td>
<td>$\tilde{\tau}$</td>
<td>$\tilde{\nu}_s$</td>
<td>$\tilde{\nu}_s$</td>
<td>$\tilde{\nu}_s$</td>
<td>spin 0</td>
</tr>
<tr>
<td>squarks</td>
<td>$\tilde{u}$</td>
<td>$\tilde{s}$</td>
<td>$\tilde{t}$</td>
<td>$\tilde{d}$</td>
<td>$\tilde{c}$</td>
<td>$\tilde{b}$</td>
<td>spin 0</td>
</tr>
</tbody>
</table>

Table 2.4: Supersymmetric partners of standard model particles

Where the $\tilde{\chi}_0$ s are the linear combination resulting in mass eigenstates for the superpartners of the $\gamma$ and $Z^3$ as well as the two neutral higgses. The same applies for the $\tilde{\chi}_\pm$ s, partners of the $W^\pm$ and a charged Higgs doublet.

### 2.3 Computing processes in SUSY

One of the virtues of supersymmetry is its ease of

---

or $B$ and $W_3$
2.3.1 Dark matter candidates

It is common to impose R-parity on supersymmetric models. This ensures that supersymmetric particles are pair-produced at accelerators. It is possible to include interaction terms in the supersymmetric Lagrangian that violate R-parity. However, these will make proton decay possible, which is excluded to $1 \times 10^{29}$ y\cite{22, p.1256}\cite{23}. The stability over very long timescale makes for an attractive dark matter candidate. Typical examples are a neutralino or a gravitino. At some point during the Big Bang, all heavier SUSY particles would have fallen out of equilibrium and decayed into the lightest supersymmetric particle. As both these particles are weakly interacting as well, making them excellent candidates, as I shall show later in the case of neutralino.

2.3.2 supergravity

If one demands a local supersymmetry, as one demands a local symmetry in the standard model when deriving the forces from the Lagrangian. In the case of supersymmetry, however, demanding a local supersymmetry will result in a spin-3 graviton

Higgs mass

in the MSSM, at tree level, the Higgs mass is bounded by the Z mass, lower than the bound of 114.4 GeV found at LEP\cite{60, p.10}. Radiative corrections may give considerably higher Higgs masses; as in the case of a large stop mass\cite{22, p.1426}:

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2m^4_t}{8\pi^2m^2_W} \left[ \ln(M_S^2/m^2_t) + \frac{X^2_t}{M_S^2} \left( 1 - \frac{X^2_t}{12M_S^2} \right) \right]$$ (2.1)

Where $M_S = \frac{1}{2}(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2)$ and $X_t \lesssim A_t - \mu\cot\beta$. 

9
2.3.3 Dark Matter Candidates

Multiple proposals have been put forth to explain excessive rotation curves of galaxies. Zwicky\cite{73} proposed extra, dark, matter to fit the rotation of the Coma Cluster. In addition to dark matter, it has been proposed to modify Newton’s \( r^{-2} \)-law of gravity at large distances. The Bullet cluster shows that the effects of dark matter does not simply track the visible matter distribution would seem to disfavor such a model. As detailed in section\cite{2.5.2} MACHOs also seem unable to explain the observations. Neutrinos are dark matter, but their masses would have to be on the order of some eV, far higher than the \( > 0.1 \text{ eV} \) that is suggested by neutrino oscillations\cite{64, p.167}. Furthermore, neutrinos would have been relativistic around decoupling, and would dampen out fluctuations. The Planck experiment finds that the number of relativistic degrees of freedom are \( N_{\text{eff}} = 3.30 \pm 0.27 \), and limits the sum of masses to \( > 0.23 \)\cite{7}.

A candidate for dark matter must be neutral, heavy (cold) enough to form structures around decoupling. It must be stable on cosmological timescales, and cannot interact much with ordinary matter. In addition, the model must be compatible with the observed relic density.

Axions are the result of introducing an additional U(1) symmetry to explain the lack of strong CP violation\cite{60, p.218}. Through non-perturbative interactions with gluons, they gain a small mass\cite{28}. They also couple to two photons, through a triangle diagram with a quark. Limits have been set at \( m_a < 0.01 \text{ eV} \) by considering stars cooling by \( \gamma\gamma \rightarrow \text{axion} \). In addition, to make up the observed dark matter, the axion would have to weigh in excess \( 6 \times 10^{-6} \text{ eV} \)\cite{28}.

Weakly interacting massive particles, WIMPs, also fit the above requirements. As with neutrinos, they will be frozen out as the cross-section drops with temperature, and the mean free path \( 1/ (N < \sigma v > ) \) approaches the size of the universe \( \sim 1/H \);

\[
1/N \langle \sigma v \rangle < 1/H \quad (2.2)
\]
The expected number density $N$ of non-relativistic fermions is $\propto (mT)^{3/2}e^{-m/T}$[64, p.140], and the Hubble constant $\propto T^2/M_{PL}$, giving an equation for freeze-out. It is clear that if the cross-section does not increase with dropping temperature, the WIMP will be frozen out. Assuming a typical weak cross-section of $G_F^2M^2$, one can compute the temperature;

$$(mT)^{3/2}e^{-m/T}G_F^2M^2 = T^2/M_{PL}K \quad (2.3)$$

Where $K$ is a constant of the order 100[64, p.171]. Where the freeze-out temperature is characterized by $P = m/T$. The equation may be solved numerically, and by using Newton's method, I find $P$ ranges from roughly 15 – 40 from $m = 1 – 1000$ GeV Thus, the number density becomes;

$$N \sim \frac{T^2}{M_{PL} \langle \sigma v \rangle} \quad (2.4)$$

At decoupling, or, today stretched by $(1 + z)^{-3}$. The CMB temperature is $\propto 1/(1 + z)$, so the density today at $T_0$ is:

$$N_0 \sim (T_0/T)^3 \frac{T^2}{M_{PL} \langle \sigma v \rangle} \quad (2.5)$$

$$\rho_0 = mN_0 \sim PT_0^3M_{PL} \langle \sigma v \rangle \quad (2.6)$$

$$\rho_0 \sim 6 \times 10^{-31} \text{GeV} \text{ s}^{-1} \langle \sigma v \rangle \quad (2.7)$$

Using $\rho_c$ from section 2.15 and $mv^2/2 = 3T/2$ giving $v \sim 0.3$, one finds that a cross-section of the order of weak interactions will close the universe[64, p.173]:

$$\Omega_{DM} \sim \frac{1 \times 10^{-25} \text{cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle}. \quad (2.8)$$

## 2.4 Cosmology

The study of the structure and history of the universe has led to a pleasing combination of particle physics and astrophysics. Observations are consistent with a universe that starts out very hot- enough to produce any standard model particle in its earliest times. Edwin
Hubble discovered a redshift in distant galaxies that increased linearly with distance [47]. He interpreted this as a Doppler effect, shifting the photon energy:

\[ \frac{E'}{E} = \sqrt{\frac{1 - v}{1 + v}} \sim_{v \ll 1} 1 - v \] (2.9)

\[ H = rv \] (2.10)

Where the Hubble constant relates velocity \( v \) and distance \( r \). \( H = (67.4 \pm 1.4) \text{ km s}^{-1} \text{ Mpc}^{-1} \) [7]. \( H = h 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \) is a common convention. For larger redshifts than Hubble considered, not only Doppler shifts, but gravitational redshifts are relevant [64, p.110]. Therefore, the redshift \( z \) is used:

\[ \frac{E'}{E} = \frac{\lambda}{\lambda'} = 1 + z \] (2.11)

If the Earth is not situated in a special spot in the universe, the explanation for everything moving away from the Earth must be that the universe is expanding uniformly. The ratio of distances at a time \( t \) and now in terms of redshift becomes;

\[ \frac{R(0)}{R(t)} = 1 + z \] (2.12)

and the Hubble constant will give the expansion:

\[ H = \frac{\dot{R}(t)}{R(t)} \] (2.13)

Assuming a homogeneous and isotropic universe, Einstein’s field equations imply:

\[ H^2 = \frac{8\pi G_N}{3} \rho_{\text{tot}} - \frac{k}{R^2} \] (2.14)

Where the energy density \( \rho \), with it’s dependence on \( R \), as well as a curvature term \( k \) determines the evolution of \( H \). The curvature may be 0, 1, −1, denoting a flat (euclidean), closed or open geometry. The matter density that will close the universe today is \( \rho_c = \frac{3}{8\pi G_N} H^2 \). how close one is to the critical density today is expressed as the closure \( \Omega \):

\[ \Omega_i = \frac{\rho_i}{h^2 1.88 \times 10^{-29} \text{ g cm}^{-3}} \] (2.15)

Current experiments suggest the universe is flat. In addition to ordinary matter and
redshifted microwave background, the current understanding of the universe includes
dark matter, that is only detected through its gravity, and dark energy, that causes the
universe to accelerate. The energy densities are tabulated below.

Table 2.5: The balance of energy densities in the current universe

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baryonic matter</td>
<td>$\Omega_b$</td>
<td>0.04906 ± 0.00060$^7$</td>
</tr>
<tr>
<td>Dark matter</td>
<td>$\Omega_{DM}$</td>
<td>0.2667 ± 0.0060$^7$</td>
</tr>
<tr>
<td>Cosmic Microwave Background</td>
<td>$\Omega_{CMB}$</td>
<td>$4.8 \times 10^{-5}^60$</td>
</tr>
<tr>
<td>Dark Energy</td>
<td>$\Omega_\Lambda$</td>
<td>0.685$^{+0.018}_{-0.016}$</td>
</tr>
</tbody>
</table>

As the universe expands, the densities will decrease; the matter and dark matter densities
today go as: $\propto (R_0/R_z)^3 = (1+z)^{-3}$, while radiation will drop as $\propto (R_0/R_z)^4 = (1+z)^{-4}$. The mass of matter is only diluted by an increasing volume, while radiation, while
relativistic particles may be envisioned as having their wavelength stretched as well.

2.5 Dark Matter

The indications that there exists dark matter in the universe is strong, and based on mul-
tiple lines of evidence or indication:

2.5.1 Rotation curves of large structures

The gravitational field $g(r) \equiv F_{\text{grav}}/m$ is governed by the equation (2.16a). By using
Gauss’ theorem, this is equivalent to equation (2.16b), where the left integral is a two-
dimensional closed integral of the inner product of the field and a normal vector $\hat{n}$ to the
surface, while the right side is a three-dimensional integral over the volume bounded by
the surface. Assuming a spherically symmetric distribution, one gets (2.5.1)

\[ \nabla \cdot g(r) = 4\pi \rho(r) \]  
(2.16a)

\[ \iiint g \cdot \hat{n} dA = 4\pi \iiint \rho dV \]  
(2.16b)

\[ g(r) = -\hat{r}G N M_{<r} \frac{r}{r^2} \]  
(2.16c)

The virial is defined as a sum over all particles [40][p.83].

\[ G = \sum_i p_i \cdot r_i \]  
(2.17)

Where each particle has a position \( r_i \), mass \( m_i \) and momentum \( p_i = \dot{r}_i m_i \). Differentiating \( G \), one gets;

\[ \frac{dG}{dt} = \sum_i (\dot{r}_i p_i + r_i \dot{p}_i) \]  
(2.18)

\[ \frac{dG}{dt} = \sum_i \left( 2|p_i|^2/2m + r_i F_i \right) \]  
(2.19)

since \( F = \dot{p} \). Taking the time average, and noting that the first term is the kinetic energy \( T \);

\[ \frac{1}{t} \int_0^t \frac{dG}{dt} = 2T + \sum_i r_i F_i \]  
(2.20)

For a bound system, the virial is finite. Therefore, in the limit \( t \to \infty \), the left hand integral above will tend to 0, giving the result;

\[ T = -\frac{1}{2} \sum_i r_i F_i \]  
(2.21)

Assuming the gravitational force from equation:

\[ T = -\frac{1}{2} \sum_i \frac{G N m_i M_{<r}(r)}{r} \]  
(2.22)

The right hand sum is the potential energy of the sum, and one observes that by measuring the velocity distribution of a collection of orbiting objects, one can deduce the
gravitational potential, and thus the mass.

The distribution of light from spiral galaxies suggests that most of the mass is concentrated in the center. In the limit that all the mass is in the center, the velocity of a circular orbit further out will be:

\[
\frac{mv(r)^2}{2} = \frac{G N M_{\text{center}}}{r} \quad \text{(2.23)}
\]

\[
v(r) = \sqrt{\frac{G N M_{\text{center}}}{r}} \quad \text{(2.24)}
\]

Thus one expects the velocities in the outer disk to drop off as \( r^{-\frac{1}{2}} \).

The Doppler shift of spectral lines measures the velocity along the line of sight. By looking at a system that has its angular momentum perpendicular to the line of sight, such as looking at a disk galaxy edge-on, a rotation curve may be constructed that will reflect the matter distribution of the system.

![Figure 1. Mass models for NGC 3198. At left a “maximum disc” model, at right a “no m = 2” model. Data from Wevers et al. (1986) for the photometry, and Begeman (1989) for the rotation curve. A Hubble constant of 50 km s\(^{-1}\) Mpc\(^{-1}\) is assumed.

\( \Gamma \) is the dimensionless shear rate. This quantity is 1.0 for exactly flat rotation curves, 1.5 for Keplerian curves and 0.5 for a curve rising as the square root of the radius. The other quantity is

\[ X = \kappa^2 R^2 \pi G m \mu \]

As can be seen, the active disc mass, \( \mu \), comes in, as well as number of arms, \( m \). The rotation curve is also represented via the epicyclic frequency, \( \kappa \).

Athanassoula (1984) rediscussed the swing mechanism presented by Toomre (1981), and calculated for various values of \( \Gamma \) the maximum growth factor of the swing amplification as function of \( X \) for 3 typical values of the Toomre parameter \( Q \). In Athanassoula et al. (1987) we use an interpolation method to determine the amplification factor for any value of \( \Gamma \) and \( X \). As a result, we can give mass model work out its consequences for the amplification of \( m=1,2,3,\ldots \) structures, and calculate graphs such as presented in Figure 2. I t c a n b e e a s i l y s e e n from Figure 2 that if we lower the mass-to-light ratio of the disc with a factor 2, the curves for \( m = 2 \) become those in the top panel, and the curves for \( m=4 \) those in the middle panel (since \( \mu \) is what matters).

For NGC 3198, it is clear that the “no m = 2” criterion leads to a disk rotation curve whose maximum velocity is 105 km s\(^{-1}\). This can be compared to the value of 100 ± 19 km s\(^{-1}\) derived by Bottema (1993) from his criterion based on his velocity dispersion work, and also by the maximum value of 93 and 100 km s\(^{-1}\) calculated by Navarro (1998) for his models, which are partly based

Figure 2.1: An example of a Density(above) and rotation curve of the galaxy NGC 3198 from [24], using results from the Palomar-Westbork survey [71] and Hydrogen line observations from Westbork and the Very Large Array [20].

Figure 2.1 shows one such rotation curve, with the contributions expected from the galac-
tic disc, dust clouds and residual attributed to a dark matter halo. It is clear that the observed stars and gas cannot account for the rotation curve.

### 2.5.2 Gravitational Lensing

Light travel in straight lines in the curved space of general relativity. If the light path is parametrised as \( x^i(s) \), where roman indices run from 1 to 3, the equation of motion is\cite{59}[p222]:

\[
\frac{d^2x^i}{ds^2} = -2 \frac{\partial \phi}{\partial x^i} + 2 \frac{\partial \phi}{\partial x^k} \frac{dx^i}{ds} \frac{dx^k}{ds} \tag{2.25}
\]

Where \( \phi \) is a weak gravitational potential. Assuming a glancing trajectory, and a small deflection, \( x = s, y = y_0, z = 0 \). The resulting equation for \( y \) and \( z \) becomes;

\[
\frac{d^2 y}{ds^2} = -2 \frac{\partial \phi}{\partial y} \tag{2.26}
\]

\[
\frac{d^2 z}{ds^2} = -2 \frac{\partial \phi}{\partial z} \tag{2.27}
\]

Where the last term of equation \eqref{2.25} vanishes due to the \( y \) and \( z \) being constant. Inserting the potential \( \phi = -G_N \frac{M}{\sqrt{x^2 + y^2 + z^2}} \), and rotating the path so that \( z = 0 \);

\[
\frac{d^2 y}{ds^2} = -2G_N M \frac{y}{(x^2 + y^2)^{3/2}} \tag{2.28}
\]

\[
\frac{d^2 y}{ds^2} = -4G_N M \frac{y}{y_0} \tag{2.29}
\]

The difference in \( \frac{dy}{dx} = \frac{dy}{ds} \frac{ds}{dx} = \frac{dy}{ds} (x = s) \) before and after the lensing measures the change in angle. Integrating the above equation, one gets;

\[
\Delta \frac{d^2 y}{ds^2} = -\frac{2G_N M}{y_0} \int_{-\infty}^{\infty} \frac{ds}{y_0} \left( (s/y_0)^2 + 1 \right)^{3/2} \tag{2.30}
\]

\[
\Delta \frac{d^2 y}{ds^2} = -\frac{4G_N M}{y_0} \tag{2.31}
\]

The last equation expresses the angular deflection, which, as one would expect is negative; gravitational lenses are convex. Unlike real lenses, it should be noted that the deflection is achromatic. This may be used to discriminate lensed images from other objects.
In both panels are the weak lensing bar indicating 200 kpc at the distance of the cluster. In the bottom panel is a 500 ks Chandra image of the cluster. Shown in green contours represents the amount of distortion due to lensing. The lensing map was compiled from many optical image sets; in addition to Magellan, the ESO/MPG telescope and the Very Large Telescope’ as well as the Hubble space telescope.

Using the distortion of galaxies behind the lens, one may construct an image of the matter distribution that is bending the light. This was famously done with the Bullet cluster[31], where two galaxy clusters have collided and passed through each other. The hot gas can be seen in the X-ray image to the right in figure 2.2. A shock wave from the collision is clearly seen. Clowe et al.[31] report an 8σ offset between the center of mass deduced by lensing and the visible matter derived by X-ray and optical observations. In contrast to e.g. rotation curves, this observation demonstrates that dark matter may be separated from visible matter.

In addition to stars and clouds of gas, we know that planets, asteroids and even black holes contribute to the mass of a galaxy. In the context of dark matter, they are termed MACHOs; Massive Compact Halo objects. Microlensing is a technique to measure the density of MACHOs. A massive object close to the line between the earth and a light source will bend more light to the earth. Since the amplification is strongly dependent

---

4It is often stated that Newtonian gravity predicts half the deflection that general relativity does. However, this supposes that one treats photons as particles with a gravitating mass equal to the energy, and that it obeys Newton’s law $F = ma$. Maxwell’s laws were the accepted description of light waves before Einstein started his work. They do not include any interaction with gravity.
on the distance between the lensing object and the line of sight, this results in a time-
dependent amplification of the source. As noted above, the achromatic nature of the
amplification is used to distinguish this from other variable objects. The simple case of a
uniform field of matter objects between the Earth and source gives the optical depth, or
the probability of scattering given by the density of lensing material $\rho$ and source distance
$D_{\text{source}}$:

$$P_{\text{lensing}} = \frac{2}{3} \pi G N D_{\text{source}}^2 \rho$$

This probability is very low for galactic densities, and the OGLE experiment report
$P_{\text{lensing}} = (1.30 \pm 1.01) \times 10^7$ and compute that 2% of the galactic halo is constituted by
MACHOs. Thus, these objects cannot explain the observed rotation curves.

### 2.5.3 Structure formation in the early universe

In the very early universe, the temperature was high enough that even heavy particles
were relativistic. As the universe expands in size $R$ and cools, the radiation density drops
as $\rho \propto R^{-4}$, while matter drops as $R^{-3}$ [64, p.119]. At some point, the matter density will
dominate over radiation. As the temperature decreased further, nuclei and electrons com-
bined into neutral atoms, decoupling matter and radiation. After this point, a fluctuation
in matter density would not be opposed by radiation, and structures may form. The
photons survive, redshifted to the cosmic microwave background. The ratio of baryon
and photon energy density is equal at a redshift of $z \approx 900$. If matter started to clump
this late, galaxies would not have had time to form [64, p.139, p.213]. If one includes dark
matter, the universe is dominated by the matter density earlier, at redshifts of $\approx 3000$.
Dark matter does not interact with photons, and so the clumping of dark matter would
not be opposed by the radiation pressure that affects baryonic matter. If dark matter has
a significant mass compared to the This means that at the last scattering, the large scale
structures of the galaxy have already formed their dark matter skeleton, upon which or-
dinary matter will clump.

The cosmic microwave background is not uniform. Small anisotropies provide a picture
of the properties of density waves that oscillated in the plasma before the last scattering.
By fitting to the correlation spectrum of the CMB, the Planck satellite has measured the
cold dark matter density to be $\Omega_c h^2 = 0.1196 \pm 0.0031$ [7]. In comparison, the best fit baryonic
matter density is $\Omega_m h^2 0.1196 \pm 0.0031$. 
3 Experiments

3.1 The Fermi Experiment

The Fermi Large Area Telescope (LAT) is a satellite-borne gamma ray telescope, capable of imaging the sky from 20 to 300 GeV. At these energies, photons will pair-convert to $e^+ e^-$ pairs as it interacts with matter. It reconstructs the photon direction using a tracker made of 18 layers of silicon strip detectors and tungsten converter material. After the tracker, CsI(Tl) crystal calorimeters measure the energy.

3.1.1 Rejecting charged particles

The LAT is surrounded by an anti-coincidence detector, the ACD. Plastic scintillator plates detect charged particles impinging on the instrument. The plates are segmented, so that charged primary particles may be distinguished from secondaries[12]. An estimator, $P_{\text{all}}$ represents the probability of an accepted event being a real photon. For the class of photons, $P_{\text{all}}$ is required to exceed a curve giving a $> 2\%$ chance of a fake photon at $> 0.9$ GeV, and $> 1\%$ at $> 2.4$ GeV[6][58].
TKR front section
TKR back section
CAL
12 × 3% $X_0$
4 × 18% $X_0$
2 × no W

Figure 3.1: Fermi schematic
Schematic of one of 16 towers of the LAT tracker and calorimeter. The ACD is laid outside them. Taken from [6]

3.1.2 Good Time Intervals

As the LAT orbits, the times it has spent with a particular spot of the sky in its field of view is summed up to compute the total livetime. The Fermi Science Tools $gtnktm$ takes the spacecraft file that the Fermi collaboration provides. The spacecraft file contains the pointing history of the satellite, as well as information of all downtime, such as when the craft passes the South Atlantic Magnetic Anomaly[12]. The result is a Healpix[43] grid, as illustrated in figure 3.2.

Energy Resolution

The energy resolution of the LAT is defined in terms of 68% containment. The resolution degrades at very high or low energies, as the photons either do not deposit enough energy in the tracker, or the calorimeter does not contain the shower[6]. The energy dispersion is not used in the standard Fermi likelihood tools. A plot of the energy dispersion is included below:
Figure 3.2: Integrated lifetimes in seconds, for the fourth of April 2008 to the 22nd of March, 2013. The grid is celestial coordinates, while the map is in galactic.

Angular Resolution

Multiple scattering degrades the Fermi angular resolution at low energies, while the high-energy photons should be limited by the segmentation in the tracker[6]. However, the simulation may have underestimated the error by a factor of 2, and a conservative limiting resolution is about 0.2° above 20 GeV[5].

Effective Area and Exposure

The effective area for the P7SOURCE photons is included with the Fermi Science Tools[1]. It is given as a function of incident angle on the spacecraft, and the log of the energy.

1 http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
When looking for dark matter signals in gamma-ray maps that cover the whole sky, it is critical to choose a target region which maximizes the corresponding signal-to-noise ratio $S/N$. The two regions that we found giving a very good $S/N$ for decaying dark matter ('halo region') or annihilating dark matter ('center region') are summarized in Table 1. Although optimized for the NFW profile, they also yield good $S/N$ for the Einasto and isothermal profiles.

Since the selection procedure leaves us with a large number of $1.3 \times 10^6 (5 \times 10^5)$ events above 1 GeV for the halo (center) region, we perform a binned analysis of the data. To this end, we distribute the events into 200 logarithmically equally spaced energy bins per decade, and sum over the angles. This gives a sequence of count numbers $c_i \in \mathbb{N}$, which is illustrated in the left panel of Fig. 1 for both target regions. Note that we do not perform a point source subtraction in this work.

The spectral feature produced by a gamma-ray line can be inferred from the Fermi LAT instrument response function (IRF). Its most recent version, 'Pass6 version 3', was determined using Monte Carlo generated samples of photon events between 18 MeV and 562 GeV, and includes effects measured in-flight, see Refs. [78, 79]. It contains the point-spread-function (PSF), as well as the energy dispersion $D(E, E_\gamma)$ which describes the distribution of the reconstructed energies $E$ as a function of the physical photon energy $E_\gamma$.

In order to integrate out the implicit dependence of the energy dispersion on the event impact angle with respect to the detector axis, $D(E, E_\gamma)$ is averaged over this impact angle weighted by its distribution in our data sample. The resulting full width at half maximum (FWHM) of the energy dispersion is shown in the right panel of Fig. 1, where the 68%

Two different responses are given, according to if the photon pair-converted in the first 12 layers (front), or if it converted in the four thicker layers (back).

The exposure is computed to take the pointing history of Fermi into account; by integrating the effective area given the line of sight $\hat{p}$, and analysis cuts over the observation period:

$$E(E, \hat{p}) = \int A_{\text{eff}}(E, \hat{v}(\hat{p}, t),)$$ (3.1)

Where $\hat{v}(p, t)$ is the line of sight in spacecraft coordinates. The angular resolution is taken into account as well in the Science tools, and results in a diffuse edge to the selected region at lower energies, where some photons originating in the selected region will not be including, and some from the outside will leak in. With larger selected regions, and a smaller uncertainty at higher energies, the exposure becomes sharper.
3.2 Dark Matter limits

Fermi-LAT has set limits on dark matter; both on the $\langle \sigma v \rangle_{\gamma\gamma}$ from line searches as above [5], and the total cross-section[4] The latter limits are set assuming that the annihilation goes to a specific pair of standard model particles, so when I read it off I must take care.

3.3 Dark matter

Recently, an apparent signal has been identified in the Fermi data[70]. Using a region optimized for dark matter detection, he found a locally significant result of $4.6\sigma$ at 130 GeV. Astrophysical sources will generally not have sharp peaks, so this would be an indication that the feature may be from dark matter. However, a line signal is seen when the LAT is
pointing towards the edge of the earth, which would point to a systematic effect\[8\]. It is not very reasonable, however to expect Fermi-Lat to be able to resolve this on their own.

Hess

3.4 The ATLAS experiment

The ATLAS (A Toroidal LHC ApparatuS) detector is one of two multipurpose-detectors at the Large Hadron Collider at CERN.

3.4.1 The LHC accelerator

The LHC is a proton-proton accelerator, 27 km in diameter, designed to accelerate the particles up to 7 TeV. In 2013, the LHC was running at beam energies of 4 TeV, and delivered luminosities of around $6 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$\[54\] to ATLAS.

The maximum center-of mass energy was 8 TeV, however, the energy of the protons must be distributed among the valence quarks, as well as among the sea of virtual gluons and quarks that make up the bulk of the proton rest mass. Therefore, the center of mass of a collision will be boosted with respect to the detector. Therefore, the total longitudinal momentum cannot be measured. The transverse momentum of the collision products, should, on the other hand balance out. In addition to the usual spherical coordinates with $z$ along the beam axis, the pseudorapidity $\eta = -\ln \tan(\theta/2)$, or rapidity $y = 1/2 \ln[(E + p_z)/(E - p_z)]$ in the case of massive particles. In the limit, rapidity approaches pseudorapidity at the limit $m \to 0$ In the case that a particle is boosted along the beam axis, differences in rapidity will be invariant, and so differences in rapidity will be stable despite the unknown longitudinal boost.
### 3.4.2 The structure of ATLAS

ATLAS is 44 m long, and 25 m tall. Two magnetic fields bend charged particles; a 2 T field in the $\hat{z}$ direction, produced by a solenoid 2.5 m in diameter, as well as a vast outer set of magnets that sets up an $\approx 0.5$ T toroidal field in the outer detector [25].

![The ATLAS detector](image)

Figure 3.5: The ATLAS detector. Starting from the middle, the inner detector in blue is contained in the transition radiation tracker in purple. The electromagnetic calorimeters in gray, and hadronic in dark blue follow after the thin magnet. Enveloping it all, the muon plates surround the detector, with one of the eight toroidal magnet visible.

**Inner Detector**

The ATLAS inner detector consists of a vertex detector, made from pixel detectors, as well as silicon microstrips. Outside these two detectors is a transition radiation tracker, consisting of gas-filled tubes that add to the resolving power of the detector. The $\eta$ coverage is up to $\pm 2.5$, which also is the $\eta$ we will cut on in the analysis to be certain of having the
tracker.

**Calorimeters**

The ATLAS calorimeters are sampling calorimeters, with lead absorbers and argon gas in the electromagnetic calorimeters, followed by steel and scintillator in the hadronic calorimeters [25].

**Muon Systems**

The bulk of the detector volume is made up of the muon spectrometer; made up of a 25 times 10 meter toroidal magnet, combined with muon detectors allowing a determination of the muon as it escapes the detector.

### 3.5 Experiments and bounds

In this section, I will write a small note on each of the limits that I use further on.

#### 3.5.1 LEP

The Large Electron-Positron collider searched for supersymmetry, and produced 95% limits for the mass of supersymmetric particles. Charginos were excluded up to 103.5 GeV, given that the difference in mass between $\tilde{\chi}^\pm$ and $\tilde{\chi}_1^0$ is greater than 3 GeV[52].

The stau mass limit ranges from 87 GeV to 93 GeV[53].
3.5.2 IceCube

The IceCube detector is a neutrino telescope that detects Cherenkov light of muons resulting from neutrino interactions. The sun may capture dark matter if it interacts weakly with ordinary matter, and the captured dark matter may coannihilate. Over sufficient time, an equilibrium will be reached, and the number of dark matter particles annihilating will be equal to the number captured. Searching for excess neutrino fluxes from the sun, possibly arising from dark matter coannihilation may then be directly related to the dark matter capture, that mainly depends on the spin-dependent WIMP-nucleon cross section. The IceCube experiment reports 90% limits down to $1 \times 10^{-39}$ cm$^2$, depending on the WIMP mass [3].

3.5.3 XENON100

The XENON100 experiment searches for dark matter in the recoil of very pure xenon. The collaboration gives 90% limits that reaches $1 \times 10^{-44}$ cm$^2$ at $m_{WIMP} \sim 40$ GeV [14]. The limit, in addition to results from some previous direct detection experiments are plotted in Figure 3.6. XENON100 robustly excludes the favored regions of the experiments that report one.

3.5.4 CTA

The Cherenkov Telescope Array is a planned array of telescopes of different sizes, that together will provide improved coverage of the energy range; A handful of big, sensitive telescopes for low energies, as well as a number of small telescopes to cope with the big showers at high energy.[21]
3.5.5 LHCb

The rare decay $B_s \rightarrow \mu^-\mu^+$ has been observed at LHCb. They measure a branching ratio $3.2^{+1.5}_{-1.2} \times 10^{-9}$. To be within one standard deviation, then, would mean $BR_{1\sigma} < 4.7 \times 10^{-9}$ is the upper limit.
4

Analyses

4.1 Likelihood analysis of Fermi

One of the most convincing signatures of dark matter would be a sharp peak in an otherwise continuous photon spectrum resulting from the annihilation of two dark matter particles. The discovery of a line in the Fermi data around 130 GeV by Weniger [70] has caused great interest in this signature. The local significance of the line was 4.6σ. The discovery of a similar line feature when observing the edge of the Earth, and the ambiguous nature of the time evolution of the significance strengthens the imperative to reproduce the result at another experiment. To support an exploration of the sensitivity of the planned CTA Cherenkov Telescope [26], I have adapted the software used in the analysis to perform a simple maximum likelihood search for a line in the spectrum using the publicly available photon data from the Fermi experiment.

4.1.1 The maximum likelihood method

To estimate parameters of a distribution, the maximum likelihood method is used. As the name suggests; the method searches for the probability distribution that would make it most probable to get the observed data. As with any fit method, the result will be
constrained by the function you are fitting. For a fit probability density function \(f(x, \theta)\), where \(x\) is a vector of the measured properties of one data point, and the \(\theta\)\(s\) are the parameters being fitted. Assuming that the individual measurements are not correlated, the likelihood \(\mathcal{L}\) is the product of the individual probability densities:

\[
\mathcal{L}(\theta) = \prod f(x_i, \theta)
\]  

(4.1)

For an easier computation, the logarithm of the likelihood is the quantity one actually maximizes:

\[
\log \mathcal{L}(\theta) = \sum \log (f(x_i, \theta))
\]  

(4.2)

The ratio between the maximum log likelihood given the signal and null hypothesis will tend to a \(\chi^2\)-distribution as the number of data points go to infinity[69]:

\[
2(\log(\mathcal{L}) \log(\mathcal{L}_0)) = 2 \ln \left[ \frac{\max_{\theta \in \Theta} \prod f(x_i, \theta)}{\max_{\theta \in \Theta_0} \prod f(x_i, \theta)} \right] \sim \chi^2(\nu)
\]  

(4.3)

Where the number of degrees of freedom, \(\nu\), is the difference in degrees of freedom in the null hypothesis and signal case. The \(\chi^2\)-distribution may then be used to set limits. For example, a 95% confidence interval is the region where \(\log \mathcal{L}(\theta)\) is smaller than \(\max \log \mathcal{L}(\theta_0) + \frac{1}{2} \chi^2(\nu)_{.95}\). For one degree of freedom, the critical value is \(\chi^2(1)_{.95} = 3.841\).

### 4.1.2 Model of spectrum

The fit function used to model the flux is the sum of a power-law spectrum, representing the usual background of the galactic center[29], and a Gaussian distribution with the width of the detector resolution representing a line spectrum:

\[
\Phi_{\text{line}}(E, m) = \Phi_{0\text{line}} e^{-\frac{(E - m)^2}{2 \sigma^2_E}}
\]  

(4.4a)

\[
\Phi_{\text{background}}(E, \Gamma) = \Phi_{0\text{background}} \left(\frac{E}{1\text{TeV}}\right)^{-\Gamma}
\]  

(4.4b)
The number of photons hitting an area is $n_\gamma(E) = \Phi(E) \cdot A_{eff}(E)$ Both formulas are normalized over the energy range being fitted, and added so that the line spectrum constitutes a fraction $\alpha$ of the total probability density.

$$f_i(E, m, \Gamma, \sigma_E) = \Phi_i \left( \int_{E_{\text{min}}}^{E_{\text{max}}} \Phi_i(E, m, \gamma, \sigma) dE \right)^{-1}$$

(4.5a)

$$f(E, m, \Gamma, \sigma_E, \alpha) = \alpha f_{\text{line}}(E, m, \sigma_E) + (1 - \alpha) f_{\text{background}}(E, \Gamma)$$

(4.5b)

### 4.1.3 Data utilized

The photons used in the analysis were taken in a 20° radius around the galactic center, located at 266.417°, −29.007° in celestial coordinates. This corresponds to the center region of [5] The time period was from the fourth of October 2008 until the eight of May 2013. The photon energy is chosen between 100 MeV and 300 GeV. The variability in effective area at energies below 100 MeV leads to the cut at this energy[34].

Using the Fermi Science Tools, I impose standard quality cuts on the lists retrieved from the Fermi photon database[1]

- Photons must meet the P7SOURCE_V6 quality criteria, as recommended for galactic point and diffuse analyses[34].
- DATA_QUAL==1, LAT_CONFIG==1 excludes periods of bad data.
- The zenith angle must be less than 100°, to avoid gamma rays from the Earth at 113°.
- Times when Fermi was pointed at a specific source is suppressed by requiring the rock angle < 52.

After using gtselct to cut on these qualities, gtmktime restricts the photons to those occurring in Good Time Intervals, when the instrument was running smoothly, as well

Figure 4.1: The Galactic Center as imaged by Fermi, in celestial coordinates. The image is weighted by energy, and on a logarithmic scale.

as requiring the instrument to have the region of interest in its field of view[30]. The resulting photon file is translated from .fits to .root and imported into the analysis program using pyfits. The gtltcube computes the integrated livetime for the selected region, and gtexpmap computes the exposure map in the region of interest as a function of energy.

4.1.4 Analysis

The analysis is performed using the TMinuit[10] implementation of the Minuit[48] optimization algorithms. The likelihood function of the photon collection is fitted to the power law, assuming no signal. The fit is performed in a window that is six times the Fermi energy resolution up and down from a fixed energy. Using the fitted background
power, the signal fraction is unfrozen, and a bisection search[2] performed to identify the 95% limit corresponding to a gap in the log likelihood of 3.841.

The search is repeated over the range of masses to probe. For easier comparison with [5], I probe 20 to 200 GeV in 10 GeV increments, as well as 7, 10 and 15 GeV.

When the 95% limit on signal fraction in the window is computed, this correspond to 

\[ n_{\gamma\gamma95\%} = n_{\text{window}} \alpha_{95\%} \]

where \( n_{\text{window}} \) is the number of photons in the mass window.

To translate the limit on excess photons into a cross-section, it is necessary to consider the amount of dark matter you expect to look at.

### 4.1.5 Limits on Cross-Sections

The flux of photons over the selected region of interest is approximated by \( \Phi = n/\bar{\varepsilon} \).

The variation in exposure over the region of interest RMS(\( \varepsilon \)) is below 10% above 1 GeV. Approaching the problem from the other direction; the expected flux is:

\[
\Phi = \frac{\langle \rangle}{2\pi m^2_\chi} \int_{\Delta\Omega} \int_{\text{LOS}} \rho^2(r) ds
\]

Where the \( s \) integral runs over the line of sight, and \( r \) is the distance between the volume element and the galactic center. In the case of the Milky Way, the integral runs over \( 0 < s < 150 \text{ kpc} \) and galactic latitude and longitude from \( 0^\circ \) to \( 20^\circ \).

### The Dark Matter Distribution

The density distribution of dark matter will affect the computed limit. Many distributions have been proposed to fit the observed rotation curves; in this analysis the Einasto distribution is used[38]:

\[
\rho(r) = \rho_s \exp \left( -\frac{r}{r_s} \right) - 1 \right)
\]

---

2I.e. divide the area in two, assume the function is monotonic and go to the half where it is. Repeat.
With $\alpha = 0.17$ and $r_s = 20$ kpc. The density is normalized by requiring a density at the sun $r = r_{\text{sun}}$ of 0.4 GeV cm$^{-3}$.

### 4.2 Computation of supersymmetric parameters

#### 4.2.1 Program packages used

**ISAJET**

The ISAJET program package contains ISASUSY routines to compute the masses and decay modes given the mSUGRA parameters at the unification scale:

- the sfermion mass $m_0$,
- the gaugino mass $m_{1/2}$,
- the trilinear coupling $A_0$,
- the Higgs vacuum expectation value $\tan \beta$,
- and Higgsino mass sign $\text{sgn} \mu$.

ISASUSY takes these parameters, as well as the top mass, and computes the renormalization group equations. Gauge couplings, Yukawa couplings and soft breaking terms are computed to two loops.

In addition to the supersymmetric spectrum, the IsaBSMM routine computes the branching fraction of the flavor changing process $BF(B_s \rightarrow \mu^+ \mu^-)$. The $BF$ is strongly dependent of $\tan \beta$, [63, p.91].

The LHCb experiment has measured the branching fraction of $B_s \rightarrow \mu^+ \mu^-$ to $3.2_{-1.2}^{+1.5} \times 10^{-9}$ [2].
DarkSusy

The DarkSusy [41] package computes the properties of neutralino dark matter in the MSSM. It reads the .slha mass spectrum from IsaJet to

Since R-parity is assumed to hold, as detailed in section ??, all supersymmetric particles will decay into the lightest supersymmetric particle. Therefore, to compute the number of stable relics, it suffices to sum up the number of all supersymmetric particles. After the heavier supersymmetric particles have decayed, the relic density $n$ will evolve with the expansion of the universe, scattering off of other particles. In addition, DarkSusy computes thermally averaged cross-sections for LSP-LSP annihilation $<\sigma v>$. The LSP-nucleon cross sections are computed both in spin-dependent and independent versions, to be compared with limits from direct detection.

Lastly, DarkSusy computes the decay $b \rightarrow s\gamma$, which, like $B_s \rightarrow \mu^+\mu^-$ may be enhanced by new decay diagrams in SUSY[42]. DarkSusy implements a formula due to Misiak et al.[57], and constrains it within $2.71 \times 10^{-4} \geq BR[B \rightarrow X_s\gamma] \geq 4.39 \times 10^{-4}$[13].

FeynHiggs and HiggsBounds

In the light of the recent Higgs discovery, it is imperative to include Higgs constraints in SUSY. FeynHiggs provides a dedicated program package to compute the Higgs mass, as well as other properties[39, 35, 46, 45]. This package is compiled together with HiggsBounds, which receives the results from FeynHiggs, and flags models that are excluded at 95%, and prints the Higgs mass. The version used is HiggsBounds 3.8.0 and FeynHiggs 2.9.2. HiggsBounds 3.8.0 includes results from ATLAS, CMS and Fermilab up to 2012[15].

\[^3\text{The manual contains an exhaustive list}\]

36
4.2.2 Errors

top mass

**ISAJET** takes the top mass as input. Some supersymmetric parameters show a strong dependence on the tau mass. The Higgs mass is strongly affected:

![Graphs showing Higgs masses for two top masses](image)

(a) $m_t = 172.5$ GeV  
(b) $m_t = 174.5$ GeV

**Figure 4.2**: Higgs masses for the Higgs-aware grid, for two top masses $m_{t\pm} = m_t \pm \sigma_{m_t}$. The $m_{top}$ dependence mentioned in section 2.3.2 is clear.

**Higgs masses**

The Higgs mass computed by FeynHiggs

4.2.3 Running

I use a python steering script to call Isajet 7.82, DarkSusy 5.0.5 and FeynHiggs 2.9.2 +HiggsBounds 3.8.0 in sequence. The .slha file computed by Isajet is input to the other program packages unless a severe error, such as a charged lightest supersymmetric particle or other theoretical inconsistency is reported from Isajet.
As far as possible, I have attempted to modify the individual program packages into black boxes that may be called by command line arguments without any interaction. Calling these boxes for each run eliminates race conditions between the programs that depend on input from each other, as well as a significantly more robust if one point should crash.

Each program outputs their parameters to a temporary text file, all of which are collated into a .root NTuple for easy access.

To check the computations, I compare my results to Profumo[66]. The paper examines grids in $m_0, m_{1/2}$. These correspond to the sparticle masses at unification, and their masses at the weak scale will be roughly proportional to $m_0$ and $m_{1/2}$. An example is the chargino limit at low $m_{1/2}$ due to imposing the LEP chargino limit. A comparison is included in figure 4.3. In this, and all subsequent limit plots, accelerator constraints will be colored red, while astrophysical constraints will be in blue. Allowed relic densities are plotted in green.

![Figure 4.3: mSUGRA grids at $\tan \beta = 3, A_0 = 0$ GeV, $\mu > 0$](image)

(a) Result from Profumo[66]  (b) My result- including XENON100 exclusion

Figure 4.3: mSUGRA grids at $\tan \beta = 3, A_0 = 0$ GeV, $\mu > 0$ Note that: -I have not plotted the Tevatron or LHC results, since I am checking my computations, not reproducing every line. -The XENON100 experiment has improved their exclusion greatly since Profumo's paper was first written. -and, the relic density plotted on the right agrees with other plots from the paper.
Limits that depend on multiple parameters are included as graphs where points are excluded if they fall above the interpolated line. An example is the spin-independent cross-section for WIMP-nucleon scattering in Figure 4.4.

![Graph showing the spin-independent cross section as function of neutralino mass for mSUGRA tanβ = 3.](image)

Figure 4.4: The spin-independent cross section as function of neutralino mass for mSUGRA tanβ = 3

These exclusion limits are read off from text files which in turn were read off from the cited reference.

### 4.3 A one-tau search for supersymmetry with ATLAS

A search for supersymmetry with hadronically decaying taus was performed with the ATLAS detector\textsuperscript{4}. A mSUGRA model was among the models considered. The analysis was able to exclude regions close to the coannihilation region. This is where where the

\textsuperscript{4}For this analysis, I worked together with others at the particle physics group at the University of Bergen. I will endeavor to talk of the one-τ analysis when I was not chiefly responsible for the work, and use the first person otherwise. Even in the case that I was responsible for an aspect of the analysis, however, I enjoyed help and advice of the others.
stau approaches the neutralino mass, allowing coannihilation in the early universe, and therefore a relic density compatible with measurements.

### 4.3.1 Definitions

Kinematic variables used in the analysis are: [16]. Note that the definitions of $H_T$ in particular was defined differently for the concurrent $2 - \tau$ analysis.

- $\eta$ as defined in section 3.4.1
- $\Delta R = \sqrt{\Delta \phi \Delta \eta}$, the separation between two objects in azimuthal angle and pseudorapidity,
- The transverse scalar sum: $H_T = \sum p_T^{\tau > 20 \text{GeV}} + \sum p_T^{\text{jet} > 30 \text{GeV}}$
- The effective mass: $m_{\text{eff}} = H_T + E_T$
- The smallest azimuthal separation $\Delta \phi_{\text{min}}$
- The transverse mass of the candidate tau and the $E_T$: $m_T = \sqrt{m_{\tau}^2 + 2 m_{\tau} E_T \cdot (1 - \cos \Delta \phi (\tau, E_T))}$

### Missing Transverse Energy

A common feature of searches for R-parity conserving SUSY is a stable Lightest Superparticle. In many SUSY models, the LSP is a candidate for dark matter, and so will not interact strongly with matter. Therefore, the typical search for supersymmetry will use the $E_T$ to select events. The missing energy computation used is MET_Egamma10noTau, which consists of jets $> 20 \text{GeV}$, as well as clusters that have not been assigned to a physics object. Jets are calibrated by their energy, and corrections due to other physics objects are applied [16].
Objects

Throughout the analysis, reconstructed physics objects using SUSYTools 00-02-05 were used. The jets, electrons and muons are subjected to $\eta$ and $p_T$ cuts. Other cuts for each objects are also imposed, such as the distribution of energy deposits for the jets, a neural network to identify $b$-jets, and

If two objects overlap, i.e are separated by $\Delta R > 0.2$, this may be one particle or jet that is reconstructed by multiple object chains. If this is the case[16];

- Taus are discarded if they overlap with an $e$ or $\mu$.
- Jets are discarded if they overlap with an $e$ or $\tau$.
- Muons or electrons are rejected when they overlap with jets with a bigger $\Delta R = 0.4$

The tau decays into a $W$ and a $\nu_\tau$. The neutrino escapes the detector, adding to the $E_T$, while the $W$ may produce another neutrino and an electron or muon. Alternatively, the $W$ may produce a quark pair. The one-tau analysis is focused on the hadronic decay of the tau. Thus one avoids one of the neutralinos that would otherwise have been produced by the $W$. The $\tau$ mass is 1776.8 MeV, which allows it to decay into hadrons, such as pions at $\sim 139$ GeV[22] unlike the lighter leptons. Typical decays are to one or three light mesons$^5$. Therefore, tau jets are typically narrow, and a boosted decision tree is used to discriminate the shape of a $\tau$-jet that is seeded from a calorimeter cluster, with the candidate to have a total charge of $\pm 1$.

4.3.2 Backgrounds

The main backgrounds of the analysis are processes that will produce a significant missing energy and a true or fake $\tau$ lepton. A $W$-boson decaying to a tau will give a signal-like signature, while $Z$ production giving fake taus may also contribute.

$^5$π and $K$, e.g. $\pi^+\pi^-\pi^-$[22]
To estimate the expected backgrounds, simulated events using the atlasfull simulation are compared with data in control regions that are selected away from the signal region. From there, scaling factors are obtained to normalize the different contributions. The $W$, $t$ and $Z$ backgrounds are split according to whether they have a true or fake tau, as the relative contribution may change between control and signal regions\cite{16}. The estimate of the background in the signal region is then computed by passing the background Monte Carlo samples through the signal cut chain, and weighting the events with the scaling factor. In effect, one is using the shape of the simulated data while normalizing it to the observed distributions.

$W$, $Z$ and top

None of the control regions used are completely pure. What you count is the amount of data in each control region, and the amount of each kind of background Monte Carlo that pass your control region cuts.

The result is a matrix that may be solved for the scaling factors given the amount of data and Monte Carlo in the control region. The one tau analysis performs this matrix method on four classes of background:

- $W$ bosons with a true reconstructed tau.
- $W$ and $Z$ bosons with a fake reconstructed tau.
- top with a true reconstructed tau
- top with a fake reconstructed tau

The $Z$ and $W$ fakes were seen to be present in similar levels in the $W$ fake control region, and since the cuts precluded a comparison with $Z \rightarrow \mu\mu$, it was settled to use this scale factor, which the one tau analysis validated at less stringent cuts\cite{16}.
The results are reproduced in equation \[4.8\]:

\[
\begin{pmatrix}
\omega_{W/Z}^{\text{true}} \\
\omega_{W/Z}^{\text{fake}} \\
\omega_{\text{top}}^{\text{true}} \\
\omega_{\text{top}}^{\text{fake}}
\end{pmatrix}
= \begin{pmatrix}
0.89 \pm 0.03^{\text{stat}} + 0.06^{\text{syst}} \\
0.66 \pm 0.25^{\text{stat}} + 0.43^{\text{syst}} \\
0.99 \pm 0.06^{\text{stat}} + 0.07^{\text{syst}} \\
0.56 \pm 0.79^{\text{stat}} + 0.27^{\text{syst}}
\end{pmatrix}.
\] (4.8)

The number \(N_{W}^{\text{SR}}\) of \(W\) background expected in the signal region given by the scale factors and the unscaled number in the signal region \(N_{W}^{\text{MC,SR}}\) is then:

\[
N_{W}^{\text{SR}} = \omega_{W}^{\text{truth}} N_{W,\text{truth}}^{\text{MC,SR}} + \omega_{W}^{\text{fake}} N_{W,\text{fake}}^{\text{MC,SR}} \quad (4.9)
\]

With an analogous computation for \(Z\) and top backgrounds.

**QCD**

The QCD contribution was estimated using the ABCD-method, in which four signal regions are chosen by changing the cuts made to exclude QCD in the signal region two by two, and then for each pair choose a tau conforming either to the nominal tau cuts, or an extra loose cut. The QCD contribution to the signal region was estimated to \(0.03 \pm 0.01^{\text{stat}}\)\[16\].

**Diboson**

The one tau analysis use the unscaled Monte Carlo in the case of diboson background, as it is seen to be a small contribution, and a significant challenge to obtain scale factors for. The expected number of dibosons in the signal region is \(0.12 \pm 0.10^{\text{stat}}\).
4.4 Event files

All data used in the analysis were SUSY D3PDs with the tag p1328. The cross-sections are Next to NLO where possible, and NLO otherwise [16].

4.4.1 Simulated data

The simulated data for standard model backgrounds were all computed as part of the MC12 Monte Carlo effort. The cross-sections used follow the guidance of the SUSY working group [11], and

4.4.2 The Higgs Aware grid

The Higgsaware signal grid, with the parameters $\tan \beta = 30$, $A_0 = -2m_0$, $\mu > 0$ was computed using the ATLAS full simulation with SOFTSUSY3.6.1 and Herwig++. The UEE3 and CTEQ parton event and parton model was used. The cross-sections are computed to next-to-leading order in the strong coupling [19, 51, 50, 17, 18]. The cross-sections and uncertainties are constructed the range of multiple sets of computations with different Parton Density Functions and mass scales [49].

The nominal cross section and the uncertainty are taken from an envelope of cross section predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [67].

The grid has the following parameters:

- $m_0$ in 200 GeV to 500 GeV steps
- $m_{1/2}$ in 50 GeV steps
- $\tan \beta = 30$

6These are the recommended references for the ATLAS cross-sections, as detailed in [67]
7The ATLASTwiki overview of the cross-sections
\[ A_0 = -2m_0 \]
\[ \mu > 0 \]

Table B.1 lists the Higgs aware points at \( m_0 \leq 2000 \text{ GeV} \).

### 4.4.3 2012 Data

The data used in the analysis are proton-proton collisions, with a center-of mass energy \( \sqrt{s} = 8 \text{ TeV} \) which were recorded from April to December 2012, with runs A through L, excluding F and K [16]. The periods which were free from detector issues, such as malfunctioning subsystems, are recorded on the Good Run Lists (GRL), and make up an integrated luminosity of \( 20.7 \text{ fb}^{-1} \).

### 4.4.4 Event selection

**Trigger**

The huge amounts of data generated by ATLAS is filtered by triggers that pick signatures of interest. In the 1-tau analysis, the \( \text{EF}_j80_a4tchad_xe100_tclcw_veryloose \) must have been activated, i.e at the minimum a jet with \( p_t > 80 \text{ GeV} \), and \( E_T > 100 \text{ GeV} \).

After the trigger, quality cuts are applied [16]:

- If the event is from real data, it must be part of the Good Run List.
- The trigger is required to have fired for data.
- A primary vertex with minimum five track is required.
- No calorimeter noise flag was set.
- No cosmic muon candidate or badly reconstructed muon.
When the quality cuts have been applied, more cuts are imposed to make sure no events are in regions where the trigger efficiency has not yet plateaued:

- At least two jets with $p_{t1} > 130$ GeV and $p_{t1} > 30$ GeV
- $E_T > 150$ GeV

The one-tau analysis rejects any events with muons or electrons, and requires exactly one reconstructed $\tau$ with $p_t > 30$ GeV. This was found to be effective at reducing the $Z$ background compared to a cut on 20 GeV. If a second $tau$ with $p_t > 20$ GeV is present, the event is rejected to preserve orthogonality to the 2-tau analysis.

**QCD**

To discriminate against QCD, the azimuthal separation $\Delta\phi_{\text{min}}$ between $E_T$ and the closest jet must be $> 0.3$. This will help to exclude instances where $E_T$ is the result of a badly measured jet. In addition, $E_T/m_{\text{eff}} > 0.3$ is required. Note that $m_{\text{eff}}$ will only use the two leading jet.

### 4.4.5 Other Cuts

The penultimate cut is $m_t > 140$ GeV, which will reject $W[16]$. In the end the analysis cuts $H_T > 800$ GeV. This will exclude a lot of background, for a detailed discussion of why 800 GeV was chosen, refer to section 4.6.1. The separation between signal and background is evident in Figure 4.8.

### 4.5 Computing the expected number of events

When the events have been selected, it is necessary for me to weigh them according to the cross-section and number of events that are chosen. The signal file contains events that
have been produced in different processes, such as squark-squark, gluino-gluino &c. The events in the

The solution is to count and weigh each sub-process \( p \) individually and sum them up at the end, denoting the index of each Monte Carlo event with \( i \):

\[
\text{n}\text{expect} = \sum_p \sum_i \mathcal{L} \cdot \sigma_p \cdot \frac{N_{i,p}^\text{passed}}{N_{i,p}^\text{total}} \cdot P(\mu_i) \tag{4.10}
\]

Where \( P(\mu_i) \) is a factor reweighting the event according to the pileup, as detailed in section 4.5, \( \mathcal{L} \) is the integrated luminosity, the \( \sigma_p \) is the sub-process cross section as taken from the SignalUncertainties file, and the \( N \) are the number of Monte Carlo events either passing the cuts or present in the original D3PD.

It is clear that if you wish to have the weight of each event, you will need to check the total number of events before you can weigh the Monte Carlo events\(^8\). This is not appropriate if I wishes to save plots etc. along the cutflow, and not solely at the end.

To solve this problem, as well as the prohibitively large file size of the total 219 points of the Higgs aware grid, I decided to first skim the files on the grid, selecting events with \( m_T > 50 \text{ GeV} \) and one medium tau with \( p_t > 20 \text{ GeV} \). During this skim, all events are recorded in a map that is used in the subsequent run. Removing the summation signs from equation 4.10 and using the skim data for the \( N_{i,p}^\text{total} \)s, I can fill histograms with individual weights.

**Pileup corrections**

In the ATLAS detector, each crossing of two beam bunches will, on average, result in multiple interactions. When the data was taken, the average number of pileup events was around 20\(^5\). The simulated background and signal samples are generated with pileup events in a distribution to roughly match the expected conditions. In the analysis, events are reweighted based on the amount of pileup in each events

---

\(^8\)When I talk about a Monte Carlo event, this will refer to a single simulated event at ATLAS, independent of any reweighting.
so that the pileup-distribution matches the empirical distribution. In the analysis, the PileupReweighting tool was used to obtain these weights \[65\][16].

### 4.6 Errors

The weight of a single event is equation \[4.12\]. The statistical uncertainty is \[\sqrt{\sum_i w_i^2}\]. The special case where all the weights are the same is obvious. The theory error is straightforward to compute, and is included in Equation \[4.12\]:

\[
    w_i = \mathcal{L} \cdot \sigma_p(i) \cdot \frac{N_{\text{passed}}_{i,p(i)}}{N_{\text{total}}_{i,p(i)}} \cdot P(\mu_i) \quad (4.11)
\]

\[
    \Delta(n_{\text{expect}})_{\text{Theory}} = \sqrt{\sum_p \left( \frac{\Delta\sigma_p}{\sigma_p} \sum_i w_{i,p(i)} \cdot P(\mu_i) \right)^2} \quad (4.12)
\]

Where, to avoid confusion the standard deviations are termed \(\Delta\).

In addition to statistical errors, and the errors due to uncertainties on the signal cross sections, both of which I compute per process from equation \[4.10\] systematic effects need to be taken into account. For example; the reconstructed energy in the calorimeters for jets and taus are subject to systematic errors. Another is if the amount of pileup in the detector is systematically over- or under-estimated, then all simulated events would gain a new weight to match the data.

To compute the systematic effects, the program loops over each point for each systematic variation as well as the central value. Taus that would have passed but do not when the tau energy scale is shifted, etc. shift the expected value, and gives a measure of the size of the potential systematic error.
4.6.1 $H_T$ cut

The cut on $H_T$ is the last cut made in the analysis. To choose an appropriate cut value, it is necessary to study the relative amount of signal and background that will pass the cut. It is important to note that this is done entirely with Monte Carlo and scaling factors; the analysis was blinded for $H_T > 600$ GeV before the cut on $H_T$ was chosen.

The experiment is a counting experiment, and the number of events observed will follow a Poisson distribution. The Asimov significance offers a measure of the median significance for this data. This provides a better agreement than the usual $s/\sqrt{b}$ when signal and background is of the same magnitude[33]:

$$z_A \equiv \sqrt{2 \left[ (N_{\text{Sig}} + N_{\text{BG}}) \ln \left( 1 + \frac{N_{\text{Sig}}}{N_{\text{BG}}} \right) - N_{\text{Sig}} \right]} ,$$

where the signal $N_{\text{Sig}}$ is one of the benchmark points used for optimization and the background $N_{\text{BG}}$ is the sum of all SM backgrounds, expected for 20.7 fb$^{-1}$ of data.

If the expected number of background events have a significant uncertainty, this must also be taken into account for the expected significance. This calls for a modified Asimov significance, with the background uncertainty $\sigma_{N_{\text{BG}}}$[32]:

$$x_A \equiv \sqrt{2 \left\{ (N_{\text{Sig}} + N_{\text{BG}}) \ln \left[ \frac{(N_{\text{Sig}} + N_{\text{BG}})(N_{\text{BG}} + \sigma_{N_{\text{BG}}}^2)}{N_{\text{BG}}^2 + (N_{\text{Sig}} + N_{\text{BG}})\sigma_{N_{\text{BG}}}^2} \right] - \frac{N_{\text{BG}}^2}{\sigma_{N_{\text{BG}}}^2} \ln \left[ 1 + \frac{N_{\text{Sig}}\sigma_{N_{\text{BG}}}^2}{N_{\text{BG}}(N_{\text{BG}} + \sigma_{N_{\text{BG}}}^2)} \right] \right\} }$$

To compute this parameter, I save a histogram in $H_T$ of the weighed events before the ultimate cut for the signal and the different backgrounds. I scale each background according to the scale factors, and integrate the distribution from $H_{T\text{cut}}$ upwards. In addition to the statistical uncertainty of the background histogram, I add the statistical uncertainty given for the scale factor, as well as a conservative 20% systematic uncertainty. The resulting graph, figure ??, plotted for two signal grid points for the higgsaware grid, as well as two points from the GMSB signal grid.
Figure 4.5: The Asimov approximation, including the background and its uncertainties from the one tau analysis, of the signal significance of the GMSB point $\Lambda = 50$, $\tan\beta = 15$ as well as those for the mSUGRA signal points $m_0 = 400\,\text{GeV}, m_{1/2} = 600\,\text{GeV}$ and $m_0 = 400\,\text{GeV}, m_{1/2} = 650\,\text{GeV}$.

### 4.6.2 Expectations

The figures 4.6 to 4.8 display the agreement between the scaled background and the data for the $m_T$, the tau transverse momentum and the $H_T$. Note that the plots in general are filled before the cut on the variable is imposed, with the exception of $p_T$. The separation in $H_T$ between signal and background is very good.

#### Predicted background

After running the analysis script over the backgrounds, and scaling them with the various scale factors, I produce the following cut-flow in Table 4.1. Note that the QCD is completely cut away in the cut-flow, but is estimated with another method.

Including systematics, Table ?? displays the full expected background, including statistical and systematic errors:
Figure 4.6: $m_T$ for signal, background and data

Figure 4.7: $p_{T\tau}$ for signal, background and data
The Higgs Aware grid

In addition to expected background,

<table>
<thead>
<tr>
<th>After cut</th>
<th>Top</th>
<th>W+jets</th>
<th>Z+jets</th>
<th>Di-boson</th>
<th>QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1τ &amp; no other lepton</td>
<td>5522±751</td>
<td>11601±436</td>
<td>1670±399</td>
<td>59.8±2.2</td>
<td>320±43</td>
</tr>
<tr>
<td>∆Φ_{min} &gt; 0.3</td>
<td>3847±367</td>
<td>7923±260</td>
<td>837±163</td>
<td>42.1±1.8</td>
<td>32±12</td>
</tr>
<tr>
<td>$E_T/m_{eff} &gt; 0.3$</td>
<td>2067±209</td>
<td>5613±186</td>
<td>574±138</td>
<td>28.1±1.4</td>
<td>–</td>
</tr>
<tr>
<td>$m_T &gt; 140$ GeV</td>
<td>163±106</td>
<td>128±32</td>
<td>173±68</td>
<td>6.5±0.6</td>
<td>–</td>
</tr>
<tr>
<td>$H_T &gt; 800$ GeV</td>
<td>0.75±0.58</td>
<td>1.85±0.58</td>
<td>2.1±1.3</td>
<td>0.12±0.10</td>
<td>0.03±0.01_{stat}</td>
</tr>
</tbody>
</table>

Table 4.1: Cut-flow for the kinematic cuts defining the SR after the baseline event selection. All numbers are from MC scaled to an expected data luminosity of 20.7fb$^{-1}$ with scale factors applied to top, W+jets and Z+jets, except for the final estimate of QCD events. The errors are statistical only.
<table>
<thead>
<tr>
<th>Category</th>
<th>Expected Events</th>
<th>Stat Error</th>
<th>Syst Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>top (truth)</td>
<td>0.47 ± 0.39^\text{stat} ± 0.19^\text{syst}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>top (fake)</td>
<td>0.27 ± 0.43^\text{stat} ± 0.25^\text{syst}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets (truth)</td>
<td>1.19 ± 0.43^\text{stat} ± 0.29^\text{syst}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets (fake)</td>
<td>0.67 ± 0.38^\text{stat} ± 0.59^\text{syst}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z+jets</td>
<td>2.1 ± 1.2^\text{stat} ± 1.7^\text{syst}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCD</td>
<td>0.03 ± 0.01^\text{stat} ± 0.02^\text{syst}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diboson</td>
<td>0.12 ± 0.10^\text{stat} ± 0.08^\text{syst}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.8 ± 1.5^\text{stat} ± 1.8^\text{syst}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Number of expected events at 20.7fb\(^{-1}\) that are expected to pass the analysis cuts.

Figure 4.9: Expected number of events passing...
Figure 4.10: The total cross section of the Higgs aware grid points. It decreases monotonically towards higher $m_{1/2}$. Comparing this result to Figure 4.2, one sees that the fraction of events that pass the analysis is a lot bigger in the coannihilation region.

Figure 4.11: The uncertainty of the Higgs-aware cross section. In the region where we expect events, the uncertainty is around 10%
5

Results

5.1 Fermi

The excluded cross section of the line search is included in figure 5.1. A significant less powerful limit is seen at 130 GeV, in line with 70. A measure of the significance of the line is $z = \sqrt{2(\log L_s + \log L_b - \log L_b)}$. $z^2$ is included in Figure 5.2. At 130 GeV, $z = 2.51$. In addition, a strong deviation is seen at 7 GeV with $z \sim 3$.

The two most significant features at 7 and 130 GeV have been seen in Fermi analyses of the galactic center, 8. It is clear that the optimized signal regions used in the papers that found the line is important to achieve a higher significance. However, I see that my linesearch reproduces the result with quite good fidelity, if not with the same high numerical confidence.

The fit to $m = 130$ is displayed in Figure 5.3. It
Figure 5.1: The 95\% confidence limit for a line signal

$2(\log \mathcal{L}_{s+b} - \log \mathcal{L}_{b})$ for the tested masses.
Figure 5.3: The best fit of the model to data at $m = 130$ GeV, with $\Gamma = 2.460 \pm 0.064$ and $f = (2.44 \pm 0.99) \times 10^{-2}$
5.2 Results of mSUGRA computations

5.2.1 Slices of the mSUGRA parameter space

\[ \tan \beta = 3 A_0 = 0 \text{ GeV} \]

The low tan \( \beta \) grids are subject to strong limits, both from XENON100, as is seen in Figure 5.4. ATLAS and CMS have provided strong limits in this case. In addition, the mass of the lightest Higgs boson in this grid only reaches 110 GeV, and is therefore excluded by the LEP results.

\[ m_{\text{SUGRA}} \tan(\beta)=3, A_0 = 0 \text{ GeV}, \mu>0 \]

![Figure 5.4: A mSUGRA slice at tan \( \beta = 3 \), \( A_0 = 0 \text{ GeV} \)](image)

\[ \tan \beta = 10 A_0 = 0 \text{ GeV} \]

As the ratio of Higgs expectation values increase, the exclusion limits change. Like the \( \tan \beta = 3 \) case, the \( \tan \beta = 10 \) slice in Figure 5.5 has a Higgs mass that ranges too low. The maximum is around \( m_H \sim 120 \text{ GeV} \).
The $b$-physics exclusions on $\text{Br}(B_s \to \mu^+\mu^-)$ and $\text{BR}(b \to s\gamma)$ are much stronger at higher $\tan\beta$. In the case of $B_s \to \mu^+\mu^-$, there are Feynman loops $\propto (\tan\beta)^6$ [22, p. 1430]. Figure 5.6 suggest comparative advantages of accelerators and astrophysical constraints; while accelerators will in general probe the lower-mass quadrant in the parameter space, astrophysical constraints will reach along regions of higher dark matter cross sections, such as along the hyperbolic branch, which is the region of allowed relic density at high $m_0$. In this region, the neutralino has a large higgsino component, and the annihilation to Higgs or gauge bosons is enhanced[37]. It can be seen that CTA would be able to exclude dark matter in this region due to the large annihilation cross-section.

$\tan\beta = 30A_0 = -2300$ GeV

The discovery of a Higgs boson imposed a new constraint on the slices. Above, all slices had too low Higgs masses. A scan made by Burgess et al. [27] highlighted regions of $m_0$, $m_{1/2}$ around 500 GeV, $\tan\beta \sim 30$, and $A_0 \sim -2300$ GeV with allowed relic densities and Higgs masses. A slice with these $A_0$, $\tan\beta$ values in Figure 5.7. The Higgs mass reaches
125 GeV in the coannihilation region around $m_{1/2} = 800$ GeV.

### 5.2.2 $\tan \beta = 30A_0 = -2m_0$

Another slice that contains viable Higgs-masses has been used in ATLAS analyses, particularly in the one-tau analysis that I participated in. Therefore, I will describe the properties of this grid in more detail. The grid of points used in ATLAS, nicknamed the Higgs-aware grid was constructed to maximize the stop-mixing. In addition, the grid features regions of allowed relic density.

A Higgs mass upper bound given in Equation 2.1. The bound may be increased in two ways; either the $M_S$ term may be big, and the stop correspondingly heavy, or the stop mixing, given by $X_t = A_t - \mu \cot \beta \sim \sqrt{6}M_S$ may give the necessary contribution. The stop mass, like other sfermions, are roughly proportional to $m_0$, and the top trilinear coupling $A_t$ to $A_0$. A broad region of acceptable Higgs masses is plain to see in Figure 5.8. As mentioned in section 4.2.2, the uncertainty in the top mass will shift this band in $m_0$, but the near maximal stop mixing clearly shifts the Higgs mass upwards.
mSUGRA $\tan(\beta) = 30, A_\beta = -2300 \text{ GeV}, \mu > 0$

Figure 5.7: A mSUGRA slice at $\tan \beta = 3$.

$m_{h\text{iggs}} [\text{GeV}]$ mSUGRA $\tan(\beta) = 30, A_0 = -2m_0, \mu > 0$

Figure 5.8: Higgs masses in the mSUGRA Higgs-aware grid.
**Accelerator bounds**

The neutralino and stau masses are plotted in Figure 5.9. The low mass of the stau in the coannihilation region is accompanied by an enhanced stau pair production cross section, and branching ratio of charginos to staus\[56\]. As the stau is close to the coannihilation region it is the Next to Lightest Supersymmetric Particle (NLSP), and so any staus must decay to a neutralino and a tau. This favors an accelerator search that takes taus into account, such as the one tau search that will be detailed in the next section.

![Figure 5.9: Stau and neutralino masses in the Higgs-aware slice](image)

The branching fraction $B_s \rightarrow \mu^+\mu^-$ is enhanced by $\tan \beta$, and is higher than the LHCb central value in the grid. The red area in Figure 5.10 is farther than 1$\sigma$ from the central value. The 95% confidence limit $BR > 6.2 \times 10^{-9}$ is highlighted in black.

**Astrophysical bounds**

The relic density of the Higgs-aware grid follows the same pattern as the other slices; a large region of excessive relic density and a sliver along the coannihilation region where the neutralino and stau may coannihilate, reducing the relic density to physical levels.

The astrophysical experiments do not exclude significant portions of the grid, although if the sensitivities were increased, the searches for a photon-photon line would be relevant in the coannihilation region. If the dark matter is lumpy, the $\rho^2$ dependence would drive
the exclusion downwards and possibly exclude models through the total $\langle \sigma v \rangle$. This boost factor is not necessarily very high, however [9].

**Summary**

The Higgs-aware slice demonstrates that for the time being, there are viable Higgs masses in mSUGRA. Beyond that, the coannihilation region stands out as an interesting region for physics; the coannihilation cross sections are the largest here, and a tau-based analysis looks to have some promise. The summary Figure 5.16 shows the grid of points used in the atlas analysis, as well as the B-physics constraints on the lower left part of the slice. Figure 5.17 displays the region of allowed relic density at a higher resolution.
Figure 5.11: caption

Figure 5.12: The $\gamma\gamma$ coannihilation cross section computed by DarkSusy, with a comparison to the Fermi limit and a CTA projection.
Figure 5.13: The total coannihilation cross section computed by DarkSusy 5.0.5, with a comparison to the Fermi limit and a CTA projection.

Figure 5.14: The spin-independent neutralino-nucleon cross-section from DarkSusy 5.0.5, with a comparison to the XENON limit.
Figure 5.15: The spin-dependent neutralino-nucleon cross-section from DarkSusy 5.0.5, with a comparison to the IceCube limit.

Figure 5.16: Exclusion contours, as well as a contour for the LHCb $B_s \to \mu^+ \mu^-$. Points that are included in the ATLAS Higgs-aware grid are marked.
5.3 Results from ALTAS search

5.3.1 Observed events

Three data events pass the analysis cuts. This may be compared with an expected number of $4.8 \pm 1.5 \pm 1.8$. No excess over the standard model is seen. Table 5.1 displays the cut-flow for data, background and some signal points.

<table>
<thead>
<tr>
<th>After cut</th>
<th>Data $\sqrt{s} = 8$ TeV</th>
<th>All Std.Mod. backgrounds</th>
<th>GMSB $\Lambda = 60$, $\tan \beta = 30$, $m_1/2 = 600$</th>
<th>mSUGRA $m_0 = 400$, $m_1/2 = 600$</th>
<th>mSUGRA $m_0 = 400$, $m_1/2 = 650$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \tau$ &amp; no other lepton</td>
<td>14423</td>
<td>13460±529</td>
<td>22.4±0.9</td>
<td>45.7±1.6</td>
<td>21.9±0.7</td>
</tr>
<tr>
<td>$\Delta \Phi_{min} &gt; 0.3$</td>
<td>13268</td>
<td>12646±482</td>
<td>18.1±0.8</td>
<td>38.2±1.5</td>
<td>17.5±0.6</td>
</tr>
<tr>
<td>met/meff &gt; 0.3</td>
<td>8898</td>
<td>8279±313</td>
<td>7.4±0.5</td>
<td>20.5±1.0</td>
<td>10.4±0.5</td>
</tr>
<tr>
<td>$m_T &gt; 140$GeV</td>
<td>401</td>
<td>460±130</td>
<td>4.7±0.4</td>
<td>13.1±0.9</td>
<td>6.51±0.37</td>
</tr>
<tr>
<td>$H_T &gt; 800$GeV</td>
<td>3</td>
<td>4.8±1.5</td>
<td>1.9±0.3</td>
<td>11.0±0.8</td>
<td>5.62±0.34</td>
</tr>
</tbody>
</table>

Table 5.1: Cut-flow for background, data and some signal points. The expected numbers of events for all standard model backgrounds and for the example of one GMSB and two mSUGRA parameter space points correspond to an integrated luminosity of $20.7$ fb$^{-1}$.
Figure 5.18: The unblinded $H_T$ distribution. The three passed events, with $H_T = 850, 855, 881$ is easy to see as they have clustered in one bin.

### 5.3.2 Setting a limit

Given the estimates of the background and signal, as well as the uncertainties of both, the 1−τ analysis is able to set limits on what signal points have a low enough expectation value to be compatible with the data at 95% confidence level. The files from the signal analysis include each systematic uncertainty separately- so that if, for example, all signal and background contributions increase the same, the systematic background will not affect the exclusion contour. If that kind of systematic effect was just added in quadrature with all the others, the correlations between data sets, and possibly exclusion power would be lost.

The limit conforms well to the expected number of events seen in the analysis section. In response to the promise of excluding parts of the Higgs aware coannihilation region, it was decided to produce 9 extra points. These are the irregularly spaced markers in Figure 5.19 mSUGRA1taulimitorjan9points.pdf
Figure 5.19: Exclusion contours from the one-tau analysis. The irregular spacing of the nine new points made plotting the uncertainties a challenge. Using the central value, however, and it is clear that the one-tau group has excluded parts of the coannihilation region. This also means that dark matter is excluded in the same region.
Figure 5.20: The nine new mSUGRA points, close to and in the coannihilation region. The one tau exclusion curve is from before the nine new points is added as a dashed line. Figure 5.19 shows the entire exclusion plot.
Conclusions

In this thesis, I have explored dark matter searches along three prongs.

First, I studied the Fermi-LAT exclusion limit in response to a dark matter coannihilation line. While the search did not utilize the powerful techniques of the original tentative discovery paper\cite{70}, a possible discovery of such magnitude warranted a thorough look at the method and data, especially when an investigation into the future exclusion power of CTA was being investigated.

The second was to compute variables of mSUGRA slices. The Higgs constraint is a strong one, but with the large parameter space of supersymmetry, there is always the option to extend the space and gain allowed quantities. The Non-Universal Higgs Mass scenario is essentially the mSUGRA with a Higgs mass \cite[p1428]{22} as an input parameter. Together with other efforts \cite{27}, I have seen that some slices of mSUGRA have yet to be excluded.

Third; I participated in an ATLAS search for supersymmetry. Included in the search was an mSUGRA grid that was in much the same area of the parameter space as those slices that were considered in the previous part. In fact, when new points were added to the grid in response to the result, the analysis was able to impose limits in parts of the coannihilation region, which is also the most interesting area from the view of astrophysics.

This work follows a now long-established tradition of not finding supersymmetry. The
parameter space of supersymmetry is vast, and with 124 parameters in play, it is hard to see that it could be ruled out in all versions. To search for supersymmetry, it becomes practical to either choose a simplified model, such as mSUGRA, or to focus on model-independent searches and measurements such as the Higgs mass.

That high energy physics has shaped the very largest and oldest structure of the universe is an awe-inspiring thought, and means that supersymmetry may be sought in the sky as well as at the LHC. Thus, the possible properties of dark matter in bulk may be measured or constrained; the relic density and the scattering and annihilation cross-sections.

During my work, the advantage of including such measurements in constraining supersymmetric models has become clear. Since they are simply one observable number given by the model, the process of computing their confidence limit for any sets of supersymmetric parameters is much more straightforward than computing a limit in supersymmetry. Searches for supersymmetry, and other models of physics beyond the standard model with large parameter spaces will benefit greatly if they let their choice of parameter points be guided by astrophysical observations.

The photon line in the Fermi Data, while tentative at the moment, would drastically influence physics. It would be the first evidence of physics beyond the standard model. It is also important to note that in the case of a discovery, both accelerators and astrophysical measurements will be needed to confirm the nature of dark matter.

As this thesis comes to an end, work is ongoing in the Efforts are underway to re-optimize the $1 - \tau$ analysis with respect to the Higgs-aware signal grid. The Fermi collaboration, the Hess Cherenkov telescope, and the planned CTA will all attempt to examine the reported gamma line.
Bibliography

[1] “Combined measurements of the mass and signal strength of the Higgs-like boson with the ATLAS detector using up to 25 fb$^{-1}$ of proton-proton collision data”. In: (2013).


[26] Trygve Buanes et al. “Sensitivity for observing dark matter through a gamma line emission from the galactic centre region with Cherenkov Telescope Array”. On behalf of the CTA collaboration, To be submitted.


[56] Stephen Martin, Tapas Sarangi, and Xavier Portell. Considering Scenarios with Higgs Constraints. https://indico.cern.ch/getFile.py/access?contribId=14&sessionId=1&resId=0&materialId=slides&confId=188153


Appendix A

Computer Programs

A.1 Software Acknowledgments

During my work, I have used many computer programs and packages. Much of the work I have done would be slower or even impossible to accomplish in time if these tools were not provided freely to the scientific community.

- Fermi Science Tools
- Python
- C++
- Root
- Minuit
• Fortran

• Healpix

• Healpy

• numpy

• \LaTeX

• pyfits

The \LaTeX template used for the thesis was made by Alexander Skjæveland Larsen [https://github.com/ogrim/uib-latex]
Appendix B

ATLAS supporting material

B.1 Signal Samples
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>( m_0 )</th>
<th>( m_{1/2} )</th>
<th>( \sigma_{\text{total}} ) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>166732</td>
<td>400</td>
<td>400</td>
<td>0.363</td>
</tr>
<tr>
<td>166733</td>
<td>400</td>
<td>450</td>
<td>0.173</td>
</tr>
<tr>
<td>166734</td>
<td>400</td>
<td>500</td>
<td>0.0843</td>
</tr>
<tr>
<td>166735</td>
<td>400</td>
<td>550</td>
<td>0.0424</td>
</tr>
<tr>
<td>166736</td>
<td>400</td>
<td>600</td>
<td>0.0217</td>
</tr>
<tr>
<td>166737</td>
<td>400</td>
<td>650</td>
<td>0.0111</td>
</tr>
<tr>
<td>166738</td>
<td>400</td>
<td>700</td>
<td>0.00595</td>
</tr>
<tr>
<td>166739</td>
<td>400</td>
<td>750</td>
<td>0.00310</td>
</tr>
<tr>
<td>166740</td>
<td>400</td>
<td>800</td>
<td>0.00169</td>
</tr>
<tr>
<td>166741</td>
<td>600</td>
<td>400</td>
<td>0.244</td>
</tr>
<tr>
<td>166742</td>
<td>600</td>
<td>450</td>
<td>0.1179</td>
</tr>
<tr>
<td>166743</td>
<td>600</td>
<td>500</td>
<td>0.0580</td>
</tr>
<tr>
<td>166744</td>
<td>600</td>
<td>550</td>
<td>0.0296</td>
</tr>
<tr>
<td>166745</td>
<td>600</td>
<td>600</td>
<td>0.0153</td>
</tr>
<tr>
<td>166746</td>
<td>600</td>
<td>650</td>
<td>0.00801</td>
</tr>
<tr>
<td>166747</td>
<td>600</td>
<td>700</td>
<td>0.00429</td>
</tr>
<tr>
<td>166748</td>
<td>600</td>
<td>750</td>
<td>0.00233</td>
</tr>
<tr>
<td>166749</td>
<td>600</td>
<td>800</td>
<td>0.00126</td>
</tr>
<tr>
<td>166750</td>
<td>600</td>
<td>850</td>
<td>0.000654</td>
</tr>
<tr>
<td>166751</td>
<td>600</td>
<td>900</td>
<td>0.000371</td>
</tr>
<tr>
<td>166752</td>
<td>600</td>
<td>950</td>
<td>0.000200</td>
</tr>
<tr>
<td>166753</td>
<td>800</td>
<td>400</td>
<td>0.167</td>
</tr>
<tr>
<td>166754</td>
<td>800</td>
<td>450</td>
<td>0.0787</td>
</tr>
<tr>
<td>166755</td>
<td>800</td>
<td>500</td>
<td>0.0388</td>
</tr>
<tr>
<td>166756</td>
<td>800</td>
<td>550</td>
<td>0.0198</td>
</tr>
<tr>
<td>166757</td>
<td>800</td>
<td>600</td>
<td>0.0103</td>
</tr>
<tr>
<td>166758</td>
<td>800</td>
<td>650</td>
<td>0.00549</td>
</tr>
<tr>
<td>166759</td>
<td>800</td>
<td>700</td>
<td>0.00295</td>
</tr>
<tr>
<td>166760</td>
<td>800</td>
<td>750</td>
<td>0.00160</td>
</tr>
<tr>
<td>166761</td>
<td>800</td>
<td>800</td>
<td>0.000872</td>
</tr>
<tr>
<td>166762</td>
<td>800</td>
<td>850</td>
<td>0.000477</td>
</tr>
<tr>
<td>166763</td>
<td>800</td>
<td>900</td>
<td>0.000247</td>
</tr>
<tr>
<td>166764</td>
<td>800</td>
<td>950</td>
<td>0.000144</td>
</tr>
<tr>
<td>166802</td>
<td>800</td>
<td>1000</td>
<td>7.96e-05</td>
</tr>
<tr>
<td>166765</td>
<td>1000</td>
<td>400</td>
<td>0.123</td>
</tr>
<tr>
<td>166766</td>
<td>1000</td>
<td>450</td>
<td>0.0561</td>
</tr>
<tr>
<td>166767</td>
<td>1000</td>
<td>500</td>
<td>0.0270</td>
</tr>
<tr>
<td>166768</td>
<td>1000</td>
<td>550</td>
<td>0.0134</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>( m_0 )</th>
<th>( m_{1/2} )</th>
<th>( \sigma ) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>166769</td>
<td>1000</td>
<td>600</td>
<td>0.00693</td>
</tr>
<tr>
<td>166770</td>
<td>1000</td>
<td>650</td>
<td>0.00373</td>
</tr>
<tr>
<td>166771</td>
<td>1000</td>
<td>700</td>
<td>0.00198</td>
</tr>
<tr>
<td>166772</td>
<td>1000</td>
<td>750</td>
<td>0.00108</td>
</tr>
<tr>
<td>166773</td>
<td>1000</td>
<td>800</td>
<td>0.000594</td>
</tr>
<tr>
<td>166774</td>
<td>1000</td>
<td>850</td>
<td>0.000327</td>
</tr>
<tr>
<td>166775</td>
<td>1000</td>
<td>900</td>
<td>0.000180</td>
</tr>
<tr>
<td>166776</td>
<td>1000</td>
<td>950</td>
<td>9.99e-05</td>
</tr>
<tr>
<td>166803</td>
<td>1000</td>
<td>1000</td>
<td>5.56e-05</td>
</tr>
<tr>
<td>166948</td>
<td>1200</td>
<td>300</td>
<td>0.657</td>
</tr>
<tr>
<td>166938</td>
<td>1200</td>
<td>350</td>
<td>0.243</td>
</tr>
<tr>
<td>166777</td>
<td>1200</td>
<td>400</td>
<td>0.0989</td>
</tr>
<tr>
<td>166778</td>
<td>1200</td>
<td>450</td>
<td>0.0437</td>
</tr>
<tr>
<td>166779</td>
<td>1200</td>
<td>500</td>
<td>0.0205</td>
</tr>
<tr>
<td>166780</td>
<td>1200</td>
<td>550</td>
<td>0.0101</td>
</tr>
<tr>
<td>166781</td>
<td>1200</td>
<td>600</td>
<td>0.00511</td>
</tr>
<tr>
<td>166782</td>
<td>1200</td>
<td>650</td>
<td>0.00267</td>
</tr>
<tr>
<td>166783</td>
<td>1200</td>
<td>700</td>
<td>0.00142</td>
</tr>
<tr>
<td>166784</td>
<td>1200</td>
<td>750</td>
<td>0.000766</td>
</tr>
<tr>
<td>166785</td>
<td>1200</td>
<td>800</td>
<td>0.000418</td>
</tr>
<tr>
<td>166786</td>
<td>1200</td>
<td>850</td>
<td>0.000230</td>
</tr>
<tr>
<td>166787</td>
<td>1200</td>
<td>900</td>
<td>0.000128</td>
</tr>
<tr>
<td>166788</td>
<td>1200</td>
<td>950</td>
<td>7.08e-05</td>
</tr>
<tr>
<td>166804</td>
<td>1200</td>
<td>1000</td>
<td>3.97e-05</td>
</tr>
<tr>
<td>166949</td>
<td>1400</td>
<td>300</td>
<td>0.525</td>
</tr>
<tr>
<td>166950</td>
<td>1400</td>
<td>350</td>
<td>0.201</td>
</tr>
<tr>
<td>166790</td>
<td>1400</td>
<td>400</td>
<td>0.0832</td>
</tr>
<tr>
<td>166791</td>
<td>1400</td>
<td>450</td>
<td>0.0366</td>
</tr>
<tr>
<td>166792</td>
<td>1400</td>
<td>500</td>
<td>0.0169</td>
</tr>
<tr>
<td>166793</td>
<td>1400</td>
<td>550</td>
<td>0.00818</td>
</tr>
<tr>
<td>166794</td>
<td>1400</td>
<td>600</td>
<td>0.00408</td>
</tr>
<tr>
<td>166795</td>
<td>1400</td>
<td>650</td>
<td>0.00209</td>
</tr>
<tr>
<td>166796</td>
<td>1400</td>
<td>700</td>
<td>0.00110</td>
</tr>
<tr>
<td>166797</td>
<td>1400</td>
<td>750</td>
<td>0.000587</td>
</tr>
<tr>
<td>166805</td>
<td>1400</td>
<td>800</td>
<td>0.000319</td>
</tr>
<tr>
<td>166975</td>
<td>1400</td>
<td>850</td>
<td>9.65e-05</td>
</tr>
<tr>
<td>166798</td>
<td>1400</td>
<td>900</td>
<td>5.38e-05</td>
</tr>
</tbody>
</table>

Table B.1: List of MC samples for the SUSY signal in the mSUGRA Higgs boson-aware grid. Masses are quoted in GeV. Another 105 samples with \( m_0 > 2000 \text{GeV} \) have been generated, but they are far away from the region where \( \tilde{\tau} \) is the NLSP.
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$m_0$</th>
<th>$m_{1/2}$</th>
<th>$\sigma$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>166951</td>
<td>280</td>
<td>550</td>
<td>0.051</td>
</tr>
<tr>
<td>166952</td>
<td>300</td>
<td>620</td>
<td>0.019</td>
</tr>
<tr>
<td>166953</td>
<td>320</td>
<td>640</td>
<td>0.014</td>
</tr>
<tr>
<td>166954</td>
<td>320</td>
<td>660</td>
<td>0.011</td>
</tr>
<tr>
<td>166955</td>
<td>350</td>
<td>550</td>
<td>0.047</td>
</tr>
<tr>
<td>166956</td>
<td>350</td>
<td>680</td>
<td>0.0083</td>
</tr>
<tr>
<td>166957</td>
<td>230</td>
<td>420</td>
<td>0.36</td>
</tr>
<tr>
<td>166958</td>
<td>250</td>
<td>460</td>
<td>0.19</td>
</tr>
<tr>
<td>166959</td>
<td>250</td>
<td>500</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table B.2: List of nine additional MC samples close to the coannihilation region for the SUSY signal in the mSUGRA Higgs boson-aware grid. Masses are quoted in GeV.