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# Cosmic ray validation of electrode positions in small-strip thin gap chambers for the upgrade of the ATLAS detector

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## Abstract

68 The Large Hadron Collider (LHC) is used to generate subatomic physics processes at the  
69 energy frontier to challenge our understanding of the Standard Model of particle physics.  
70 The particle collision rate at the LHC will be increased up to seven times its design value in  
71 2025-2027 by an extensive upgrade program. The innermost endcaps of the ATLAS muon  
72 spectrometer consist of two wheels of muon detectors that must be replaced to maintain  
73 the muon momentum resolution in the high-rate environment. The so-called New Small  
74 Wheels (NSWs) are made of two detector technologies: micromegas and small-strip thin gap  
75 chambers (sTGCs). The sTGCs are gas ionization chambers that hold a thin volume of gas  
76 between two cathode boards. One board is segmented into copper readout strips of 3.2 mm  
77 pitch that are used to precisely reconstruct the coordinate of a passing muon. Modules of  
78 four sTGCs glued together into quadruplets cover the NSWs. Quadruplets were designed  
79 to achieve a 1 mrad angular resolution to fulfill the spectrometer's triggering and precision  
80 tracking requirements. To achieve the required angular resolution the absolute position of  
81 the readout strips must be known in the ATLAS coordinate system to within 100  $\mu\text{m}$ . At  
82 McGill University, the performance of sTGC quadruplets was characterized using cosmic ray  
83 data before being sent to CERN, where the charge profile left by x-rays is used to measure  
84 the offset of the strip patterns with respect to nominal at a limited number of points on  
85 the surface of each quadruplet. The x-ray strip position measurements have acceptable but  
86 limited precision and do not span the whole area of the strip layers. Given the importance of  
87 knowing the absolute position of each readout strip to achieve the performance requirements  
88 of the NSWs, the x-ray method must be validated by an independent method. Cosmic ray  
89 data is used to characterize the relative alignment between layers and validate the x-ray  
90 method.

## Résumé

Le collisioneur LHC est utilisé pour générer des processus de la physique subatomique à la frontière d'énergie pour remettre en cause le modèle standard de la physique des particules. Le taux des collisions du collisioneur LHC augmentera jusqu'à sept fois le taux nominal en 2025-2027 par un programme d'amélioration majeur et varié. Une partie du spectromètre à muons est composée de deux roues de détecteurs de muons qu'il faut remplacer pour maintenir la résolution d'élan après l'augmentation du taux. Appelées les Nouvelles Petites Roues (NSWs), elles en utilisent deux technologies: des chambres micromegas et des chambres sTGCs (chambres à petites bandes et à intervalles fins). Les sTGCs sont des chambres d'ionisation de gaz, qui contiennent un volume de gaz fin entre deux panneaux cathodiques. Un panneau est segmenté à petites bandes en cuivre avec une pente de 3.2 mm qui se servent comme des voies de signal pour reconstruire précisément la coordonnée d'un muon qui passe. Des modules de quatre sTGCs collés ensemble en quadruplets couvrent les NSWs. Les quadruplets étaient conçus pour réaliser une résolution angulaire de 1 mrad pour satisfaire les exigences des systèmes de déclenchement et de mesures de précision. Pour réaliser la résolution angulaire il faut que la position absolue de chaque bande soit connue dans ATLAS avec une précision à moins de 100  $\mu\text{m}$ . À l'Université de McGill, la performance des quadruplets étaient caractériser avec des rayons cosmiques avant les envoyer à CERN, où le profil de charge laisser par des rayons-X est utilisé pour mesurer le déplacement du motif des bandes par rapport à nominal à un nombre de position limité sur la surface des quadruplets. Les déplacements mesurés pas les rayons-X ont une précision acceptable mais limitée, et ne couvrent pas la région entière des panneaux. Étant donné l'importance de savoir la position absolue de chaque bande pour réaliser les exigences de performance des NSWs, il faut une méthode indépendante pour valider la méthode des rayons-X. Les données recueillies avec les rayons cosmiques sont utilisées pour charactariser l'alignement relatif entre les panneaux et pour valider la méthode des rayons-X.

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## Contribution of authors

I, the author, was involved in collecting the cosmic ray data from September 2019 - March 2021. I did not design the cosmic ray testing procedure nor write the data preparation software, but I participated in using the software to analyze cosmic ray results. In the thesis, the terms “clustering,” “local offset” and “relative local offset” are defined. Cosmic ray clustering was done in the data preparation software, but I redid the fit afterwards to explore sensitivity to the fit algorithm. With help from Dr. Lefebvre and Dr. Vachon, I helped design the software that calculated the relative local offsets from cosmic ray data. I wrote that software on my own. I was not involved in the design, data collection, data preparation or analysis of the x-ray data. I also was not involved in creating an alignment model from the x-ray data. I used the x-ray local offsets calculated using x-ray data analysis software to calculate relative local offsets with x-rays. I did the comparison between the x-ray and cosmic ray data.

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

# <sup>147</sup> Chapter 1

## <sup>148</sup> Introduction

<sup>149</sup> High energy particle physics seeks to explain the existence of a set of fundamental particles  
<sup>150</sup> whose interactions determined the evolution of the universe. The set and their interactions  
<sup>151</sup> are described shockingly well by the Standard Model (SM) of particle physics; however, the  
<sup>152</sup> questions the SM does not address motivate more experimentation.

<sup>153</sup> Accelerators collide particles to generate interactions that can be captured by detectors and  
<sup>154</sup> subsequently studied. The Large Hadron Collider (LHC) [1] at CERN will remain the world's  
<sup>155</sup> most energetic particle accelerator for at least the next decade [2], making it an indispensable  
<sup>156</sup> tool for studying interactions in an environment as close as can be simulated to the early  
<sup>157</sup> universe. The ATLAS experiment [3] is one of the LHC's general-purpose particle detector  
<sup>158</sup> arrays, used to detect the products of LHC collisions. A feat of engineering, every detail  
<sup>159</sup> matters. This work showcases one example of how precise positioning of electrodes in particle  
<sup>160</sup> detectors is necessary to study the interactions of particles in high-energy collisions.

<sup>161</sup> The High-Luminosity Large Hadron Collider (HL-LHC) project [2] was approved to combat  
<sup>162</sup> the plateau in statistical gain of recording particle collisions at the LHC. Being the most  
<sup>163</sup> energetic particle accelerator, the LHC still offers unique physics opportunities for studying  
<sup>164</sup> the Higgs and electroweak sectors of the SM [4]; if study at the energy frontier is to continue,  
<sup>165</sup> the LHC must go on. The HL-LHC upgrade aims to increase the luminosity of the LHC by  
<sup>166</sup> up to a factor of 7 in the next 10 years, which ultimately increases the number of meaningful  
<sup>167</sup> collisions. Naturally, various sub-systems of the experiments used to capture the outcomes of  
<sup>168</sup> the collisions will require upgrades to handle higher collision rates and background radiation  
<sup>169</sup> rates than they were designed for.

<sup>170</sup> During the 2019-2022 Long Shutdown of the LHC, the most complex upgrade of the ATLAS  
<sup>171</sup> experiment is the replacement of the small wheels of the muon spectrometer with the so-  
<sup>172</sup> called New Small Wheels (NSWs) [5]. The NSW upgrade addresses both the expected

decrease in hit efficiency of the precision tracking detectors 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 [5]. sTGCs provide 100  $\mu\text{m}$  position resolution per detector plane [6], and are stacked in four (called an sTGC quadruplet) to provide 1 mrad angular resolution on tracks [5, 7]. sTGCs are gas ionization chambers where a thin volume of gas is held between two cathode boards. One board is segmented into strip electrodes of 3.2 mm pitch. The position of the particle track in the precision coordinate can be reconstructed from the strip signals [5] to within the required position resolution [6].

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  $\mu\text{m}$ . The internal geometry of the detectors must be controlled or corrected for to within the chambers' position resolution [5]. 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) [8]*I'm citing Carlson but should I be citing a paper that deals with the global context? E.g. something at the collaboration level.* At the quadruplet level, sTGC quadruplets are characterized with cosmic rays over the whole area and with an x-ray gun at positions that will be tracked by the alignment system. Cosmic muon data (cosmics data) can be used to measure relative strip position offsets in a local area with respect to the strip patterns on other layers, which characterizes the strips' alignment but does not allow the strips to be positioned in the absolute ATLAS alignment system. The x-ray method [9] 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, cosmics data is used to measure relative strip offsets, the x-ray method is validated with cosmics data, and how this work fits into the overall alignment scheme is presented.

Chapters 2 and 3 give more background on particle physics, the LHC, ATLAS, the NSWs, and sTGCs. In chapter 4, the cosmic ray testing procedure and how the position of the strips can be probed with cosmics data is presented. Chapter 5 introduces the x-ray method, and

<sub>210</sub> in chapter 6, the x-ray offsets are validated with cosmic muon data. The thesis concludes  
<sub>211</sub> with a summary and outlook in chapter 7.

212 **Chapter 2**

213 **High energy particle physics at the  
214 LHC and the ATLAS experiment**

215 The LHC, ATLAS, and the upgrades they are undergoing are all motivated by the study  
216 of the SM and the open questions the SM does not address. Particle physics aims to study  
217 the indivisible constituents of matter. Understanding the fundamental building blocks and  
218 how they interact informs our understanding of the evolution of the Universe from the Big  
219 Bang to the forms of matter we recognize today. This chapter provides context for the NSW  
220 upgrade. The study of particle physics using accelerators is introduced, before moving on  
221 to the LHC, HL-LHC and the ATLAS experiment. The connection to physics questions of  
222 interest will be highlighted at each stage.

223 The information on particle physics and the SM presented here is rather general; the reader  
224 is referred to [10, 11, 12] for more information.

225 **2.1 The Standard Model**

226 The SM describes all the fundamental particles and their interactions. It is a collection of  
227 quantum field theories able to explain the existence of all the particles discovered in the past  
228 century and predict how they interact to incredible precision. In fact, when it was being  
229 developed in the 1960s-1970s, it began motivating the search for yet undiscovered particles,  
230 like the tau neutrino with DONUT in 2002 [13].

231 The SM represented in figure 2.1, consists of six quarks, six leptons, and five force-particles.  
232 Note that each particle also has an anti-particle, which are not represented. The force-  
233 carrying bosons are exchanged between interacting (coupled) particles to produce what is

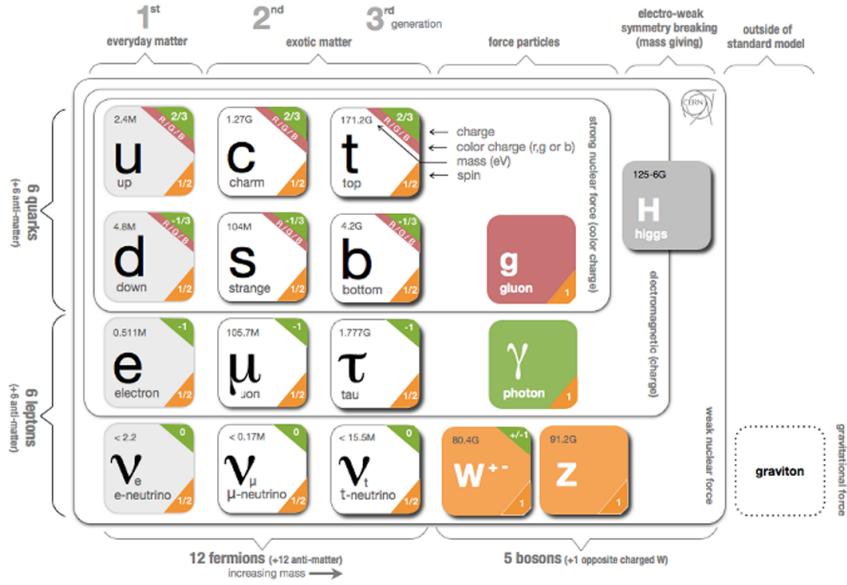


Figure 2.1: Representation of the SM of particle physics. There are three main types of particles: quarks, leptons and force-particles. The version highlights which groups of particles each force-particle interacts with. The force-particle in each black enclosure interacts with all quarks/leptons within the enclosure [14].

perceived as: the strong force mediated by gluons; the electromagnetic force mediated by photons; and the weak force mediated by the charged W-bosons and neutral Z-boson. The SM actually presents a theory of the electromagnetic and weak force as one force stemming from the same phenomenon: the unified electroweak force. The Higgs boson field interacts with the particles mediating the unified electroweak force to distinguish the weak and electromagnetic forces from each other and give all particles (except neutrinos) a mass. This is called electroweak symmetry breaking.

Quarks are fermions that are sensitive to all forces; notably they are the only particles sensitive to the strong force. Protons and neutrons are made up of quarks and gluons, and the strong force is responsible for their existence and mutual attraction into nuclei [15]. Leptons are particles not sensitive to the strong force. Charged leptons include the electron, which once part of atoms is responsible for chemistry. Neutrinos are neutral, almost massless particles that only interact through the weak force.

Common matter is made up of the lightest constituents of the SM: up and down quarks, electrons and photons. The other particles are or were generated in high-energy environments and decay eventually to the lightest constituents. Such high energy environments include the Big Bang [16], astrophysical sources, and accelerators. The presence of the particles of the SM at the beginning of the Universe means that their interactions and decays are fundamental for the study of the origin of the Universe [16]. Many high energy astrophysical sources, like supernovae, generate particles that rain down on Earth as cosmic rays [17]. Accelerators were built to create controlled, high energy and high rate environments where the production and decay of fundamental particles can be manufactured, detected and studied.

## 2.2 Beyond the Standard Model

The SM provides no explanation for several open questions in particle physics.

First, gravity is not included in the SM. One might expect a force-particle to exist that mediates the gravitational force, but the strength of gravity is so weak that the “graviton” will elude detection for a long time. Moreover, there is no theory of gravity that does not require dark energy or dark matter [12]. The universe is expanding at a rate irreconcilable with the known energy density of the Universe, and the nature of this “dark energy” is unknown [16]. Similarly, dark matter is the name given to mass in the universe whose gravity is measurable, but for which there is no SM explanation [18].

Second, neutrinos in the SM are massless; they do not interact with the Higgs field. However, in 2013 neutrino oscillations were confirmed, which can only occur if neutrinos do have mass [19].

268 Third, the unification of the electromagnetic and weak force begs the question of if there is  
269 a Grand Unified Theory (GUT) that includes the strong force and encompasses the SM in a  
270 more complete theory [20].

271 Theories beyond the standard model (BSM) aim to answer these questions. Often, BSM  
272 theories predict new particles. For example, super-symmetry (SUSY) predicts that each  
273 SM particle has a heavier super-symmetric partner. SUSY would explain the origin of dark  
274 matter with weakly interacting massive particles, would solve the so-called "naturalness"  
275 problem in the SM at energies above the tera-electronvolt scale, and is often a part of  
276 GUTs [21]. Ideally, a BSM theory predicts a measurable signature that can be searched for  
277 at accelerators or elsewhere.

## 278 2.3 Studying high energy particle physics with accelerators

279

280 Accelerators of increasingly high energy have a long history of enabling the discovery of new  
281 particles. Only calling on one example, one of the main goals when the LHC, the ATLAS  
282 experiment and the CMS experiment were proposed was to detect the long-predicted Higgs  
283 boson particle – a triumph accomplished in 2012 [22, 23]. Being the last particle of the SM  
284 to be discovered, the discovery marked the completion of the SM as it is known today.

285 Since then, measurements of the cross section of particle physics processes have been enabled  
286 by the LHC. A summary of the cross sections measurements done at the ATLAS experiment  
287 is shown in figure 2.2. Given the precision to which the SM predicts cross sections and the  
288 precision to which many can be measured, any discrepancy between theory and experiment  
289 could be an indication of new physics. The questions the SM does not address require new  
290 physics; searching for it at accelerators is a natural choice.

291 Accelerators and detectors can also be used to search for signatures of rare processes predicted  
292 by the SM and BSM theories. The controlled, high rate environment enables the search for  
293 signatures that would be impossible to discern in other environments. If the signature is not  
294 found, exclusion limits can be set [25].

295 Through measurements and searches, accelerators play a key role in making precision mea-  
296 surements, searching for rare processes predicted by the SM, and testing BSM theories.

297 *Is there a good citation for the defintion of search vs measurement?*

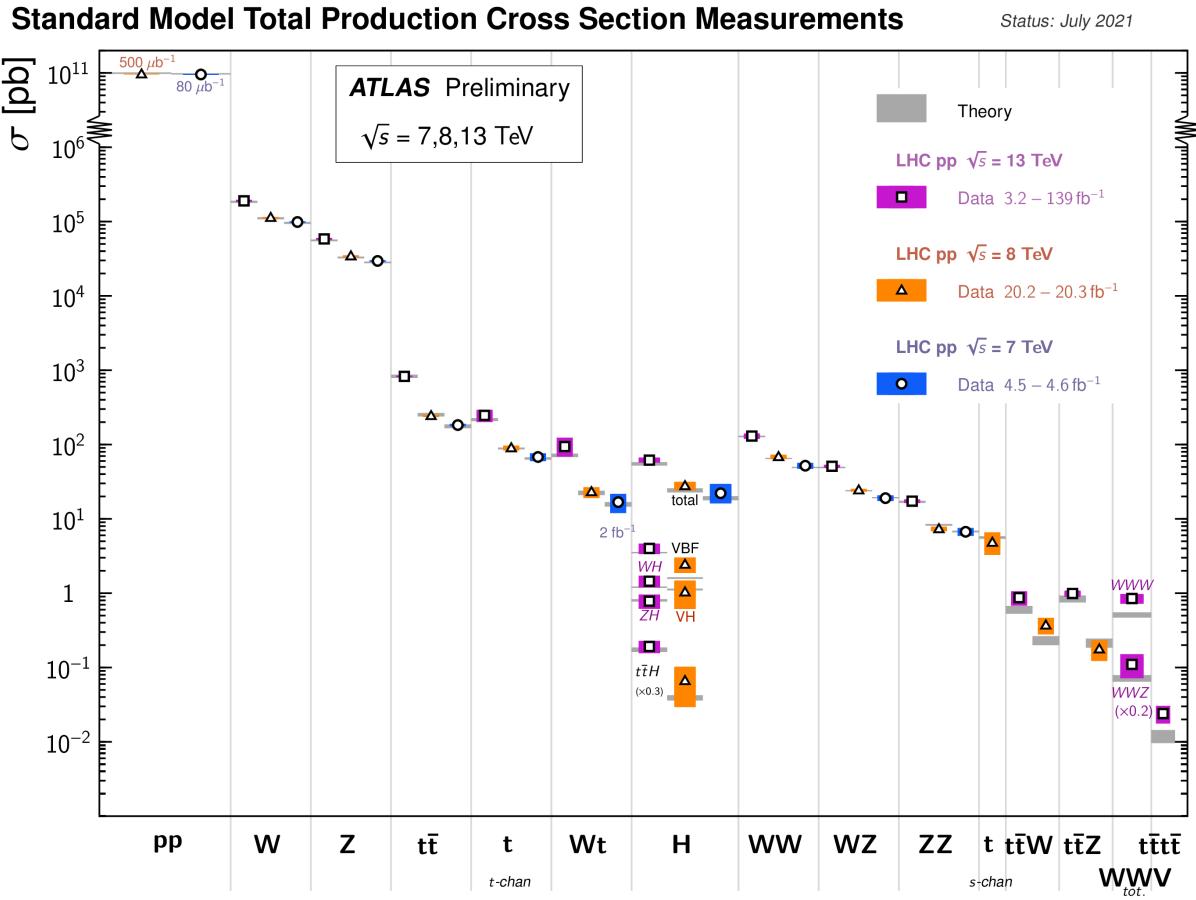


Figure 2.2: Cross sections of select SM physics interactions measured using the ATLAS experiment at the LHC. The comparison with theoretical predictions is also shown [24].

298 **2.4 The Large Hadron Collider**

299 The LHC is an accelerator 27 km in circumference and located  $\sim$ 100 m underground at  
300 CERN near Geneva, Switzerland [1]. It has two beam pipes that counter-circulate bunches  
301 of protons<sup>1</sup> before colliding the bunches in the center of one of four major experiments, such  
302 as the ATLAS experiment (discussed in section 2.7). In the previous run of the LHC (run-2),  
303 protons were collided with a center of mass energy of 13 TeV. It is not actually the protons  
304 that interact, but the constituent quarks and gluons (partons) that each carry some fraction  
305 of the energy and momentum of the collisions.

306 **2.5 Luminosity**

307 The number of proton-proton interactions generated by the LHC directly affects the statis-  
308 tics available to make measurements of cross sections, SM parameters, etc. Predicting the  
309 number of proton-proton interactions requires defining a metric called luminosity [12]. It is  
310 the number of particles an accelerator can send through a given area per unit time. It is  
311 calculated from the measurable quantities in equation 2.1:

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

312  $f$  is the frequency of the bunch crossings (25 ns),  $N_1$  and  $N_2$  are the number of protons in  
313 each bunch ( $\sim 10^{11}$  protons / bunch), and  $\sigma_x$  and  $\sigma_y$  are the RMS of the spatial distributions  
314 of the bunch. Therefore, luminosity is a property of accelerator beams, which are set by the  
315 capabilities of the accelerator. The design luminosity of the LHC was  $10^{34}$  cm $^{-2}$ s $^{-1}$ . The  
316 units of luminosity are an inverse area; multiplying the luminosity by the cross section of a  
317 given process gives the expected rate for that process.

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

$$L = \int \mathcal{L}(t) dt \quad (2.2)$$

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

---

1the LHC also accelerates lead ions, but ATLAS is best at recording proton-proton collisions. The ALICE experiment [26] was designed for lead-lead interactions.

322 collected. So far, the LHC provided an integrated luminosity of  $28.26 \text{ fb}^{-1}$  in run-1 [27] and  
323  $156 \text{ fb}^{-1}$  in run-2 [28].

## 324 2.6 The High-luminosity LHC

325 The HL-LHC upgrade [2] was accepted because without increasing the luminosity of the LHC  
326 tenfold, running the accelerator will not provide significant statistical gain on measurements.  
327 Also, some systems will need repair and replacement to operate past  $\sim 2020$ . The LHC will  
328 be the most energetic accelerator in the world for years to come and is the only accelerator  
329 capable of directly producing the Higgs boson (and top quarks), so the European Strategy for  
330 Particle Physics made it a priority “to fully exploit the physics potential of the LHC” with  
331 “a major luminosity upgrade” [29]. The goal is for the HL-LHC to provide an integrated  
332 luminosity of  $3000 \text{ fb}^{-1}$  in the 12 years following the upgrade. The luminosity actually  
333 achieved will depend on a combination of technological advances and upgrades in progress  
334 that affect the factors contributing to luminosity defined in equation 2.1 [2].

335 The most anticipated measurement at the HL-LHC is of the triple-Higgs coupling. Measuring  
336 the coupling allows the shape of the Higgs potential responsible for electroweak symmetry  
337 breaking to be measured. Any discrepancy with the SM prediction will show that there  
338 must be other sources of electroweak symmetry breaking, and hence currently unpredicted  
339 particles. The LHC is the only accelerator where the Higgs can be produced directly and  
340 the HL-LHC upgrade is required to have sufficient di-Higgs production to make a meaning-  
341 ful measurement [4, 31]. Accordingly, detector sensitivity to various Higgs decays will be  
342 important at the HL-LHC.

## 343 2.7 The ATLAS experiment

344 The ATLAS experiment [3] was designed to support all the physics goals of the LHC. It is  
345 44 m long and 25 m in diameter, and weighs 7000 tones. It is an array of particle detector  
346 subsystems arranged concentrically around the beam pipe and centered around one of the  
347 LHC’s interaction points (a place where the beams collide), as shown in figure 2.4. ATLAS is  
348 cylindrical because it aims to provide  $4\pi$  coverage around the interaction point. It is helpful  
349 to separate the subsystems of ATLAS into the so-called “barrel” and “endcap” / “forward”  
350 regions, referring to the cylindrical geometry.

351 For analysis, ATLAS is typically described in spherical coordinates. The azimuthal angle  
352  $\phi$  is measured around the beampipe and the polar angle  $\theta$  is measured from the beam



Figure 2.3: LHC/HL-LHC plan [30]. The integrated luminosities collected and projected for each run of the LHC are shown in blue boxes below the timeline and the center of mass energy of the collisions is shown in red above the timeline. The top blue arrow labels the run number. “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.

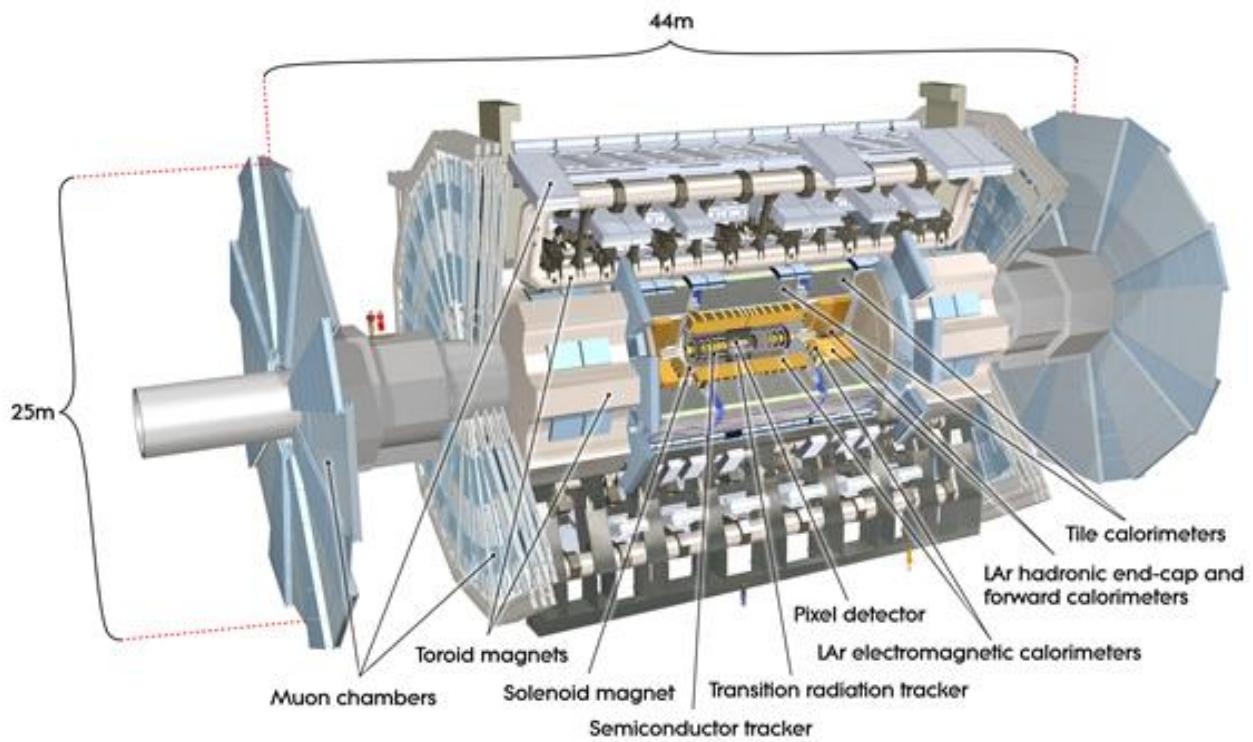


Figure 2.4: Diagram of the ATLAS experiment, with the various detector subsystems labelled [3].

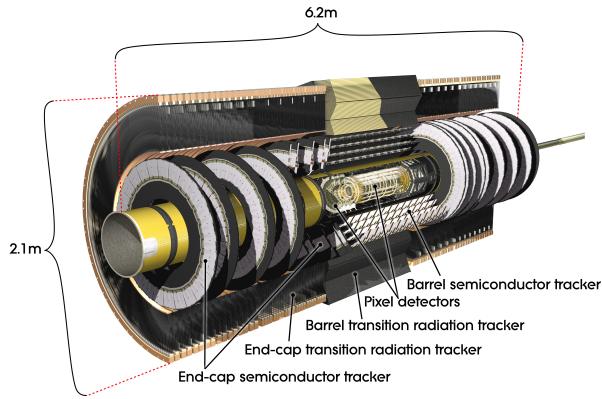


Figure 2.5: Diagram of the ATLAS experiment’s inner detector, with the different segments and the technology used labelled [3].

353 pipe. A more useful coordinate than  $\theta$  is the pseudo-rapidity,  $\eta = -\ln \tan(\theta/2)$ , because  
 354 it approaches the rapidity of a particle when its momentum is much greater than its mass  
 355 and differences in rapidity are approximately invariant to a Lorentz boost parallel to the  
 356 beam. The range of  $\eta$  is 0 (perpendicular to the beam) to  $\pm\infty$  (parallel to the beam, or the  
 357 z-direction). Typically,  $\eta$  is the physically interesting coordinate because the  $\phi$  coordinate  
 358 follows the cylindrical symmetry of the beam.

359 ATLAS provides identification and kinematic measurements for each particle created after  
 360 the initial collision. Predictions made using SM and BSM theories can then be compared  
 361 to the data. Each subsystem of ATLAS collects certain information and a complete  
 362 description of each recorded collision can be assembled offline. An overview of the main  
 363 ATLAS subsystems is given below.

### 364 The inner detector

365 The inner detector [32, 33] (figure 2.5) is for precision tracking, vertex measurements and  
 366 electron identification. A 2 T solenoid with field parallel to the beam bends the track of  
 367 outgoing particles. The innermost part is made of high-resolution semiconductor pixel and  
 368 strip detectors while the outermost part are straw-tubes that generate and detect transition  
 369 radiation

### 370 Calorimetry system

371 Electromagnetic and hadronic sampling calorimeter units are used to record the energy  
 372 of electrons, photons and jets. A combination of liquid-argon (LAr) electromagnetic and

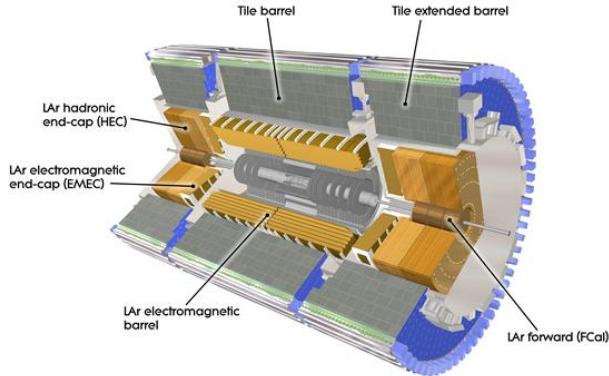


Figure 2.6: Diagram of the ATLAS calorimeter system, with the different segments and the technology used labelled [3].

373 hadronic calorimeters [34] and tile-scintillator hadronic calorimeters [35] cover the rapidity  
374 range  $|\eta| < 4.9$ , as shown in figure 2.6.

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

### 379 Trigger system

380 It would be impossible to record all the data from bunch crossings every 25 ns, corresponding  
381 to a rate of  $\sim 40$  MHz. ATLAS has a multi-level trigger system to select events of interest  
382 for permanent storage. The Level-1 (L1) hardware trigger [36] uses partial-granularity infor-  
383 mation from the muon spectrometer and calorimeter to trigger on high  $p_T$  muons, electrons,  
384 jets, high missing transverse energy, and  $\tau$  decaying to hadrons. The maximum L1 trigger  
385 rate ATLAS can accommodate is 100 kHz with a latency of 2.5  $\mu$ s. After run-3 an upgrade  
386 of the trigger system will allow for a higher rate and more latency, but for now these are the  
387 working limits [37].

388 The L1 trigger is used to define regions of interest that are fed into the software high level  
389 trigger (HLT), in which the full granularity of the muon spectrometer and calorimeter are  
390 used with information from the inner detector to reduce the trigger rate to 1 kHz. Events  
391 that pass the L1 and HLT trigger are recorded for use in offline analysis [38].

392 The ATLAS trigger system is described in the references above but the trigger rates quoted  
393 here are after the upgrades implemented for run-2, described in [39].

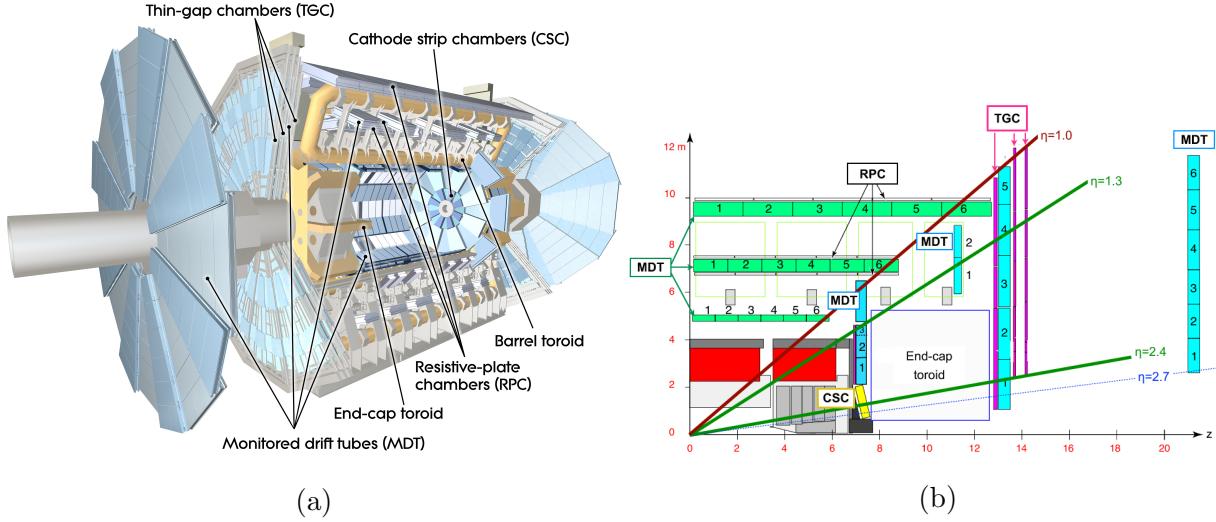


Figure 2.7: (a) The ATLAS muon spectrometer [3]. (b) A quarter-cut of ATLAS, with the interaction point in the bottom left corner. The small wheel is just left of the end cap toroid, the big wheel is to its right, and the outer wheel is the rightmost structure [41].

### 394 Muon spectrometer

395 The muon spectrometer has multiple layers, each of which records the position of a passing  
 396 muon. Magnetic deflection by superconducting air-core toroid magnets bend the muon  
 397 tracks. The position information recorded in each layer and the magnetic field are used to  
 398 reconstruct each muon's momentum. In the barrel of ATLAS, eight coils bent into "race-  
 399 tracks" arranged around the beampipe provide the magnetic field. In the forward region,  
 400 two end-cap toroids each with eight smaller racetrack-shaped coils arranged symmetrically  
 401 around the beampipe are inserted in the ends of the barrel toroid [40]. Figure 2.7 shows the  
 402 toroid magnets and the different parts of the ATLAS muon spectrometer [3].

403 The muon spectrometer [42] is separated into detectors used for precision offline tracking  
 404 and for triggering. Three layers of monitored drift tubes (MDTs) or cathode strip chambers  
 405 (CSCs) are used for tracking. The position of the muon track in each of the three layers allows  
 406 reconstruction of the track and hence momentum. For the design momentum resolution of  
 407  $\Delta p_T/p_T < 1 \times 10^{-4}$   $p$  / GeV for  $p_T < 300$  GeV and a few percent for lower  $p_T$  muons,  
 408 the MDTs and CSCs required position resolution of 50  $\mu\text{m}$  each. Accordingly, an optical  
 409 alignment system was designed to monitor and correct for chamber positions [42, 43].

410 Resistive plate chambers (RPCs) are used for triggering in the barrel and thin-gap chambers  
 411 (TGCs) are used for triggering in the endcaps. The positions of each type of chamber are  
 412 sketched in figure 2.7b. Often, the endcap muon spectrometer is separated into three wheels –

413 the small wheel, big wheel, and outer wheel – ordered by proximity to the interaction point.  
414 In run-1, low (high)  $p_T$  muons were triggered on at L1 if two (three) of the RPCs or TGCs  
415 layers around the big wheel fired in coincidence, for the barrel and endcaps respectively [36].  
416 After run-1 it was discovered that up to 90% of the triggers in the endcap were fake, caused  
417 by background particles generated in the material between the small wheel and the big  
418 wheel [5]. To reduce the fake rate in run-2, the TGCs on the inside of the small wheel also  
419 had to register a hit. The added condition reduced the trigger rate by 50% in the range  $1.3 < |\eta| < 1.9$  [39]. The effectiveness of the solution was limited since the  $|\eta|$ -range of the small  
421 wheel TGCs was limited to  $1.0 < |\eta| < 1.9$  and the position resolution of the small wheel  
422 TGCs is coarse [5].

423 **Chapter 3**

424 **The New Small Wheels**

425 **3.1 Motivation for the New Small Wheels (NSWs)**

426 The hit rate of all detector systems will increase with the HL-LHC not only because of the in-  
427 crease in luminosity, but also because the background radiation rate increases proportionally  
428 with luminosity. The combined rate presents problems for both the tracking and triggering  
429 capabilities of the muon spectrometer [5].

430 In term of tracking, the efficiency of the MDTs decreases by 35% (mostly due to long dead-  
431 times) already when exposed to the maximum hit rate at the current luminosity, 300 kHz.  
432 At the threefold increase in luminosity predicted for run-3, most of the small wheel will be  
433 subjected to a hit rate well above 300 kHz and it will begin missing hits. Losing hits in the  
434 small wheel will reduce the high  $p_T$  muon momentum resolution. The decrease in resolution  
435 will affect the ability to search for, for example, the decay of heavy bosons ( $W'$ ,  $Z'$ ) or a  
436 pseudo-scalar Higgs predicted by some SUSY models [4].

437 Already, the forward muon trigger system copes with a very high fake rate, even when  
438 including TGC data from the small wheel in the trigger as in run-2. At the luminosity  
439 expected in run-3, 60 kHz of the maximum 100 kHz of the L1 trigger would be taken by the  
440 endcap muon spectrometer. A possible solution would be to raise the minimum  $p_T$  threshold  
441 from 20 GeV to 40 GeV, but the ability to study several physics processes of interest depend  
442 on low  $p_T$  muons, particularly the Higgs decay to two muons, the Higgs decay to two tau's  
443 and SUSY particle decays to leptons [5].

444 The NSWs will solve both these problems. It will be covered with precision tracking cham-  
445 bers suitable for the expected hit rates and triggering chambers capable of 1 mrad angular



Figure 3.1: A schematic of a quarter cross section of the ATLAS detector, with the collision/interaction point (IP) in the bottom left corner. Three possible tracks are labelled. Ideally, track A would be triggered on while track B and C discarded. With the small wheel, all three tracks would be recorded. With the NSW, only track A would be recorded [5].

446 resolution. The idea behind the triggering chambers is to match the small wheel track seg-  
 447 ment with the track segment from the big wheel to discard tracks not originating from the  
 448 interaction point. Figure 3.1 illustrates this point: the run-1 trigger system would have  
 449 triggered on all three tracks, while with the NSW the trigger system would only trigger on  
 450 track A. Reducing the fake trigger rate means the NSWs will not miss as many muon hits  
 451 and that the low  $p_T$  threshold will not have to be raised to cut particles not produced in the  
 452 collision. The NSWs allow ATLAS to maintain the high  $p_T$  muon resolution and the low  
 453 muon  $p_T$  threshold at the HL-LHC collision rate [5].

454 **3.2 Design of the NSWs**

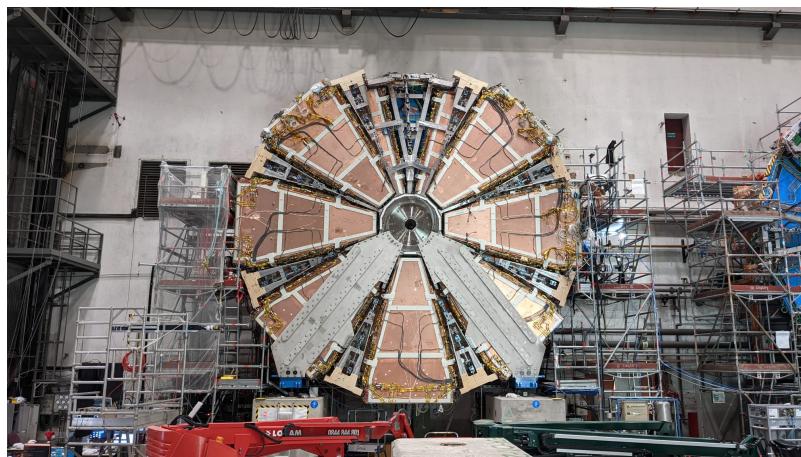
455 The NSWs are covered with two detector technologies: micromegas and small-strip thin gap  
456 chambers. MMs are the primary tracking detectors and sTGCs are the primary triggering  
457 detectors, but for redundancy sake both are designed to do either. Both sets of detectors are  
458 to have position resolution better than  $\sim 100 \mu\text{m}$  per plane. Four chambers of each type are  
459 glued together to create quadruplet modules. Quadruplets of different sizes are assembled  
460 into wedges. Two sTGC wedges and two MM wedges are layered to create sectors (with  
461 the sTGC wedges on the outside) [5]. Different stages of the construction process are shown  
462 in figure 3.2. At the time of writing, both NSWs have been assembled. The first has been  
463 lowered into the ATLAS cavern and is being commissioned. The second will be lowered  
464 shortly.



(a) An sTGC quadruplet module. The left image highlights the trapezoidal shape. The right image shows the short edge corner. The four sTGC layers and each layer's gas inlet are visible. The gas outlets and high voltage cables are at the long edge in the back of the photo. The green printed circuit board along the sides are the adaptor boards where the front end electronics are attached.



(b) Left: An sTGC wedge. The white frame outlines the individual quadruplet modules. Right: A completed sector, with two sTGC wedges on the outside and two MM wedges on the inside.



(c) The New Small Wheel. All sectors except one large sector at the top are installed, revealing two of the smaller sectors that are normally hidden under the large sectors and support bars. The NSWs are 10 m in diameter.

Figure 3.2: Images breaking down some of the construction units of the NSWs.



Figure 3.3: Internal structure of an sTGC, zoomed into the area under a pad. High voltage is applied to wires suspended in the gas volume to create an electric field. A passing muon causes an ionization avalanche that is picked up by the wire, strip and pad electrodes [9].

### 465 3.3 Small-strip thin gap chambers

466 sTGCs are gas ionization chambers operated with a CO<sub>2</sub>:n-pentane ratio of 55:45. Gold-  
467 plated tungsten wires, 50 µm in diameter and with 1.8 mm pitch, are suspended between  
468 two cathode planes made of FR-4, each 1.4 mm away (see figure 3.3). One cathode board is  
469 segmented into pads of varying area (around 300 cm<sup>2</sup> each), and the other segmented into  
470 strips of 3.2 mm pitch, perpendicular to the wires. High voltage is applied to the wires and  
471 the cathode planes are grounded [5, 7]. When a muon passes through, the gas is ionized and  
472 the electric field in the gas gap causes an ionization avalanche [44]. The motion of the ions  
473 and electrons are picked up on the nearby wire, strip and pad electrodes [5]. The gas mixture  
474 was chosen to absorb excess photons produced in the avalanche that delocalize the avalanche  
475 signal [45]. The resistivity of the carbon coating and capacitance of the pre-preg sheet tune

476 the spread of the charge distribution [46] and the speed of the response [47] to optimize  
477 the rate capability. The hatching of the strips and wires establishes a coordinate system  
478 from which to extract the coordinate of the muon as it passes through the chamber. The  
479 small pitch of the strips is what allows the quadruplets to deliver good angular resolution to  
480 improve the fake trigger rate and meet the precision tracking requirements [5].

481 A 3-out-of-4 coincidence in pad electrodes from each layer of a quadruplet define a region of  
482 interest where the strip and wire electrodes should be readout. The pad triggering scheme  
483 greatly reduces the number of electrodes that require read-out so that a track segment of  
484 the required angular resolution can be provided quickly enough to the hardware trigger [5].

485 Signal is readout from groups of successive wires, so the position resolution in the direction  
486 perpendicular to the wires is 10 mm. The wires give the symmetric azimuthal coordinate in  
487 ATLAS so the position resolution in this direction is sufficient. Good resolution on the  $\eta$   
488 coordinate, perpendicular to the strips, is important [5]. The average single chamber position  
489 resolution in the strip coordinate was 45  $\mu\text{m}$  for perpendicular muon tracks as measured in a  
490 test beam [6] – well within design specifications. When four sTGCs are glued together into a  
491 quadruplet the design angular resolution of 1 mrad in the strip coordinate is achievable [5, 7].

492 Therefore, sTGCs are able to meet the triggering and precision tracking goals they were  
493 designed for. To ensure they can deliver once installed in ATLAS, knowing the position of  
494 the strips to within their position resolution in the ATLAS coordinate system is necessary.  
495 The NSW alignment system, detailed in section 3.5, monitors the position of alignment  
496 platforms installed on the surface of the wedges. The alignment platforms are installed with  
497 respect to an external reference on the sTGCs: two brass inserts on each strip layer on one  
498 of the angled sides of each quadruplet (shown in figure 3.4). So the challenge of positioning  
499 the strips in ATLAS was separated into two steps: first, position the strips with respect to  
500 the brass inserts; second use the alignment system to position the alignment platforms. The  
501 next section provides some pertinent details on the sTGC construction process, with steps  
502 that affect the position of the strips with respect to the brass inserts highlighted.

### 503 3.4 sTGC Quadruplet Construction

504 Five countries were responsible for producing the sTGC modules of varying geometries for  
505 the NSW: Canada, Chile, China, Israel and Russia. Canada was responsible for 1/4 of the  
506 required sTGCs, of three different quadruplet geometries. The steps of the construction  
507 process in each country were similar [5]. The process followed in Canada is detailed.  
508 TRIUMF in Vancouver, British Columbia was responsible for preparing the cathode boards.  
509 The boards were made and the electrodes etched on at a commercial laboratory, Triangle



(a) Brass insert near long edge.

(b) Brass insert near short edge.

Figure 3.4: The brass inserts sticking out from the gas volumes of an sTGC quadruplet. These inserts were pressed against alignment pins when the individual sTGCs were being glued together.

510 Labs, in Carson City, Nevada. Once completed they were sent to TRIUMF to be sprayed with  
511 graphite and otherwise prepared [8]. The boards are commercial multilayer printed circuit  
512 boards, but the strip boards required precision machining to etch the strip pattern [5].  
513 Triangle Labs also machined the two brass inserts into each strip board. A coordinate  
514 measuring machine (CMM) was used to digitize a set of reference strips. Four quality  
515 parameters describing non-conformities in the strip pattern of each board with respect to  
516 the brass inserts were derived from the data and the results are available on a QA/QC  
517 database. The parameters and the CMM data collection is described in full in [8]. Due to  
518 time constraints, tolerances on the non-conformities in the etched strip pattern with respect  
519 to the brass inserts were loosened, with the condition that the strip positions in ATLAS  
520 would have to be corrected for [8].

521 The prepared boards were sent to Carleton University in Ottawa, Ontario for construction  
522 into sTGCs and quadruplets. First, the wires were wound around the pad cathode boards  
523 using a rotating table and the wires were soldered into place. A wound pad cathode board  
524 was held by vacuum on a granite table, flat to within 20  $\mu\text{m}$ , and a strip cathode board glued  
525 on top to create an sTGC. Holding one sTGC flat with the vacuum, another was glued on  
526 top to create a doublet, then two doublets were glued together to create a quadruplet. When  
527 gluing sTGCs together, the brass inserts were pushed against alignment pins with the goal of  
528 keeping the strip layers aligned within tolerance. However, non-conformities in the shape of  
529 the brass inserts, non-conformities in the position of the alignment pins and shifts between  
530 sTGCs while the glue cured resulted in misalignments between the brass inserts and strip  
531 layers. Precise alignment of the pad boards or wires with respect to the strip boards did not  
532 have to be so tightly controlled because pads do not measure the precision coordinate.

533 The Carleton team finished the quadruplets by installing adaptor boards on the angled sides  
534 of each layer that allow front end electronics to be attached. Completed quadruplets were  
535 sent to McGill University where they were characterized with cosmic rays. The details of  
536 cosmic ray testing are described in chapter 4. Tested quadruplets were sent to CERN where  
537 they were assembled into wedges and alignment platforms installed. The alignment platforms  
538 were installed using a jig positioned with respect to the brass inserts. Completed wedges  
539 were assembled into sectors then installed on the NSWs.

540 The quadruplet construction process had two steps where strip positions could be shifted off  
541 of nominal. At board-level, there could be non-conformities in the etched strip pattern with  
542 respect to the brass inserts, described by the four quality parameters [8]. At the quadruplet  
543 level, misalignments between the brass inserts and strips on different layers were introduced  
544 during the gluing. The result was that the brass inserts were not a reliable reference point  
545 and that the strips can be offset from their design position by up to hundreds of micrometers.  
546 Offsets in strip positions from nominal in Canadian quadruplets were shown to be random [8],

547 so no one correction would suffice. The offsets must be measured and corrected for in the  
548 ATLAS offline software that does the precision tracking. Understanding the work ongoing  
549 to make measurements of offsets and correct for them requires understanding the strategy  
550 of the NSW alignment system.

## 551 3.5 NSW alignment

552 The idea of the NSW alignment system is presented in [5], but the details have only been  
553 presented internally so far. After the wedges are constructed, alignment platforms are in-  
554 stalled on every sTGC quadruplet and optical fibres routed to them, as shown in figure 3.5.  
555 Light from the optical fibres will be monitored in real time by cameras (BCAMs) mounted on  
556 the alignment bars of the NSWs. The system will thus record the positions of the alignment  
557 platforms in the ATLAS coordinate system, accessible at any point during operation.

558 The original alignment scheme was to use the brass inserts as a reference between the align-  
559 ment platforms and the individual strips, as shown in the solid arrows in figure 3.6 – this  
560 will no longer work. The position of the alignment platforms will be known thanks to the  
561 alignment system, so a different method to get the position of the strips with respect to  
562 the alignment platforms is currently in its final stages. It uses the yet-unmentioned x-ray  
563 dataset to calculate offsets of the strip pattern of an sTGC layer in a local area (local offset)  
564 with respect to the nominal geometry by analyzing the beam profile left by an x-ray gun  
565 attached to different positions on the alignment platforms. Effectively, the reference to the  
566 brass inserts is skipped, represented as the dashed line in figure 3.6. The alignment plat-  
567 forms provide the link to the nominal geometry because their position with respect to the  
568 strips can be calculated from the nominal geometric parameters assuming that the strips  
569 are perfectly etched and aligned. Cosmic muon track positions cannot be compared to the  
570 nominal geometry because the alignment platforms are not installed when cosmics data is  
571 collected, so there is no external reference to provide a link to the nominal geometry.

572 The x-ray method does not have the sensitivity to measure the offset of each strip from  
573 nominal, but instead the offset of the strip pattern in a local area around the position of  
574 the gun can be measured. *Local offsets* are used to build an alignment model for each strip  
575 layer. Formally defined, an alignment model is a set of parameters used to estimate the true  
576 position of a strip given its nominal position. The alignment model currently being worked  
577 on takes x-ray and CMM data as input to calculate an offset and rotation of each strip  
578 layer with respect to nominal [9]. The alignment parameters could be described as “global”,  
579 meaning over the whole layer instead of local. Without the x-ray dataset, there would be no  
580 input to the alignment model that takes into account inter-layer misalignments introduced

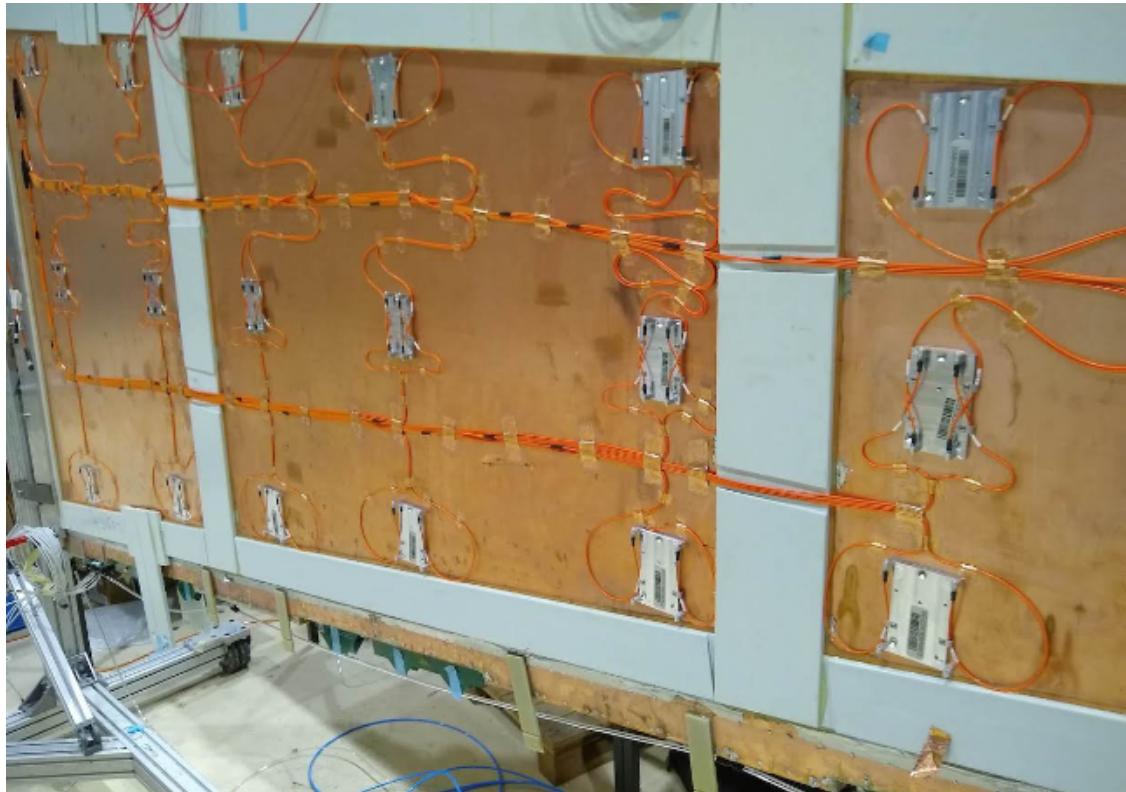


Figure 3.5: An sTGC wedge with alignment platforms (silver) installed on the quadruplet. Optical fibres (orange) are routed to the alignment platforms. Cameras on the frames of the NSWs will record light from the optical fibres to position the alignment platforms in the ATLAS coordinate system.

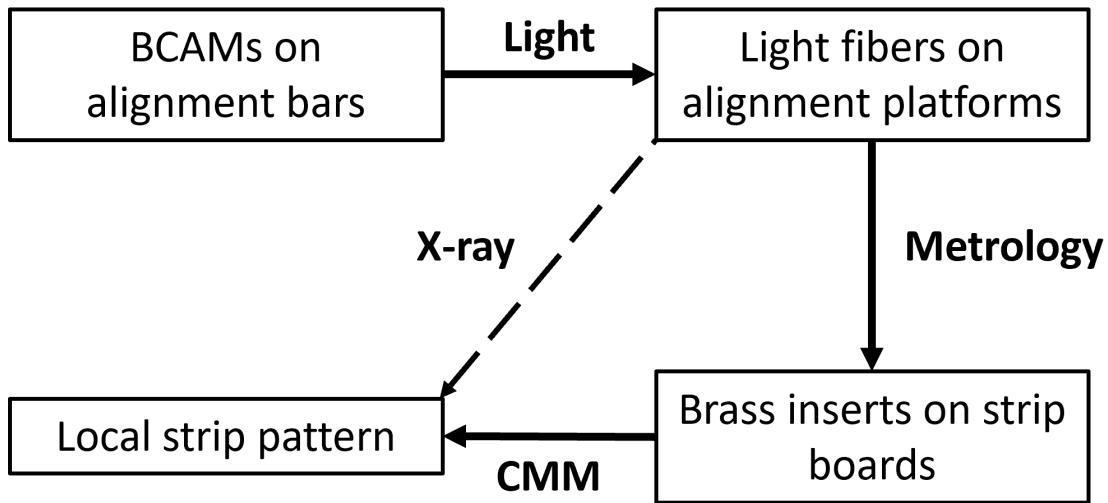


Figure 3.6: How the different elements of the sTGC alignment system relate to one another. The solid arrows denote the planned alignment scheme. The dashed arrow shows the modification being finalized now. This figure was originally designed by Dr. Benoit Lefebvre.

<sup>581</sup> in construction.

<sup>582</sup> Given that the x-ray local offsets can only be measured at positions where the gun can be  
<sup>583</sup> attached and that they are an important part of the alignment scheme, the x-ray method  
<sup>584</sup> needs to be validated. The goal of this thesis is to validate the x-ray local offsets while  
<sup>585</sup> exploring how cosmics data complements and adds to the understanding of strip positions  
<sup>586</sup> and overall alignment.

587 **Chapter 4**

588 **Using cosmic muons to measure  
589 relative strip position offsets**

590 At McGill, among other quality and functionality tests, each Canadian-made quadruplet was  
591 characterized with cosmic muons. In this chapter, the experimental setup and how the data  
592 was analyzed to provide relative strip position offsets is presented. The analysis method  
593 was motivated by the how it could be compared to data collected with the x-ray method  
594 (chapter 5) but also stands alone as a characterization of the alignment between strips of  
595 different layers. First, a brief introduction to cosmic rays.

596 **4.1 Cosmic rays**

597 The Earth is being bombarded by particles from the sun, galactic sources and extra galactic  
598 sources – collectively called cosmic rays [17, 12]. Cosmic rays are mostly protons, but also  
599 heavier ions, gamma rays and the term sometimes includes neutrinos. The primary (initial)  
600 cosmic ray interacts with the atmosphere causes electromagnetic and hadronic showers of  
601 particles. Hadronic showers result from the primary cosmic ray interacting strongly with the  
602 target of the atmosphere and the most abundant products are pions. Charge pions mostly  
603 decay to muons (there is a lesser contribution to the muon flux from kaons as well) [48].  
604 Thanks to time dilation extending the muon’s lifetime as measured on Earth, a flux of  
605 approximately 1 muon/cm<sup>2</sup>/ min reaches the ground [12]. Measuring the muon flux and  
606 energy spectrum reveals information about primary cosmic rays [48] which is interesting to  
607 high energy physicists and astrophysicists. The muon flux is also terribly convenient for  
608 testing muon detectors.

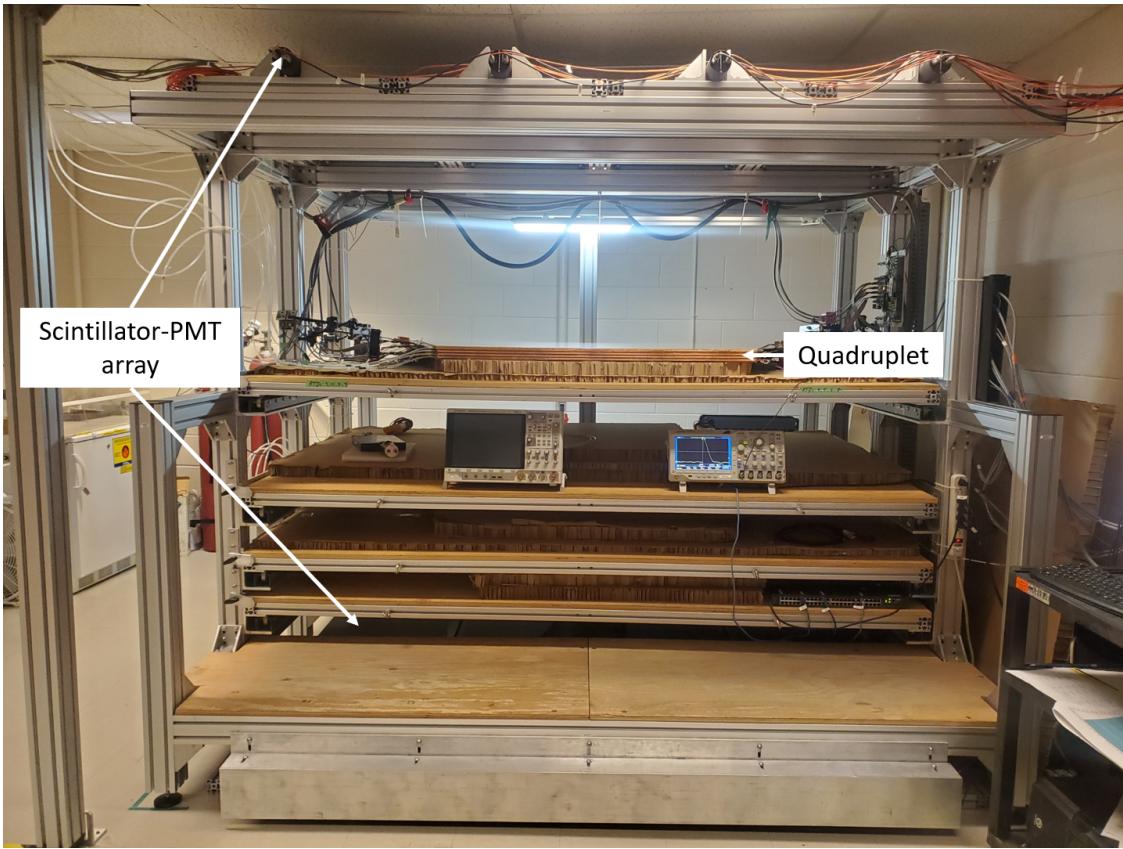


Figure 4.1: Cosmic muon hodoscope at McGill University with sTGC quadruplet in the test bench.

## 609 4.2 Experimental setup

610 Cosmic muon characterization was done with a hodoscope, a complete description of which  
 611 can be found in [49]. The quadruplet was placed in the center of the test bench. Above  
 612 and below it was a layer of scintillator-PMT arrays, labeled in figure 4.1. When a cosmic  
 613 muon passed within the acceptance of the hodoscope, at least one scintillator from the top  
 614 array and at least one from the bottom array fired in coincidence. The coincident signal was  
 615 used to trigger the readout of the quadruplet's electrodes using NIM modules. The trigger  
 616 was passed to the front-end electronics attached to the adaptor boards of each layer of the  
 617 quadruplet.

618 Operating the chambers also required gas and high voltage. A pentane-CO<sub>2</sub> mixture was  
 619 mixed and delivered to each sTGC with a gas system designed and made at McGill University.

620 The gas system was controlled by a slow control program, also made in-laboratory [50].  
621 Although gas mixture is flammable, it allows the chambers to operate in high amplification  
622 mode without production of excess photons saturating the signal across many strips because  
623 pentane absorbs a wide energy of photons [45]. To prepare the quadruplets for operation,  
624 CO<sub>2</sub> was flushed through them overnight to remove impurities. Then, five gas volumes of  
625 the pentane-CO<sub>2</sub> mixture was flushed through (approximately 3 hours). High voltage was  
626 provided by CAEN boards.

## 627 4.3 Data acquisition

628 Each sTGC electrode was connected to a channel on a prototype ASIC<sup>1</sup> on the front-end  
629 electronics, attached to the adaptor boards on each layer of a quadruplet. The ASIC ampli-  
630 fied the signal and was set to measure and record the signal peak amplitude from electrodes.  
631 For each trigger, the signal peak amplitude of all channels above threshold was recorded  
632 as an event and stored in a binary file. Channel thresholds were estimated [52] and ad-  
633 justed manually in the configuration/readout software before the start of data acquisition.  
634 There was an exception to the threshold rule: the signals on strips adjacent to a strip above  
635 threshold were also readout using the so-called “neighbour triggering” function of the ASIC.  
636 The quadruplets were held at 3.1 kV for approximately two hours to collect data from 1  
637 million muon triggers.

## 638 4.4 Data preparation

### 639 4.4.1 Cuts on electrode hits

640 Corrupted data is removed while the raw data is being recorded in a binary file. The binary  
641 file is decoded into a usable ROOT [53] tree offline.  
642 A hit is defined as a signal recorded from a channel that was above threshold or (in the  
643 case of strips) neighbour triggered. In addition to hits from muons, the quadruplets record  
644 noise from the electronics and  $\delta$ -rays (electrons liberated with sufficient energy to cause more  
645 ionization before acceleration). Therefore, cuts are applied to reduce the number of noise  
646 hits. The edge strips are very noisy, so all strip hits on layers with strip hits on either  
647 edge channel are cut. A default pedestal value is subtracted from the recorded signal peak

---

<sup>1</sup>the VMM3 [51], designed for the MMs and sTGCs of the NSW

648 amplitude of each electrode for a more realistic estimate of the signal amplitude. Also, events  
649 that only have hits on pad electrodes (no strips or wires) were cut because the large area of  
650 the pads made them susceptible to noise.

#### 651 4.4.2 Clustering and tracking

652 Many of the high-level characterization metrics require rebuilding muon tracks. For events  
653 passing quality cuts, the  $x$ - and  $y$ -coordinates of the ionization avalanche on each layer are  
654 extracted from the signal on the wires and strips respectively for each event, as is sketched in  
655 figure 4.2. In this work,  $x$  is the coordinate perpendicular to the wires and  $y$  is the coordinate  
656 perpendicular to the strips.

657 The  $x$ -coordinate is taken as the center of the wire group with the maximum peak signal  
658 amplitude, since the wire groups' pitch (36 mm) is larger than the typical charge spreading.  
659 Assuming that the true  $x$ -position of the hit is sampled from a uniform distribution over the  
660 width of the wire group, the uncertainty in the  $x$ -position was given by  $\frac{36}{\sqrt{12}}$  mm = 10 mm [54].

661 The  $y$ -coordinate is taken as the Gaussian mean of the peak signal amplitude distribution  
662 across groups of contiguous strips. The process of grouping contiguous strip hits on a layer is  
663 called clustering, and the resulting group is called a cluster. Figure 4.2 sketches the clustering  
664 process and a sample cluster is shown in figure 4.3. The data acquisition system recorded  
665 the electrode ID of the strip hit and in the clustering process the position of the center  
666 of the strip electrode is calculated based on the nominal quadruplet geometry. Typically,  
667 clusters are built of 3-5 strips. The thickness of the graphite coating over the cathode boards  
668 determined how many strips picked up the ionization image charge. Larger clusters were  
669 more likely caused by  $\delta$ -rays since they spread the cloud of ionization.

670 Events are cut from the analysis if there are two clusters on one layer's set of strips (indicative  
671 of noise). Clusters are cut if the cluster size is lesser than three (which should not happen for  
672 real events thanks to neighbour triggering), and if the cluster size is greater than 25. After  
673 all the cuts on hits and clusters, roughly half as many muon tracks as triggers collected  
674 remain.

675 The uncertainty in the  $y$ -coordinate could have been taken as the fitted cluster mean's  
676 statistical uncertainty; however, after comparing the difference in cluster means for different  
677 fitting algorithms in appendix A.2, 60  $\mu\text{m}$  of uncertainty was assigned.

678 The coordinates of the avalanches' on all layers were used to reconstruct tracks in  $x$  and  $y$   
679 respectively. The tracks were then used to calculate characterization metrics like electrode  
680 efficiency and spatial resolution, the details of which are discussed in [49].

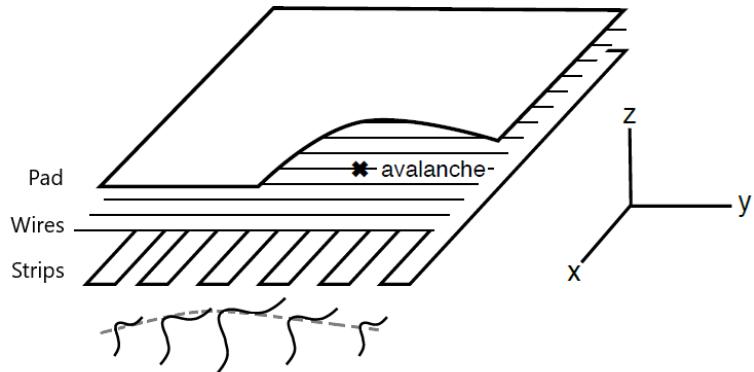


Figure 4.2: A sketch of an sTGC-like detector. The position of the avalanche is extracted from the wires and strips that picked up the avalanche signal. The signals on individual strips are sketched. Clustering was the processs of fitting a Gaussian to the peak value of the signals on individual contiguous strips, as is done in figure 4.3. In this work, the  $x(y)$ -coordinate will always refer to the coordinate perpendicular to the wires (strips) [49, 46].

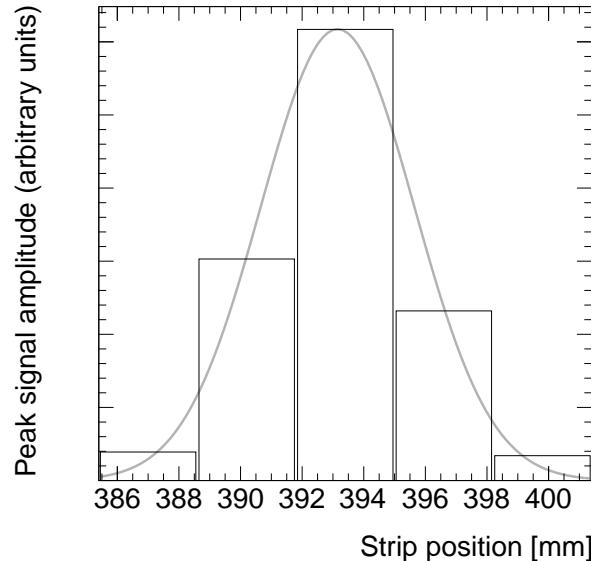


Figure 4.3: A sample cluster resulting from the current picked up on a group of strips after the passing of a muon (presumably). The grey curve is a Gaussian fit.

## 681 4.5 Measuring relative local offsets

682 The offset of a strip from its nominal position can be modeled as a passive transformation.  
683 For each area of a strip layer, the local offset is the shift of the strip pattern in that area with  
684 respect to the nominal geometry. Local offsets systematically change the set of strips nearest  
685 to muons passing through the area. The data preparation software assumes that strips are  
686 in their nominal positions, so the recorded muon  $y$ -position on layer  $i$ ,  $y_i$ , is shifted opposite  
687 to the layer's local offset,  $d_{local,i}$ , by

$$y_i = y_{nom,i} - d_{local,i}, \quad (4.1)$$

688 where  $y_{nom,i}$  is the position of the muon that would have been recorded on layer  $i$  if there  
689 was no local offset. Equation 4.1 ignores other factors that affect the cluster position, like  
690 position resolution. With cosmics data, the local offset is unknown and there was no external  
691 reference to measure  $y_{nom,i}$ . Therefore, only relative local offsets could be calculated.

692 The minimal relative coordinate system uses two reference or fixed layers [49]. The hits  
693 on the two fixed layers were used to create tracks that can be interpolated or extrapolated  
694 (polated) to the other two layers. The set of two fixed layers and the layer polated to are  
695 referred to as a tracking combination. The residual of track  $i$ ,  $\Delta_i$  is defined as,

$$\Delta_i = y_i - y_{track,i}, \quad (4.2)$$

696 where  $y_{track,i}$  is the polated track position. Track residuals are affected by the relative local  
697 offset in the area of each layer's hit. As an example, in figure 4.4, the residual on layer  
698 2 perhaps indicates that layer 2 is offset with respect to layers 1 and 4 in the area of the  
699 track. Of course, a single track residual says nothing of the real relative local offset because  
700 of the limited spatial resolution of the detectors and fake tracks caused by noise or delta  
701 rays. However, the mean of residuals for all tracks in a region will be shifted systematically  
702 by the local offsets between layers [49]. For a quadruplet with nominal geometry, the mean  
703 of residuals should be zero in all regions and for all reference frames, unlike the example  
704 regions in figure 4.5. The value of the mean of residuals is a measure of the relative local  
705 offset of the layer with respect to the two fixed layers.

706 To study the relative local offsets, residual distributions across each strip layer of a quadruplet  
707 for all tracking combinations were assembled and fitted. The residual distributions were  
708 wider for tracking combinations where the extrapolation lever arm was largest, as in the  
709 example distributions shown in figure 4.5. In general, residual means from distributions of  
710 residuals with geometrically less favourable tracking combinations have larger statistical and  
711 systematic uncertainties. The bin size of 200  $\mu\text{m}$  for the distributions shown in figure 4.5 was

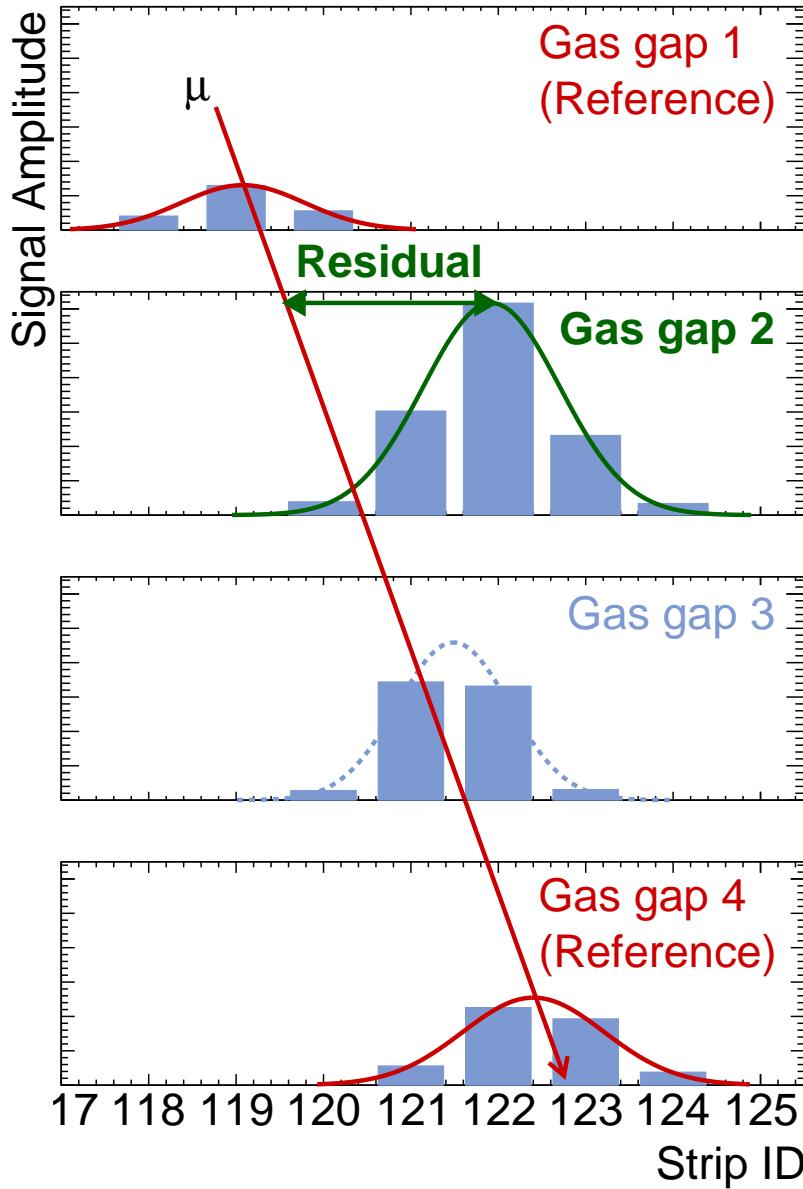
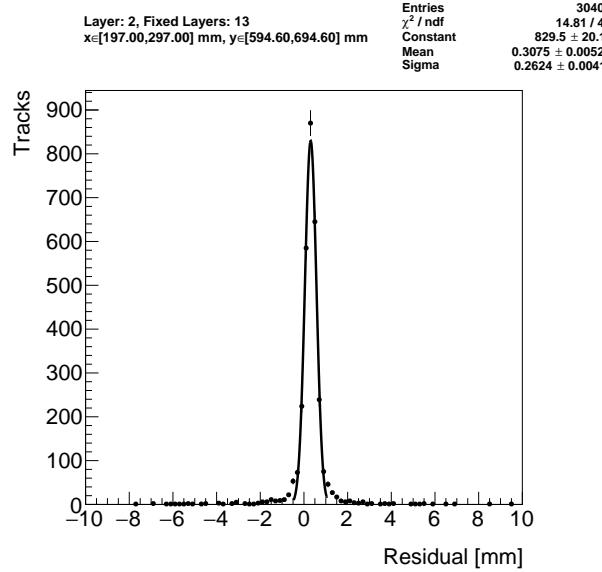
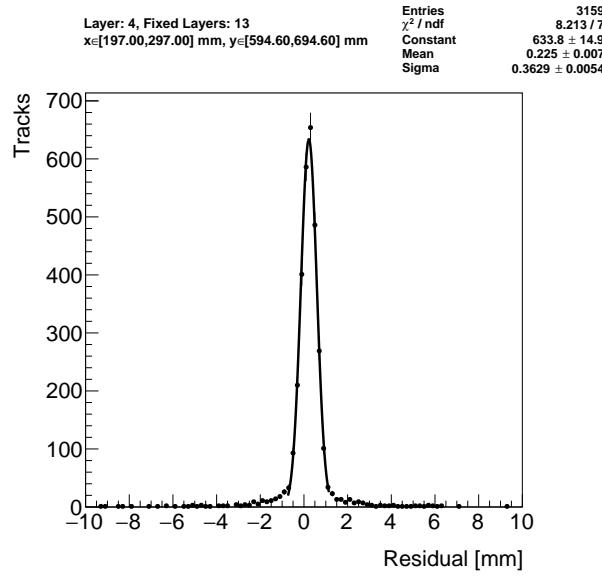


Figure 4.4: Representation of a muon event recorded by an sTGC. The clusters are fit with a Gaussian and the mean is taken as the hit position. A track is built from the chosen reference layers, 1 and 4, and the residual calculated on layer 2. The clusters come from a real muon, but their positions were modified to highlight the residual on layer 2.



(a) Tracks on layer 2, reference layers 1 and 3.



(b) Tracks on layer 4, reference layers 1 and 3.

Figure 4.5: Residual distribution in the region  $x \in [197, 297]$ ,  $y \in [594.6, 694.6]$  mm (100 mm by 100 mm area) for two different tracking combinations. Data from quadruplet QL2.P.11.

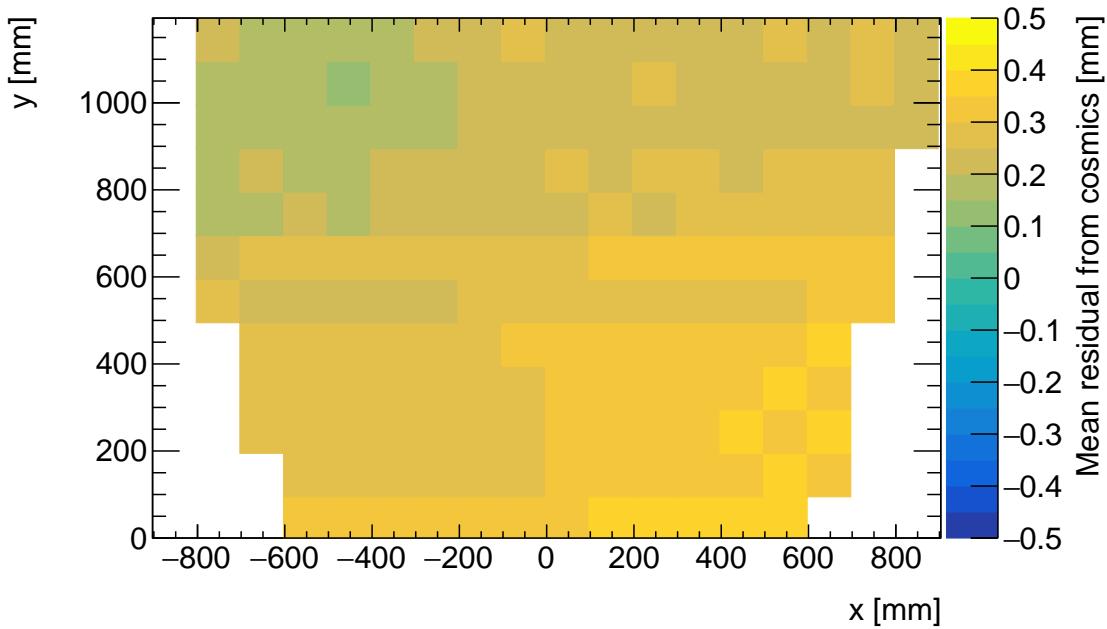
712 chosen based on the uncertainty on residuals calculated from tracks on layer 4 (1) built from  
713 hits on layers 1 and 2 (3 and 4) given a cluster  $y$ -position uncertainty of  $60\text{ }\mu\text{m}$  (appendix A.3),  
714 since these tracks yield residuals with the largest uncertainties.

715 A gaussian fit was used to extract the mean of the residual distributions. Theoretically, a  
716 double gaussian distribution is more apt, but for this analysis the gaussian fit was sufficient,  
717 as discussed in appendix C.1.

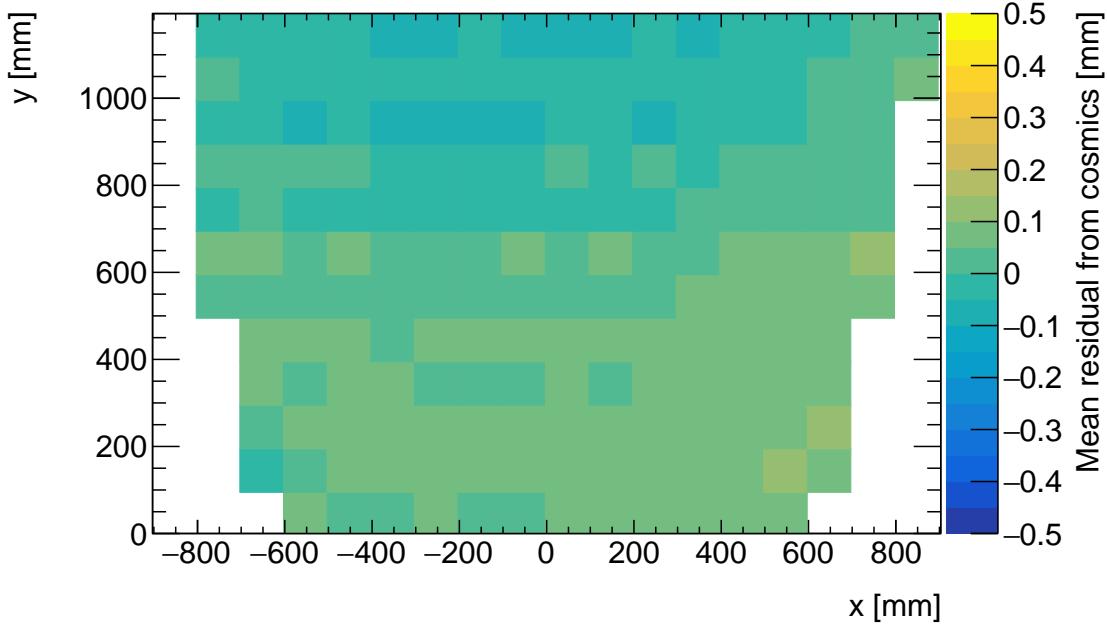
718 The area of the region of interest was  $100\text{ mm by }100\text{ mm}$ . The size balanced the amount of  
719 tracks falling in the region of interest to give a small statistical uncertainty on the extracted  
720 mean while being smaller than the order on which local offsets were expected to change  
721 significantly. The change in local offsets over the surface of a layer can be modeled using  
722 global alignment parameters. Using a base alignment model with a global offset and rotation  
723 of each strip layer, “significantly” was defined by the distance in  $x$  that a large but possible  
724 rotation of  $1000\text{ }\mu\text{rad}$  would change the local offset by more than  $50\text{ }\mu\text{m}$  – half the required  
725 position resolution of the sTGCs [5].

## 726 4.6 Visualizing relative alignment between layers

727 The mean of residuals was plotted across entire strip layers for every tracking combination to  
728 get a picture of the how relative local offsets change over the layers’ surface. Figure 4.6 shows  
729 the mean of residuals on layer 2 with reference layers 1 and 3 for two different quadruplets,  
730 referred to as QL2.P.11 and QL2.P.8, for  $100\text{ mm by }100\text{ mm}$  areas across the surface of  
731 layer 2. To understand these plots, realize that the Gaussian mean of the distribution in  
732 figure 4.5a is the entry in area bin  $x \in [197, 297], y \in [594.6, 694.6]\text{ mm}$  in figure 4.6a.



(a) Mean of residuals of tracks on layer 2, reference layers 1 and 3, for QL2.P.11.



(b) Mean of residuals of tracks on layer 2, reference layers 1 and 3, for QL2.P.8.

Figure 4.6: Mean of residuals in each 100 mm by 100 mm bin over the area of the layer 2 cathode board. The entry in  $x \in [197, 297]$ ,  $y \in [594.6, 694.6]$  mm of figure 4.6a corresponds to the fitted Gaussian means in figures 4.5a. The mean of residuals is an estimate of the local offset of layer 2 with respect to layers 1 and 3.

Many of the residual means are non-zero and change smoothly over the layer, indicating that there are relative local offsets stemming from misalignments between entire strip layers. Given that the residual mean changes with  $x$  in figure 4.6a, there is likely a rotation of layer 2 with respect to layers 1 and 3 on QL2.P.11, combined with an offset of the entire layer. The residual means are smaller in figure 4.6b indicating that QL2.P.8 is less misaligned overall than QL2.P.11; however the relative local offsets range between  $\pm 200 \mu\text{m}$  so they are still significant considering the order on which the chambers must be sensitive to position,  $\sim 100 \mu\text{m}$ .

## 4.7 Systematic uncertainty

The statistical uncertainty on the local residual means was typically around  $10 - 20 \mu\text{m}$ , and appendix B shows that the analysis was not statistically limited by the number of triggers collected for each quadruplet. The systematic uncertainties were more significant.

Systematic uncertainties were assigned per tracking combination as the RMS of the distribution of the difference in local residual means each calculated in a different way. For example, the RMS associated with fitting the local residual distributions with a Gaussian or double Gaussian is  $25 \mu\text{m}$  for the geometrically least favourable tracking combinations. The distribution is shown in appendix C.1. For geometrically similar tracking combinations (like: tracks on layer 1 built from hits on layers 3 and 4, and tracks on layer 4 built from hits on layers 1 and 2), the systematic uncertainty was assigned as the average RMS of both.

Other choices were: whether to use data collected at 2.9 kV or 3.1 kV (both are collected at McGill); what cluster fitting algorithm to use; and whether or not to apply a differential non-linearity (DNL) correction to the cluster  $y$ -positions. A systematic uncertainty was assigned using the method above to account for the effect of each choice and quantify the robustness of the mean of residuals. The reasons for each choice are listed below.

Data taken at 3.1 kV was used over 2.9 kV because the strip and wire tracking efficiency increases with higher voltage [49] (appendix C.2).

The Minuit2 package [55] was used to fit clusters over Guo's method [56] because it provided automatic statistical uncertainty estimates and is the standard fit algorithm of ROOT [53] (appendix C.3).

The DNL correction was not applied because its effect on the residual means was negligible (appendix C.4).

A summary of the systematic uncertainties assigned for each tracking combination is given in table 4.1.

Tracking geometry	Residual distribution fit function <a href="#">(C.1)</a>	Cosmics data collection voltage <a href="#">(C.2)</a>	Cluster fit algorithm <a href="#">(C.3)</a>	Apply DNL correction or not <a href="#">(C.4)</a>	Total
Similar to layer 3, fixed layers 1, 2	0.01	0.04	0.02	0.01	<b>0.05</b>
Similar to layer 4, fixed layers 1, 2	0.03	0.01	0.03	0.01	<b>0.10</b>
Similar to layer 2, fixed layers 1, 3	0.01	0.02	0.01	0.000	<b>0.03</b>
Similar to layer 4, fixed layers 1, 3	0.01	0.04	0.01	0.01	<b>0.04</b>
Similar to layer 2, fixed layers 1, 4	0.01	0.04	0.01	0.01	<b>0.04</b>

Table 4.1: Systematic uncertainty assigned for each analysis option, detailed in appendix [C](#).

766 The uncertainty in each mean of residuals was assigned as the sum in quadrature of the sta-  
767 tistical uncertainty in the mean and the appropriate systematic uncertainty for the tracking  
768 combination.

## 769 4.8 Discussion

770 Cosmics data is being used to calculate relative alignment parameters using two other meth-  
771 ods [49]. A cross-check of this analysis would be to compare their results; however the studies  
772 in appendix C show that the mean cosmics residuals are robust, so the comparison was not  
773 prioritized.

774 Given that the uncertainty in the residual means is lesser than or near to the order of the  
775 required position resolution of the sTGCs (100  $\mu\text{m}$  [5]) they are relevant input for alignment  
776 studies.

777 The relative local offsets as calculated from the mean of residual distributions provide a  
778 complete picture of the relative alignment between detectors planes. In fact, cosmic muon  
779 testing is the only characterization technique where the entire surface of quadruplet layers  
780 can be probed since muons hits are distributed almost uniformly; the CMM [8] and x-ray  
781 methods [9] depend on measurements at reference points, and test beams only have a limited  
782 beam spot [6]. By looking at 2D-histograms of residual means like figure 4.6 for all tracking  
783 combinations, it is easy to identify quadruplets that suffer large relative misalignment since  
784 many residual means differ significantly from zero. Moreover, the pattern in the relative  
785 local offsets can be used to motivate a physical interpretation of misalignments. The relative  
786 local offsets can be used as a reference, cross check, or input in other alignment studies.

787 Relative local offsets cannot be used to position strips in the absolute ATLAS coordinate  
788 system because there was no external reference to measure positions on all layers with re-  
789 spect to. The lack of external reference means that there is not enough information to unfold  
790 relative local offsets into absolute local offsets (with respect to the nominal quadruplet ge-  
791 ometry). As an example, assuming that the residual on layer 2 in figure 4.4 is representative  
792 of the relative local offset, the residual on layer 2 could be caused by the strips on layer 2  
793 being misaligned from nominal, but it could also be caused by strips on layers 1 and 4 being  
794 offset from nominal while the strips on layer 2 are in their nominal positions! Any number  
795 of combinations of local offsets on layers 1, 2 and 4 could produce the residual on layer 2.  
796 Absolute local offsets must be calculated another way.

797 **Chapter 5**

798 **Using x-rays to measure relative strip  
799 position offsets**

800 Local offset measurements were done with the x-ray method. The reader is referred to the  
801 paper describing the x-ray method [9], although some minor changes have been made to the  
802 experimental setup since it was written. The experimental setup described here is current  
803 and was used to collect the data presented in this thesis.

804 **5.1 Experimental setup**

805 The x-ray tests were performed after the quadruplets arrived at CERN, were assembled into  
806 wedges, and alignment platforms installed. Essentially, an x-ray gun was attached to one  
807 of the alignment platforms glued to the surface of the wedge and the x-ray beam profile  
808 recorded by the strips.

809 The wedges were installed on carts that could rotate their surface to a horizontal position. A  
810 mounting platform was installed on top of the alignment platform using a three-ball mount.  
811 The x-ray gun used was an [Amptek Mini-X tube](#). The gun was placed in a brass holder  
812 with built-in 2 mm collimator and 280  $\mu\text{m}$  copper filter. The holder was mounted on one  
813 of five positions on the mounting platform, as shown in figure 5.1. Gun positions were  
814 chosen to avoid wire support structures in the sTGCs that reduce hit efficiency [49] and  
815 boundaries between sets of strips read out by two different ASICs that could each have  
816 different thresholds.

817 As with cosmics data collection, each sTGC also needed gas and high voltage to operate.

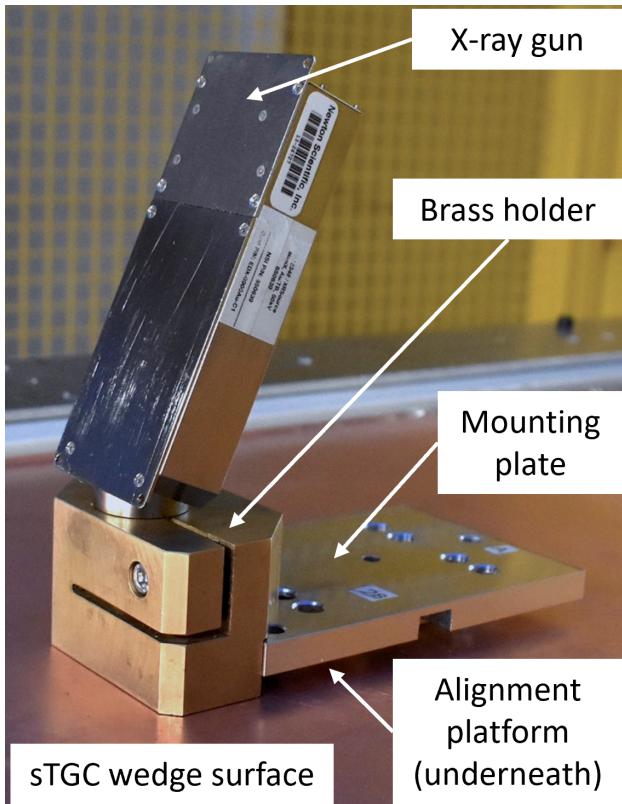


Figure 5.1: The x-ray gun mounted to the alignment platform on the surface of the wedge.  
Adapted from [9].

818 Each layer was operated at 2.925 kV with high voltage from a NIM crate. The chambers  
819 were flushed with CO<sub>2</sub> before and during data collection.  
820 The gun produced x-rays with energies under 40 keV with peaks in the 7-15 keV range. The  
821 x-rays mostly interacted with the wedge's copper electrodes and gold-plated tungsten wires  
822 via the photo effect. The resulting photoelectrons caused ionization avalanches that were  
823 picked up by the strips.

## 824 5.2 Data acquisition

825 A different version of the same front end electronics, but the same ASIC, as used in cosmics  
826 testing were used for the x-ray testing to amplify the data and measure the peak signal  
827 amplitude. Data was collected for two minutes per gun position with random triggers. A  
828 trigger recorded all signals above threshold. Pad and wire data was not recorded.

## 829 5.3 Data preparation

830 Like with cosmics analysis, a default pedestal is subtracted from the signal peak amplitude  
831 on each electrode.  
832 Clusters are defined as groups of contiguous strip hits collected within 75 ns. The peak signal  
833 amplitude of each electrode in a cluster is fit with a Gaussian, and the mean of the Gaussian  
834 is taken as the cluster position. Cluster positions are corrected for DNL (see definition in  
835 appendix C.4). Only clusters composed of hits on 3-5 strips were used in the x-ray analysis.  
836 Clusters with signal on more than 5 strips were cut because they were most likely caused by  
837 photoelectrons ejected with enough energy to be  $\delta$ -rays.  
838 The x-ray analysis diverges entirely from the cosmics analysis algorithm here because the  
839 x-rays do not leave tracks. The signals picked up by the strips are from photoelectrons  
840 liberated from the metals of the sTGCs, which only travel through one gas volume and are  
841 ejected at all angles. Instead of creating tracks, the cluster position distribution on each  
842 layer is used to define the beam profile. A typical beam profile is shown in figure 5.2.

## 843 5.4 Measuring local offsets

844 The mean of the cluster position distribution is taken as the x-ray beam profile center.  
845 The expected center is calculated assuming a wedge with nominal geometry given the gun



Figure 5.2: Distribution of x-ray cluster mean positions after the analysis cuts and corrections. The strip cluster multiplicity,  $m$ , was limited to 3, 4 and 5. The red curve is a Gaussian fit of the distribution and the pink dashed lines denote the edges of the strips [9].

position, corrected for: the geometry of the brass holder, the positioning and angle of the alignment platforms and the beam angle. The difference between the expected and reconstructed beam profile center is a measure of the local offset. Applying the logic of equation 4.1 to the beam profile, the Gaussian mean of cluster positions on the given layer acts as the recorded position,  $y_i$ , the expected center is  $y_{nom,i}$  and the local offset is  $d_{local,i}$  as before, where  $i$  denotes the layer. Since the position of the alignment platforms will be monitored by the alignment system in ATLAS [5], the position of the strips that should have been at the gun position are shifted by  $d_{local,i}$  and so are known in the ATLAS coordinate system for every position where x-ray data was taken.

The x-ray working group accepted an uncertainty of 120  $\mu\text{m}$  on the beam profile centers. The largest uncertainty comes from the effect of the gun angle, which proved difficult to measure and correct for.

The local offsets are not presented here as the author did not conduct this work. However, the author used the local offsets to calculate relative local offsets.

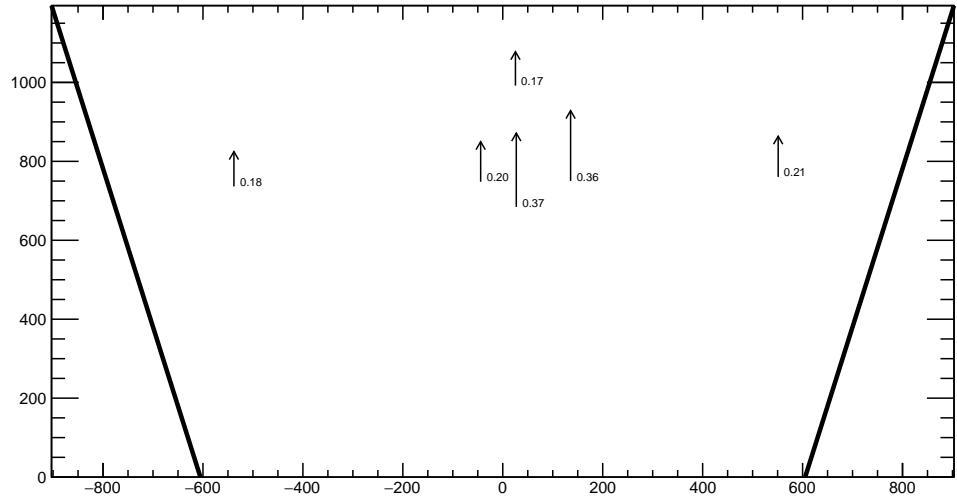
## 5.5 Measuring relative local offsets

The x-ray local offsets were shown to be correlated with the local offsets calculated from the CMM data, but the CMM data does not include the effect of inter-layer misalignments so the degree of correlation measurable was limited. Cosmics data is affected by inter-layer misalignments. Since the local offsets for x-rays and cosmics data are measured in different coordinate systems, they cannot be compared directly. Bringing the cosmics relative local offsets into an absolute coordinate system is impossible; however, the x-ray local offsets can be brought into a relative coordinate system.

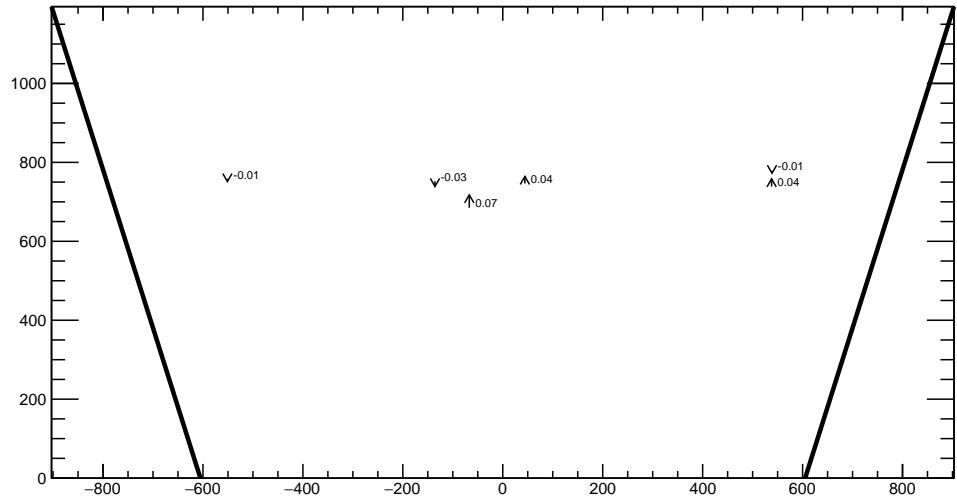
The measured x-ray beam profile centers were systematically affected by local offsets in the same way as the mean cosmics residuals, as modeled by equation 4.1. Therefore, if a 2-layer track is built from the beam profile centers on each layer and the residual calculated on a third layer, that residual should match the local mean cosmics residual. The residual is the difference between the beam profile center on the layer of interest and the polated track position from the beam profile centers recorded on the two fixed layers. The beam profile center on the layer of interest acts as  $y_i$  and the polated track position acts as  $y_{track,i}$  in equation 4.2.

The built track is not an actual track of the x-ray beam. A beam profile center is actually the Gaussian mean of all selected mean cluster positions recorded during the x-ray data taking period, not a single hit of a track. Building an “abstract” track was necessary because

- 879 the x-rays cause signal in the chamber via the photoeffect so there were not individual “x-  
880 ray tracks” to record. In fact the x-ray data could be collected separately for each layer.  
881 Nonetheless, since the effect of local offsets on the beam profile centers was the same as their  
882 effect on the recorded cosmics cluster positions the difference in algorithm between x-ray  
883 and cosmics analysis was allowed.
- 884 For each x-ray survey position, the x-ray residual was calculated for all possible tracking  
885 combinations (which required an x-ray beam profile on at least three layers). The x-ray  
886 residuals on layer 2 calculated from the beam profile centers recorded on layers 1 and 3 are  
887 represented as arrows in figure 5.3 as arrows for QL2.P.11 and QL2.P.8. For QL2.P.11, a  
888 negative offset at all x-ray survey positions is clear.



(a) QL2.P.11 x-ray residuals on layer 2, reference layers 1 and 3.



(b) QL2.P.8 x-ray residuals on layer 2, reference layers 1 and 3.

Figure 5.3: The x-ray residuals on layer 2 calculated from the beam profile centers recorded on layers 1 and 3 for QL2.P.11 and QL2.P.8. The arrows originate from the expected position of the beam profile center assuming a nominal geometry, and the lengths are proportional to the calculated x-ray residuals. The tip of the arrow represents where the recorded hit was with respect to where it should have been recorded nominally. The value of the x-ray residuals are annotated in millimeters and have an uncertainty of  $\pm 0.15$  mm.

889 The uncertainty on the x-ray residuals was the error propagated through the tracking, taking  
890 an uncertainty of 120  $\mu\text{m}$  on each beam profile center. The uncertainty on the x-ray residuals  
891 ranged from 0.15 mm to 0.4 mm from the most to least geometrically-favourable tracking  
892 combination. There is no discernible pattern to the x-ray residuals on QL2.P.8 because they  
893 are smaller than the uncertainty. The x-ray residual uncertainties are significantly larger  
894 than the uncertainties on the relative local offsets calculated with cosmics data.

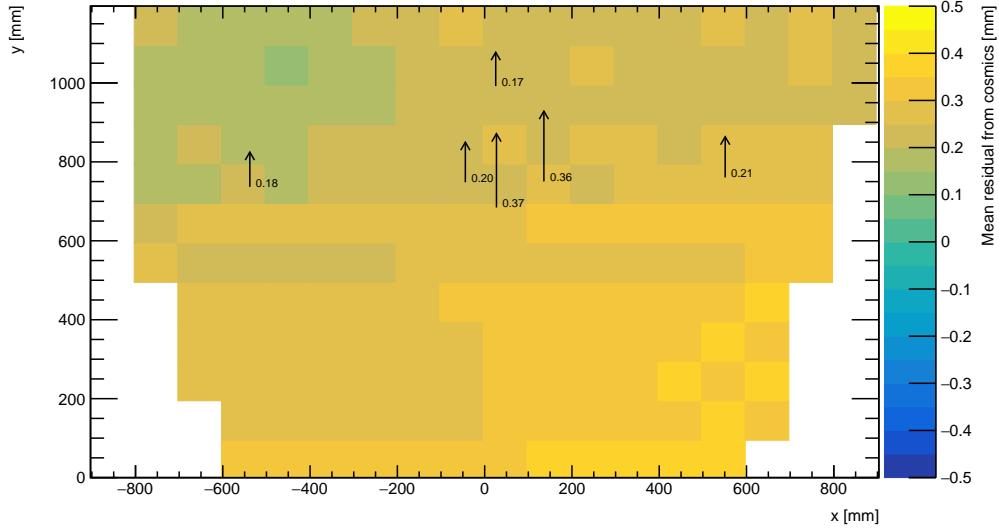
895 **Chapter 6**

896 **Comparing cosmic muon and x-ray  
897 relative strip position offsets**

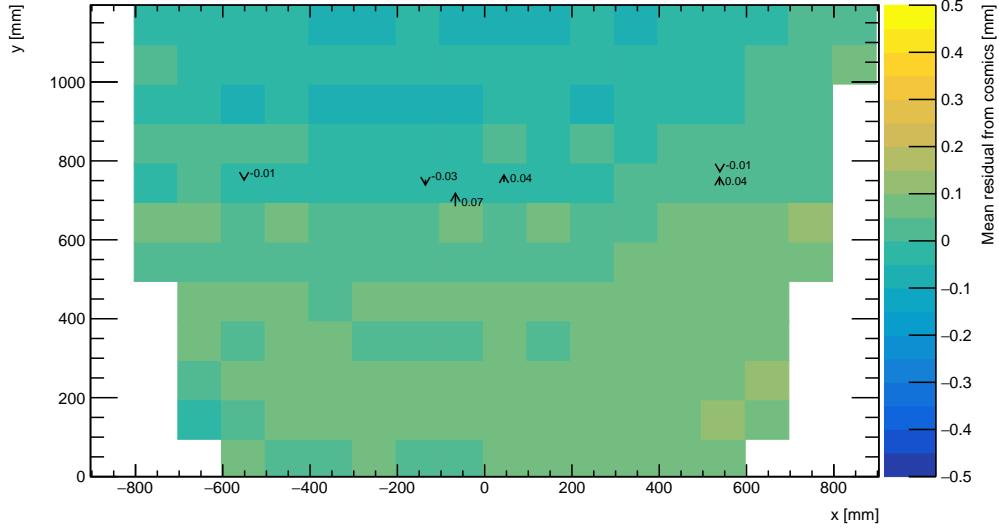
898 The goal was to validate the local offsets extracted from the x-ray data with cosmics data.  
899 The complication was that the x-ray dataset provided absolute local offsets while the cosmics  
900 dataset provided relative local offsets, which could not be compared directly. The solution  
901 was to use the x-ray local offsets to calculate relative local offsets. The x-ray relative local  
902 offset is the x-ray residual reconstructed from an abstract track using the beam profile  
903 centers on each layer as the track hits. The cosmics relative local offset was taken as the  
904 Gaussian mean of muon track residuals in a 100 mm by 100 mm area, referred to as the  
905 mean cosmics residual. Relative local offsets of each type calculated using the same  
906 reference layers are compared for each area where x-ray data is available. The results of the  
907 comparison are presented here.

908 **6.1 Assessing correlation**

909 The 2D visualizations of the mean cosmics and x-ray residuals for tracks on layer 2 with  
910 reference layers 1 and 3 on QL2.P.11 and QL2.P.8 are shown in figure 6.1. Figure 6.1 is a  
911 superposition of figures 4.6 and 5.3.



(a) QL2.P.11 residuals of tracks on layer 2, reference layers 1 and 3.



(b) QL2.P.8 residuals of tracks on layer 2, reference layers 1 and 3.

Figure 6.1: The mean cosmics residuals are shown using colour. The x-ray residuals available at nominal gun positions are drawn as arrows and the value of the residual annotated in millimeters with uncertainty  $\pm 0.15$  mm. The length of the arrows is 500 times the value of the x-ray residual, scaled for visibility. These plots are a superposition of figures 4.6 and 5.3.

912 Figure 6.1a shows that for QL2.P.11 the x-ray residuals are of the same sign and order as  
913 the mean cosmics residuals, as can be seen by comparing the the annotated value of the  
914 x-ray residual to the mean cosmics residual represented by colour; QL2.P.11's mean cosmics  
915 and x-ray residuals are correlated to some degree. For QL2.P.8, the x-ray residuals are of  
916 the right order compared to the mean cosmics residuals, but the correlation is less apparent.  
917 While x-ray residuals do not reveal a pattern across the layer's surface, the mean cosmics  
918 residuals show a structure to the relative local offsets since they vary smoothly over the  
919 surface of layer 2.

920 The comparison of mean cosmics and x-ray residuals was done for several quadruplets for  
921 all tracking combinations (not just layer 2 residuals calculated with fixed layers 1 and 3 like  
922 in figure 6.1). Scatter plots of the x-ray and mean cosmics residuals on QL2.P.11 and -2  
923 for all tracking combinations shown in figures 6.2 and 6.3 reveal the degree of correlation  
924 between the datasets. In the correlation plots, each rectangle is centered on the value of a  
925 mean cosmics and x-ray residual pair calculated with a given tracking combination for every  
926 gun position where data is available; the height and width of the squares are the uncertainty  
927 in the mean cosmics and x-ray residuals respectively. Note that in the scatter plots, the  
928 regions of interest where cosmics tracks are included in the calculation of mean of residuals  
929 are exactly centered on the nominal x-ray beam position, unlike in figure 6.1.

930 The fitted slope and offset in figure 6.2 show that the two QL2.P.11 datasets are correlated.  
931 The large uncertainty on the x-ray residuals set a limit on the sensitivity of the analysis,  
932 for if the absolute value of the x-ray residuals of a quadruplet were smaller than the x-ray  
933 residual uncertainties, no conclusion about the correlation could be drawn, like for QL2.P.8  
934 (figure 6.3). This result is reflected in the small x-ray residuals shown in figure 6.1b that  
935 do not reveal a pattern in the relative local offsets across the surface of layer 2. However,  
936 figure 6.3 shows that the x-ray and mean cosmics residuals are centered around zero, as is  
937 expected for a quadruplet with small relative misalignments between layers.

938 There are three patterns in the residuals on the scatter plot explained by geometry. First,  
939 for both datasets the uncertainty in the extrapolated track residuals were larger than the  
940 interpolated track residuals because of the extrapolation lever arm. For the x-ray residuals,  
941 the effect of the lever arm on the uncertainty was direct since the residual was calculated from  
942 a single abstract track; for the mean cosmics residuals it was the widening of the residual  
943 distribution due to the extrapolation lever arm that increased the uncertainty in the fitted  
944 mean of residuals. Second, residuals calculated through extrapolation tend to be larger  
945 because the extrapolation lever arm can produce more extreme values of the track position  
946 on the layer of interest. Third, the points in figure 6.2 are geometrically correlated (e.g.  
947 they seem to be roughly mirrored around the origin). This is expected since the residuals  
948 calculated using a given set of three layers should be geometrically correlated by the local

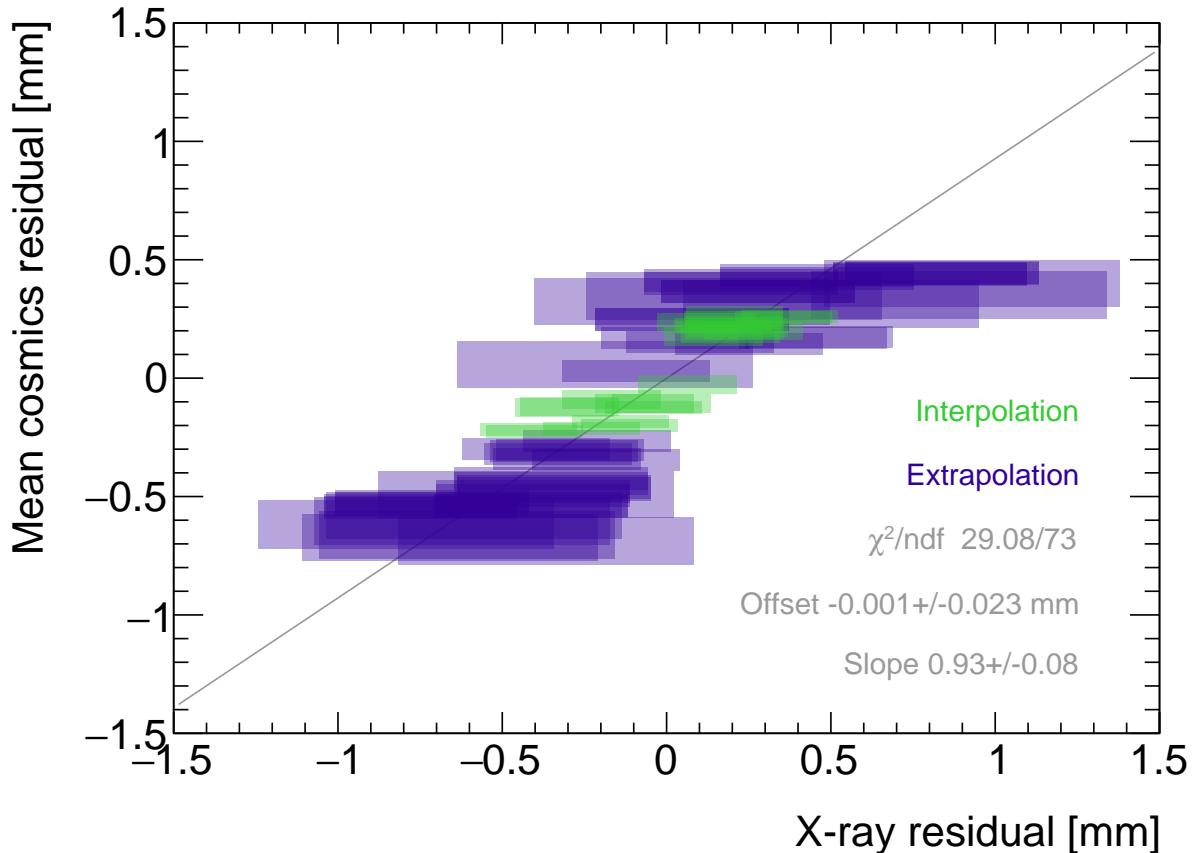


Figure 6.2: Correlation plot between x-ray and mean cosmics residuals for all tracking combinations for QL2.P.11. Each rectangle is centered on an x-ray and mean cosmics residual pair calculated at a given gun position and for a certain tracking combination. The width of the rectangles in  $x$  and  $y$  are the uncertainty in the x-ray and mean cosmics residual respectively. A printer-friendly version of this plot is available in appendix D.

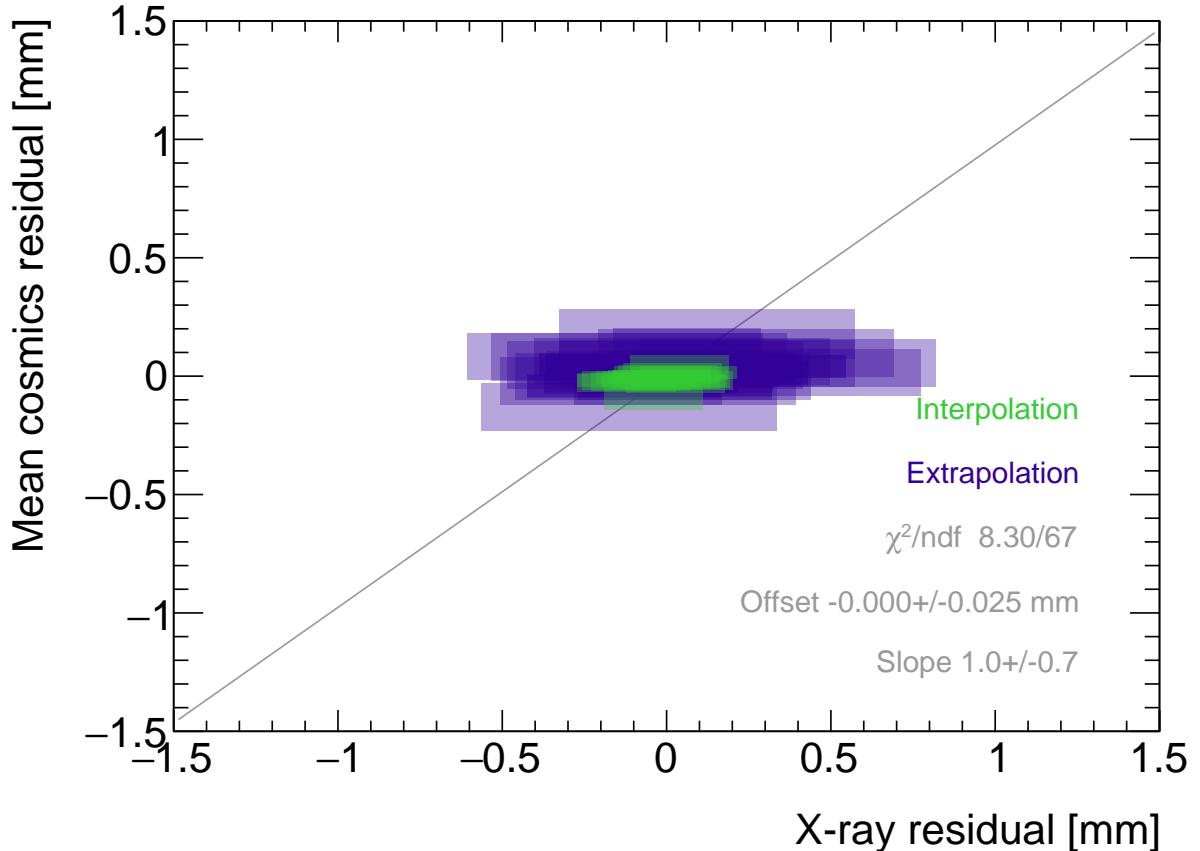


Figure 6.3: Correlation plot between x-ray and mean cosmics residuals for all tracking combinations for quadruplet 2. Each rectangle is centered on an x-ray and mean cosmics residual pair calculated at a given gun position and for a certain tracking combination. The width of the rectangles in  $x$  and  $y$  are the uncertainty in the x-ray and mean cosmics residual respectively. A printer-friendly version of this plot is available in appendix D.

949 offsets on the fixed layers and the layer of interest (the  $d_{local,i}$  on each layer as defined in  
950 equation 4.1).

## 951 6.2 Discussion

952 Several quadruplets were tested for each quadruplet construction geometry built in Canada.  
953 Each quadruplet fell into one of the two categories: residuals large enough to see a correlation,  
954 or residuals too small to see a correlation. Since the x-ray and mean cosmics residuals  
955 were measures of the relative local offsets between the layer and the two reference layers,  
956 quadruplets with the largest relative misalignments had the largest range of residuals. the  
957 correlation plots were an easy visual way to identify quadruplets with large relative misalign-  
958 ments.

959 The most significant limit on measuring the degree of correlation between the x-ray and  
960 mean cosmics residuals was the uncertainty on the x-ray residuals, which stemmed from  
961 the systematic uncertainty of 120  $\mu\text{m}$  in the x-ray beam profile centers used to build the  
962 abstract tracks. For example, in figure 6.3 the uncertainty in the x-ray residuals makes  
963 detecting correlation impossible. The x-ray method was limited primarily by the systematic  
964 uncertainties in the relative alignment of the platforms and the gun, especially the gun angle.

965 The analysis of certain quadruplets was limited by the availability of data. Sometimes,  
966 less than three layers were surveyed for a given x-ray gun position so no residuals could  
967 be calculated. Too few x-ray residuals prevented the analysis from detecting a significant  
968 correlation, should it even be measurable. Often, the analysis of smaller quadruplets (placed  
969 innermost on the wheel) suffered as a result because they had fewer alignment platforms, and  
970 hence gun positions, on their surfaces. The analysis was also limited to certain quadruplets.  
971 The wedges constructed the earliest (typically small wedges) were surveyed when the x-ray  
972 method was still being designed and so have limited x-ray residuals calculated from beam  
973 profiles of lower quality. In addition, not all cosmic muon test sites had enough front end  
974 electronics to collect data on three layers simultaneously, which is the minimum required to  
975 be able to calculate residuals.

976 Nonetheless, the comparison of x-ray and cosmics residuals was really to confirm the x-ray  
977 method's ability to measure local offsets with an independent dataset. The x-ray local offsets  
978 allow the calculation of relative local offsets that have been correlated to the cosmics relative  
979 local offsets. Therefore, the analysis of quadruplets with relative local offsets large enough  
980 to detect a correlation validates the x-ray method's ability to measure local offsets.

981 The potential of using relative local offsets calculated from cosmics data to study relative  
982 alignment between sTGC layers stands on its own. For example, although the x-ray relative

983 local offsets of QL2.P.8 in figure 6.1b do not reveal a pattern, the variation in the cosmics  
984 relative local offsets do. Identifying the pattern is possible because mean cosmics residuals  
985 can be calculated across the entire area and are sensitive to smaller relative local offsets since  
986 their uncertainty is significantly smaller.

987 The advantage of the x-ray dataset over the cosmics dataset is that absolute local offsets  
988 are measurable thanks to the reference frame provided by the alignment platforms. This is  
989 required to measure the position of strips in the ATLAS coordinate system to satisfy the  
990 NSWs' precision tracking goals. The x-ray local offsets are being used to build an alignment  
991 model of strips in each quadruplet. It is compelling to imagine using the cosmics relative  
992 local offsets to improve the model considering their precision and ability to capture effects  
993 across the entire area of the quadruplet.

994 **Chapter 7**

995 **Outlook and summary**

996 The cosmic muon dataset was used to independently confirm the absolute local offsets mea-  
997 sured by the x-ray method. The x-ray offsets are being used to complete the sTGC alignment  
998 scheme of the NSWs: the NSW alignment system monitors the position of alignment plat-  
999 forms on the surface of sTGC wedges, and the x-ray measurements provide the offsets of  
1000 the strip pattern with respect to each alignment platform. The continuation of this anal-  
1001 ysis is detailed next (section 7.1) before summarizing and considering the larger context  
1002 (section 7.2).

1003 **7.1 Outlook**

1004 Next all quadruplets with suitable cosmics and x-ray data should be surveyed to flag anom-  
1005 lous quadruplets (as a first step). If a quadruplet’s correlation plot like figure 6.2 or 6.3  
1006 reveals an unexpected correlation or has a large scatter, it would indicate an issue with ei-  
1007 ther the cosmics or x-ray data collection to be investigated further. The uncertainty in each  
1008 set of tracking points would inform the interpretation of the anomaly. Then, the quality of  
1009 the correlation should be evaluated over all quadruplets instead of individually.  
1010 For now, the correlation for the individual quadruplets tested support the use of the x-ray  
1011 data to build an alignment model [9]. Work on creating an alignment model is ongoing.  
1012 Currently, the algorithm compares the  $y$ -position of a local group of strips at each x-ray gun  
1013 position as measured by the x-ray and CMM methods in a fit to extract a global slope ( $m$ )

1014 and offset ( $b$ ) per layer,  $i$ , where the  $\chi^2$  is given by equation 7.1.

$$\chi^2 = \frac{[dy_{cmm,corr} - dy_{xray}]^2}{\delta dy_{xray}^2 + \delta dy_{cmm,corr}^2}, \quad (7.1)$$

1015

$$dy_{cmm,corr} = y_{cmm} + b_i + m_i x - y_{nom} \quad (7.2)$$

1016 Here,  $dy$  refers to the corrected CMM and x-ray local offsets, and  $\delta dy$  refers to their re-  
1017 spective uncertainties. The CMM measurements were taken before the cathode boards were  
1018 assembled into quadruplets, so alignment parameters for the given layer were extracted from  
1019 the  $\chi^2$  fit by stepping the corrected CMM  $y$ -position towards the x-ray  $y$ -position by adjust-  
1020 ing the layer's slope and offset parameters. The plan is that the alignment parameters will  
1021 be provided to the ATLAS experiment's offline software to reconstruct muon tracks from the  
1022 NSWs' sTGCs. The large uncertainty on the x-ray local offsets (120  $\mu\text{m}$ ) and the sparseness  
1023 of the measurements means that including input from other characterization datasets could  
1024 reduce the uncertainty on the alignment model parameters.

1025 The uncertainty in the mean cosmics residuals was smaller than the desired position reso-  
1026 lution of the sTGCs, so they provide relevant information about strip positions. Moreover,  
1027 they can be calculated over the entire area of the quadruplet instead of at specific posi-  
1028 tions. It would be great to use the cosmics residuals as input to calculate and reduce the  
1029 uncertainty on the alignment parameters. Since mean cosmics residuals can only provide  
1030 relative alignment information, one idea would be to use them to constrain the fit of the  
1031 alignment parameters. In this case, the alignment parameters would need to be fitted on all  
1032 layers at once, and the shifting  $y$ -positions on each layer forced to create an abstracted track  
1033 residual equal to the local mean cosmics residual (within uncertainty) for each x-ray point.  
1034 Or, instead of constraining the fit, it could be penalized if the resulting parameters do not  
1035 result in abstracted track residuals equal to the mean cosmics residuals within uncertainty.  
1036 Some work on using the three datasets at once in a fit has been started.

## 1037 7.2 Summary

1038 The LHC [1] will be at the energy frontier of particle physics for at least the next decade,  
1039 making it a unique tool with which to study particle physics. With the HL-LHC [2], high  
1040 statistics on rare particle physics processes will enable more precise measurements of param-  
1041 eters of the Standard Model and increase the sensitivity to signatures of physics beyond the  
1042 Standard Model [4]. To capitalize on the increased collision rate, the NSWs of the ATLAS  
1043 experiment must be replaced to keep the triggering and tracking performance [5].

1044 Small-strip thin gap chambers are gas ionization chambers optimized for a high rate envi-  
1045 ronment [5]. Using the pad electrodes to define a region of interest makes it possible to get  
1046 track segments of  $\sim 1$  mrad angular resolution quickly, which will be used as input to check  
1047 if a collision originated from the interaction point and should be triggered on or not [5, 7].  
1048 sTGCs are also able to provide better than  $100 \mu\text{m}$  position resolution on each detector plane  
1049 to fulfill precision offline tracking requirements [6].

1050 Ultimately, the positions of the sTGC strip electrodes need to be known in ATLAS to within  
1051  $\sim 100 \mu\text{m}$  so that they can deliver the required position resolution. The ATLAS alignment  
1052 system will position alignment platforms on the surface of the sTGC wedge, and an alignment  
1053 model will be used to position the strips with respect to the alignment platforms [5]. Input  
1054 to the alignment model comes from the datasets used to characterize the quadruplets. The  
1055 x-ray method [9] is used to measure offsets of strips from their nominal position to achieve  
1056 this goal. The alignment model could be built on x-ray data alone, but the sparseness of  
1057 and large uncertainty on the local offsets mean that the alignment model could benefit from  
1058 more input. Comparing the x-ray offsets to the CMM data [8] allows the effect of inter-layer  
1059 misalignments to be isolated and increases the input to the alignment model.

1060 The cosmics dataset was used to confirm the local offsets measured with the x-ray gun. It  
1061 provides relative local offsets between sTGC strip layers. The 2D visualizations of relative  
1062 local offsets allow personnel to quickly identify areas of misaligned strips and make hypothe-  
1063 ses of the physical origin of those misalignments. The correlation seen between the x-ray and  
1064 cosmics relative local offsets in quadruplets with large relative misalignments both confirms  
1065 the validity of the x-ray local offsets and again is a quick way to identify quadruplets with  
1066 large misalignments. Moreover, the mean of track residuals in an area is a robust estimation  
1067 of the relative local offset, as shown by the estimation of systematic uncertainties; the relative  
1068 local offsets for all two-fixed layer reference frames do not change by more than  $100 \mu\text{m}$  given  
1069 variation in data collection conditions and analysis algorithms. The cosmics relative local  
1070 offsets are therefore relevant input for alignment studies and could improve the alignment  
1071 model that will position each strip.

1072 Achieving the required position resolution on each layer of the NSWs in the particle track  
1073 bending plane achieves the design momentum resolution for muons ejected towards the end-  
1074 caps of ATLAS. Muons are important signatures of electroweak and Higgs sector events  
1075 of interest for the ATLAS Collaboration’s future physics goals [5]. Being the second of two  
1076 tracking technologies on the NSWs, an effective alignment model of sTGC quadruplets layers  
1077 is a necessary part of making the NSWs redundant for 10 or more years of recording collisions  
1078 in the High Luminosity era of the LHC.

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<sup>1240</sup> APPENDICES

1241 **Appendix A**

1242 **Uncertainty in cluster positions**

1243 **A.1 Cluster definition**

1244 A cluster is a series of contiguous strip channels on a layer with non-zero amplitude, all  
1245 part of the same trigger and having the same event number [49]. Clusters result from the  
1246 drift of ionization products generate in the ionization avalanche caused by a muon [44]. The  
1247 peak-detector-output (PDO) of the signal on each strip of a cluster is fit with a Gaussian.  
1248 The y-position of a particle as it passed through the layer is mean of the cluster, referred to  
1249 here as the hit position.

1250 **A.2 Effect of fit algorithm on cluster mean**

1251 The clusters were fit with Guo's method [56] and Minuit2 for ROOT [55]. The difference in  
1252 cluster means between the two algorithms is shown in figure A.1.

1253 The RMS of the distribution in figure A.1 is 57  $\mu\text{m}$ , which is much larger than the statistical  
1254 uncertainty in the mean for the Minuit2 algorithm, which peaks around 7  $\mu\text{m}$ . An RMS of  
1255 60  $\mu\text{m}$  is common for data taken with most quadruplets at 3.1 kV. Therefore, the uncertainty  
1256 in the y-hit positions is assigned 60  $\mu\text{m}$ .

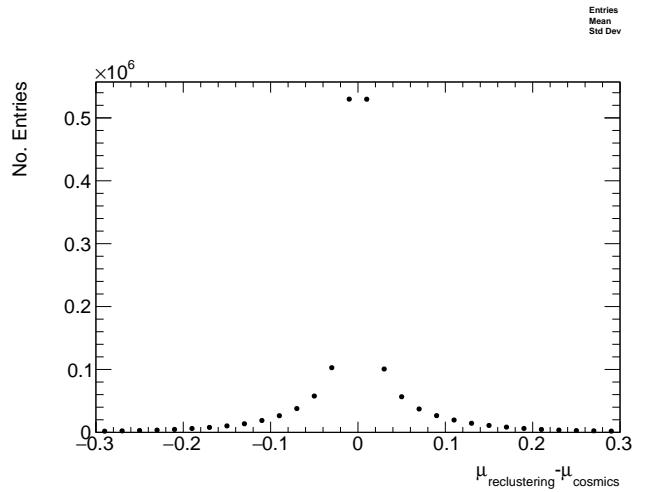


Figure A.1: The difference between cluster means calculated with Guo's method [56] in `tgc_analysis/CosmicsAnalysis` and `Minuit2` for `ROOT` [55] in `strip_position_analysis/ReClustering` for data collected with QL2.P.8 at 3.1 kV.

1257 **A.3 Effect of uncertainty in cluster mean on track residuals**

1258

1259 The uncertainty assigned to the hit position affected the uncertainty in the extrapolated/interpolated  
1260 position of the track, and in the residuals. The bin size of the residual distributions was set  
1261 to 200  $\mu\text{m}$  because that was the uncertainty in the residuals calculated from the tracks with  
1262 the least favourable geometry (like tracks built from hits on layers 1 and 2 and extrapolated  
1263 to layer 4).

1264 **Appendix B**

1265 **Study of cosmics for alignment  
1266 analysis statistical uncertainty**

1267 Typically, one million triggers (cosmic muon events, noise, photons and  $\delta$ -rays) were collected  
1268 for each Canadian quadruplet at McGill University, resulting in roughly half the number of  
1269 viable tracks after cuts. For QS3.P.18, 3.5 million triggers were collected. To gauge the  
1270 sensitivity of the analysis to the available statistics, partitions of this data with each with  
1271 a different number of triggers were analyzed separately. Ultimately, the quantity of interest  
1272 was the gaussian mean of the residual distribution in regions of interest, so the peak in the  
1273 distribution of the statistical uncertainty in the residual means for each area of interest for  
1274 a specific tracking combination was used to gauge the quality of the analysis. How the peak  
1275 in the residual mean uncertainty distribution changes with the number of triggers is shown  
1276 in figure for tracks on layer 1 built from layers 3 and 4 [B.1](#).

1277 The uncertainty is already around 20  $\mu\text{m}$  at 1 million triggers, suitable for distinguishing  
1278 differences in offsets of order 50  $\mu\text{m}$  as required. Although increased statistics could decrease  
1279 the statistical uncertainty, it is not required for the goals of this analysis. Moreoever, the  
1280 systematic uncertainty is around 50  $\mu\text{m}$  and the systematic uncertainty on the x-ray residuals  
1281 is 150  $\mu\text{m}$  so the statistical uncertainty of 20  $\mu\text{m}$  is nearly negligible.

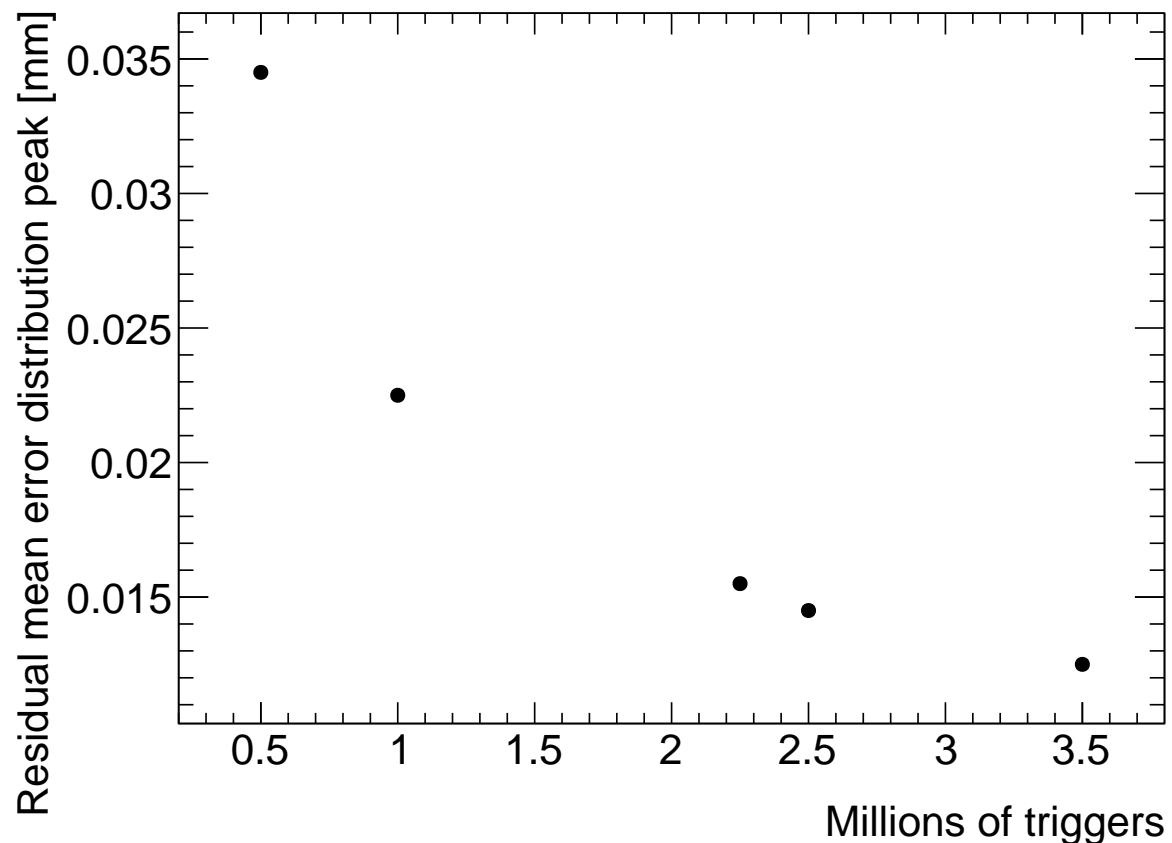


Figure B.1: How the peak of the distributions of uncertainties in the residual means in regions of interest for tracks on layer 1 built from layers 3 and 4 changed with the number of triggers used in the analysis. The distribution falls off as  $\frac{1}{\sqrt{N}}$  as expected.

## <sup>1282</sup> Appendix C

# <sup>1283</sup> Study of systematic uncertainties <sup>1284</sup> when using cosmics data for <sup>1285</sup> alignment studies

### <sup>1286</sup> C.1 Residual distribution fit function

<sup>1287</sup> The distribution of residuals should be modelled by a double gaussian fit[49]:

$$G(r) = A_s \exp \left[ \frac{-(r - \mu)^2}{2\sigma_s^2} \right] + A_b \exp \left[ \frac{-(r - \mu)^2}{2\sigma_b^2} \right] \quad (\text{C.1})$$

<sup>1288</sup> where  $r$  is the residual,  $A$  is the gaussian amplitude,  $\mu$  is the gaussian mean,  $\sigma$  is the  
<sup>1289</sup> gaussian sigma, and the subscripts  $s$  and  $b$  stand for signal and background respectively.  
<sup>1290</sup> One gaussian captures the real (signal) tracks and the other captures the tracks built from  
<sup>1291</sup> noise (background). The gaussian with the smaller width is identified as the signal.

<sup>1292</sup> A single gaussian fit failed less often than a double gaussian fit. The gaussian fits were  
<sup>1293</sup> performed by initially estimating the amplitude to be 100 tracks, the gaussian mean to be  
<sup>1294</sup> the histogram mean, and gaussian  $\sigma$  to be the RMS. The fit range was restricted to  $\pm 1$  RMS  
<sup>1295</sup> from the histogram mean. The modification helped the gaussian fit capture the signal peak.  
<sup>1296</sup> An example residual distribution is shown in figure C.1.

<sup>1297</sup> For all residual distributions in 100 mm by 100 mm bins on layer 4 built from hits on layers 1  
<sup>1298</sup> and 2, the difference in gaussian and double gaussian means and  $\sigma$ 's is shown in figure C.2.  
<sup>1299</sup> Since the RMS of the residual mean differences distribution is less than 50  $\mu\text{m}$  the gaussian

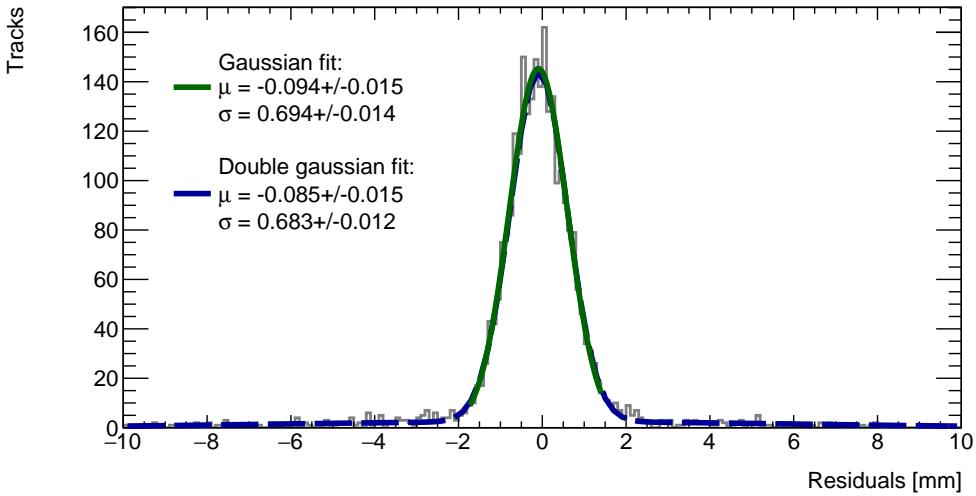


Figure C.1: Residual distribution for tracks on layer 4 built from hits on layers 1 and 2 for  $x \in [-3.00, 97.00]$ ,  $y \in [394.60, 494.60]$  mm for QL2.P.8 fit with a double gaussian and a single gaussian in a range of  $\pm 1$  RMS from the histogram mean.

1300 fit gave the same result within the required precision. Moreover, this is for the tracking  
1301 combination with the worst extrapolation lever arm and the widest distribution of mean  
1302 differences; the interpolation combinations have narrower distributions.

1303 The gaussian  $\sigma$  should be larger than the double gaussian  $\sigma$  because the gaussian distribution  
1304 includes the effect of the noise tracks with large residuals, while the double gaussian models  
1305 signal and background residuals separately. For this analysis, only the residual mean was  
1306 important, so the systematic overestimate of the signal  $\sigma$  in the gaussian fit shown on the  
1307 right of figure C.2 was allowed.

## 1308 C.2 Cosmic muon data collection voltage

1309 Cosmic muon data was collected at 2.9 kV and 3.1 kV because although 2.9 kV is closer to  
1310 the operating conditions the chambers will be subject to in ATLAS, the extra gain provided  
1311 by operating at 3.1 kV increased the signal to noise ratio for pad signals. Also, the tracking  
1312 efficiency was higher with data collected at 3.1 kV. The difference in gain affected the relative  
1313 population of clusters of different sizes, which in turn affected the uncertainty in the strip hit  
1314 positions on each layer, the uncertainty in the track positions and the residual distributions.  
1315 The residual distributions for 3.1 kV data are narrower, as shown in figure C.3.

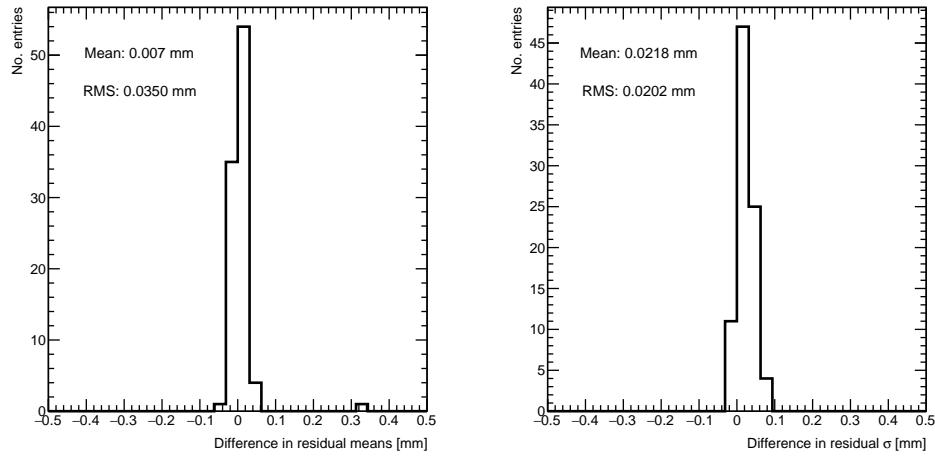


Figure C.2: Difference in residual distribution means and  $\sigma$ 's for a gaussian and double gaussian fit, for all residual distributions in 100 mm by 100 mm bins on layer 4 built from hits on layers 1 and 2 for QL2.P.8.

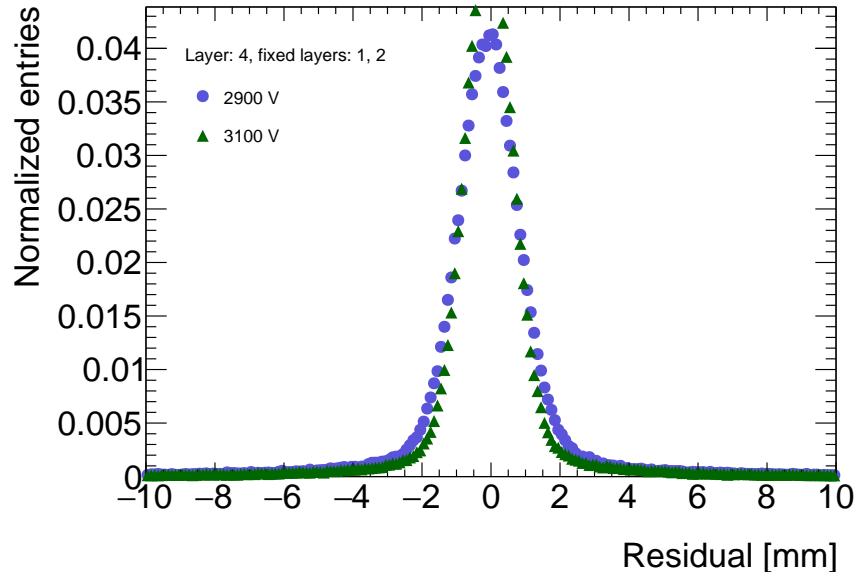
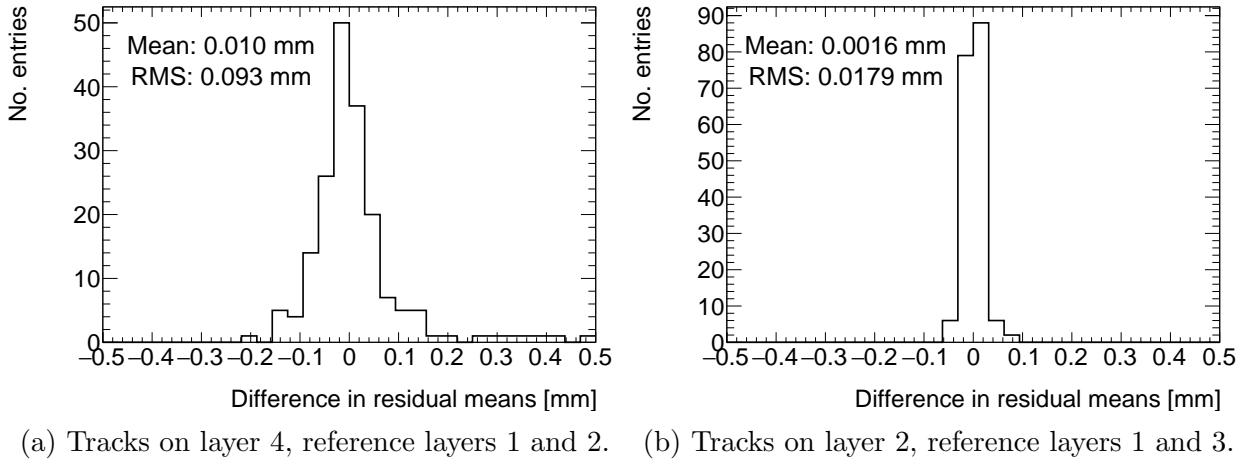


Figure C.3: Residual distribution for tracks on layer 4 built from hits on layers 1 and 2 for QL2.P.8 for data collected at 2.9 kV and 3.1 kV.



(a) Tracks on layer 4, reference layers 1 and 2. (b) Tracks on layer 2, reference layers 1 and 3.

Figure C.4: Difference in residual means for data collected with QL2.P.8 at 2.9 kV and 3.1 kV respectively in 100 mm by 100 mm bins for (a) tracks on layer 4 built from hits on layers 1 and 2 and (b) tracks on layer 2 built from hits on layers 1 and 3.

1316 Neither dataset is better for calculating the mean of residuals in a given area, so a systematic  
 1317 uncertainty can be assigned based on the difference in residual means calculated for 2.9 kV  
 1318 and 3.1 kV data; namely, the systematic uncertainty was approximated as the RMS of the  
 1319 residual mean difference distribution. Data taken with QL2.P.8 was used to estimate the  
 1320 RMS, as in figure C.4a.

1321 Tracks built from hits on layers 1 and 2 and extrapolated to layer 4 have the worst lever arm  
 1322 and hence the most uncertainty. The width of the distribution for geometrically favourable  
 1323 tracks are much narrower. The narrowest width of the residual mean difference distribution  
 1324 is for tracks on layer 2 built from hits on layers 1 and 3 (see figure C.4b).

1325 Therefore, for each tracking combination, a systematic uncertainty equal to the RMS of the  
 1326 residual mean difference distribution was assigned.

### 1327 C.3 Cluster fit algorithm

1328 To ensure that changing the cluster fitting algorithm like in appendix A would not change  
 1329 the calculated mean of residuals in each region of interest significantly, the residual means  
 1330 were compared in both cases. The distribution of the difference in residual means is plotted  
 1331 in figure C.5 for the tracking combination with the worst extrapolation lever arm.

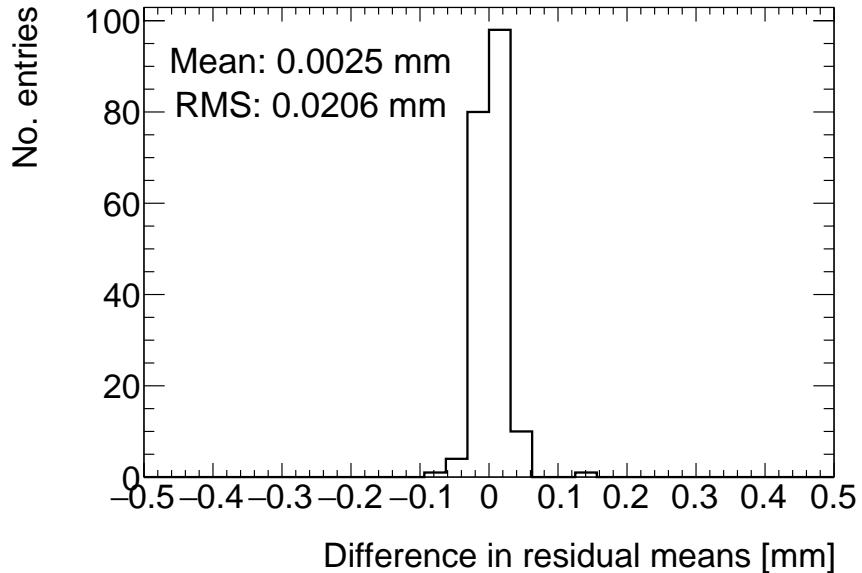


Figure C.5: Difference in residual means when the cluster fit algorithm is `Minuit2` [55] versus Guo’s method [56] for tracks on layer 4 built from hits on layers 1 and 2 for QL2.P.8.

1332 The other tracking combinations had smaller RMS values. Differences on the order of 50  $\mu\text{m}$   
 1333 are important, so figure C.5 shows that the clustering algorithm had a small but notable  
 1334 effect. Therefore, the RMS for each tracking combination will be used to add a systematic  
 1335 uncertainty on the residual means.

## 1336 C.4 Differential non-linearity

### 1337 Definition

1338 In this context, differential non-linearity (DNL) is when the reconstructed cluster mean is  
 1339 biased by the fit of the discretely sampled PDO distribution over the strips. The bias depends  
 1340 on the relative position of the avalanche with respect to the center of the closest strip. For a  
 1341 summary of DNL, refer to page 40 of Lefebvre’s thesis [49] and for an example application,  
 1342 refer to [6].

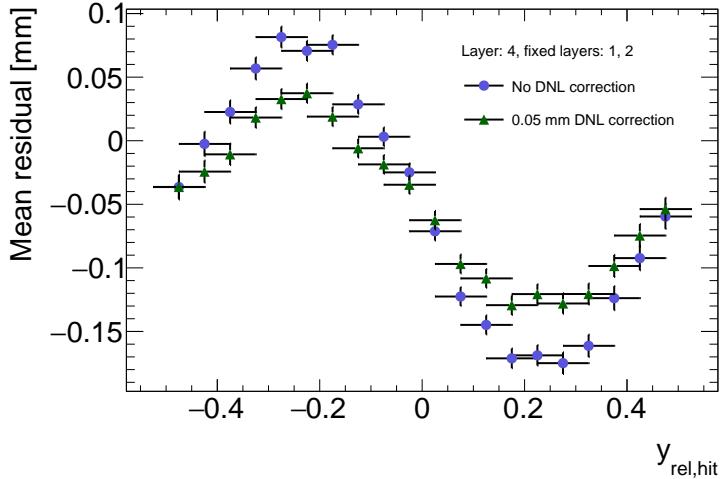


Figure C.6: Effect applying a 50  $\mu\text{m}$  DNL correction to the cluster means on the residual vs  $y_{rel}$  distribution for tracks built from layers 1 and 2 and extrapolated to layer 4 for QL2.P.8.

1343 **Application and effect of DNL**

1344 The cluster mean was corrected for DNL using the equation:

$$y' = y + a \sin(2\pi y_{rel}) \quad (\text{C.2})$$

1345 where  $y$  is the cluster mean,  $y_{rel}$  is the relative position of the cluster mean with respect to  
1346 the strip's center,  $a$  is the amplitude of the correction, and  $y'$  is the corrected cluster mean.  
1347 The amplitude can be derived by comparing the reconstructed hit position to the expected  
1348 hit position, as done in Abusleme, 2016 [6]. With cosmic muons, there is no reference hit  
1349 position to compare to, so track residuals were used as a proxy [49]. The hallmark of the DNL  
1350 effect is the periodic pattern in the residual versus  $y_{rel}$  profile, and the effect of correcting  
1351 the cluster means using an amplitude of 50  $\mu\text{m}$  is shown in figure C.6. An amplitude of  
1352 50  $\mu\text{m}$  was based on Lefebvre's estimate of the DNL amplitudes by layer, quadruplet and  
1353 cluster size using exclusive cosmic muon tracks in `tgc_analysis/CosmicsAnalysis`. Little  
1354 variation was seen in the amplitude parameters with respect to the quadruplet tested, the  
1355 layer and the cluster size so a universal correction was used.

1356 Although the correction is not large enough in this case, the figure shows that the correction  
1357 does reduce the DNL effect. Slightly better performance is seen in the interpolation tracking  
1358 combinations where the quality of the residuals is better. DNL corrections for cosmic muon  
1359 data are difficult because the DNL effect is obscured by the effect of misalignments and

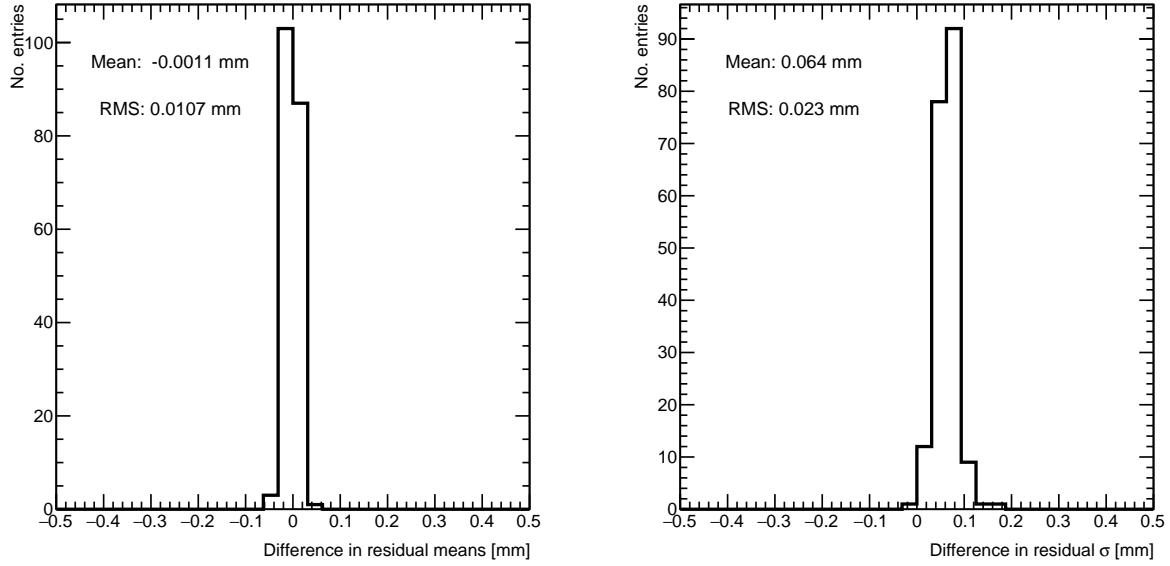


Figure C.7: Difference in residual distribution means and  $\sigma$ 's with and without DNL correction for residuals on layer 4 from reference layers 1 and 2 for QL2.P.8.

1360 noise. Misalignments cause the center of the sine pattern in figure C.6 to be shifted off of  
 1361 zero, since the mean of residuals is shifted.

1362 In figure C.7, it is apparent that the effect of the DNL correction on the mean of the  
 1363 residual distribution in 100 mm by 100 mm areas is on the order of micrometers in the worst  
 1364 extrapolation case. Although the  $\sigma$ 's of the residual distributions shrink with the DNL  
 1365 correction, the mean is the parameter of interest. Therefore, for this analysis DNL was not  
 1366 corrected for.

1367 The  $\sigma$ 's of the residual distributions do shrink with the DNL correction but not so much to  
 1368 affect the residual means, which are the important parameter for this analysis. Therefore,  
 1369 since the effect of the DNL correction is negligible, it was not pursued further.

<sub>1370</sub> Appendix D

<sub>1371</sub> Printable plots

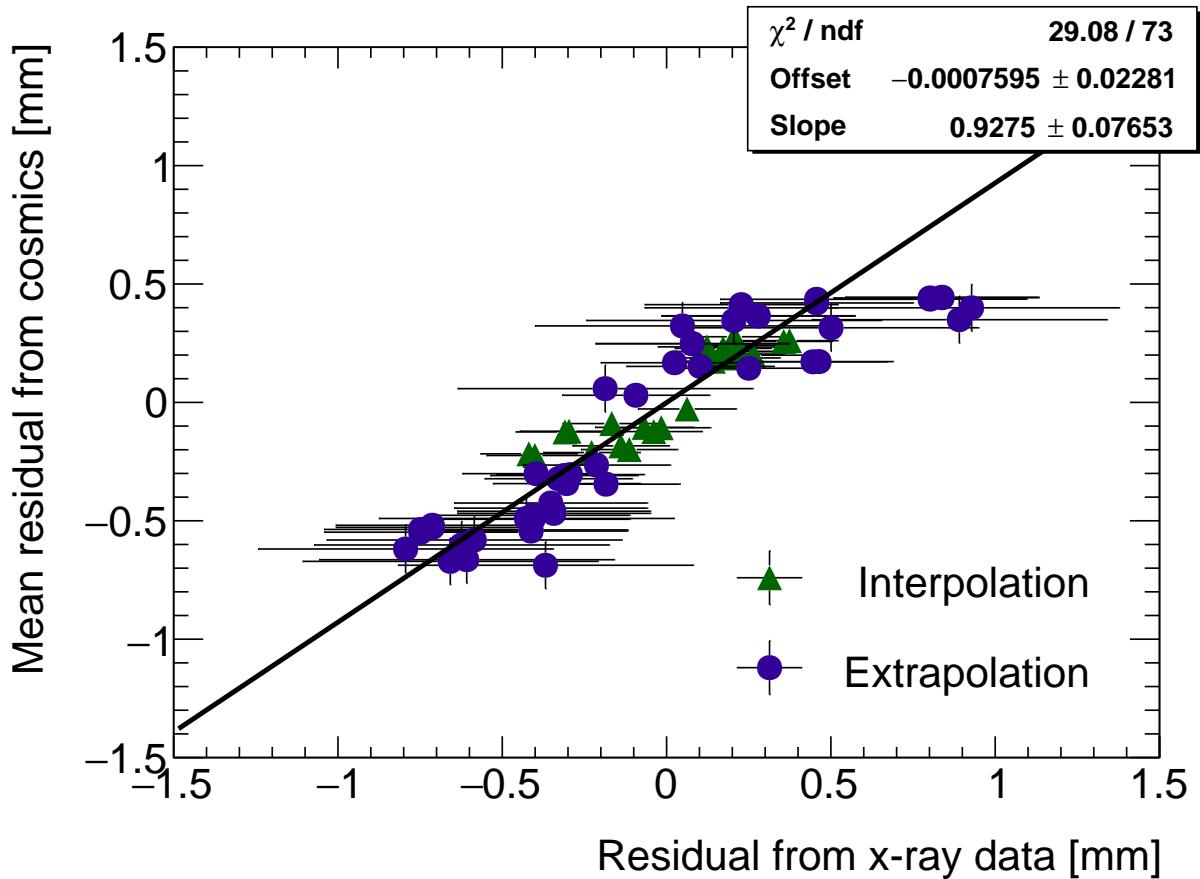


Figure D.1: Correlation plot between x-ray and cosmics residuals for all tracking combinations for QL2.P.11. Each rectangle is centered on an x-ray and mean cosmics residual pair. The width of the rectangles in  $x$  and  $y$  are the uncertainty in the x-ray and mean cosmics residual respectively. This is a printable version of figure 6.2 in section 6.1.

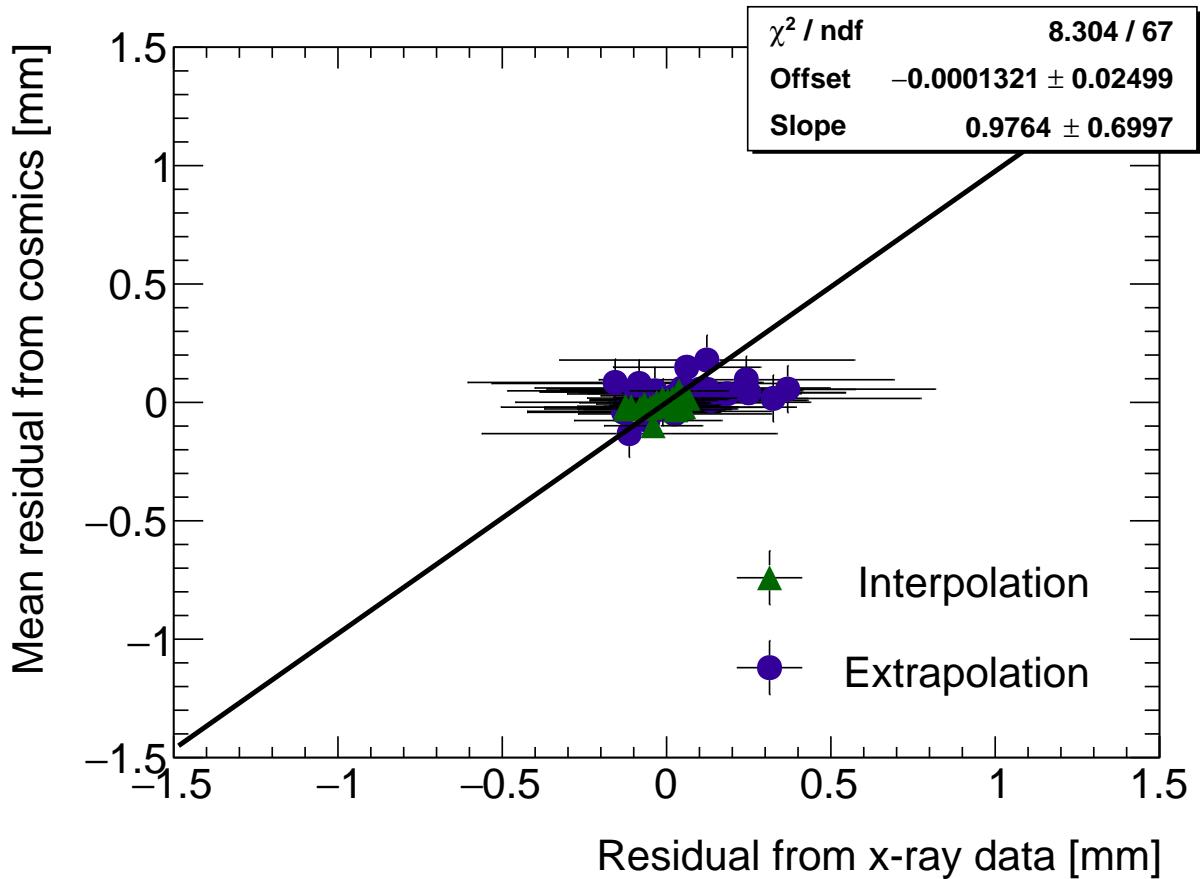


Figure D.2: Correlation plot between x-ray and cosmics residuals for all tracking combinations for QL2.P.8. Each rectangle is centered on an x-ray and mean cosmics residual pair. The width of the rectangles in  $x$  and  $y$  are the uncertainty in the x-ray and mean cosmics residual respectively. This is a printable version of figure 6.3 in section 6.1.