sTGC Single Point Resolution Analysis for ATLAS' New Small Wheel

Michael Sloan
Carleton University, Ottawa, Canada

Abstract—With the upgrade of the Large Hadron Collider (LHC) to the High Luminosity LHC (HL-LHC), many changes need to be made to the ATLAS detector to be able to perform as desired at the increased luminosity and collision rate. One of these modifications is the replacement of the current Small Wheel with the New Small Wheel (NSW), which will provide better tracking and triggering to the older counterpart. To be able to accurately make predictions for the HL-LHC, detailed simulations of each component of the NSW, including the small-strip Thin Gap Chamber (sTGC), must be able to reproduce the output of prototype components constructed for the NSW. As part of the tuning of these simulations, an analysis into the single point resolution of the simulated sTGC layers are performed in hopes of better reproducing results from test beam data.

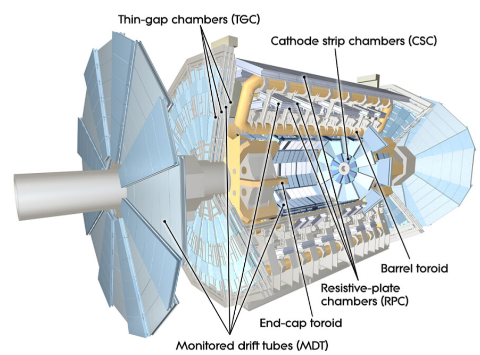

Fig. 1: Diagram of ATLAS detector

I Introduction

The ATLAS detector is one of the many experiments analysing the shower of particles from collisions in the LHC. With the higher luminosity in the coming run, many upgrades to the muon spectrometer must take place. One of these upgrades is the replacement of the Small Wheel with the New Small Wheel (NSW). it was found in previous runs, that approximately %90 of triggers from the Big Wheel (BW) are fake triggers coming from secondary particles produces in other sections of the detector[1]. The upgraded NSW will now provide an extra set of triggers to remove these fake events and select those events coming from the interaction point (IP).

The NSW uses a combination of sTGC and Micro Mega (MM) detectors to provide both fast triggering and precise position reconstruction of muons exiting the IP. The NSW contains 4 layers of sTGC, followed by 8 layers of MM and another 4 layers of sTGC. It is mainly the MM layers that provide the precise position reconstruction used in reproducing a given particle track, where as the triggering of muon events comes from the sTGC layers. These sTGC layers demands an offline position resolution of 100μm for the proper online track reconstruction necessary in the triggering. From test beam data collected in 2014, using a prototype sTGC quadruplet, a single point resolution of 50μm was recorded for a 32GeV pion beam normally incident of the sTGC surface at Fermi Lab[2], which more than satisfies the requirements.

II sTGC Design

The sTGC layers used in the NSW are a type of Multiwire proportional chamber that uses a series of strip, wire and pad layers as shown in figure 2. Each of the strips have a width of 2.7mm with a center to center distance of 3.2mm. The distance between the strip plane and the wire plane as well as the distance between the wire plane and the pad plane is 1.4mm. The wires have a diameter of 50μm with a spacing of 1.8mm between each wire. Finally, the pads are square sections with a width between 2cm-3cm depending on the sTGC sector. The region in between the gap is filled with a gas of 45:55 n-pentane:CO_2. The wires are kept at a potential of 2.9kV so as to generate an electric field to guide ionized electrons to the closest wire. A resistive coating is also applied to the strip and pad layers to reduce the chance of discharge between the strip/pad layers and the wire layer, as well as to help spread the induced charge over each layer.

As a particle enters the gas gap of the sTGC, given enough energy, some of the gas will ionize, producing primary electrons. Due to the applied electric fields, the electrons will be-

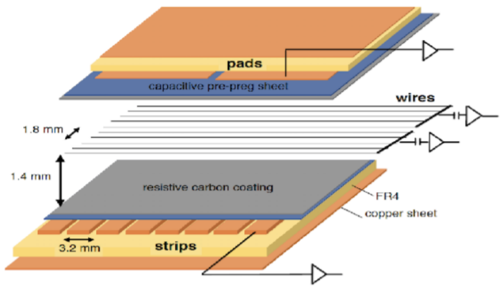

Fig. 2: Diagram of a single sTGC layer used in the NSW

gin to migrate to the wire plane while the ions move towards to the cathode planes (pad plane and strip plane). Due to the geometry of the electric field, as the electrons approach the wire plane, they begin to accelerate and gain energy resulting in secondary ionization. The rate of secondary ionization increases closer to the anode wire causing an avalanche of charge, on typically only a single wire, which can be read out by the VMM system. This rapid accumulation of charge on the wire will also induce an opposite charge on the strip and the pads which is also read out by the VMM. Each of the individual channels of strips, wires or pads that register an amount of charge are read out as "digits", which are used to reconstruct the position of the particle hit. The wire digits and the pad digits together are used to determine the x-coordinate of the hit while the strip digits are used to reconstruct the y-coordinate of the hit.

Only channels that register a charge greater than a predefined threshold will be recorded as a digit. However, the VMM has an additional Neighbor functionality in which the all the strips adjacent to a strip that passed the charge threshold will also be read out as a strip digit. Hence, with the neighbor functionality on, the strips on each side of a cluster of strips passing the charge threshold are added to the strip digits.

III Simulation of sTGC Layers

To be able to completely simulate the response of the sTGC layers to an incident muon, due to the ionization of the gas and multiplication of the charge, the interactions of multiple thousand to millions of particles would have to be tracked. This while giving a faithful representation of the physics of the detector is not computationally viable due to the large amount of memory and long simulation times for even a small amount of events. To remedy this, many of the interactions of the micro system, such as the energy deposited per collision, or the multiplication of the primary electrons, are parametrized by larger scale variables. The way in which values for these variables are chosen on an event by event basis and the way in which these affect the detector response are based off of more detailed simulations using the Garfield software, where each individual particle is tracked and the interactions between each particle are taken into account.

Due to the parameterization of the simulation, some of the parameters must be fit to data such that the simulated response matches the tests on the prototype sTGC layers. One of the main parameters considered in the following analysis is the 'charge width' of the event, which measures how much the induced charge spreads over the strip plane. A proof of concept as to how the parameters, such as charge width, can be tuned to test beam data is shown in figure 3, in which the average number of strip digits in an event, denoted as the multiplicity, is compared to the charge width of the sample.

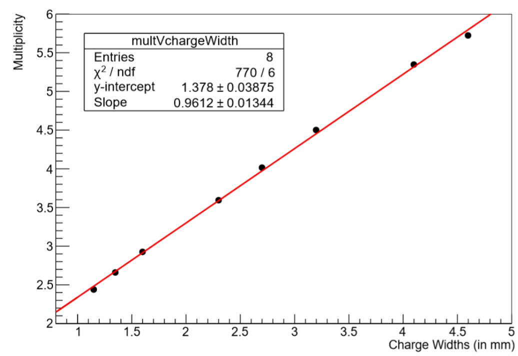

Fig. 3: Average number of strip digits, multiplicity, for different values of charge width in sTGC simulation

IV Simulated Single Point Resolution of the sTGC Layers

One important property of the sTGC that can be used to tune the simulation parameters is the single point resolution. This value gives a measure of how accurately the detector can reconstruct the truth position of an incidence muon based on the detectors response to that muon. Shown in figure 4 is the charge distribution among the strip digits for a sample simulated muon event. From this charge distribution, the detector attempts to reconstruct the y-position of the hit through a weighted sum in which the charge on the strip is proportional to the weight.

The difference between the reconstructed position of the hit and the truth position of the hit is denoted by the residual. To get an estimate for the resolution of the sTGC layers, we can look at how the residual is distributed about zero. This distribution of residual is seen to be approximately Gaussian in nature, and so an estimate for the resolution of the sTGC layers is given by the standard deviation of the residual distribution, as shown in figure 5 for a simulated sample of 10,000 muon events, originating from the IP.

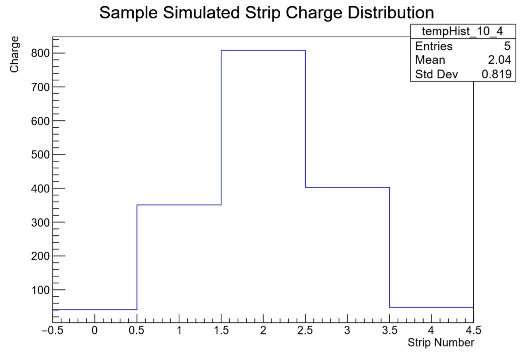

Fig. 4: Charge distribution of strip digits for a sample simulated muon event

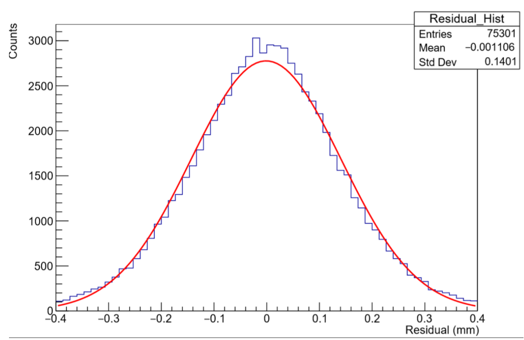

Fig. 5: Distribution of hit residuals for a simulated sample of ten thousand muon events

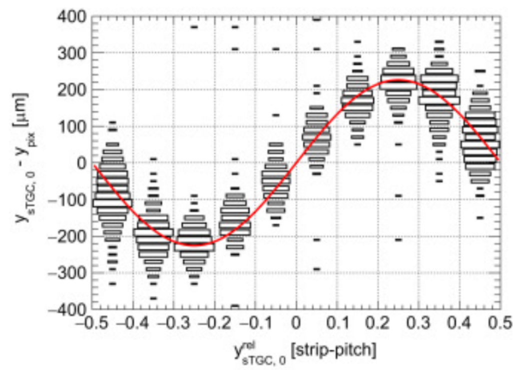

Fig. 6: residual dependence on relative strip position from 2014 test beam data

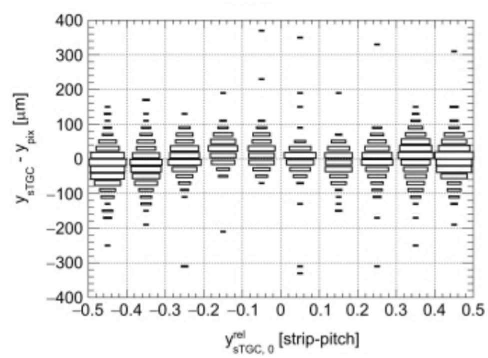

Fig. 7: residual compared to relative strip position, after correction

A Bias in Residual

The way in which the charge is spread along the strip plane is assumed to be Gaussian in nature. However, since a Gaussian distribution of charge is being converted into a discrete distribution based on the charge for each strip, there is expected to be some bias in the reconstructed position of the of the hit based on where the truth position of the hit occurred in relation to the strip width. By defining the relative strip position of the hit as -0.5 if the hit occurred at the bottom of the strip and 0.5 if the hit occurred at the top of the strip, we see a clear sine dependence in relative strip position in the 2014 test beam data[2], shown in figure 6.

Note that by projecting figure 6 onto the y-axis we recover a Gaussian distribution similar to figure 5, but it is clear that this no longer gives an accurate representation of the resolution of the sTGC layers. It is only after correcting for this observed sine dependence do we get a distribution centered around a residual of zero, as shown in figure 7. If figure 7 is then projected onto the y-axis, the resulting Gaussian distribution becomes much slimmer. It is the standard deviation of this, now corrected sample, that we denote as the single point resolution of the sTGC layer, and it is this value that the simulation should be tuned on.

B Residual Bias in Simulations

As shown in figure 3, the average multiplicity of a hit is dependent on the charge width of the sample, and after some thought, it should be clear that hits that register more strip digits should be reconstructed closer to the truth position of the hit. For this reason, it is expected that the magnitude of this relative strip position dependence should change with varying charge widths. Figure 8 confirms this by showing this dependence on a few samples with varying charge widths.

Starting at very low charge widths (1.6mm), the relative strip position is the most pronounced, with events tending to reconstruct closer to the center of the strip. As the charge width approaches 2.3mm, the relative strip position dependence flattens out before being recovered again at higher charge widths, but with events now reconstruction closer to the edges of the strips. Extending the charge widths to smaller than 1.6mm or larger than 2.5mm, this sine dependence quickly breaks down, which would indicative some additional process affecting the residual bias.

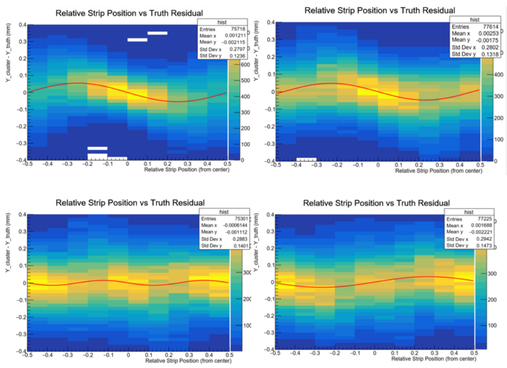

Fig. 8: Residual dependence on relative strip position for varying charge widths; 1.6mm (top left), 1.95mm (top right), 2.3mm (bottom left), 2.5mm (bottom right)

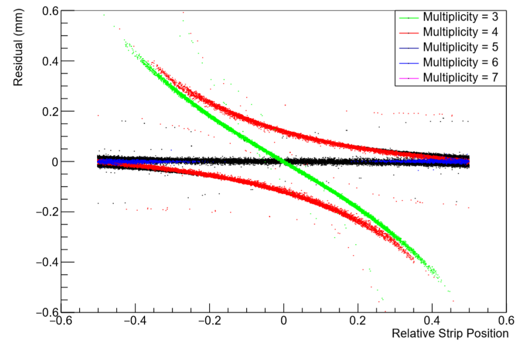

Fig. 9: Residual dependence on relative strip position with no smearing

C Removing Smearing and Cross-talk in the Simulation

During the simulation of a muon event passing through the sTGC layers, due in part to the parameterized approach of the simulation, there are many values that are smeared slightly from the generated value to better represent the statistical nature of the processes involved in the muon-sTGC interaction. For example, the hit specific charge width for an individual sTGC layer hit is sampled from a Gaussian with peak located at the charge width of the sample. Additionally, when charge is applied to the strip, there is a small amount of smearing on the total charge deposited on the strip. There are also many physical processes that act to smear out the charge through out the strips. Cross talk for example is the effect of the charge on one strip inducing an opposite charge on the few surrounding strips, and vice versa. Additionally, there is a small dependence on the angle of incidence of the particle entering into the gas gap, due to events with a large angle of incidence travelling through a larger volume of gas, hence depositing more energy in the gap.

Each of these processes can have a small impact on where the detector reconstructs the hit, and hence the residual. To get a clearer picture of how the relative strip position of a hit affects the resulting residual, we can remove all of these smearing processes. Figure 9 shows the residuals dependence on relative strip position in which the only values relevant to the residual that are not fixed are the energy deposited in the gas gap and the position of the hit.

From figure 9, the hits are clearly separated into different bands based on the multiplicity of the strip clusters (the number of strip digits). Each of the bands can be parameterized by a hyperbolic sine function of the form

$$res = p_1 \sinh(p_2 r)$$

for events with an odd multiplicity, and

$$res = p_1 \sinh(p_2(r+0.5))$$

or

$$res = p_1 \sinh(p_2(r-0.5))$$

for events with an even multiplicity, where r is the relative strip position and p_1 and p_2 are fitting parameters. It should also be noted that each band, when crossing a relative strip position of 0.5 or -0.5, wrap around to the other end of the plot. For hits with an even multiplicity, this should be clear as the events that occur in the middle of two strips have the charge shared equally on strips on both sides, and thus reconstruct closest to the truth position, but this trend is also found in bands with odd multiplicities as will be explained later.

Figure 10 shows only those events from figure 9 with a multiplicity of 4, giving two distinct bands, one running into the positive residual, the other running into the negative residual. Interestingly, all events that have a relative strip position near 0 fall into one of these two bands, but almost never have a residual in between them. This is due solely on how the charge is spread throughout the strips in the cluster. Due to the hits having a multiplicity of 4, regardless of whether most of the charge is found on the first two strips or the last two strips, the reconstructed position will tend to be pulled closer to the point in between the second and third strip. Hence if the truth position of the hit occurred somewhere on the second strip, the second strip will receive the most amount of charge and the reconstructed hit will be pulled closer to the third strip, resulting in a positive residual. Similarly, if the truth position of the hit occurred somewhere on the third strip, the third strip will receive the most charge and the reconstructed position will be pulled closer to the second strip, resulting in a negative residual. In other words, if the second strip receives the most charge, the hit is placed in the upper band, where as if the third strip receives the most charge, the hit is placed in the lower band.

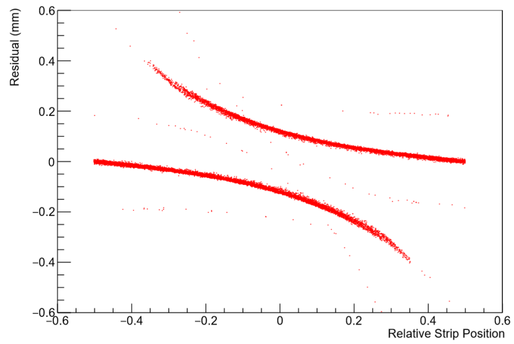

Fig. 10: Residual dependence on relative strip position with no smearing and multiplicity = 4

Figure 11 now shows all the events from figure 9 with a multiplicity of 5. From this, it is clearer that there are seemingly 3 bands for this multiplicity, all being parameterized by a single hyperbolic sine function that wraps around to the other side of the plot when passing a relative strip position of -0.5 or 0.5. Similarly to the events with a multiplicity of 4, the band that an event falls into is based on which of the strips receives the most amount of charge. All the events in the long center band are those events in which the most amount of charge is found on the center strip (third strip of five), where as the upper band near 0.5 contains all the events with the second strip receiving the most amount of charge and the lower band near -0.5 has the fourth strip gaining the most charge.

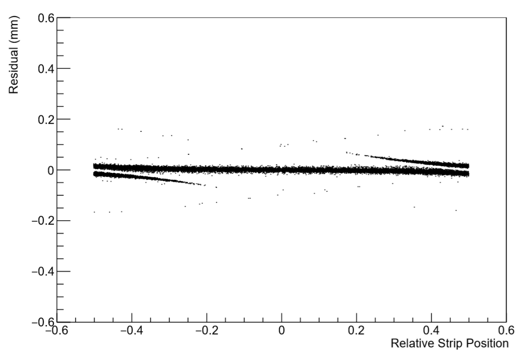

Fig. 11: Residual dependence on relative strip position with no smearing and multiplicity = 5

D Dependence of Fitting Parameters on Charge Width

As mentioned previously, the average multiplicity of a sample of hits is linearly correlated with the charge width of the sample. Since the relative strip position dependence is different in magnitude and shape for different hit multiplicities, it is not a surprise that the overall trend in residual for different relative strip positions changes with varying charge widths. However, as shown in figure 12, for a fixed multiplicity, the fitting parameters of the fitted sine hyperbolic function are seen to also be dependent on the charge width.

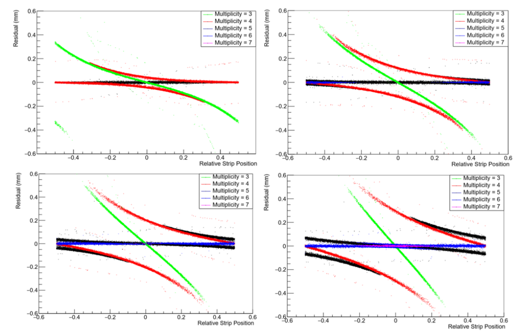

Fig. 12: Residual dependence on relative strip position for different charge widths; 1.95mm (top left), 2.3mm (top right), 2.5mm (bottom left), 2.7mm (bottom right)

Figures 13 and 14 show the fitted parameters for hits with multiplicity 3, 4 and 5 for seven different charge widths.

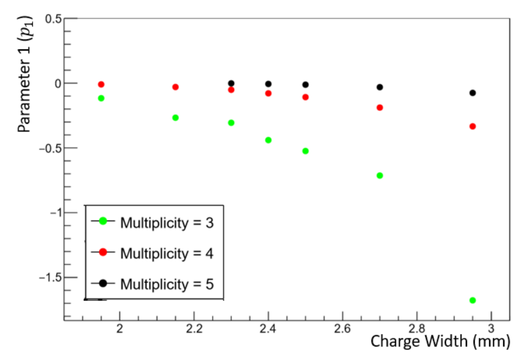

Fig. 13: Amplitude parameter dependence on charge width

E Reintroducing Smearing and Cross-talk

Running simulations of the sTGC response to an incident muon without charge smearing or cross-talk gives a good idea of how the residual changes based on the relative strip position in the simplest of cases, however, this is not an accurate representation of a real detector response. Figure 15 shows how, at a first glance, much of the dependence on the relative strip position gets blurred out by the charge smearing and cross-talk. However, isolating for individual bands based on the strip that received the most charge, it is clear that this relative strip dependence still has a significant effect. This is shown for hits with a multiplicity of four with the second strip receiving the most charge in figure 16.

From figure 16, there starts to appear a cluster of events with relative strip position of around -0.5 and negative residual, that were not present in the samples without smearing.

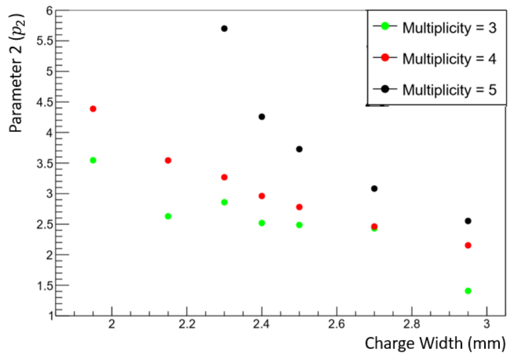

Fig. 14: Frequency parameter dependence on charge width

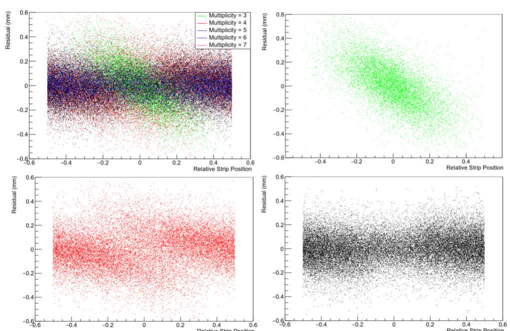

Fig. 15: Residual dependence on relative strip position for different multiplicities; all multiplicities (top left), multiplicity = 3 (top right), multiplicity = 4 (bottom left), multiplicity = 5 (bottom right)

These events, while having the second strip receive the most charge, are hits in which the truth position of the event actually occurred on the third of the four strips. Before the charge smearing and cross-talk was added during the simulation, these events had the bulk of the charge on the third strip, but since the charge smearing is different for each individual strip, when the digits are recorded, the second strip had the most charge of the bunch. Because of this, these events should be treated as events from the lower of the two bands to be corrected properly. These clusters of misplaced events can be found for each band and can easily be isolated for using the charge fraction q'/q_{max}, where q_{max} is the charge on the strip that registered to most charge, and q' is the charge on the next closest strip to the center of the strip cluster. Figure 17 shows this for the events with multiplicity 4 and strip 2 register the most charge. All of the miss placed events in this band are found at the top left corner of this figure and can easily be cut out and placed in the corrected band.

With each hit now placed in the proper band, and each band being fit with a hyperbolic sine function, we can now correct the reconstructed position of each of the hits to get a better idea of the single point resolution the sTGC layers.

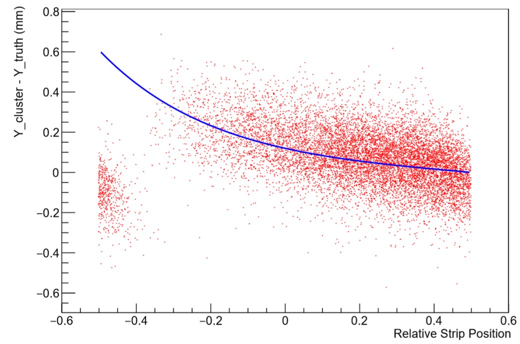

Fig. 16: Residual dependence on relative strip position with smearing, multiplicity = 4, and max charge on strip 2

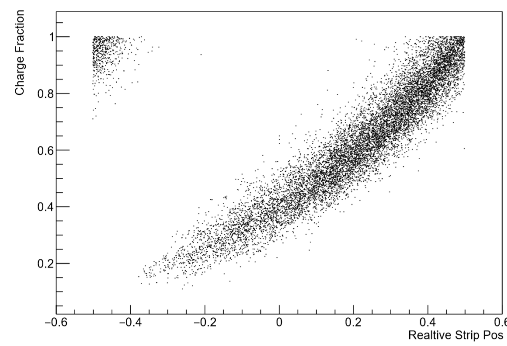

Fig. 17: Charge fraction $q'/q_{max} = q_{strip3}/q_{strip2}$ compared to relative strip position

Figure 18 shows the computed resolution of samples with different charge widths both before the relative strip position corrections and after.

V Conclusions and Further Studies

In an attempt to better tune parameters of the sTGC simulation, the single point resolution of simulated muon events were analyzed. Due to a sinusoidal dependence of the residual on the relative strip position of a hit, observed in 2014 test beam data[2], the dependence on relative strip position in the simulated sTGC layers was analysed. A very clear dependence was seen in the simulation when separating events with different multiplicities. For each multiplicity, a hyperbolic sine dependence was observed, but with different fitting parameters for each multiplicity. With this dependence, the reconstructed positions of the hits were corrected, which had a significant impact on the single point resolution of the sTGC layers.

Further investigation need to be done into the resolution of both the test beam data as well as the simulated samples. It would be useful to analyse the dependence of the residual on the relative strip position of the test beam data for individual multiplicities in a similar way to the simulated sample pre-

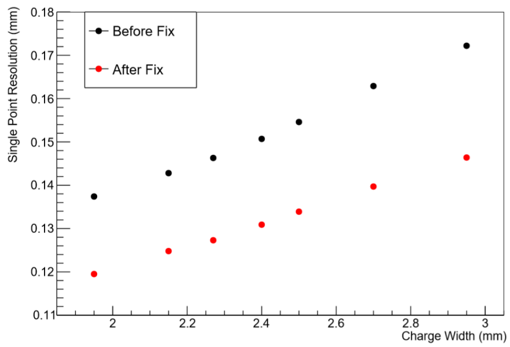

Fig. 18: Single Point Resolution of different charge widths before and after relative strip position corrections

sented in this report. Additionally, it should be noted that the simulated samples use in this analysis were generated over the entire surface of the NSW, where as the test beam data was generated from samples with normal incidence on the prototype layers. This means the angle of incidence in the gas gap is much greater in the simulations, which as previously mentioned, can increase the smearing of the charge on the strips and potentially lead to larger residuals. This could partially explain why, even after correcting for the relative strip position dependence, the simulated residuals are much larger than the $50\mu m$ found from the 2014 test beam data. At the moment, the reconstruction algorithms for the simulations utilize the entire muon spectrometer to reconstruct a muon track, rather than just the NSW. Hence, modifications to the reconstruction algorithms would need to be applied to properly reconstruct events entering the NSW at normal incidence. This is a very important improvement that should be implemented for further studies of the sTGC single point resolution.

VI References

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