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Stranger Things at the LHC

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Stranger Things at the LHC

by

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Dissertation

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of the Requirements
for the degree of

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To my sister, who didn't ask for this thesis to be dedicated to her...

Stranger Things at the LHC

Publication No. ____________________

Ryan Patrick Hannigan, Ph.D.
The University of Texas at Austin, 2022

Supervisor: Christina Markert

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Chapter One: Introduction

The purpose of this chapter is to transform a scientifically literate reader who may be vaguely familiar with the idea of a "quark" into one who can understand the motivation and techniques behind the analysis presented in the rest of this thesis. If you are an extremely educated physicist who regularly performs lattice quantum chromodynamics calculations in their head, I would also encourage you to read this chapter it its entirety as it may contain egregious errors that need to be corrected.

1.1 What is fundamental?

The answer to the question "What are the fundamental building blocks of our universe?" has changed drastically over the course of human history. The idea that all matter is composed of smaller, uncuttable pieces has been around since 5th century BCE when Greek philosophers Democritus and Leucippus first introduced the concept of an atom. While this idea was initially ignored in favor of more theological descriptions of our universe, over the span of a millennium or two the atom became the de facto indivisible building block of nature. However, everything changed around the turn of the 20th century when scientists like Rutherford and Chadwick determined that the supposedly indivisible atom was composed of even smaller particles, eventually named protons and neutrons. The notion that protons and neutrons were unbreakable was relatively short lived, as not even half a century later the deep inelastic scattering experiments performed by Kendall, Friedman and Taylor revealed that protons (and subsequently neutrons) were actually composed of even smaller particles, dubbed "partons". This discovery was one of the largest contributing factors to the creation of the so-called Standard Model of particle physics, a theory which describes all of the fundamental particles and the way in which they interact with each other. A diagram of those fundamental particles can be seen in Figure 1.1. It should be noted that all of the particles labeled as quarks and leptons – collectively as "fermions" – have corresponding anti-particles with opposite electric charge. The

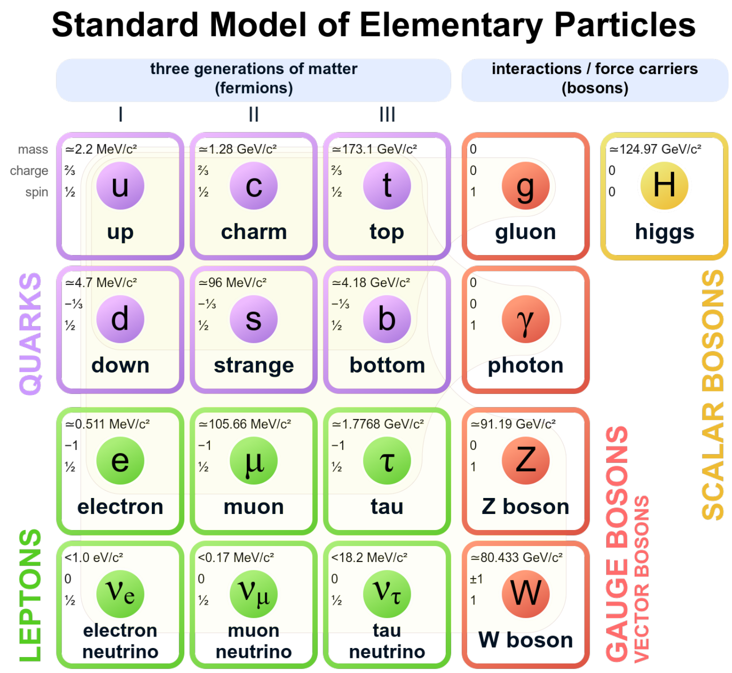

Figure 1.1: A diagram depicting the particles we currently believe are fundamental within the so-called "Standard Model" of particle physics.

equation that describes all of these particles and their interactions, often incorrectly[1] referred to as the "Standard Model Lagrangian", can be compactified into a relatively palatable form that can easily fit on a coffee cup like the one shown in Figure 1.2.

While this equation may appear brief[1], it can be used to completely describe three of the four fundamental forces of nature:

1. The Electromagnetic Force, which is responsible for the electrons pushing against each other to keep you from falling through your chair,

2. The Weak Nuclear Force, which is responsible for the initiating the nuclear fusion reactions that fuel our sun, and

3. The Strong Nuclear Force, which is responsible for holding quarks and gluons

[1] It is "incorrect" because this is technically a Lagrangian density (i.e. Lagrangian per unit volume), but as it is usually integrated over all space the distinction is mostly irrelevant.

[1] Here "brief" is in the eye of the beholder, but certainly its brevity is misleading as even in the first line the $F_{\mu\nu}$ refers to three completely different gauge field tensors...

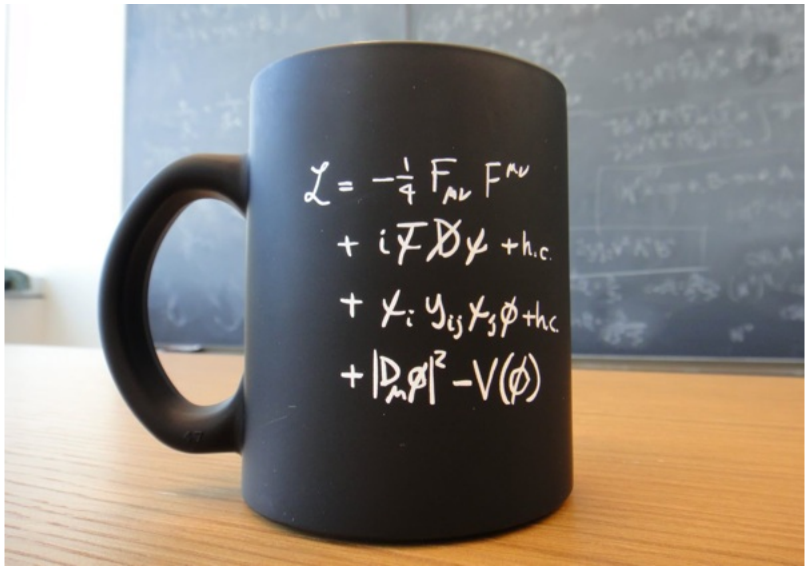

Figure 1.2: A coffee cup with the Standard Model Lagrangian density printed on its side. Please ignore the "+ h.c." term following the $i\bar{\psi}\not{D}\psi$, it is the result of a small lapse in judgement from the mug makers.

together in bound stands known as hadrons, like the protons and neutrons that make up everyday matter.

The only fundamental force missing from this list is the Gravitational Force, which is described by a completely separate set of equations[2]

Each of the three forces that are described within the Standard Model are mediated by different gauge bosons. For example, the electromagnetic force is mediated by the boson known as the photon, the weak nuclear force is mediated by the W and Z bosons, and the strong nuclear force is mediated by bosons known as gluons. In this thesis we will be primarily focusing on the Strong Nuclear Force, which acts solely on particles with color charge – an intrinsic property of quarks and gluons. The "color" charges are red, green, and blue with antio

Even though each of the electromagnetic, weak and strong forces can be described using the Standard Model Lagrangian, the way in which they appear within the equation is not easy to determine. For example, the electromagnetic force actually corresponds to line 1

[2]Specifically, the Einstein Field Equations, $G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$, but this is the thesis of a particle physicist so gravity is taboo.

Chapter Two: More

A good thesis has references **bib:somebook**. Usually siting a name, such as **bib:someart**. The best citation is autocite, since it always gets the spacing right [**bib:somethesis**].

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Figure 2.1: This is a caption.

2.1 One

2.1.1 Mini

2.2 Two

2.2.1 Miny

2.2.1.1 Mo

2.3 Three

2.4 This is very very very very very very long to test the guideline for wrapping in the table of contents

Chapter Three: Experimental Apparatus

As this thesis is focused on the physics of heavy-ion collisions, it stands to reason that the data analyzed in this thesis was gathered using the only detector along the LHC dedicated to studying such collisions: the ALICE detector. In this chapter, a brief synopsis of the LHC will be provided, followed by a much more detailed overview of the ALICE detector and its corresponding sub-detectors.

3.1 The LHC

Located along the Swiss-French border near Geneva, Switzerland, the Large Hadron Collider (LHC) is the largest particle accelerator on the planet. At a circumference of 27 kilometers, its tunnels lie almost 200 meters beneath the surface of the earth. Inside the tunnels are two high-energy particle beams pointing in opposite directions, with the beam pipes being kept inside of an ultra-high vacuum. The particles inside the beam are guided by a multitude of superconducting magnets: 393 quadrapole magnets keep the beam focused, while 1232 dipole magnets bend the particles along the circular path. The beams are designed to collide at four intersection points along the LHC, each with a corresponding detector surrounding the collision points: (1) ALICE, which specializes in heavy-ion collisions; (2) ATLAS, which specializes in studying high-p_T particles produced in pp collisions, (3) CMS, which TODO and (4) LHCb, which is designed to study CP violations through measurements of B mesons at forward rapidity. A diagram of the LHC with these four intersection points can be seen in Figure X.

Currently, the highest center of mass energies achieved for each of the main collision systems are $\sqrt{s} = 13$ TeV for pp, $\sqrt{s} = 7$ TeV for p-Pb and $\sqrt{s} = 5.02$ TeV for Pb-Pb. The LHC underwent a long shutdown from XXXX to YYYY, in order to upgrade the beam luminosity and COM energies. The projected final COM energies for each collision system will be ...

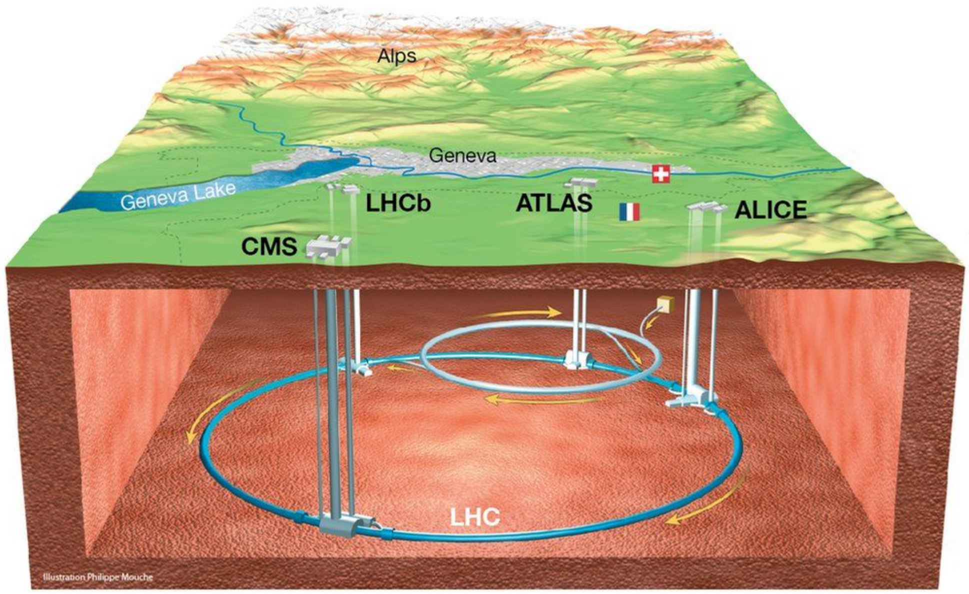

Figure 3.1: A diagram depicting the LHC with its various main detectors shown underground. Illustration by Phillipe Mouche, from BBC News.

3.2 The ALICE Detector

The detector used by the ALICE collaboration, unsurprisingly known as the ALICE detector, has the primary focus of investigating the physical properties of the strongly interacting quark-gluon plasma created during heavy-ion collisions. Building the detector was a massive effort, requiring the help from over 1000 people from 105 institutes in 30 different countries. The detector itself is also massive, weighing in at around 10,000 tons and spanning 26 meters in length with a 16-meter height and width. It is composed of 18 sub-detector systems, all of which work together to help reconstruct the event. A diagram of the detector with its corresponding sub-detector systems can be seen in in Figure N.2, which contains a banana for scale. As the primary focus of the ALICE detector is to study heavy-ion collisions, all of its components must work together to reconstruct very high multiplicity events.

3.2.1 The Inner Tracking System

The Inner Tracking System (ITS) of the ALICE detector is composed of six cylindrical layers of silicon detectors. Each layer has hermetic structure and it is coaxial

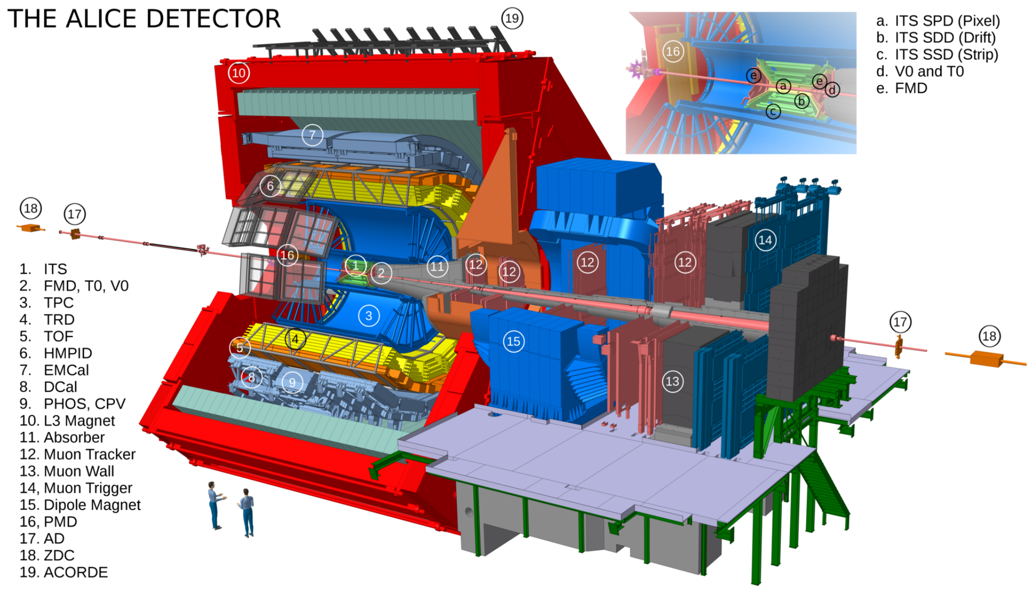

Figure 3.2: A 3-D schematic of the ALICE detector, with labels for all of the sub-detectors. Note the humans-for-scale in the bottom left of the diagram.

with the beam pipe. The ITS covers the pseudorapidity range $|\eta| \leq 0.9$ and the distance from the nominal beam line ranges from 3.9 cm for the innermost layer up to 43 cm for the outermost. The two innermost layers are made of Silicon Pixel Detectors (SPD), the two central layers of Silicon Drift Detectors (SDD) and the two outermost layers of double sided Silicon Strip Detectors (SSD). The ITS has the main purposes of providing both primary and secondary vertices reconstruction and of improving the ALICE barrel tracking capabilities in the vicinity of the interaction point. Furthermore, as a standalone tracker, the ITS recovers particles which do not reach or are missed by the external barrel detector, due to acceptance limitations and momentum cutoff. After a short summary on the status of spatial alignment and detector calibration, this paper will focus on the ITS performances with with proton and lead beams in 2010 for what concerns vertexing and tracking.

3.2.1.1 ITS Upgrade

The LHC underwent a fairly substantial upgrade to the beam luminosity from X to Y. In order to utilize all of the The writer of this thesis was the main reason why the ITS Upgrade actually finished, as he is the smartest person of all time and actually hand built the entire thing.

3.2.2 The V0 Detector

V0 is made of two arrays of scintillator counters set on both sides of the ALICE interaction point, and called V0-A and V0-C. The V0-C counter is located upstream of the dimuon arm absorber and cover the spectrometer acceptance while the V0-A counter will be located at around 3.5 m away from the collision vertex, on the other side. It is used to estimate the centrality of the collision by summing up the energy deposited in the two disks of V0. This observable scales directly with the number of primary particles generated in the collision and therefore to the centrality. V0 is also used as reference in Van Der Meer scans that give the size and shape of colliding beams and therefore the luminosity delivered to the experiment.

3.2.3 The Time Projection Chamber

The largest component of the ALICE detector is know nas the Time Projection Chamber (TPC). The TPC is a gas-filled volume with The ALICE Time Projection Chamber (TPC) is a large volume filled with a gas as detection medium and is the main particle tracking device in ALICE.[19][20] Charged particles crossing the gas of the TPC ionize the gas atoms along their path, liberating electrons that drift towards the end plates of the detector. The characteristics of the ionization process caused by fast charged particles passing through a medium can be used for particle identification. The velocity dependence of the ionization strength is connected to the well-known Bethe-Bloch formula, which describes the average energy loss of charged particles through inelastic Coulomb collisions with the atomic electrons of the medium. Multiwire proportional counters or solid-state counters are often used as detection medium, because they provide signals with pulse heights proportional to the ionization strength. An avalanche effect in the vicinity of the anode wires strung in the readout chambers, gives the necessary signal amplification. The positive ions created in the avalanche induce a positive current signal on the pad plane. The readout is performed by the 557 568 pads that form the cathode plane of the multi-wire proportional chambers (MWPC) located at the end plates. This gives the radial distance to the beam and the azimuth. The last coordinate, z along the beam direction, is given by the drift time. Since energy-loss fluctuations can be considerable, in general many pulse-height measurements are performed along the particle track in order to optimize the resolution of the ionization measurement. Almost all of the TPC's volume is sensitive to the traversing charged particles, but it features a minimum material budget. The straightforward pattern recognition (continuous tracks) make TPCs the perfect choice for high-multiplicity environments, such as in heavy-ion collisions, where thousands of particles have to be tracked simultaneously. Inside the ALICE TPC, the ionization strength of all tracks is sampled up to 159 times, resulting in a resolution of the ionization measurement as good as 5

3.2.4 The Electromagnetic Calorimeter

The EMCal is a lead-scintillator sampling calorimeter comprising almost 13,000 individual towers that are grouped into ten super-modules. The towers are read out by wavelength-shifting optical fibers in a shashlik geometry coupled to an avalanche photodiode. The complete EMCal will contain 100,000 individual scintillator tiles and 185 kilometers of optical fiber, weighing in total about 100 tons. The EMCal covers almost the full length of the ALICE Time Projection Chamber and central detector, and a third of its azimuth placed back-to-back with the ALICE Photon Spectrometer – a smaller, highly granular lead-tungstate calorimeter. The super-modules are inserted into an independent support frame situated within the ALICE magnet, between the time-of-flight counters and the magnet coil. The support frame itself is a complex structure: it weighs 20 tons and must support five times its own weight, with a maximum deflection between being empty and being fully loaded of only a couple of centimeters. Installation of the eight-ton super-modules requires a system of rails with a sophisticated insertion device to bridge across to the support structure. The Electro-Magnetic Calorimeter (EM-Cal) will add greatly to the high momentum particle measurement capabilities of ALICE.[26] It will extend ALICE's reach to study jets and other hard processes.

Appendix A: First

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Appendix B: Second

B.1 Part one

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B.2 Part two

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Figure B.1: This is also a caption.