Department of Physics, Chemistry and Biology

Master's Thesis

Search for Dark Matter in the Upgraded High Luminosity LHC at CERN

Impact of ATLAS phase II performance on a mono-jet analysis

Sven-Patrik Hallsjö

Thesis work performed at Stockholm University

Linköping, June 4, 2014

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Titel
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Sökandet efter mörk materia i den uppgraderade hög luminositets LHC i CERN

Search for Dark Matter in the Upgraded High Luminosity LHC at CERN

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Påverkan av ATLAS fas II prestanda på en mono-jet analys

Impact of ATLAS phase II performance on a mono-jet analysis

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Sammanfattning
Abstract

If your thesis is written in English, the primary abstract would go here while the Swedish abstract would be optional.

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Acknowledgments

I wish to dedicate this thesis to my mathematics teacher Ulf Rydmark without whom I would not have studied physics.

A big thank you to my family, fiancée and friends who have supported me throughout my education. A warm thank you to my friend Joakim Skoog who altered some of the images for me.

I want to thank my supervisor Christophe Clément and all those who helped me at Stockholm University.
I also want to thank my examiner Magnus Johansson, who always took time to answer any question from and support his students.
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Finally I want to thank someone someone for proofreading my

Linköping, June 2014
Sven-Patrik Hallsjö

Contents

Notation

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[1]Originally, Conseil Européen pour la Recherche Nucléaire

1

Introduction

Discrepancies in measurements of the rotations of galaxies indicate the presence of a large amount of matter which interacts through gravity, though not electromagnetically making it invisible to our telescopes. This matter is commonly referred to as dark matter. Since no known or hypothesised particle in the standard model of particle physics can be used as a candidate for dark matter, this has opened the door for new physics. Aside from dark matter there are other phenomena, such as the neutrino mass and the hierarchy problem, that can not be explained today. One of the proposed models to correct these discrepancies is known as Supersymmetry (SUSY).

At the Organisation européene pour la recherche nucléaire (CERN) the interest now lies to discover any evidence of SUSY. Among other searches one is fixed at looking for so called weakly interacting massive particles (WIMPS) which may be a candidate for dark matter. It is usually impossible to detect any interaction of dark matter candidates on the subatomic scale, however through looking at proposed interactions, searching for assumed decay channels and inconsistencies in momentum conservation it is hoped that signs will be found. Though as of March 26, 2014, none have been found.

Both these experiments and current theories now show that higher energies are required at the LHC to be able to see any signs. This is why the LHC and all detectors are undergoing a vast upgrading program [1]. In this thesis focus will be on the last part of the upgrade due for completion in 2023, known as the high luminosity-LHC phase II upgrade; and also on the ATLAS detector.

In this chapter an introduction to both the theoretical and experimental details required to understand the method and results is given.

1.1   Research goals

This research took place at Stockholm University from January 7th until **when?** During the research period the following tasks were set up and performed/answered:

- Implement a C++ programme that loops over the collisions inside the signal and background datasets.

- For each collision retrieve the relevant observables (variables used to extract the signal over the background) and apply "smearing functions" to emulate the effect of the high luminosity on the observables.

- For both signal and background datasets, compare observables before and after smearing. What observables are the least/most affected?

- Implement selection criteria that selects the signal collisions efficiently while reduces significantly the background. In a first step the selection criteria should be taken from existing studies.

- Selection criteria can be evaluated and compared with each other using a figure of merit P, that measures the sensitivity of the experiment to the dark matter signal. Calculate P for the given selection criteria before and after smearing.

- What is the effect of the high luminosity (smearing) on the value of P?

- Investigate other selection criteria and observables, to mitigate the effect of high luminosity. Use P to rank different criteria after smearing.

- Conclude on the effect of the high luminosity on the sensitivity for dark matter and possible ways to mitigate its effects using alternative observables and selection criteria.

1.2   Theoretical Background

The following is a short description of the theory which is required to understand this thesis.

1.2.1   Quantum mechanics and quantum field theory

In the beginning of the 20th century, some physical phenomena could not be explained by classical physics, for example the ultra-violet disaster of any classical model of of black-body radiation, and the photoelectric effect [2]. It was these phenomena that led to the formulation of quantum mechanics (QM), where energy transfer is quantized and particles can act as both waves and particles at the same time [3].

Combining QM with classical electromagnetism proved harder than expected, colliding a photon(em-field) and an electron (particle/wave) is quite tricky. This can be seen when trying to calculate the scattering between them both in a QM schema. One idea that came from this was to explain them both in the same framework, field theory. Also, trying to incorporate special relativity into QM suggested a field description where space-time is described using the metric formalism from differential geometry. The culmination of both of these problems is the first part of a Quantum field theory (QFT), Quantum electrodynamics (QED) which with incredible precision explains electromagnetic phenomena including effects from special relativity[4]. It is in this merging that antimatter was theorised, since it is a requirement for the theory to hold. After the discovery of antimatter, the theory was set in stone. Since this the theory has been altered somewhat to explain more and more experimental data. This is discussed more in subsection 1.2.2 and subsection 1.2.3.

To be able to calculate properties in QFT one uses the Lagrangian formalism [5]. Which gives a governing equation for the different physical processes. In general the Lagrangian used for the Standard model is quite complicated, one can thus focus on one of the different terms corresponding to a specific force. This can be done to calculate the so called cross-section for a process, which is related to the probability that that process will occur. A step to simplify the calculations is to use the so called Feynman diagrams, an example of which is given in figure 1.1.
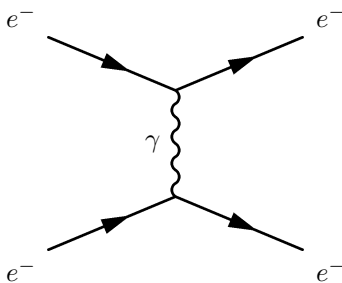

Figure 1.1: *An example of a Feynman diagram explaining an electron-electron scattering using QED.*

Through the figure, which comes with certain rules, and knowing what the major

process (in this case QED) one can calculate the cross-section [4]. it is this that is needed to predict is one will be able to detect new particles.

1.2.2 Nuclear, particle and subatomic particle physics

Many could argue that these branches of physics started after Ernest Rutherford famous gold foil experiment [6], where he discovered that matter is composed of matter with a nucleus, a lot of empty space and electrons.

It was this and other things that sparked the curiosity to see what the nucleus is made of and what forces govern the insides of atoms. After this, and the combination of the theoretical description given by QM, a lot more has been discovered and still more has been predicted. The newest of these is of course the Higgs particle, which was predicted through QFT and then discovered by CERN [7].

The discovered particles are often divided into different groups depending on the fundamental particles that build them up. For instance, particles build up of three quarks are known as hadrons. Particles with an integer spin are known as bosons whereas half-integer particles are known as fermions.

1.2.3 The standard model of particle physics

The standard model of particle physics, referred to simply as the standard model (SM), is the particle zoo which tries to categorize all the particles and that have been discovered experimentally. QFT has tried its best to explain the interactions between these particles and it has also predicted several particles by including symmetries [6]. Regarding SM, Gauge bosons are the force carriers for the different forces, quarks are the and leptons are the fundamental blocks that we know of so far. The difference between the later two is if they interact via the strong force or not.

Figure 1.2: *The standard model of particle physics where the three first columns represent the so called generations, starting with the first. [9].*
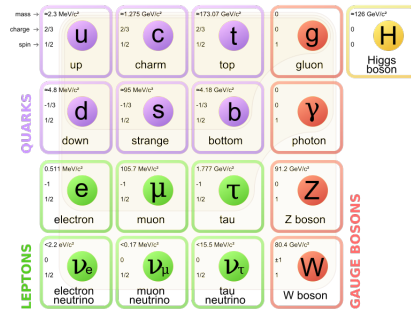
SM is today the pinnacle of particle physics and can be used to explain almost everything that occurs around us. There are however some problems [8]:

- No QFT for general relativity! Thus there is no link between gravity and the SM.

- Experimentally it has been shown that neutrinos have mass, though in SM they do not!

- Asymmetry between matter and antimatter can not fully be described.

- No dark matter candidate!

- No explanation that can contain dark matter.

In this thesis focus lies with dark matter, some more introduction to possible dark matter and different candidates in extensions to SM are explained in subsection 1.2.4.

1.2.4   Dark matter

A very quick introduction was given in the beginning of this chapter. Dark matter is the name given to the solution to the discrepancies of galactic rotations.

To explain this, focus on matter in a galaxy which are rotating around the center of the galaxy. Through Newtons law of gravity and the centrifugal force one can calculate the rotation speed dependent on the distance to the center of the galaxy. Since one of these forces is attractive and the other repulsive, if the matter is in a stable orbit around the galactic center (which they are) they must be equal and give us an expression for the speed depending on the distance. Newtons law can be written as the following:

$$F_{Gravitational} = G\frac{Mm}{r^2} = G_M\frac{m}{r^2} \qquad F_{Centrifugal} = m\frac{V^2}{r} \tag{1.1}$$

where G is the gravitational constant, M the mass of the centre object, m the mass of the matter, r the distance between the two and V is the rotation speed. It has been simplified using G_M since all matter orbits the same galactic center. Setting the equations in (1.1) results in:

$$G_M\frac{m}{r^2} = m\frac{V^2}{r} \Leftrightarrow V^2 = \frac{G_M}{r} \Rightarrow V = \sqrt{\frac{G_M}{r}} \propto \frac{1}{\sqrt{r}} \tag{1.2}$$

where the speed is assumed to be positive and $\propto$ means proportional. Through these simple calculations it shown that the rotation speed should decrease with and increased distance. The same reasoning can be applied to, our solar system where this is the case figure 1.3a. The relation in these units is $V = \frac{107}{\sqrt{r}}$ where 107 can be used in (1.2) to calculate the mass of the sun. However when looking at galaxies, even when taking into account that one has to see the galaxies as a mass distribution and that the above is only true when outside of the inner mass half, this is not the case! In figure 1.3b experimental data can be seen from the galaxy NGC3198 with a fitted curve which does not decrease with the distance but is instead constant. This is the discrepancy which is solved by postulating the existence of dark matter. After this the big question arises, what could this dark matter consist of? What is known so far lies in the name. Dark since no electromagnetic interaction and matter since gravitational interaction. This means that it can not be made up of any barionic matter or anything in the Standard
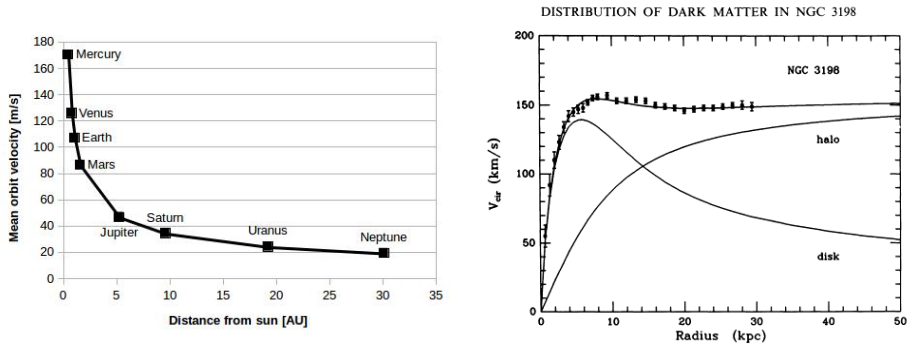
(a) Rotation speed of planets in our so-larsystem. Based on data from [10].

(b) Rotation speed of mater in NGC3198 with a curve fitting and three different models, if only a dark model halo existed, if there was no dark matter and the correct, if both exist [11].

Figure 1.3: *Different rotation curves, both for planets in our solar system and matter in the NGC3198 galaxy.*

Model apart from neutrinos. The main topic and also the main contributor to the rotational discrepancies is known as cold dark matter. This is due to the matter having as low kinetic energy and have mass in the GeV scale [8, 12, 13]. This means however that neutrions can not be a candidate, thus the standard model is ruled out. One possible explanation comes from SUSY where there exists particles that are massive enough and which will not interact electromagnetically. This is discussed more in subsection 1.2.5. There are several different ideas for how dark matter can be detected, [8]

- Ordinary matter interacting with ordinary matter can produce dark matter, known as production.

- Dark matter interacting with ordinary matter can produce dark matter, known as direct detection.

- Dark matter interacting with dark matter can produce ordinary matter, known as indirect detection.

In this theses the focus lies with production. There are several theories how to detect dark matter in proton-proton collisions such that occur at CERN this is covered more in subsection 1.2.7.

1.2.5   Beyond the standard model: Supersymmetry

In the early 1970:s similar as QED expansion with antimatter due to (integral which one diverged?). Similarly to this, an expansion with a similar symmetry having bosons instead of fermions and the reverse. These symmetrical particles

are known as supersymmetrical partners. The SUSY partner of a boson is denoted as sfermion (squarks and sleptons) whereas the SUSY partner of a fermion is denoted as bosinos (gauginos). **Image used by Sara particles with their equivalents.**

Different problems, hierarchy, etc

Bring up different expansions. Here I will talk about supersymmetry (SUSY) end with neutrilino Explain how we get wimps: Weakly interacting massive particles (WIMPS) are a candidate to explain Dark matter, it is this candidate which is considered in this thesis. Where these WIMPS. Minimal Supersymmetric Standard Model

Supersymmetry: Every boson has a supersymmetrical fermion, and the reverse.

From: [8, 14–16]

1.2.6   Effective field theory

In quantum field theory the objective is usually to find the part of the Lagrangian which explains a type of interaction, known as the operator of the interaction and also to find the probability amplitude (cross-section) for a certain interaction. For complicated processes it is easier to employ certain conditions so that the small scale phenomena are simplified and the whole picture understood. This called using an effective field theory and the idea can be in figure 1.4. The operator can be found through assuming the possible interactions and using the effective field theory [4]. The cross-sections can be found through the Feynman diagrams as described in subsection 1.2.1.

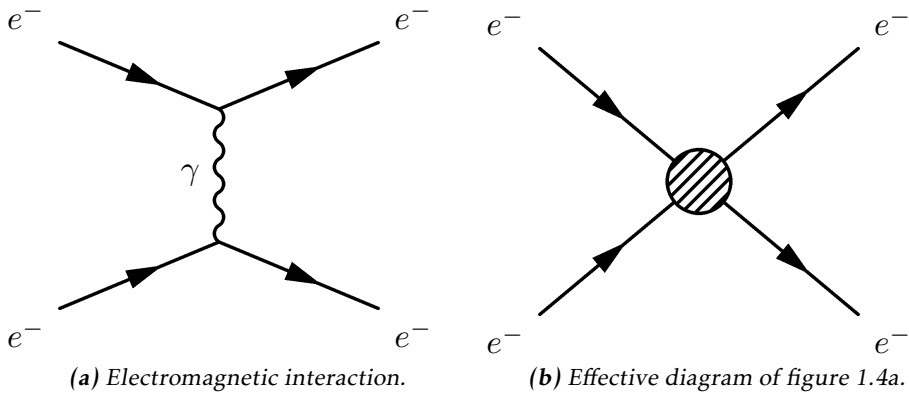*(a) Electromagnetic interaction.*   *(b) Effective diagram of figure 1.4a.*

Figure 1.4: *Feyman diagram of an electron-electron scattering, both as an ordinary diagram and as its effective version, where the details are hidden in the blob.*

In this thesis the same effective field theory as in [12, 17] will be considered. The

WIMP (usually denoted χ) is assumed as the only particle in addition to the standard model fields. χ will be assumed odd under some Z_2 symmetry. This means that an even number of χ must be in every coupling. It is assumed that the whatever mediator exists is heavier that the WIMPS, meaning that their interactions are in higher order terms of the effective field theory and thus not included in the operators. For simplicity, the WIMPS are assumed to be SM singlets, thus invariant under SM gauge transformations, and the coupling to the Higgs boson is neglected.

The focus for the operators will be quark bilinear operators on the form $\bar{q}\Gamma q$ where Γ is a 4×4 matrix of the complete set,

$$\Gamma = \left\{1, \gamma^5, \gamma^\mu, \gamma^\mu \gamma^5, \sigma^{\mu\nu}\right\} \tag{1.3}$$

This will dictate how the operators are written, more of why this is done can be found in [4, 12, 17].

This, together with the coupling with the strong force defines an effective field theory of the interaction of singlet WIMPS with hadronic matter. It is a non-renormalizable field theory which will break down when the mediator mass is close to the mass of the WIMP. The condition for this is derived in [17] and gives:

$$M > 2m_\chi \tag{1.4}$$

where m_χ is the mass of the WIMP and M is the mass of the mediator. There is also the requirement that:

$$M \lesssim 4\pi M_* \tag{1.5}$$

where M_* is the energy scale where the effective theory is no longer a good approximation.

In this work, WIMPS are assumed to be Dirac fermions (half integer spin and is not its own antiparticle).

In table 1.1 the operators which are integrated out via the effective field theory and are of interest in this thesis are given.

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Table 1.1: Table based on discussion in [13]

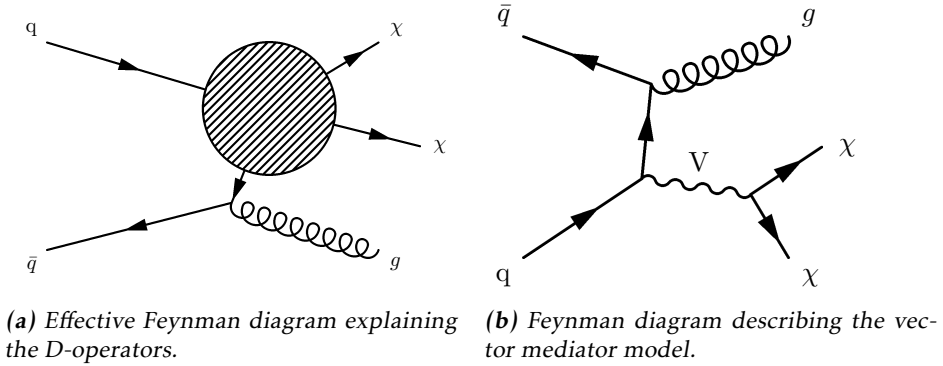Where D denotes that the WIMPS are assumed to be Dirac fermions. These can all be described using figure 1.5a

(a) Effective Feynman diagram explaining the D-operators.

(b) Feynman diagram describing the vector mediator model.

Figure 1.5: *Feynman diagrams describing the used signal models.*

Another model which is considered is when the WIMP mass is close to the mediator mass. Then the effective theory fails and the process is assumed to be described by figure 1.5b.

1.2.7 Search for WIMPS

The search of WIMPS is based on a mono-jet analysis which is described in subsection 1.3.7.

Since the search for WIMPS at the LHC is based on looking at E_T^{Miss} it will be canonical though the experiment can no establish if a WIMP is stable on a cosmological time scale and thus if it is a Dark matter candidate [13]

What is it? Why at CERN/ATLAS? Candidates?

WIMPS, wimps as candidates. How is this detectable at ATLAS? Finish with this. Refer next chapter and that neutralinos are a candidate. **(THEY ARE MAJORANA PARTICLES! so does not coincide with our effective field theory.)**

1.3   Experimental overview

What was used in this research and what needs to be explained?

1.3.1   LHC

The Large hadron collider (LHC) is a particle accelerator located at CERN near Geneva in Switzerland, see figure 1.6. The accelerator was built to explore physics beyond the standard model and to make more accurate measurements of standard model physics. Before it was shut down for an upgrade in 2012 it was able to accelerate two proton beams to such a velocity that they had an energy of 4 TeV which gives a center of mass energy, $\sqrt{s} = 8$ TeV. It should be noted that the proton beam is not homogeneous, it is comprised of bunches of protons with enough spacing that bunch collisions can happen independent of each other.Apart from the energy, the ability for an accelerator to produce interactions can be calculated through the instantaneous luminosity of the LHC was 10^{34} cm^{-2}s^{-1} or 10nb^{-1}s^{-1} where 1 barn(b)= 10^{-24} cm^2. All values taken from [18].
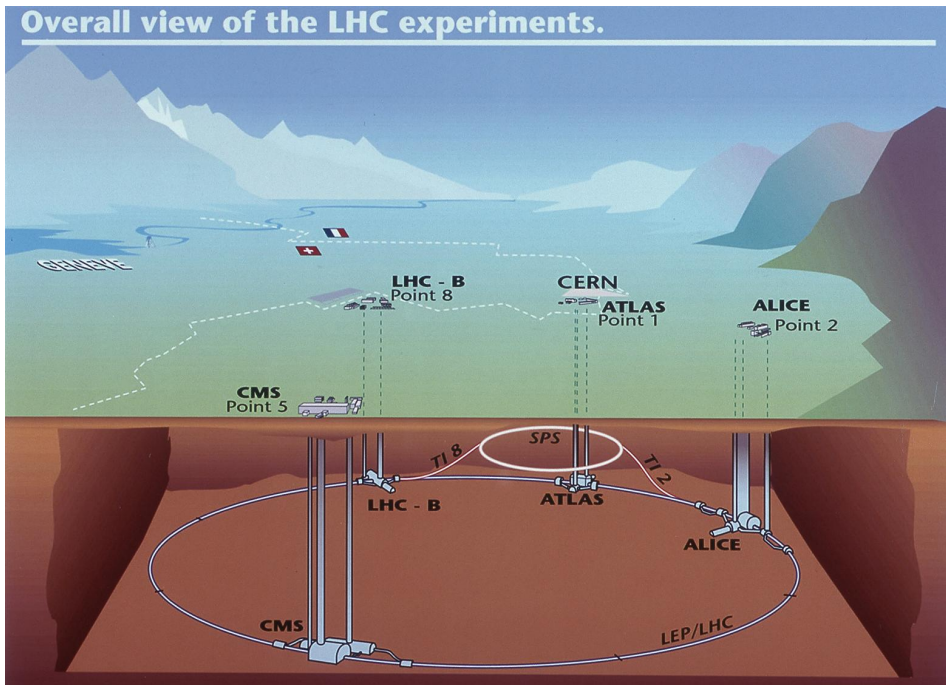

Figure 1.6: Figure showing the LHC and the different detector sites[19]

The instantaneous luminosity can be defined in different ways depending on how the collision takes place. For two collinear intersecting particle beams it is de-

fined as:

$$\mathscr{L} = \frac{fkN_1N_2}{4\pi\sigma_x\sigma_y} \tag{1.6}$$

where N_i are the number of particles in each of the bunches, f is the frequency at which the bunches collide , k the number of colliding bunches in each beam, and σ_x (σ_y) is the horizontal (vertical) beam size at the interaction point. Since the instantaneous luminosity increases quadratically with more particles in each bunch this would be a good strategy. However aside from the difficulties to create and maintain a beam with more particles, a large N_i increases the probability for multiple collisions per bunch crossing, referred to as pile-up. Pile up will be a key aspect which is described more in subsection 1.3.6.

The expected number of events can be calculated by using the instantaneous luminosity through the following:

$$N = \sigma \int \mathscr{L} dt := \sigma\mathcal{L} \tag{1.7}$$

where $\mathcal{L}$ is the luminosity and σ is the cross section which is often measured in barn. The luminosity is a measurement of total number of interactions that have occurred over time. Before the LHC was shut down this values was 20.8 fb^{-1}.

The cross section is defined through the integral of the differential cross section, as explained in subsection 1.2.1, over the whole solid angle:

$$\sigma = \oint d\Omega \frac{d\sigma}{d\Omega} \tag{1.8}$$

The cross section is therefore a measure of the effective surface area seen by the impinging particles, and as such is expressed in units of area. The cross section is proportional to the probability that an interaction will occur. It also provides a measure of the strength of the interaction between the scattered particle and the scattering center. Further details can be found in reference [20]

1.3.2   ATLAS

As seen in figure 1.6, there are several detectors at CERN. One of these is a large toroidal LHC apparatus (ATLAS) which is a general purpose detector that uses a toroid magnet. Its goal is to observe several different production and decay channels. The detector is composed of three concentric subdetectors, the Inner detector, the Calorimeters and the Muon spectrometer.

Most and more in [21]

1.3.3   Coordinate system

The coordinate system of ATLAS, seen in figure 1.7 is a right-handed coordinate system with the x-axis pointing towards the centre of the LHC tunnel, and the z-axis along the tunnel/beam (counter clockwise) seen from above. The y-axis points upward. The origin is define as the interaction point. A cylindrical coor-

dinate system is also used for the transversal plane. (R,ϕ,Z). For simplicity the pseudorapidity of particles from the primary vertex is defined as:

$$\eta = -\ln(\tan\frac{\theta}{2}) \tag{1.9}$$

where θ is the polar angle (xz-plane) of the particle direction measured from the positive z-axis. η is through this definition invariant under boosts in the z-direction.

It is quite common to calculate the distance between particles and jets in the (η, ϕ) plane, $d = \sqrt{\Delta\eta + \Delta\phi}$
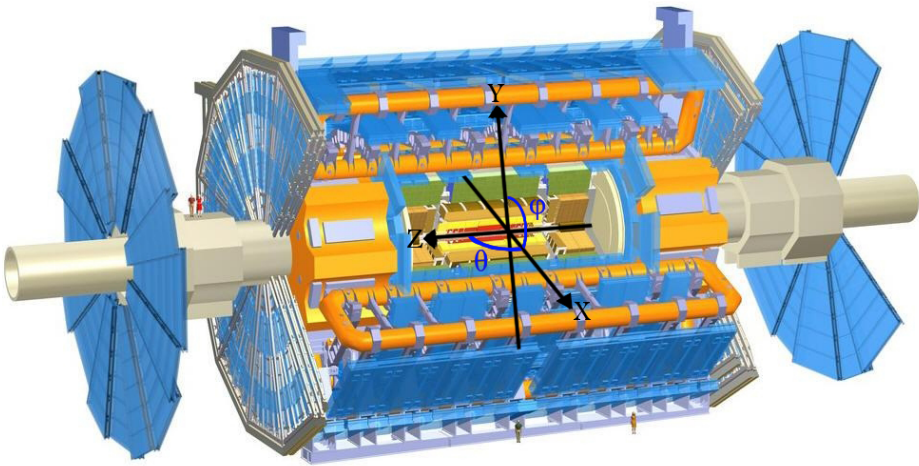

Figure 1.7: *Figure showing the* ATLAS *detector and the definition of the orthogonal Cartesian coordinate system. Image altered from[22]*

1.3.4   Calorimeter

1.3.5   Reconstructing data

Give a general description.

In this thesis, truth = Montecarlo. Reconstructed data = that which is seen in the detectors, which is the smeared data.

1.3.6   Pile-up

1.3.7   Mono-jet analysis

What is a jet? why are we only looking at transverse missing energy?

1.3.8 Phase II high luminosity upgrade

Talk about the upgrade schedule. [1] I am looking at the upgrade which will be done at CERN and will be completed around 2022-2023 and is denoted High Luminosity-LHC Phase 2 upgrade. When this is running the following is expected:

Entity	Expected	Last run (2012)
Luminosity	1000-3000 fb^{-1}	20.8 fb^{-1}
Pile-up	$\langle \mu \rangle = 200$	$\langle \mu \rangle = 20.7$
Center of mass energy	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 8$ TeV

Table 1.2: Expected running values for the Phase II HL-upgraded LHC with older values for comparison. REFERENCE?

Taken from "a short explanation of different terminology by me" Find a cern source. Assumed effects, timespan when will it be done?

1.3.9 Monte Carlo simulation, truth data

What it is in short detail. How it is set-up and what it produces for us in this context. Where does it come from? Perhaps quick explanation of different programs? PYTHIA which is the generator? [23]

1.3.10 ROOT

A wonderful tool for processing data by programming in C++ and so on... Reference to root homepage?

2

Method

In this chapter the methodology used to perform the tasks given above in section 1.1.

2.1   Validation of smearing functions

Find more information in my presentation. also mention no pile-up dependence of leptons. For the proposed upgrade of the LHC.

The validation was done for **what MCdata? and validated for which pile-up?**

2.1.1   Smearing

One might assume that using a Monte Carlo simulation it would be easy to model and simulate the whole process, from collision to detection and reconstruction in the upgraded LHC. It is possible, but it requires a lot of computing power. Instead one can use one simulation and a mathematical model to calculate the estimated response in the detector. This was validated and used in this thesis to be able to create the data needed for further analysis.

This was done by using a Monte Carlo simulation of a proton-proton collision the applying official Truth to reco code that was developed using previous studies [24]; to simulate the effect that pile-up would have on the signals that come from the detectors and the reconstruction of these. **Code from where?**

The code uses the experimental data from the previous studies to smear the reconstructed energy and momenta; It does not however alter the direction of the momenta. Other experimental data was used and shows that only jets and E_T^{miss} are affected by pile-up.

The data was taken from these processes:

- Electron, W$\rightarrow e\nu$

- Muon, W$\rightarrow \mu\nu$

- γ, γ + Jet sample.

- Tau, W$\rightarrow \tau\nu$

- Jets, Jet sample.

- E_T^{Miss}, Z$\rightarrow \nu\nu$ + Jet sample

That this is true can be shown from **figures and references from nonpileupdep.txt presentation!**. The smearing functions should be given!

Perhaps under results?

2.1.2   Validation

To validate the smearing code comparisons were made with [24].

Parametrization used according to the paper [24]. What results and what did I get/say in my presentation? Use that in results Perhaps even write something better than the original that can be used to explain this again.

- For electron, photon:
  $\sigma = 0.3 \oplus 0.1\sqrt{E(GeV)} \oplus 0.01E(GeV), |\eta| < 1.4,$
  $\sigma = 0.3 \oplus 0.15\sqrt{E(GeV)} \oplus 0.015E(GeV), 1.4 < |\eta| < 2.47$

- For muon: $\sigma = \frac{\sigma_{id}\sigma_{ms}}{\sigma_{id}\oplus\sigma_{ms}}$
  $\sigma_{id} = P_T(a_1 \oplus a_2 P_T), \sigma_{ms} = P_T(\frac{b_0}{P_T} \oplus b_1 \oplus b_2 P_T)$

- For tau: $\sigma = (0.03 \oplus \frac{0.76}{\sqrt{E(GeV)}})E(GeV)$, for 3 prong.

- For Jet: $\sigma = P_T(GeV)(\frac{N}{P_T} \oplus \frac{S}{\sqrt{P_T}} \oplus C)$
  Where N, S, and C are parameters found in the paper, that depend on η.
  N is also dependent on the pile-up that is simulated.

- For E_T^{miss}: $\sigma = (0.4 + 0.09\sqrt{\mu})\sqrt{\sum E(GeV) + 20\mu}$

Here each sigma represents the **absolute?** rms.

One prong for tau exists, though was not used!

Remember for the discussion to mention different types of rms, relative or absolute. and the problem which occurred with this and the papers faults.

2.2   Evaluating dark matter signals

The main goal of the thesis is to investigate if certain dark matter signals can be detected after the high luminosity upgrade. One immediate worry is that the background will be large in comparison to the signal, thus making it undetectable.

The following signals models have been used: **Here only the operators should be explained, or different models. The names and the MC here or in appendix?** They are explained somewhat in the introduction. Each of these has been evaluated in different signal regions and the detectability has been evaluated using a statistical P-value. This process has been performed at different pile-up values.

What background existed? How was it simulated in MC? Should that be here or in appendix?

2.2.1   Signal to background ratio

What I am doing now, looking at what signal? What are the different background processes? What and why was the weight used?

Signals should be explained somewhat in the introduction.

Look at presentation, is it worth bringing up the first signal regions when the data has already been filtered? Should that be here?

2.2.2   Selection criteria

What criteria were used and more importantly why? It is quite important that you can explain why this was used.

2.2.3   Comparing with published papers

To verify that the background data was correct it was compared with [25], in which the luminosity if 10 fb^{-1} and thus the expected values from the paper scaled up with a factor 100. **Also, somewhat unexpectedly is that the difference in center of mass energy required the cross-sections to be lowered than compared with the upgrade.** The signal region used in the article were the following:

- Jet veto, require no more than 2 jets with $p_T > 30 GeV$ and $|\eta| < 4.5$

- Lepton veto, no electron or muon, leading jet with $|\eta| < 2.0$ and $\Delta\phi(jet, E_T^{miss}) > 0.5$ (second-leading jet)

- Leading jet with $p_T > 500 GeV$ and $E_T^{miss} > 500 GeV$

The article has several different signal regions, the difference is the last item, unfortunately since the simulated events are already filtered before the analysis only one of the regions could be used.

Process	Simulated events	Expected events (Scaled to 1000 fb^{-1})
Z$\to \nu\nu$	27675.1	27000
W$\to \tau\nu$	6506.09	3900
W$\to e\nu$	1660.06	1600
W$\to \mu\nu$	2048.77	4200
Total background	37890	36700

Table 2.1: *Comparison of the simulated and expected events from [25].*

In table 2.1 a comparison has been made. It can be seen that the simulated events and expected events coincide on all accounts apart from W$\to \tau\nu$, W$\to \mu\nu$ and thus the total as well. **This can be explained by better separation of μ, τ and missing energy.**

2.2.4   Figures of merit

P-value, see more in Majas phd thesis when completed.

2.3   Other selection criteria and observables

2.4   Mitigating the effect of the high luminosity

3

Results

3.1 Validation of smearing functions

Figures from validation: Take from the presentation, explain somewhat more but keep to the electron.

3.2 Signal to background ratio

3.3 Other selection criteria and observables

3.4 Mitigating the effect of the high luminosity

4

Discussion

4.1 Validation of smearing functions

4.2 Mitigating the effect of the high luminosity

4.3 Viability of different signals

5

Conclusions

5.1 Recommendations to mitigate the effect of the high luminosity

5.2 Suggestions for future research

Sätt av ett kort kapitel sist i rapporten till att avrunda och föreslå rikningar för framtida utveckling av arbetet.

Saving as reference. test citing as: Here we cite Duck [26] [26].

If the above works, remember to edit myreferences.

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