# Probing CLFV with the Mu2e Experiment at Fermilab

S. E. Müller for the Mu2e-Collaboration

*Helmholtz-Zentrum Dresden-Rossendorf*

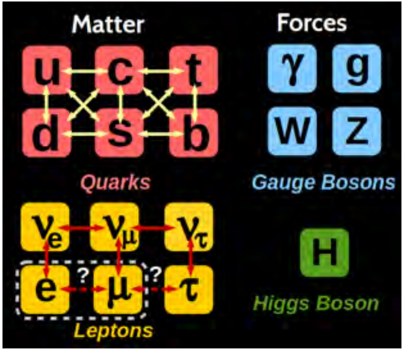
*International Workshop on Baryon and Lepton Number Violation*
*Karlsruhe, October 8 - 11, 2024*

# Motivation

The Standard Model of particle physics currently contains:

- Quark mixing
- Transitions between charged and neutral leptons of same flavor
- Neutrino oscillations

No charged lepton flavor violation (CLFV) observed so far!




**Mu2e** will search for the neutrinoless conversion of a muon into an electron in the coulomb field of a nucleus ($\mu N \to eN$) with a projected

**upper limit of $8\times10^{-17}$ (90% CL)**

Current limit by SINDRUM-II (PSI): $BR(\mu Au \to eAu) < 7 \times 10^{-13}$(90% CL)

$\nu$SM prediction via neutrino mixing is $\sim 10^{-54}$, but extensions of SM predict values up to $\sim 10^{-14}$ (Leptoquarks, heavy neutrinos, SUSY,...)

$\Rightarrow$ Unique possibility to test for New Physics

# New physics

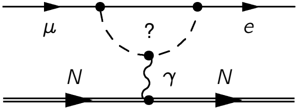
Model independent Lagrangian:

$$L_{CLFV} = \underbrace{\frac{m_\mu}{(\kappa+1)\,\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}}_{\text{“Dipole term”}} + \underbrace{\frac{\kappa}{(\kappa+1)\,\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)}_{\text{“Contact term”}}$$

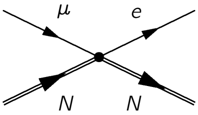
$\Lambda$: effective mass scale of New Physics

$\kappa$: relative contribution of contact term

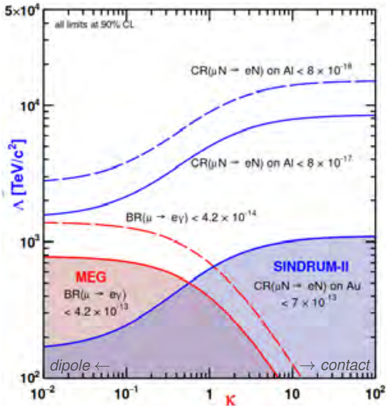
Dipole term: dominates for $\kappa \ll 1$




Contact term: dominates for $\kappa \gg 1$




Mu2e will probe $\Lambda \sim$ O($10^3$ -$10^4$) TeV/$c^2$



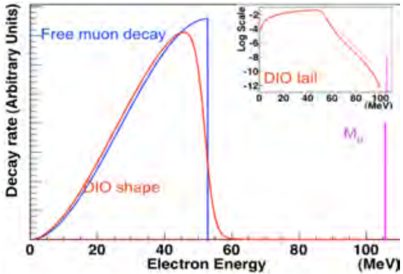

Derived from arXiv:1303.4097

# The Mu2e experiment

The **Mu2e** experiment will search for CLFV in the process $(\mu^- + \text{Al} \rightarrow e^- + \text{Al})$

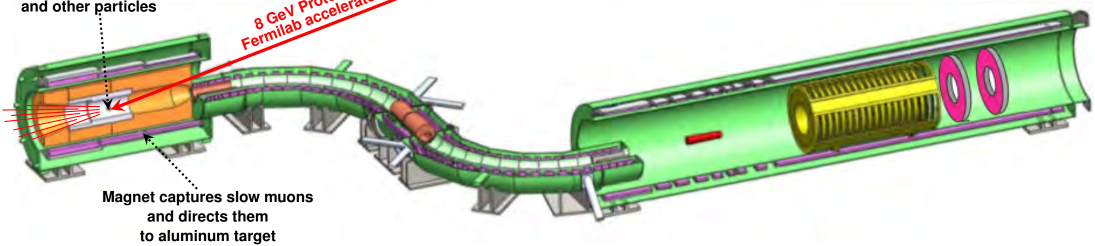
Stopped muons have a lifetime of 864 ns in the 1s-orbital of the Al nucleus

- about 60% of stopped muons undergo the muon capture reaction (e.g. $\mu^- + {}^{27}\text{Al} \rightarrow \nu_\mu + {}^{27}\text{Mg}$)
- $\sim$ 40% of stopped muons decay in orbit (DIO)
  - Michel spectrum of decay electrons dies around $M_\mu/2$
- CLFV signal for $\mu \rightarrow e$ conversion gives single mono-energetic electron
  - $E_e = 104.973\text{ MeV} \simeq M_\mu$



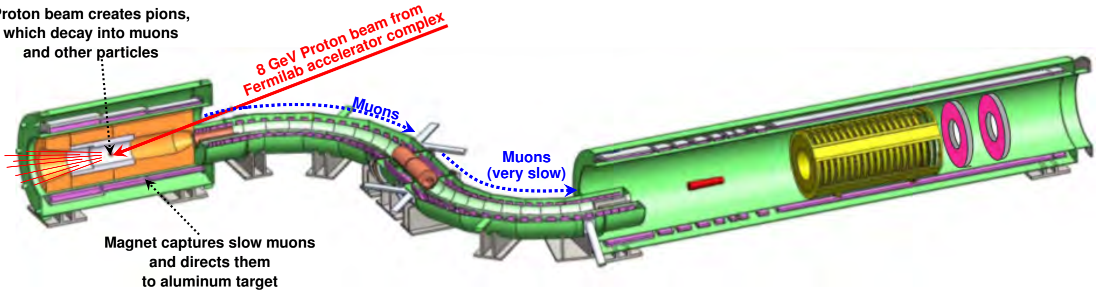

$$\text{Normalized ratio } R_{\mu e} = \frac{N(\mu^- + \text{Al} \rightarrow e^- + \text{Al})}{N(\mu^- + \text{Al} \rightarrow \text{nuclear capture})}$$

# The Mu2e experiment



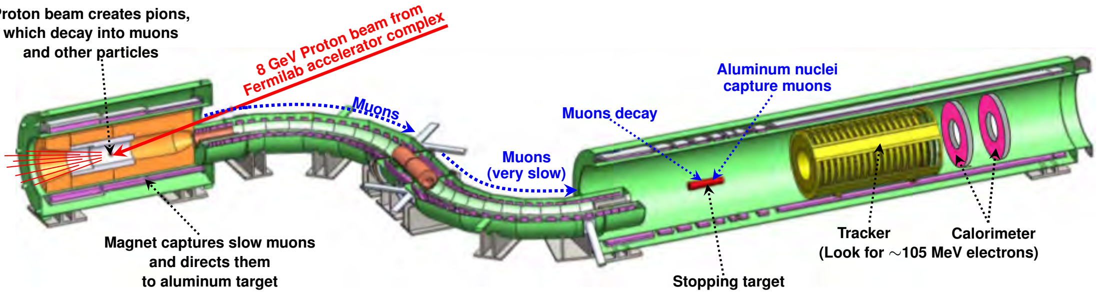

- Muons are produced by 8 GeV proton beam on tungsten target
  - time-averaged beam power: 7.3kW
  - $4 \times 10^7$ protons/pulse, pulse separation: 1.695µs
  - Magnetic field in Production Solenoid guides produced pions towards Transport Solenoid
  - Pions decay into muons

# The Mu2e experiment



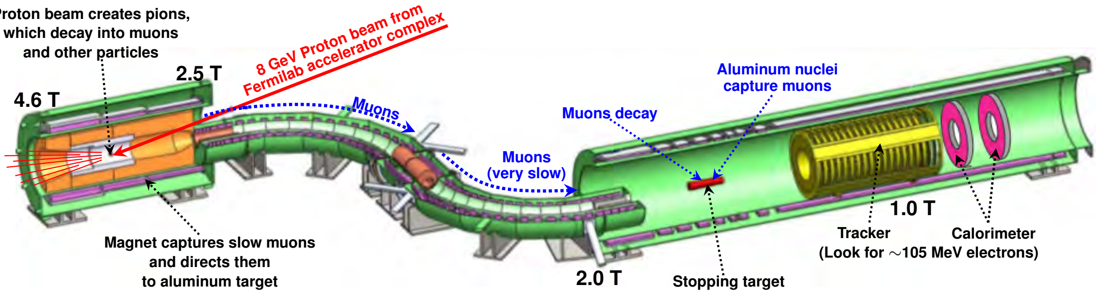

- Muons are transported in s-shaped Transport Solenoid
  - Absorber foils remove antiprotons
  - Solenoidal magnetic fields separate oppositely charged particles
  - Collimators select low-momentum negatively-charged muons.

# The Mu2e experiment




- Muons are stopped on aluminum target foils in Detector Solenoid
  - stopped muons decay in orbit or are captured by the Al nucleus
  - decay electrons are detected by a tracking detector and a calorimeter
  - look for $\sim$ 105 MeV conversion electron signal

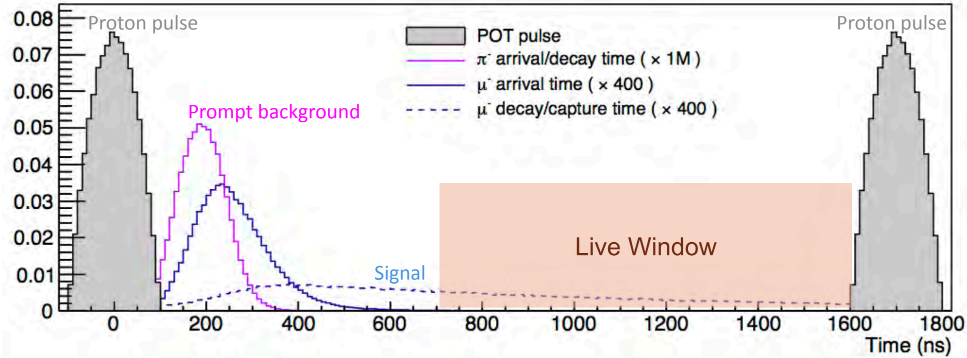
# The Mu2e experiment




- Graded fields in the 3 solenoid systems are important
  - to increase muon yields
  - to suppress backgrounds
  - to improve geometric acceptance for signal electrons

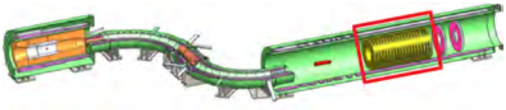
# The Mu2e experiment

Pulsed proton beam allows definition of a “Live Window” for the signal to suppress prompt background (1695 ns peak-to-peak):




- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- 700 ns delay allows to suppress prompt background from pions by $\sim 10^{-11}$
- Must achieve extinction ($N_{p^+}$ out of bunch)/($N_{p^+}$ in bunch) $\leq 10^{-10}$

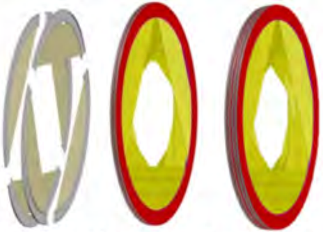
# Straw drift tube tracker

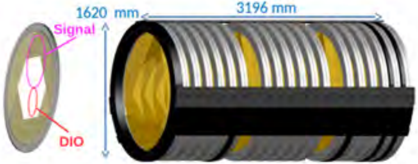


- low mass straw drift tubes (5mm diam.)
- $> 20\,000$ straws
- straws are read out from both ends
- needs to operate in vacuum and at $\sim$1 T magn. field
- momentum resolution $\sigma_p < 200$ keV/c


- inner 38 cm not instrumented
  $\rightarrow$ "blind" to low-momenta DIO electrons

# Straw drift tube tracker

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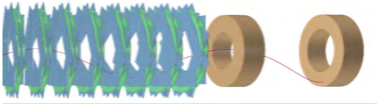
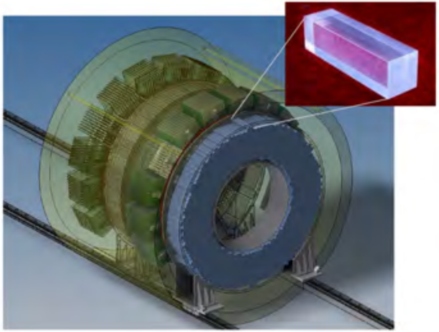
# Calorimeter

- composed of two rings separated by half a wavelength of signal electron trajectory helix
- each ring composed of ∼700 pure CsI crystals read out by SiPMs
- independent measurement of
  - energy ($\sigma_E/E \sim 5\%$)
  - time ($\sigma_t \sim 0.5$ns)
  - position ($\sigma_{Pos} \sim 1$cm)
- independent trigger information
- particle ID
- calibration with activated liquid source and laser system

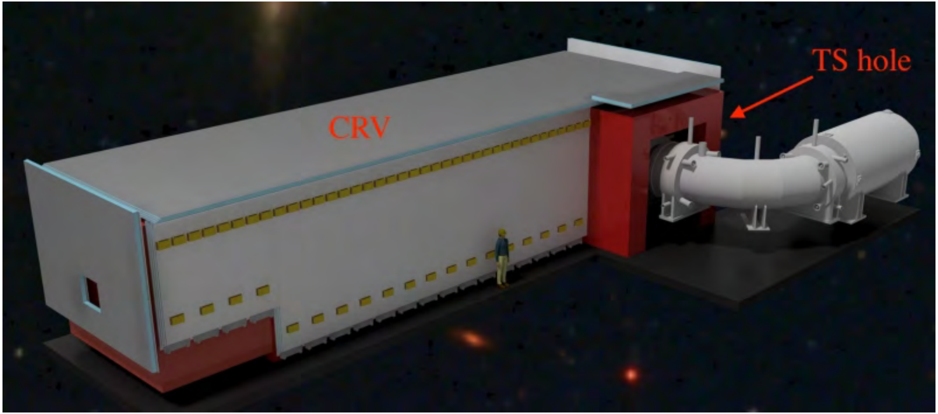




HZDR

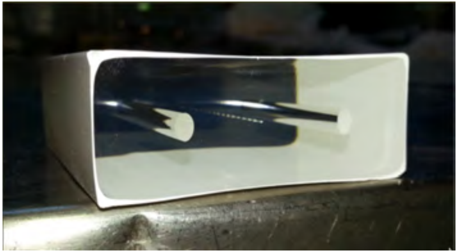
# The cosmic ray veto detector

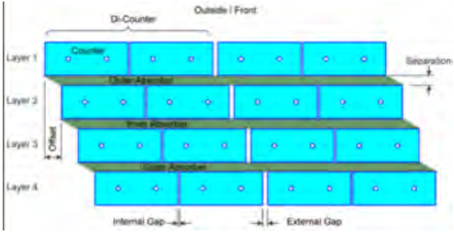
The cosmic ray veto system (CRV) covers entire Detector Solenoid and half of the Transportation Solenoid (TS)



# The cosmic ray veto detector

Without CRV, $\sim$ 1 background event per day mimicking signal produced by cosmic-ray muons

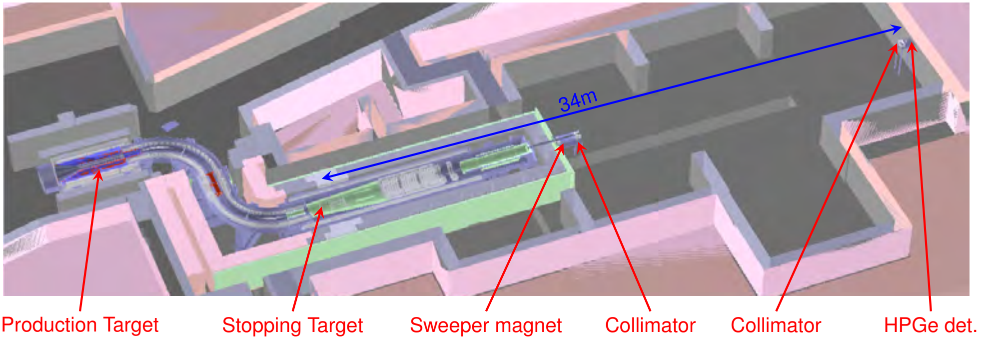





- 4 overlapping layers of scintillator bars ($5 \times 2 \times \sim 450$ cm$^3$)
- 2 wavelength-shifting fibers/bar
- Read out both end of each fiber with SiPMs
- required inefficiency $\sim 10^{-4}$

# The Stopping-Target Monitor

High-purity Germanium detector to determine overall muon-capture rate on Al to the level of 10%

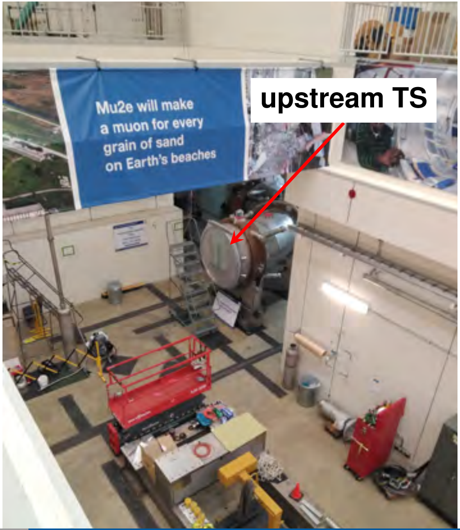



- measure X- and $\gamma$-rays from muonic Aluminum
  - 347 keV 2p-1s X-ray (80% of muon stops)
  - 844 keV delayed $\gamma$-ray (5% of muon stops)
  - **1809 keV** $\gamma$-ray (30% of muon stops)
- line-of-sight view of Muon Stopping Target
- behind tungsten collimator with 0.5 cm$^2$ holes
- sweeper magnet to reduce charged particle background and radiation damage to detector

- It was decided to accompany the HPGe detector with a $LaBr_3$ detector (worse energy resolution, but can take higher rates)

# Mu2e status: Transport Solenoid

The upstream part of the Transport Solenoid was installed in Mu2e hall in December 2023:



# Mu2e status: Transport Solenoid

On February 20, 2024, the downstream part of the Transport Solenoid was brought to the Mu2e hall:

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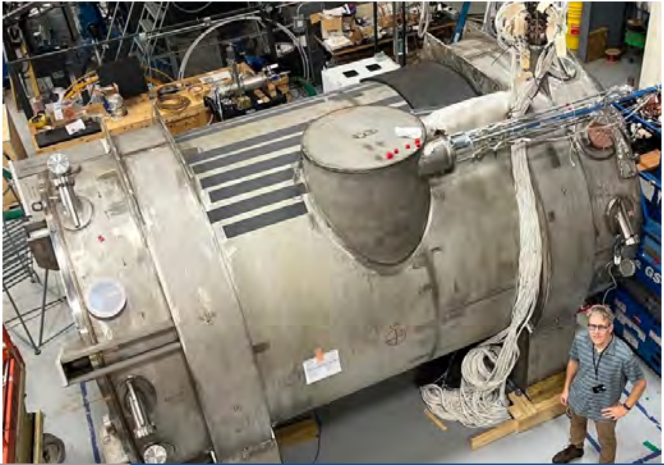
# Mu2e status: Transport Solenoid

Both Up- and Downstream TS in final position, collimators installed. Cryo connection work ongoing:

# Production and Detector Solenoid status

## Production Solenoid:

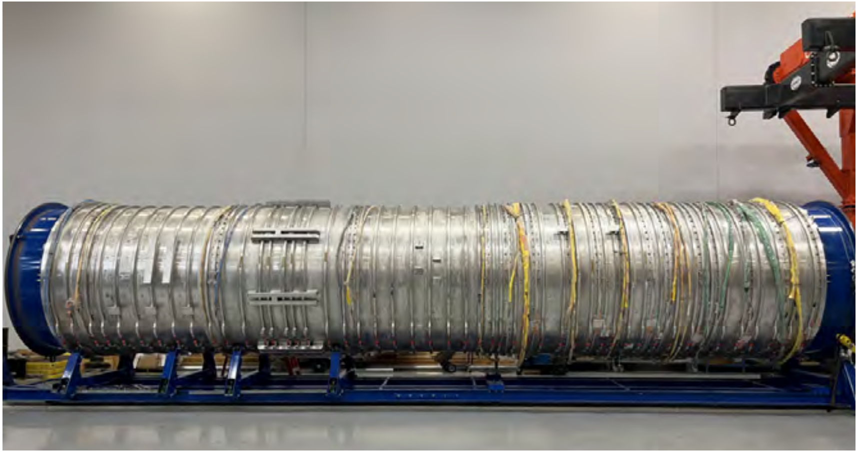
- Assembly completed, preparing for cold test
- Expected delivery date to FNAL: End of 2024



# Production and Detector Solenoid status

## Detector Solenoid:

- All 11 coils assembled into cold mass. Work going on with thermal shields of inner bore and outer vessel. Expected delivery date to FNAL: Spring 2025.



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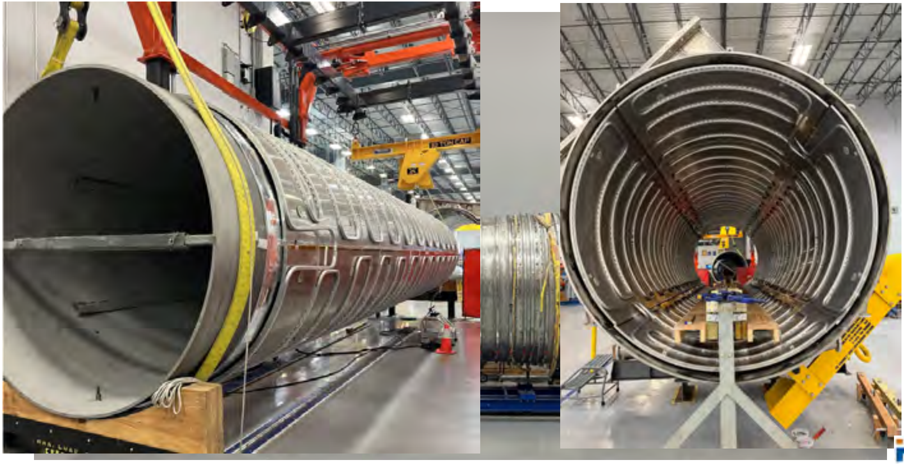
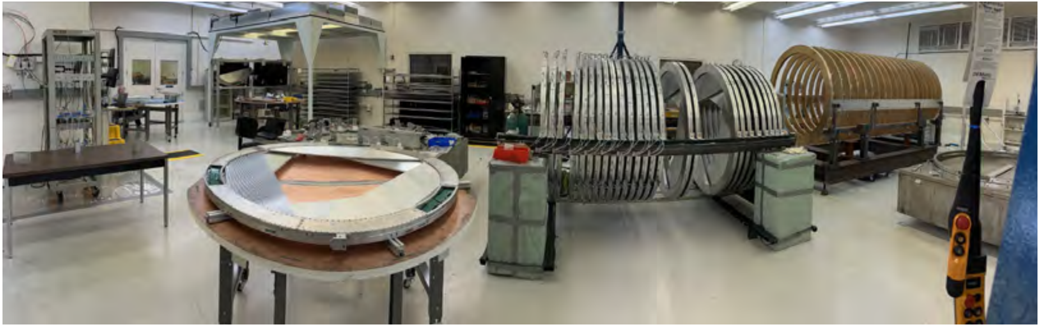


# Tracker status

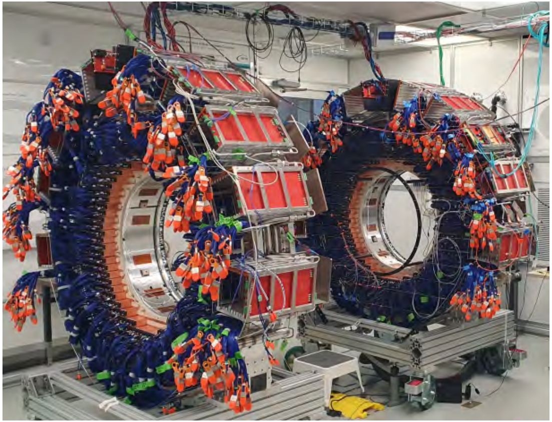
- All 20736 straws produced
- All 216 panels produced
- 35 / 36 planes built
- Currently installing electronics
- Quality Control and leak testing ongoing

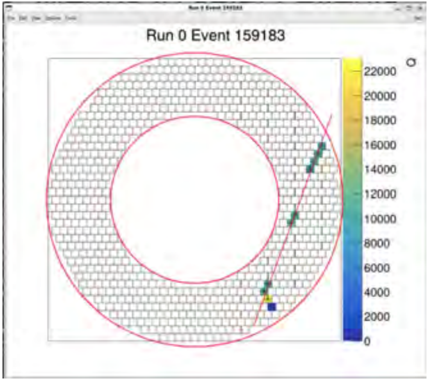
**Tracker production Lab:**



# Calorimeter status

- All crystals and SiPMs installed on the two discs
- Both disks fully cabled
- First cosmic rays seen





# CRV status

- All CRV modules produced and delivered to FNAL
- Efficiency studies using cosmic rays
- Working on cabling and electronics

# Conclusion & Outlook

- The **Mu2e** experiment at **FERMILAB** will search for the neutrinoless conversion of a muon into an electron in the coulomb field of an Aluminum nucleus
  - projected upper limit: $8 \times 10^{-17}$ (90% CL)
- The experiment is now entering the on-site installation of magnets and detectors
  - Transport Solenoid already installed in Mu2e hall
  - Detector construction well advanced
- Commissioning of detectors with cosmic rays in spring 2025
- **Mu2e** Run I data taking in 2027
  - Improve SINDRUM II result by 3 orders of magnitude
- Use accelerator shutdown for neutrino beam upgrades in 2028 to upgrade detectors and shielding
- Second **Mu2e** run after shutdown with higher beam intensity aims to improve the results by another order of magnitude

# Mu2e Collaboration

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# Backup Slides

# Mu2e backgrounds Run I

Expected background contributions for Run I (assuming $6 \times 10^{16}$ stopped muons)

| Channel | Mu2e Run I |
|---|---|
| SES | $2.4 \times 10^{-16}$ |
| Cosmic rays | $0.046 \pm 0.010$ (stat) $\pm 0.009$ (syst) |
| DIO | $0.038 \pm 0.002$ (stat) $^{+0.025}_{-0.015}$ (syst) |
| Antiprotons | $0.010 \pm 0.003$ (stat) $\pm 0.010$ (syst) |
| RPC in-time | $0.010 \pm 0.002$ (stat) $^{+0.001}_{-0.003}$ (syst) |
| RPC out-of-time ($\zeta = 10^{-10}$) | $(1.2 \pm 0.1$ (stat) $^{+0.1}_{-0.3}$ (syst)$) \times 10^{-3}$ |
| RMC | $< 2.4 \times 10^{-3}$ |
| Decays in flight | $< 2 \times 10^{-3}$ |
| Beam electrons | $< 1 \times 10^{-3}$ |
| Total | $0.105 \pm 0.032$ |

*Mu2e Run I Sensitivity Projections for the Neutrinoless $\mu^- \rightarrow e^-$ Conversion Search in Aluminum", Universe 9 (2023) 1, 54*