# The Mu2e experiment

## Current status and future prospects


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*on behalf of the Mu2e Collaboration*


**57th Fermilab Users Meeting**

July 11th, 2024

# PART I:

# Physics motivation

# Notions of lepton number and flavor violation

Flavor transitions have been observed in nature:

- In the quark sector, transitions are characterized by the mixing elements of the CKM matrix.
- In the lepton sector, neutrino oscillations are constrained by the mixing parameters of the PMNS matrix: $\theta_{ij}$, $\Delta m_{ij}$, $\delta_{\text{CP}}$.

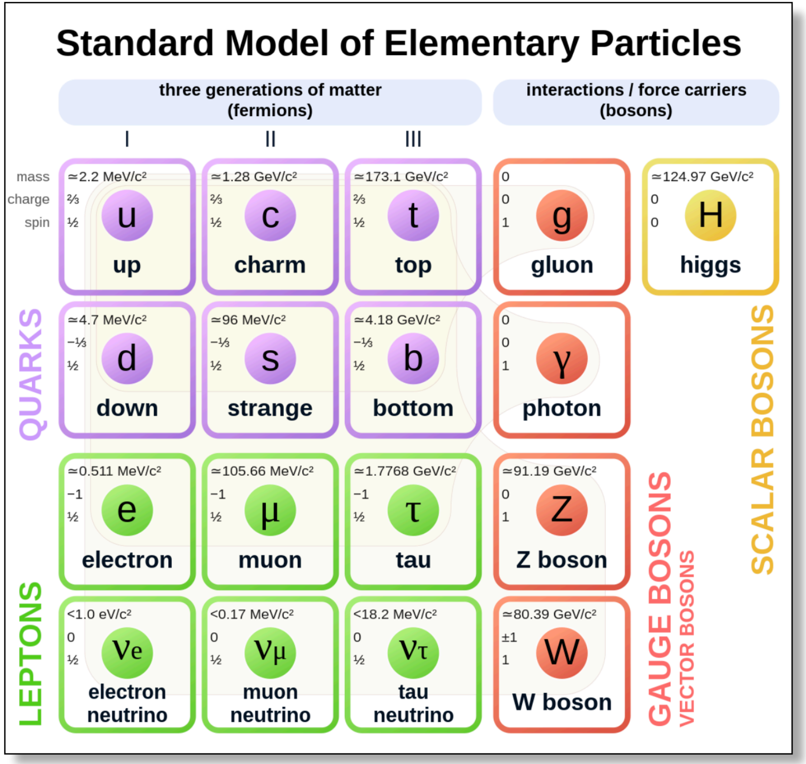
Lepton family number ($L_e$, $L_\mu$, $L_\tau$) is a quantum number conserved under the Standard Model (SM).

In the **charged** lepton sector, all observed transitions conserve lepton family number (*e.g.*, muon decay):

| | $\mu^-$ | $\rightarrow$ | $e^-$ | $\nu_\mu$ | $\bar{\nu}_e$ |
|---|---|---|---|---|---|
| $L_e$ | 0 | $\rightarrow$ | 1 | 0 | -1 |
| $L_\mu$ | 1 | $\rightarrow$ | 0 | 1 | 0 |

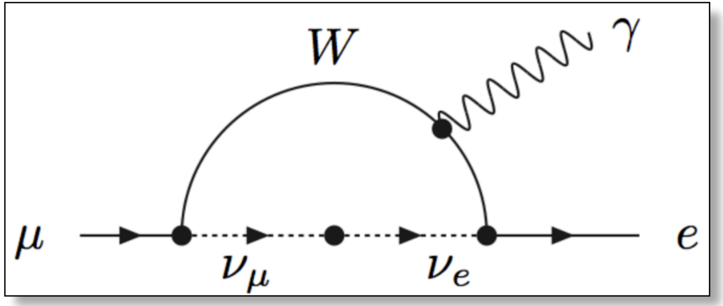
But neutrino oscillations prove it is not conserved in the **neutral** lepton sector:

$$P(\nu_\alpha \rightarrow \nu_\beta) \geq 0, \text{ for } \alpha \neq \beta$$



# Charged lepton flavor violation






$$\Gamma(\mu \to e\gamma) \propto \frac{3\alpha}{32\pi} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \left| \frac{\Delta m_{13}^2}{M_W^2} \right|^2 < 10^{-50}$$

Charged lepton flavor violation (CLFV) is a transition among electrons, muons, or taus that does not conserve lepton family number.

For instance, SM muon decay is not a CLFV process.

Transitions like $\mu^- \to e^-\gamma$ or $\mu^- N \to e^- N$ can occur through neutrino oscillations in loop diagrams.

Using those loops, models predict CLFV branching ratios (B.R.) smaller than $10^{-50}$.

CLFV in the Standard Model does not occur at all:

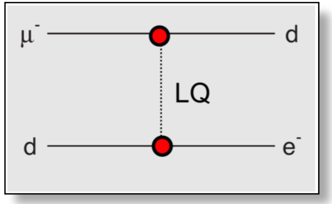
- It can be modeled introducing neutrino oscillations.
- It is essentially unmeasurable.

$\Rightarrow$ **Measurable CLFV would be evidence of beyond the Standard Model (BSM) physics!**

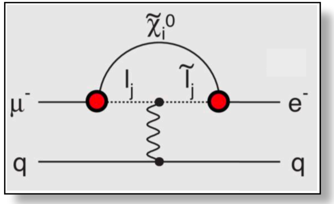
# CLFV searches in BSM rare decays

Current BSM studies aim to explain the possibility of CLFV processes with B.R. much higher than the SM prediction, up the order of ~$10^{-15}$ (*e.g.*, leptoquarks, supersymmetry, heavy neutrinos).

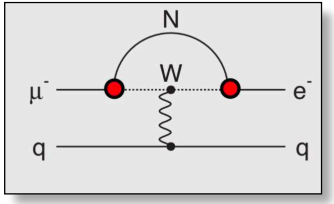
**Leptoquarks**




**Supersymmetry**

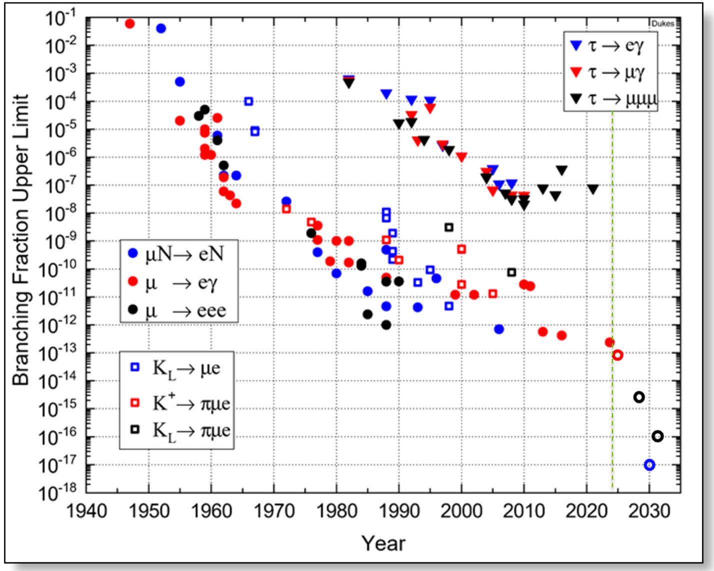



**Heavy neutrinos**




*Adapted from W. Marciano*

*Adapted from Y. Wu*
*(Original from E. C. Dukes)*




One of those process include *rare decays* of muons, taus, kaons and B mesons.

Muons in particular are of high interest:

- Prominence of high-intensity muon sources.
- Minimal irreducible backgrounds.
- Smaller B.R. limits.

Three “golden channels” have the highest potential sensitivity:

1. $\mu^+ \to e^+\gamma$
2. $\mu^+ \to e^+e^-e^+$
3. $\mu^-N \to e^-N$

Determining evidence of CLFV requires investigating all of these “golden channels.” $\Rightarrow$ Searches are not exclusive, but complementary.

# Current limits in CLFV searches with $\mu^{\pm}$

CLFV searches with the "golden channels" of muon rare decay have been studied by dedicated experiments.

The current upper limits up to a 90% confidence level of their B.R. are:

| Channel | B.R. upper limit (90% C.L.) | Experiment |
|---|---|---|
| $\mu^+ \to e^+\gamma$ | Less than $3.1 \times 10^{-13}$ | MEG and MEG II |
| $\mu^+ \to e^+e^-e^+$ | Less than $10^{-12}$ | SINDRUM |
| $\mu^- N \to e^- N$ | Less than $7 \times 10^{-13}$ | SINDRUM II |

The next generation of muon CLFV experiments aim to improve these limits up to four orders of magnitude: Mu2e, COMET, Mu3e.

In particular, Mu2e focuses on measuring the B.R. of **muon-to-electron conversion** in the presence of a nuclear field.

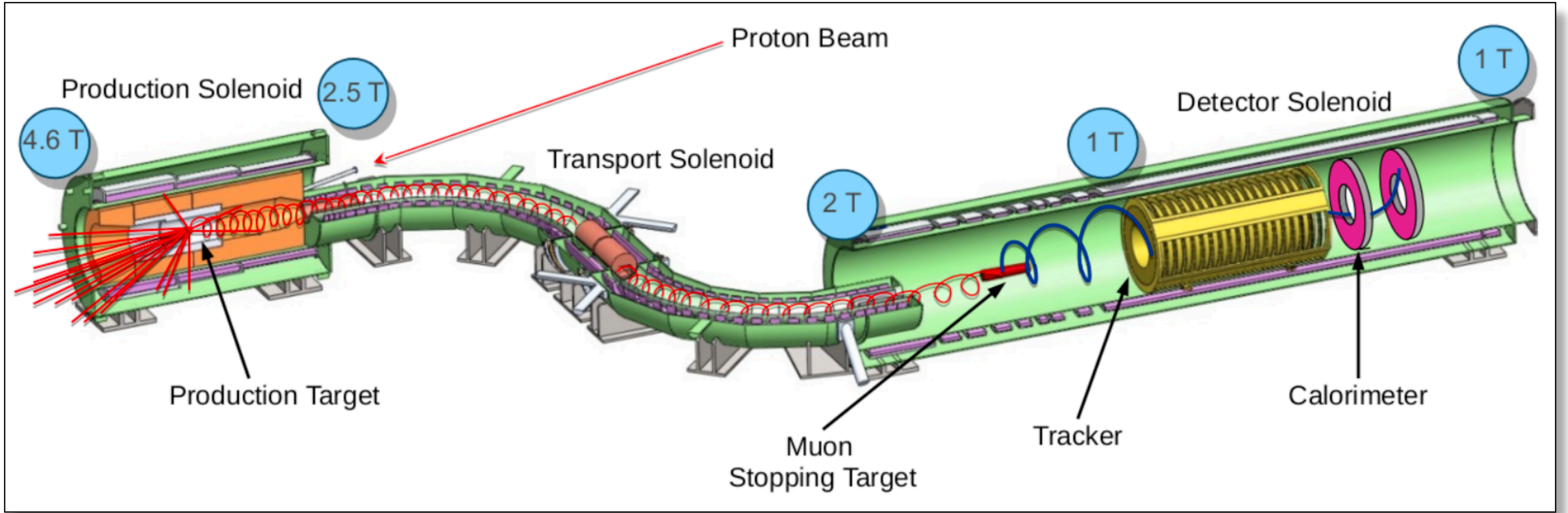
# PART II:
# Experimental concept

# The Mu2e experiment

Mu2e will look for a neutrinoless, coherent muon-to-electron conversion in the field of an atomic nucleus:

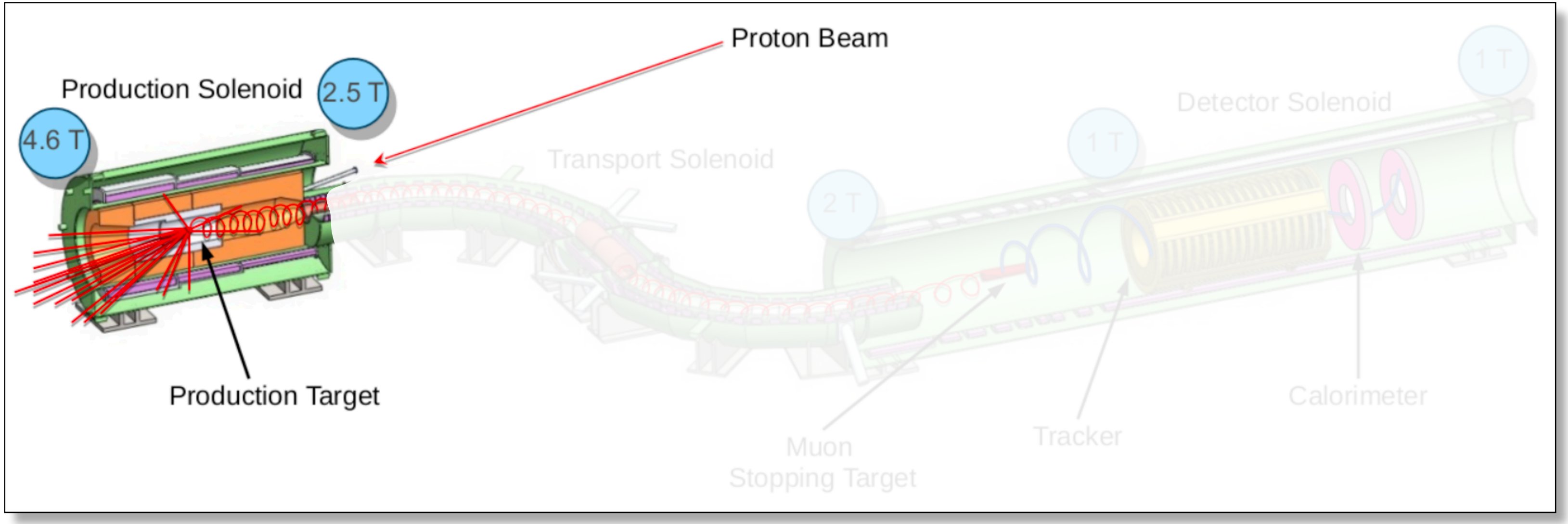
$$\mu^- + N(Z, A) \rightarrow e^- + N(Z, A)$$

The chosen nucleus is **aluminum** ($Z$ = 13), different from the SINDRUM II experiment which opted for gold ($Z$ = 79).



# The Mu2e experiment

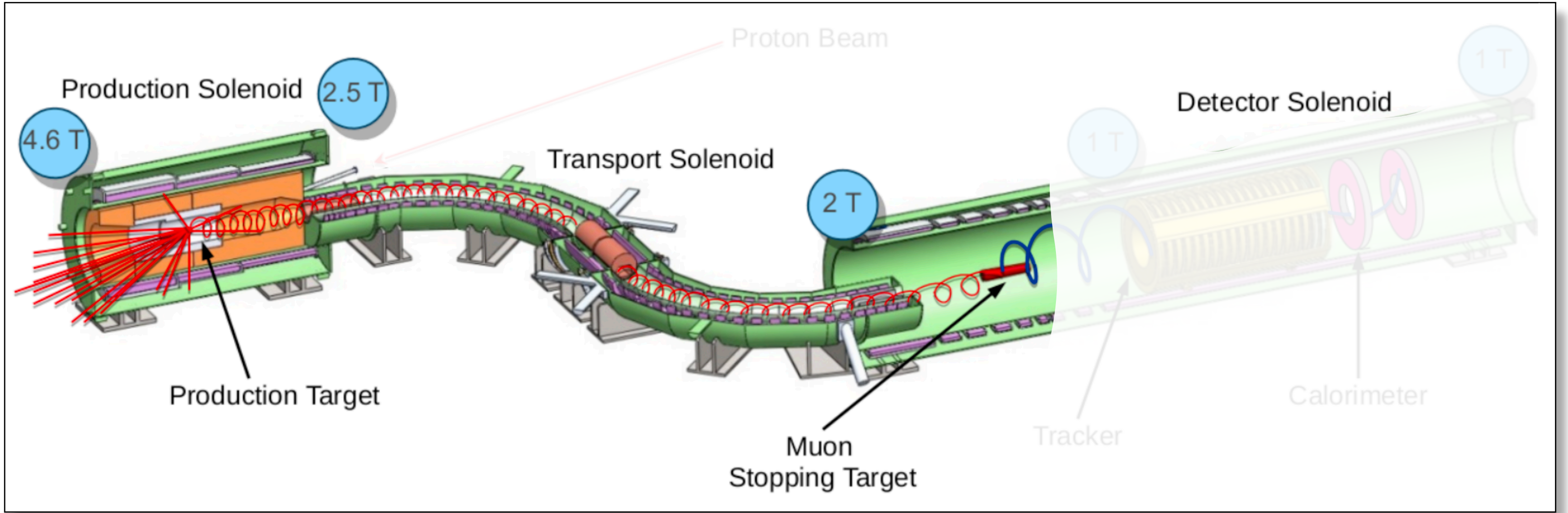
The experimental concept is begins with a pulsed proton beam of 8 GeV from the Booster hitting a tungsten **production target** inside the **production solenoid**, and generating pions that decay into muons.



# The Mu2e experiment

Some of the those pions are driven into the **transport solenoid**, a S-curved structure that selects them based on their charge and momentum.

The selected pions decay into low-momentum muons inside the transport solenoid and are directed into the **muon stopping target** located at the front of the **detector solenoid**.

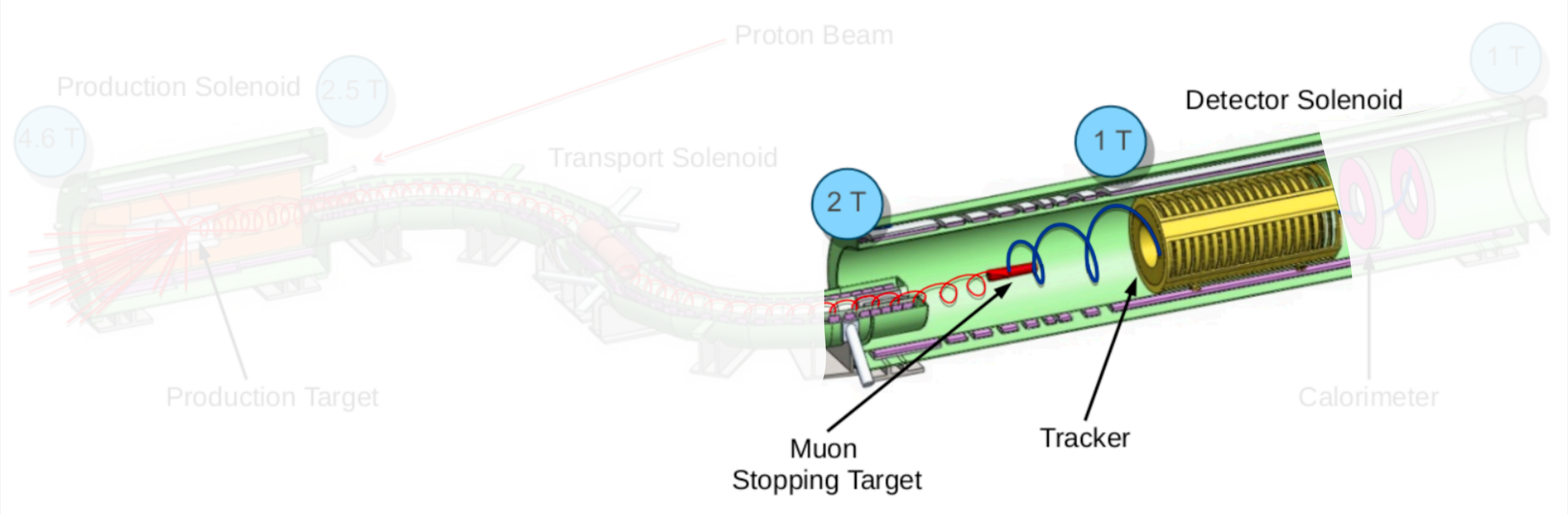


# The Mu2e experiment

The **stopping target** is formed of 37 thin aluminum foils.

Some of the low-momentum muons are captured by the atomic orbit of the aluminum, forming a muonic atom that cascades to the 1s orbit state.

The muon in the muonic atom state converts into an electron and is directed to the **tracker**.

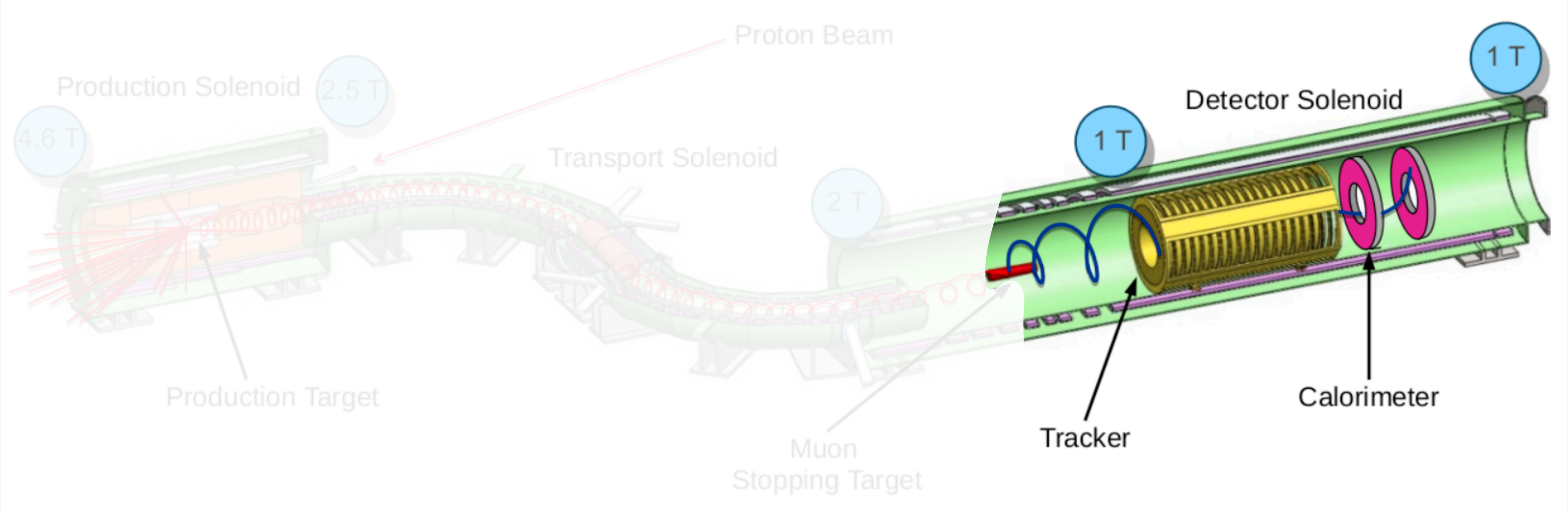


# The Mu2e experiment

The converted electron travels through the **tracker**, a gas drift chamber, leaving a recognizable, helical signature track.

Afterward, it stops at the **calorimeter**, which performs particle identification and can seed the electron track pattern.

The structure of the tracker and calorimeter allows additional identification of background muons.



# $\mu^- \to e^-$ conversion signal

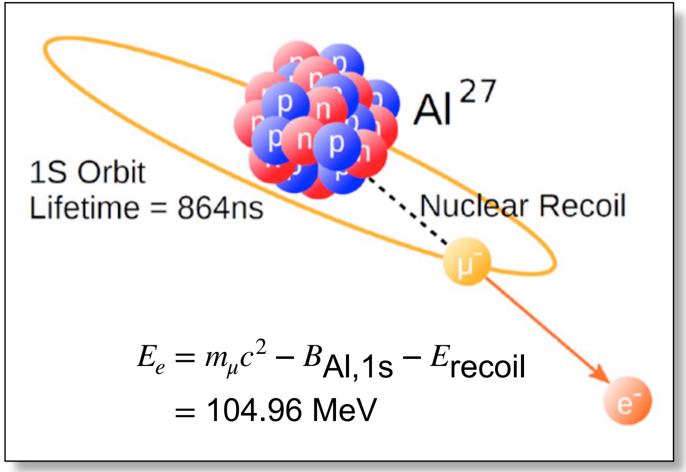
The muon in the 1s orbit state interacts with the aluminum nucleus and converts into an electron:

$$\mu^- + \text{Al} \to e^- + \text{Al}$$

Since this is a coherent two-body state, the electron is **mono-energetic** and flies away from the nucleus:

$$E_e = m_\mu c^2 - B_{\text{Al,1s}} - E_{\text{recoil}}$$

- Aluminum binding energy in 1s orbit: $B_{\text{Al,1s}}$
- Coherent nuclear recoil energy: $E_{\text{recoil}}$




$E_{\text{recoil}} = 0.21$ MeV

$B_{\text{Al,1s}} = 0.48$ MeV

The motivation of the experiment is to calculate the branching ratio of conversions normalized to all muon nuclear captures:

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

The current limit is $R_{\mu e} < 7 \times 10^{-13}$ by SINDRUM II using gold.

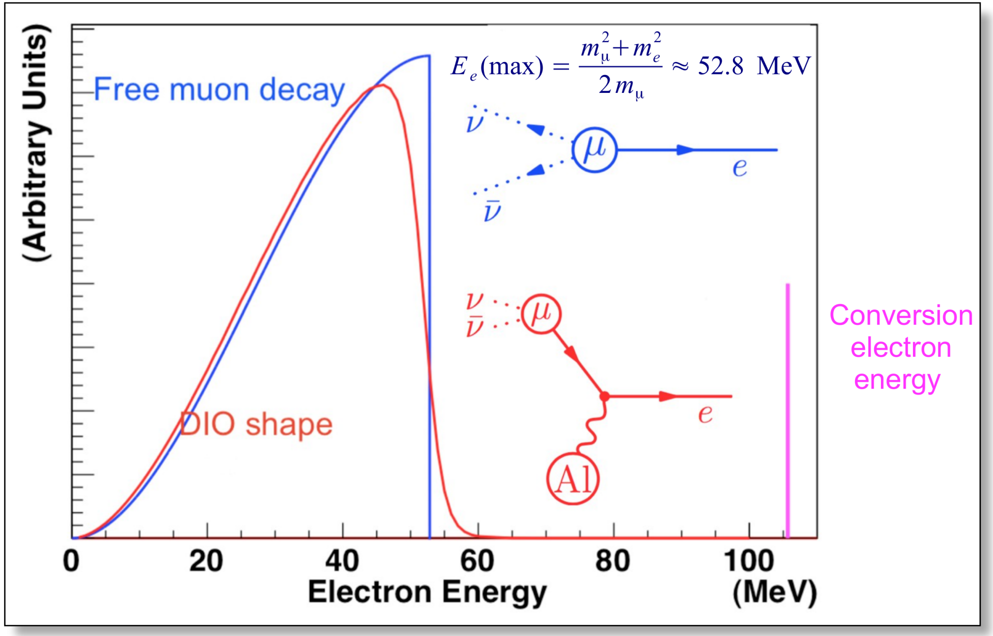
Mu2e aims to increase sensitivity:

- $R_{\mu e} < 8 \times 10^{-17}$ at a 90% confidence level.
- $R_{\mu e} < 2 \times 10^{-16}$ for discovery sensitivity (5σ).

The total exposure of the entire experiment should be $\mathcal{O}(10^{18})$ muons with $\ll 1$ background event.

# Decay-in-orbit background

A. Edmonds
(Adapted from Phys. Rev. D 94, 051301(R), 2016)




In the 1s muonic atom state in aluminum ($\tau_{\mu,1s}$ ~ 864 ns), the muon could undergo three scenarios:

- Nuclear capture (~61%).
- Decay-in-orbit (~39%).
- Conversion.

Free muon decay: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

- Characterized by the Michel spectrum with an endpoint of ~52.8 MeV.
- Mu2e will be insensitive at that energy.

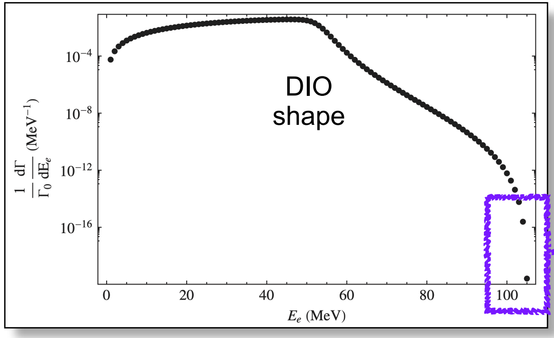
However, the energy of the electrons from the **decay-in-orbit** (DIO) of muons bound to atoms is distorted by the nucleus pass the Michel endpoint up to the energy point of conversion (~105 MeV).

DIO represents one a significant background. Minimizing it **drives the structure of the active detector**.

A suppression of DIO background demands a <u>momentum resolution of ~180 keV/c</u> with small tails of Gaussian characterization.

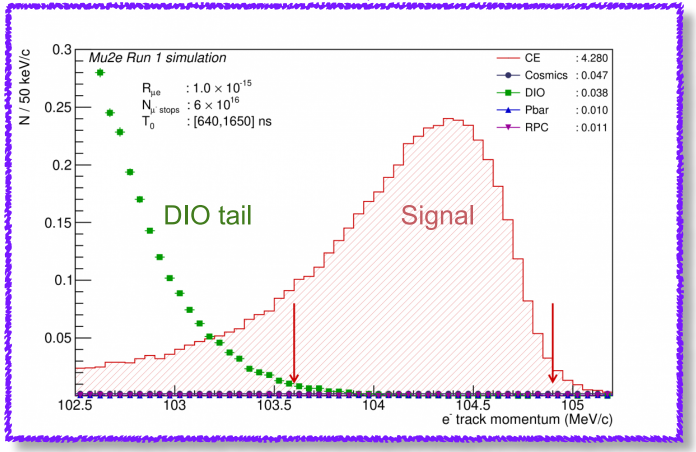
# Decay-in-orbit background

*Phys. Rev. D 94, 051301(R), 2016*




Muon decay-in-orbit spectrum in logarithmic scale

*A. Edmonds*




DIO spectrum tail and expected signal (including resolution effects) from simulation of 10% of final dataset

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However, the energy of the electrons from the **decay-in-orbit** (DIO) of muons bound to atoms is distorted by the nucleus pass the Michel endpoint up to the energy point of conversion (~105 MeV).

DIO represents a significant background. Minimizing it **drives the structure of the active detector**.

A suppression of DIO background demands a momentum resolution of ~180 keV/c with small tails of Gaussian characterization.

# Prompt backgrounds and radiative pion capture

Prompt backgrounds are particles produced from the proton pulse that interact with the detector.

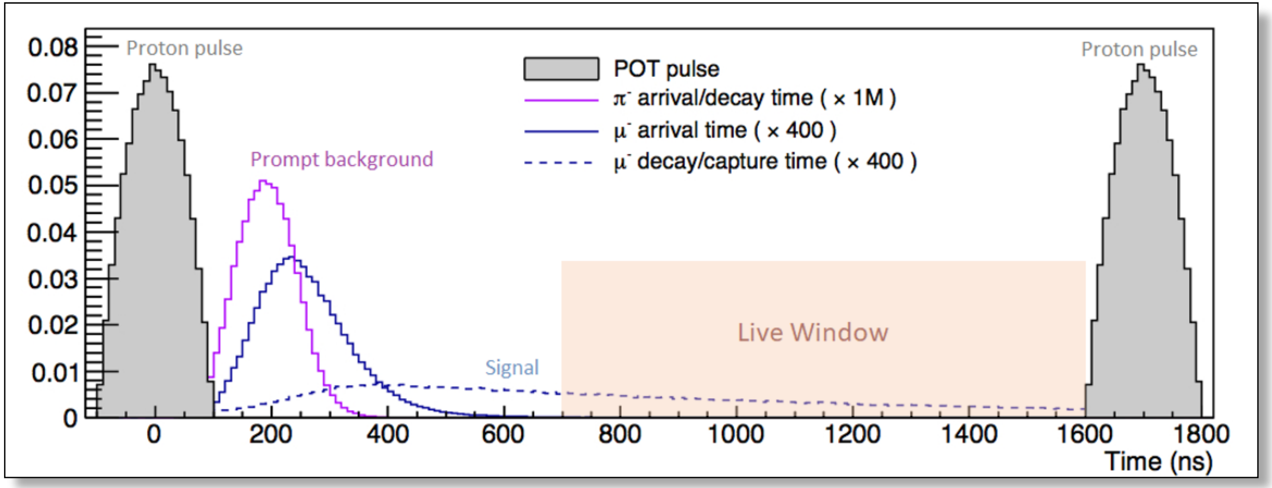
The most important prompt background is the **radiative pion capture** (RPC):

$$\pi^- N \to \gamma N' \text{ (with } N' \text{ being a nuclear excited state)}$$

Pions from the production target can interact with the aluminum in the stopping target, producing photons with energy peaking at 120 MeV. These photons can pair-produce an electron that can fake signal.

Internal conversion ($\pi^- N \to e^+ e^- N'$) can also produce electrons close to the conversion energy.

Minimizing RPC background **drives the structure of the beam pulse**.




- Narrow proton pulses: width < 250 ns
- Live window of ~900 ns wide separated ~700 ns from proton pulse.
- Enough separation between pulses: $2 \times \tau_{\mu,1s} \approx 1695$ ns
- Extinction: process of keeping protons out of life window. Fraction of protons out < $10^{-10}$

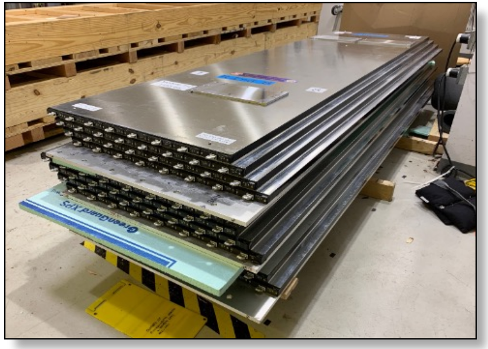
# Cosmic rays background

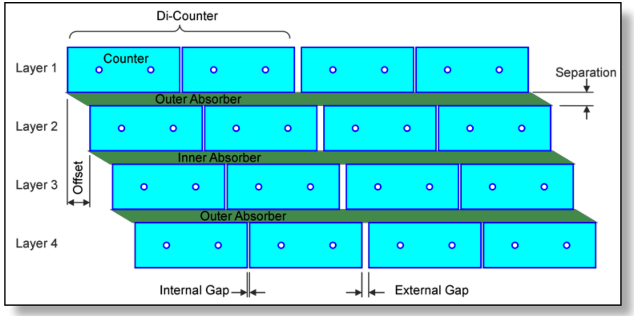
**Muons from cosmic rays** is the largest source of background.

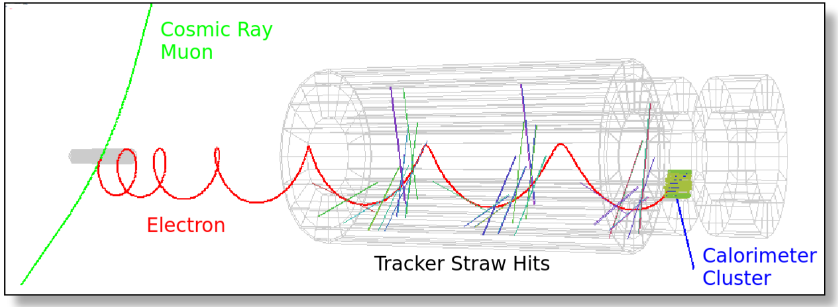
It is expected approximately one cosmic-produced electron per day in the detector.

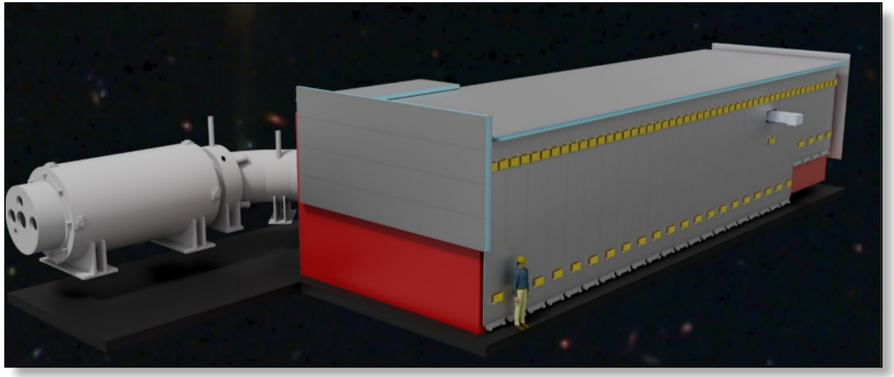
A **cosmic ray veto** (CRV) formed by four overlapping layers of polystyrene bars will cover the entire detector solenoid and part of the transport solenoid.

It is highly-efficient (99.99%), and will reduce cosmic background to ~0.5 events during the entire experiment run.





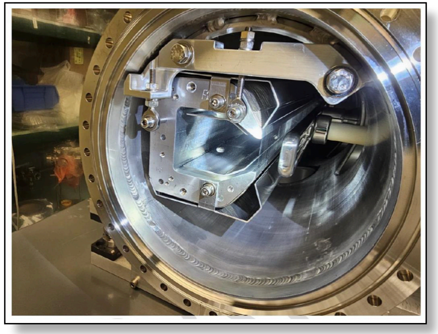



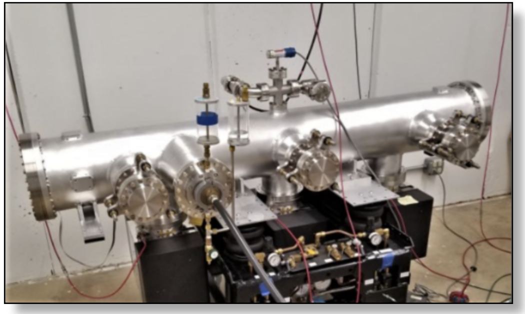
# PART III:
# Status and future plans

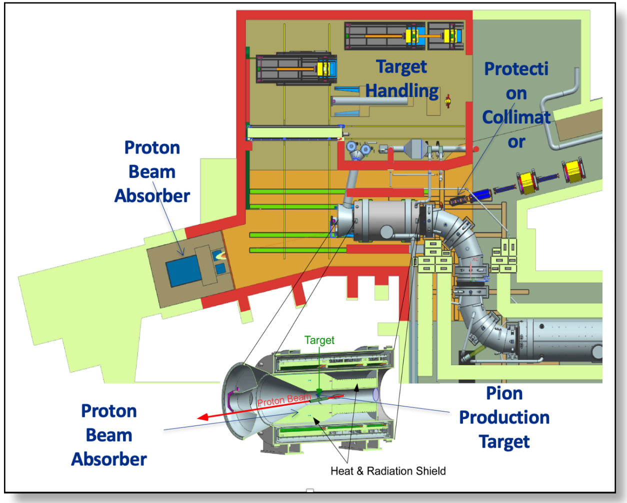
# Beamline and target station

Resonant extraction based on two electrostatic septa:

- First septum already fabricated.
- Second septum fabrication ongoing.








Heat and radiation shield of the production target constructed and ready for installation.

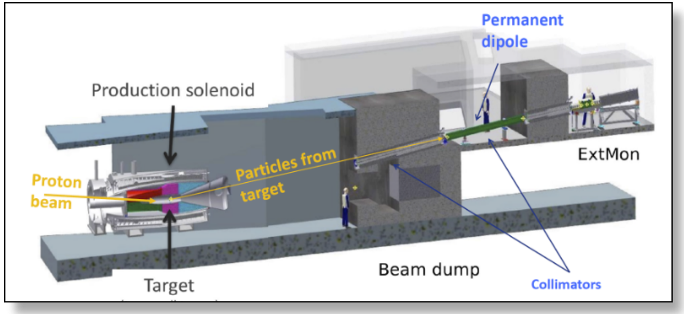
# Extinction system

Extinction is the suppression of protons out of the detection window.

The technique works in two steps:

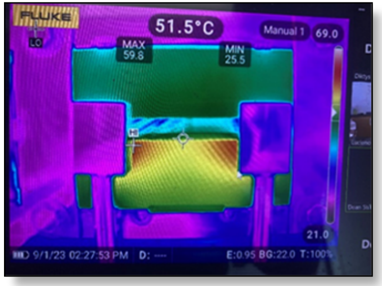
- High-oscillating magnetic fields that deflects any beam outside the pulse.
- Monitors that will detect protons that are scattered off the target.

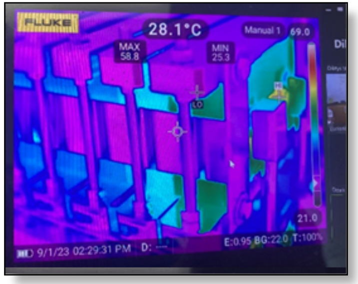
Mu2e requires an **extinction level of $10^{-10}$ or better**.




Extinction monitor:

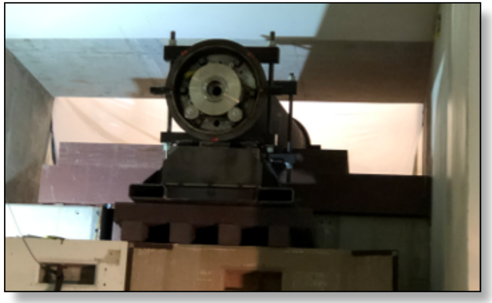
- Pre-installation of the entrance collimator complete.
- Assembly of the exit collimator complete.



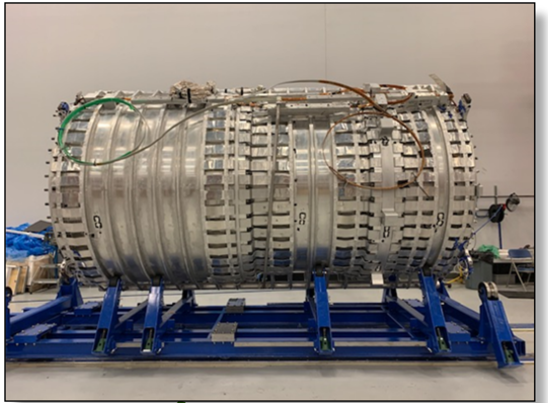

Fabrication of the first AC dipole magnet of the external beamline is complete.

Two more magnets in process.



# Production solenoid

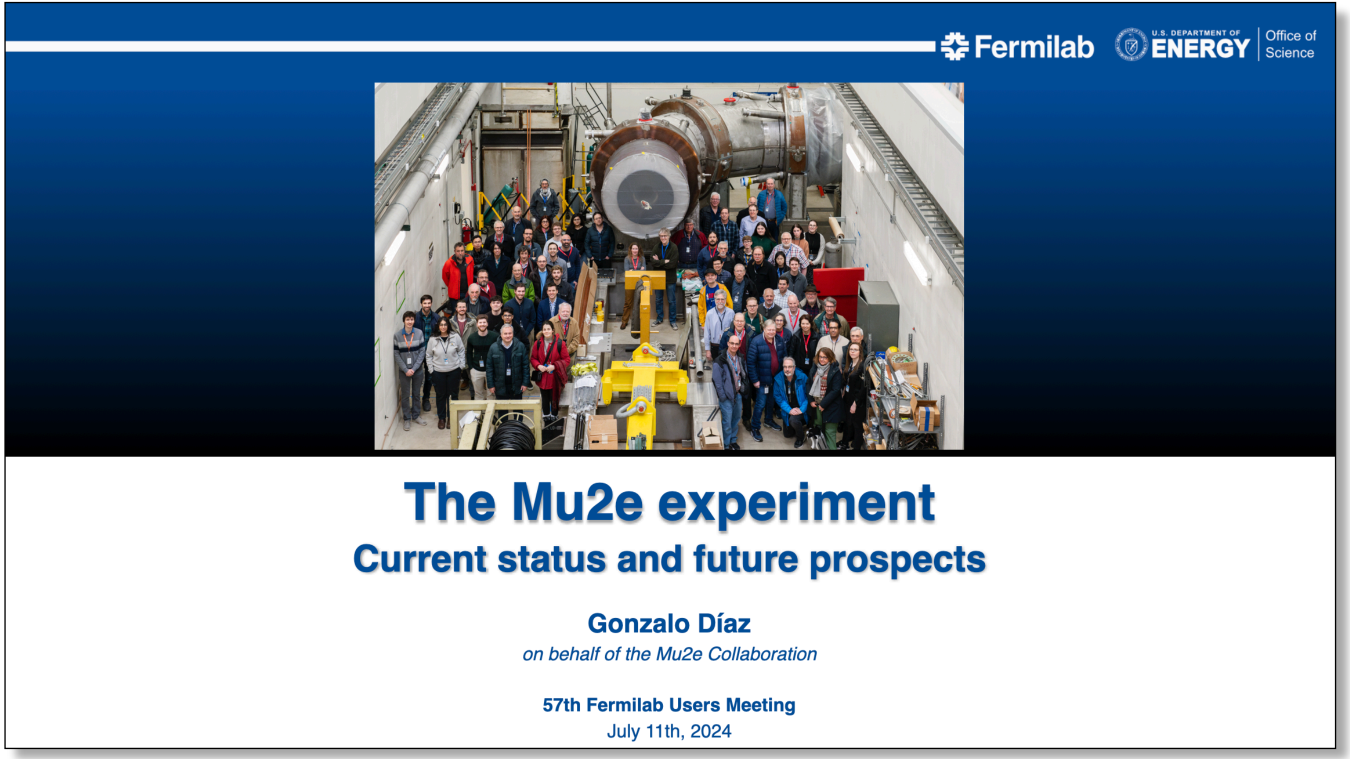
Cold mass completed.



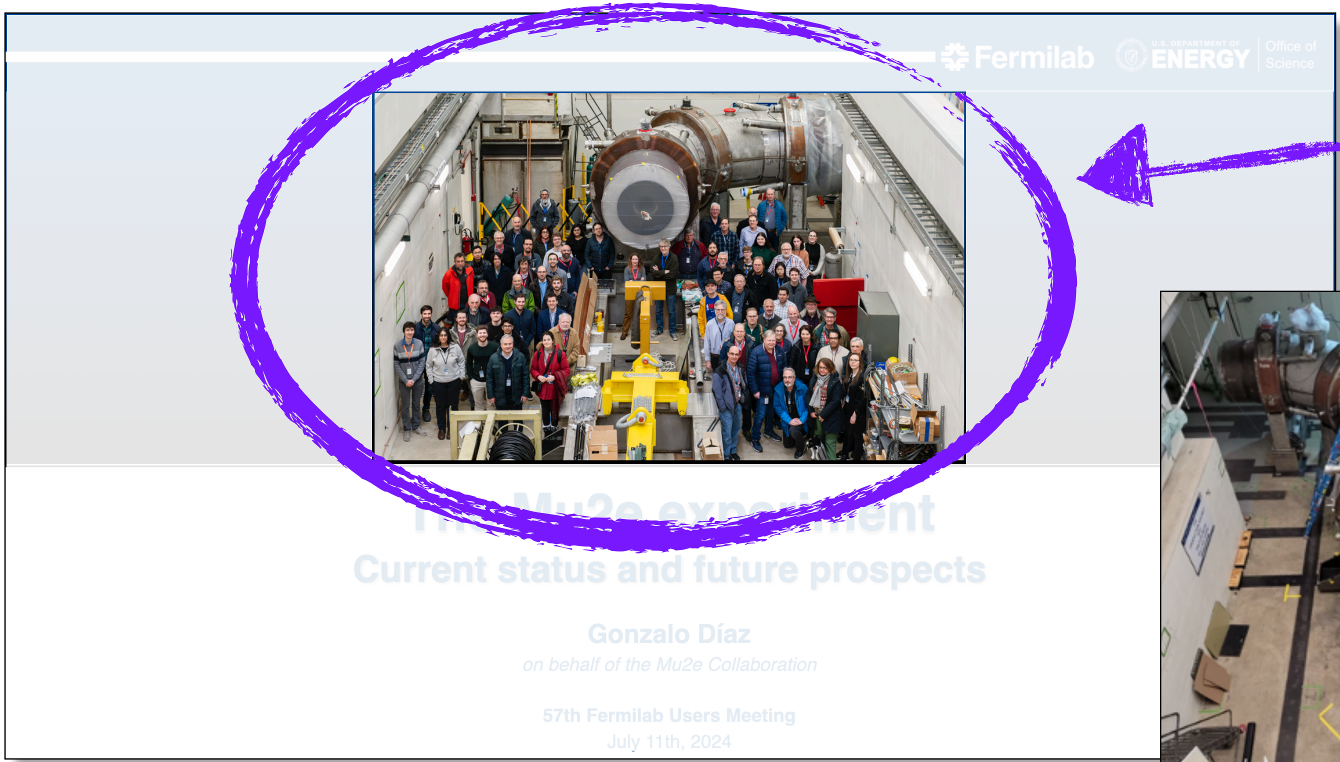
Cryostat welded up.

Cold mass filled with inner bore and inserted into cryostat.

# Transport solenoid

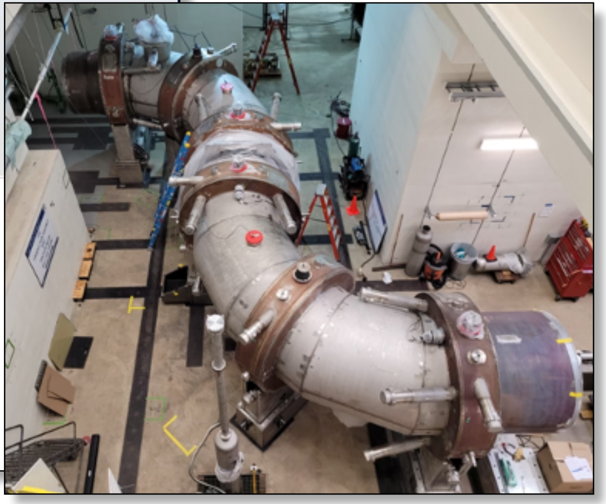


# Transport solenoid

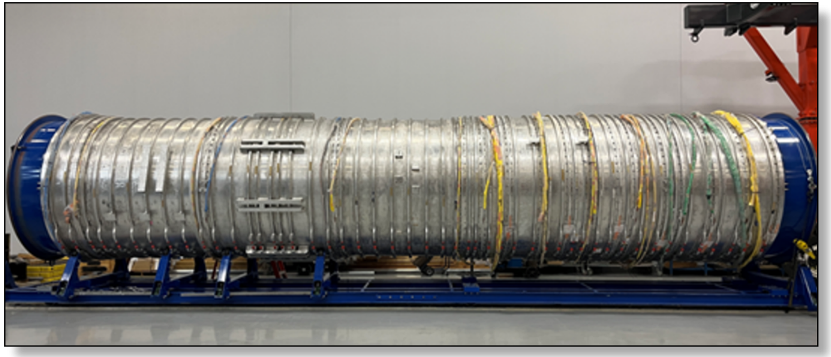



**Already installed in the Mu2e hall last March!**

(Allow a pretty collaboration picture)



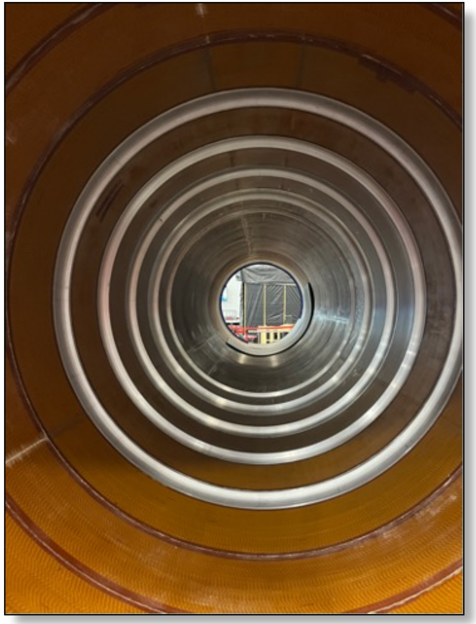
# Detector solenoid



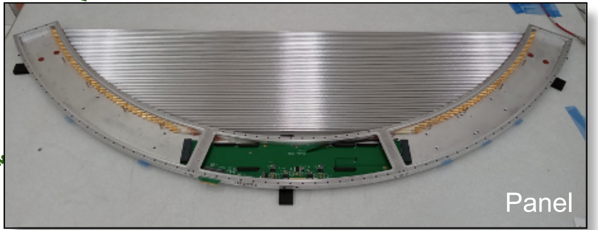
Coil fabrication and testing completed.

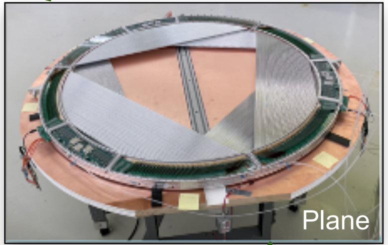
Cold mass assembled.

Cryostat system components under assembly.



# Tracker

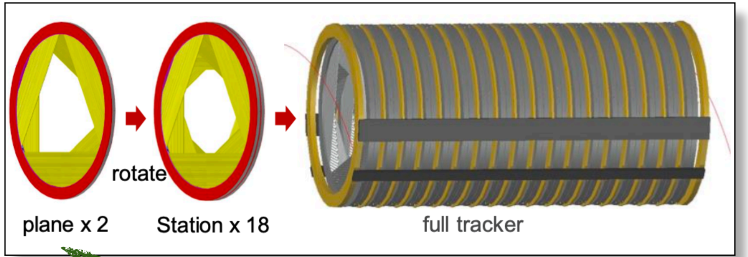



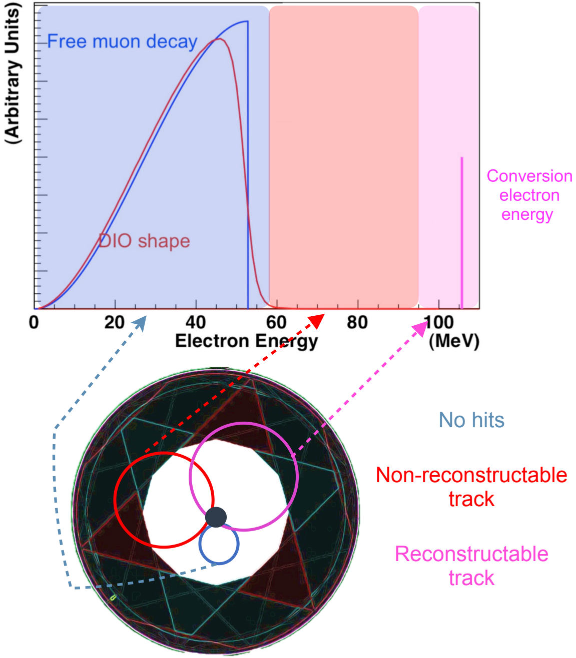




Minimum element is a **straw**: 25 µm gold-plated tungsten wire at the center of a 15 µm thick Mylar and aluminum tube of 5 mm radius.

96 straws form a **panel**. 6 panels form a **plane**. 2 planes form a **station**. Tracker is formed by 18 stations ⇒ **20736 channels**.

Each straw is a drift tube filled with ionizing gas: 80% Ar, 20% $CO_2$.

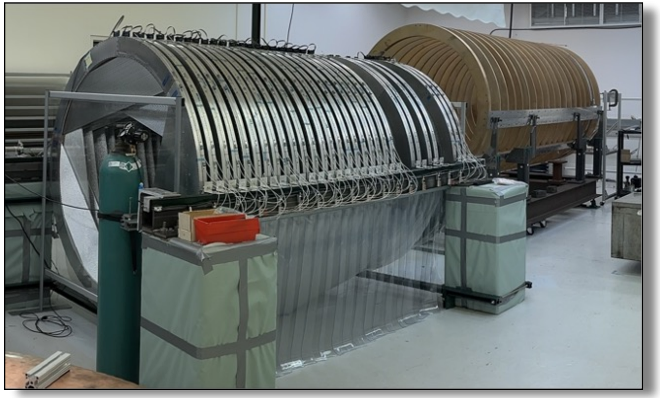



Tracker structure is designed to capture and recognize conversion electrons while minimizing DIO background.

Low-mass detector in vacuum
⇒ Minimal multiple scattering
⇒ Improved resolution (< 180 keV/c)

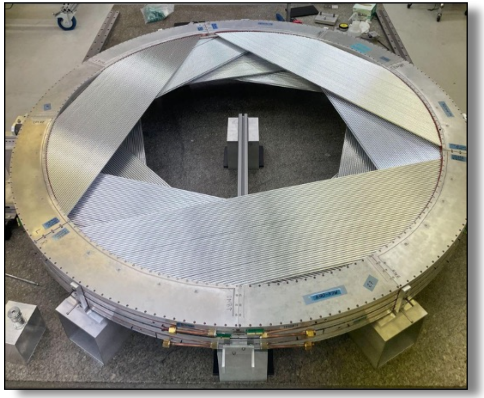
# Tracker



33 out of 36 planes assembled (92%).

Remaining 3 planes in progress, expected by this fall.

“Training station” made with test panels to evaluate assembly and metrology procedures.

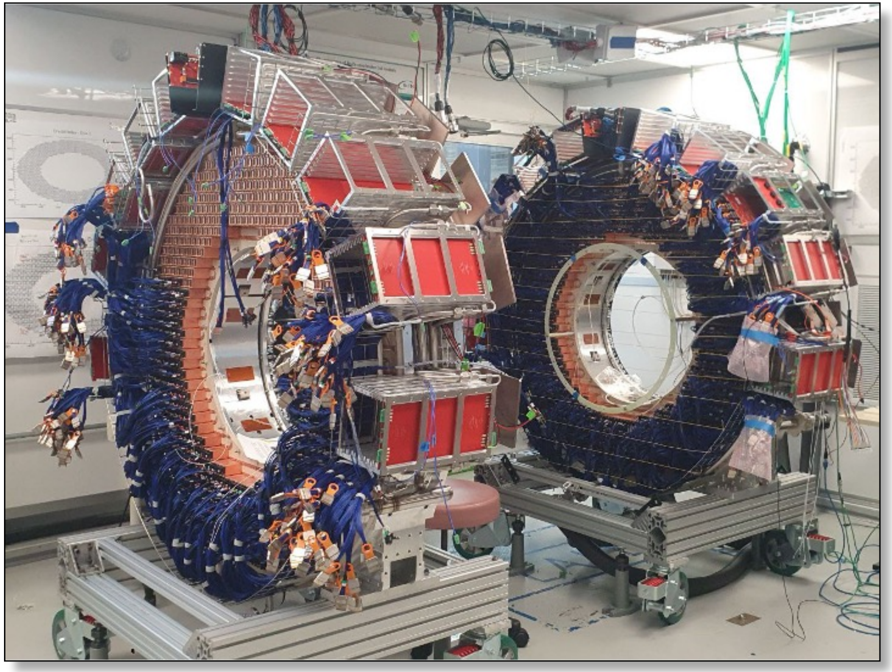


Front-end electronics installed in 10 planes (28%).

Expected to be completed by end of year.

# Calorimeter

S. Giovannella



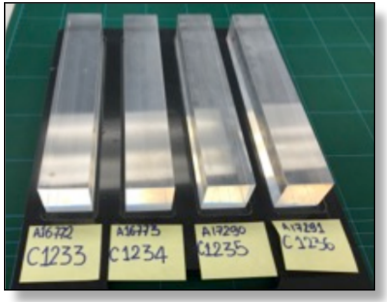
Formed by two annular disks: “disk-0” and “disk-1.”

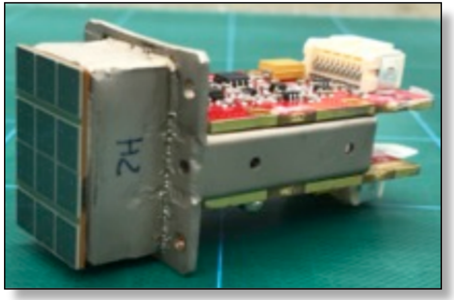
Each disk contains 674 CsI crystals coupled to silicon photomultipliers.

Disks are separated by 70 cm: 1/4 of the helix trajectory of a 105 MeV electron

Main functions:

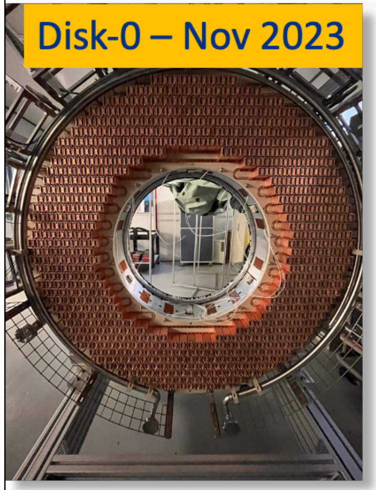
- Particle identification.
- Timing.
- Seeding for track reconstruction.

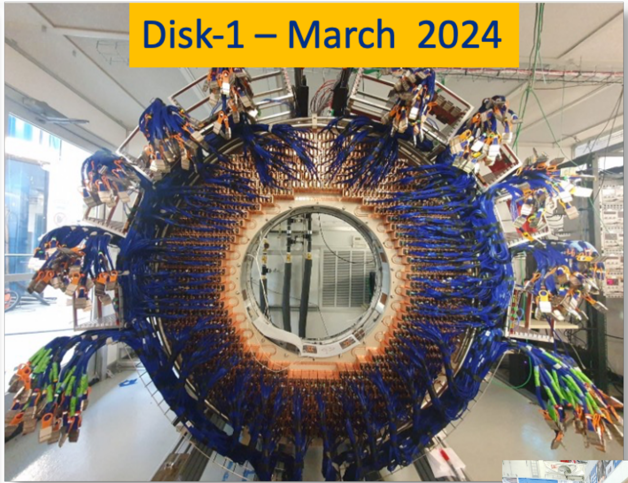


# Calorimeter

S. Miscetti



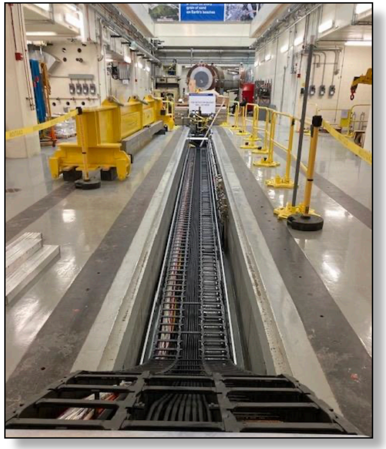


For both disks, mechanics, analog electronics and power distribution is completed.
Cable routing completed for Disk-1 and 2/3 for Disk-0
→ It will be completed beginning of September
At Mu2e Hall:
- ✓ LV/HV power supplies installed
- ✓ Service cables in the south-side done
- ✓ Service cables in the north side in progress now

# Short- and mid-term plans

## Short-term

- Mu2e will complete detector assembly by the end of this year.
- Simultaneously, the detector hall is being conditioned.
- Once all detectors are assembled, installation is expected to be done early 2025.
- DAQ progress at 90%, it is expected to be complete next year.
- Cosmic muon **commissioning run** is planed for **spring 2025**.



## Mid-term

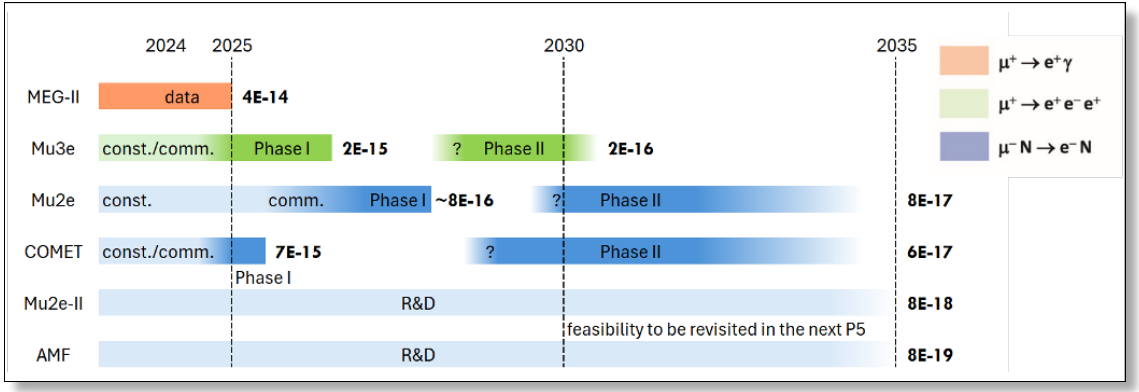
- Full operations for the **Physics Run I**, expected to begin **January 2027**.
- Mu2e will take one year of data until the PIP-II long shutdown scheduled for the beginning of 2028.
  - The plan is to improve from SINDRUM II limits by an order of ~1000.

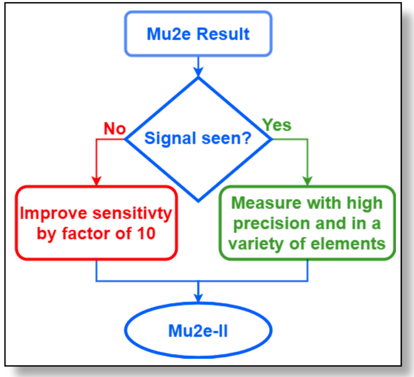
# Long-term plans and PIP-II possibilities

- After the PIP-II long shutdown, Mu2e plans to resume operations until mid-2030s with Phase II.
- Full dataset aims to improve current SINDRUM II limits by an order of ~10⁴:
  - $R_{\mu e} < 8 \times 10^{-17}$ at 90% C.L.

- The proposed **Mu2e-II** experiment aims to enhance the capabilities of Mu2e using the PIP-II beamline.
- Depending if $\mu^- \rightarrow e^-$ conversion signal is seen in Mu2e:
  - Yes: Measure other target nuclei with higher precision.
  - No: Improve sensitivity by ~$10^5$ over the current limits.

- Another proposal for an **Advanced Muon Facility** (AMF) is in discussion.
  - Possibility of exploring simultaneously all three muon "golden channels."



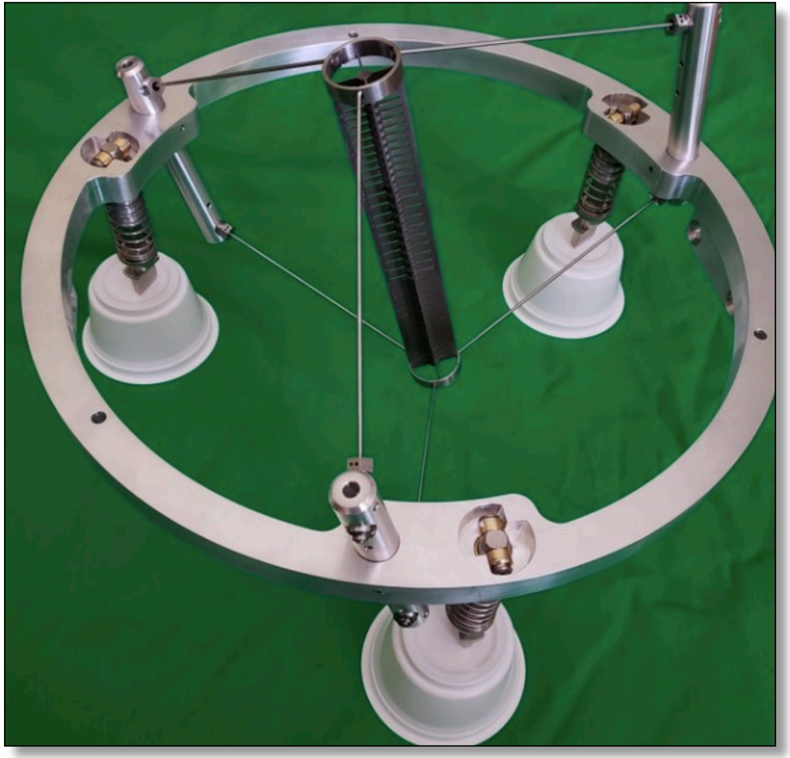
# Summary and conclusions

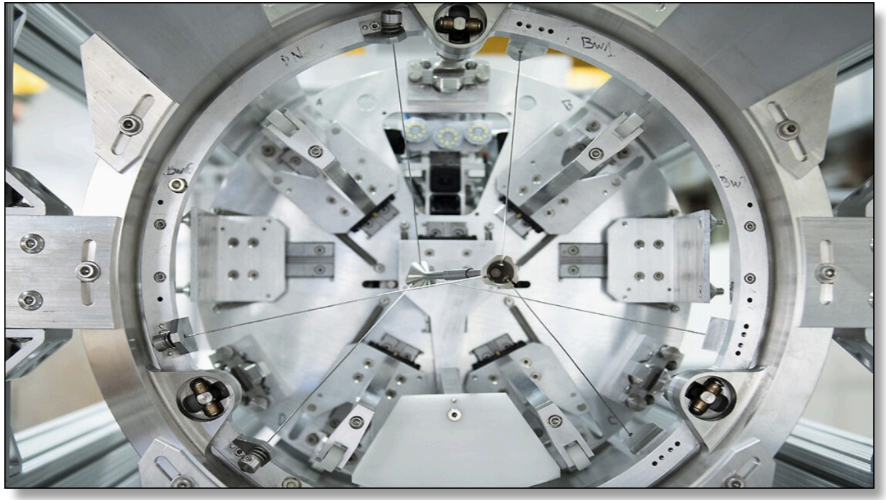
- Mu2e looks to improve the current limits of the CLFV search with muon-to-electron conversion in a nuclear field by up to four orders of magnitude.
- Introduces detection techniques that aims to minimize primarily cosmic, prompt and DIO backgrounds.
- Detector construction and infrastructure is in a mature stage and the plans are to start a commissioning run early next year.
- An estimated of one year of physics run is planned before the PIP-II long shutdown.
- After the shutdown, operations will restart until the next decade.
- Plans for future CLFV searches with muons beyond Mu2e have been proposed and are under consideration.


Thank you

# Complementary material

# Production target

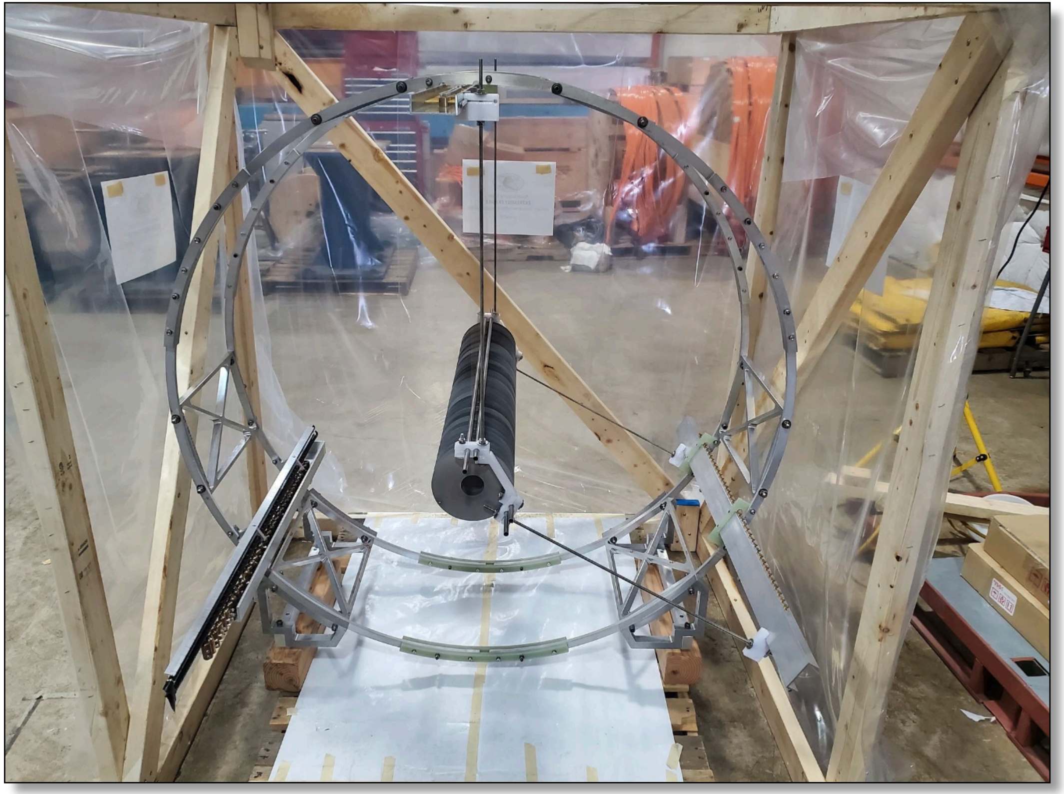






Fermilab

# Stopping target



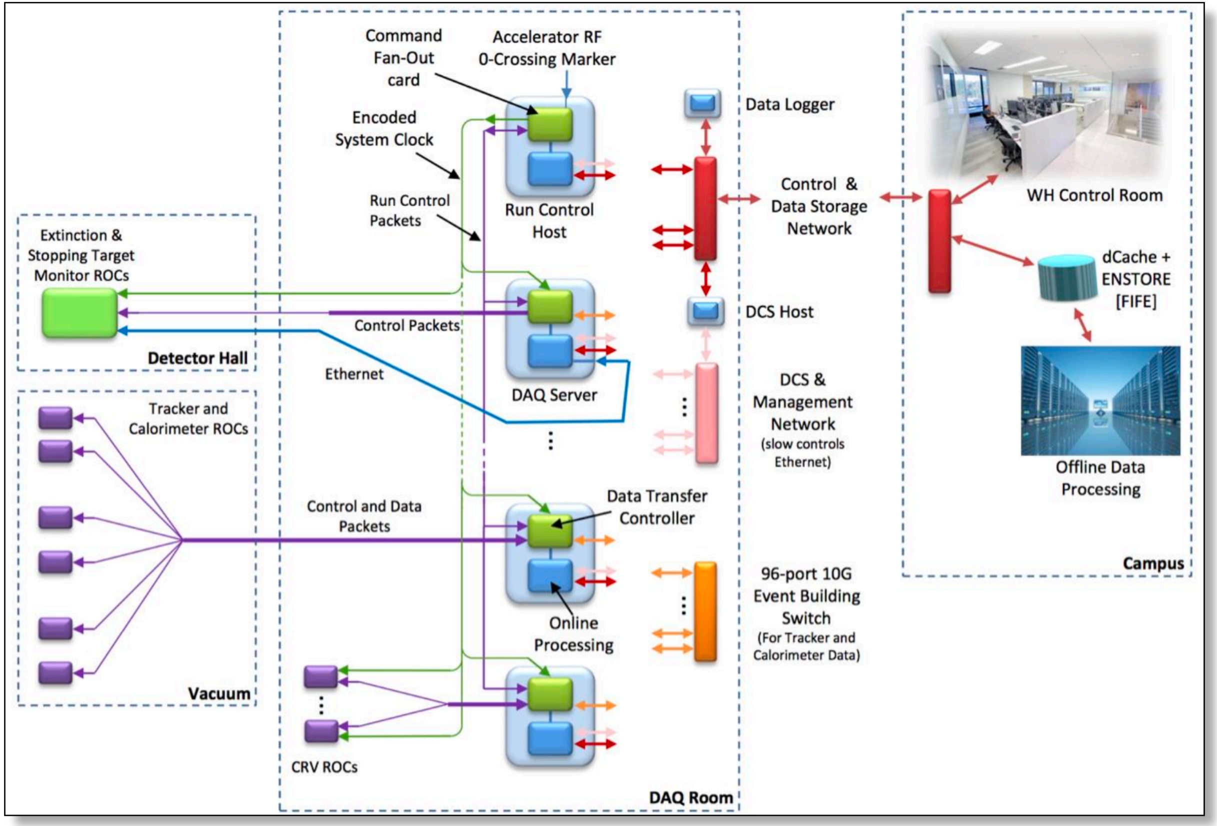
# Estimated backgrounds

⋆ Simulation results for $3.6\times10^{20}$ POT

| Process | Expected event yield |
|---|---|
| Cosmic rays | $0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$ |
| DIO | $0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$ |
| Antiprotons | $0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$ |
| Pion capture | $0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$ |
| Muon DIF | $< 0.003$ |
| Pion DIF | $0.001 \pm < 0.001$ |
| Beam electrons | $(2.1 \pm 1.0) \times 10^{-4}$ |
| RMC | $0.000^{+0.004}_{-0.000}$ |
| Total | $0.41 \pm 0.13(\text{stat+syst})$ |

*Y. Wu*

# TDAQ system



Command
Fan-Out
card
Accelerator RF
0-Crossing Marker
Encoded
System Clock
Run Control
Packets
Run Control
Host
Data Logger
Control &
Data Storage
Network
WH Control Room
dCache +
ENSTORE
[FIFE]
Extinction &
Stopping Target
Monitor ROCs
Control Packets
Detector Hall
Ethernet
DAQ Server
DCS Host
DCS &
Management
Network
(slow controls
Ethernet)
Offline Data
Processing
Tracker and
Calorimeter ROCs
Control and Data
Packets
Data Transfer
Controller
Campus
96-port 10G
Event Building
Switch
(For Tracker and
Calorimeter Data)
Online
Processing
Vacuum
CRV ROCs
DAQ Room