

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 Stockholms universitet

Linköping, May 27, 2014

LiTH-IFM-EX--YY/NNNN--SE



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## **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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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.

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Finally I want to thank: Someone someone for proofreading my

*Linköping, May 2014*  
*Sven-Patrik Hallsjö*



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# Notation

## ABBREVIATIONS

Abbreviation	Meaning
ATLAS	A large Toroidal LHC ApparatuS
CERN	Organisation européenne pour la recherche nucléaire
LHC	Large Hadron Collider
SUSY	SUperSYmmetry



# 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. 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 this there are other phenomena that can not be explained today. One of the proposed models to correct these discrepancies is known as Supersymmetry (SUSY).

In this chapter an introduction to both the theoretical and experimental details are given. Explain the phase 2 high luminosity upgrade? Or atleast refer to where more is written. Why was this topic chosen? What is the purpose of the introduction?

## 1.1 Research goal

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  $Z$ , that measures the sensitivity of the experiment to the dark matter signal. Calculate  $Z$  for the given selection criteria before and after smearing.
- What is the effect of the high luminosity (smearing) on the value of  $Z$ ?
- Investigate other selection criteria and observables, to mitigate the effect of high luminosity. Use  $Z$  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. Find more information in (references).

### 1.2.1 Quantum mechanics and quantum field theory

Speak about: Why QM, Lagrangian refer to classical mechanics, end with hand of to particle physics. need to explain observables.

Dont forget to explain cross-sections from qft.

### 1.2.2 Four-vectors

### 1.2.3 Effective field theory

Which one do we use? What parameters have we joined? How does this pertain to the rest?

### 1.2.4 Nuclear, particle and subatomic particle physics

Can be seen as the experimental counterpart to quantum mechanics. Many could argue that these branches started after Ernest Rutherford famous gold foil experiment (reference), where he discovered that matter is composed of matter with a nucleus, a lot of empty space and electrons. This and more sparked the curiosity to see what the nucleus was made of and so on...

The discovery of the quark diving of bosons/fermions different generations. Fundamental particles. Basically all of 20th century physics.

Some thing so that a description of particles are in here, end with standard model. Content should be enough for the rest of the thesis regarding collisions etc. Luminosity!

### 1.2.5 The standard model of particle physics

How and why is there a standard model? give the Lagrangian and refer to all the different interactions that are included. Which then combines QM with subatomic particle physics.

Mention Antimatter! Is it proved? What problems exist?

### 1.2.6 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)

Different problems, hierarchy, etc

Bring up different expansions. Here we will talk about supersymmetry (SUSY) end with neutrino/WIMPS. Minimal Supersymmetric Standard Model

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

## 1.2.7 Dark matter: Concept

## 1.2.8 Dark matter: Candidates

Weakly interacting massive particles (Wimps) are a candidate to explain Dark matter, it is this candidate which is considered in this thesis. In addition the condition that the WIMPS are Dirac fermions (fermions which are not their own antiparticle) is implied.

In 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	$\frac{1}{4M_*^3} \bar{\chi} \chi \alpha_s (G_{\mu\nu}^a)^2$

**Table 1.1:** From [1]

Where D denotes that the WIMPS are assumed to be Dirac fermions.

Alot here taken from [2]

## 1.2.9 Search for WIMPS

Since the search for WIMPS at the LHC is based on looking at  $E_T^{Miss}$  it will be canonical though the experiment can not establish if a WIMP is stable on a cosmological time scale and thus if it is a Dark matter candidate [1]

What is it? Why at CERN/ATLAS? Candidates? Dark matter is something which does not interact electromagnetically however it does have a gravitational effect on nearby bodies. Cold dark matter? Non-barionic dark matter. Why not barionic? WIMPS, wimps as candidates. How is this detectable at ATLAS? Finish with this. Refer next chapter and that neutralinos are a candidate.

## 1.3 Experimental overview

What was used in this research and what needs to be explained? Upgrade, pileup etc. Somewhere here explain how the radial coordinate system is defined.

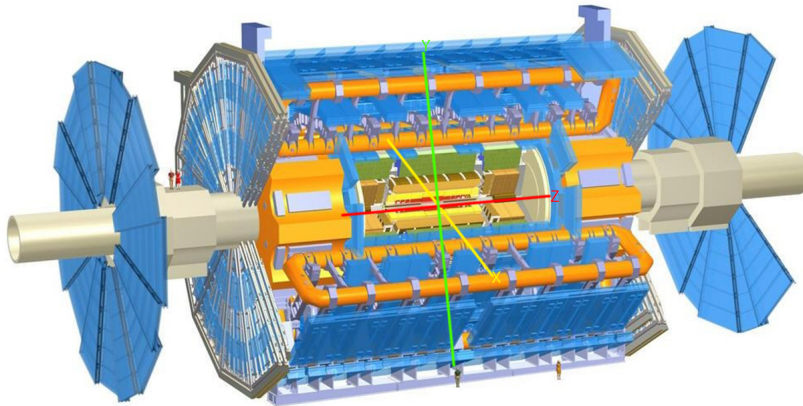
### 1.3.1 Cern

### 1.3.2 LHC

### 1.3.3 ATLAS

### 1.3.4 Coordinate system

Something something



*Figure 1.1: Figure showing the ATLAS detector and the definition of the coordinate system. Image altered from original taken from[3]*

### 1.3.5 Commonly used four-vectors

### 1.3.6 Calorimeter

### 1.3.7 Truth and reconstructed data

Give a general description.

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

### 1.3.8 Jet and missing energy

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

1.3.9 Phase II high luminosity upgrade

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 <sup>-1</sup>	20.8 fb <sup>-1</sup>
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?

# 2

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## Method

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

## 2.1 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?

## 2.2 ROOT

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

## 2.3 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.

### 2.3.1 Smearing

By using the simulation given above one might assume that it would be easy to model and simulate the whole process, from collision to detection 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. The programming code used was the **official something that can be found somewhere**. Several histogram are given regarding this here. Some minor detail about them though most of it should be given in results and discussion also refer perhaps to my presentation? Does one self refer?

Why did we use this, what does it produce for us? A "simple" simulated effect of what can be detected in the detectors without having to run a full simulation.

The functions smear both the energy and the momenta of the four vector. However not the angles. Explain four vector somewhere?

Explain why leptons were not affected by pile-up. Presentation 2?

### 2.3.2 Validation

Parametrization used according to the paper [4]. What results and what did I get/say in my presentation? Use that. Perhaps even write something better than the original that can be used to explain this again.

## 2.4 Signal to background ratio

What I am doing now, looking at what signal? What are the different background processes?

### **2.4.1 Selection criteria**

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

### **2.4.2 Figures of merit**

what is it? how is it calculated?

## **2.5 Other selection criteria and observables**

## **2.6 Mitigating the effect**





# 3

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## Results

Saving as reference. test citing as: Here we cite Duck [5] [5]. If the above works, remember to edit myreferences.

### **3.1 Validation of smearing functions**

Figures from validation:

### **3.2 Signal to background ratio**

### **3.3 Mitigating the effect**



# 4

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## Discussion



# 5

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## Conclusions

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



# Appendix





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## Bibliography

- [1] ATLAS Collaboration. Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the atlas detector. *J. High Energy Phys.*, 04(arXiv:1210.4491. CERN-PH-EP-2012-210):075. 58 p, October 2012. URL <http://cds.cern.ch/record/1485031>. Cited on page 4.
- [2] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait, and H.-B. Yu. Constraints on dark matter from colliders. *Phys.Rev.D*82:116010,2010, 82 (11):116010, December 2010. doi: 10.1103/PhysRevD.82.116010. Cited on page 4.
- [3] Joao Pequenaio. Computer generated image of the whole ATLAS detector, Mar 2008. URL <http://cds.cern.ch/record/1095924>. Cited on page 5.
- [4] ATLAS Collaboration. Performance assumptions for an upgraded ATLAS detector at a High-Luminosity LHC. Mar 2013. URL <https://cds.cern.ch/record/1527529/>. Cited on page 8.
- [5] Donald Duck. The history of automatic control. *Duckburg Journal of Science*, 106(3):345–401, 2005. Cited on page 11.



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