IPP Summer Student Fellowship Report

Adding McGill Cosmic Data to the Analysis of the Strips Position in ATLAS NSW sTGC

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Abstract

In the optic of observing phenomena beyond the Standar Model of particle physics, the luminosity and the energy of the Large Hadron Collider (LHC) at the CERN will be increased in the next few years (the Run 3 of the HiLumi LHC project will start in 2022). Some detectors part of LHC's experiments are going to be replaced in order to detect more energetic particles and increase the precisicion of measurements. This is the case for the Small Wheels, muon detectors of the ATLAS experiment, that will be replaced by the New Small Wheels (NSW). The NSW use a technology called small-strip thin gap chamber (sTGC), an ionization chamber, and are made of four identical layers glued together that detect the position of a particle passing through the detector (quadruplets). For each layer, the strips give the y measurement of the position of the particle with respect to the CERN's coordinate system. This report presents an analysis using three datasets (CMM measurements, X-ray measurements and cosmic-ray measurements) to find the position of each strip and the misalignments that occured during the construction of the quadruplets. The results of this analysis are not conclusive since the addition of cosmic-ray measurements to an analysis that uses the two other datasets does not lead to adequate values for the layers' misalignment.

Résumé

Dans l'optique d'observer des phénomènes non expliqués par le modèle standard des particules, la luminosité et l'énérgie du Grand collisioneur de hadrons (LHC) du CERN vont être augmentées au cours des prochaines années (la troisième partie de prises de mesures du projet HiLumi LHC commencera en 2022). Certains détecteurs des expériences faisant partie du LHC devront ainsi être remplacés afin de détecter des particules plus énergétiques et d'améliorer la précision des mesures. C'est le cas des petites roues, des détecteurs de muons de l'expérience ATLAS, qui seront remplacées par les nouvelles petites roues (NSW). Les NSW utilisent une technologie appelée *small-strip thin gap chamber* (sTGC) qui agit comme une chambre d'ionisation, et sont composées de *quadruplets*, un assemblage de quatre couches identiques qui détectent chacunes la position d'un muon qui traverse le détecteur. Dans chaque couche, les *strips* donnent l'information sur la composante y de la détection par rapport au système de coordonnées du CERN. Ce rapport présente une analyse utilisant trois différents jeux de données, soient les données CMM, les données de rayons-x et les données de rayons cosmiques, pour mesurer la position de chacun des *strips* et évaluer les désalignments apparus lors de l'assemblage des *quadruplets*. Les résultats de cette analyse ne sont pas concluants puisque l'ajout des données de rayons cosmiques à une analyse déjà existante utilisant les deux autres jeux de données ne semble pas converger vers des valeurs préscises de désalignement.

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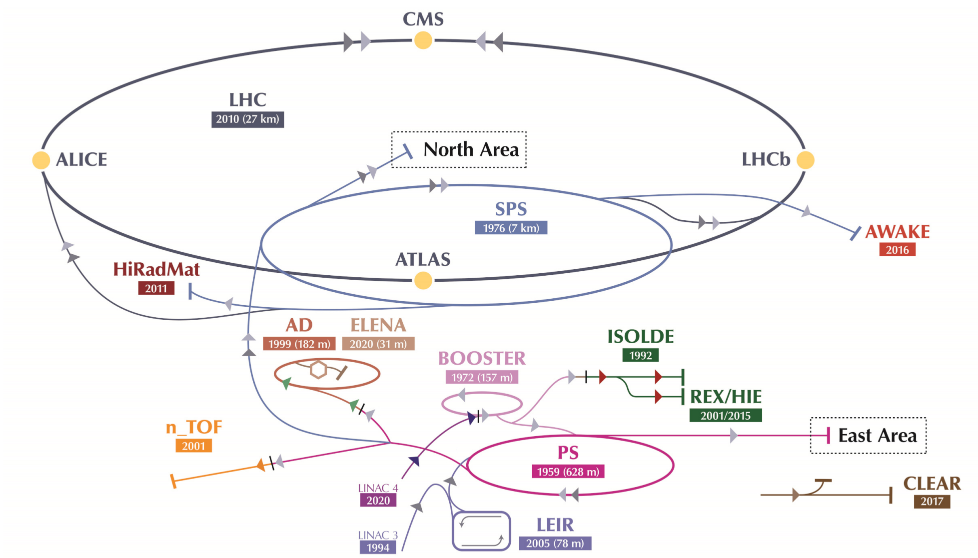


Figure 1.1: *The CERN accelerator complex. The ATLAS experiment (yellow point) is part of LHC (black circle), an high-energy particle collider. [4]*

1 Introduction

Although it gives a good description of the subatomic world, the Standard Model of particle physics (SM) still doesn't explain some phenomena and aspects of the universe such as dark matter. In fact, the SM gives us information of only 5% of the whole universe, an hypothesis suggesting that the unknown universe would be composed of particles beyond the SM (i.e. not included in the SM, [9]). In order to find out those new particles, experiments such as ATLAS, part of the Large Hadron Collider (LHC) at CERN (European Organization for Nuclear Research, see Figure 1.1), aim to concentrate a huge quantity of energy at a specific point in space by colliding high-energy particles. The more energy is concentred in a single point and the higher is the number of collisions, the more unknown high-energy particles could be created and the more the measurements would be accurate. With the objective of finding out new types of particles, the energy (speed of the particles) and the luminosity (number of particles per area per second) of the LHC need to be increased. The High-Luminosity LHC project (HiLumi) will double the energy of the LHC and multiply by ten its luminosity compared to the levels available in 2011 ([2], see Figure 1.2 for the planning of the project). The increase of energy and luminosity at LHC will force the detectors of the experiments (ATLAS among others) to be upgraded to collect more precise measurements.

In ATLAS, the product of the collision of high-energy particles is analyzed by a large number of detectors, different detectors measuring different types of particles (see Figure 1.3). The Small Wheel (SW) is a muon detector part of ATLAS. During ATLAS experiment Phase-1 upgrade (long shutdown 2 of HiLumi), this detector will be replaced by the New Small Wheel (NSW) to increase tracking ability and inputing track information to trigger. Before the installation of the NSW at LHC, the charachterization and the testing of this detector are essential in order to obtain appropriate measurements.

Figure 1.2: *The High Luminosity LHC project planing. From 2011 to the end of the project, the energy of the particles would have been doubled and the luminosity multiplied by ten. The NSW will be installed during ATLAS experiment Phase-1 upgrade (LS2). [2]*

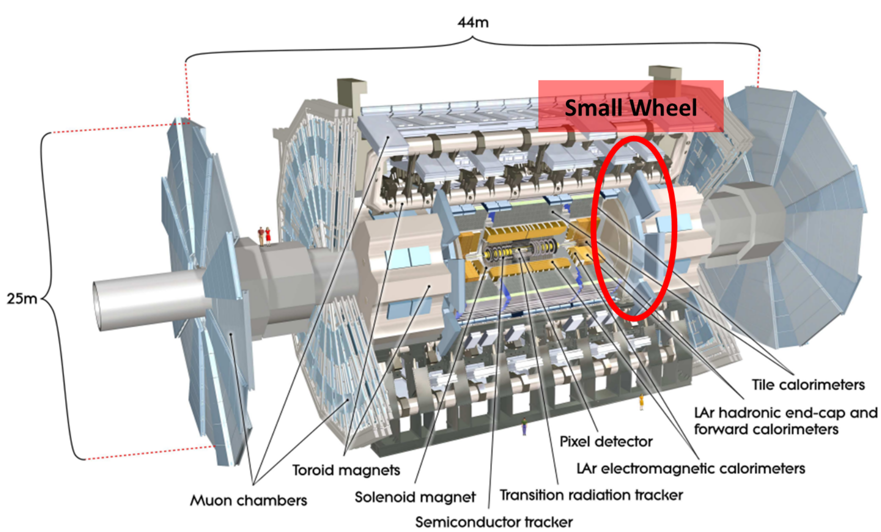


Figure 1.3: *The ATLAS experiment. The collision between beams of particles happens at the center of the detector and the created particles are detected by various instruments. The future emplacement of one of the NSW is shown in red. [5]*

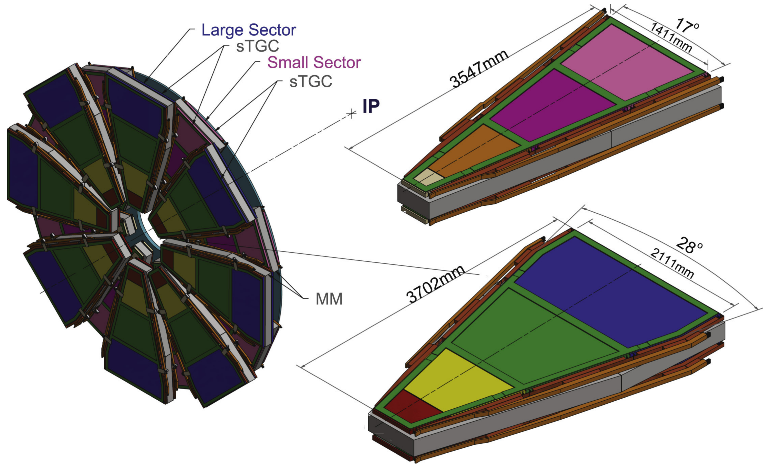


Figure 1.4: *Schema of the New Small Wheel. sTGC are a technology used in this muon detector. [1]*

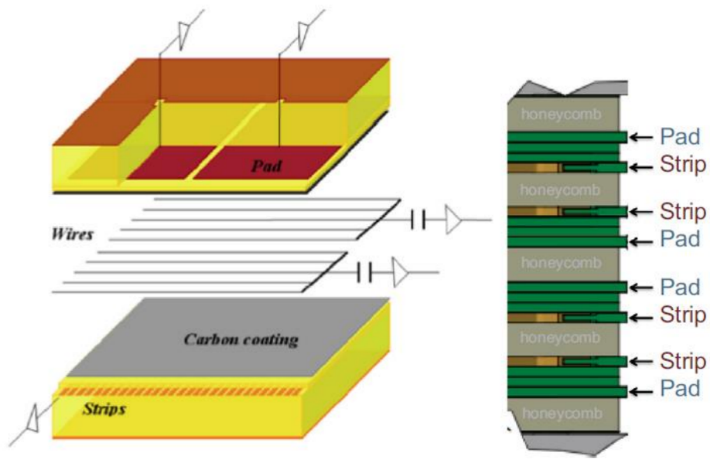


Figure 1.5: *Components of a layer of an sTGC. The pad, the wires and the strips give the position of the measurement. [1]*

The NSW is composed of eight large sectors and eight small sectors disposed in a circle (see Figure 1.4). This detector uses a technology called small-strips thin gap chambers (sTGC) that we can describe as a gas ionization chamber. When a charged muon passes through a layer of the detector, it ionizes the gas (mixture of n-pentane and carbon dioxyde) and creates an electric field that is detected by three different components (i.e. pad, wires and strips), each of them giving information on the position of the measurement. The small and large sectors are made of trapezoidal quadruplets, a superpostion of four layers (see Figure 1.5). In order to reconstruct the path of the particle within the detector, it is important to know precisely the position of each of the components. This project focused mostly on the position of the strips, that give the y value of the measured position according to CERN's system of coordinates [3].

This report presents the analysis of the position of each strips of sTGC's quadruplet

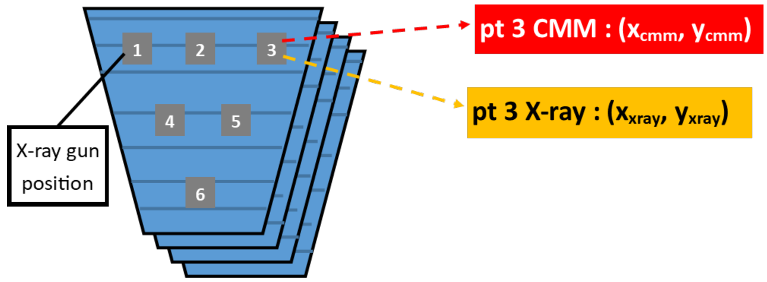


Figure 2.1: *Schematic representation of x-ray gun positions along the surface of a quadruplet. For each x-ray points, there is a set of coordinates for CMM measurements* (x_{cmm}, y_{cmm}) *and another for x-ray measurements* (x_{xray}, y_{xray}).

using different datasets. In Section 2, we explain the method that we took to achieve this goal. We present our results in Section 3, and in Section 4, we discuss the problems we have been facing and future challenges related to the analysis.

2 Methodology

2.1 CMM data

Before the construction of the quadruplet, each layer is manufactured separately. The strip-board is constructed in such a way that the strips are parallel to each other, and the strip-board, the two cathode boards and the pad-board are assembled aiming to be perfectly aligned. Nevertheless, some misalignments occurs during the construction of the layer and the strips are not are not exactly at the position they were designed to be. Thus, the measured position of a particle would be wrong if these misalignments are not considered. Quality control (QC) tests are performed on the strip-boards: the real position of each strip is measured by the coordinates measuring machine (CMM) and is taken into account in the correction of the measured particle position. When each layer of a given quadruplet is rightly constructed, they can be glued together to form the quadruplet.

2.2 X-ray data

After the step of construction, the quadruplets are sent at CERN where other QC tests can be performed. At some precise points along the surface of the quadruplet are sent x-ray (see Figure 2.1). Those x-rays ionize the gas and produce an electric field detected by the components. For each layer of the quadruplet and for each x-ray point, we obtain a y value for the detected position, y_{xray}. Moreover, for the same layer, we find the y value of the measurement in respect to CMM data, y_{cmm}, for each x-ray point.

2.3 Misalignements

For each x-ray point of a given layer, we obtain a definite y_{cmm} and y_{xray}. Nevertheless, these two values might not be the same because some misalignments can occur during the construction of the quadruplet. For this reason, we consider two types of misalignment: an

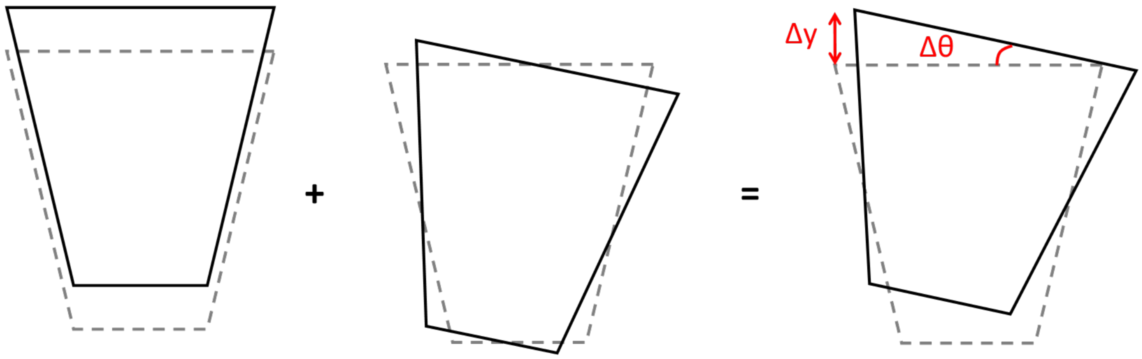


Figure 2.2: *The misalignments occuring during the quadruplets' construction considered in the analysis. For each layer, there is a definite offset and a definite slope.*

offset (Δy) and a slope ($\Delta\theta$) (see Figure 2.2). Thus, by correcting y_{cmm} with a slope and an offset, we should obtain a value of y'_{cmm} identical to y_{xray}. This correction is shown at the Equation 1, where x is the x position of the measurment according to the system of coordinates used at CERN [3].

$$y'_{cmm} = y_{cmm} + \Delta y + \Delta\theta \cdot x \tag{1}$$

I has to be noted that even if we modify the y position of the CMM measurements to obtain y'_{cmm} here, the y position of the x-ray measurements could be modified (y'_{xray}) without changing the values of fitted parameters.

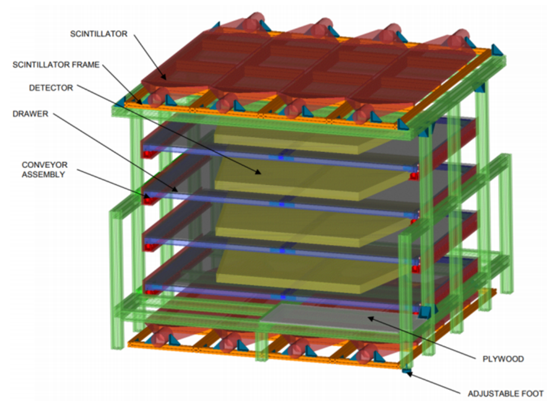
For each x-ray point of the same layer of a given quadruplet, we should find the same Δy and $\Delta\theta$. Due to other types of misalignments non-considered in the analysis, these parameters could change from one x-ray point to another. Aiming to find the parameters (Δy, $\Delta\theta$) that minimize the sum of the difference between y_{xray} and y_{cmm} of each x-ray point and the uncertainty on those parameters, we use a χ^2 function (see Equation 2, where σ^2 is the variance).

$$\chi^2 = \sum_{\substack{X-ray\\points}} \frac{(y_{xray} - y'_{cmm})^2}{\sigma^2} \tag{2}$$

2.4 McGill cosmic-ray data

When a cosmic particle enters in the atmosphere, it produces a large variety of secondary particles detected at the surface of the Earth. Some of these secondary particles are muons that can be detected by sTGC. As a result, these particles represent an adequate QC test for the detectors. Before to be sent at CERN, the quadruplets go to McGill where they can be tested in McGill cosmic ray test stand (see Figure 2.3). It is important to note that a properly defined system of coordinates does not exist for the measurements of McGill cosmic-ray data as we have for x-ray and CMM measurements. Then, we cannot compare directly the cosmic-ray dataset with the two other datasets. The solution to this problem is the use track residuals.

(a)



(b)

Figure 2.3: *McGill cosmic ray test stand. (a) is the setup that detects muons at McGill [6] and (b) is a schematic of the cosmic-ray detector [7]*

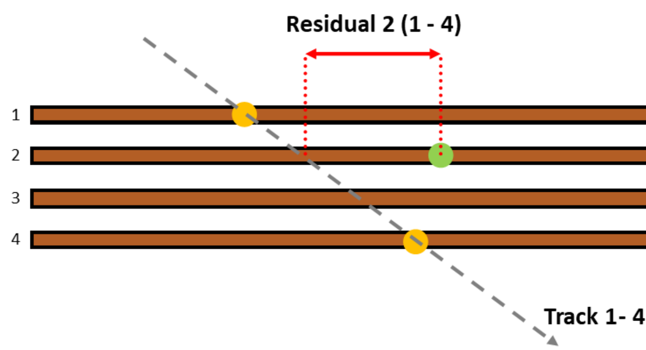


Figure 2.4: *Definition of a track residual. The residual 2 (1-4) (in red) is the difference between the real position of the measurment in the layer 2 (in green) and the position obtained by taking into account the reconstruction of the track with fixed layer 1 and 4 (grey array).*

2.5 Track residuals

A quadruplet is composed of four layers. As a result, when a muon passes through the quadruplet, we should obtain four detections, one for each layer. Because we assume that the path of the particle throughout the sTGC is linear, one could think that we would be able to predict the position of the measurement in one layer by taking into account the measurement on two fixed layers. Nevertheless, strip misalignments are responsible for a wrong readout position value of the measurement and the linear reconstruction is then impossible. The difference between the measurement position and the position that would have been detected by reconstructing the path with two fixed layers is called a track residual (see Figure 2.4). For each layer, there are three different track residuals that could be calculated, one for each different combinaison of fixed layers (i.e. for layer 1, we have residuals 1(2-3), 1(2-4) and 1(3-4)). Track residuals can be found for cosmic-ray measurements, as well as for x-ray measurements and CMM measurements simply by making a linear reconstruction.

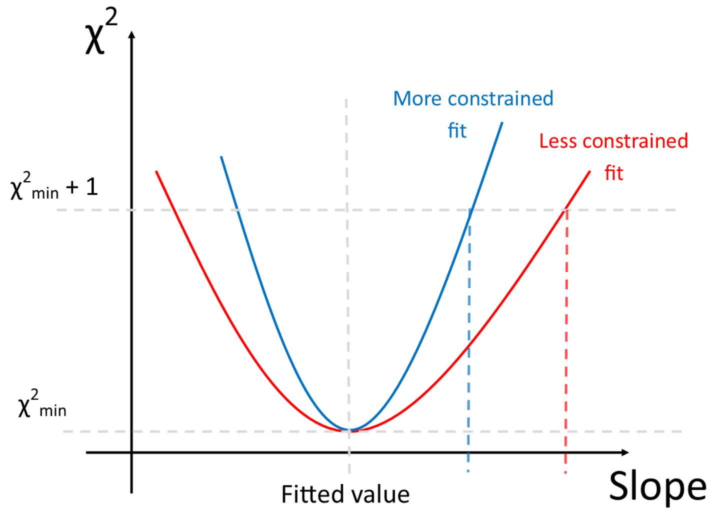


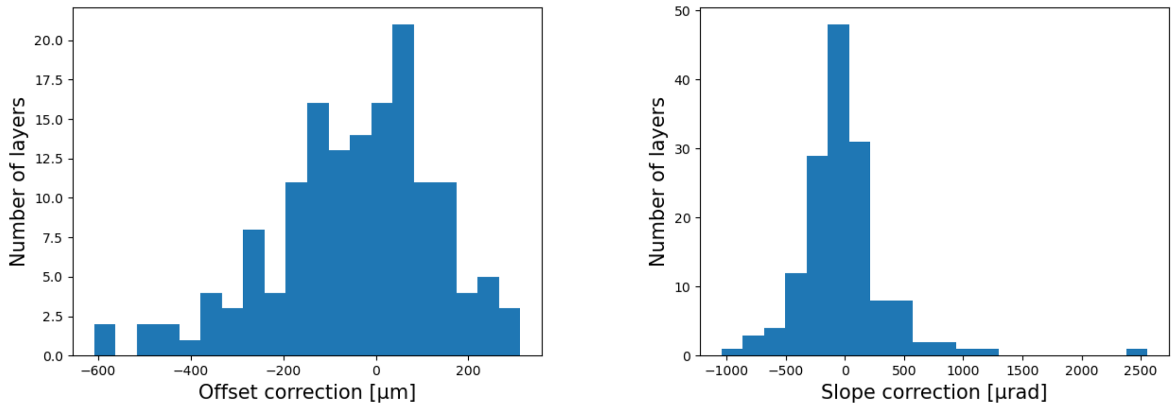
Figure 2.5: *Representation of the minimum of a χ^2 function, related to the uncertainty on the value, as a function of the slope or the offset. Most of the time, adding a constraint to the minimization of the function leads to a narrower "parabola-like" function around the minimum, and so it gives a smaller uncertainty on the value.*

2.6 Use of McGill cosmic-ray data to find parameters

The goal of this project was to add the cosmic-ray measurments to the analysis of the position of the strips within the sTGC. It is common knowledge in statistics that adding constraints to the minimization of a χ^2 function leads to a smaller uncertainty on the value we are looking for (see Figure 2.5). Then, the cosmic-ray data could be added to the fit as a constraint. The constraint we chose here is to let the difference between residuals obtained with cosmic-ray data (res_{cosm}) and residuals obtained with x-ray (res_{xray}) data be null. Lagrange multipliers (λ_i) are also used in order to give a certain weight to the constraint. As there are three residuals that can be calculated for each layer, we add three constraints to the fit (see Equation 3).

$$\chi^2 = \sum_{\substack{X-ray\\points}} \left\{ \frac{(y_{xray} - y'_{cmm})^2}{\sigma^2} + \sum_{i=1,2,3} \lambda_i (res_{xray} - res_{cosm})_i \right\} \tag{3}$$

An alternative version of the Equation 3 would use only one constraint to the χ^2 function. To calculate the residuals associated to this constraint, we would take the two fixed layers the most distant from each other in order to have an overview of all the quadruplet (for example, we would take fixed layers 1 and 4 for the residuals on layer 2).



(a) (b)

Figure 3.1: *Correction of the misalignments that occured during the quadruplets' construction for 153 layers. Corrections of a few hundred micrometers and a few hundred microradians are respectively observed for the offset ((a)) and the slope ((b)).*

3 Results

3.1 Misalignment parameters without cosmic-ray data

A code developed by [8] was used to perform the minimization of the χ^2 function presented at Equation 2. The obtained misalignment parameters are in the order of a few hundred micrometers for the offset and a few hundred microradians for the slope (see Figure 3.1 for an histogram of the misalignments for layers of quadruplets WLAC and WLAP). This code also returned histograms showing the difference between y'_{cmm} and y_{xray} after the correction by a slope and an offset for the x-ray points of a chosen layer (see Figure 3.2). This is precisely on the sum of these differences that the code made a minimization. As a result, their average is equal to zero. The x-ray points for which CMM measurements and/or x-ray measurements were not available were not used in the analysis.

3.2 Cosmic-ray track residuals

In order to use cosmic-ray measurements, an analysis of the track residuals has been performed by [6]. As it can be seen in Figure 3.3, track residuals have been obtained everywhere in the layers (for each layer, there are three different figures, one for every combination of fixed layers). A pixel of the Figure 3.3 was obtained by applying a gaussian fit on the detections that occured near this pixel. The error on these measurements are then given by the standard deviation of this gaussian function. The cosmic-ray measurements of every x-ray point were extracted to be added in a modified version of [8]'s code.

3.3 Misalignment parameters with cosmic-ray data

The code developped by [8] analyzes only one layer at a time. Because the calculation of the track residuals requires x-ray measurements from other layers, the code needed to be

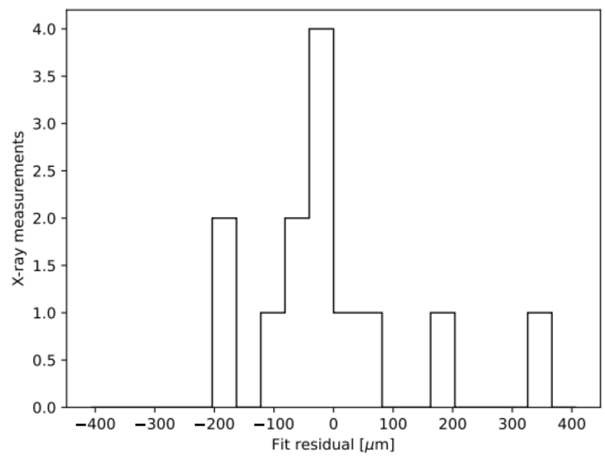


Figure 3.2: *Histogram of the difference between y'_{cmm} and y_{xray} for the QL3P05 quadruplet's layer 4 x-ray points. As a result of the fit, the sum of these differences is minimal.*

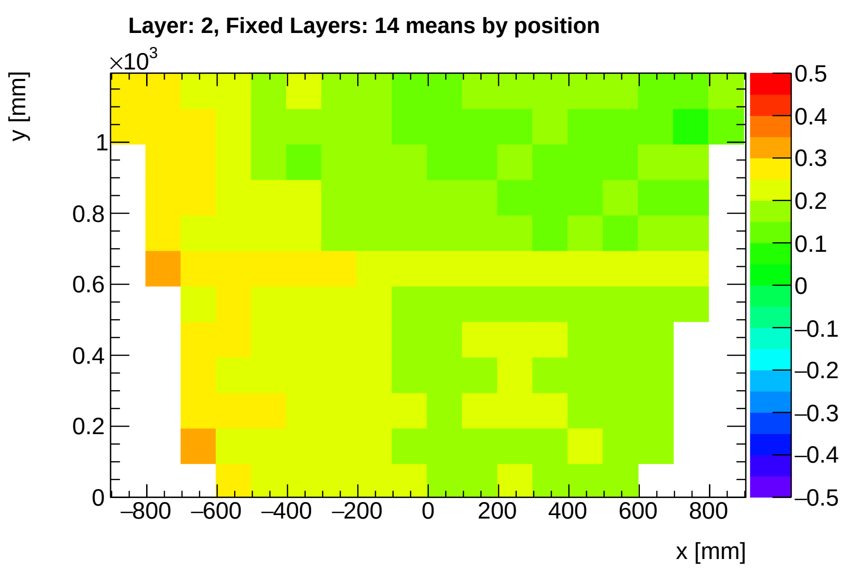


Figure 3.3: *Track residuals 2 (1-4) of the QL2C04 quadruplet (3100V). For different point along the layer, the track residual is calculated. [6]*

modified to take in input data from a complete quadruplet (and not only for one layer of this quadruplet). The minimization of Equation 3 was then added to the code. If the residual obtained from x-ray and/or cosmic ray measurements was unavailable for a x-ray point, the code did not use any constraint for this specific point. Nevertheless, this minimization has been unsuccesful. It seemed that the minimization was over-constrained and that a minimum of the χ^2 was too hard to find by modifying five parameters (slope, offset and three Lagrange multipliers). This will be discussed more in detail in the next section.

4 Discussion

The minimization of Equation 3 was not successful. We first thought that there was too many constraints in the fit (five fitted parameters overall). For this reason, the alternate version of this equation, discussed in the Section 2, that used only one Lagrange multiplier instead of three, was implemented. Nevertheless, it was also unable to give definite values for the offset and the slope misalignments. Different parameters of the minimization have been adjusted in order to fix this problem (the number of iterations, the tolerance in the variation of the minimal value, etc.) without any significant improvement. Another *python* function (different from *scipy.optimize.minimize*) could be used to perform the minimization to determine if this function was part of the problem (by not being able to minimize a function with too many parameters).

The code developed during this project used the x-ray residuals as a comparaison to cosmic-ray residuals. However, the use of CMM residuals could give better results for the minimization. Indeed, the x-ray and the cosmic-ray measurements are made on the same quadruplets (the strips do not change between the two sets of data acquisition). Thus, it could be relevant to view the effect that would have the comparaison of the residuals that would be less alike on the minimization of Equation 3.

5 Conclusion

Because of the increase of energy and luminosity of the LHC, ATLAS NSW will be installed in the ATLAS experiment. The precise position of the strips within these detectors is needed in order to reconstruct accurately the path of the particles created during the collision. This report presented an analysis of the position of the strips adding McGill's cosmic-ray measurements to an already existing code. The minimization of this implemented function was unsucceful and might be associated with an over-constrained fit. The next step of this project could be to try to compare cosmic-ray measurements with CMM measurements instead of x-ray measurements (that has been presented in this report) to see if this could fix the problem encountered during the minimization. A succesful minimization would allow a better knowledge of the position of the strips and a smaller uncertainty on the values of misalignments that would result in a better tracking of the particles produced in the ATLAS experiment.

Aknowledgements

I would like to thank Prof. Brigitte Vachon for the great opportunity that was offered to me during the summer as well as Lia Formenti and Dr. Tony Kwan for their support and their participation in this project. I also acknowledge the support of the Natural Sciences and Engineering Council of Canada (NSERC), McGill University, the *Fonds de recherche du Québec en nature et technologies* (FRQNT) and the Institute of Particle Physics (IPP).

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