STAR Forward Tracker Alignment

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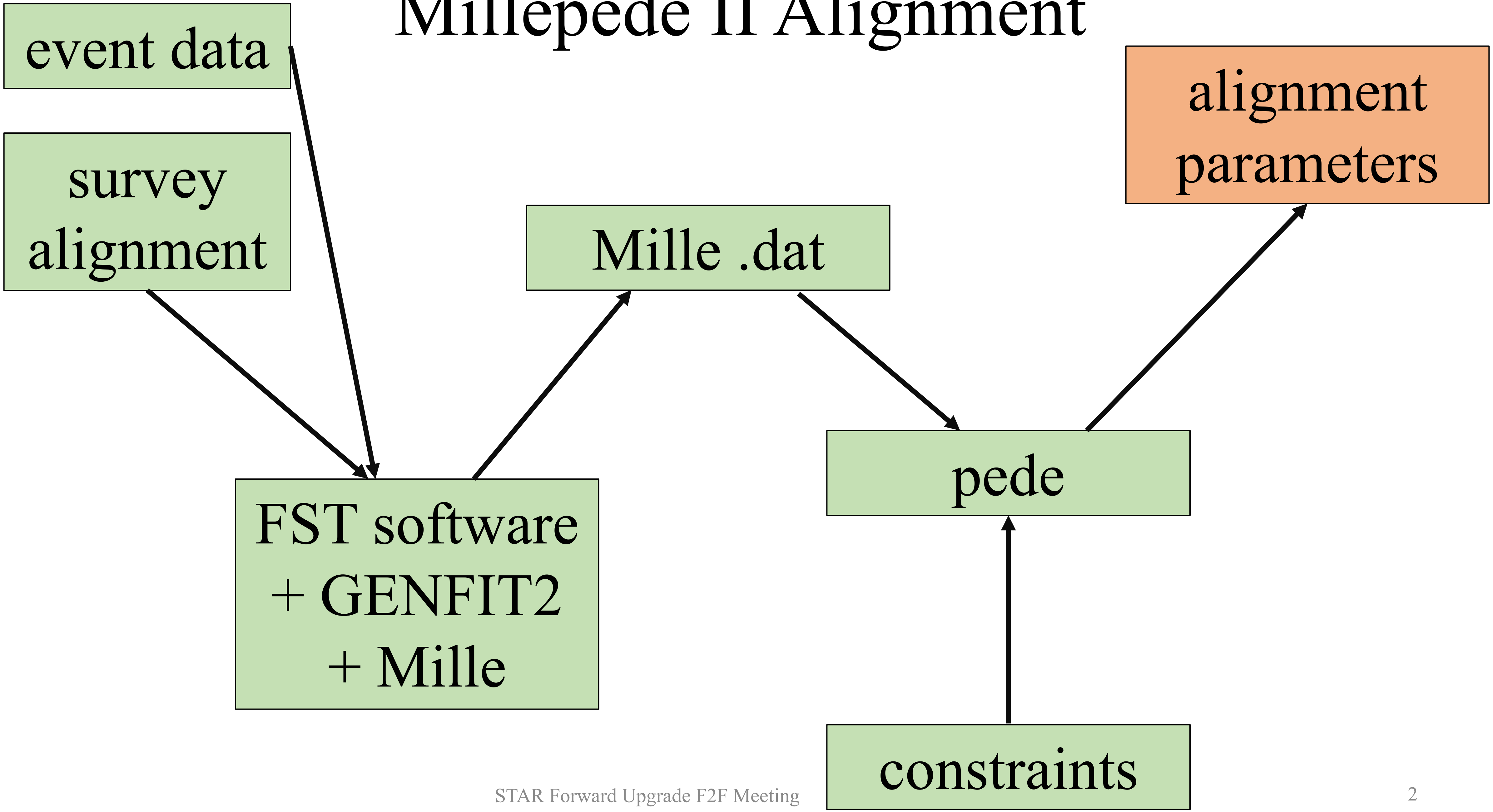
Millepede II Alignment



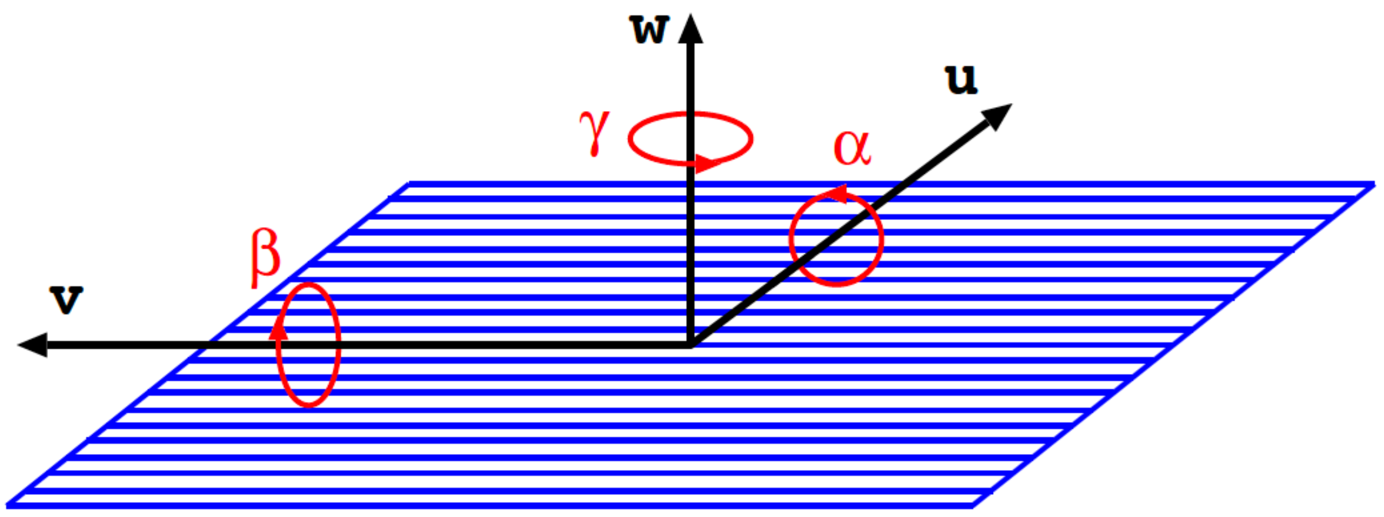
Alignment (global) Parameters

FST

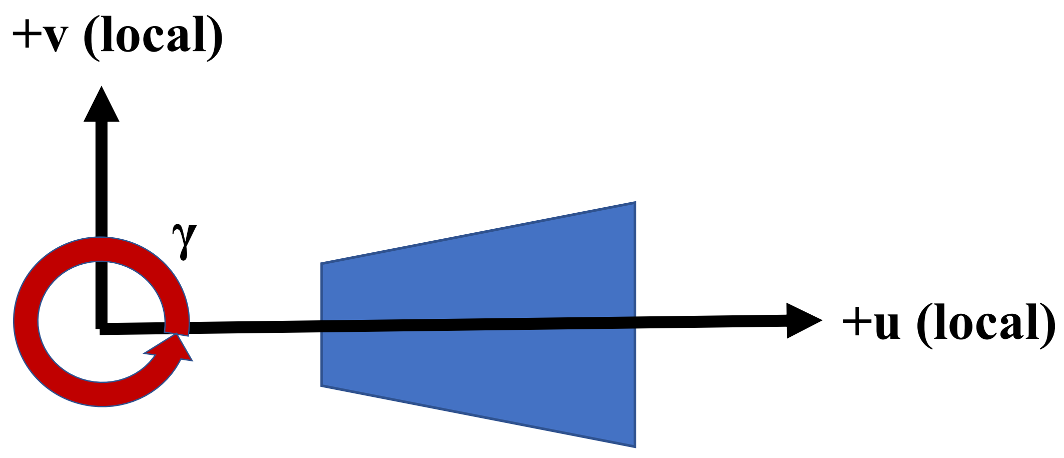
Translations: Δu, Δv, Δw

Rotations: $\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$

- 3 alignment parameters for a sensor (108 sensors).
  - Δw, $\Delta\alpha$, $\Delta\beta = 0$, since we assume they lie flat on the wedge.
- 6 per wedge (36 wedges).
- 6 per FST half (2 halves).
- 6 for FST.
- 558 alignment parameters.



CMS, doi:10.1088/1748-0221/9/06/P06009.



Changes to Simulation and Tracking Code

- FTT hits now added in proper order to GBL track.
- φ-gap between outer sensors is properly accounted for FST hit reconstruction.
- Hit selection for FST has been updated (as of 12/02/22):
  - If two or more hits exist within the acceptance zone on the same sensor, we accept the closest one.
  - If two or more hits exist within the acceptance zone on different sensors in the same FST plane, we accept both.
    - Small portion of tracks, but it is possible, especially with misalignment.

Single Inner Sensor Alignment

- Misalign 1 inner sensor (sensorIdx = 36) in FST simulated geometry.
- Throw mu+ with particle gun with following settings:
  - $4.99 < p_T < 5.0$ GeV/c
  - $2.9 < \eta < 4.4$
  - $0.9 < \varphi < 1.7$ rad
  - B = 0 T
- Require hits on sensor 36.
- Fit with GenFit Kalman filter and then refit with GenFit GBL.
- Output all necessary data to Mille.dat files. Mille.dat files are then fed to pede.
- Fix rotations about u-axis and v-axis, in addition to w translation all to 0.
- Matrix inversion used to solve for alignment parameters.

Single Inner Sensor Alignment

Real Track Finding + No Seed (Real Case)

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	50.0	32.8	2.4	0.002
Δv (μm)	50.0	28.3	1.2	0.955
$\Delta\gamma$ (mrad)	2.000	2.074	0.014	0.955

MC Track Finding + No Seed

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	50.0	42.3	2.4	0.006
Δv (μm)	50.0	31.7	1.2	0.955
$\Delta\gamma$ (mrad)	2.000	2.064	0.014	0.955

Real Track Finding + Use MC Track as Seed

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	50.0	38.3	2.2	0.003
Δv (μm)	50.0	50.7	1.2	0.955
$\Delta\gamma$ (mrad)	2.000	1.954	0.013	0.955

MC Track Finding + Use MC Track as Seed

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	50.0	46.8	2.2	0.004
Δv (μm)	50.0	50.2	1.2	0.955
$\Delta\gamma$ (mrad)	2.000	1.975	0.013	0.955

2σ away from input

Single Inner Sensor Alignment

Real Track Finding + MC FST hits + No Seed

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	50.0	41.3	2.4	0.002
Δv (μm)	50.0	27.9	1.2	0.955
Δγ (mrad)	2.000	2.093	0.014	0.955

Real Track Finding + MC FST hits + MC Seed

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	50.0	45.7	2.2	0.001
Δv (μm)	50.0	50.6	1.2	0.955
Δγ (mrad)	2.000	1.971	0.013	0.955

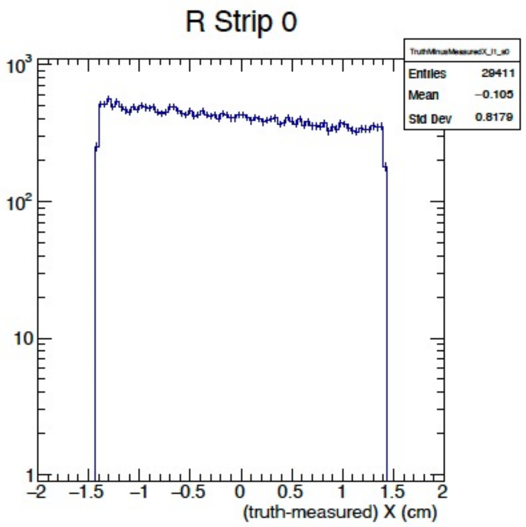
Single Inner Sensor Alignment

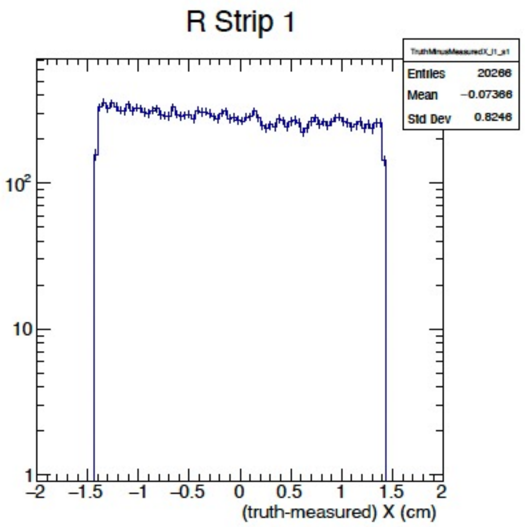
Track Finding Method (FTT)	Hit Finding Method (FST)	Seed?	# “Good” Parameters	# “Bad” Parameters
Real	Real	No	0	3
Real	Real	Yes, MC Track	1	2
Real	MC	No	0	3
Real	MC	Yes, MC Track	2	1
MC	MC	No	0	3
MC	MC	Yes, MC Track	3	0

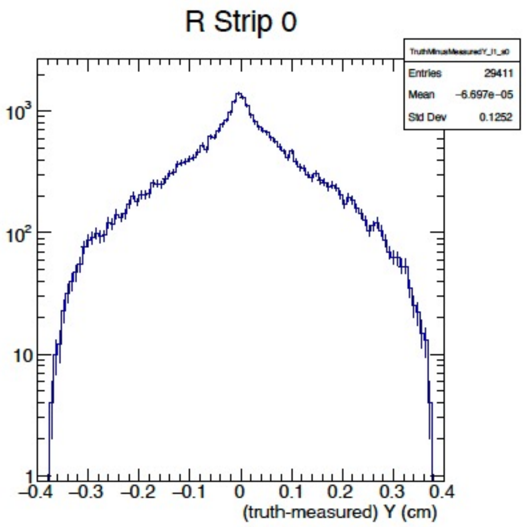
Status of Alignment:
- “Good”: Parameter found within 2σ of its input.
- “Bad”: Parameter found outside 2σ of its input.

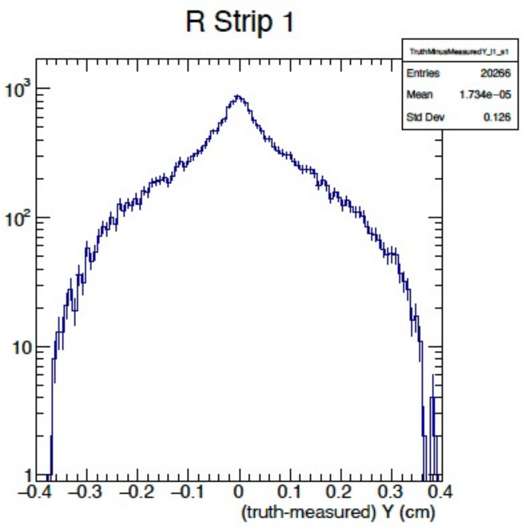
With zero field alignment, it seems that poorly determined track momentum may be causing “Bad” output alignment parameters.

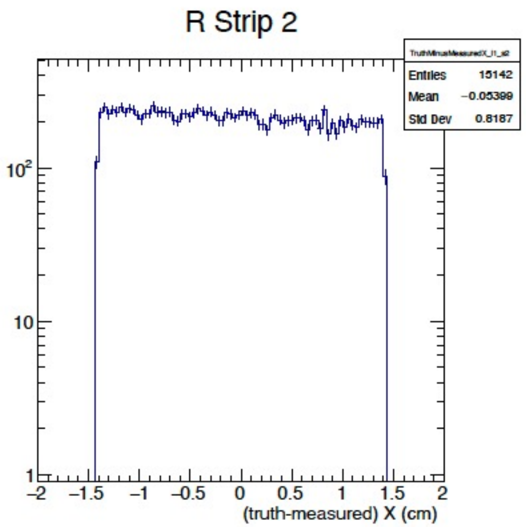
Inner Sensor MC – RC (x and y) No Misalignment

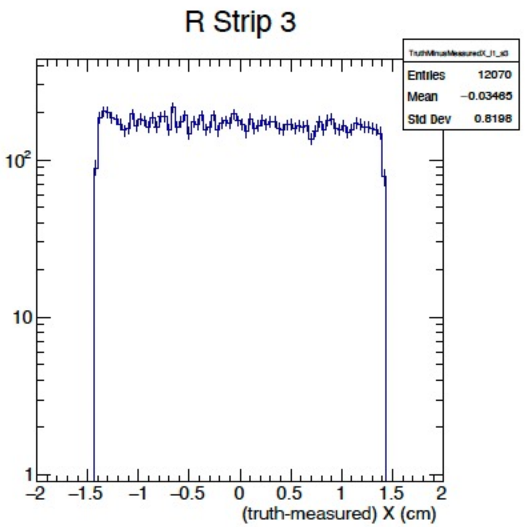


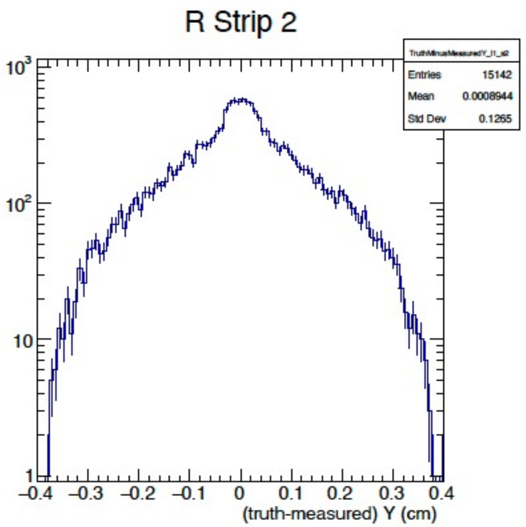


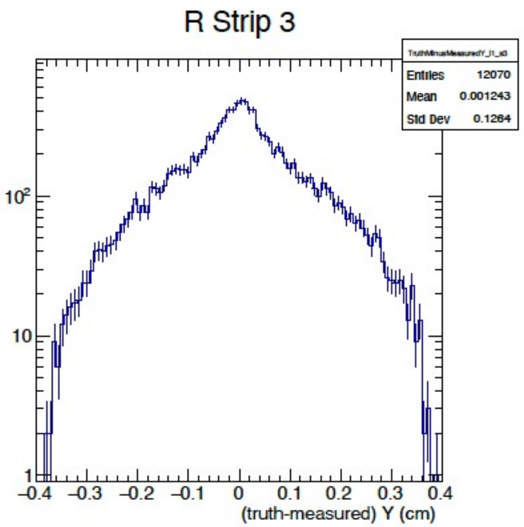




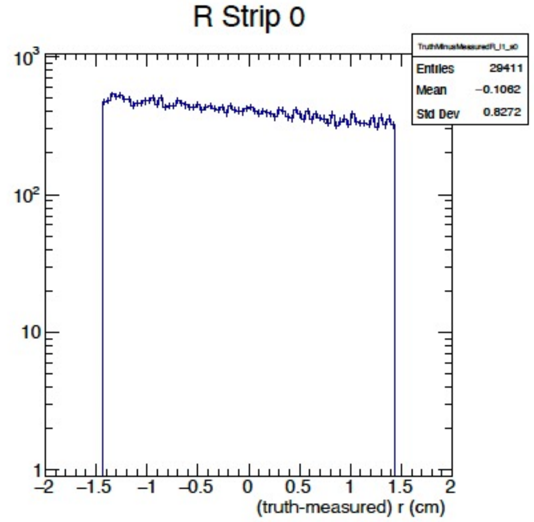


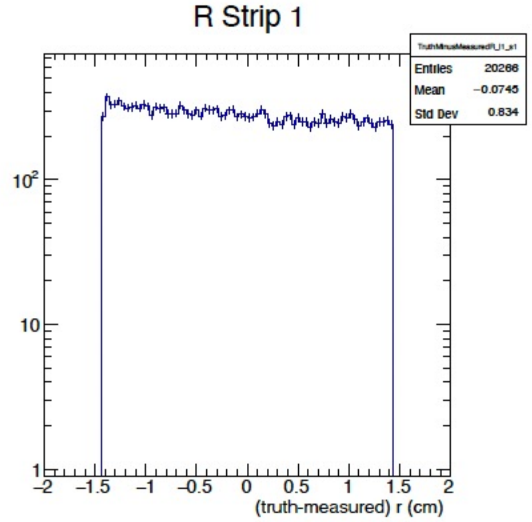


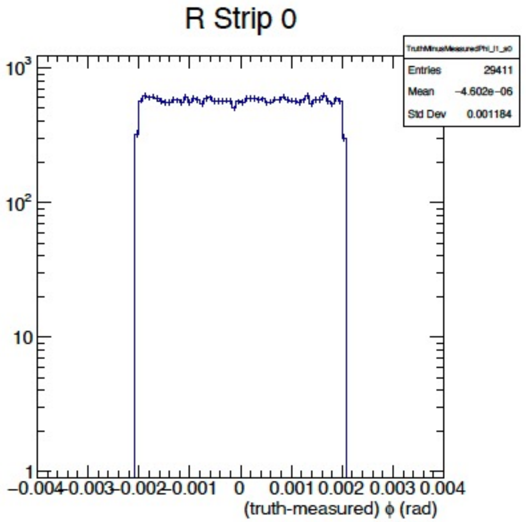


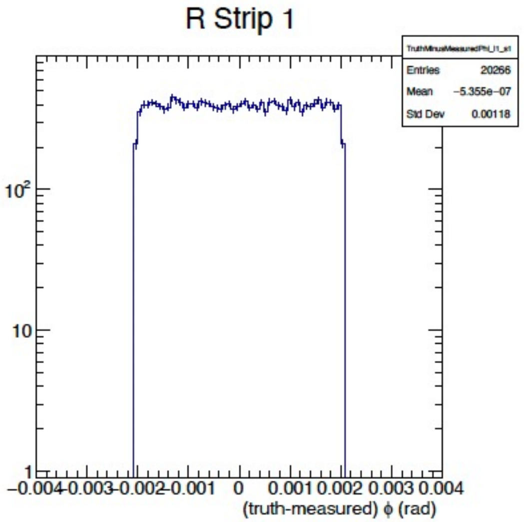


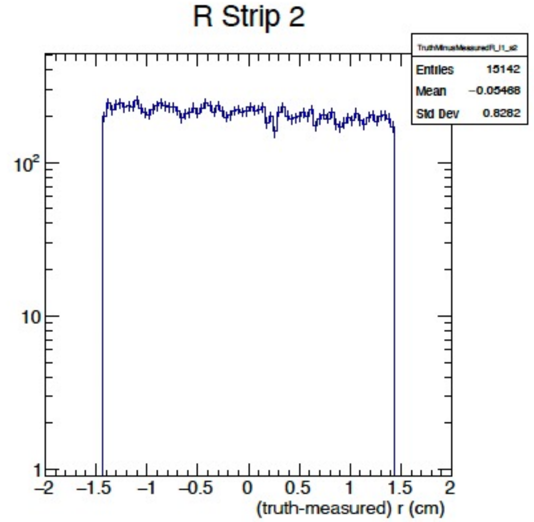
Inner Sensor MC – RC (r and φ) No Misalignment

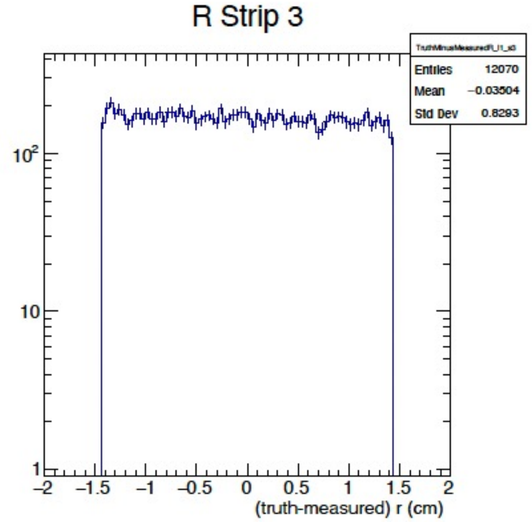


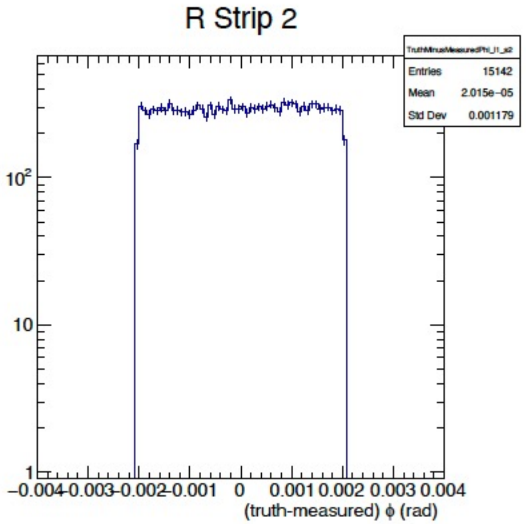


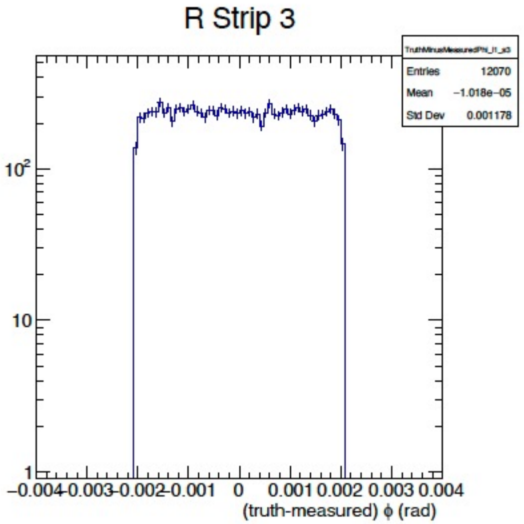




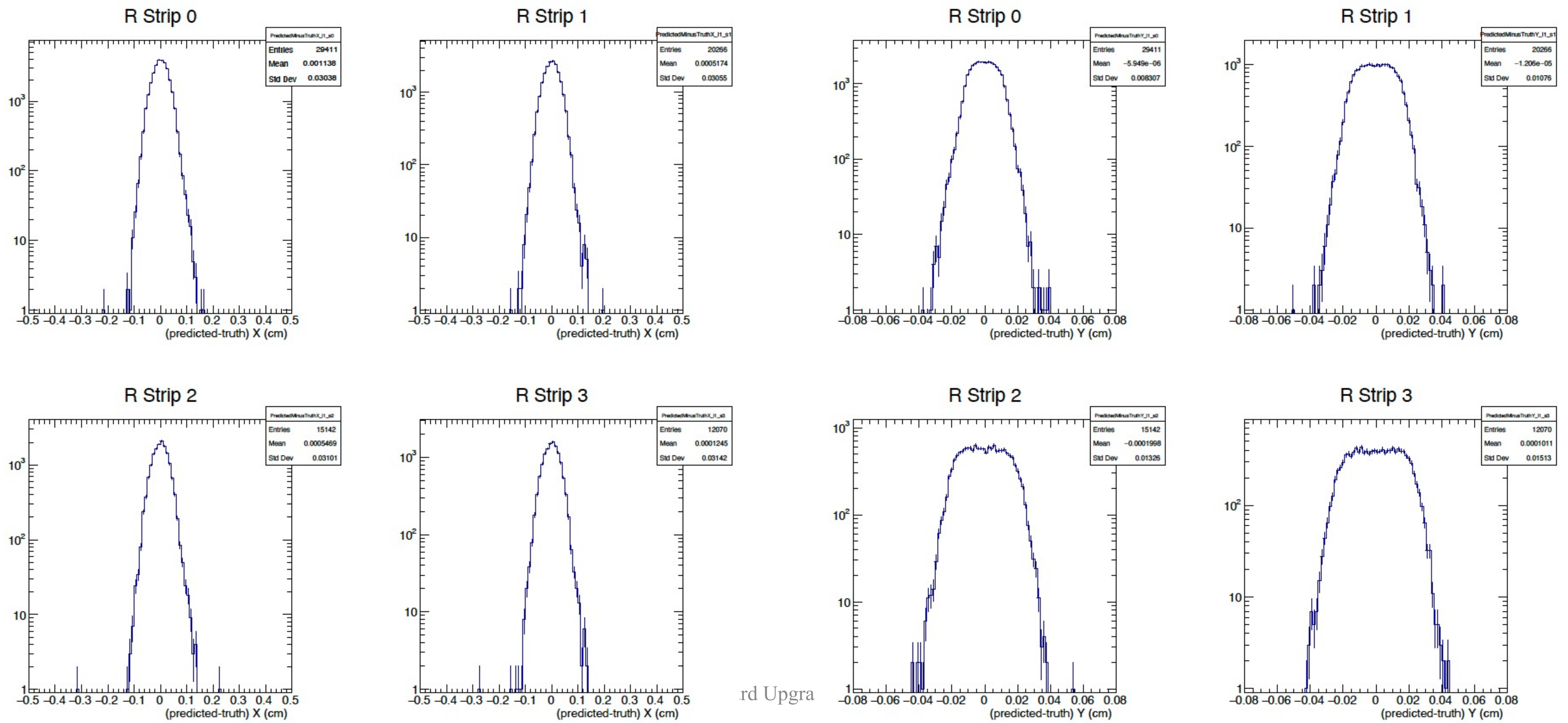




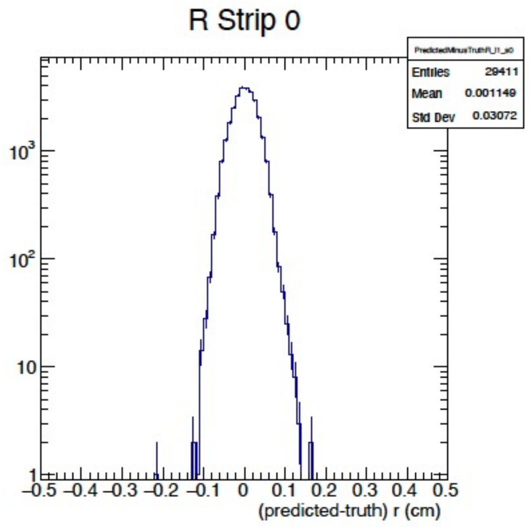


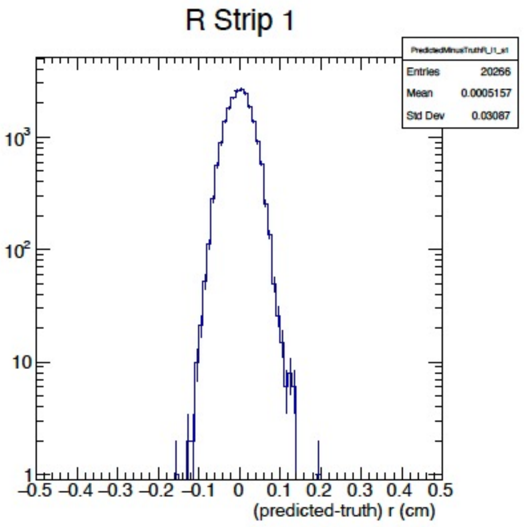


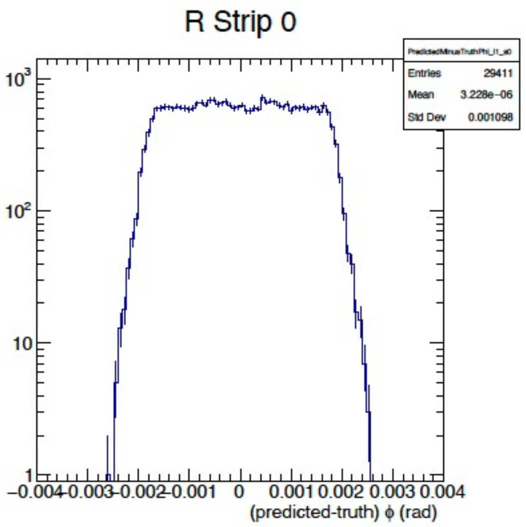
Inner Sensor Predicted – Truth (x and y) No Misalignment

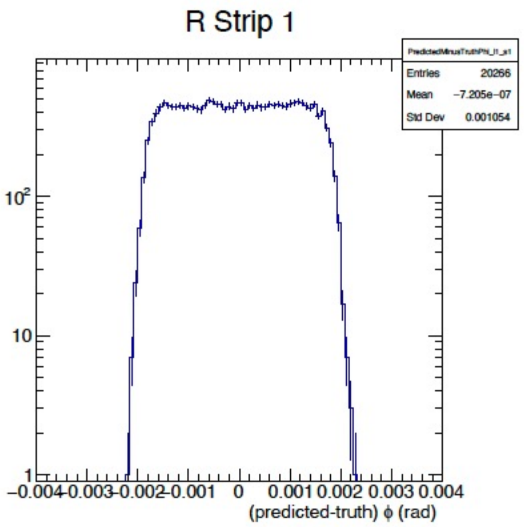


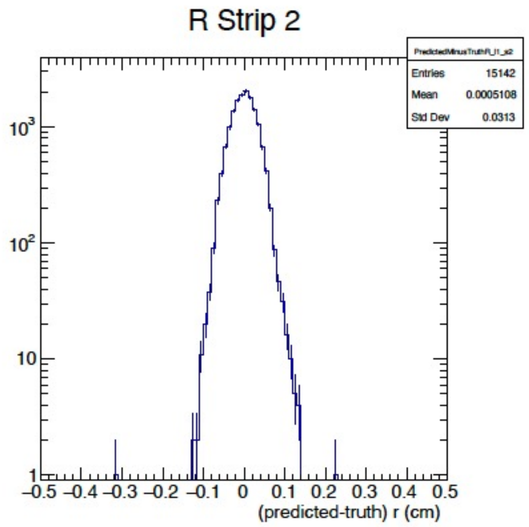
Inner Sensor Predicted – Truth (r and φ) No Misalignment

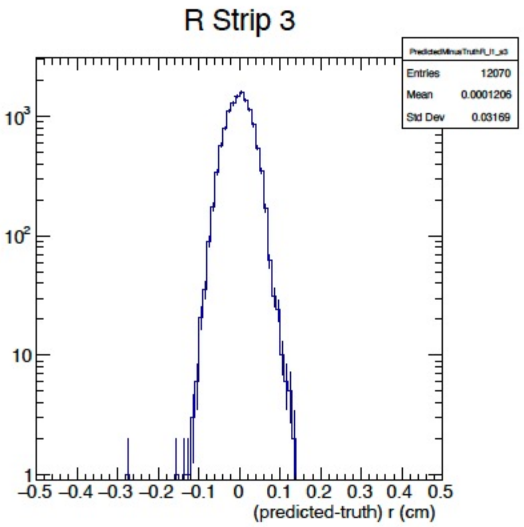


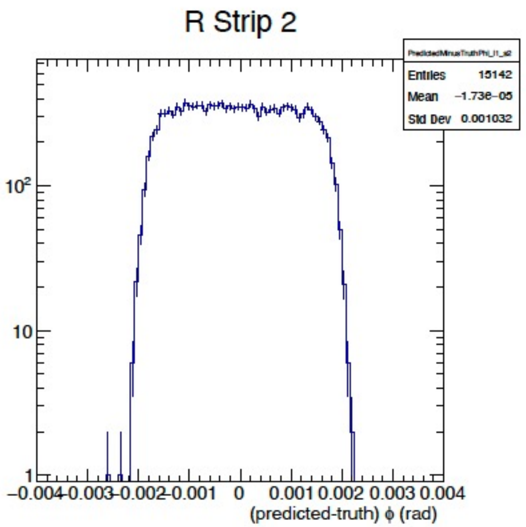


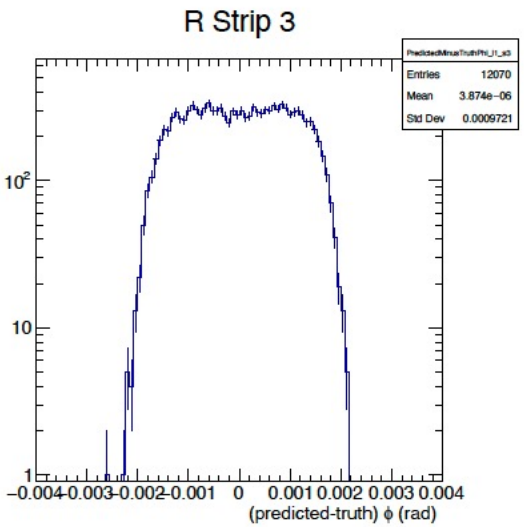






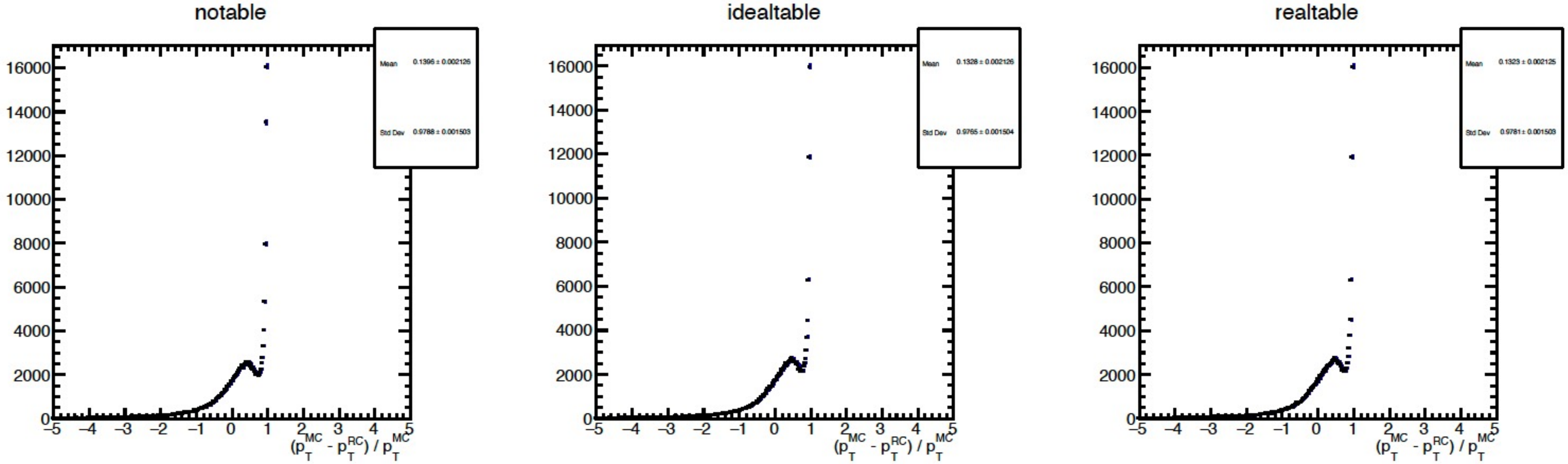






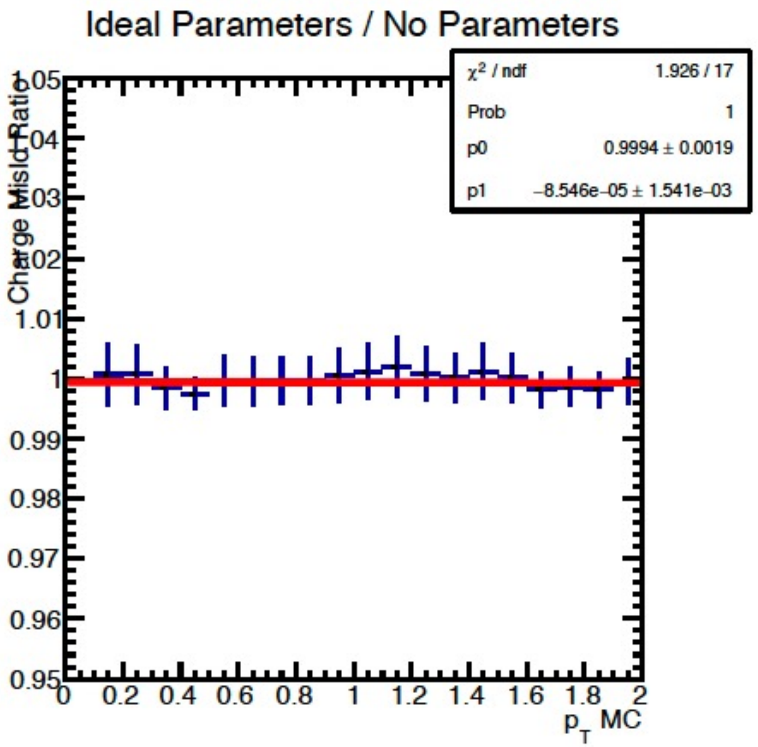
p_T Resolution

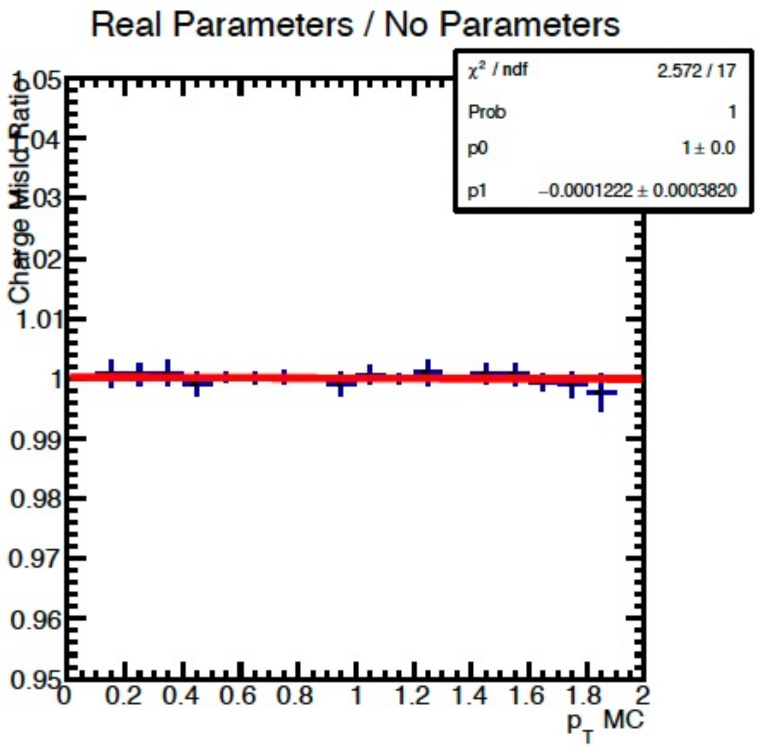
- Simulate μ+ with Field ON using or not using alignment parameters
- Throw particles in same region as alignment simulation but use wider p_T range.
- Large peak around 1?
- On the plus side, the mean and std. dev. consistent within uncertainties for real and ideal alignment tables in reconstruction.

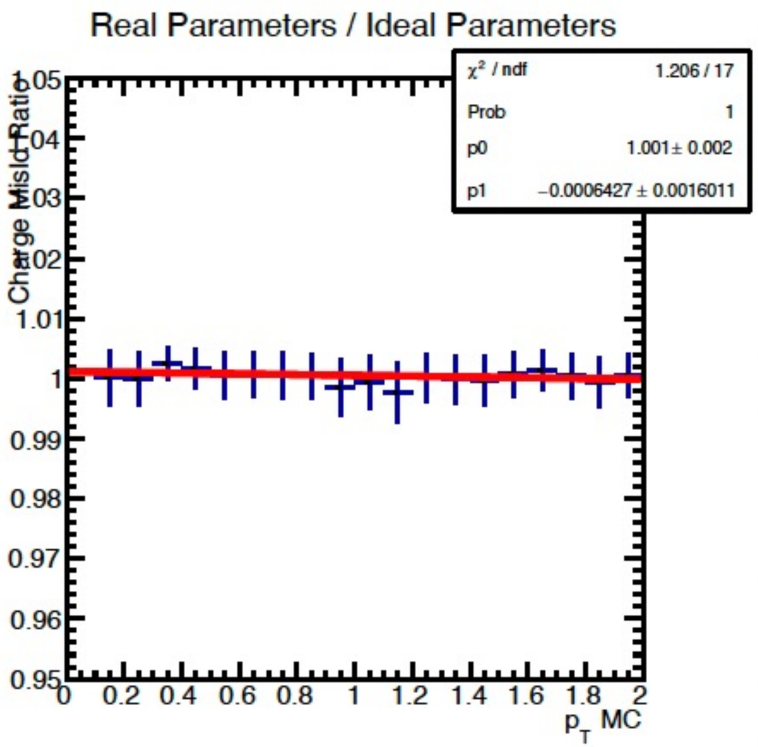


Charge MisID

- Simulate μ+ with Field ON using or not using alignment parameters
- Throw particles in same region as alignment simulation but use wider p_T range.
- No significant slope in the ratio plot for Real / Ideal parameters.





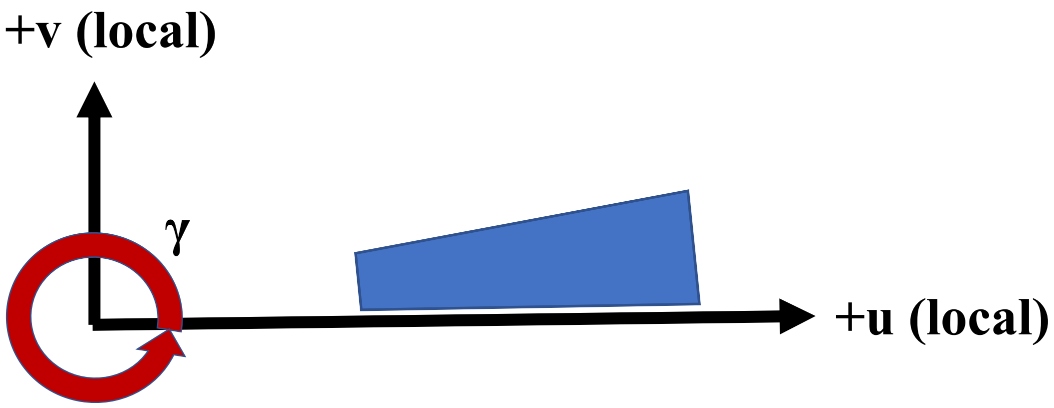


Outer Sensor Alignment

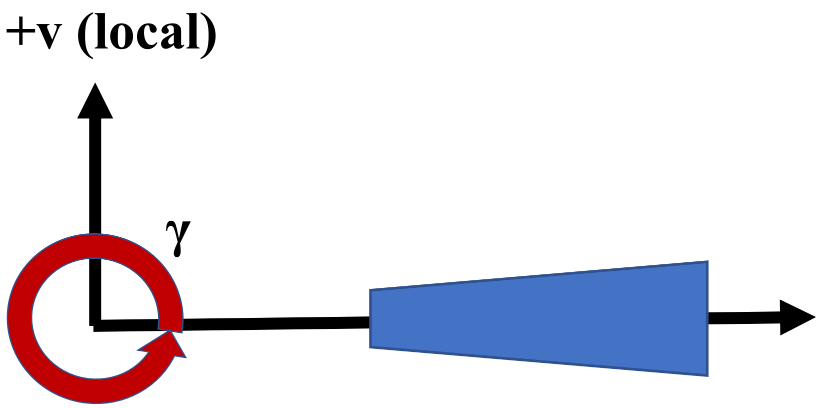
NOTE: These results do not include changes to FST hit selection.

- Similar procedure to inner sensor alignment.
- Throw mu+ with following settings for sensor (37, 38, 37+38):
  - $4.99 < p_T < 5.0$ GeV/c
  - $2.3 < \eta < 3.5$
  - ($0.9 < \varphi < 1.4$, $1.2 < \varphi < 1.7$, $0.9 < \varphi < 1.7$)
  - B = 0 T

Original Local Coordinate System



New Local Coordinate System



- Local coordinate system shifted such that the +u axis is along the center of the strip.

NOTE: These results do not include changes to FST hit selection.

Sensor 37 Only

Original Coordinate System

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	0.0	-61.2	14.5	0.855
Δv (μm)	0.0	7.1	8.6	0.990
Δγ (mrad)	0.000	0.012	0.040	0.990

New Coordinate System

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	0.0	-61.7	14.6	0.003
Δv (μm)	0.0	-0.8	8.5	0.990
Δγ (mrad)	0.000	0.009	0.040	0.990

Sensor 38 Only

Original Coordinate System

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	0.0	-58.9	14.5	0.855
Δv (μm)	0.0	0.8	8.7	0.990
Δγ (mrad)	0.000	-0.043	0.040	0.990

New Coordinate System

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	0.0	-57.4	14.7	0.003
Δv (μm)	0.0	9.1	8.5	0.990
Δγ (mrad)	0.000	-0.043	0.040	0.990

Sensor 37 and 38 with 1 set of parameters

Original Coordinate System

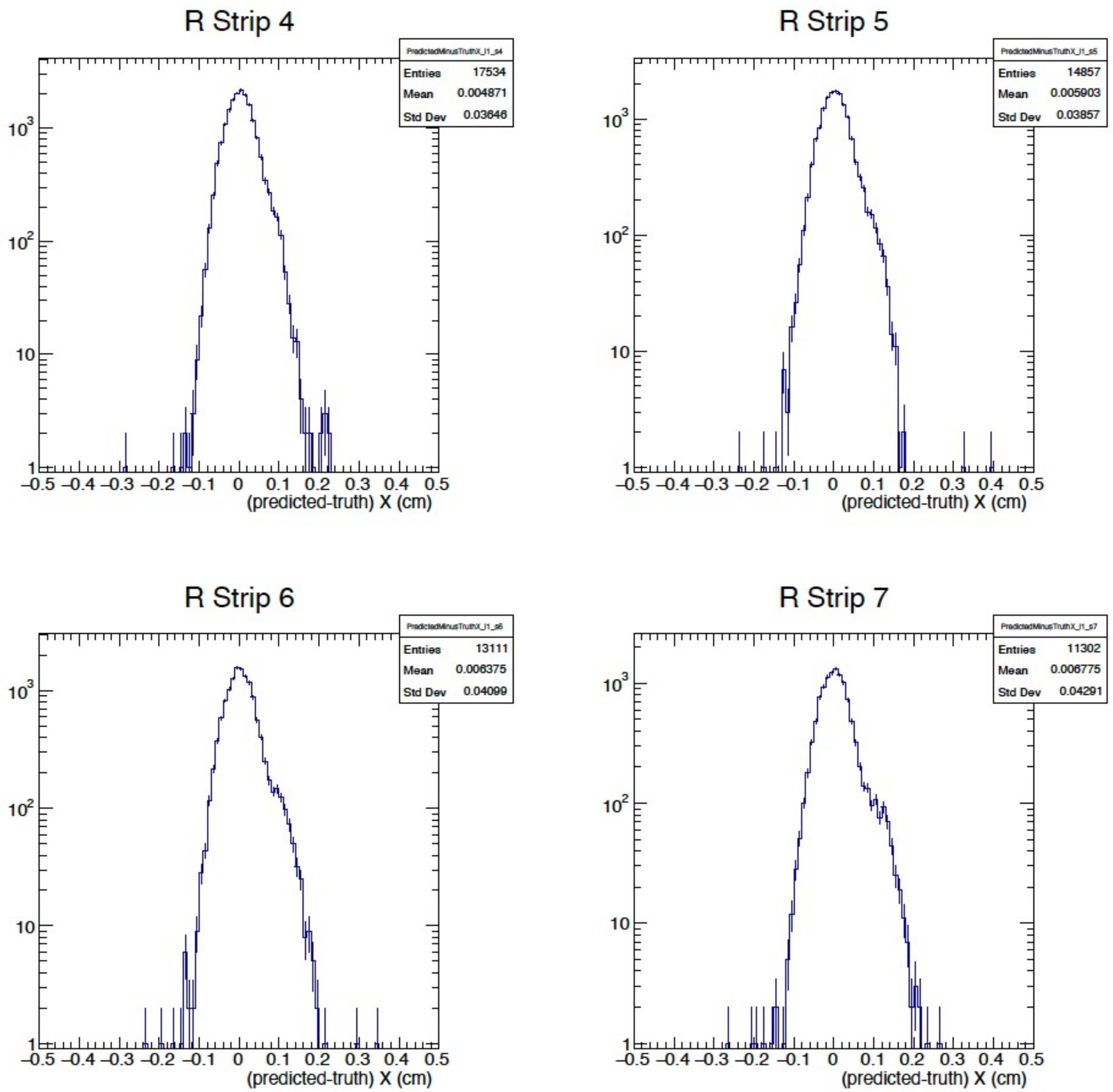
Parameter	Input	Output	Error	Global Corr.
Δu (μm)	0.0	-10.9	6.7	0.004
Δv (μm)	0.0	-3.9	7.7	0.990
Δγ (mrad)	0.000	0.015	0.036	0.990

New Coordinate System

Parameter	Input	Output	Error	Global Corr.
Δu (μm)	0.0	-48.1	13.1	0.003
Δv (μm)	0.0	-4.0	7.6	0.990
Δγ (mrad)	0.000	0.016	0.036	0.990

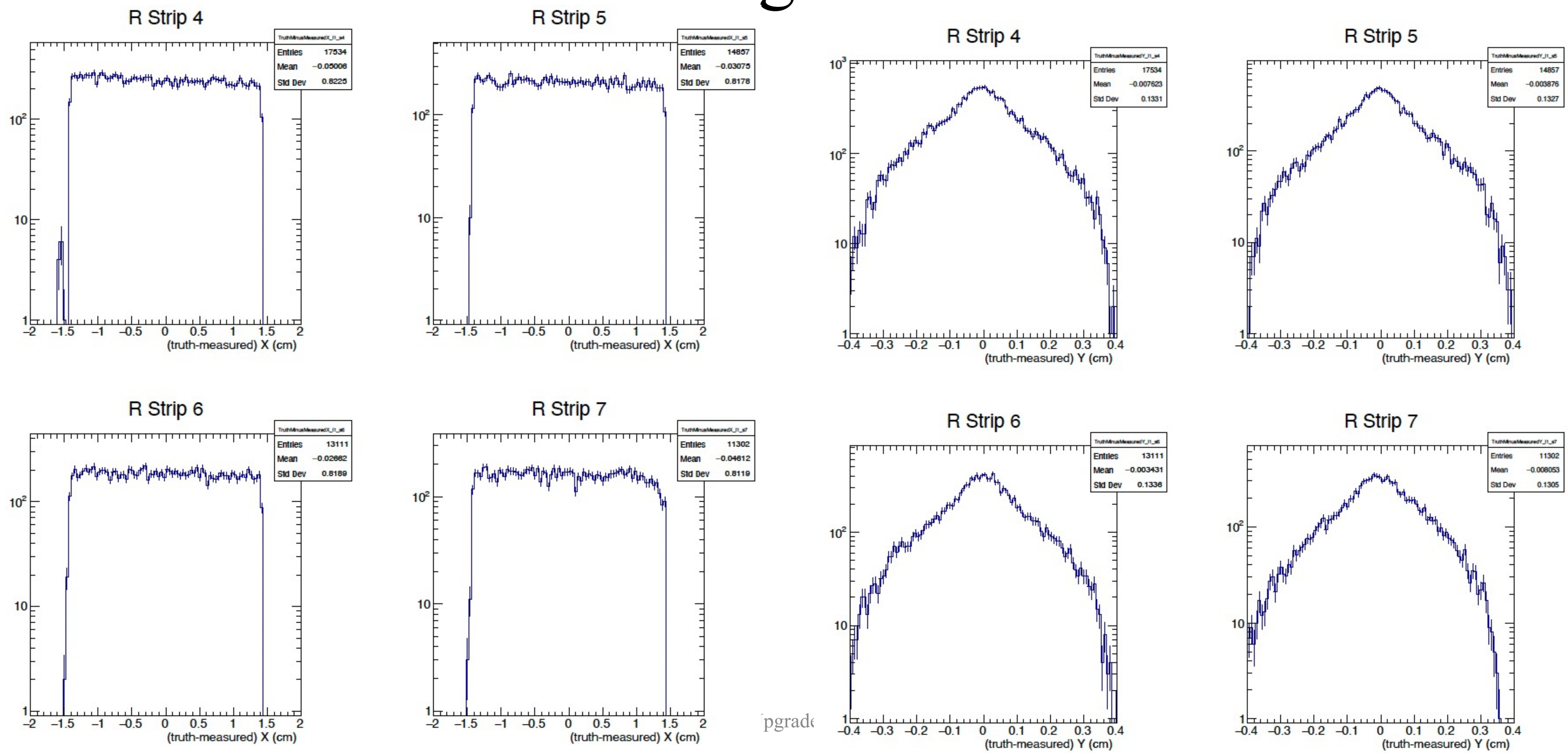
Δu in Outer Sensor Alignment?

- With no misalignment we find a non-zero Δu.
- Consistent with residuals.
  - Need to understand why this occurs.
  - Geometry bias?

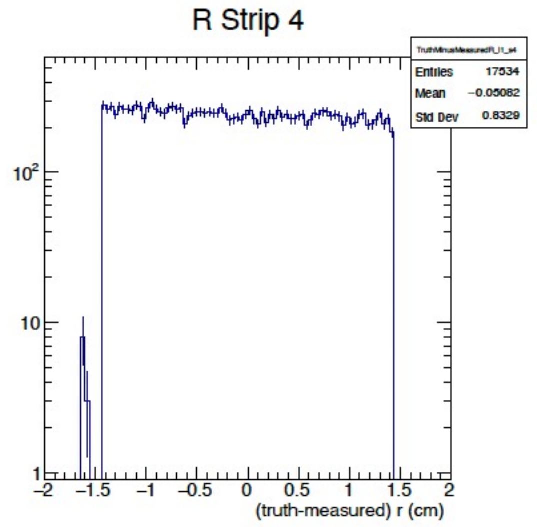


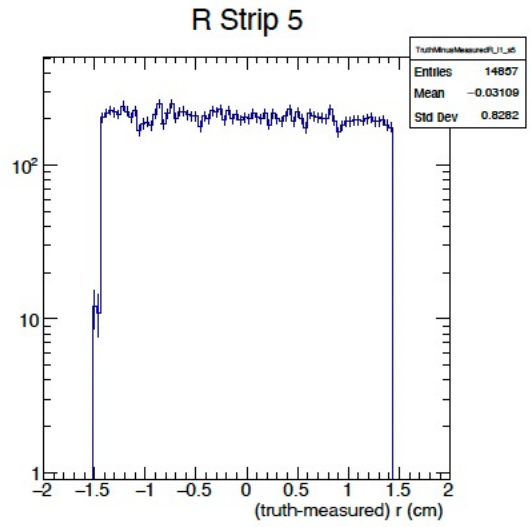
NOTE: These results do not include changes to FST hit selection.

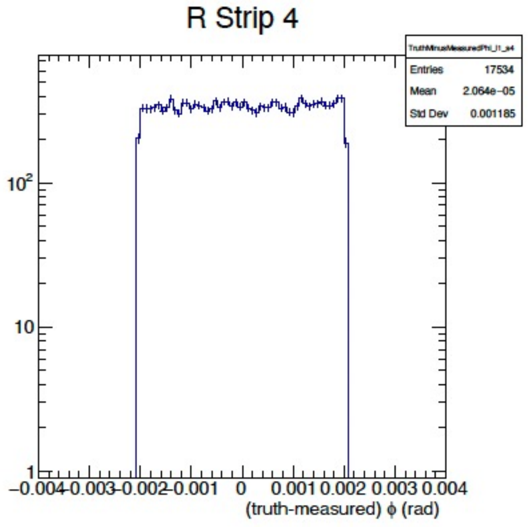
Outer Sensor MC – RC (x and y) No Misalignment

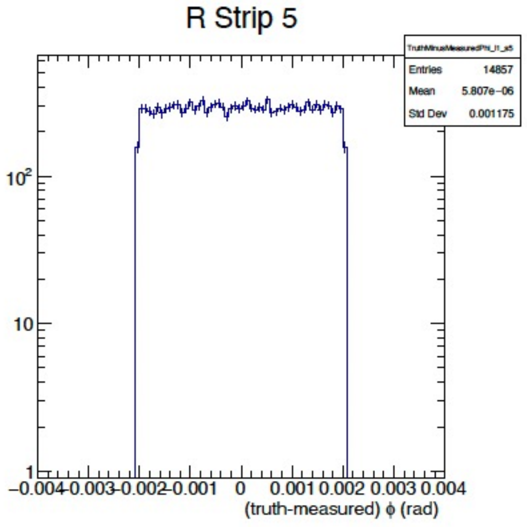


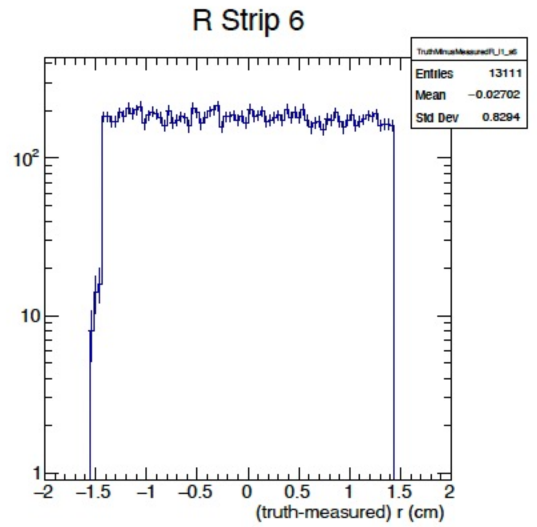
Outer Sensor MC – RC (r and φ) No Misalignment

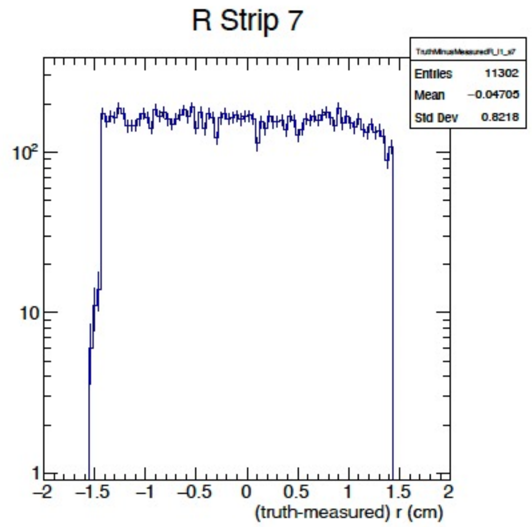


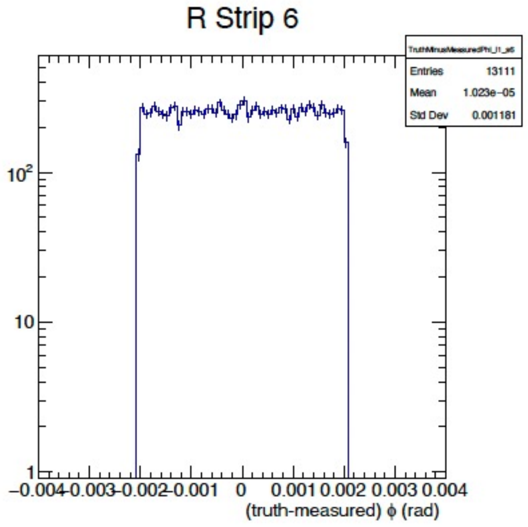


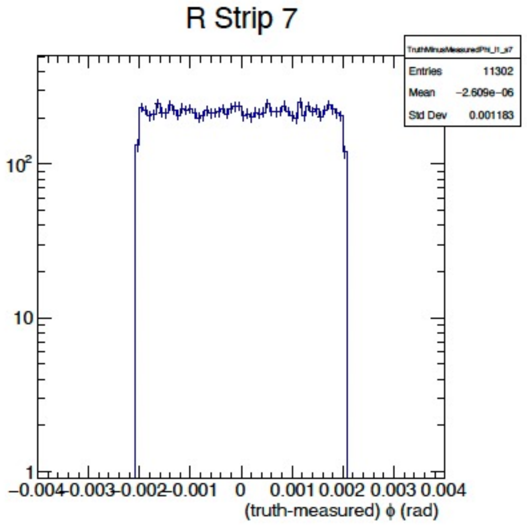




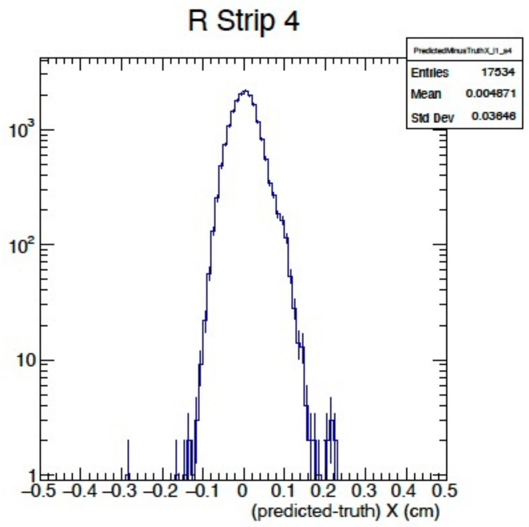


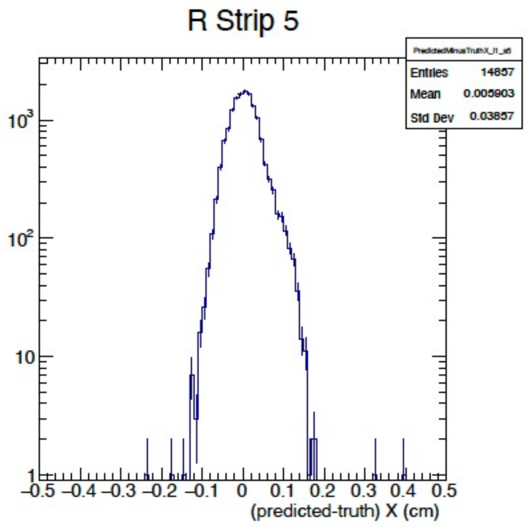


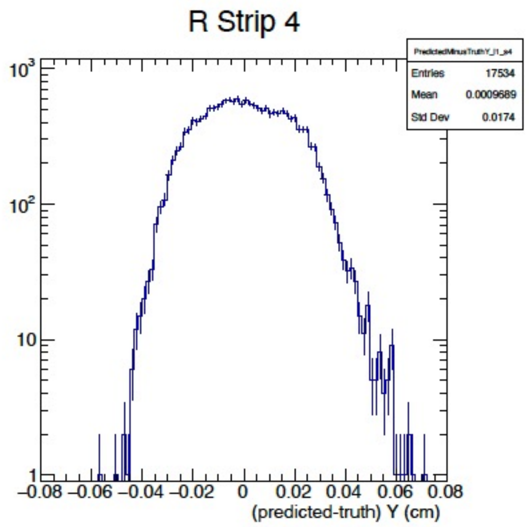


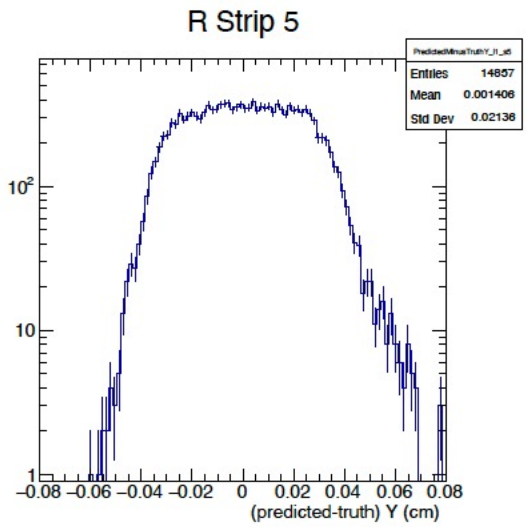


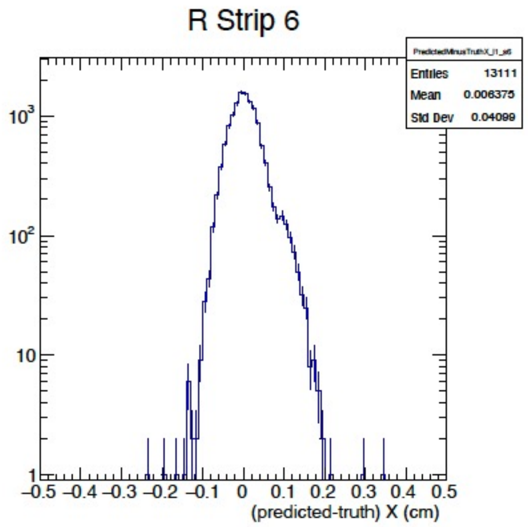
Outer Sensor Predicted – Truth (x and y) No Misalignment

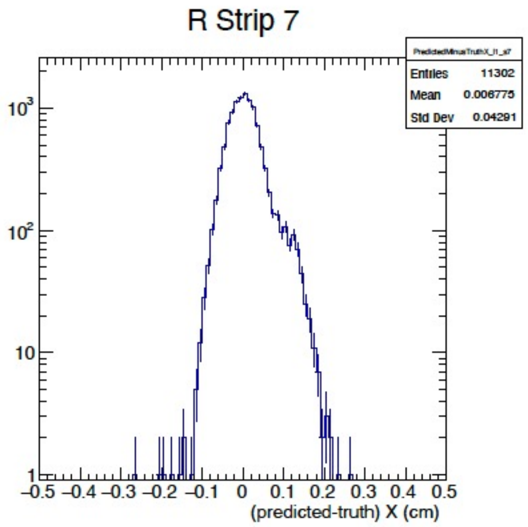


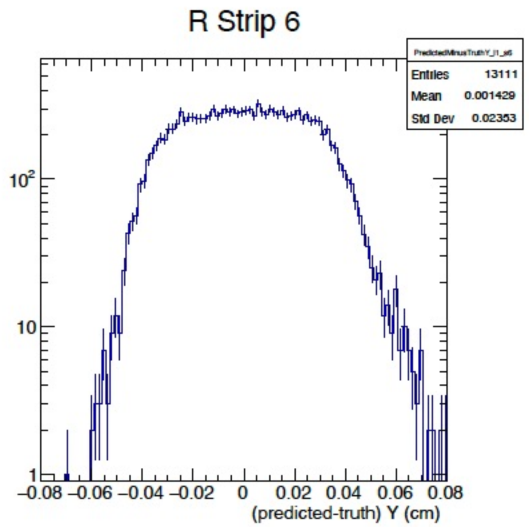


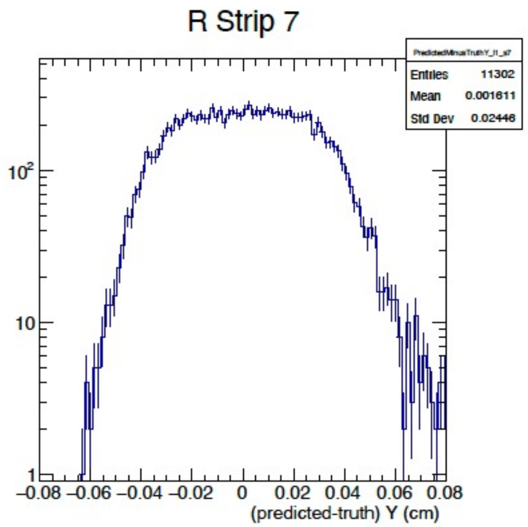




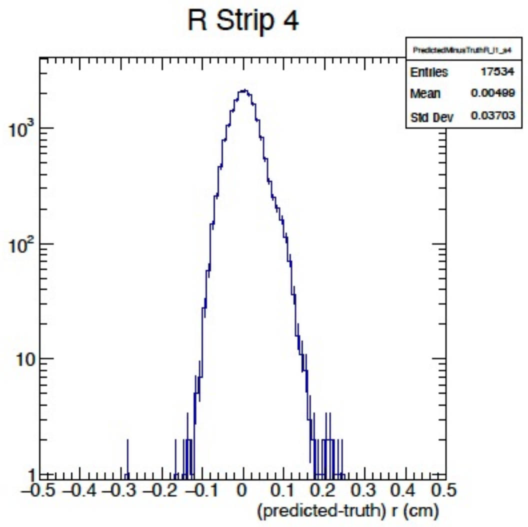


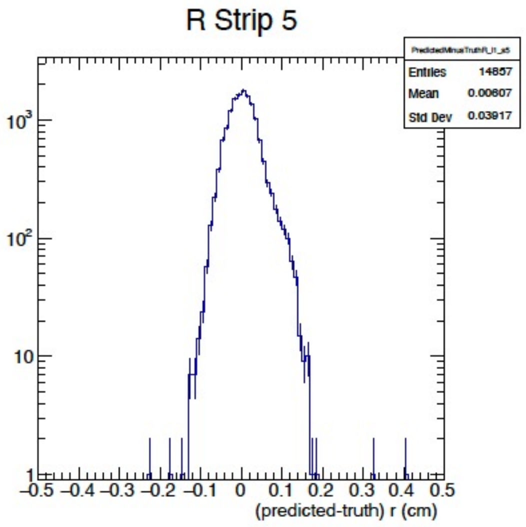


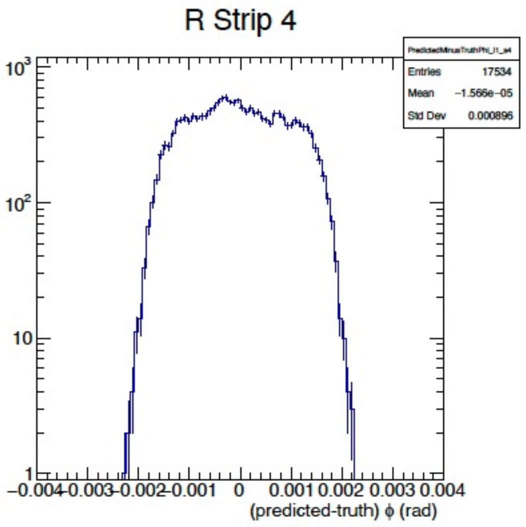


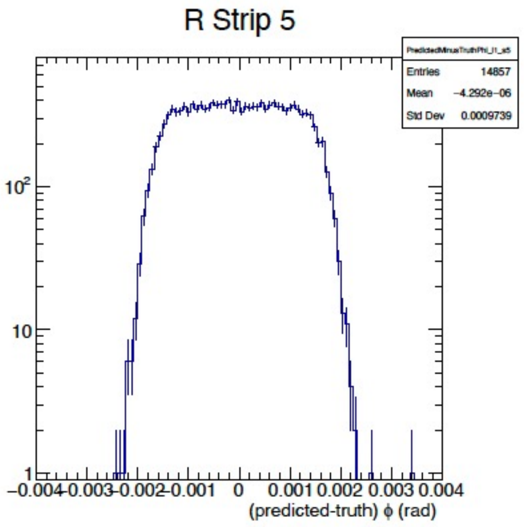


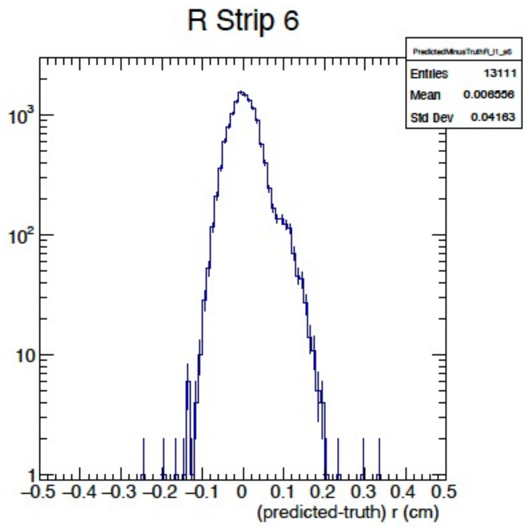
Outer Sensor Predicted – Truth (r and φ) No Misalignment

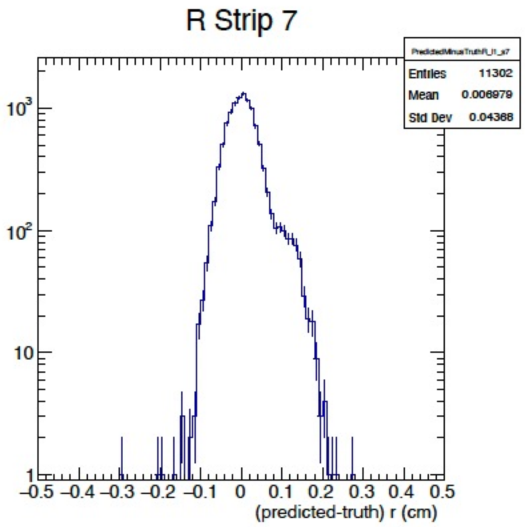


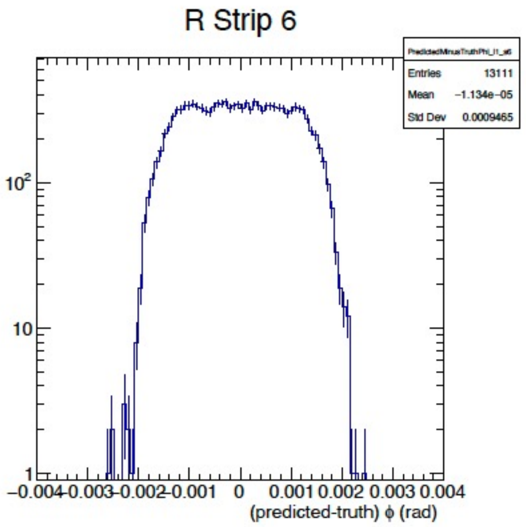


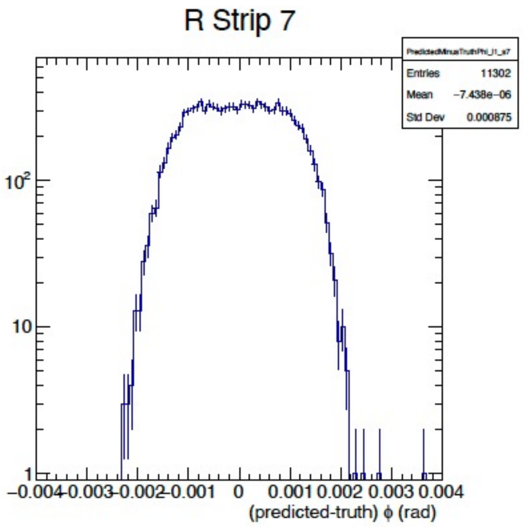












Summary and Outlook (Inner)

- We can find the correct alignment parameters for the most ideal case.
- Using MC momentum as the seed of the fit appears to be the most crucial component.
- Charge Mis-ID and p_T Resolution match whether we use the ideal alignment tables or the real alignment tables directly from Millepede.
  - Why is there a large peak at 1 for all cases?
  - Try Misaligning two sensors and then three sensors and repeat this test.

- There is an updated sTGC geometry that implements alignment tables.
  - Add sTGC misalignment in alignment and tracking software.
  - Test cartesian vs polar detector for alignment.

Summary and Outlook (Outer)

- Consistently extract non-zero Δu for single sensors no matter the local coordinate system.
  - Investigate possible Geometry bias.
- Combining the sensors can somehow reduce this unknown bias.
  - Related to the possible bias above.

- Track for aligning the test inner sensor can pass through the outer sensors on the other planes and could therefore be impacted.

BACKUP

Millepede-II with GBL

- Track parameterized by $\boldsymbol{q} = (\boldsymbol{u_i}, \dots, \boldsymbol{u_{\#planes}})$, where $\boldsymbol{u_i}$ vectors are offsets at FST or sTGC plane.
- Minimize the following function, where **p** are the alignment parameters and $\mathbf{q_j}$ are the track parameters.

$$\chi^2(\mathbf{p}, \mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{\text{measurements}} \left(\frac{m_{ij} - f_{ij}(\mathbf{p}, \mathbf{q}_j)}{\sigma_{ij}} \right)^2$$

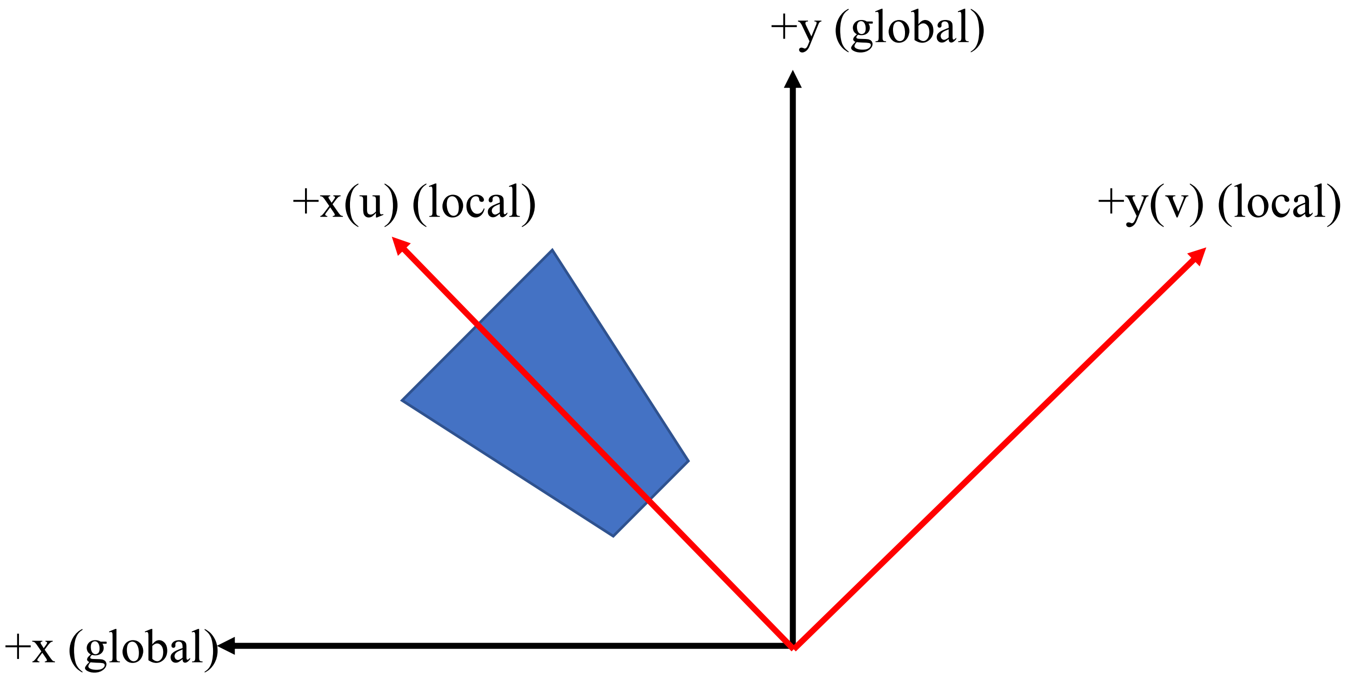
- Data necessary to run Millepede-II:

\# of local parameters
\# of global parameters
residuals = $m_{ij} - f_{ij}(\boldsymbol{p}, \boldsymbol{q}_j)$
σ = standard deviation of the measurement

array: $\left(\frac{\partial f}{\partial q_j}\right)$
array: $\left(\frac{\partial f}{\partial p_l}\right)$
label array, l

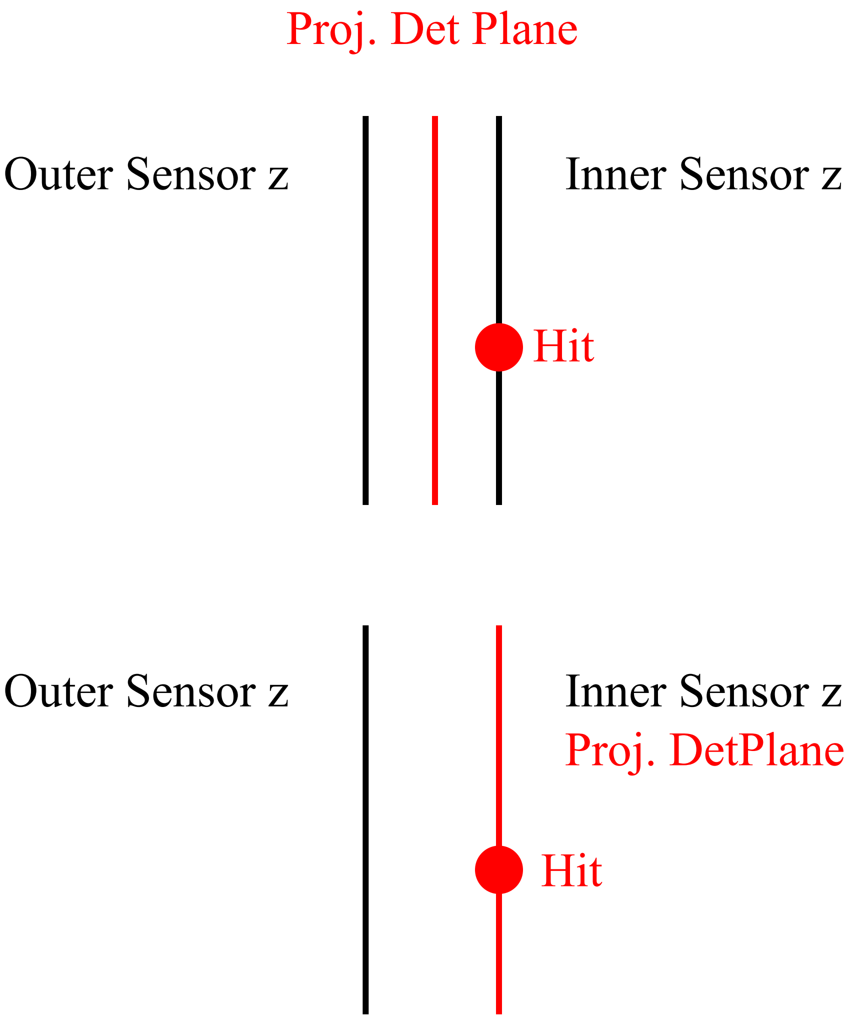
https://www.desy.de/~kleinwrt/MP2/doc/html/draftman_page.html

Changes to Tracking Code



- GenFit DetPlanes are placed with coordinate system (u,v,w) matching the sensor coordinate systems.
  - DetPlanes can be misaligned.
- Sensor hits are placed in local coordinate system.
  - When measurement is added to track, plane is specified. (Proper global placement)
- Sensor ID added to FwdHit object.

Changes to Tracking Code

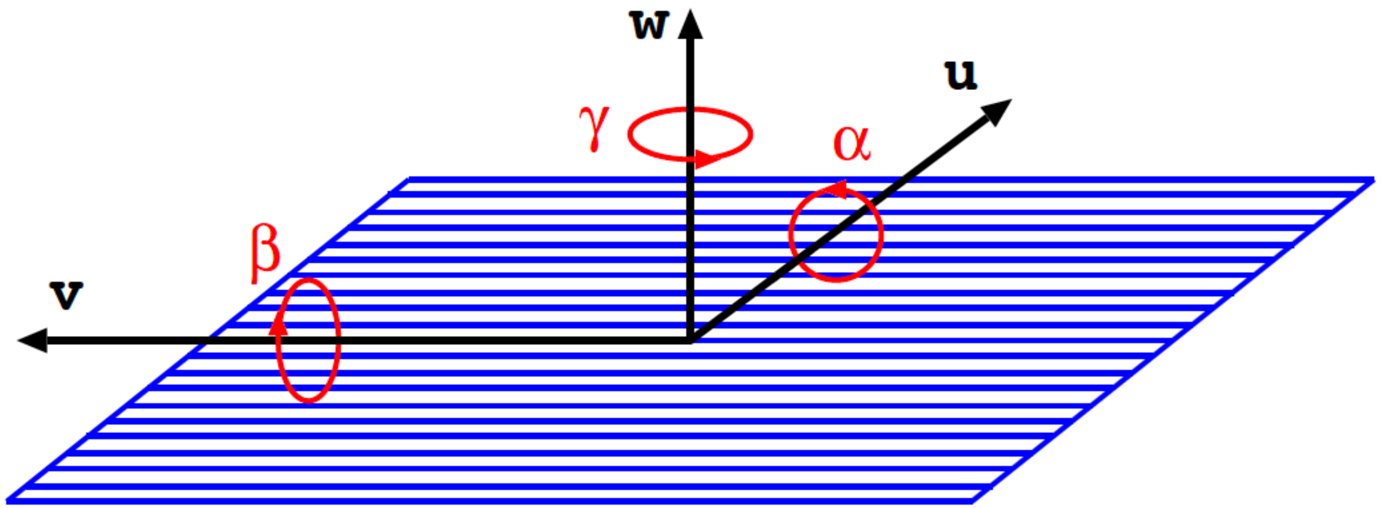


- Track is now projected to individual FST sensor GenFit::DetPlane.
- Previously projected to (x,y) position on midplane between sensors.
- Could be important if there are xz, yz rotations.
- Higher precision for alignment at cost of computation.

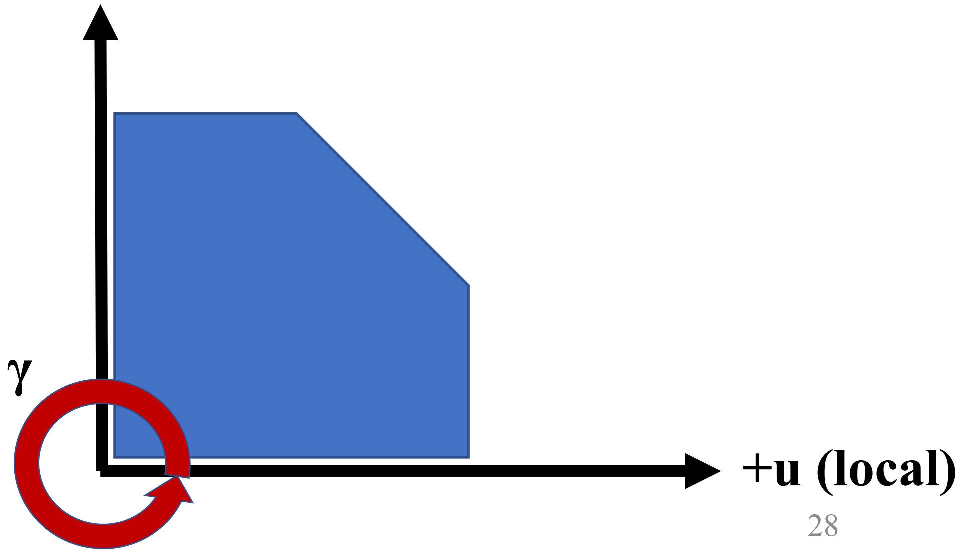
Alignment (global) Parameters

<u>FTT (sTGC)</u>

- 6 alignment parameters per pentagon (16 pentagons).
- 6 per plane (4 planes).
- 6 for sTGC.
- 126 alignment parameters.



CMS, doi:10.1088/1748-0221/9/06/P06009.



Hierarchy of Alignment Parameters

- Each track prediction for a sensor relies on the larger structures it is contained within.
  - Sensor on wedge, wedge on FST half, half on Full FST, full on TPC.
- We can calculate the all the global derivatives using chain rule

$$\frac{\mathrm{d}f_{u/v}}{\mathrm{d}\boldsymbol{\Delta}\mathbf{p}_l} = \frac{\mathrm{d}\boldsymbol{\Delta}\mathbf{p}_s}{\mathrm{d}\boldsymbol{\Delta}\mathbf{p}_l} \cdot \frac{\mathrm{d}f_{u/v}}{\mathrm{d}\boldsymbol{\Delta}\mathbf{p}_s},$$

$f_{u/v}$ = track prediction
$\mathrm{d}\Delta\mathbf{p}_\mathbf{s}$ = change in sensor global parameter
$\mathrm{d}\Delta\mathbf{p}_\mathrm{l}$ = change in containing structure global parameter

- The sum of all sensors global parameters pertaining to a larger substructure are constrained to zero to prevent shift of overall structure by the sub-components.
- Constraints added by .txt file input to pede.

CMS, doi:10.1088/1748-0221/9/06/P06009.

Multiple Scattering in GBL

- Multiple scattering covariance from the previous measurement plane accounted for at the current measurement plane in the GBL trajectory.
- The covariance matrix of scattering angle (w.r.t track direction) is calculated using:

$$\sigma_\theta = \frac{0.0136}{p}\sqrt{x/\chi_0}[1 + 0.038ln(x/\chi_0)].$$

$$V_k = \begin{pmatrix} \sigma_\theta^2 & 0 \\ 0 & \sigma_\theta^2 \end{pmatrix}.$$

- Where x is track length within the sensor, χ_0 is the radiation length of the material and p is the magnitude of momentum.
- Kalman filter can treat material as continuous, while GBL uses discrete scatters.

J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

GENFIT2 Classes for GBL

GblPoint.h/cc: contains all data for 2D measurements (derivatives, residuals, covariance, etc.).

GblTrajectory.h/cc: holds all GblPoints, can be fit or used directly for Mille output.

MilleBinary.h/cc: Organizes the data from GblTrajectory into the exact format required for pede.

GFGbl.h/cc: GBL fitter class implementing Mille binary file output and data collection. Originally written for BELLE II alignment.

StFwdGbl.h/cc: Adapted version of GFGbl for use with the Forward Tracker Alignment.

Single Sensor Alignment

- Mille.dat files are then fed to pede.
- Can specify initial values of alignment parameters and their pre-sigma (helps stabilize a poorly defined parameter).

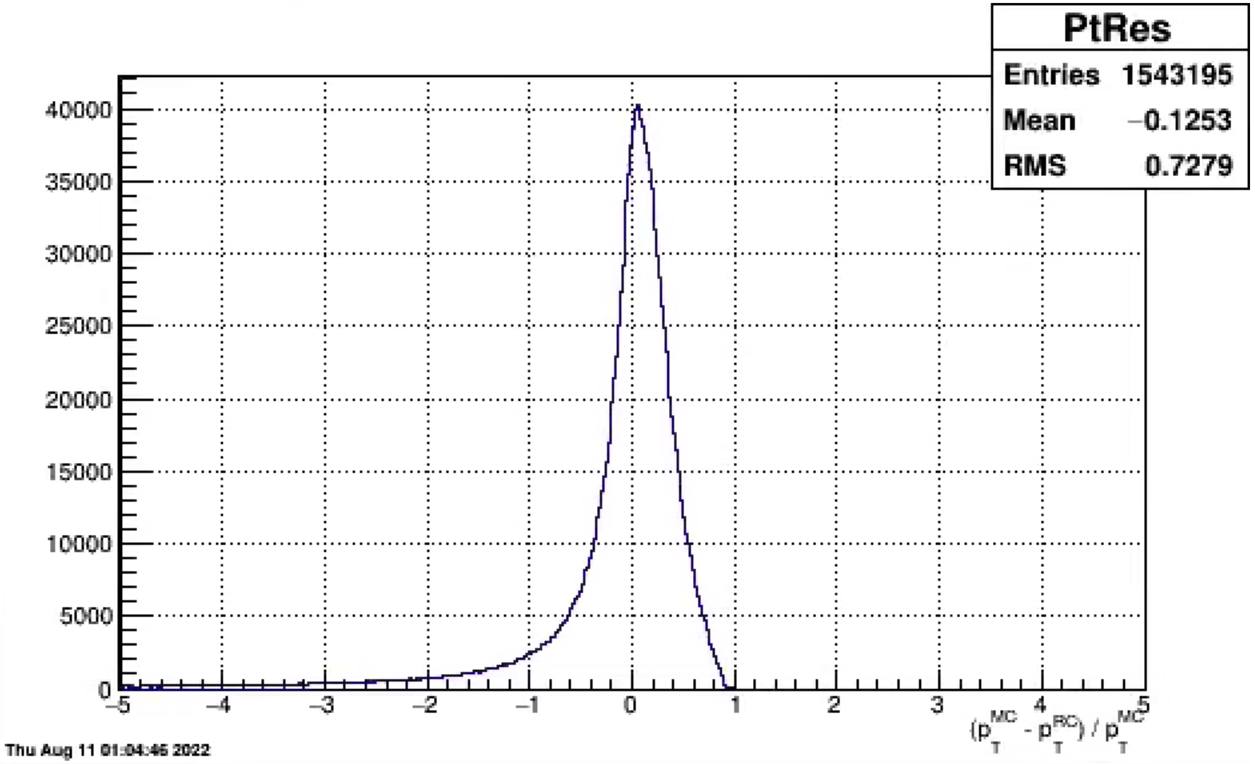
```
Parameter
label   initial_value   presigma
 ...
label   initial_value   presigma
```

Example of pede parameter entries.

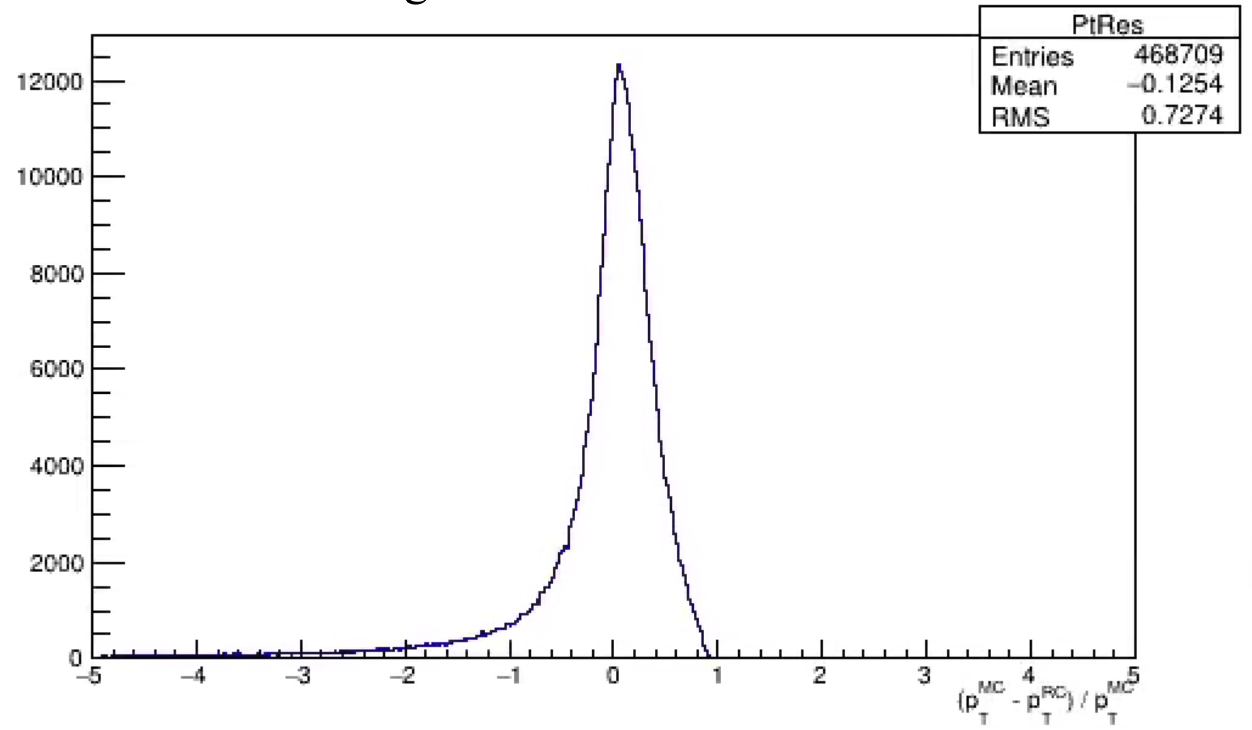
- Fix rotations about u-axis and v-axis, in addition to w translation by setting pre-sigma < 0.0.
- Matrix inversion used to solve for alignment parameters.
- ~50k tracks used for each trial.

Tracking performance

Original Tracking

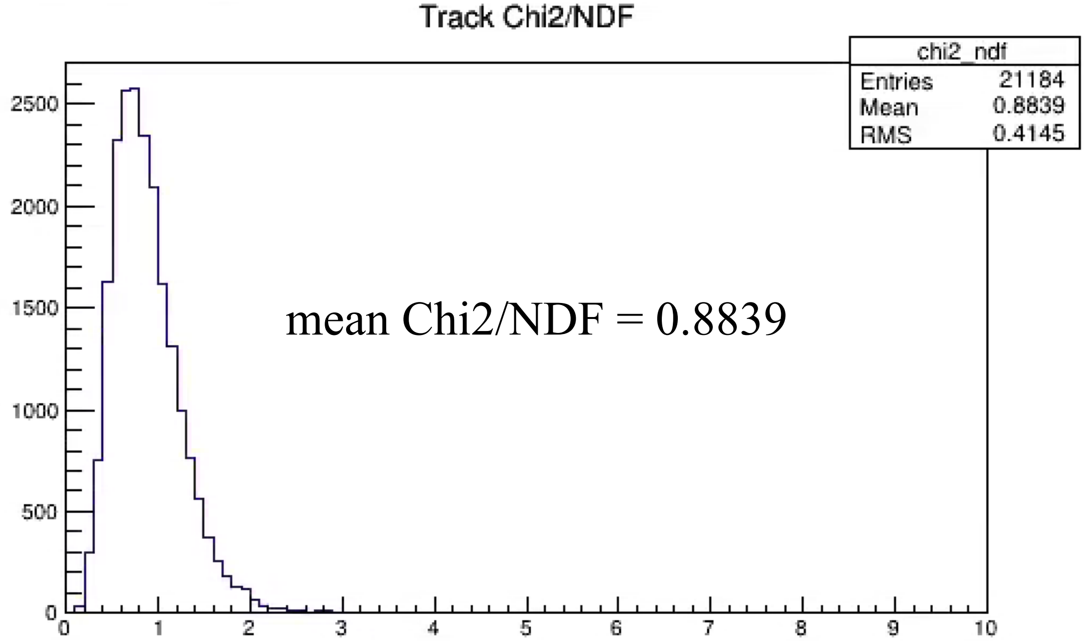


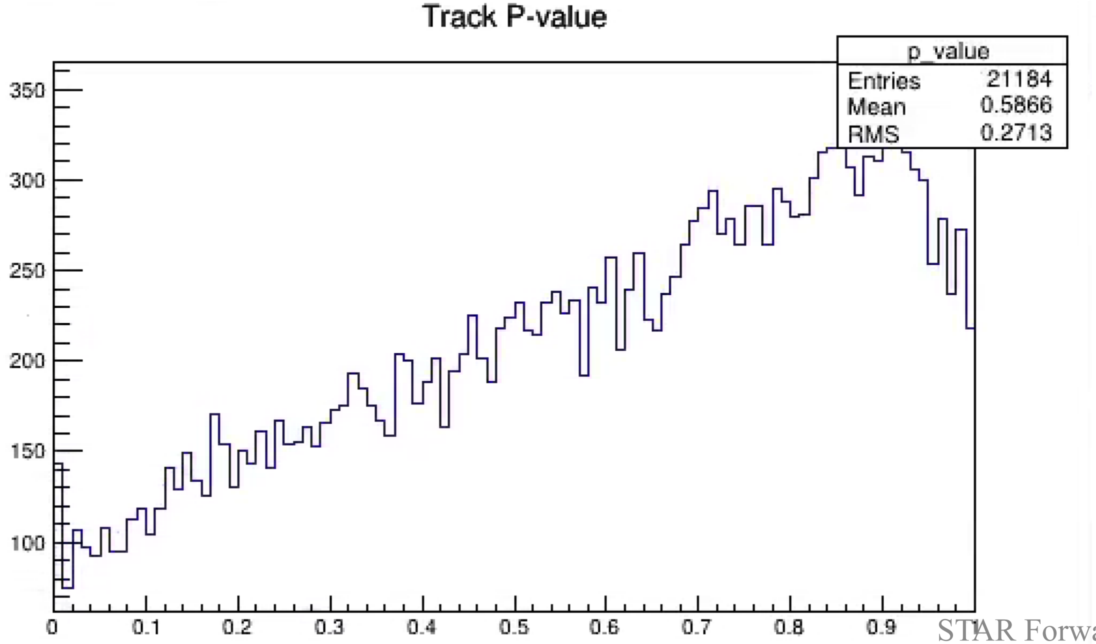
After tracking updates for alignment



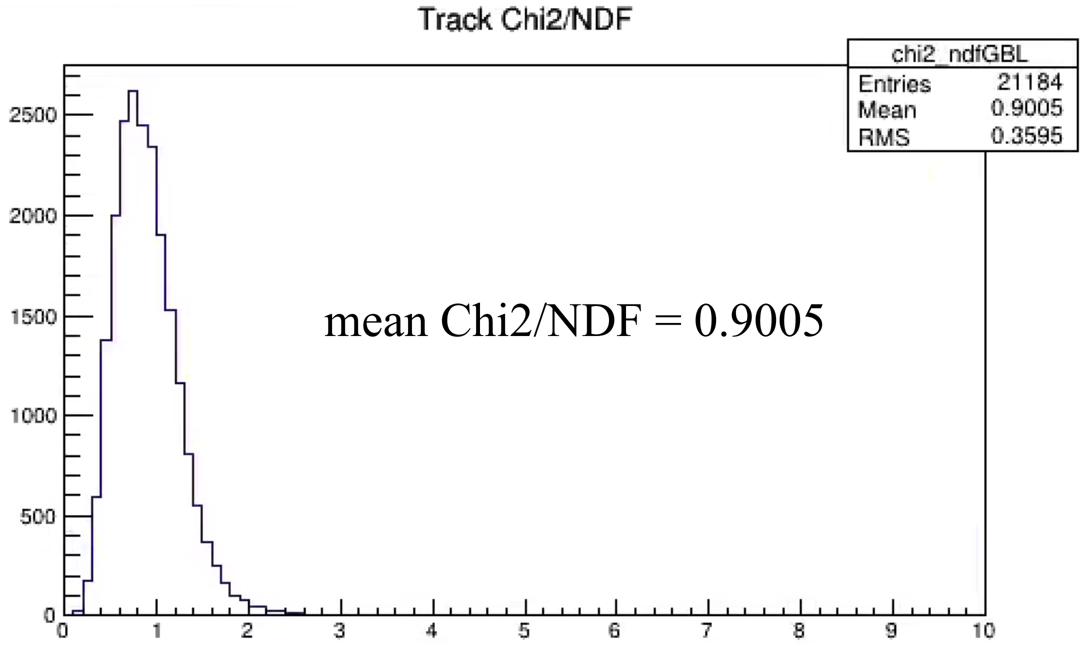
- With ideal sensor placement, pT resolution is nearly identical.

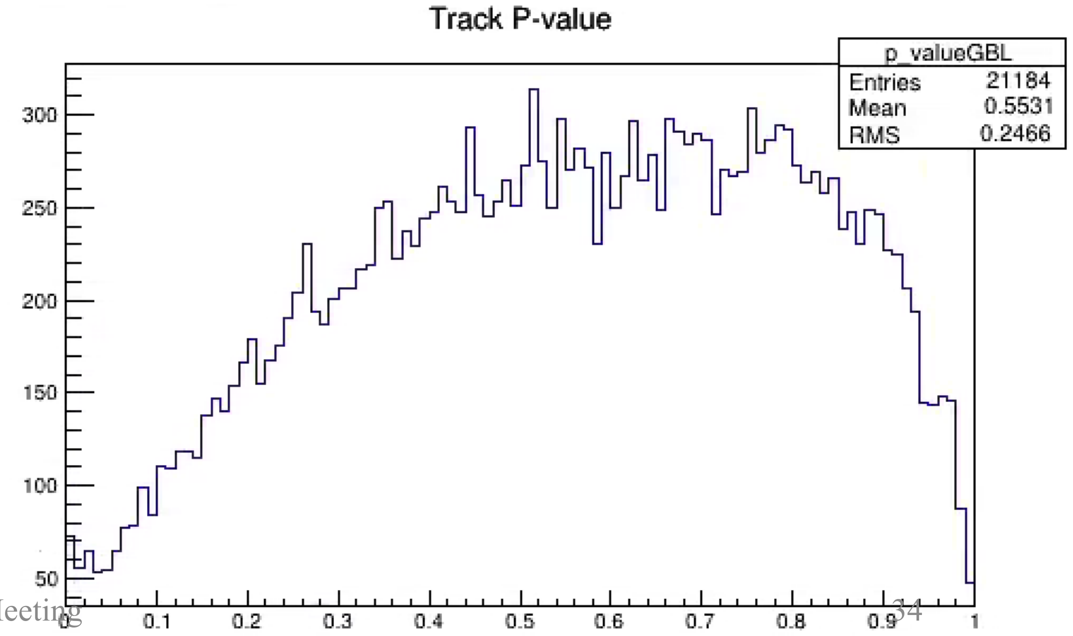
Kalman Filter Fitted





GBL refitted





Single Sensor Alignment Results

No Misalignment

Parameter	Input	Output	Error
Δu (μm)	0.0	-0.3	2.9
Δv (μm)	0.0	0.0	1.5
Δγ (mrad)	0.0	4.3E-3	1.7E-2

w-axis rotation

Parameter	Input	Output	Error
Δu (μm)	0.0	-0.2	3.2
Δv (μm)	0.0	-2.1	1.7
Δγ (mrad)	2.00	1.91	0.02

u shift

Parameter	Input	Output	Error
Δu (μm)	50.0	46.4	2.9
Δv (μm)	0.0	-1.2	1.5
Δγ (mrad)	0.0	1.0E-2	1.7E-2

v shift

Parameter	Input	Output	Error
Δu (μm)	0.0	1.6	2.9
Δv (μm)	50.0	44.1	1.6
Δγ (mrad)	0.0	2.9E-2	1.8E-2

Single Sensor Alignment Results

u,v shift + w-axis rotation (~50k tracks)

Parameter	Input	Output	Error
Δu (μm)	50.0	46.1	3.2
Δv (μm)	50.0	43.2	1.7
$\Delta\gamma$ (mrad)	2.0	1.92	0.02

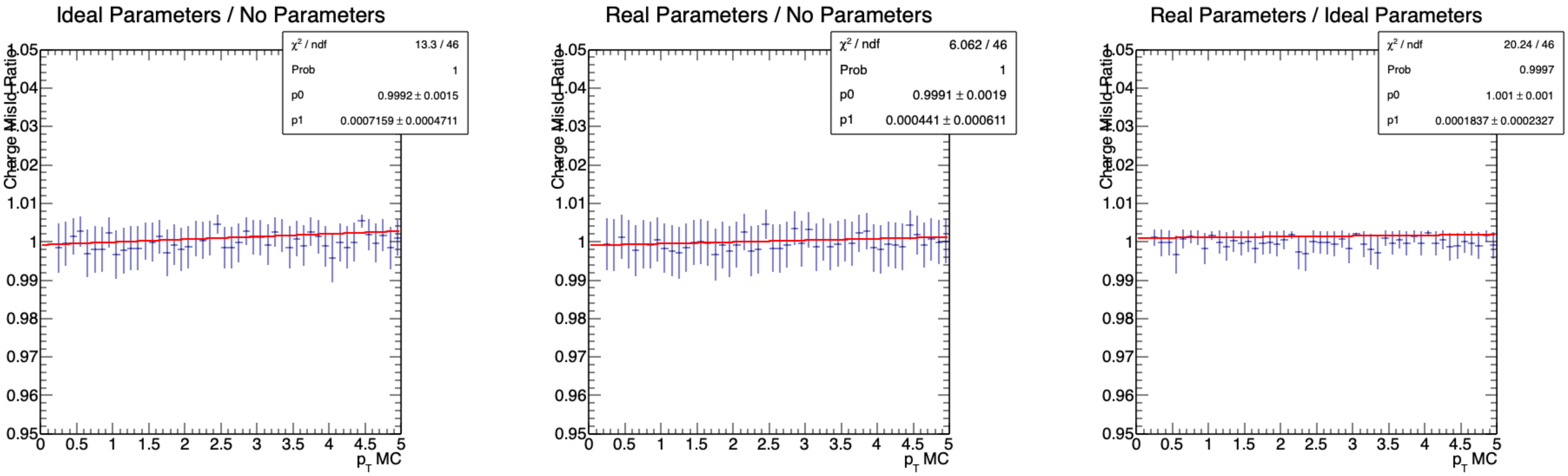
u,v shift + w-axis rotation (~850k tracks)

Parameter	Input	Output	Error
Δu (μm)	50.0	49.3	0.9
Δv (μm)	50.0	41.5	0.5
$\Delta\gamma$ (mrad)	2.0	1.938	0.006

- Single FST inner sensor can be aligned to some degree with GenFit + Millepede II.
  - Slight discrepancy between input and output parameters.
  - Perhaps due to correlation between u and v coordinates?
    - Covariance is diagonalized for use in Millepede.

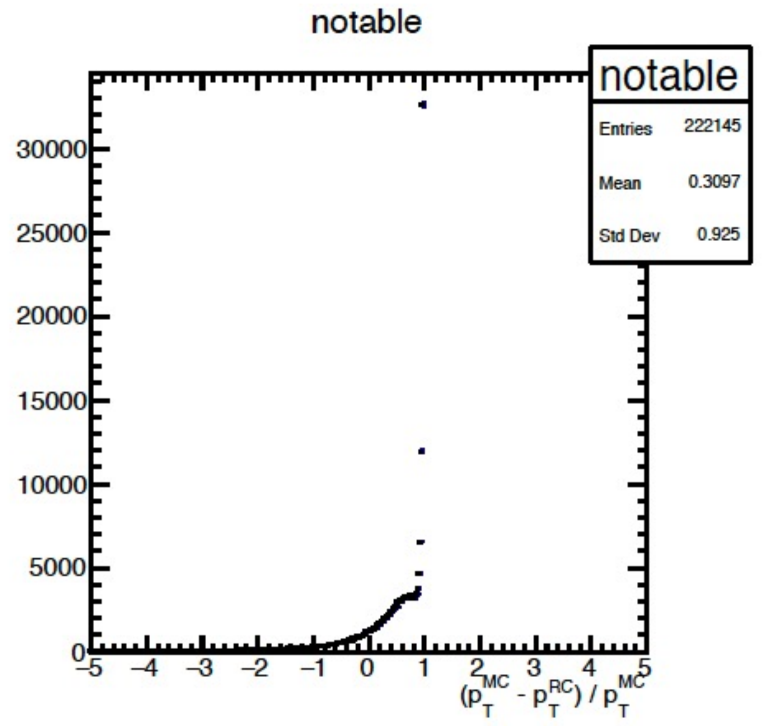
Charge MisID

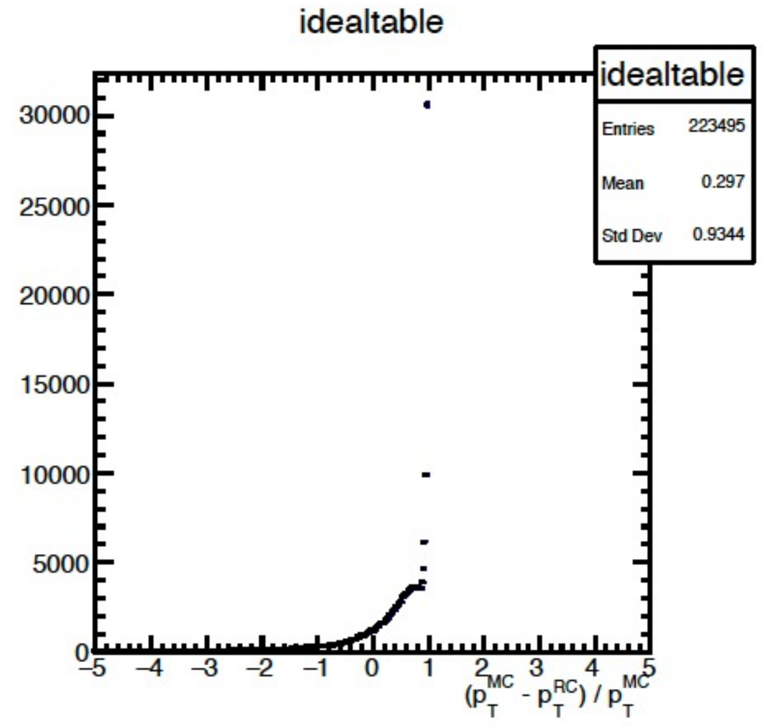
- Simulate μ+ with Field ON using or not using alignment parameters
- Throw particles in same region as alignment simulation but use wider p_T range.
- No significant slope in the ratio plot for Real / Ideal parameters.

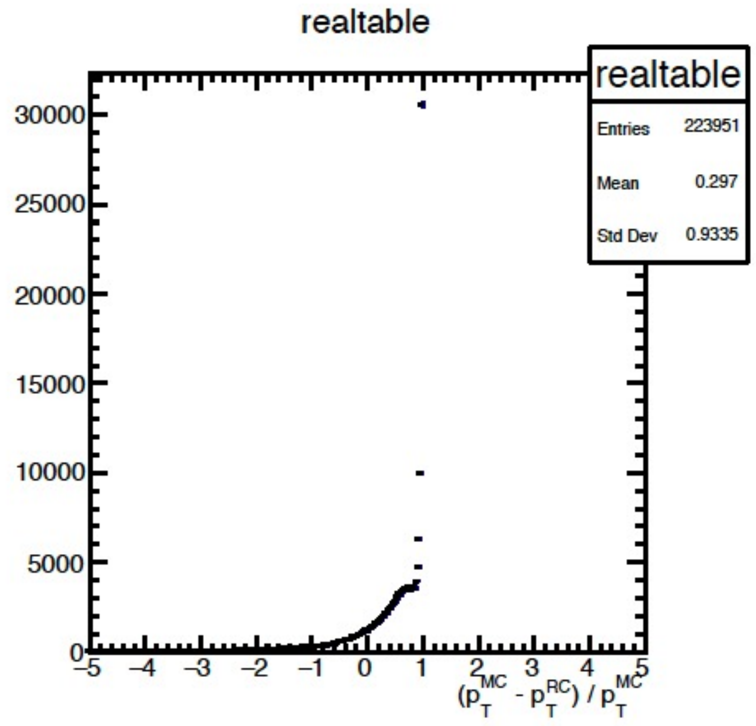


p_T Resolution

- Simulate μ+ with Field ON using or not using alignment parameters
- Throw particles in same region as alignment simulation but use wider p_T range.
- Large peak around 1 ➔ Try investigating lower p_T range.
- On the plus side, the mean and std. dev. are nearly identical for real and ideal alignment tables in reconstruction.







Summary and Outlook

- Single FST inner sensor has been somewhat successfully aligned using GenFit + Millepede II.
  - Discrepancy between input and output due to correlation between u and v coordinates?
- Attempt alignment of the following:
  - Outer silicon sensors
  - Multiple sensors simultaneously (just inner, just outer, and both)
  - Build up hierarchy (wedge and sensor simultaneously, etc.)
  - Single sTGC pentagon module
- Study effect of small misalignments on tracking performance and improvement after alignment.