Development, Simulation, and Prototype Performance Measurements of the Mu2e Straw Tracker

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Fermilab Users Meeting

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Lawrence Berkeley National Lab

Outline

1. Brief overview of Mu2e and physics motivation
2. Mu2e straw tracker design
3. Tracker Prototype low level measurements
4. Simulating the tracker
5. Comparing resolution + efficiency from prototype data and simulation

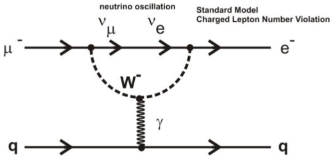
See upcoming talk by Tomonari Miyashita for more details on the experiment!

Charged Lepton Flavor Violation

- Mu2e will search for neutrinoless conversion of a muon to an electron in a nuclear environment:

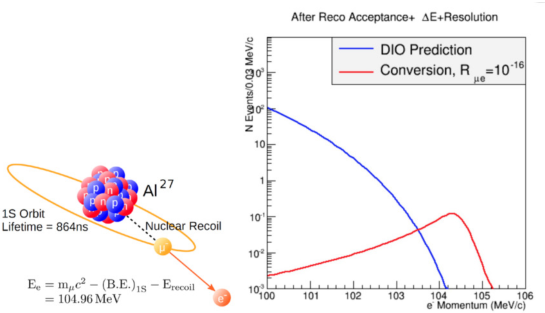
$$\mu^- N \to e^- N$$

- This would violate **charged lepton flavor**, something that has never been seen before



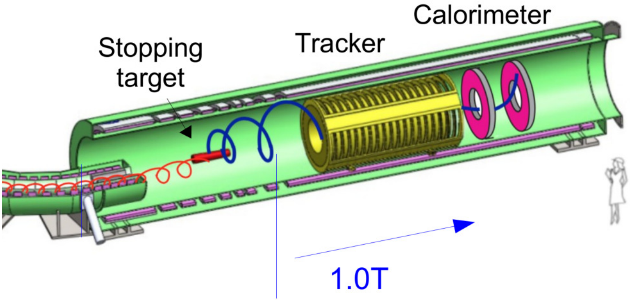
- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics! (SM contribution is $< 10^{-50}$)
- Mu2e goal is a 10^4 improvement!

The Mu2e Experiment at Fermilab



- Stop 10^{18} muons on Aluminum
- Conversion produces monoenergetic 105 MeV electrons
- Main background is decay-in-orbit electrons
- Only distinguishable by momentum, want high precision measurement that can handle high rate

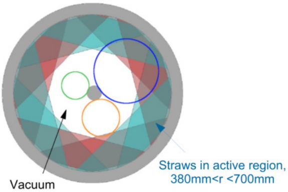
The Straw Tracker Detector

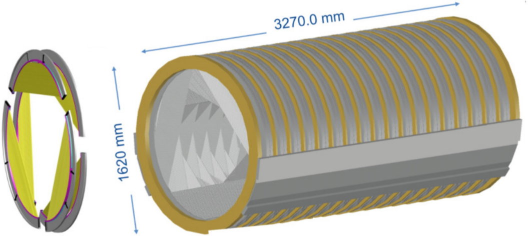


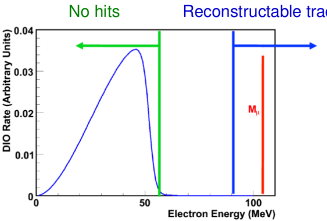
- Cylindrical straw tracker operating in uniform field
- Tracker is in vacuum
  - Measurement is multiple scattering dominated
  - Entire detector much less than one radiation length of material

Tracker Configuration

- 18 stations, each containing 12x 120° panels for stereo measurement
- Blind to DIO electron momentum peak and beam flash
- Expected resolution better than 200 keV/c

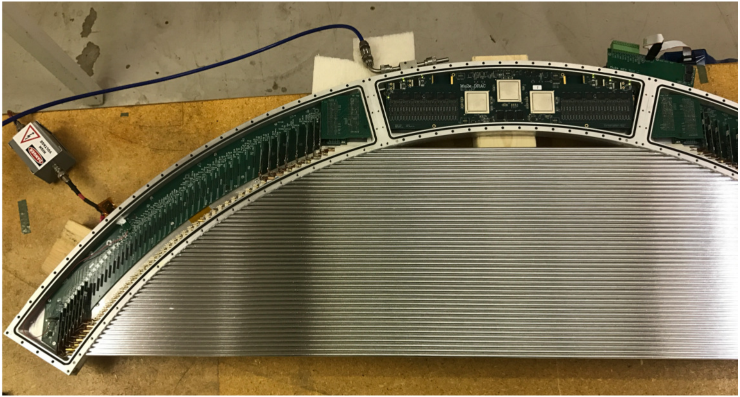




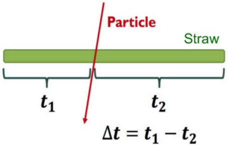


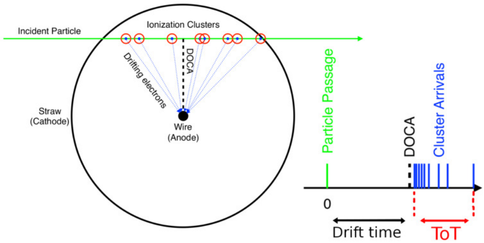
The Straw Tracker Detector

- $\sim$21,000 low mass straw tubes in vacuum
  - 5mm diameter, 0.5-1.2m long
  - 15μm mylar wall, 25μm tungsten wire
  - 1 atm of 80/20 Ar:CO_2, wire at 1425V



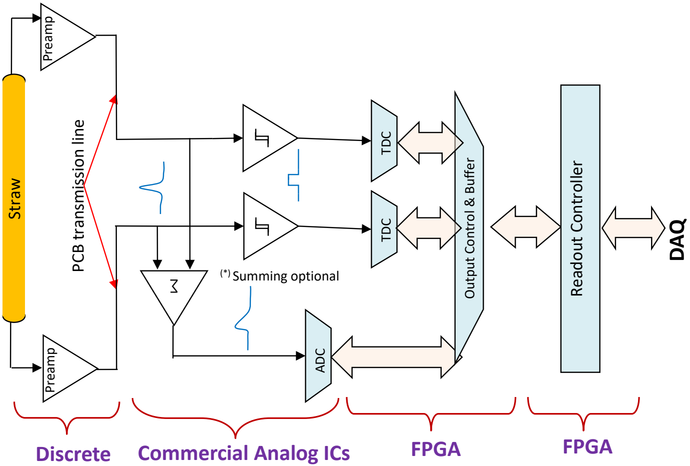
What are we measuring



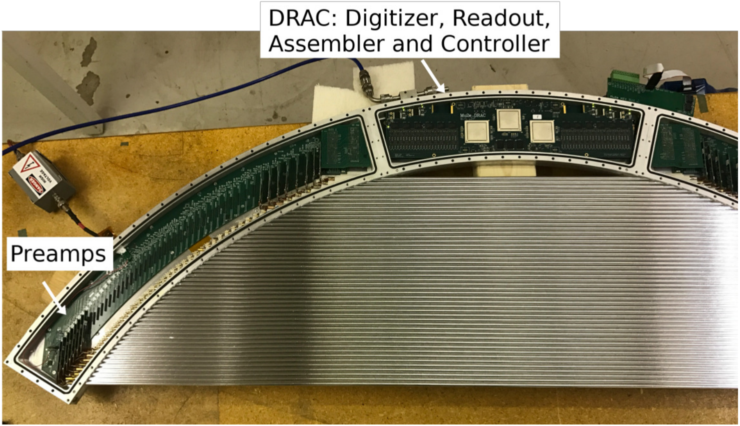


- Individual threshold crossings digitized in time (TDC)
  - Drift time → radial resolution ∼200 μm
- Straws are instrumented on both sides
  - Time division → longitudinal resolution ∼4 cm
- Falling edge digitized for Time over threshold
  - Measure of path length / radius independent of t_0
- ADC measures pulse waveform for background rejection

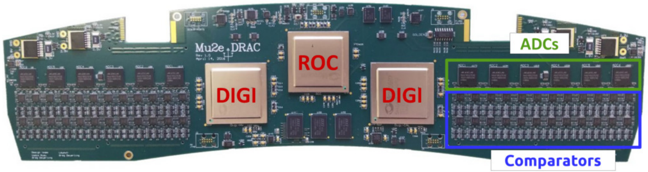
Tracker Electronics



Tracker Electronics

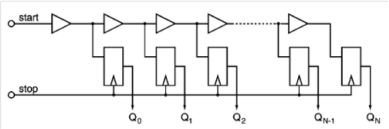


Tracker FPGAs and Firmware



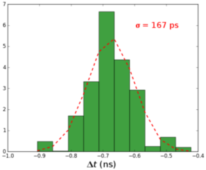
- Most of functionality in FPGAs - highly configurable
  - Have already taken advantage to add new features (Time over threshold)
  - Originally had Altera FPGAs, now using Microsemi SmartFusion2 for radiation tolerance
- 2x Digi FPGAs that digitize 48 channels each
  - Separate TDCs for each end of straw
  - Continous readout of summed ADC waveform at 50 MHz
- Data buffering, DAQ communication, tracker slow controls in ROC FPGA

Firmware TDC Design

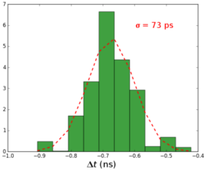


- Need ∼4cm resolution longitudinally along straw
  - Near speed of light signal → <100ps time resolution
- Achieve resolution in firmware while minimizing resource usage
  - Initial design based on wave-union design by Jinyuan Wu
  - Delay chain for sub-clock tick precision
  - Average multiple chains to subdivide large delays
  - Auto calibration of bin widths

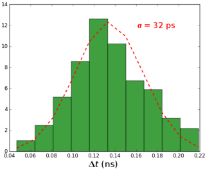
1 delay chain



3 delay chains

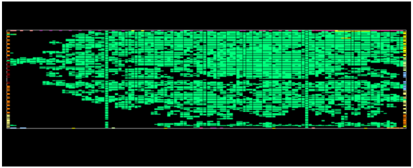


8 delay chains



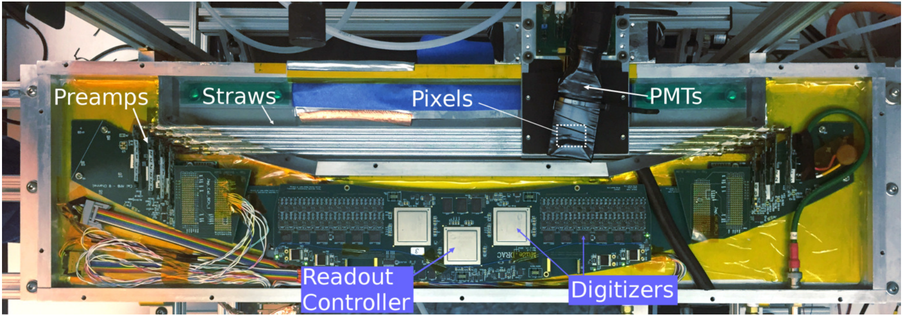
Firmware Design

FPGA resource usage for 48 channel design



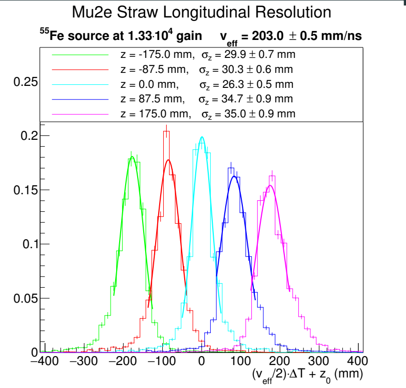
- Have managed to implement design that fits all 48 channels in a single chip
- Learning process dealing with Microsemi FPGAs
  - Architecture changes from Altera version
  - Much smaller community, support resources
  - Difficulties with timing constraints - manual placement of delay chains and ADC interface
  - Several hour compilation time for full design
- Demonstrated readout chain from digitizing FPGAs through to DAQ computer over SERDES

An 8-straw tracker prototype for testing and performance measurements



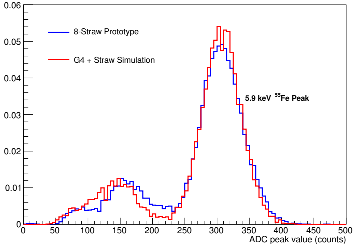
- Portable self-contained setup
  - Cross talk → proton beam from 88" cyclotron at Berkeley Lab
  - Radiation sensitivity → UC Berkeley High Flux Neutron Source
  - Straw and electronics parameters → radioactive sources
  - Efficiency/resolution → cosmic rays
- Read out over USB serial using custom DAQ

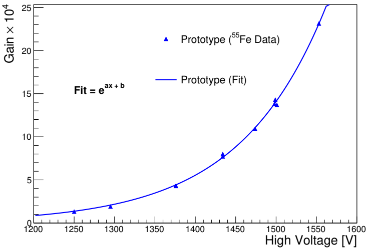
Sources used to measure gain, energy resolution, time division, simulation tuned to results



(Tom-Erik Haugen)

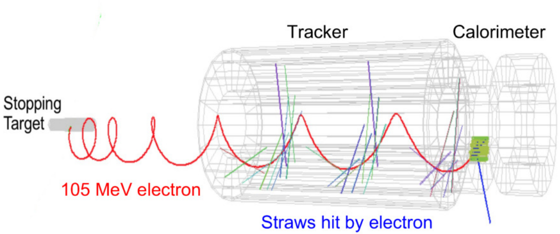
- Gas gain by measuring current with ^{55}Fe
- Energy resolution using 5.9 keV x-ray peak





(Andrew Edmonds)

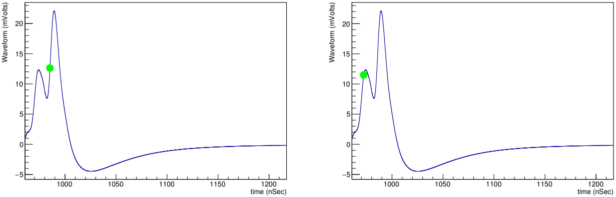
Simulation of the straw tracker response



- Detailed Geant4 simulation of full detector
- Custom code takes energy deposition in each straw and models physics and electronics response

Simulation of the straw tracker response

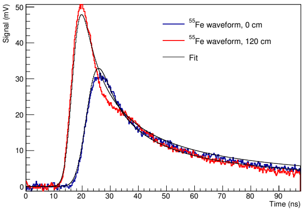
Simulation of waveform threshold crossing at each end of straw



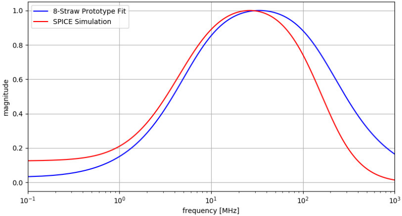
- Each ion cluster modelled individually, including drift, wire propagation, and electronics response

Simulation of the electronics response

Input pulse shape $\longrightarrow$ Apply electronics response



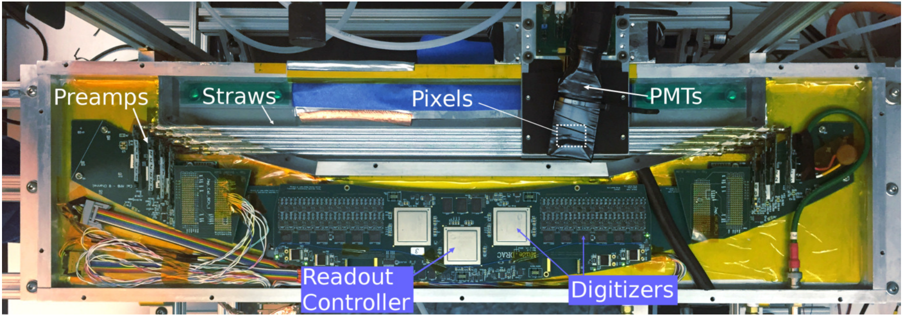
(Data from Manolis Kargiantoulakis)



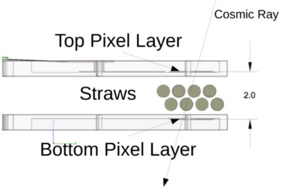
(SPICE sim from Vadim Rusu)

- Use unshaped waveforms from source at different distances to model attenuation, dispersion
- Fit for transfer function describing preamp and integrator response
  - Model includes saturation effects, pulse shape distortion
  - Important for accurately determining proton discrimination, modelling pileup

Reconstructing track position for performance measurements



- Use PMT trigger and ATLAS FEI4 pixel detectors to allow precise reconstruction of cosmic ray tracks
  - MIPs similar to conversion electron signal
  - Allow resolution and efficiency measurements



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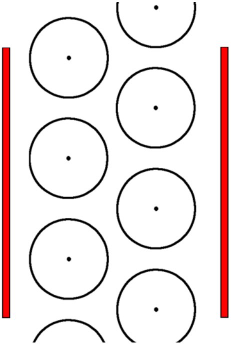
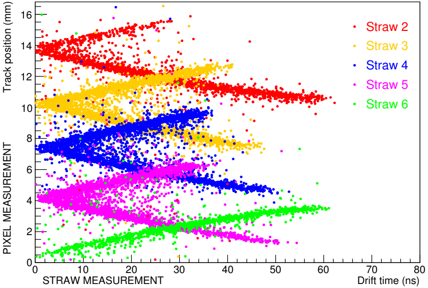
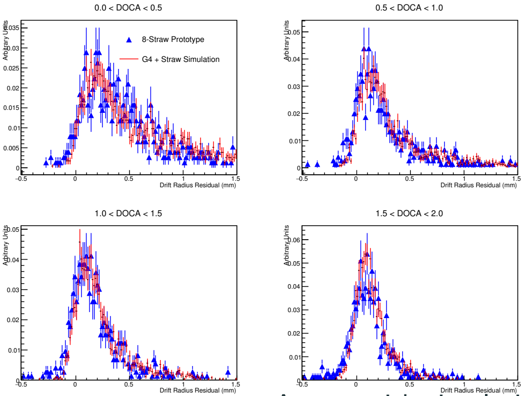
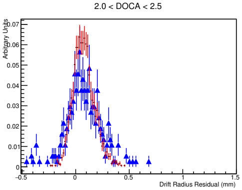




- ATLAS FEI4 detectors measure track position
  - 2.0x1.9cm chips, 250x50μm pixels
- PMT trigger gives t_0 for drift time measurement
  - $\sim$600ps time resolution
- Reconstruct relative position and timing of pixels, PMTs, straws, wires with maximum likelihood fit

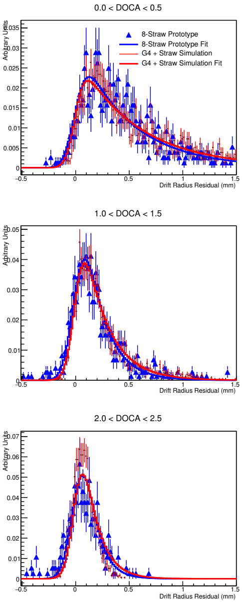
Transverse resolution

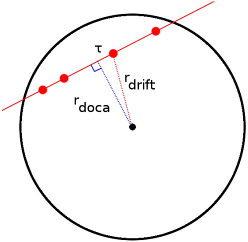




- Agrees with simulation tuned to low level parameters
- Model and simulation include full DOCA dependence of resolution
  - gaussian smearing $\times$ exponential with constant τ
  - τ encodes effect of cluster statistics

Transverse resolution





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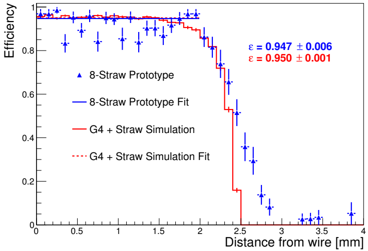
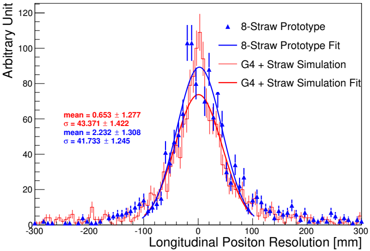
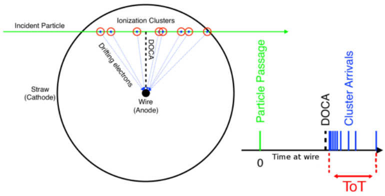
Longitudinal resolution and efficiency

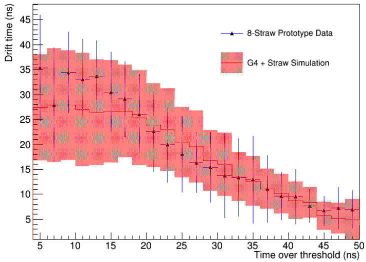




- Efficiency measured at many voltages/thresholds to determine optimal running conditions

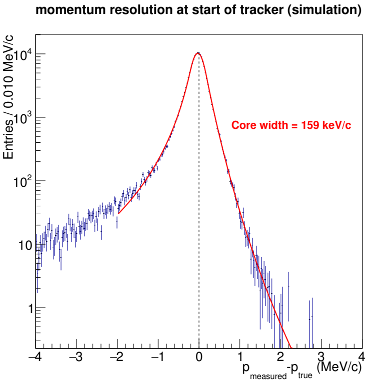
Time over threshold





- With just hit time measurement, require t_0 estimate from track reconstruction before drift time can be determined
  - Time over threshold allows a measure of path length (and thus radial distance) independent of t_0
- Implemented in firmware, being added to reconstruction
- Simulation agrees well with data
  - Shows predictive power of detailed model

Track Resolution



- Sensitivity studies now include results of simulation tuned to prototype measurements
- Track resolution depends on hit level resolution and efficiency, as well as reconstruction techniques

Conclusion

- Mu2e will search for CLFV with greatly improved sensitivity
- Straw tracker provides a precise momentum measurement, made possible by timing and waveform measurements from the straws
- 8-straw prototype was used to tune detailed simulation of straw physics and electronics
- Hit level performance proven with prototype
- Momentum resolution will allow us to reach our sensitivity goals!