WIFAI 2025: Workshop Italiano sulla Fisica ad Alta Intensità

Status of the Mu2e experiment at Fermilab

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INFN
Mu2e
Fermilab

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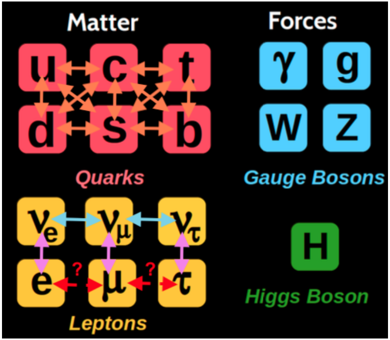
Mu2e: Searching for new physics, why?

The **Standard Model** of particle physics allows:

- Quark mixing
- Transitions between charged and neutral leptons of same flavor
- Neutrino oscillations (neutral lepton flavor violation)

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



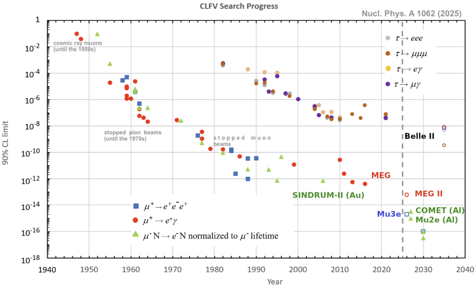
In the Standard Model with massive neutrinos the rate for CLFV is:

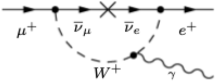
$$Br(\mu \to e\gamma)_{SM} = \frac{\Gamma(\mu \to e\gamma)_{SM}}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$ **Unmeasurably small!**

⇒ **observing any CLFV process experimentally** would imply presence of physics beyond SM (**predicted by many SM extensions**).

Charged Lepton Flavor Violation (CLFV) Searches

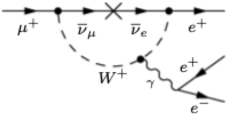
- **CLFV experiments** primarily focus on muons (μ) and taus (τ).
- The current **best limits** on CLFV come from **muon experiments**.
- **Muons** are abundant (cosmic rays, pion decay, high intensity facilities) with a relatively long lifetime ($\tau_\mu \approx 2.2\ \mu$s)
- Three most searched modes with muons:





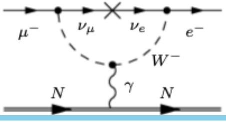
$$\boxed{\mu^+ \to e^+\gamma}$$

- MEG and MEG-II experiments at PSI
- best current limit on CLFV: $\mathcal{B}(\mu^+ \to e^+\gamma) < 1.5 \times 10^{-13}$
  MEG-II experiment at PSI [Eur.Phys.J.C(2025)85:1177]



$$\boxed{\mu^+ \to e^+e^+e^+}$$

- Mu3e experiment at PSI
- best current channel limit: $\mathcal{B}(\mu^+ \to e^+e^+e^+) < 1.0 \times 10^{-12}$
  SINDRUM experiment at PSI [Nucl. Phys. B 299 (1988)]

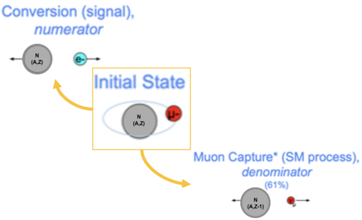


$$\boxed{\mu^- + N \to e^- + N}$$

- Search for the conversion of muons to electrons without emission of neutrinos $\Rightarrow$ **Mu2e@Fermilab**

Muon to Electron Conversion

Search for neutrinoless, coherent conversion of muon to electron in the field of a nucleus by measuring:



$$R_{\mu e} = \frac{\Gamma(\mu^- + N(Z,A) \to e^- + N(Z,A))}{\Gamma(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A))}$$

Advantages of this channel:

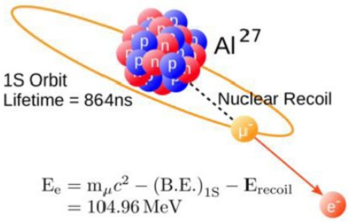
- **signal** is a mono-energetic single particle (the outgoing electron)
  $\Rightarrow$ almost no combinatorial background
- can **explore a range of new masses** up to 10^4 TeV/c^2
  $\Rightarrow$ sensitivity to a large range of NP scenarios unaccessible for current (or foreseen) high-energy colliders
- rate in different nuclei
  $\Rightarrow$ **unique information regarding underlying NP operators**

Current best limit set by SINDRUM II experiment at PSI (Au target):

$$R_{\mu e} < 7 \times 10^{-13} \text{ (90\% C.L)}$$

[Eur.Phys.J. C47,337 (2006)]

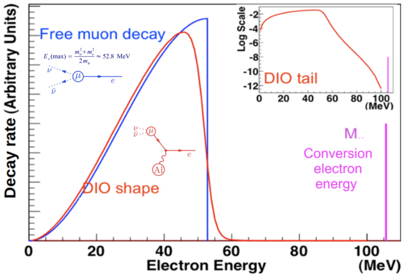
The Mu2e Experiment @ Fermilab



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

Muonic aluminum **lifetime is** $\sim$ **864 ns**

- the conversion (CLFV) signal is an **almost mono-energetic electron of** E_e $\sim$**105 MeV**$\approx M_\mu$
- about 31% of stopped muons decay in orbit (DIO) tail ends at the signal peak
  - outgoing electron exchange momentum with the nucleus it is not a Michel spectrum (continuum spectrum that dies around $M_\mu/2 \approx 52$ MeV)
- about 69% of stopped muons undergo the muon capture reaction ($\mu^- + \text{Al} \to \nu_\mu + \text{Mg}$)

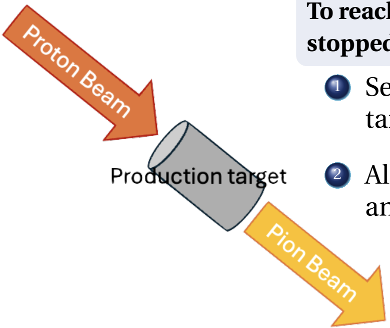


Mu2e goal is to improve by a factor 10^4 the sensitivity on $R_{\mu e}$ with a **projected upper limit of** $\mathbf{8 \times 10^{-17}}$ **(90% CL)**

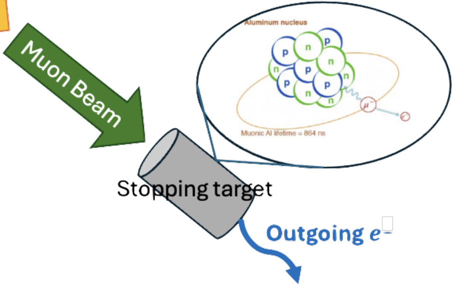
Experimental concept

To reach the required sensitivity: collect $\sim 10^{18}$ stopped muons with < 1 background events

1. Send a proton beam into a production target and create pions
2. Allow the pions to decay into muons, and collect the negative muons (μ^-)

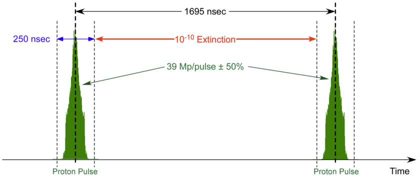


3. Form muonic atoms by stopping the low-momentum negative muons in an aluminum stopping target
4. Search for and measure the momentum of the conversion electrons ($\mu^- \to e^-$)
   - need good tracker momentum resolution to reject DIO



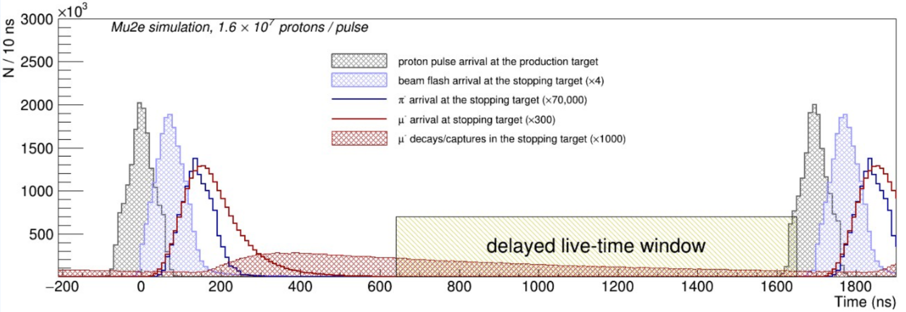
Proton Beam from the FNAL Accelerator Division

- 400 MeV protons from the **LINAC** are injected into the **Booster Ring** where they are accelerated to 8 GeV and then inside the **Recycler Ring** are divided in 4 bunches of $\sim 10^{12}$ protons each
- 8 bunches are sent to the **Delivery Ring** from which they are resonantly extracted each 1695 ns to create the proton pulses directed to the **Mu2e beam line** ($\sim 4 \times 10^7$ protons/pulse):



Beam Timing & Purity: the Mu2e "Live Window"

- Fermilab accelerator complex provides optimal pulse spacing for Mu2e allows definition of a **"Live Window" for the signal** to suppress prompt background from pions by $\sim 10^{-11}$:



Pulsed Proton Beam Structure:

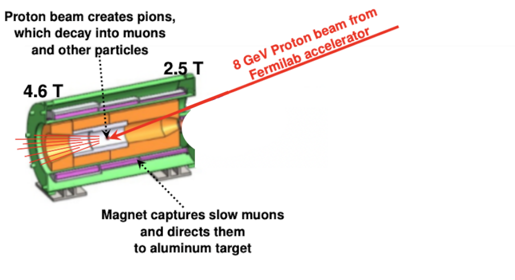
Proton pulse period: **1.695 μs** ~ $2\tau_{\mu}^{Al}$ (τ_{μ}^{Al} = 864 ns)

Delayed analysis window to suppress prompt backgrounds

Out of bunch proton fraction ("extinction factor") **< 10^{-10}**

(measured by an extinction monitor downstream of the beam)

Production Solenoid



The 8 GeV proton beam from the Mu2e beam line is directed into the **Production Solenoid**:

- where it strikes a **pion production target** and produces pions.
- the resulting pions, as they decay into muons, are guided by the Production Solenoid's magnetic field toward the Transport Solenoid.

Pion Production Target

- First prototype made from tungsten with its support structure
- Other material options (carbon, Inconel,...) and geometrical designs are explored.

Requirements:

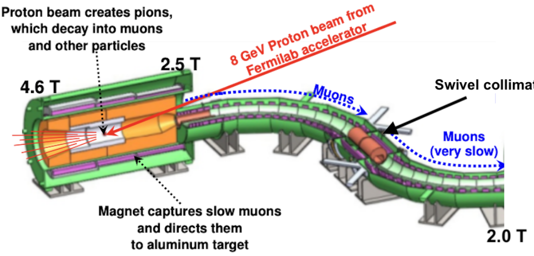
- Must resist to $6 \cdot 10^{12}$ protons/s
- Sufficiently high cross section for pion production
- Since it will absorbs about 10% of the 7.3 kW proton beam needs gaps and fins to help heat dissipation
- Needs to cope with thermal shocks due to pulsed
- proton beam
- Needs to have sufficient radiation hardness to last for one year in beam
  - robotic replacement takes 1-2 months

Production Solenoid Status

Production Solenoid arrived at FNAL in June 2025, and was lifted into Mu2e hall August 2025:

Heat- and Radiation Shield (HRS) has been inserted into PS.

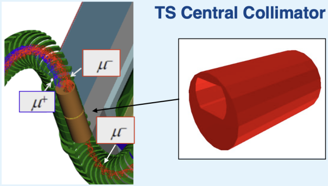
Transport Solenoid



Muons are transported in the s-shaped **Transport Solenoid**:

- small magnetic field gradient to avoid trapped particles
- thin absorber window to reduce antiproton background
- internal swivel collimators to select -/+ particles of wanted momentum

TS Central Collimator



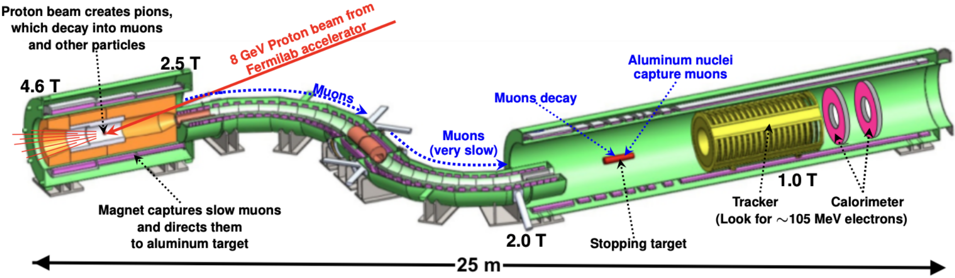
- Negative and positive particles have a different trajectory → central collimator **can choose particle charge**: absorbs the positively charged particles (blue) while allowing the negatively charged particles within a particular momentum window to pass through.
- **can be rotated**, allowing positively charged beam to be delivered to the Detector Solenoid for purposes of calibration.
- Embedded in the middle there is a thin window made of low-Z material **to absorb slow moving antiprotons** created in the pion production target

Transport Solenoid Status

S-shaped **Transport Solenoid** arrived at FNAL in Dec 2023 (upstream part) and Feb 2024 (downstream part):

- ✓ it is installed in final position in Mu2e hall
- ✓ the central rotating collimator installed and tested
- ✓ upstream and downstream part are welded together
- × Installation of Antiproton absorber blade planned
- × Cryogenic system connection in progress

Detector Solenoid



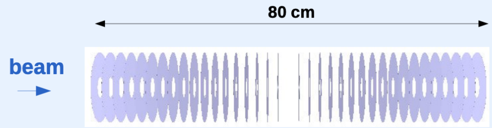
Muons enter the **Detector Solenoid** (which houses the stopping target and the detectors) and are stopped on aluminum target foils:

- stopped muons either decay in orbit (DIO) or are captured by the Al nucleus
- electrons from the decay/conversion process are detected by a **tracking detector and a calorimeter**
- Magnetic field:
  - gradient in the target region to collect backward electrons
  - uniform in the detector region

Detector Solenoid Status: Not arrived yet, project estimate sets delivery for Mar 2026

Muon Stopping Target

Muons are slowed down and **stopped inside the aluminum discs** (then undergo muon capture, decay-in-orbit or direct conversion):



The stopping target:

37 foils of Al
105 μm thick
75 mm radius
22 mm central hole radius

- segmented geometry to reduce electron energy losses (improving momentum resolution)
- hollow geometry to reduce radiation in the detector

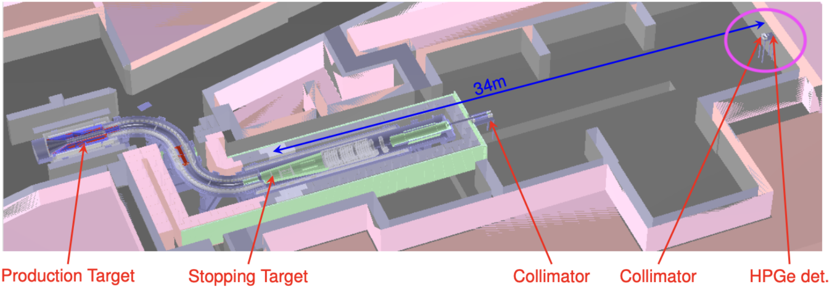
Why aluminum as stopping material ?

- Muon lifetime on $^{27}_{13}Al$ is 864 ns and matches the proton beam pulsing (1695 ns) $\Longrightarrow$ "Live Window"
- Studying the muon conversion on different nuclei may give NP complementary information
- Other options: Titanium Ti (Z=22)

Stopping Target Monitor (STM)

Goal: Count muons that stops in the stopping target

- Two detectors:
  - → solid state high-purity Germanium detector (high-precision)
  - → scintillating $LaBr_3$ detector (high-rate)
- Located ≈ 34 m downstream of detectors, measures photons emitted during muon capture in Al

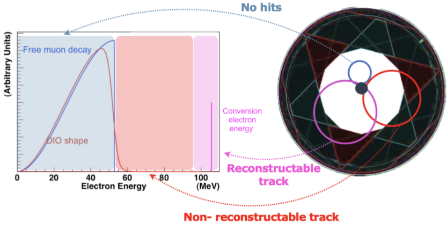


- measure X- and γ-rays from muonic Aluminum
  - 347 keV 2p-1s X-ray (80% of muon stops)
  - 844 keV delayed γ-ray (5% of muon stops)
  - **1809 keV** γ-ray (30% of muon stops)
- line-of-sight view of Muon Stopping Target
- behind tungsten collimator with 1 cm^2 holes

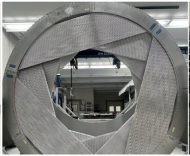
Tracker

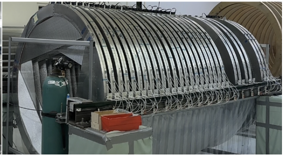
Goal: Measure the momentum of conversion electrons

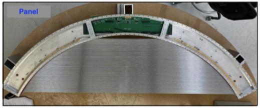
- **low-mass detector** to reduce energy loss and multiple scattering
- **annular geometry** to reject most of DIO electron tracks.
- **excellent momentum resolution** of up to 180 keV/c.



- composed of 18 stations
  - → each **station** is made up of two planes
  - → each **plane** consists of six panels
  - → each **panel** contains 96 straws.
- **straws:** 25 μm diameter gold plated tungsten sense wire centered in a 5 mm diameter aluminized mylar tubes
  - → straw lengths from 40 to 120 cm.
  - → filled with Ar:Co_2 (80:20)

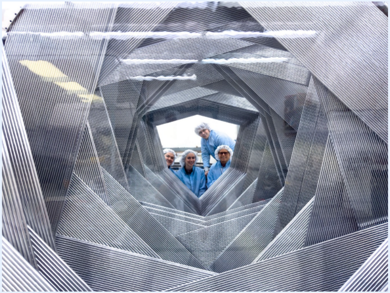


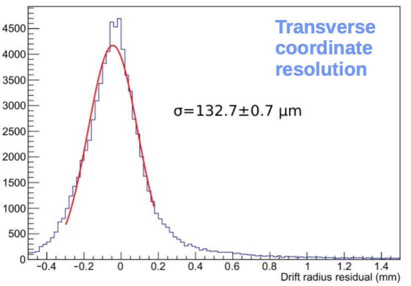


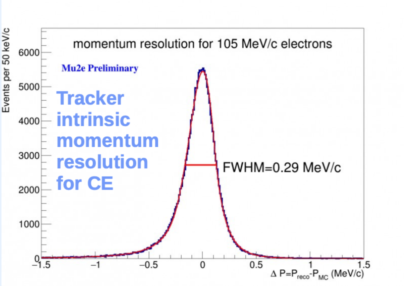


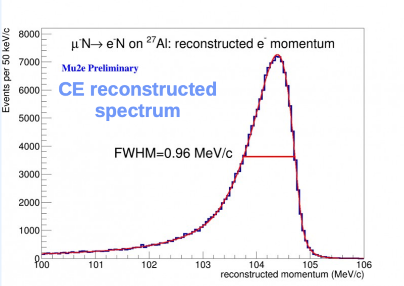
Tracker Status: All stations assembled, planned to move to the hall Nov 2025

Tracker: expected performances

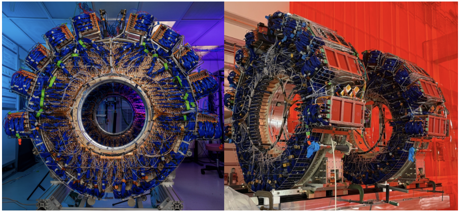






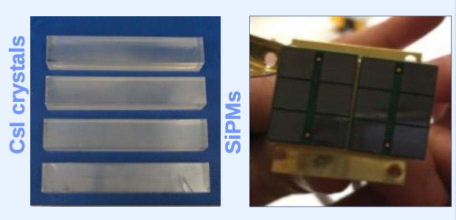


Calorimeter

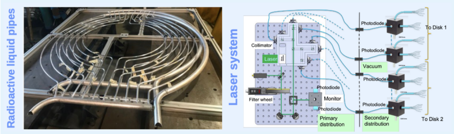


Goal:

- provide 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

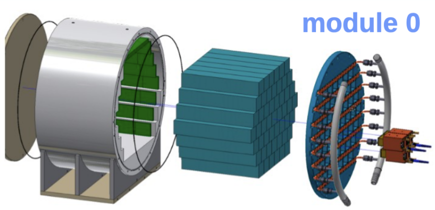


- compose of **two rings** separated by 70 cm (half a wavelength of signal electron trajectory helix)
  - → each ring composed of ~ 700 pure **CsI crystals read out by SiPMs**
- **Calibration** with activated liquid source + laser system for energy and time calibration



Calorimeter Status: Construction completed, moved to the hall in September 2025; cosmic ray runs underway

Calorimeter: test beam performances



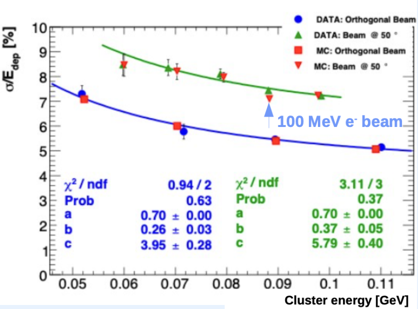
A **module 0** prototype with

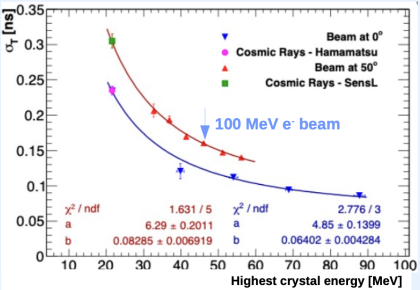
- 51 crystals
- 102 SiPMs+FEE boards
- a commercial digitizer
- Cooling lines for SiPMs

The 2017 test with a beam in Frascati has measured for 100 MeV e- with 50° impact angle*:

$\sigma_E/E = 7.3\%$

$\sigma_t/t = 230$ ps (only 1 sensor)



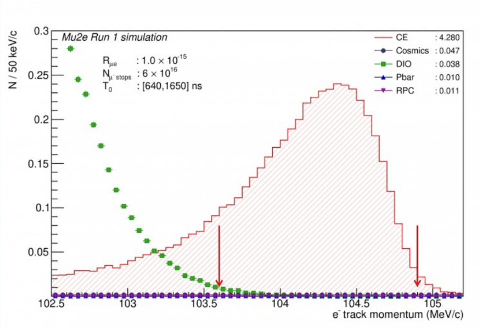


* *"Electron beam test of the large area Mu2e calorimeter prototype", J.Phys.Conf.Ser. 1162 (2019) 1, 012027*

Detectors: background rejection expected performances

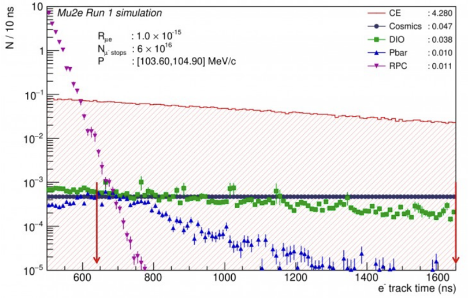
Electron momentum: Decays in Orbit suppression

- **Decay In Orbit (DIO)** spectrum falls as $(E_{max}-E)^5$ close to the end point
- Suppressed by the momentum window cut



Electron time: radiative pion capture suppression

- **Radiative Pion Captures (RPC)** in the Al target produce photons that convert into e^+e^- pairs
- **Delayed pions** coming from antiproton annihilation constitute another background source
- Suppressed by the time window cut

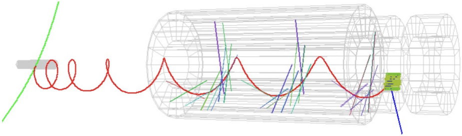


Time and momentum windows have been optimized to get the best discovery sensitivity

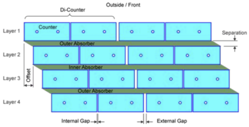
Cosmic Ray background and Cosmic Ray Veto

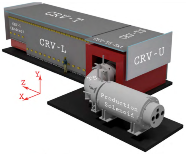
Cosmic ray tracks can mimic a 105 MeV/c electron track

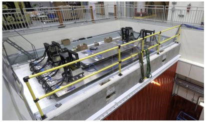
→ cosmic muon can decay or knock out electrons from detector material



- to reduce and detect cosmic ray events: **Cosmic Ray Veto (CRV) System**
  - → four layers of scintillators with embedded WLS fiber and SIPM readout, separated by aluminum absorbers.
  - → surrounded by 1 m of concrete that serves as passive shielding
  - → covers the entire Detector Solenoid and part of the Transport Solenoid







- Without a CRV: 1 signal-like cosmic ray event per day !

CRV Status: All modules built; modules for cosmic ray run placed in the hall.

Timeline: 2025/2026

Beam commissioning run:

- beam established on Muon Campus at the beginning of May 2025
- 2 months run completed in July very successful run!
- ready for startup a 7 months commissioning in 2026

Cosmic ray data-taking:

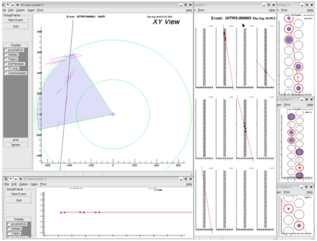
- Cosmic rays are used to commission tracker, calorimeter and CRV
- This allows to perform noise studies and commissioning of the DAQ infrastructure

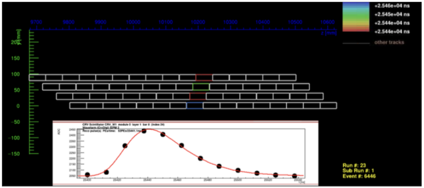
Done in 2025:

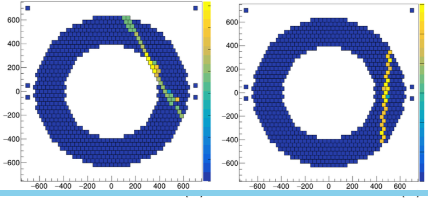
➔ Injection understood and improved
➔ Profile monitors in M4 beamline are commissioned
➔ Extraction frequency improved
➔ Spill regulation system was commissioned
➔ Resonant Extracted beam with full ESS splitting voltage to the M4 diagnostic absorber established

To do in 2026

- Improve machine acceptance, center the orbits







Timeline: 2027/2028

- Mu2e Run1 will begin in 2027, collecting data until the long shutdown at FNAL in January 2028
- Run-1 plan assumes running with a low intensity beam, followed by a slow ramp-up at high intensity for ~ 4 months running time.

Mu2e expected sensitivity for Run 1

Given the very low background level a **5σ discovery** will require Mu2e to observe just **5 events** of muon conversion

The $R_{\mu e}$ corresponding to a **5σ discovery** in Run 1 is:

$$R_{\mu e} = 1.1 \cdot 10^{-15}$$

Mu2e Run 1
5σ discovery

If no events will be observed the **90% CL limit** will be:

$$R_{\mu e} < 6.2 \cdot 10^{-16}$$

Mu2e Run 1
90% CL limit

that is more than **x1000 better** than current best limit!

If DS preparation slips of few months: minimize CRV installation .. reach x 100 sensitivity

Summary and Outlook

- **Mu2e at Fermilab will search for the SM forbidden CLFV process** of a muon converting to an electron, to largely improve current sensitivity
- The detectors and solenoids construction is well progressed: **Cosmic Ray commissioning is planned for next year**.
- **Mu2e Run I** is expected to start in 2027 and to improve Sindrum II sensitivity by a factor 10^3.
- **Mu2e Run II** will start after the shutdown for neutrino beam upgrade (presumably in 2029) aiming to achieve the final 10^4 improvement goal.
- A **Mu2e upgrade proposal (Mu2e II)**, inserted in the Snow Mass white paper (arXiv:2203.07569v2), aims to exploit the higher intensity and lower energy PIP-II proton beam to obtain a further $\times 10$ improvement in sensitivity.

Thanks!