Calculation of the Supersymmetric top quark mass at CLIC

Georgios Billis

August 18, 2017

MSc in Theoretical Physics
The University of Edinburgh
2017

Abstract

In this project I calculate the mass of the Supersymmetric top quark in CLIC experiment at $\sqrt{s} = 3$ TeV in e^- e^+ collisions. I assume the following decay for the top squark $\tilde{q} \rightarrow q\ \chi_0$, and I focus on the fully hadronic channel of decay i.e $\tilde{q} \rightarrow q\ \chi_0 \rightarrow Wb\tilde{\chi}_1^0$. The mass was found to be $m_{\tilde{t}} = 861 \pm 19$ GeV using the Boosted Descision Trees Multivariate Analysis and $m_{\tilde{t}} = 812 \pm 20$ GeV using the Gradient Boosted Descision Trees Multivariate Analysis.

Declaration

Contents

List of Tables

List of Figures

Acknowledgements

Put your acknowledgements here. Thanking your supervisor for his/her help is standard practice, but you don't have to do this...

This template is is modification of the one for the MSc in High Performance Computing, which is apparently descended from a template developed by Prof Charles Duncan for MSc students in Meteorology. His acknowledgement follows:

This template has been produced with help from many former students who have shown different ways of doing things. Please make suggestions for further improvements.

Some parts of this template were lifted unashamedly from the Edinburgh MPhys project report guide, with little or no modification. I have no idea who wrote the first version of that...

You don't have to use LaTeX for your dissertation. You can use Microsoft Word or Apple Pages if you wish, but it's *much* easier to typeset equations in LaTeX, and references look after themselves. Whatever you use, your dissertation should have the same general structure, and it should look similar to this one – especially the front page.

Chapter 1

Introduction

On July 2012 the discovery of the Higgs boson was announced at CERN's Large Hadron Collider (LHC). This marked the begining of a new era for experimental High Energy Physics motivating the design of new experiments for further and deeper exploration of the Higgs boson itself but also, a huge marathon addressing the questions/problems that arose with it.

One of these proposed experiments is Compact Linear Collider (CLIC), a high-luminosity linear e^- e^+ collider. It is designed for a staging scenario of three main centre of mass energies at $\sqrt{s}$ = 380 GeV, $\sqrt{s}$ = 1.5 TeV and $\sqrt{s}$ = 3 TeV targeting optimal physics output based on the current landscape. The main difference of CLIC with LHC is that in the latter, protons collide which are non fundamental particles as they consist of quarks and gluons bound alltogether. One of the disadvantages of LHC is the inability to know beforehand the initial state of the colliding particles as quarks exist in a "sea of gluons" making it impossible to know their momenta. This sets some restrictions with resprect to the precision that it can probe various observables.

On the other hand, CLIC is designed to invastigate the interactions of elementary particles, an important advantage since initial states of the colliding particles is known. In advance, LHC suffers from energy loss due to Synchrotron radiation since protons are accelerated in a 27 km circular accelerator whereas CLIC, being linear does not.

The main targets of CLIC are dependent of the energy stage. In the first it will focus on prescision standard model physics such as Higgs and Top quark measurements and in the two subsequent, among others, there will be searches for new physics [1]. One of the theories that aspires to give solutions to many of the problems of Standard Model is Supersymmetry (SUSY). In this theory every particle has a Supersymmetric partner that differs in the spin by 1/2, thus relating bosons with fermions and fermions with bosons.

In the Minimal Supersymmetric Standard Model, the top squarks $\tilde{t}$ decay almost all the times into a top quark t and a dark matter candidate, the neutralino $\tilde{\chi}_1^0$. In this project I will use Multivariate Analisis to discriminate the best it can be achieved between signal and background with the goal to measure the top squark mass at $\sqrt{s} = 3$ TeV in the CLIC accelerator environment.

Chapter 2

CLIC

2.1 Outline of the experiment

CLIC is a proposed e^- e^+ linear collider optimised to perform in three centre of mass stages at $\sqrt{s} = 380$ GeV, $\sqrt{s} = 1.5$ TeV and $\sqrt{s} = 3$ TeV. The purpose of the different energy stages is to fully exploit its scientific potential including precision measurements and searches for physics Beyond the Standar Model.

Specifically, at $\sqrt{s} = 380$ GeV and with an integrated luminosity of $\mathcal{L}_{int} = 500$ fb^{-1}, prescision measurements can be made in the Higgs and the top quark sector. At this enegy stage the Higgsstrahlung process ($e^+e^- \to ZH$) alongside the WW fusion ($e^+e^- \to H\nu_e\tilde{\nu}_e$) are the dominant and can shed light to properties of the Higgs boson in a model independent way [1]. In CLIC there is also a dedicated program for top quark physics, as it is one of the most important particles in SM because it couples strongest to the Higgs field due to its mass but also it has an important role in many of the BSM scenarios. Furthermore at the next two stages leading role will play the proposed scenarios for physics BSM with most importantly Supersymmetry at $\sqrt{s} = 3$ TeV and with $\mathcal{L}_{int} = 2000$ fb^{-1}. This is because CLIC has the potential for direct particle detection up to the kinematic limit of $\sqrt{s}/2$ for pair production but also through indirect detection of observables that are sensitive to BSM scenarios through precision measurements and comparison with the SM expectations, taking advantage of the full energy potential.

Given the linear nature of CLIC, there are no energy losses induced by Synchrotron radiation which appears in circular colliders, but due Beamsstrahlung radiation. As the colsliding bunches get closer to the vertex, the strong electromagnetic fields (up to 10 Tesla) created by the opposing beam, cause deflection of the partices trajectories resulting to emit Synchrotron radiation. The effect is energy-dependent with huge impact at higher energies [2] as it can be seen in the following image [3].

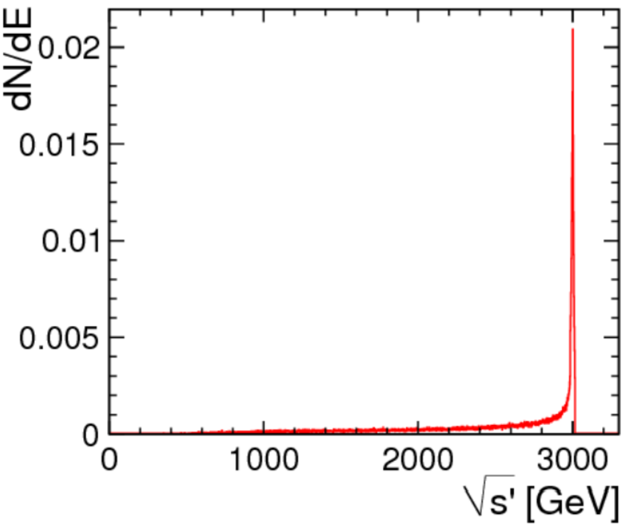


Figure 2.1: The luminosity spectrum for CLIC operating at $\sqrt{s} = 3$ TeV, where $\sqrt{s'}$ is the effective centre-of-mass energy after beamstrahlung and initial state radiation

CLIC is designed to operate for seven, five and six years respectively in each energy stage while the upgrading periods will last two years. The total run will last for 22 years with the following table summarising the luminosities achieved in each stage:

$\sqrt{s}$ (GeV)	$\mathcal{L}$
380	500 fb^{-1}
1.5	1.5 ab^{-1}
3	2 ab^{-1}

Furthermore, the experiment has two detector concepts CLIC SiD and CLIC ILD in order to serve the required jet energy resolution. The latter has been developed for the International Linear Collinder but it has been adapted according to the needs of CLIC. Both detectors have strong central solenoid magnets creating an axial magnetic field of 5T for CLIC SiD and 4T for CLI ILD [3].

Chapter 3

Supersymmetry

3.1 Motivation

The model that describes elementary particle physics is the Standar Model. It involves matter fields (fermions) and vector gauge bosons (force carriers) that they stem from the fact that the SM Lagrngian is subject to $SU(3) \otimes SU(2) \otimes U(1)$ symmetries. An important part of this theory is the existence of the Higgs field which appeared during the unification of the electromagnetic and the weak force. It is known for the fact that it "gives" mass to the elementary particles (besides photons and gluons which they are protected by the $U(1)$,$SU(3)$ symmetries respectively) via Spontaneous Symmetry Breaking .

It is true that even with the great success that the SM has been probed does not consist a flawless theory. Many parts of it are still to be answered or contain significant controversies. One example is the Hierarchy problem. In the electroweak sector of the SM there is a parameter that has the dimensions of energy, the vacum expectation value of the Higgs field which phenomenologicaly is

$$v \approx 246 \quad GeV \tag{3.1}$$

The importance of this parameter is that it sets the masses of the the theory and as well as the Higgs boson itself as it is

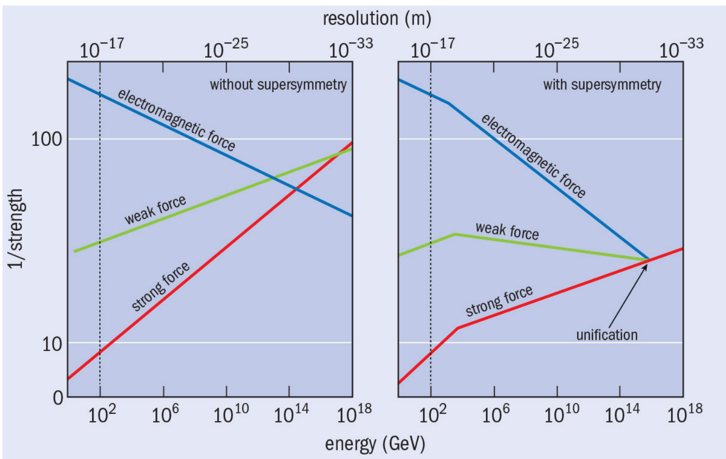
$$M_H = v\sqrt{\frac{\lambda}{2}} \tag{3.2}$$

where λ is the constant of the Higgs self interaction. The problem arises when we try compute higher order corrections to the mass of the Higgs field. The self energy of the higgs boson has a term of the form

$$\int^{\Lambda} d^4k \quad f(k, external \quad momenta) \tag{3.3}$$

where Λ represents the scale of the new physics such as the effects of quantum gravity. In dimensional regularisation, when $\Lambda \to \infty$ the renormalisability of the theory assures that there is no inconsistency, but if we take into account a scale, for example, for the quantum gravity then $\Lambda \to M_P \approx 1.2 \times 10^{19} \quad GeV$ which is the Plank mass, then the additive quantum corrections for the Higgs mass become too big dragging the value of the Higgs mass up. Because the VEV of the Higgs boson has a fixed phenomenologicaly value, one way to circumvent this problem is by relating bosons with fermions since in the latter, the algebraic terms for their self energies come with a minus sign giving the desired calcelations without any "fine tuning" from our side. This results into the SUSY theory stabilising the Hierarchy $M_H \ll M_P$ with the constraint that the SUSY particles should be visible at a scale not too much greater than 1-10 TeV [4].

One other feature that makes SUSY attractive is the fact that it includes the convergence of the couplings, something that it is known as Grand Unification. From the point of view of SM, something like that is unable to achieve since two of the couplings decrease with energy (weak and strong coupling) whereas one (electromagnetic) increases. In the MSSM, by the inclusion of the sparticles such unification is actually achievable as it can be seen in the following figure:



3.2 SUSY Phenomenology

Inside SUSY every boson is related to a fermionic supersymmetric partner and every fermion has a bosonic one. The fermion superpartners are called sfermions and differ in the spin value by 1/2 whereas the boson particles which are the force carries are related to a spin 1/2 particles, the gauginos. In the following table I show the correspondance between SM and SUSY gauge particles.

Standard Model		SUSY	
Photon	γ	Photino	$\tilde{\gamma}$
Gluon	g	Gluino	$\tilde{g}$
Z Boson	Z	Zino	$\tilde{Z}$
W Boson	$W^{\pm,0}$	Wino	$\tilde{W}^{\pm,0}$
B Boson	B	Bino	$\tilde{B}$

The framework of this project is the Minimal Supersymmetric Standard Model which besides the SM particles includes the sleptons $\tilde{\ell}^{\pm}$, the sneutrinos $\tilde{\nu}_l$, the squarks $\tilde{q}$, the gluinos $\tilde{g}$, two pair of charginos $\tilde{\chi}_i^{\pm}$ where $i = 1, 2$, four neutralinos $\tilde{\chi}_i^0$, $i = 1, ..., 4$ and five Higgs bosons h^0, H^0, A^0,$H^{\pm}$.

Both particles and sparticles belong to the same super-multiplet having the same mass and the same quantum numbers as their SM partners but with different spin. Because no such degenerate fermion-boson pair exists in nature, then it is deduced that SUSY must be a broken symmetry. In order to constitute a solid solution to the Hierarchy problem, then the difference in the masses of the particles and their supersymmetric partners must be of the order of $\mathcal{O}(1TeV)$ [5].

In Standard Model, for the Spontaneous Symmetry Breaking one Higgs doublet is needed with 4 degrees of freedom. For the SUSY model on the other hand two such doublets are required with a total of eight degrees of freedom where three of them are absorbed to give mass to the SM particles such as $W^{\pm}$ and Z, and the remaining five give rise to five physical Higgs bosons $\tilde{h}$,$\tilde{H}^{\pm}$,$\tilde{A}$, $\tilde{H}^0$. Those in turn, mix further to become the neutralinos and the charginos : $\tilde{\chi}_i^0$, $\tilde{\chi}_i^{\pm}$.

It is known that within the SM the fermions carry chirality denoted by L or R whether they are left or right respectively, according to the way they transform under the symmetry group $SU(2)\otimes U(1)$. Thus given the SUSY relation of fermions-bosons that means that the sfermions (bosonic superpartners), come into doublets of the form $(f_i, \tilde{f}_i)$, where i=L,R. The sfermions mix further to make the eigenstates of the mass matrix. This mixing is expected to be strong for third generation sfermions since the Yukawa couplings can be large, more precisely in our case the stop quark mixing effects can be large because of the large mass of the top quark.

The following matrix is the mixing matrix expressed in the $(\tilde{f}_L, \tilde{f}_R)$ basis:

$$\mathcal{M}^2_{\tilde{f}} = \begin{pmatrix} M^2_{\tilde{f}_L} & \alpha_f m_f \\ \alpha_f m_f & M^2_{\tilde{f}_R} \end{pmatrix}$$

where the $M^2_{\tilde{f}_L}$ are terms that depend on the mass of the quark, the charge and the third component of the weak isospin. The off diagonal elements α_f are dependent on the soft SUSY breaking trilinear scalar coupling parameters.

In this project I will focous on the top squarks where the mixing $\tilde{t}_R - \tilde{t}_L$ is important due to the large top quark mass. By computing the eigenvalues of the previous matrix and for the right flavour we obtain:

$$m^2_{\tilde{t}_{1,2}} = \frac{1}{2}(M^2_{\tilde{t}_L} + M^2_{\tilde{t}_R} \mp \sqrt{(M^2_{\tilde{t}_L} - M^2_{\tilde{t}_R})^2 + 4m_t^2\alpha_t^2}) \tag{3.5}$$

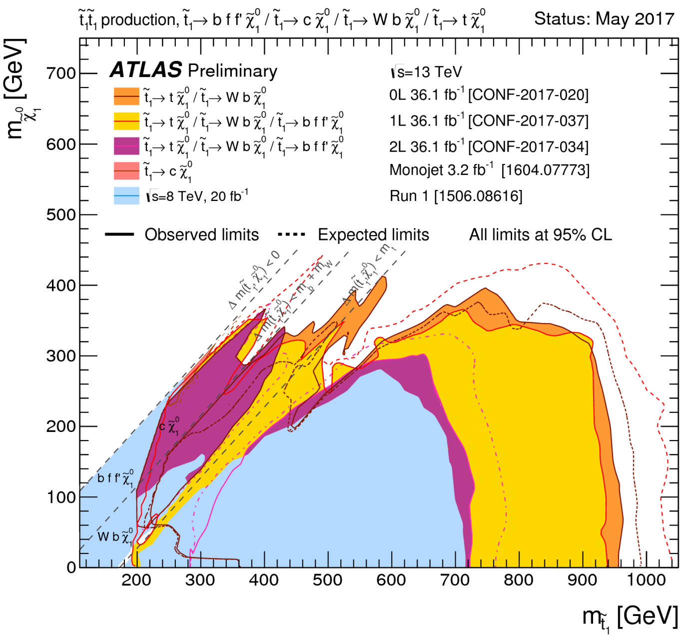
It is obvious that the $m^2_{\tilde{t}_1}$ will have the lowest mass, something that makes it the lightest squark.

3.3 Results from LHC for SUSY

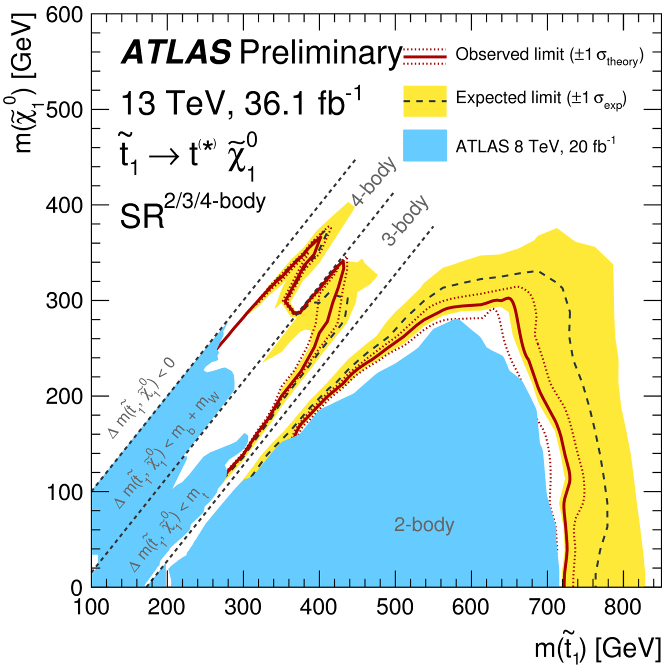
The search for indications for Supersymmetry is not new as LHC has been optimized and focused among other to the direct or indirect detection of sparticles. The majority of the cases that have been studied, consider as main decay channel of the sparticles the following:

$$BR(\tilde{q} \to q\chi_i^{0,\pm}) = 100\% \tag{3.6}$$

So far thought no indication of SUSY has been found in LHC but through each analysis the exclusion limits for the SUSY observables become bigger and bigger as it can be seen in the following figures that summarises the latest of them for the stop quark mass at $\sqrt{s} = 8{,}13$ GeV in proton proton collisions [6]:



Whereas in the following figure there are the exclusion limits in ATLAS for p-p collisions at 13 TeV for the channel invastiged in this project



Chapter 4

Methods

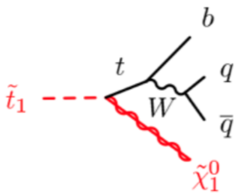
4.1 Introduction

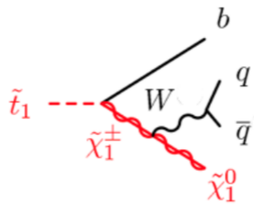
In this chapter I will describe the exact conditions and methods that were followed in this project for the calculation of the stop quark mass at CLIC Conceptual experiment.

I will invedtigate the production of a pair of stop quarks at $\sqrt{s} = 3$ TeV and assumig an integrated luminosity of $\mathcal{L}_{int} = 2000$ fb^{-1}. The channel of interest is the following:

$$e^+e^+ \rightarrow \tilde{t}\tilde{\bar{t}} \rightarrow t\tilde{\chi}_1^0\bar{t}\tilde{\chi}_1^0 \rightarrow W^+W^-b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \tag{4.1}$$

and for this model the mass of the top squark is $m_{\tilde{t}} = 844$ GeV whereas the mass of the neutralino is $m_{\tilde{\chi}_1^0}$. This is not the only possible decay of a top squark but it is the dominant one. In what follows I show the top three branching ratios of the top squark decay and two of the corresponding Feynmann diagrams:





1. BR($\tilde{t} \to t\tilde{\chi}_1^0$) = 52.4 %
2. BR($\tilde{t} \to b\tilde{\chi}_1^\pm$) = 34.1 %
3. BR($\tilde{t} \to t\tilde{\chi}_2^0$) = 13.2 %

As also the branching ratios for the decay of the W boson to either in a hadronic final state or in a leptonic one are:

- BR($W \to q\bar{q}$) = 67.8 %
- BR($W \to l\nu_l$) = 32.2 %

In the following I summarise the possible decays of the stops indicating the branching pair fraction for each one:

- $e^-e^+ \to \tilde{t}\tilde{\bar{t}} \to t\tilde{\chi}_1^0\chi_1^\pm b \to W^+W^-b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad (35.8\%)$
- $e^-e^+ \to \tilde{t}\tilde{\bar{t}} \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad (27.4\%)$
- $e^-e^+ \to \tilde{t}\tilde{\bar{t}} \to t\bar{t}\tilde{\chi}_1^0\chi_2^0 \to W^+W^-b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 h \quad (13.7\%)$
- $e^-e^+ \to \tilde{t}\tilde{\bar{t}} \to b\bar{b}\chi_1^+\chi_1^- \to W^+W^-b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad (11.6\%)$
- $e^-e^+ \to \tilde{t}\tilde{\bar{t}} \to t\tilde{\chi}_2^0\chi_1^\pm b \to W^+W^-b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 h \quad (9\%)$

4.2 Calculation of SUSY particle masses

Chapter 5

Results and Analysis

This section should detail the obtained results in a clear, easy-to-follow manner. It is important to make clear what are original results and what are repeats of previous calculations or computations. Remember that long tables of numbers are just as boring to read as they are to type-in!

Use graphs to present your results wherever practicable.

Results or computations should be presented with uncertainties (errors), both statistical and systematic where applicable.

Be selective in what you include: half a dozen *e.g.* tables that contain wrong data you collected while you forgot to switch on the computer are not relevant and may mask the correct results.

5.1 Some results

Here are some results.

5.1.1 More results

When showing results you are likely to use tables and graphs. You can create tables easily in LaTeX.

If you want to produce fancier tables than shown in Table 5.1 refer to the LaTeX manual or ask Google.

One of the simplest ways to produce simple graphs is to use gnuplot which produces LaTeX output. Graph (5.1) was produced using gnuplot with output

File names	Satellite	Resolution
worldr	Meteosat	5km
worldg	Meteosat	5km
worldb	Meteosat	5km

Table 5.1: This is a simple table. More complicated tables can have headings which pass over more than one column

designated as LaTeX so that a LaTeX output file is produced which you can include directly or keep separate and refer to using the *include* command.

Another approach is to draw simple figures using *xfig* which allows you to export diagrams in LaTeX picture format so that the diagram can be included directly.

Perhaps the most robust way to include graphs is to convert them to PostScript or PDF and include them in the same was as was done in Figure **??** for the University Crest. You can usually do this with most packages, including Microsoft ones; one trick for producing PostScript is to print to a dummy PostScript printer.

5.2 Discussion of your results

This section should give a picture of what you have taken out of your project and how you can put it into context.

This section should summarise the results obtained, detail conclusions reached, suggest future work, and changes that you would make if you repeated the project.

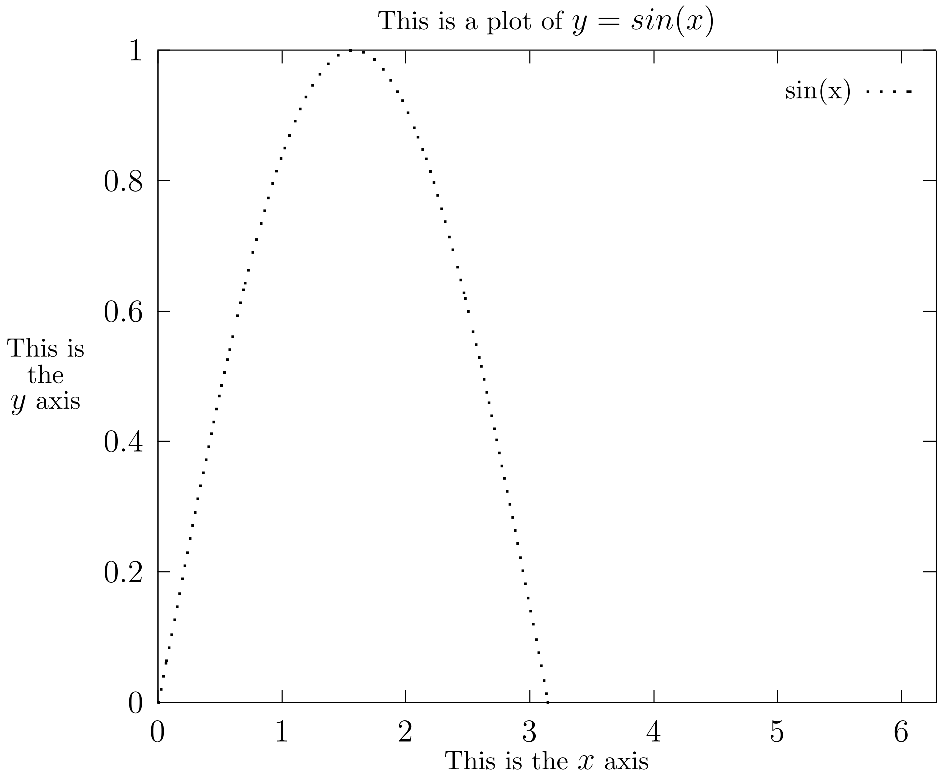


Figure 5.1: Simple Gnuplot example

Chapter 6

Conclusions

This is the place to put your conclusions about your work. You can split it into different sections if appropriate. You may want to include a section of future work which could be carried out to continue your research.

The conclusion section should be at least one page long, preferably 2 pages, but not much longer.

Appendix A

Stuff that's too detailed

Appendices should contain all the material which is considered too detailed to be included in the main body of the text, but which is important enough to be included in the thesis.

Perhaps this is a good place to mention BibTeX.

You can do references in the simple way explained in the introduction, or you can use BibTeX.

A.1 BibTeX

It is convenient to use BibTeX to compile your bibliography. First you need to create a .bib file e.g. you may call it ref.bib Then you can put all your references into the file with entries such as

```
@Book{ob:bornwolf,
     author = "Born, M and Wolf, E",
     title  = "Principles of Optics",
     publisher = "Cambridge University Press",
     year = 1999,
     edition = {7th},
}

@Article{jr:ashkin,
Author = {A. Ashkin and J.M. Dziedzic and J.E. Bjorkholm and S. Chu},
Title = "Observation of a single beam gradient force optical tap for
dielectric particles",
```

```
Journal = "Optics Letters",
Volume = 11,
Pages = "288-290",
Year = 1986}

@INPROCEEDINGS{seger,
 author = {J. Seger and H.J. Brockman},
 title = {What is bet-hedging?},
 editors={P.H. Harvey and L. Partridge},
 booktitle = {Oxford Surveys in Evolutionary Biology},
 year={1987},
 page={18},
 publisher={Oxford University Press},
 place={Oxford}}
```

for a book, an article in a journal or an article in a proceedings volume respectively.

Inside your LaTeX file you should include

```
\bibliographystyle{unsrt}
and
\bibliography{ref}
```

The first command determines the reference style, here plain and unsorted. With this referencing style a numerical referencing system (which is now the most common in physics literature) is used and the numbering of references will be the order in which they appear in the document. Alternatively, you could use a customised 'style file' but there is no real need. The second command just inputs your .bib file Note that only the references cited in the text will appear in the bibliography so you can have spare references in your .bib file.

You use the name you have given to an entry (e.g. for the book example above the name is ob:bornwolf) to cite the relevant article by using the cite command in your LaTeX file e.g. [**?**]

A.2 Producing your documents using `pdflatex`

To use pdflatex your figures need to be in pdf format. You can convert almost any image file to pdf using `convert`. e.g. `convert myfigure.png myfigure.pdf`.

The first time you should type:

```
pdflatex ProjectReport
bibtex ProjectReport
pdflatex ProjectReport
pdflatex ProjectReport
```

This first time you run`pdflatex` it will produce a `ProjectReport.aux`. The BibTeX command reads in the bibliography file and makes the files `ProjectReport.bbl` and `ProjectReport.blg` files. These files are read in the next `pdflatex` command, but you'll still have "undefined cross-reference" errors which are sorted out by the last `pdflatex` command.

Subsequently, you should only need to do one (or two) `pdflatex`s, or `pdfbibtex` followed by `pdflatex` twice if you change any references.

You may also use plain `latex` instead of `pdflatex`. This requires you to use postscript graphics instead of pdf.

Appendix B

Stuff that won't be read by anyone

Some people include in their thesis a lot of detail, particularly lots of tables containing raw results, figures of intermediate results, or computer code which no-one will ever read. You should be careful that anything like this you include should contain some element of uniqueness which justifies its inclusion.

Bibliography

[1] The CLIC, MJ Boland, U Felzmann, PJ Giansiracusa, TG Lucas, RP Rassool, C Balazs, TK Charles, K Afanaciev, I Emeliantchik, et al. Updated baseline for a staged compact linear collider. *arXiv preprint arXiv:1608.07537*, 2016.

[2] Giovanni Bonvicini, E Gero, R Frey, W Koska, C Field, N Phinney, and A Minten. First observation of beamstrahlung. *Physical review letters*, 62(20):2381, 1989.

[3] H Abramowicz, A Abusleme, K Afanaciev, N Alipour Tehrani, C Balázs, Y Benhammou, M Benoit, B Bilki, J-J Blaising, MJ Boland, et al. Higgs physics at the clic electron–positron linear collider. *The European Physical Journal C*, 77(7):475, 2017.

[4] Ian JR Aitchison. Supersymmetry and the mssm: An elementary introduction. *arXiv preprint hep-ph/0505105*, 2005.

[5] Yorikiyo Nagashima. *Beyond the standard model of elementary particle physics*. John Wiley & Sons, 2014.

[6] Morad Aaboud, G Aad, B Abbott, J Abdallah, O Abdinov, B Abeloos, R Aben, OS AbouZeid, NL Abraham, H Abramowicz, et al. Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in s= 13 tev p p collisions with the atlas detector. *Physical Review D*, 94(5):052009, 2016.