The current status of the Mu2e experiment at Fermilab

S. E. Müller, A. Ferrari, O. Knodel, and R. Rachamin for the Mu2e-collaboration

Helmholtz-Zentrum Dresden-Rossendorf

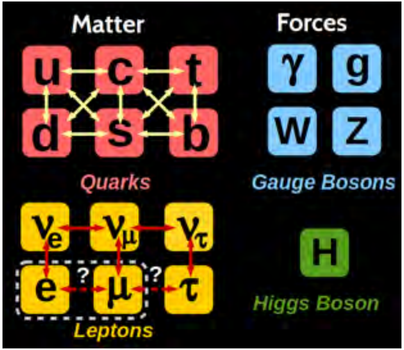
DPG Spring Meeting - Karlsruhe, March 08, 2024

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 8×10^{-17} (90% CL)

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

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

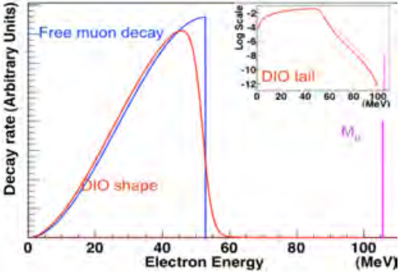
$\Rightarrow$ Unique possibility to test for New Physics

The Mu2e experiment

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

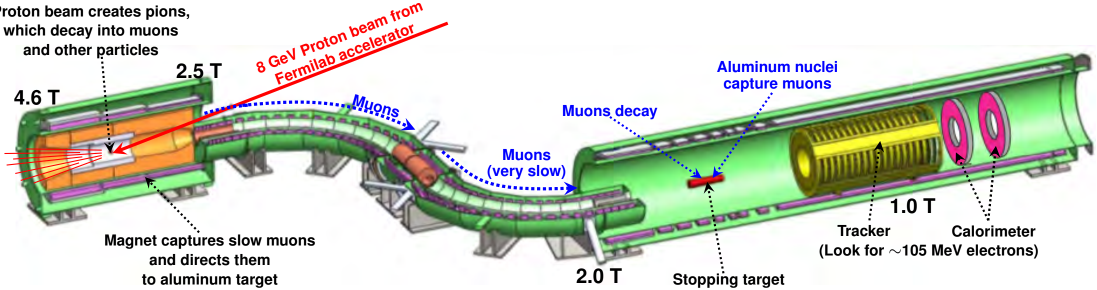
Stopped muons have a lifetime of 864 ns in the 1s-orbital of the Al nucleus

- 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 $\simeq M_\mu$



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

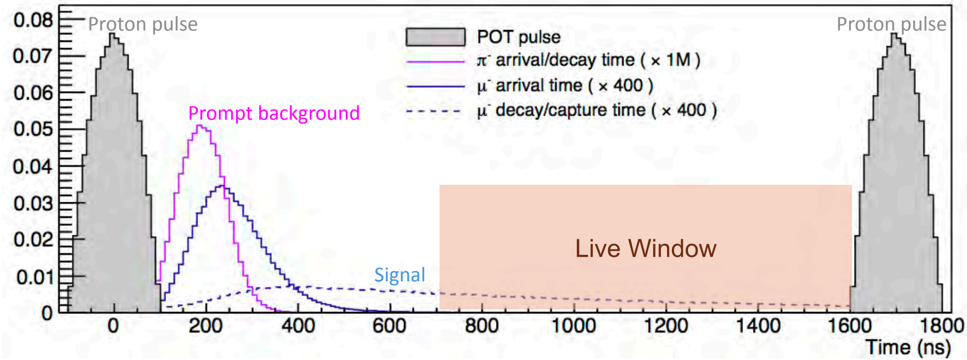
The Mu2e experiment



- 8 GeV proton beam hits tungsten target and produces pions
- Pions are transported in s-shaped Transport Solenoid where they decay into muons
- Muons are stopped on aluminum target foils in Detector Solenoid
- Detectors (tracker and calorimeter) search for 105 MeV conversion electrons

The Mu2e experiment

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



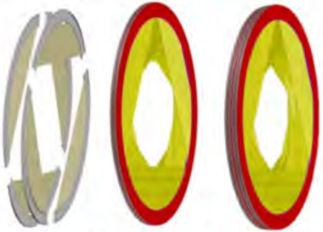
- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- 700 ns delay allows to suppress prompt background from pions by $\sim 10^{-11}$
- Must achieve extinction (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$

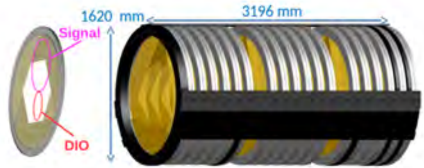
Straw drift tube tracker

- low mass straw drift tubes (5mm diam.)
- $> 20\,000$ straws
- in vacuum and at $\sim$1 T magn. field
- momentum resolution $\sigma_p < 180$ keV/c

- inner 38 cm not instrumented
  → "blind" to low-momenta DIO electrons

Straw drift tube tracker





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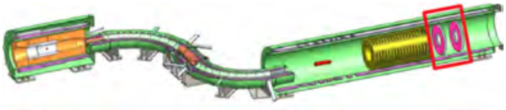
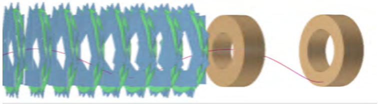
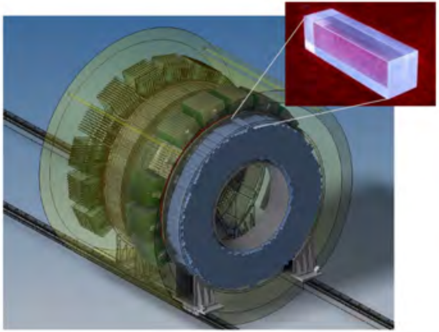
Calorimeter



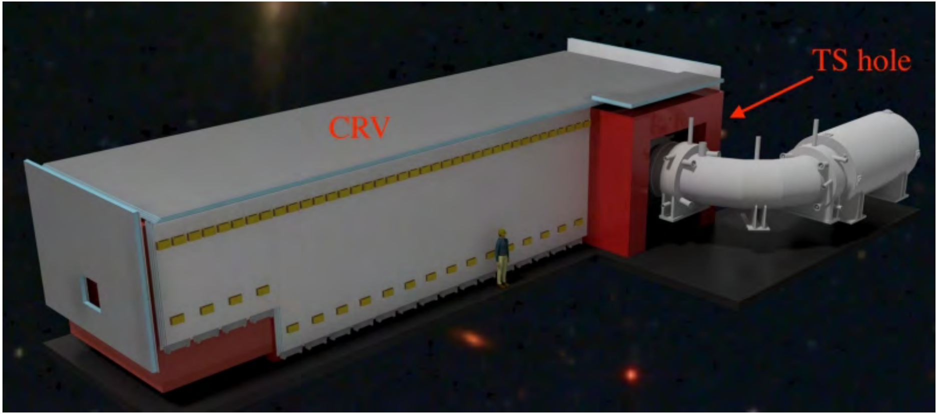
- composed of two rings separated by half a wavelength of signal electron trajectory helix
- each ring composed of ~700 pure CsI crystals read out by SiPMs
- independent measurement of
  - energy ($\sigma_E/E \sim 5\%$)
  - time ($\sigma_t \sim 0.5$ns)
  - position ($\sigma_{Pos} \sim 1$cm)
- independent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





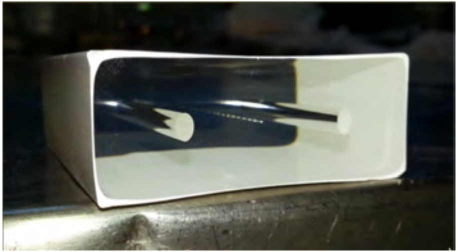
The cosmic ray veto detector

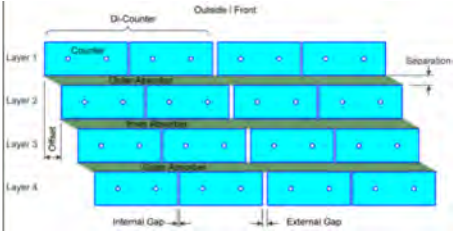
The cosmic ray veto system (CRV) covers entire Detector Solenoid and half of the Transportation Solenoid (TS)



The cosmic ray veto detector

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

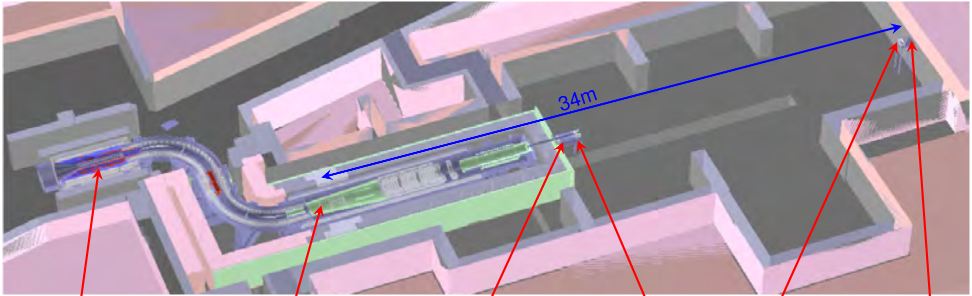




- 4 overlapping layers of scintillator bars ($5 \times 2 \times \sim 450$ cm^3)
- 2 wavelength-shifting fibers/bar
- Read out both end of each fiber with SiPMs
- required inefficiency $\sim 10^{-4}$

The Stopping-Target Monitor

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



Production Target Stopping Target Sweeper magnet Collimator Collimator HPGe det.

- 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)

Status Mu2e hall

September 2022:

Status Mu2e hall

February 2024:

Status Mu2e hall

February 2024:

upstream TS

(installed Dec 2023)

Status Mu2e hall

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

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Production and Detector Solenoid status

Production Solenoid:

- Thermal shield end plates and insulation installed
- Installing piping for liquid nitrogen and liquid helium in chimney

Production and Detector Solenoid status

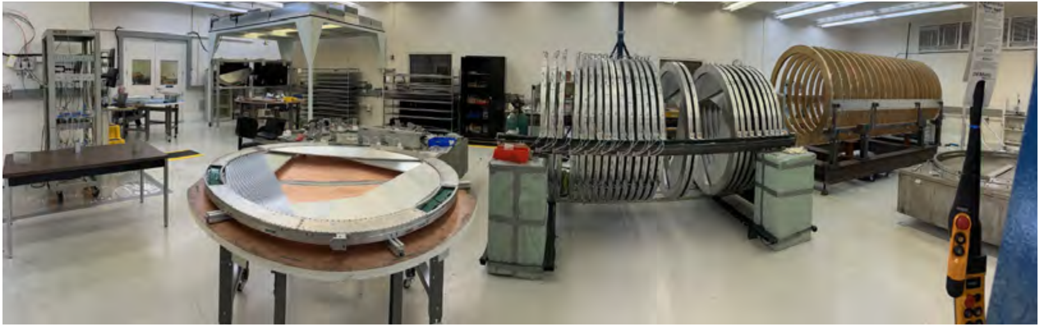
Detector Solenoid:

- Cold mass assembly in progress: coils 1-8 assembled, 9 being aligned, 10-11 subassembly in progress

Tracker status

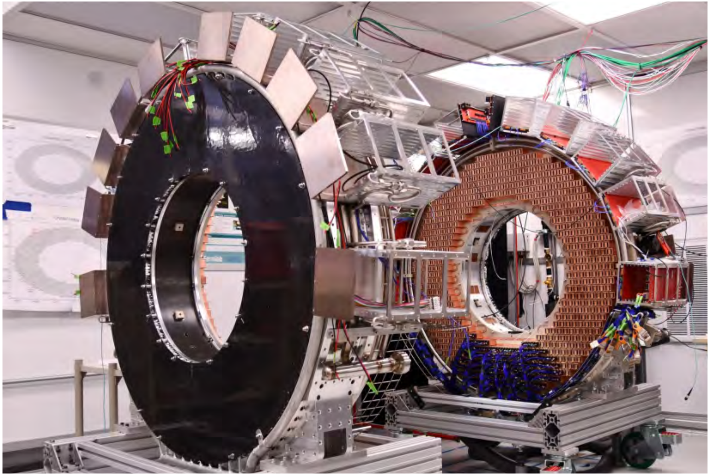
- All 20736 straws produced
- All 216 panels produced
- 33 / 36 planes built
- Currently installing electronics
- Quality Control and leak testing ongoing

Tracker production Lab:



Calorimeter status

- All crystals and SiPMs installed on the two discs
- Read-Out Units assembled and attached
- Currently working on cabling and electronics



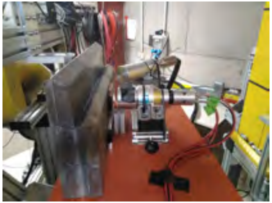
CRV status

- 81/83 CRV modules produced
- Testing with cosmic rays
- Working on cabling and electronics

HZDR contributions to Mu2e

At **HZDR**, we contribute in the following areas to the **Mu2e** experiment:

- Beamtimes at the **ELBE** Center for High-Power Radiation Sources
  - Test of radiation hardness of detector components and electronics
  - Full test of the **Stopping Target Monitor** detector system, including the **DAQ** chain



- Simulation of the full experiment using the **FLUKA** radiation transport package
  - Shielding assessments, number of stopped muons per POT, particle yields, ...
  - Runs on `fermigrid` machines

- Planned involvement in **DAQ** development using FPGAs

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
- **HZDR** contributes with beamtimes at the **ELBE** Center for High-Power Radiation Sources
  - Radiation hardness of crystals and electronics
  - Detector tests for Stopping Target Monitor
- We are also setting up **FLUKA** simulations to cross check simulation results obtained with **GEANT4** and **MARS**
- With the first run of physics dataking starting in the end of 2026, and the following runs after the long shutdown due to **PIP-II** installation at FNAL, **Mu2e** will either unambiguously discover **CLFV** or push the limit on muon $\rightarrow$ electron conversion by four orders of magnitude