

MU2E STRAW TUBE TRACKER PRE-PRODUCTION PANEL PERFORMANCE STUDIES

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APS DPF Meeting

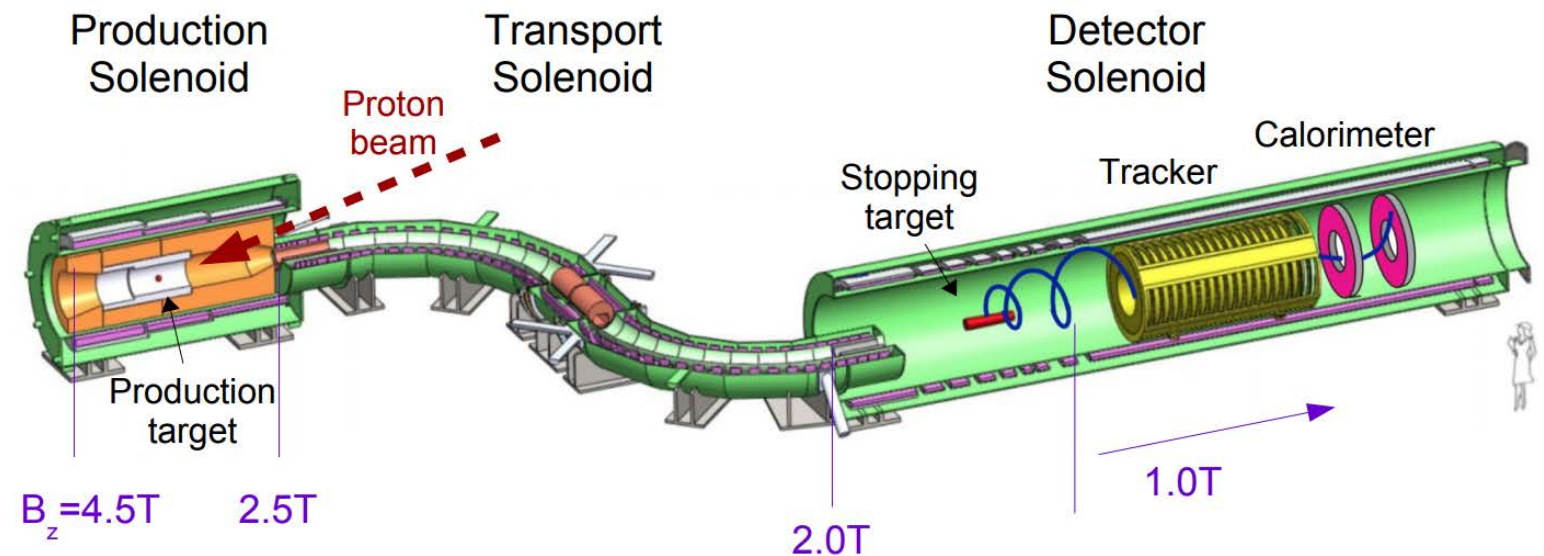
July 12-14, 2021



UNIVERSITY OF
MICHIGAN

THE MU2E EXPERIMENT

- Search for Charged Lepton Flavor Violation
- Looking for neutrino-less muon to electron conversion in the field of a nucleus
 $\mu^- N \rightarrow e^- N$
- Signature mono-energetic electrons of 105 MeV
- 4 orders of magnitude improvement in Single Event Sensitivity



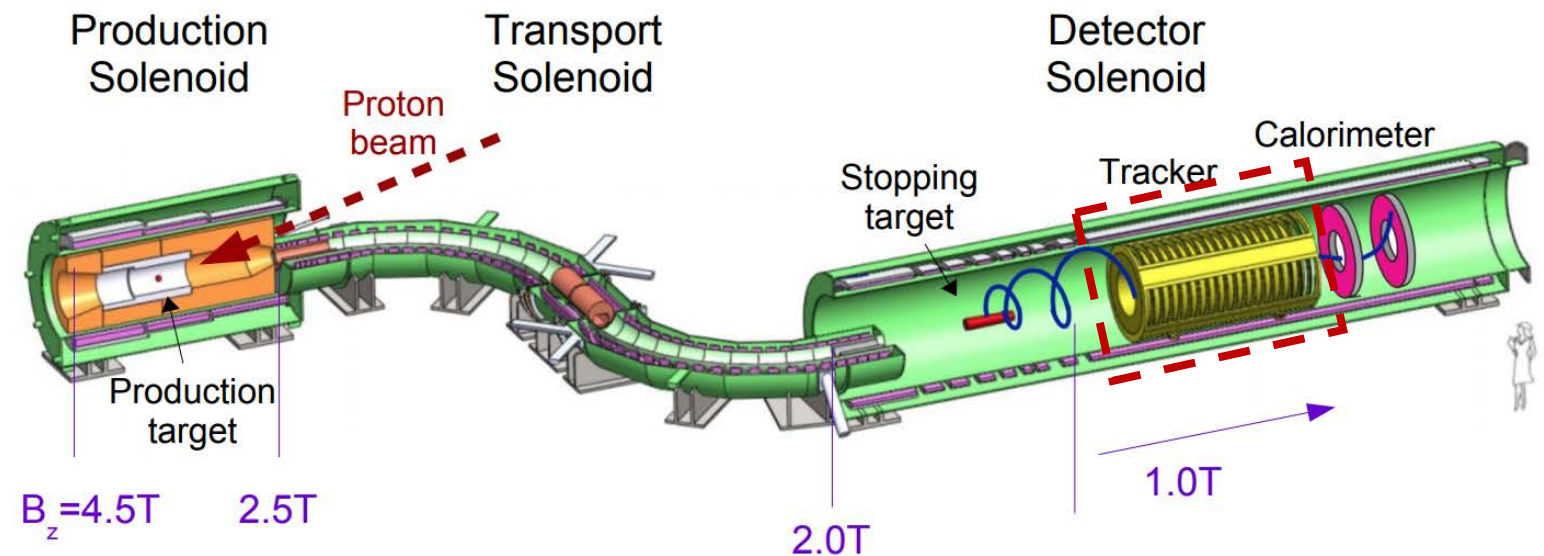
A schematic view of the Mu2e experiment (not including the Cosmic Ray Veto)

* More detailed talk on the Mu2e Experiment by K. Ciampa on Wed 7/14 in *Lepton Flavor and Precision Measurements* session

THE MU2E EXPERIMENT

Tracker is a primary detector, which provides the conversion electron's momentum measurement

- Resolution ~ 180 keV/c
- Operates in vacuum, magnetic field, and radiation, low material budget
- Rejects backgrounds from conventional processes



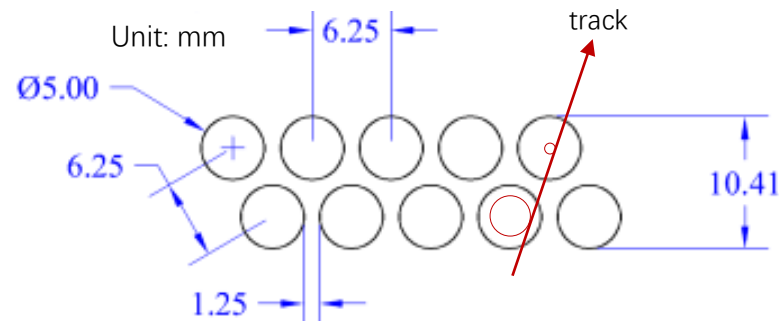
A schematic view of the Mu2e experiment (not including the Cosmic Ray Veto)

STRAW TUBE TRACKER

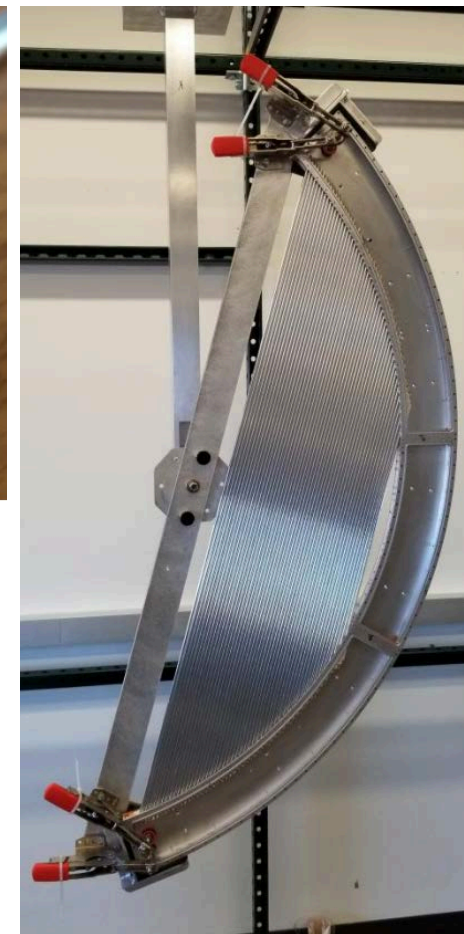
- Gas drift tube (“straw tube”) is the detecting element
 - 5 mm diameter, 0.44~1.14 m in length
 - 15 μm -thick metallized mylar wall, thinnest straw in a straw tube tracker to date
 - 25 μm gold-plated tungsten wire
 - 80/20 Ar/CO₂, 1 atm within the gas volume, vacuum outside
 - High voltage ~ 1500 V
 - Read out from both ends
- A panel consists of 96 straws arranged in two staggered layers, spanning 120°



Straw tube (with termination) compared to a pencil



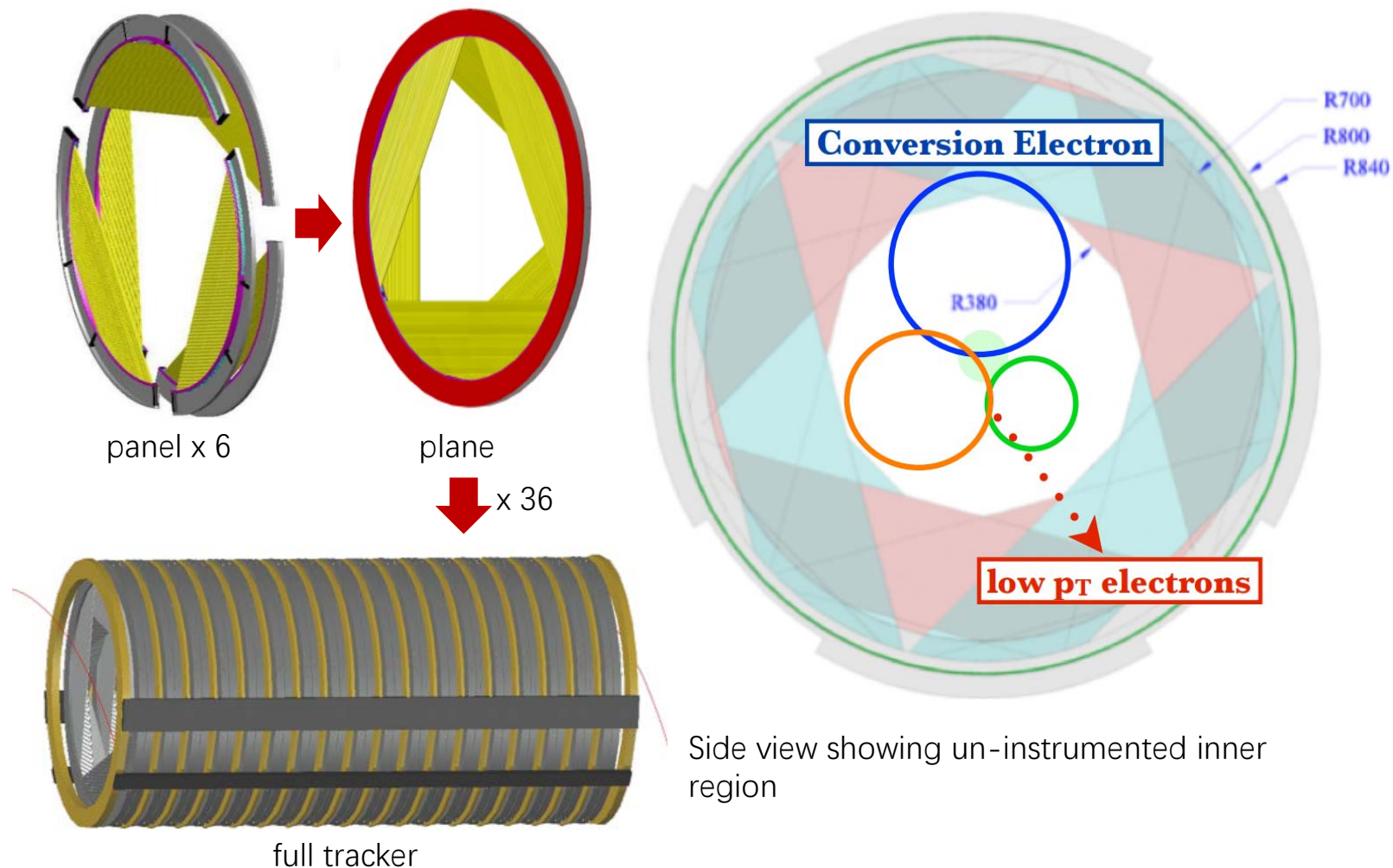
Spatial arrangement of straw tubes



Panel

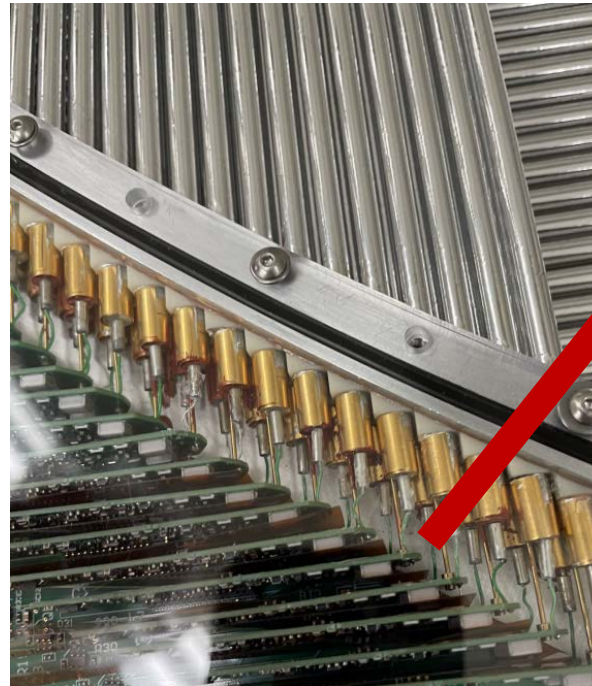
STRAW TUBE TRACKER

- 6 panels are assembled into a plane, and the whole tracker consists of 36 planes
- Inner 38 cm region of the tracker is not instrumented
 - Blind to muon beam and associated activity
 - Blind to most of the lower energy electrons coming from Standard Model muon decay

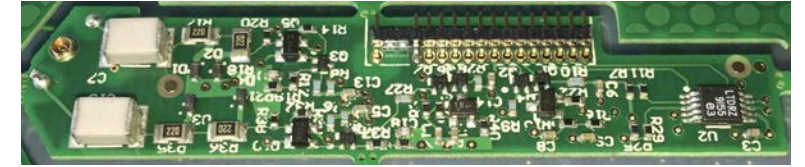


FRONT-END ELECTRONICS: PREAMP

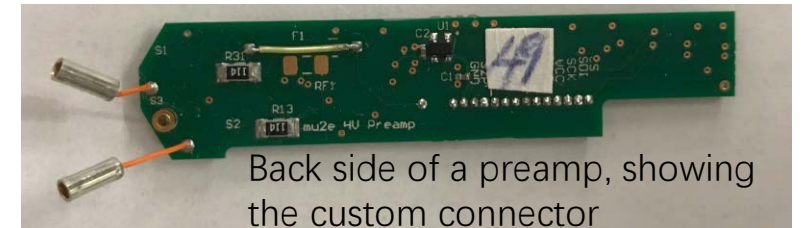
- Front-end electronics are housed in the outer part of the panel
- Signals from straw tubes are read out from both ends by pre-amplifiers (preamps)
- Preamps...
 - turn signal current to voltage
 - amplify, shape and bias signal
 - distribute high voltage (“HV side”)
 - provide calibration charge injection (“CAL side”)
- Gain and bias offset can be independently changed through control signals



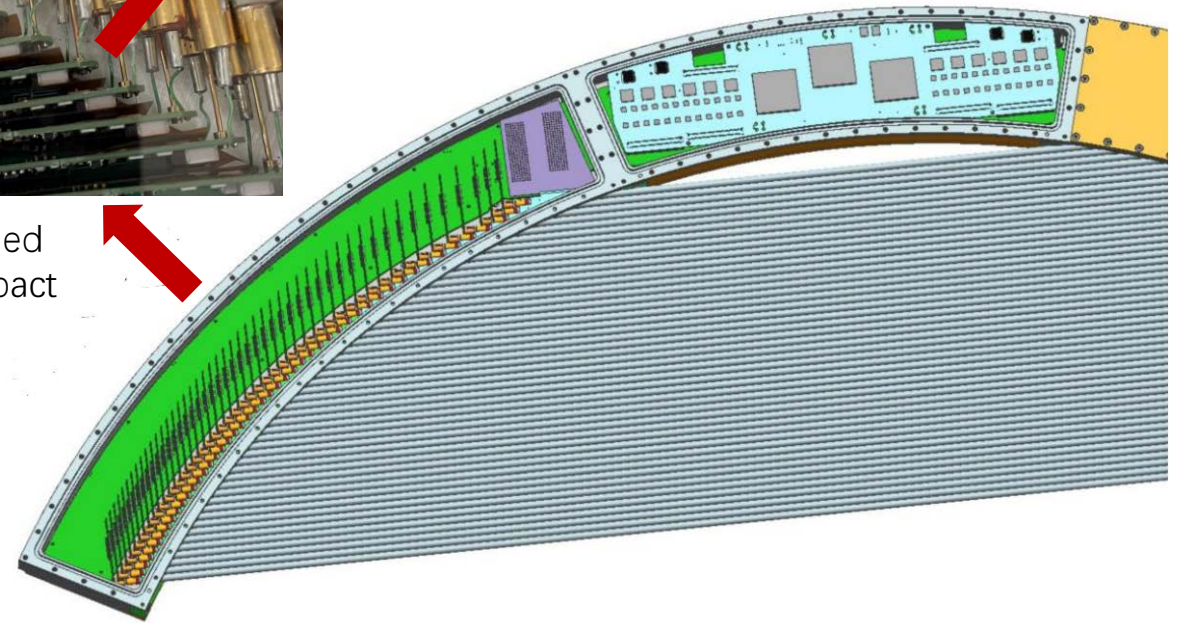
Preamps are installed vertically in a compact manner



Front side of a preamp. Each preamp serves two straws

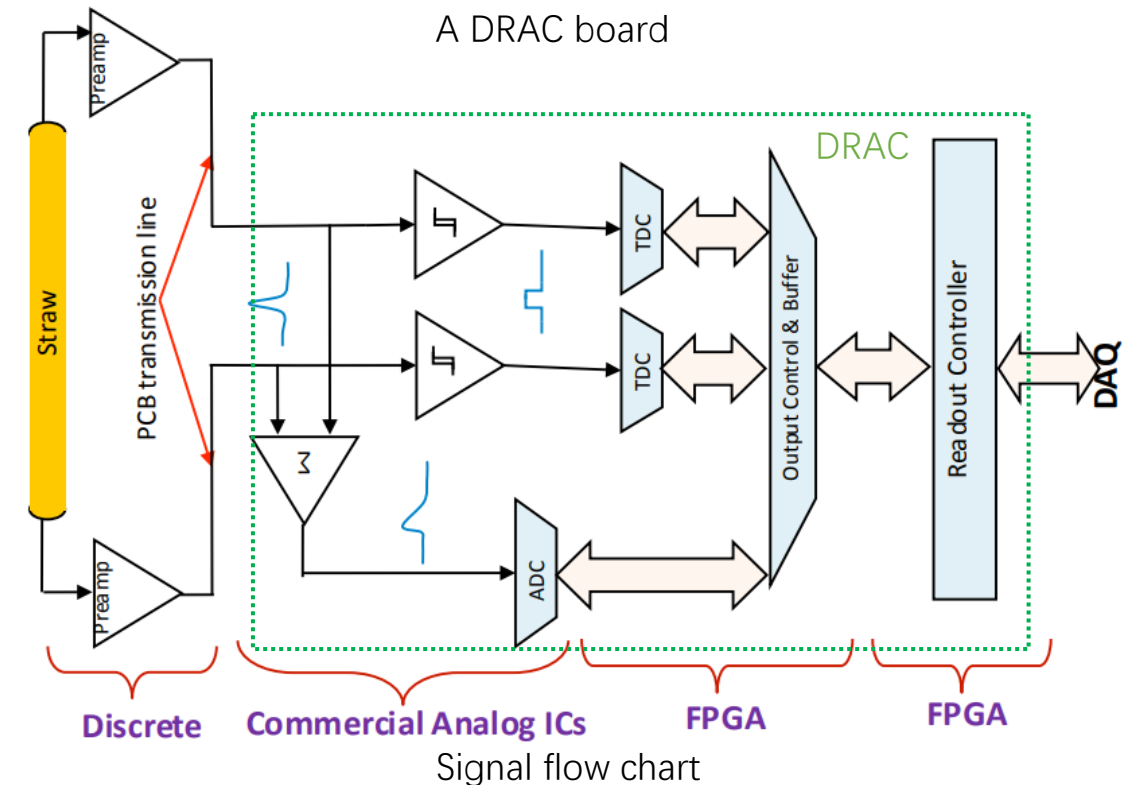
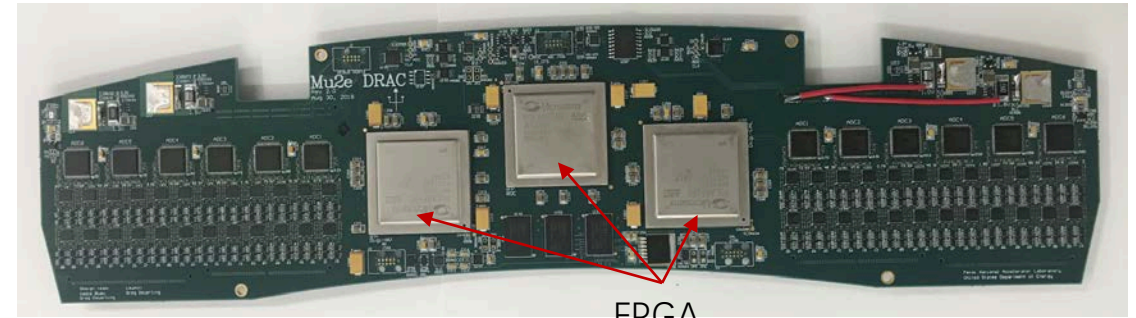


Back side of a preamp, showing the custom connector



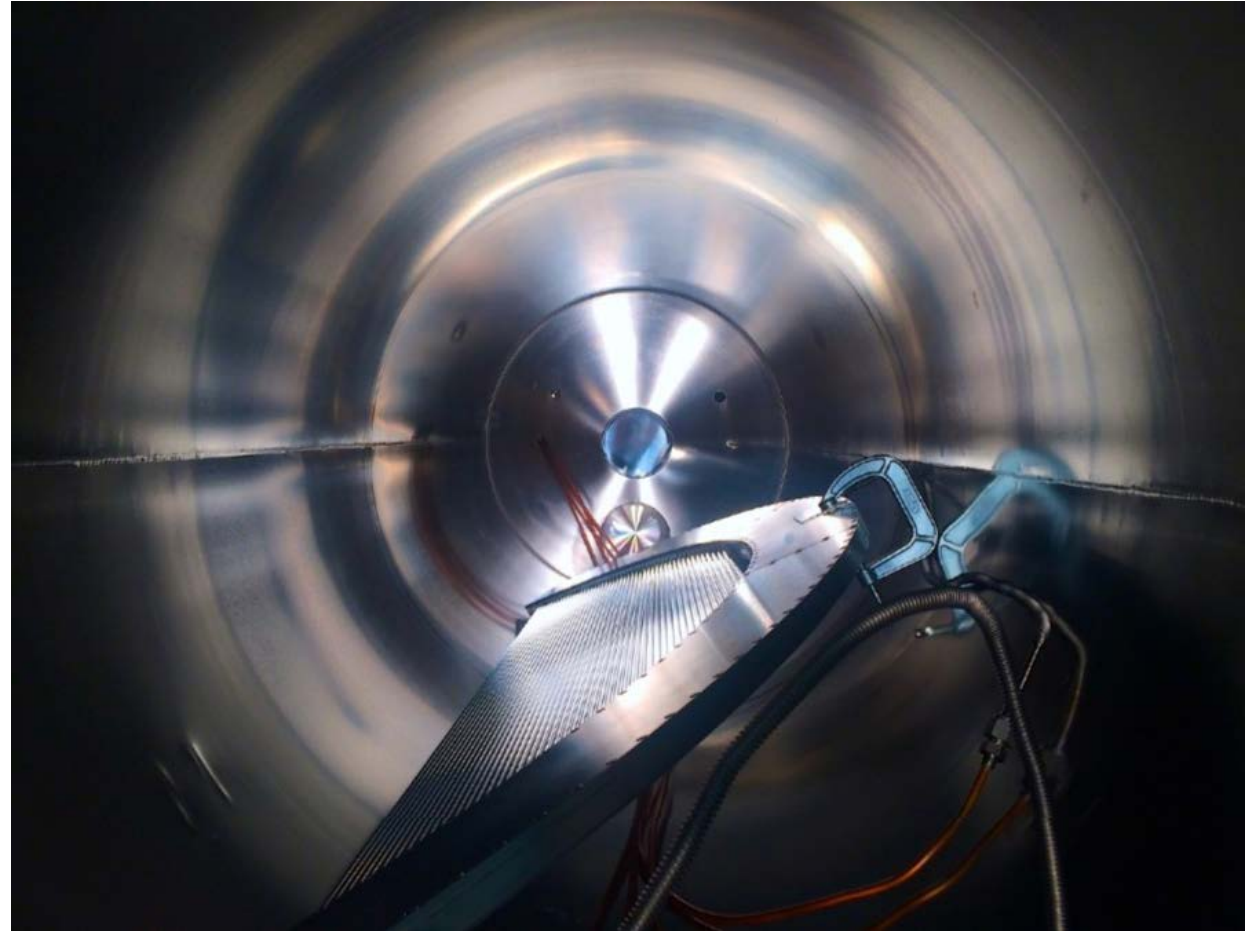
FRONT-END ELECTRONICS: DRAC

- Analog signals from preamps are routed through several PCBs to a Digitizer Readout & Assembler Controller (DRAC) for further processing
- Comparator outputs are fed to TDCs (~20 ps/tick), a normal trigger requires coincidence between two straw ends
- Integrator adds the signals from both ends of a straw and ADC digitizes the signal
- Three Microsemi PolarFire Field-Programmable Gate Arrays (FPGAs)
- Two FPGAs control data output, buffer data, and assemble data packages
- Another FPGA manages communications, monitors slow control variables, and controls panel operations
- Components extensively tested in radiation (200 kRad)



STUDIES WITH PRE-PRODUCTION PANELS

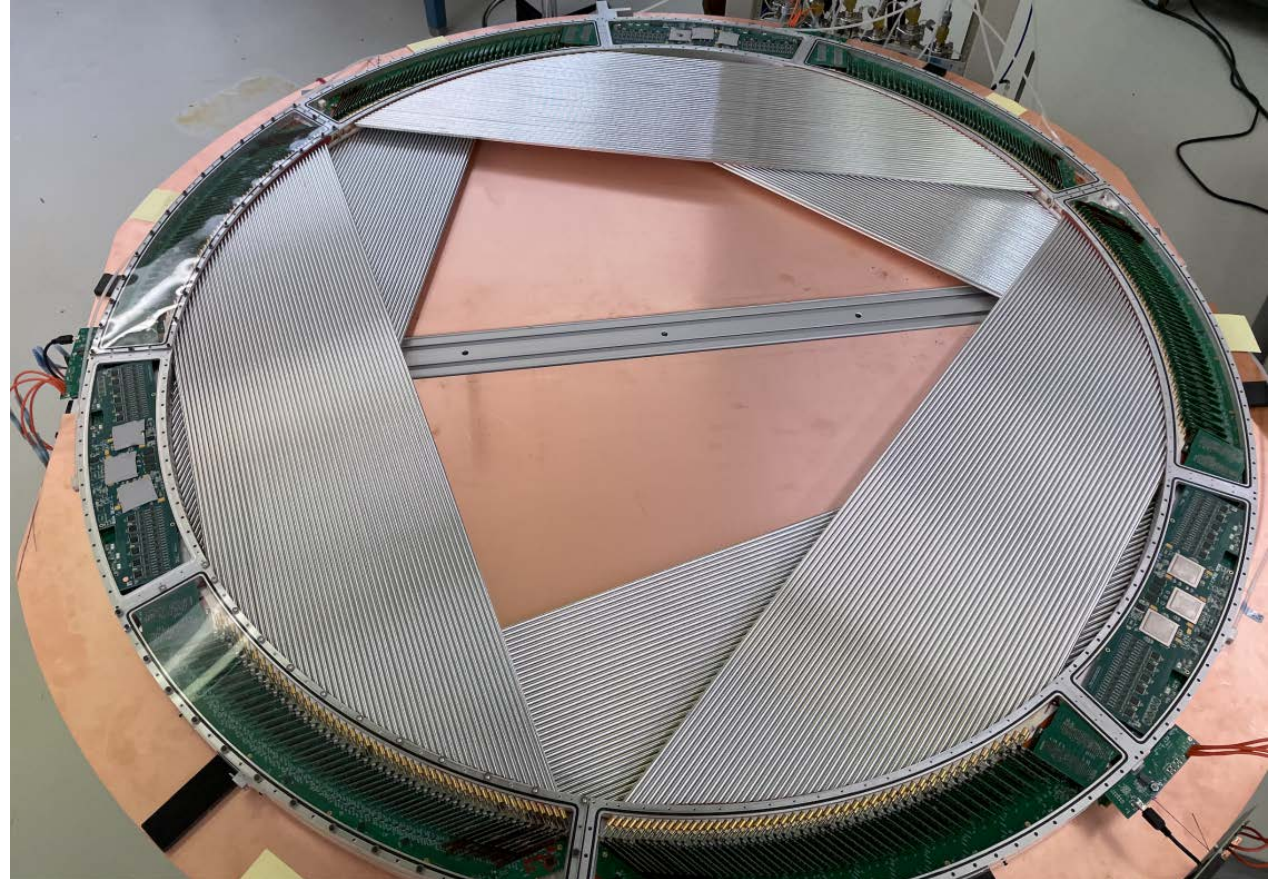
- Single panel vacuum test conducted in 2018
- Exercised single panel operations and readout
- The panel remained undamaged in the vacuum
- A few channels experienced sparks when high-voltage tested. Knowledge from debugging such channels improved production procedures so mass-production panels have good high voltage performances
- Leakage and outgassing of the panel met the experiment requirement
- Cooling system was capable to maintain a reasonable operating temperature



Tested panel sitting in a vacuum chamber

STUDIES WITH PRE-PRODUCTION PANELS

- Full plane test (6 panels, 1/36 of full detector, vertical slice test) is ongoing
- Using a full plane to exercise the full tracker operation and readout chain, from the amplified wire signal, to DRAC, to experiment DAQ system, and to its storage in tape
- Diagnostic and horizontal position run:
 - Check operations
 - Finalize communications with experiment DAQ system through an optical fiber link
 - Use an ^{55}Fe source to perform a scan for calibration
 - Use cosmic rays to test abilities to synchronize between panels
- Vertical position cosmic run:
 - Same orientation as in full detector, exercising track reconstruction and preparing for commissioning



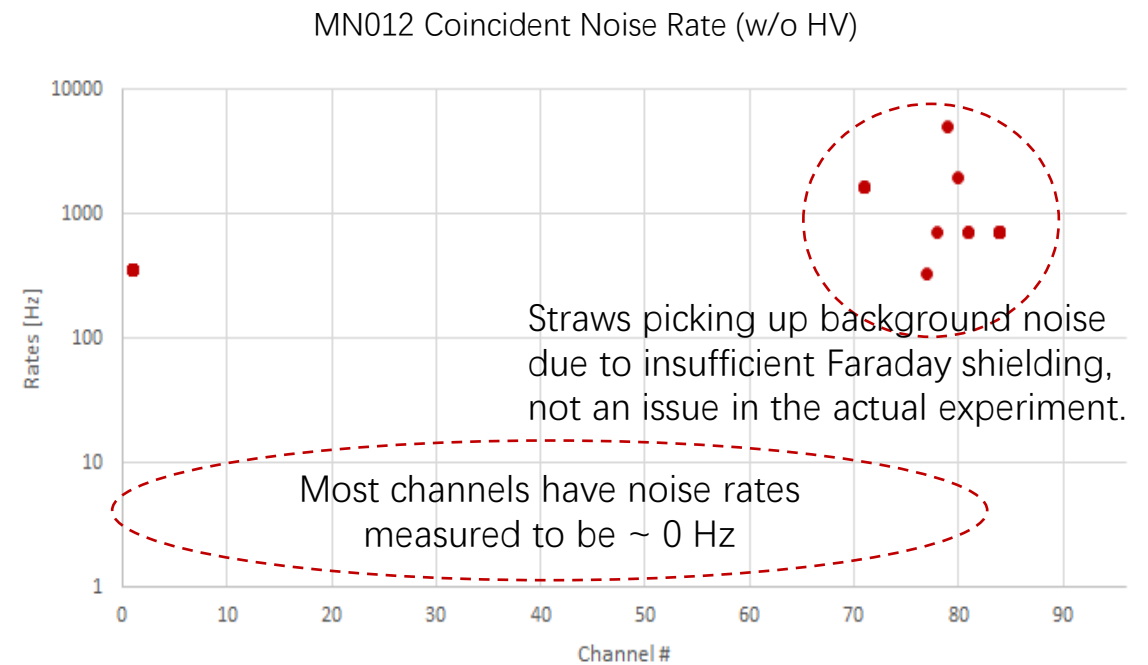
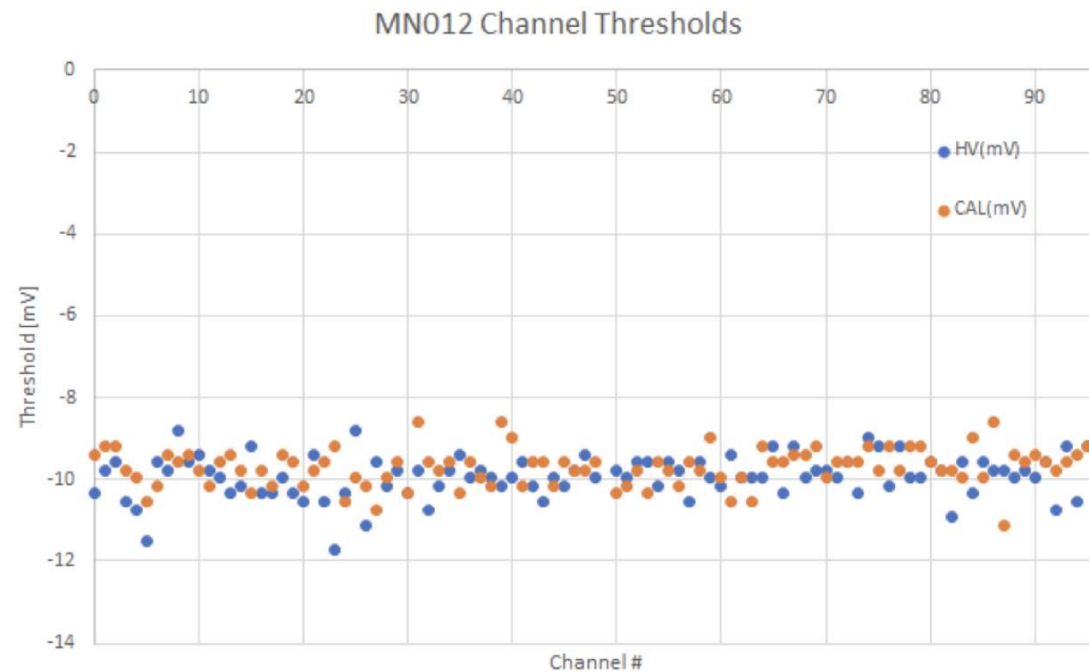
Tested plane in horizontal position, viewed from above

OPERATIONS AND DIAGNOSTICS

- Tracker operation methods were implemented in the firmware; corresponding control scripts are also developed
- Available panel operation methods include:
 - Setting gain and threshold (preamp bias offset) for any channel
 - Reading straw hit data
 - Measuring channel rates
 - Measuring channel thresholds using the biased pedestal
 - Monitoring slow control variables
 - Controlling charge injection for calibration
- Based on these operation methods, a diagnostic scheme was developed to identify problematic channels. This prepares for quality control when mass production panels are delivered.

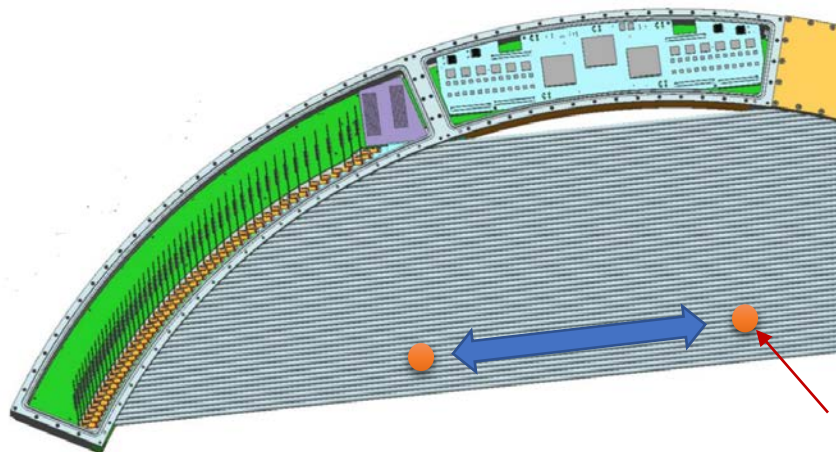
ELECTRONICS NOISE

- At a threshold level of ~ 10 mV, the panel demonstrated close-to-zero noise levels in all channels (requirement being < 5 kHz at 90% efficiency threshold)
- Physics simulations ran with a 12-mV threshold
- Even at a lower threshold level, the panel demonstrated lower noise level than the requirement. The requirement is well satisfied.

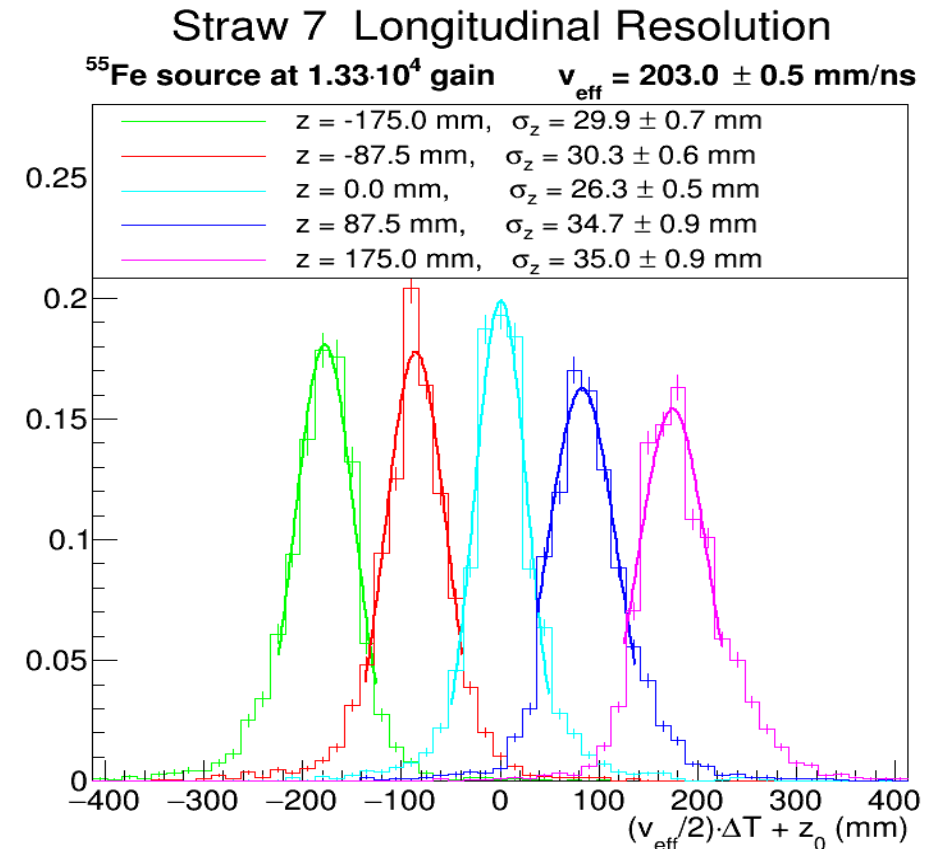


TIME DIVISION AND LONGITUDINAL RESOLUTION

- As straws are readout on both ends, time difference between the two ends of the straw (a.k.a. “time division”) provides information on the hit position
- As part of the plane horizontal position test, we are planning to map the time division for calibration and measure the longitudinal resolution
- Using an ^{55}Fe source and placing it at multiple positions along the straw
- An earlier measurement using this method on a prototype with shorter straws gave a longitudinal resolution < 35 mm



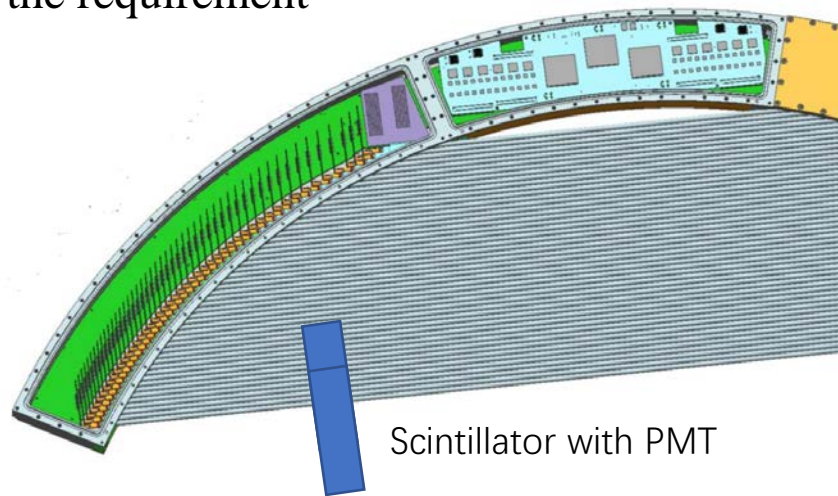
Fe-55 source



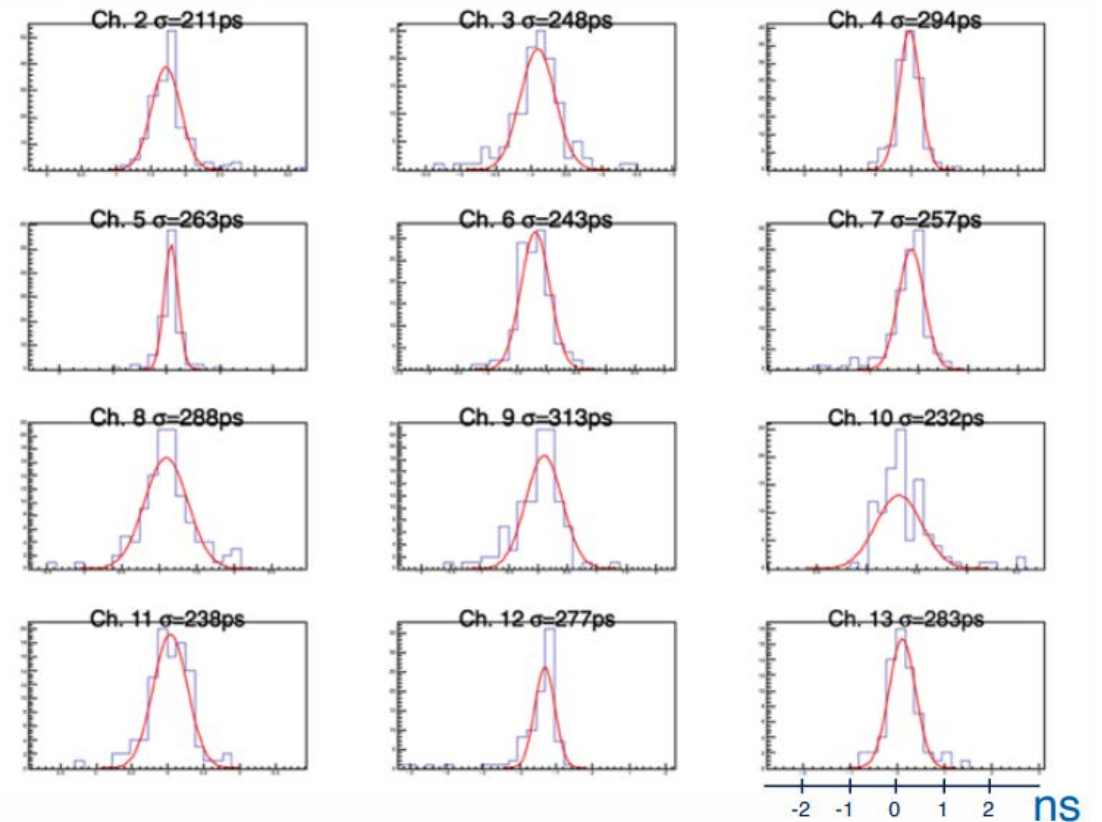
Longitudinal resolution measured with Fe-55 source on an early prototype

TIME DIVISION AND LONGITUDINAL RESOLUTION

- The momentum resolution of ~ 180 keV/c requires a longitudinal resolution along the straw to be ~ 50 mm for reconstruction, or ~ 250 ps in time
- ^{55}Fe is a gamma emitter and the response is not identical to that of minimum ionizing particles. A more representative measurement was done using cosmic rays
- Using small scintillator block coupled with photo-multiplier tube (PMT) as a trigger, cosmic events incident at relatively well-defined locations along the straws were taken. The spreads of the time division meet the requirement



Time division in PMT tagged cosmic events

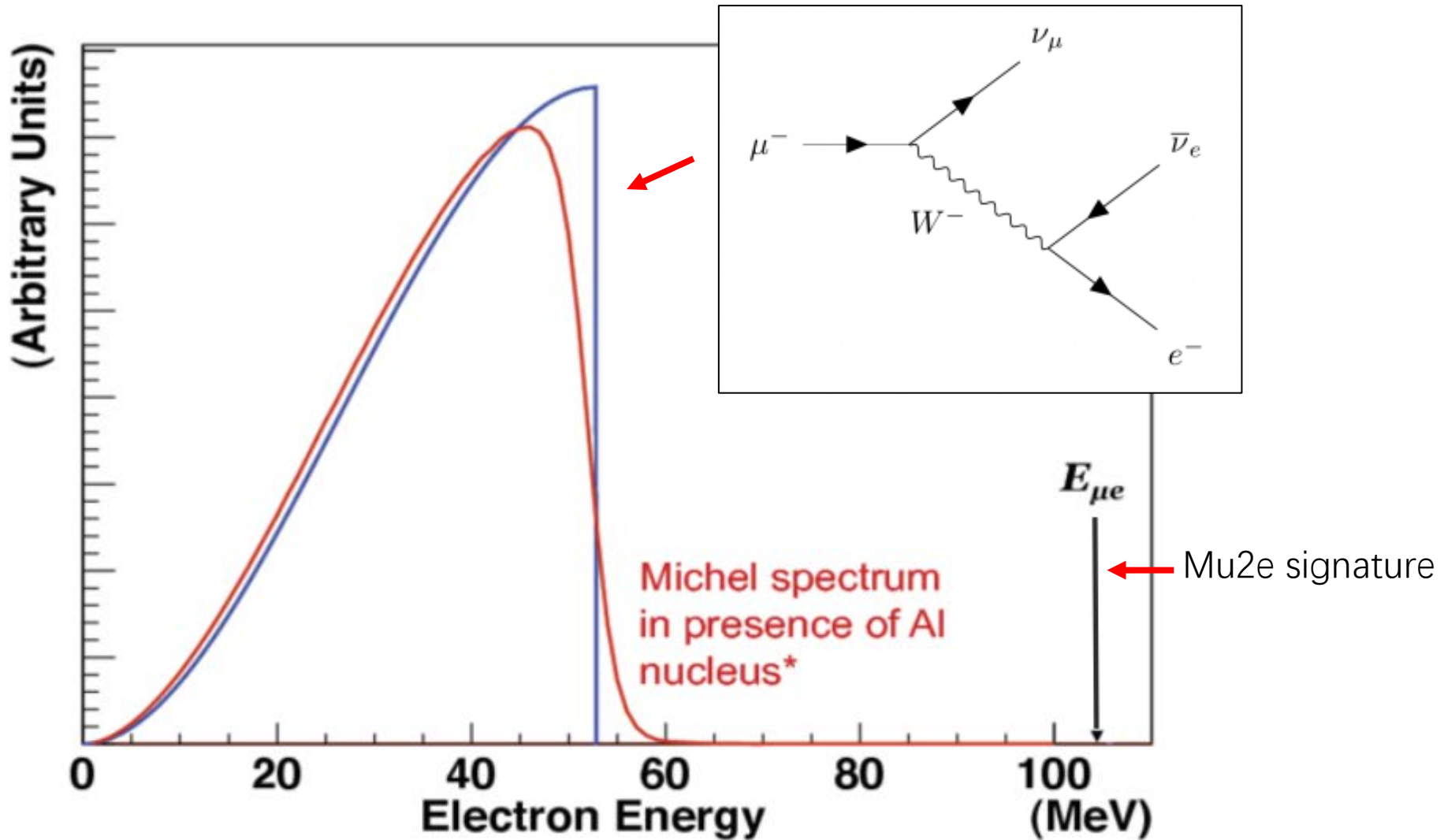


SUMMARY

- Mu2e searches for the non-conventional $\mu^- N \rightarrow e^- N$ decay process
- The Mu2e Tracker measures conversion electron momenta with ~ 180 keV/c resolution
 - Thin gas straw tubes as detecting element
 - Empty center region lowers background rates
 - Signals are read out from both ends of each straw
- Studies with pre-production panels
 - Single panel vacuum test proved panel's ability to operate normally in a vacuum
 - Test of a full plane is on-going
 - Operations and diagnostics schemes are developed and implemented
 - Electronics noise level is low
 - Past time division measurements showed we can reach the desired resolution. More measurements using radioactive sources will follow

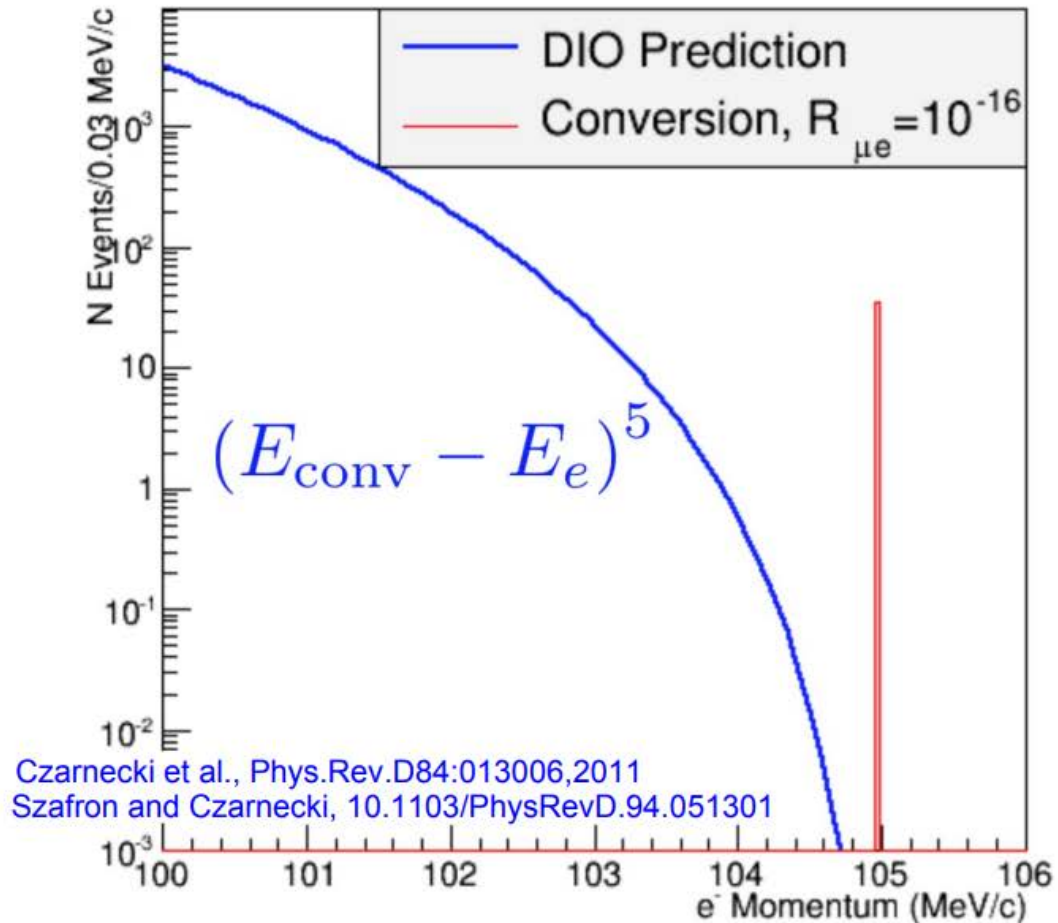
BACKUP

MICHEL SPECTRUM OF DECAY-IN-ORBIT

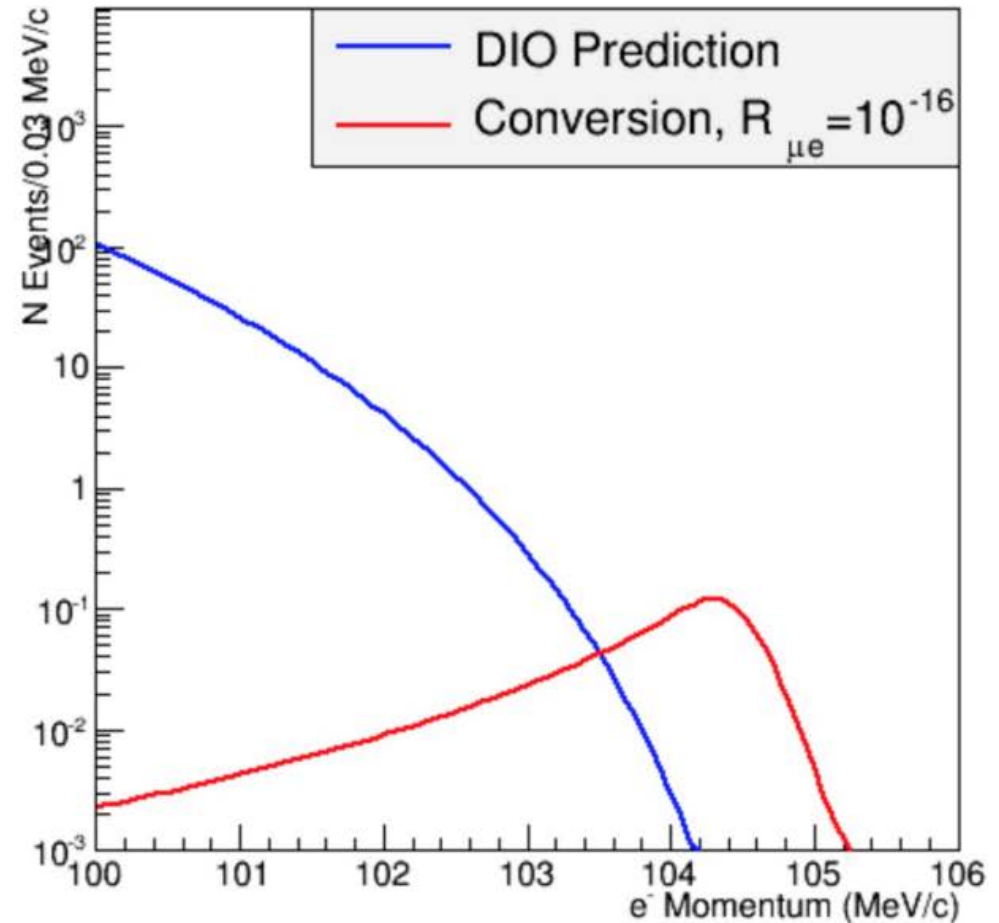


MICHEL SPECTRUM OF DECAY-IN-ORBIT

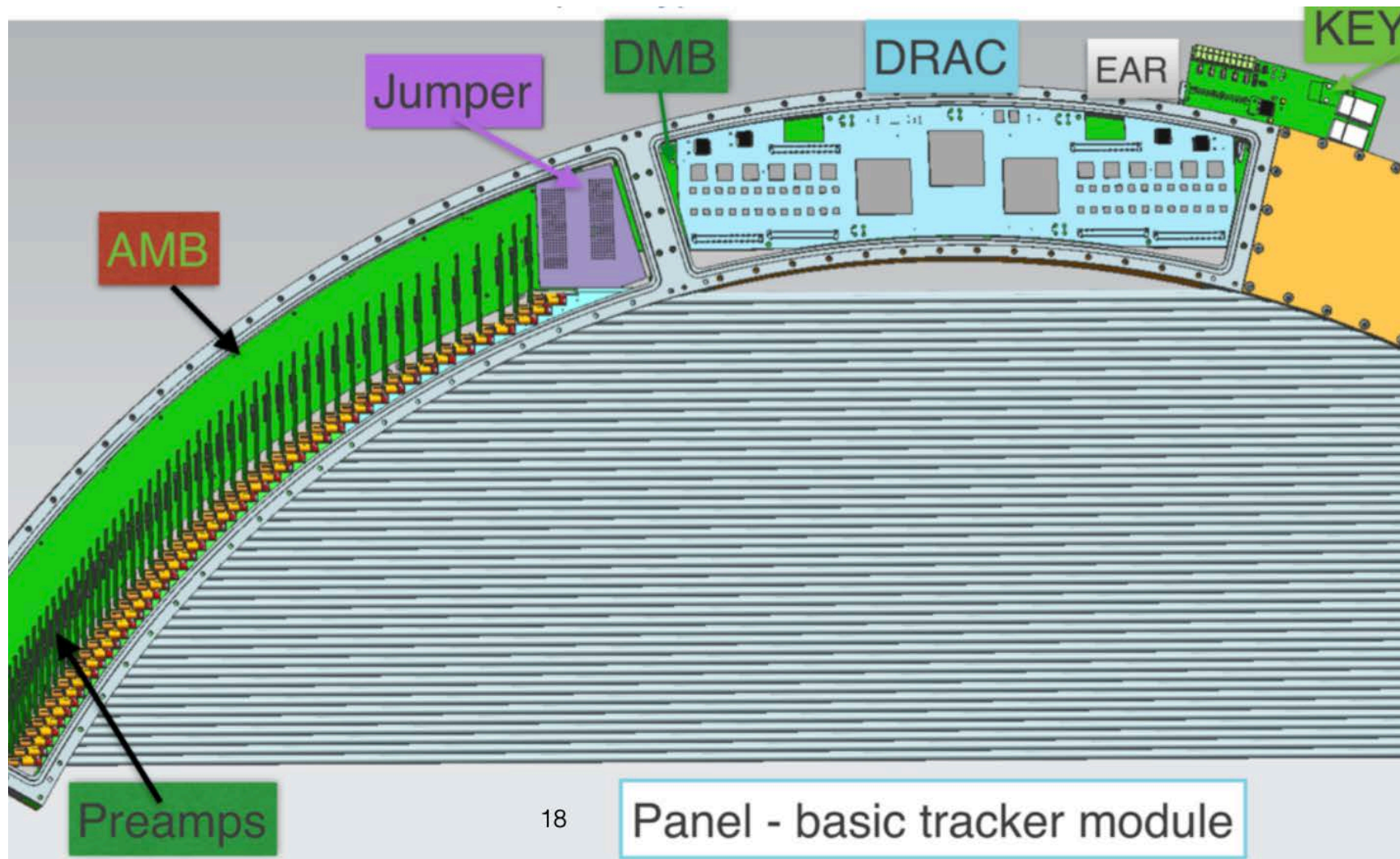
Theory Predictions



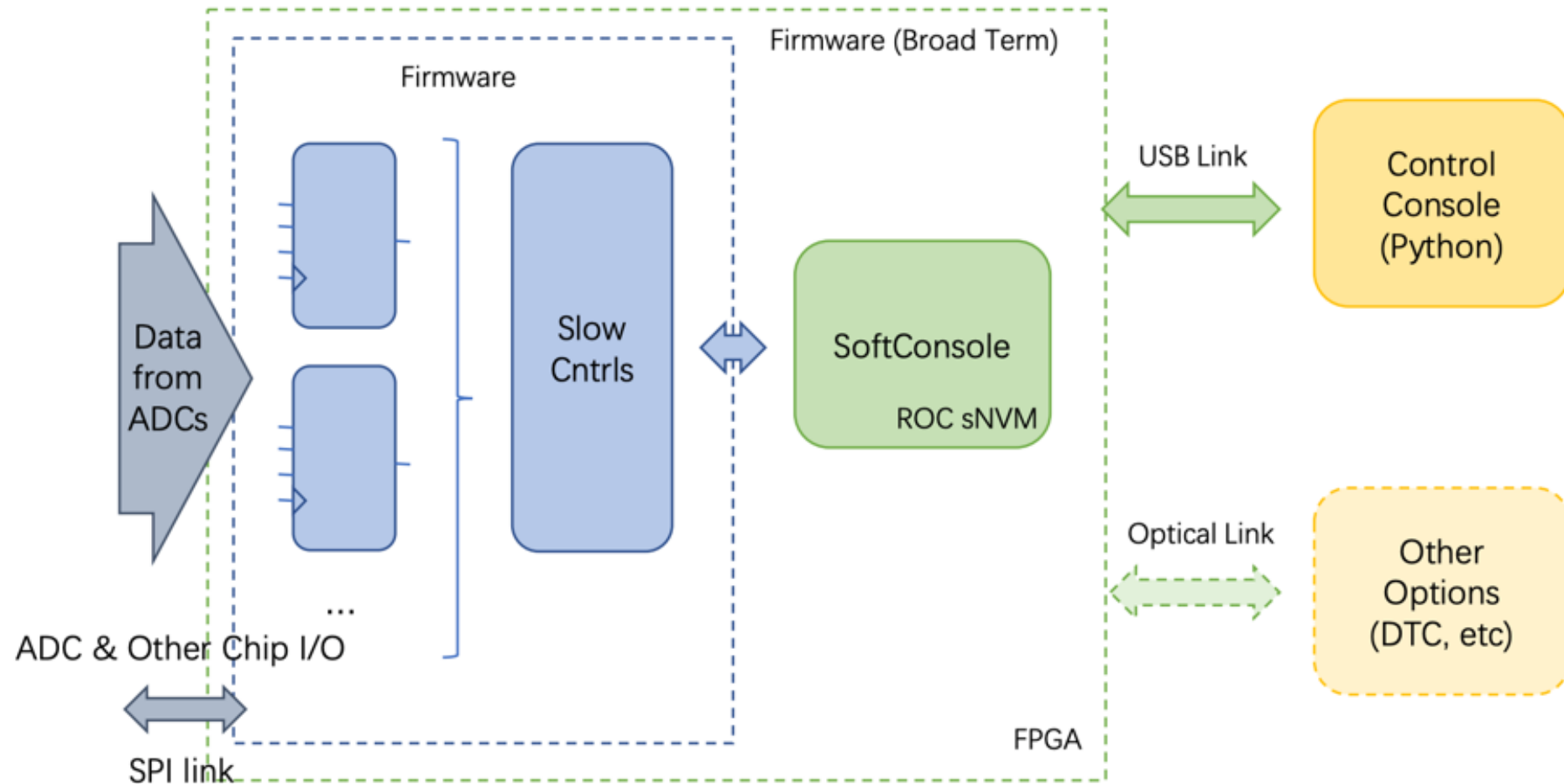
After Reco Acceptance+ ΔE +Resolution



OTHER FEE COMPONENTS



TEST COMMUNICATION SCHEME

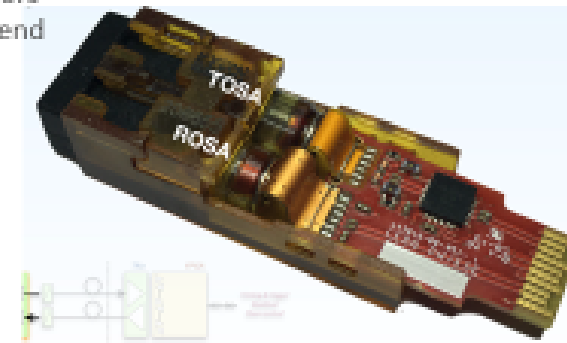


VTRx used in Mu2e tracker and calorimeter

- VTRx Background

- Rad-tolerant optical transceiver
- Developed at CERN for LHC
- 5 Gbps bidirectional
- Kick-off: 2008; Production: 2015 → 18K units
- Used by all LHC experiments & a few others (like Mu2e)

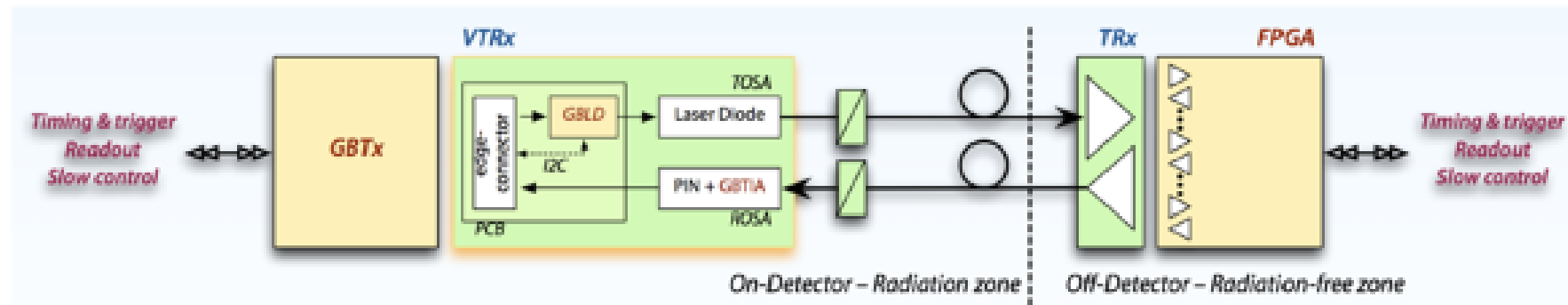
Fiber LC connectors
plug in from this end



Board connection
from this end

⇒ **Selected by Mu2e for Rad-tolerance**

TOSA: Transmitter Optical Sub-Assembly
ROSA: Receiver Optical Sub-Assembly



Pictures and graphics courtesy of Jan Traska, CERN

VTRx Issue (cont.)

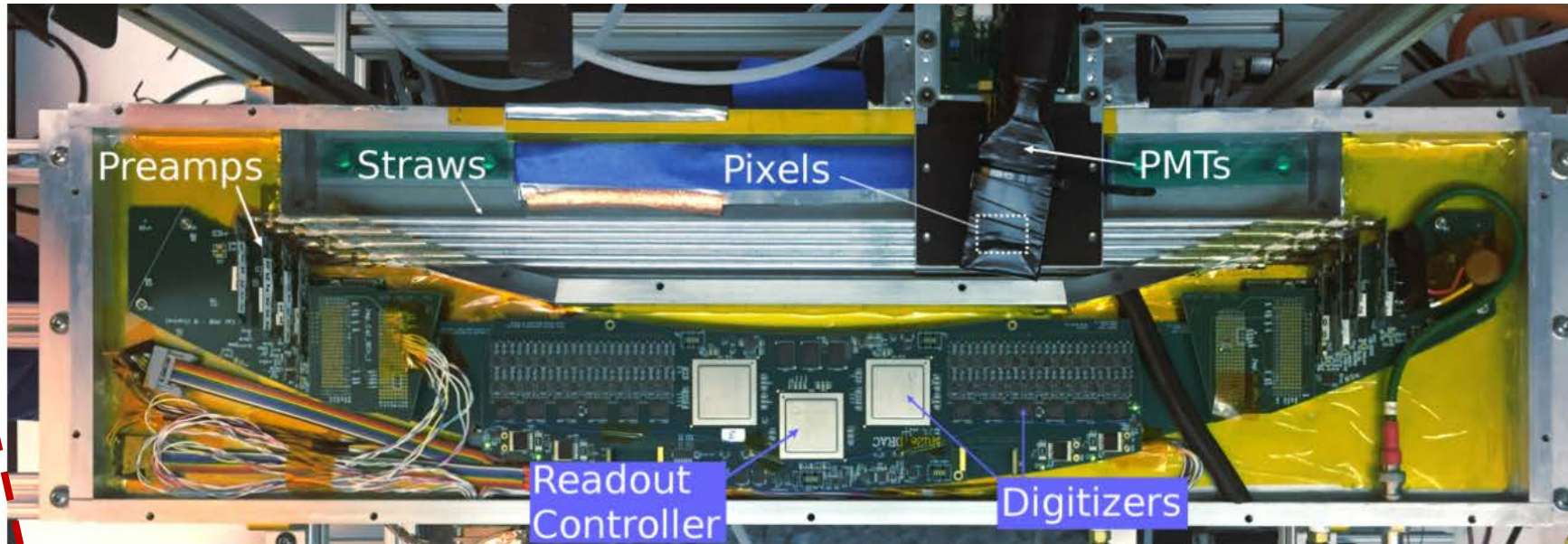
- Failures reported by several LHC experiments
 - Loss of received power
 - Measured by RSSI monitor (which we can do also...)
 - Often followed by link failure – Sometimes recoverable, sometimes not
- CERN convened a Task Force to study the problem in Feb., 2021
 - Epoxy outgassing due to residue on the LC connector was identified as the cause of failure
 - A mitigation plan to address this has been developed by CERN
 - Bakeout at 85C for 3 weeks
 - Mu2e is sending VTRx's to CERN and they will perform the bakeout and then test the devices in Aug/Sept.2021

⇒ ***Optimistic that the bake-out will fix the reliability problem***

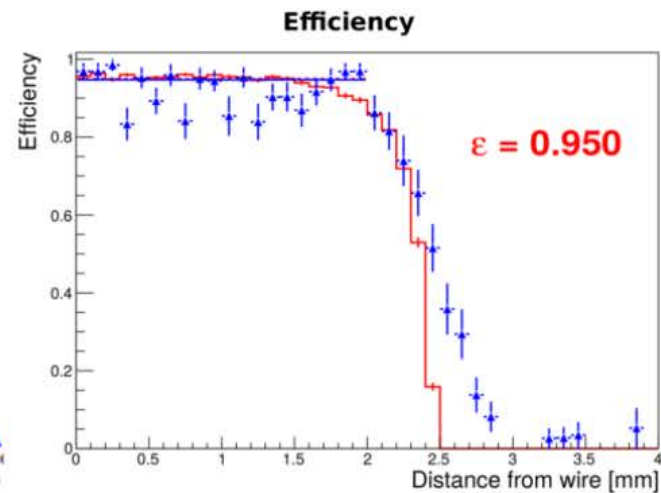
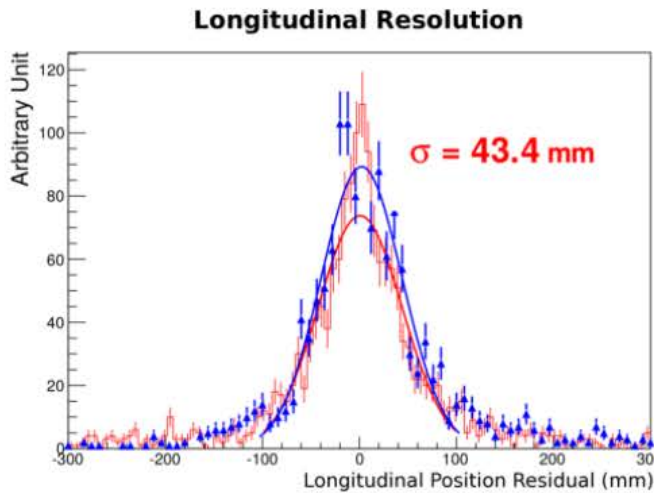
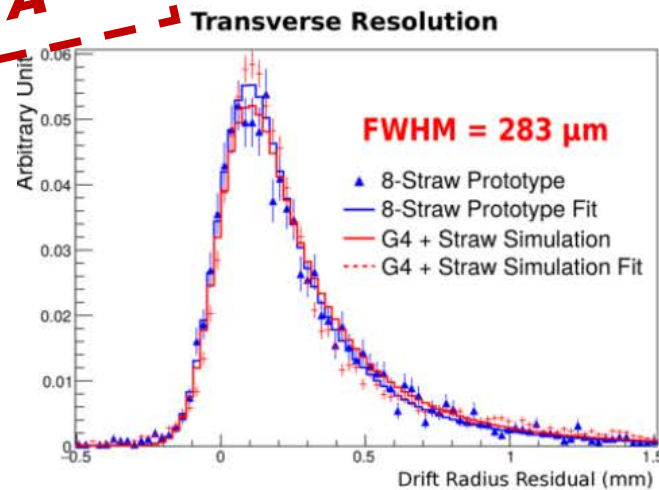
⇒ ***Mu2e will also need to address the cooling of the devices***

⇒ ***Operation in a vacuum***

DRIFT RESOLUTION AND EFFICIENCY

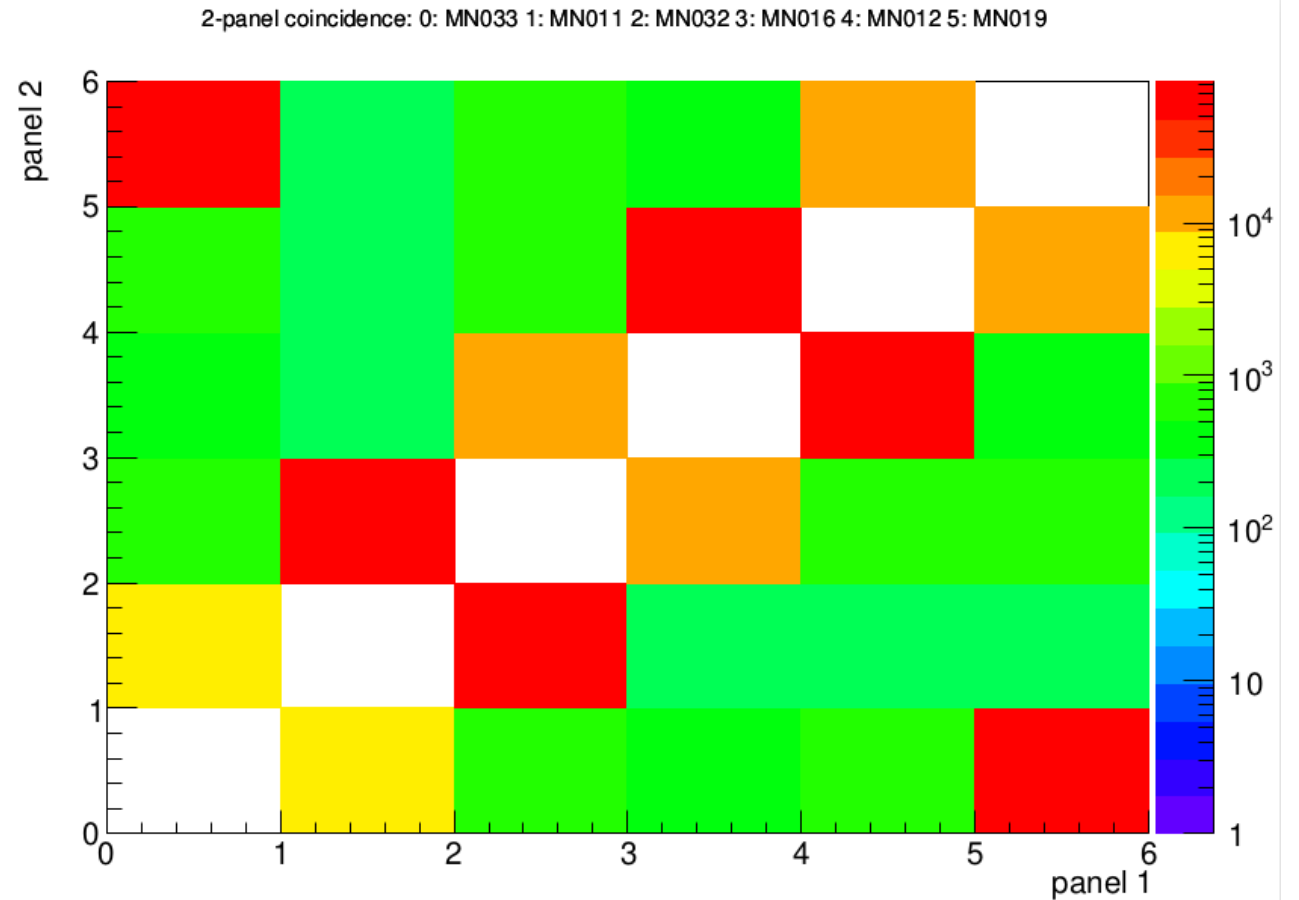
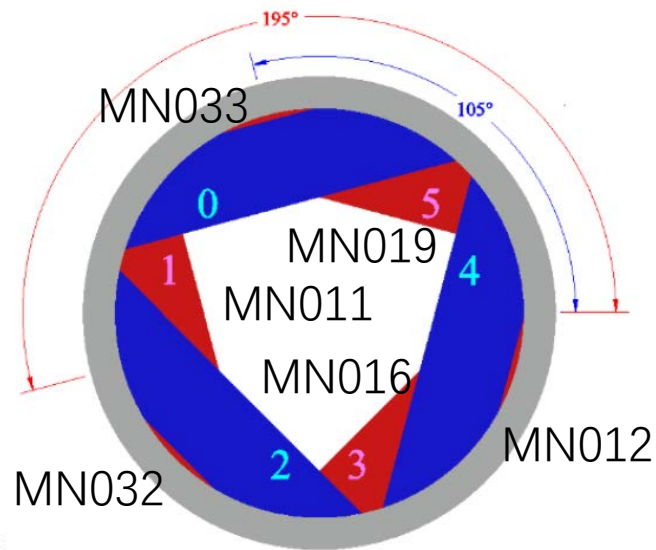


PROTOTYPE DATA



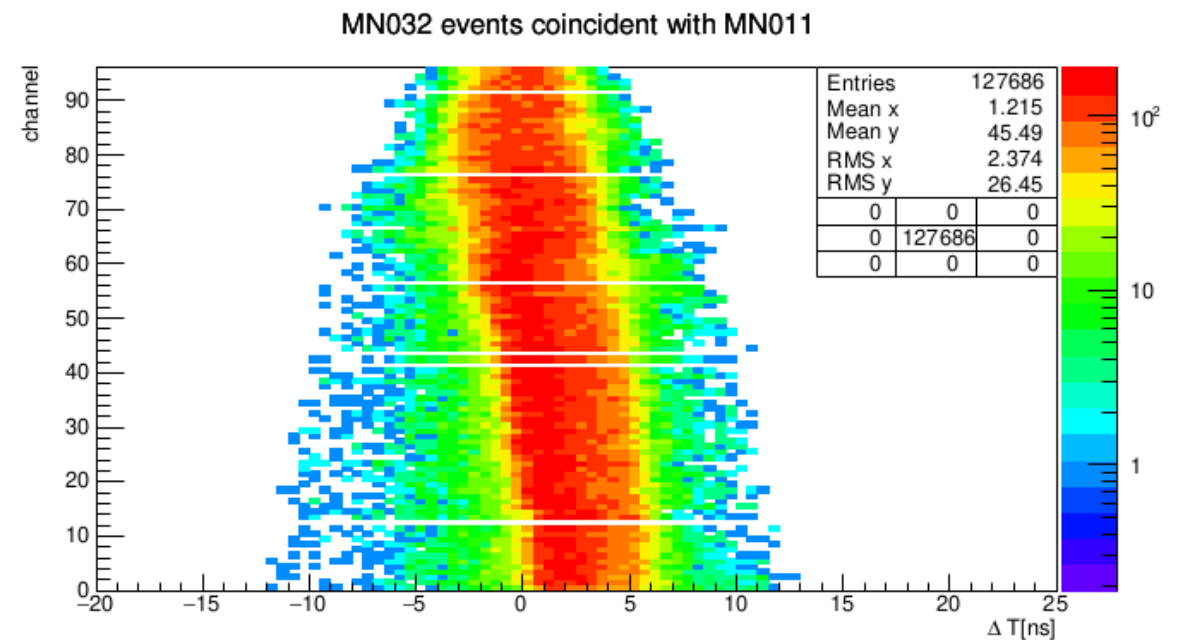
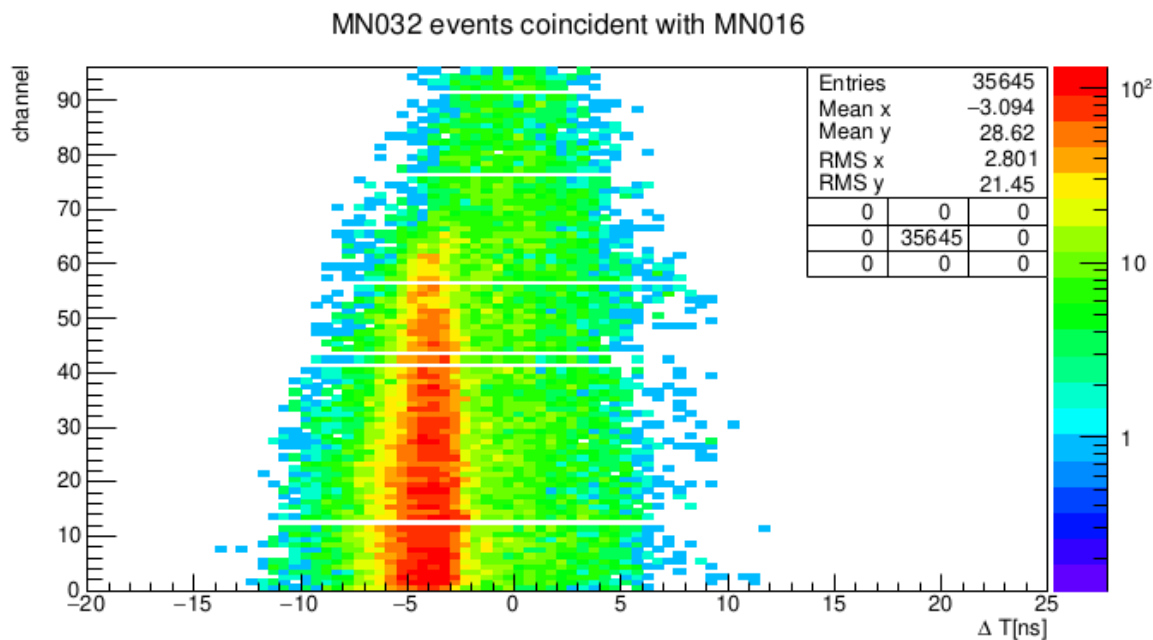
COSMIC DATA: COINCIDENCE EVENTS

- Using cosmic data taken with the plane in the horizontal position
- Staggering pattern of rate in the 2-panel coincidence matrix reflects the level of overlap between panels.

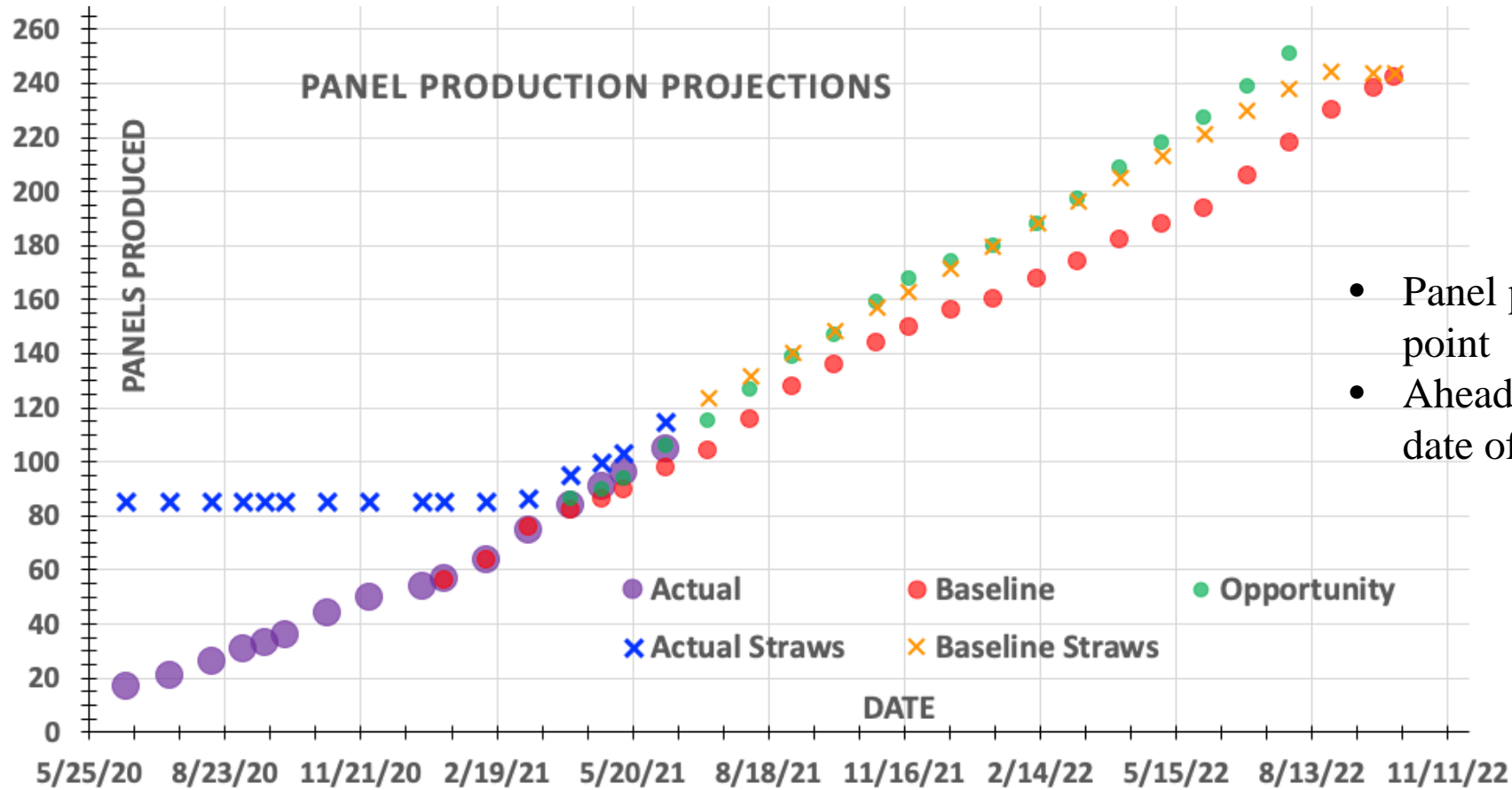


TIME DIVISION IN COINCIDENCE EVENTS

- Time division between two ends of the straw provides information on hit position. Triggers in coincident with the neighboring channel are clustered in the overlapping area as expected.



PANEL AND STRAW PRODUCTION



- Panel production over half point
- Ahead of baseline completion date of November 2022