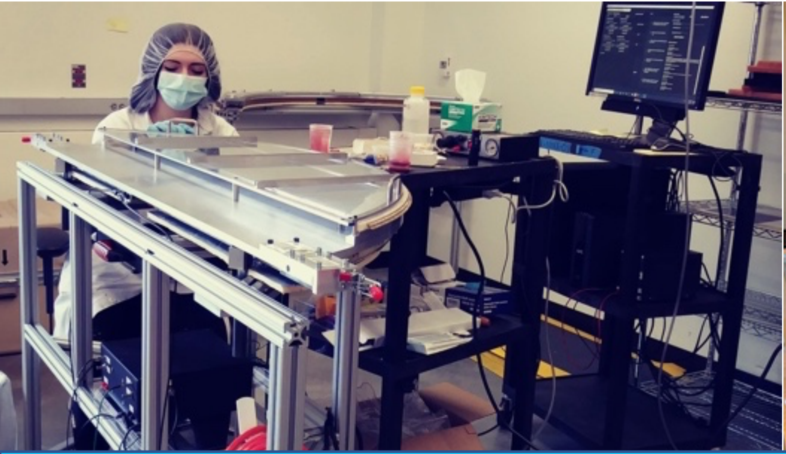
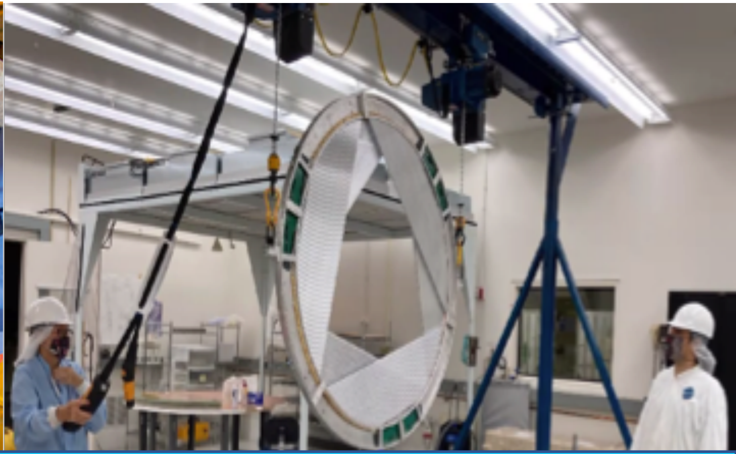




# Mu2e Tracker Construction and Mu2e-II Tracker Opportunities

**Dan Ambrose**

**University of Minnesota**

**On Behalf of Mu2e and Mu2e-II Collaborations**

**CPAD Instrumentation Frontier Workshop 2021**

**Mar 18-22, 2021**

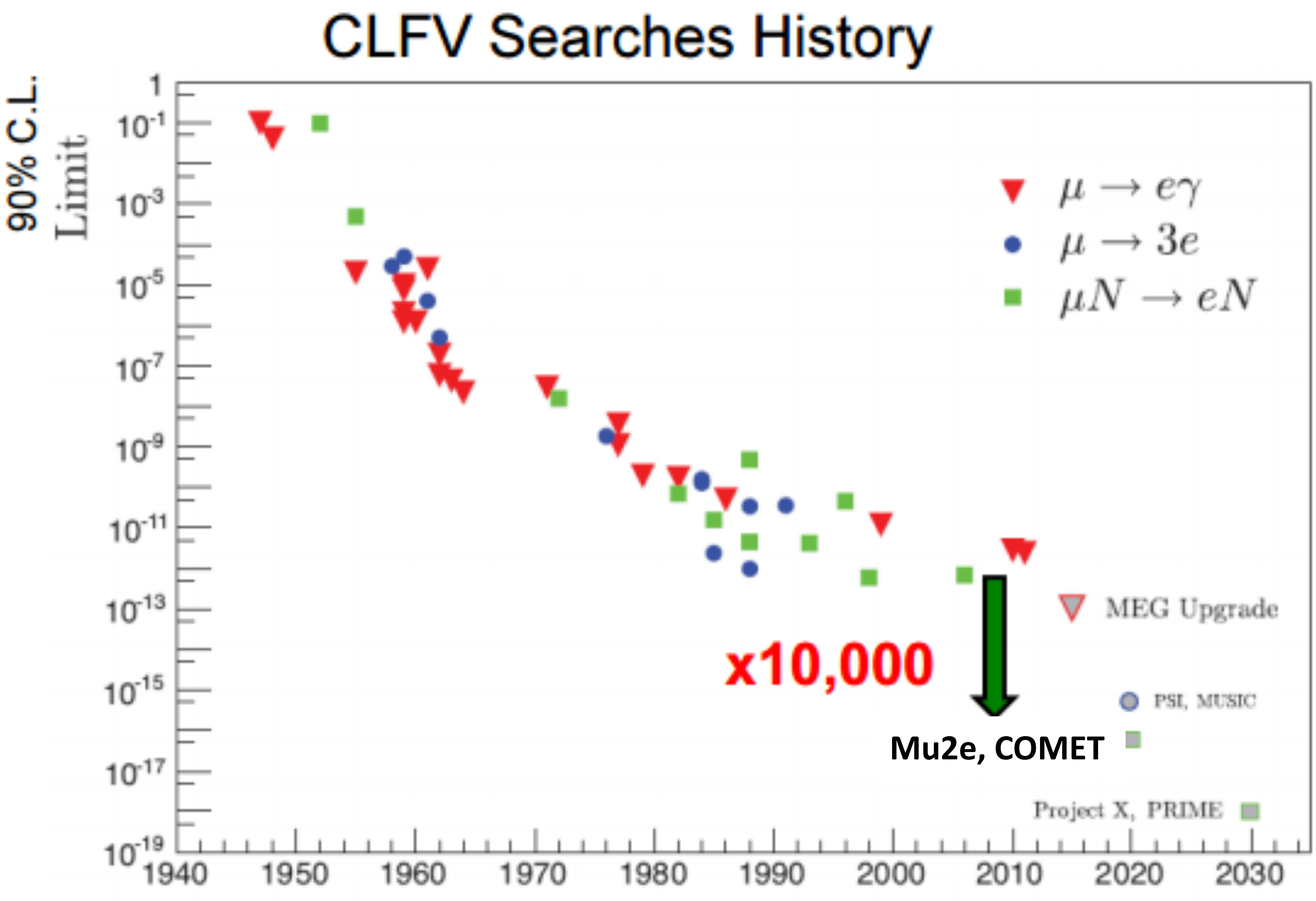
# Introduction

**Brief Overview of Mu2e Experiment**
**Low Mass Drift Tube (Straw) Electron Tracker**
**Building the Tracker**
**Tracker Component Performance**

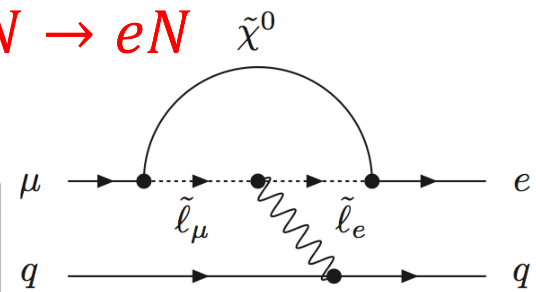
**Mu2e-II Tracker Requirements**
**Possible Designs**
**Opportunities for detector improvement**

# Mu2e's Concept

## μ → e in the presence of a nucleus




R. H. Bernstein & P. S. Cooper, Phys. Rept. 532 (2013) 27

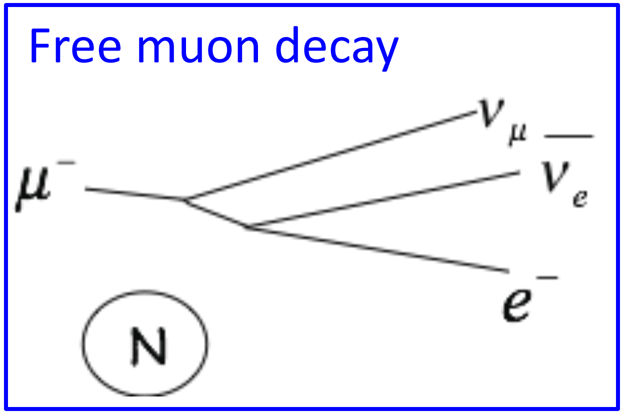


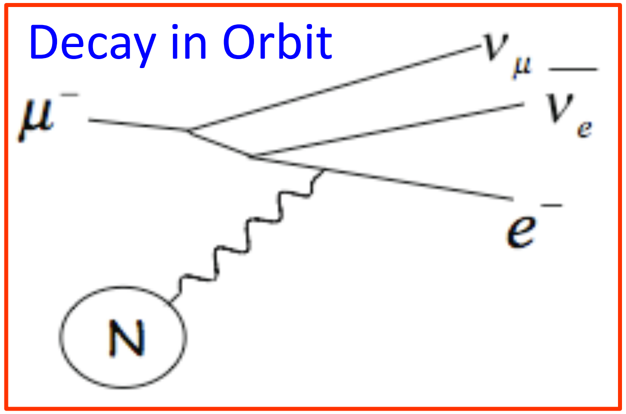

**Charge Lepton Flavor Violation (CLV): neutrinoless muon conversion into an electron in the presence of an aluminum nucleus.**

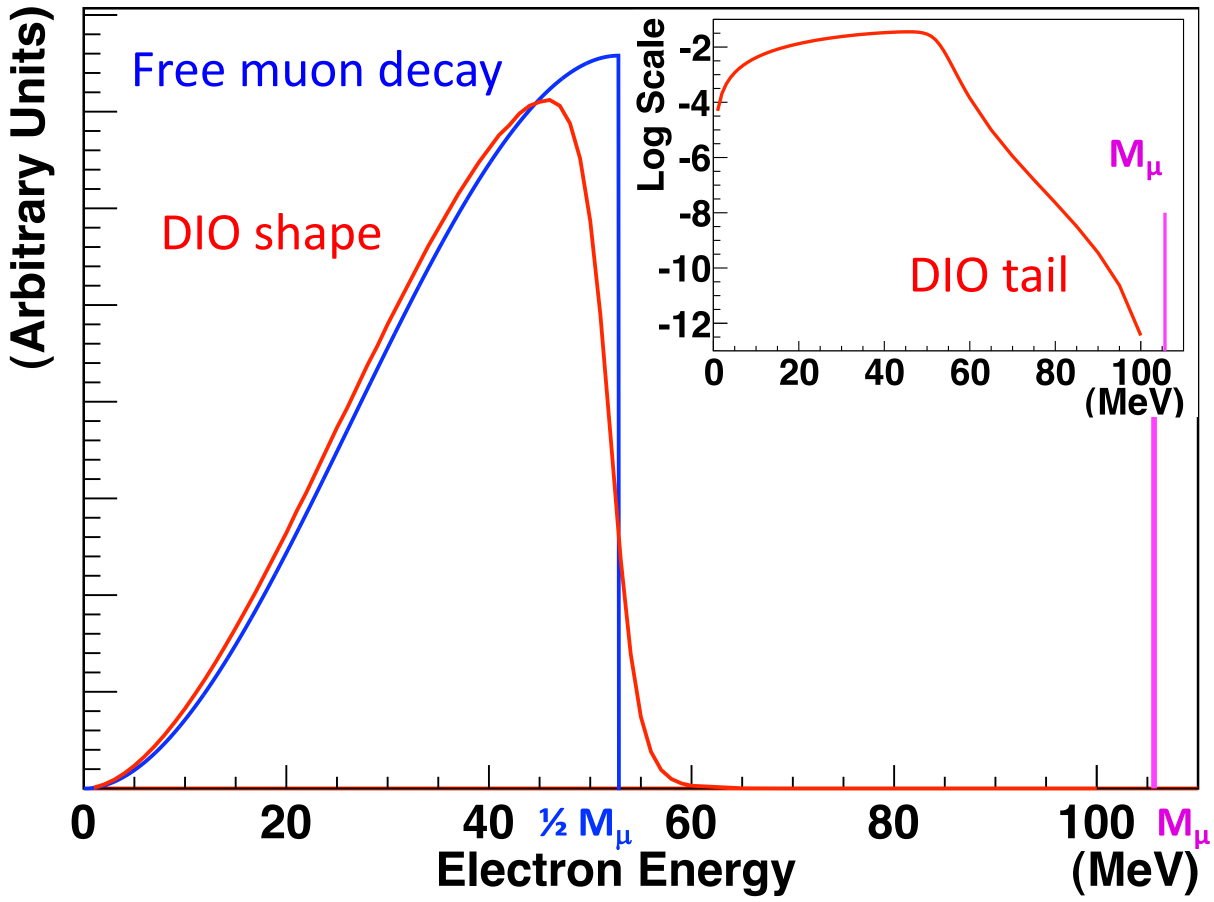
**Standard Model estimate ~$10^{-54}$**

**Any observation is a clear sign of new physics**

# Muon Decay in Atomic Orbit: Electron Energy Spectrum

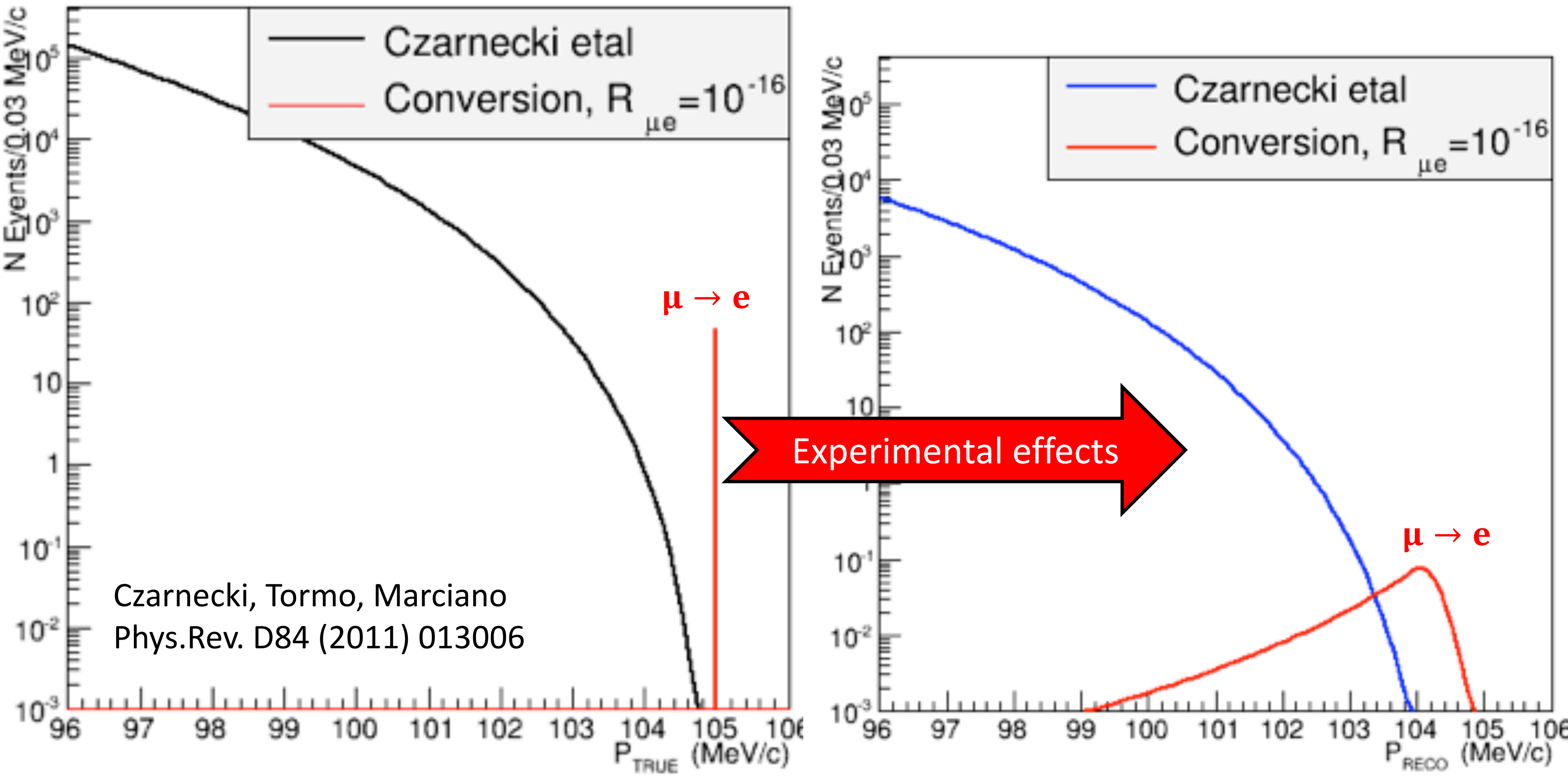


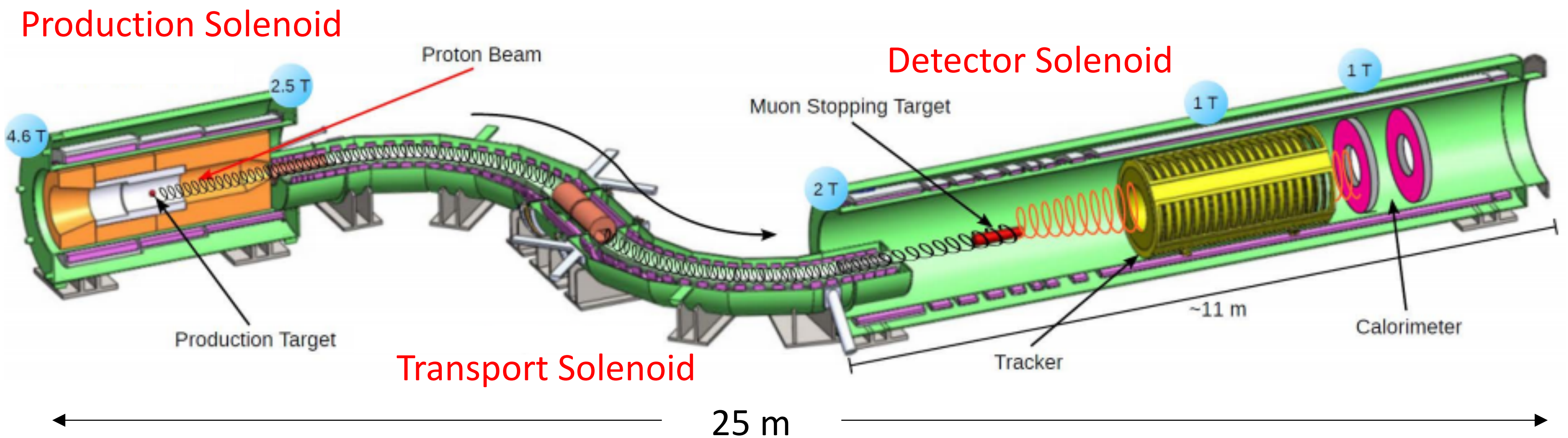



# Experimental Resolution Affects DIO electrons

- **Tail of DIO falls as $(E_{Endpoint} - E_e)^5$**
- **Separation of ~few 100 keV for $R_{\mu e} = 10^{-16}$**



# The Mu2e Experiment




**Mu2e experiment consists of many technically demanding components.**

- **High intensity**
- **Precise high magnetic fields**
- **Vacuum**
- **Production target**
- **Stopping target**

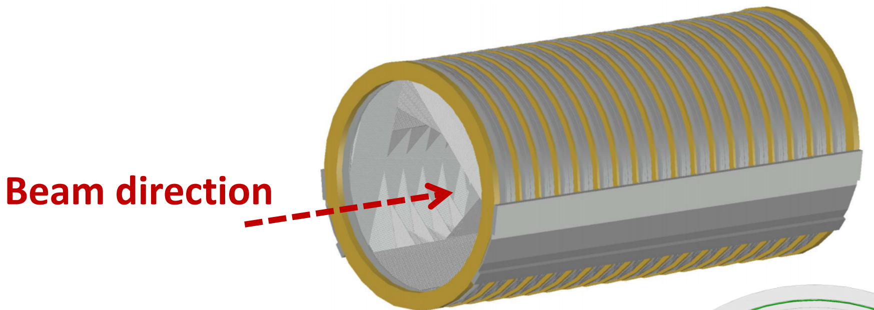
**The calorimeter in CPAD talks:**
**Calorimeter crystals: Ren-yuan Zhu**
**Calorimeter readout: David Hitlin**

**This talk focuses on the tracker which measures the electron trajectory in a 1T magnetic field.**

**A momentum resolution better than 180 KeV/c**

# Tracker Requirements

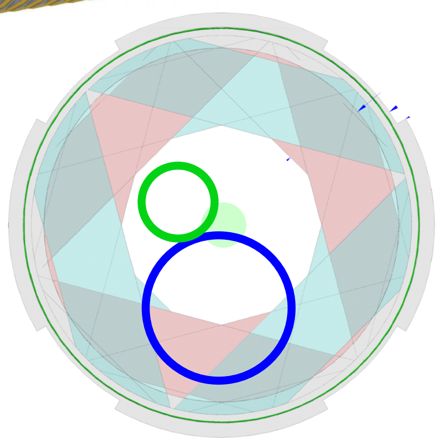
- **Electron momentum resolution: < 180 keV/c at 105 MeV/c**
- **Efficiency for acceptance and reconstruction of 105 MeV/c electron tracks: >20%**
- **Outgassing rate :< 6 sccm (standard cubic cm per minute)**
- **Hit rate: > 5MHz/channel, 500 ns after proton bunch hits production target**
- **Access : < once per year**
- **Operation time: > 10 yrs**




## Solution

**Straw drift tubes measure track curvature through a 1 T magnetic field.**

- **High segmentation to minimize occupancy**
- **Very thin wall to minimize multiple scattering**
- **No support structure in tracking region**
- **High radiation survival (structure & electronics)**



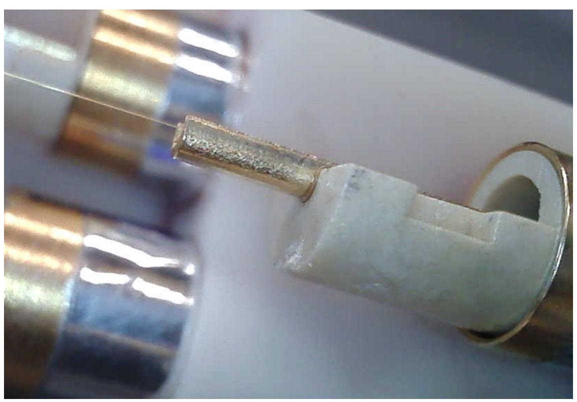
**Beam's-eye view of Tracker**

# Tracker Components: The Drift Tubes

**Spiral wrap seams**

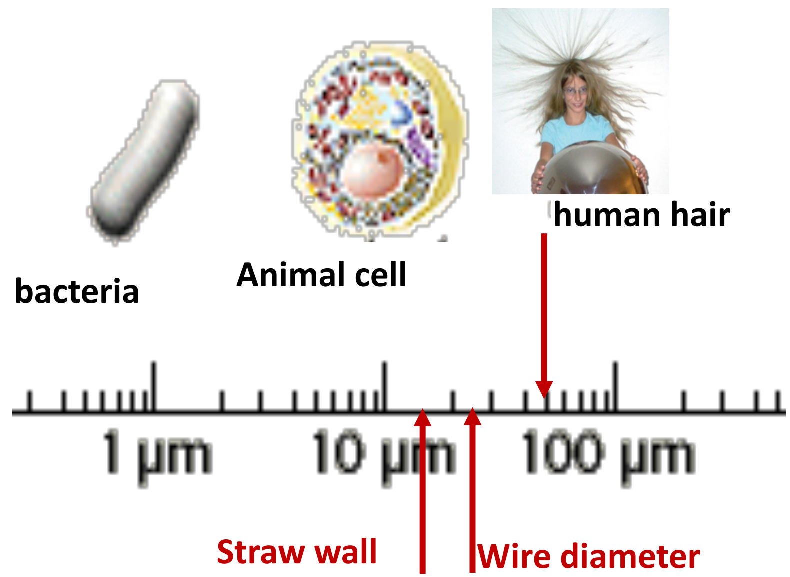
**Two layers of Mylar are wound together to produce straws**

- **Detector has 20,736 straws**
- **6 μm Mylar + 3 μm adhesive + 6 μm Mylar double helical wrap**
- **5 mm diameter**
- **Lengths: 45 to 120 cm**
- **Inner wall coating: 500Å Al + 200Å Au**
- **Outer wall coating: 500Å Al**

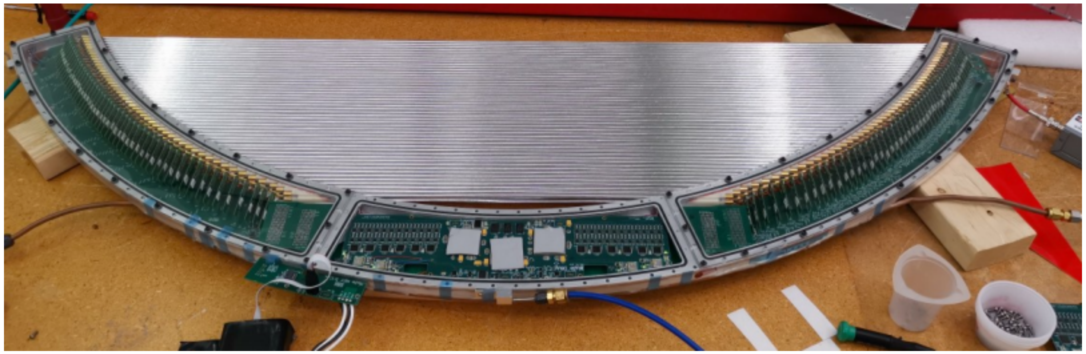


**Gold plated Tungsten Sense Wire**

- **25 μm diameter**



# Base tracker unit



1 panel = 96 straws

**Harp structure**

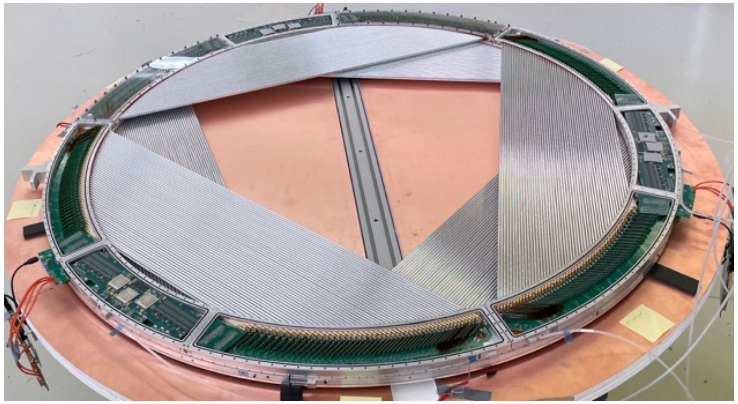
harpnotation.com

## Panel is smallest self-contained unit of the detector

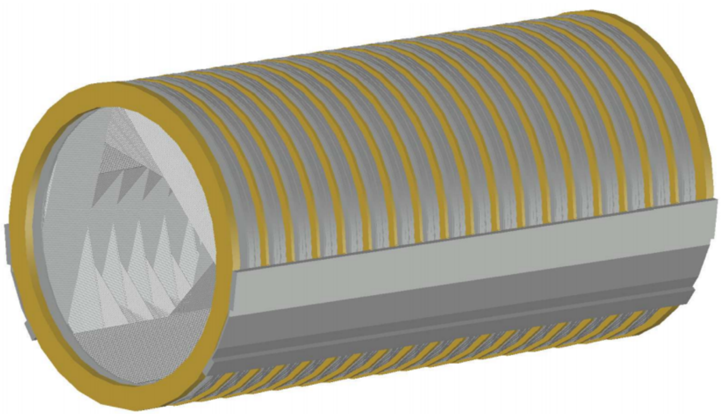
- Detector has 216 identical panels
- 120º arc
- Detection region has only straws, sense wire, and Ar/$CO_2$ gas.
  - Straws held at tension (initially 750 gf) at their ends with no additional support
- Gas manifold holds the electronics.
- Support structure built of Aluminum, 3D printed plastic, and epoxy.

# Drift Tube Tracker

**6 panels are bolted together to form a plane**



**1 plane = 6 modules**



**Tracker = 36 planes**

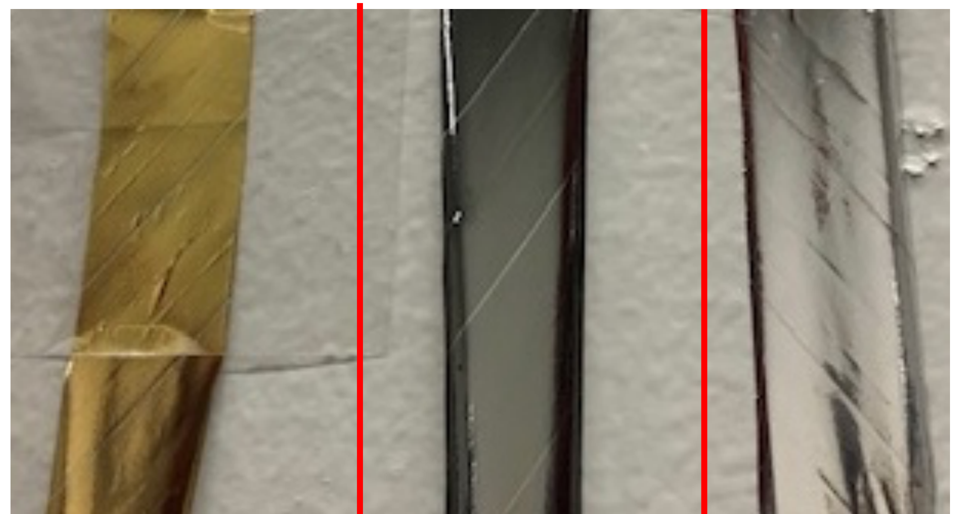
- **Planes are supported in the tracker frame.**
- **Bronze radiation shielding rings between each set of two planes.**

# Straw Material

- **Outside layer: 6μm mylar with a deposition of 0.05 μm of Aluminum.**
- **Inside layer: 6μm mylar & 0.05 μm of Aluminum with a deposition of 0.02 μm of gold on the Aluminum.**
- **Depositing Gold on Aluminum over time leads to the formation of a Gold/Aluminum Intermetallic.**

**Decreases inside conductivity but does not affect performance**

**Inside** | **Inside** | **Outside**



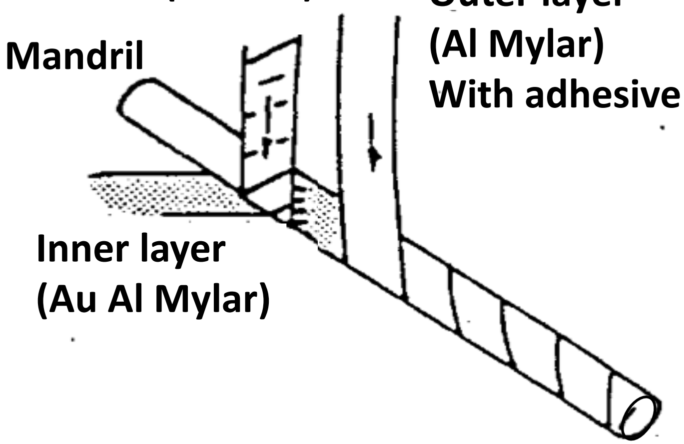
**Gold on Aluminum No mixing** | **Gold/Aluminum Intermetallic** | **Aluminum No gold**

# Straw Winding

**Used a company that makes drinking straws that adapted their spiral winding technique to make our straws.**

**On site QC actively monitored :**

- **Seam Widths**
- **Wall/Adhesive Thickness**
- **Conductivity**
- **Gas leak rate**




**Shipped bundle of 24 straws**

**Bundles ready to assemble**

# Straw Assembly by Students

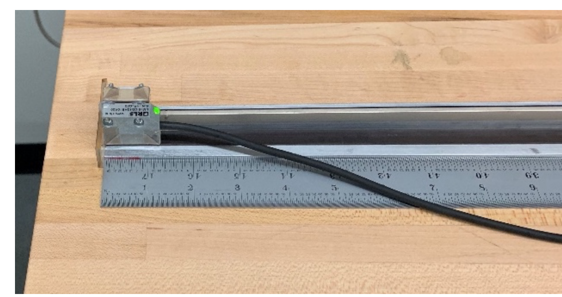
**Paper Removal**

**Conductivity Test**

**$CO_2$ Leak Test**

**Laser Cut to length**

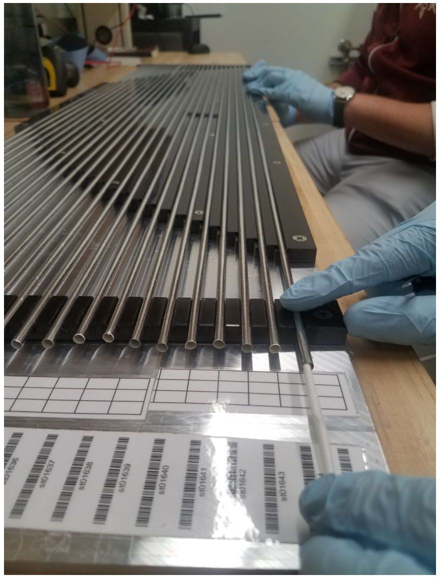
**Insert Terminations**



**Length Verification**

# Straw Handling in Pallets

**Straws travel through the processing in special pallets to keep them safe.**



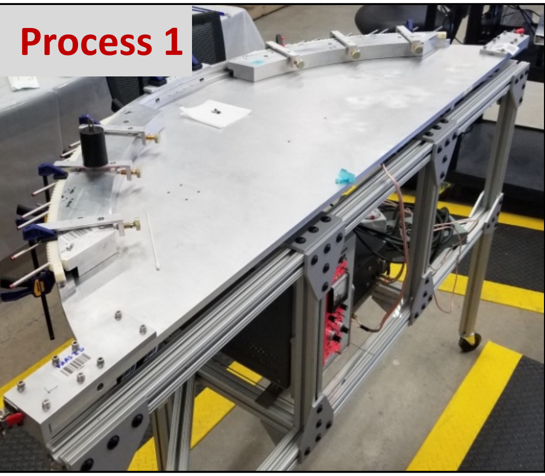
**Straw tubes in cutting pallet before cut to length using a programmed laser cutter.**

**Stored straw tubes cut to length in storage pallets**

**Fully assembled straws stored in a pallet**

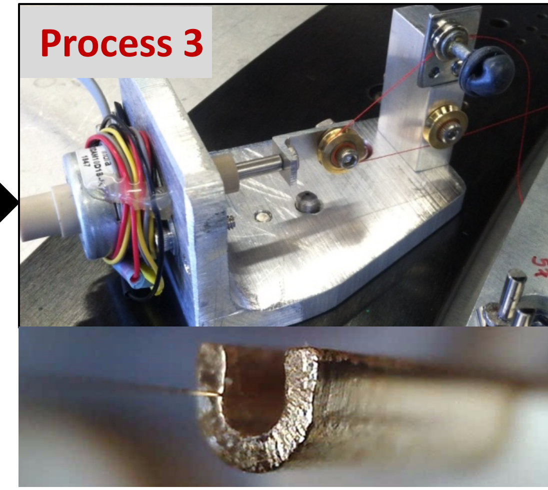
# Building the Panels

# Panel Building Process by Students

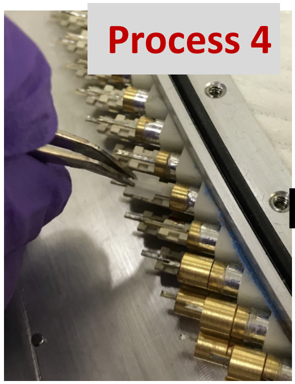



**Inner Ring Building (2 days)**

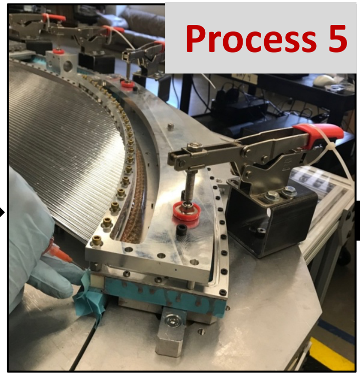

**Straw Installation (1 day)**



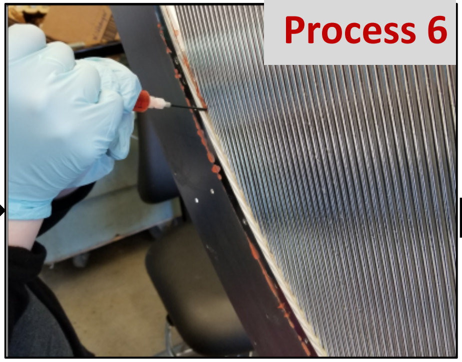

**Wire Installation (3 days)**



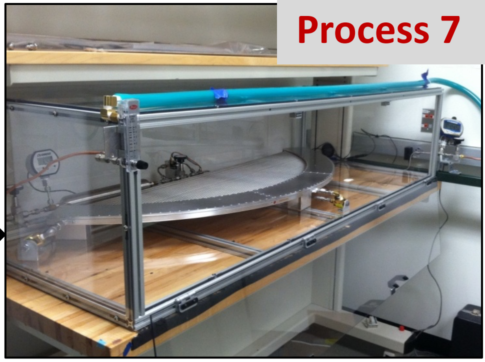

**Pin Protector & Ground Clip Installation (1 day)**




**Manifold Installation (1 day)**




**Alcohol Leak Check and Flooding (2 days)**




**Resistance Check & Leak Test (3 days)**

# 3D Printed Inner Ring

**Inner ring that holds the straws was 3D printed.**

**This allowed for epoxy injection holes in places they could not be installed being machined.**

**Material was picked for its radiation tolerance and a thermal expansion similar to aluminum, which the rest of the manifold is made from.**

**Parameters outside tolerance and slight warping in some of the pieces have created some additional work for panel alignment.**

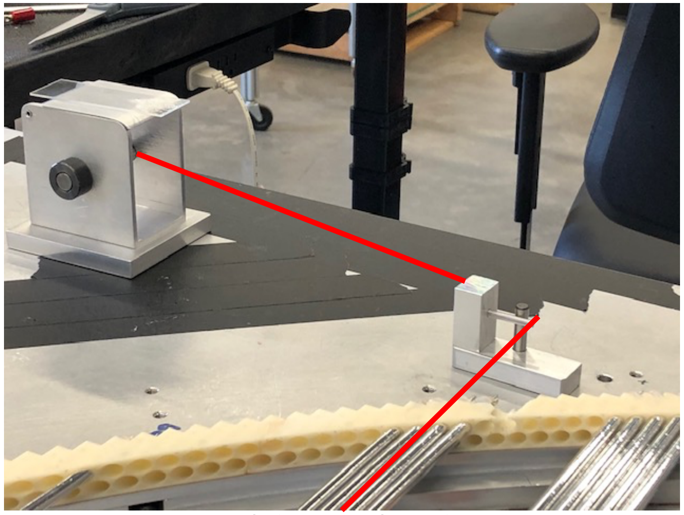
# Sense wire installation

**The sense wires are installed horizontally into the panels.**

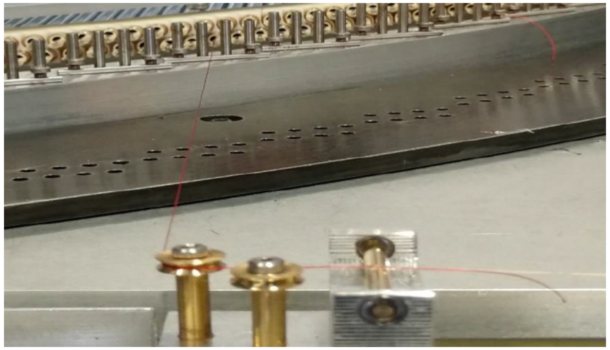
**This is done by blowing a string through a straw, attaching the wire to the string and pulling it through.**

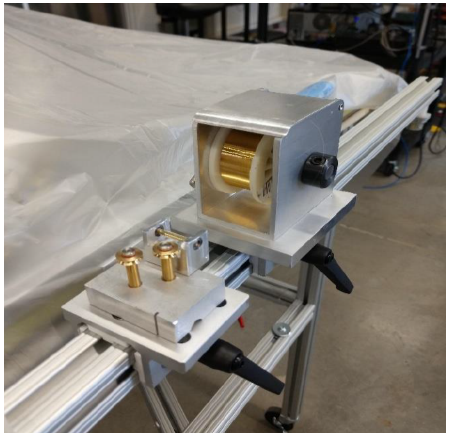
**Early prototype panels saw large dark current which corresponded to hot straws when testing electronics.**

**It was determined wire contact with dowel pins and alignment combs caused the wire to show high current.**



Old Method

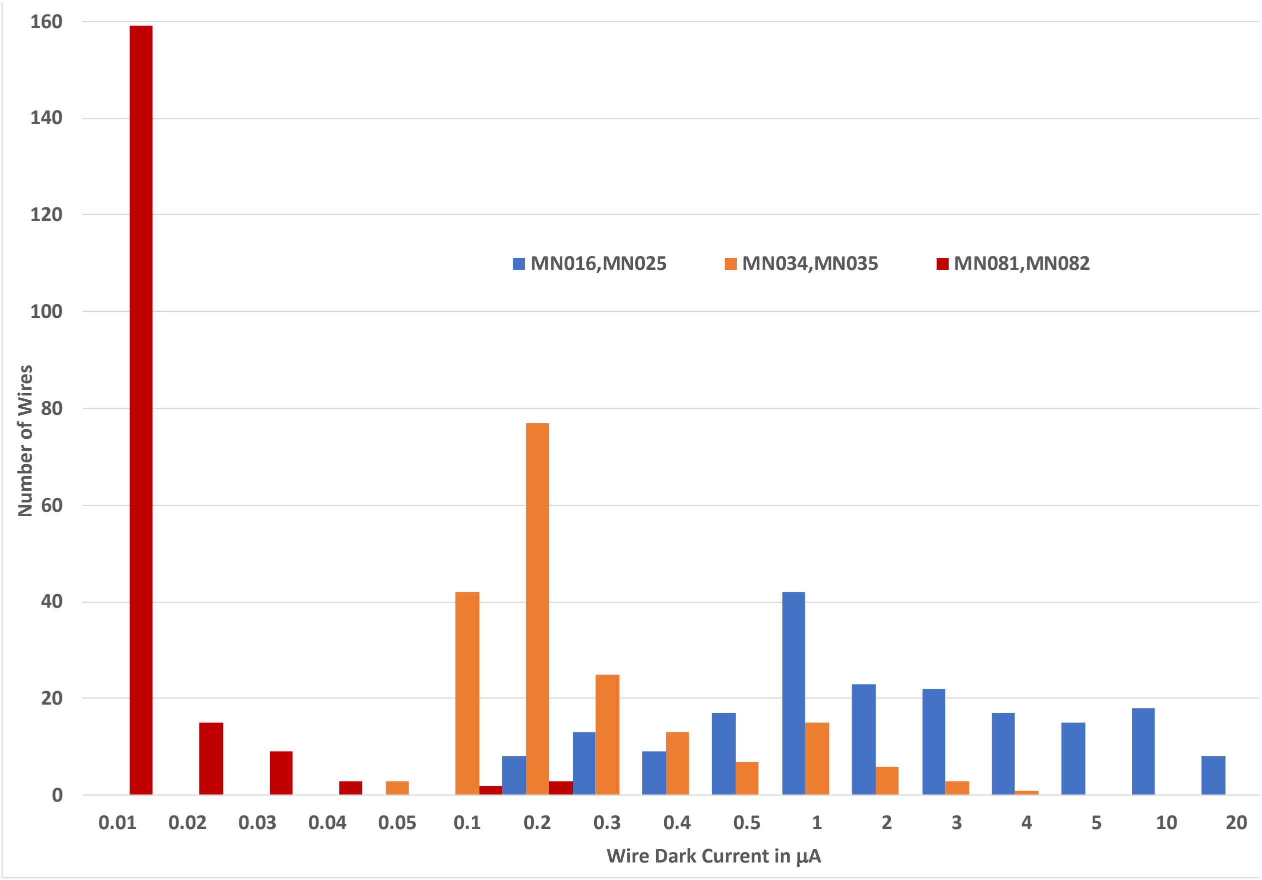




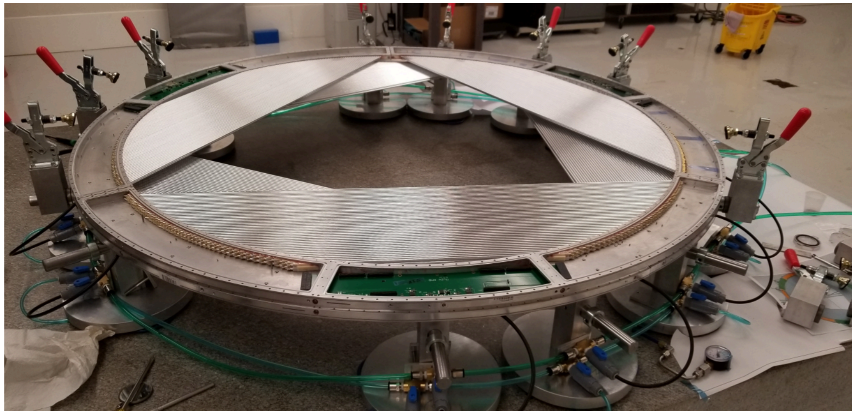
New Method

# Dark Current in Wires

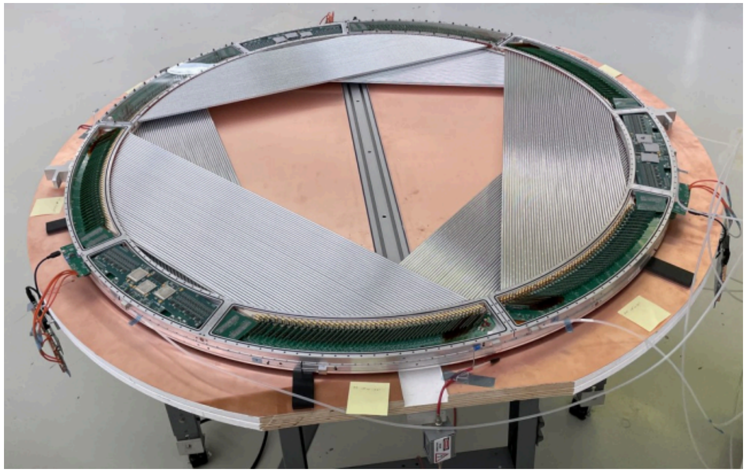
**Reduction of dark current in almost all straws allowed us to identify and replace any bad wires which would have otherwise gone unnoticed until electronics were installed.**



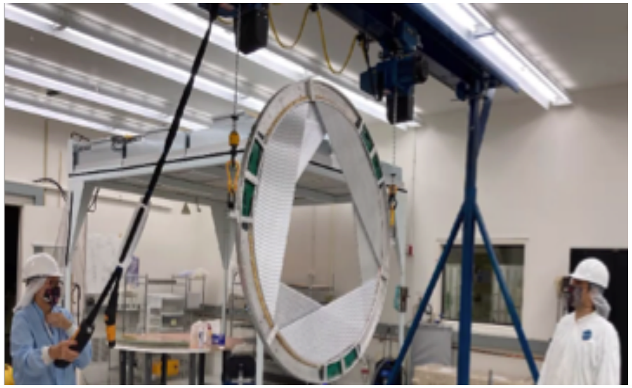
# Building the Tracker at Fermilab

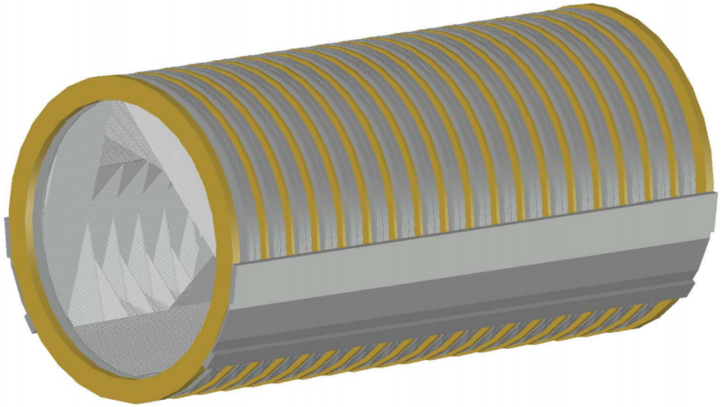


Planes Constructed



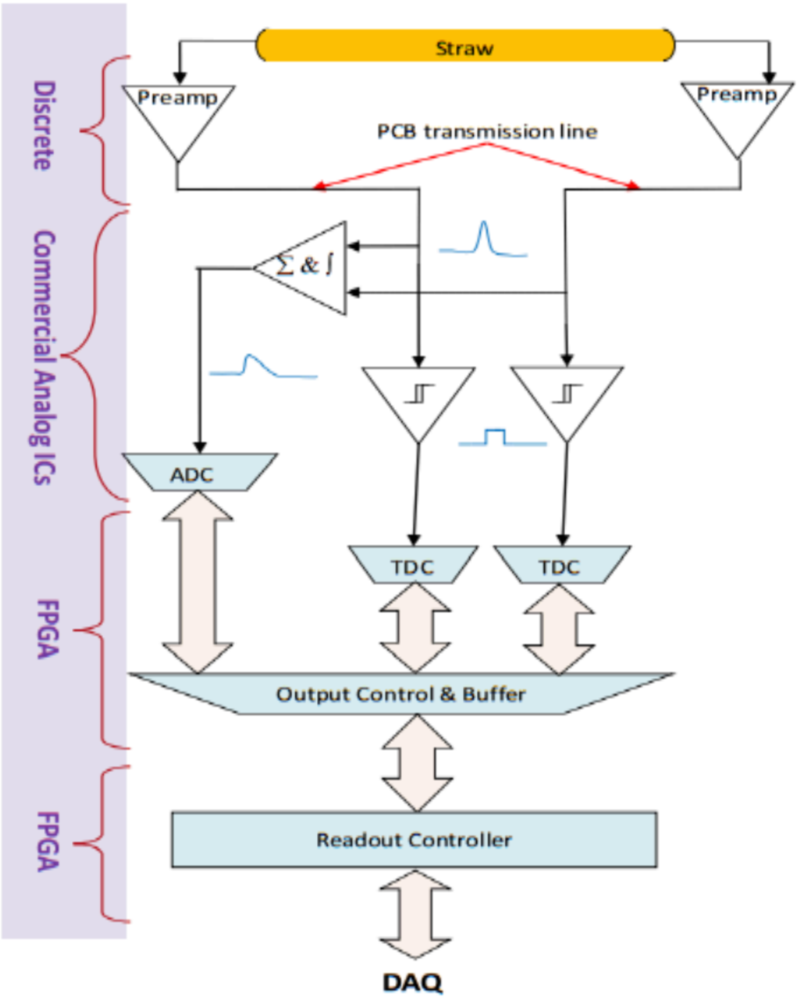
Electronics installed

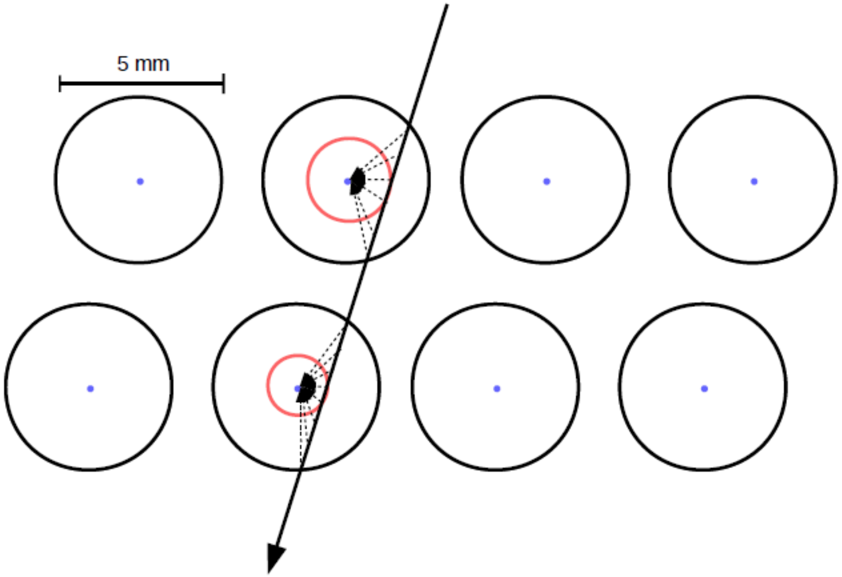


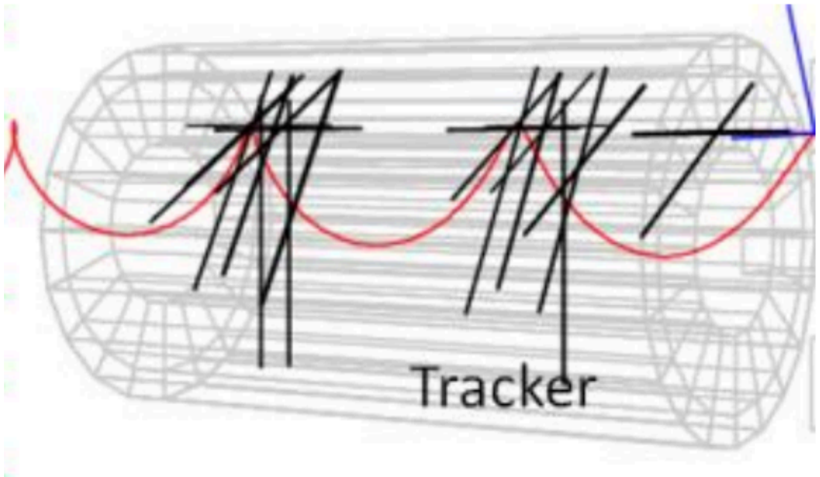


Planes then installed into detector train

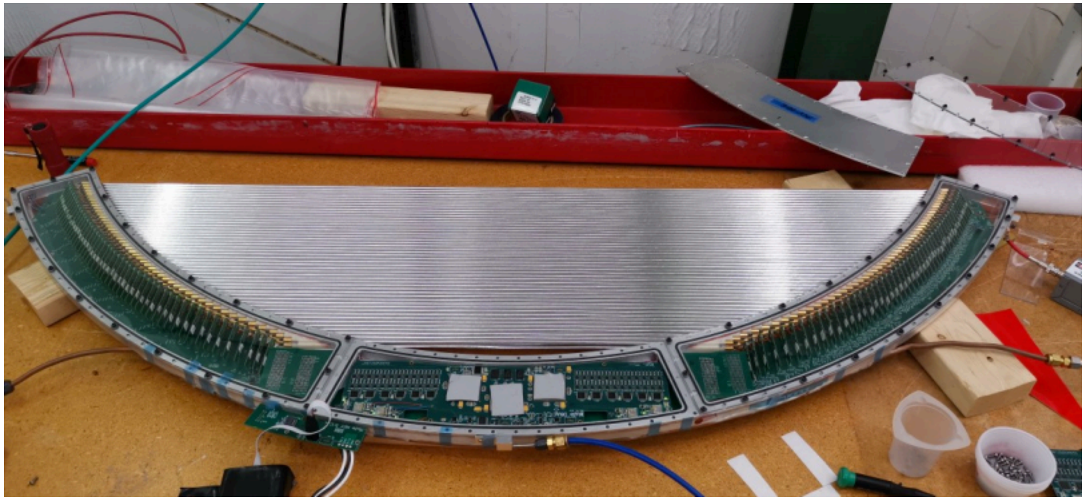
# Drift Straw Tube Operation

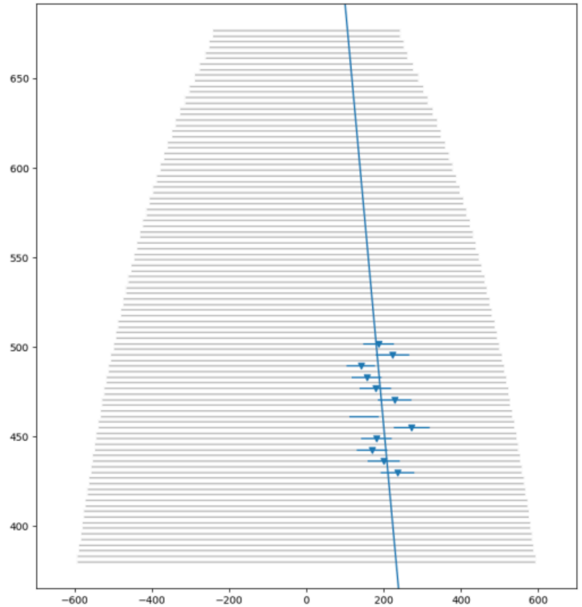


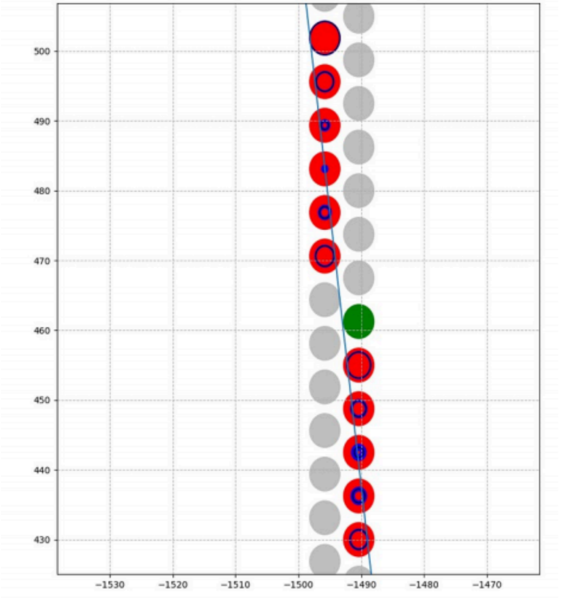



# Successes in Detector Production






Cosmic Ray single panel testing was successful, providing nice straight tracks.

Demonstrated stable gain across many channels using Fe55.

Similar work is currently being done with a full plane.

# Mu2e-II Experiment

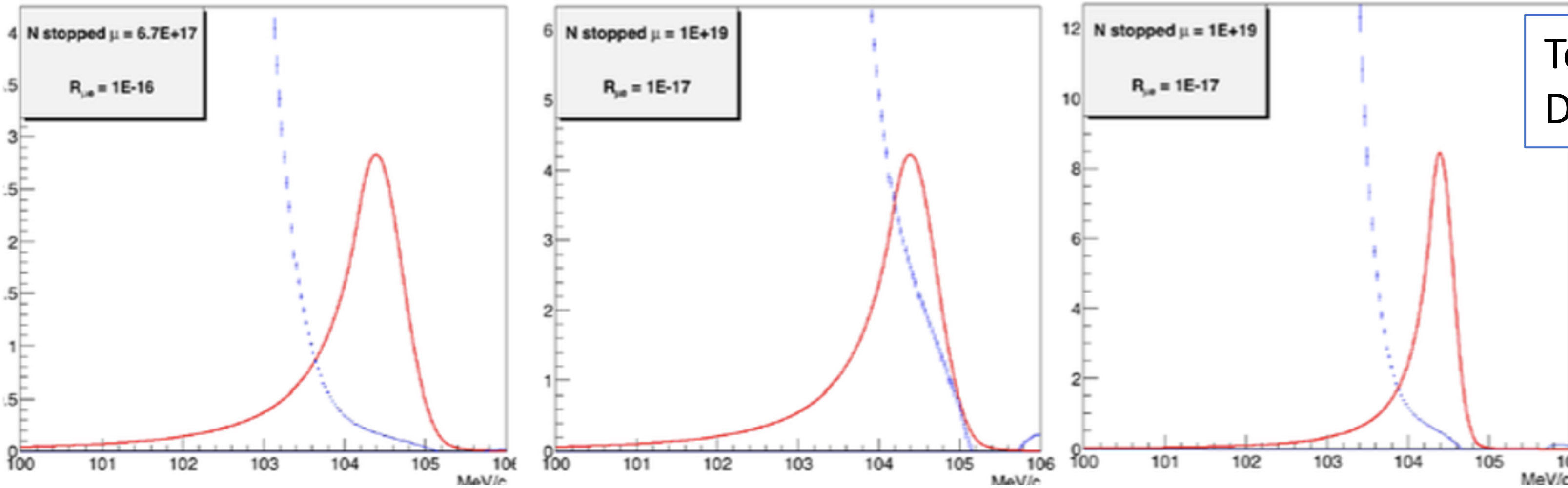
**Mu2e-II is the proposed upgrade to the Mu2e experiment.**
**The exact extent of the upgrade has not been finalized, but current aims include:**

- **At least 10x measurement sensitivity increase ($10^{-18}$ level)**
- **Possible different material for the stopping target (Titanium)**
- **Continue to use as much of the Mu2e components as reasonably possible**
  - **Tracker must be improved**

**Timeframe -**

- **Starts about 2 years after Mu2e ends ( ~2028 - 2030)**
- **~3 years of data taking at full intensity**

# Mu2e-II Tracker Requirements




Toy MC
D. Brown

**Mu2e Rate and Background**

**Mu2e-II Rate and Background**
**With Mu2e Tracker**
**(15 μm wall straws)**

**Mu2e-II Rate and Background**
**With Lower Mass Tracker**
**(8 μm wall straws)**

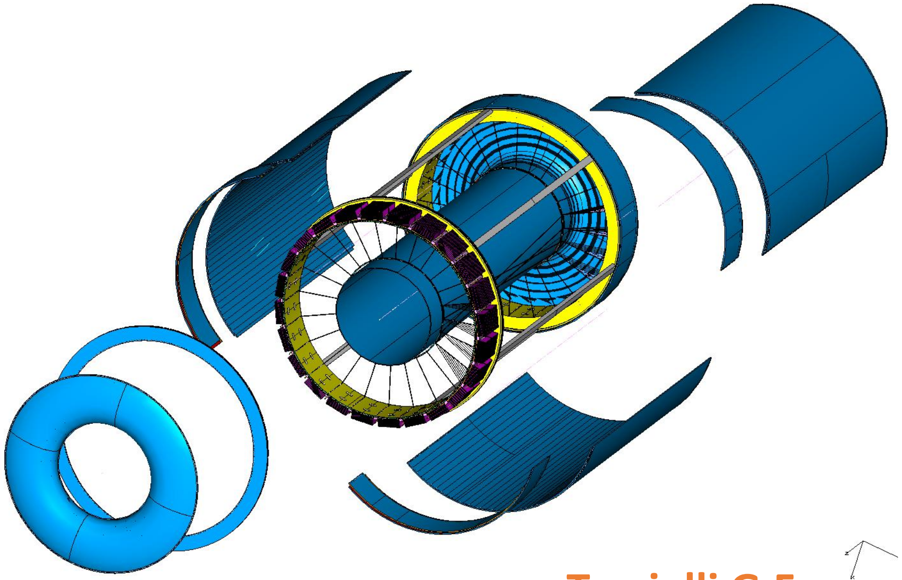
- **Lower mass**
  - **To meet Mu2e-II momentum resolution/background separation goals**
  - **Looking into :**
    - **Thinner straws**
    - **Different Geometry and technologies**
    - **Different gas**
- **Increased hit occupancy and timing window**
  - **4x increase in Proton bunch intensity is estimated to reduce reconstruction efficiency by 30%**

# Other Mu2e-II Tracker Design Options

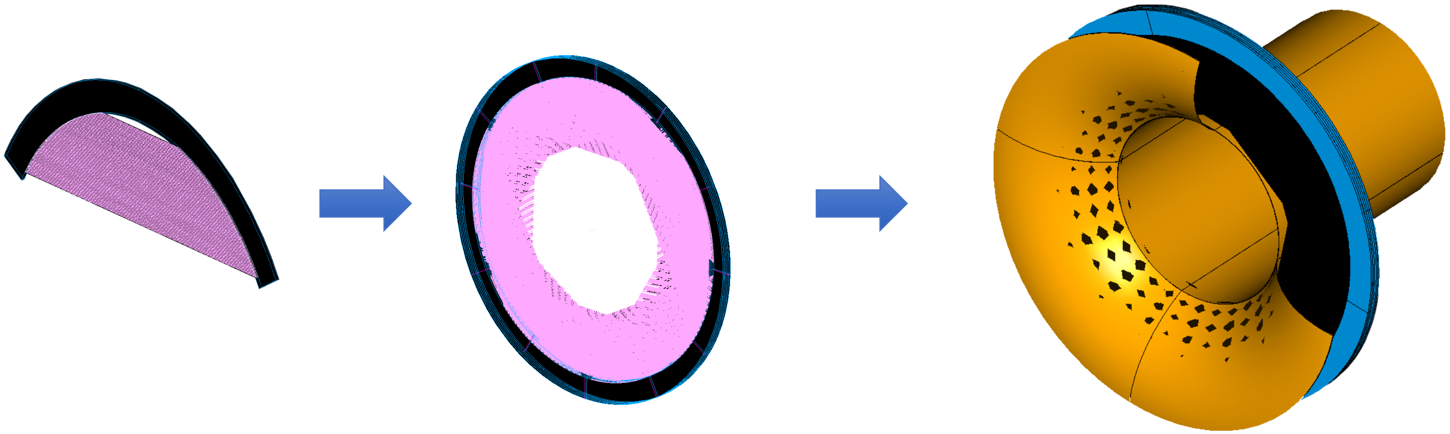
Researching possibility of other geometries or drift chamber designs which could improve resolution.

Exploring construction technique of high granularity and high transparency Drift Chambers as used for MEG-II.

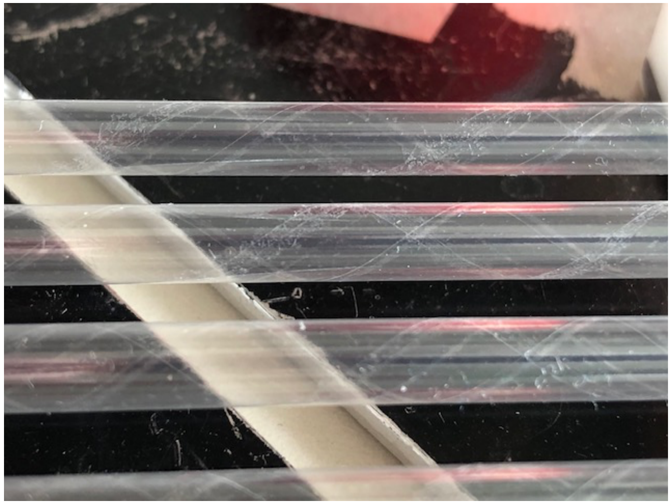
Wired drift chamber can be designed in such a way that much of the Mu2e layout can still be applied.



Tassielli G.F.



# Prototype Straws



**Pressurized 8 $\mu$m Mylar Straws**

**8 $\mu$m Mylar Straw**

**We returned to our straw winder and worked with them developing even thinner straws. Using 3.5 µm Mylar + 1 µm adhesive + 3.5 µm Mylar double helical wrap we were able to make 8 $\mu$m Mylar Straws.**

**These straws held 15 PSI for multiple days and 400 g Tension without visible distortion.**

# Handling Prototype Straws

**Handling the 8 $\mu$m straws with internal outward force**

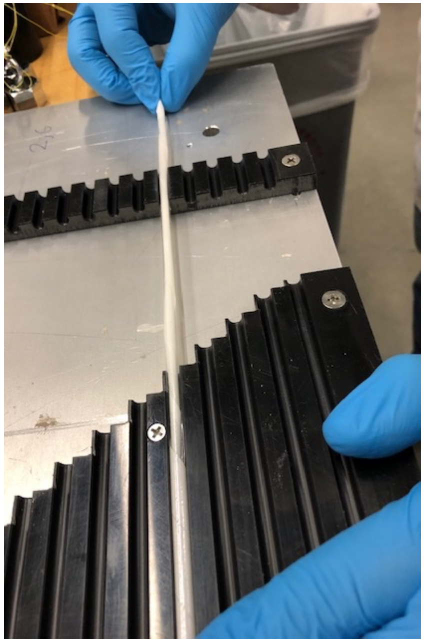
- **Paper is inside**
- **Straws are inflated**

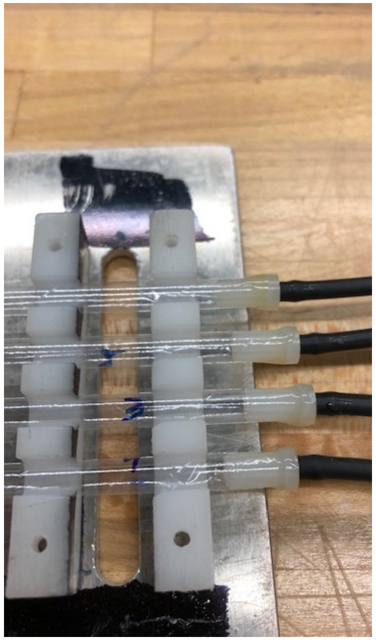
**has been fine with no obvious damage to the straws.**

**Without an outward force they collapse under own weight or static.**

**Almost no compression force can be applied which makes installing terminations difficult.**

**If ends will be removed, sealing terminations can be installed and the straws can remain inflated throughout installation.**





# Welcoming people and ideas

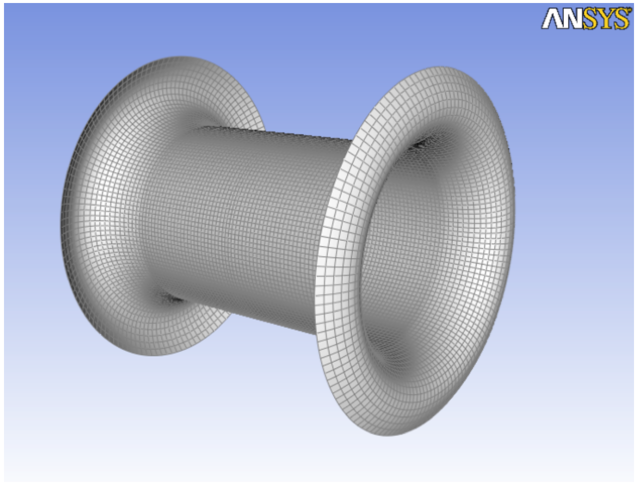
**There is a lot of exciting ideas being tested through simulation and prototypes in the Mu2e-II Tracker Workgroup.**

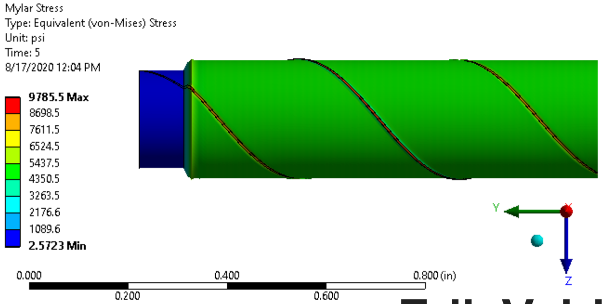
**If you are interested in joining us, please contact**

**me (ambr0028@umn.edu), Gianfranco(giovanni.tassielli@le.infn.it),**

**or stay informed though the list-serve**

**(MU2EII-TRACKER@fnal.gov)**




Erik Voirin

# Conclusion

- The Mu2e tracker is under production with initial tests succeeding in matching expectations.
- Quality design and developed techniques are leading to a state-of-the-art detector.
- Scheduled for commissioning in 2023
- In Mu2e-II research, we continue to push the boundaries of what is possible for gaseous detectors.

For more detailed information on Mu2e ask or check out our :
Technical Design Report   http://arXiv.org/abs/1501.05241
Experiment web site   http://mu2e.fnal.gov

For Mu2e-II :
Expression of Interest  https://arxiv.org/pdf/1802.02599.pdf