Mu2e Status and Future Plans

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10th November 2023

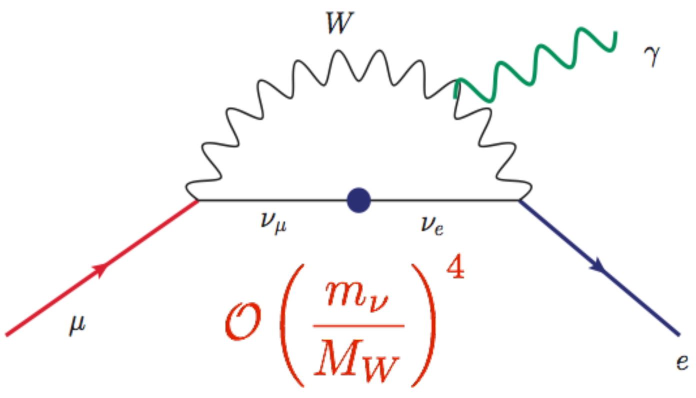
Charged Lepton Flavour Violation

Mu2e, COMET, Mu3e and MEG-II look for the neutrinoless conversion of a muon to an electron

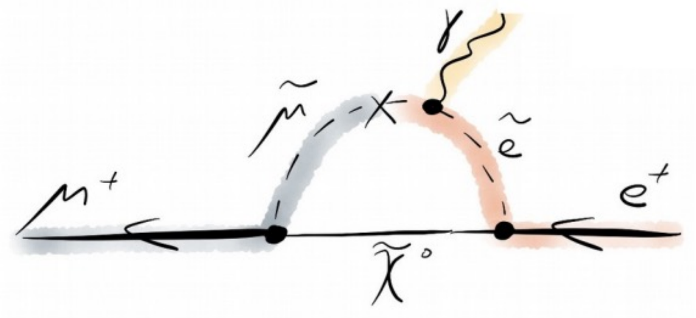
Observed in the neutral sector through neutrino oscillations

In the SM rate is $O(10^{-50})$

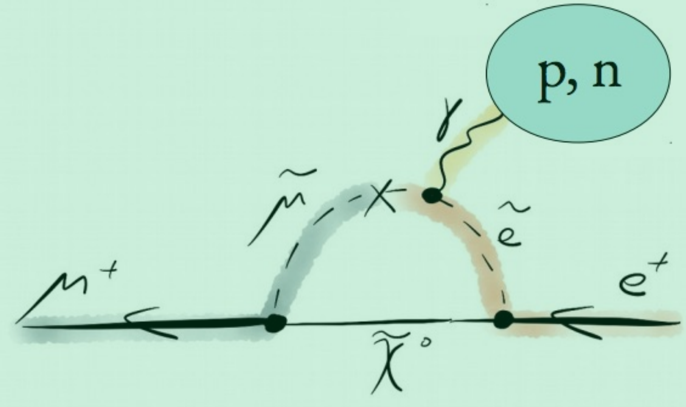
→ **Any observation is a sign of new physics**



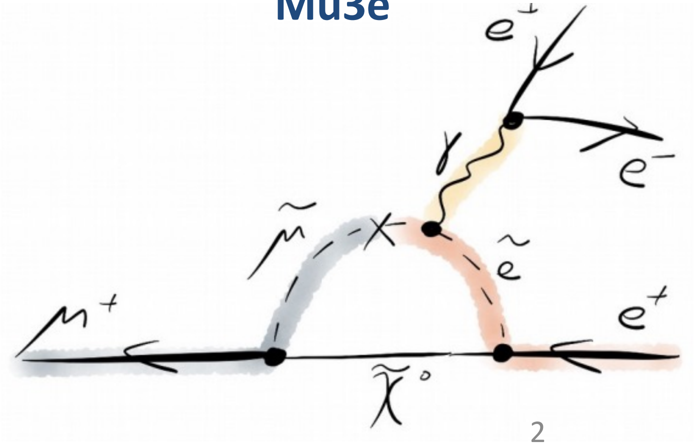
MEG-II



Mu2e/COMET

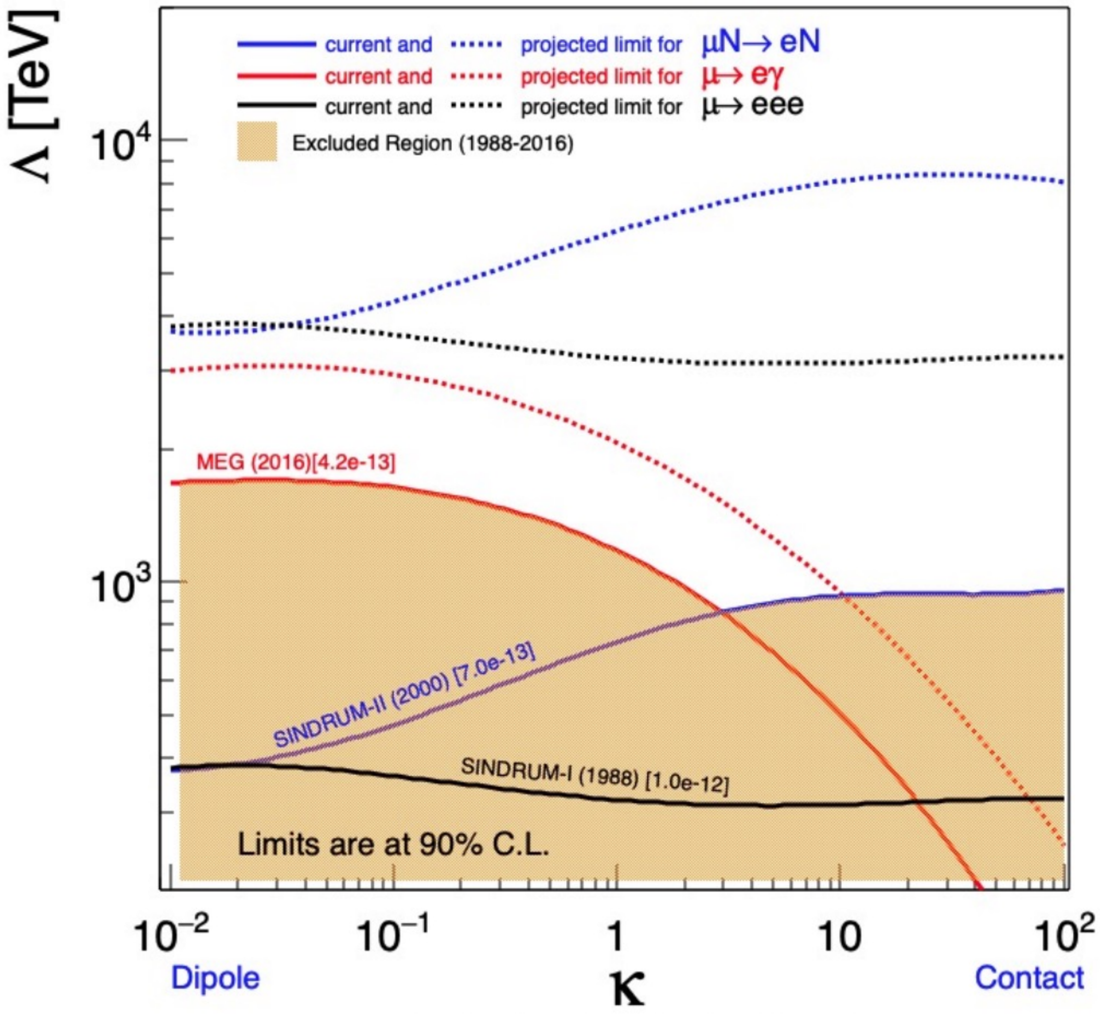


Mu3e



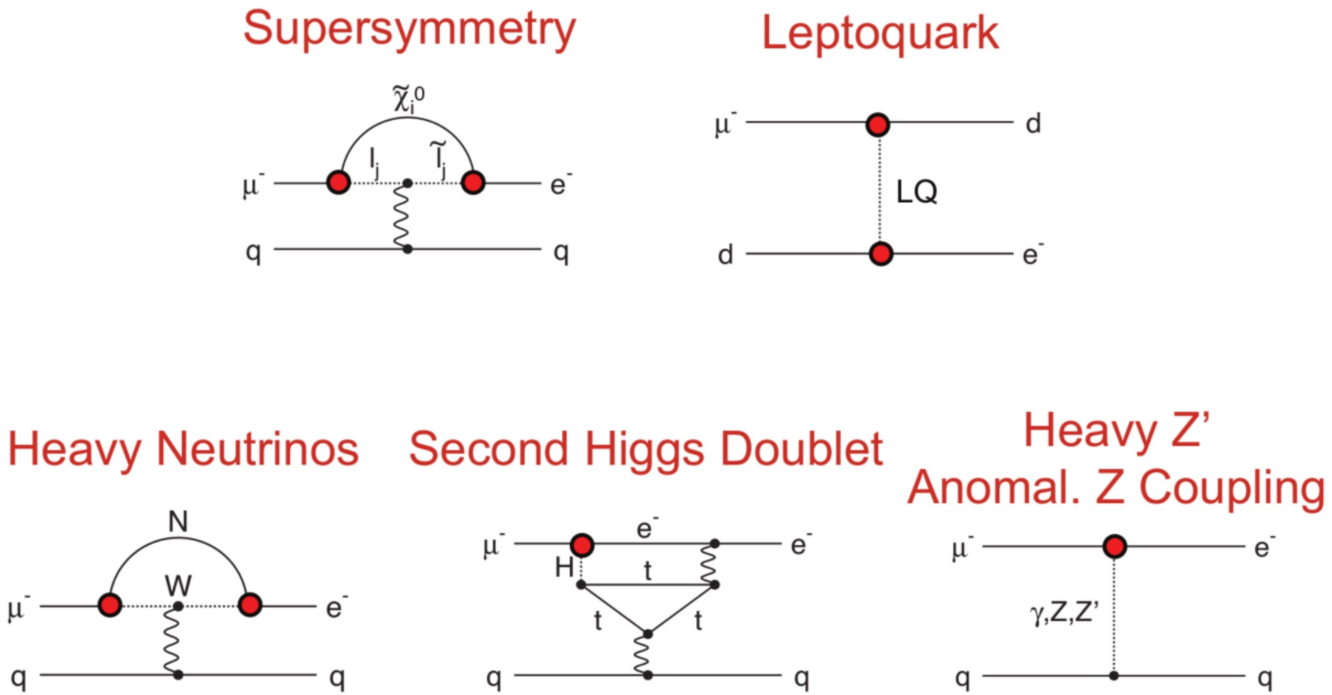
Mu2e

The Mu2e experiment looks for the neutrinoless conversion of a muon to an electron in the field of a nucleus



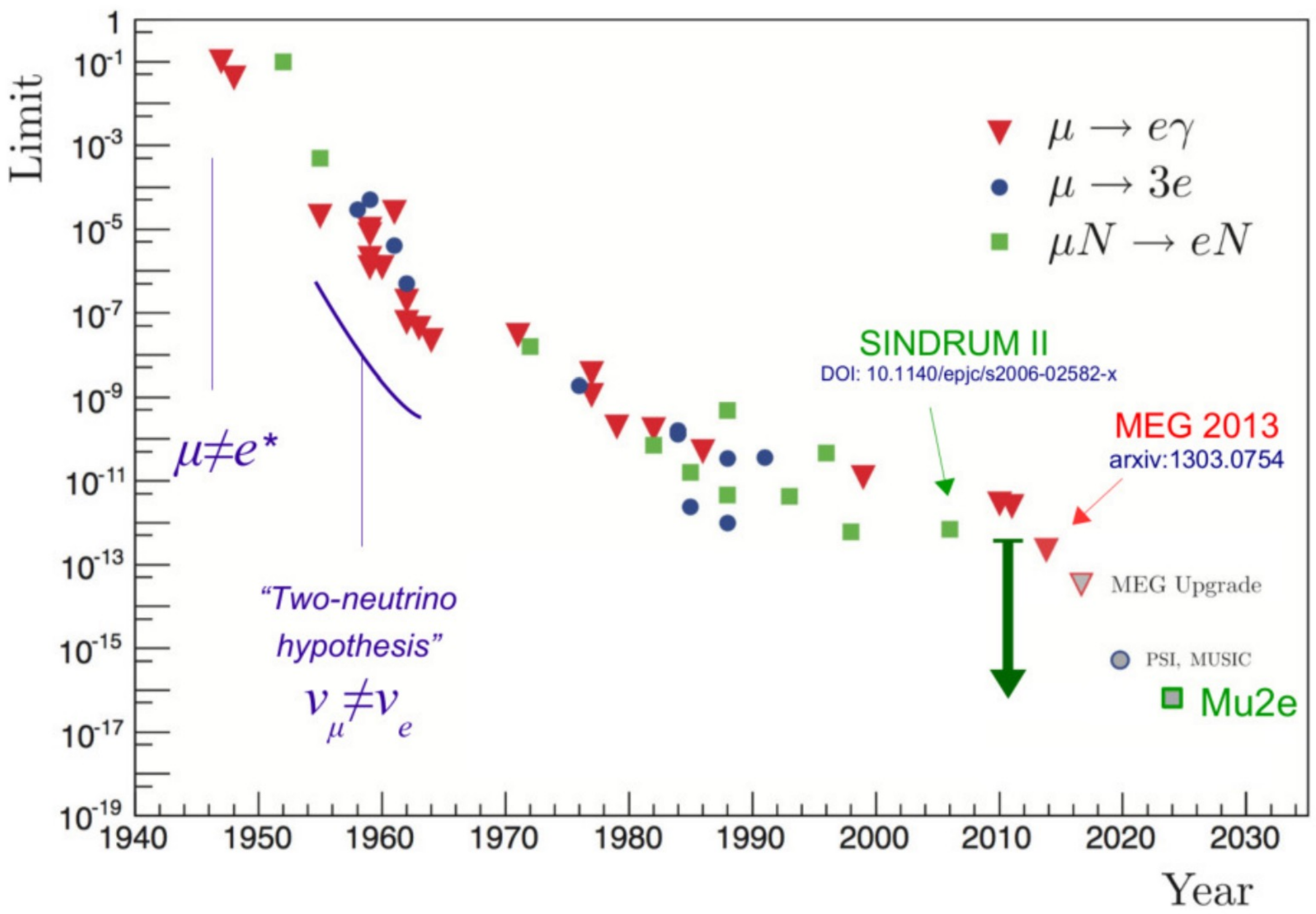
Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

- Probes many different new physics models
- Improves sensitivity by 10^4



History of CLFV

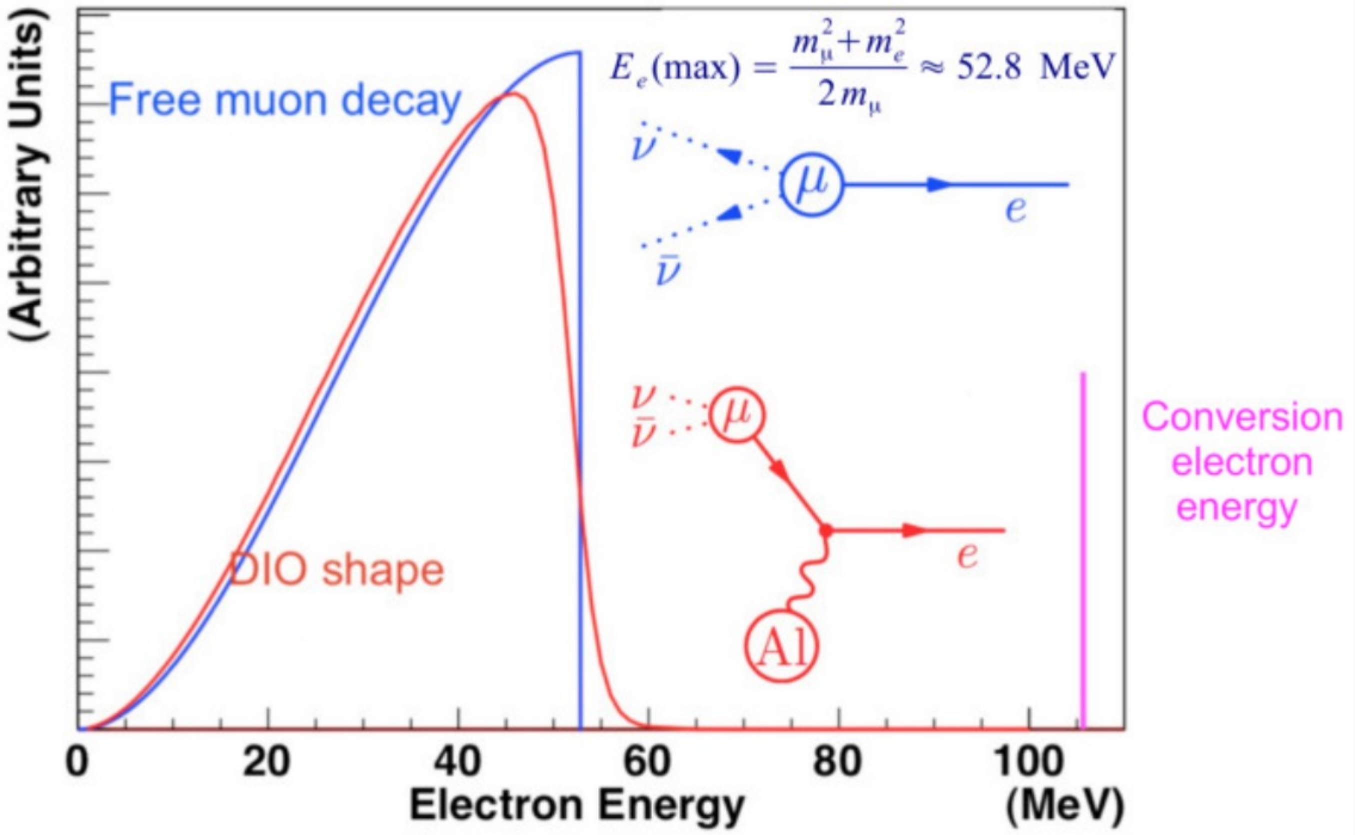
The Mu2e experiment looks for the neutrinoless conversion of a muon to an electron in the field of a nucleus



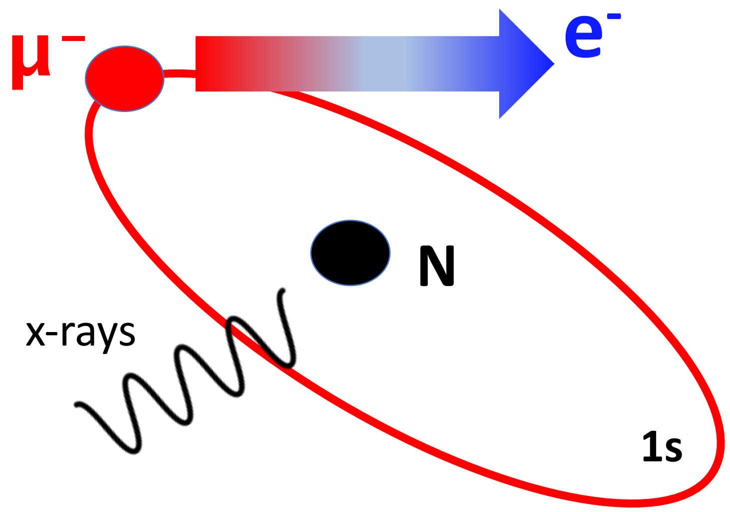
The Mu2e experiment

The neutrinoless conversion of a stopped muon to an electron produces a mono-energetic electron signal

Measure the ratio : $\dfrac{\text{Muon to electron conversion}}{\text{Muon capture on the nucleus}}$



Signal



$$E_e = m_\mu - E_{bind} - E_{recoil}$$
$$= 105.67 - 0.47 - 0.22\ MeV$$
$$= \mathbf{104.98\ MeV}$$

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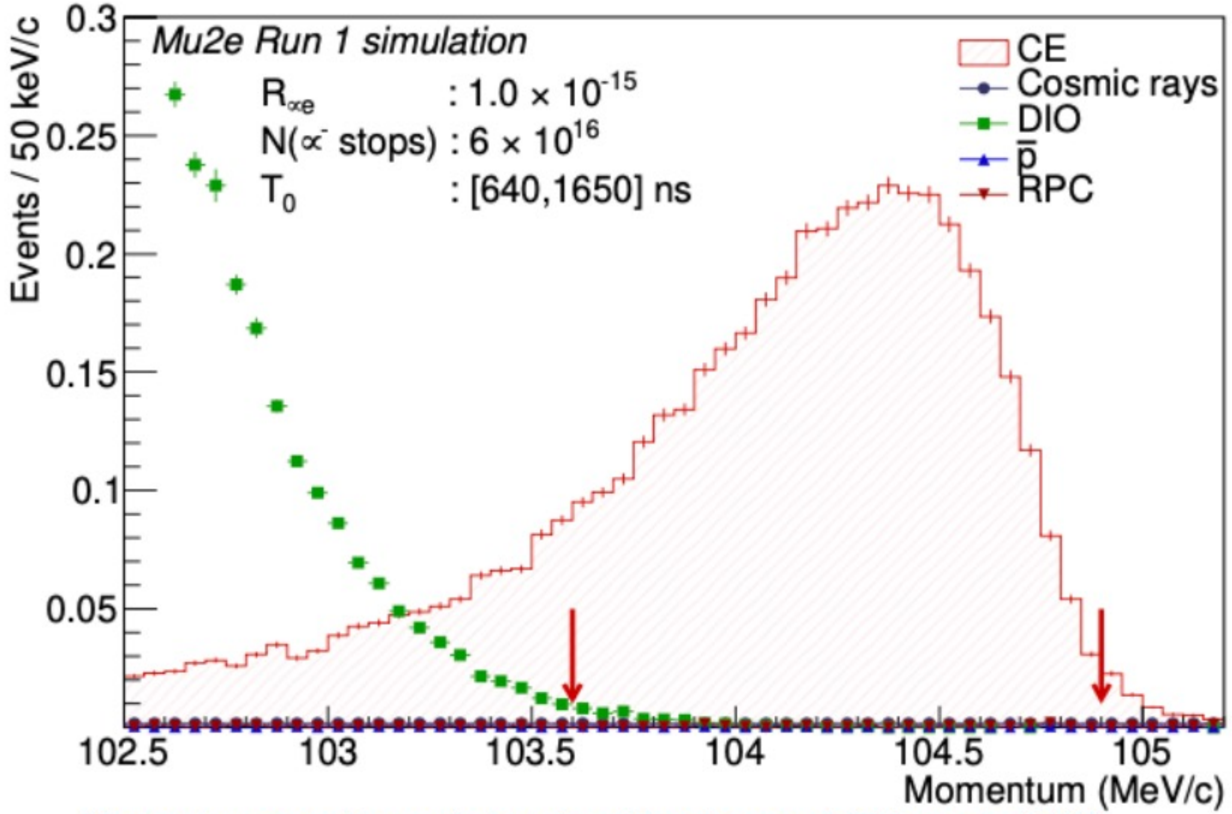
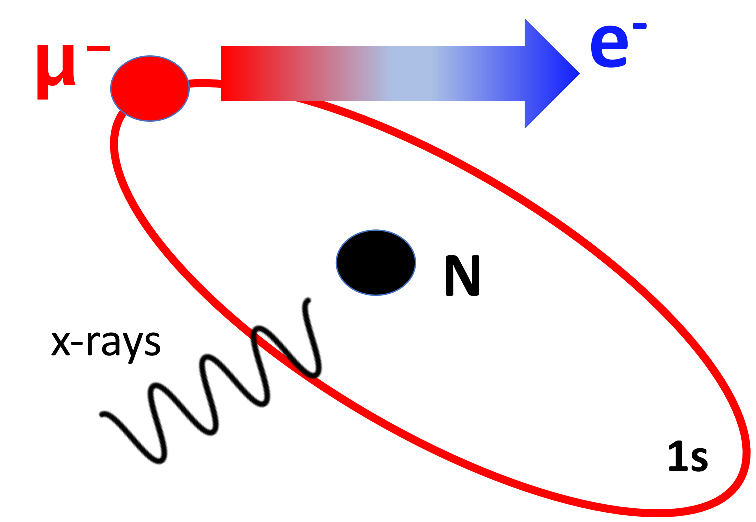


Momentum spectrum of signal and background (Edmonds 2023)

Signal



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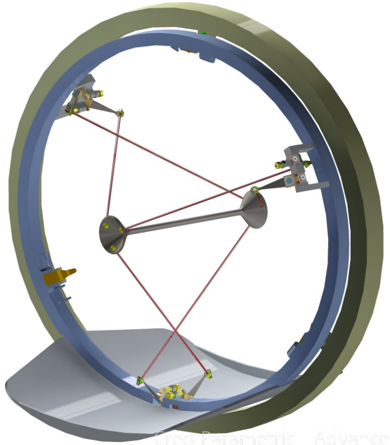
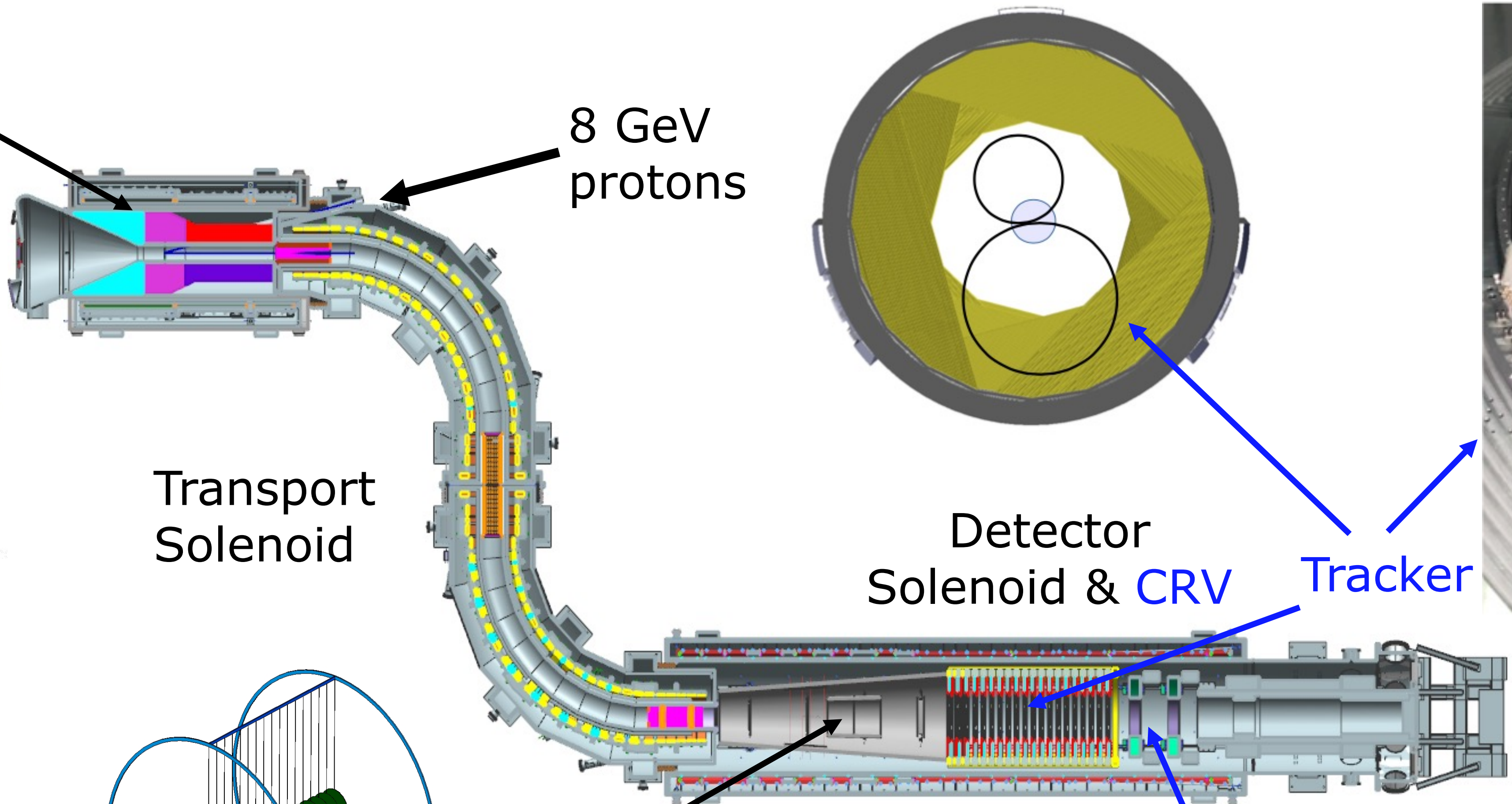
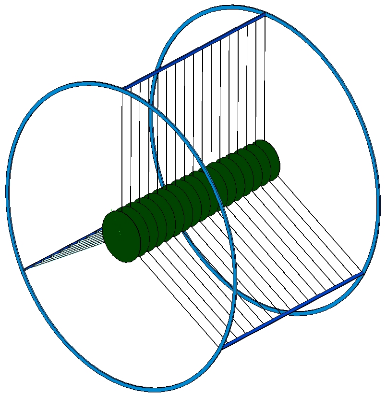
The Mu2e experiment

The experiment is designed to produce a low energy beam of muons which are captured on a stopping target





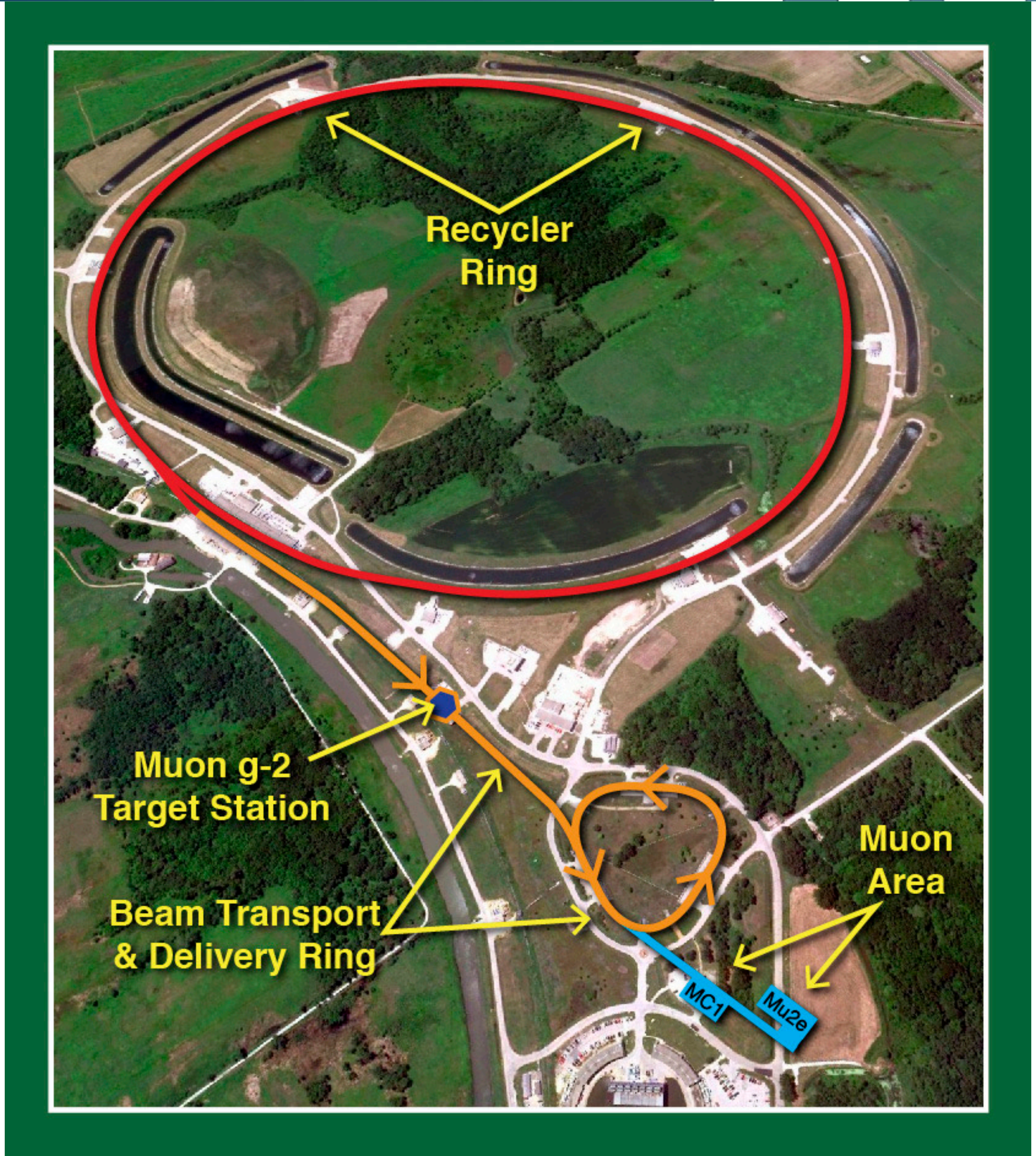


Commissioning with beam to start in 2023

Fermilab Accelerator Complex

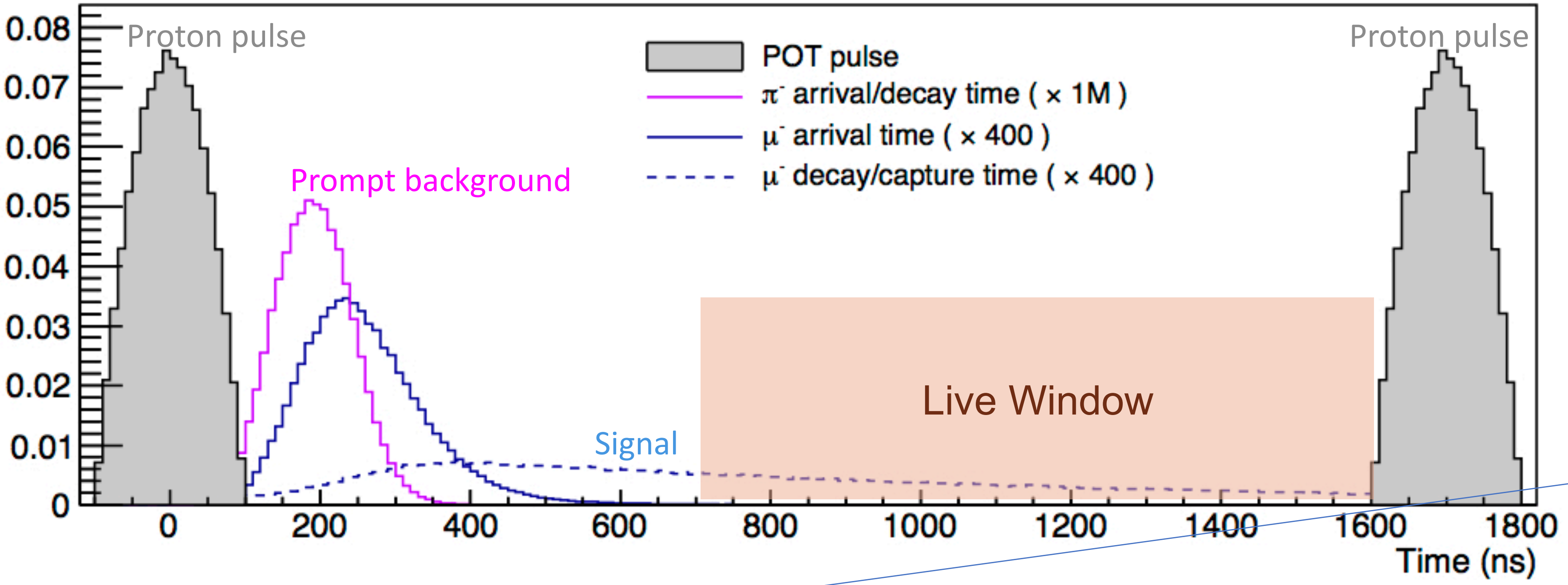
Takes place at the Fermilab muon campus

Uses the 8GeV pulsed proton beam coming from the booster



The Mu2e experiment

The long lifetime of muonic aluminium in combination with a pulsed beam is important for reducing the backgrounds



Prompt backgrounds :

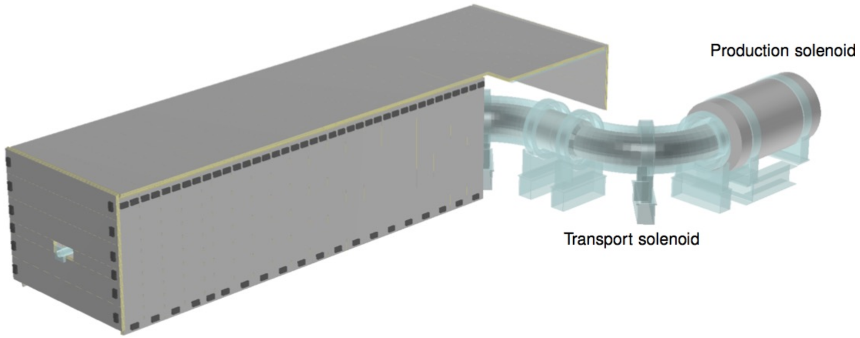
- Scattered beam electrons
- In flight muon/pion decay
- Radiative pion capture

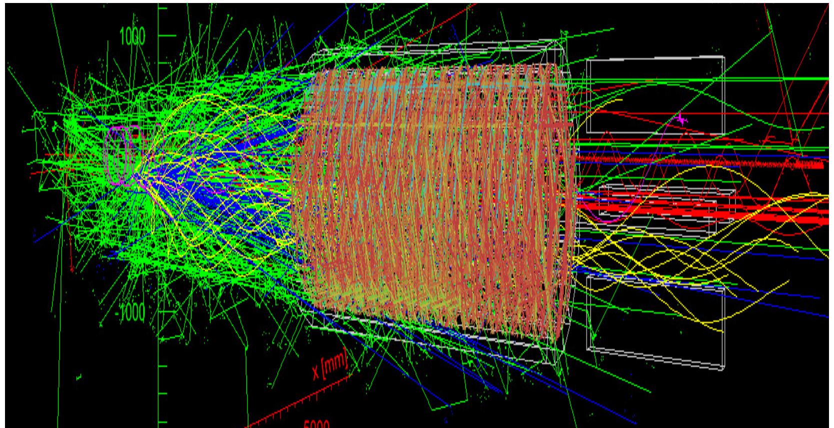
$$\pi^- + N \rightarrow \gamma + N^*$$
$$\gamma \rightarrow e^- e^+$$

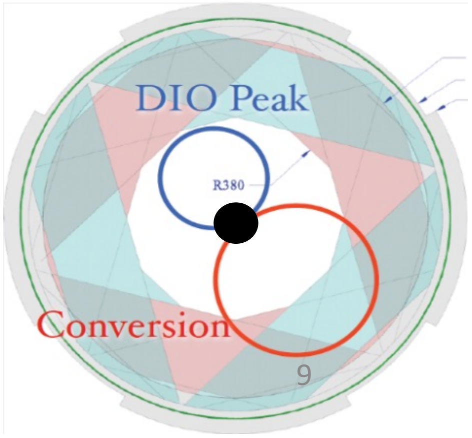
Other backgrounds :

- Cosmic rays
- Reconstruction errors

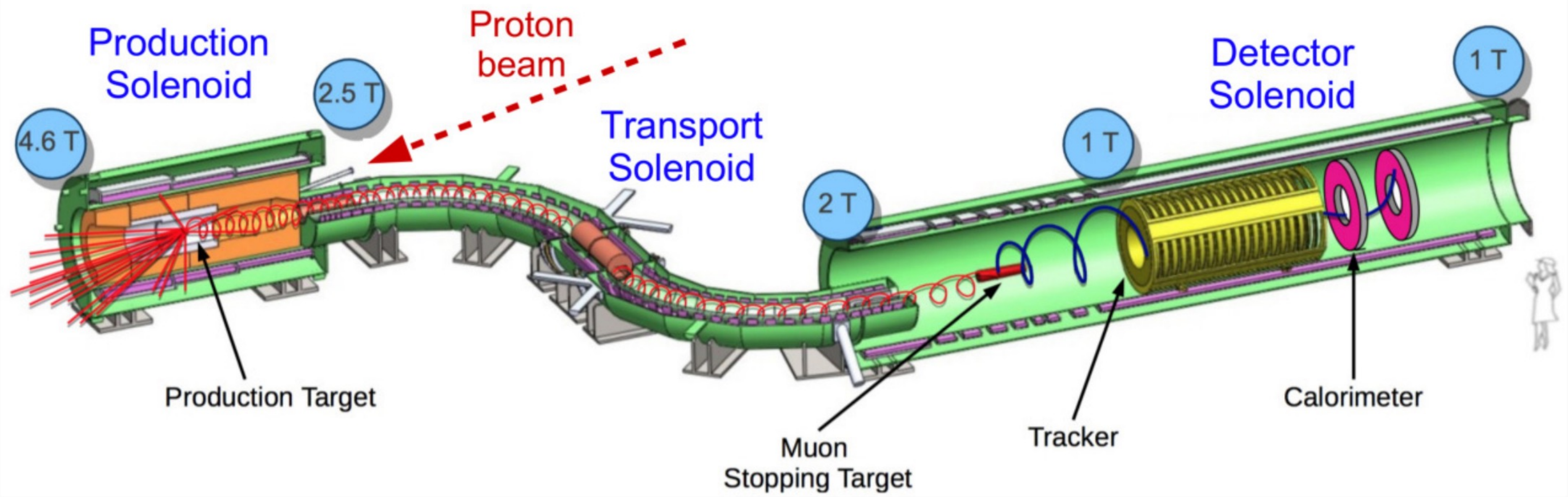
Cosmic ray veto







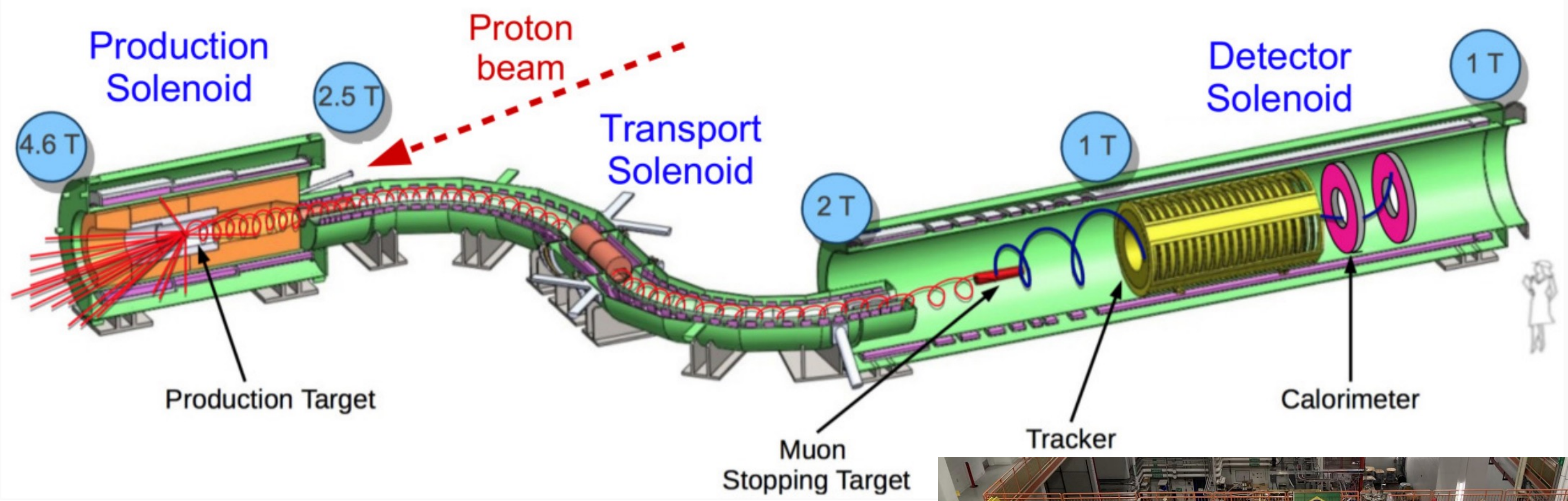
Production Solenoid



Production solenoid uses magnetic mirror to select low energy backwards going pions

Completing final tests, delivery December 2023

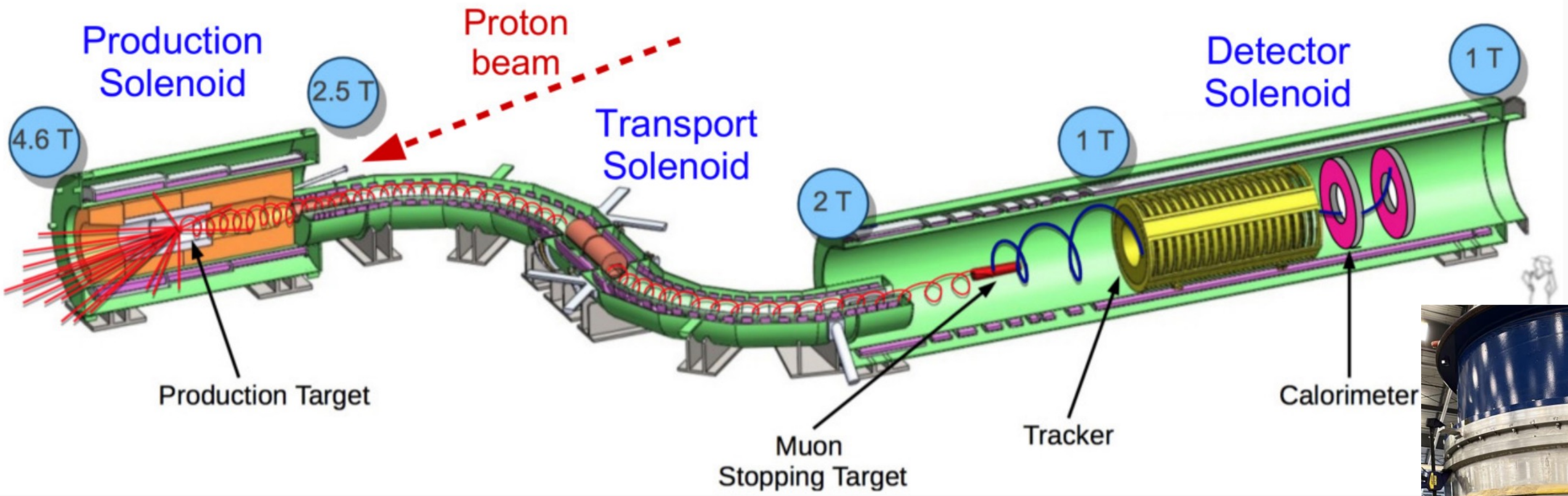
Transport Solenoid



S-shaped transport solenoid for muon momentum selection

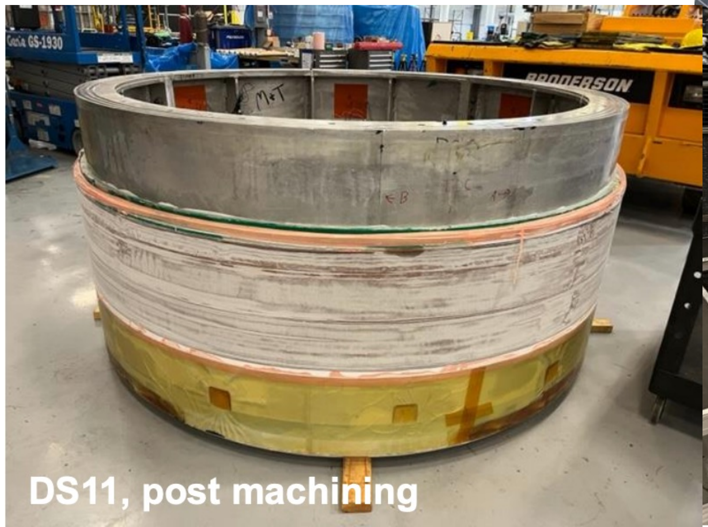
Close to completetion, TSU delivered in January

Detector Solenoid

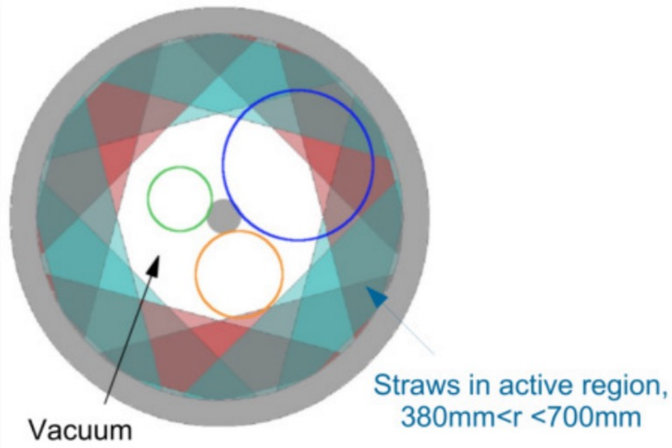


Provides magnetic field for detection of 105 MeV electrons

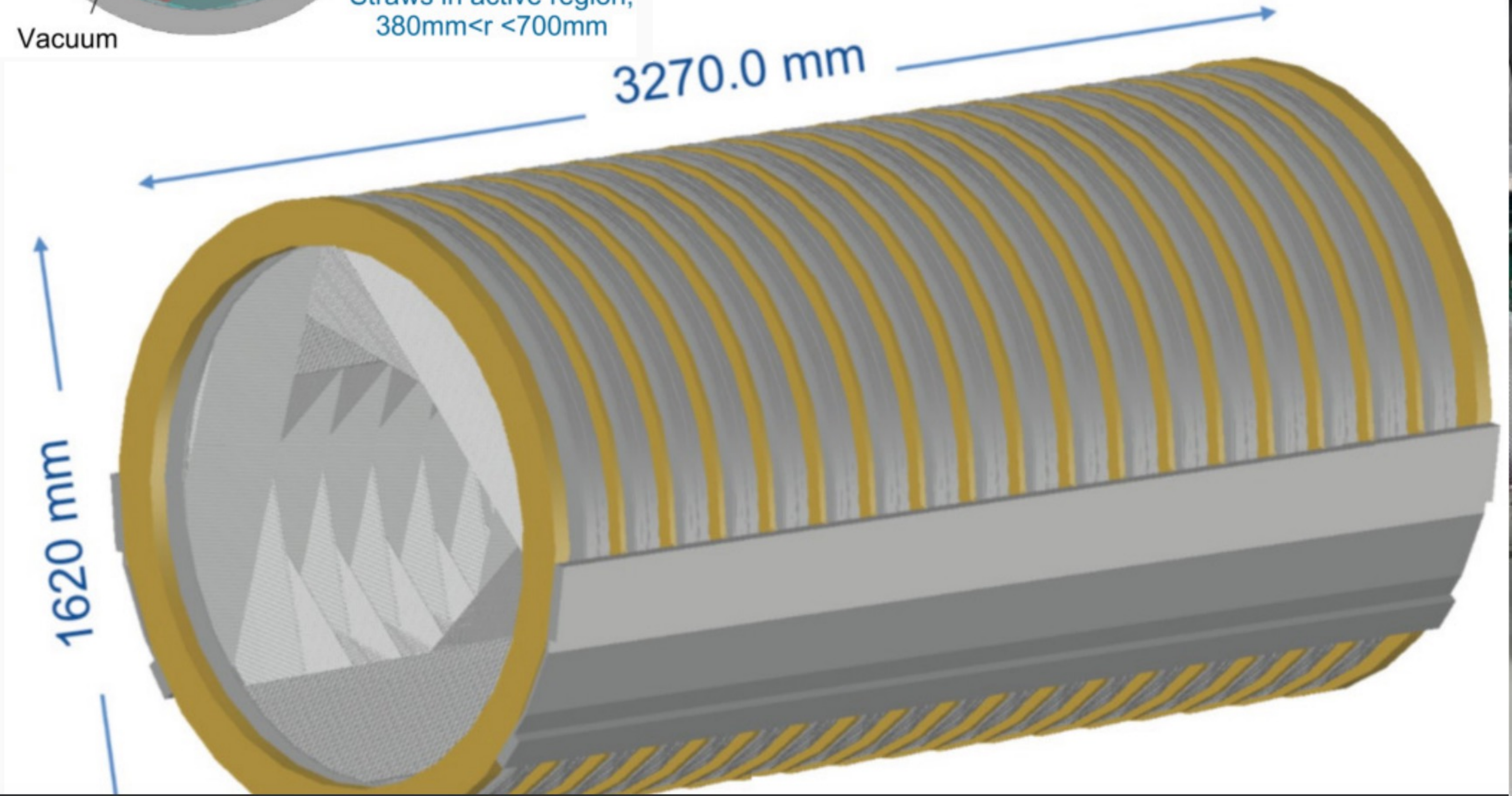
Expected completion in Summer 2024



Tracker



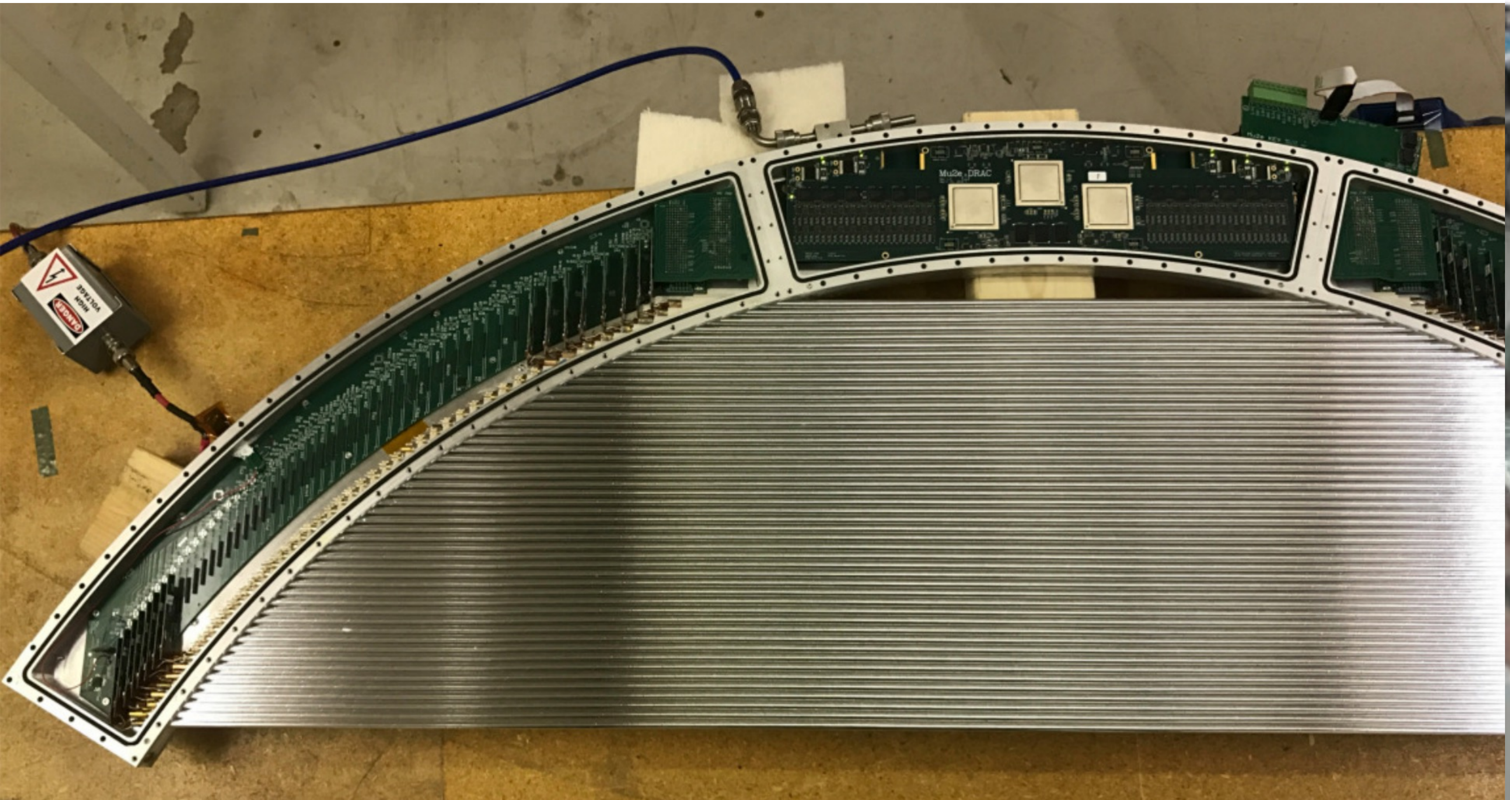
Precise momentum measurement with better than 200 keV momentum resolution

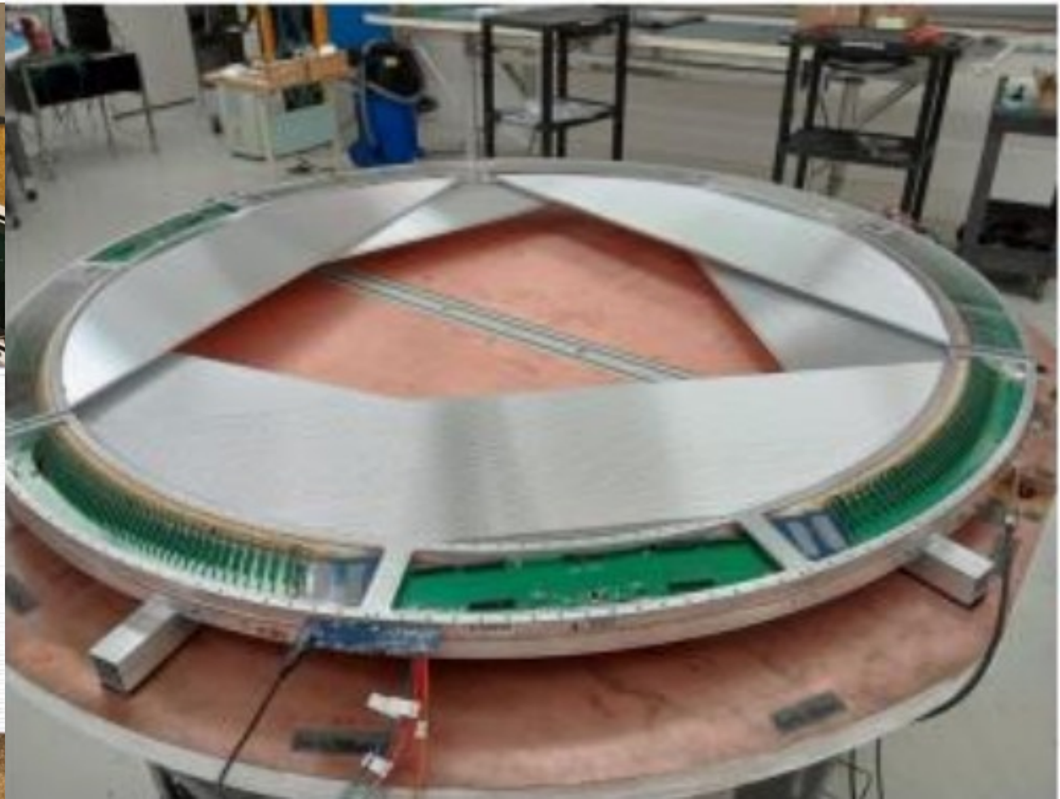


Tracker

Constructed using 15um thick mylar straws operated in vacuum

Same straws as g-2 experiment



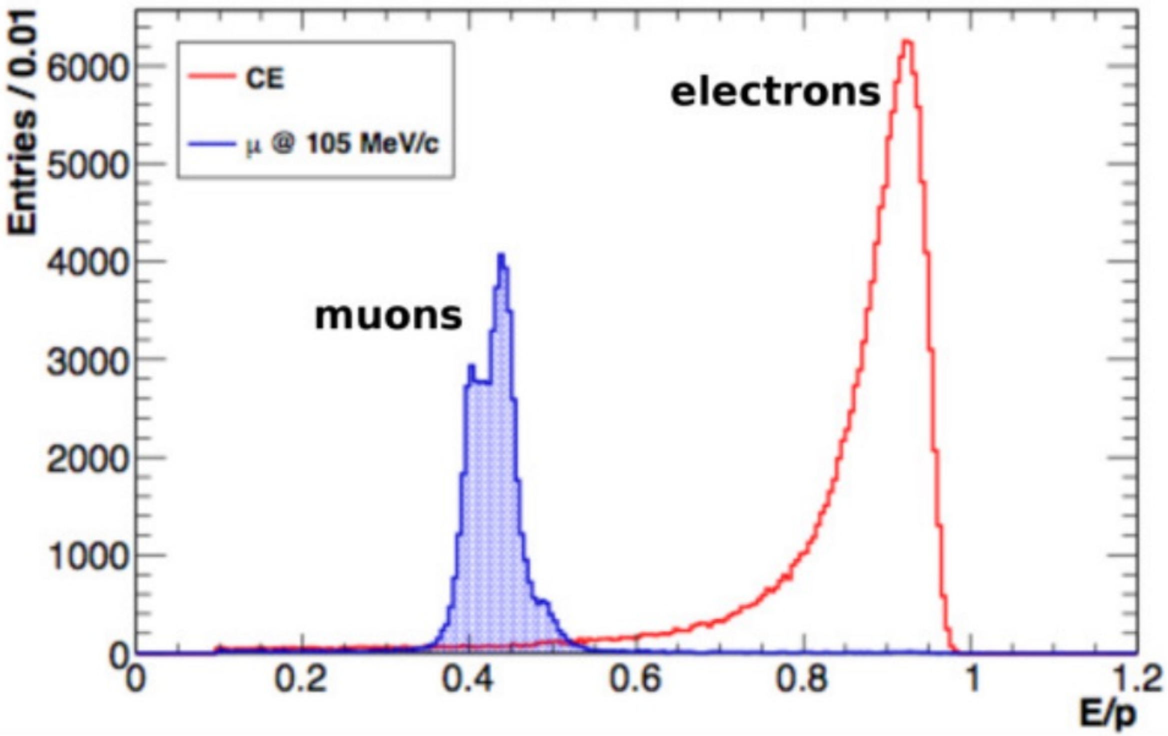


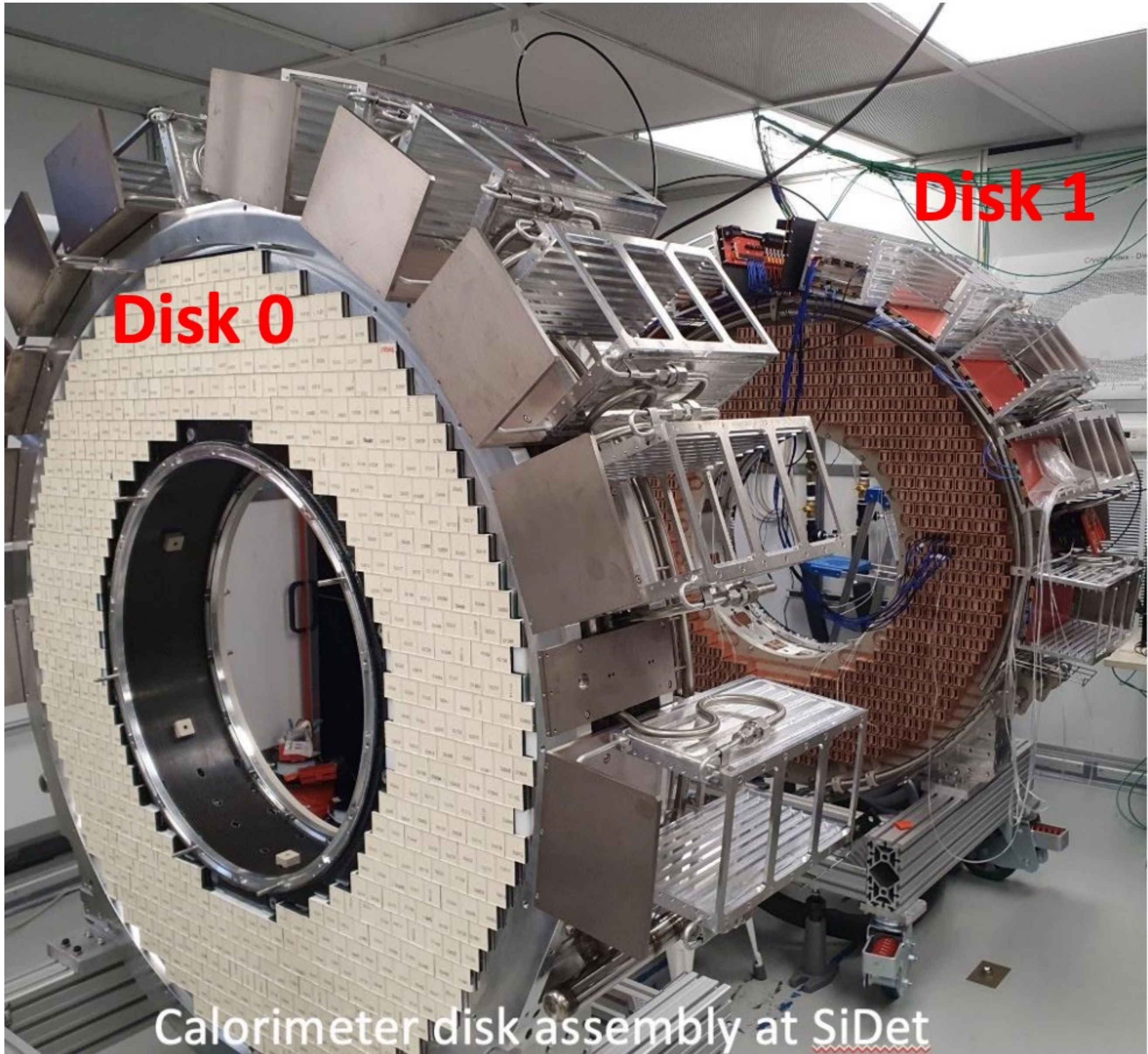
Calorimeter

Formed of 2 disks of 674 undoped CsI crystals

Used for particle identification and track seeding

0.5 ns time, 10% energy, 1 cm position measurement





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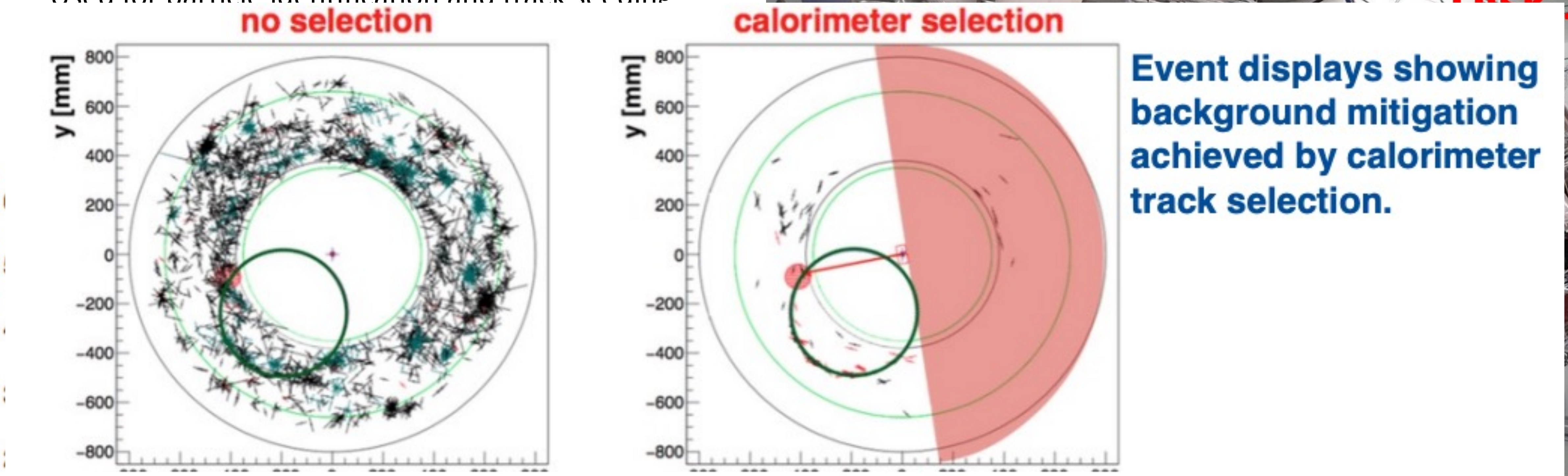
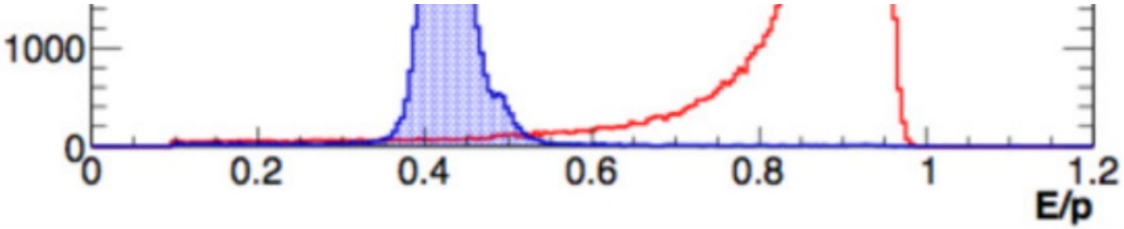


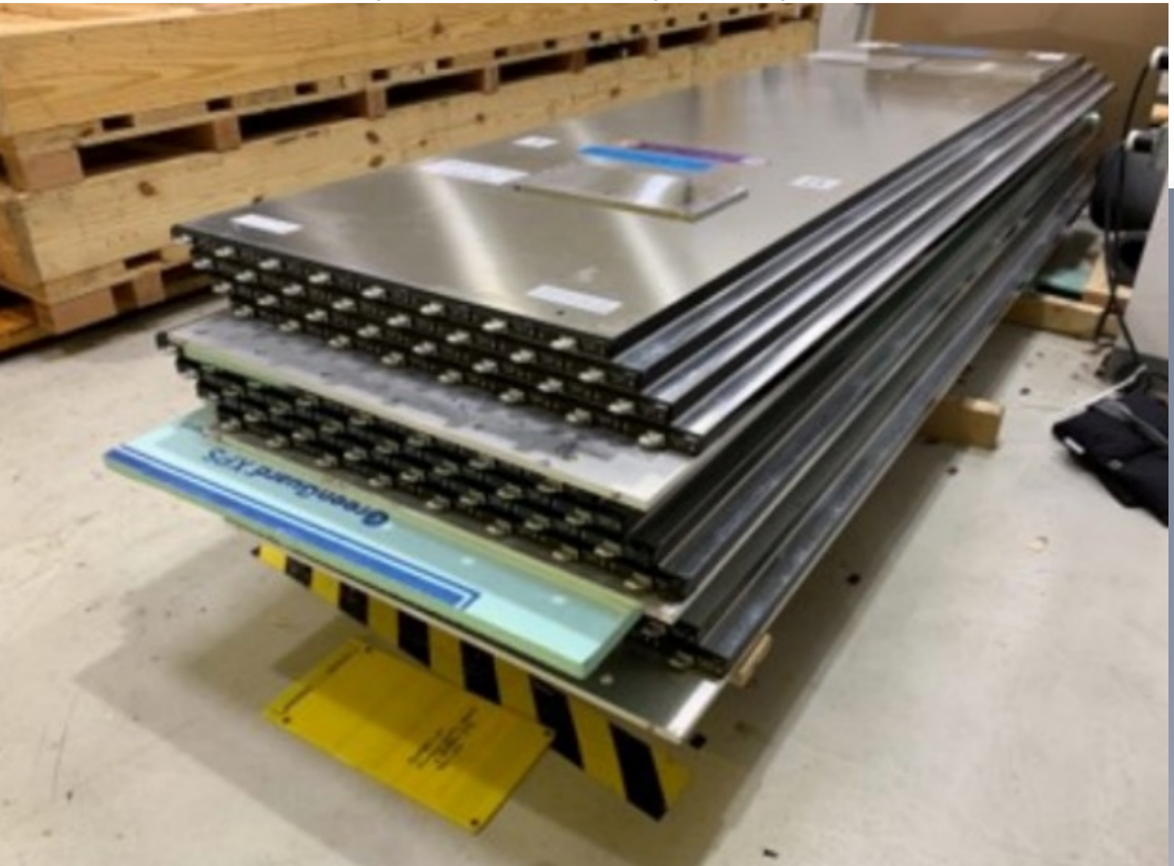


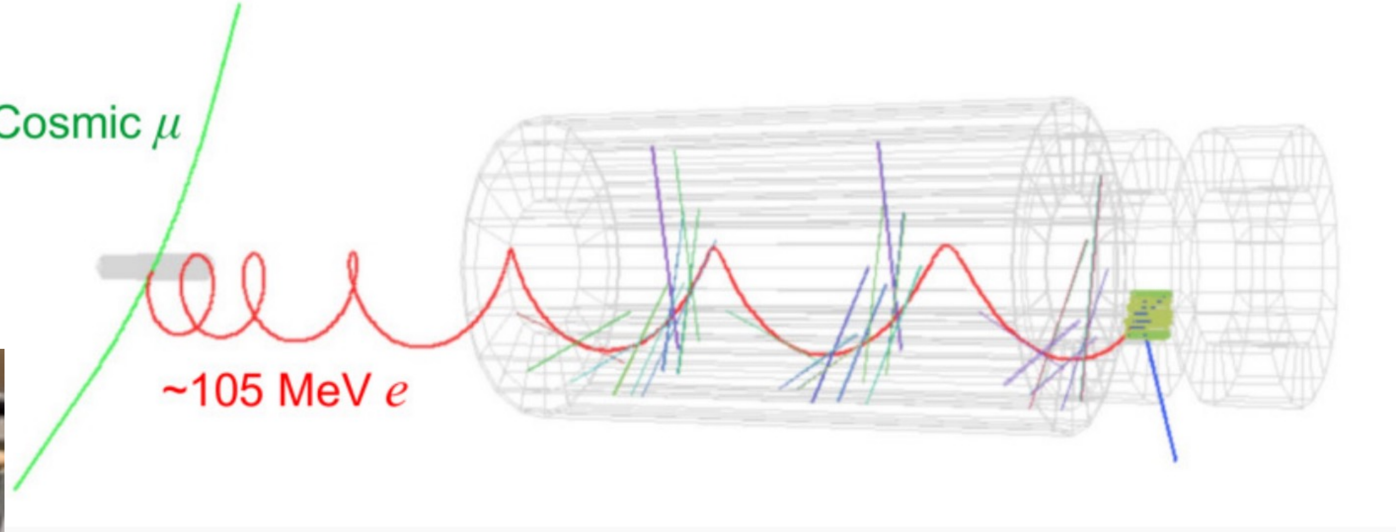
Cosmic Ray Veto

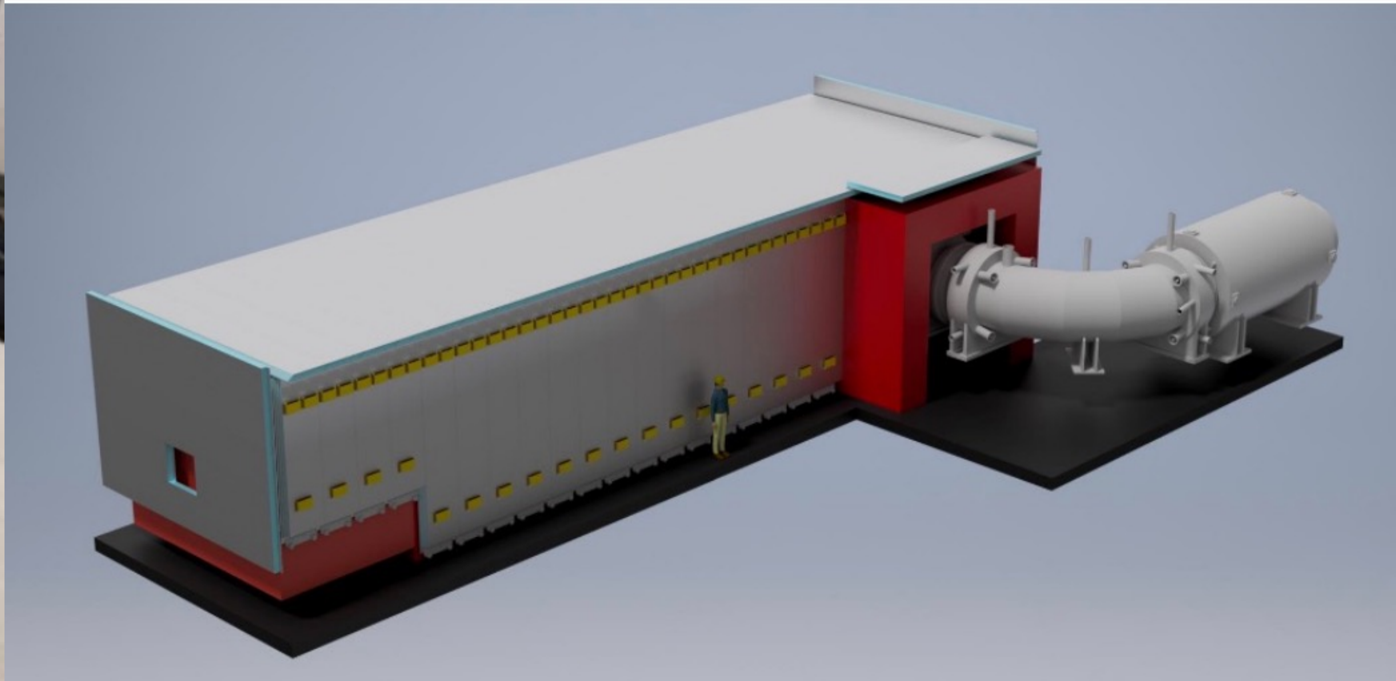
4 layers of overlapping scintillators

Fakes signal electron either from the muon track or due to decay in the detector region

Expect ~1 event per day



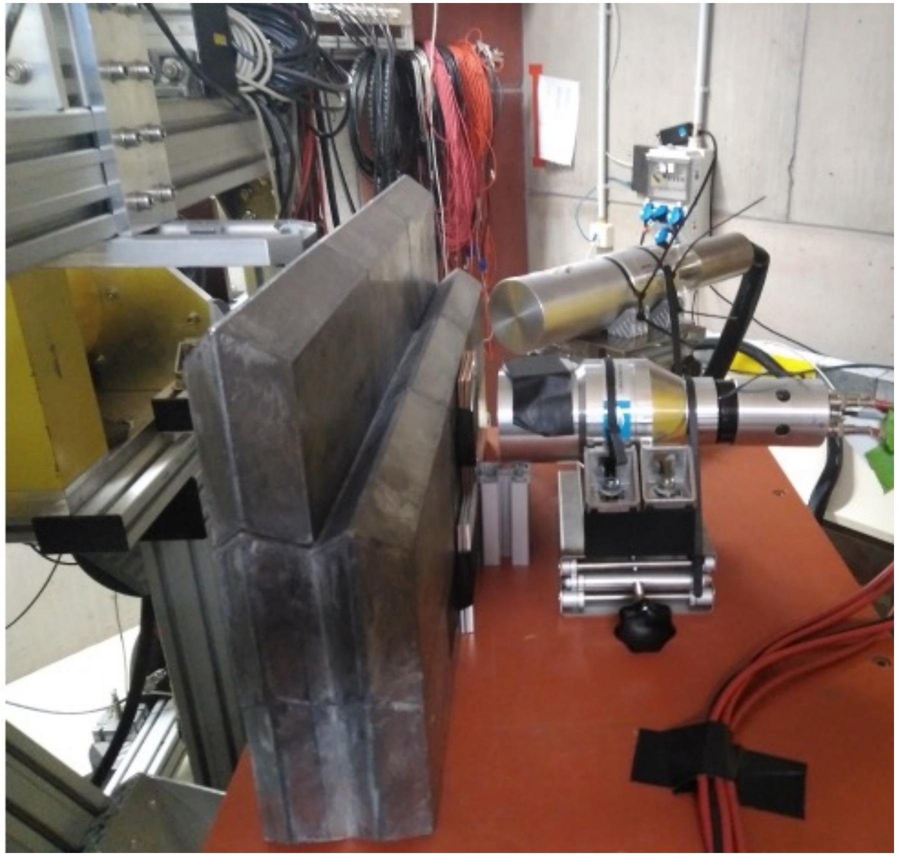




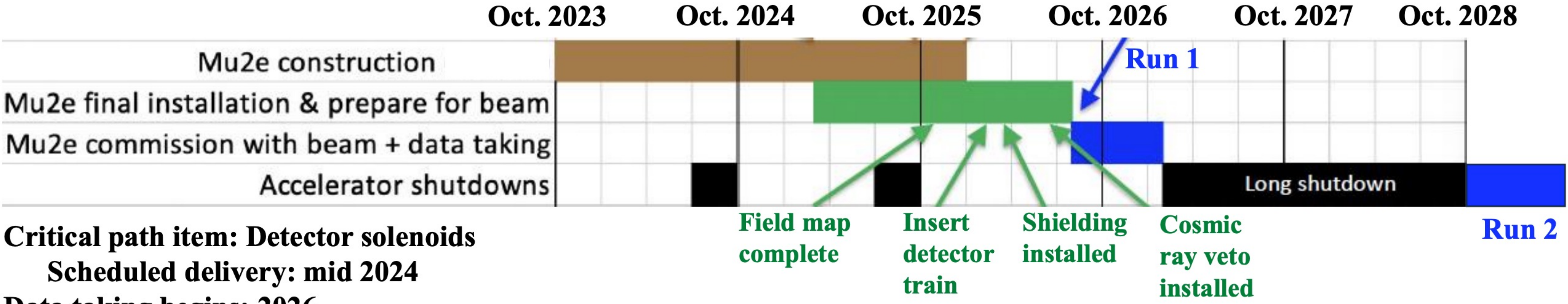
Stopping Target Monitor (UK)

Determines the overall rate for normalization of the experiment

Need excellent energy resolution at high rate to detect the x-rays from muon capture on the nucleus



Current Status and Schedule



Critical path item: Detector solenoids
Scheduled delivery: mid 2024
Data taking begins: 2026

Run-I to start in 2026 to reach 10^{-16} sensitivity

Run-II after long shutdown gains a further factor of 10

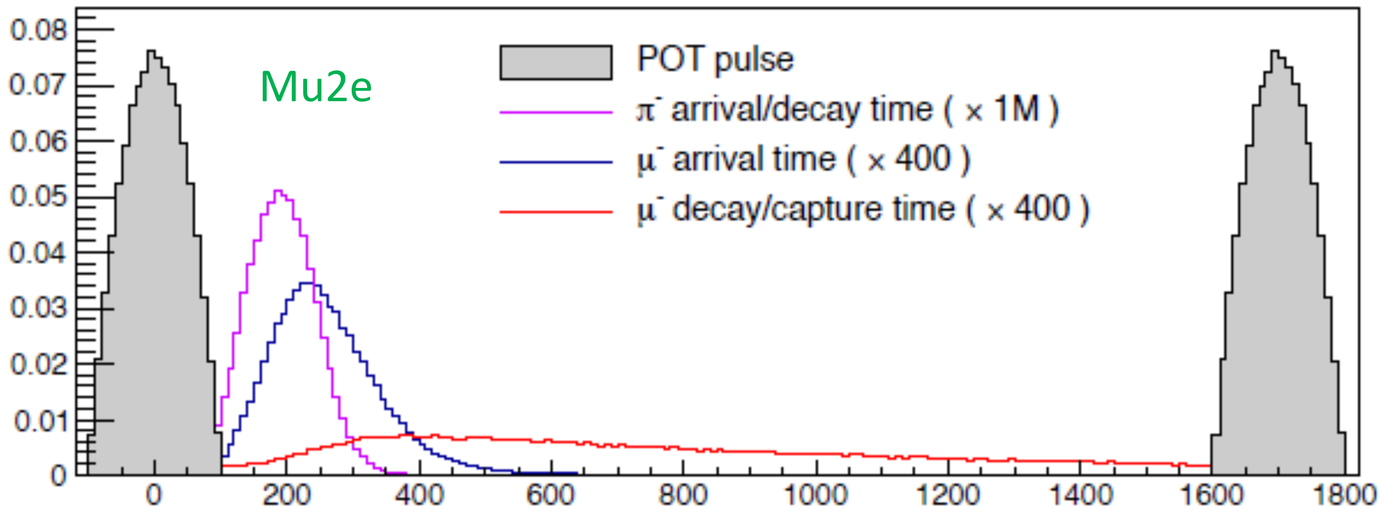
Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	0.046 ± 0.010 (stat) ± 0.009 (syst)
DIO	0.038 ± 0.002 (stat) $^{+0.025}_{-0.015}$ (syst)
Antiprotons	0.010 ± 0.003 (stat) ± 0.010 (syst)
RPC in-time	0.010 ± 0.002 (stat) $^{+0.001}_{-0.003}$ (syst)
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1$ (stat) $^{+0.1}_{-0.3}$ (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

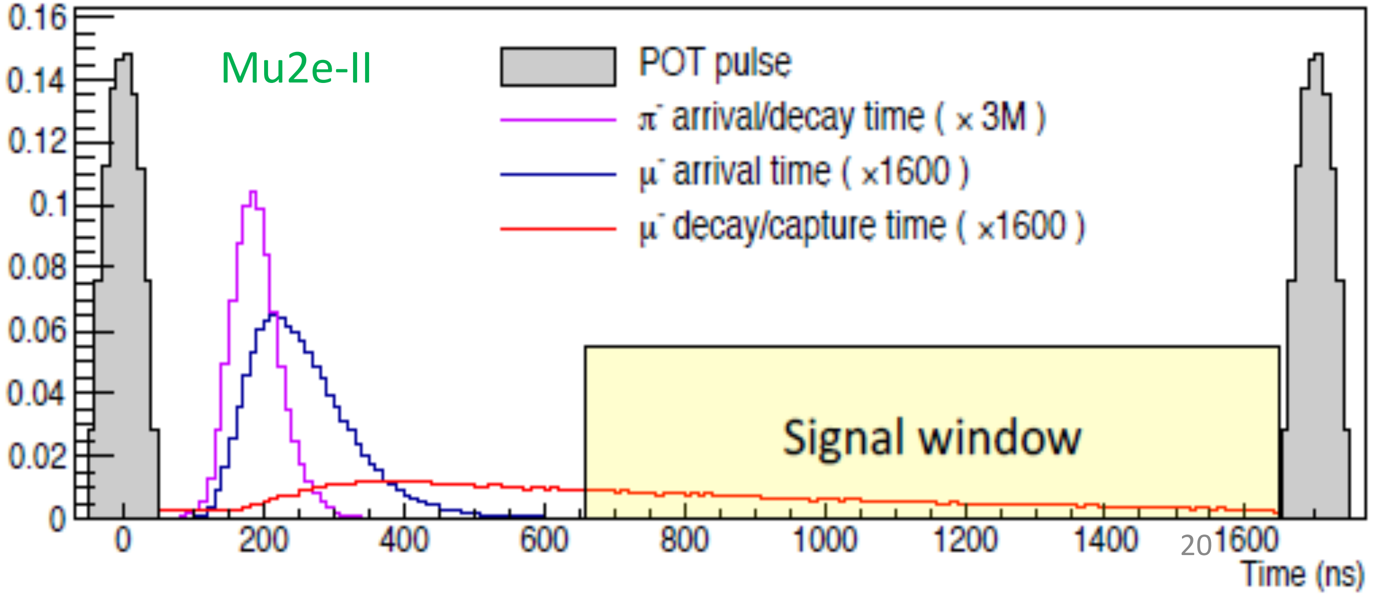
Mu2e-II

Mu2e-II proposes to improve by a further order of magnitude using the PIP-II beam:

- Narrower pulses
- Less pulse to pulse variation
- Higher intensity
- Higher duty factor

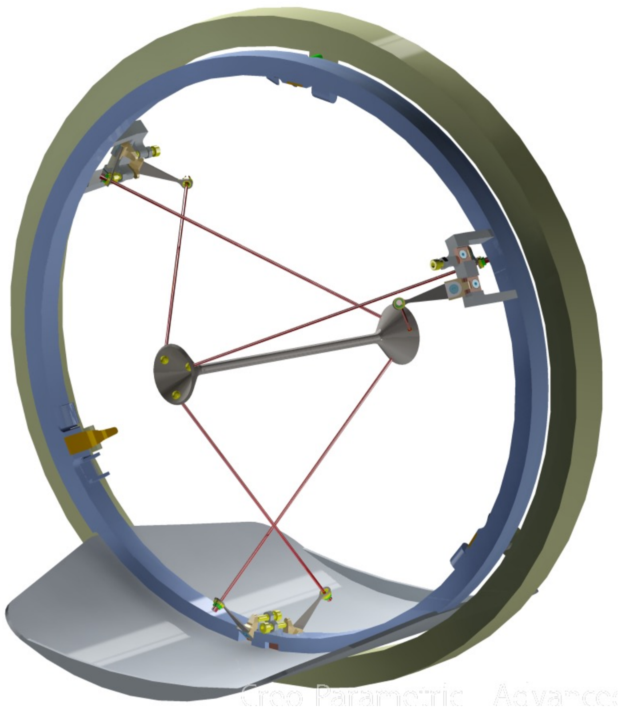
Also involves improvements to most other parts of the experiment





Production Target

The goal of the production target is to stop the maximum number of muons per incident proton



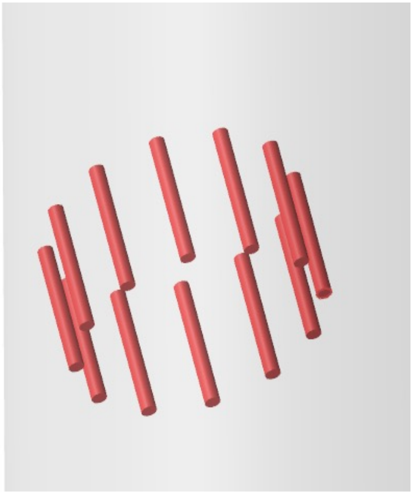
For Mu2e-II the use of the PIP-II beamline means:

- 20-25% more fractional power deposition in the target (10% for Mu2e)
- Significantly increased radiation damage

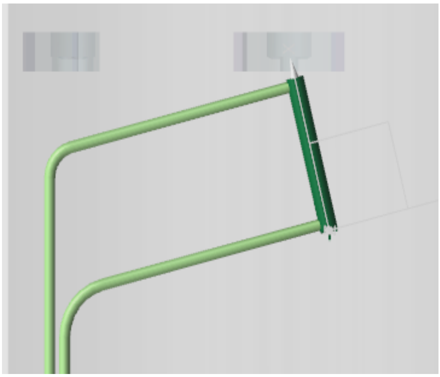
Needs active cooling and mitigation of radiation damage

3 potential designs :

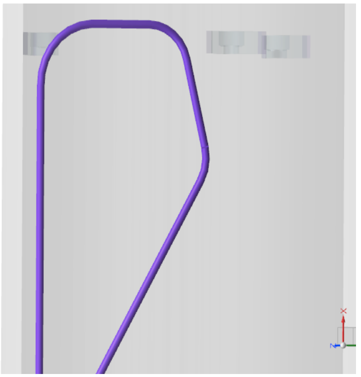
- Rotating system
- Granular system
- Conveyor of spherical target balls



Rotating Elements



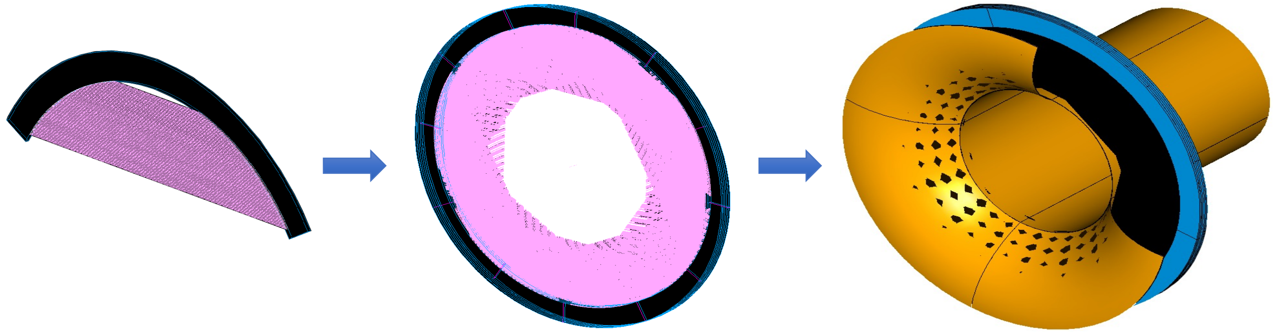
Fixed Granular with Gas Cooling



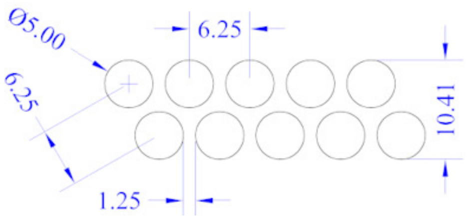
Conveyor

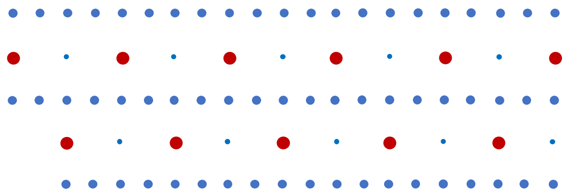
Tracker

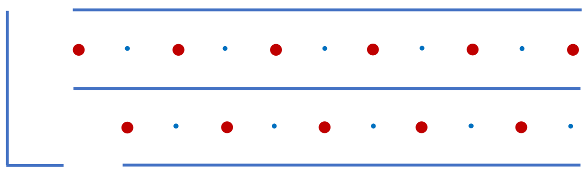
The increased muon intensity in the Mu2e-II experiment means the resolution of the tracker needs to be improved by about a factor 2

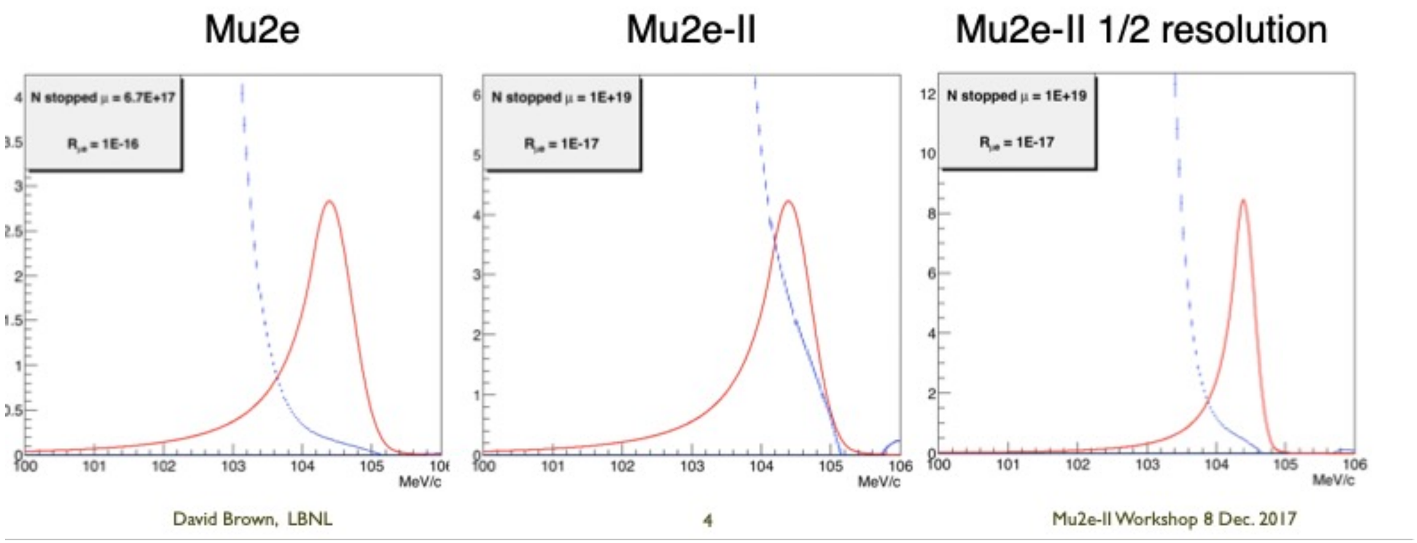


- Reduction in the tracker mass
- Different detector geometry
- Different detector technology (e.g. Si sensors)





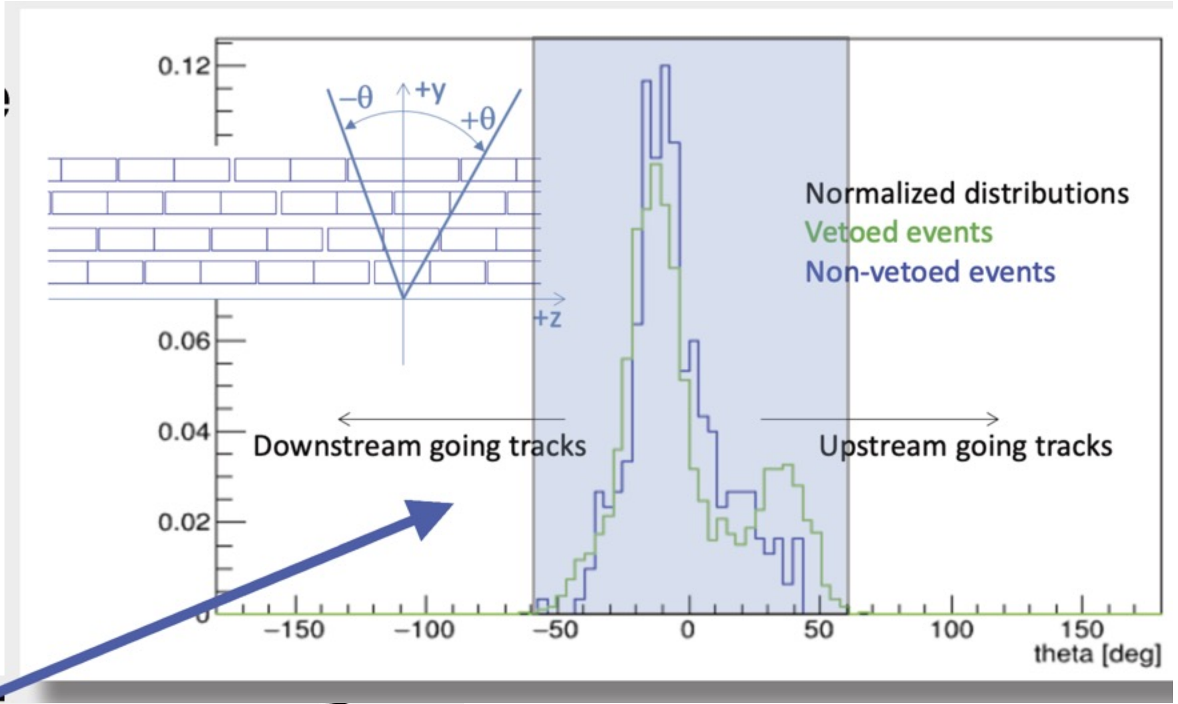


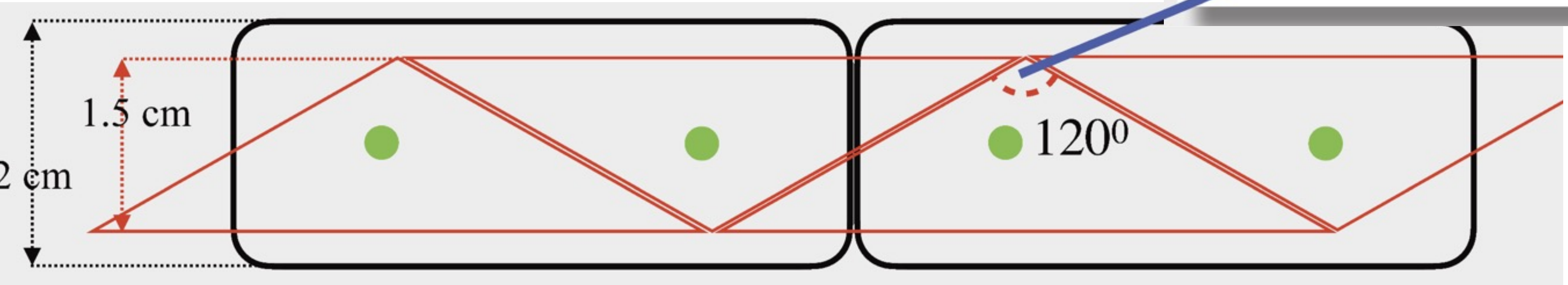


Cosmic Ray Veto

The increases in beam intensity and live time produces challenges for the CRV in Mu2e-II

- Cosmic ray background scales with live time (3x Mu2e)
- The increase in beam rate results in a higher deadtime
- The increase in radiation dose to the electronics
- The reduction in efficiency due to aging



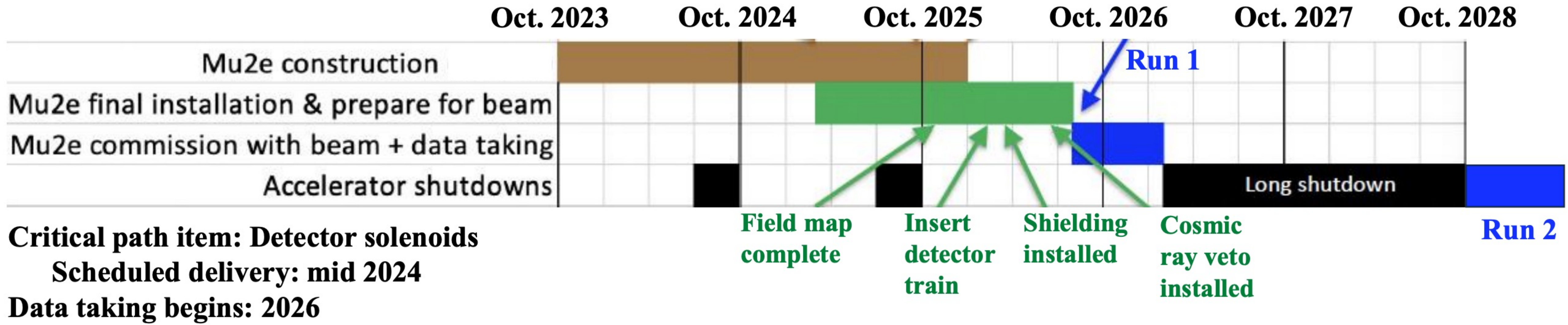


Summary

The Mu2e experiment is coming together with commissioning starting in 2025 and data-taking starting in 2026:

- Run-I to reach a sensitivity of 10^{-16} (1000 times increase in sensitivity)
- Run-II after the PIP-II shutdown to reach factor 10^4 improvement in sensitivity

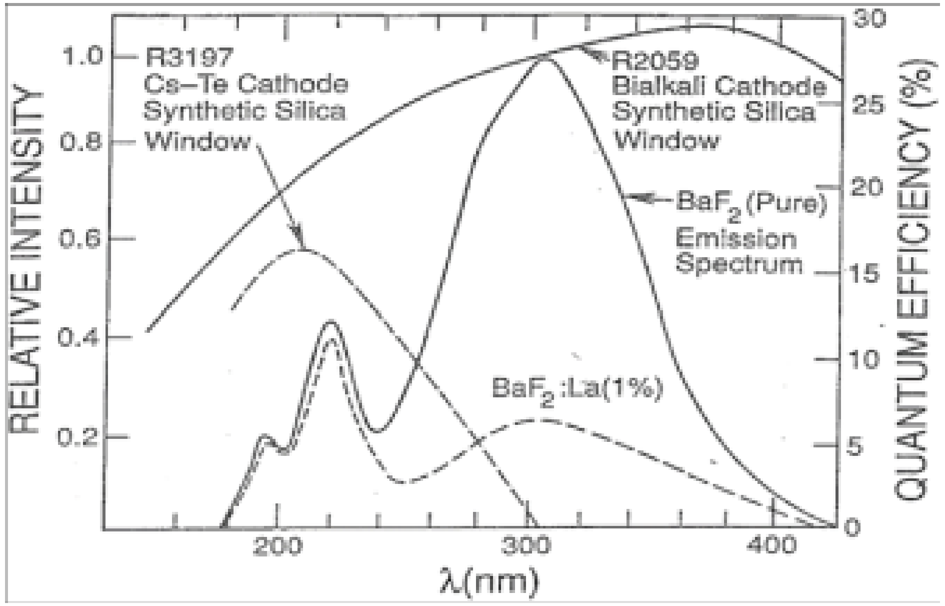
Plans ongoing for Mu2e-II to start following Mu2e to reach a further factor 10 in sensitivity



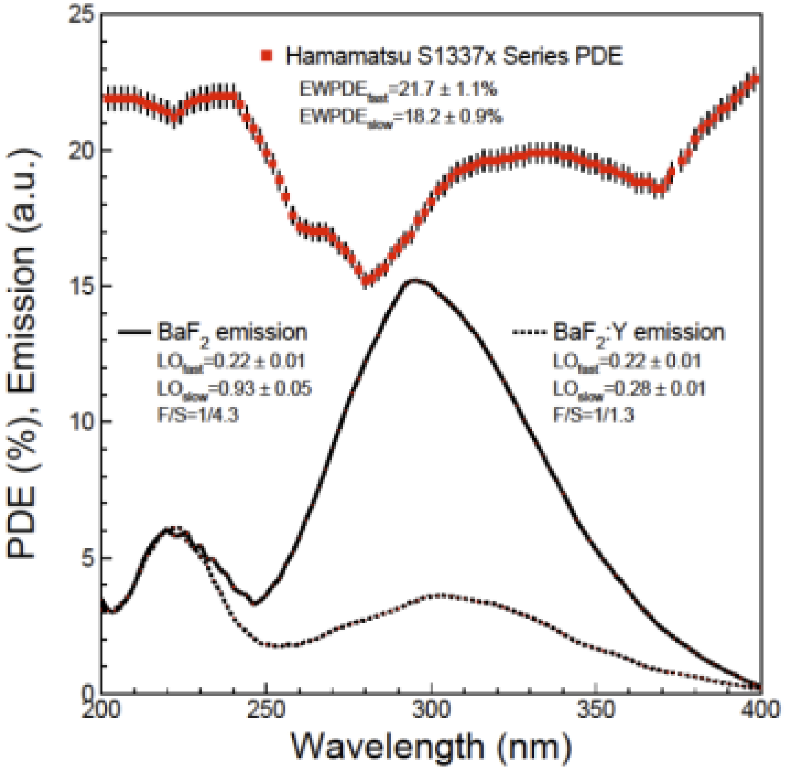
Back-up

Calorimeter

The increased radiation levels and instantaneous rate in Mu2e-II requires more radiation hard crystals and a faster readout scheme



Currently concentrating on Barium Fluoride crystals which have a fast (0.6ns) and slow (600ns) component of scintillation light



Looking to suppress the slow component through :

- Yttrium doping
- Use of a solar-blind photosensor
    - Interference filter with thin layers of earth oxides
    - Nanoparticles in a silicon cookie

The radiation hardness of the crystals and the readout electronics is also currently under investigation

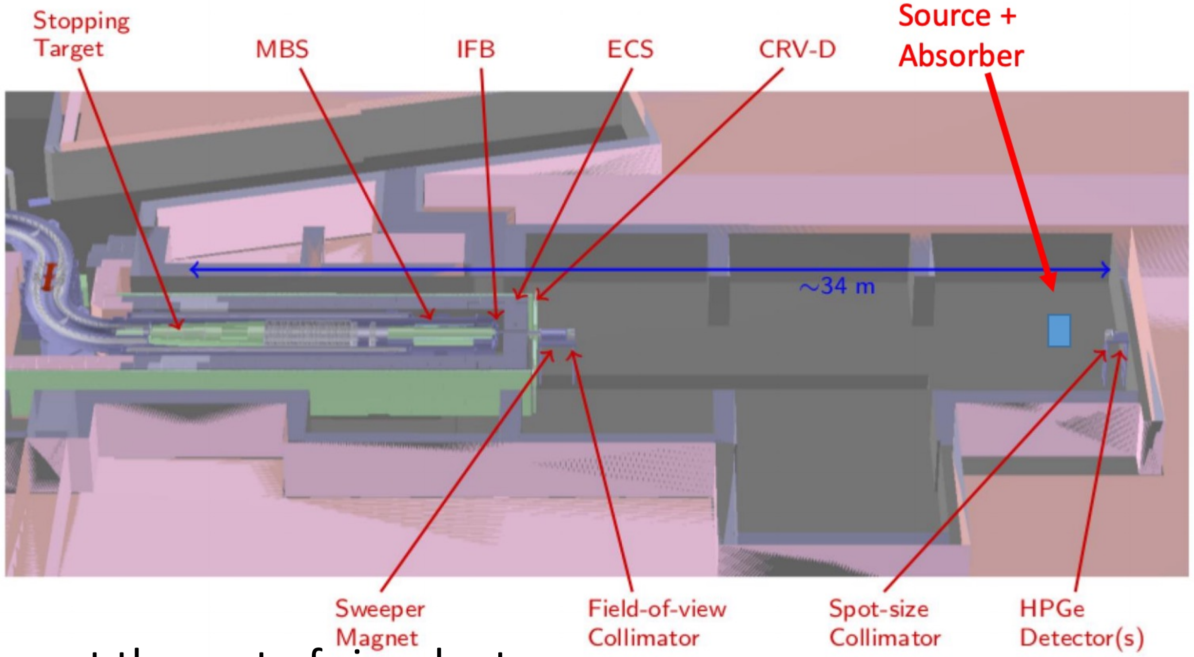
These approaches will be refined over the year and other ideas looked into

Stopping Target Monitor

The Mu2e STM provides the normalisation for the experiment using an HPGe and LaBr detector placed in the line of sight of the stopping target

The Mu2e-II environment poses significant challenges for the HPGe detector :

- The more intense prompt beam induced flash with the slow recovery time
- The higher levels of neutron damage



Mitigation strategies being considered :

- Reduce the beam flash by increasing the absorber thickness at the cost of signal rate
- Use the LaBr and calibrate with the HPGe during special low intensity runs
- Gate off the LaBr photodetector during the flash (only for materials with delayed emission lines)
- Move the detector off axis although space may be an issue
- Replace some crystals in the calo with LYSO or LaBr
- Create a tertiary photon beam

These will be refined as the detectors are further characterised throughout the coming year