Using cosmic-ray hodoscope data to validate the misalignment model of small-strip thin gap chambers for the ATLAS new small wheels

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Abstract

ATLAS is a multi-purpose particle detector system designed to capture the outcome of proton-proton collisions at the Large Hadron Collider (LHC) at CERN. The innermost end-caps of the ATLAS muon spectrometer consist of two wheels of muon detectors that must be replaced to improve the angular resolution of tracks for precision muon momentum reconstruction in the next phase of LHC operation. The New Small Wheels (NSWs) will be covered with two detector types that must trigger on and track outgoing particles - one type is small-strip thin gap chambers (sTGCs). Canada is responsible for one quarter of the required sTGCs. At McGill University, modules with four layers of sTGCs (called quadruplets) are characterized using a cosmic ray hodoscope before being sent to CERN for further testing and integration into the wheels. Quadruplets must be able to reconstruct particle tracks with 1 mrad angular resolution. Misalignments between sTGC layers must be corrected for to achieve this goal. The charge profile left by an x-ray gun and coordinate measuring machine (CMM) measurements of quadruplet layers are being used to define these parameters. Work on using cosmic ray data to validate misalignment parameters derived using the above-mentioned methods will be presented.

Résumé

C'est le résumé.

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Acknowledgements

Something along the lines of . . . I would like to thank all the little people who made this thesis possible.

Contribution of authors

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Chapter 1

Introduction

The High-Lumnosity Large Hadron Collider (HL-LHC) project [?] was approved to combat the plateau in statistial gain of recording particle collisions at the LHC [?] at CERN. Being the most energetic particle accelerator, the LHC still offers unique physics opportunities for studying the Higgs and electroweak sectors of the standard model[?]; if the study at the energy frontier is to continue, the LHC must go on. The HL-LHC upgrade aims to increase the luminosity of the LHC by up to a factor of 7 in the next 10 years, which ultimately increases the number of meaningful collisions. Naturally, various sub-systems of the experiments used to capture the outcomes of the collisions will require upgrades to handle higher collision rates and background radiation rates than they were designed for.

The ATLAS experiment [?] is one of the LHC's general-purpose particle detector arrays, positioned around one of the collision points of the LHC. It detects the products of LHC collisions ~~at a rate of 40 MHz using many detector subsystems, including a trigger system that ultimately reduces the rate of recorded interactions to 1 kHz [?, ?]~~. The largest upgrade the ATLAS experiment is undergoing is the replacement of the small wheels of the muon spectrometer with the so-called New Small Wheels (NSWs) [?]. The NSW upgrade addresses both the expected decrease in hit efficiency in the precision tracking detectors of the current small wheel expected and the high fake trigger rate of the muon spectrometer. Two different detector technologies will be installed, stacked on the NSW frame: micromegas (MMs) and small-strip thin gap chambers (sTGCs). MMs are optimized for precision tracking while sTGCs are optimized for rapid triggering, although each will provide complete coverage and redundancy over the area of the NSW. Canada was responsible for providing 1/4 of the required sTGCs.

To reduce the fake trigger rate, the NSW will provide better track angular resolution to the ATLAS trigger system to reject tracks that do not originate from the collision [?]. sTGCs provide 100 μm position resolution per detector plane [?], and are stacked in four (called an sTGC quadruplet) to provide 1 mrad angular resolution on tracks [?, ?]. To be fast enough to provide this information to the trigger, they were designed with the smallest number of readout electrodes [?]. sTGCs are gas ionization chambers where a thin volume of gas is held between two cathode boards. One boards is segmented into pad electrodes (of varying areas around 300 cm^2) and one is segmented into strip electrodes of 3.2 mm pitch. The signals picked up by the pads due to a passing charged particle are used to select which strip electrodes to readout. The position of the particle track in the precision coordinate can then be reconstructed from the strip signals to provide the track angle to the trigger fast enough for the trigger to decide if the particle came from the interaction or not [?].

Precise position resolution is naught without accurate positioning of readout electrodes in ATLAS. The ATLAS alignment system is able to position the surface of three sTGC or MM quadruplets traversable by a muon track with respect to one another within 40 μm. The internal geometry of the detectors must be controlled or corrected for to within the chambers' position resolution [?]. Corrections to the position of strip electrodes in sTGC quadruplets are in their final stages. The corrections are done with characterization data collected throughout the construction process. At the cathode board level, strip electrode positions are digitized with a coordinate measuring machine (CMM) [?]. At the quadruplet level, sTGC quadruplets are characterized with cosmic rays and with an x-ray gun at positions that will be tracked by the alignment system. The x-ray method [2] is able to measure offsets of the strip pattern near the x-ray gun in a coordinate system accessible to the alignment system; however, it is limited to a handful of positions on the surface of the quadruplet and should be validated by an independent method. In this work, cosmic muon data is used to measure relative strip offsets, the x-ray method is validated with cosmic muon data, and how this work fits into the overall alignment scheme is presented.

Chapters 2 and 3 give more details on ATLAS, the LHC, the NSW, and sTGCs required to understand the context of this work. In chapter 4, the cosmic ray testing procedure is presented, and chapter 5 explains how the position of the strips can be probed with cosmics data. Chapter 6 introduces the x-ray method, and in chapter 7, the x-ray offsets are validated with cosmic muon data. The thesis concludes with a summary and outlook in chapter 8.

Chapter 2

The LHC and ATLAS experiment

The LHC and ATLAS experiment are introduced here to provide context for the New Small Wheel upgrade.

2.1 The Large Hadron Collider

The LHC is an accelerator 27 km in circumference and located ∼100 m underground at CERN near Geneva, Switzerland [?]. It has two beam pipes that counter-circulate bunches of protons[1] before colliding the bunches in the center of one of four major experiments, such as the ATLAS experiment (discussed in section 2.2). There, the partons interact and many physics processes can occur. The LHC enables physicists to study particle physics at the energy frontier. In the previous run of the LHC (run-2), protons were collided with a center of mass energy of 13 TeV.

The number of proton-proton interactions generated by the LHC directly affects the statistics available to make fundamental measurements of cross sections, event rates, etc. Predicting the number of proton-proton interactions requires defining a metric called luminosity [?]. It is the number of particles an accelerator can send through a given area per unit time. It is calculated from the measurable quantities in equation 2.1.

$$\mathcal{L} = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y} \tag{2.1}$$

[1]the LHC also accelerates lead ions, but this paper is written in the context of proton-proton collisions

In equation 2.1, f is the frequency of the bunch crossings (25 ns), N_1 and N_2 are the number of protons in each bunch ($\sim 10^{11}$ protons / bunch), and σ_x and σ_y are the RMS of the spatial distributions of the bunch. Therefore, luminosity is a property of the accelerator and its operating parameters. The design luminosity of the LHC was 10^{34} cm^{-2}s^{-1}. The units of luminosity are an inverse area; multiplying the luminosity by the cross section of a given process gives the expected rate for that process.

Integrating the *instantaneous* luminosity (equation 2.1) over a period of data collection gives the integrated luminosity,

$$L = \int \mathcal{L}\left(t\right)\, dt \tag{2.2}$$

which is related to the total number of interactions. In this way, the luminosity is the link between the accelerator and the statistical power of measurements to be made with the data collected.

So far, the LHC provided an integrated luminosity of 28.26 fb^{-1} in run-1 [?] and 156 fb^{-1} in run-2 [?], as shown in figure 2.1. The HL-LHC upgrade [?] was accepted because without increasing the luminosity of the LHC tenfold, running the accelerator will not provide significant statistical gain on measurements. Also, some systems will need repair and replacement to operate past ∼2020. The energy accessible at the LHC offers irreplaceable ability to study Higgs- and electroweak-sector physics [?], so the European Strategy for Particle Physics made it a priority "to fully exploit the physics potential of the LHC" with "a major luminosity upgrade" [?]. The goal is for the HL-LHC to provide an integrated luminosity of 3000 fb^{-1} in the 12 years following the upgrade. The luminosity actually achieved will depend on a combination of technological advances and upgrades in progress that affect the factors contributing to luminosity defined in equation 2.1 [?].

2.2 The ATLAS experiment

The ATLAS experiment [?] was designed to support all the physics goals of the LHC. It is 44 m long and 25 m in diameter, and weighs 7000 tones. It is an array of particle detector subsystems arranged concentrically around the beam pipe and centered around one of the LHC's interaction points (a place where the beams collide), as shown in figure 2.2. ATLAS is cylindrical because it aims to provide 4π coverage aound the interaction point. It is helpful to separate the subsystems of ATLAS into the so-called "barrel" and "endcap" or "forward" regions.

Figure 2.1: LHC/HL-LHC plan [?]. The integrated luminosity collected and projected for each run of the LHC is shown in red below the timeline. The center of mass energy of the collisions is shown in red above the timeline. “LS” stands for “long shutdown” and indicates periods where the accelerator is not operating. During the shutdowns, upgrades to the LHC and the experiments are being installed. This timeline was last updated in January, 2021, and reflects changes in the schedule due to the ongoing pandemic.

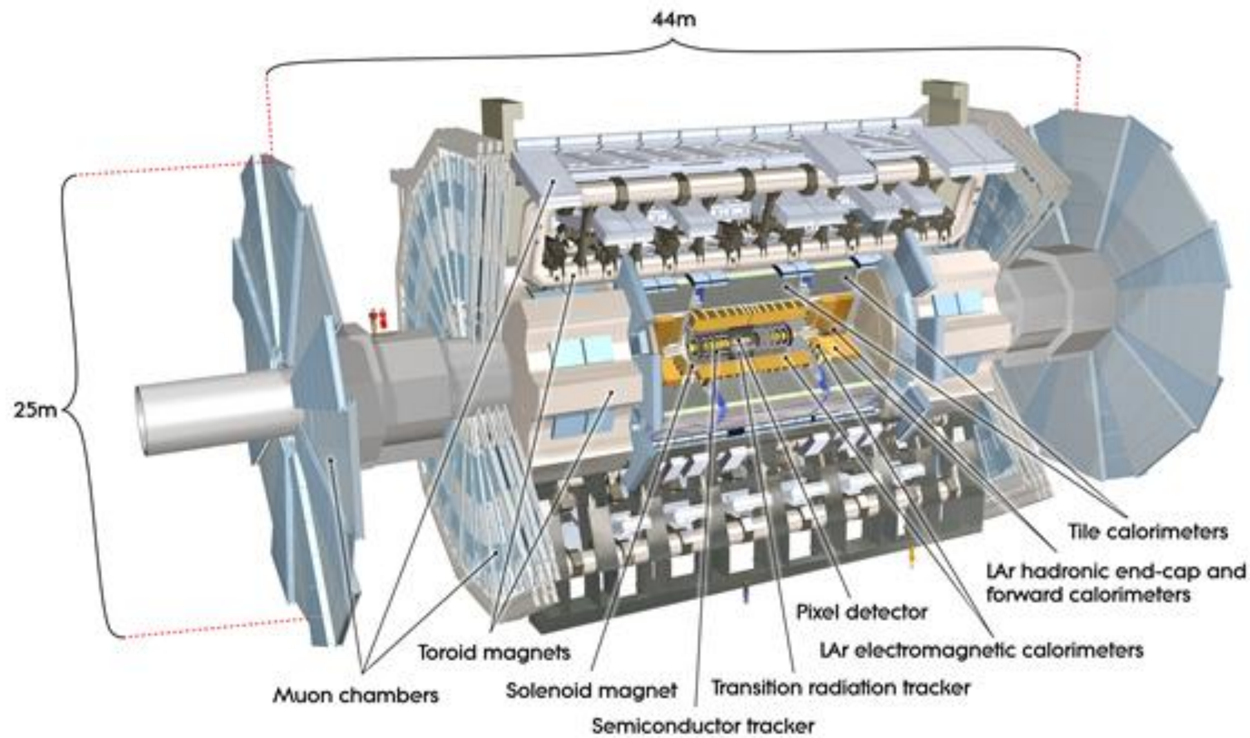


Figure 2.2: Diagram of the ATLAS experiment, with the various detector subsystems labelled. Figure from [?], which also contains more details about the ATLAS experiment.

For analysis, ATLAS is typically described in spherical coordinates. The azimuthal angle ϕ is measured around the beampipe and the polar angle θ is measured from the beam pipe. A more useful coordinate than θ is the pseudo-rapidity, $\eta = -\ln\tan(\theta/2)$, because it approaches the rapidity of a particle when its momentum is much greater than its mass and differences in rapidity are approximately invariant to a Lorentz boost parallel to the beam. The range of η is 0 (perpendicular to the beam) to $\pm\infty$ (parallel to the beam, or the z-direction). Typically, η is the physically interesting coordinate because the ϕ coordinate follows the cylindrical symmetry of the beam.

It is not actually the proton bunches that collide and generate physics processes, but their constituent partons. Since the partons may carry an unknown fraction of the momentum, ATLAS analyses are based on the sum of the transverse momentum (p_T) and energy of outgoing particle being approximately zero (transverse meaning perpendicular to the beam). The goal of ATLAS is to reconstruct the transverse momentum of each collision product to understand what happened in each collision. -¿ *Do I have this right?* A brief overview of the sub-systems of ATLAS is given, starting from the system closest to the beam and moving outwards. Each sub-system is responsible for a different group of collision products.

2.2.1 The inner detector

The inner detector [?, ?] (figure 2.3) is for precision tracking, vertex measurements and electron identification. A 2 T solenoid with field parallel to the beam bends the track of outgoing particles to make momentum measurements possible. The innermost part is made of high-resolution semiconductor pixel and strip detectors for precision tracking while the outermost part are straw-tubes that generate and detect transition radiation for electron identification.

2.2.2 Calorimeters

Electromagnetic and hadronic sampling calorimeter units are used to record the energy of electrons, photons, jets and missing transverse energy (from neutrinos, for example). A combination of liquid-argon (LAr) electromagnetic and hadronic calorimeters [?] and tile-scintillator hadronic calorimeters [?] cover the rapidity range $|\eta| < 4.9$, as shown in figure 2.4.

The calorimeters cause incoming charged particles to shower and deposit their energy in the sensitive volume. Only muons and neutrinos are known to pass the calorimeters to the muon spectrometer. Particles other than those mentioned would have decayed in the inner detector before reaching the calorimeter.

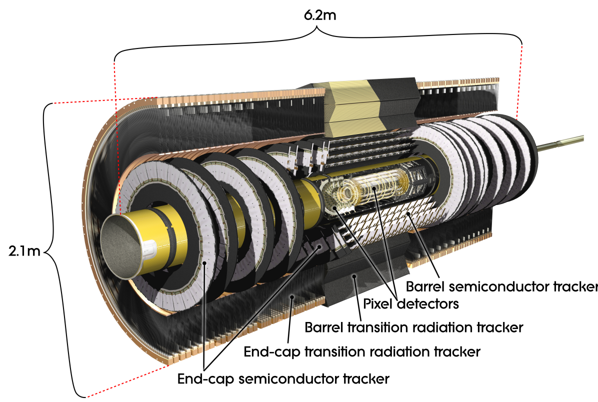


Figure 2.3: Diagram of the ATLAS experiment's inner detector, with the different segments and the technology used labelled. Figure from [**?**].

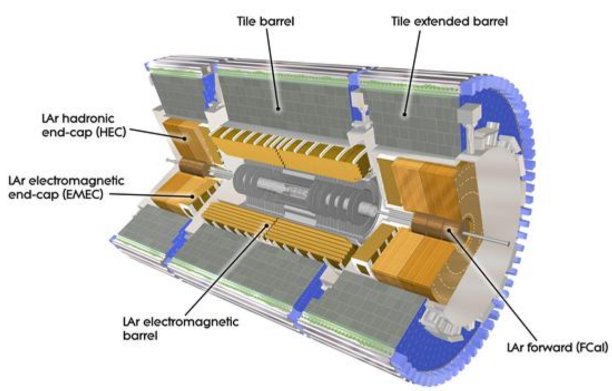


Figure 2.4: Diagram of the ATLAS calorimeter system, with the different segments and the technology used labelled. Figure from [**?**].

2.2.3 Trigger system

It would be impossible to record all the data from bunch crossings every 25 ns, corresponding to a rate of ∼40 MHz, so ATLAS has a multi-level trigger system to select events of interest for permanent storage. The Level-1 (L1) hardware trigger [?] uses partial-granularity information from the muon spectrometer and calorimeter to trigger on high p_T muons, electrons, jets, high missing transverse energy, and τ decaying to hadrons. The maximum L1 trigger rate ATLAS can accommodate is 100 kHz with a latency of 2.5 µs.

The L1 trigger is used to define regions of interest that are fed into the software high level trigger (HLT), in which the full granularity of the muon spectrometer and calorimeter are used with information from the inner detector to reduce the trigger rate to 1 kHz. Events that pass the L1 and HLT trigger are recorded for use in offline analysis [?].

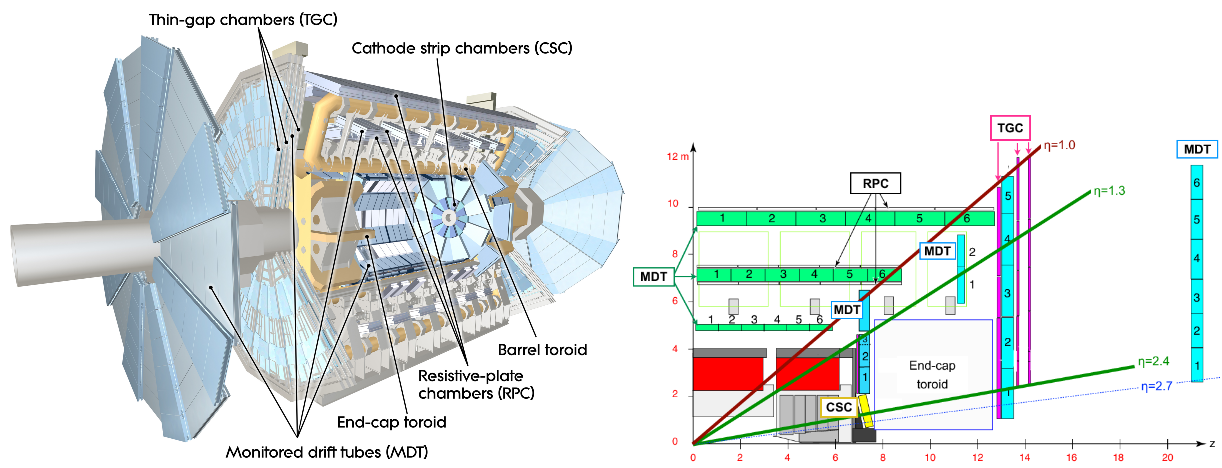
The ATLAS trigger system is described in the references above but the trigger rates quoted here are after the upgrades implemented for run-2, described in [?].

2.2.4 Muon spectrometer

Magnetic deflection by superconducting air-core toroid magnets is used to measure muon momentum and energy. In the barrel of ATLAS, eight coils bent into "racetracks" are arranged around the beampipe provide the magentic field. In the forward region, two endcap toroids each with eight smaller racetrack-shaped coils arranged symmetrically around the beampipe are inserted in the ends of the barrel toroid [?]. Figure 2.5 shows the toroid magnets and the different parts of the ATLAS muon spectrometer.

The muon spectrometer [?] is separated into detectors used for precision offline tracking and for triggering. Three layers of monitored drift tubes (MDTs) or cathode strip chambers (CSCs) are used for tracking. The position of the muon track in each of the three layers allows reconstruction of the track sagitta and hence momentum. For the design momentum resolution of $\Delta p_T/p_T < 1{\times}10^{-4}\ p$ / GeV for $p_T < 300$ GeV and a few percent for lower p_T muons, the MDTs and CSCs required position resolution of 50 µm each. Accordingly, an optical alignment system was designed to monitor and correct for chamber positions [?, ?].

Resistive plate chambers (RPCs) are used for triggering in the barrel and thin-gap chambers (TGCs) are used for triggering in the endcaps. The positions of each type of chamber are sketched in figure 2.5b. Often, the endcap muon spectrometer is separated into three wheels – the small wheel (SW), big wheel, and outer wheel – ordered by proximity to the interaction point. In run-1, low (high) p_T muons were triggered on at L1 if two (three) of the RPCs or TGCs layers around the big wheel fired in coincidence, for the barrel and endcaps



(a) (b)

Figure 2.5: (a) The ATLAS muon spectrometer [**?**]. (b) A quarter-cut of ATLAS, with the interaction point in the bottom left corner. The small wheel is just left of the end cap toroid, the big wheel is to its right, and the outer wheel is the rightmost structure [**?**]

respectively [**?**]. After run-1 it was discovered that up to 90% of the triggers in the endcap were fake, caused by background particles generated in the material between the small wheel and the big wheel [**?**]. To reduce the fake rate in run-2, the TGCs on the inside of the small wheel also had to register a hit. The added condition reduced the trigger rate by 50% in the range $1.3 < |\eta| < 1.9$ [**?**]. The effectiveness of the solution was limited since the $|\eta|$-range of the small wheel TGCs was limited to $1.0 < |\eta| < 1.9$ and the position resolution of the small wheel TGCs is coarse [**?**].