Measuring the performance of the Mu2e Tracker Prototype using a pixel cosmic ray telescope

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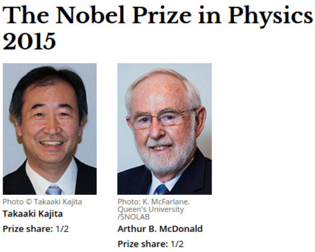
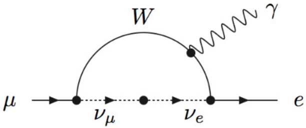
January 20, 2016

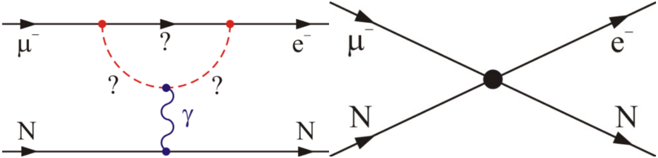
Lepton Flavor Violation





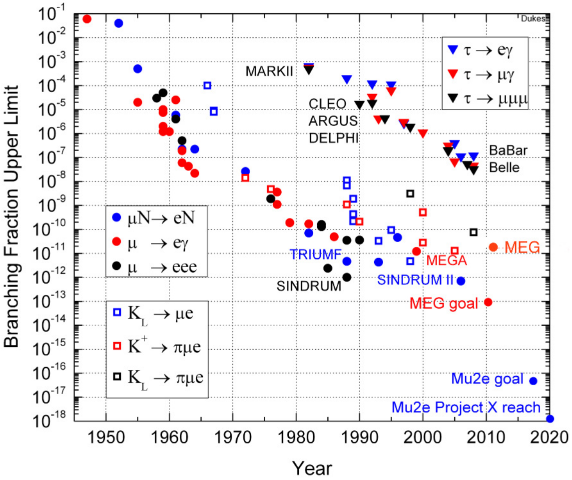
- Mu2e is looking for charged lepton flavor violation (CLFV)
- Discovery of neutrino mass and mixing, lepton flavor violation
- Neutrino mixing implies CLFV, but rate is extremely small (10^{-54})
- Observation would be an unambiguous sign of new physics

Beyond the Standard Model possibilities



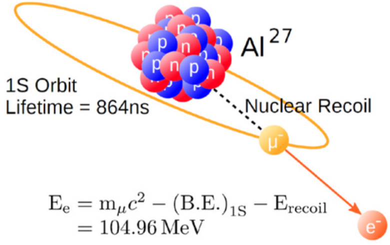
- Effective Lagrangian for CLFV has two types of terms, loop and contact
- Signal is either $\mu \to e\gamma$ or $\mu N \to eN$
- Many models of new physics enhance CLFV and predict measurable rates:
  - Supersymmetry
  - Leptoquarks
  - Heavy neutrinos
  - Second Higgs doublet
  - Compositeness
  - Heavy Boson / anomalous couplings
- allows sensitivity to extremely high mass scales not accessible with accelerators (O(10,000 TeV))

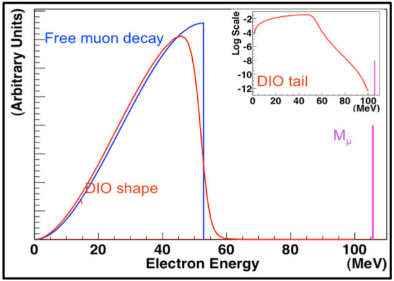
Current Limits



- $\mu N \to eN$: SINDRUM-II limit at 6x10^{-13}
- $\mu \to e\gamma$: MEG limit at 5.7x10^{-13}
- Mu2e sensitivity target is 3x10^{-17}

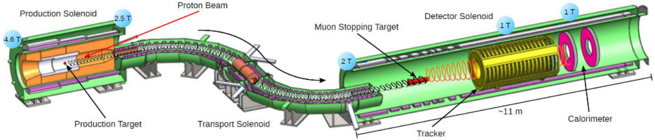
Mu2e Experiment





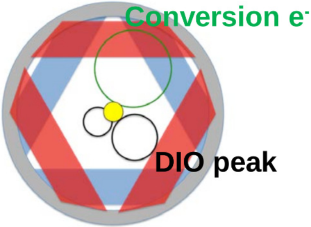
- Muons capture on Al
- Conversion produced mono energetic electron at 105 MeV
- Main background is muon decay in orbit (DIO), require very good momentum resolution
- Measure $R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$

Mu2e Experiment



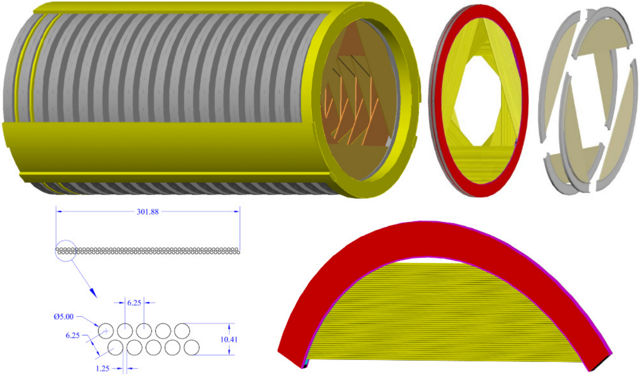
- High intensity proton beam (require $> 10^{18}$ stopped muons)
- Three areas with superconducting solenoids
- Straw tracker, calorimeter, cosmic ray veto

Mu2e Straw Tracker



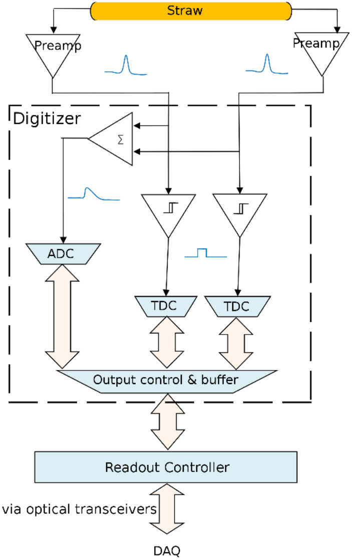
- 20,000 straws in total
- 5mm diameter, 15μm thick mylar wall
- 25μm gold plated tungsten sense wire
- Cylindrical tracker, insensitive to $<$53 MeV electrons

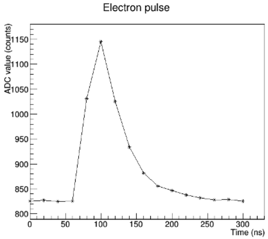
Mu2e tracker design



- 96 straws form 120° arc called a panel
- 12 rotations form a station
- 18-20 stations in total (20,000 straws)
- Electronics enclosed in panel around straws

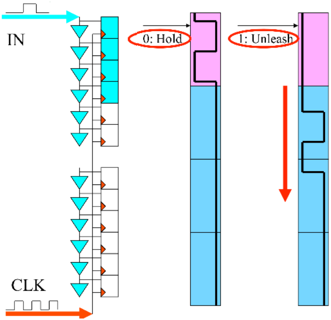
Straw electronics





- Straws are instrumented on both ends
- After preamp, signal routed to ADC and TDC on digitizer board
- 50 MHz 12 bit ADC to measure pulse height

Firmware "Wave Union" TDC

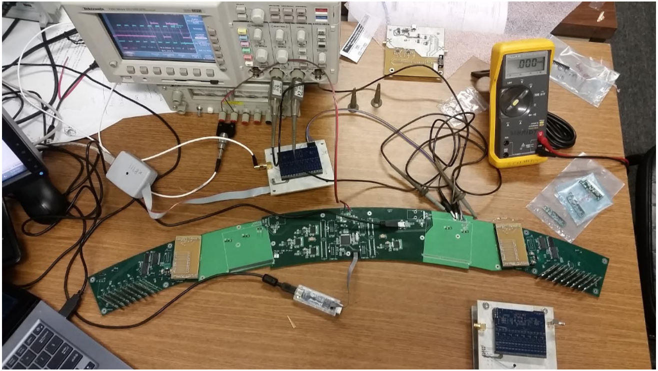


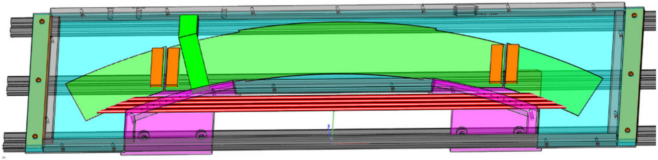
- Delay chain
- Creates histogram to calibrate bin widths
- Can use multiple edges to deal with large bins
- ∼30 ps resolution

Proposal to build a tracker prototype at LBL

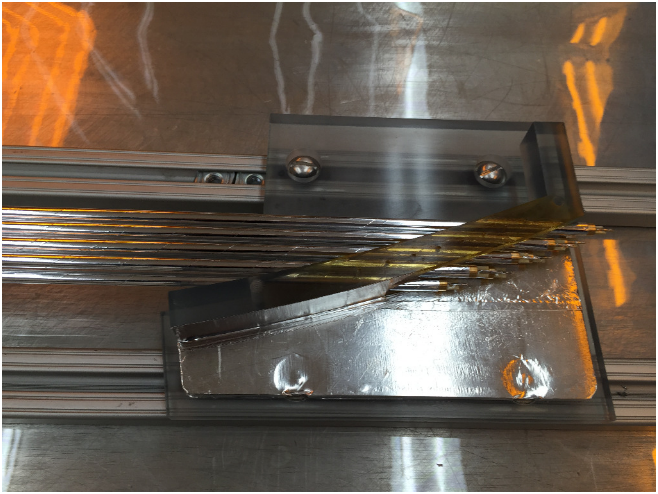
- Many new elements had yet to be tested
  - Curved manifold
  - New electronics
- No other multi-straw setup, full system setup
- Want to measure straw timing resolution
- Many measurements used for CD3 review

Designing the LBL tracker prototype



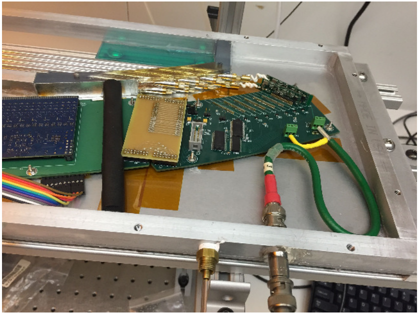


Designing the LBL tracker prototype



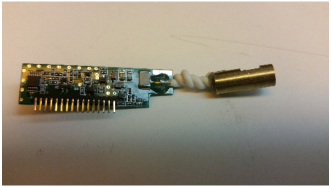
- Straws held in 3D printed manifold

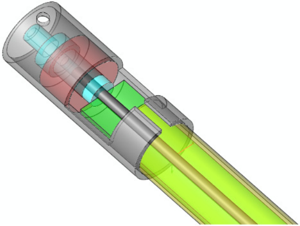
Construction of the LBL tracker prototype



- Lot of help from Cory Lee
- Fixing gas seal around manifold, change in straw gluing procedure
- Designed temporary "rib" to force gas through the straws

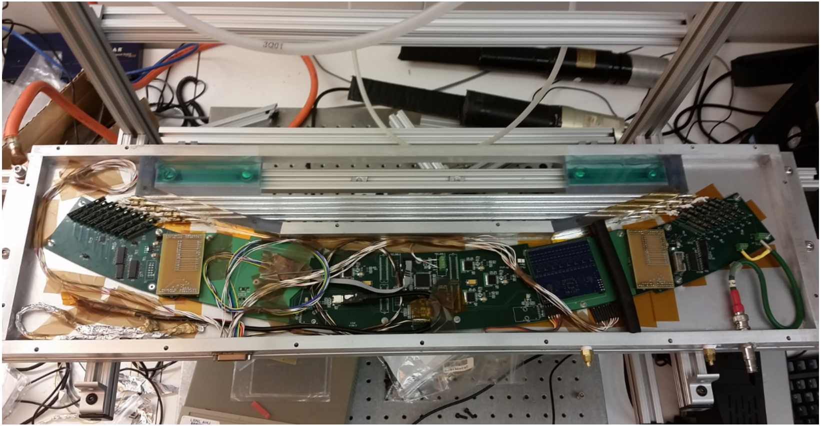
Straw end connector





- Needed to develop method for connecting preamps to straws
- Flexible twisted pair, brass connector

The LBL tracker prototype chamber

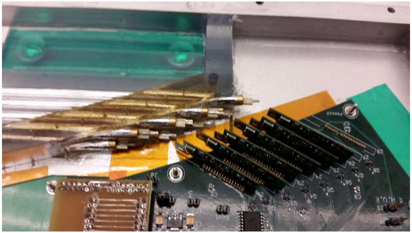


- (Downstairs in 50-2155)

Prototype readout and DAQ development

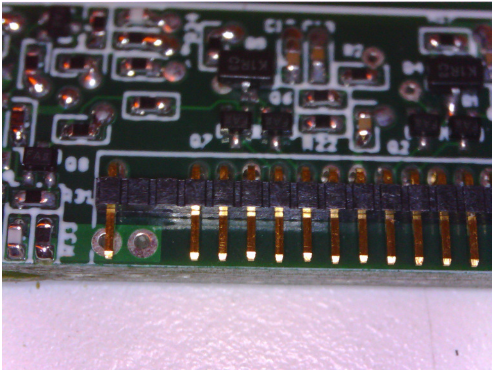
- Readout controller still being developed, prototypes use microcontroller
- Communicates to PC by serial over USB, simple python DAQ
- Can send calibration pulses to each channel with variable height and frequency
- Map out per channel noise rates, set gains and thresholds
- Readout speed 1000 hits per second (limited by serial communication on uC)
- Final ROC expect 30+ Gbps

Electronics testing



- Feedback led to design changes in next preamp iteration
- Noise issues, threshold step size, HV breakdown points

Electronics testing



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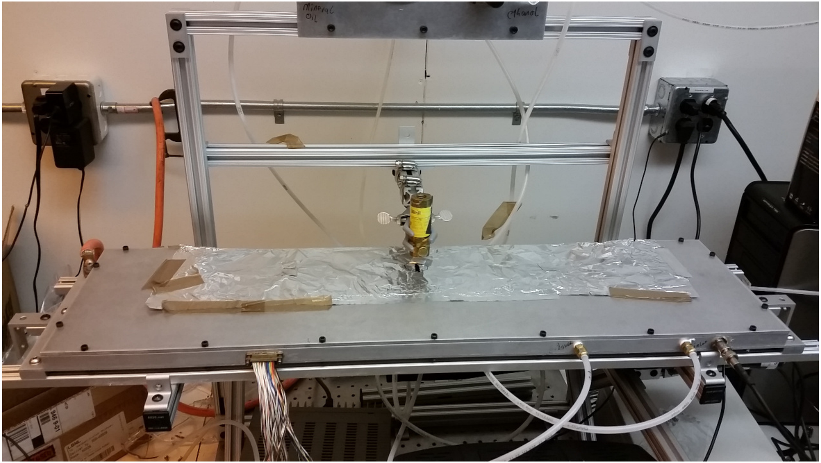
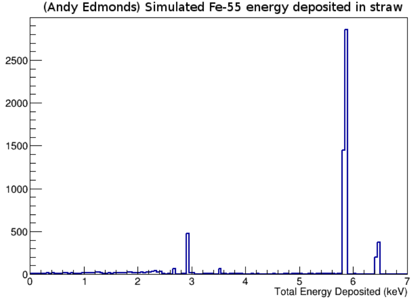
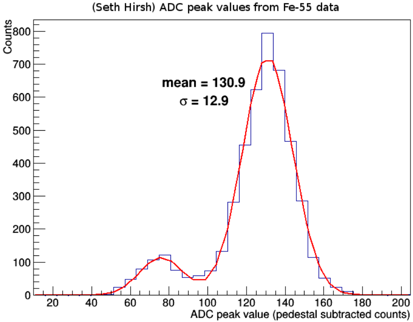
- Noise issues, threshold step size, HV breakdown points

Testing with sources



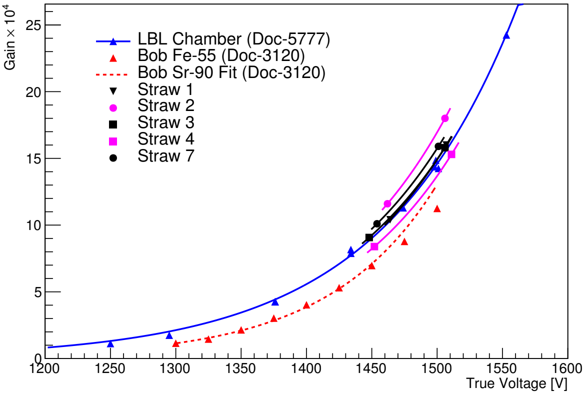
Can resolve ^{55}Fe peaks using ADC data





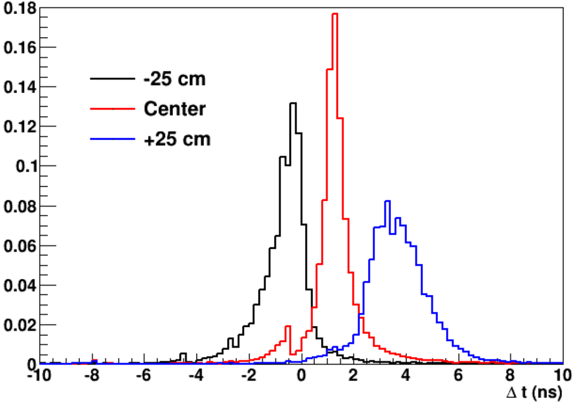
- From simulation, without electronics effect expect best possible resolution is 6.8%
- Peak - pedestal ADC value gives 9.9%

(Andy Edmonds) Measuring gas gain with ^{55}Fe data



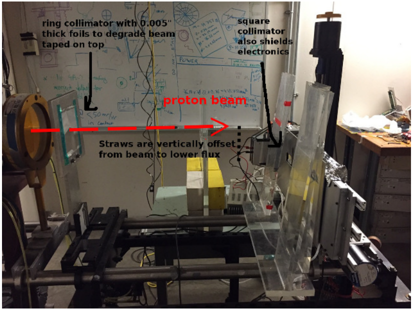
- Record hit rate, voltage, and HV supply current
- $\text{Gain} = \dfrac{\text{HV supply current}}{\text{Rate} \times \frac{\text{E per gamma}}{\text{Ionization energy}} \times \text{Electron charge}}$

Using ^{90}Sr source, able to see change in time measurement as a function of position on straw



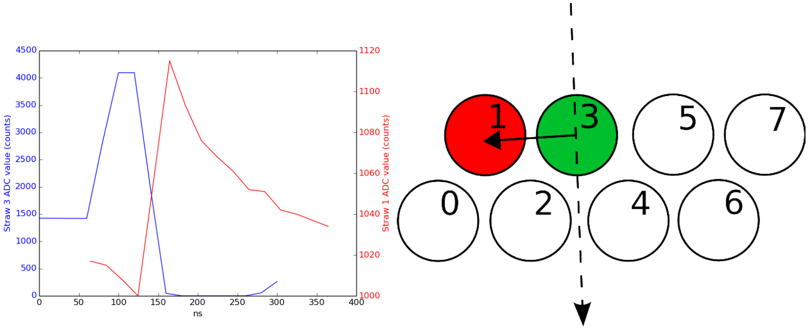
- $v_{propagation}$ consistent with expectations

Proton beam testing at 88 inch cyclotron



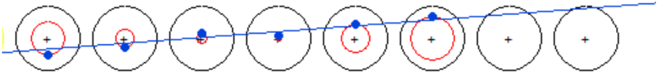
- Protons are produced after muon capture by Aluminum
- Looking for cross talk from straw to straw from large proton signals
- Ran twice, once with each model preamp

Cross talk from protons



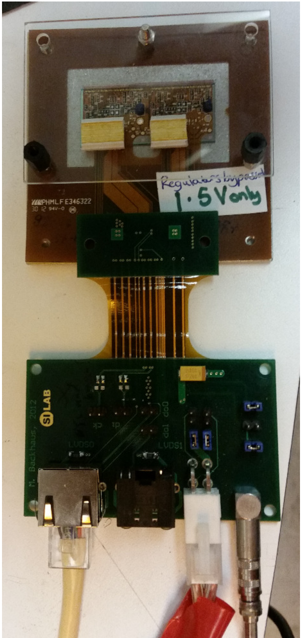
- Old preamps had clear cross talk signals
- New preamps fixes this, still some cross talk within preamp

Measuring resolution



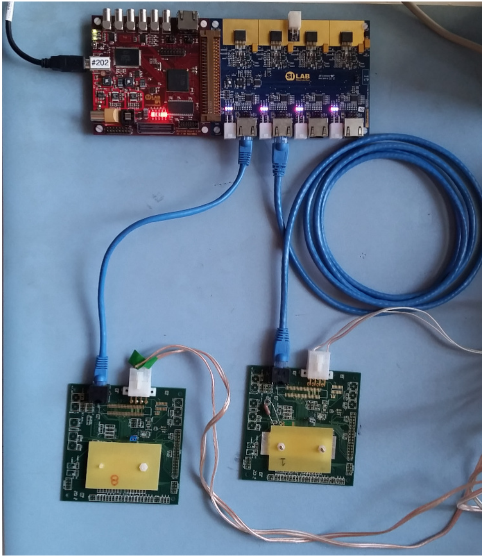
- Measurement of drift time tells us radial position of track
- Simulations show 200 μm resolution is sufficient for reconstruction
- To determine resolution need independent measure of track position

ATLAS FEI4 pixel chips



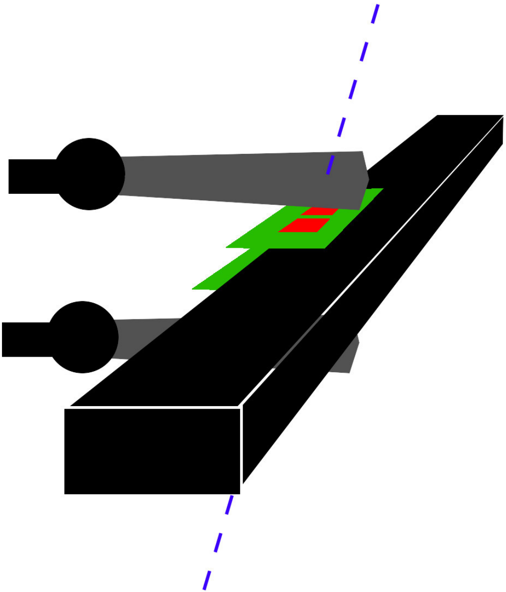
- 80x336 pixel array (26680 total)
- 250x50um, 2.0x1.9cm chips
- Data is row, column, TOT (pulse size), BCID (gives time from trigger in 25ns ticks)

Bonn USBpix readout system

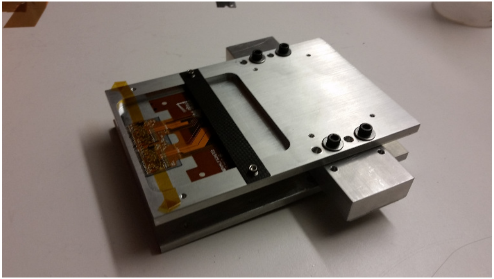


- Read out over USB
- External trigger input
- pyBAR - python based DAQ, developed multichip support
- Thanks to Maurice + pixel group, Rebecca Carney, Jens Janssen for lots of help

Development of cosmic setup

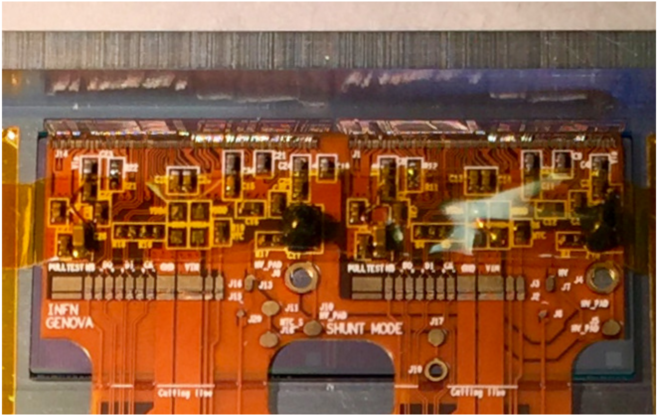


Pixel Mount



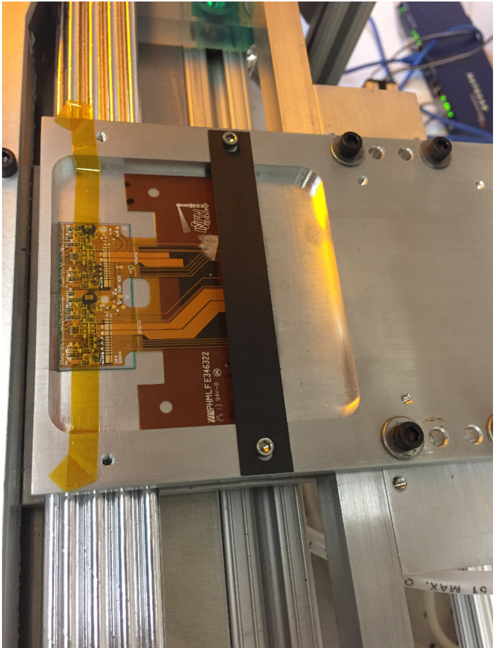
- Want to put pixels as close to straws as possible
- Need to ensure consistent pixel position
- Want to be able to move along straw, adjust relative pixel positions
- Non destructive

Mounting the pixel modules

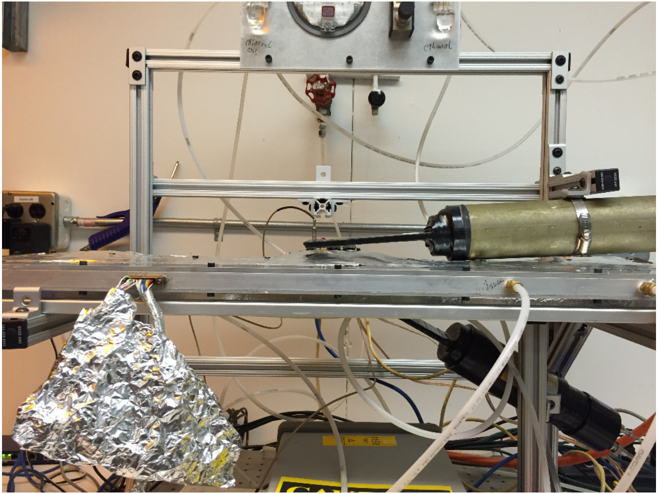


- Positioned by hand by Rhonda Witharm
- Want to ensure they are parallel

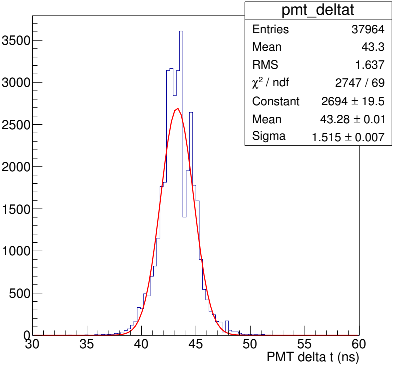
Mounting the pixel modules



Mounting the pixel modules

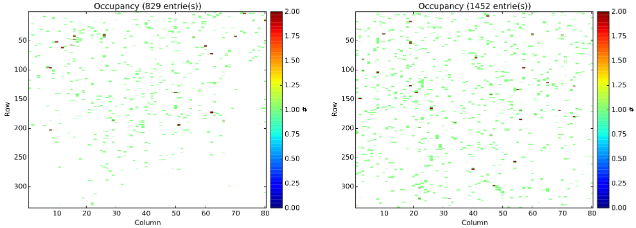


Readout and PMT coincidence / triggering logic



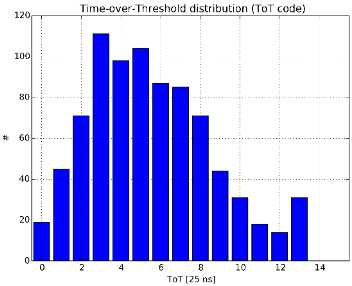
- Create PMT coincidence, need to get to both pixels and chamber, but 40 MHz vs 50 MHz clocks
- Input into digitizer TDC, get measurement in straw clock domain
- Input into USBpix as external trigger for pixels, keep track of trigger count in both systems

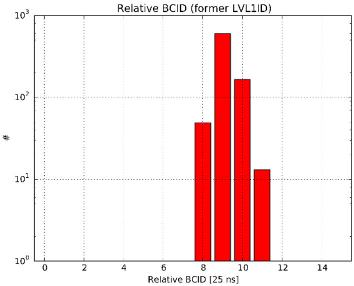
Pixel results



- Chips individually calibrated with pulser circuit, threshold $\sim$ 2500 electrons
- Cosmic rays fire a single pixel
- Negligable noise rate

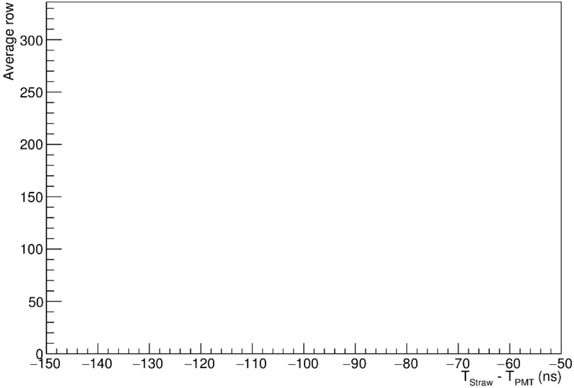
Pixel results





- Not sure why hits spread out over 100 ns

Sanity check - assume all events are straight down



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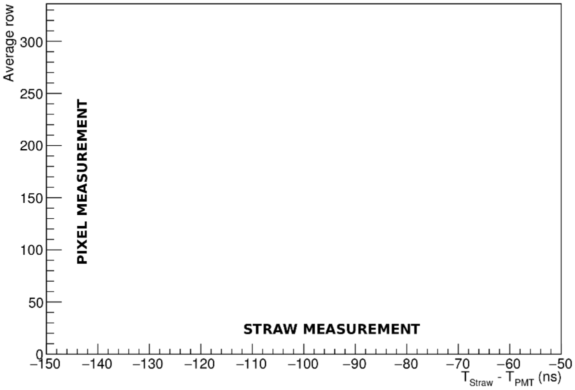

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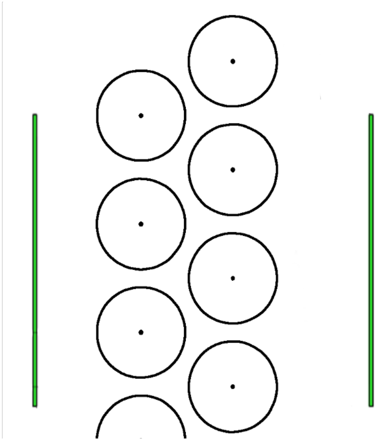

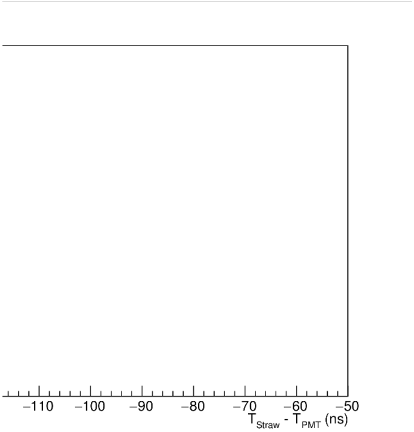

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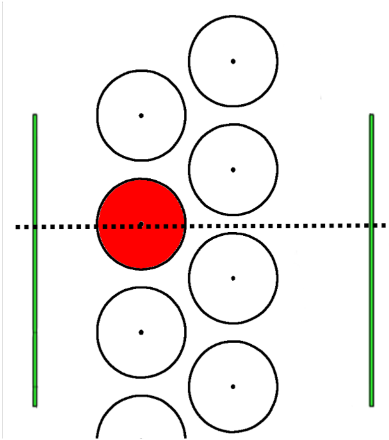

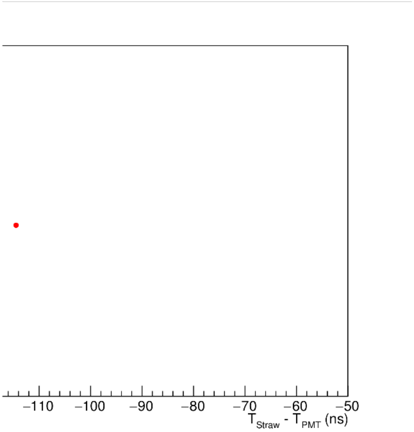

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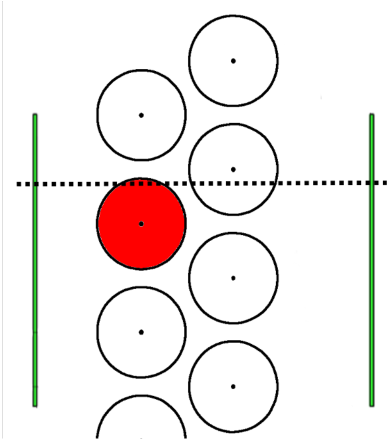

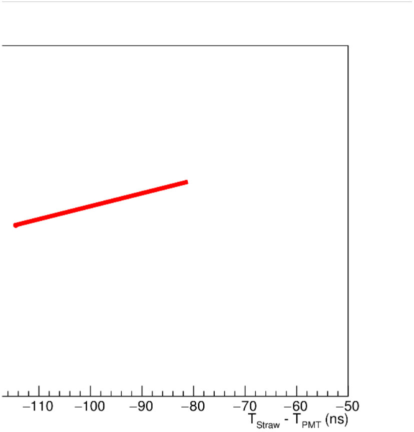

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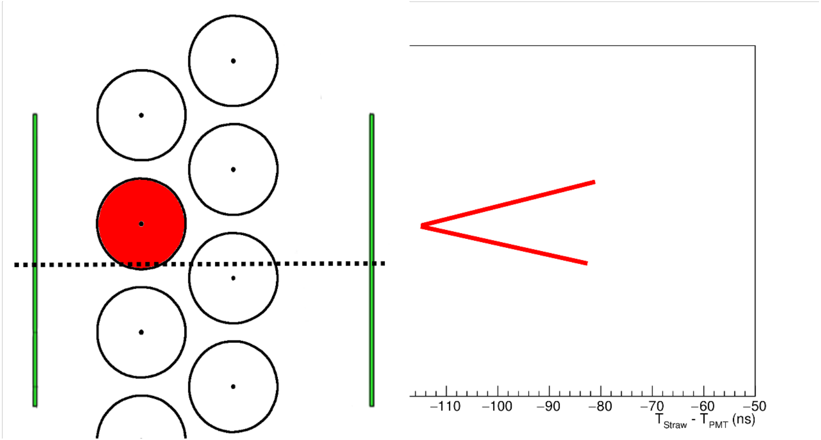

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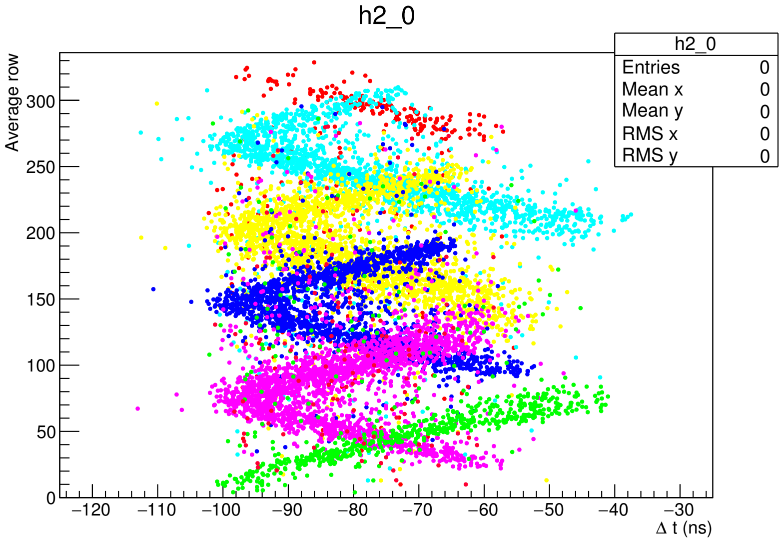
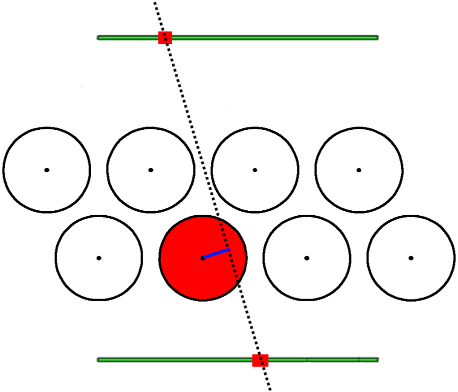
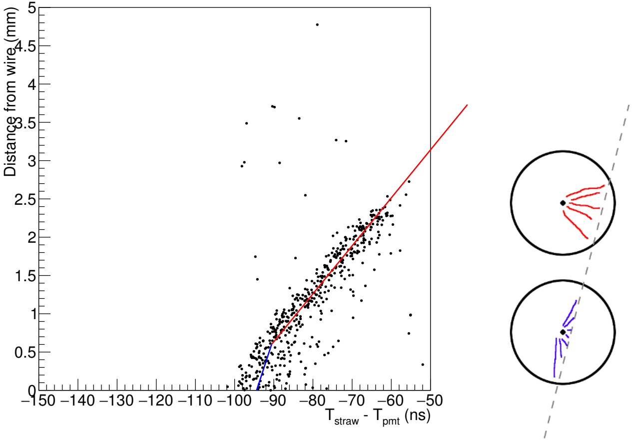


Full data analysis



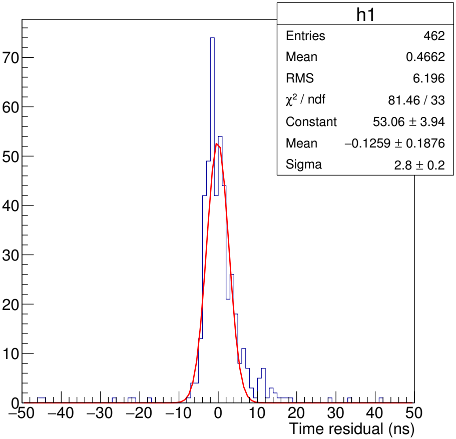
- Assuming perfectly parallel pixels and straws, no offset between pixels
- Maximum likelihood fit for 2-D wire position, drift velocity
- For each event calculate minimum distance to wire and expected drift time

Resolution and drift velocity (at 1425V)



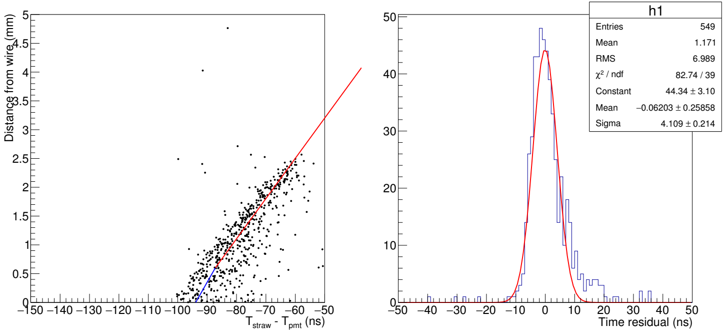
- Model drift velocity as being constant at a distance of 0.6mm to the wire and farther
- Drift velocity $= 62.6 \pm 0.5\ \mu\text{m}/\text{ns}$, agrees well with analysis by Jason Bono

Resolution and drift velocity (1425V)



- Subtracting PMT time spread (assuming $1.5/\sqrt{2}$ ns), get position resolution of 162 ± 13 μm
- 6-7% of hits coming late, not yet understood

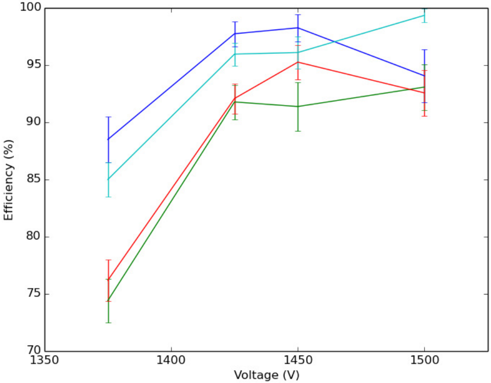
Looking at 1375V



- Original target voltage was 1375V
- Much worse efficiency and resolution than expected

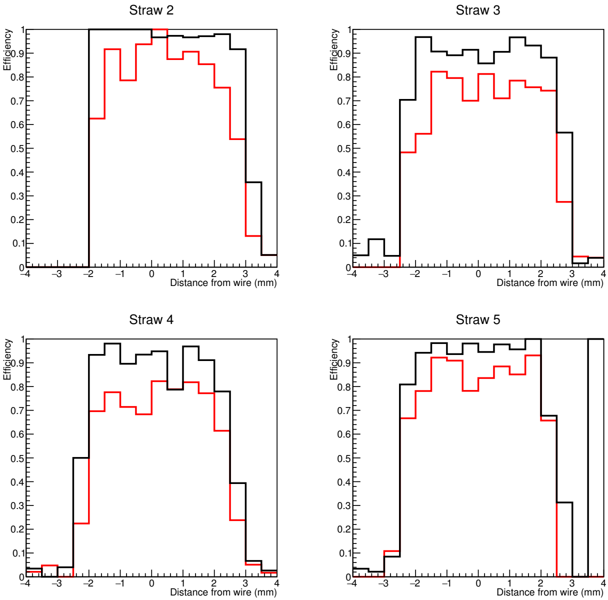
Efficiency (%)

- Look for events where pixels say track goes through straw, see if there is a hit
- Exclude outer 0.5 mm of radius

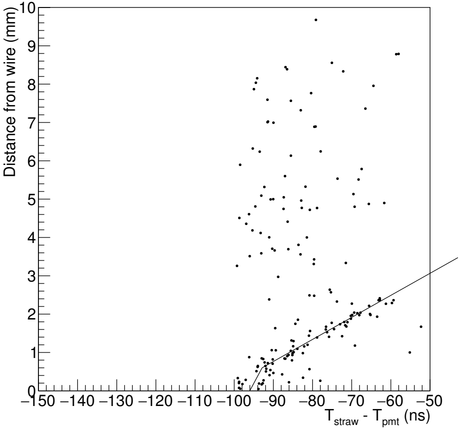


Efficiency (%)

black: 1425V, red: 1375V

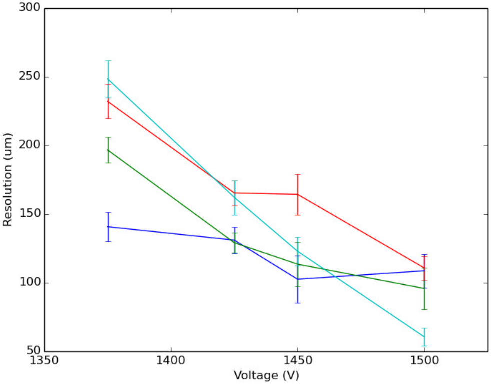


Missing efficiency



- Events with hits in non-adjacent straws (3-5% of hits) show signs of showers or scattering
- Possible similar effect fooling the efficiency measurement

Resolution (μm)

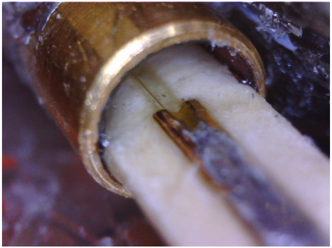


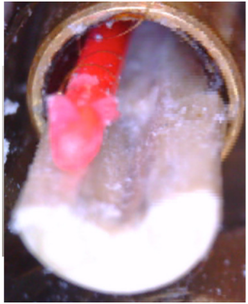
Conclusions

- LBL prototype allowed us to test many different components of the tracker system
- FEI4 pixel modules allow for precision measurement of straw response as a function of track position
- Were able to demonstrate required time resolution
- Fed back many design changes to full system
- Future plans:
  - High rate source for aging and gain saturation
  - Measuring electronics gains, thresholds, calibration pulse
  - Stability tests
  - Publication of results

Backup

Positioning of wires





- After first few weeks of running noticed wires out of expected positions
- Several straws had also been broken
- Restrung straws in place, but some offset remains