Design, construction, and vertical slice performance tests of the Mu2e straw tracker

Richie Bonventre *on behalf of the Mu2e collaboration*

NuFact 2022

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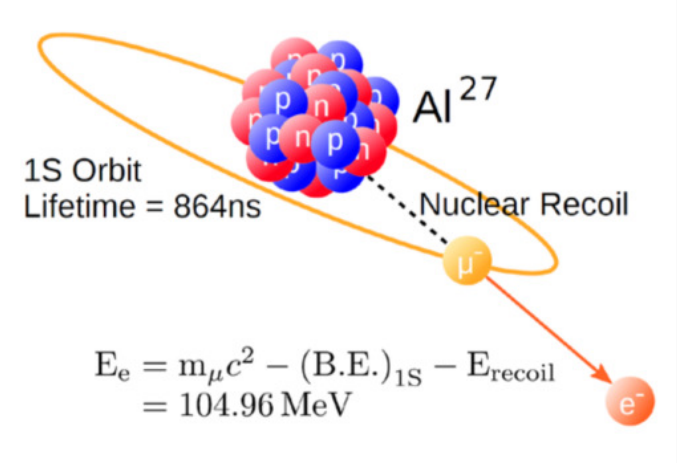
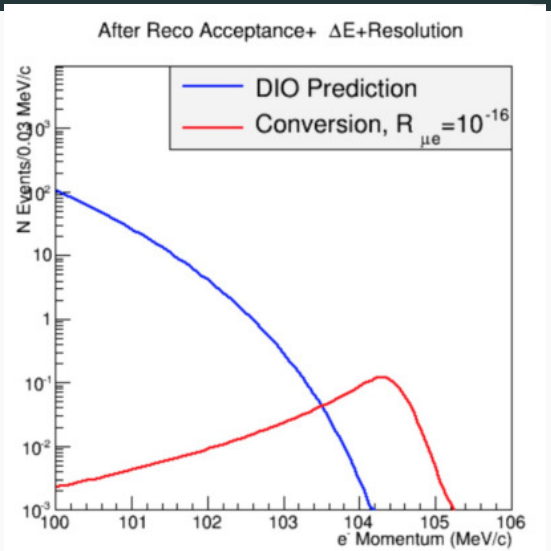
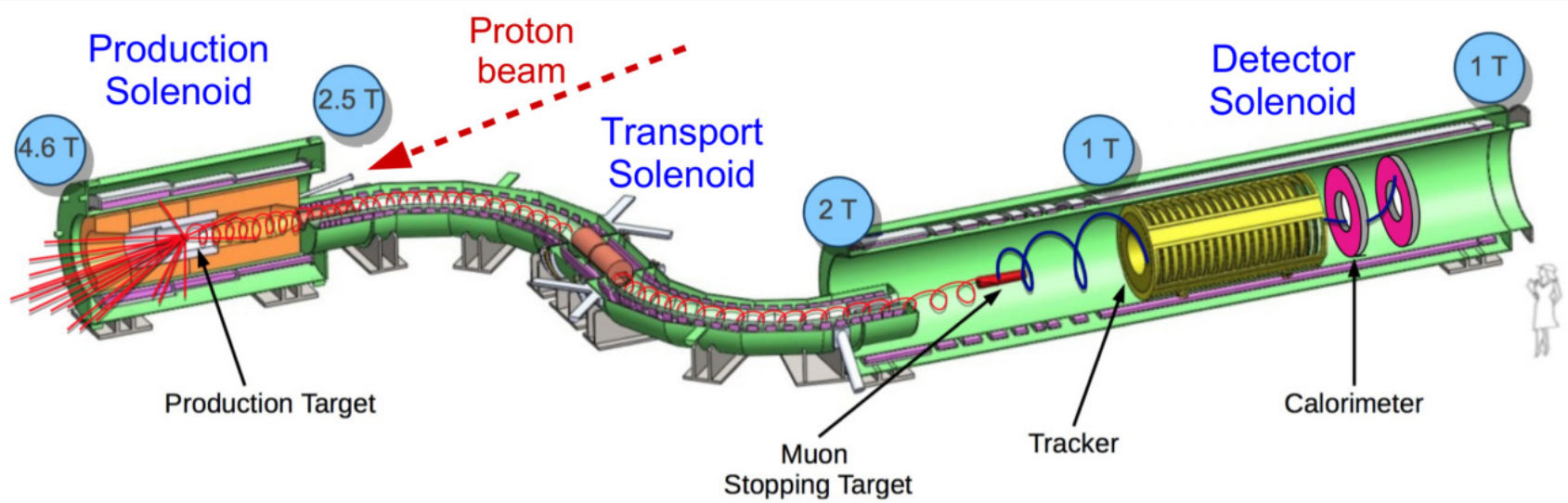
Mu2e will search for charge lepton flavor violation through $\mu \to e$ coherent conversion



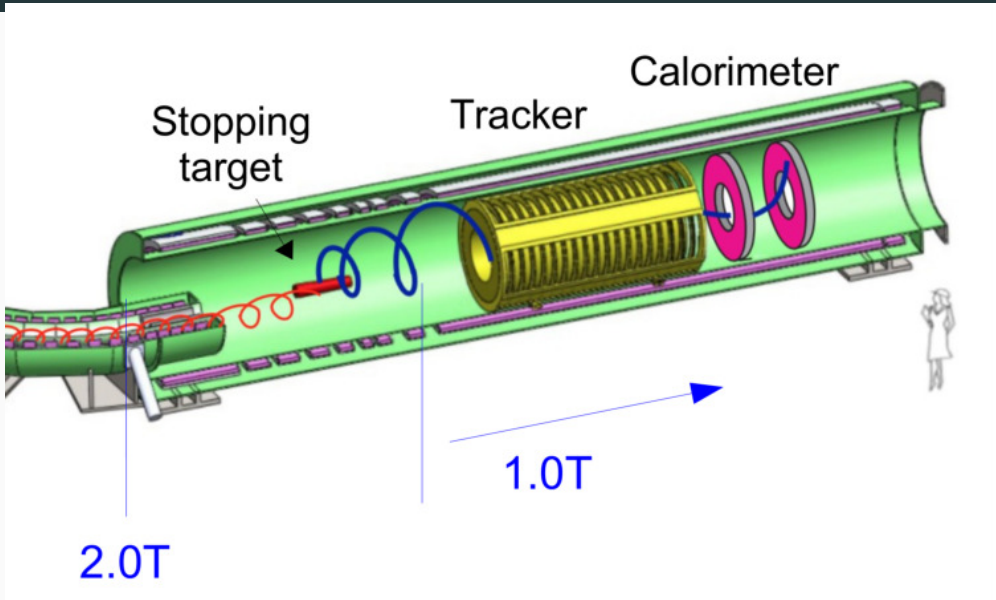


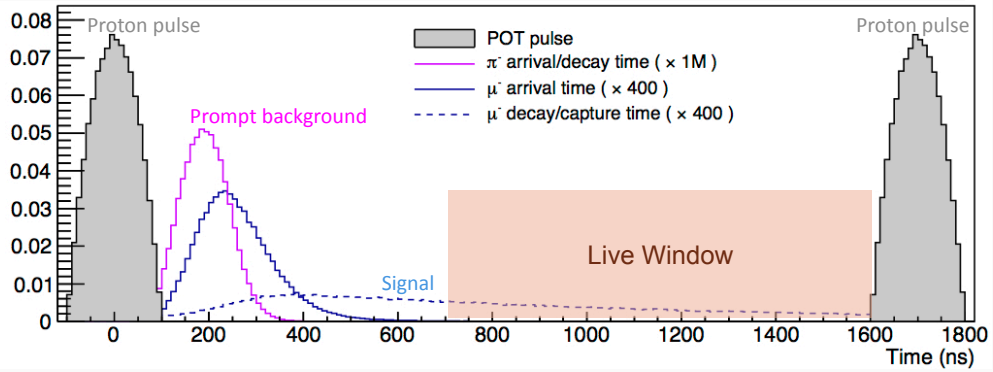
Toy MC simulated reconstructed momentum

Tracker makes the key momentum measurement



Challenges for Mu2e tracker design

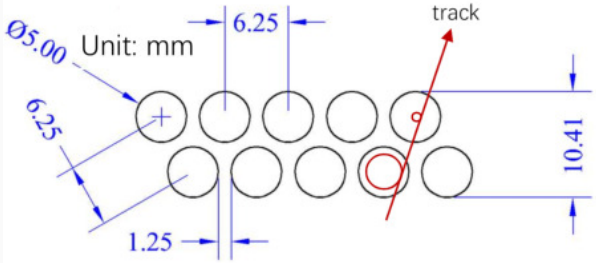


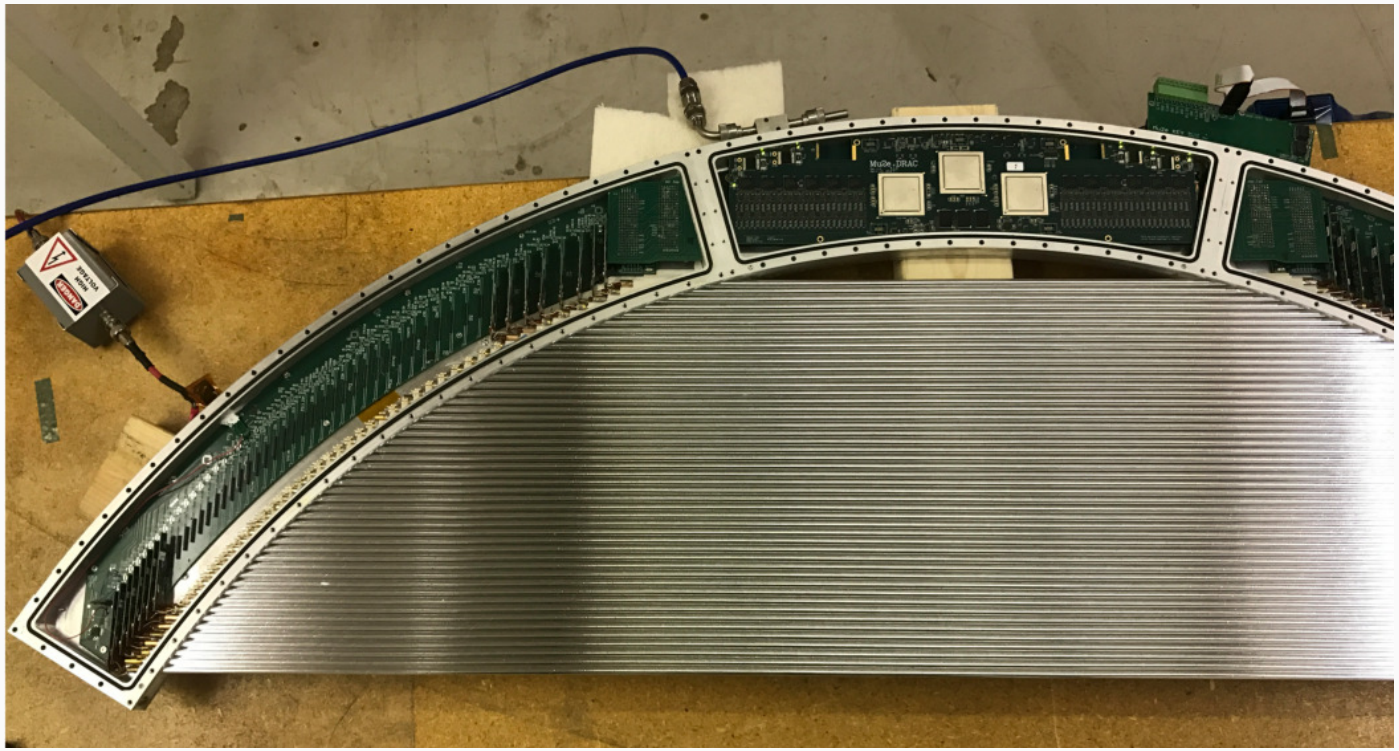


- To reach target sensitivity, need momentum resolution <200 KeV/c
  - Must precisely reconstruct helix
  - Detector needs to be low mass + in vacuum
- Design needs to provide enough information to reconstruct signal starting with minimal external constraints
  - Don't know t_0 (1 μs event window)
  - Don't known starting vertex
  - Signal is single track

Low mass straw tracker design

- ~21,000 low mass straw tubes in vacuum
- 5 mm diameter, 0.5-1.2m long, held at tension
- 15 μm thick mylar walls, 25μm tungsten wire
- 1 atm of 80/20 Ar:CO_2
- Assembled in 'panels' of 96 straws in two staggered layers
- 3-D printed plastic curved gas manifold

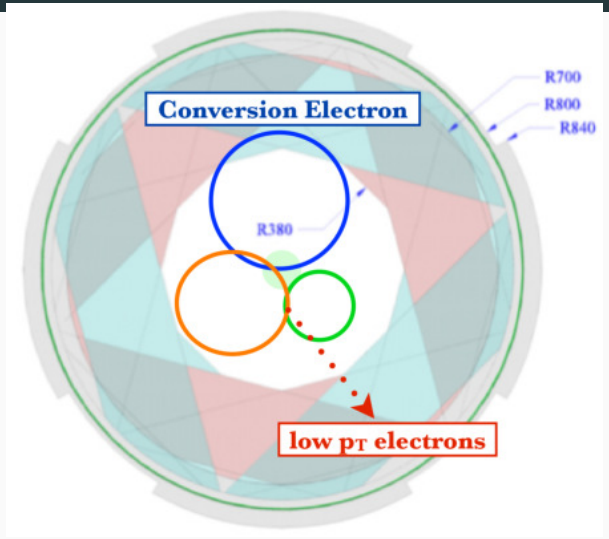


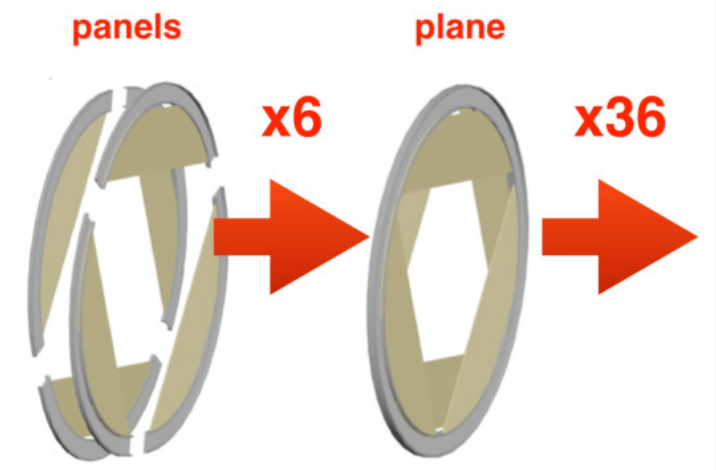


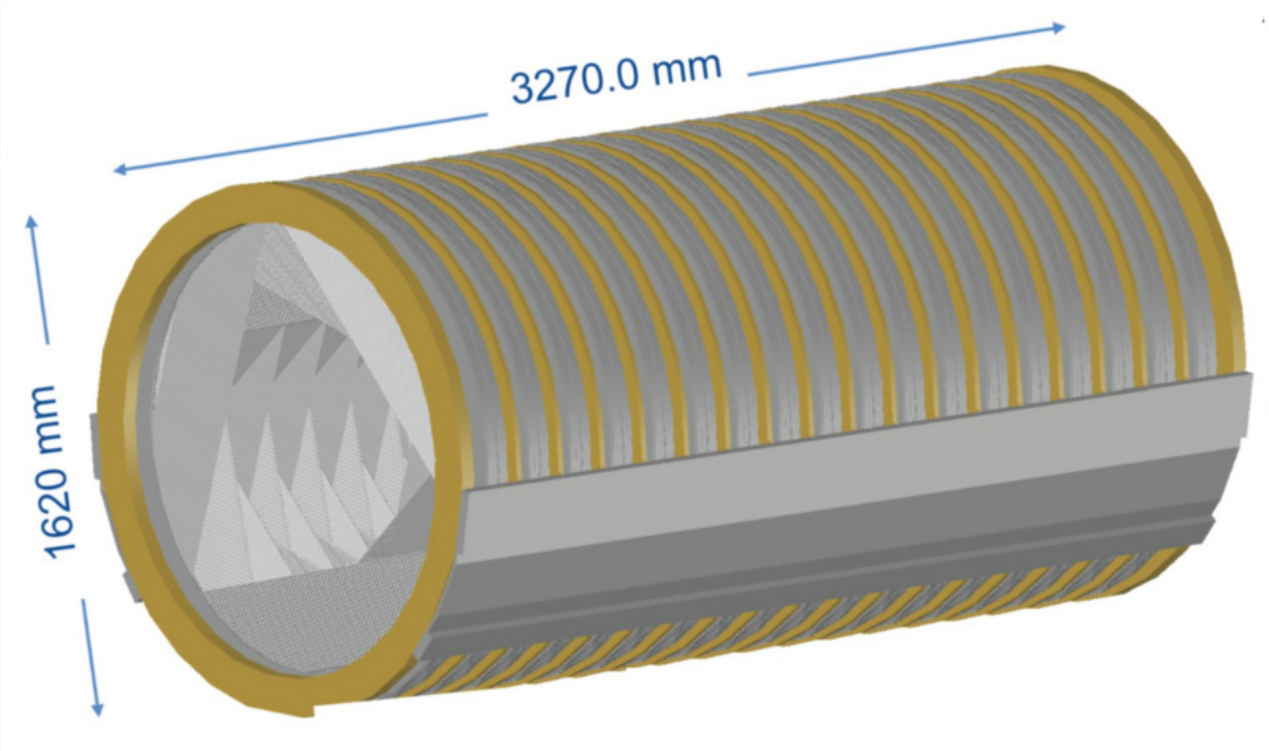
A single 'panel' of 96 straws

Low mass straw tracker design

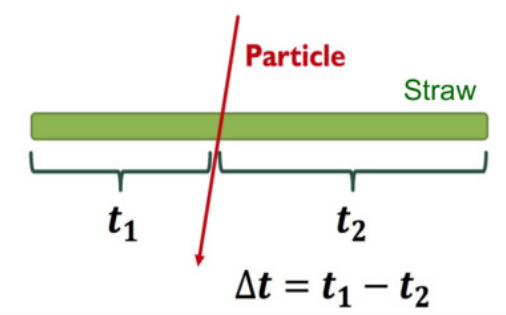
- 36 planes, each containing 6x 120° panels for stereo measurement
- Blind to decay-in-orbit background momentum peak and beam flash
  - Reduces radiation load, hit rate

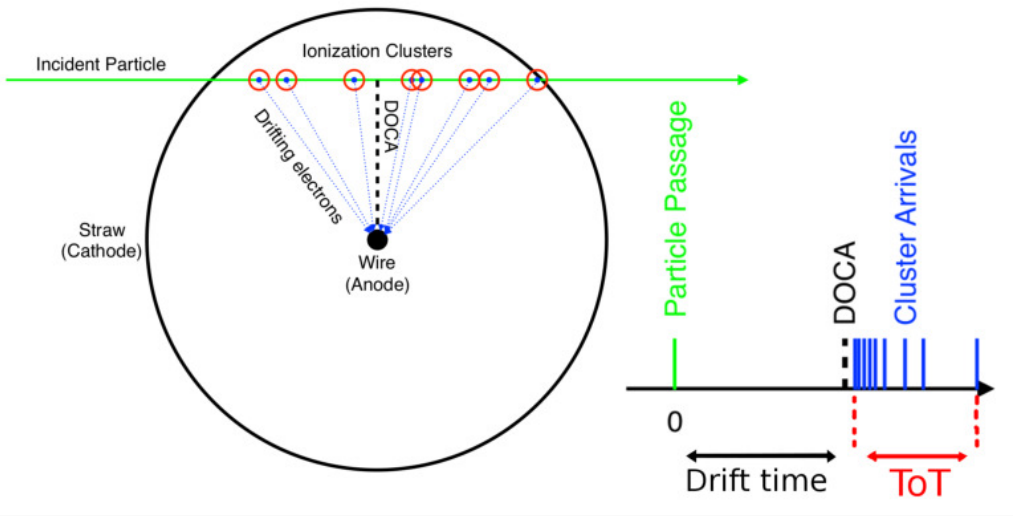






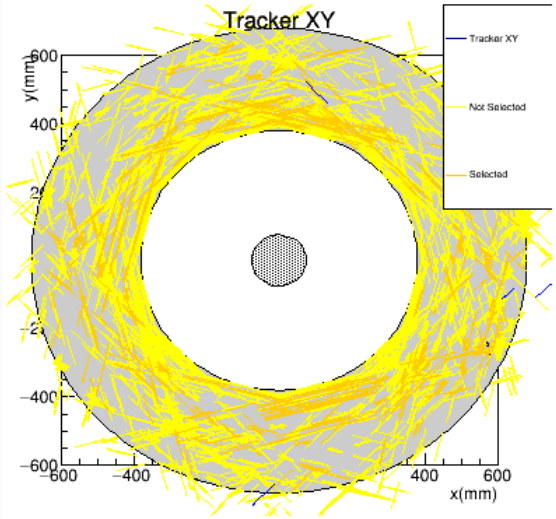
Measurements from each hit straw



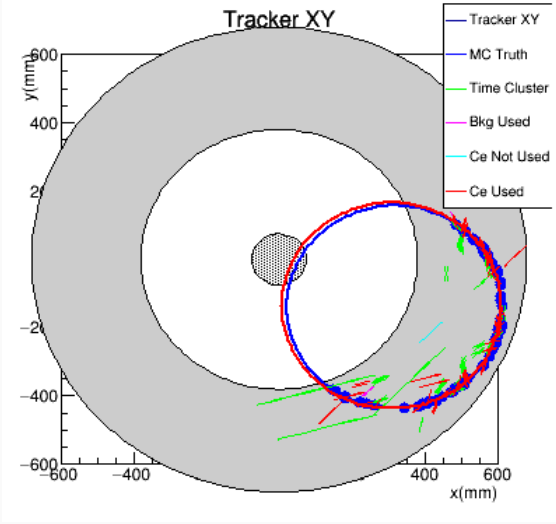


- Drift time $\rightarrow$ radial resolution $\sim$250 μm
- Time division $\rightarrow$ longitudinal resolution $\sim$4 cm
- Time-over-threshold $\rightarrow$ Measure of path length / radius independent of t_0
- Digitize waveform to reject highly ionizing backgrounds

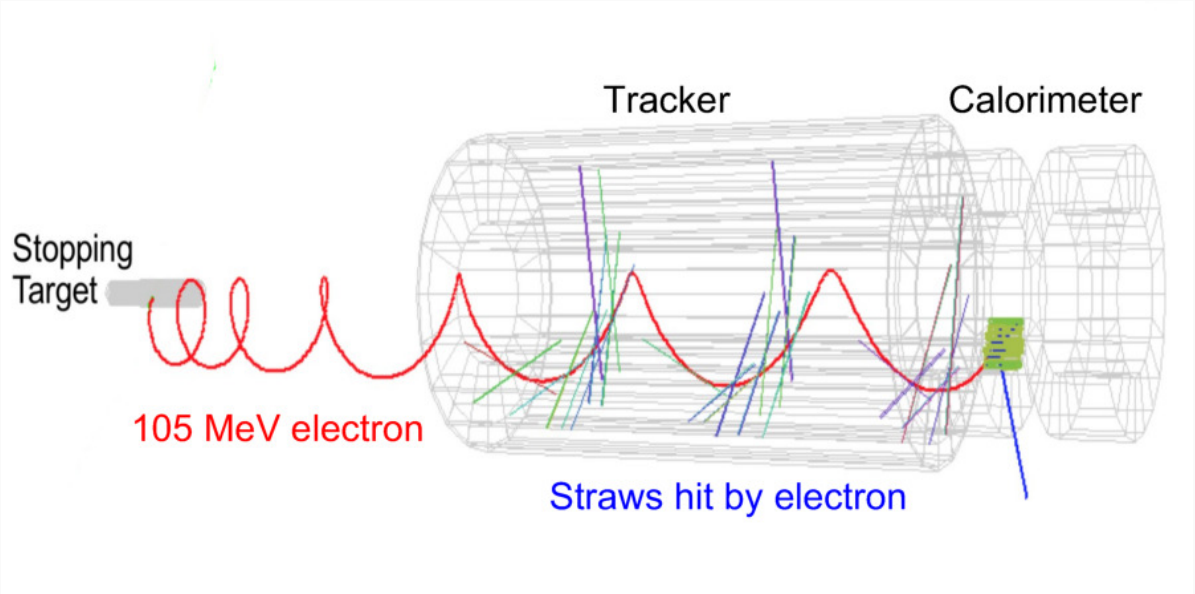
Helix reconstructed using Kalman Filter fit



1 μs selection window after beam flash

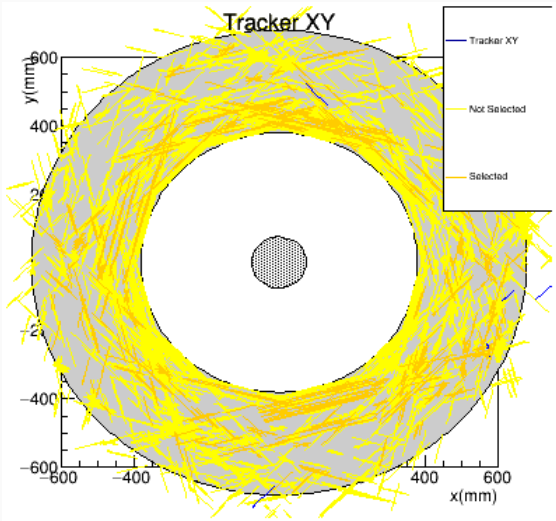


Hits selected by track finder within $\pm$50 ns selection window

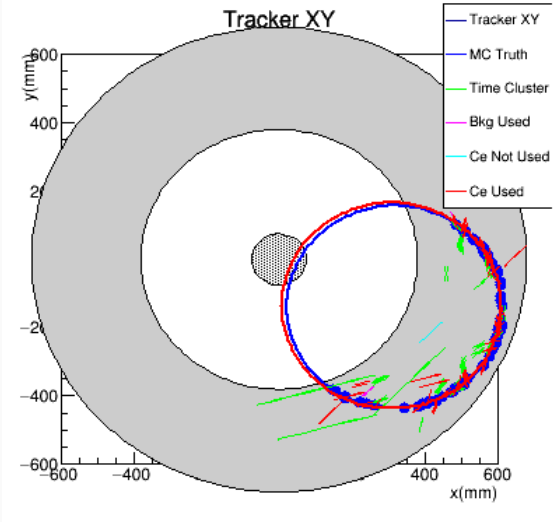


- Initial time clustering and circle finding
- Iterative Kalman Filter fit for helix

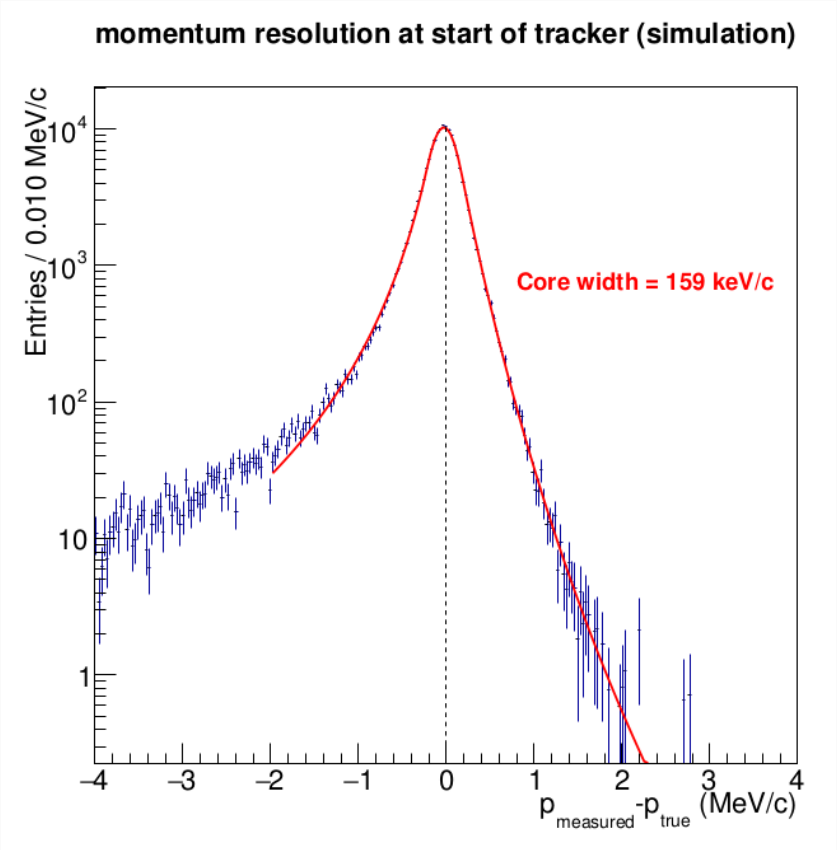
Helix reconstructed using Kalman Filter fit



1 μs selection window after beam flash

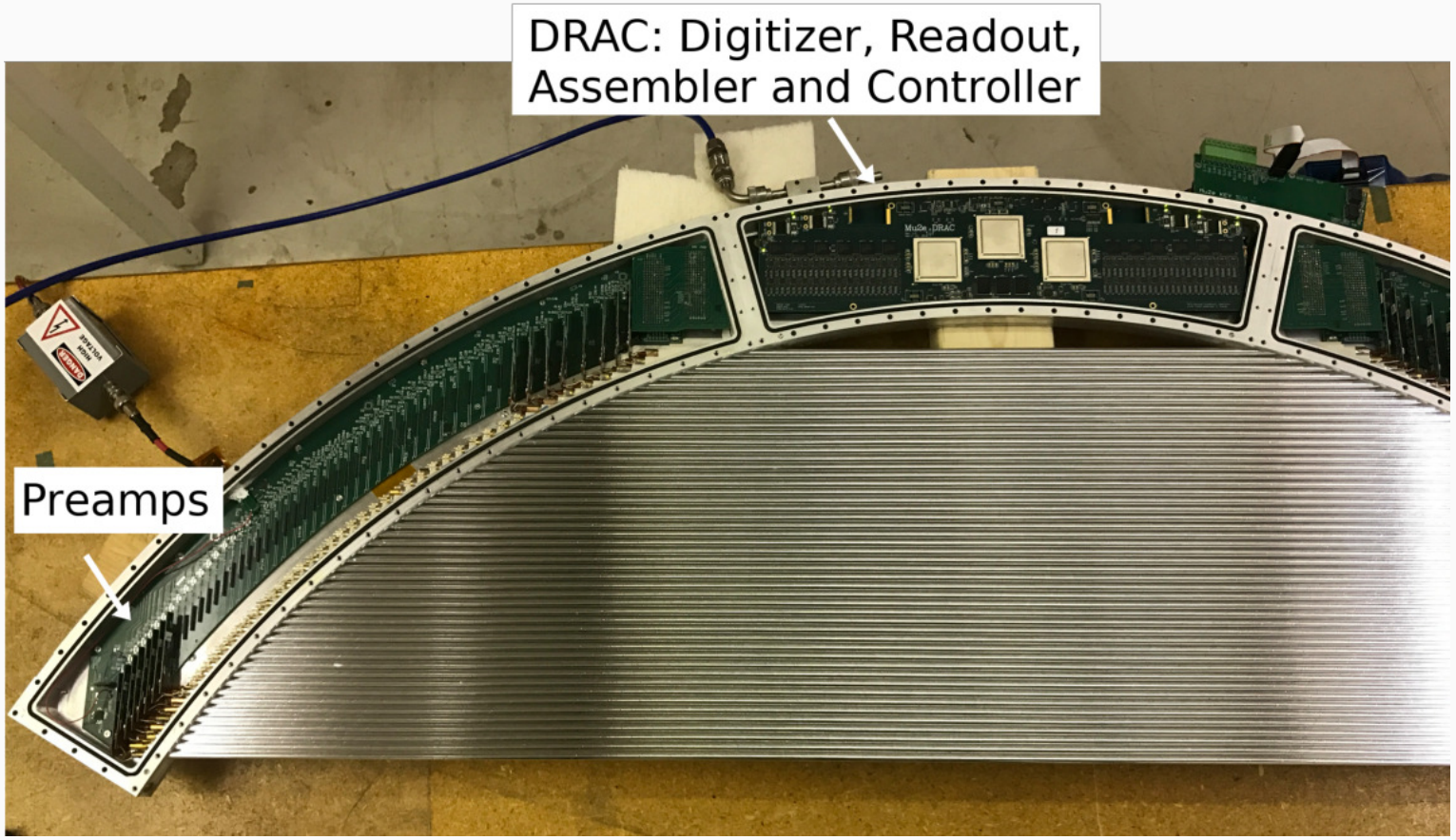


Hits selected by track finder within $\pm$50 ns selection window



- Initial time clustering and circle finding
- Iterative Kalman Filter fit for helix

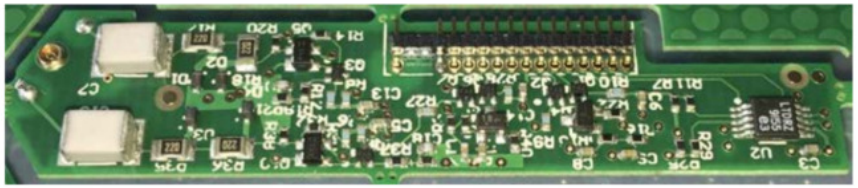
Front end electronics positioned directly next to straws inside vacuum



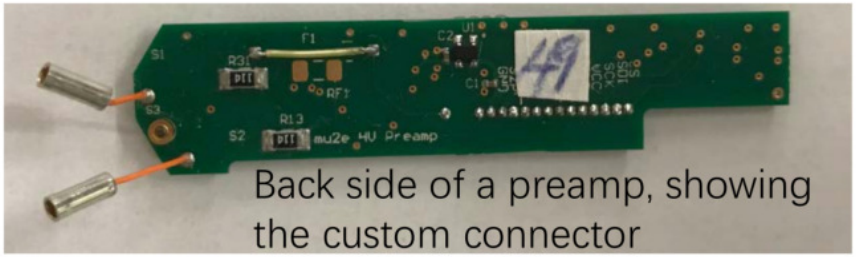
- Preamps on both ends of each straw
- Single digitization and readout board for each panel

Front end electronics: preamps

- Compact vertical installation
- Custom connectors to straws
- Charge injection for calibration



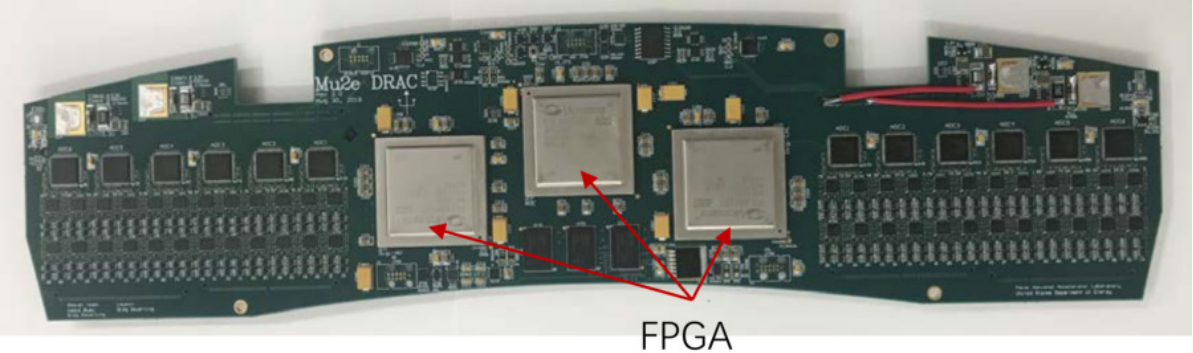
Front side of a preamp. Each preamp serves two straws



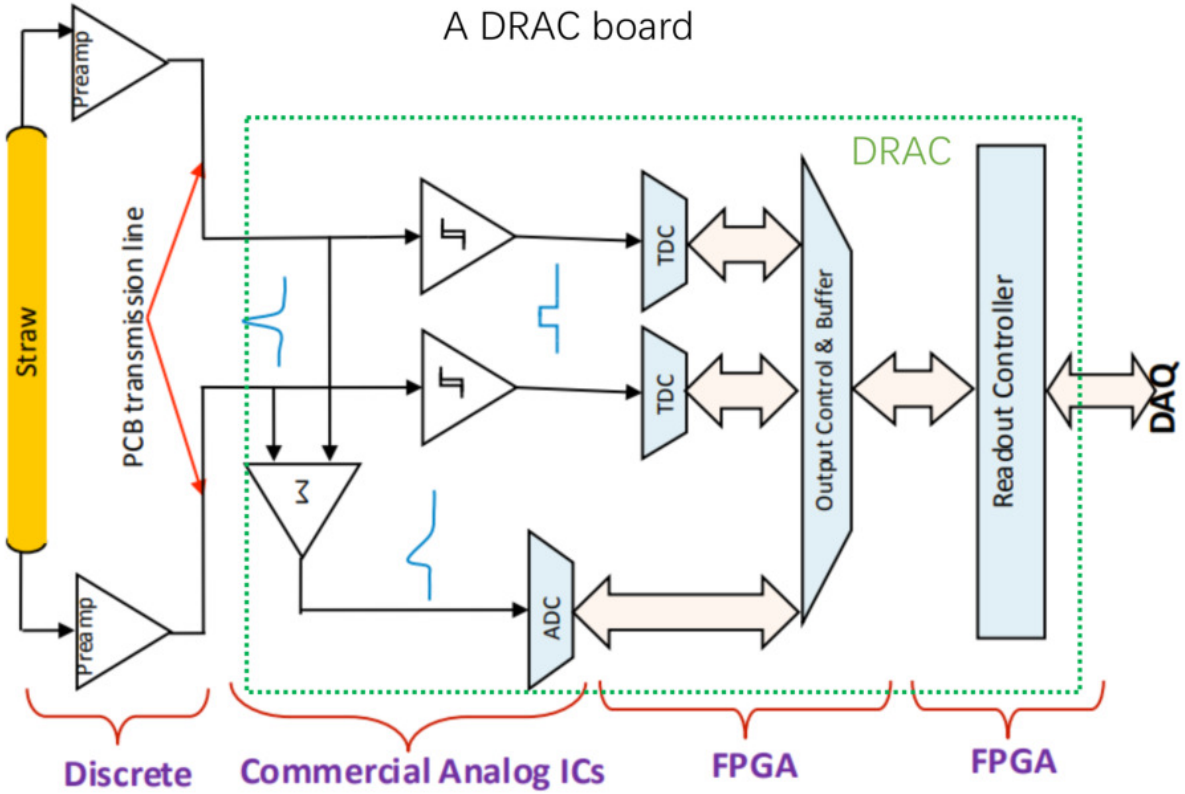
Back side of a preamp, showing the custom connector

Front end electronics: DRAC

- 3x Microsemi PolarFire FPGAs
  - Two digitizers and one readout controller
  - Two firmware TDCs with <70 ps resolution per channel
- 50 MHz commercial ADCs to digitize waveform
- DDR3 memory for buffering
  - Takes advantage of ∼30% beam dutyfactor
- VTRx optical transceivers to TDAQ
  - 200 MHz detector clock and time synchronization from TDAQ over fiber

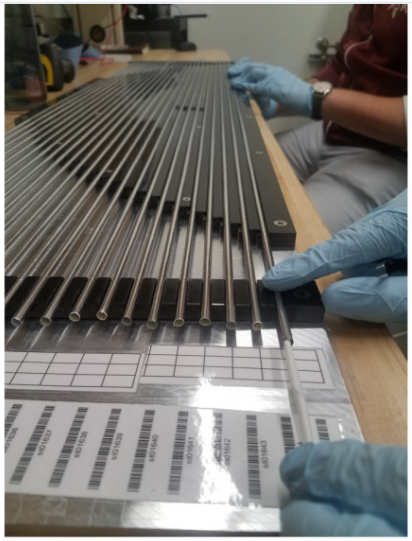


A DRAC board

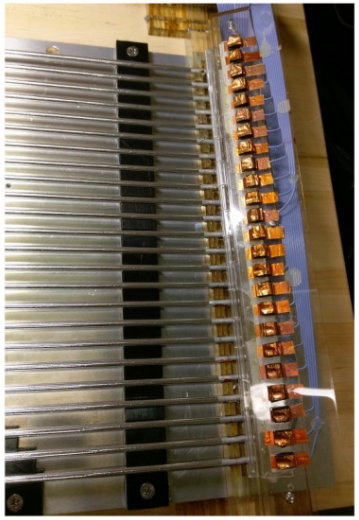


Signal flow chart

Tracker construction starts with assembly and testing of the straws



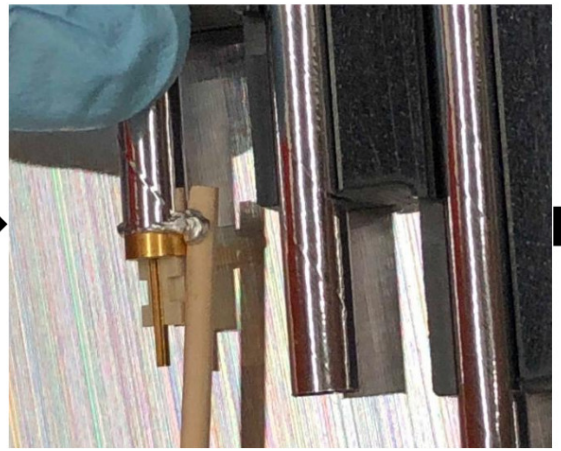
Paper Removal



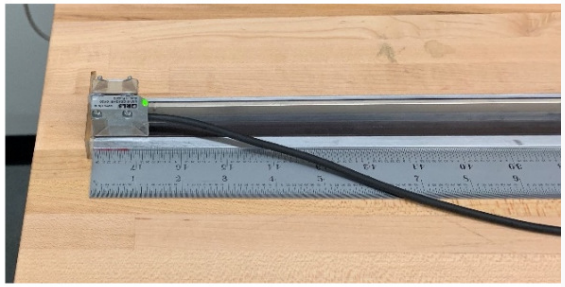
Conductivity Test

CO_2 Leak Test

Laser Cut to length

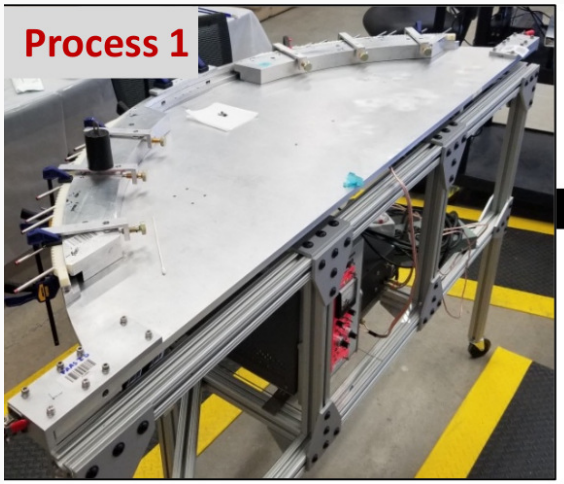


Insert Terminations



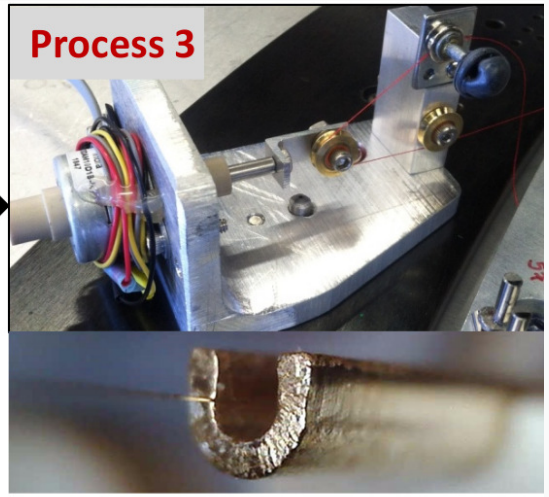
Length Verification

Then about three weeks to build and test each panel

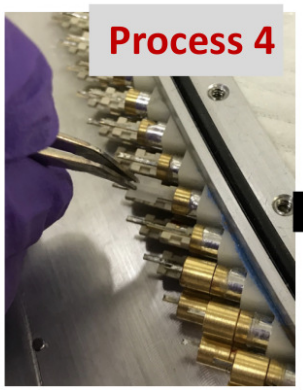


Inner Ring Building (2 days)

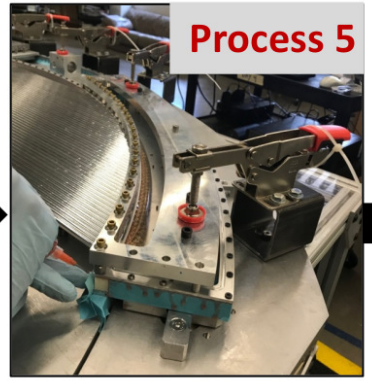
Straw Installation (1 day)



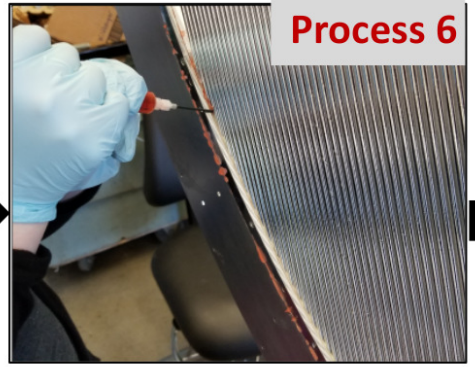
Wire Installation (3 days)



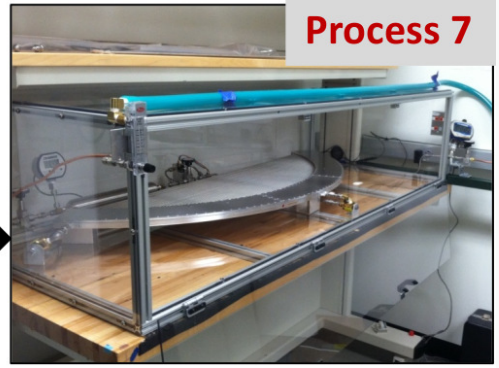
Pin Protector & Ground Clip Installation (1 day)



Manifold Installation (1 day)

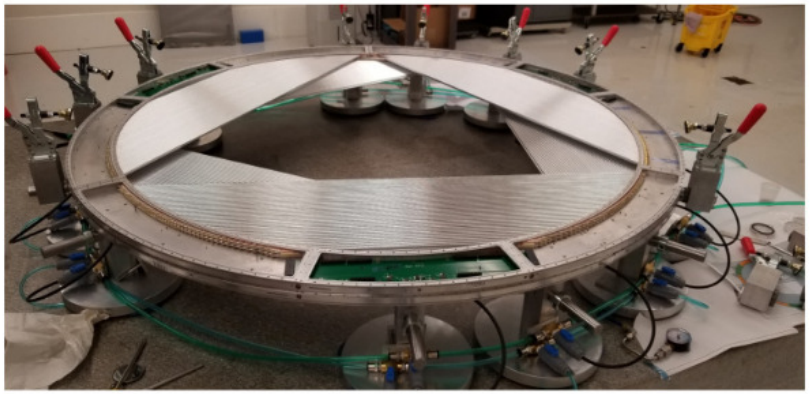


Alcohol Leak Check and Flooding (2 days)



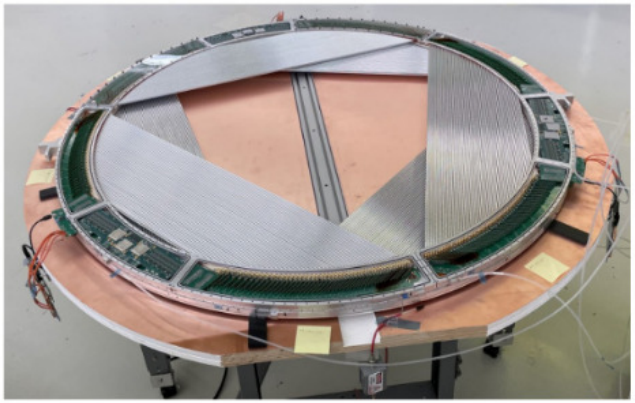
Resistance Check & Leak Test (3 days)

Finally panels are combined into planes and installed into the detector frame

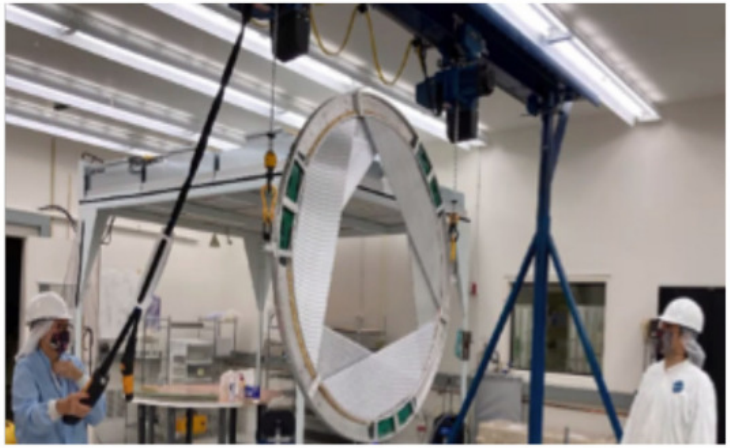


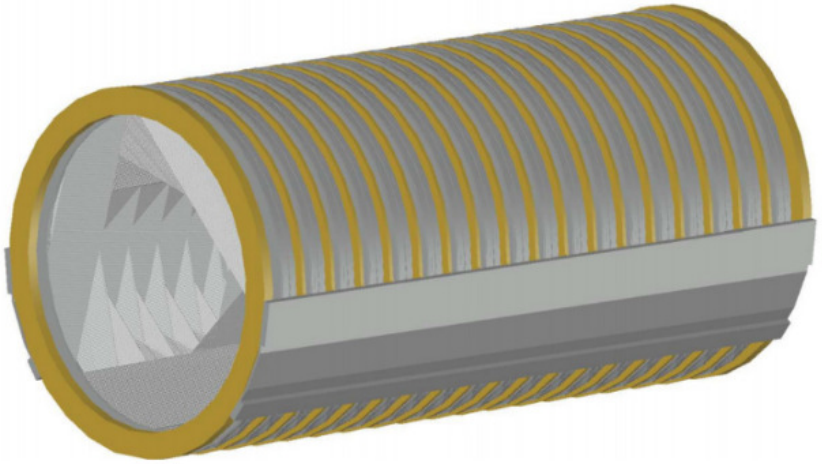
Planes Constructed

6 panels make a plane



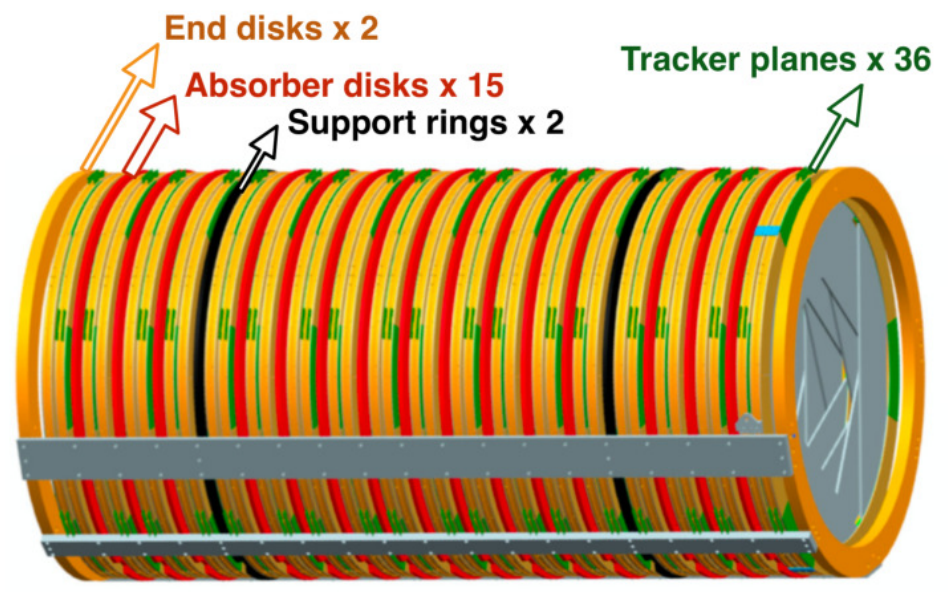
Electronics installed

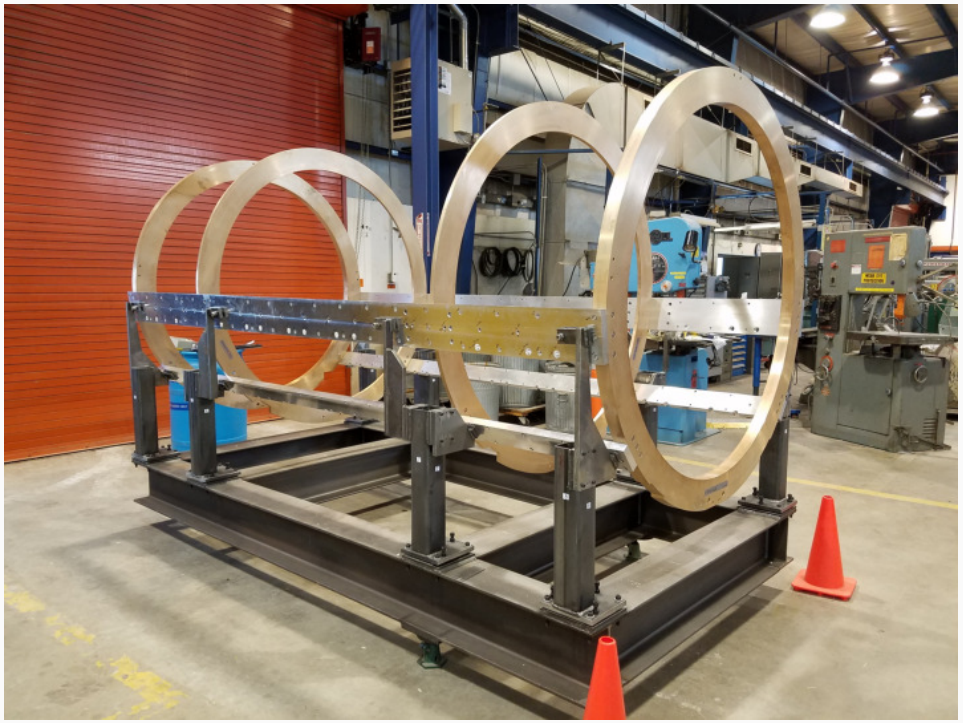




36 planes make the tracker

Tracker frame provides structural support and holds the planes in alignment

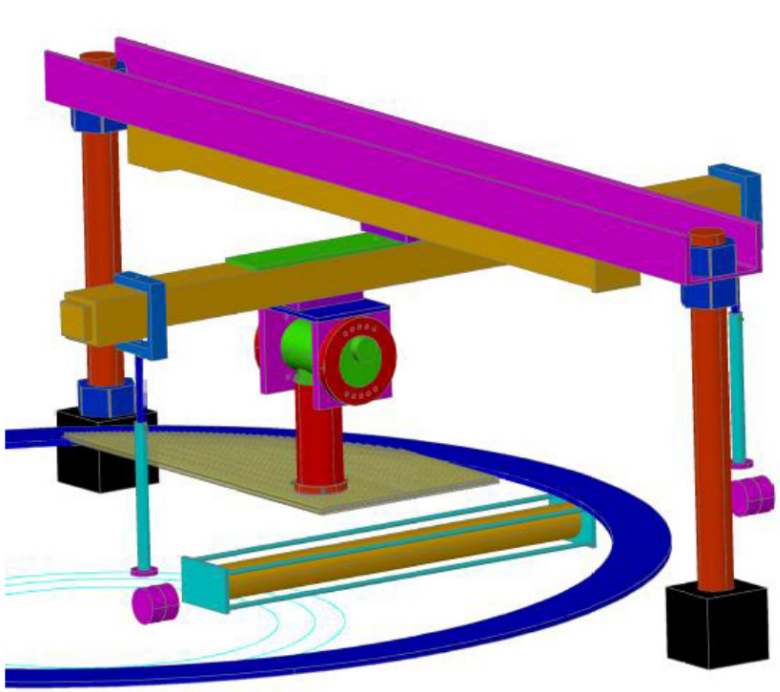


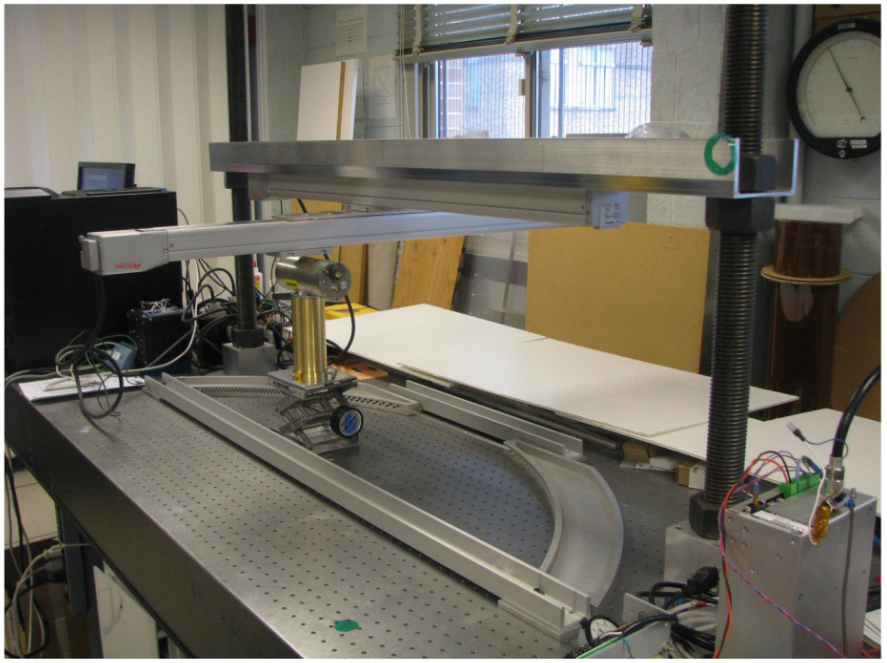


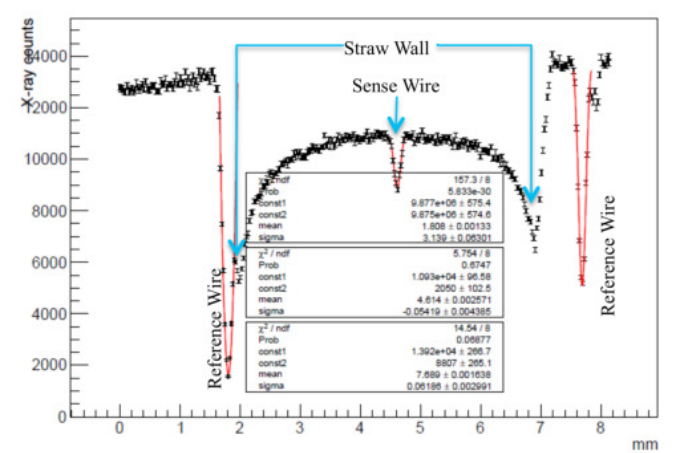
Tracker frame dry fit test

- Tracker assembled on frame and then can be inserted into magnet as single unit
- Bronze absorber disks to reduce radiation and dissipate heat

Each panel x-ray scanned to measure straw and wire positions



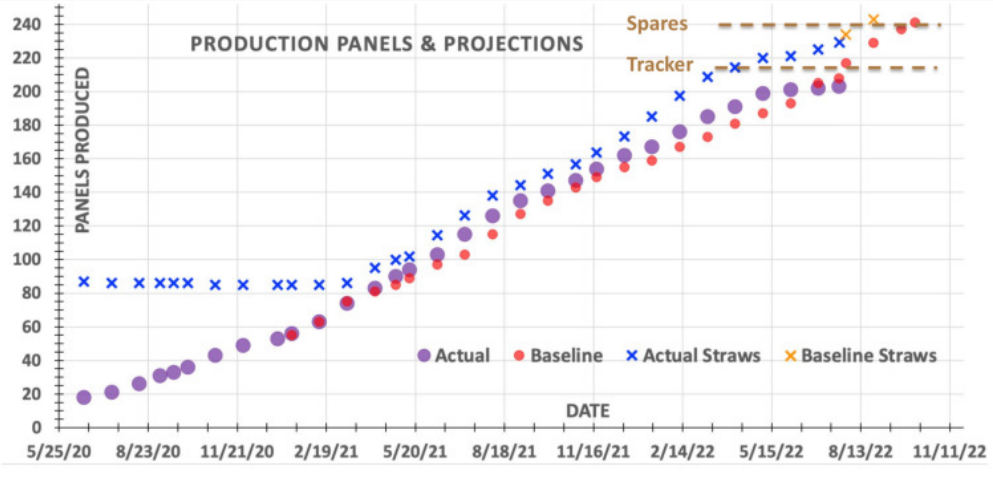




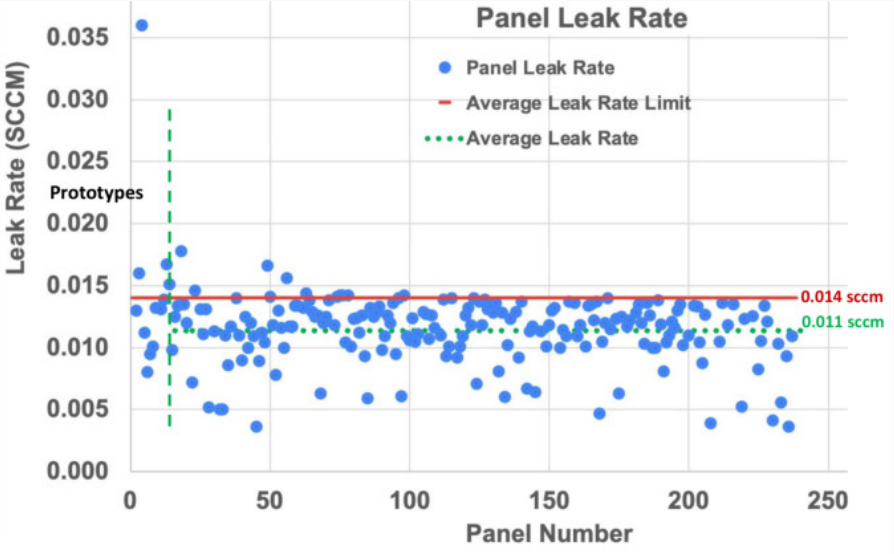
Example scan of Mu2e straw

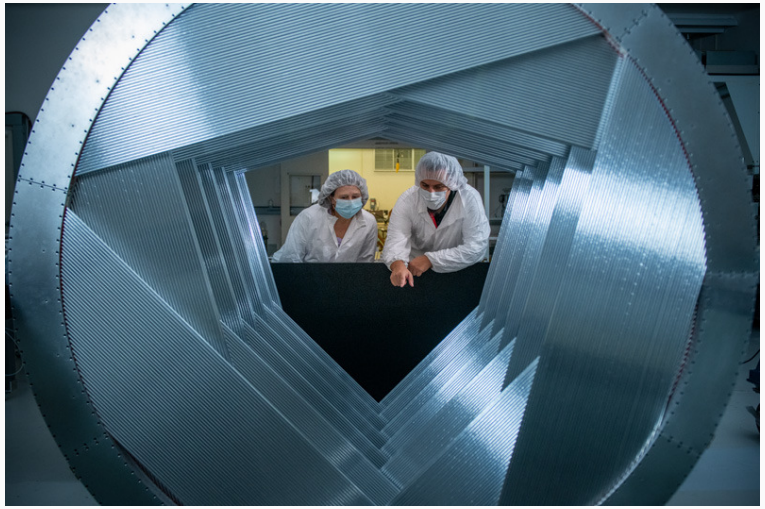
- X-ray scan measures position of each straw and wire to 25 μm/75 μm in y and z respectively
- First stage in determining final tracker alignment
  - 3 points on each panel for optical survey after tracker assembly
  - In-situ alignment using reconstructed tracks and Millepede-II

Construction of tracker elements is well underway

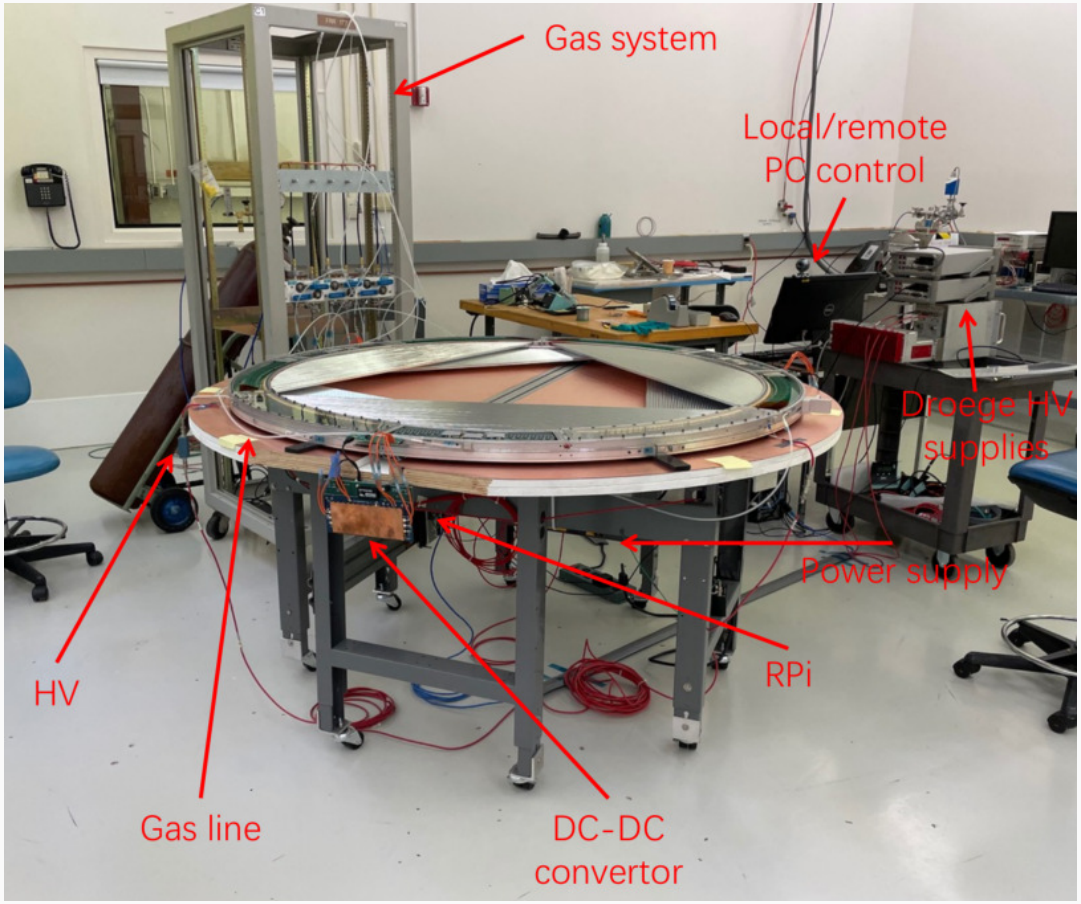


- All straws produced
- ∼85% of panels complete (including spares)
- 16 of 36 planes produced





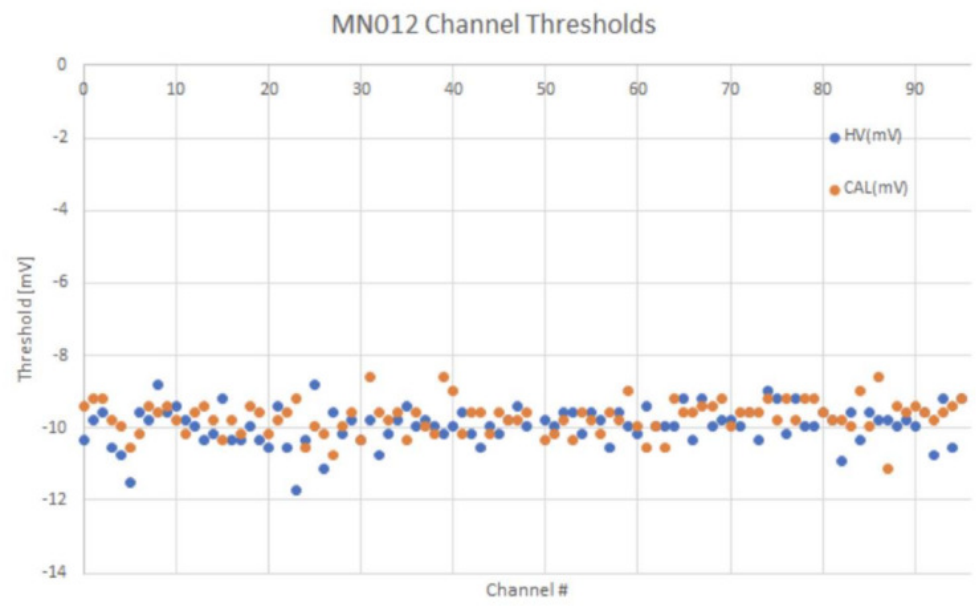
Completed 'vertical slice test' (VST) using first assembled plane

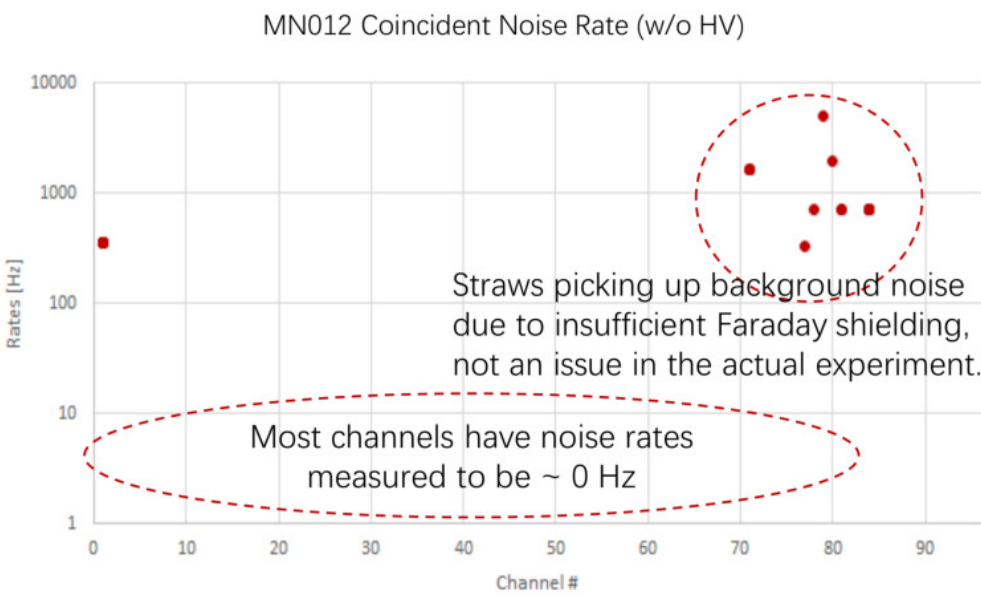


- 'Vertical slice': Testing full chain from straws to readout to processed data on disk
- Six fully instrumented pre-production panels in plane configuration with associated HV/gas/cooling infrastructure
- Read out by TDAQ over optical fiber
- Source and cosmic ray data taken in several configurations
- Demonstrates performance under realistic conditions

Very low noise seen at required channel thresholds

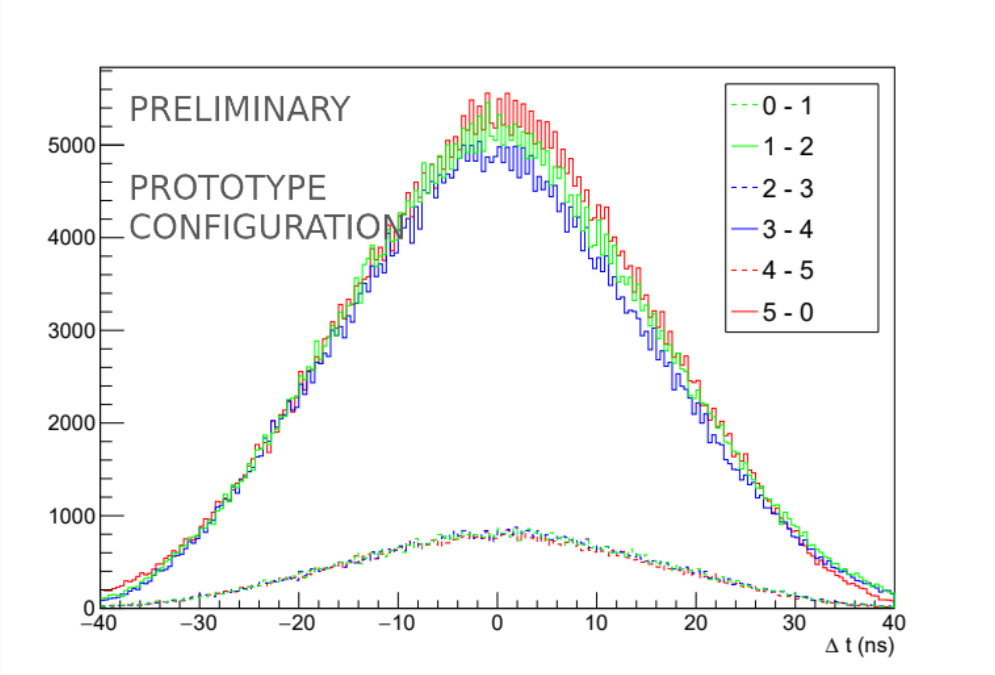
- Physics simulation and analysis studies assume 12-mV threshold
- At thresholds of ∼10 mV, demonstrated close-to-zero noise level in all channels (requirement is < 5 kHz at 90% efficiency threshold)





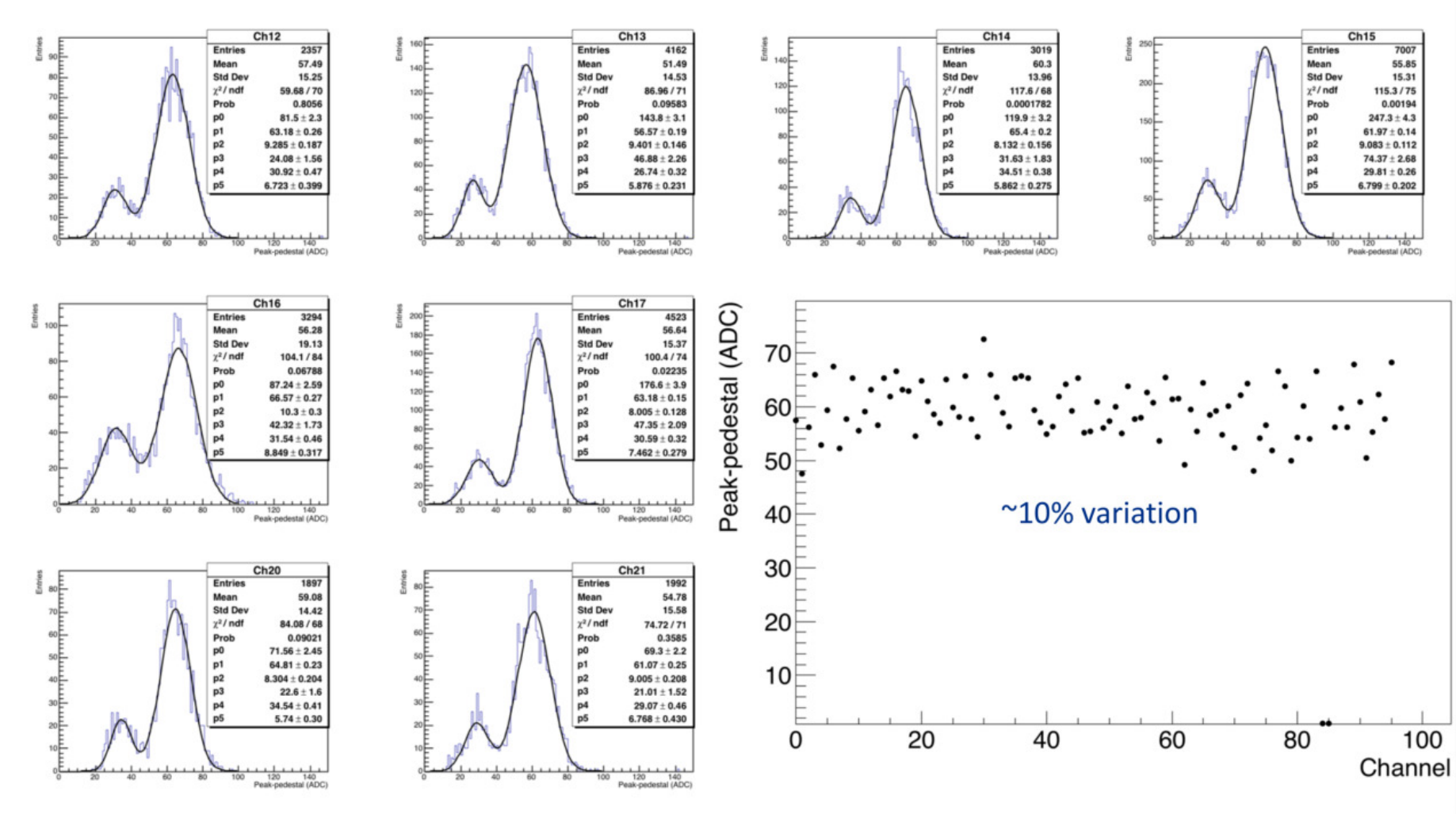
Coincident hits from cosmic rays used to demonstrate time synchronization between front end boards

- Mean gives absolute time offset between panels
  - Measured to be much less than one clock tick
- Demonstrate successfull recovery of clock and clock phase from fiber (clock tick is 5 ns)
- Synchronization of absolute timing
- Consistent over runs and power cycles



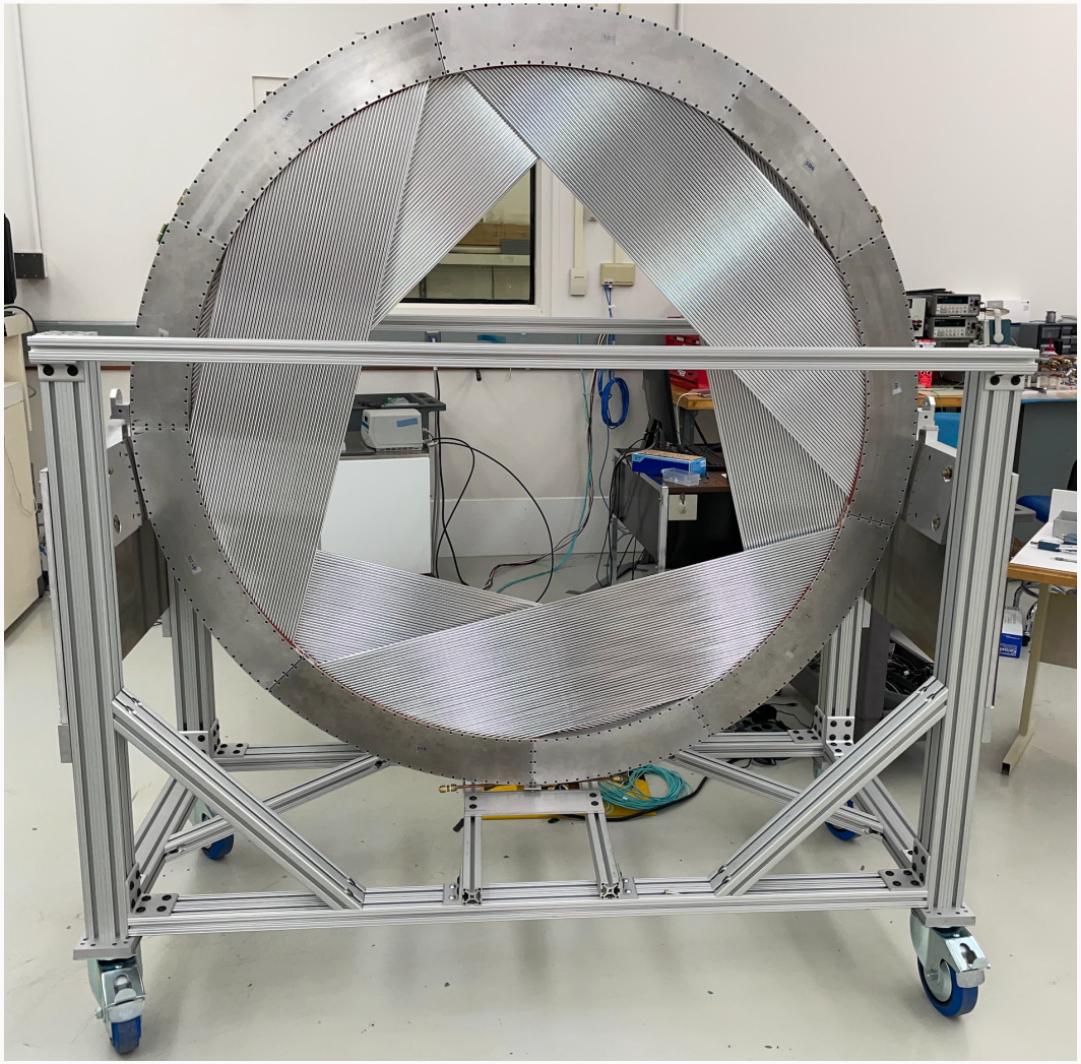
Time difference between coincidence hits in pairs of panels (VST data)

Fe55 source measurements show consistent performance across channels



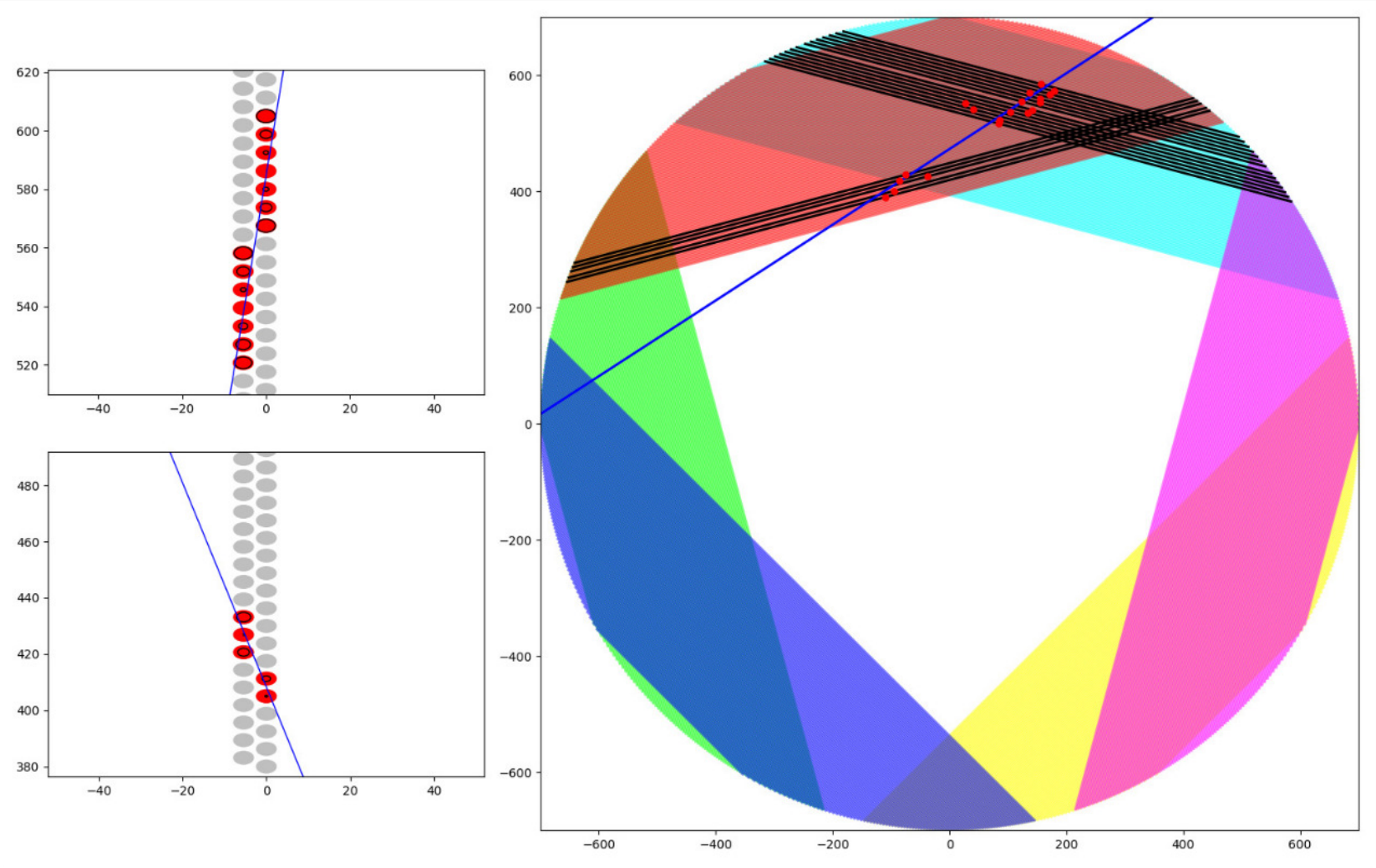
Measured pulse height for different straws (VST data)

Cosmic ray data taken in vertical configuration allow track reconstruction and measuring straw hit resolution

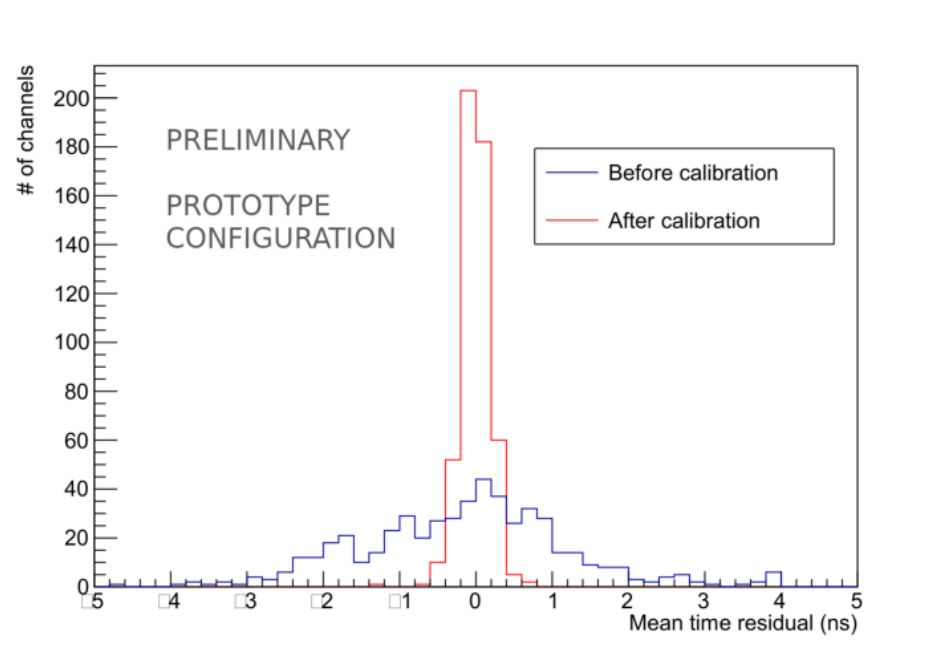


- Simplified track reconstruction
  - Assumes straight line track
  - Minuit based likelihood fit
- Includes both drift time and time division measurements
- Uses detailed drift response model including non-linear velocity and cluster statistics effects
- Uses x-ray scan alignment information

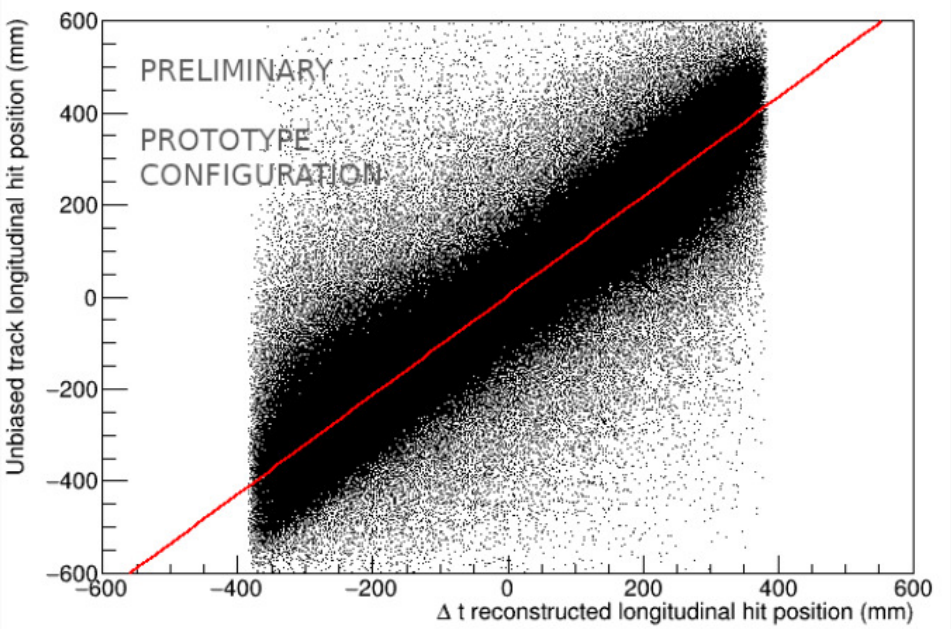
Example straight line track fit (VST data)



Calibrated time offsets, hit reconstruction using fit residuals

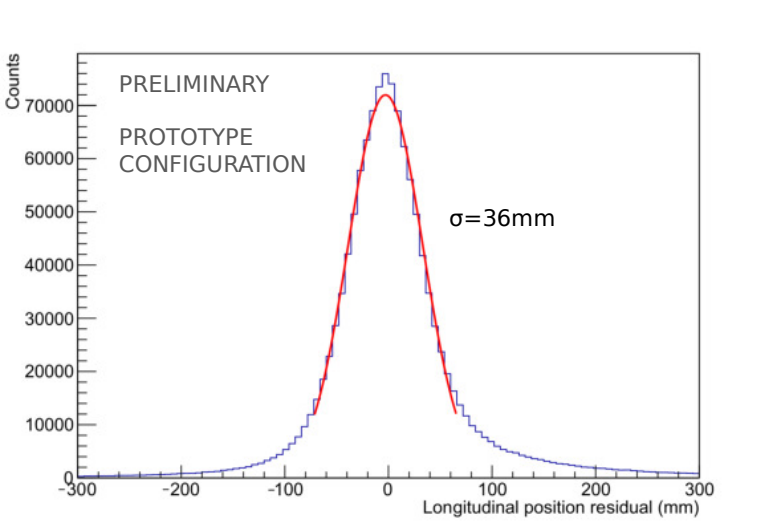


Mean time residuals for each straw before and after calibration (VST data)

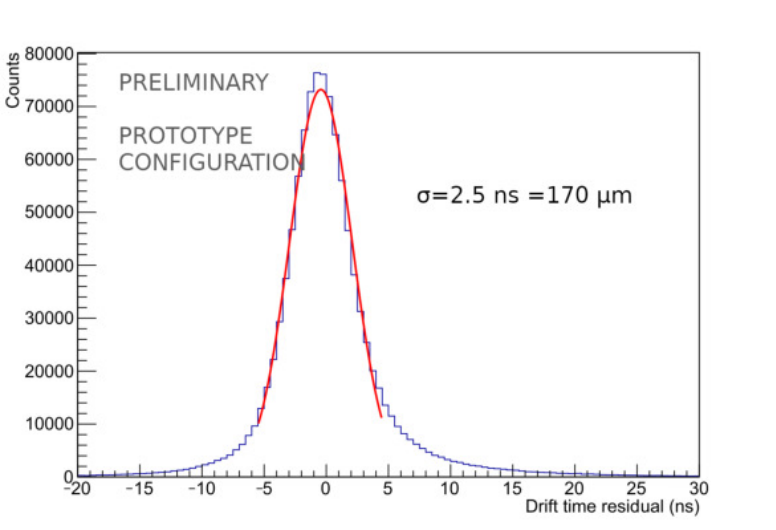


Example fit for longitudinal propagation velocity calibration (VST data)

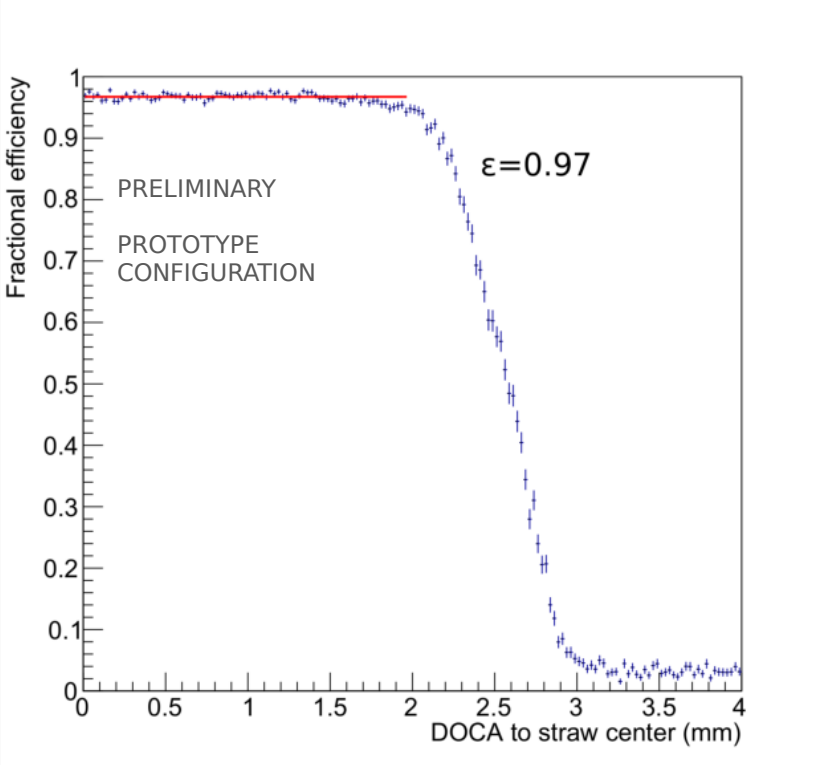
Hit level performance demonstrated across entire VST plane



Longitudinal resolution, middle 80% of straw length (VST data), requirement <40 mm



Drift resolution, excluding inner 0.5mm (VST data), requirement <250 mm



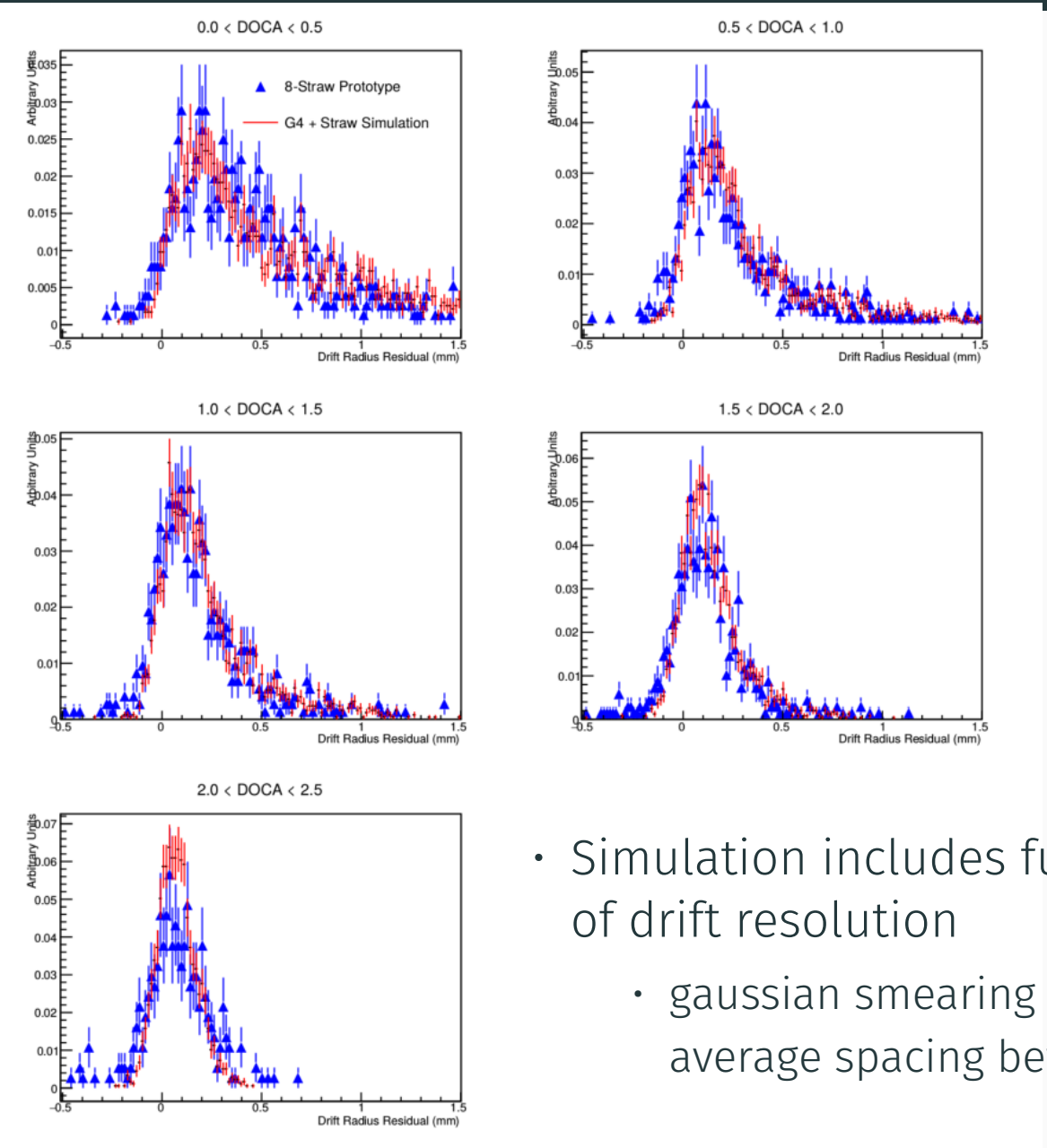
Efficiency vs distance to wire (VST data), requirement >90%

Summary

- The Mu2e tracker has been designed to measure the conversion electron momentum with a resolution of $<$200 MeV/c
- Vertical slice tests have demonstrated that the performance of pre-production panels in a realistic configuration meets requirements
- Construction of the tracker is well underway
  - Panel production complete by end of 2022
  - Plane and station production completed by end of 2023
- Cosmic ray tests of full tracker in detector hall expected to be completed by end of 2024

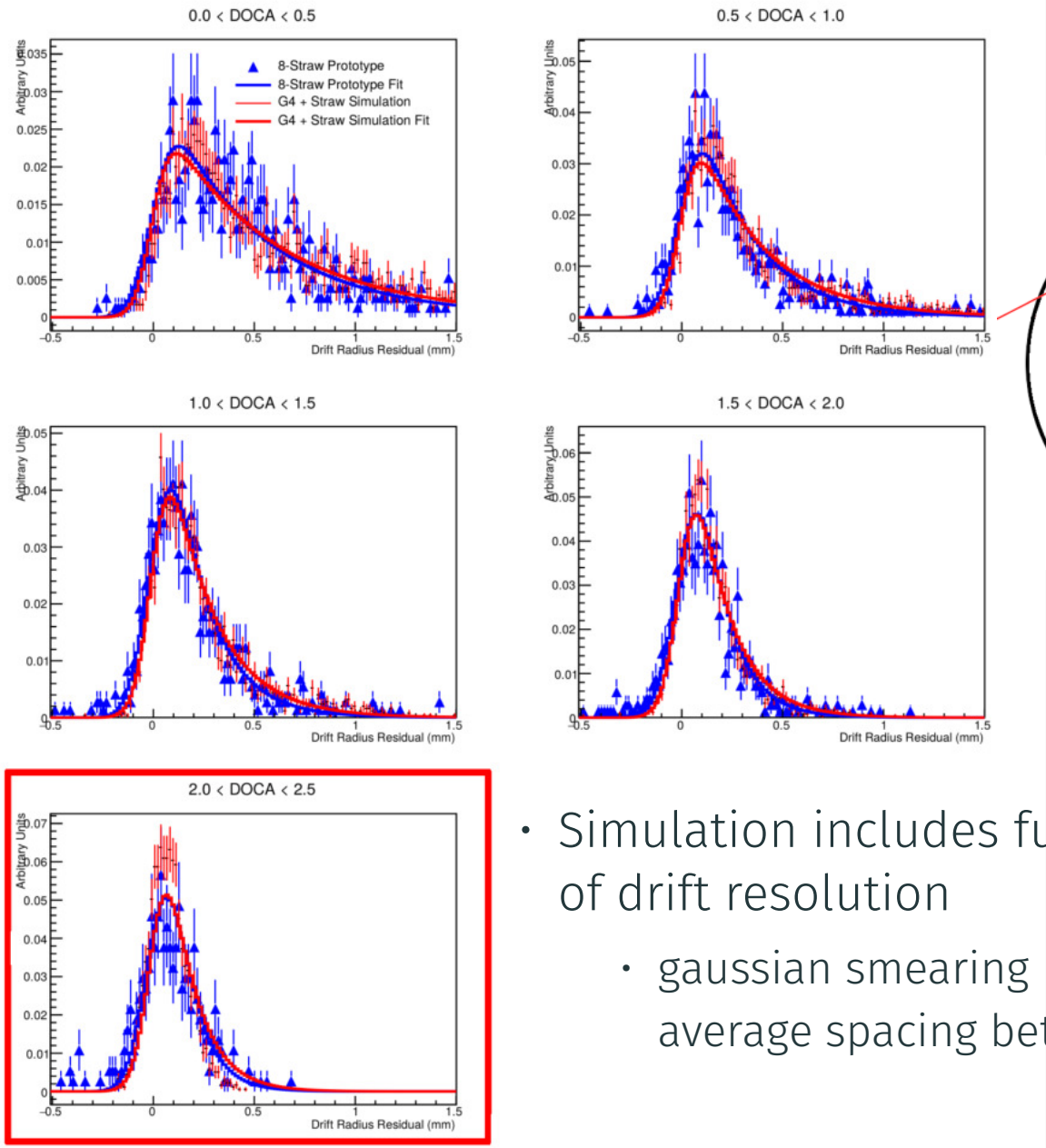
Backup

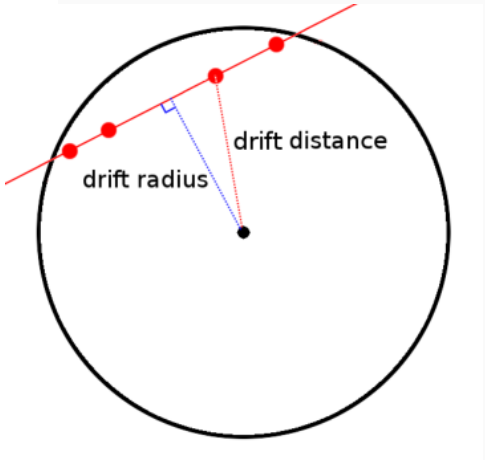
Drift response model



- Simulation includes full radius dependence of drift resolution
  - gaussian smearing $\times$ exponential encoding average spacing between ionizations

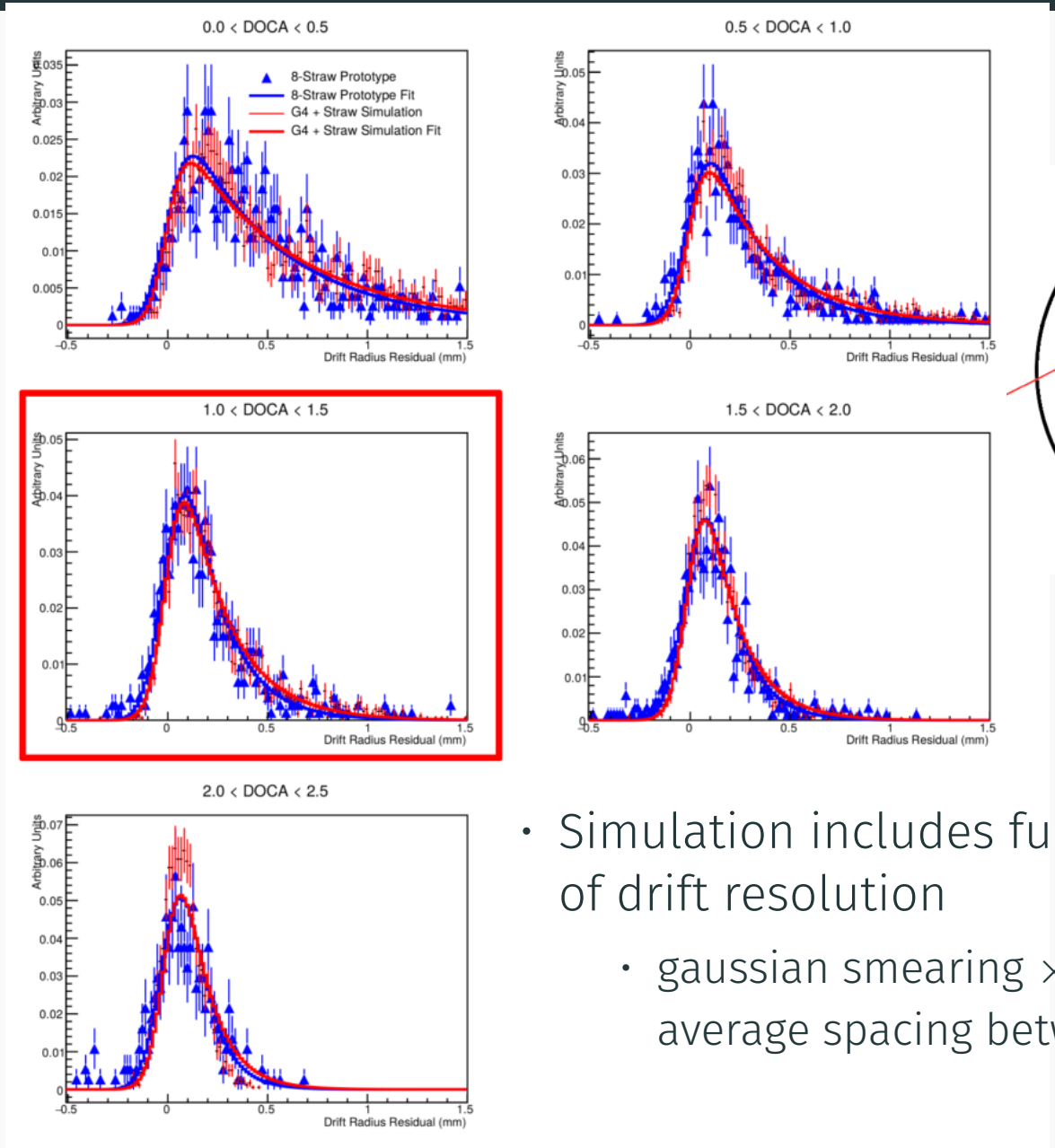
Drift response model

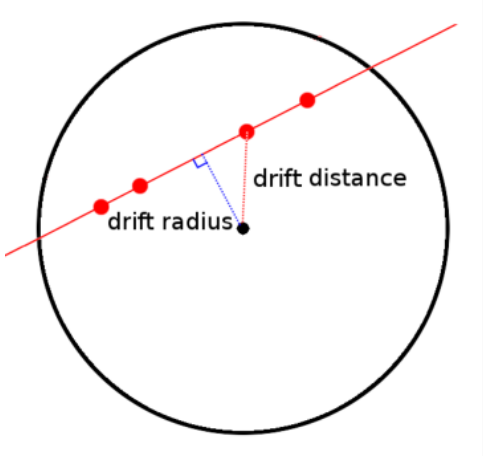




- Simulation includes full radius dependence of drift resolution
  - gaussian smearing $\times$ exponential encoding average spacing between ionizations

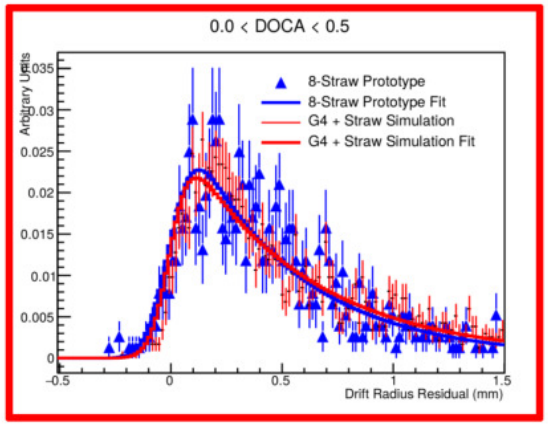
Drift response model

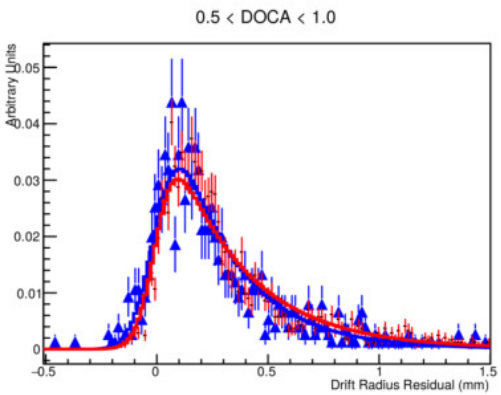


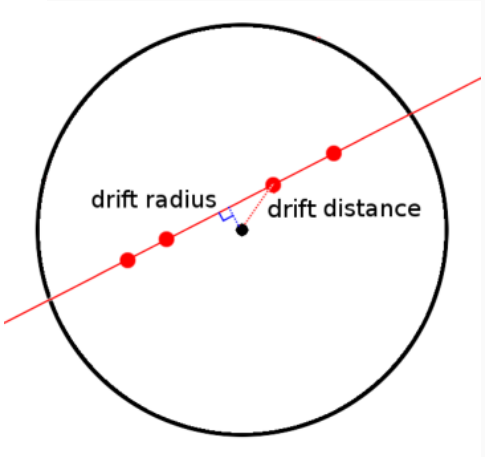


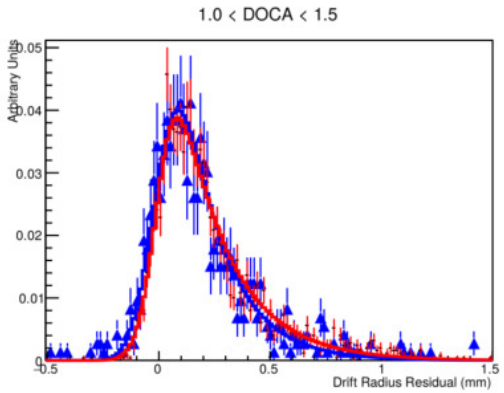
- Simulation includes full radius dependence of drift resolution
  - gaussian smearing $\times$ exponential encoding average spacing between ionizations

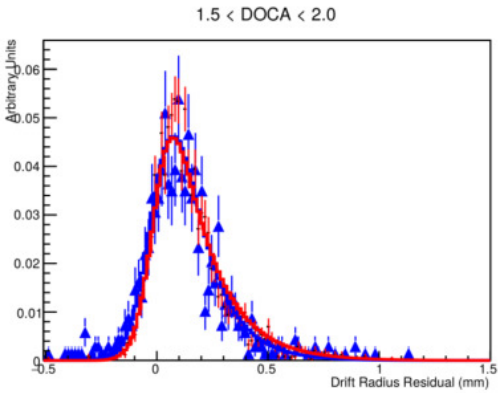
Drift response model

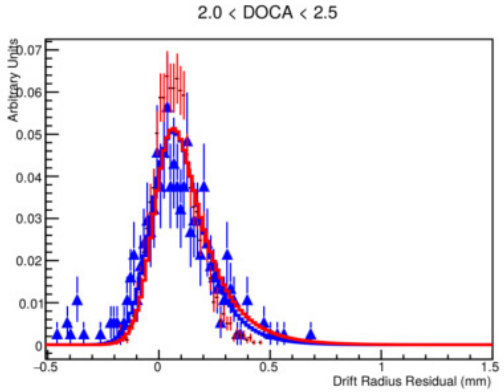












- Simulation includes full radius dependence of drift resolution
  - gaussian smearing $\times$ exponential encoding average spacing between ionizations

8 STRAW TRACKER PROTOTYPE USED TO TUNE SIMULATION AND VERIFY EXPECTED RESOLUTION