# MVTX Alignment

LBL-EIC Meeting
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September 30th, 2025

# Overview

- What is alignment?
- The sPHENIX MVTX
- Metrology of the MVTX, lessons for SVT
- *In situ* alignment with data
- Takeaways

# What is alignment?

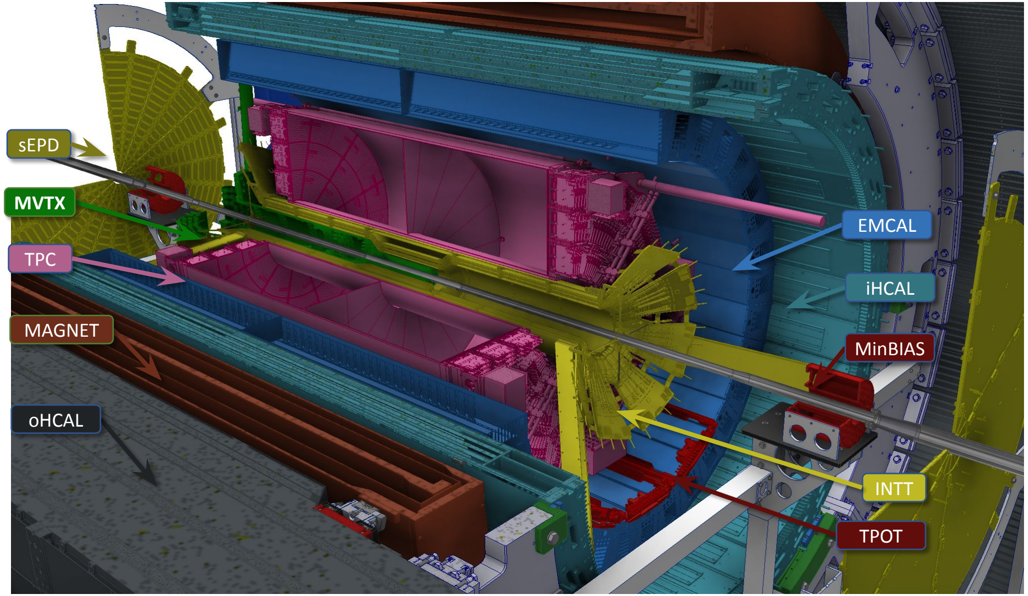
- Modern nuclear and particle physics experiments rely on precision tracking of charged particles for a variety of physics analyses
- In the last several decades, silicon based sensors have become the gold standard for tracking reconstruction due to their fast readout, high precision, and radiation tolerance
- These detectors are composed of individual sensors that are segment at the chip level (i.e. as pixels or strips), and attached to a mechanical support
- In order to achieve the highest position resolution, the position of each sensor must be known to a high degree of precision
- The process of determining the deviation in space from the idealized position of each sensor is commonly referred to as alignment
- Alignment usually uses a combination of metrology and *in situ* approaches

# The sPHENIX detector

- sPHENIX is a (relatively) new experiment based at RHIC, designed with full tracking coverage to |eta|<1.1 as well as electromagnetic and hadronic calorimetry

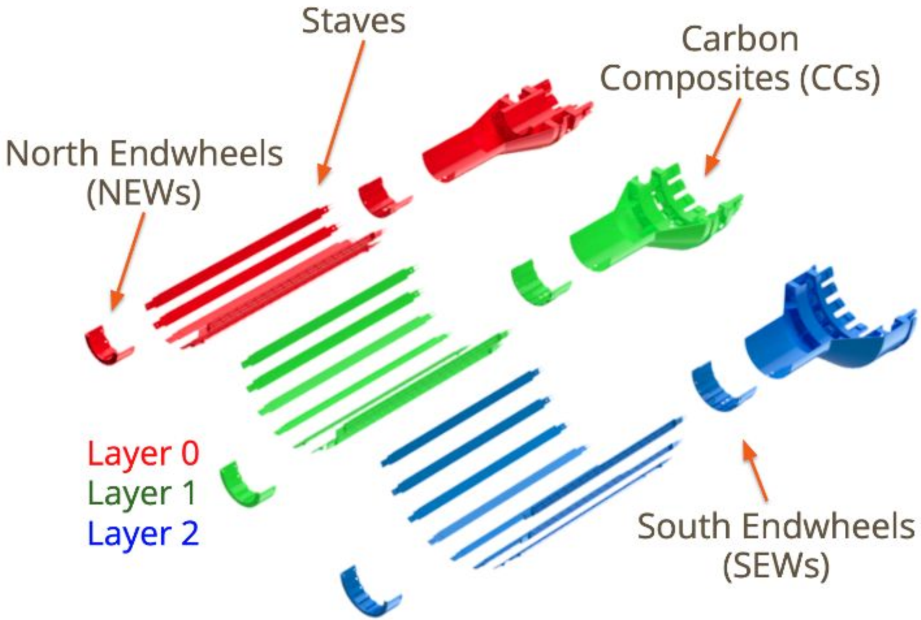
sPHENIX Tracking Detectors:

- **MVTX -** Maps based vertex detector for precision determination of PV and SVs
- INTT - Intermediate tracker for fast timing readout
- TPC - Time Projection chamber for momentum resolution and PID
- TPOT - TPC Outer Tracker for data driven distortion corrections in the TPC



# sPHENIX MVTX

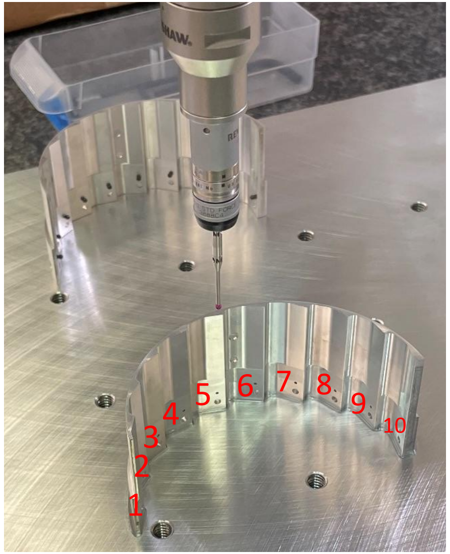
- MVTX is Maps VerTeX detector at sPHENIX
- 3 layers of Silicon, with r0 at ~2.5 cm from beamline
- 492 sensors in 3 layers (12, 16, and 20 staves)
- Alpide chip (same as ALICE ITS2)
- Low mass (~0.3% X0 per layer)
- More information here

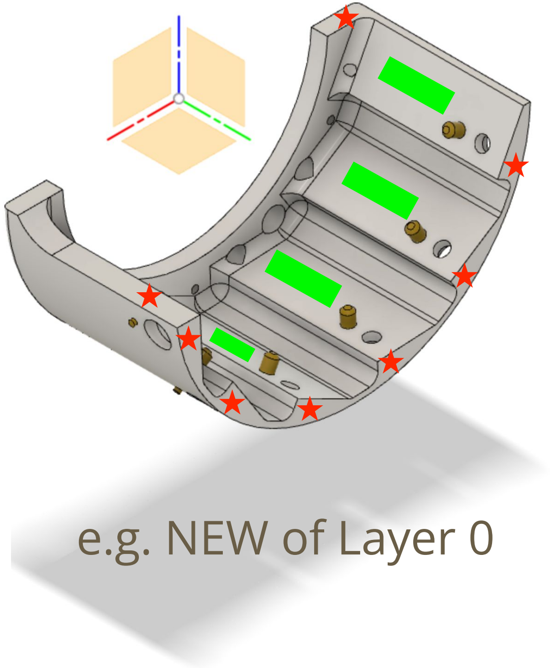


# Metrology

- During assembly, a coordinate measuring machine (CMM) was used to guide and measure the planar surfaces to which the staves were mounted
- CMM measurements transformed into planar objects as a geometric description, wrt global origin
  - 8 points, 4 per planar surface, 2 planes corresponding to N and S ends of staves
  - Distilled to 1 plane per staves, using LS best fit of measurements, with outliers removed by hand in cases that there was a large disagreement with the model
  - In principle, this allows for the determination of the relative angle of each stave in the detector construction

# CMM Measurements



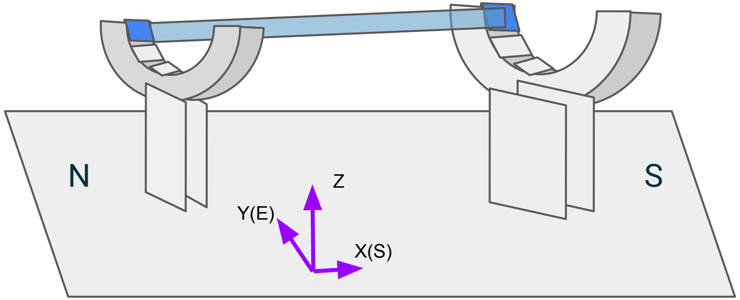



e.g. NEW of Layer 0

1. Least-squares fit touched points on multiple faces of the part to its CAD model ★
2. Constrain 6DOF of a rigid body
3. Define an origin of the rigid body
4. Define axes from the origin of the rigid body

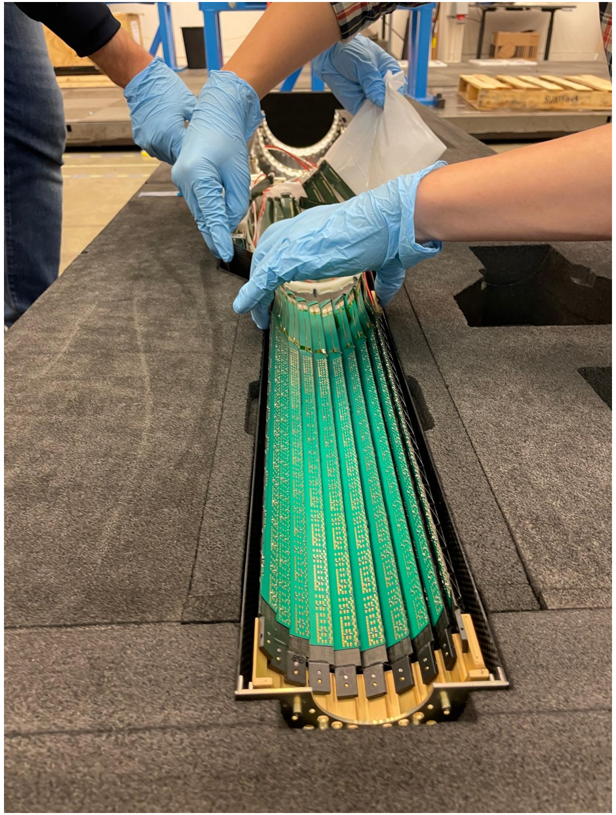
# Local geometry, per layer

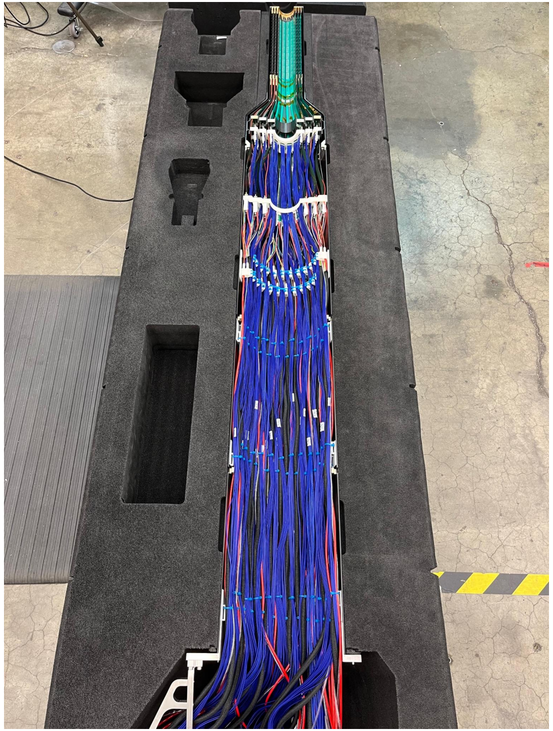
- CMM measurements performed by LBL
- >4 pts measured for each stave end (N and S), with a best fit plane to these points defining the measured stave plane
- Origin, per layer, is extracted from the center of a cylindrical fit to all planes in the half layer, and aligned with the model origin for comparison




Cartoon shows one example, 4 points are measured on each blue face, defining the stave plane (best fit to 8 pts).
Light blue indicates the measured stave plane, extracted from both faces

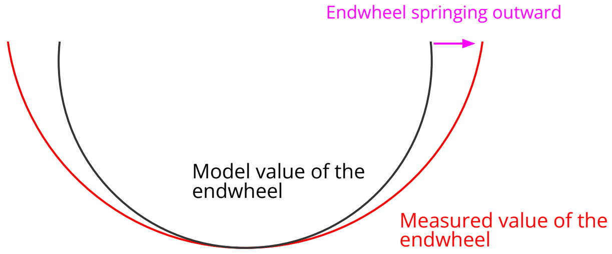
# Assembly

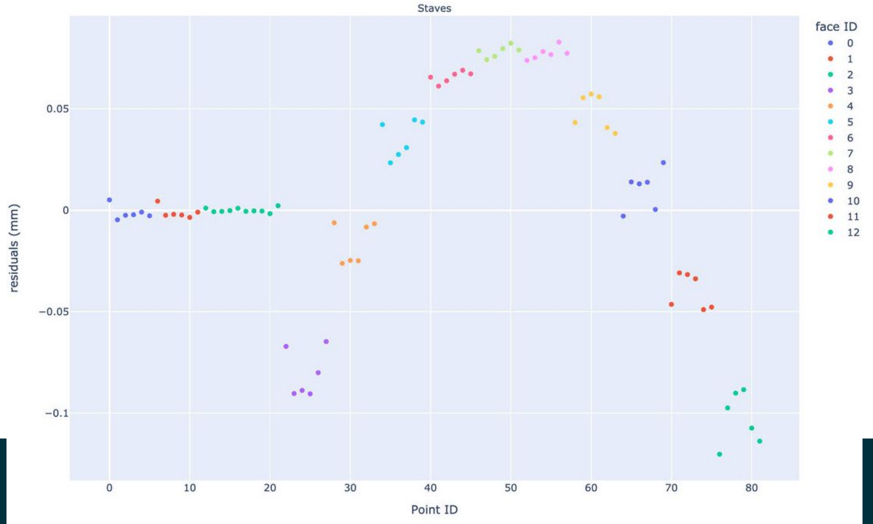




# Local geometry, combining layers

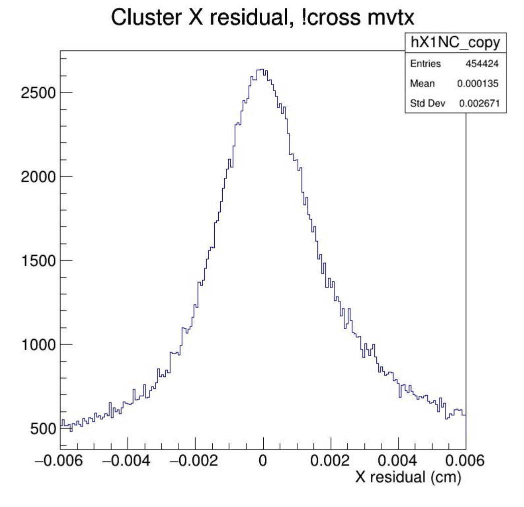
- Once the measured and modeled stave planes measured for each layer, they need to be combined to have useful interlayer information
- This is non trivial, as there is known deformation, due to insufficient iterations between part mechanical design and manufacturing, that prevents trivially combining the layers together
- **Optimal strategy: align the origins of each of the measured rigid bodies (L0,1,2) and use Finite Element Method to model measured deformations**
- This was **not** done for the MVTX

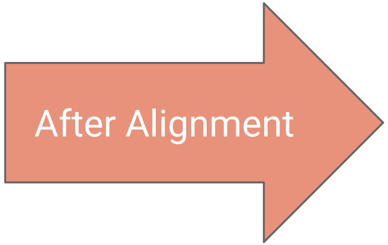


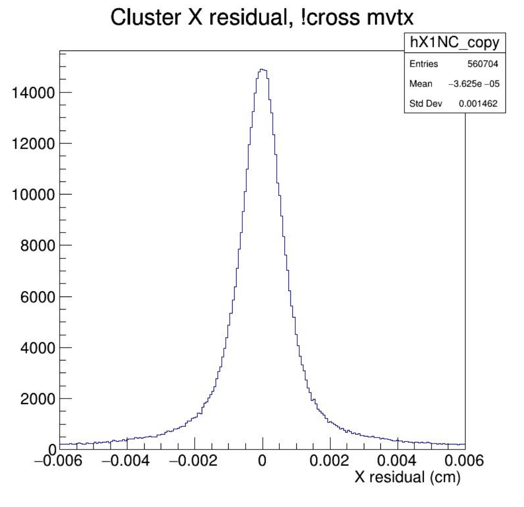



# Moving offline, what is alignment?

- Position of detector elements deviate from ideal position by a six dim affine transformation (3 translations and 3 rotations)
- Total transformation of detector is thus a large least square problem, of which an individual track correlates some number of unknown parameters
- Alignment is the process of reducing the width of the residual distribution to the intrinsic detector resolution * projection uncertainties



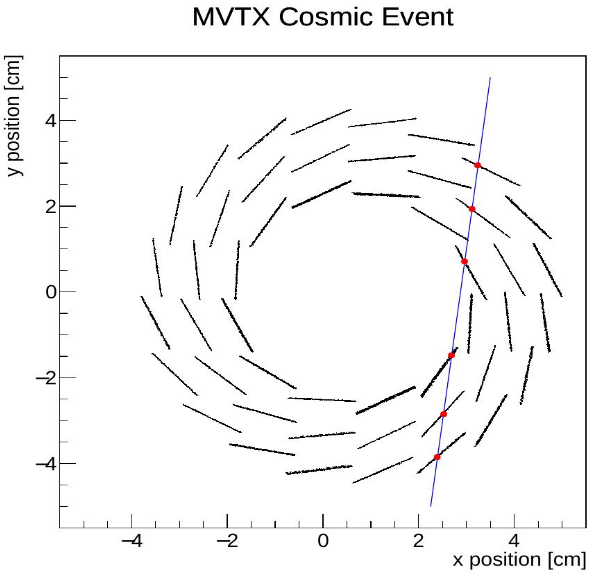



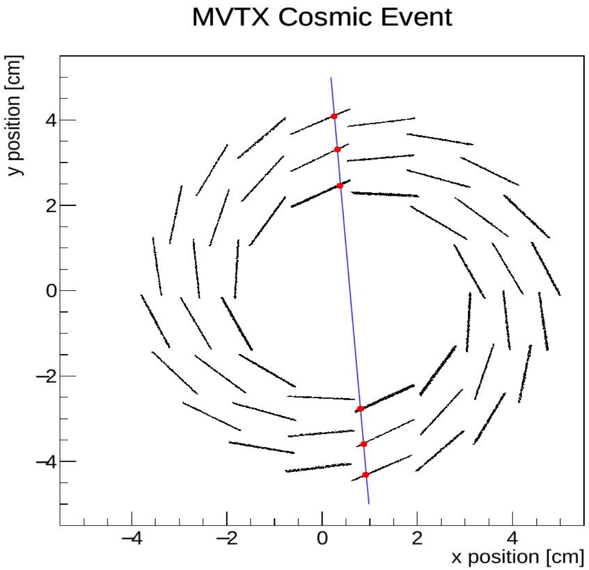
# sPHENIX offline alignment implementation

- Alignment in sPHENIX is parameterized by 3 global translations and 3 local rotations per active surface e.g. per MVTX chip
- Parameters are changes wrt "simulation" geometry
  - Simulation geometry currently is ideal geometry **+ a global shift** of the entire detector wrt the global origin to accurately place the MVTX in the Interaction Region
    - Global shift known from surveys and xy position of vertex
  - Global shift should not impact cosmics, which is the data set shown here today
- Misalignments are applied to cluster positions at run time, when data is read in by analysis code
- Alignment is iterative to account for bias in track residuals
  - Take advantage of existing Millepede II software

# Alignment strategy, *in situ*

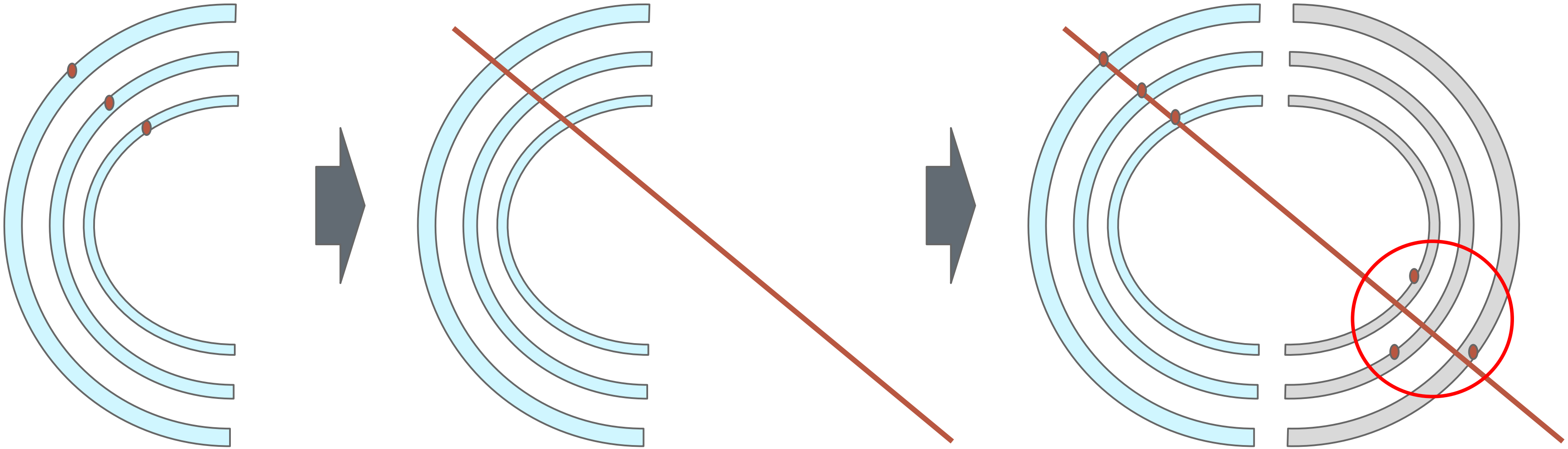
- In principle, collision events should provide sufficient information to constrain the position of tracking detector elements
- Practically, certain constraints ('weak modes', non radial alignment) are better constrained by tracks that are not strictly radial
- Significant focus, esp for vertexing, is internal and half to half MVTX alignment



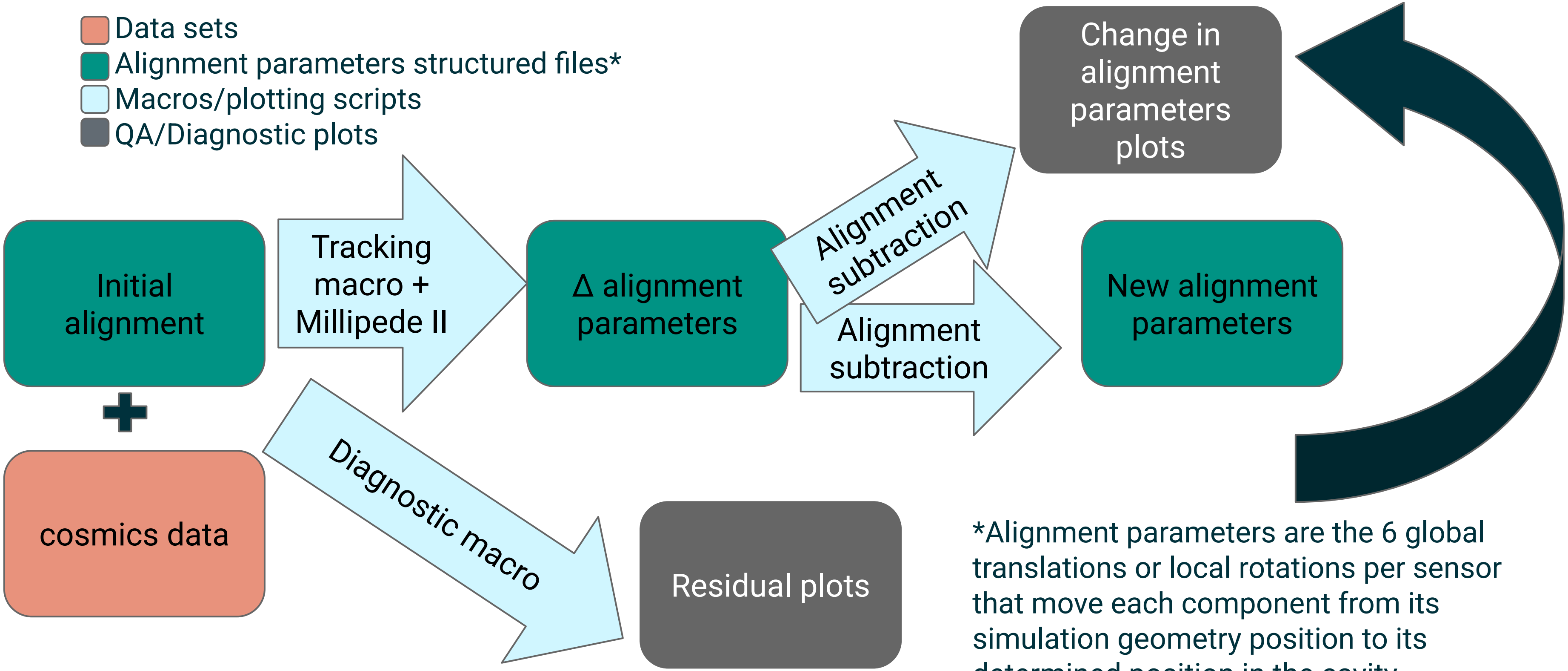



# Alignment strategy, *in situ*

- Track fits are applied to **all** clusters in MVTX to determine alignment
- Projected residual is calculated to determine quality of half to half alignment
  - Computed as a linear fit in one half of the detector, projected to the opposite half, and the residual is then computed wrt to the projection



# Alignment strategy, *in situ*




*Alignment parameters are the 6 global translations or local rotations per sensor that move each component from its simulation geometry position to its determined position in the cavity

# Alignment status, data sets and strategy

- Approx 180 hours of cosmic runs taken in Oct '24, > 200 hours in 2025
- Only 70 hours processed for todays results
- 26 iterations applied to cosmic data at varying scales in each MVTX half

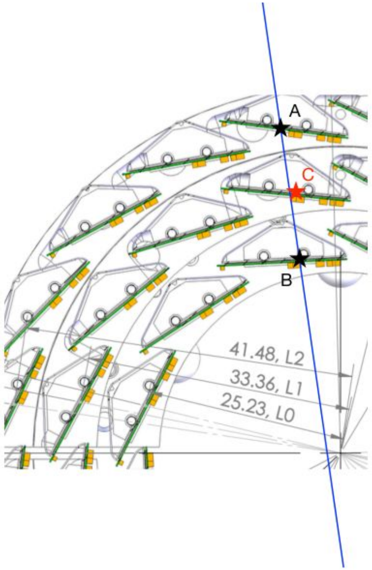
| Iterations | East | West |
|---|---|---|
| 0 | Half detector trans | Fixed |
| 1-2 | Stave trans | Fixed |
| 3-5 | Sensor trans | Fixed |
| 7-9 | Fixed | Stave trans |
| 10-11 | Fixed | Sensor trans |
| 12-13 | Stave trans | Fixed |

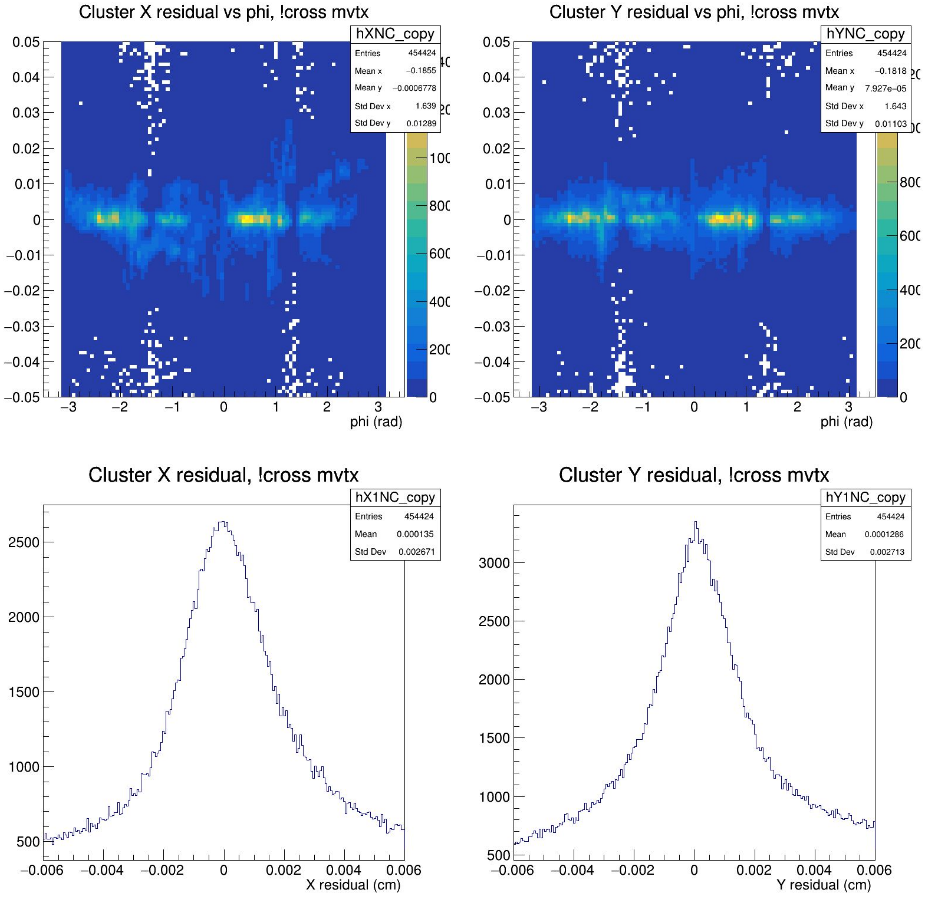
| Iterations | East | West |
|---|---|---|
| 14-17 | Sensor Trans | Fixed |
| 18-19 | Fixed | Stave trans |
| 20-21 | Fixed | Sensor trans |
| 22-23 | Sensor trans | Fixed |
| 23-25 | Sensor local angle | Fixed |
| 27 | Fixed | Sensor local angle |

# 0 Iterations on MVTX cosmics: one side

Expected biased residual width
~12 um

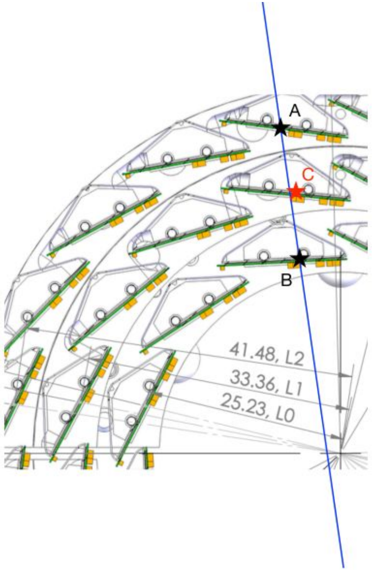
X in local sensor coor: r-phi
Y in local sensor coor: z

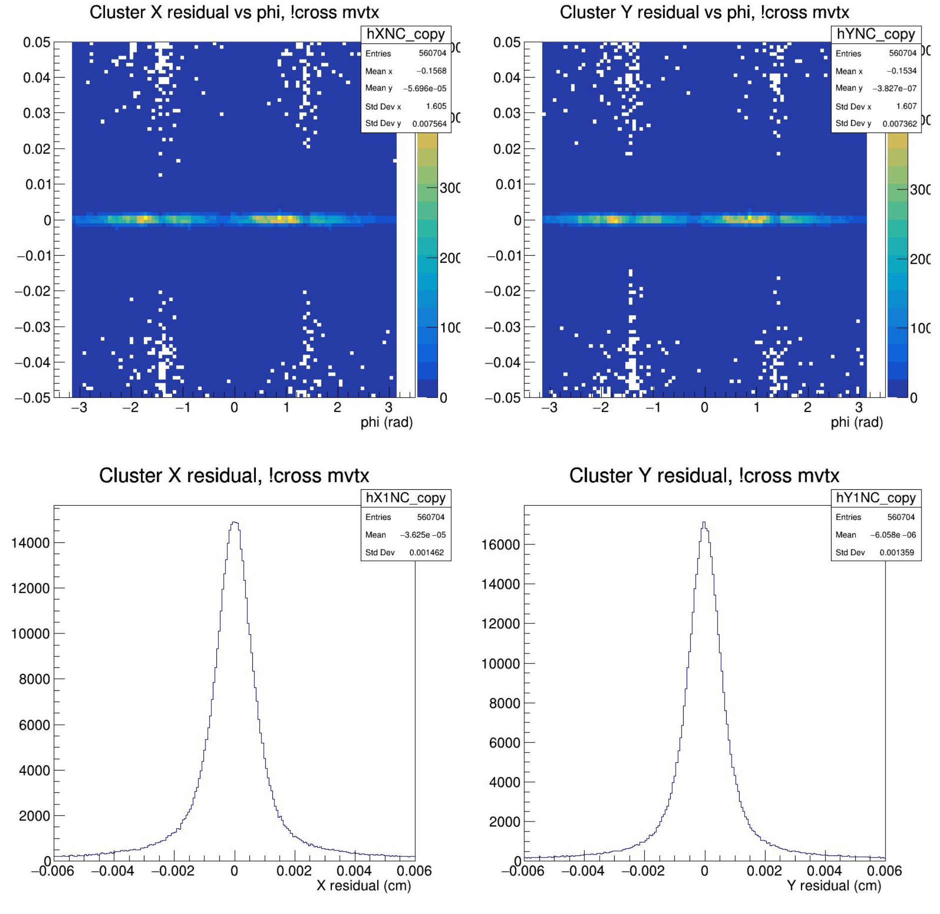


# 26 Iterations on MVTX cosmics: one side

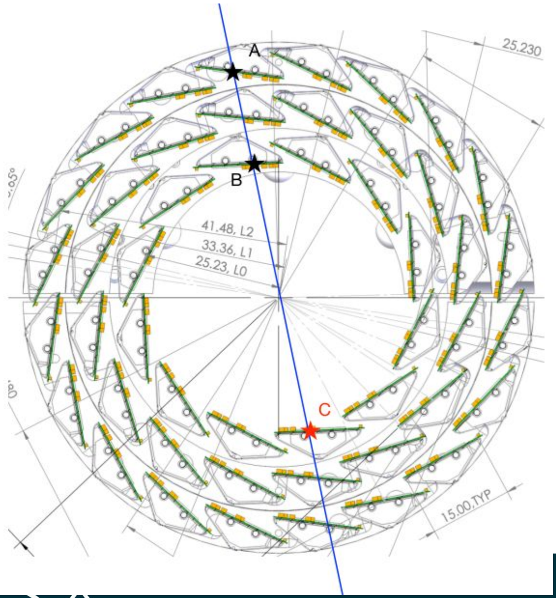
Expected biased residual width ~12 um

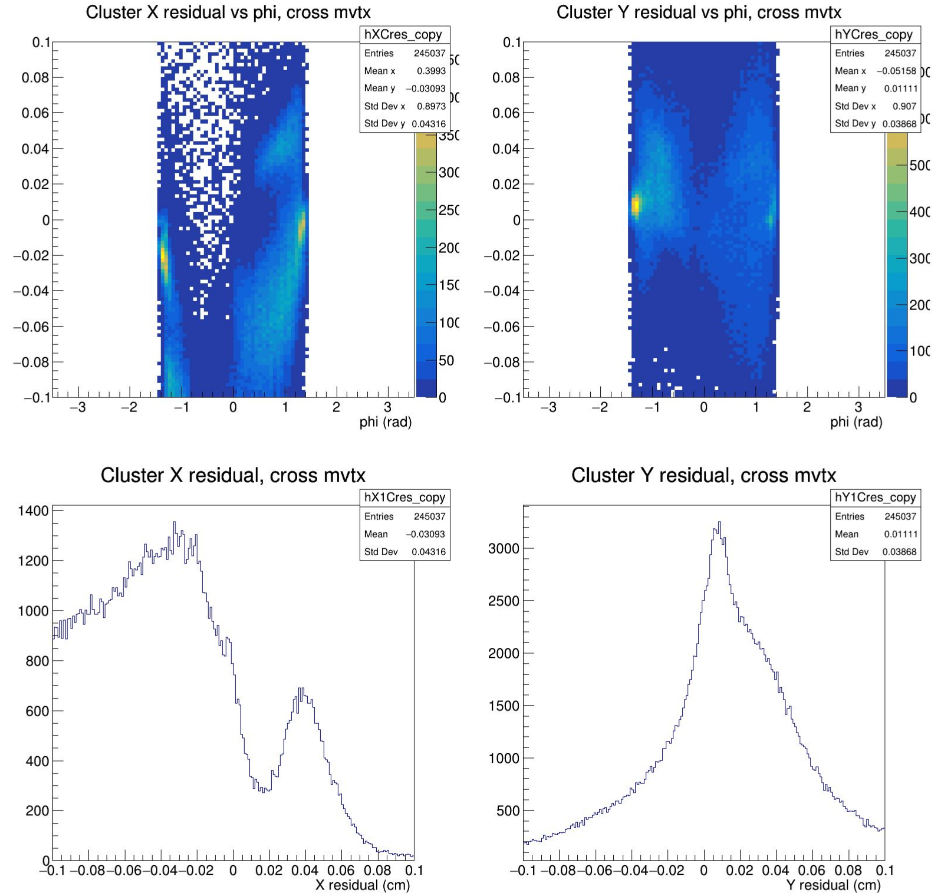


# 0 Iterations on MVTX Cosmics: projected

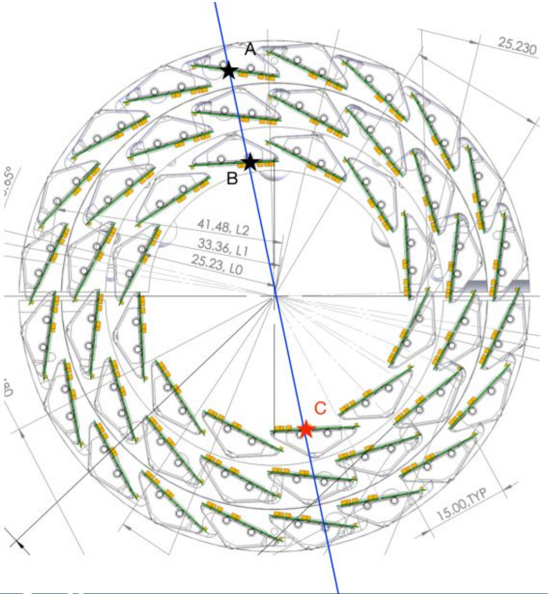
Expected unbiased residual width ~60 um (1 GeV muon)

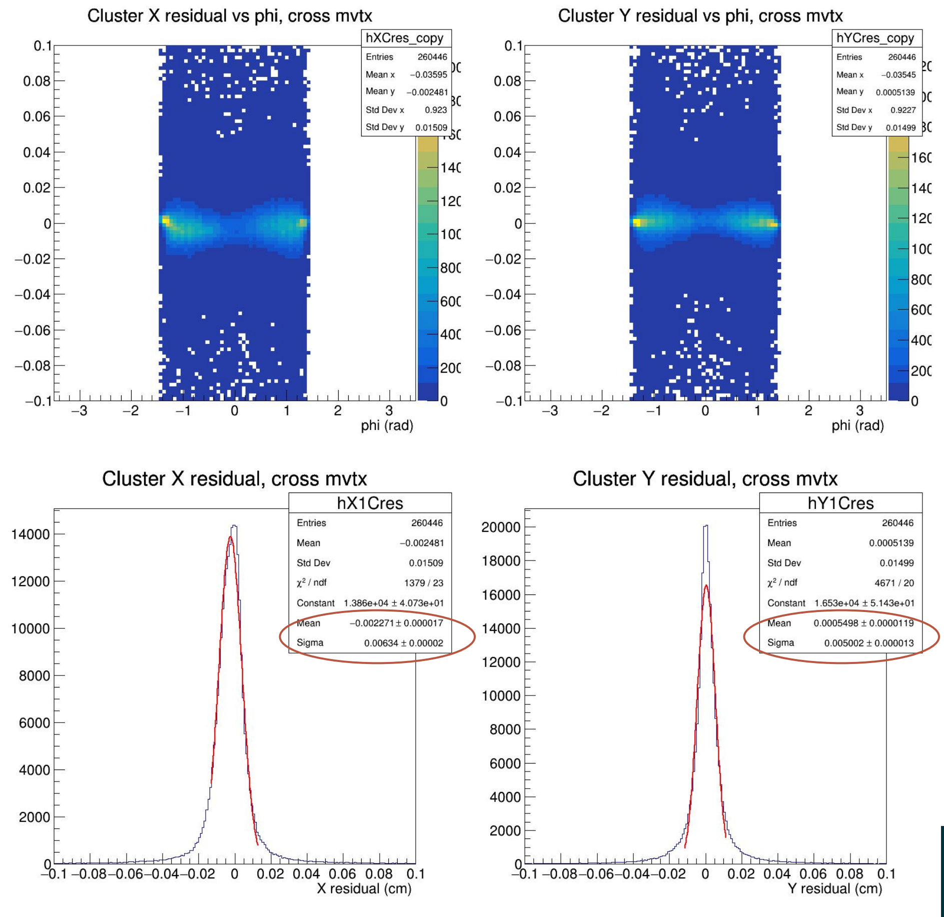


# 26 Iterations on MVTX Cosmics: projected

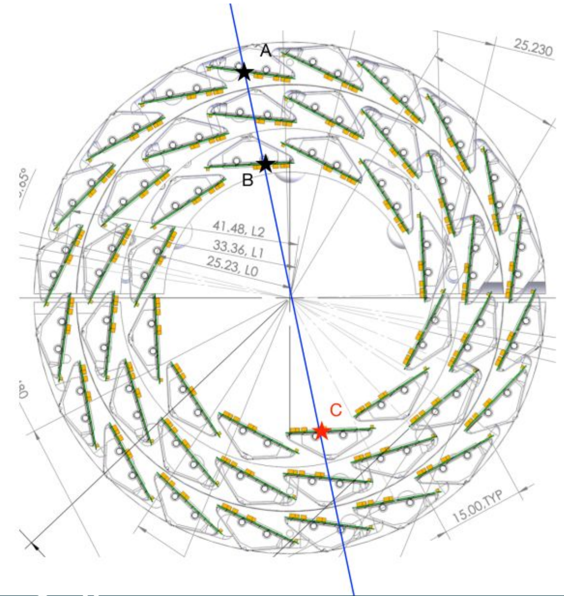
Expected unbiased residual width ~60 um (1 GeV muon)

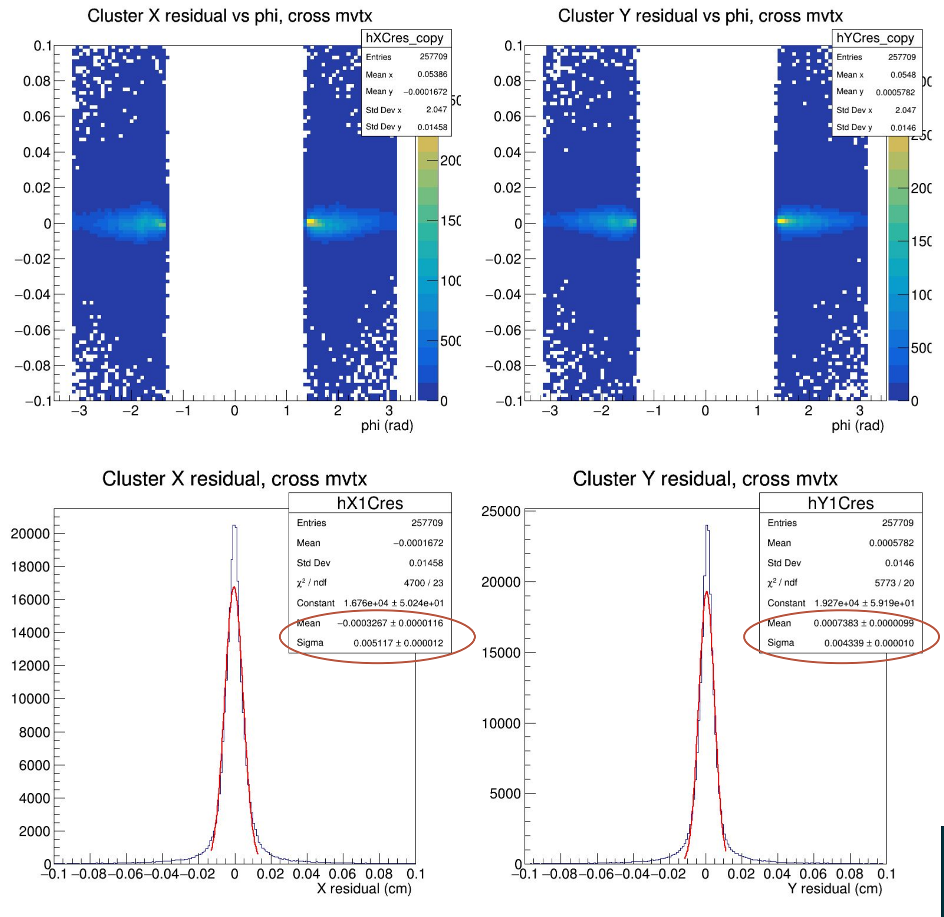


# 26 Iterations on MVTX Cosmics: projected opp

Expected unbiased residual width ~60 um (1 GeV muon)



# Comments on CMM vs *in situ* results

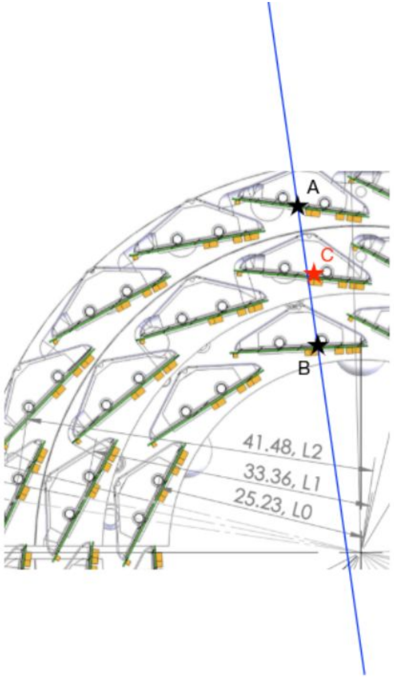
- Both the CMM data and the offline analysis can produce alignment parameters in the sPHENIX format which can then be used to cross check the impact on the residual distribution
- Disagreement between two methods, in particular in the angle between staves in different layer
- Post mortem with Yuan Mei provided lots of insight
  - CMM data, particularly between MVTX layers, is not a rigid body and would require a Finite Element Transformation to appropriately characterize the transformations
- Ultimately, CMM data was not used to constrain the MVTX, slowing the MVTX alignment process

# Takeaways

- Concluded by Yuan Mei in 2023
  - Designers must be with the assembly (debugging) team and the actual hardware all the time
    - A lead engineer should have led the project
  - Use short intense bursts of work to boost efficiency
    - Everybody's onsite with undivided attention
    - Communicate, plan, and solve problems on the spot
  - Although the staves are constructed out of Carbon composite space frames, the overall rigidity is not high enough to warrant a one-sided mechanical constraint. This choice in MVTX produces global torsional distortion
- I would add
  - Ensure continuity for personnel on the project
  - Clear documentation and management of code/resources
  - If metrology is used for alignment, ensure that final data output is formatted as transformation parameters that can be brought into the offline codebase trivially
  - Install your detector in the correct position by ensuring sufficient fine control near active sensor area

# Backup

# Estimated unbiased residuals (H/T Xin)




**Estimation of the Half-Detector Residual Width at L1**

Measurements A (L2), B (L0) to form a straight-line and project to L1, calculate residual of measurement C w.r.t the projection

$$\sigma^2 = \sigma_A^2 + \sigma_B^2 + \sigma_C^2$$

$\sigma_{A,B}$ not resolution of A,B, but the residual width contribution from measurement A,B, respectively coupled with projection level arm

For simplicity, single hit resolution $\sigma_0 = 30/\sqrt{12} = 8.7\ \mu m$
and L0-L1, L1-L2 are roughly equal distanced: 8mm

$\sigma_A = \sigma_0/2 = 4.4\ \mu m$ only single hit resolution contribution from A

$\sigma_B$ two components: hit resolution from B (same as A) + MCS due to L1

resolution due to MCS from L1 (0.3%X0), assuming 1 GeV muon:

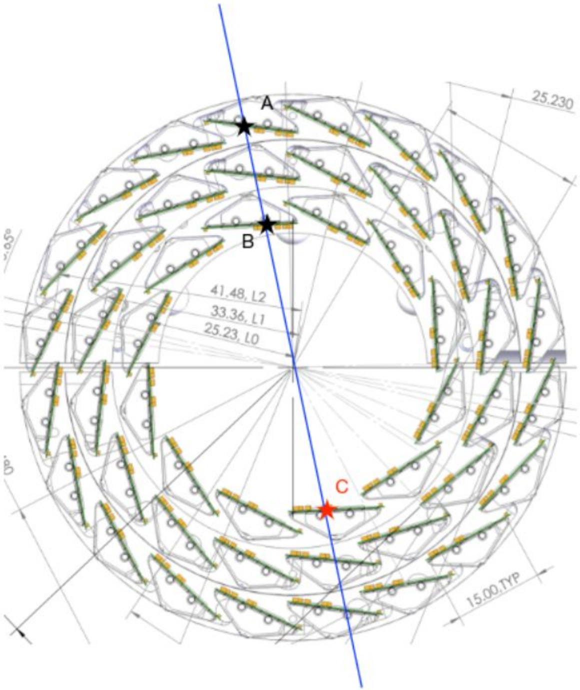
$$\sim 13.6\ \mathrm{mrad} * \sqrt{0.003} * 8\ \mathrm{mm} = 6.0\ \mu\mathrm{m}$$

$$\sigma_B = \sqrt{4.4^2 + 6.0^2} \sim\ 7.4\ \mu m$$

$$\sigma_C = \sigma_0 = 8.7\ \mu m$$

$$\sigma = \sqrt{\sigma_A^2 + \sigma_B^2 + \sigma_C^2} = \sqrt{4.4^2 + 7.4^2 + 8.7^2} = 12.2\ \mu m$$

# Estimated unbiased residuals (H/T Xin)




**Estimation of the Half-to-Half Residual Width**

For simplicity, considering only measurements A (L2), B (L0) to form a straight-line and project to opposite half, calculate residual of measurement C w.r.t the projection

$$\sigma^2 = \sigma_A^2 + \sigma_B^2 + \sigma_C^2$$

$\sigma_{A,B}$ not resolution of A,B, but the residual width contribution from measurement A,B, respectively coupled with projection level arm

$$\sigma_A = \sigma_0 * (25.2 * 2)/(41.5 - 25.2) = 27 \ \mu m$$

only single hit resolution contribution from A + projection level arm

$\sigma_B$ two components: hit resolution from B (similar as A) + MCS due to L0 hit resolution + projection

$$\sigma_A = \sigma_0 * (41.5 + 25.2)/(41.5 - 25.2) = 36 \ \mu m$$

resolution due to MCS from L1 (0.3%X0), assuming 1 GeV muon:

$$\sim 13.6 \text{ mrad} * \sqrt{0.003} * 25.2 * 2 \text{ mm} = 37 \ \mu m$$

$$\sigma_B = \sqrt{36^2 + 37^2} \sim \ 52 \ \mu m$$

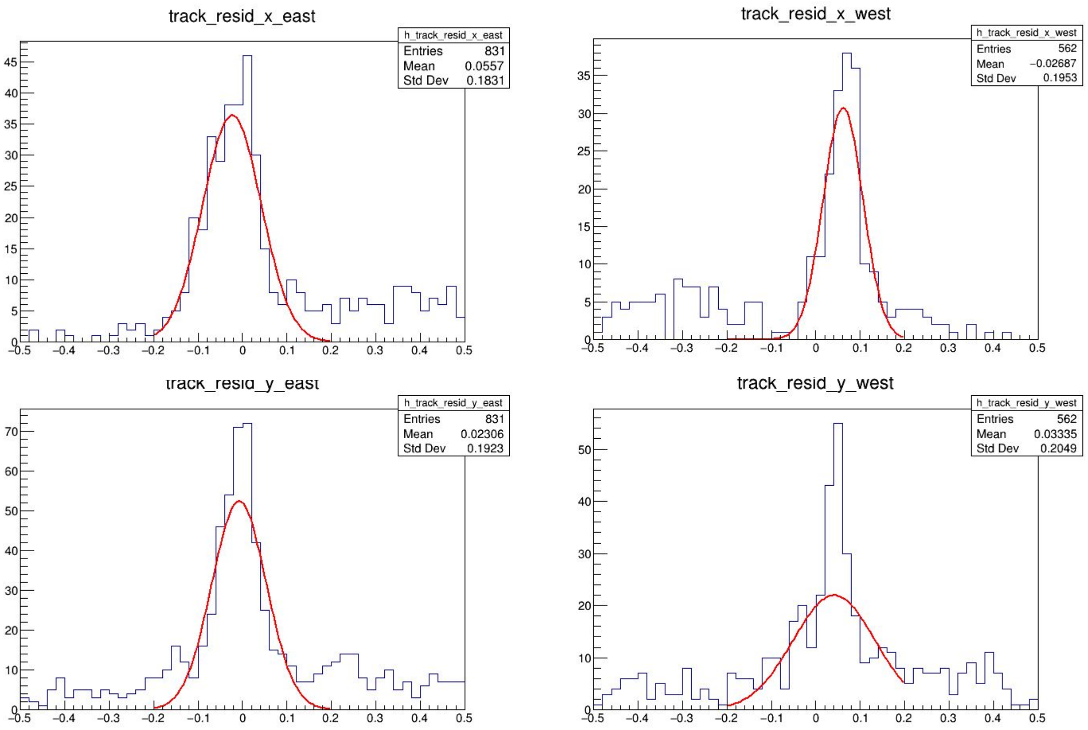
$$\sigma_C = \sigma_0 = 8.7 \ \mu m$$

$$\sigma = \sqrt{\sigma_A^2 + \sigma_B^2 + \sigma_C^2} = \sqrt{37^2 + 52^2 + 8.7^2} = 64 \ \mu m$$

# Residuals in ideal geometry

- Baseline case is *model* geometry only
- Relevant parameter here is the width of the distribution, approximated with a gaussian

| Coor | mean | sigma |
| --- | --- | --- |
| x east | -(2.37±.39)e-2 | (6.60±.41)e-2 |
| x west | (6.13±.36)e-2 | (4.47±.46)e-2 |
| y east | -(7.85±.31)e-3 | (6.12±.54)e-2 |
| y west | (4.10±.68)±e-2 | (9.24±1.17)e-2 |

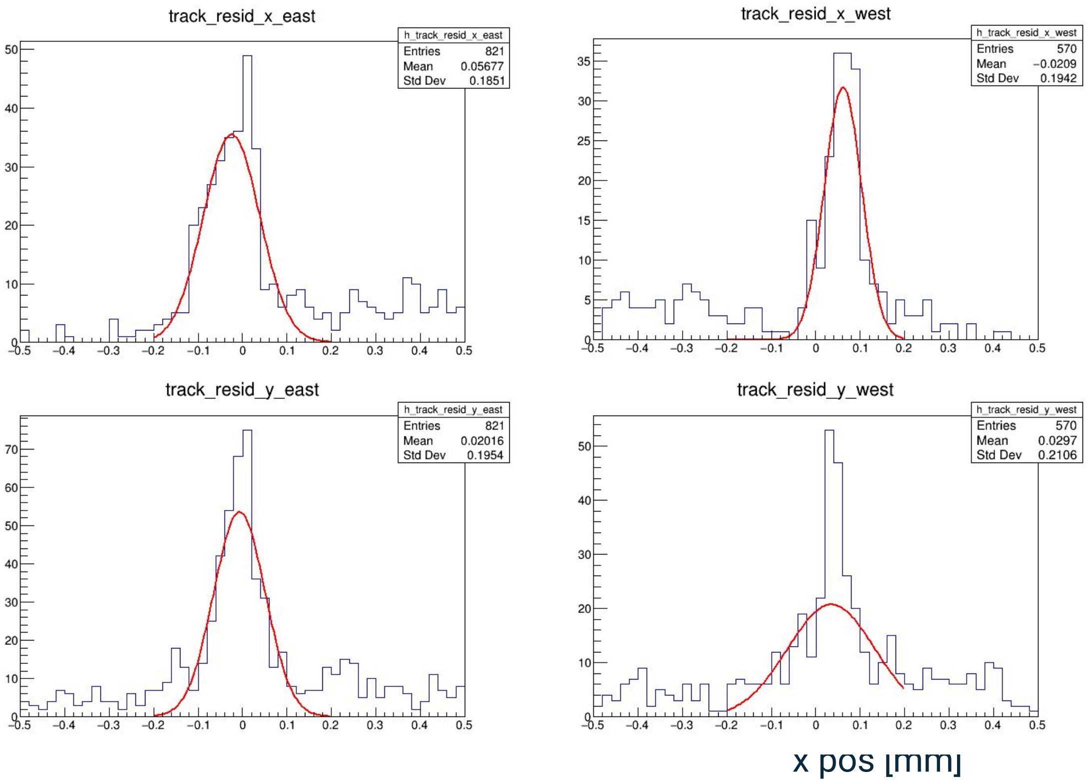



x pos [mm]

# Residuals w/ chip metrology and stave rotation

- Chip metrology and stave rotation applied
- Holding off on translations until q's are resolved
- General decrease in widths of gaussian fits

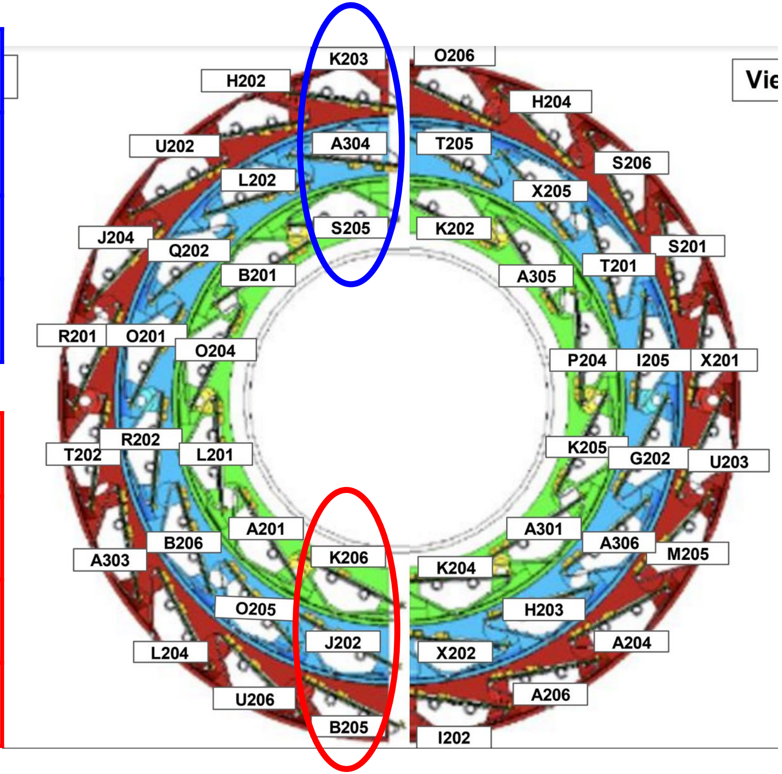
| Coor | mean | sigma |
|---|---|---|
| x east | -(2.48±.39)e-2 | (6.37±.44)e-2 |
| x west | (6.12±.34)e-2 | (4.19±.46)e-2 |
| y east | -(7.04±.30)e-3 | (5.81±.45)e-2 |
| y west | (3.46±.73)e-2 | (9.85±1.23)e-2 |



# SecW: S9S12S15 & S2S3S4

| Angle (mrad) | CMM (model) | Alignment (model) |
|---|---|---|
| L12 | 37.70 (34.91) | 34.56 (34.86) |
| L01 | 147 (148.4) | 149.6 (149.2) |
| L02 | 184.7(183.3) | 184.1 (184.1) |

| Angle (mrad) | CMM (model) | Alignment (model) |
|---|---|---|
| L12 | 37.48 (43.63) | 44.62 (43.68) |
| L01 | 17.48 (17.46) | 18.75 (18.34) |
| L02 | 20.01 (26.17) | 25.88 (25.34) |

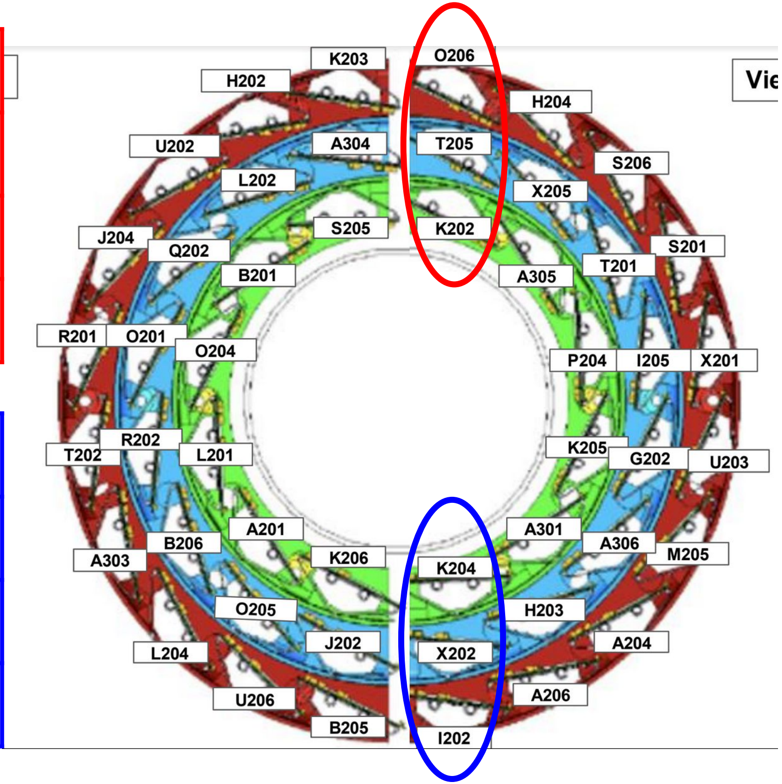



* note difference in “model” angles is the result of rounding in the Alignment column

# SecE: S3S4S5 & S8S11S14

| Angle (mrad) | CMM (model) | Alignment (model) |
|---|---|---|
| L12 | 46.76 (43.63) | 43.05 (43.68) |
| L01 | 16.45 (17.46) | 17.95 (18.34) |
| L02 | 30.32 (26.17) | 25.10 (25.34) |

| Angle (mrad) | CMM (model) | Alignment (model) |
|---|---|---|
| L12 | 39.14 ( 34.91) | 35.26 (35.86) |
| L01 | 132.0 (148.8) | 149.2 (149.2) |
| L02 | 171.2 (183.3) | 183.3 (184.1) |




* note difference in “model” angles is the result of rounding in the Alignment column