MEASURING THE STANDARD MODEL AND SEARCHING FOR NEW PHYSICS WITH JET SUBSTRUCTURE USING THE ATLAS DETECTOR

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF PHYSICS
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Maximilian Swiatlowski
March 2015

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

(Ariel Schwartzman) Principal Adviser

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

(Su Dong)

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

(Jay G. Wacker)

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

(Blas Cabrera (???))

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

(???)

Approved for the Stanford University Committee on Graduate Studies

Preface

This thesis tells you all you need to know about...

Acknowledgments

I would like to thank...

Contents

List of Tables

List of Figures

Chapter 1

Introduction

...

Chapter 2

The Standard Model, and the Theory of Strong Interactions

2.1 Overview

2.2 Spontaneous Symmetry Breaking, the Electroweak Force, and the Origin of Mass

2.3 Quantum Chromodynamics and Strong Interactions

Chapter 3

Jets and Substructure

3.1 The Goal of Jets, and Jet Algorithms

3.2 Jet Substructure: Going Deeper

3.3 Calculations with Jets

Chapter 4

Supersymmetry, R-Parity, and Naturalness

4.1 The Problem of the Standard Model

4.2 Supersymmetry: The Solution?

4.3 R-Parity, and How to Violate It

4.4 Naturalness, or the Pursuit of Beauty

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Chapter 5

The Large Hadron Collider

The Large Hadron Collider (LHC) is a 27 km long proton-proton (pp) synchotron built on the border of France and Switzerland, near the city of Geneva. The accelerator is nestled beneath mostly bucolic French farmland, as seen in Figure 5.

The total costs of the accelerator and the detectors it serves are estimated at \$20 billion, making the LHC one of the largest scientific enterprises ever attempted. [***Ed:*** *cite this*] The project is full of similar superlatives: the accelerator is the largest machine, the ATLAS detector is the largest detector, the CMS detector is the heaviest. 10,000 scientists from 113 countries work on some aspect of the project, making it one of the best examples of international cooperation that mankind has produced.

The machine is composed of eight essentially identical sectors,

The machine was designed to deliver collisions at $\sqrt{s} = 14$ TeV energy at a rate of 10^{34} cm^{-2}/s, but as of 2012 collisions had only occured at 8 TeVand a rate of 5×10^{33} cm^{-2}/s.

[***Ed:*** *Describe sectors, luminosity, energy, helium*]

5.1 History

The LHC was first discussed publically at the ECFA-CERN Workshop held at Lausanne and Geneva in March of 1984 [1][1]. This was a very active time for proposing new collider experiments, as extensive work on the 40 TeVpp Superconducting Supercollider (to be built in Waxahachie, Texas) had recently displaced a proposal for a 4 TeV $p\bar{p}$ Dedicated Collider at Fermilab [1, 3], though construction continued on Fermilab's 2 TeV $p\bar{p}$ Tevatron collider. The Soviet Union was even planning a 6 TeV $p\bar{b}$ collider, the Accelerator and Storage Complex (UNK) [4][***Ed:*** *This needs a better citation*]. In this busy landscape, the proposal of another machine at CERN– which was currently building the Large Electron Positron (LEP), the world's largest e^+/e^- collider– was very ambitious indeed.

[1] 4 years and 1 month before the author was born!

Figure 5.1: An aerial view of Geneva, with the location of the LHC superimposed. The individual detectors (described in chapter 6, as well as the main CERN Meyrin site, are also highlighted. Image courtesy CERN.

Several characteristics made the proposed LHC unique and worth pursuing in such a competitive environment. First, with the construction of the LEP tunnel on track for completion in 1988, the civil-engineering component of the project was greatly reduced, especially compared to the enormous expense of constructing the SSC tunnel. Second, while the design goals of 20 TeV collisions were at a significantly lower energy than the SSC, the projected luminosity was eventually designed to be a factor of 10 higher (10^{34} cm^{-2}/s, though the initial designs focused on 10^{33} cm^{-2}/s) and so the LHC could potentially gain sensitivity by accumulating data more quickly. Finally, as figure 5.1 shows, the initial designs for the LHC invisaged the LHC beamlines actually sitting on top of the existing LEP beamlines. The resulting hybrid collider would be able to run pp, ep, and ee collisions. This would not only extend the reach of the physics program by allowing for the study of deep inelastic scattering at higher energies than the HERA collider at DESY [***Ed:*** *Cite this– HERA and e/p if possible.*], but would also allow for the study of Z bosons from ee, which could potentially be used as a calibration source for detectors before pp collisions [1].

With the approval of the SSC in 1987 and the subsequent start of construction in 1991, CERN was mostly focused on the construction and operation of LEP but did not stop planning for the LHC. This proved remarkly prescient, as in the face of changing budget priorities and the end of the Cold War, the SSC ended up being cancelled in 1993. [***Ed:*** *This probably needs citations.*] CERN, on the other hand, approved a staged construction plan for the LHC in 1994, targetting first 10 TeV collisions in 2004 and then 14 TeV in 2008. Japan and the US joined CERN as observer states in 1995 and 1997 respectively, each contributing signficantly to the construction of the LHC and joining the physics program of CERN.[***Ed:*** *Statement about internation collaboration, compared to SSC? Statement about the 10 TeV plan being dropped?*]

The Conceptual Design Report [5] published in 1995 reflected the changed landscape with the demise of the SSC and the results of more detailed cost estimates. The design energy was lowered to 14 TeV– higher energies would have required more costly magnets– while the design luminosity was actually increased to 10^{34} cm^{-2}/s. This increase in luminosity came at a cost: the number of interaction points was reduced to four instead of eight, and only two would receive collisions at a high rate. [***Ed:*** *Mention pileup here or no?*] Critically, it was also decided to remove the LEP beamline and magnets, as it was deemed too costly to follow the existing LEP infrastructure. While this reduced the physics program of the LHC substantially, being the only high energy hadron collider was still a rather broad portfolio.

With the shutdown of LEP in 2001[2], the construction of the LHC began in earnest. It would take till 2007 to install the last magnet in the LHC, and the detectors finalized their own installations only in 2008. Figure 5.1 shows the final state of the LHC tunnel (without the originally planned LEP beamline). The first low-energy collisions occured on September 10, 2008, putting the LHC almost on track of its initial goal of 14 TeVcollisions in 2008. [***Ed:*** *Probably want to add a bit more*

[2] Not without controversy, as there was perhaps a tantalizing sign of an excess in Higgs-boson like events during the final runs of LEP.[***Ed:*** *cite me*]

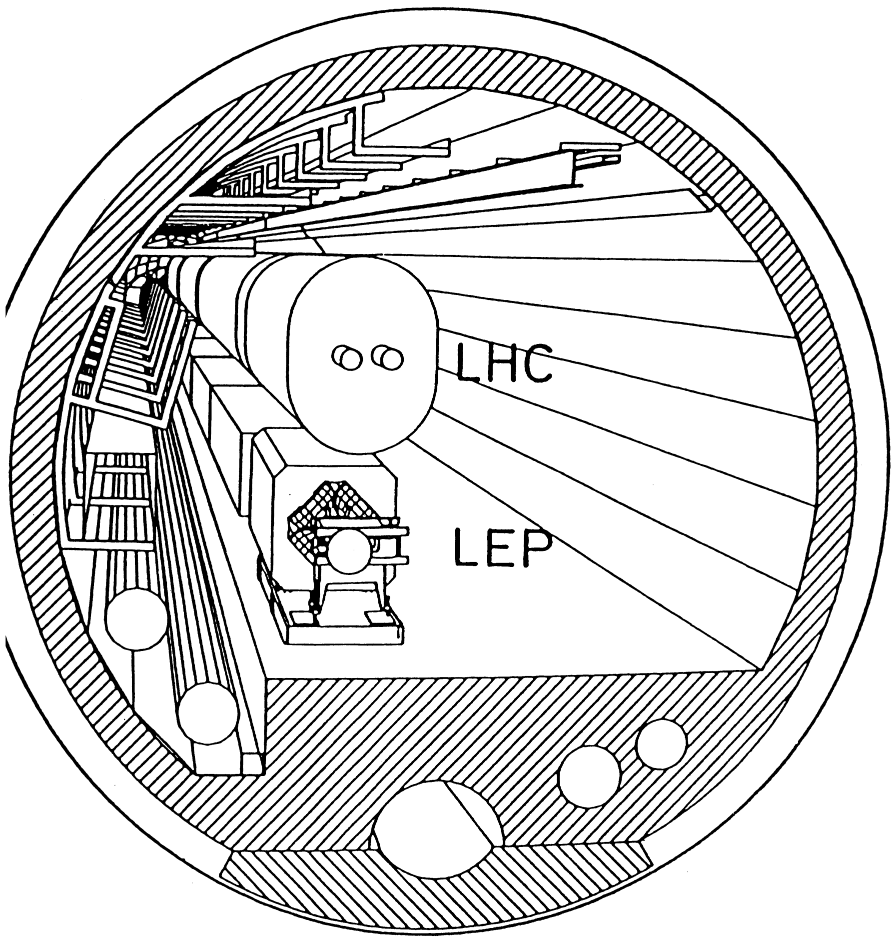

Figure 5.2: A schematic drawing of the initial design of a shared LEP/LHC tunnel, with the LHC beamline positioned on top of the existing LEP beamline [1].

Figure 5.3: A photo of the final LHC tunnel, no LEP beamline, in contrast to the first plans shown in Figure 5.1. Photo courtesy of USLHC.

on construction.]

However, an “incident” on September 19 ended up delaying the full startup for a year [6]. On that day, the operators were testing the last sector of the LHC at current levels appropriate fo 5.5 TeVbeams. A resistive zone developed in the electrical bus connection between a dipole and quadrupole magnet. While the power supply detected this and shut down within 0.39 seconds and the quench protection circuitry began to engage at 0.89 seconds, it was already too late: an electrical arc had sparked and punctured the liquid helium enclosure and the insulation vacuum along the cryostat. This, along with the electrical noise induced by the power supply shutdown and the heat dissipation caused by the quench protection circuitry, triggered a chain reaction in which several other magnets also began to quench and other vacuum systems were degraded. As the helium began to escape the cryostat, pressure relief valves correctly opened and vented the helium to atmosphere. However, an additional complication proved to be a problem: neighboring subsectors had their vacuum systems separated by vacuum barriers, meant to isolate the vacuum systems of neighboring areas. The vacuum barriers could only sustain a rather low pressure difference, and the extreme pressures generated by the evacuating helium overwhelmed these connections. The attendant large pressure forces ended up displacing dipoles from their support structures, and knocked the cryostats from their support jacks– in some cases even ripping the anchors from the concrete floor. A total of six tons of helium, five quadrupoles, and twenty-four dipoles were lost in the incident.

Collisions would begin in earnest at a lowered energy of 7 TeVin 2010 and 2011. After two years of successful and safe operations at the reduced energy, 2012 saw a large increase in luminosity and an increase of the collision energy to 8 TeV. [***Ed:*** *A bit more on operations at 8 TeV.*] The LHC then proceeded to shut down in 2013 until mid-2015 for a further round of repairs and consolidations of electrical connections to guarantee the safety of operations at near the design energy. As the restart of the LHC approaches in the coming months, we are anticipating collisions at 13 TeVwith luminosity likewise reaching near design levels. The LHC will have broken energy records twice in the span of five years, making this an incredibly exciting time to be working in particle physics.

5.2 Machine Design

5.3 Luminosity, and Pileup

5.4 Operations in 2010-2012

Chapter 6

The ATLAS Detector

The design of the LHC, with two high-luminosity interaction points at opposite ends of the ring, called for two general purpose detectors to be built in these locations. Their charge was to accurately reconstruct collision events in the most hostile conditions yet seen in a collider: with a bunch spacing of 25 ns and the unprecedented introduction of pile-up the detectors would have an enormous challenge ahead of them in dealing with both the rate and the reconstruction of events. ATLAS (A Toroidal LHC APparatus) [7] and CMS (Compact Muon Solenoid) [8] were the two detectors built for this task, with ATLAS occupying the (much more convenient) Point 1 and CMS located at the (very distant) Point 5. The data presented in this thesis was collected by the ATLAS experiment in pp collisions at $\sqrt{s} = 8$ TeV in 2012.

[***Ed:*** *Paragraph on general principles?*]

Particle detectors measure particles via their interactions with matter, as drawn schematically in Figure 6. For example, charged particles (such as electrons and some hadrons) interact electromagnetically with silicon and gas tubes, leaving hits in different layers of detectors which can be traced back to form a track. Electrons and photons, with their low masses and high rate of interaction with matter, are measured by the electromagnetic calorimeter. The calorimeter is composed of alternating layers of metal meant to cause the particle to interact and lose energy, and active materials which measure the energy left behind in these interactions. The hadron calorimeter follows a similar principle, and alternately placed layers of metal and active material again aim to stop and measure the hadrons which the electromagnetic calorimeter did not stop. Muons, which do not interact very much with matter most matter but do leave hits in trackers, survive past even the hadronic calorimeter, and a special set of muon detectors can be used to identify them there. Neutrinos, as they interact with matter only via the weak force and thus very rarely, escape detection and are reconstructed only by inferring their presence from the lack of momentum conservation in the transverse plane. [***Ed:*** *this isn't great?*]

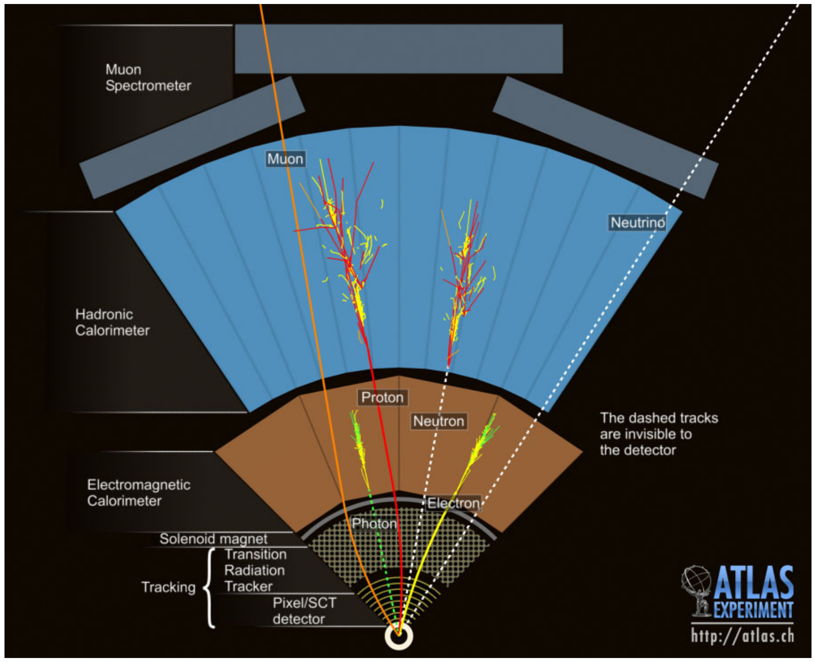

Figure 6.1: A schematic diagram of the interactions of various particles with detector components. Copyright CERN.

General purpose particle detectors thus demand the following characteristics: [***Ed:*** *define radiation lengths? above?*]

1. Tracking systems must be able to identify primary and secondary vertices, while minimizing the radiation lengths before the calorimeters
2. Strong calorimetry systems are required to accurately measure the energy and position electrons, photons, and hadrons
3. Muon systems must be able to precisely reconstruct muons

To this end, the ATLAS detector is built in the traditional onion-layer configuration, which measures particles as they travel perpendicular to the beam. The Inner Detector, composed of the concentric Pixel, SCT [***Ed:*** *define*], and Transition-Radiation-Tracker (TRT) subsystems, lies at the center of the detector and precisely measures tracks created by charged particles. A 2 T solenoid encloses the Inner Detector, bending charged particles and enabling the measurement of their momenta. Next the Electromagnetic Calorimeter (ECal), composed of liquid argon (LAr) and copper, sits outside of the solenoid in a liquid nitrogen cryostat, and measures energy deposits from electrons and photons (as well as hadrons to a lesser extent). The Hadronic Calorimeter, built to measure and stop any remaining hadronic particles, is composed of steel and scintillating tile in the

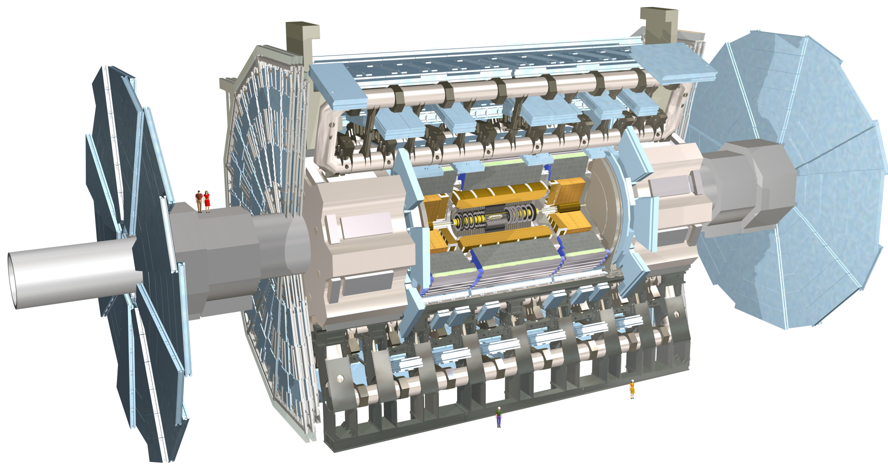

Figure 6.2: A computer-generated view of the ATLAS detector, with people for scale. Copyright CERN.

center (referred to as the barrel), and LAr and copper in forward regions (referred to as end-caps). Surrounding these are an additional set of magnets: the superconducting air-core toroids of the barrel and endcaps, which bend particles in the plane perpendicular to that of the bending due to the solenoid. [***Ed:*** *That needs cleaning.*] The Muon Spectrometer (composed of MDT, RPC, TGC, and CSC subsystems) sits outside of (and next to) these magnets, and provides a final measurement of the charged particles which reach that far. The entire detector is shown in Figure 6. The incredible size of the detector– 25 m in diameter, and 46 m long– is dominated by the Muon Spectrometer and the toroids. On the other hand, the detector is comparatively light (only 7000 tons, compared to 14,000 tons for CMS), as the air-core toroids do not add substantial weight to the detector. [***Ed:*** *decide how to cite all this*]

In keeping with the principle of "similar, but opposite" established by their locations, the ATLAS and CMS detectors take complementary approaches to the various aspects of event reconstruction in collisions. All general purpose detectors have the same basic goals: the must reconstruct the outgoing, stable particles produced in collisions and the subsequent decays of particles in these collisions. Different particles are detected with different general classes of detectors, of which there are many possible types. For example, electrons and photons are measured by the ECal, for which

ATLAS used a liquid argon (LAr) and copper system while CMS used a crystal lead tungstate system. Each had their own advantages and disadvantages (ATLAS's was less costly and already proven technology with better position resolution, while CMS took a riskier route which promised better energy resolution), but overall performance between the detectors tends to be very similar because of various trade-offs. In the case of the ECals, the precision of ATLAS and CMS's $H \to \gamma\gamma$ measurements ended up being largely similar [***Ed:*** *cite?*], in no small part because CMS's all-silicon tracking system introduced greater radiation lengths before the calorimeters, thereby prompting more photons to convert and losing precision in the measurement. On the other hand, CMS's comparatively weak brass hadronic calorimeter (compared to ATLAS's higher resolution tile calorimeter), is compensated by their tracking system, which enables a particle-flow reconstruction algorithm to combine information from all detectors and improve jet performance to levels very similar to ATLAS. [***Ed:*** *consider citations, and substantial revisions here*]. Similarly, the large size and extra toroid magnets of ATLAS allow for a larger lever-arm and an additional set of measurements of muons (enabling reconstruction with or without the inner detector): however, muon reconstruction performance in CMS is very similar because the stronger solenoidal magnetic field (4 T compared to 2 T) allows for a better measurement using the inner detector only (with the muon systems on CMS providing only a tag of a passing muon, and not a complete reconstruction).

6.1 History

The first public discussion of the proposals which became the ATLAS detector occurred in 1992 at the General Meeting on LHC Physics at Evian-les-Bains [9, 10]. At the time, four general purpose detectors (much like the four detector configuration in place at LEP) were seriously considered: EAGLE, ASCOT, CMS, and L3 (as an upgrade to the existing LEP detector, including a movable stage which would allow it to take data from both e^+/e^- and pp collisions). Several additional single purpose (heavy ion, neutrino, and B-physics) detectors were also proposed.

ATLAS emerged in a later 1992 Letter of Intent as a merger of the ASCOT and EAGLE collaborations [2]. ASCOT (Apparatus with SuperCOnducting Toroids) contributed the physically-defining feature of the secondary toroidal magnet system and standalone muon measurement system, as well as the tradition of using a tortured amalgamation of letters to form a name. EAGLE (Experiment for Accurate Gamma, Lepton and Energy measurements) on the other hand featured a stronger 2 T magnetic field, and inner-detector and calorimeter designs more similar to some of the final ATLAS systems. The detector described in the Letter of Intent already resembled ATLAS in many important ways, featuring the superconducting air-core toroids, accordion-shaped liquid Argon electromagnetic calorimeters, scintillating tile hadron calorimeters, and multi-design inner detector. 6.1 shows an early drawing of ATLAS from the Letter, and already the detector looks recognizable to its current form.

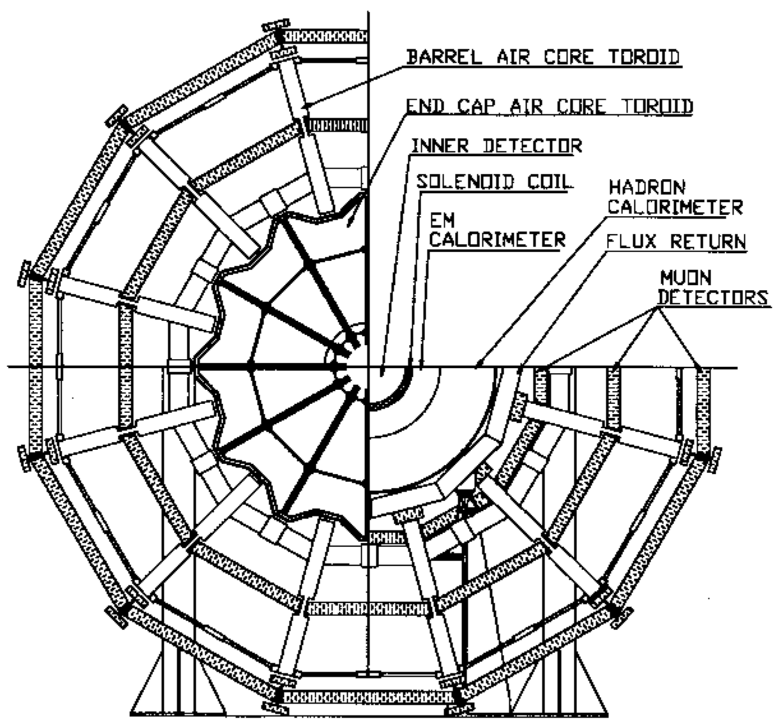

Figure 6.3: An early view of a potential superconducting air-core toroid magnet system for the ATLAS detector from the 1992 Letter of Intent [2].

Figure 6.4: A photograph of the ATLAS solenoid shortly after the winding of the coils was finished. Copyright CERN.

6.2 Magnet Systems

6.2.1 Solenoid

6.2.2 Toroids

6.3 Inner Detector

6.3.1 Silicon Pixel Detector

[***Ed:*** *Citationsssss*]

The innermost ATLAS sub-detector is the Silicon Pixel Detector. 80.4 million independent pixel channels, with a size of 50×400 μm, , are read out by 1744 bump-bonded modules attached to the active sensors. Each of the modules are composed of 16 front-end chips. This corresponds to a combined active area of 1.7 m^2. The detector is arranged in three radial layers in the barrel section, and three disks in the end-caps. In the radial layers, the pixels have a resolution of 10×115 μm in $r-\phi$ and z respectively, and in the end-caps the orientation is reversed and the resolution is 10×115 μm in z and $r - \phi$: the orientations are always chosen such that the most precise measurement takes place in the direction most relevant to the measurement of the track p_T. [***Ed:*** *Check these numbers, especially end-cap*] [***Ed:*** *Anything about occupancy?*]

The innermost radial layer, known as the b-layer, sits only 50.5 mm from the center of the beampipe, while the outermost layer is located at 122.5 mm. By placing detectors so close to the

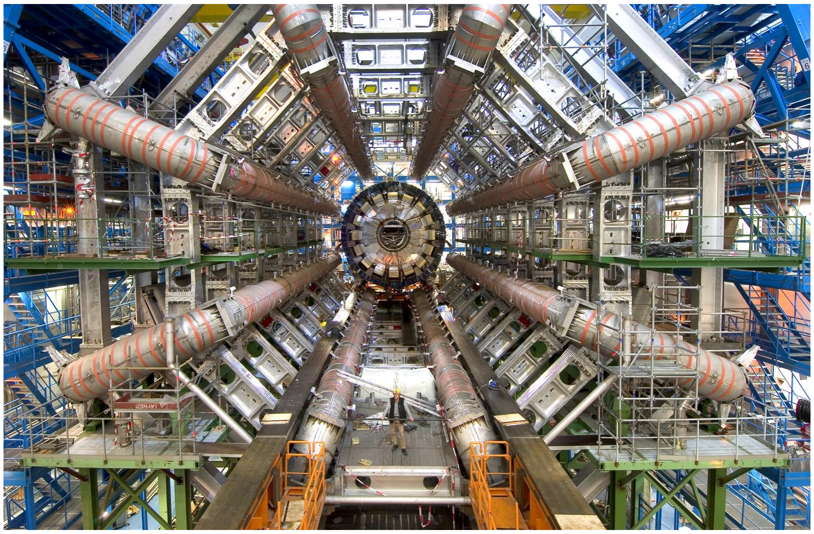

Figure 6.5: A photograph of the ATLAS barrel toroids after their installation. Note person in the center for scale. Copyright CERN.

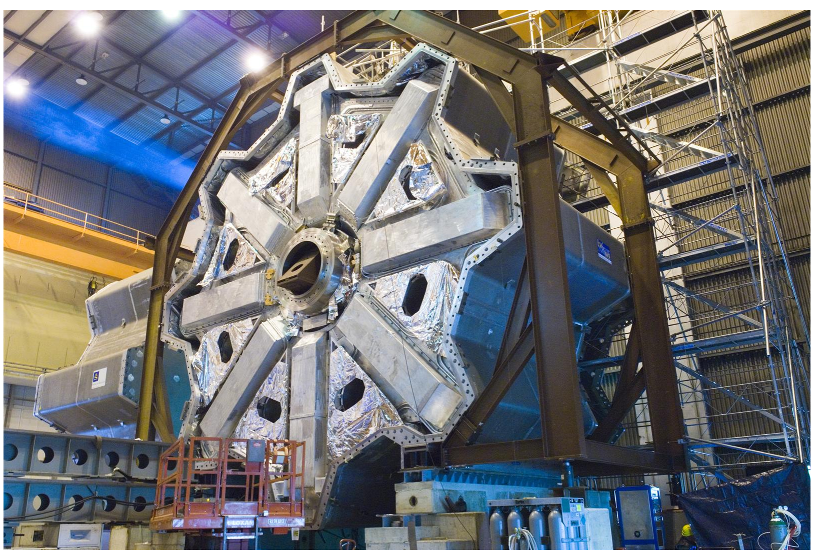

Figure 6.6: A photograph of an ATLAS endcap toroid shortly before its installation in the detector. Copyright CERN.

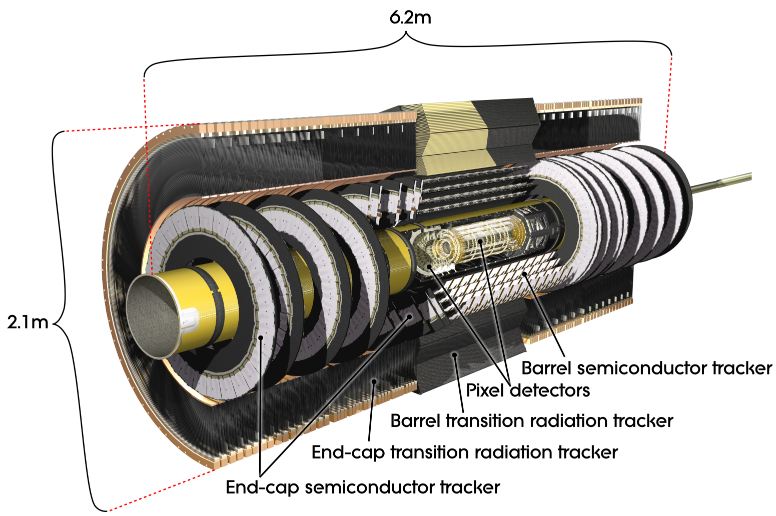

Figure 6.7: A computer-generated view of the ATLAS inner detector, with relevant sizes of the detector marked out. Copyright CERN.

interaction point, it is possible to very accurately measure the location of both primary vertices– the locations of $p-p$ collisions– and second vertices– the locations of the displaced decays of particles with long lifetimes, such as B-hadrons.

Placing the detector so close to the beamline comes at a price, however, as the detector is particularly susceptible to radiation damage due to the high flux of particles through a small area. At design luminosity, this is expected to be about 158 kGy/year at the b-layer, reduced to 25.4 kGy/year at the outermost layer. As the performance of the detector is thus expected to degrade over time (indeed, the entire inner detector is planned to be replaced after 300 fb^{-1} are collected), [***Ed:*** *This is not the nicest way of putting this.*]

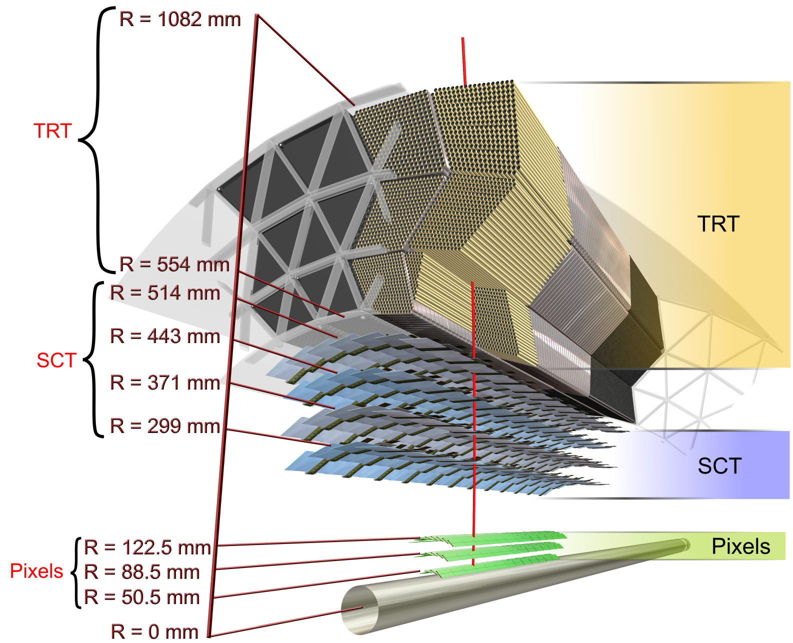

Figure 6.8: A cut-out view of the ATLAS inner detector, showing the layers a particle would interact with as it passed outward from the collision point. Copyright CERN.

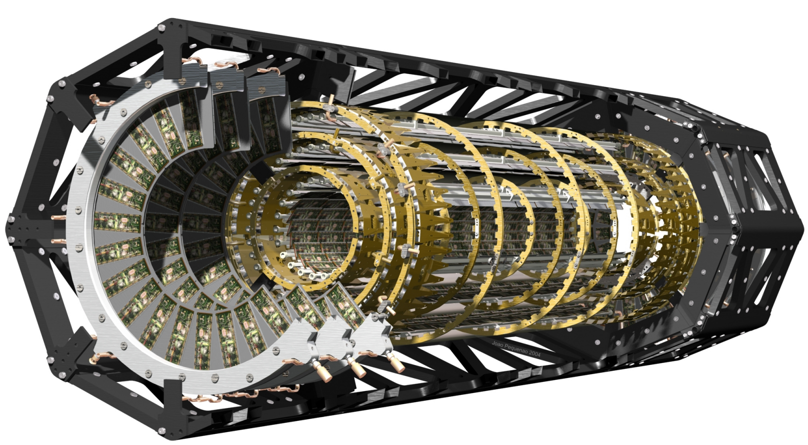

Figure 6.9: A computer-generated view of the ATLAS pixel detector. Copyright CERN.

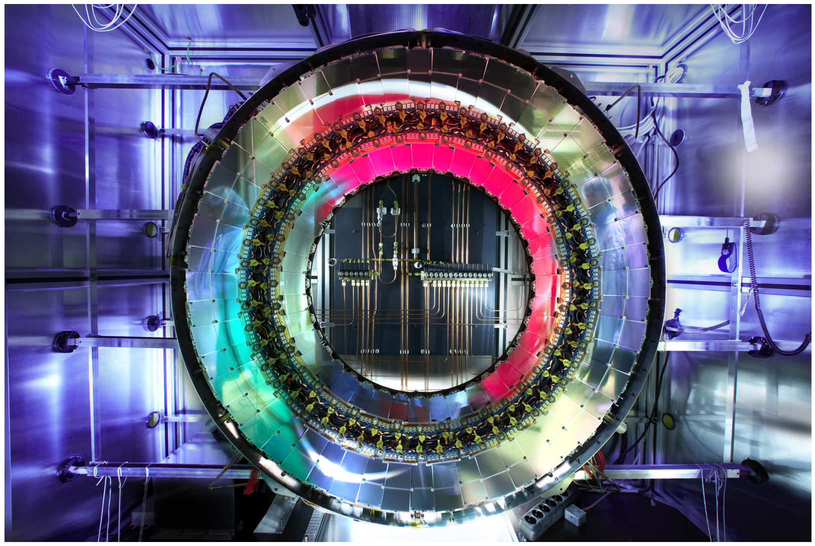

Figure 6.10: A photograph of one segment of the ATLAS SCT barrel system. Copyright CERN.

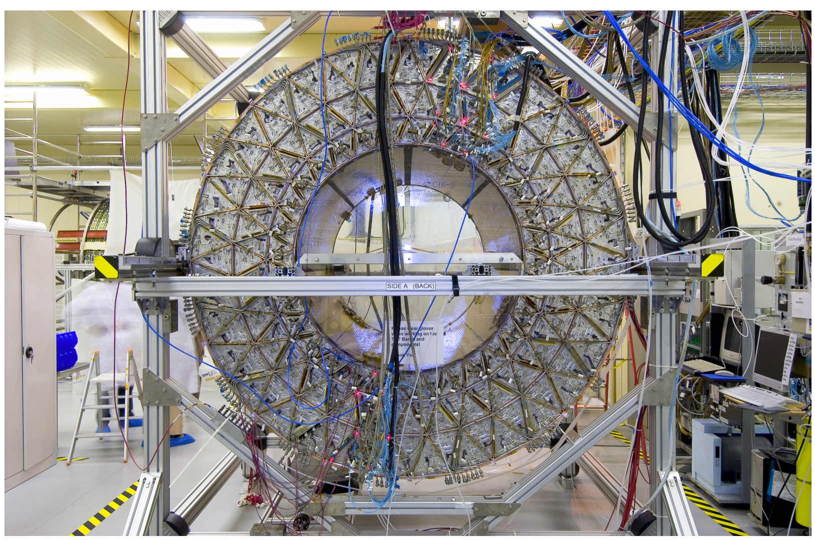

Figure 6.11: A photograph of the ATLAS TRT system during testing. Copyright CERN.

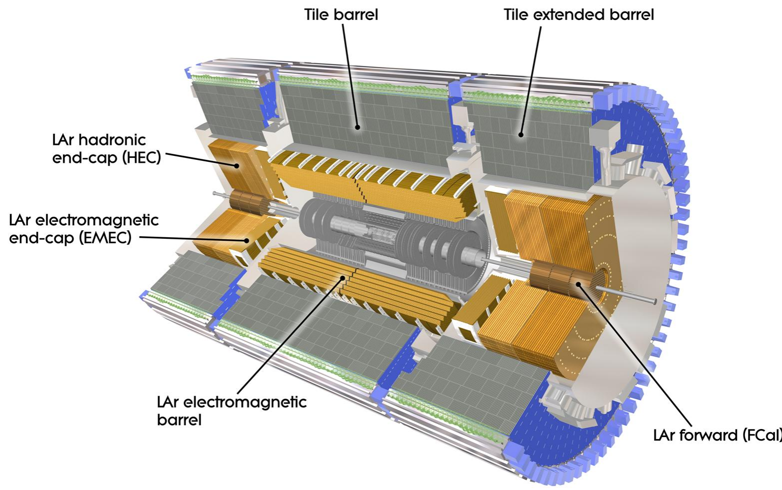

Figure 6.12: A computer generated image of the ATLAS calorimeter system, showing the locations of each different subdetector. Copyright CERN.

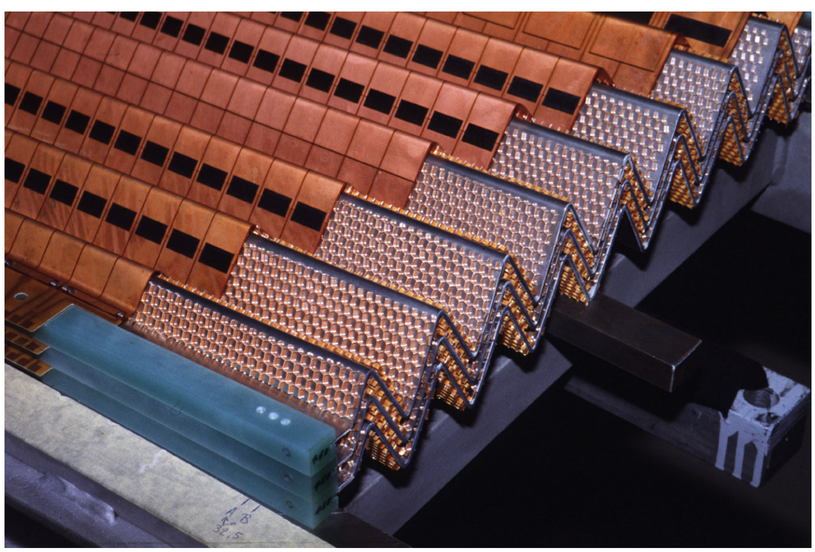

Figure 6.13: A photograph of the accordion structure used in the LAr barrel. Copyright CERN.

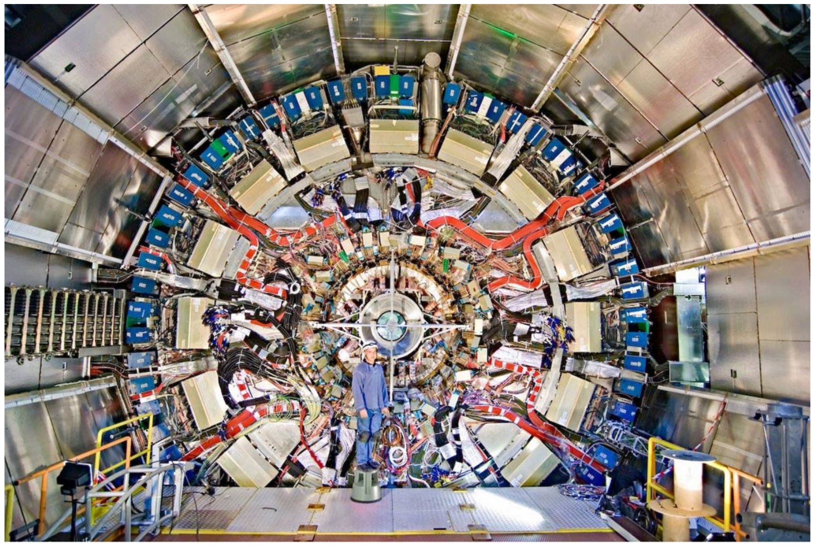

Figure 6.14: A photograph of the LAr endcap after installation in the cryostat system. Copyright CERN.

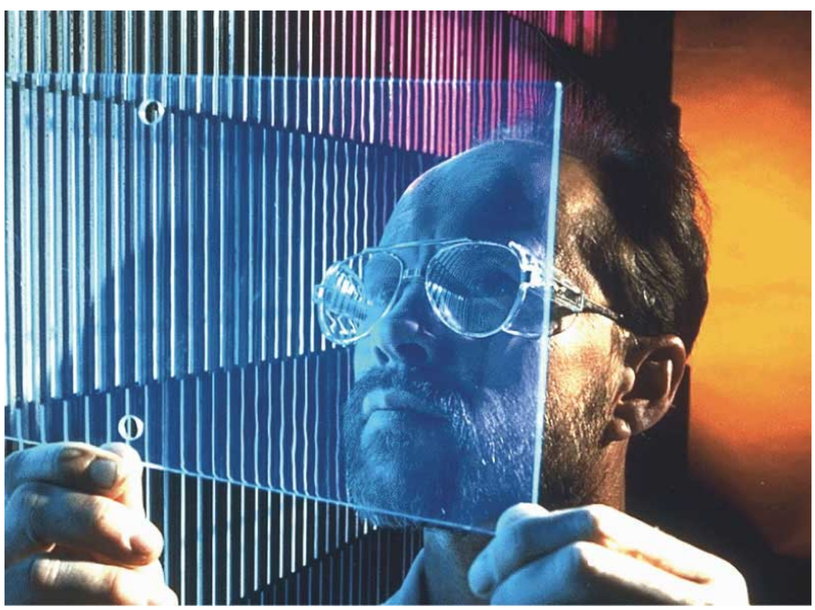

Figure 6.15: A photograph of one of the scintillating tiles which give the tile calorimeter its name. Copyright CERN.

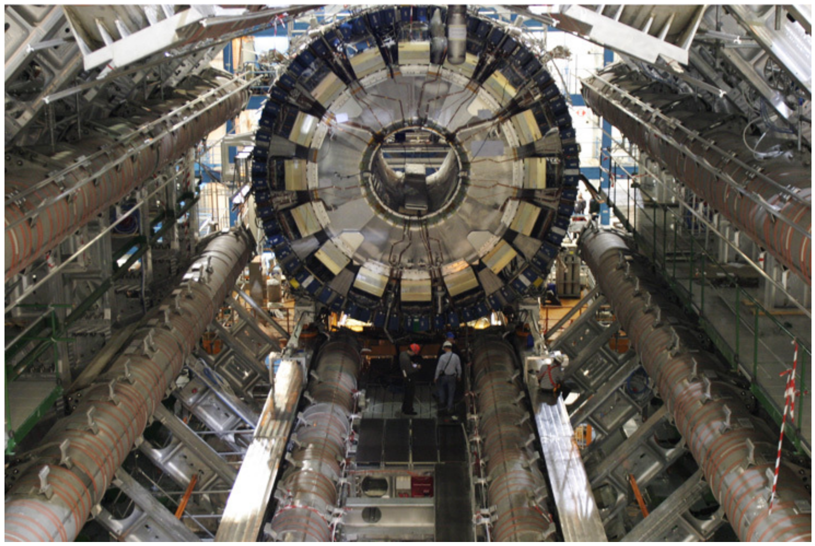

Figure 6.16: A photograph of the installation of the barrel tile calorimeter. Copyright CERN.

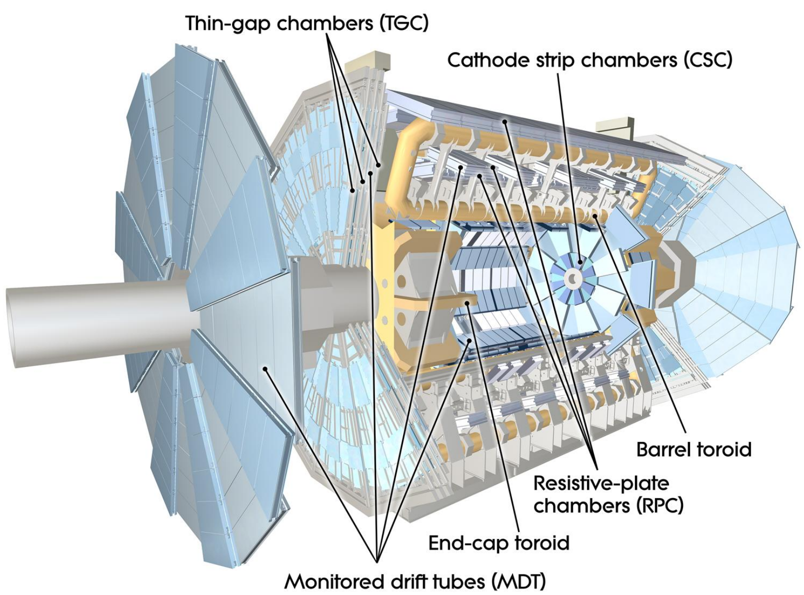

Figure 6.17: A computer generated image showing the locations of each of the muon spectrometer subsystems. Copyright CERN.

6.3.2 Silicon Strip Tracker

6.3.3 Transition Radiation Tracker

6.4 Calorimeters

6.4.1 Electromagnetic Calorimeter

6.4.2 Hadron Calorimeter

6.5 Muon Spectrometer

6.6 Triggering

6.7 Data Quality

Chapter 7

Jet Reconstruction with ATLAS

7.1 Clusters, Towers, and Tracks, Oh My

7.1.1 Cluster Calibration

7.2 Jet Calibration

7.3 Quark/Gluon Discrimination

7.3.1 Lots of subsections

...

Chapter 8

Seeing Color at the LHC

8.1 Motivation

8.2 Reconstructing Color

8.2.1 Finding Top Quarks

8.2.2 Origin Corrections

8.2.3 Resolution Effects

8.2.4 Track and Cluster Uncertainties

8.3 Measuring Color

8.3.1 Unfolding

8.3.2 Results

8.3.3 Future Prospects

...

Chapter 9

Searching for Supersymmetry with Super Jets

9.1 Motivation

9.2 Why Jet Substructure?

9.2.1 Total Jet Mass, and Other Variables

9.2.2 Jet Mass Templates

9.3 Constructing a Search

9.3.1 Background Estimates

9.3.2 Limits

9.3.3 Future Prospects

...

Chapter 10

Conclusions

...

Appendix A

A Long Proof

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