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, May 27, 2014

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

Författare
Author

Sven-Patrik Hallsjö

Sammanfattning
Abstract

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Nyckelord
Keywords

ATLAS, Beyond standard model physics, CERN, Dark matter, Elementary particle physics, High energy physics, SUSY, something, this is in mythesis.sty

Abstract

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

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.

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Finally I want to thank someone someone for proofreading my

Linköping, May 2014
Sven-Patrik Hallsjö

Contents

Notation

Notations

Notation	Explanation
barn(b)	1 barn(b)= 10^{-24} cm^2
$\oplus$	$a \oplus b = \sqrt{a^2 + b^2}$, $a \oplus b \oplus c = \sqrt{a^2 + b^2 + c^2}$

Abbreviations

Abbreviation	Expansion
ATLAS	A large Toroidal LHC ApparatuS
CERN	Organisation européenne pour la recherche nucléaire[1]
LHC	Large Hadron Collider
SM	the Standard Model of particle physics
SUSY	SUperSYmmetry
WIMP	Weakly Interacting Massive Particle
WIMPS	Weakly Interacting Massive ParticleS
QED	Quantum ElectroDynamics
QM	Quantum Mechanics

[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 14, 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 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.

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. (Refer to scattering) 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. (Metric description and bending of gravitational fields). The culmination of both of these problems is Quantum electrodynamics (QED)which with incredible precision explains electromagnetic phenomena including effects from special relativity.[4]

Something something Lagrangian of these processes something something can be simply viewed through Feynman diagrams. Explain four-vectors quickly. Somehow end up with Feynman diagrams.

Also mention special rel + qm expects and now proven antimatter.

Speak about: Why QM, Lagrangian refer to classical mechanics, end with hand of to particle physics. need to explain observables. Theoretical Particle physics comes from Feynman diagrams!

Dont forget to explain cross-sections from qft.

Find more information in [2, 4, 5].

1.2.2 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.

Something 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!

Explain hadrons...

From [6]

1.2.3 The standard model of particle physics

The standard model of particle physics, simply the standard model (SM). 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.

From [6] and more for the problems?

Mention Antimatter! Is it proved? What problems exist?

- 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!
- Dark energy?

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.

After this the big question arises, what could this dark matter consist of? One possible explanation comes from SUSY where there exists particles that are massive though will not interact electromagnetically.

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)

Different problems, hierarchy, etc

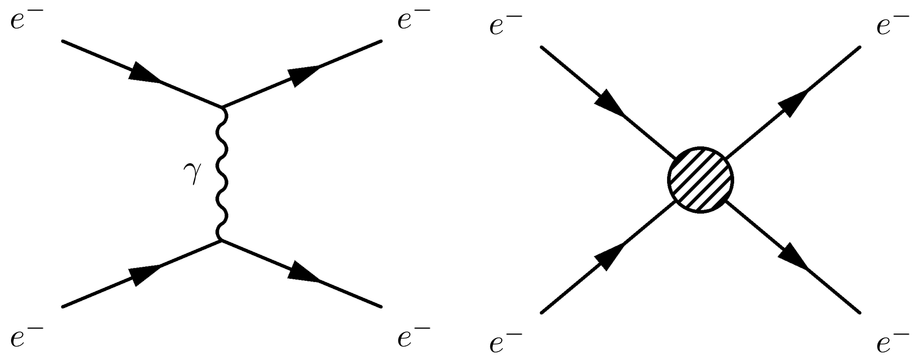
Bring up different expansions. Here we will talk about supersymmetry (SUSY) end with neutrilino Explain how we get wimps: Weakly interacting massive particles (WIMPS) are a candidate to explain Dark matter, it is this candidate which is considered in this thesis. Where these WIMPS. Minimal Supersymmetric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

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

Some from, else from licentiates [7–9]

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 1.1. 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 1.1a.*

Figure 1.1: *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 [10, 11] 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,

$$\Gamma = \left\{1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\right\} \tag{1.1}$$

This will dictate how the operators are written, more of why this is done can be found in [4, 10, 11].

This, together with the **couplings to GG define** 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 [10] and gives:

$$m_\chi \leqslant 2\pi M_* \tag{1.2}$$

where m_χ is the mass of the WIMP and M_* is the mass of the mediator.

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: *From [12]*

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

Also what is looked at is light vector-mediators similar to Z!

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 [12]

Include SUSY-feynman?

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 LHC

The Large hadron collider (LHC) is a particle accelerator located at CERN near Geneva in Switzerland, see figure 1.2. 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 [13].

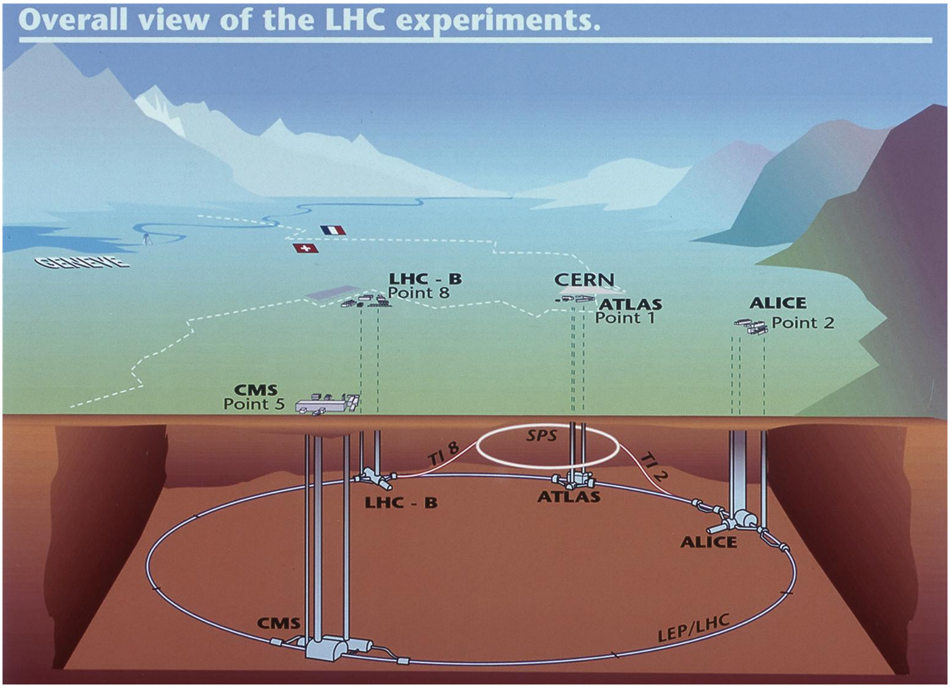


Figure 1.2: *Figure showing the LHC and the different detector sites[14]*

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

$$\mathscr{L} = \frac{fkN_1N_2}{4\pi\sigma_x\sigma_y} \tag{1.3}$$

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:

$$N = \sigma \int \mathscr{L} dt := \sigma \mathcal{L} \tag{1.4}$$

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:

$$\sigma = \oint d\Omega \frac{d\sigma}{d\Omega} \tag{1.5}$$

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 [15]

1.3.2 ATLAS

As seen in figure 1.2, 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 [16]

1.3.3 Coordinate system

The coordinate system of ATLAS, seen in figure 1.3 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 coordinate system is also used for the transversal plane. (R,ϕ,Z). For simplicity the pseudorapidity of particles from the primary vertex is defined as:

$$\eta = -\ln(\tan\frac{\theta}{2}) \tag{1.6}$$

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, $d = \sqrt{\Delta\eta + \Delta\phi}$

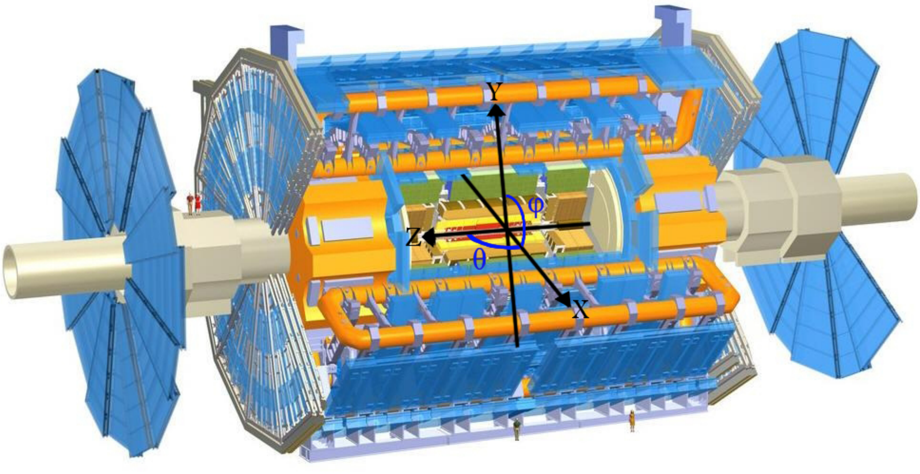


Figure 1.3: *Figure showing the ATLAS detector and the definition of the orthogonal Cartesian coordinate system. Image altered from[17]*

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?

1.4 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?

1.5 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, then applying code, that was developed using previous studies [18] , 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. That this is true can be shown from **figures and references from nonpileupdep.txt presentation!**. The smearing functions should be given!

2.1.2 Validation

To validate the code comparisons were made with [18].

Also include the following so that readers will understand the smearing functions.

$$a \oplus b = \sqrt{a^2 + b^2} \tag{2.1}$$

$$a \oplus b \oplus c = \sqrt{a^2 + b^2 + c^2} \tag{2.2}$$

Parametrization used according to the paper [18]. 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.

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 opperators should be explained, or different models. The names and the MC here or in appendix?** 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 [19], 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 $p_T > 30GeV$ 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 $p_T > 500GeV$ and $E_T^{miss} > 500GeV$

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.

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$\rightarrow \tau\nu$, W$\rightarrow \mu\nu$ and thus the total as well. **This can be explained by better separation of μ,τ and missing energy.**

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

Table 2.1: *Comparison of the simulated and from [19] expected events*

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

3
Results

Saving as reference. test citing as: Here we cite Duck [20] [20]. 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

Discussion

5 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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