

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

A DISSERTATION
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FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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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.

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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

Preface	v
Acknowledgments	vi
1 Introduction	1
2 The Standard Model, and the Theory of Strong Interactions	2
3 Supersymmetry, <i>R</i> -Parity, and Naturalness	3
4 The Large Hadron Collider	4
4.1 History	4
4.2 Machine Design	9
4.3 Luminosity, and Pileup	9
4.4 Operations in 2010-2012	9
5 The ATLAS Detector	10
5.1 History	10
5.2 Magnet Systems	14
5.2.1 Solenoid	14
5.2.2 Toroids	14
5.3 Inner Detector	14
5.3.1 Pixel Detector	14
5.3.2 Silicon Strip Tracker	14
5.3.3 Transition Radiation Tracker	14
5.4 Calorimeters	14
5.4.1 Electromagnetic Calorimeter	14
5.4.2 Hadron Calorimeter	14
5.5 Muon Spectrometer	14
5.6 Triggering	14

5.7	Data Quality	14
6	Measuring Jets with ATLAS	20
7	An Overview of Jet Substructure	21
8	Seeing Color at the LHC	22
9	Searching for Supersymmetry with Super Jets	23
10	Conclusions	24
A	A Long Proof	25
	Bibliography	26

List of Tables

List of Figures

4.1	An aerial view of Geneva, with the location of the LHC superimposed. The individual detectors (described in chapter 5, as well as the main CERN Meyrin site, are also highlighted. Image courtesy CERN.	5
4.2	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].	7
4.3	A photo of the final LHC tunnel, no LEP beamline, in contrast to the first plans shown in Figure 4.1. Photo courtesy of USLHC.	8
5.1	A computer-generated view of the ATLAS detector, with people for scale. Copyright CERN.	11
5.2	An early view of a potential superconducting air-core toroid magnet system for the ATLAS detector from the 1992 Letter of Intent [2].	12
5.3	A photograph of the ATLAS solenoid before it was lowered to the cavern. Copyright CERN.	12
5.4	A photograph of the ATLAS barrel toroids after their installation. Note person in the center for scale. Copyright CERN.	13
5.5	A photograph of an ATLAS endcap toroid shortly before its installation in the detector. Copyright CERN.	13
5.6	A computer-generated view of the ATLAS inner detector, with relevant sizes of the detector marked out. Copyright CERN.	14
5.7	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.	15
5.8	A computer-generated view of the ATLAS pixel detector. Copyright CERN.	15
5.9	A photograph of one segment of the ATLAS SCT barrel system. Copyright CERN.	16
5.10	A photograph of the ATLAS TRT system during testing. Copyright CERN.	16
5.11	A computer generated image of the ATLAS calorimeter system, showing the locations of each different subdetector. Copyright CERN.	17
5.12	A photograph of the accordion structure used in the LAr barrel. Copyright CERN.	17

5.13 A photograph of the LAr endcap after installation in the cryostat system. Copyright CERN.	18
5.14 A photograph of one of the scintillating tiles which give the tile calorimeter its name. Copyright CERN.	18
5.15 A photograph of the installation of the barrel tile calorimeter. Copyright CERN.	19
5.16 A computer generated image showing the locations of each of the muon spectrometer subsystems. Copyright CERN.	19

Chapter 1

Introduction

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Chapter 2

The Standard Model, and the Theory of Strong Interactions

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Chapter 3

Supersymmetry, R -Parity, and Naturalness

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Chapter 4

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 4.

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 occurred at 8 TeV and a rate of 5×10^{33} cm $^{-2}$ /s.

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

4.1 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 TeV pp 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.

¹4 years and 1 month before the author was born!



Figure 4.1: An aerial view of Geneva, with the location of the LHC superimposed. The individual detectors (described in chapter 5, 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 ($10^{34} \text{ cm}^{-2}/\text{s}$, though the initial designs focused on $10^{33} \text{ cm}^{-2}/\text{s}$) and so the LHC could potentially gain sensitivity by accumulating data more quickly. Finally, as figure 4.1 shows, the initial designs for the LHC envisaged 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 remarkably 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 significantly 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 $10^{34} \text{ cm}^{-2}/\text{s}$. 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 2001², 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 4.1 shows the final state of the LHC tunnel (without the originally planned LEP beamline). The first low-energy collisions occurred on September 10, 2008, putting the LHC almost on track of its initial goal of 14 TeV collisions in 2008. [*Ed: Probably want to add a bit more*

²Not 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]*

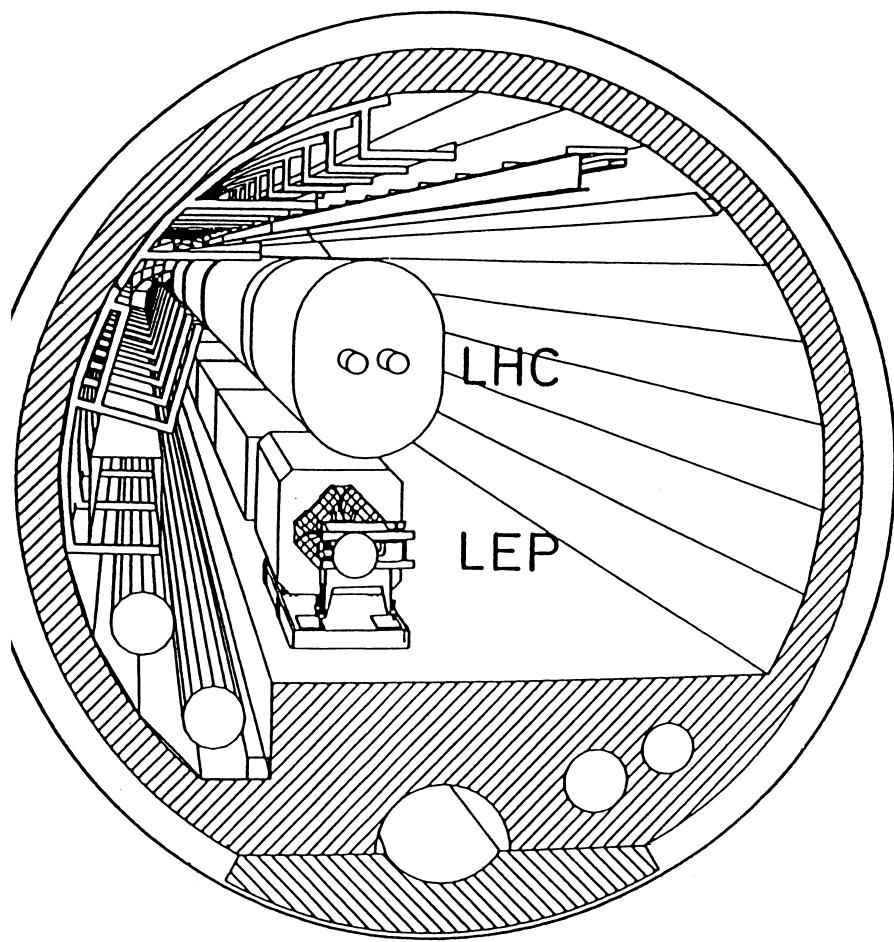


Figure 4.2: A schematic drawing of the initial design of a shared LEP/LHC tunnel, with the LHC beamline positioned on top of the existing LEP beamline [1].



Figure 4.3: A photo of the final LHC tunnel, no LEP beamline, in contrast to the first plans shown in Figure 4.1. 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 for 5.5 TeV beams. 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 TeV in 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 TeV with 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.

4.2 Machine Design

4.3 Luminosity, and Pileup

4.4 Operations in 2010-2012

Chapter 5

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. 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.

In keeping with the principle of “similar, but opposite” established by their locations, the ATLAS and CMS detectors take

The ATLAS detector

The data presented in this thesis was collected by the ATLAS experiment in pp collisions at $\sqrt{s} = 8$ TeV in 2012.

5.1 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

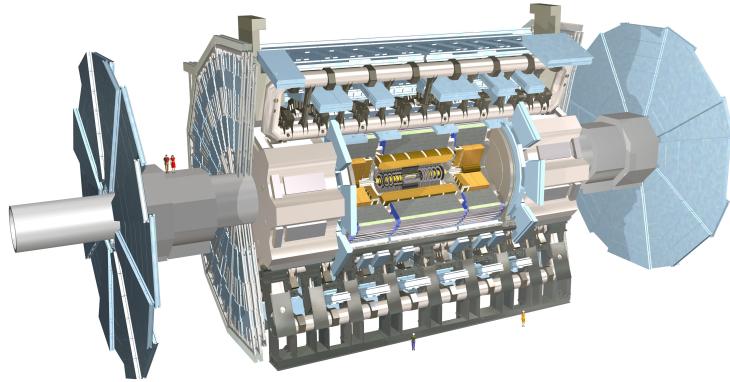


Figure 5.1: A computer-generated view of the ATLAS detector, with people for scale. Copyright CERN.

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. 5.1 shows an early drawing of ATLAS from the Letter, and already the detector looks recognizable to its current form.

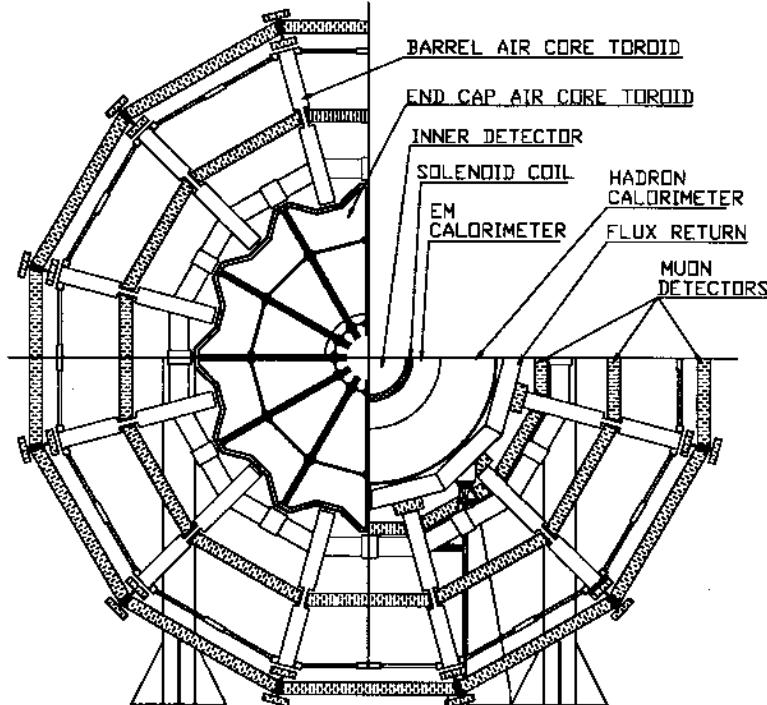


Figure 5.2: An early view of a potential superconducting air-core toroid magnet system for the ATLAS detector from the 1992 Letter of Intent [2].



Figure 5.3: A photograph of the ATLAS solenoid before it was lowered to the cavern. Copyright CERN.

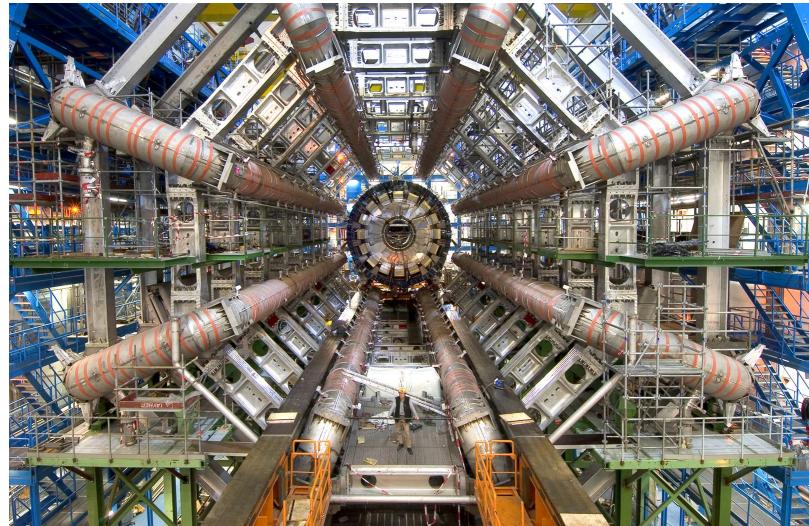


Figure 5.4: A photograph of the ATLAS barrel toroids after their installation. Note person in the center for scale. Copyright CERN.



Figure 5.5: A photograph of an ATLAS endcap toroid shortly before its installation in the detector. Copyright CERN.

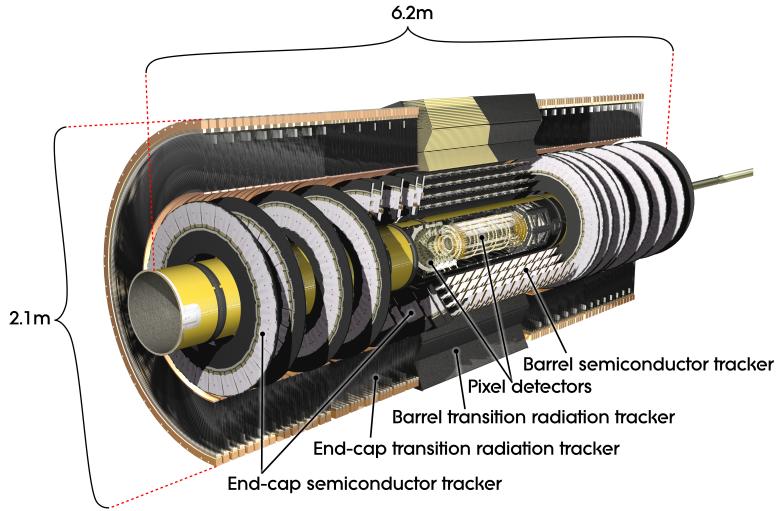


Figure 5.6: A computer-generated view of the ATLAS inner detector, with relevant sizes of the detector marked out. Copyright CERN.

5.2 Magnet Systems

5.2.1 Solenoid

5.2.2 Toroids

5.3 Inner Detector

5.3.1 Pixel Detector

5.3.2 Silicon Strip Tracker

5.3.3 Transition Radiation Tracker

5.4 Calorimeters

5.4.1 Electromagnetic Calorimeter

5.4.2 Hadron Calorimeter

5.5 Muon Spectrometer

5.6 Triggering

5.7 Data Quality

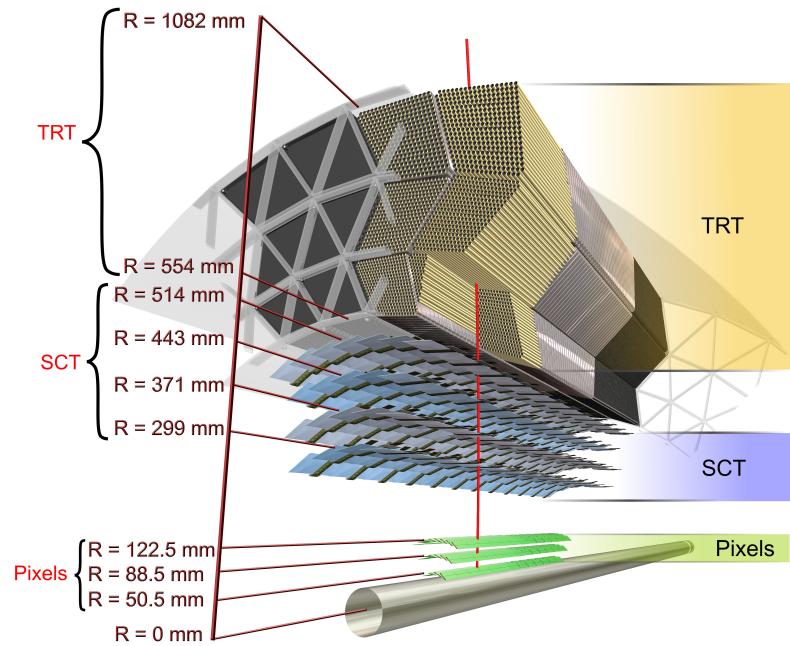


Figure 5.7: A cut-out view of the ATLAS inner detector, showing the layers a particle would interact with as it passed outward from the collision point. Copyright CERN.

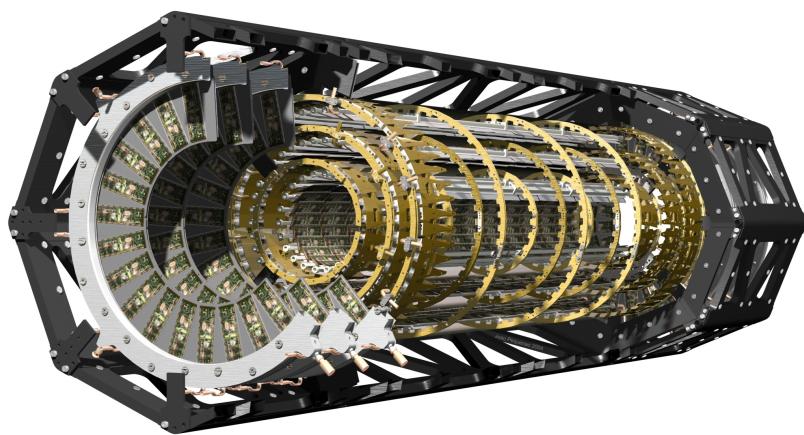


Figure 5.8: A computer-generated view of the ATLAS pixel detector. Copyright CERN.

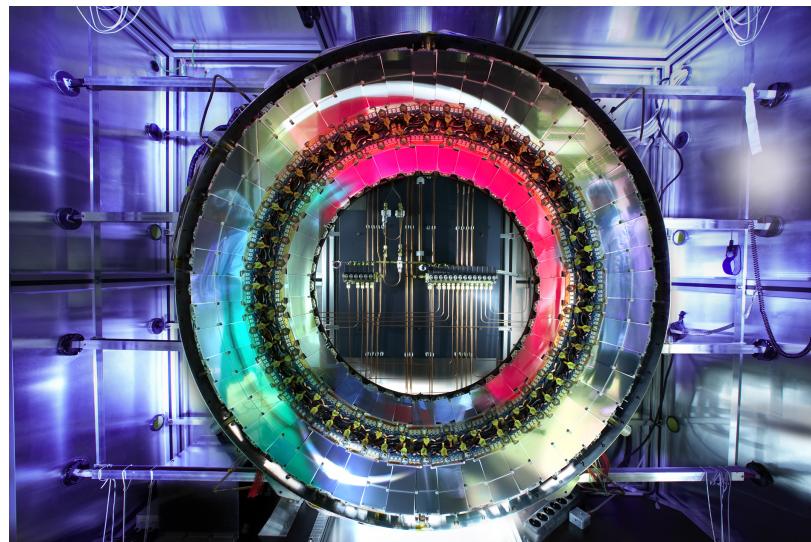


Figure 5.9: A photograph of one segment of the ATLAS SCT barrel system. Copyright CERN.

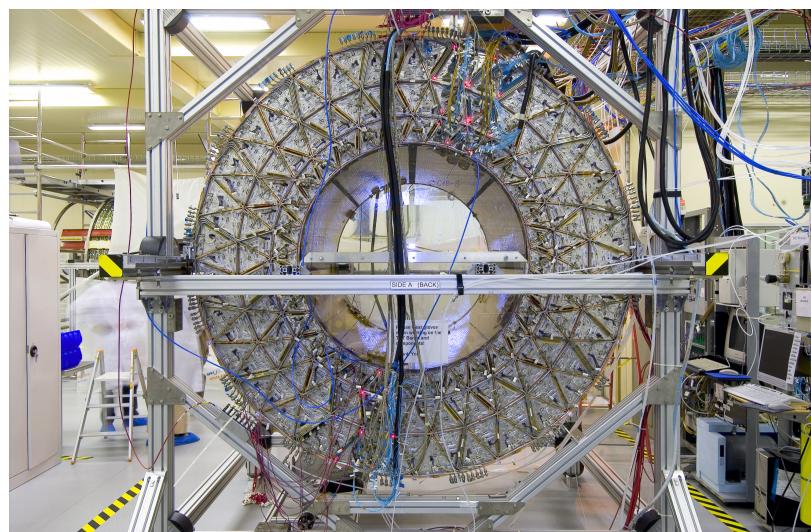


Figure 5.10: A photograph of the ATLAS TRT system during testing. Copyright CERN.

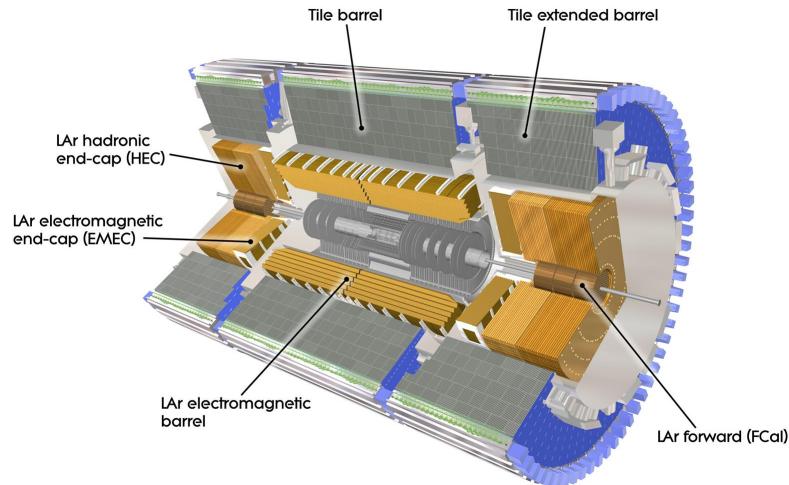


Figure 5.11: A computer generated image of the ATLAS calorimeter system, showing the locations of each different subdetector. Copyright CERN.

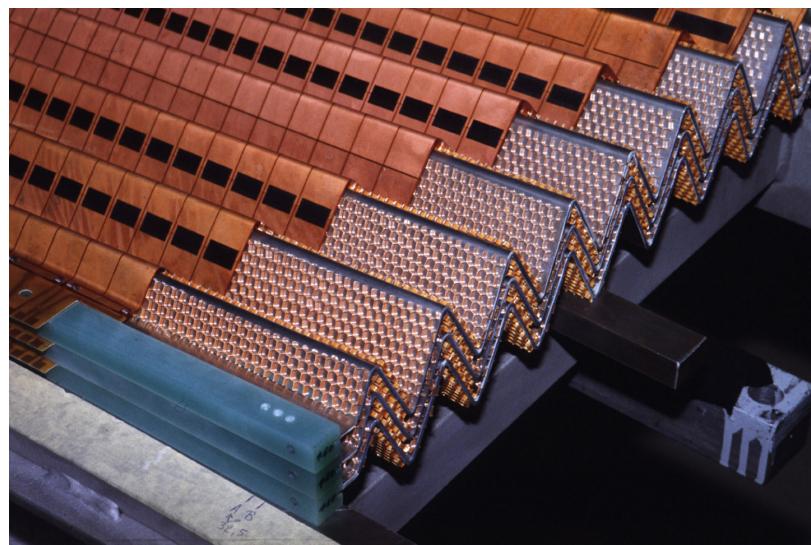


Figure 5.12: A photograph of the accordion structure used in the LAr barrel. Copyright CERN.

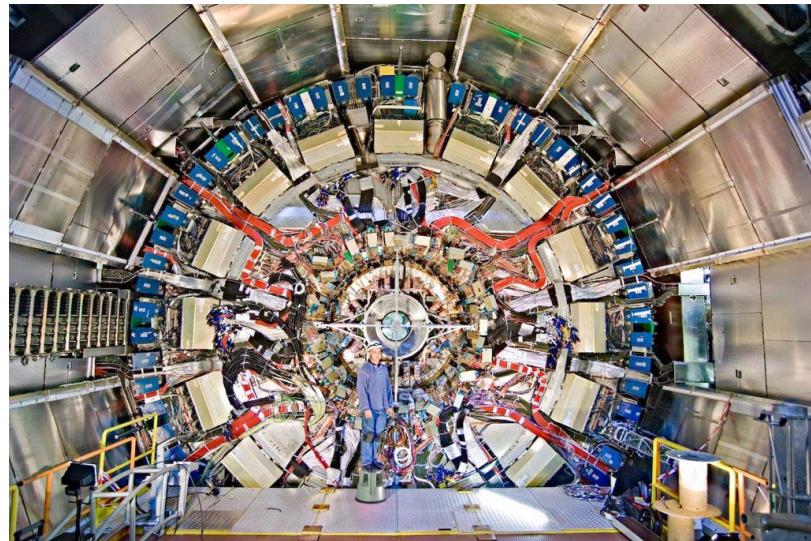


Figure 5.13: A photograph of the LAr endcap after installation in the cryostat system. Copyright CERN.

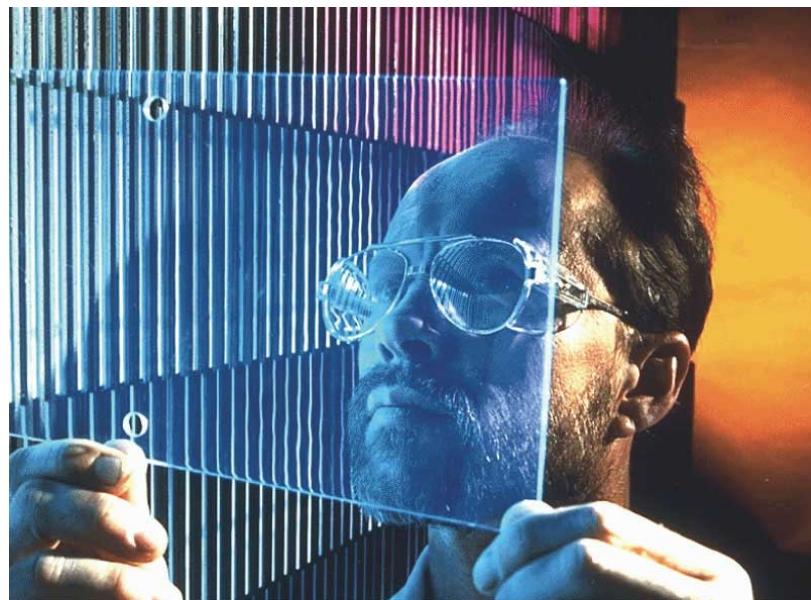


Figure 5.14: A photograph of one of the scintillating tiles which give the tile calorimeter its name. Copyright CERN.

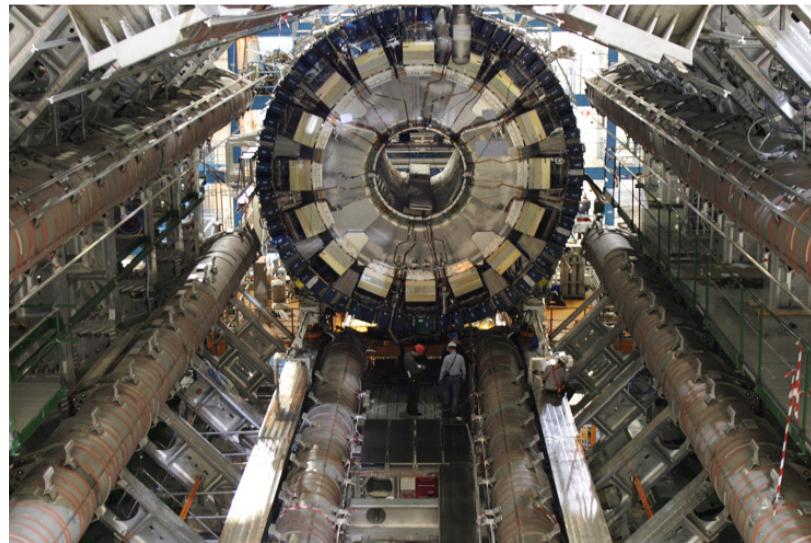


Figure 5.15: A photograph of the installation of the barrel tile calorimeter. Copyright CERN.

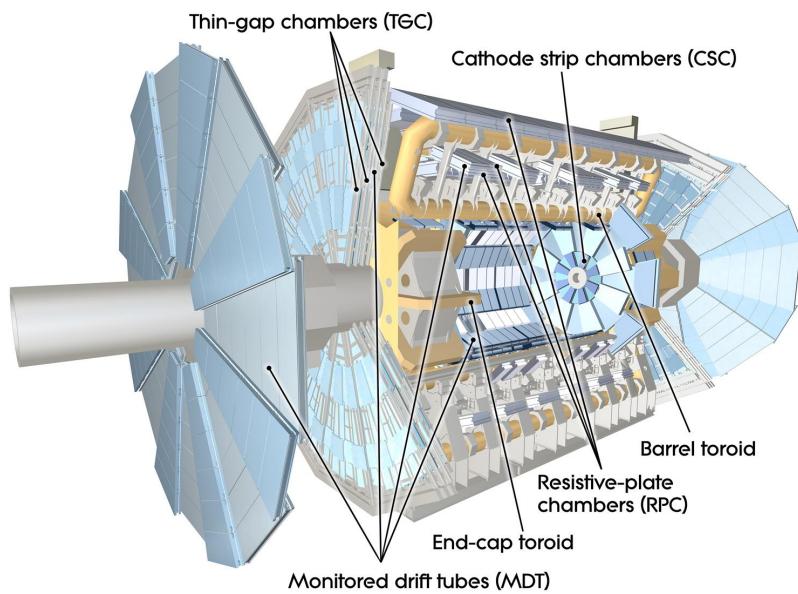


Figure 5.16: A computer generated image showing the locations of each of the muon spectrometer subsystems. Copyright CERN.

Chapter 6

Measuring Jets with ATLAS

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Chapter 7

An Overview of Jet Substructure

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Chapter 8

Seeing Color at the LHC

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Chapter 9

Searching for Supersymmetry with Super Jets

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Chapter 10

Conclusions

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Appendix A

A Long Proof

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