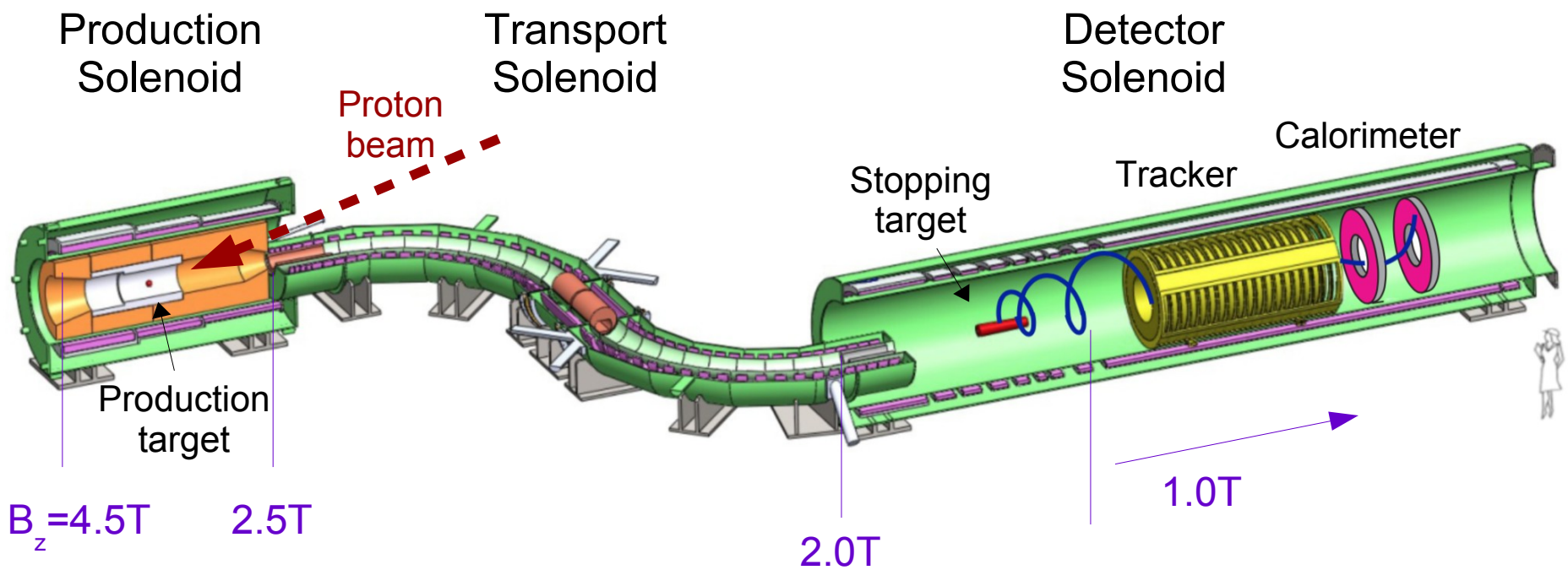
Front-End Electronics Scheme for the Mu2e Straw Tracker

DPF 2017

Manolis Kargiantoulakis, for the Mu2e Collaboration

08/03/2017

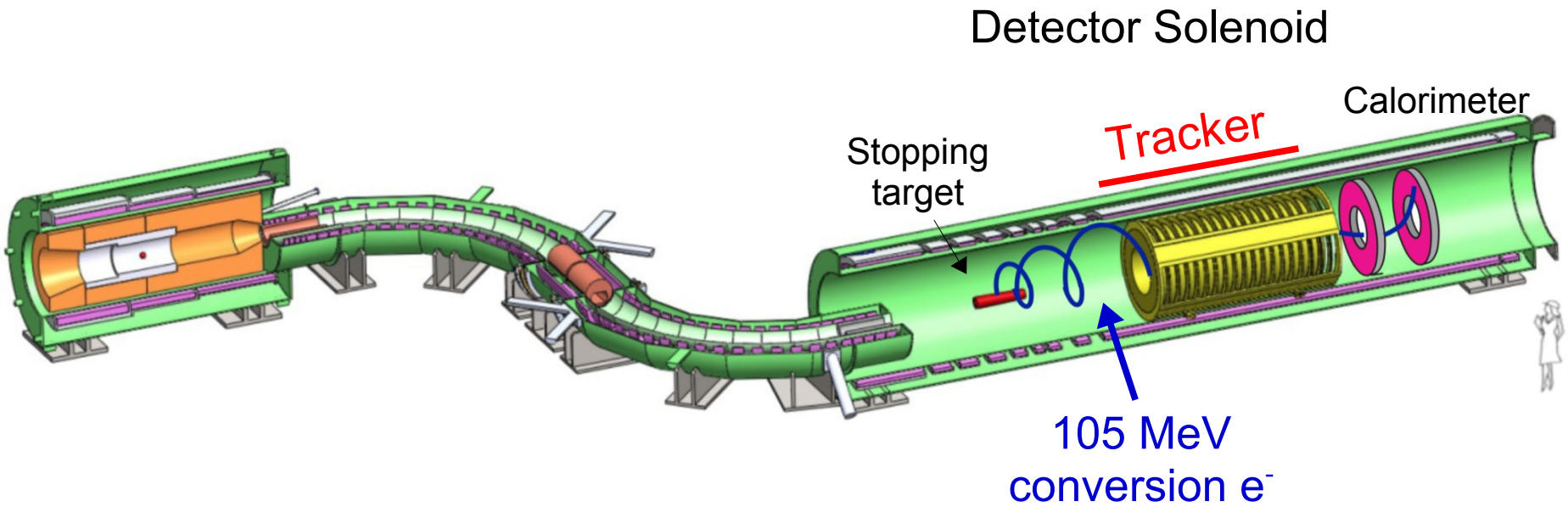
Mu2e in a slide



- Overview of experiment and apparatus
  - Y. Oksuzian: *The Mu2e experiment in Fermilab*

- Mu2e will search for signatures of Charged Lepton Flavor Violation (CLFV)
  - New Physics sensitivity up to mass scales of 10,000 GeV
  - A very important test to guide future of HEP theory and experiments

The Mu2e Tracker



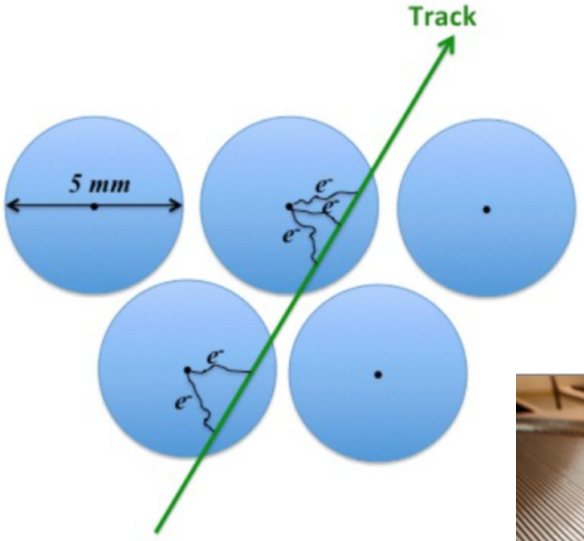
- CLFV process: Neutrino-less conversion of muon into electron in field of Al nucleus.
  - Characteristic signature: ~105 MeV conversion electron
  - Spiraling in helical orbit from Al stopping target

- The Mu2e Tracker: primary detector for the experiment.
  Designed to efficiently detect conversion electron and reconstruct trajectory
  - Required resolution 180 keV @ 105 MeV, or <0.18%
  - Operation in vacuum and in magnetic field
  - Must reject backgrounds from conventional processes

Tracker straw tubes

Detecting element:
Gas drift tubes, or "straws"

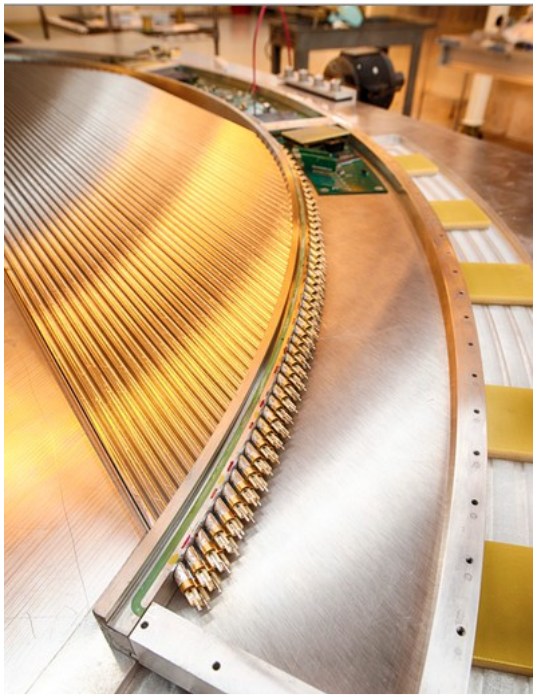
- 5mm diameter, 0.5-1.2m long
- 15μm mylar wall, metalized
- 25μm gold-plated tungsten wire at ~1450V
- Gas Ar:CO_2 80:20 at 1atm



Excellent fit to tracker requirements

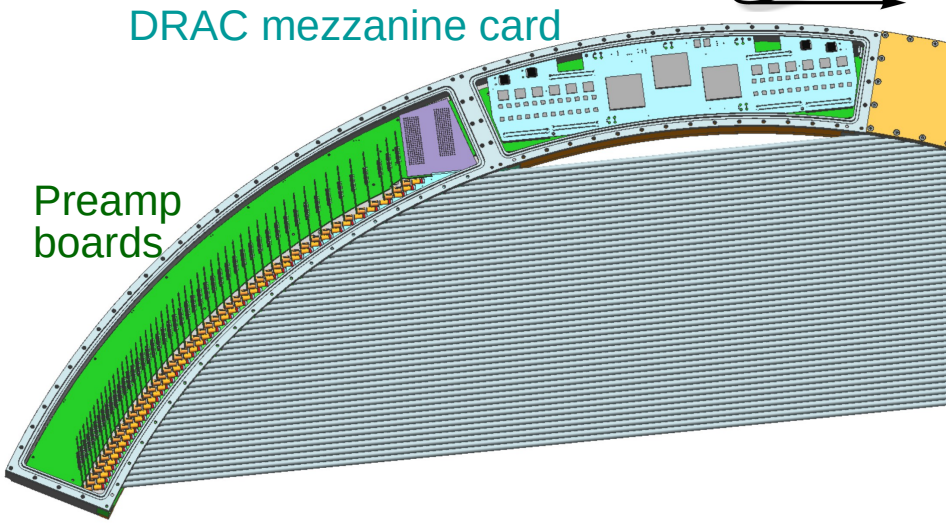
- Low mass, minimize multiple scattering
- Highly segmented, handle high rates
- Operation in vacuum (10^{-4} Torr), straws must not leak
- Reliable – lifetime of 10 yrs, must operate for a full year without service

Minimal unit fully instrumented, including front-end electronics: 120° panel of 96 straws



120° panel of 2x48 straws, two staggered layers

Tracker Front-End Electronics



Front-End Electronics (FEE)

- Readout of straw signals
- Signal shaping and processing
- Digitization and transmission to DAQ

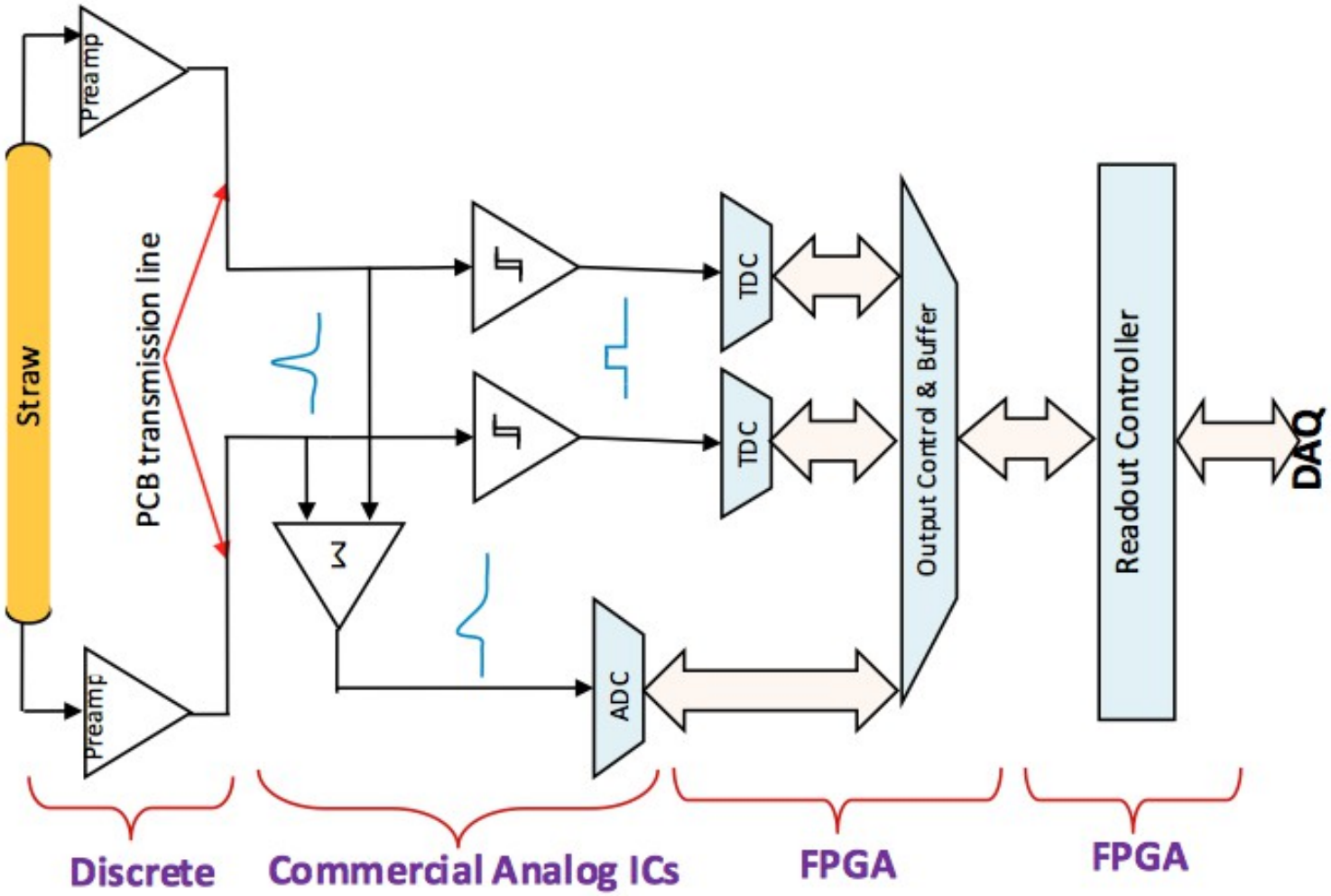
Requirements:

- Supply HV to straws (and capability for remote HV disconnect)
- B-field perturbation <1G in the active detector region
- Sustain radiation damage from target
- Low power <10kW within cooling capabilities
- <12 × 96 dead channels in 5 yrs at 90% CL

Measurements:

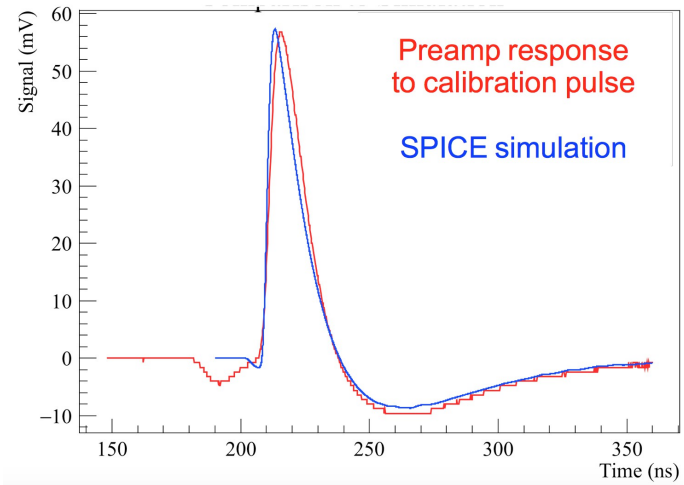
- TDC measurement of drift time – resolution: 1 ns (<200 μm drift radius)
- Straw readout from both ends for time-difference measurement
  - yields hit position along straw axis, <4cm resolution
- ADC for dE/dx measurement to identify highly-ionizing proton hits

FEE design schematic



Preamplifier and Shaper

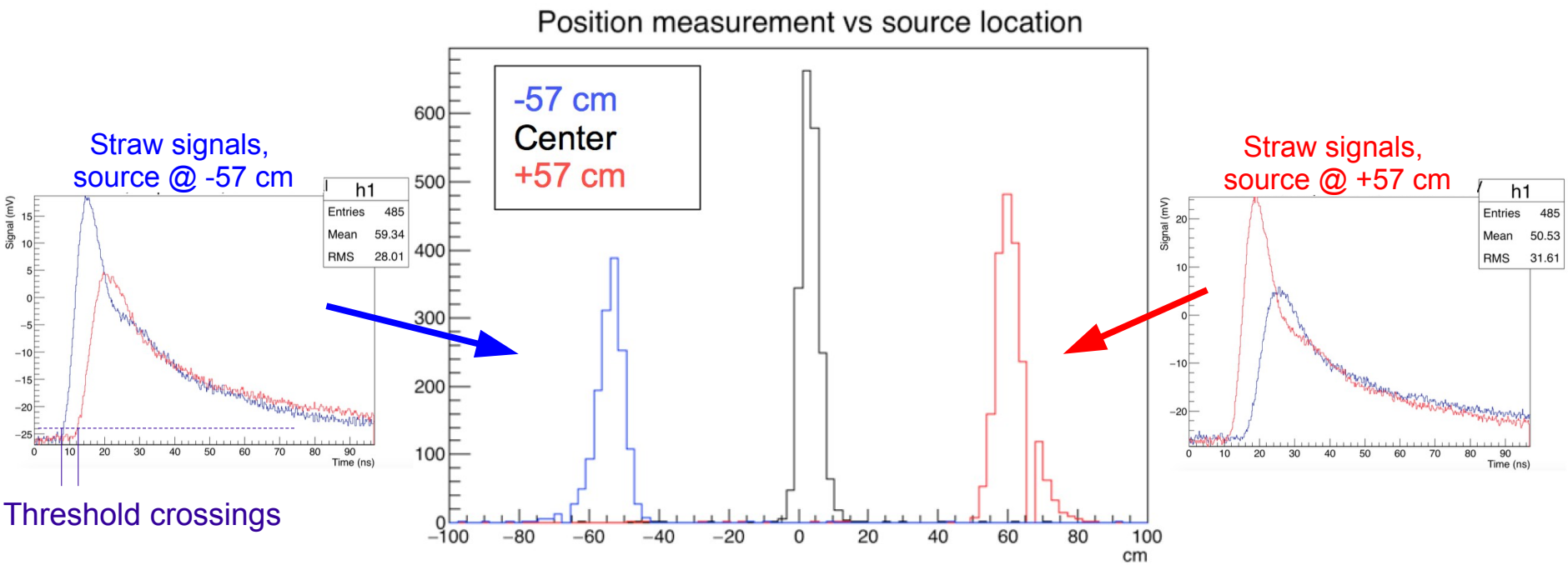
- 2- channel preamp boards connecting to straws, mounted on analog motherboard
- Straw signal readout
  - Low-noise high-speed input stage
  - SiGe technology BJT
  - Active 300Ω termination to avoid reflections
  - Differential output for good CMRR
- Provide HV and ground to straws
  - Remote disconnect from HV via thermal fuse
- Shaping of straw signal before digitization
  - Fast rise, remove long tail from ion motion
- Calibration system for charge injection that mimics e^- pulse



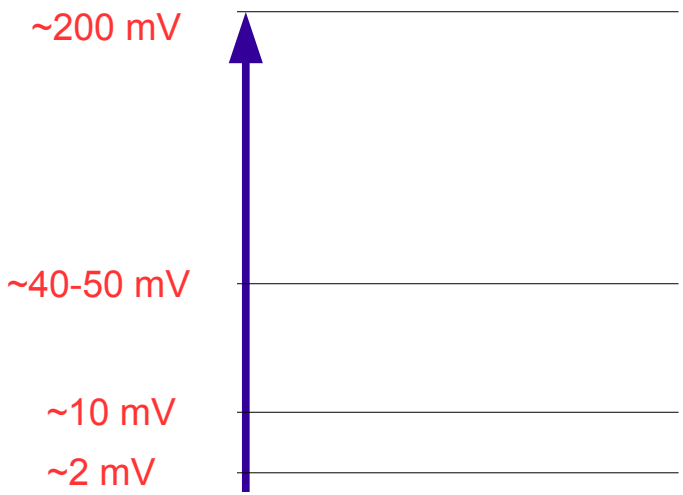
Time difference measurement

- Reading out both straw ends allows measurement of time difference Δt between threshold crossings
  - Also significantly reduces noise rate by requiring coincidence

- Δt dependent on hit location along straw axis
  - Position resolution from Fe55 source measurement shown below: < 3 cm
  - Very important for pattern recognition



Competing requirements



Signal level at preamp output

Preamp range – Signals that rail output are identified as proton hits and rejected, ~95% p rejection efficiency

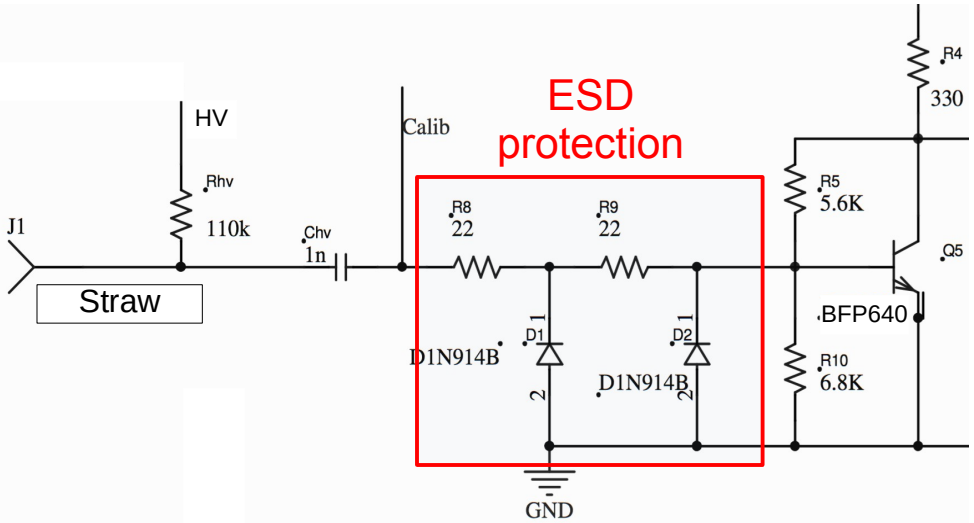
Avg e⁻ signal – 4-5x threshold for efficiency

Threshold – at 5x noise RMS defines noise hit rate ~100Hz

Noise RMS – mostly proportional to BW, but lower BW limits resolution

Example: ESD protection at preamp input

- R8,R9: current limiting R's
  - Increase noise RMS
    → More noise hits or efficiency loss
- D1,D2: diodes offer shunt path to ground
  - Their capacitance limits BW
    → loss in rising edge timing resolution



Digitization and Readout

All signals routed to DRAC – Digitizer Readout Assembler and Controller

- Serves entire panel (2×96 TDCs and 96 ADCs)

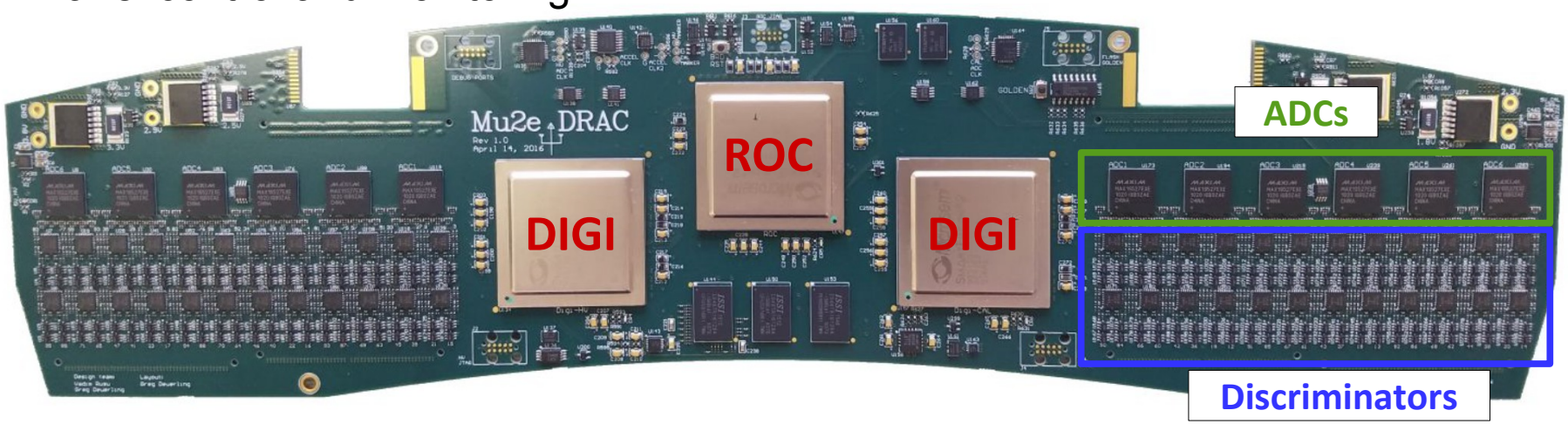
Digitization

Each straw end goes into comparator and TDC (implemented in FPGA)
Two ends are analog summed and into 12-bit ADC, sampling at 50MHz
Data packaged (FPGA) and sent to ROC

Readout Controller

Receives and buffers data from digitizer FPGAs
Duplex optical communication to DAQ
Panel control and monitoring

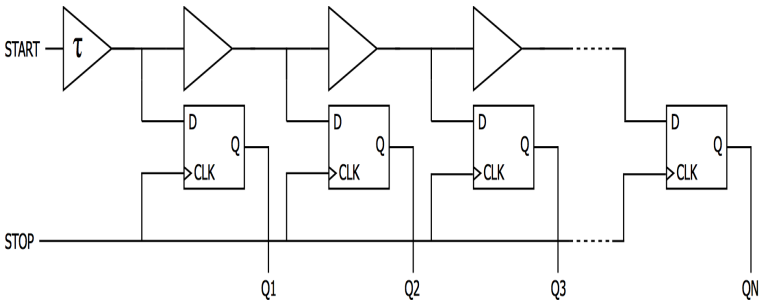
FPGAs:
Microsemi™ SmartFusion2



TDC in FPGA

- Scheme loosely based on:
  Wu et al., The 10-ps Wave Union TDC, FERMILAB-CONF-08-498-E

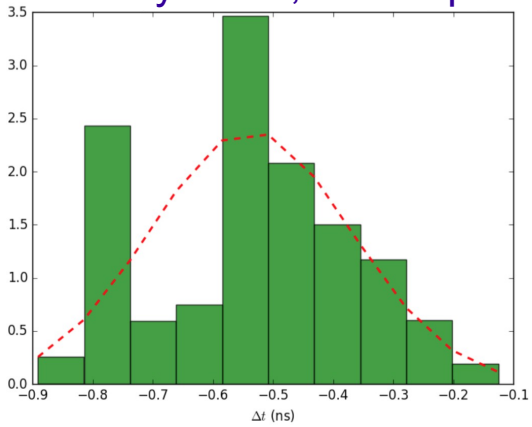
- Subdivide between clock ticks by freezing a fast signal propagating through a delay chain



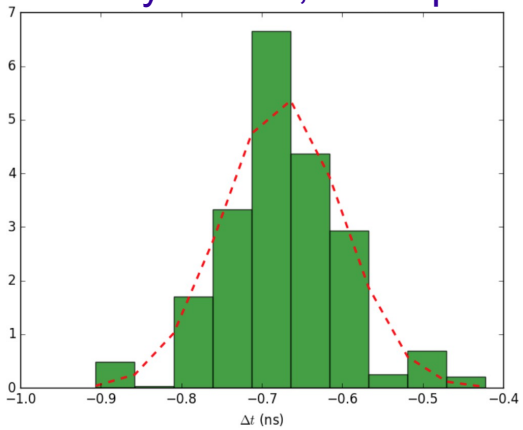
- Non-uniform delays between bit transitions. Resolution limited by transitions across boundaries.

- Implement multiple chains to improve resolution
  → Resolution requirement ~70 ps already achieved with adequate resources

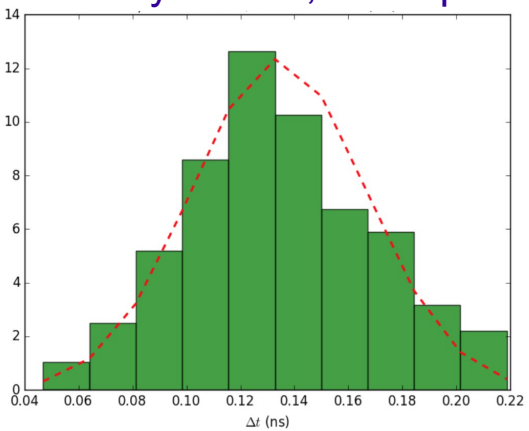
1 delay chain, σ~170 ps



3 delay chains, σ~70 ps



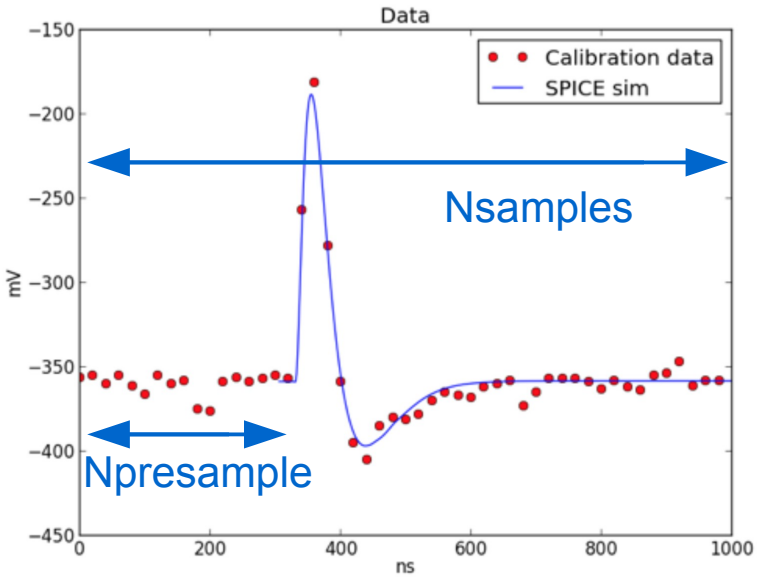
8 delay chains, σ~30 ps



ADC data from complete FEE chain

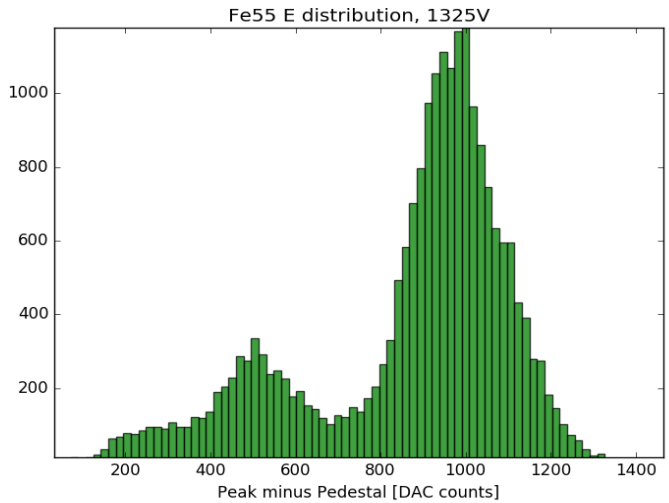
- ADC for dE/dx measurement to identify and reject proton hits
  - 12-bit, 50MS/s

- Data shown here acquired through complete FEE chain:
  Straws → Preamp → DRAC → PC
  - HDMI cables instead of motherboards
  - No optical link to DAQ, just serial readout
  → A very significant milestone



ADC samples from calibration charge injection. Parameters configurable at run time.

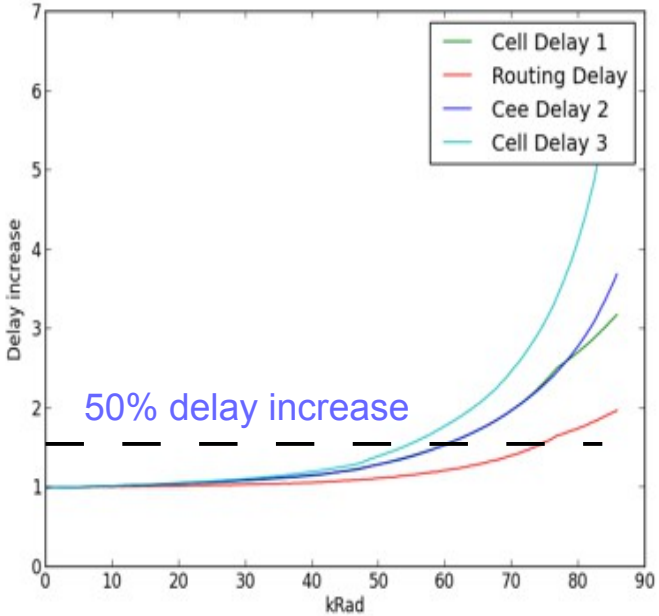
Fe55 spectrum from source placed on straws



Radiation tolerance

- Maximum absorbed dose at front planes. Expected over experiment: 12.9 krad
  - After large simulation efforts for shielding and mitigation options
- Conservative approach adopted by experiment that FEE survives x12 of expected dose.
- Radiation campaign identified weak points in the system. One is SF2 FPGA
  - Lost programmability at ~15 krad
  - Significant delay increases at ~60 krad
- Plan to replace with next line from Microsemi: PolarFire FPGA, preliminary showed no degradation after 100's krad dose

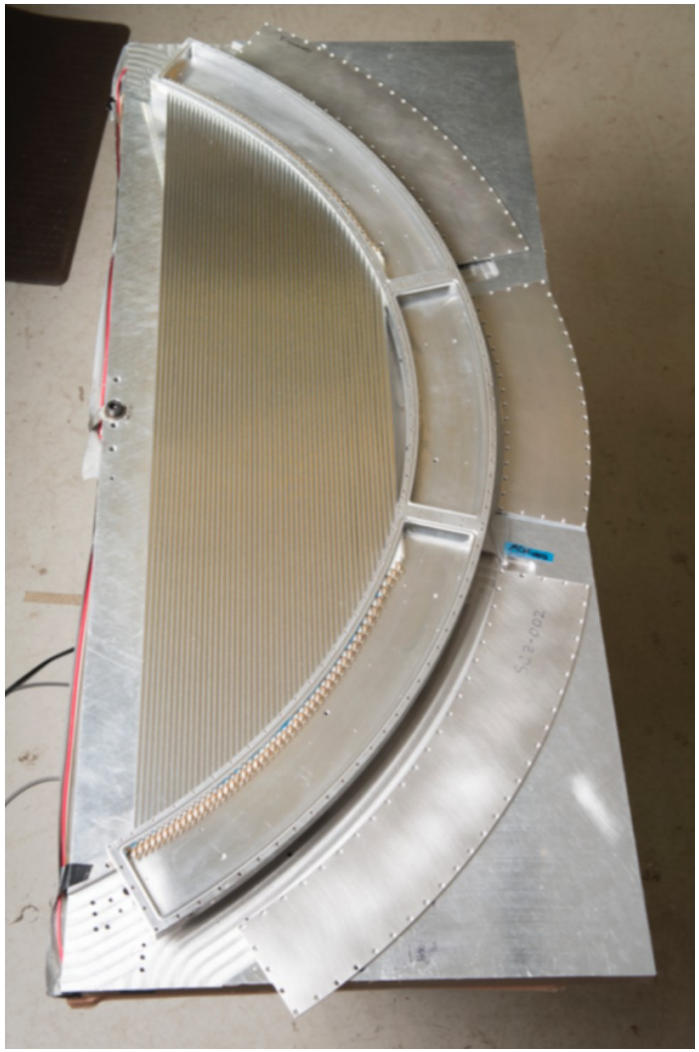
TID studies performed at LUMC



→ FEE components should be able to withstand ~155 krad

Status/Outlook

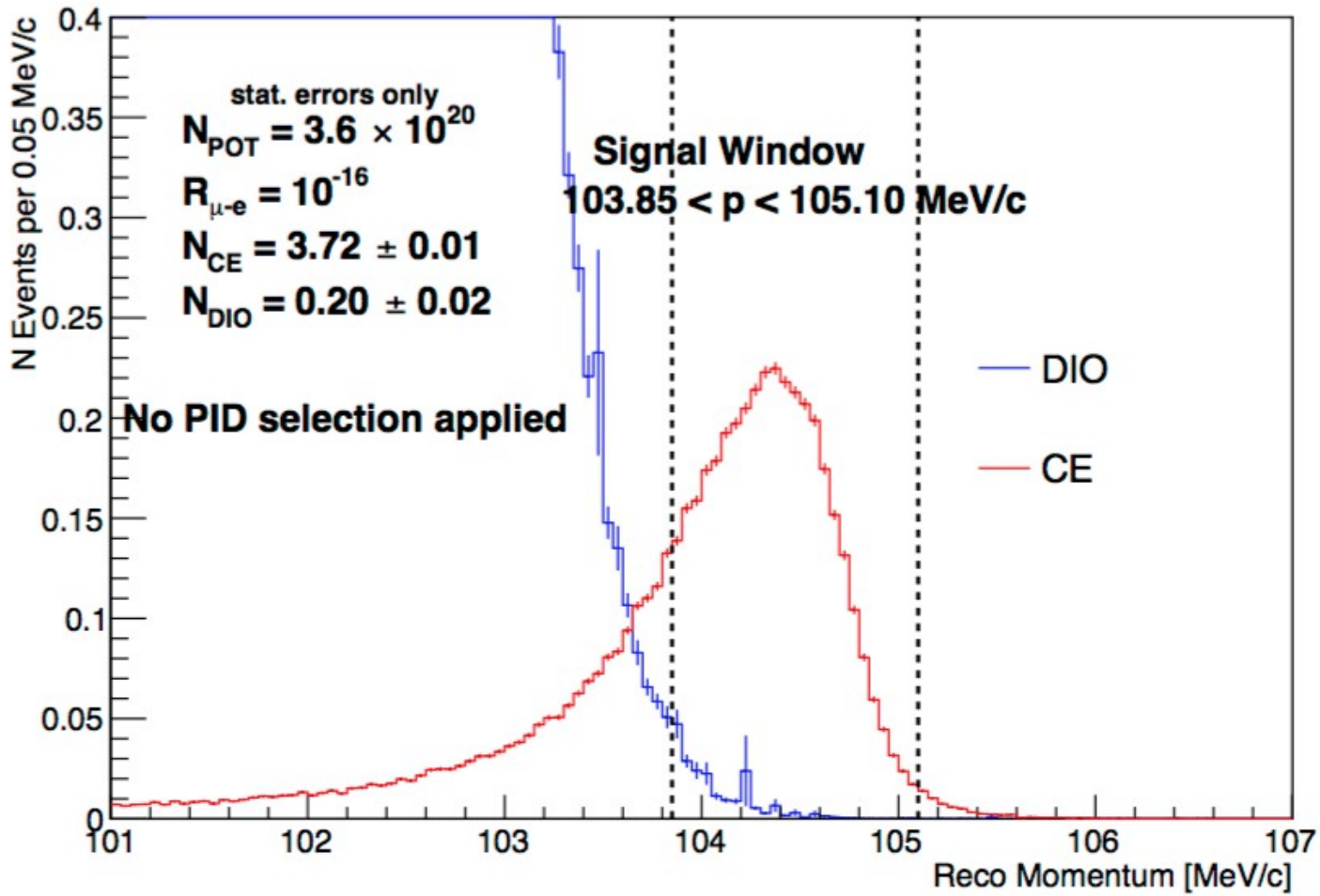
- Latest panel prototype recently constructed in Fermilab and being tested
  - A. Lucá: *A Panel Prototype for the Mu2e Straw Tube Tracker at Fermilab*
- Entire FEE chain has been tested successfully, meeting functionality and resolution requirements.
  - Next implementation on panel prototype, including motherboards
- Vertical slice test to be performed on fully instrumented plane (6 panels)
  - Ground loops, noise, crosstalk
- Detector installation in 2020, followed by Mu2e commissioning and data



Tracker panel prototype

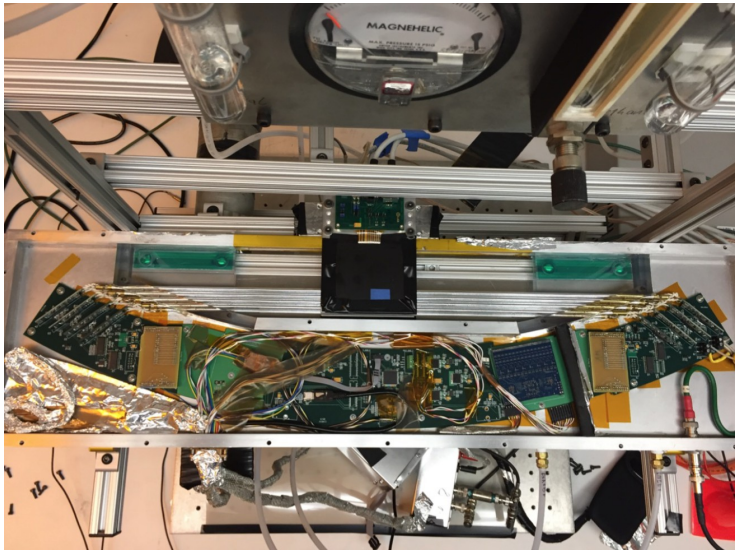
Backup

Signal and DIO Background



For $R_{\mu e} \approx 10^{-16}$ we expect to see ~4 conversion events without background contamination

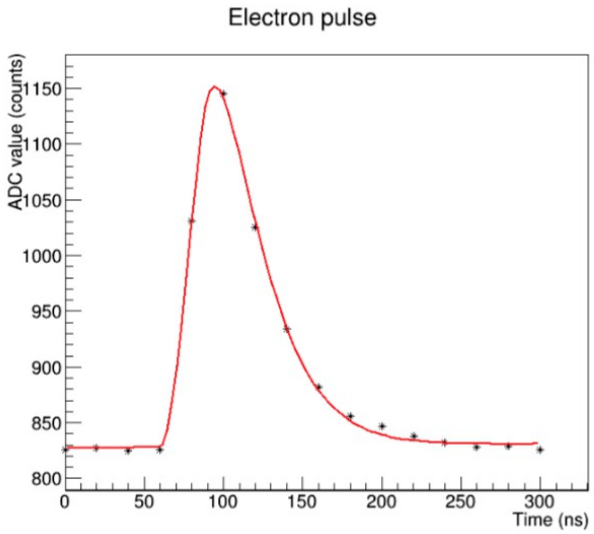
Small-scale prototype

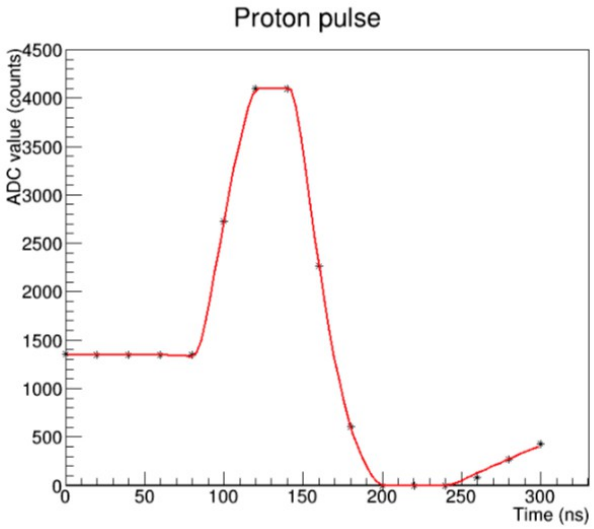


FEE chain tested in 8-channel prototype.

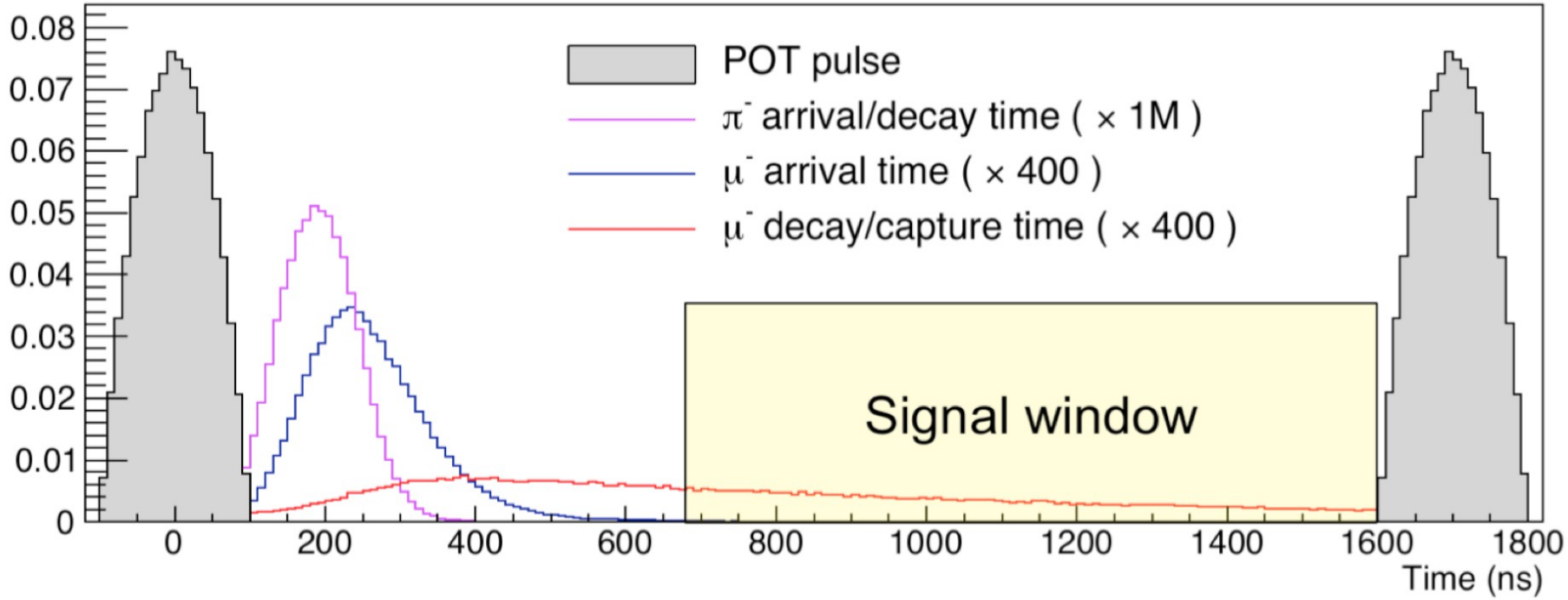
ADC output from electron and proton pulses shown below.

Preamp saturation allows identification of proton hits.





Pulsed Beam and Delayed Signal Window



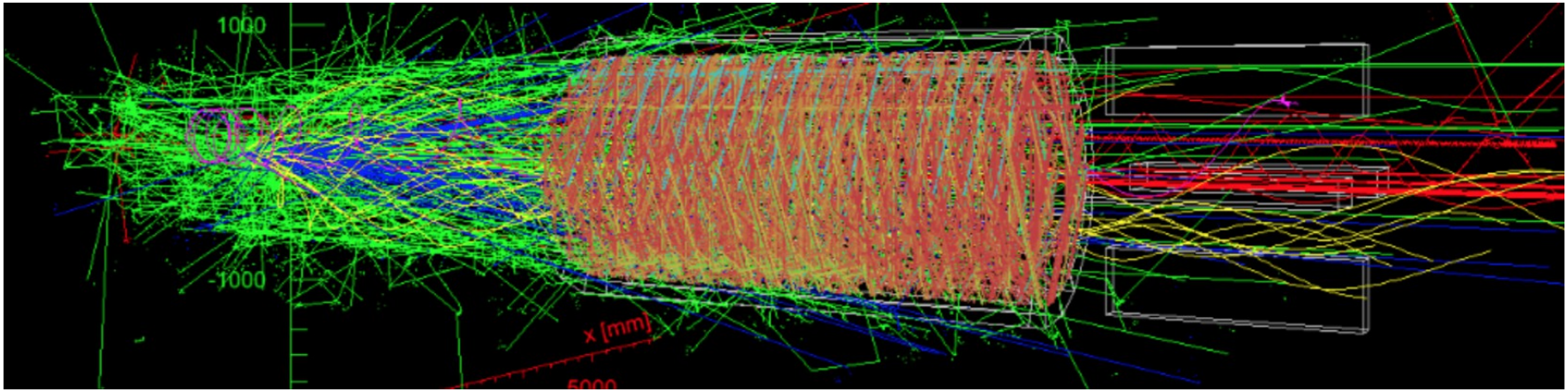
- Proton pulse period: 1695 ns (FNAL Delivery Ring)
- Delayed signal window: 700 → 1600 ns
- Pion lifetime: 26 ns – <u>prompt backgrounds decay before signal window</u>
- Muonic Al lifetime: 864 ns – reason for selecting Al target

Require beam extinction (fraction of beam between pulses): $\varepsilon < 10^{-10}$

Tracking

From individual straw hits in tracker we need to:

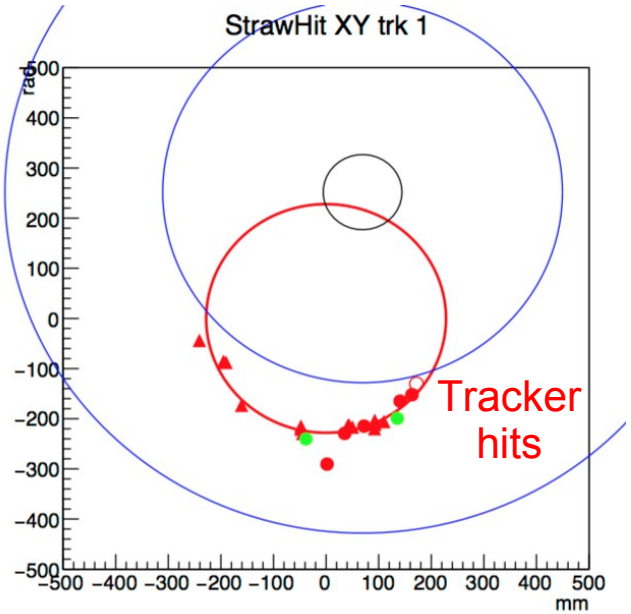
- Remove background hits
- Identify hits from single particle (pattern recognition)
- Reconstruct particle's trajectory (helix fitting)

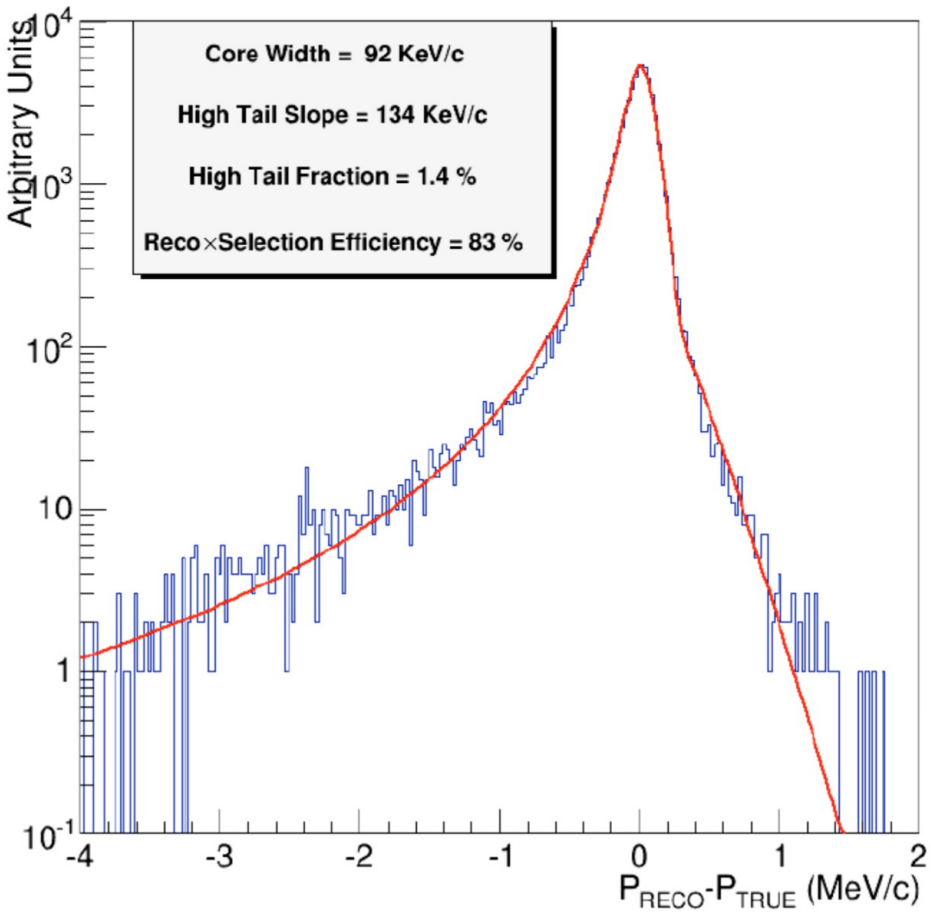


Signal electron + all hits over 500-1695 ns window

Detailed G4 model: straws, electronics, supports, B-fields

Tracker Momentum Resolution





Least squares helix fit, followed by iterative Kalman Filter track fit

Tracker momentum resolution requirement:
σ_p/p<0.2% for a 105 MeV electron, or σ_p<180 keV/c