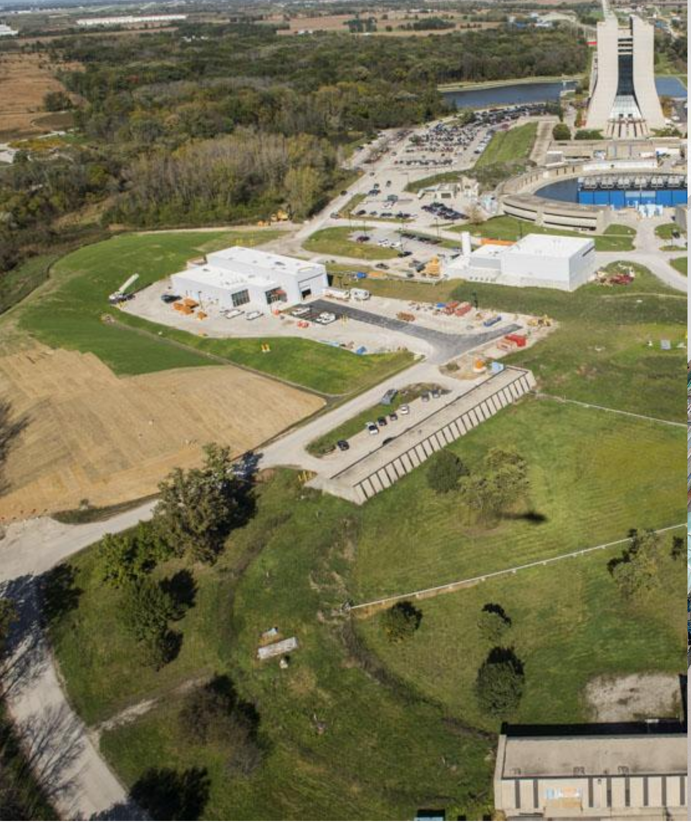
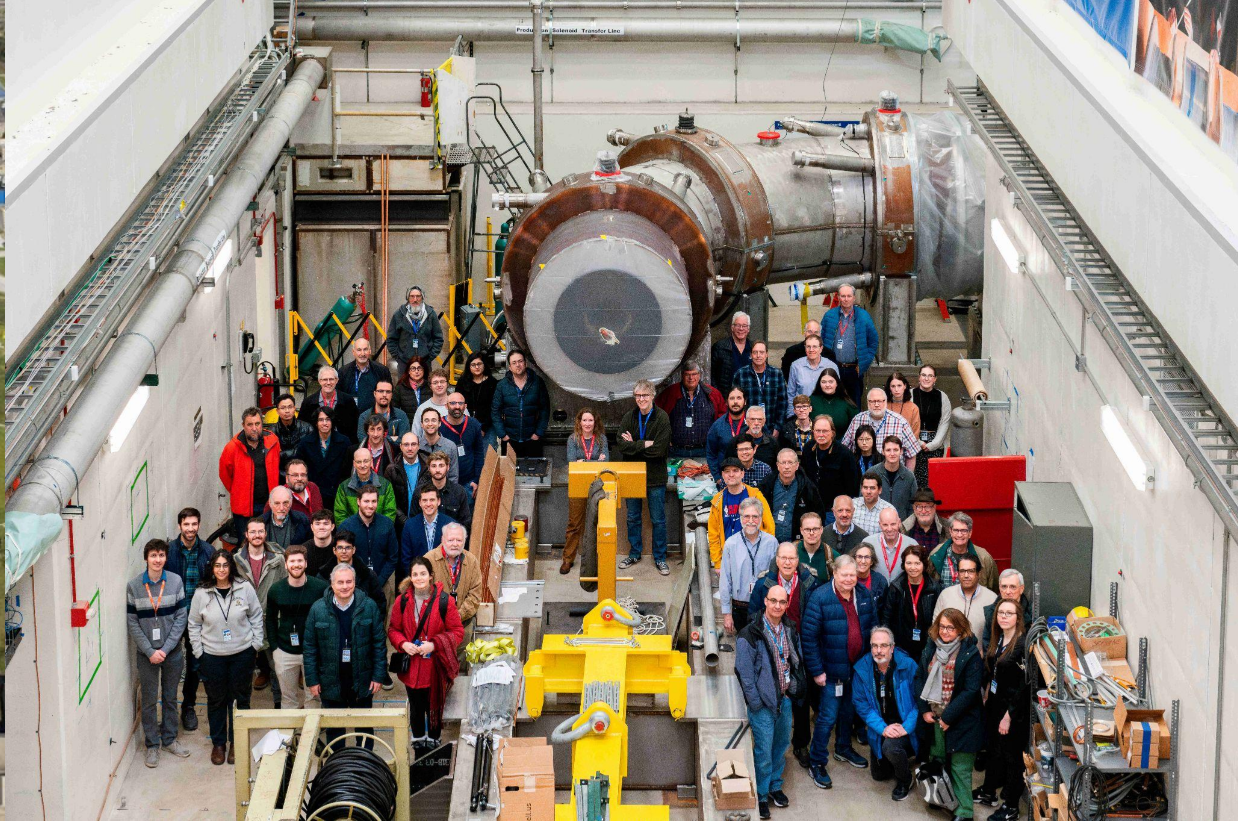




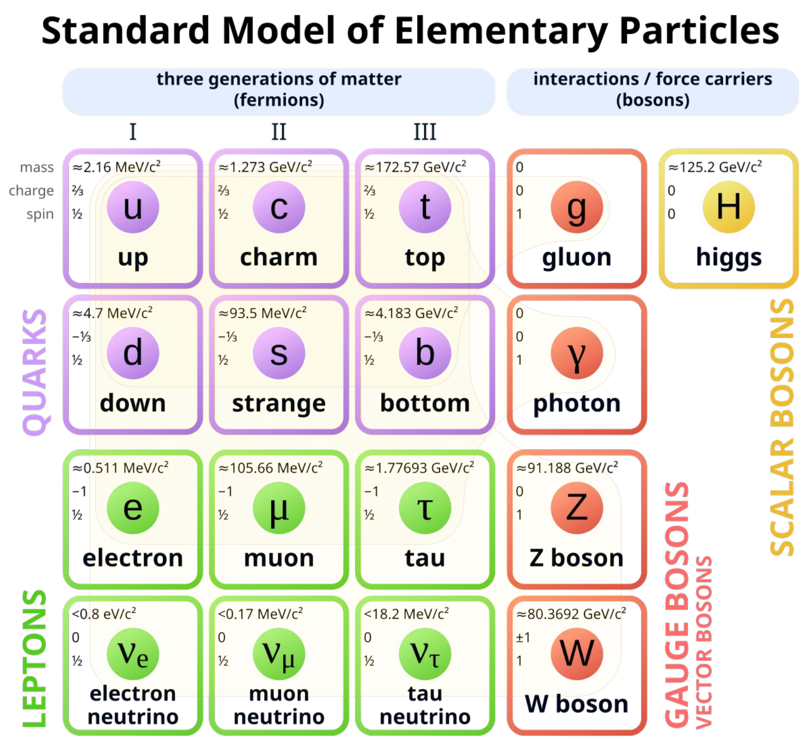
Overview and status of the Mu2e experiment

George Sweetmore

MPP25 - UoL

The University of Manchester

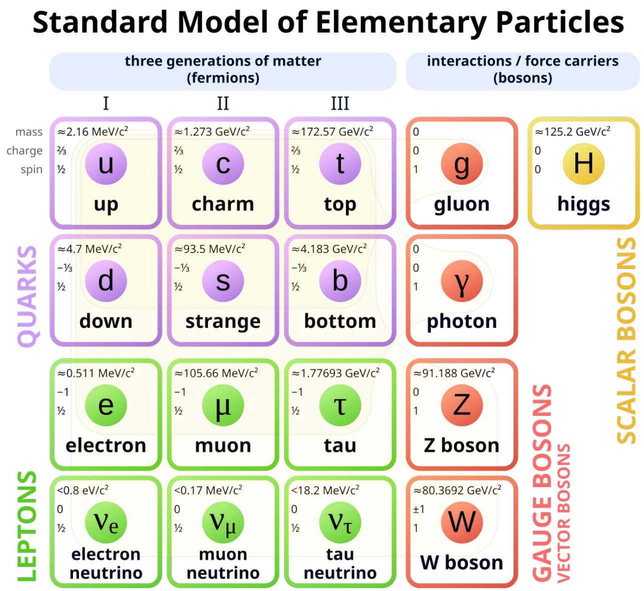
The Standard Model

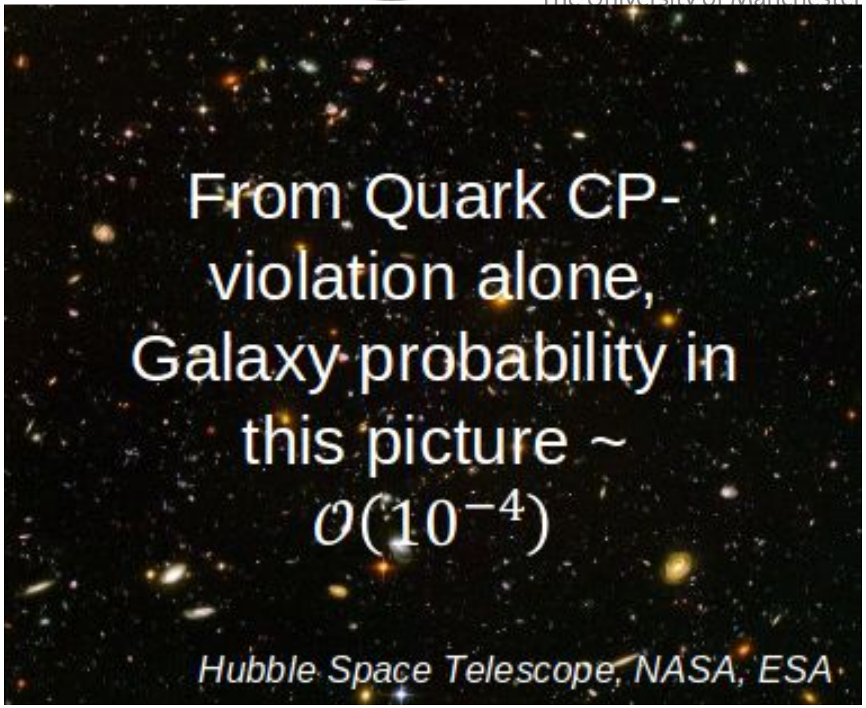


Standard Model has proven its robustness and predictability time and time again but it isn't without its shortcomings:

- Universal Baryon Asymmetry not yet explained (NEED MORE CP-Violation)
- Where is dark matter?
- How do we unify it with gravity?

The Standard Model



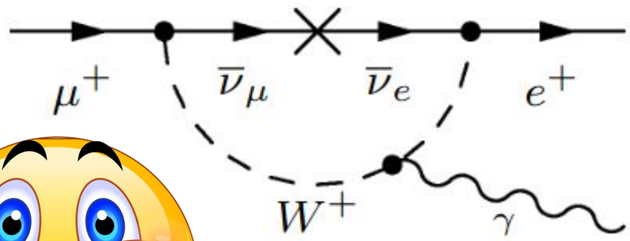


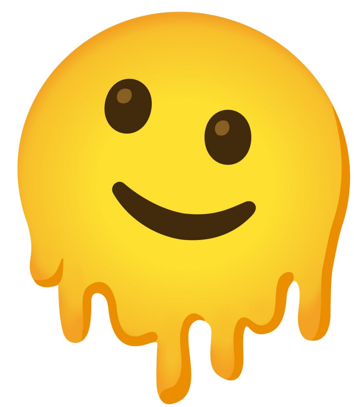
We have some CP-violation through quark mixing

We now know neutrinos oscillate (Neutral lepton flavour violation)

We need signs of new physics!

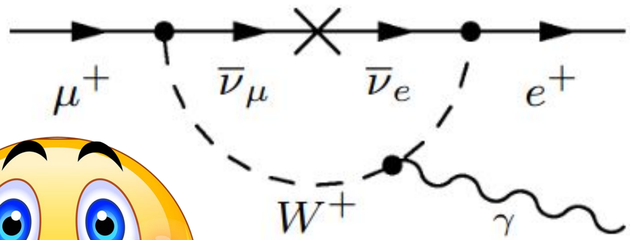
Charged lepton flavour violation

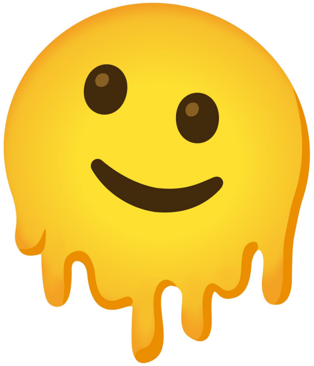




<u>Some flavour violations are better than others!</u>

Charged lepton flavour violation





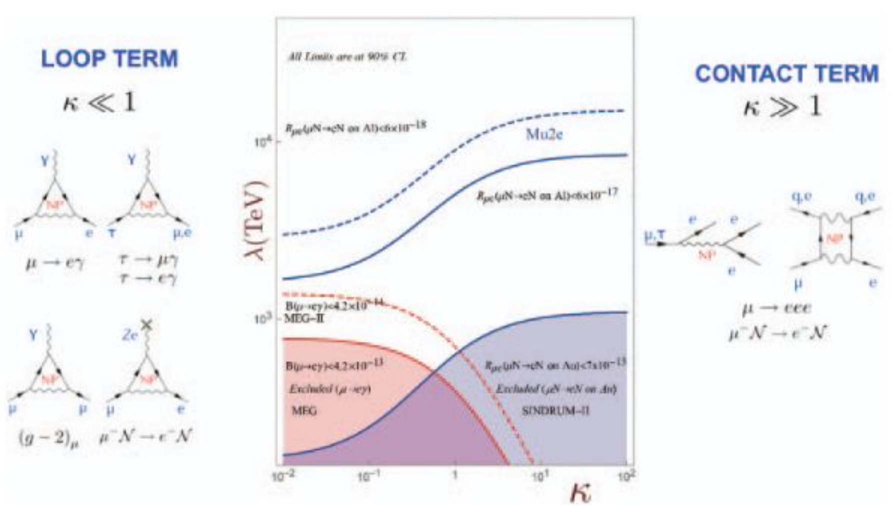
$$Br(\mu \to e\gamma)_{SM} = \frac{\Gamma(\mu \to e\gamma)_{SM}}{\Gamma(\mu \to e\nu\overline{\nu})} = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$

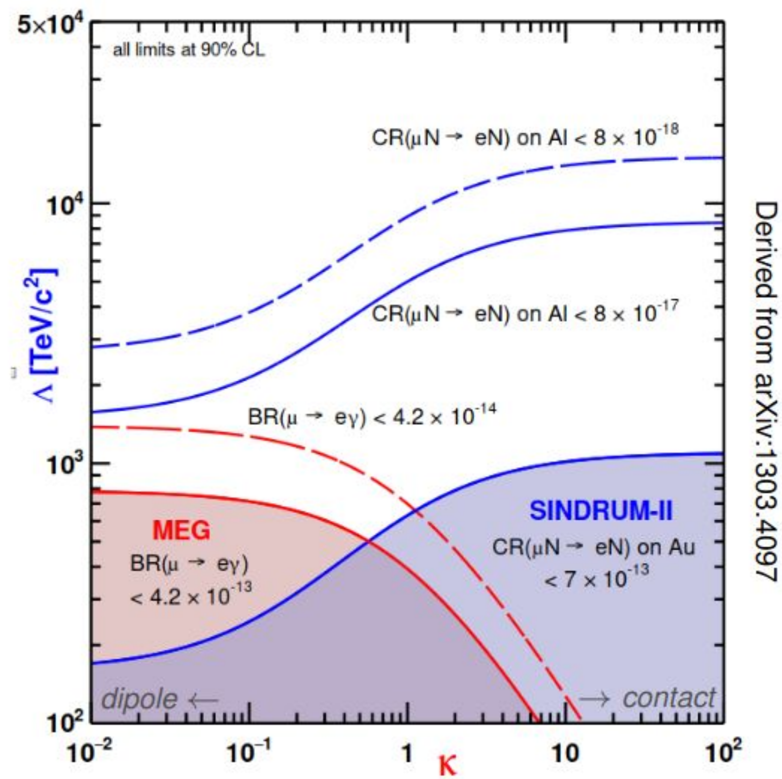
Neutrino mixing allows for non-zero CLFV where before it was forbidden
However it is unmeasurably small! So if we see it we have clear signs of New Physics!

Model independent Lagrangian

How sensitive to new physics are we?

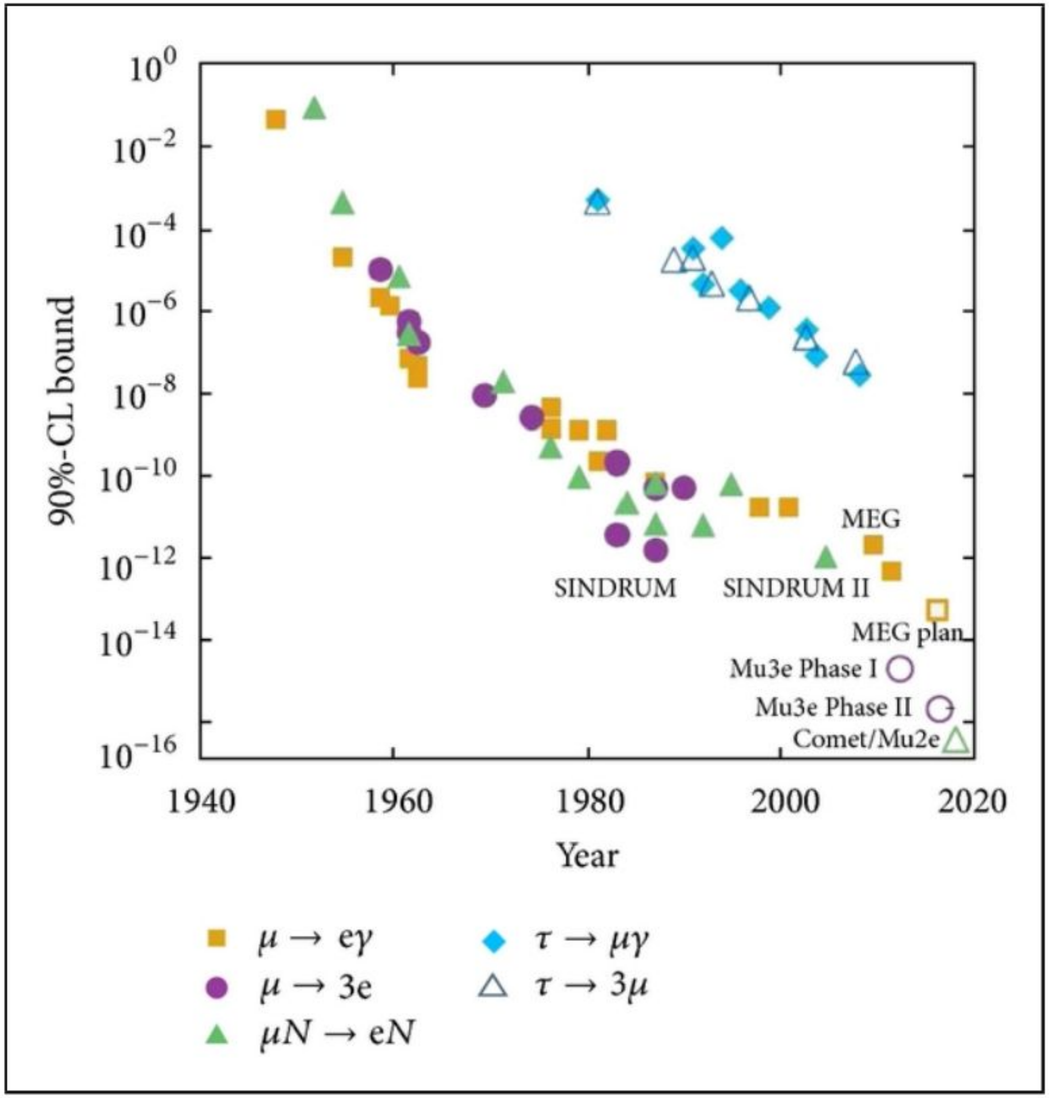
$$L_{CLFV} = \underbrace{\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}}_{\text{“Dipole term”}} + \underbrace{\frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)}_{\text{“Contact term”}}$$



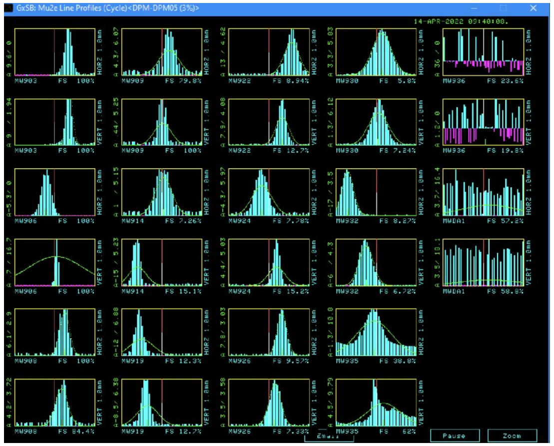


Allows us to probe large range of BSM models

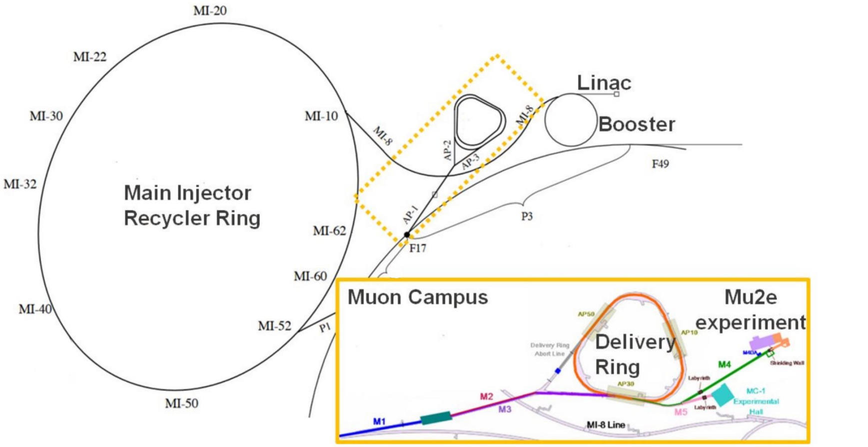
CLFV searches



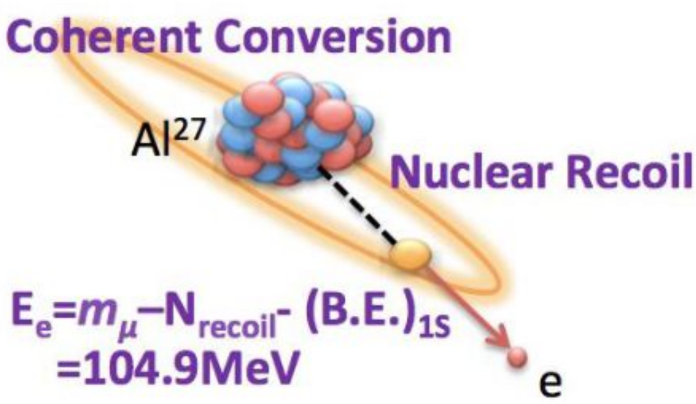
The Mu2e Experiment at FNAL



First beam recorded just prior to Mu2e Hall

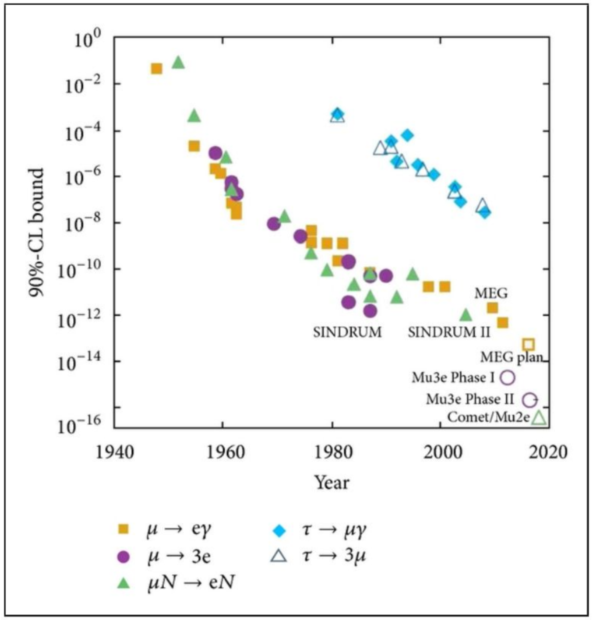


$\mu N \longrightarrow eN$ and Mu2e



Mu2e will measure neutrinoless conversion from muon to electron in proximity of a nucleus

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



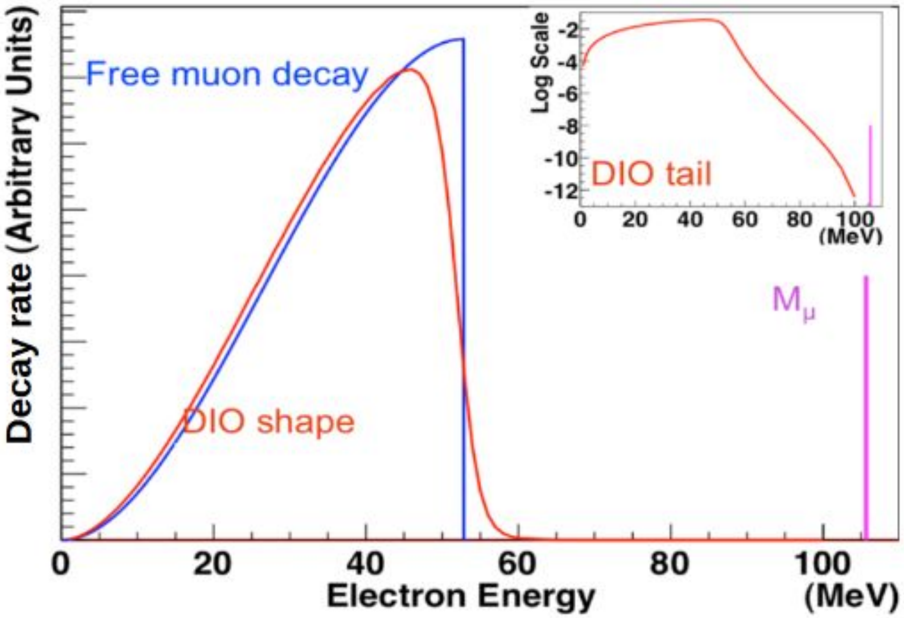
Target Sensitivity:

$$R_{\mu e} = \frac{\Gamma\left[\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)\right]}{\Gamma\left[\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N+1)\right]} < 6.7 \times 10^{-17} (90\%\mathrm{CL})$$

4 orders of magnitude better than current limits: SINDRUM II [W. Bertl et al., Eur. Phys. J. C 47, 337-346 (2006)]

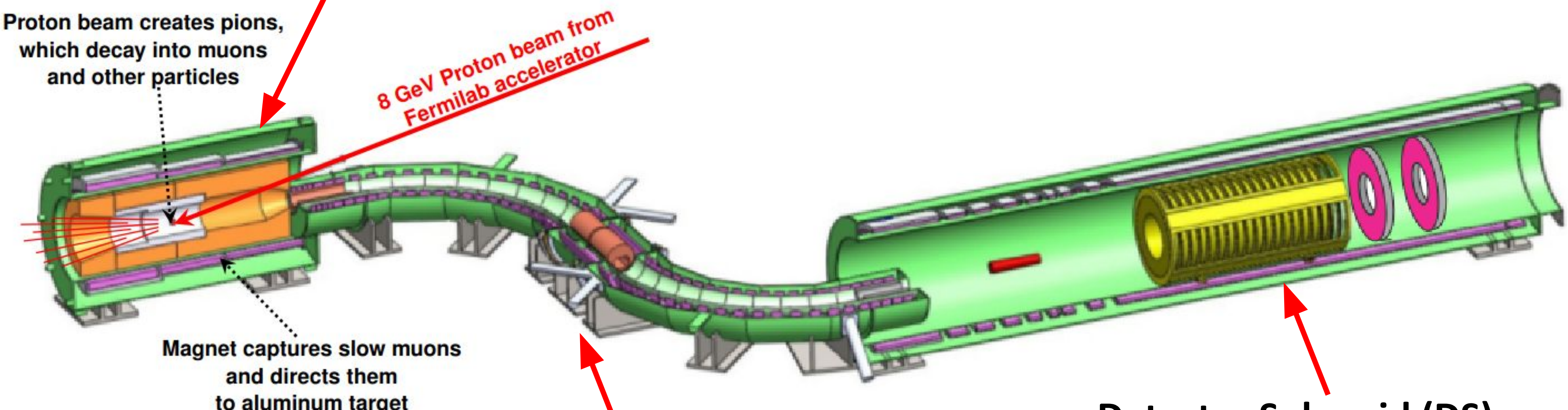
The Measurement

- Approximately 60% of stopped muons undergo the muon capture reaction (e.g. $\mu^- + {}^{27}Al \rightarrow \nu_\mu + {}^{27}Mg$)
- ~ 40% of stopped muons decay in orbit (DIO)
- CLFV signal for $\mu \rightarrow e$ conversion gives single mono-energetic electron $E_e = 104.973$ MeV



Experiment overview

Production Solenoid (PS)



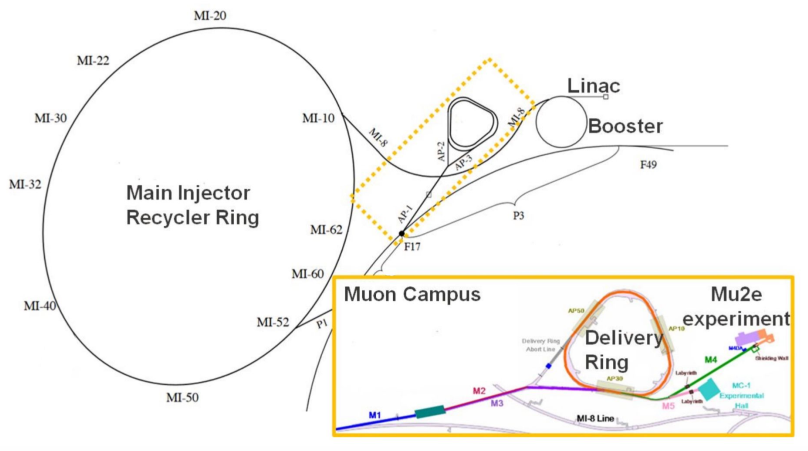
Detector Solenoid (DS)

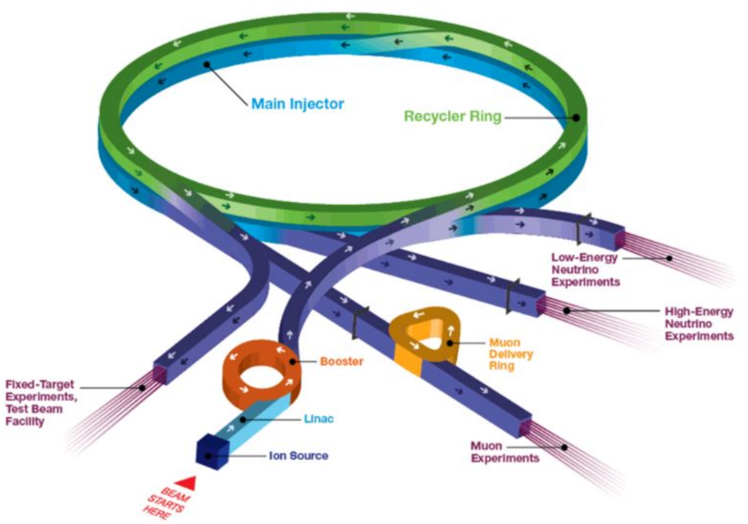
Transport Solenoid (TS)

The proton beam

1. LINAC produces 400MeV protons which are injected into the Booster Ring. Here they are accelerated to 8GeV and grouped in batches
2. A single batch is then sent into the Recycler Ring every 67ms and grouped into 4 - 1E12 proton bunches
3. From the Recycler Ring 8 bunches are sent to the Delivery Ring and a single bunch is extracted every 1.695us and directed to the Mu2e beamline. This creates the 4E7 protons/pulse beam needed for the experiment.

Beam will be delivered to Mu2e for 380ms over a full 1440ms Recycler Ring cycle.



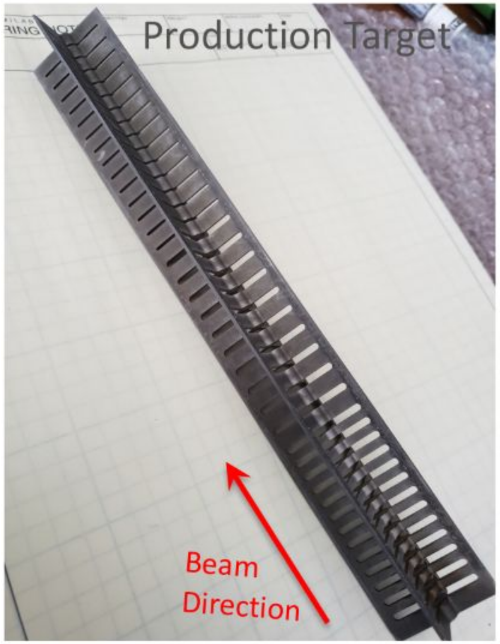


The pion production target (PPT)

The PPT needs to pass a high-level of criteria to be viable for the experimental operation of Mu2e:

1. It of course must be radiation hard and able to cope with thermal shocks from the pulsed proton beam
2. The target will absorb approximately 10% of the 7.3kW proton beam - this calls for a ‘fin-like’ design to allow for radiative cooling in the harsh beam conditions
3. Most importantly it must have a high cross-section for pion production as the generated pions are needed to produce the muon beam.

Current prototype has been built out of Tungsten but other options such as Inconel are being explored

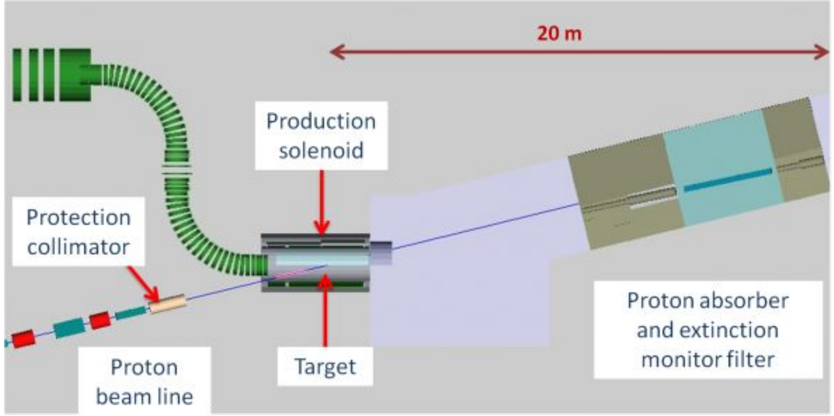


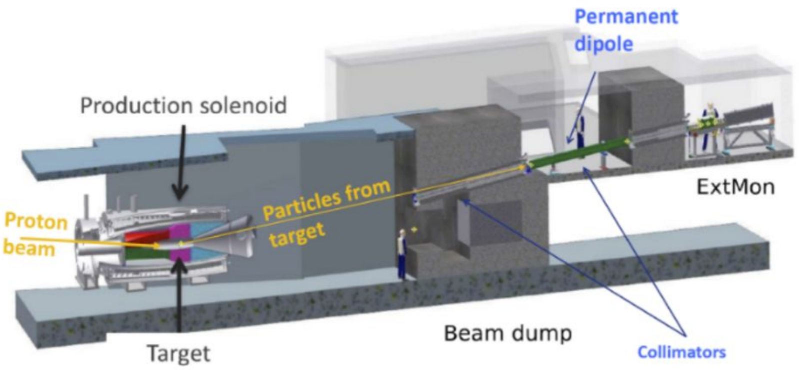
The Extinction Monitor

Remember that beam is only delivered for 380ms of the RR cycle meaning there is a non-live time for beam to the experiment.

If protons arrive within this down time they will produce a background.

An extinction monitor is set up to measure the protons on target during the down-time to ensure we have a good measure of these spurious protons and a good understanding of this background.

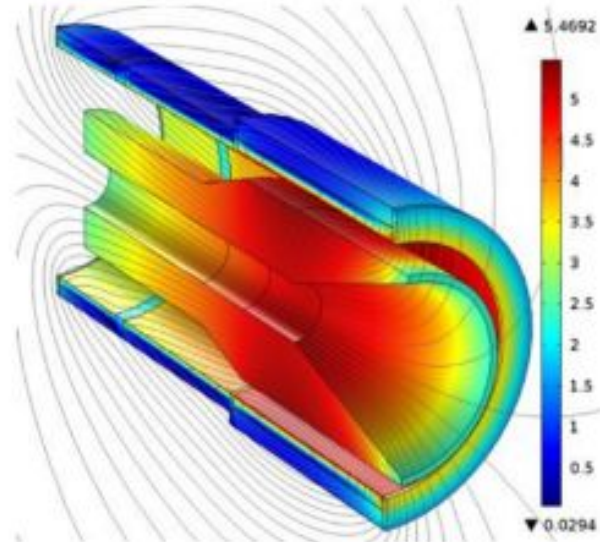




Production Solenoid

Uses a gradient magnetic field to collect backwards going muons to help alleviate beam flash intensity

Has radiation and thermal shielding to protect the target



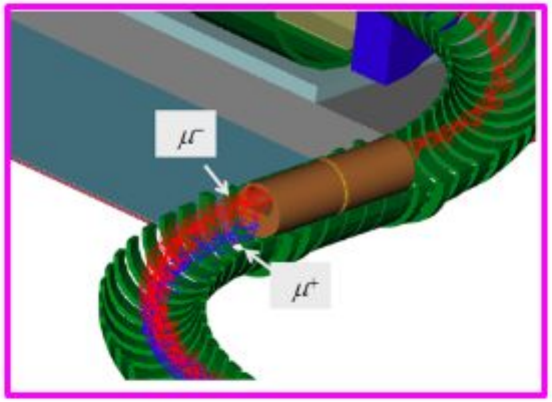
Transport Solenoid

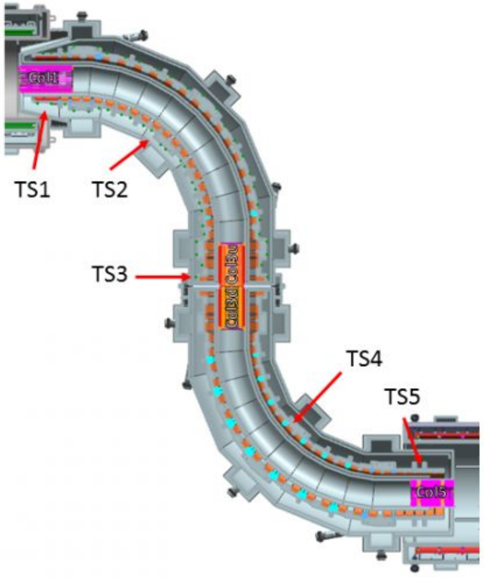
The transport solenoid allows the pions time to decay into muons before reaching the detector solenoid.

It uses an S-shape design to remove all neutral particles

Absorbers placed in the TS allow for removal of residual anti-protons that have made there way into the solenoid.

It features a rotating collimator allowing for particle charge selection (particle trajectory in the TS depends on the charge)





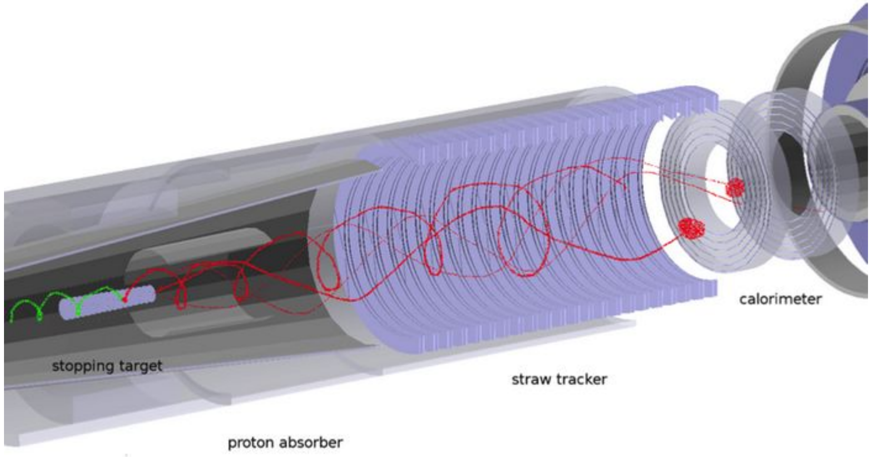
Detector Solenoid

The detector solenoid houses the muon stopping target

It also houses both the straw-tracking detector and the calorimeter

The DS features a continuous gradient magnetic field to direct the electrons produced from the stopping target towards the detectors in the target region

In the detector region it features a uniform magnetic field



Muon Stopping Target

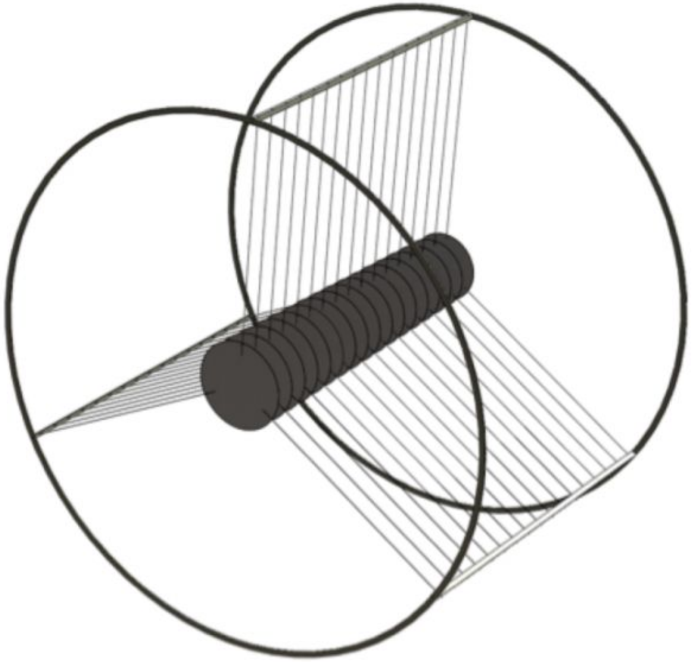
For low Z nuclei, the sensitivity to electron conversion is roughly proportional to Z, therefore Z should be maximized.

However in order to avoid radiative pion capture backgrounds the conversion signal search window must start ~700ns after the proton pulse arrives.

The target must also be designed in such a way that it minimises any risk of absorbing the outgoing electrons

The decision was made to use Aluminium for the target design as the lifetime of muonic Aluminium is ~864ns allowing for the 700ns wait time for the beam flash to die down.

It will consist of 34 aluminium foils of thickness 100 µm with radii 75mm



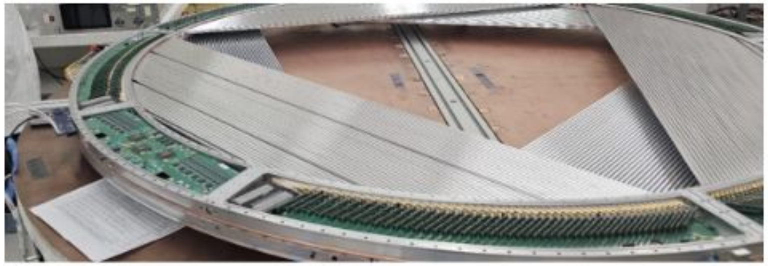
Straw Tracker

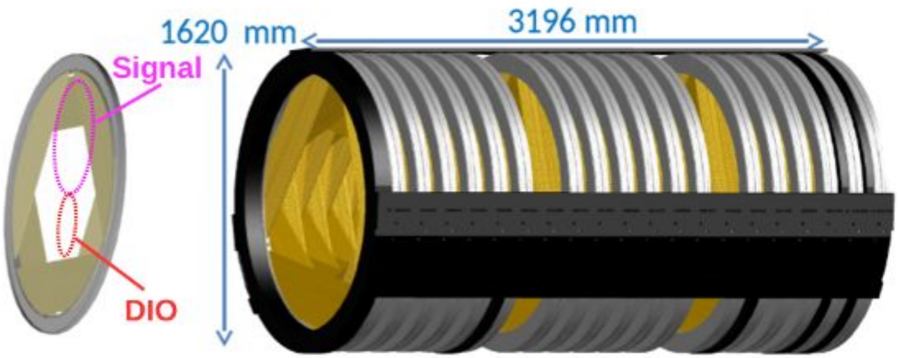
Measures momentum of traversing charged particles using their helical path

Momentum resolution $\sigma_p < 180$ keV/c

Highly-segmented low-mass tracker made of 23,040 straw drift tubes (5 mm diameter) in 18 stations containing:

- Metallized Mylar straws (15 µm wall thickness) filled with 80%:20% Ar:CO_2 gas
- 25 µm gold-plated tungsten wire in the center

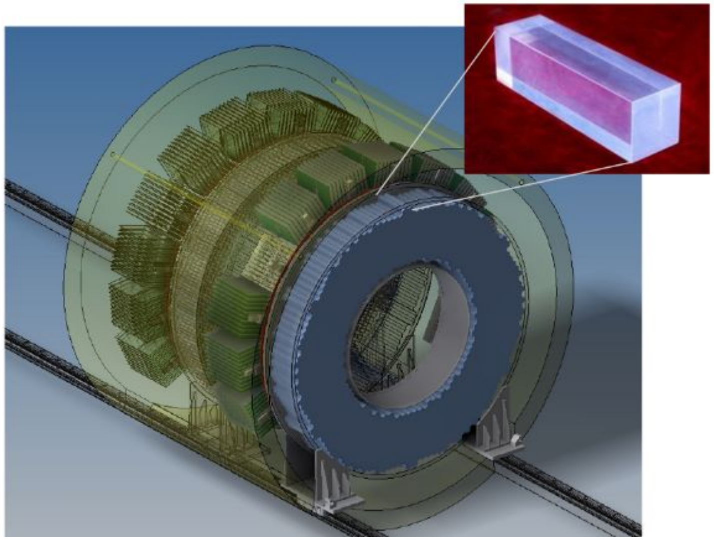




Calorimeter

The Mu2e ECal will be necessary for measuring the energy of the incident particles.
The requirements for the ECal are :

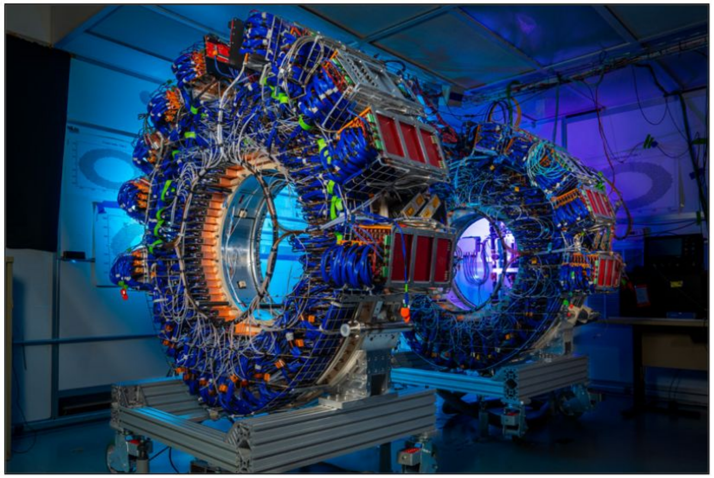
- Provide energy resolution σE/E of O(< 10 %)
- Provide timing resolution σ(t) < 500 ps
- Work in vacuum @ 10-4 Torr
- Work in a 1T B-Field
- Withstand harsh radiation environment



The ECal will allow for evaluating particle ID

Provide a fast independent trigger

2 disks, each containing 674 CsI crystals each read out by 2 Silicon PhotoMultipliers



Cosmic Ray Veto (CRV)

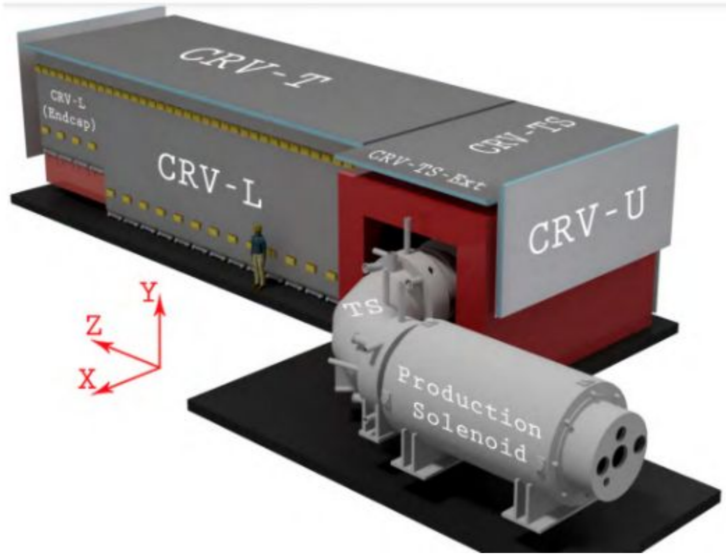
Cosmic rays without a veto in place will mimic the conversion signal at approximately ~1 event per day

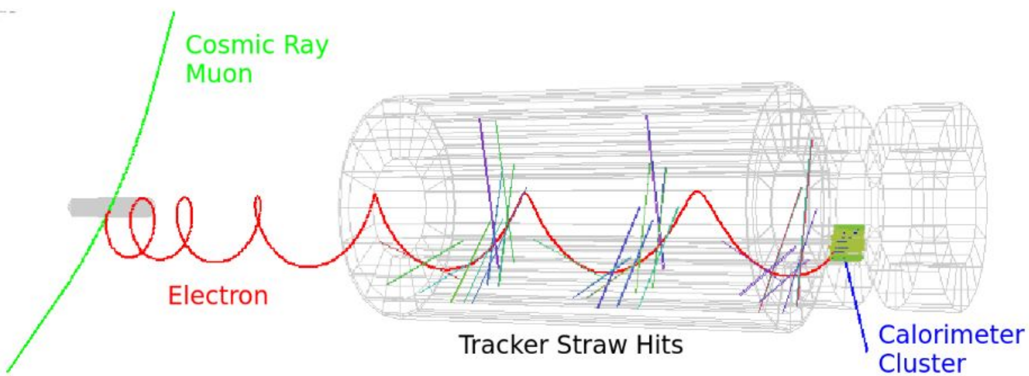
To stop this a live active veto is put in place.

The CRV will consist of:

- 4 overlapping layers of scintillator bars (5 × 2 × ~450 cm^3)
- 2 wavelength-shifting fibers/bar
- SiPMs to readout at both end of fibres
- Aluminium absorber between each scintillator layer
- Passive shielding: 1m of concrete

Goal is to achieve 99.99% efficiency





Stopping Target Monitor

Target Sensitivity:

$$R_{\mu e} = \frac{\Gamma\left[\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)\right]}{\Gamma\left[\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N+1)\right]} < 6.7 \times 10^{-17} (90\%\mathrm{CL})$$

4 orders of magnitude better than current limits: SINDRUM II [W. Bertl et al., Eur. Phys. J. C 47, 337-346 (2006)]

$3d \rightarrow 2p$ — 62% of stops emit 66 keV
- $2p \rightarrow 1s$ — 62% of stops emit 347 keV
  - 24.2% of stops DIO
  - 37.8% of stops OMC — Emit 844 keV, 1809 keV X-rays or nothing

$2p \rightarrow 1s$ — 18% of stops emit 347 keV
- 7% of stops DIO
- 11% of stops OMC — Emit 844 keV, 1809 keV X-rays or nothing

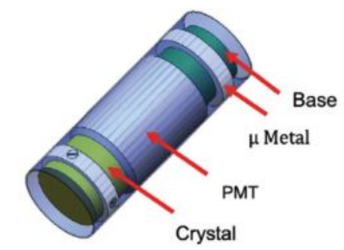
stopped in: $1s$ — 20% of stops
- 7.8% of stops DIO
- 12.2% of stops OMC — Emit 844 keV, 1809 keV X-rays or nothing

Lower rates(<100kHz)
High resolution (~1keV for 1809keV)

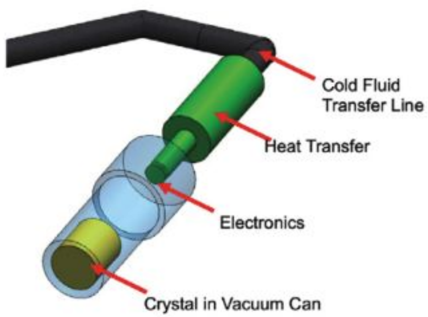
Placed 30m downstream of the DS to allow for measurement of the rate of stopped muons

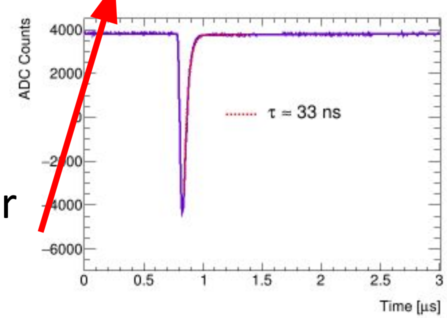
High rates(>100kHz)
Low resolution (~12keV for 1809keV)

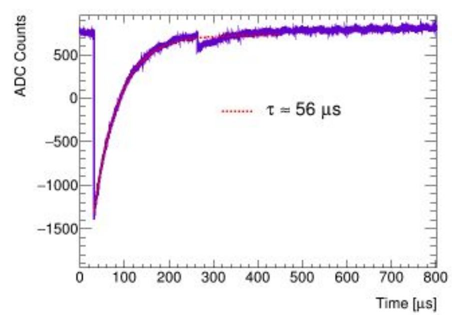
LaBr3



HPGe

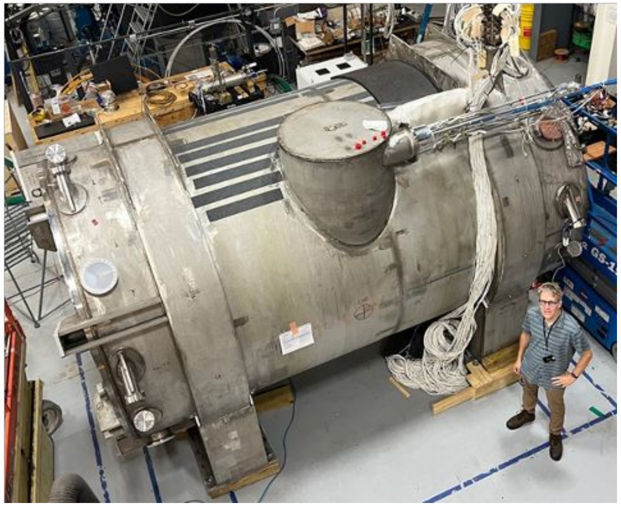


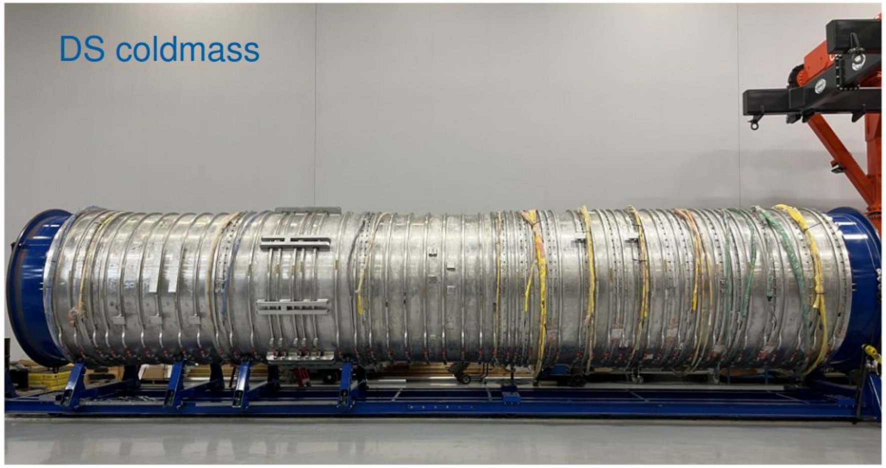




Status (Solenoids)

- Transport Solenoid and Production Solenoid have now arrived at FNAL!
- Transport Solenoid is now installed in its final location after thorough testing
- The Production Solenoid is now undergoing final testing before it will be installed in its final location
- Detector Solenoid all 11 coils have been installed into coldmass but is undergoing more testing. This has meant its delivery to FNAL has been delayed until March 2026



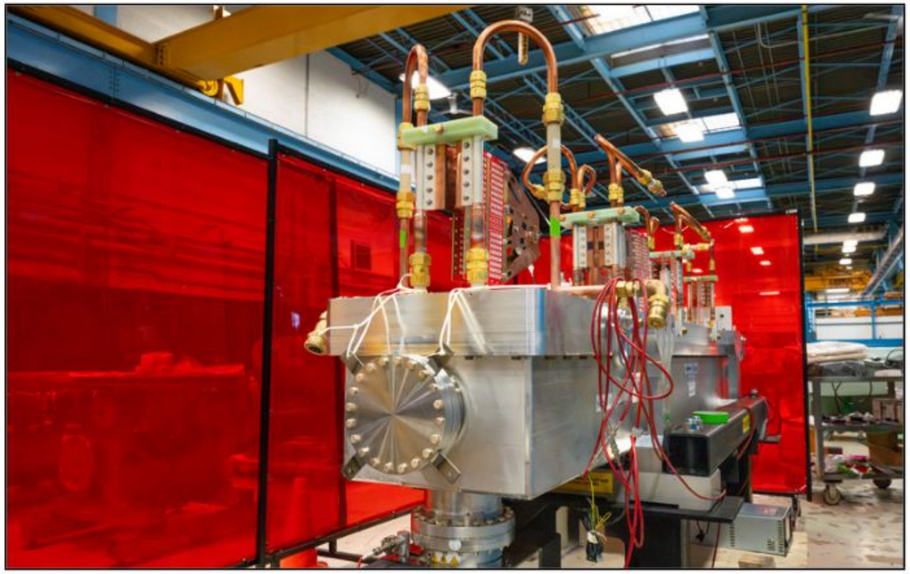


Status (Beamline and Extinction Monitor)

The electrostatic septa and AC dipoles for beam extraction are installed and being tested

Extinction monitor collimators have been installed

The dipole magnet is undergoing fabrication and the monitor itself is being assembled

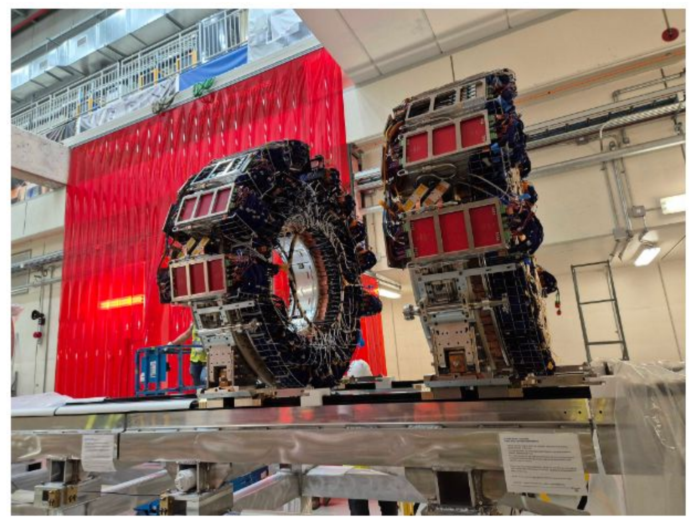


Status (Tracker)

- All 20736 straws and 216 panels produced
- Quality Control and leak testing ongoing
- All stations assembled, planned to move to the hall in the coming weeks!!

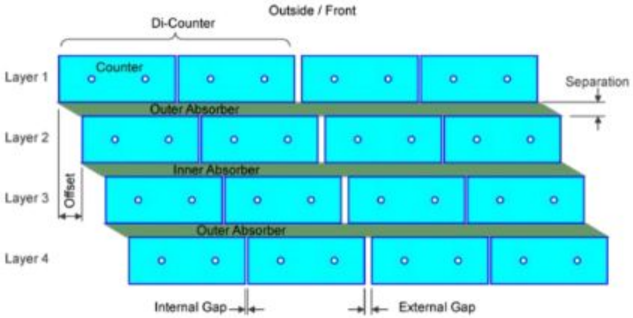
Status (ECal)

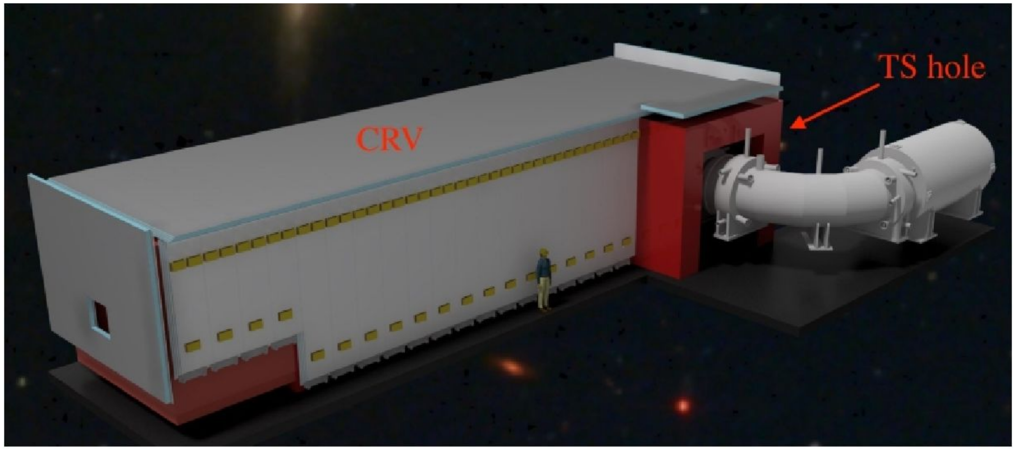
- All 1348 crystals and SiPMs have been produced
- Both disks have been fully assembled
- Test beam runs show well within specification crite
- Both disks now installed in the hall!



Status (CRV)

- All 5344 counters have been produced
- All 83 modules constructed
- Achieving the necessary 99.99% efficiency in testing
- 8 modules installed in hall for Cosmic-ray run





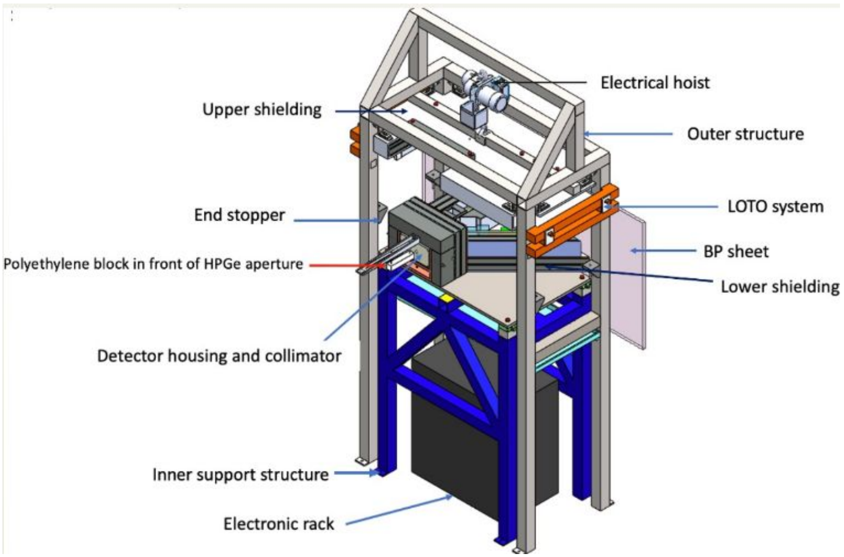
Status (STM)

- Both LaBr3 and HPGe detectors in-situ in the hall
- DAQ commissioning ongoing
- Both detectors have been tested and data analysis is in progress
- Fabrication of support structure to still be completed

Detectors

FPGA

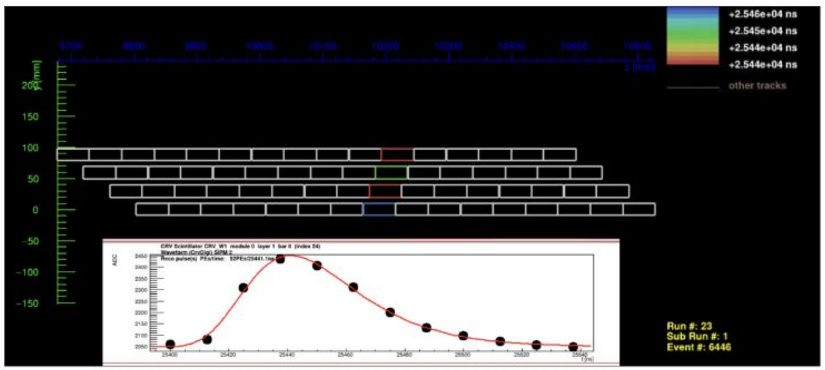
Server

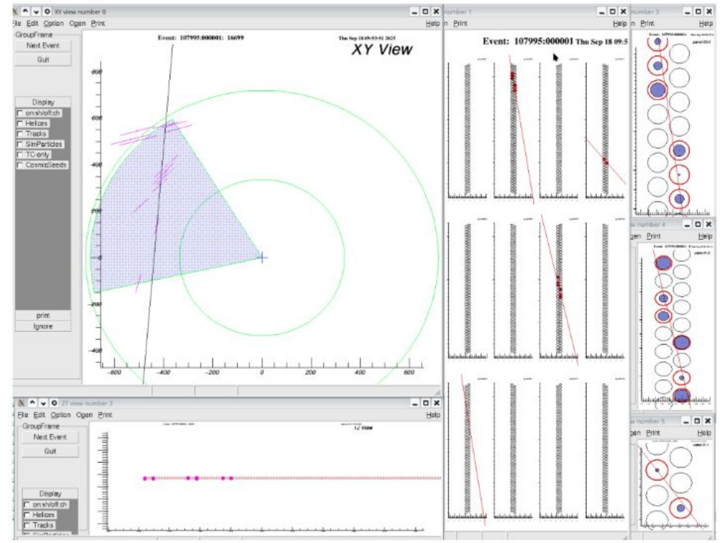


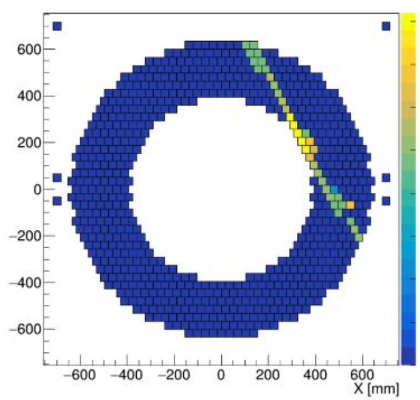
Key Performance Parameter Run

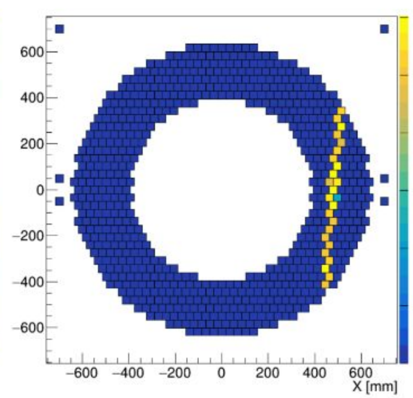
In April 2026 a dedicated KPP is set to take place to help with commissioning of the CRV, Tracker, ECal and STM.

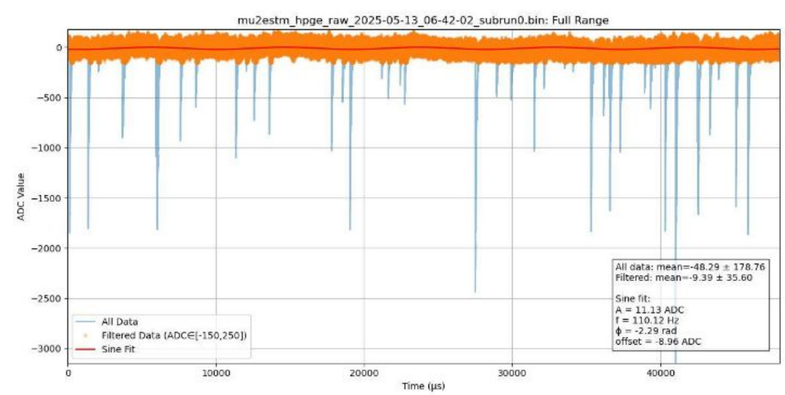
This allows for understanding of detector noise and final live-run DAQ commissioning











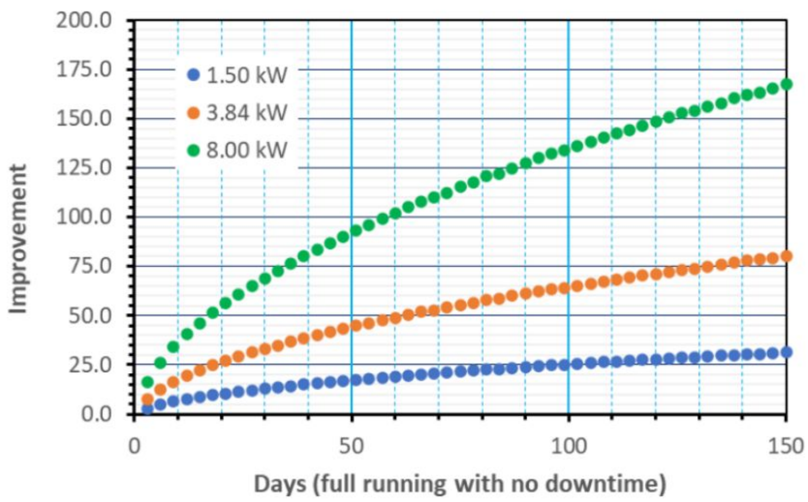
Run 1

Mu2e will begin data taking in 2027 and continue until the long shutdown at FNAL ready for the PIP-II upgrade.

Mu2e will run in a reduced operating mode before the long shutdown:

- Run 1 will only use CRV coverage above the detector (The full CRV cannot be installed until DS is installed and tested)
- Reduced proton beam intensity (one booster batch instead of two)

Even with a reduced 4kW beam intensity and only CRV coverage above the detector, Mu2e will reach a sensitivity for muon-to-electron conversion of approximately 50 better than the current value of the SINDRUM-II experiment.



Conclusions

After the long shutdown at FNAL - Mu2e will continue to take data for 2 more full years

We will reach an increase in sensitivity for muon-to-electron conversion of a factor of ~10,000 better than the current limits set by SINDRUM-II

Mu2e will perform integrated cosmic ray measurements with the calorimeter and CRV at the end of this year and integrate the STM and tracker in early 2026.

Mu2e will begin its first data taking in 2027 achieving a factor of 50 improvement on the current limits

If we do see a signal we have direct confirmation of new physics although we will not know which BSM model is responsible.

If we don't see a signal we will set stringent limits on viable BSM models for future experiments.


That's all Folks!