Mu2e at Fermilab : Charged Lepton Flavor Violation (CLFV) Experiment

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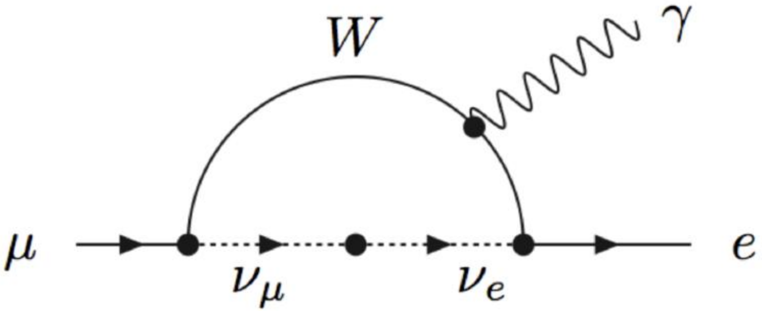
Motivation : CLFV

Quarks mixing : CKM matrix

Neutrinos mixing : PMNS matrix

The mixing in the charged leptons is not forbidden and Charged Lepton Flavor Violation is therefore expected!

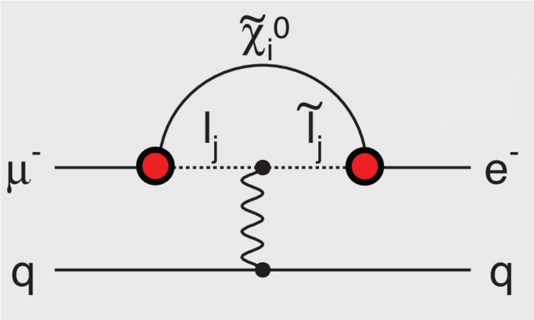
- As per standard model :



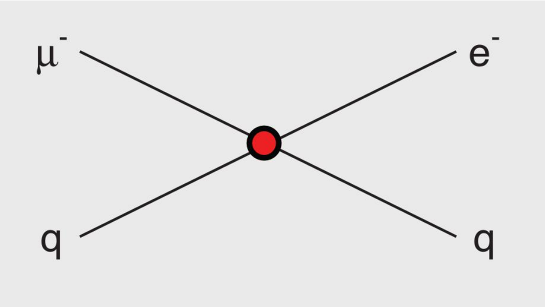
$$\underbrace{BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2}_{\text{Highly suppressed!!}}$$

- However, various physics models (BSM) shows an enhancement in the branching ratio for the CLFV processes which are within the level of measurement capabilities.

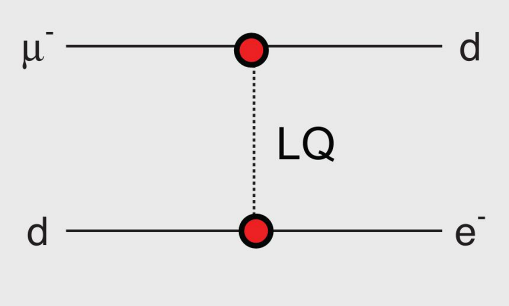
Different theoretical models for the CLFV



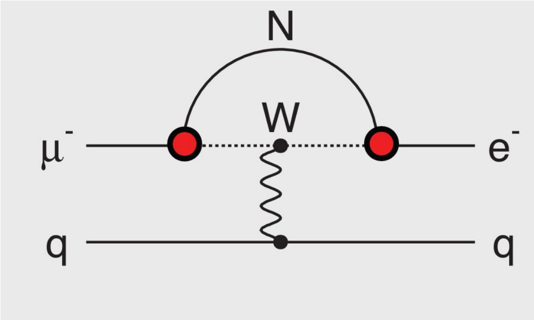
Supersymmetry



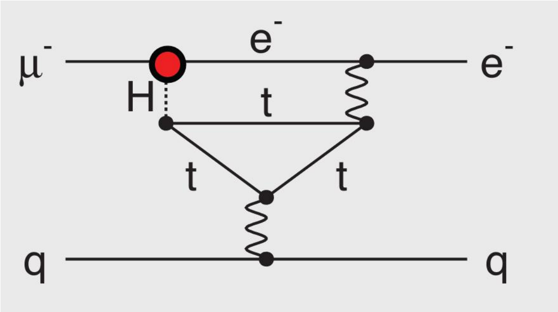
Compositeness



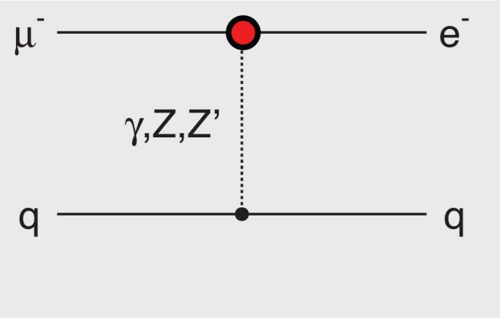
Leptoquark



Heavy Neutrinos



Second Higgs Doublet



Heavy Z' Anomal. Z Coupling

Diagrams originally by W. Marciano

CLFV signatures

In muon sector, different experiments have been looking for different CLFV channels mainly :

$\mu^+ \rightarrow e^+ \gamma$, $\mu^- N \rightarrow e^- N$, $\mu^+ \rightarrow e^+ e^- e^+$

- $\mu^+ \rightarrow e^+ \gamma$:
  - Back-to-back **positron and photon**
  - Monoenergetic: E ≈ 52.8 MeV each
  - Coincident in time

- $\mu^- N \rightarrow e^- N$:
  - **Monoenergetic electron** (E ≈ 105 MeV)
  - Electron emerges from stopped muon in material

- $\mu^+ \rightarrow e^+ e^- e^+$:
  - **Two e^+s and an e^-** : Three charged tracks from common vertex
  - no neutrinos
  - Invariant mass = m_μ

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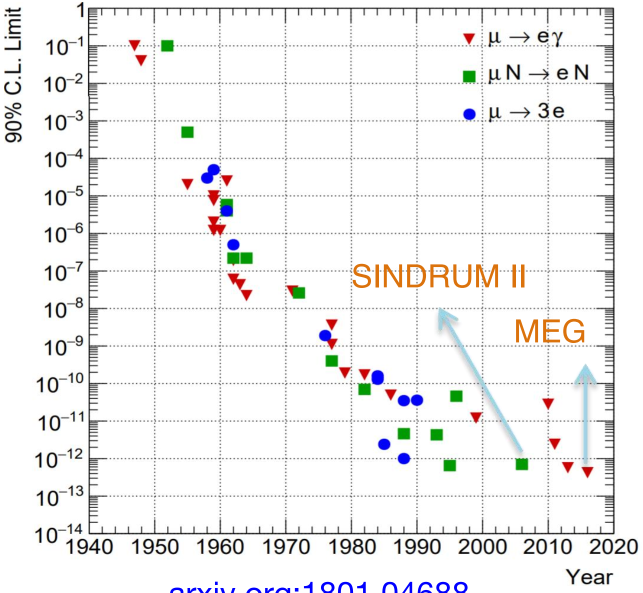
CLFV channel's history

Clearly, overtime a significant improvement on the the upper limits of the CLFV processes have been observed due to improved techonlogies and the upgraded detector systems.

Latest results from MEG-II : Upper limit of 1.5×10^{-13} at 90 %CL!!

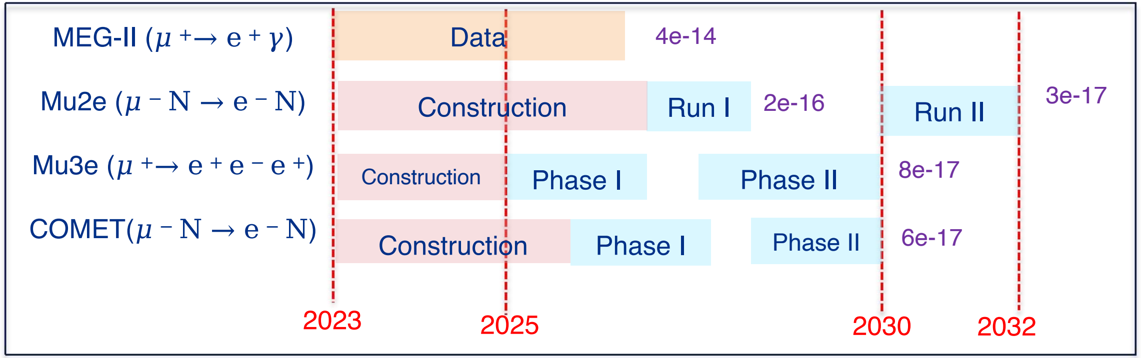
(arXiv:2504.15711v, 22 April 2025)

Chronology of upper limits on CLFV processes



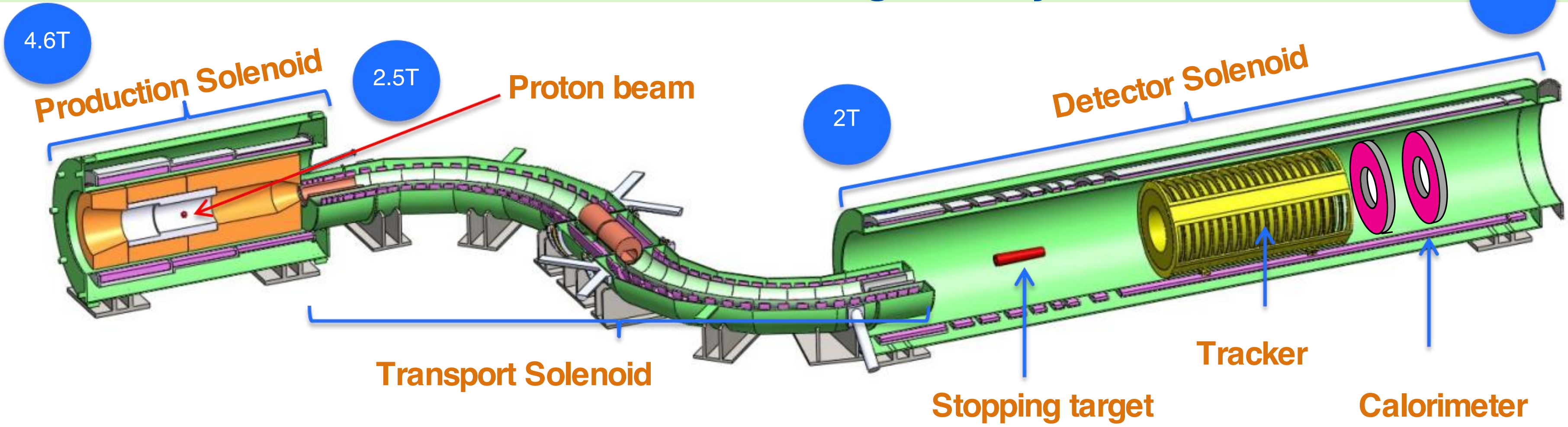
arxiv.org:1801.04688

A few upcoming CLFV experiments with expected timeline



arxiv.org:2210.04765

Mu2e : Overall geometry

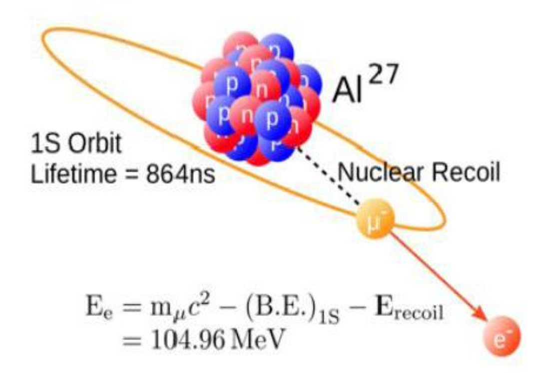


- Superconducting Solenoids (PS, TS and DS)
- Proton beam : 8GeV K.E. at 8kW power
- The solenoids magnetic fields

Mu2e signal

- When muons stopped in Al, a muonic atom is formed. 61% undergo nuclear capture, 39% decay in orbit.
- Neutrino-less conversion of a negative muon to an electron in the presence of a nucleus

$$\mu^- + {}^{27}Al \rightarrow e^- + {}^{27}Al$$



- Signal : Monochromatic energy electron

$$E_{e-} = M_{\mu-} - E_b - E_{recoil} = 104.96 \text{ MeV}$$

- Mu2e aims to improve the current upper limit on the sensitivity by **four orders of magnitude**

$$R_{\mu e} = \frac{\mu^- N \text{ -> } e^- N}{\mu^- N \text{ -> all muon captures}}$$

Current upper limit on $\mu^- N \rightarrow e^- N$ is set by SINDRUM II (Au target)* $R_{\mu e} < 7\times10^{-13}$ (90% CL)

*W. Bertl et al., Eur.Phys.J. C47,337 (2006)

Improvement factor of 10^4

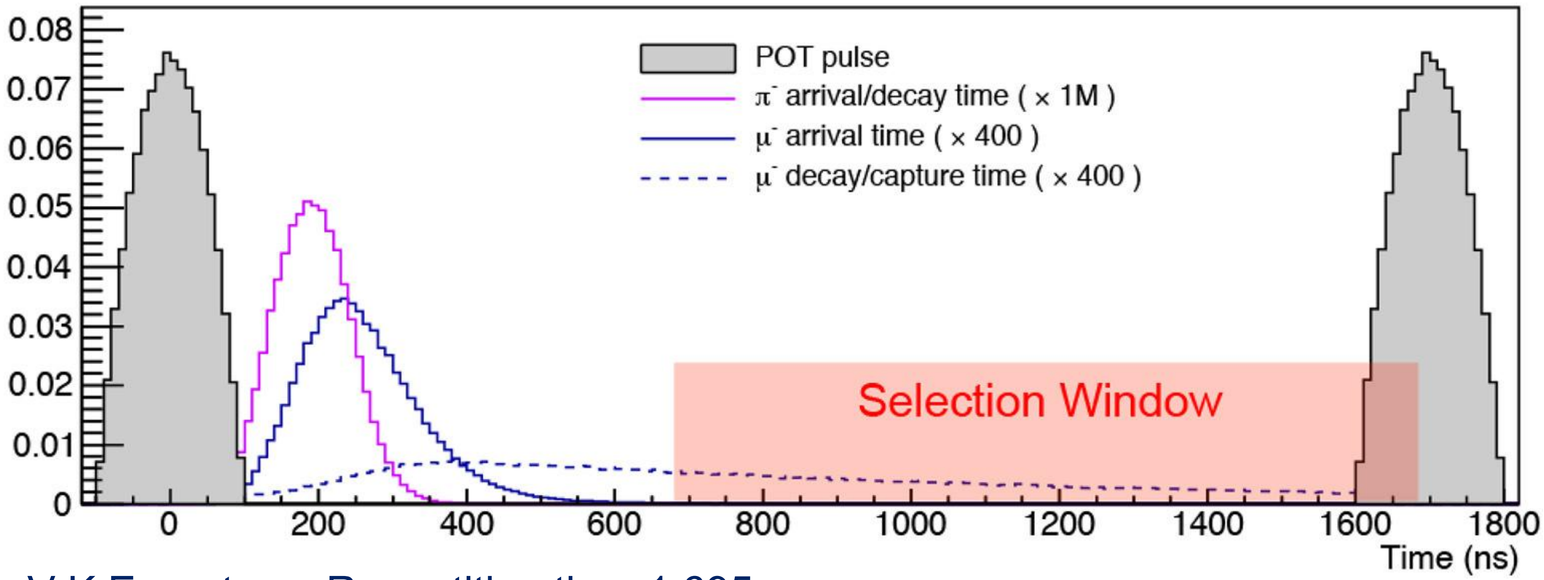
To achieve the improvement factor of 10^4 on the current upper limit, the key points are :

- Higher statistics :
  - Requires 10^{18} stopped muons, will be achieved using high intensity FNAL muon beam
  - Solenoid system for the formation of sign selected muon beam
- Suppress background :
  - High precision detectors to reduce the backgrounds coming from Decay In Orbit (DIO) electrons and cosmic background
- Pulsed beam structure :
  - Reduce prompt backgrounds from Radiative Pion Capture (RPC), muons or pions decay in flight or the beam electrons
  - Good extinction

Pulsed beam structure

Beam related background : Radiative Pion Capture (RPC), muons or pions decay in flight, beam e^-s

» **Solution** : **Pulsed beam**



- 8 GeV K.E. protons, Repeatition time 1,695 ns.
- The signal window starts after 700 ns of the pulse arrival, the loss is acceptable at the start of the window as the muon lifetime (in Al) is 864 ns
- Significant reduction in the prompt background (~10^{11}).

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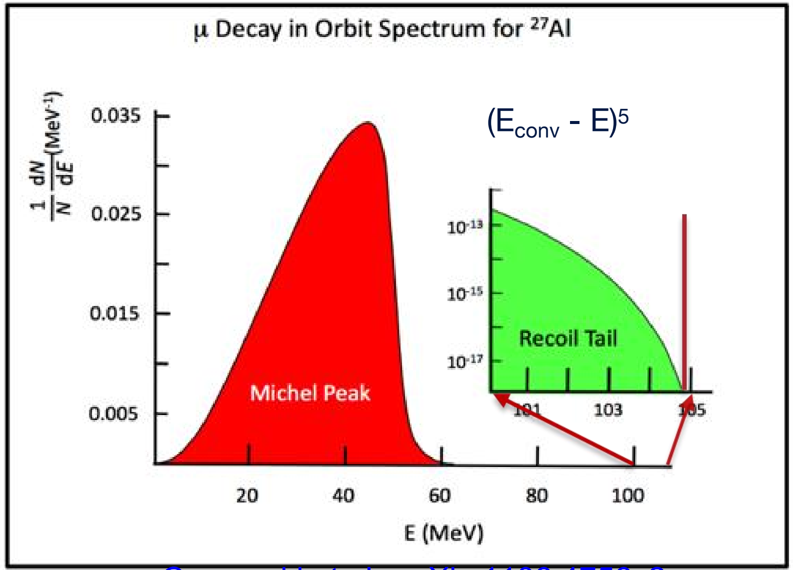
Background

Intrinsic background : Decay in Orbit (DIO) electrons

- No background from the free muon decay
- The electrons from decay of a bound muon can have final energy equal to the conversion energy
- Need to separate the signal e^- from the tail of the DIO e^-
- **Solution** : Tracker with momentum resolution ~ 180keV/c



Czarnecki et al., arXiv:1106.4756v2

Cosmic background :

- Cosmic muon can produce an e^- with signal e^- energy
- ~ 1signal like event/day is expected in absence of the suppression
- **Solution** : Cosmic Ray Veto system is required with 99.99% veto efficiency

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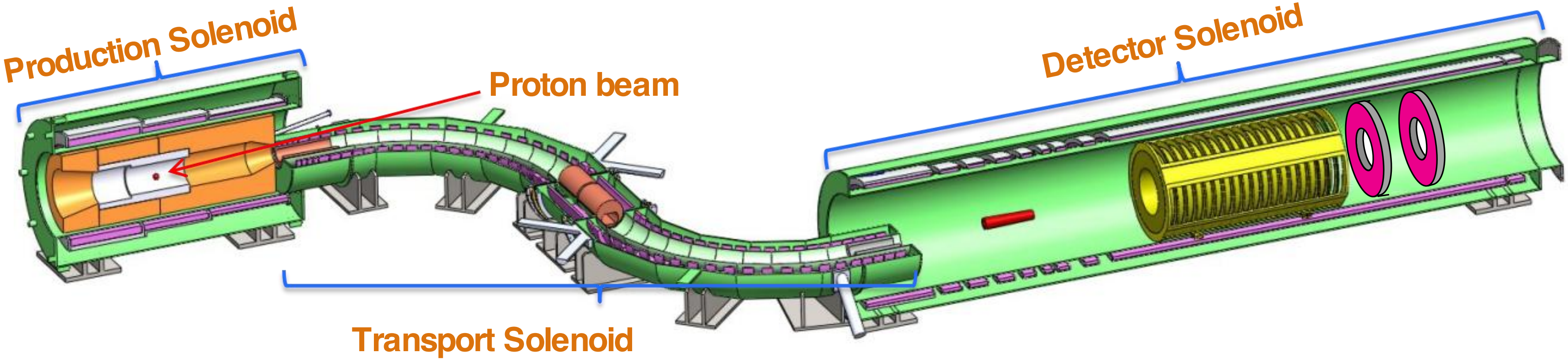
Detector installations and their current status

Mu2e Solenoids



Production Solenoid (PS) :

- Contains production target, mostly produces pions from the interactions
- Directs outgoing muons and the undecayed pions to the transport solenoid (backward direction)
- Overwhelming flux of particles from the interactions and the leftover incoming proton beam gets aborbed in the forward direction

Transport Solenoid (TS) :

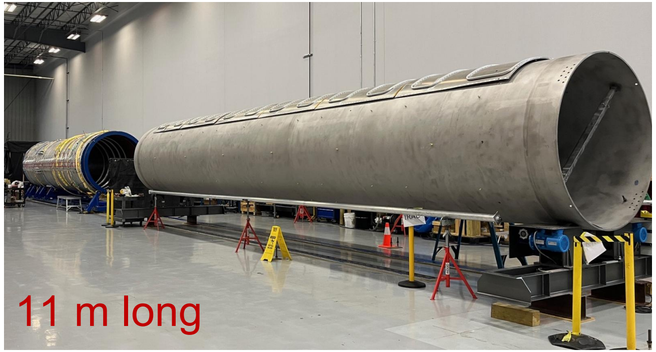
- Three collimators : at the entrance, center and the exit COL1, COL3, COL5
- ‘S’ shape (curved magnetic field) causes charge dependent drift and will transmit only negative charged particles further
- Rotatable COL3 collimator selects the beam sign, and low momentum particles

Detector Solenoid (DS) :

- Houses the stopping target, tracker and the calorimeter
- The graded field in the upstream region of the DS causes the signal electrons to be pitched forwards towards the acceptance of the tracker
- The downstream region of the DS have a uniform field of 1T

Mu2e Solenoids : Current status

Production Solenoid



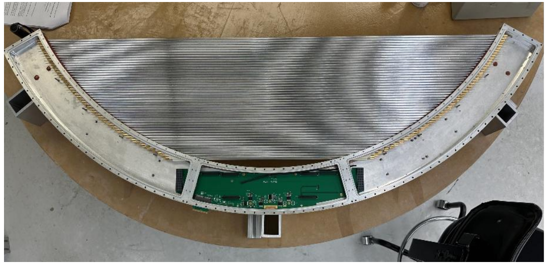
Detector Solenoid

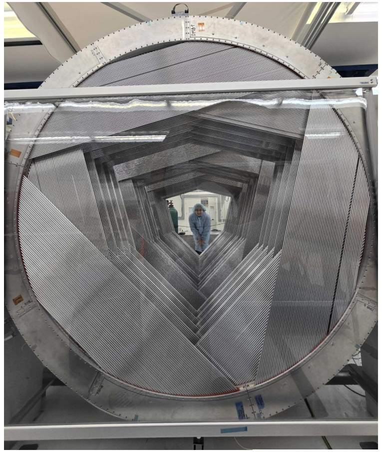
Transport Solenoid : Installed (Mu2e hall)

Tracker

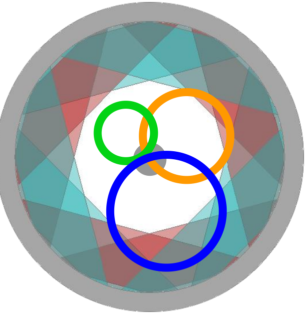
Straw tube tracker :

- Main detection element for the signal electrons
- High resolution and minimum energy loss >> Straw tubes : Low mass, short drift times, good resolution
- 25μm gold plated tungsten sense wire centered in a 5 mm diameter aluminized mylar tubes
- Two layers of straws to improve the efficiency
- Readout on both side to determine position along the straw
- **Tracker :18 stations**





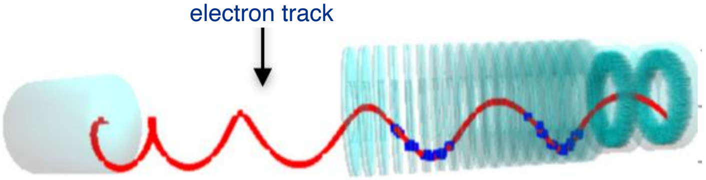
p = qBR



Free muon decays, maximum momentum of 52.8 MeV/c : too small to produce hits

Most of the higher momentum DIO electrons have too low a momentum to be successfully reconstructed as well

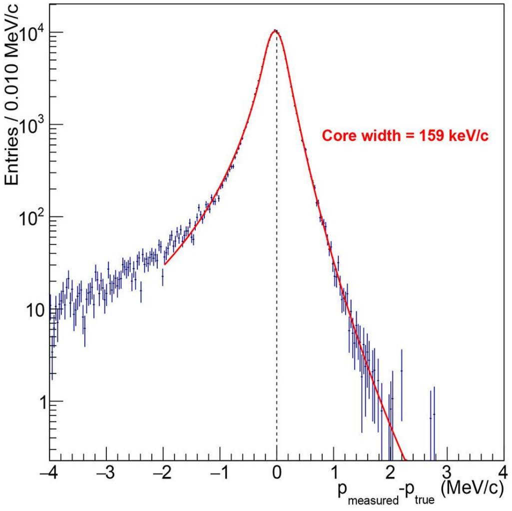
Conversion energy electron



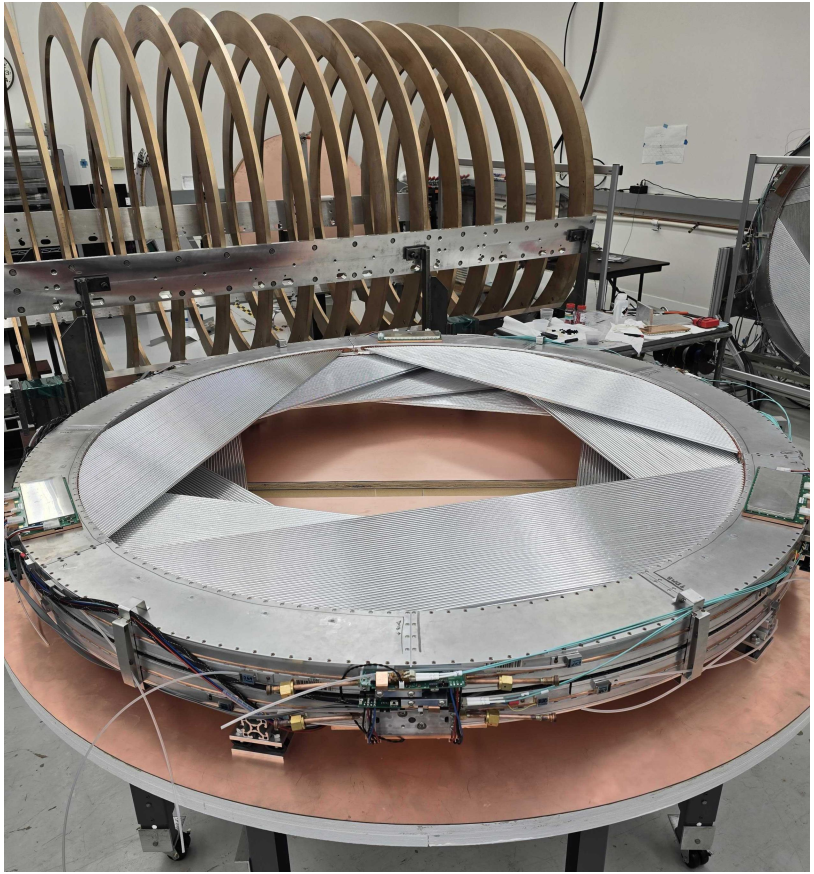
Tracker - Current Status

- The backgrounds (specially due to DIO) sets the requirement to have excellent momentum resolution ~180keV/c.
- The asymmetric low side tail is because of the stochastic nature of energy loss in the tracker.
- “Core resolution” : fit to the central part of the resolution

Momentum resolution (from simulations)



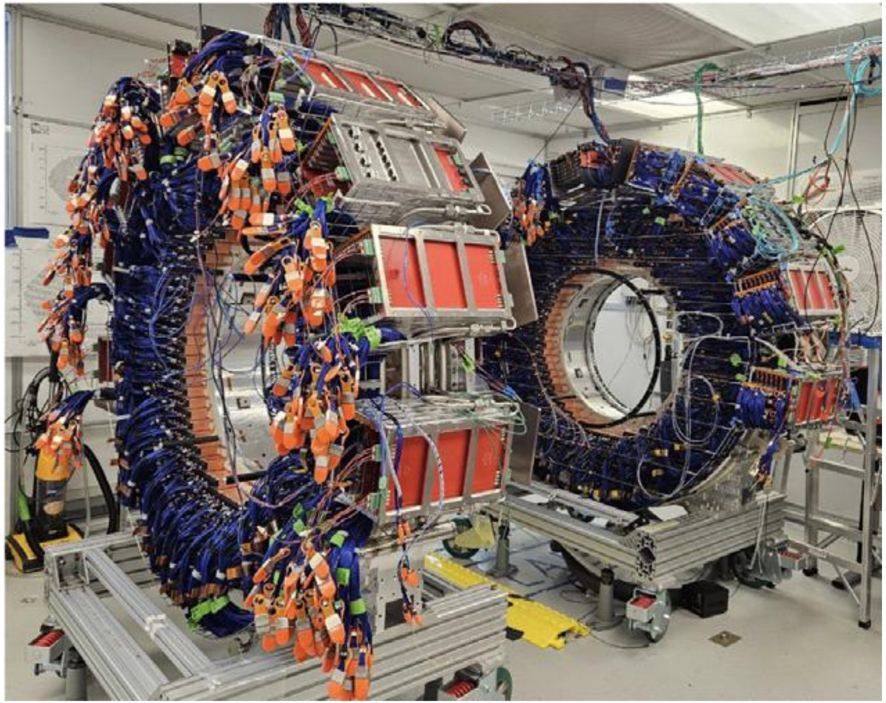
Courtesy : Mu2e Collaboration



- All the planes have been assembled and High Voltage Quality Control is performed.
- Electronics installations in progress
- 10 planes have been assembled into station, 5 stations ready
- Cosmic runs and noise runs are being taken with the first station
- Likely to be done by **September** this year

Calorimeter

- Consists of annular disks with a hole at the center for the passage of beam flash, remnant muon beam
- Each disk have CsI crystals readout by Silicon-photomultipliers



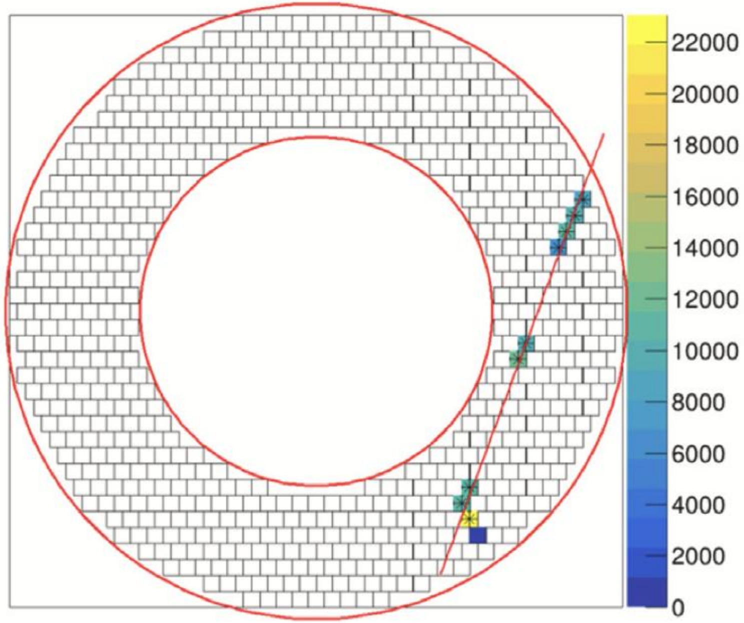
LNF INFN, ITALY

Purpose :

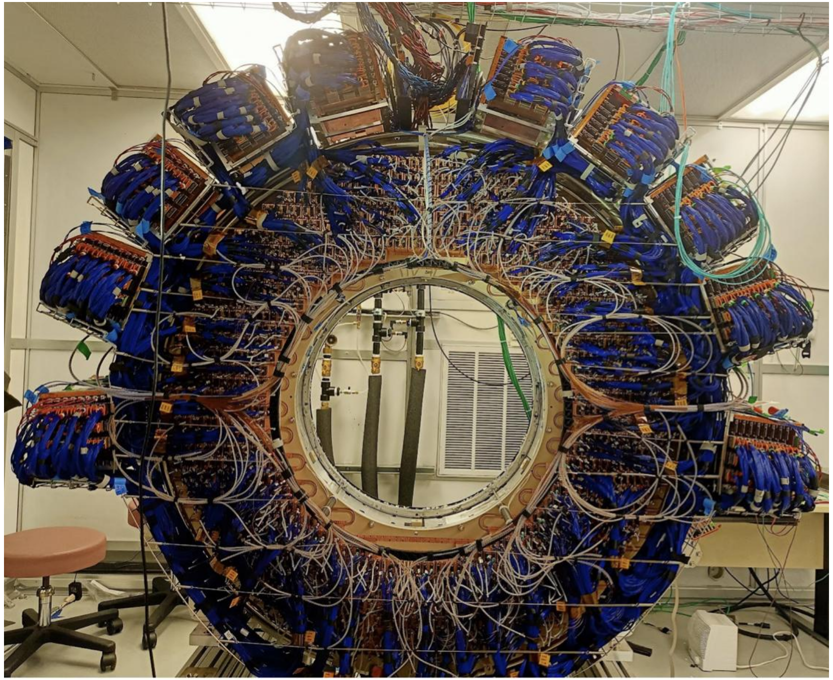
- Improves tracker reconstruction
    - (need <0.5ns timing resolution)
- Particle identification : e/μ separation
- Standalone trigger for the experiment

Calorimeter - Current status

- Caloimeter assembly is completed
- Electronics and FEE cable installations for both the disks are completed.
- Noise runs - baseline and threshold evalaution for zero suppression, noise or light leaks
- Laser runs and cosmic runs have been taken - Any broken fibres or dead channels.
- Likely to move in the Mu2e hall by **end of June** this year.

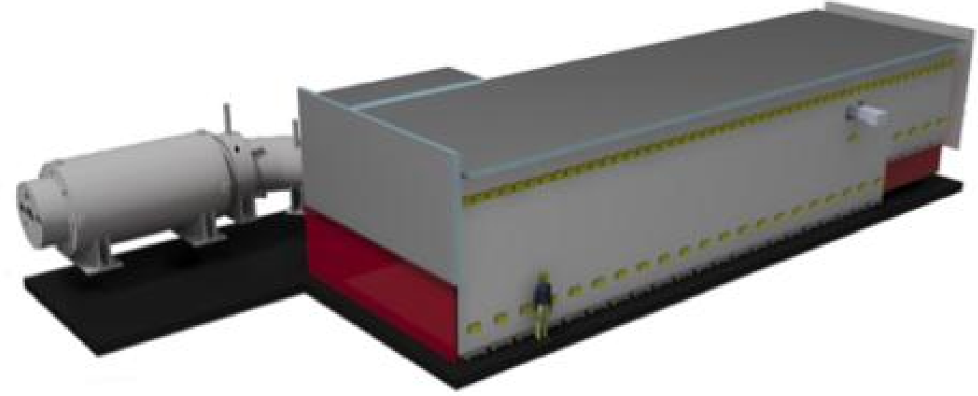


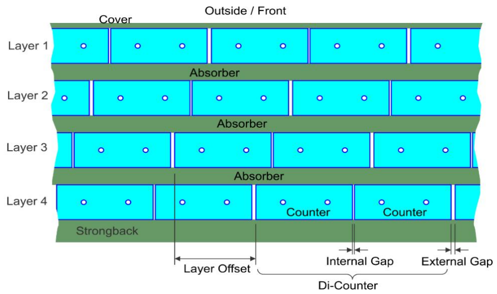
Cosmic ray event

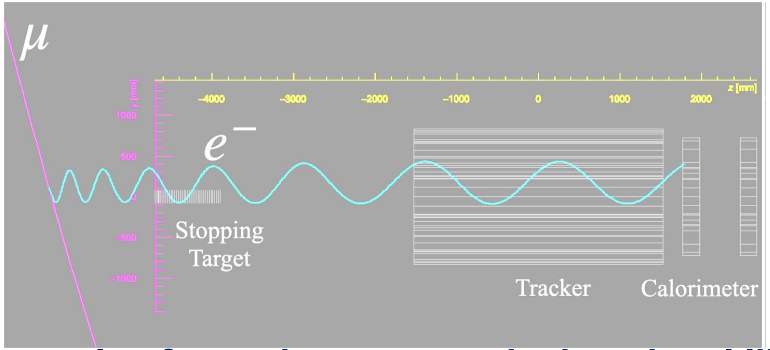


Cosmic Ray Veto (CRV)

- Eliminate the backgrounds from the cosmics
- Covers part of the TS and all of the DS
- Consists of extruded plastic scintillators (polystyrene based with a coating of TiO_2), WLS fibres and Hamamatsu SiPMs for the readout (on both sides).
- In absence of suppression, 1 signal like event/day is expected from the cosmics
- Mainly coming from the muons striking the detector, or beamline components, and knocking out electrons with signal like electron energies
- The veto efficiency should be 99.99% or better, so the experiment will use 4 layers of scintillators with some staggering to avoid the inefficiency due to the gaps.

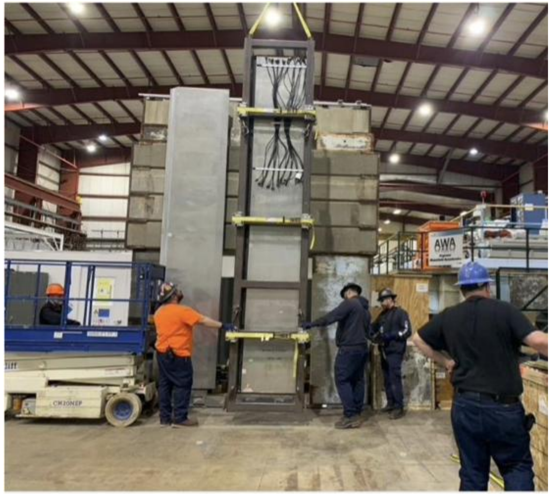


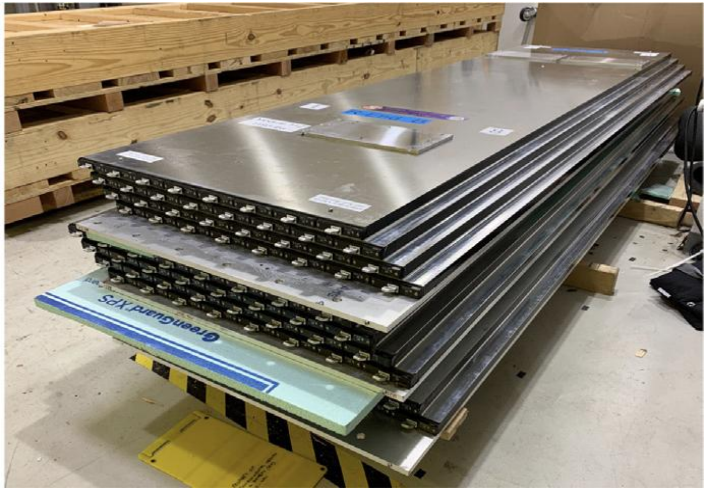




An example of cosmic muon producing signal like e-

Cosmic Ray Veto (CRV) - Current Status



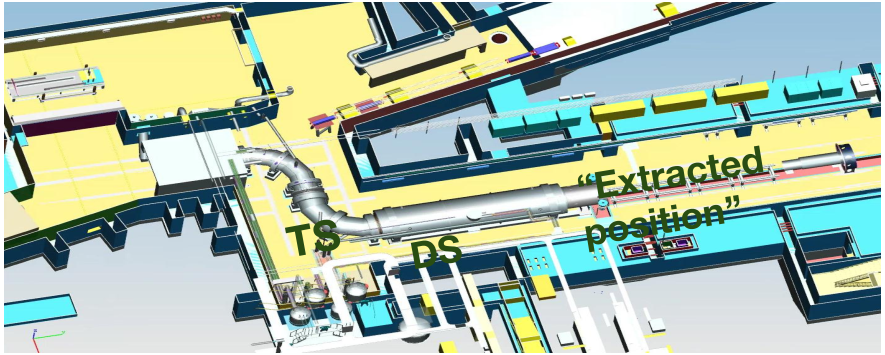


- All the counters (scintillator with fibre and SiPM) have been tested
- Support structure: design to be completed by late summer this year
- Installation scheduled for August-October 2026

Commissioning and run plan

Cosmic ray commissioning :

- Cosmic Run (**starting late June, 2025**) with Calorimeter and a fraction of CRV in the extracted position
- Tracker - September this year
- Test the functionality of TDAQ and the detectors
- Calibrate detectors in-situ
- Keep taking Cosmic data, while waiting for the beam



Solenoids commissioning and installation :

- DS and PS : Expected this year, TS in the hall

RUN 1 :

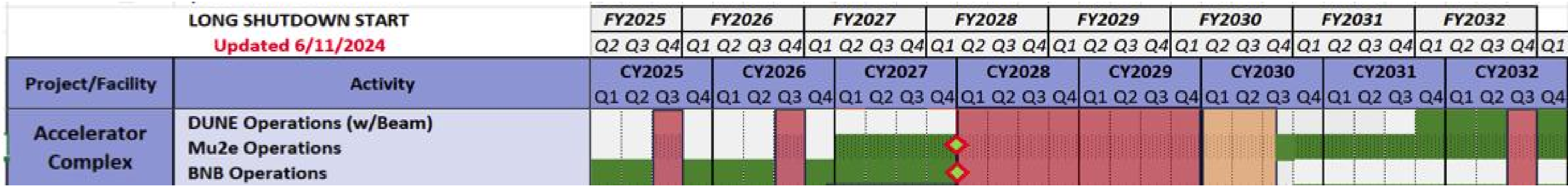
Expected to start in 2027

Long shutdown :

2 -year shutdown

RUN2 :

Expected to start in 2030



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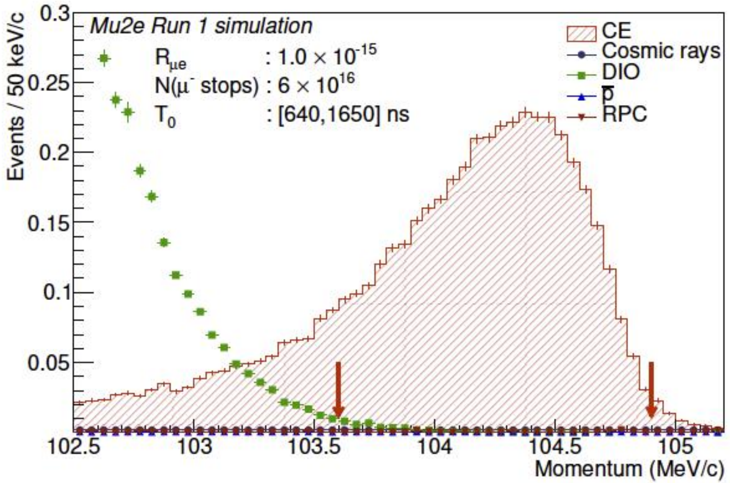
Expectations from Run-1

- RUN-1 with 10% of the total expected muon flux, improving the search sensitivity by three orders of magnitude. RUN-2 will further enhance the search sensitivity by another order of magnitude.

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



https://doi.org/10.3390/universe9010054

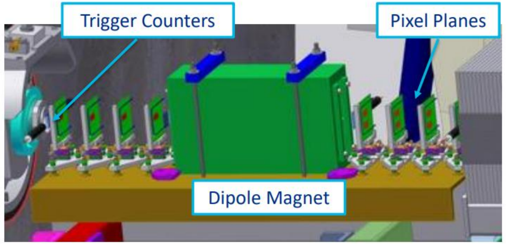
Summary

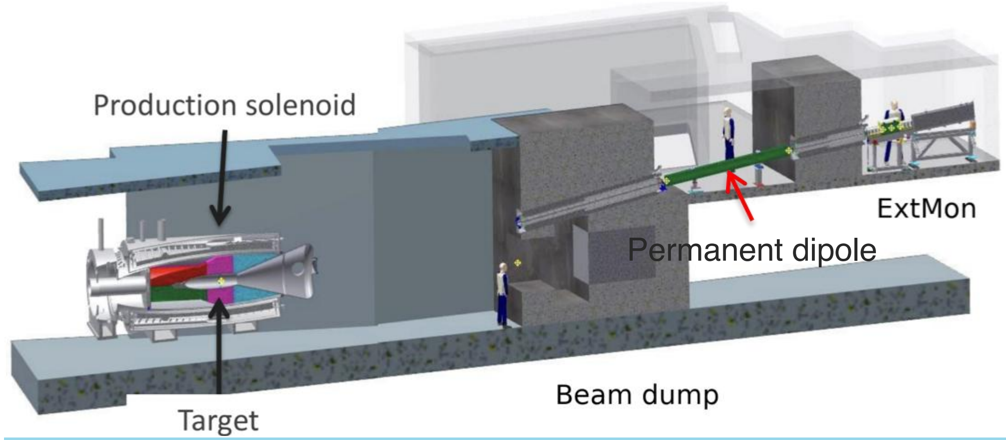
- Any detection of CLFV processes will be an indisputable evidence of the new physics beyond the Standard Model
- The Mu2e experiment aims to improve the current sensitivity for **$\mu^- \rightarrow e^-$ conversion** by four orders of magnitude
- One year commissioning run is expected to start in late 2025 followed by RUN-1 beam physics data collection in 2027 before the 2-year long shutdown
- RUN-1 goal is to collect 10% of the total number of Mu2e stopped muons, the simulation shows that it will improve the current sensitivity by O(1000)
- This will be a learning phase to get ready for reaching our goal in a long extended RUN-2 after the long shutdown.

THANK YOU !!

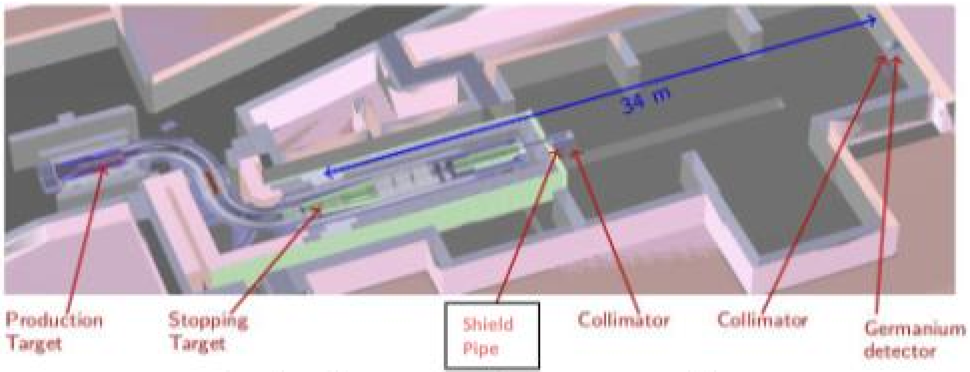
Extinction Monitor

- **Upstream EXTMON before the AC dipole** : A Cherenkov counter detector measures the single pulse extinction from the Recycler by looking at off-axis counts before the AC dipoles - **being commissioned**
- **Downstream EXTMON :** located above and behind the primary beam dump
  - Extinction filter : 2 collimators + a permanent dipole - select a p/pi beam of ~ 4 GeV/c
  - Silicon pixel sensors : 8 planes of pixels sensors, four upstream and four downstream of a bending magnet
  - Scintillators : Provide an extrernal trigger for the silicon pixels sensors and also dteremines the arrival time of out of time-partciles
  - It provides an average extinction value (not pulse by pulse) over ~ 8 hrs

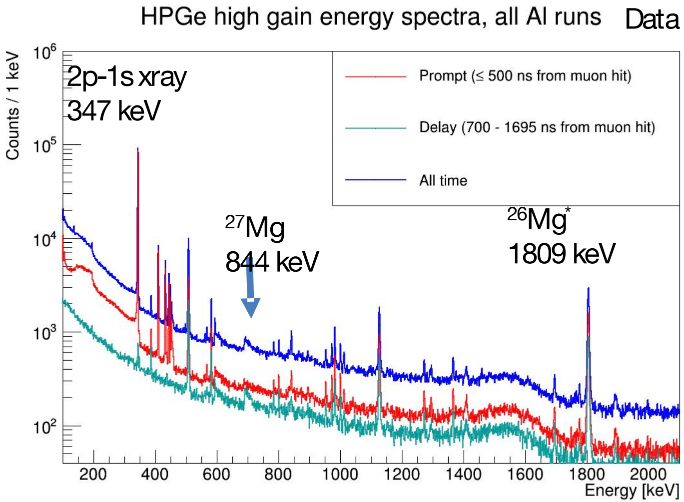




Stopping Target Monitor



Installed at the Mu2e hall



- Measurements : Muonic atomic transition 2p->1s X-ray and gamma lines associated with muon captures from the Stopping Target
- Detectors : High resolution, slow time response HPGe and lower resolution, faster time response LaBr3
- 34 m away from the target looking for 3 lines :
  - 347 keV "prompt"
  - 844 keV delayed
  - 1809 keV "semi- prompt"

Future plans

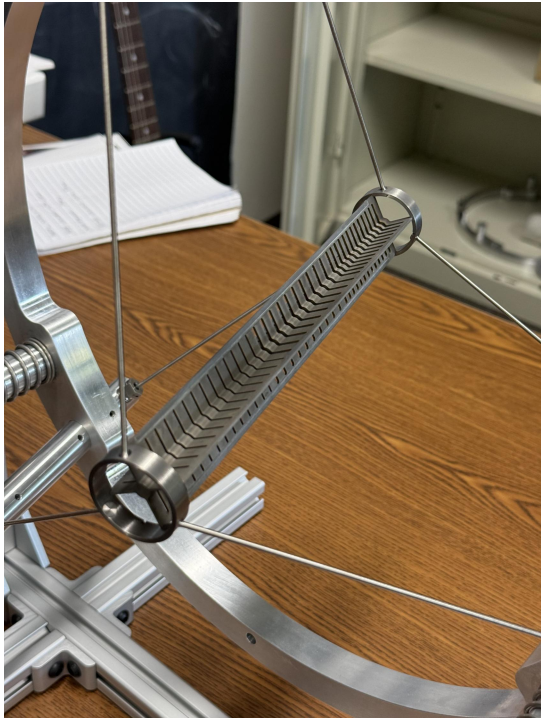
Mu2e II :

- Will Utilize the PIP-II linac at Fermilab, 800 MeV proton beam (100kW on target)
- Improve sensitivity by another two orders of magnitude beyond the level Mu2e will achieve
- Detector layout may remain unchanged but handling a more powerful beam while keeping the background under control requires significant changes :
  - Significant changes to PS and the shielding to handle higher rates
  - Improve tracker resolution to reject the muon DIO background
  - Calorimeter composed of crystals which would provide fast timing component
  - Upgrading CRV geomtery to reduce detection inefficiency

Advance Muon Facility (AMF) :

- Will also Utilize the PIP-II accelerator
- PRISM (Phase Rotated Intense Source of Muons) system to produce muon beam with well defined momentum

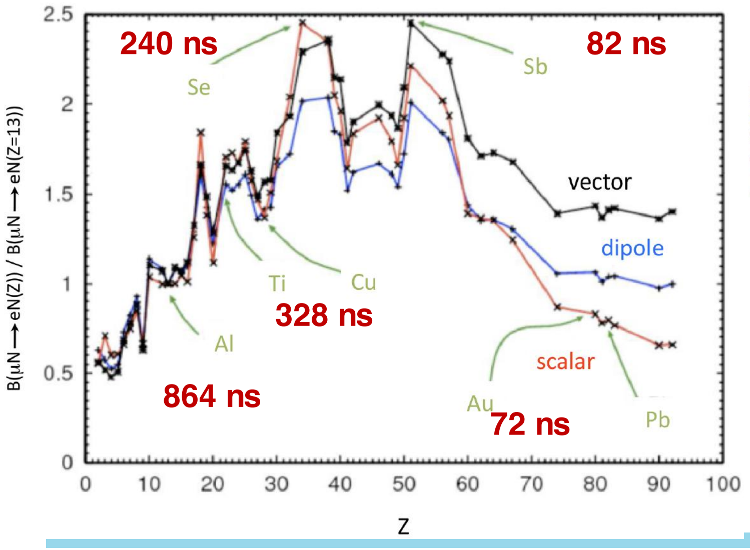
Production target

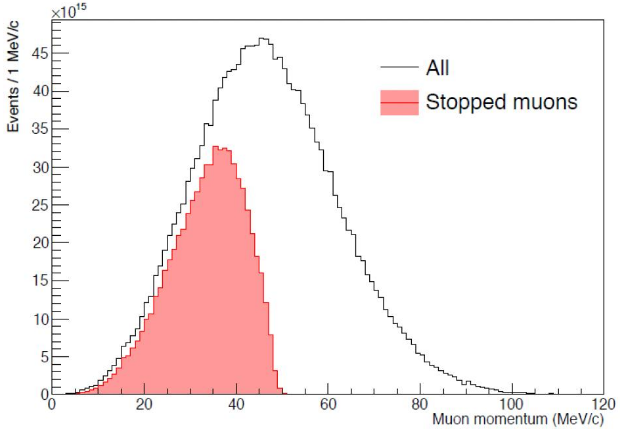


Stopping target

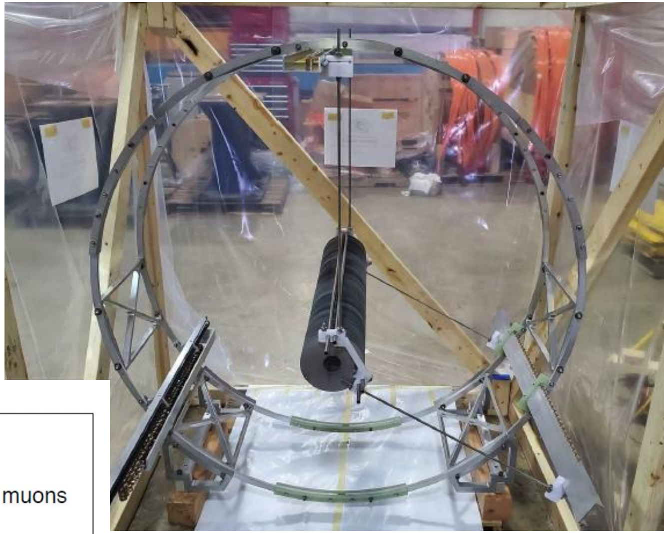
Purpose : Stop the muons coming from the low momentum muon beam

Requirements :
- At least 40% of the muons must stop in the target.
- The stopped muon lifetime should be long enough that we could avoid the prompt beam background and could still have enough muons to masure in the signal window.



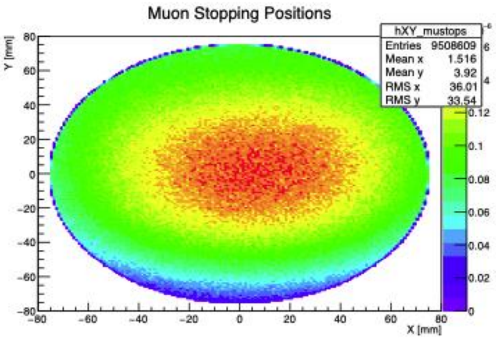


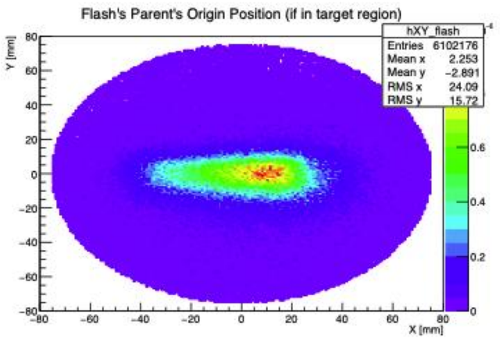
Aluminum

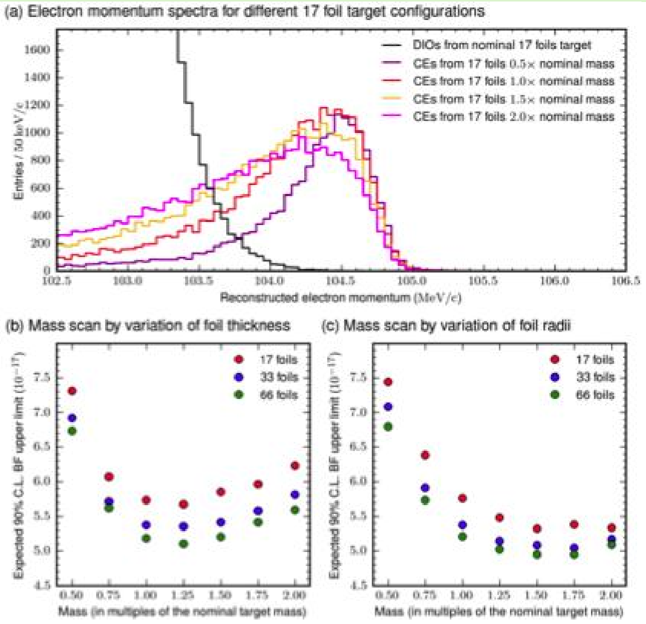


- 37 Al foils
- 100um thickness, Radius 75mm
- Length 740mm, Spacing 22.2mm,
- Supported by 3 mil gold plated tungsten wires

Backup : Stopping target







- Right side plot shows the parent origin position (in the traget) of the flash particles which are causing straw hits. We can see that the beam flash parent origin is much less broad in XY plane as compared to the muon stops in the XY-palne.
- Adding a hole to the center of the target - Cheap way to reduce the beam flash.

- Adding a hole, we lose only 3% muon stops for the last configuration and there is a 1% increase in muon stopping rate outside the target.

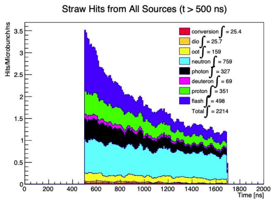


Figure 1.2: Time distribution of straw hits from all background components during the readout window ($t > 500$ ns).

Reason for the center hole : To reduce the problems occuring from the beam flash!!

Beam flash effects :

1. Track Reconstruction
2. Charge load on the tracker straws
3. Radiation damage in Tracker Electronics

Requirements and experiment design considerations

Reaction	Present limit	C.L.	Experiment	Year	Reference
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016	[48]
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988	[49]
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ †	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998	[50]
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$ †	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996	[51]
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ †	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006	[53]
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$ †	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998	[52]
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999	[54]
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010	[55]
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010	[55]
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010	[56]
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010	[56]
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007	[57]
$\tau \to \pi^0 \mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007	[58]
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011	[59]
$\tau \to \rho^0 \mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011	[59]
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$	90%	KTeV	2008	[60]
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998	[61]
$K_L^0 \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$	90%	KTeV	2008	[60]
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$	90%	BNL E865	2005	[62]
$J/\psi \to \mu e$	$< 1.5 \times 10^{-7}$	90%	BESIII	2013	[63]
$J/\psi \to \tau e$	$< 8.3 \times 10^{-6}$	90%	BESII	2004	[64]
$J/\psi \to \tau\mu$	$< 2.0 \times 10^{-6}$	90%	BESII	2004	[64]
$B^0 \to \mu e$	$< 2.8 \times 10^{-9}$	90%	LHCb	2013	[67]
$B^0 \to \tau e$	$< 2.8 \times 10^{-5}$	90%	BaBar	2008	[68]
$B^0 \to \tau\mu$	$< 2.2 \times 10^{-5}$	90%	BaBar	2008	[68]
$B \to K\mu e$ ‡	$< 3.8 \times 10^{-8}$	90%	BaBar	2006	[65]
$B \to K^*\mu e$ ‡	$< 5.1 \times 10^{-7}$	90%	BaBar	2006	[65]
$B^+ \to K^+\tau\mu$	$< 4.8 \times 10^{-5}$	90%	BaBar	2012	[66]
$B^+ \to K^+\tau e$	$< 3.0 \times 10^{-5}$	90%	BaBar	2012	[66]
$B_s^0 \to \mu e$	$< 1.1 \times 10^{-8}$	90%	LHCb	2013	[67]
$\Upsilon(1s) \to \tau\mu$	$< 6.0 \times 10^{-6}$	95%	CLEO	2008	[69]
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014	[70]
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995	[71]
$Z \to \tau\mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997	[72]
$h \to e\mu$	$< 3.5 \times 10^{-4}$	95%	LHC CMS	2016	[73]
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	95%	LHC CMS	2017	[74]
$h \to \tau e$	$< 6.1 \times 10^{-3}$	95%	LHC CMS	2017	[74]

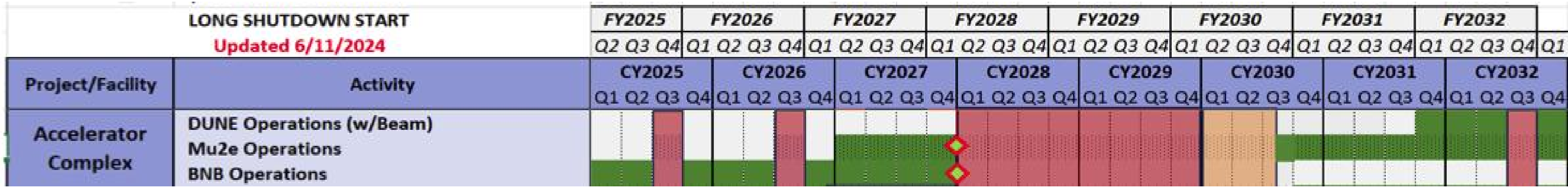
Most stringent limits are from muon to lectron conversion!!

FNAL beam

- Higher intensity FNAL beam
  - 400 MeV protons from the LINAC are injected into the **booster** where they are accelerated to **8 GeV** and grouped in batches
  - each 67 ms a **booster batch** is sent to the **Recycler Ring** (RR). Each RR cycle, lasting 1.33 s, there will be 12 batches available for Nova and 8 for Mu2e
  - initially RR will send 1 Mu2e batch, divided in 4 **bunches** of **10^{12} protons**, to the **Delivery Ring** (DR). In a second phase there will be 2 batches (8 bunches) for a total average intensity of **5.7 10^{12} protons/s**
  - DR bunches will be spilled **each 1.695 μs** to create the proton **pulses** directed to Mu2e beam line (M4)

- Solenoid system for the formation of muon beam, sign selected muons

Beam schedule



FNAL beam

Linac

Fermilab's linear accelerator, better known as the Linac, is a roughly 500-foot straight accelerator that brings proton beams up to energies of about 400 MeV, providing proton beam for the Booster accelerator and the rest of the chain of accelerators.

Booster

Proton beams enter the Fermilab Booster from the Linac, accelerating through its approximately 1,500-foot-circumference ring to an energy of 8 GeV. The Booster provides low-energy neutrino beam for the MicroBooNE experiment, as well as the Muon g-2 and Mu2e experiments. It also provides beam to the Recycler.

Recycler

The Recycler is a kind of staging area for proton beams after they exit the Booster. Once beam enters the Recycler, a 2-mile-circumference ring, it is "slip stacked" — combined into batches of protons to form a more intense beam. Once that is done, the proton beam enters the Main Injector, on top of which the Recycler sits. The Recycler also provides beams of particles called muons for Muon g-2 and, in a few years, for the Mu2e experiment.

Main Injector

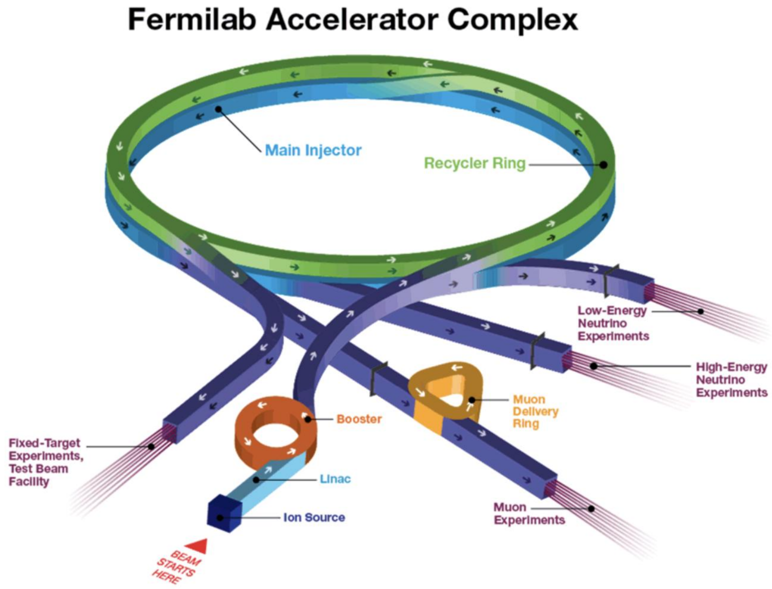
The Main Injector, situated directly beneath the Recycler in the same tunnel and two miles around, ramps up proton beam from the Recycler from 8 GeV to 120 GeV. The world's highest-intensity neutrino beams are generated from these proton beams. The Main Injector provides neutrino beams for the NOvA experiment, as well as the upcoming Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment.

Muon Delivery Ring

Some of the proton beam from the Booster will be used to produce pions in a specially designed target system. For the Muon g-2 and Mu2e experiments, these pions will then decay into particles called muons. The parent protons circulate through the 500-meter-circumference Muon Delivery Ring. The Muon Delivery Ring delivers these muons into a muon storage ring for further study.

Muon g-2 storage ring

After protons circulating through the Muon Delivery Ring (above) decay into muons, the muons are routed into the storage ring for the Muon g-2 experiment. The 50-meter-circumference electromagnet arrived at Fermilab from Brookhaven National Laboratory in 2013. Scientists study the muons in the ring to take a precise measurement of their precession rate, which can tell us about particles popping in and out of the vacuum of space-time.



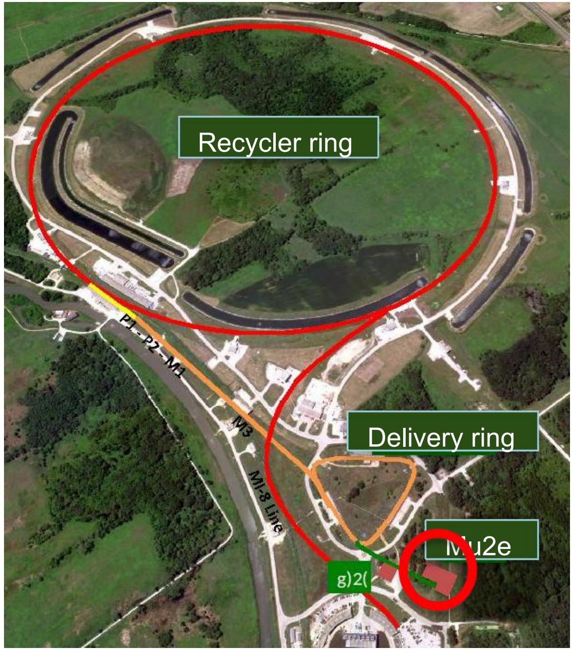
Fermilab

Improvement factor of 10^4

To achieve the improvemnt factor of 10^4 on the current upper limit, the experiment need to :

Collect 10^{18} stopped muons + Suppress background (< 1event)

- Higher intensity FNAL beam
  - 400 MeV protons from the LINAC are injected into the **booster** where they are accelerated to **8 GeV** and grouped in batches
  - **Booster batch** sent to the **Recycler Ring** (RR)
  - RR will send **bunches** of **10^{12} protons**, to the **Delivery Ring**
  - DR bunches will be spilled **each 1.695 μs** to create the proton **pulses** directed to Mu2e beam line (M4)
- Solenoid system for the formation of muon beam, sign selected muons



- Pulsed beam structure
- High precision detectors
- Proton extinction requirements

Fermilab

Improvement factor of 10^4

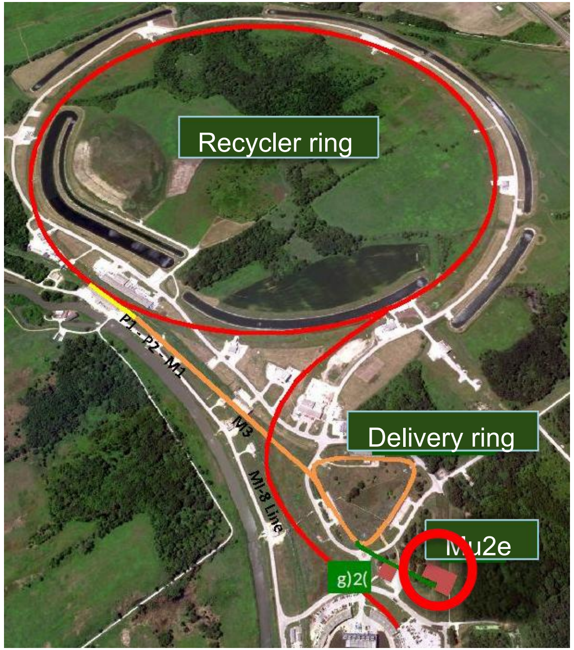
To achieve the improvemnt factor of 10^4 on the current upper limit, the experiment need to :

Collect 10^{18} stopped muons + **Suppress background (< 1event)**

- Higher intensity FNAL beam

400 MeV protons from LINAC → Booster : accelerated to 8 GeV → Recylcler Ring → Delivery Ring

- Solenoid system for the formation of muon beam, sign selected muons

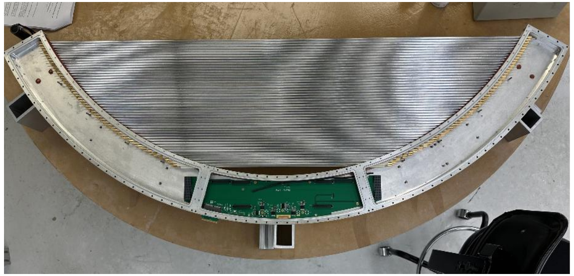


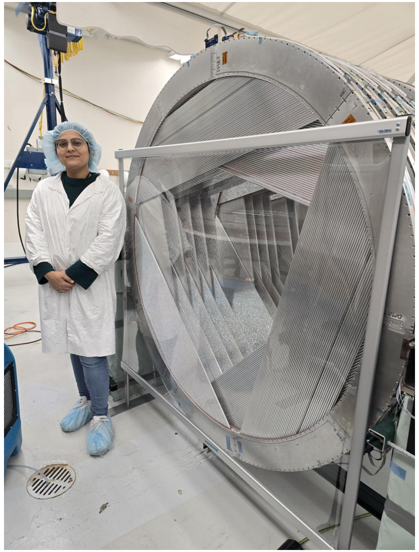
- Pulsed beam structure
- High precision detectors
- Proton extinction requirements

Tracker

Straw tube tracker :

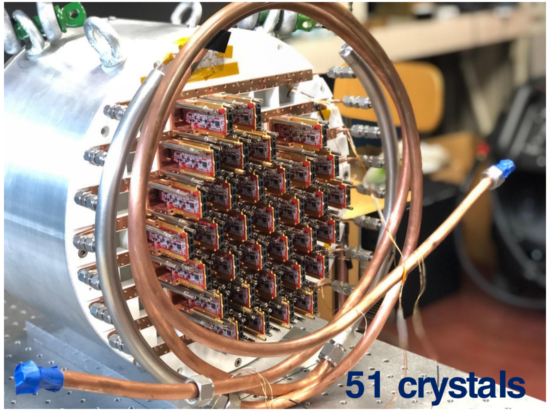
- Straw tubes : Low mass, short drift times
- 5mm diameter aluminized mylar tubes, inner coat of Al acts as cathode and outer coat is to prevent the leaks.
- Anode : 25μm gold plated tungsten wire
- Single panel : 96 straws, each panel covers 120° arc with two layers of straw to improve the efficiency.
- 6 panels make a plane.
- Tracker :18 stations : 36 planes
- 80:20 Argon:CO_2 @ 1450V

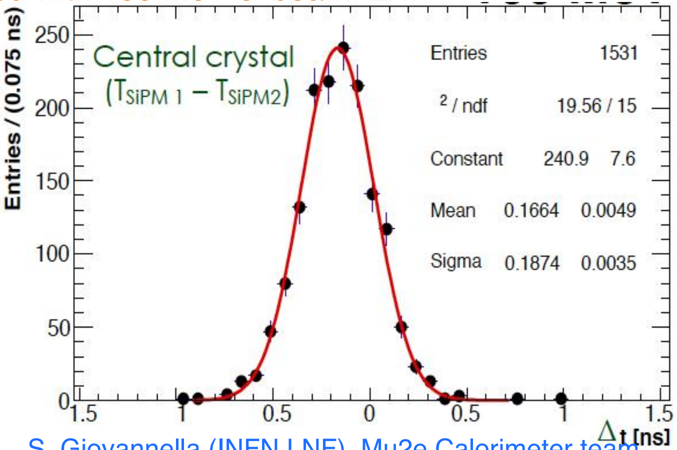




Calorimeter - Current status

Prototype tested with 100 MeV e^- beam LNF





S. Giovannella (INFN LNF), Mu2e Calorimeter team