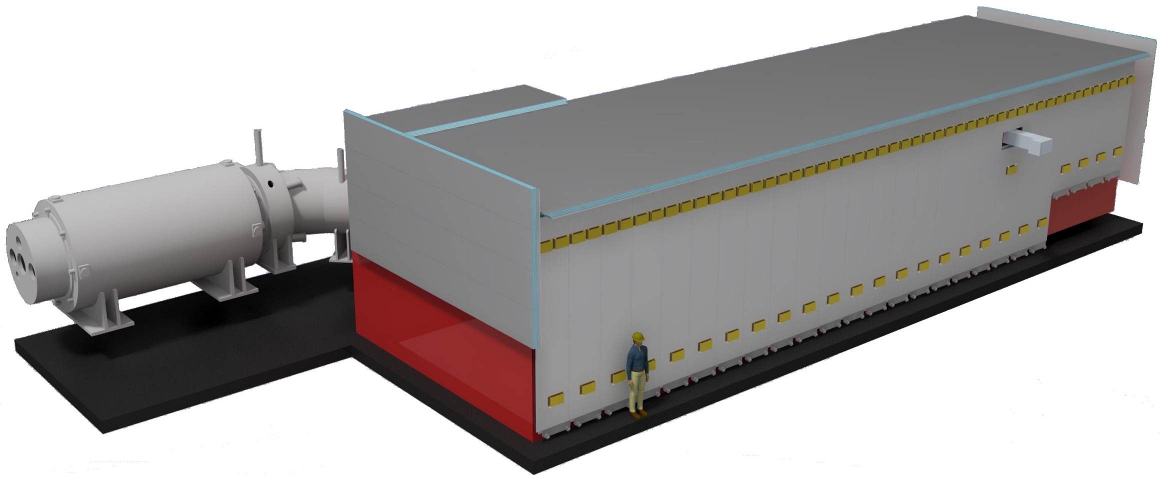


A high efficiency cosmic ray muon detector for the Mu2e experiment

Samuel Grant

DPF-PHENO 2024

Argonne NATIONAL LABORATORY

Mu2e

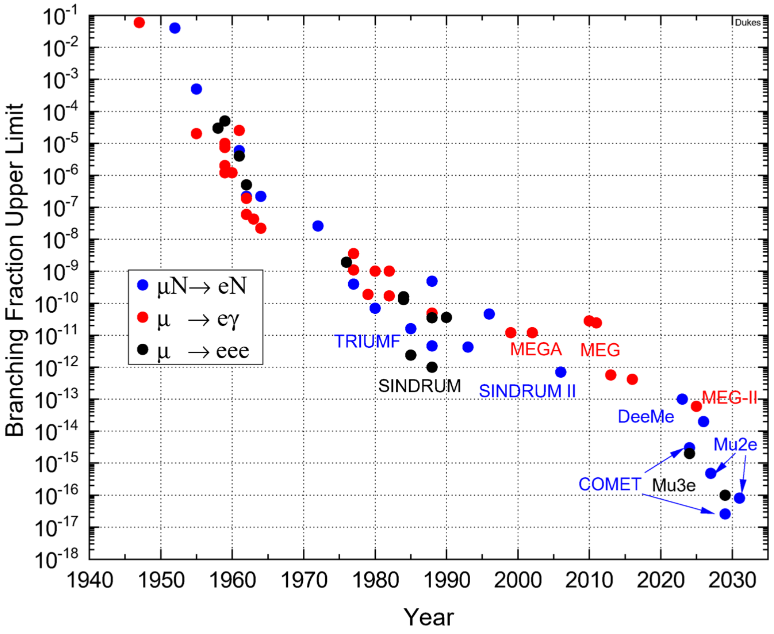
The Mu2e experiment

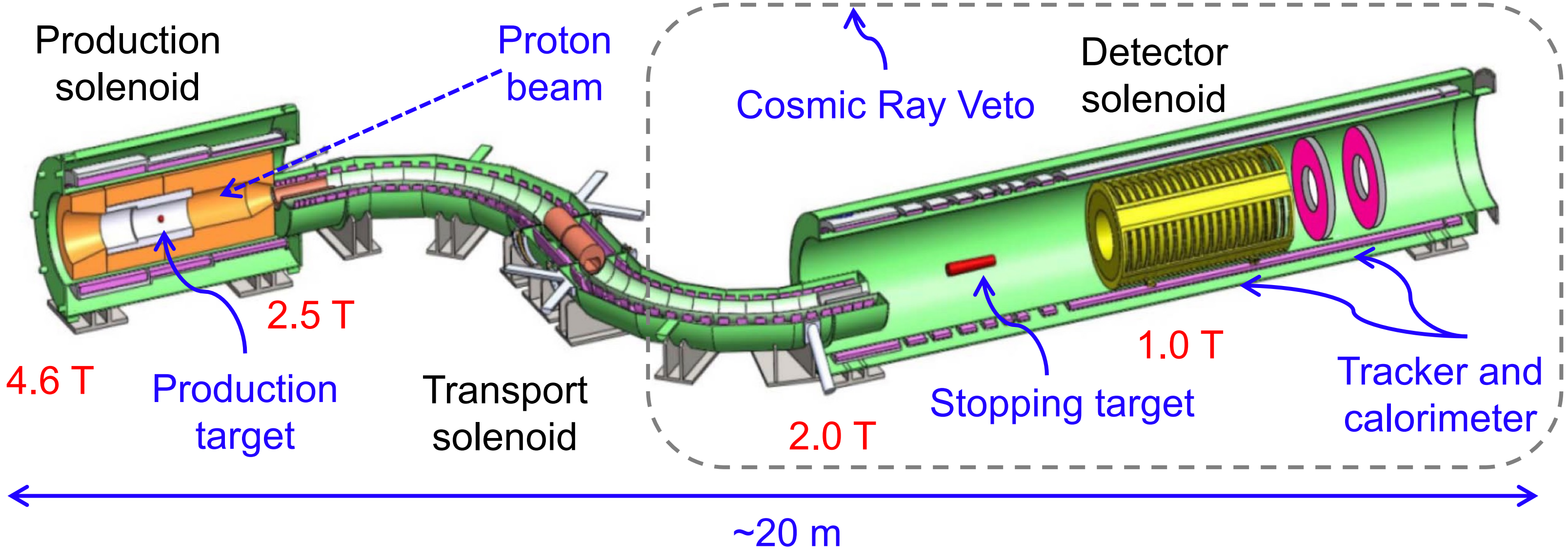
Physics

- A search for charged lepton flavour violation (CLFV) in $\mu^- N \to e^- N$.
- CLFV processes are highly suppressed, but beyond the SM (BSM) processes can enhance CLFV rates.
- Mu2e will search for CLFV with a sensitivity which will **surpass the current upper limit by a factor of 10,000** [1]!

Experimental principle

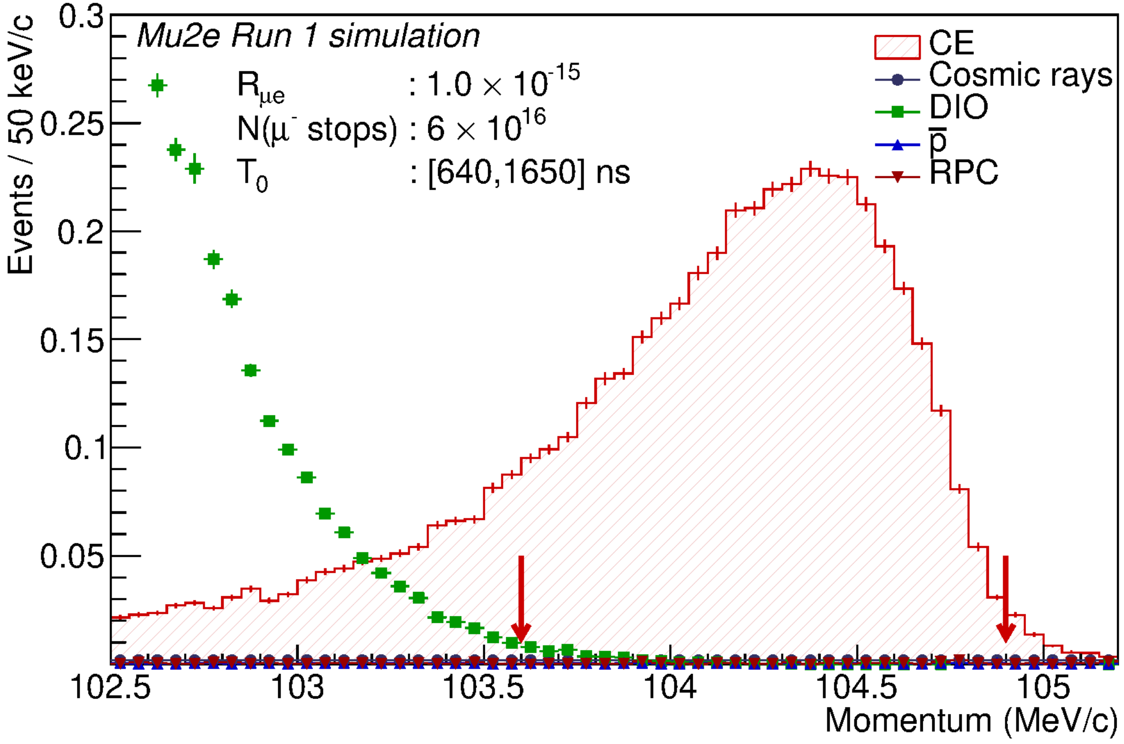
- 8 GeV proton beam a target produces pions, which in turn produce muons.
- Muons are guided through a graded magnetic field towards an Al target, where they are captured and form muonic atoms.
- Muon to electron conversion in this bound state would produce a monoenergetic ~105 MeV signal electron.

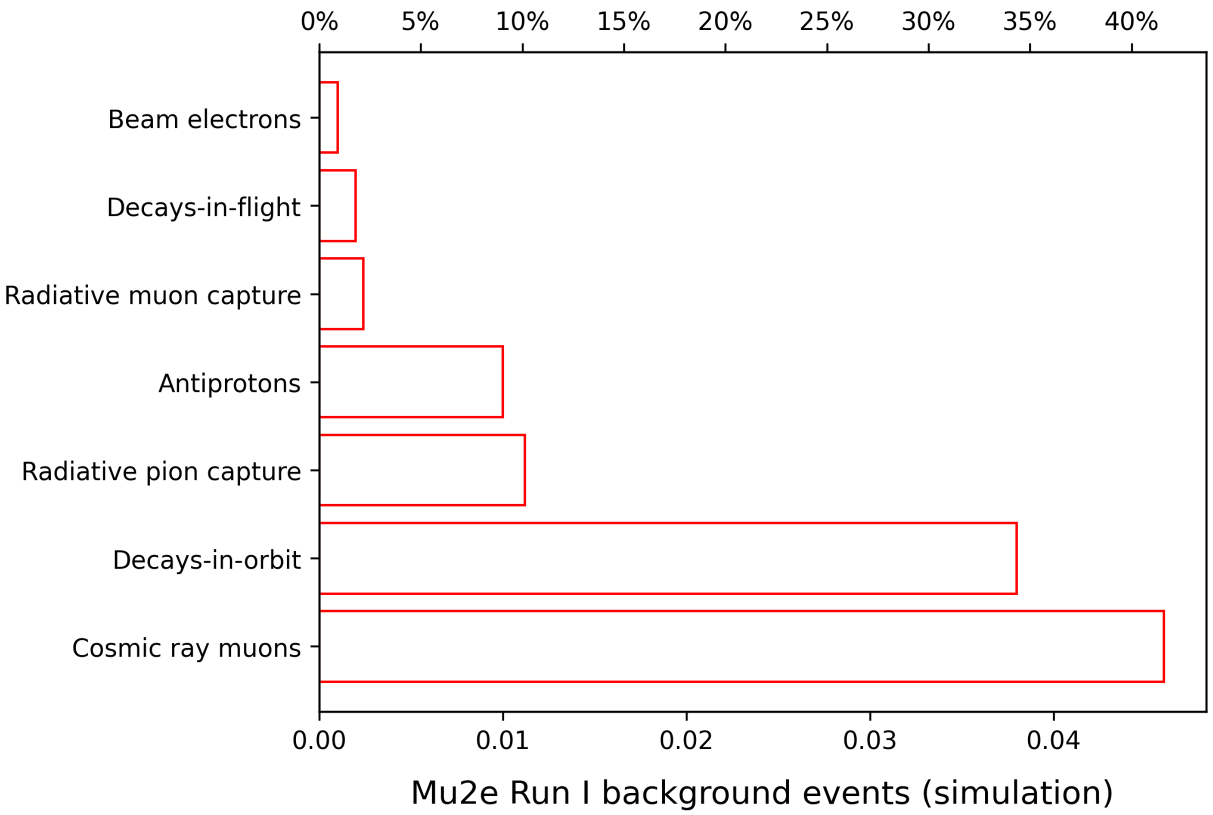




Backgrounds

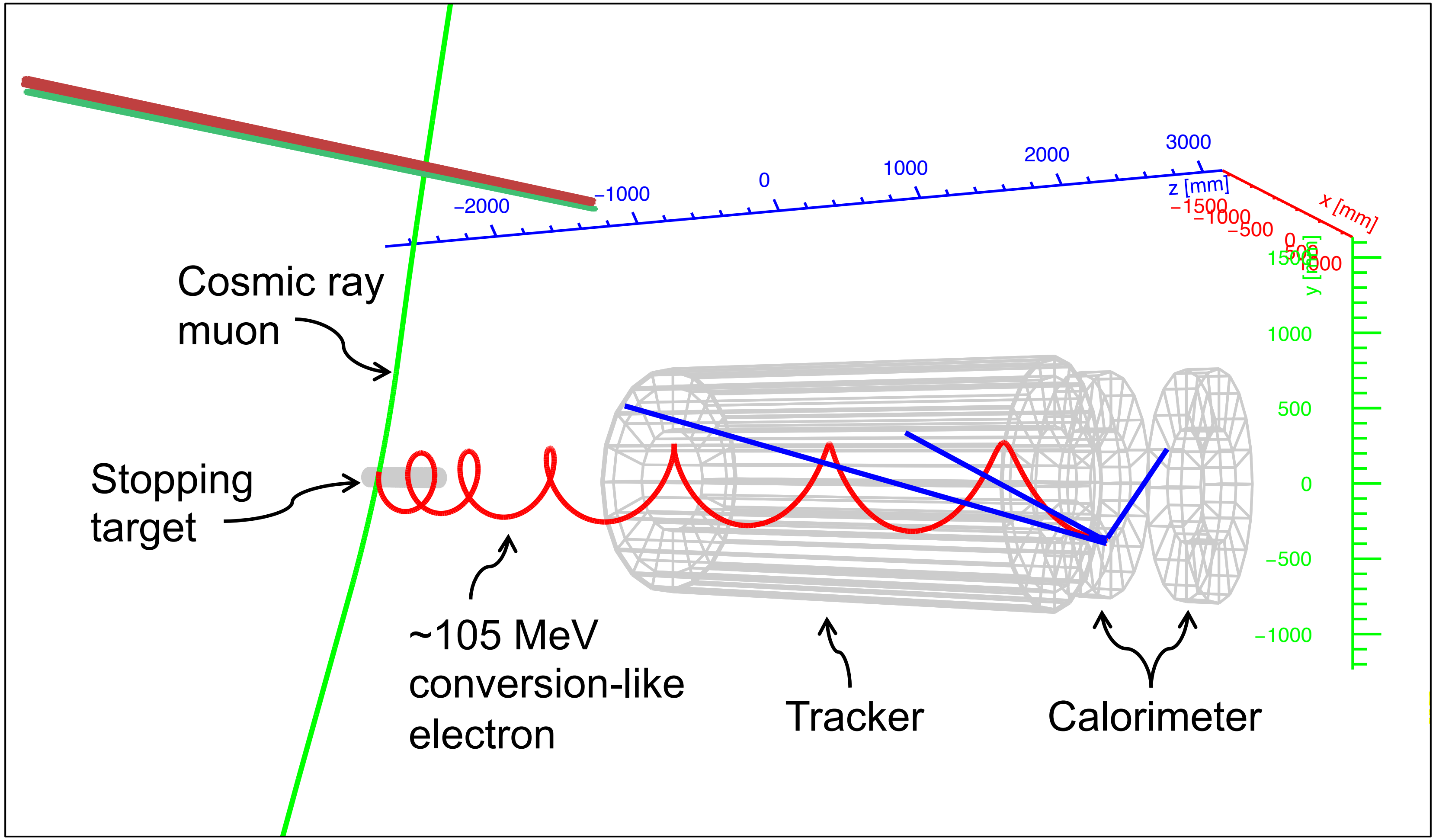
- **Mu2e will stop $\sim 10^{18}$ muons over two running periods, with < 1 background event [2]!**
- Run 1 will commence in 2027, lasting the full year, and will provide a factor of 1000 improvement in sensitivity.
- Simulation: 0.11 background events in Run I, dominant contributions arising from muon decays-in-orbit and cosmic ray muons [3].





The cosmic ray background

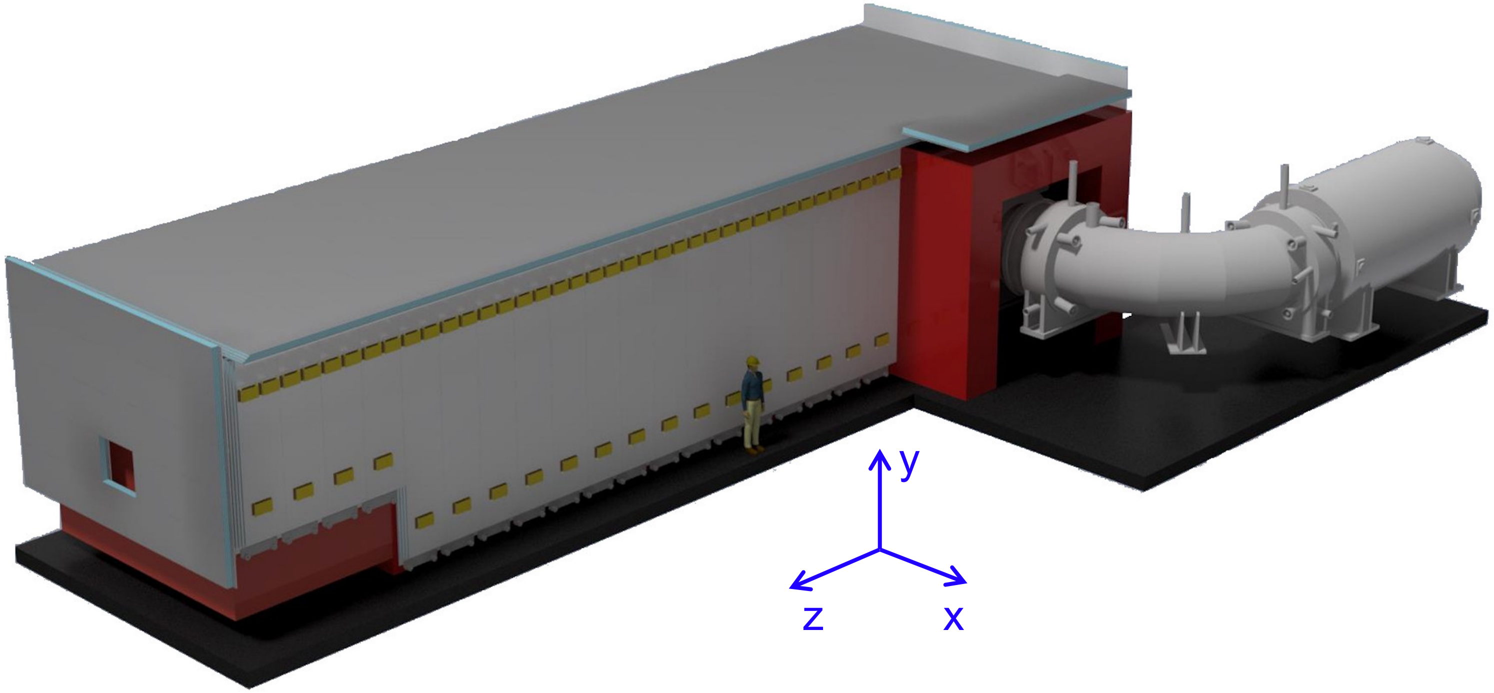
- Expected ~1 cosmic ray background per day.
- The rate of such events must be reduced by a factor of 10,000!



Simulation by Ralf Ehrlich.

The Cosmic Ray Veto (CRV)

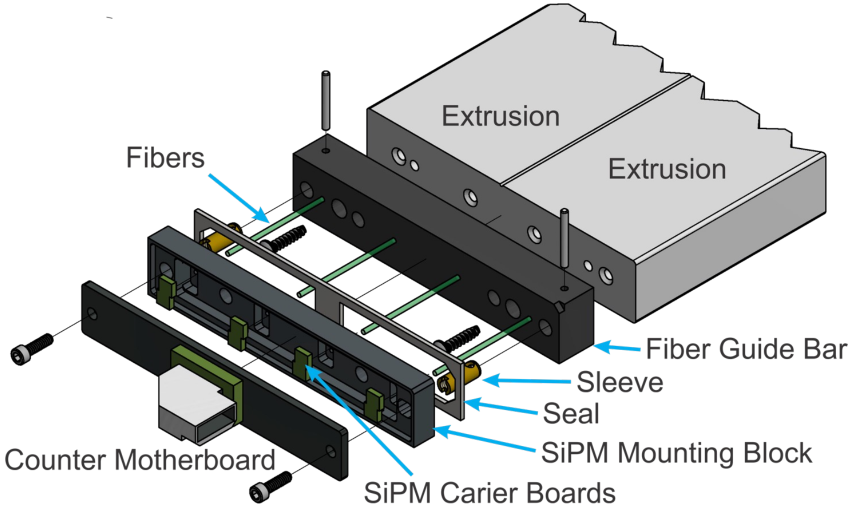
- **Cosmic ray induced background events will be defeated by an active shielding system: the CRV.**
- Layers of polystyrene scintillator counters with embedded wavelength-shifting fibres, read out with silicon photomultipliers (SiPMs).
- High efficiency, large area, small gaps, high tolerance to neutral particle flux, fit within a constrained space.
- Encloses the detector solenoid and half of the transport solenoid, above ~1 m of concrete shielding.
- Mu2e sensitivity requirements require the CRV to possess **an overall efficiency of 99.99%**.

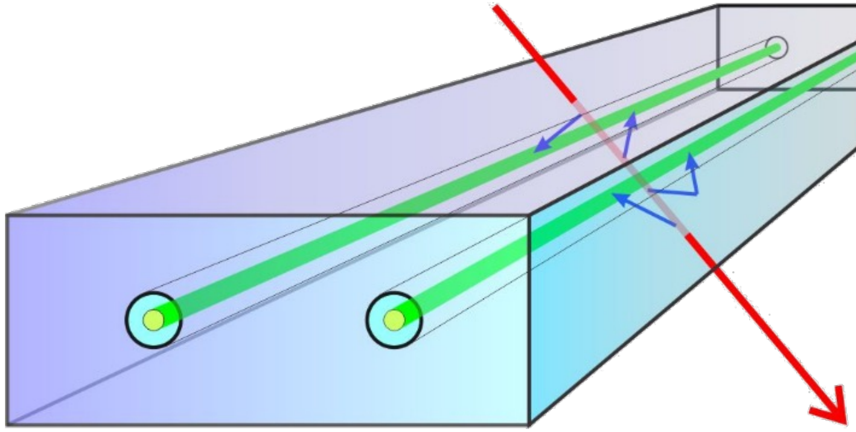


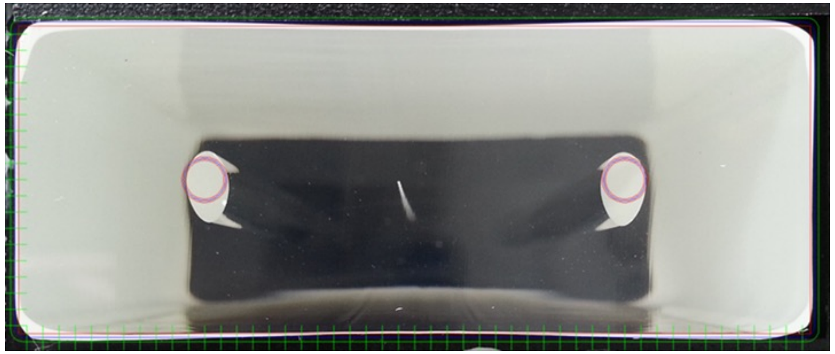
Details

- 335 m^2
- 83 modules, 10 types
- 5,344 counters
- 10,688 fibres
- 19,392 SiPMs

- The fundamental building blocks of the CRV are the 5,344 rectangular counters.
- Extruded PS (1% PPO + 0.05% POPOP), coated with TiO_2.
- 51 x 20 mm^2, 1045 mm to 6900 mm in length.
- Read out on both ends by SiPMs (handful of cases where reflectors are used).
- Each is embedded with two 1.4/1.8 mm wavelength-shifting fibres.
- Two counters are glued side-by-side to form a di-counter, which is connected to a counter motherboard.

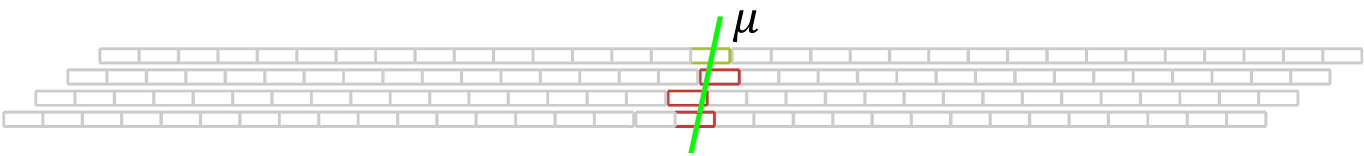


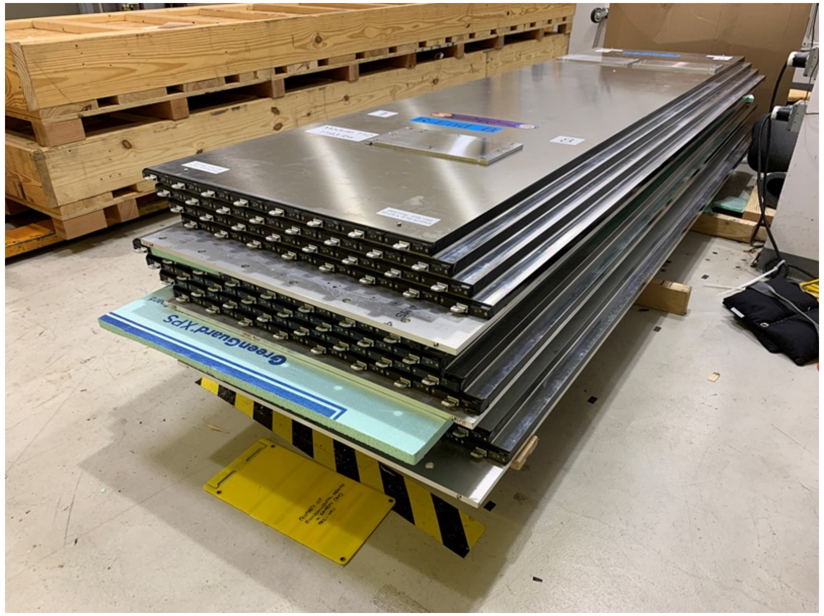




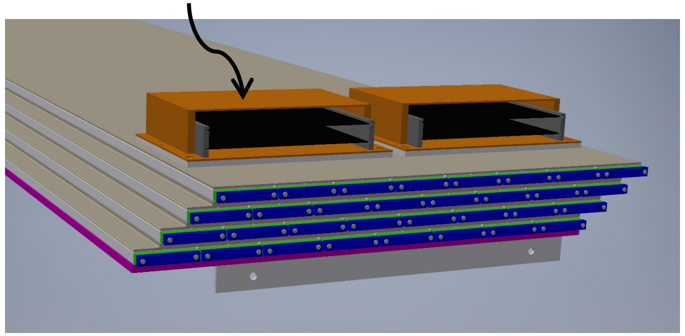
Modules

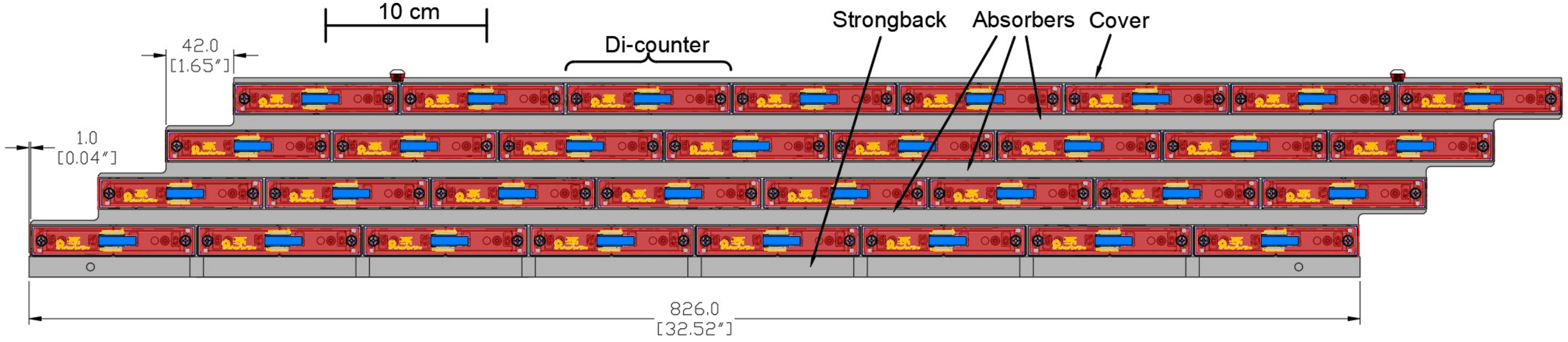
- Four layers of counters, stacked with an offset to minimise gaps.
- 16 counters (8 di-counters) per layer.
- Layers separated by Al absorbers.
- Length: 1.0 m – 6.9 m, weight: 179 kg - 1165 kg.
- CRV “track stub”, or *coincidence,* is typically defined as a minimum of 3/4 layers hit, above some photoelectron threshold, localised in time and space.





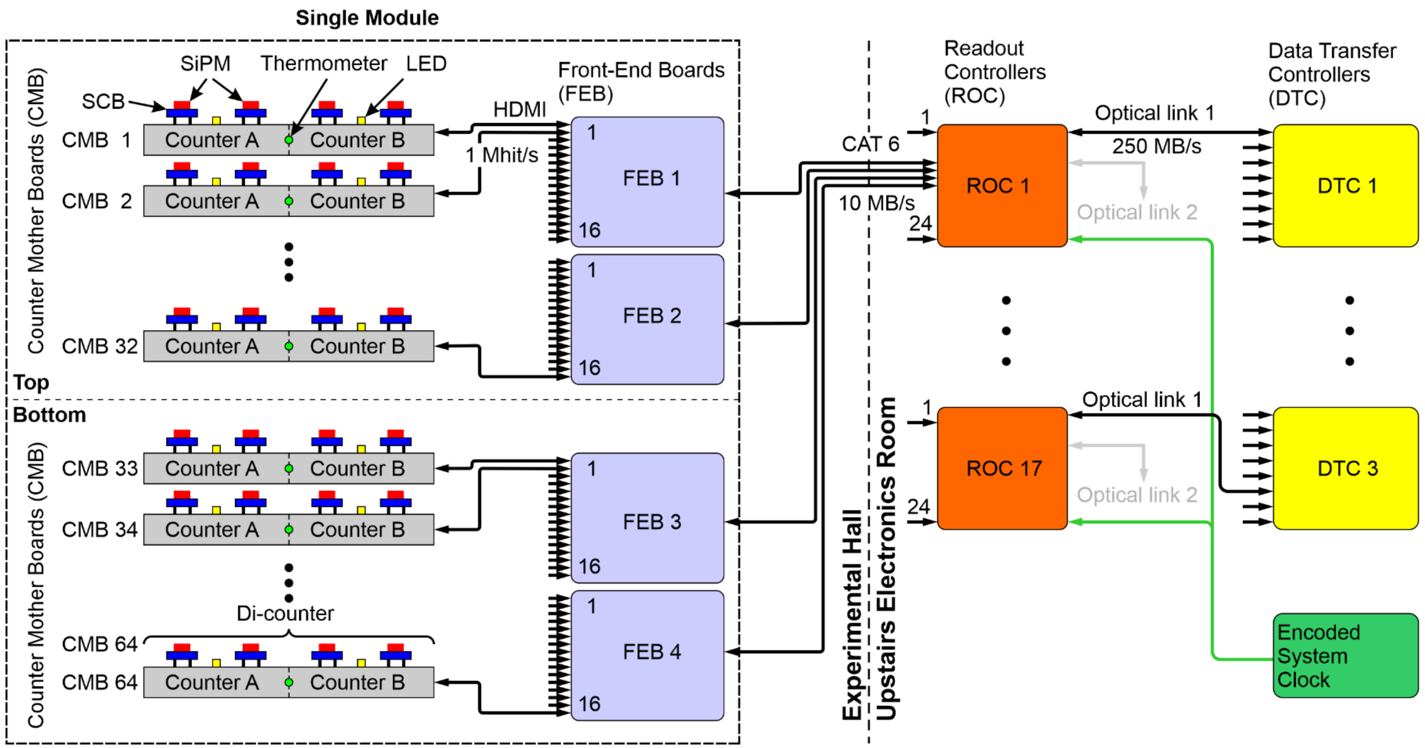
Magnetic shielding for front-end electronics.





Electronics and DAQ

- 4848 Counter Motherboards (CMBs) each connect to four SiPMs, two LED flashers, and one thermometer. They are mounted directly on the di-counters.
- 339 Front-End Boards (FEBs) receive and digitize SiPM signals, supplies SiPM bias voltages. Four on-board FPGAs each connect to four CMBs via HDMI cables.
- 17 Readout Controllers (ROCs) read data from the FEBs, connected via Cat6 Ethernet cables.
- 3 Data Transfer Controllers (DTCs) receives clock and handles readout requests, reads data from the ROC via an optical fibre link.
- 2 DAQ servers house the DTCs, runs online software, connects to lab network.



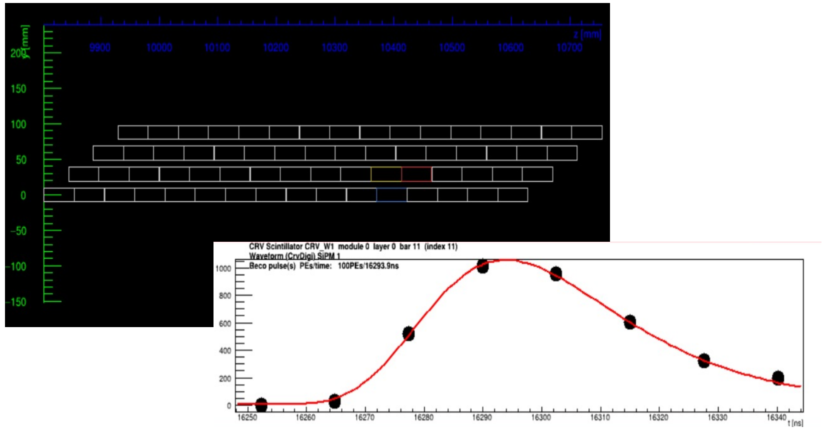
Status & schedule

- Production began at the University of Virginia in 2018.
- 83/83 completed modules delivered to Fermilab as of 2023.
- Installation in the Mu2e hall will begin later this year, in a special test configuration (see extra slides).
- CRV modules will begin taking cosmic data alongside the tracker and calorimeter in mid-2025.
- The CRV will be installed in its operations configuration in mid-2026, with commissioning at the end of 2026.
- Mu2e Run-1 will commence at the beginning of 2027.

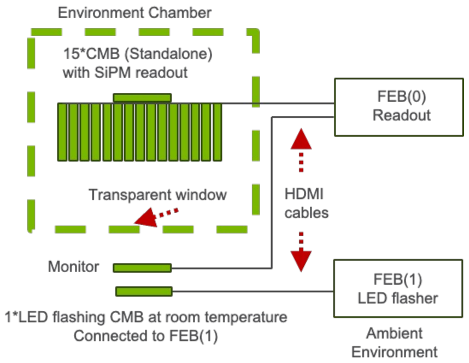
Modules at Wideband, Fermilab!

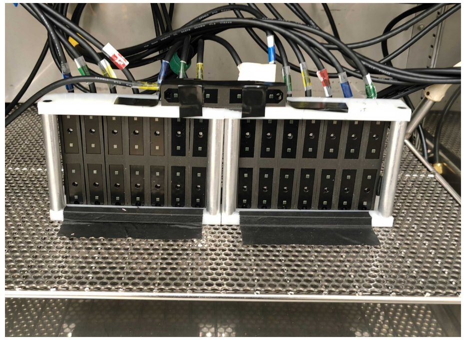
Recent highlights from the CRV team

Data-taking through full DAQ and reconstruction chain [5]
Simon Corrodi (ANL) & Ralf Ehrlich (UVA)

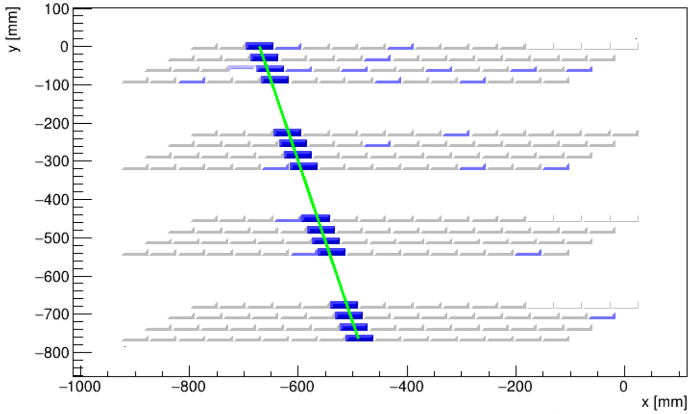


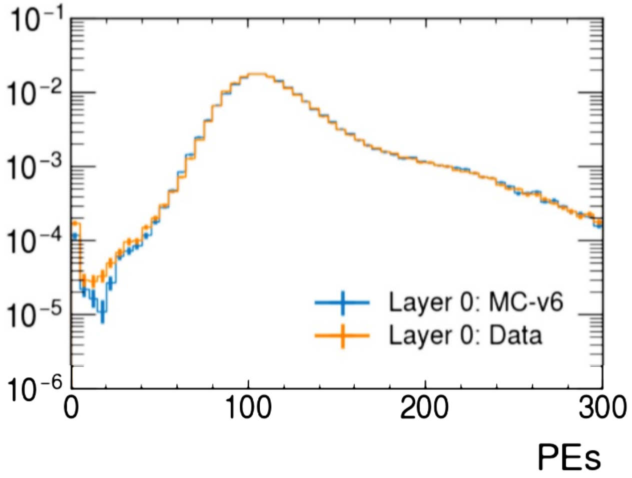
SiPM temperature dependance correction studies [6]
Yongyi Wu (ANL)

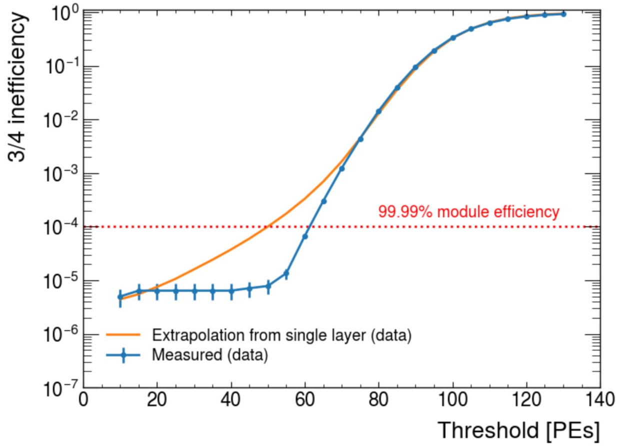




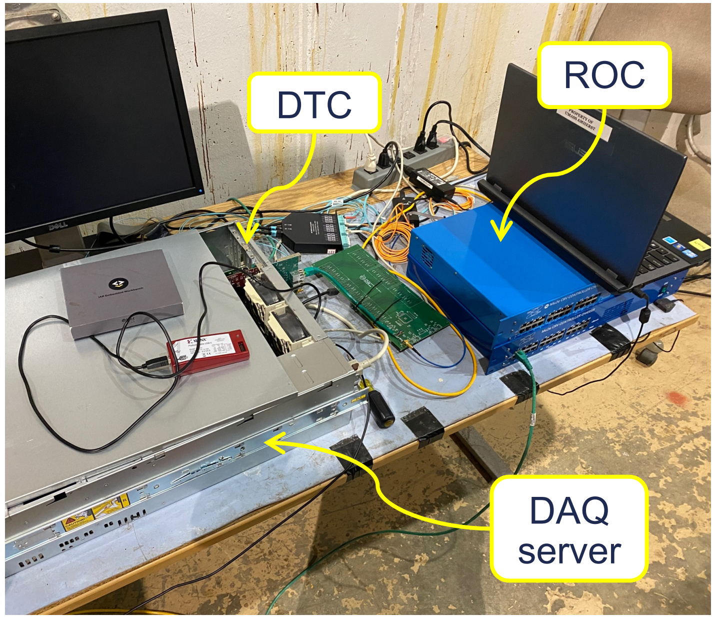
Light-yield and module efficiency studies [7]
Tyler Horoho (UVA), Yuri Oksuzian (ANL), Ralf Ehrlich (UVA)

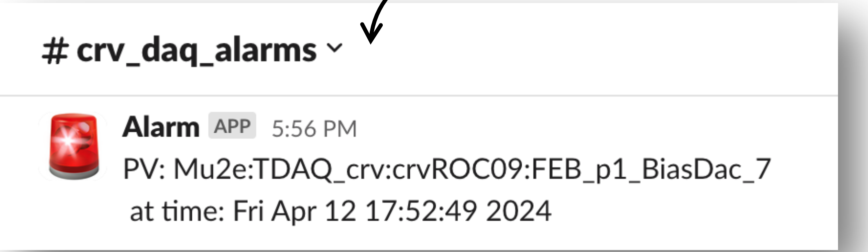




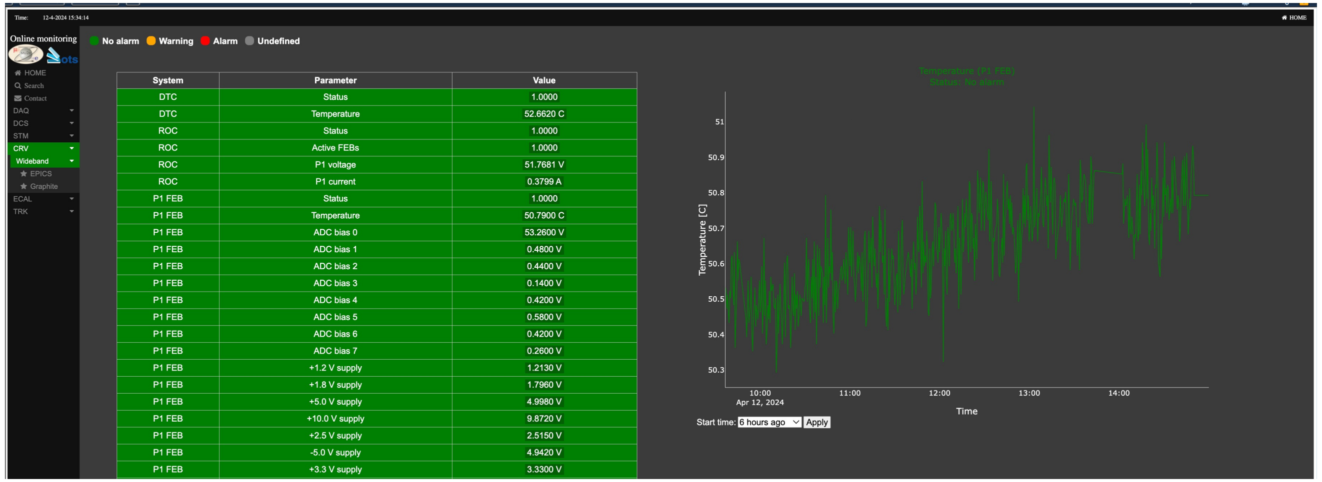


- Something that I have been working on is slow controls and monitoring, using a test stand at FNAL.
- We use Fermilab's OTS DAQ to send and receive requests to/from our ROC.
- Received metrics are passed to external **Graphite/Grafana** and **EPICS** servers.
- Developed live monitoring in our DAQ interface, as well as **alarm notification handling**…





EPICS monitoring



System	Parameter	Value
DTC	Status	1.0000
DTC	Temperature	52.6620 C
ROC	Status	1.0000
ROC	Active FEBs	1.0000
ROC	P1 voltage	51.7681 V
ROC	P1 current	0.3799 A
P1 FEB	Status	1.0000
P1 FEB	Temperature	50.7900 C
P1 FEB	ADC bias 0	53.2600 V
P1 FEB	ADC bias 1	0.4800 V
P1 FEB	ADC bias 2	0.4400 V
P1 FEB	ADC bias 3	0.1400 V
P1 FEB	ADC bias 4	0.4200 V
P1 FEB	ADC bias 5	0.5800 V
P1 FEB	ADC bias 6	0.4200 V
P1 FEB	ADC bias 7	0.2600 V
P1 FEB	+1.2 V supply	1.2130 V
P1 FEB	+1.8 V supply	1.7960 V
P1 FEB	+5.0 V supply	4.9980 V
P1 FEB	+10.0 V supply	9.8720 V
P1 FEB	+2.5 V supply	2.5150 V
P1 FEB	-5.0 V supply	4.9420 V
P1 FEB	+3.3 V supply	3.3300 V

Conclusion

- The Mu2e experiment will provide a powerful probe for new physics.
- This is a rare event search, so is sensitive to backgrounds (particularly the cosmic ray induced background).
- A high efficiency muon detector, the cosmic ray veto, will suppress cosmic ray induced backgrounds by a factor of 10,000.
- This system is well on track for commissioning and first physics data at the end of 2026, thanks to a huge amount of excellent work by the CRV team.

Thank you!

References

[1] L. Bartoszek et al. Mu2e Technical Design Report. 2015.

[2] R. H. Bernstein. Front. Phys. 7. 2019.

[3] Mu2e collaboration. Universe, 9(1). 2023.

[5] R. Ehrlich. Mu2e DocDB-47311.

[6] Y. Wu. Mu2e DocDB-48249.

[7] T. Horoho. Mu2e DocDB-48609.

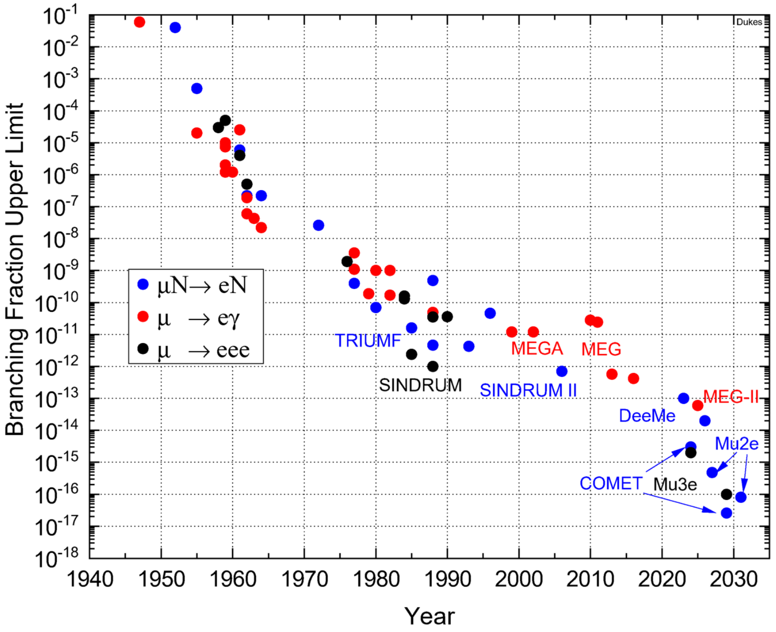
[8] W. J Marciano, T. Mori, and J. M. Roney, Ann. Rev. Nucl. Sci. 58:1 (2008).

[9] M. Raidal et al., Eur. Phys. J. C57:13–182, (2008)

Extra slides

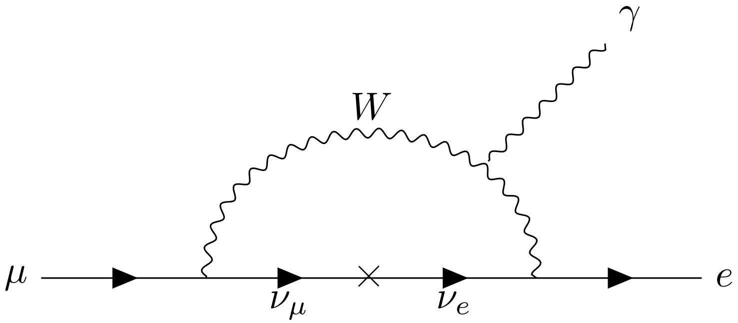
Charged lepton flavour violation

- Charged leptons, e, μ, and τ, seem to conserve flavour, quarks (via quark mixing) and neutrinos (via neutrino oscillations) do not.
- Charged lepton flavour violation (CLFV) is permitted in the Standard Model (SM), if we include neutrino masses.
- These processes are highly suppressed, but beyond the SM (BSM) processes can enhance CLFV rates.
- **Mu2e will search for CLFV** with a sensitivity which surpasses the current upper limit by a factor of 10,000 [1]!



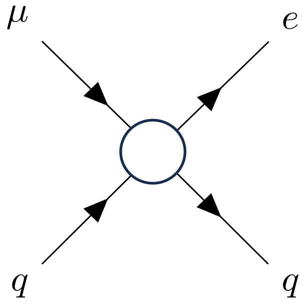
SM (not measurable)

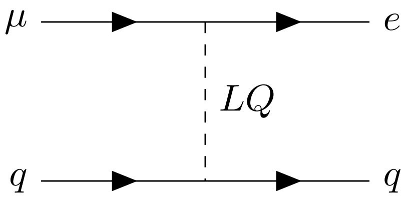
$R(\mu \to e) \propto (\Delta m_\nu{}^2 / M_W{}^2)^2 < 10^{-50}$! [8]



BSM (measurable)

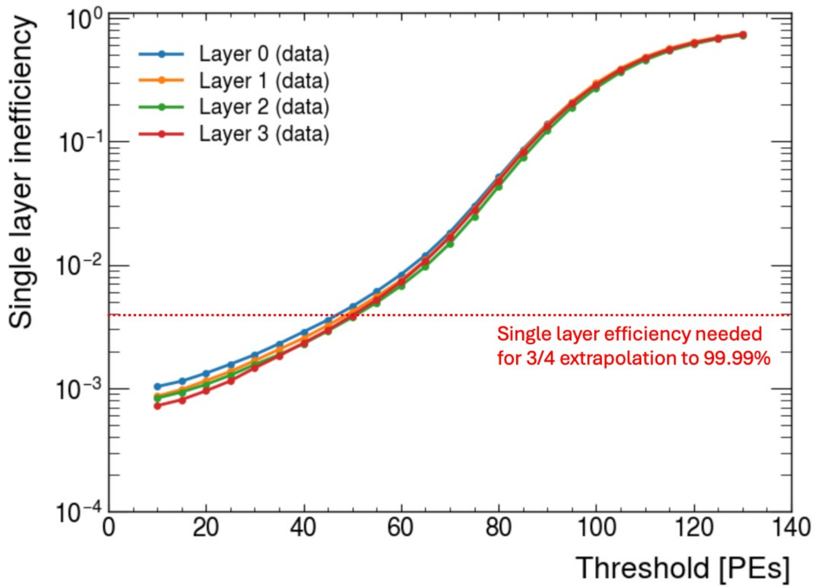
$R(\mu \to e) \sim 10^{-15} - 10^{-17}$ [9]

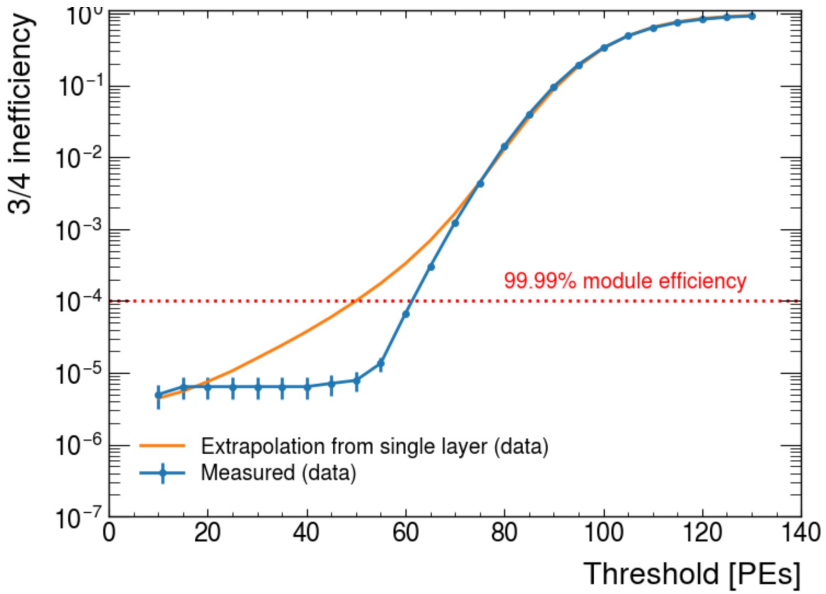


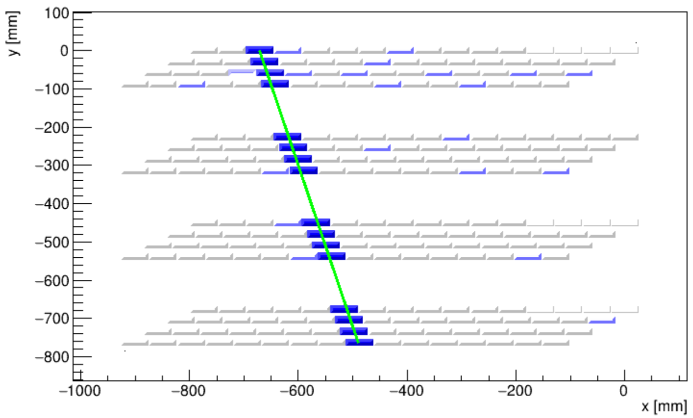


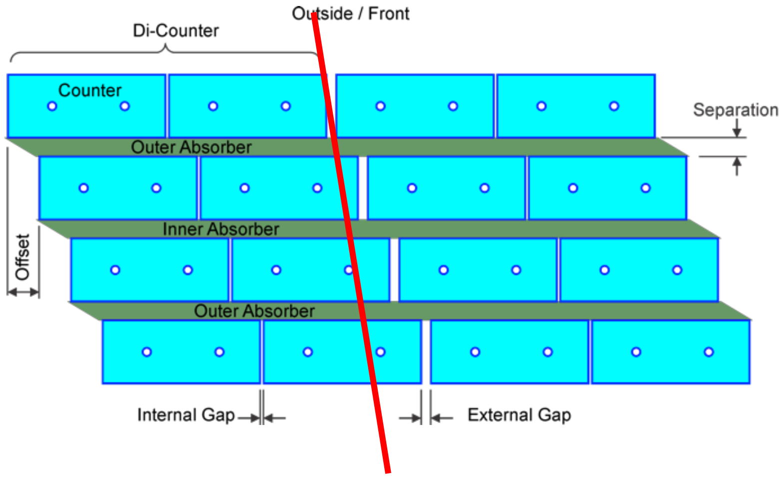
More detail on the inefficiency study

- Tyler Horoho, a graduate student at UVA, has conducted a study on module inefficiency.
- Single layer inefficiency is found by integrating the PEs per layer distribution.
- Module efficiency is found by using the modules above and below the test modules to trigger on cosmics.
- Extrapolation to 3/4 layers assumes layer inefficiencies are independent, which does not account for the staggering of layers. If a muon passes through a gap in one layer, it is much less likely to pass through a gap in the next.
- At low PEs, this becomes apparent, and the single layer efficiency extrapolation starts to break down.
- At very low PEs, the we see a plateau due to the presence of EM showers producing neutral particles in the test module.



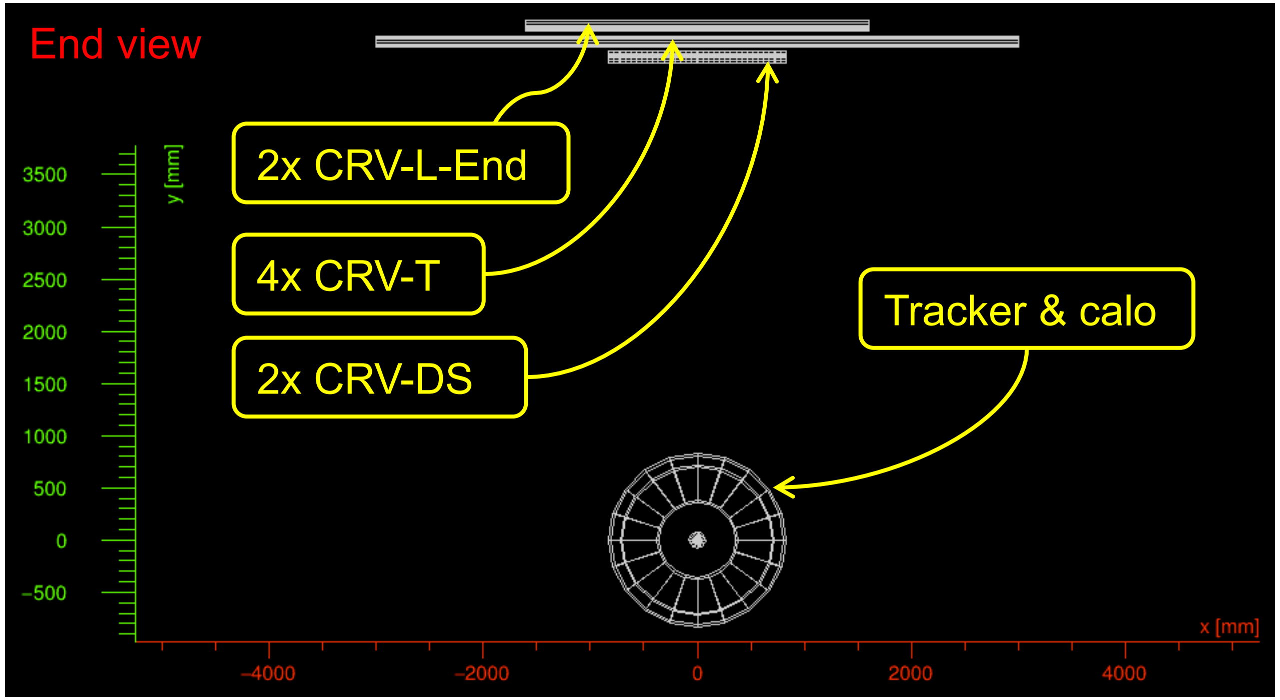




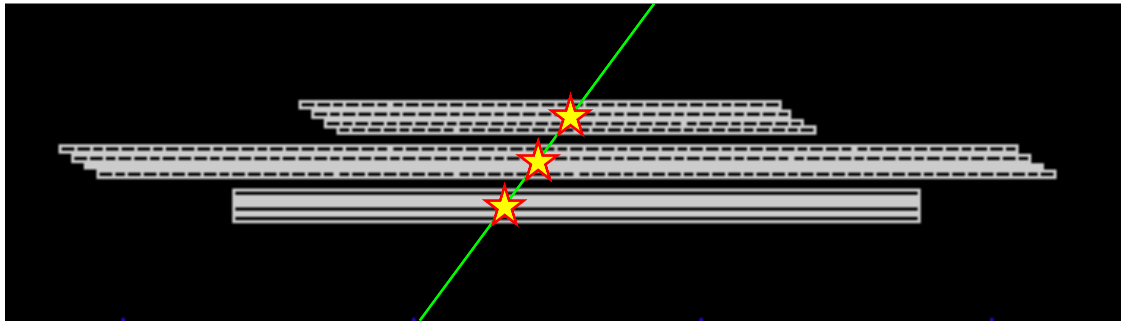


Preparation for KPP

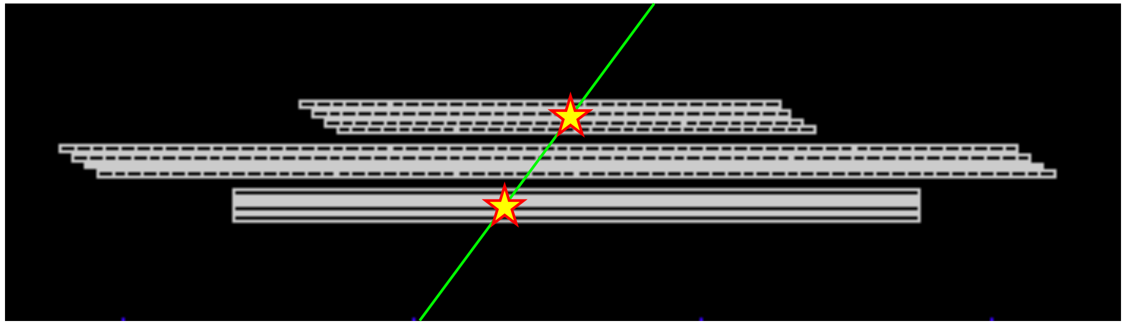
- **K**ey **P**erformance **P**arameters (KPP) configuration, scheduled for mid-2025 (preparing now!)
- Demonstrate operation of the three detectors in unison.
- Tracker and calorimeter extracted from the detector solenoid, eight CRV modules positioned above in three tiers.



Success



Failure



- This arrangement provides a means of measuring the CRV module efficiency directly!
- I have reconstructed a ~170 million cosmic event dataset to study this efficiency measurement look at this (see extra slides).

KPP simulation

- **Reconstructed a ~170 million cosmic event CRY dataset, generated using HPC resources at ANL by Yuri Oksuzian.**
- Some details in the reconstruction need further tuning, but still we see some fun results.
- Small fraction of non-muon events (well within 0.01% module inefficiency!) fail due to neutral particles in EM showers.
- Not an issue during operation due to concrete shielding, but something to be aware of for our KPP efficiency measurement.