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
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DRESDEN concept

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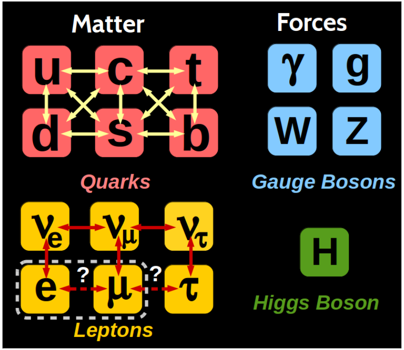
Motivation

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 8×10^{-17} (90% CL)

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

νSM 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

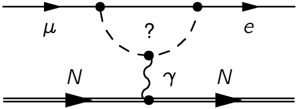
Model independent Lagrangian:

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

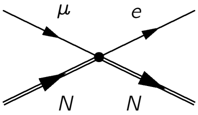
Λ: effective mass scale of New Physics

κ: relative contribution of contact term

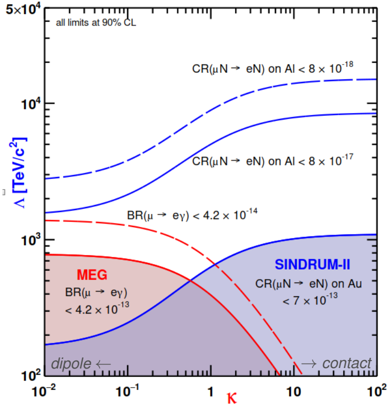
Dipole term: dominates for $\kappa \ll 1$



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



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



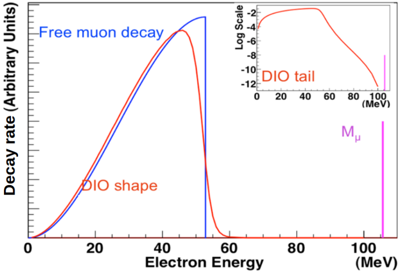
Derived from arXiv:1303.4097

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
  - $E_e = 104.973$ MeV $\simeq M_\mu$



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

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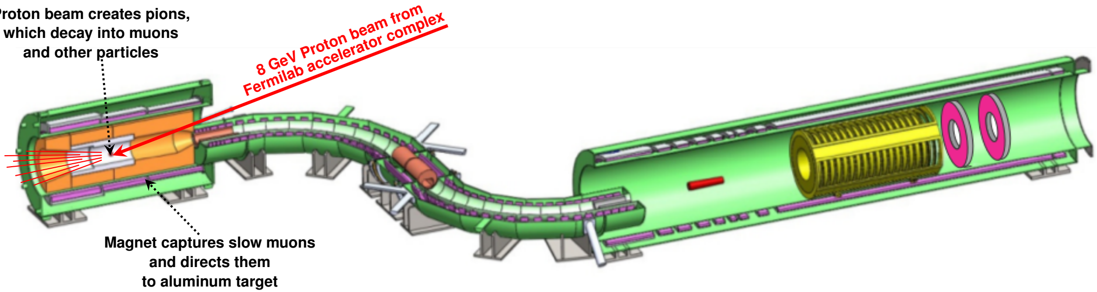
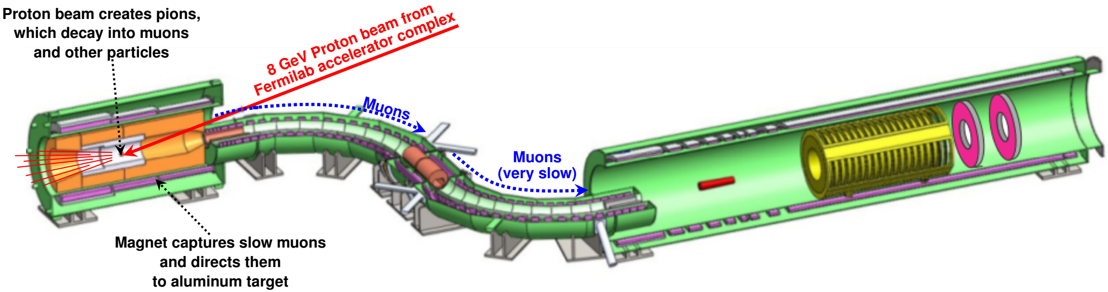
The Mu2e experiment



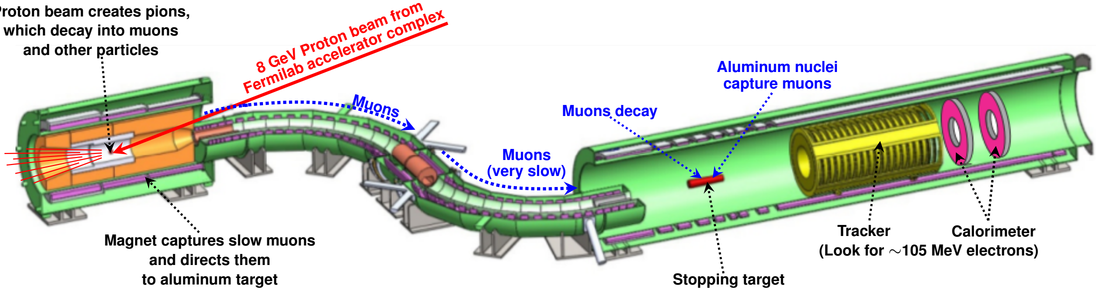
- Muons are produced by 8 GeV proton beam on tungsten target
  - time-averaged beam power: 7.3kW
  - 4×10^7 protons/pulse, pulse separation: 1.695μs
  - Magnetic field in Production Solenoid guides produced pions towards Transport Solenoid
  - Pions decay into muons

The Mu2e experiment



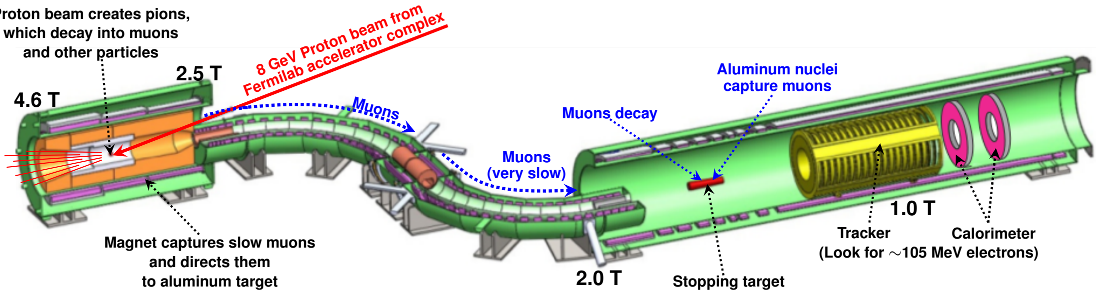
- Muons are transported in s-shaped Transport Solenoid
  - Absorber foils remove antiprotons
  - Solenoidal magnetic fields separate oppositely charged particles
  - Collimators select low-momentum negatively-charged muons.

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

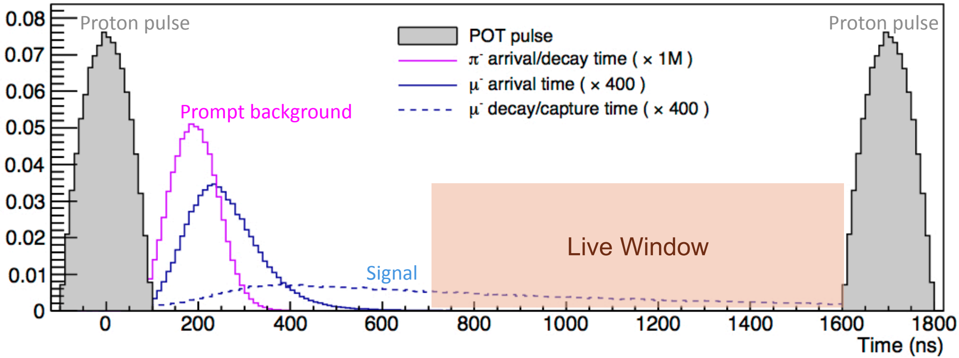
The Mu2e experiment



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

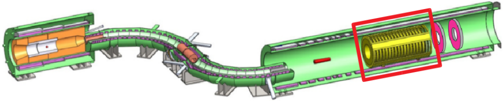
The Mu2e experiment

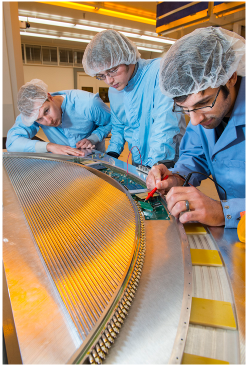
Pulsed proton beam allows definition of a “Live Window” for the signal to suppress prompt background (1695 ns peak-to-peak):



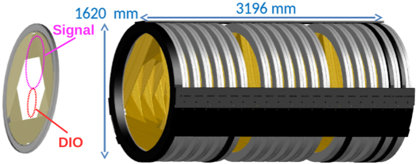
- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- 700 ns delay allows to suppress prompt background from pions by $\sim 10^{-11}$
- Must achieve extinction (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$

Straw drift tube tracker



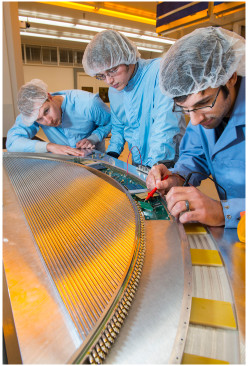


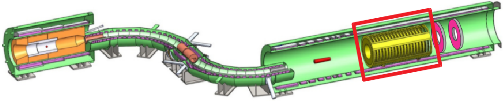
- low mass straw drift tubes (5mm diam.)
- $>$ 20 000 straws
- straws are read out from both ends
- needs to operate in vacuum and at $\sim$1 T magn. field
- momentum resolution $\sigma_{\mathrm{p}} < 200$ keV/c

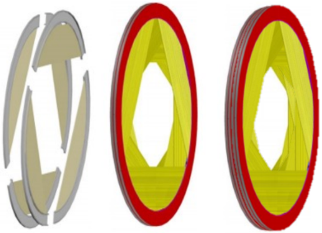


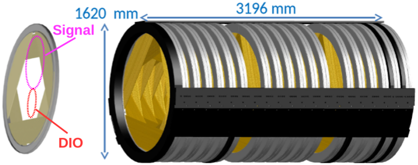
- inner 38 cm not instrumented
  $\rightarrow$ "blind" to low-momenta DIO electrons

Straw drift tube tracker









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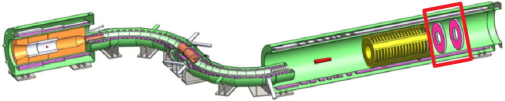
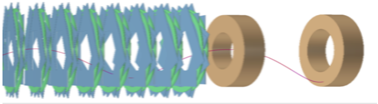
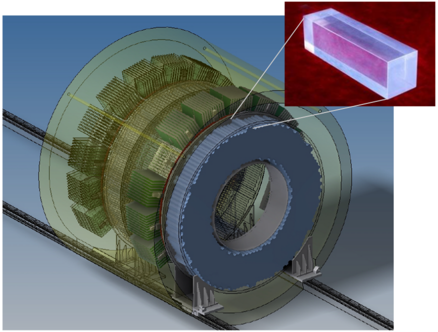
Calorimeter



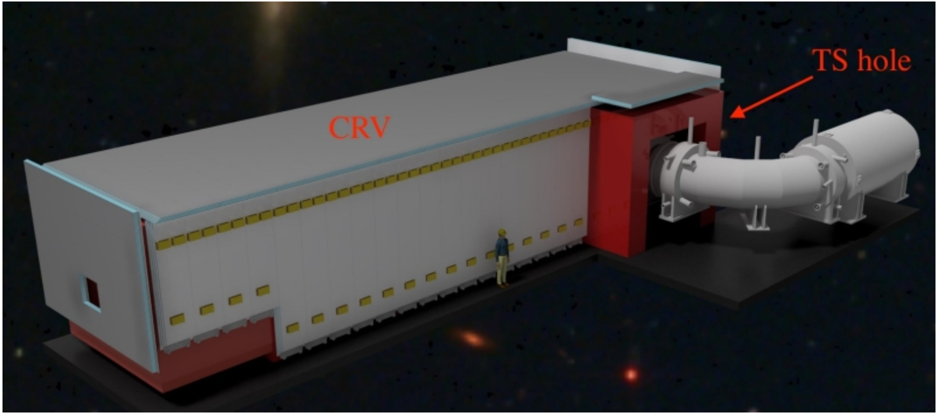
- composed of two rings separated by half a wavelength of signal electron trajectory helix
- each ring composed of ∼700 pure CsI crystals read out by SiPMs
- independent measurement of
  - energy ($\sigma_E/E \sim 5\%$)
  - time ($\sigma_t \sim 0.5$ns)
  - position ($\sigma_{Pos} \sim 1$cm)
- independent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





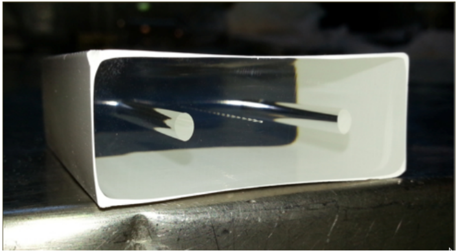
The cosmic ray veto detector

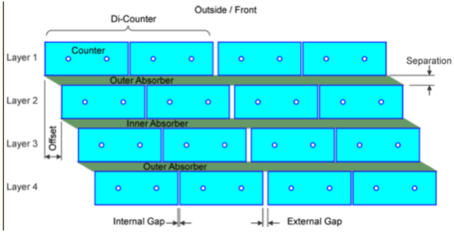
The cosmic ray veto system (CRV) covers entire Detector Solenoid and half of the Transportation Solenoid (TS)



The cosmic ray veto detector

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

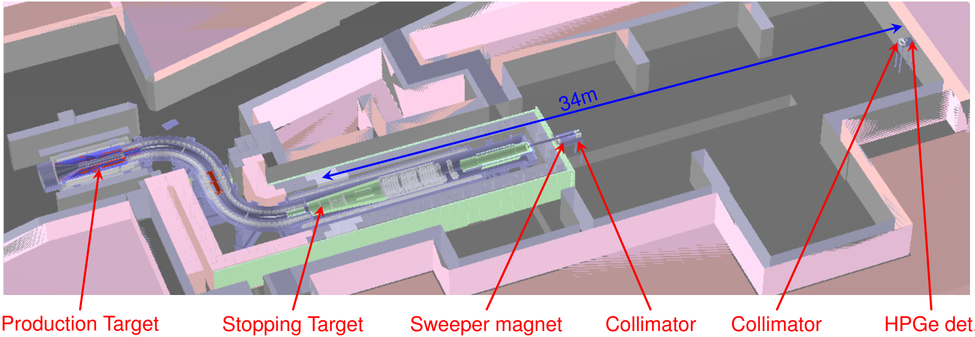




- 4 overlapping layers of scintillator bars (5 $\times$ 2 $\times \sim$ 450 cm^3)
- 2 wavelength-shifting fibers/bar
- Read out both end of each fiber with SiPMs
- required inefficiency $\sim 10^{-4}$

The Stopping-Target Monitor

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



- measure X- and γ-rays from muonic Aluminum
  - 347 keV 2p-1s X-ray (80% of muon stops)
  - 844 keV delayed γ-ray (5% of muon stops)
  - **1809 keV** γ-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)

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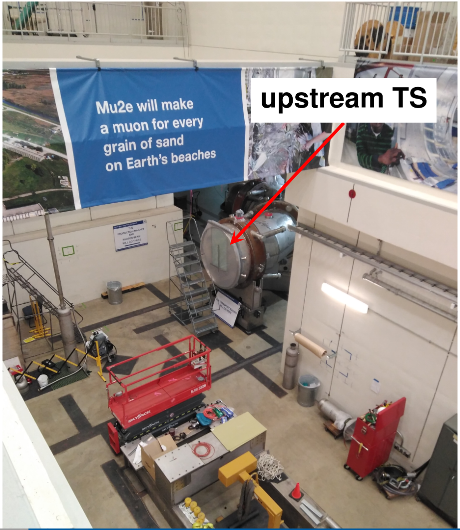
Mu2e status: Transport Solenoid

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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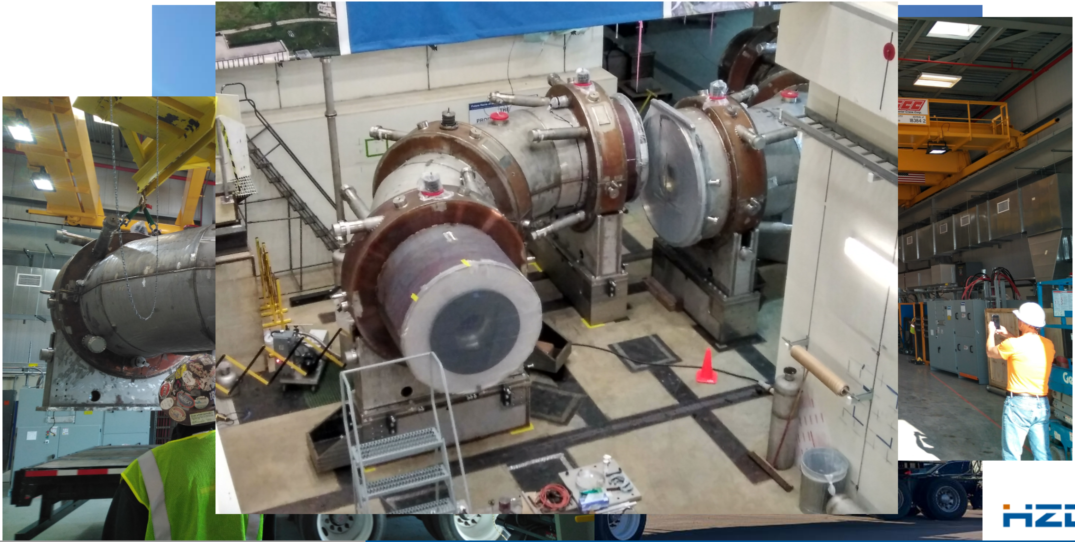


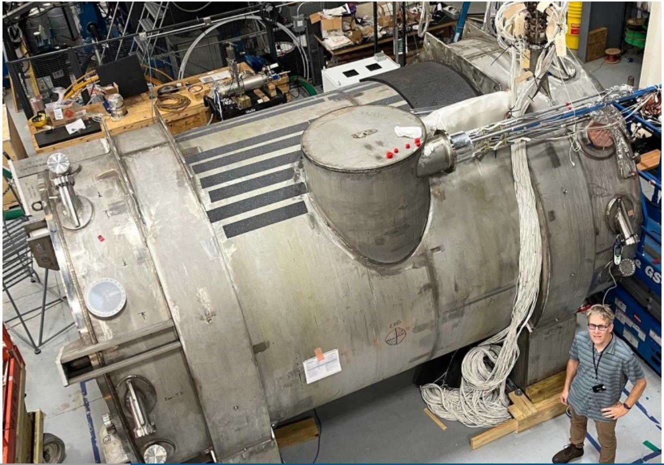
Mu2e status: Transport Solenoid

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

Production and Detector Solenoid status

Production Solenoid:

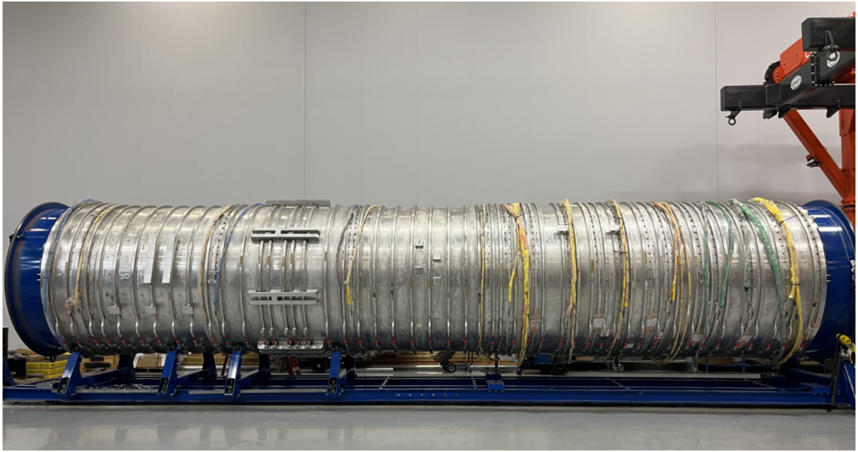
- Assembly completed, preparing for cold test
- Expected delivery date to FNAL: End of 2024



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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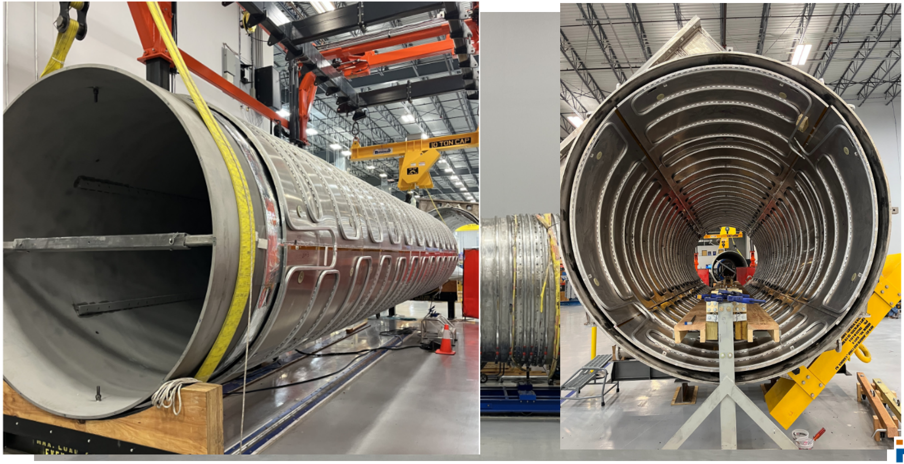
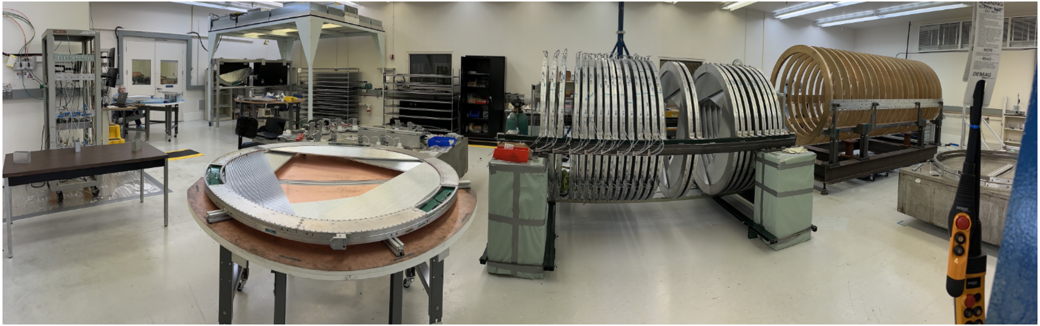


Tracker status

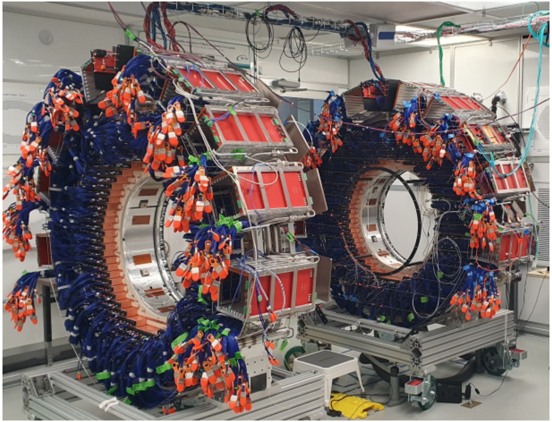
- All 20736 straws produced
- All 216 panels produced
- 35 / 36 planes built
- Currently installing electronics
- Quality Control and leak testing ongoing

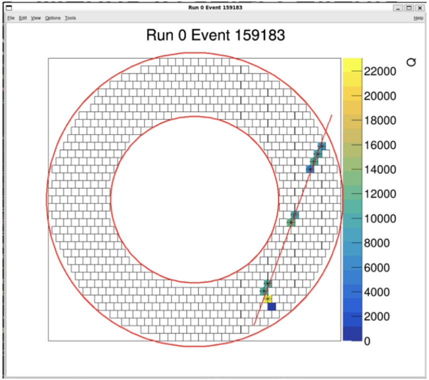
Tracker production Lab:



Calorimeter status

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





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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: 8×10^{-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

Mu2e Collaboration

Backup Slides

Mu2e backgrounds Run I

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

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	0.046 ± 0.010 (stat) ± 0.009 (syst)
DIO	0.038 ± 0.002 (stat) $^{+0.025}_{-0.015}$ (syst)
Antiprotons	0.010 ± 0.003 (stat) ± 0.010 (syst)
RPC in-time	0.010 ± 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 ± 0.032

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