The Application of Machine Learning Techniques Towards the Optimization of High Energy Physics Event Simulations within the ALICE[[1]](#footnote-2) TRD[[2]](#footnote-3) at CERN[[3]](#footnote-4)



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This dissertation is submitted in partial fulfilment of the Degree of Master of Science

This dissertation is dedicated to my mother, Elizabeth Suzanna Bloem Viljoen, who has always inspired me to follow my higher passions, despite the myriad difficulties that life makes us face; and to search fearlessly and incessantly for the deeper truths underlying our everyday world.

“

A man may imagine things that are false, but he can only understand things that are true, for if the things be false, the apprehension of them is not understanding.

”

—Sir Isaac Newton

Declaration

This dissertation is the result of my own work and includes nothing, which is the outcome of work done in collaboration except where specifically indicated in the text.

It has not been previously submitted, in part or whole, to any university of institution for any degree, diploma, or other qualification.

In accordance with the Department of Statistics guidelines, this thesis is does not exceed 20,000 words.

Signed:\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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Acknowledgements

Firstly, I would like to thank my father, Christiaan Gerhardus Viljoen, for all the support – material, emotional and financial – he has selflessly provided to me throughout my life, and particularly towards my higher education journey. You have no idea how much appreciation I have for all the sacrifices you have made for me, and all the advice you have given me.

Secondly, I want to thank my aunt, Professor Emma Ruttkamp-Bloem, for all the mentoring she has provided to me in navigating the world of academia, and for the inspiration that her own academic career instils in me.

Thirdly, I want to thank Dr Thomas Dietel for providing me with this immense opportunity to be part of the largest scientific experiment in human history, and for the rigorous scientific guidance that he has, and continues to provide to me.

Lastly, I would like to thank my larger family, on both my father’s and mother’s side, for providing the loving and stable environment that makes any place we assemble Home.

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List of Abbreviations and Acronyms

|  |  |
| --- | --- |
|  |  |
| ALICE | A Large Ion Collider Experiment |
| TRD | Transition Radiation Detector |
| CERN | European Organization for Nuclear Research |
| QGP | Quark Gluon Plasma |
| LHC | Large Hadron Collider |
| WLCG | Worldwide LHC Computing Grid |
| QCD | Quantum Chromodynamics |
| QGP | Quark-Gluon Plasma |
| ML | Machine Learning |
| Pb-Pb | Lead-Lead Collisions |
|  | Electron |
|  | Pion |
| QED | Quantum Electrodynamics |
| p | Proton |
| n | Neutron |
|  | Electron Neutrino |
|  |  |
|  |  |

List of Appendices

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# Introduction

## Background

This Masters Dissertation seeks to apply cutting edge techniques in Machine Learning (ML) towards the simulation of High Energy Physics (HEP) collision events, which routinely occur at the Large Hadron Collider (LHC) as part of the ongoing fundamental research conducted by the Counsel for European Nuclear Research (CERN).

More specifically, the focus of this thesis centres around the development of Deep Generative Models which are able to produce datasets that are indistinguishable from data produced by the Transition Radiation Detector (TRD) at the A Large Ion Collider Experiment (ALICE) collaboration at CERN, during Lead-Lead (Pb-Pb) heavy ion collisions.

## Aims & Goals

## Summary of Work Done & Major Findings

## The Structure & Organization of this Dissertation

# High Energy Physics & The CERN Experiment

## A Brief History of Atomic Theory

The earliest correct model for the atom can be traced back to 400 BCE, when Democritus proposed that the entire universe consisted of fundamental particles, or “Atoms”, which cannot be divided any further.

In 1803, Dalton refined this model to state that these indivisible atoms can have distinguishing chemical and physical traits and that they combine to form chemical compounds.

Then, in 1987, JJ Thompson discovered the electron and proposed an incorrect theory for subatomic structure in which negatively charged electrons were embedded within positive charges within the atom.

Rutherford, Marsder and Geiger disproved this model in 1911, with their seminal alpha-particle scattering experiment and put forth a more accurate model for the atom, in which most of the atom consists of empty space, with a dense core of positively charged protons.

In 1913, Bohr refined this model further, indicating that electrons orbit the positively charged atomic core at distinct energy levels. While this model did explain the emission spectrum of Hydrogen, it could not explain the emission spectra of any of the other elements.

Between 1924 – 1928, De Broglie, Heisenberg and Schrödinger each separately developed a quantum paradigm, where electrons have wave-like properties and appear in much more complex orbitals. This is still the accepted theory of atomic structure today.

There have been some refinements made to the quantum theory, as new information has come to light: a neutral subatomic particle, the neutron, was discovered in 1932, which solved the puzzle of why atoms were found to be nearly twice as heavy as expected based on proton number; this discovery also disproved Dalton’s second law, which stated that all atoms of a specific element were identical, and resulted in the concept of isotopes (atoms with the same number of protons, but differing numbers of neutrons). In the same year, Cockroft and Walton split the atom for the first time, by bombarding Lithium atoms with electrons, splitting them into two Helium particles.

The 1950s brought about a new era in nuclear physics, in which particle accelerators with collision energies of a few hundreds of MeVs became affordable, along with cosmic ray and inelastic proton-scattering experiments; since this time, a whole host of subatomic elements have been discovered, many of which are unstable. The discovery of these new particles has led, over time, to the development and refinement of the modern Standard Model of Particle Physics.

## The Standard Model of Particle Physics

### Introduction

The Standard Model of Particle Physics is a framework which allows us to understand the fundamental structure and dynamics of our universe in terms of elementary particles, where all interactions between elementary particles are similarly facilitated by an exchange of particles. In summary, based on our current understanding, our entire universe consists of a very sparse array of fundamental particles once we delve into the subatomic realm.

At an energy scale of electron Volts (an electron Volt is a unit of energy, equivalent to the amount of work required to accelerate a single electron through a potential difference of 1 Volt), the low energy manifestation of Quantum Electrodynamics (QED) allows atoms to exist in bound states with negatively charged electrons () orbiting a positively charged nucleus consisting of positively charged protons () and electrically neutral neutrons (), based on the electrostatic attraction of these opposing electrical charges.

Quantum mechanics explains the emergence of unique physical properties in different elements, which arise from their exact electronic structures. Quantum Chromodynamics (QCD) is the fundamental theory of the strong interaction, which binds protons and neutrons together within the nucleus of the atom. Similarly, at this energy scale, the weak force causes nuclear β-decays of radioactive isotopes and is involved in the nuclear fusion processes that occur within stars; the nearly massless electron neutrino ) is produced during both of the abovementioned processes.

Therefore, almost all physical phenomena that occur under normal circumstances can be explained by the Electromagnetic-, Strong- and Weak Forces, Gravity (which is very weak, but explain the large-scale structure of the universe), and just four fundamental particles: the electron, proton, neutron and electron neutrino.

### The Fundamental Particles

At higher energy scales, of the order of electron Volt (or giga-electron Volt, 1 GeV), protons and neutrons are understood to be bound states of truly fundamental particles called quarks, in the following manner: protons consist of two up-quarks and a down-quark p(uud), whereas neutrons consist of two down-quarks and an up-quark n(ddu).

At the lowest energy level of the standard model, the first generation of particles are then the electron, electron neutrino, the up-quark and the down-quark; these are currently considered to be truly elementary, in that they cannot be subdivided.

Higher energy scales, such as those achieved at modern particle accelerators, result in the second and third generation of the four elementary particles; these are heavier versions of the first generation: for example, the muon () is essentially a version of an electron which is 200 × heavier than a low energy electron, i.e. . The tau-lepton () is the third generation of the electron, and is much heavier, i.e. . These mass differences do have physical consequences, but the fundamental properties and interactions of the various generations remain identical.

Current experimental evidence indicates that there are no further generations than these three, and so all matter in the universe seems to be circumscribed by the following twelve fundamental fermions:

Table 1: The twelve fundamental fermions.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Leptons | | | | Quarks | | |
|  | Particle | Q | Mass/GeV | Particle | Q | Mass/GeV |
| First Generation | Electron () | -1 | 0.005 | Down (d) | -1/3 | 0.003 |
| Neutrino () | 0 | < | Up (u) | +2/3 | 0.005 |
| Second Generation | Muon () | -1 | 0.106 | Strange (s) | -1/3 | 0.1 |
| Neutrino () | 0 | < | Charm (c) | +2/3 | 1.3 |
| Third Generation | Tau () | -1 | 1.78 | Bottom (b) | -1/3 | 4.5 |
| Neutrino () | 0 | < | Top (t) | +2/3 | 174 |

While it is accepted that neutrinos are not massless, their masses are so small that they have not been precisely determined, however, the upper bounds for the estimated masses for neutrinos are around 9 orders of magnitude smaller than the other fermions.

The Dirac equation describes the state of each of the twelve fundamental fermions and indicates that for each fermion there is an antiparticle which has the same mass but opposite charge, which is indicated by a horizontal bar over the particle’s symbol, or a charge symbol of the opposite sign, e.g. the anti-down quark is indicated by d̅, whereas the antimuon is indicated by .

Interactions between particles are facilitated by the four fundamental forces, but the effect of gravity at this scale is sufficiently negligible that it can be ignored without loss of accuracy. All particles take part in weak interactions and are therefore subject to the weak force. The neutrinos are all electrically neutral and therefore are not involved in electromagnetic interactions and are, so to speak, invisible to this force. Quarks carry what is termed as “colour charge” by QCD and are therefore the only particles that feel the strong force.

The strong force confines quarks to confined states within hadrons and are therefore not freely observed under normal circumstances

### The Fundamental Forces

Classical electromagnetism explained the electrostatic interaction between particles using a scalar potential, Newton himself that matter could interact with any other matter without the mediation of direct contact.

Quantum Field Theory circumvents this non-material explanation and encompasses the description of each of the fundamental forces. Electromagnetism is explained by Quantum Electrodynamics (QED), the Strong Force by Quantum Chromodynamics (QCD), the weak force by the Electroweak Theory (EWT), Gravity has not been explained by the Standard Model yet; therefore, Einstein’s General Theory of Relativity is still the best explanation of this force, but it falls within the bounds of Classical Physics. As such, the search to incorporate gravity into the Standard Model is an ongoing area of research and has resulted in exciting new theoretical research avenues such as string theory and loop quantum gravity arising.

Looking at electromagnetism, the interaction between charged particles occurs via the exchange of massless virtual photons, which explains momentum transfer via a particle exchange and circumventing the issue of a non-physical potential as the medium of interaction.

Similarly, there are virtual particles (gauge bosons) for both the Strong Force (i.e. the massless gluon) and Weak Force (i.e. and bosons, which are around 80 times heavier than the proton and the Z boson, which facilitates a weak neutral-current interaction). The gauge bosons all have spin 1, compared to the fermions whom all have spin ½.

### The Higgs Boson

## The CERN Experiment

### Hardware

#### Accelerators

#### Detectors

#### The Worldwide Large Hadron Collider Computing Grid (WLCG)

### Software

### Collaborations

# The ALICE Collaboration

## Objectives of the ALICE Experiment

## Gas Detectors

Sauli 1978

Blum, Riegler, Rolandi

De/dx bethe bloche

Data/ signsl descry

Pid: trd: pionn efficidency 99% electron efficiency for full tracks

Ideal 6 tracklets per track;

Can also look at any track regardless of number of tracklets;

Alsolook at distribution of tracklets per track

## The ALICE Detector

### The Transition Radiation Detector

# Deep Learning

## Mathematical Background

## Deep Feedforward Neural Networks

## Convolutional Neural Networks

## Variational Autoencoders

## Generative Adversarial Networks

# Data

# Methods

## ROOT

## Data Extraction from WLCG

# Results

# Discussion

# Conclusion

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# Bibliography

There are no sources in the current document.

# Appendices

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Example

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2. Transition Radiation Detector [↑](#footnote-ref-3)
3. European Counsel for Nuclear Research [↑](#footnote-ref-4)