Alignment of GlueX tracking detectors

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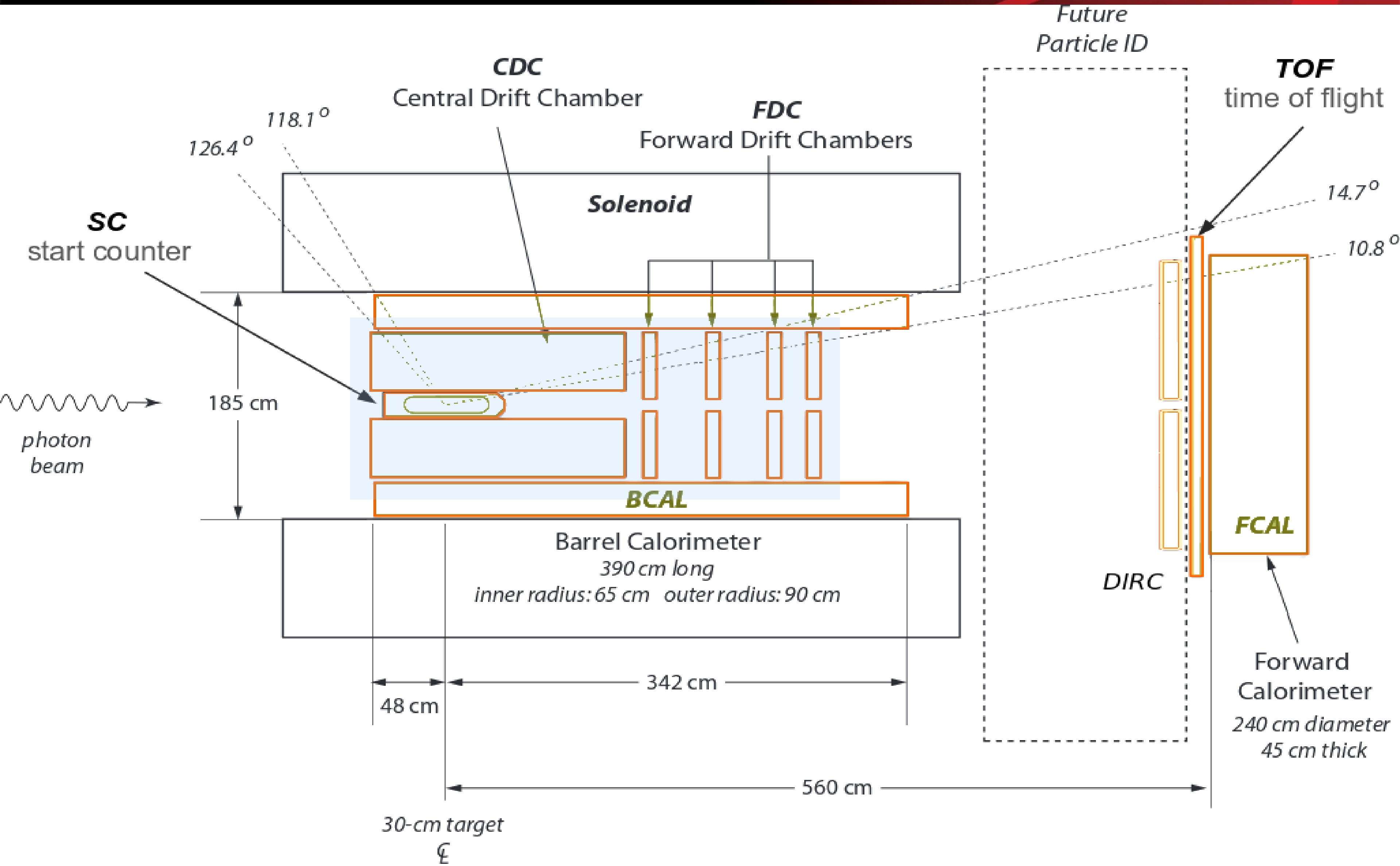
- The GlueX detector
- CDC straw tube deformations
- Time-to-distance relationships
- Alignment techniques
- First results

The lion's share of the work was done by Michael Staib (CMU)

GlueX detector

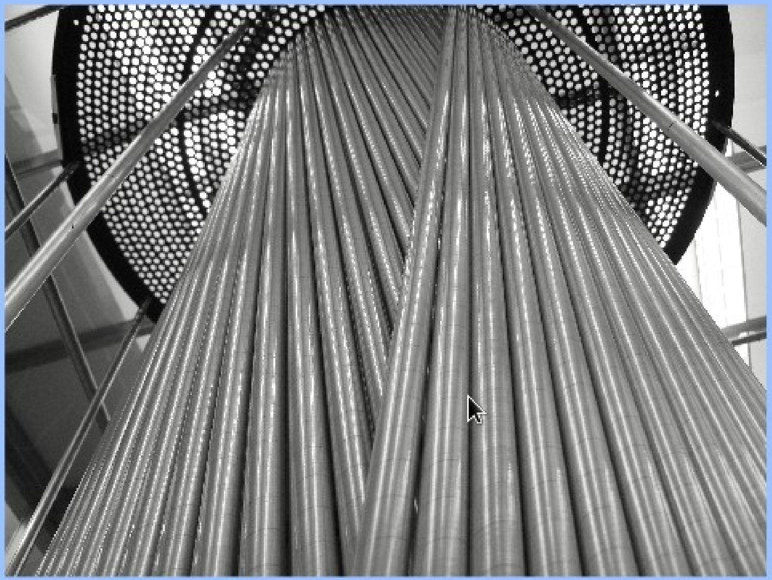


Tracking detectors

FDC

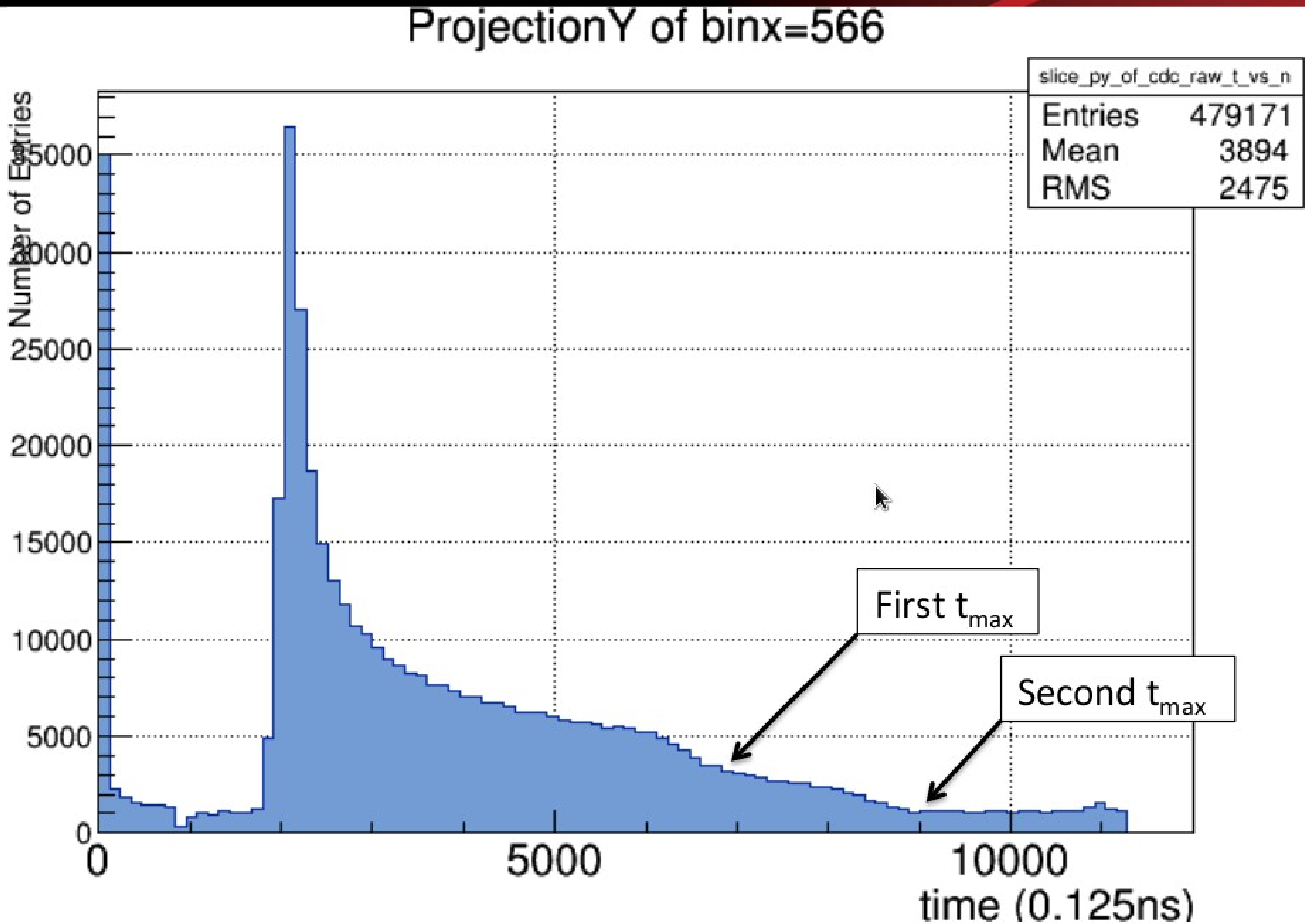
Cathode Strip Chamber
Gas Mixture: 60/40 Ar/CO2
Angular Coverage: 1º – 30º
Readout:
- 2,300 anode wires → F1TDC
- 10,200 cathode strips → FADC-125
- 3 measured projections per plane

CDC



Straw Tube Chamber
28 layers total (16 stereo layers: +/- 6º)
Gas mixture: 50/50 Ar/CO_2
Angular Coverage: 6º-155º
3522 straw tubes (r = 8mm)
Readout: FADC-125MHz – 8ns sample
Resolution: $\sigma_{r\phi}$ ~ 150 μm
σ_z ~ 1.5 mm

Evidence for straw distortion

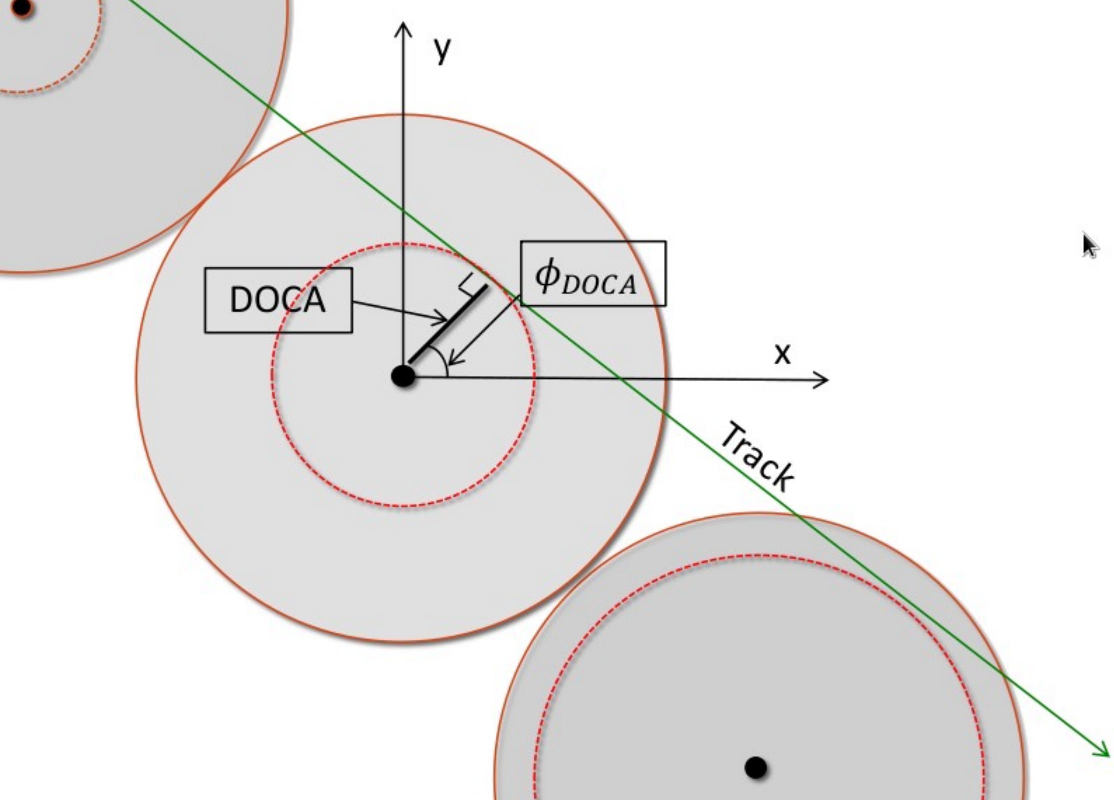


Some deformation of the straws could cause this behavior

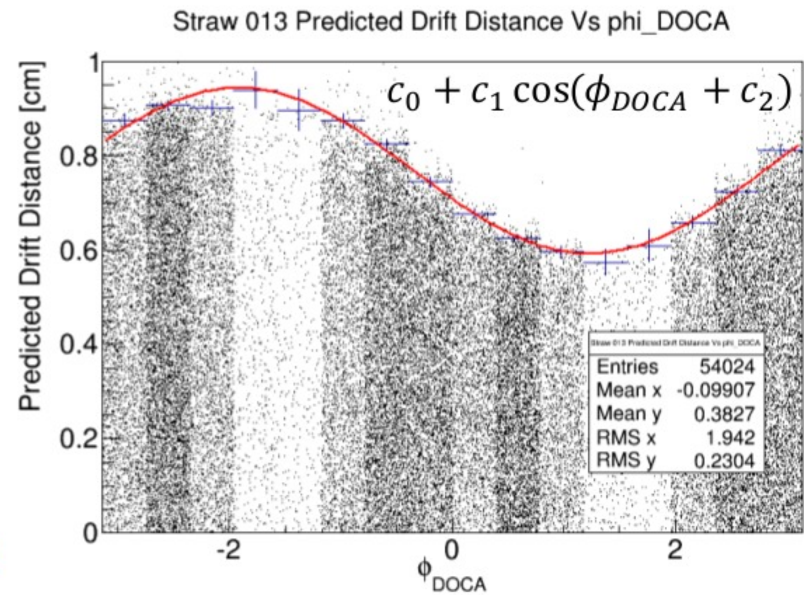
Straw deformation

Distortions in drift distributions are caused by straw tubes sagging...

To account for the shape of the straw, we are measuring the drift properties as a function of the angle of the track passing the straw ϕ_{DOCA}

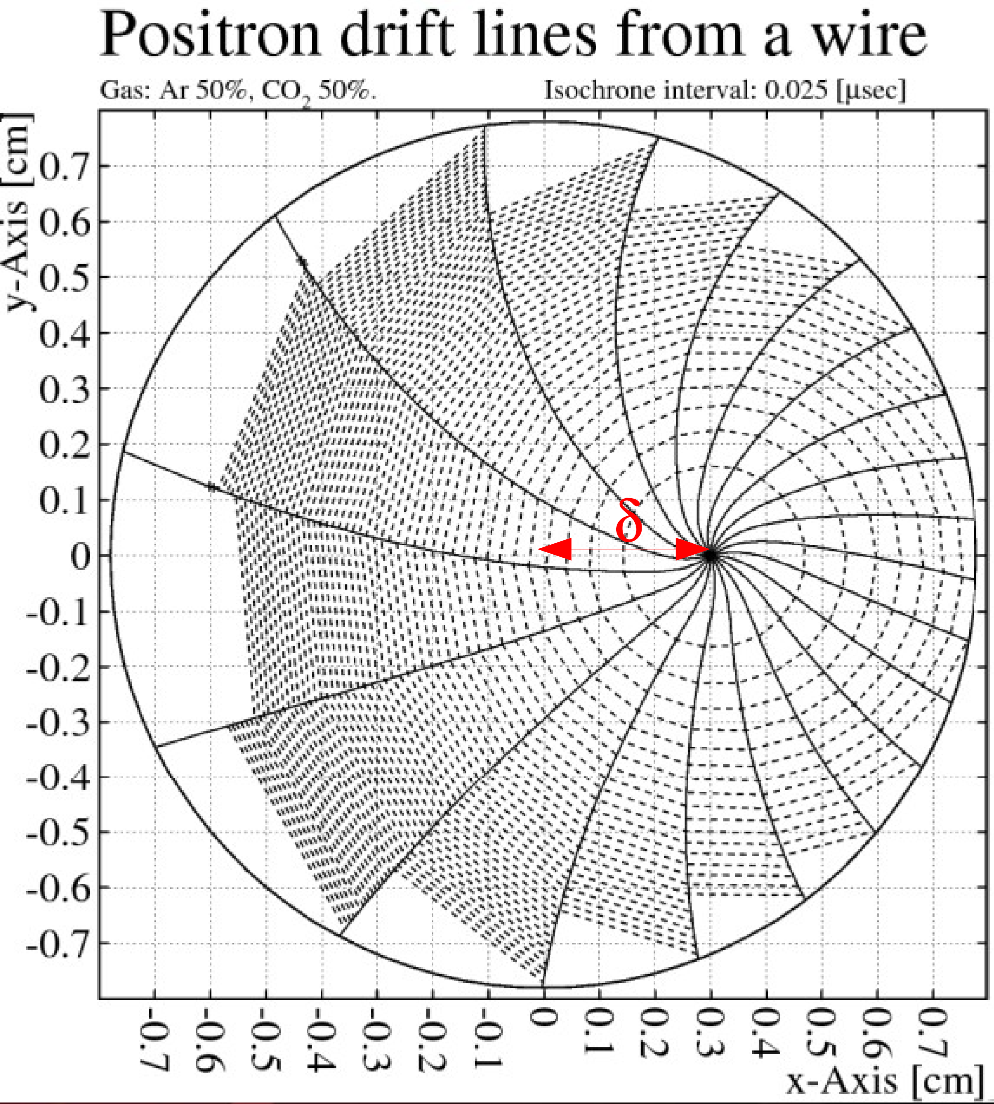


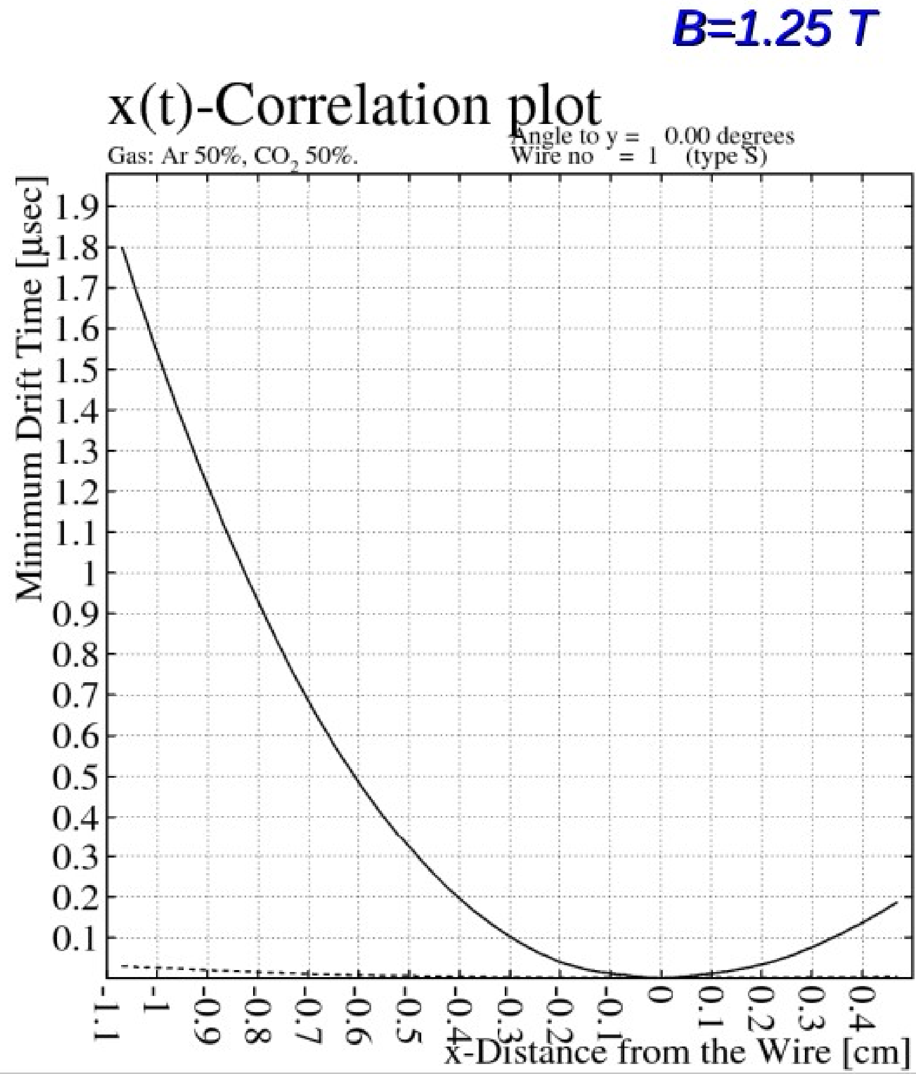
Maximum distance to wire



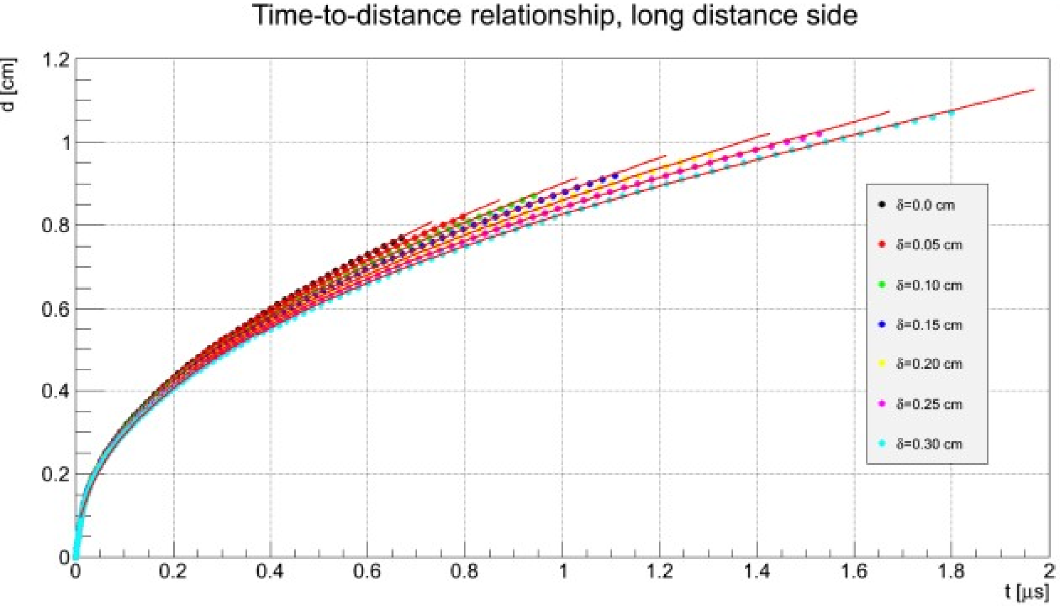
Garfield calculations

- Calculations done for δ={0,0.05,0.1,0.15,0.2,0.25,0.3} cm





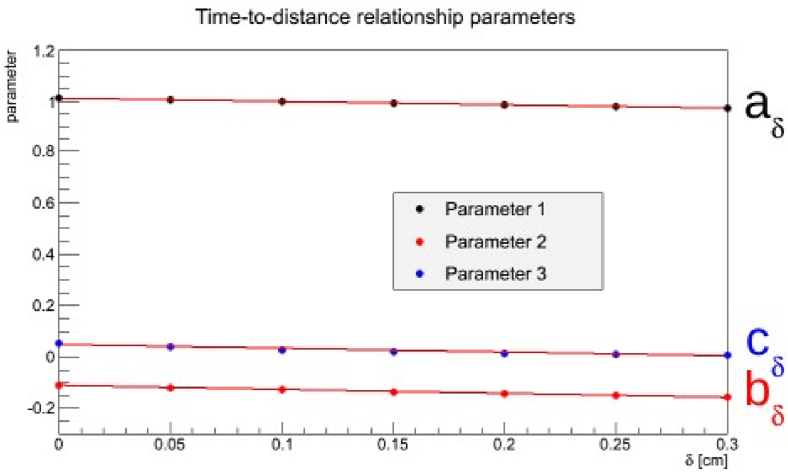
Parametrization of time-to-distance

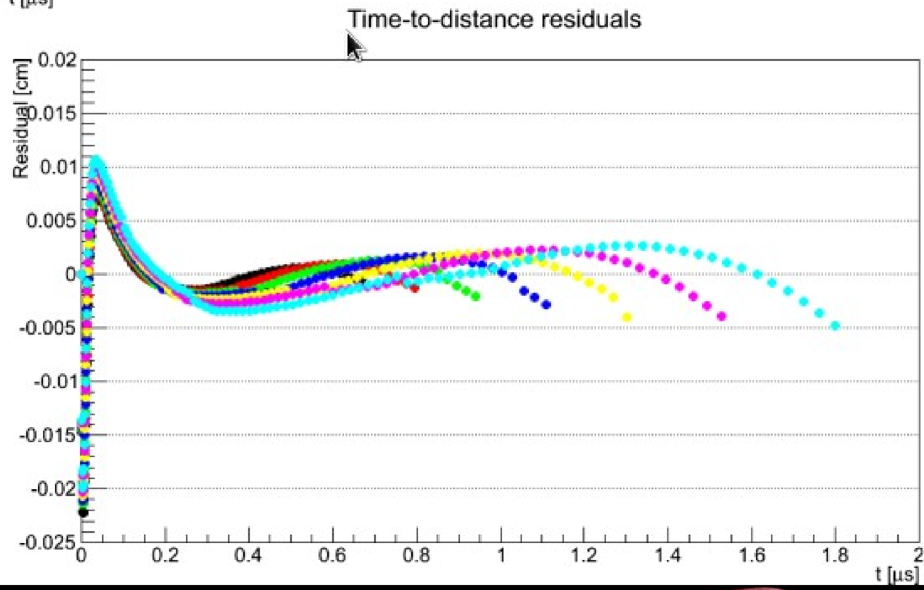


$$f_\delta(t) = a_\delta\sqrt{t} + b_\delta t + c_\delta t^3$$

table from garfield

Residual = $x_\delta(t)-f_\delta(t)$





Dealing with small drift times

$$P = \frac{t_{cut} - t}{t_{cut}} \qquad t < t_{cut}$$

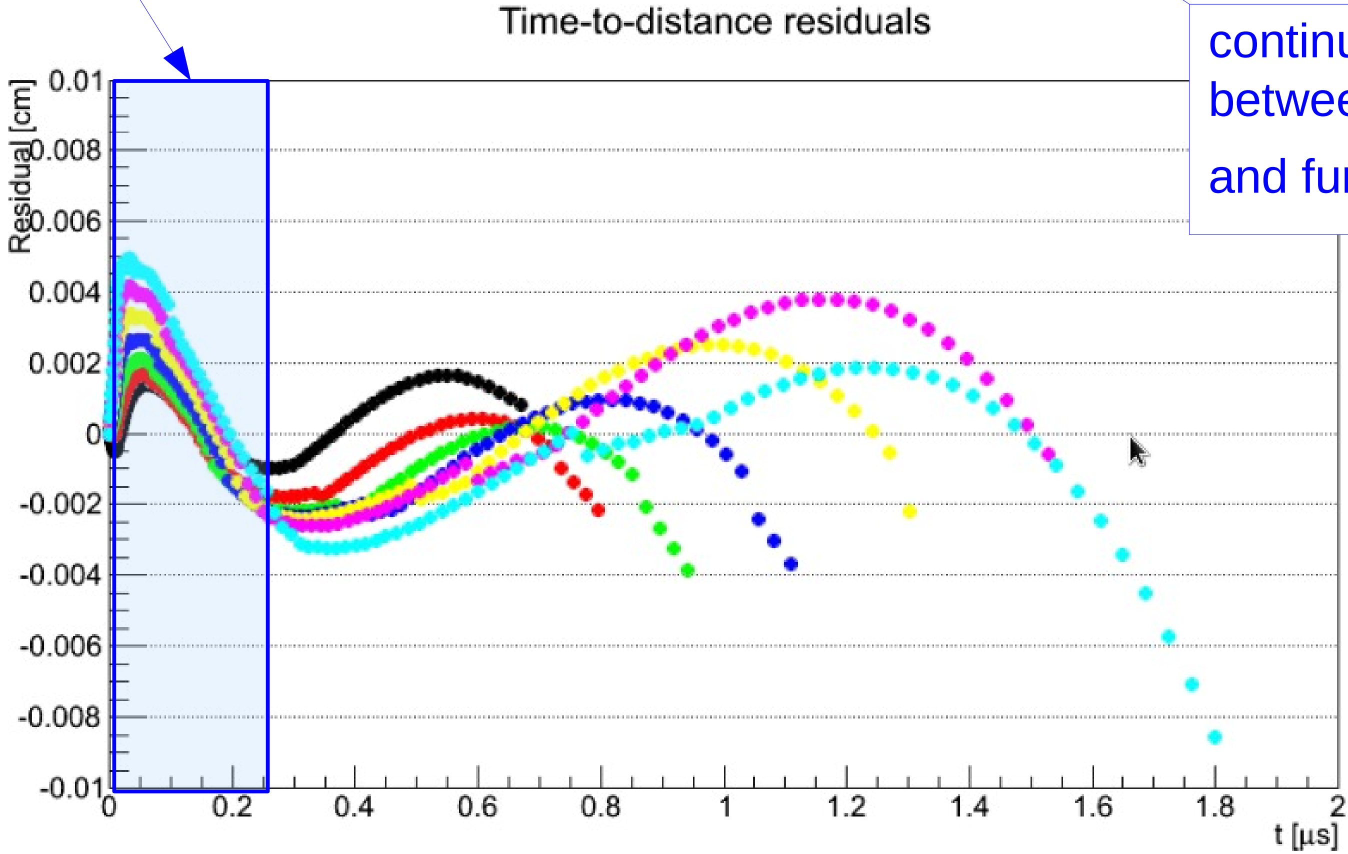
$$P = 0 \qquad t \geq t_{cut}$$

$$\Delta x = x_\delta(t) - f(\delta, t)\left(\frac{x_0(t)}{f(0,t)}P + 1 - P\right)$$

Use Garfield table
***$x_0(t)$** in this region*

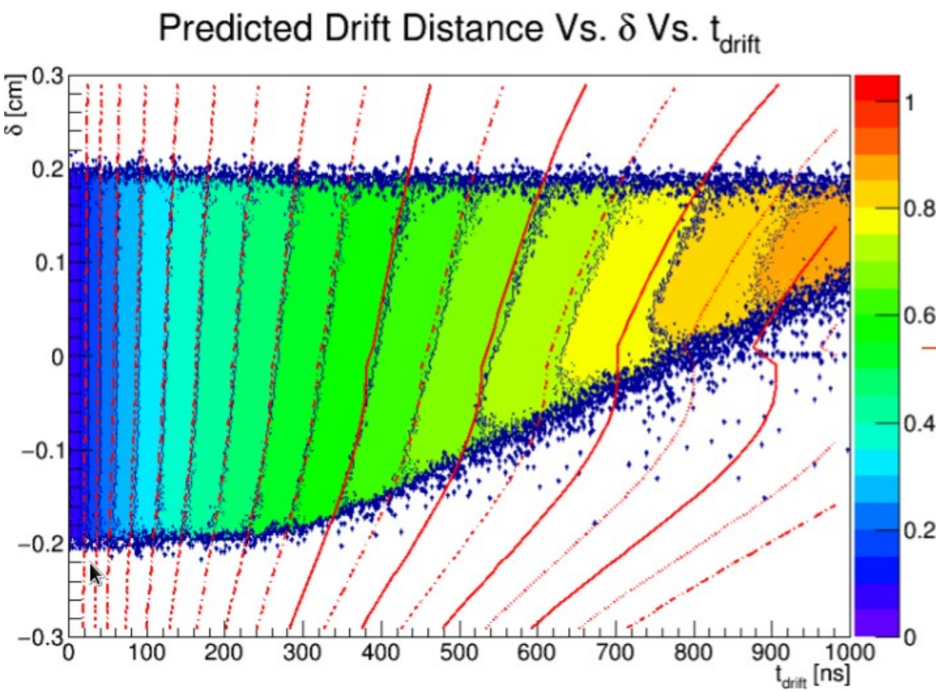
t_{cut}=0.25 μs

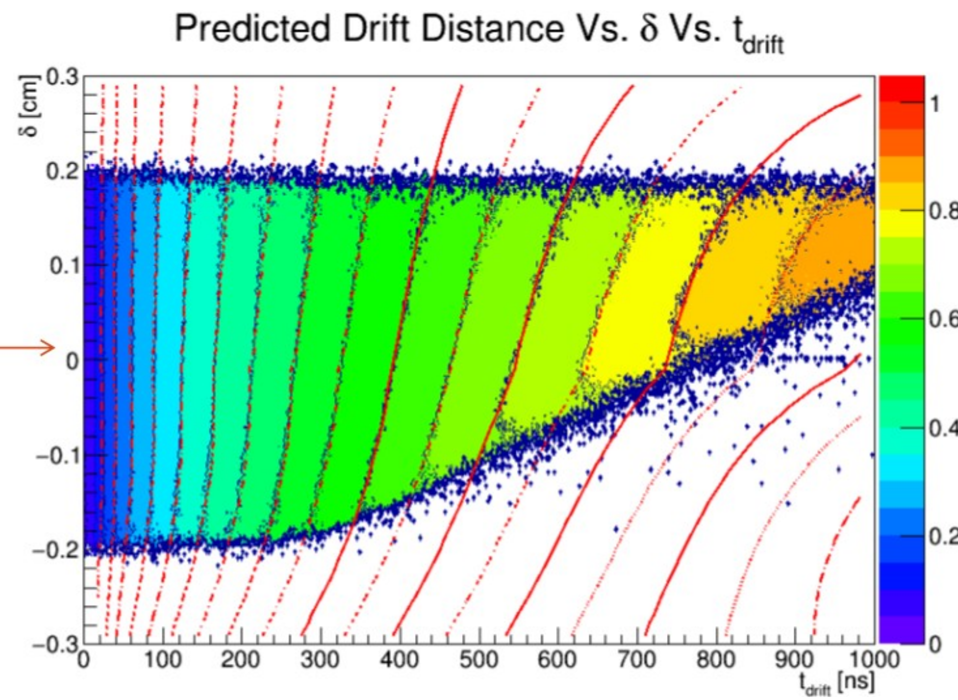
continuous transition between table $x_\delta(t)$ and function f(δ,t)



Tuning t-to-d using data

Start with Garfield to determine f(δ,t) ⟶ Refine with reconstructed cosmic tracks





Now we are ready to work on the wire alignment in the CDC...

Wire alignment methods

- We have implemented two methods for the alignment of the individual CDC wires:
  1. Extended Kalman Filter [1]
  2. MILLEPEDE [2]
- Tested (working) with simulation, early results from experimental data look good.
- In the CDC, ~14k parameters (four per straw):

$$\delta x_{upstream}, \delta x_{downstream}, \delta y_{upstream}, \delta y_{downstream}$$

[1] E. Widl, R. Frühwirth, W. Adam 2006, CMS NOTE–2006/022
[2] V. Blobel and C. Kleinwort, PHYSTAT2002, Durham, arXiv-hep-ex/0208021.

Kalman filter approach

- Use Kalman Filter formalism: update state vector S and covariance matrix C with each measurement and explicitly use current result for alignment vector a (covariance matrix E)

$$H = \frac{\partial f}{\partial \vec{S}}, G = \frac{\partial f}{\partial \vec{a}}$$

  - Measurement vector **M** = f(**S**,**a**)+**ε**
  - Measurement covariance matrix **V**
  - Update state vector:

$$\vec{S}_1 = \vec{S}_0 + C_0 H^T W (M - f(\vec{a}_0, \vec{S}_0))$$
$$C_1 = C_0 - C_0 H^T W H C_0$$

  - Weight matrix:

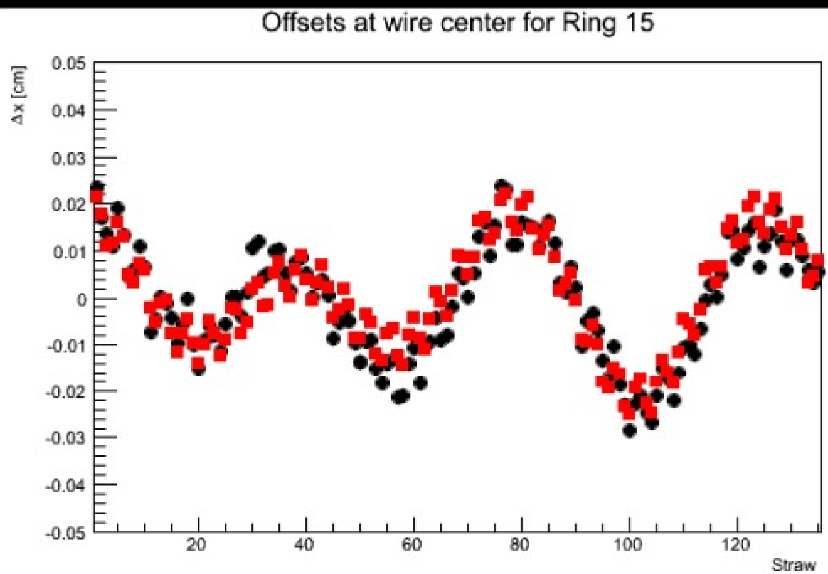
$$W = (V + HCH^T + GEG^T)^{-1}$$

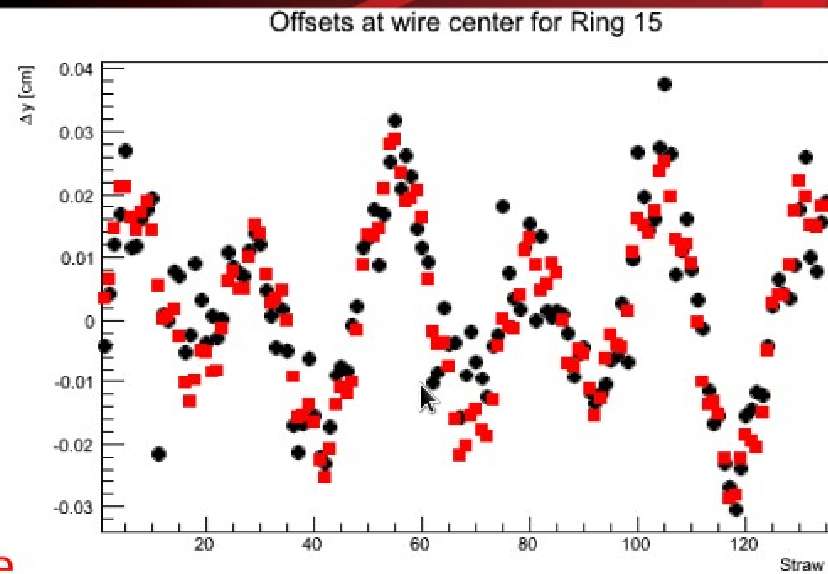
- Update alignment vector after smoothing stage
  - Start with $\vec{\mathbf{a}}=\vec{\mathbf{0}}$ and a guess for **E**, update event-by-event...

$$\vec{a}_1 = \vec{a}_0 + E_0 G^T W (M - f(\vec{a}_0, \vec{S}_0))$$
$$E_1 = E_0 - E_0 G^T W G E_0$$

State vector S={x, y, t_x=dx/dz, t_y=dy/dz}

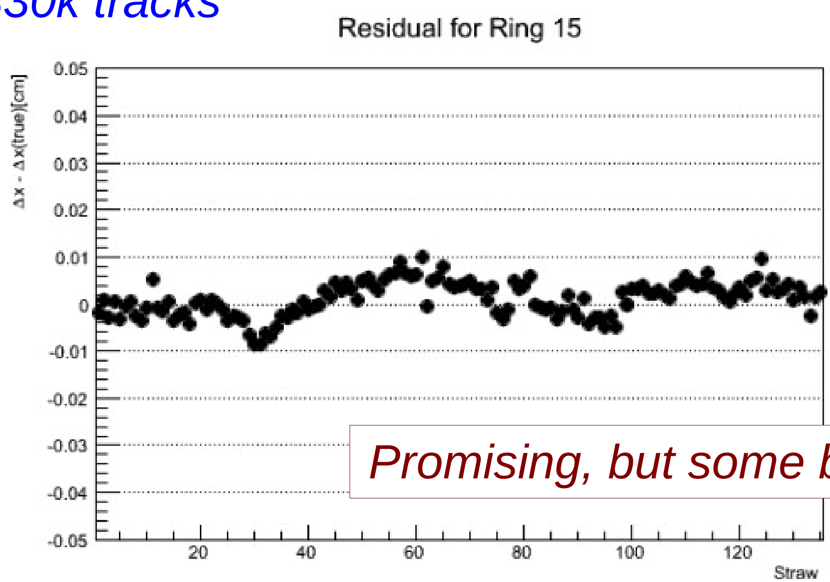
Test with simulated cosmic tracks

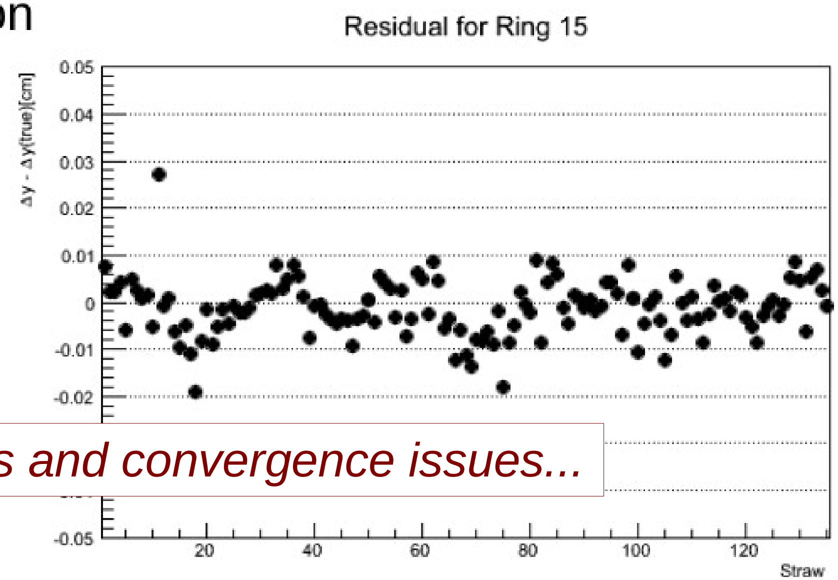




true
recon

330k tracks





Promising, but some biases and convergence issues...

MILLEPEDE

Attempts to solve a problem that comes up a lot... Try to minimize the function

$$\chi^2_{\text{Global}} = \sum_{\text{data sets}} \left[\sum_{\text{events}} \left(\sum_{\text{tracks}} \left(\sum_{\text{hits}} w_i r_i^2 \right) \right) \right]$$

$$r_i = m_i - f(\mathbf{p}, \mathbf{q}_{track})$$

$$\mathbf{p} \equiv \text{alignment (global) parameters}$$
$$\mathbf{q} \equiv \text{track (local) parameters}$$

The result we are interested in is only the set of corrections to the alignment parameters. If we have n alignment parameters, this can be achieved by only inverting a n x n matrix by the method of Schur complements while preserving the correlations of the local and global parameters.

$$\begin{pmatrix} C_{11} & C_{21}^{T} \\ C_{21} & C_{22} \end{pmatrix} \begin{pmatrix} d_1 \\ d_2 \end{pmatrix} = - \begin{pmatrix} g_1 \\ g_2 \end{pmatrix} \rightarrow \begin{pmatrix} d_1 \\ d_2 \end{pmatrix} = - \begin{pmatrix} S^{-1} & -S^{-1} C_{21}^{T} C_{22}^{-1} \\ -C_{22}^{-1} C_{21} S^{-1} & C_{22}^{-1} - C_{22}^{-1} C_{21} S^{-1} C_{21}^{T} C_{22}^{-1} \end{pmatrix} \begin{pmatrix} g_1 \\ g_2 \end{pmatrix}$$

$$S = C_{11} - C_{21}^{T} C_{22}^{-1} C_{21}$$

More about MILLEPEDE

- Provides a nice interface for users. No experiment-specific code.

- Robust tools for (approximate) large matrix inversion
  - Preconditioning (Regularization, band matrix)
  - Outlier downweighting (M-estimates)
  - Constraints
  - Survey measurements

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method inversion
method diagonalization
method fullGMRES
method sparseGMRES
method cholesky
method bandcholesky
method HIP
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- MILLE utility classes for FORTRAN and C++.
- PEDE written in FORTRAN90

User provides the following for each track

n_{lc} = number of local parameters	array : $\left(\frac{\partial f}{\partial q_j}\right)$
n_{gl} = number of global parameters	array : $\left(\frac{\partial f}{\partial p_\ell}\right)$; label-array ℓ
z = residual $(\equiv y_i - f(x_i, \boldsymbol{q}, \boldsymbol{p}))$	σ = standard deviation of the measurement

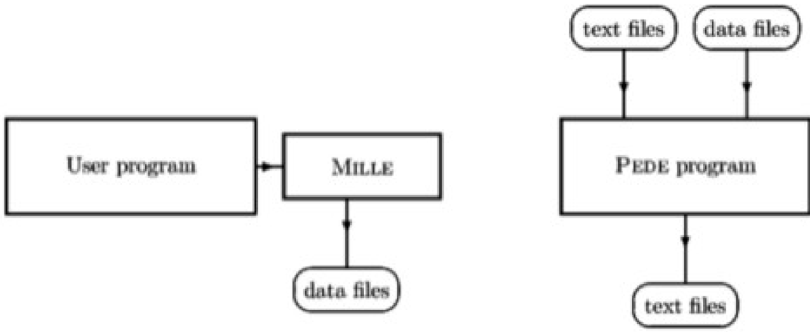
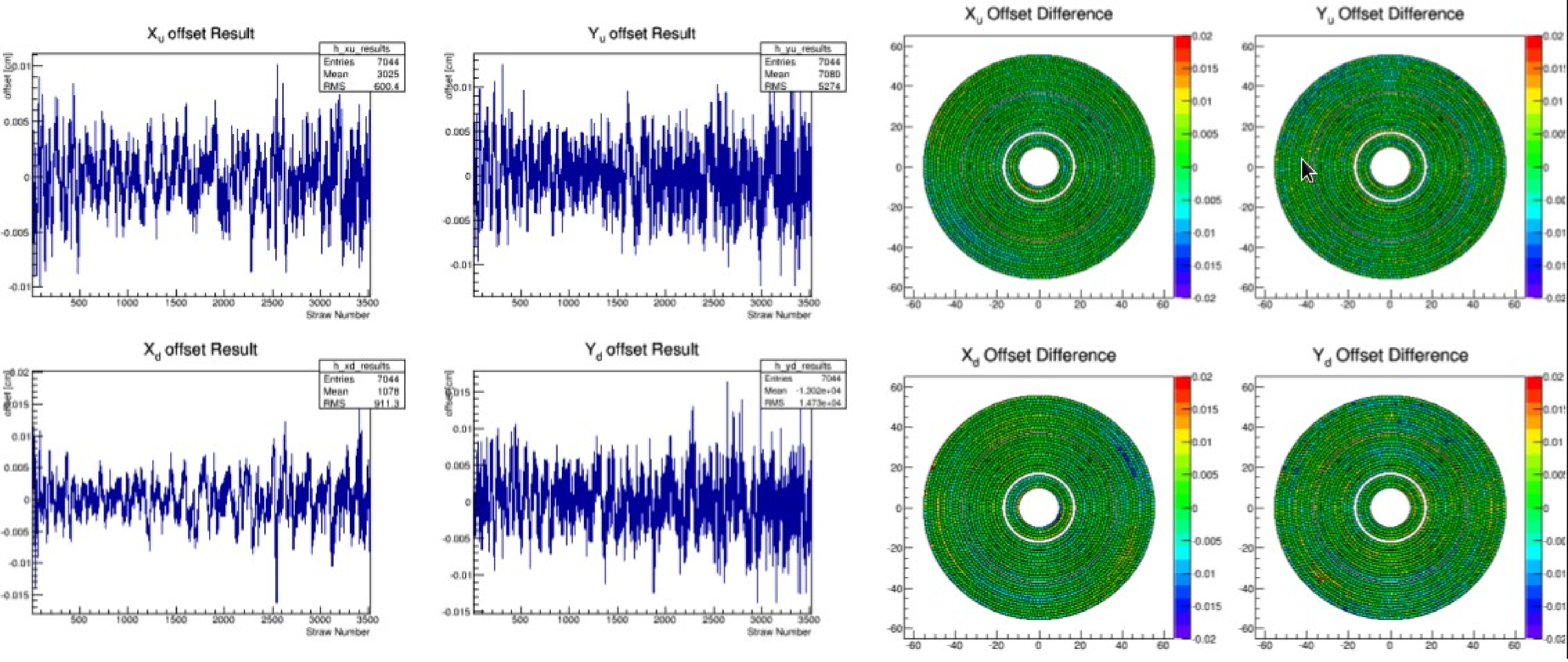


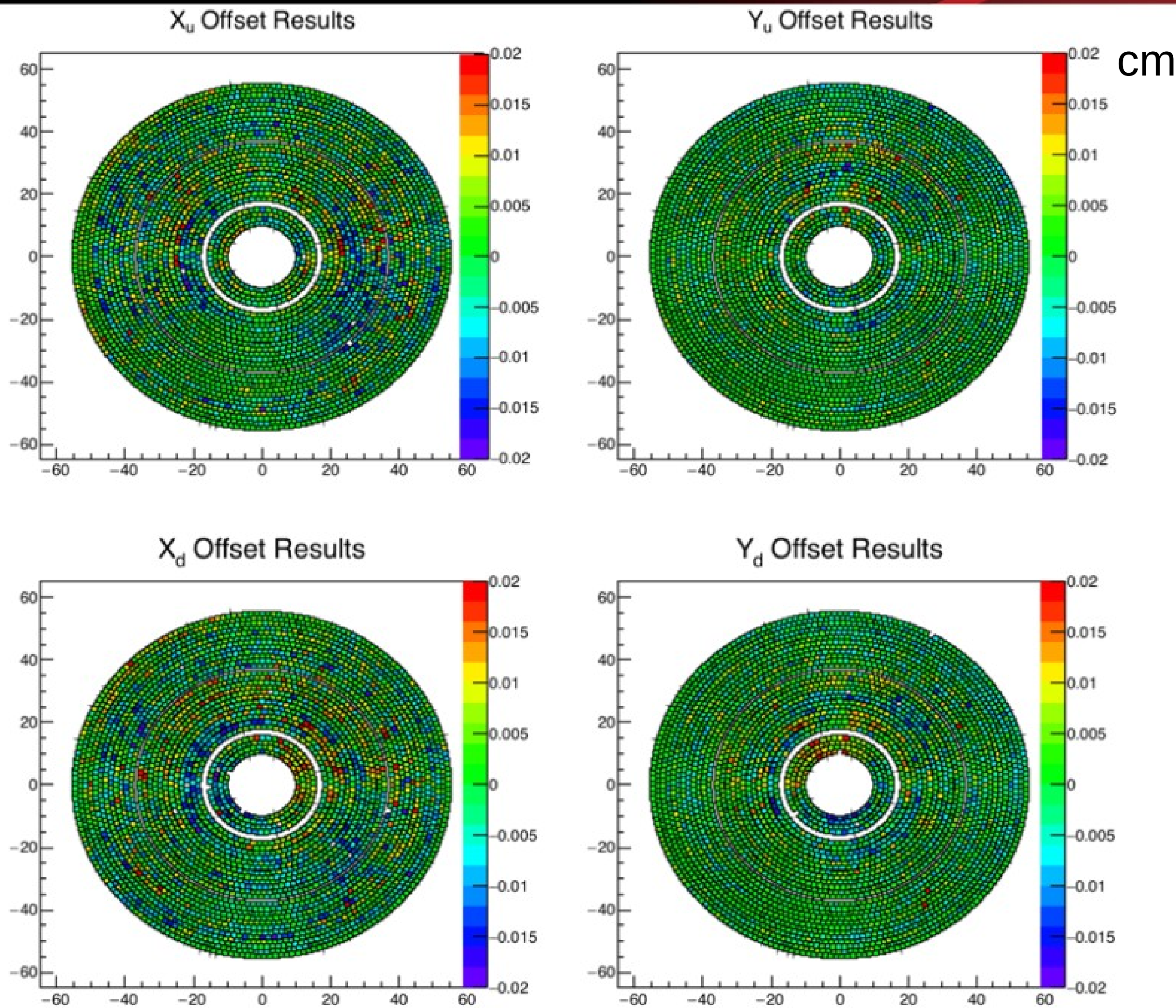
Figure 1: The subprogram MILLE (left), called inside the user program, and the stand-alone program PEDE (right), with the data flow from text and data files to text files.

Testing with simulated events

- Simulate offsets with Gaussian width of 150 µm. Generate cosmic ray muon tracks (CRY).
- These are the difference between the modeled offset and the offset determined by the MILLEPEDE procedure.
- Requires some tuning of parameters to get things looking this good – particular choice of regularization…

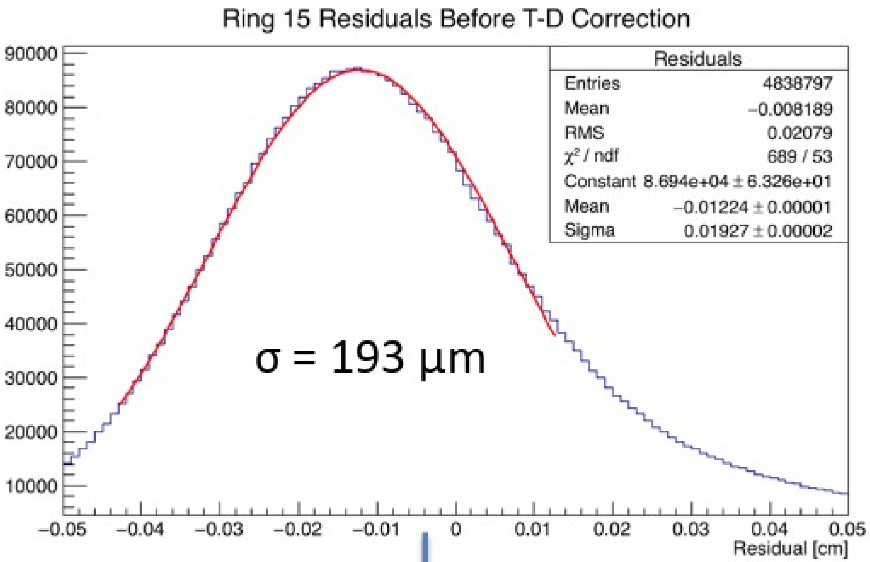


MILLEPEDE results for real data



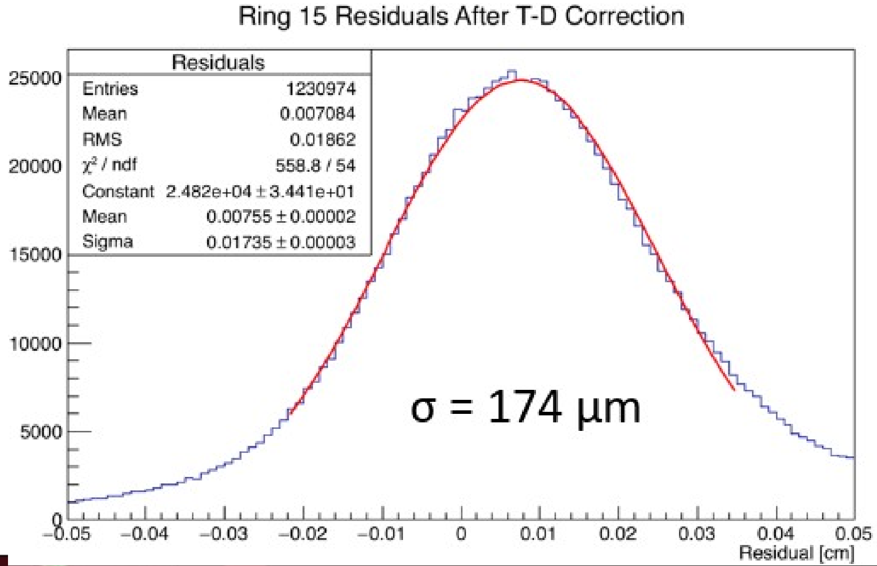
Single iteration with ~3M cosmic ray muon tracks.

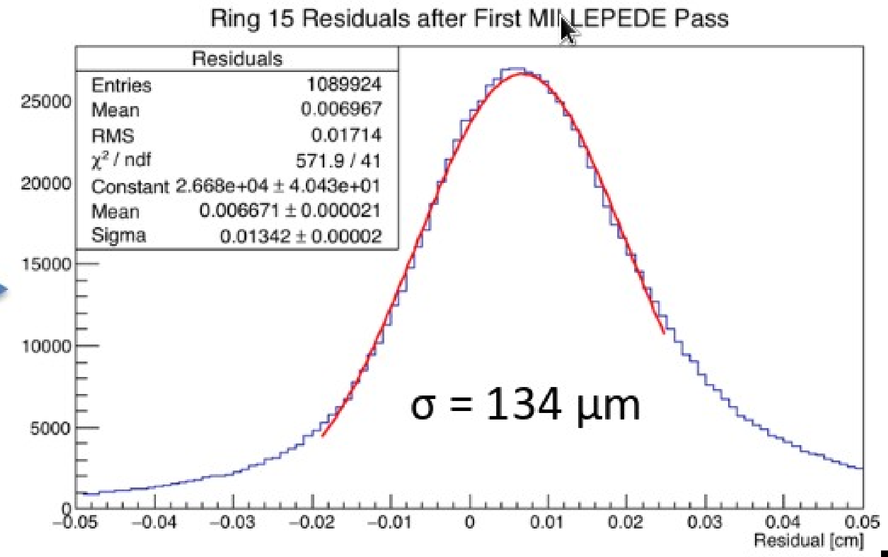
Improvements in residuals



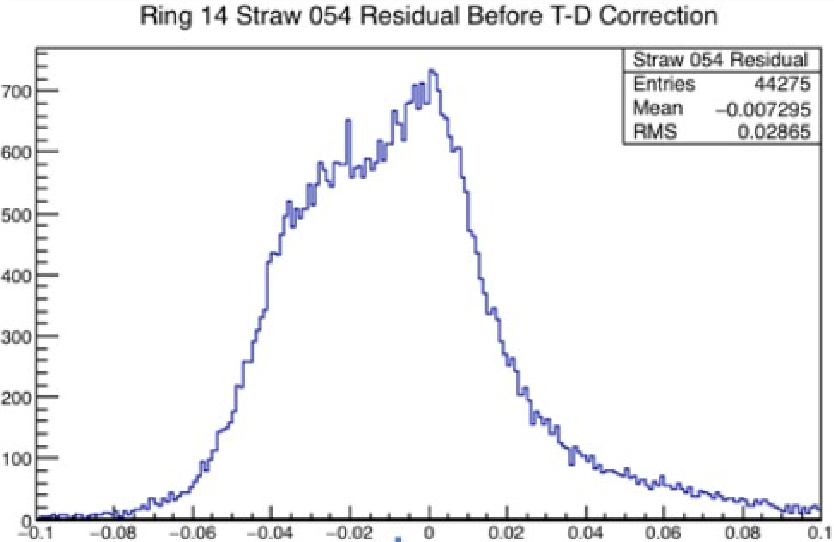
After correcting for straw deformations and a single pass at the wire alignment, biased residual widths improve from 193 µm to 134 µm.

Reminder: Design goal $\sigma_{r\phi}$ ~ 150 µm



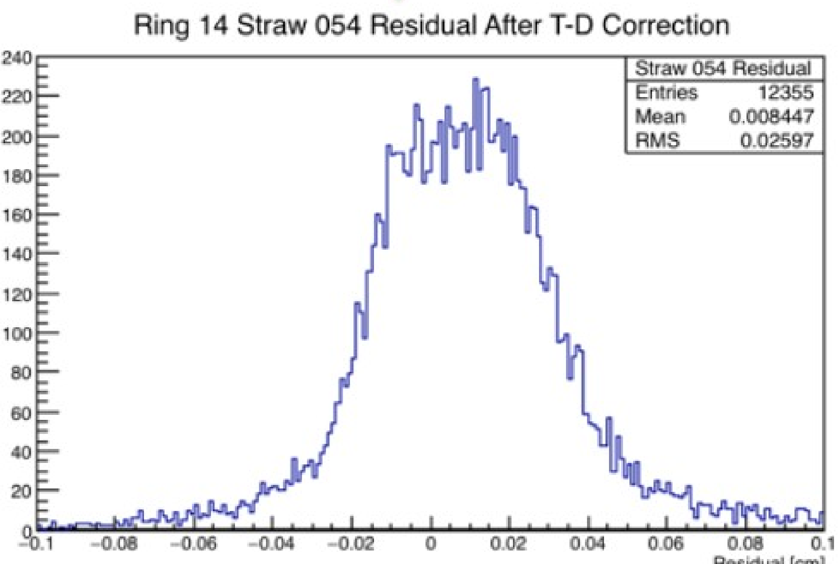


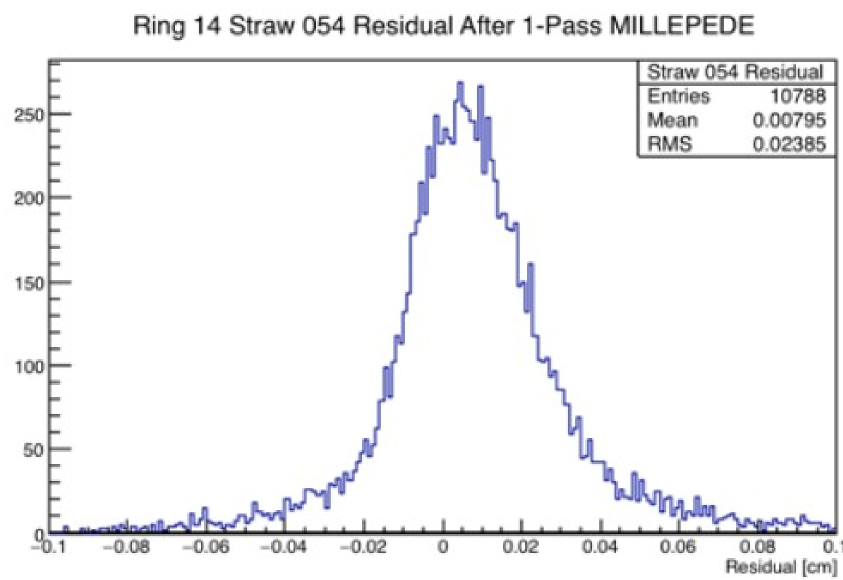
One straw: extreme case



Take an extreme case and apply the corrections.

Problem straws begin to look reasonable…





Summary

- Before alignment of wires in CDC $\rightarrow$ need to compensate for straw deformation
  - This changes time-to-distance relationship...
- We align each wire at each end of the straw $\rightarrow$ ~14k parameters!
  - First pass results with MILLEPEDE show that this can be managed...