

Possible Organization for Writing a Thesis including a \LaTeX Framework and
Examples

by

A Graduate Advisor

B.Sc., University of WhoKnowsWhere, 2053

M.Sc., University of AnotherOne, 2054

A Dissertation Submitted in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

in the Department of Whichever

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University of Victoria

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Supervisory Committee

Dr. R. Supervisor Main, Supervisor
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Dr. M. Member One, Departmental Member
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ABSTRACT

This document is a possible Latex framework for a thesis or dissertation at UVic. It should work in the Windows, Mac and Unix environments. The content is based on the experience of one supervisor and graduate advisor. It explains the organization that can help write a thesis, especially in a scientific environment where the research contains experimental results as well. There is no claim that this is the *best* or *only* way to structure such a document. Yet in the majority of cases it serves extremely well as a sound basis which can be customized according to the requirements of the members of the supervisory committee and the topic of research. Additionally some examples on using L^AT_EX are included as a bonus for beginners.

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I would like to thank:

my cat, Star Trek, and the weather, for supporting me in the low moments.

Supervisor Main, for mentoring, support, encouragement, and patience.

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I believe I know the only cure, which is to make one's centre of life inside of one's self, not selfishly or excludingly, but with a kind of unassailable serenity-to decorate one's inner house so richly that one is content there, glad to welcome any one who wants to come and stay, but happy all the same in the hours when one is inevitably alone.

Edith Wharton

DEDICATION

Just hoping this is useful!

Chapter 1

Introduction

Chapter 2

Theory

The **Standard Model of Particle Physics (SM)** [15, 17, 12, 11] is a quantized relativistic field theory that describes all known elementary particles, as well as their interactions via three of the four known fundamental forces. It has been tested extremely rigorously since its development in the 1960s and 1970s, and in every case its predictions have held true. The final piece of the puzzle fell into place with the experimental verification of the existence of the Higgs Boson in 2012 [1].

Despite its success, however, the SM is considered an incomplete theory. It does not describe the interaction of matter via the fourth fundamental force, gravity, nor does it account for the existence of *dark matter* in our universe, or the asymmetry between the observed amounts matter and anti-matter. These shortcomings provide motivation to extend the SM by searching beyond it for new phenomena.

This chapter will provide a short overview of the SM theory, before describing some of the deficiencies that motivate an extension of it.

2.1 The Standard Model

2.1.1 The Particles

The elementary particles of the Standard Model are shown in Figure 2.1. They can be categorized into two groups: *fermions* and *bosons*. *Fermions* carry half-integer spin, and constitute the matter that surrounds us. For each fermion there also exists a corresponding anti-particle with an opposite electric charge. In this document anti-particles will be denoted either by the charge (e.g. e^+ vs. e^-) or by a bar overhead e.g. (t vs. \bar{t}). The fermions can be further divided into two groups: *leptons* and

quarks. *Leptons*, the most familiar of which is the electron, interact via the weak force and, if electrically charged, the electromagnetic force. They come in three flavour generations, each of which has a neutral particle (*neutrino*) and a charged fermion with electric charge -1. Unlike leptons, which regularly exist freely, *quarks* exist mostly in bound states called *hadrons*, the most well-know of which are the proton and neutron composed of (u, u, d) and (u, d, d) quarks respectively. Like leptons, quarks come in three generations, each of which has a pair of particles with electric charges $+2/3$ and $-1/3$. They interact via all three forces of the standard model: strong, weak, and electromagnetic.

mass charge spin	$\approx 2.2 \text{ MeV}/c^2$ $2/3$ $1/2$ u up	$\approx 1.28 \text{ GeV}/c^2$ $2/3$ $1/2$ c charm	$\approx 173.1 \text{ GeV}/c^2$ $2/3$ $1/2$ t top	0 0 1 g gluon	$\approx 124.97 \text{ GeV}/c^2$ 0 0 0 H higgs
QUARKS	$\approx 4.7 \text{ MeV}/c^2$ $-1/3$ $1/2$ d down	$\approx 96 \text{ MeV}/c^2$ $-1/3$ $1/2$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$ b bottom	0 0 1 γ photon	
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$ -1 $1/2$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $1/2$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $1/2$ τ tau	$\approx 91.19 \text{ GeV}/c^2$ 0 1 Z Z boson	
	$< 1.0 \text{ eV}/c^2$ 0 $1/2$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $1/2$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $1/2$ ν_τ tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1 W W boson	GAUGE BOSONS VECTOR BOSONS
					SCALAR BOSONS

Figure 2.1: The elementary particles of the Standard Model

Bosons carry integer spin, and mediate the forces via which particles interact. Massless *gluons* and *photons* as well as massive W and Z bosons are spin-1 vector bosons, while the Higgs Boson is a spin-0 scalar boson. The massive W and Z vector bosons are the carriers of the weak force, the photon carries the electromagnetic force, and the gluons carry the strong force binding quarks. Along with interacting with fermions via exchange, bosons are also able to interact among themselves. W bosons are able to directly interact with both Z bosons and photons, as well as self-interacting. Gluons can also self-interact, but Z bosons and photons cannot. The Higgs boson interacts with all massive particles, including self-interaction, and it is

via their interaction with the Higgs field that massive bosons obtain their mass.

2.1.2 Quantum Electrodynamics (QED)

Quantum Electrodynamics (QED) [8, 17, 15] is a quantum field theory of electrodynamics and the electromagnetic force. It describes the interaction of electrically charged particles via the exchange of photons. Mathematically, QED is an abelian (commutative) gauge theory with the gauge group $U(1)$. The fundamental interactions of the theory are: the emission or absorption of a single photon by a charged particle and the creation or annihilation of a pair of charged particles. These interactions can each be represented by various orientations of the Feynman vertex shown in Figure 2.2.

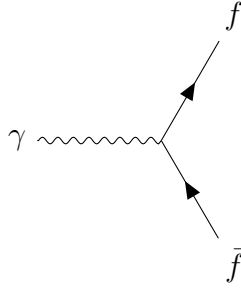


Figure 2.2: The fundamental QED vertex.

2.1.3 Weak Interactions

The weak force [12, 9, 10, 18], in contrast to the electromagnetic force, is mediated by the exchange of massive vector bosons W^+ , W^- , and Z . Owing to the charge of the W bosons, and the fact in contrast to the electromagnetic force neutral fermions also interact via the weak force, there are many more possible fundamental interactions. Figure 2.3 shows the vertices corresponding three such interactions: fermions interacting with the Z boson in a similar vertex to that of Figure 2.2 shown in (a), a charged lepton and neutrino interacting with a W boson shown in (b), and a quark-antiquark pair interacting with a W boson shown in (c).

At high energy scales, the aforementioned electromagnetic force and the weak force unify to become the electroweak interaction. Glashow, Salam, and Weinberg's Electroweak theory unites the two forces into a single $U(1) \otimes SU(2)$ gauge theory.

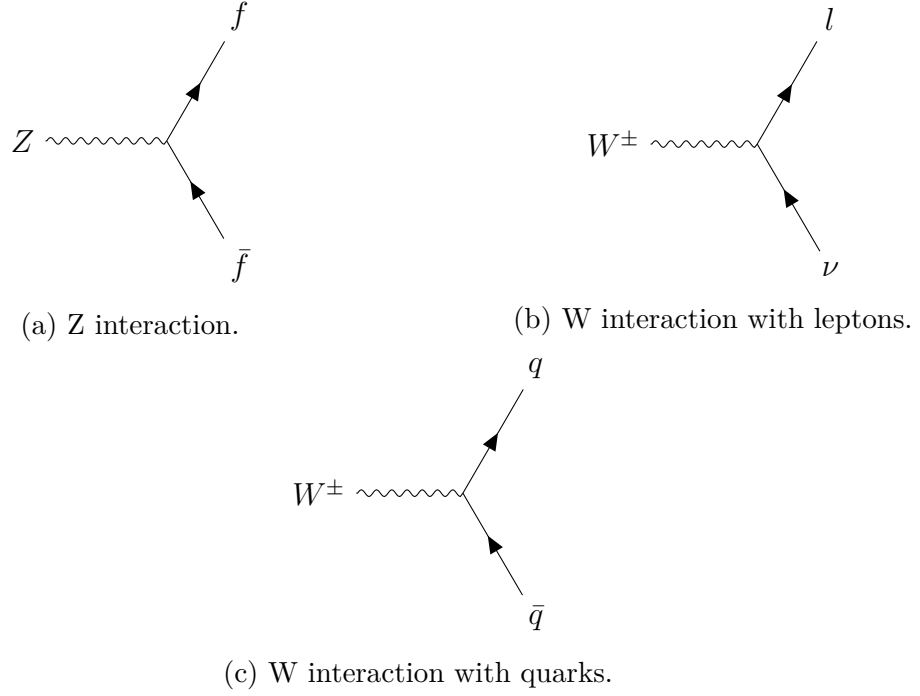
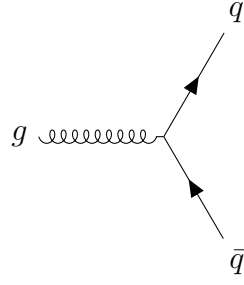


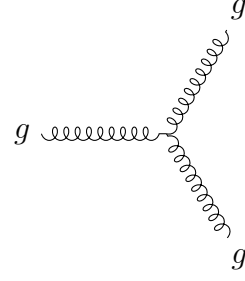
Figure 2.3: Some fundamental weak interaction vertices.

2.1.4 Quantum Chromodynamics (QCD)

Quantum Chromodynamics (QCD) [12, 3] is the theory describing the strong interaction between gluons and quarks. It is again a gauge theory, this time with the $SU(3)$ symmetry group. There are three colour charges associated with this group, which are carried by both quarks and gluons. Each of the 8 gluons carries a unique colour charge and anti colour charge pair, while quarks carry a single colour charge. Because they carry colour charge, gluons are able to both interact with quarks and self-interact. This gives rise to several possible interaction vertices in the theory, some of which are shown in Figure 2.4.



(a) Gluon interaction with quarks.



(b) Gluon self-interaction.

Figure 2.4: Some fundamental QCD interaction vertices.

2.1.5 The Higgs Boson

Electroweak theory alone does not contain a mechanism to provide particles with mass. This contrasts with the observed reality that all fermions as well as W and Z bosons are in fact massive. If the lagrangian of these theories were to contain mass terms, they would lose their gauge invariance and the standard model would not be renormalizable. Instead, these particles acquire their mass through the *Higgs Mechanism* [6, 13, 14].

A new Higgs Field Φ is introduced, with a Lagrangian which can be written as:

$$\mathcal{L}_{Higgs} = (D_\mu \Phi)^\dagger D^\mu \Phi + V(\Phi) \quad (2.1)$$

Where D_μ is the gauge covariant derivative of the electroweak theory. In order for the Lagrangian to remain gauge invariant the Higgs potential $V(\Phi)$ must take the form:

$$V(\Phi) = \mu^2 \Phi + \lambda \Phi^4 \quad (2.2)$$

where λ and Φ are free parameters. λ is forced to be greater than 0 by requiring that the potential have a stable minimum. This leads the potential to have two different possible shapes, shown in Figure 2.5, given the sign of μ^2 :

1. $\mu^2 > 0$: The trivial case of a parabolic potential with a minimum at $\Phi = 0$ arises.

2. $\mu^2 > 0$: A potential with a minimum at:

$$|\Phi| = v = \sqrt{\frac{\mu^2}{\lambda}} \quad (2.3)$$

arises, where v is known as the vacuum expectation value. This minimum is occupied by infinitely degenerate states. This is the case that gives rise to the Higgs mechanism.

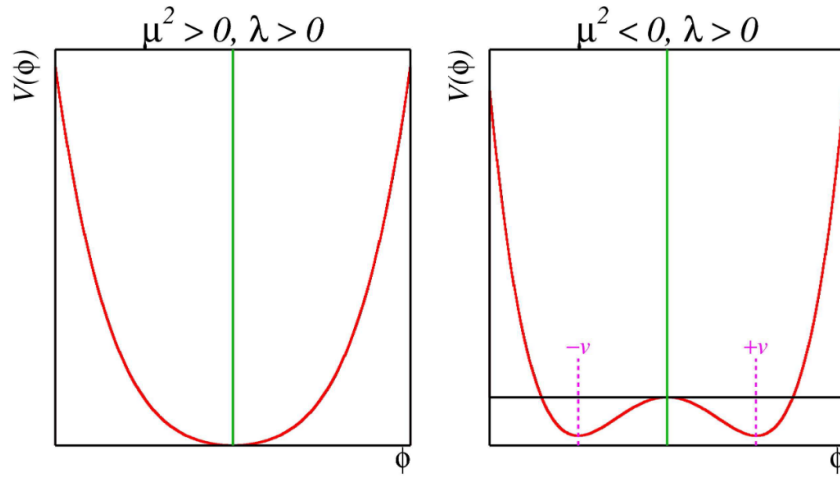


Figure 2.5: Shapes of the Higgs Potential for different cases of μ^2 .

In the second case, the ground states occupying the minimum are not equivalent under gauge transformation, which breaks the Electroweak gauge symmetry. The masses of particles are then determined by the strength of their coupling to the Higgs field.

2.2 Beyond the Standard Model

The Standard Model as described above has proven extremely robust through precise experimental testing. There are, however, many remaining questions in physics that cannot be answered within its confines. Some of those not further explored in this thesis include: whether or not there is a quantum theory of gravity that can tie it to the SM, the exact value of the neutrino masses and whether they are Majorana particles (their own antiparticles), and what the cause is of the matter-antimatter

asymmetry in the universe. The fact that these questions are unanswered in the standard model tells us we must search deeper, and test beyond its limits.

2.2.1 Dark Matter

Another currently open question is the nature of dark matter. Astrophysical observations including the dynamics of galaxy clusters [19] and rotational curves of galaxies [16] are not explained under Einstein's theory of gravitation by visible matter alone. Several theories have arisen over time to explain this discrepancy, including that Einstein's theory is not correct at galactic scales, or that these galaxies contain ordinary matter that is somehow unobservable to us.

Most evidence, however, points to the existence of a new type of matter that interacts gravitationally but not electromagnetically with ordinary matter. Perhaps the most clear evidence for this theory comes from observations of the bullet cluster [4], a pair of colliding clusters of galaxies. In such a scenario, with some normal matter and some dark matter in each cluster, the matter would collide and interact, slowing it down, while the dark matter would pass through largely undisturbed. In the case of the bullet cluster, this separation is observed when comparing the distribution of mass in the galaxies measured by gravitational lensing and the distribution of normal matter in the form of galaxy plasma, measured as emitted x-ray radiation. Figure 2.6 shows the observed separation, with gravitational density in blue and x-ray density in pink.



Figure 2.6: The bullet cluster showing separation of x-ray density (pink) and gravitational density (blue).

2.2.2 Dark Higgs Boson Model

This work involves a search for dark matter produced in association with a new hypothetical scalar “dark Higgs” boson s ¹ [5]. In this model the dark matter particle χ is a majorana fermion, whose mass is generated by a Higgs mechanism in the dark sector. This also generates the new s particle. If the mass of s is less than that of χ then the relic density is set by the process $\chi\chi \rightarrow ss$, followed by the decay of s to standard model particles. The addition of a further particle, such as a massive Z' boson allows this model to be probed at a collider.

The model proposes that the dark matter particle χ obtains its mass from the vacuum expectation value (vev) w of a new Higgs field S . A new $U(1)'$ gauge group is proposed, under which S carries a charge q_s . As a result, the vev w of S breaks the gauge symmetry, and through this mechanism the mass of the corresponding Z' boson is generated. Additionally, the dark matter particle χ couples to the Z' boson, allowing all particles in the new dark sector to interact. This gives rise to the renormalizable interaction Lagrangian, which can be written in terms of four independent parameters m_χ , $m_{Z'}$, m_s , and g_χ :

¹In this work, s will refer to the dark Higgs boson and not the strange quark, unless otherwise specified

$$\mathcal{L}_\chi = -\frac{1}{2}g_\chi Z'^\mu \bar{\chi} \gamma^5 \gamma_\mu \chi - g_\chi \frac{m_\chi}{m_{Z'}} s \bar{\chi} \chi + 2g_\chi Z'^\mu Z'_\mu (g_\chi s^2 + m_{Z'} s) \quad (2.4)$$

where m_χ is the mass of the dark matter particles, $m_{Z'}$ is the mass of the Z' boson, m_s is the mass of the dark higgs, and g_χ is the dark matter coupling constant.

Additionally, the coupling of the Z' boson to standard model quarks is described by the Lagrangian:

$$\mathcal{L} = -g_q Z'^\mu \bar{q} \gamma_\mu q \quad (2.5)$$

where g_q is the coupling constant between Z' and quarks.

A final free parameter θ is the non-zero mixing angle between the SM Higgs boson and the dark Higgs boson. The dark Higgs obtains its couplings to standard model particles through this mixing, and therefore shares the same standard model decay branching fractions as the SM Higgs boson.

For the analysis described in this work the free parameters are set as:

- $g_\chi = 1$
- $m_\chi = 200 GeV$
- $m_{Z'}$ allowed to vary
- m_s allowed to vary
- $g_q = 0.25$
- $\theta = 0.01$

The values of g_χ and g_q were chosen to facilitate comparison with other LHC searches with similar models, which traditionally use the values selected. The value of θ was chosen to match that of [5]. Its precise value is not relevant to this search, but it is sufficiently large that the dark Higgs decays promptly to standard model states and does not create a displaced vertex. The varied values m_s and $m_{Z'}$ form the parameter space covered by this search.

Chapter 3

The Large Hadron Collider and the ATLAS Experiment

The **Large Hadron Collider (LHC)** is the world's largest and most energetic proton-proton collider. It forms a 27 km circular ring beneath Switzerland and France, with its origin at the **Conseil Européen pour Recherche Nucléaire (CERN)** in Geneva. It began operation in 2008, and since then has collided over 10^{15} particles. The collider houses four major experiments: ALICE, ATLAS, CMS, and LHCb, along with several smaller projects. ALICE (A Large Ion Collider Experiment) studies heavy ion collisions, while LHCb (Large Hardon Collider beauty) specializes in studying the physics of the bottom quark. **ATLAS (A Toroidal LHC ApparatuS)** and CMS (Compact Muon Solenoid) are both general purpose experiments designed to study a wide range of interactions resulting from high-energy proton-proton collisions. This work uses data collected by the ATLAS experiment, and a description of the LHC accelerator and ATLAS detector follow in Sections 3.1 and 3.2.

3.1 The Large Hadron Collider

Built between 1998 and 2008, the LHC [7] began colliding protons in 2010 at a center-of-mass energy of 7 TeV, and most recently from 2015 to 2018 collisions occurred at 13 TeV. Successfully colliding particles at this energy is an immense technical challenge which is achieved by the many technologies of the LHC and its accelerator complex.

In order to reach a beam energy of 6.5 TeV, protons are slowly stepped up through a chain of accelerators before reaching the LHC. They begin their journey as hydrogen

The crown jewel of LHC technology is its magnets. 1,232 superconducting NbTi dipole magnets kept at 1.9 K, each spanning 14.3 m and weighing 35 tonnes, create an 8.3 Tesla magnetic. This field lies perpendicular to the beam path, bending it to its desired route. The bending dipole magnets are complemented by 392 quadrupole magnets that focus the beams to a small aperture, and many higher-order multipole magnets which provide small beam corrections.

Allong with the collisional energy of the accelerated particles, the other most important measure of a particle acceletator is the luminosity it achieves. **Luminosity** (\mathcal{L}) is used to determine the rate (R) at which a given interaction occurs using:

$$R = \mathcal{L}\sigma \quad (3.1)$$

where σ is the cross-section of the desired interaction. As a result, when searching for rare processes, a obtaining a high luminosity is crucial.

The integrated luminosity, L , gives the total number of interactions over a period of time, and is defined as:

$$L = \int \mathcal{L} dt \quad (3.2)$$

At the LHC, the luminosity is controlled by the number of bunches circulating n_b , the frequency of revolution f_r , $N_{1,2}$ the number of particles in each colliding bunch, and the cross sectional area of the colliding beams. This results in the equation:

$$\mathcal{L} = \frac{f_r n_b N_1 N_2}{4\pi\sigma_x\sigma_y} R_\phi \quad (3.3)$$

where R_ϕ is a geometrical loss factor caused by the beams crossing at an angle, and $\sigma_{x,y}$ are the horizontal and vertical widths of the beams, which are estimated to have a Gaussian profile. The LHC currently has a nominal peak luminosity of $\mathcal{L} = 10^{34} cm^{-2}s^{-1}$.

3.2 The ATLAS Experiment

The ATLAS experiment [2] uses the LHC in combination with the general-purpose ATLAS detector to test a broad range of SM and BSM predictions. Together with the CMS experiment, its greatest achievement to date was the detection and discovery of the SM Higgs boson in 2012 [1].

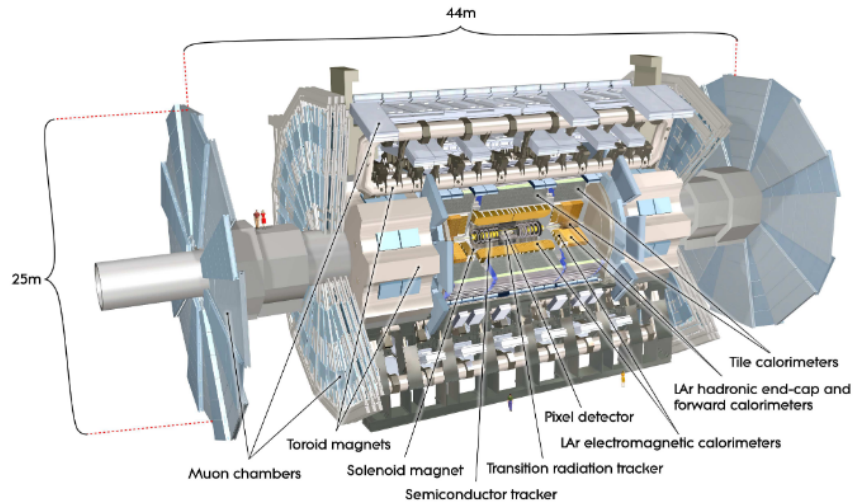


Figure 3.2: A cut-out overview of the ATLAS detector and main components. Diagram from [2].

The ATLAS detector, an overview of which is shown in Figure 3.2, is comprised of several layers, which work in tandem to detect many diverse particles. From inner-most to outer-most the layers are:

- the **inner detector**, with excellent angular resolution to track charged particles,
- the **electromagnetic calorimeters**, designed primarily to measure the energy and position of electrons and photons,
- the **hadronic calorimeters** designed to measure the energy and position of hadrons,
- the **muon spectrometer**, to track and measure muons.

When combined with the electronics required to read and trigger on measurements, the entire detector weighs over 7000 t and measures 44 m long by 25 m wide and high. Its barreled shape with end caps covers nearly the full solid angle. The following sections will describe the layout and operations of the ATLAS detector in more detail.

3.2.1 Inner Tracking Detector

The ATLAS inner detector tracks the direction and momentum of charged particles immediately after leaving the interaction point. A 2 T superconducting solenoid surrounds the inner detector, bending charged particles with the Lorentz force, allowing their momentum to be determined from the curvature of their path. Within the inner detector, there are three separate sub-detectors: the **Pixel Detector**, the **Semiconductor Tracker (SCT)**, and the **Transition Radiation Tracker (TRT)**. A cutout view of the detector is shown in Figure 3.3.

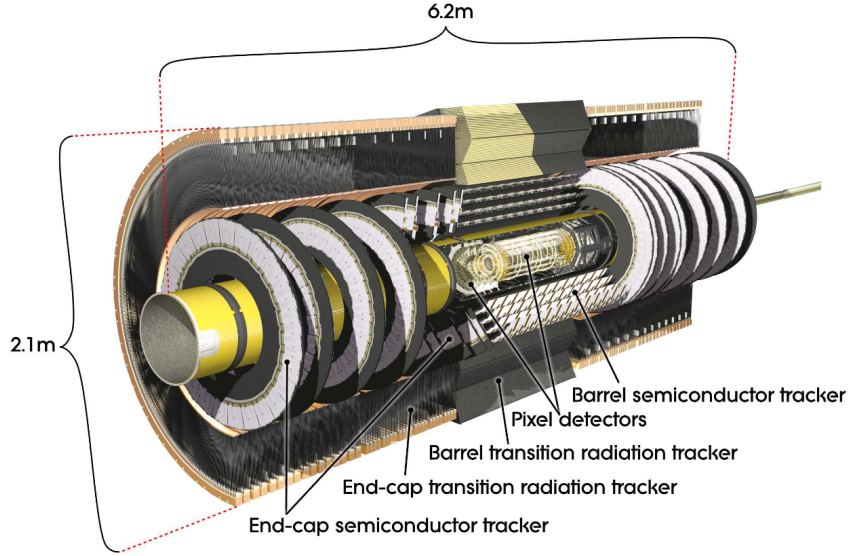


Figure 3.3: A cut-out view of the ATLAS inner detector. Diagram from [2].

The Pixel Detector consists of an array of 1744 pixel sensors, each containing 47232 silicon pixels, mostly measuring $50 \times 400 \mu m^2$. They are arranged into three cylindrical layers in the barrel and three disk-shaped layers on each end. The high granularity of these detectors ensures strong angular resolution, providing precise measurements of vertex location and track momentum. Notably, this detector must be very radiation-hard in order to maintain performance over the detector lifespan in an area that receives an immense radiation dose from the high particle flux.

Though it would be desirable, it would not be feasible to extend the high-resolution pixel detector because of the high cost and signal readout volume. As a result, in the SCT the point-like pixels are extended into silicon strip detectors, which are laid in pairs at an angle of 40 mrad to each other to allow measurements

in two dimensions. The SCT is made up of four concentric cylindrical layers in the barrel and two disk-shaped layers on each end-cap.

The TRT is the final component of the component of the inner detector. It consists of approximately 300000 drift tubes filled with majority Xenon gas, with the walls kept at -1.5 kV and a central wire at ground. When particles pass through the tubes, the gas is ionized and the resulting electrons drift to the centre where the signal is amplified. Additionally, the gaps between TRT straws are filled with polymer fibres (in the barrel) or foils (in the end caps). As a result, highly relativistic particles create transition radiation at the material interfaces, which aids with electron identification.

3.2.2 Calorimeters

The ATLAS calorimeter system measures the energy and positions of both charged and neutral particles after they leave the inner detector. In addition to measuring the energy of particles, the calorimeters must contain enough material to stop the vast majority of particles (with the exception of muons and undetected neutrinos) from reaching the muon spectrometers. To achieve this, high-density passive layers interact with passing particles and cause them to decay into showers, dispersing their energy. These layers are interleaved with active layers that detect the decaying showers to measure particle energy.

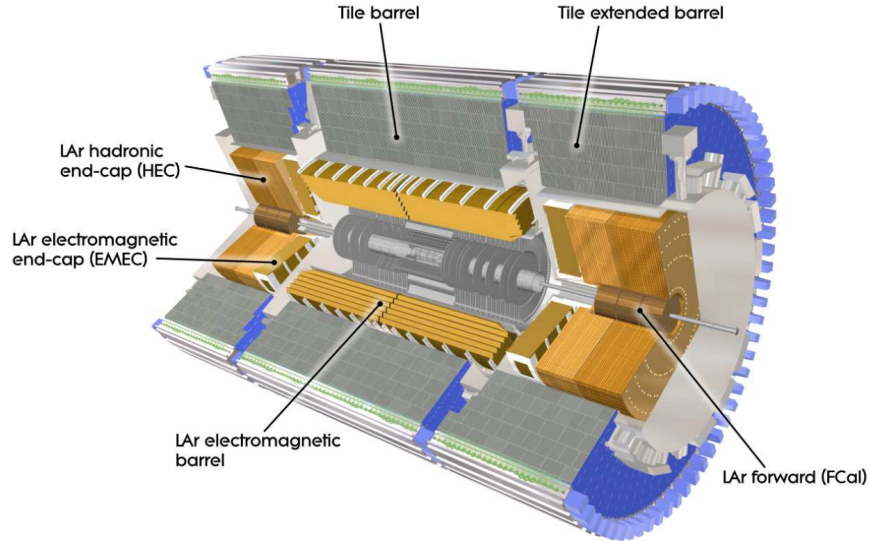


Figure 3.4: A cut-out view of the ATLAS calorimeter system. Diagram from [2].

The ATLAS calorimeters can be categorized into electromagnetic (EM) calorimeters which measure the energy of electrons and photons and hadronic calorimeters which primarily measure the energy of hadrons. ATLAS uses a combination of two different calorimeter technologies to form these detectors. In the end-cap and forward regions Liquid Argon (LAr) is used as the active layer in both the hadronic and EM calorimeters, while in the barrel region plastic scintillating tiles are employed in the hadronic calorimeter. Figure 3.4 depicts the layout of the ATLAS calorimeter system.

Electromagnetic calorimeters

The electromagnetic LAr calorimeter lies just outside the solenoid surrounding the inner detector. Layers of lead are used as the passive material. In the lead, electrons and photons interact with the closely spaced atoms, initiating a cascading shower of decays. The charged electrons in the shower pass through the active layers and ionize the LAr inside. The electrons and ions then drift across the 2 kV difference to opposite electrodes, where they are amplified into an electrical signal.

Like the inner detector, the LAr EM calorimeter can be divided into an **Electromagnetic Barrel (EMB)** calorimeter and two **Electromagnetic End-Cap (EMEC)** calorimeters. In the barrel region, the layers are placed together in a folded accordion-like geometry to create uniformity and allow easy electronic read-out. The barrel and end-cap regions are 53 cm and 63 cm thick respectively, and cover a minimum of 22 and 24 radiation lengths (X_0), keeping shower leakage to a minimum.

Hadronic Calorimeters

In the end cap regions, the **Hadronic End-Cap (HEC)** calorimeter shares a similar design to the EM LAr calorimeters, but with copper as the passive absorbing material between active layers. In the barrel region, the hadronic calorimetry is performed by the **Tile Calorimeter** with plastic scintillators as the active detectors. Particle showers passing through the plastic tiles produce scintillating light, which is directed to photomultipliers to be converted to an electrical signal. In the tile calorimeter, steel is the passive material laid between active layers. The depth of the combination of electromagnetic and hadronic calorimeters is important to prevent particles from punching through to the background-sensitive muon spectrometer. The total thickness, including supporting materials, is approximately 11 interactions lengths,

which keeps punch-through below the levels of irreducible backgrounds in the muon spectrometer and also ensures an accurate measurement of E_T^{miss} as very little energy escapes measurement.

The final calorimeter in the ATLAS detector is the **Forward Calorimeter (FCal)**, located nearest the beam path. It has three layers of passive absorbing metals: an inner copper layer optimized for electromagnetic measurements and two outer tungsten layers to measure hadronic interactions. It too employs liquid argon as the active material, this time in a matrix of longitudinal channels parallel to the beam line.

3.2.3 Muon Spectrometers

After the calorimeters have stopped the vast majority of particles exiting the interaction point, muons and neutrinos remain undetected. The ATLAS experiment does not directly detect neutrinos, and instead reconstructs them from missing transverse momentum, but muons are measured by the muon spectrometer. A diagram of the muon system is shown in Figure 3.5. The centerpiece of this system is an arrangement of three air-core toroidal magnets, a barrel toroid and two end-cap toroids. Each toroid consists of eight coils in loops in a radially symmetric pattern around the beam line. Together they form a 4 T magnetic field to bend muons.

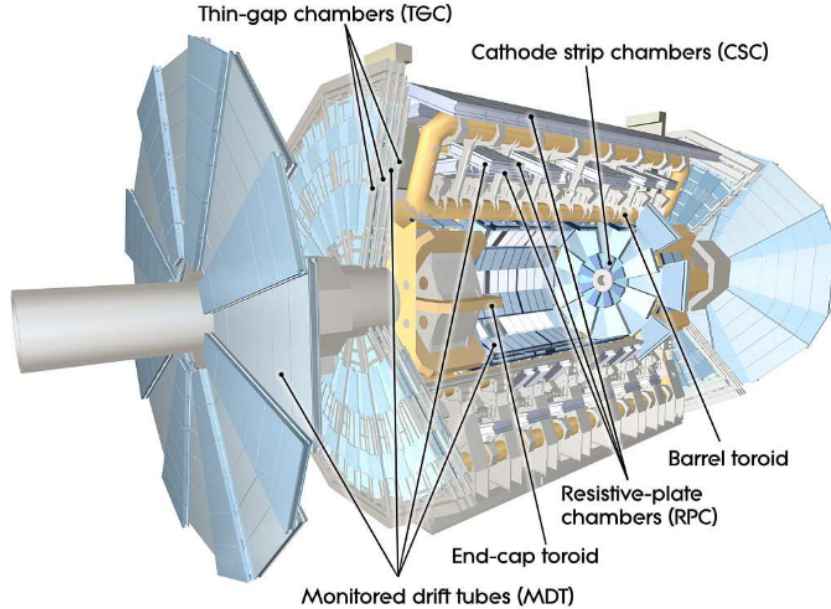


Figure 3.5: A cut-out view of the ATLAS muon spectrometer system. Diagram from [2].

Four different detector types are used to measure the muons. **Monitored Drift Tubes (MDTs)** are pressurized gas drift tubes that collect ionized electrons to measure track coordinates in the bending direction of the magnetic field. They are supplemented by finer-grained and more radiation-hard **Cathode Strip Chambers (CSCs)** at $|\eta| > 2$. **Resistive Plate Chambers (RPCs)** and **Thin Gap Chambers (TGCs)** measure the muon track coordinates in the direction orthogonal to the magnetic bending direction, and are also used by the trigger system to provide bunch-crossing identification and p_T thresholds.

3.2.4 Trigger and Data Acquisition

The ATLAS detector can see as many as 1.7 billion proton-proton collisions per second, but to save and process all of the information from each collision would require a prohibitive amount of readout electronics, computing power, and storage space. Instead, the trigger system quickly selects events based on key observables to slim down the data. On the detector itself, the **Level-1 (L1) trigger** uses custom electronics within the detector, and works with reduced granularity information from the muon chambers and calorimeters to select potentially interesting events with high- p_T objects or high E_T^{miss} . The detector readout systems can handle a maximum acceptance rate of 100 kHz from the L1 trigger. The **Level 2 (L2) trigger** is outside the detector and uses traditional computing resources. It takes regions of interest where the L1 trigger finds interesting objects and reconstructs them more fully to further reduce the event rate below 3.5 kHz. Together with the L2 trigger, the **event filter** forms the second half of the **High-Level Trigger (HLT)**. At this stage, events are fully reconstructed before being further filtered to a rate of approximately 200 Hz to be analyzed offline.

Chapter 4

Experiments

Assuming you have some experimental results to support your claims this is where all the data is reported. There are a few issues you should consider before dumping a lot of stuff here, or it will lose its effectiveness.

First of all you must describe precisely the experimental setup and the benchmarks you used. In any scientific discipline an experimental result is only good if it is reproducible. To be reproducible then somebody else must have sufficient details of the setup to be able to obtain the same data. Thus the first section in this chapter is a super precise history of the decisions made towards experimentation, including mentions of the paths which became infeasible. The setup must be valid and thus your description of it must prove that it is indeed sound. At times, terrifying times, when writing this section, both supervisor and student realize belatedly that something is missing and more work needs to be done!

The second portion of this chapter is dedicated to the actual results. At least two issues arise here:

1. Should all the data be reported here or should some be placed in the Appendix?
2. Should this be an exposition of the raw facts and data or should it include its analysis and evaluation?

There are no definite answers here, but I follow a few rules.

Should all the data be reported here or should some be placed in the Appendix?

- If there is a large number of tables of data, it might be better to present here only a handful of the most significant ("best") results, leaving all the rest of the data in the Appendix with proper linkages, as it would make the chapter

so much more easily readable (not to mention limiting the struggle with a word processor for the proper placement of tables and text).

- Use an example throughout, call it a "case study" to make it sound better, so that all the data and results are somehow linked in their logic, and even better if this is one of the examples you used in Chapter 2 to describe the original problem.
- Highlight in some manner the important new data, for example the column of your execution speed where all the numbers are much smaller. Make the results highly easy to read!
- It is normally expected that data should be presented only in one form and not duplicated, that is, you are not supposed to include both a table of raw numbers and also its graphical representation from some wonderful Excel wizard. I tend to disagree. I would not wish to see every results repeated in this manner, but some crucial ones need to be seen in different manners, even with the same information content, in order to show their impact. One good trick is to place the more boring tables in the Appendix and use wonderful graphs in this chapter.
- This is the one chapter where I would splurge and use colour printing where necessary, as it makes an *enormous* difference.

Should this be an exposition of the raw facts and data or should it include its analysis and evaluation?

- Is the evaluation of the data really obvious? For example you have 10 tables to show that your chemical process is faster in development and gives purer material - you may simply need to highlight one column in each table and state the obvious.
- Most results are not that obvious even if they appear so. Moreover this is where you are comparing your *new* results to data from other people. I usually describe other people's work at this point and make comparisons. That is why I prefer to talk about the analysis and evaluation of the results in a separate chapter.
- There is absolutely no clear structure here which is best.

Chapter 5

Evaluation, Analysis and Comparisons

For a Master's research this chapter represents the critical part where **you** are truly evaluated to determine whether you should be given your degree. Even more so for a PhD. Consider carefully what the University calendar states regarding the expectations for a master's thesis, paraphrased here.

1. *A Master's thesis is an original lengthy essay.* The main implication here is that the essay is original, that is, it is completely newly written by you and does not contain any writings from others unless precisely quoted. Any paraphrased items must be cited.
2. *It must demonstrate that:*
 - students understand research methods;
 - students are capable to employ research methods;
 - students demonstrate command of the subject.
3. *The work may be based on:*
 - original data;
 - original exercise from scholarly literature;
 - data by others.
4. *The work must show that:*

- appropriate research methods have been used;
- appropriate methods of critical analysis supplied.

5. *The work must contain:*

- evidence of some new contribution;
- evidence of a new perspective on existing knowledge.

Only the last point uses the attribute *new* and it refers almost entirely to giving a new perspective and analysis, even if based on data from others. This truly implies that this current chapter on evaluation and analysis of results is the most important and must be written with care. You are demonstrating here that, even if given data and methods from others, your skills of critical judgment and analysis are now at the level that you can give professional evaluations.

Things are slightly different for a PhD. According to the Graduate Calendar: *a doctoral dissertation must embody original work and constitute a significant contribution to knowledge in the candidate's field of study. It should contain evidence of broad knowledge of the relevant literature, and should demonstrate a critical understanding of the works of scholars closely related to the subject of the dissertation. Material embodied in the dissertation should, in the opinion of scholars in the field, merit publication.*

The general form and style of dissertations may differ from department to department, but all dissertations shall be presented in a form which constitutes an integrated submission. The dissertation may include materials already published by the candidate, whether alone or in conjunction with others. Previously published materials must be integrated into the dissertation while at the same time distinguishing the student's own work from the work of other researchers. At the final oral examination, the doctoral candidate is responsible for the entire content of the dissertation. This includes those portions of co-authored papers which comprise part of the dissertation.

The second paragraph makes it clear that one must emphasize what is new and different from others, without arrogance, yet without being too subtle either. The first paragraph implies that for a PhD it is required that one approached an important open problem and gave a new solution altogether, making chapters 3, 4, 5 all part of the body of research being evaluated. In fact at times even the problem may be entirely new, thus including chapter 2 in the examination. This is in contrast to a Master's degree where the minimum requirement is for chapter 5 to be original.

Chapter 6

Conclusions

My first rule for this chapter is to avoid finishing it with a section talking about future work. It may seem logical, yet it also appears to give a list of all items which remain undone! It is not the best way psychologically.

This chapter should contain a mirror of the introduction, where a summary of the *extraordinary* new results and their wonderful attributes should be stated first, followed by an executive summary of how this new solution was arrived at. Consider the practical fact that this chapter will be read quickly at the beginning of a review (thus it needs to provide a strong impact) and then again in depth at the very end, perhaps a few days after the details of the previous 3 chapters have been somehow forgotten. Reinforcement of the positive is the key strategy here, without of course blowing hot air.

One other consideration is that some people like to join the chapter containing the analysis with the only with conclusions. This can indeed work very well in certain topics.

Finally, the conclusions do not appear only in this chapter. This sample mini thesis lacks a feature which I regard as absolutely necessary, namely a short paragraph at the end of each chapter giving a brief summary of what was presented together with a one sentence preview as to what might expect the connection to be with the next chapter(s). You are writing a story, the *story of your wonderful research work*. A story needs a line connecting all its parts and you are responsible for these linkages.

Appendix A

Additional Information

This is a good place to put tables, lots of results, perhaps all the data compiled in the experiments. By avoiding putting all the results inside the chapters themselves, the whole thing may become much more readable and the various tables can be linked to appropriately.

The main purpose of an Appendix however should be to take care of the future readers and researchers. This implies listing all the housekeeping facts needed to continue the research. For example: where is the raw data stored? where is the software used? which version of which operating system or library or experimental equipment was used and where can it be accessed again?

Ask yourself: if you were given this thesis to read with the goal that you will be expanding the research presented here, what would you like to have as housekeeping information and what do you need? Be kind to the future graduate students and to your supervisor who will be the one stuck in the middle trying to find where all the stuff was left!

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