Mu2e: The Search for Charged Lepton Flavor Violation
A Progress Report

Fermilab

- **Ken Heller**
- **University of Minnesota**

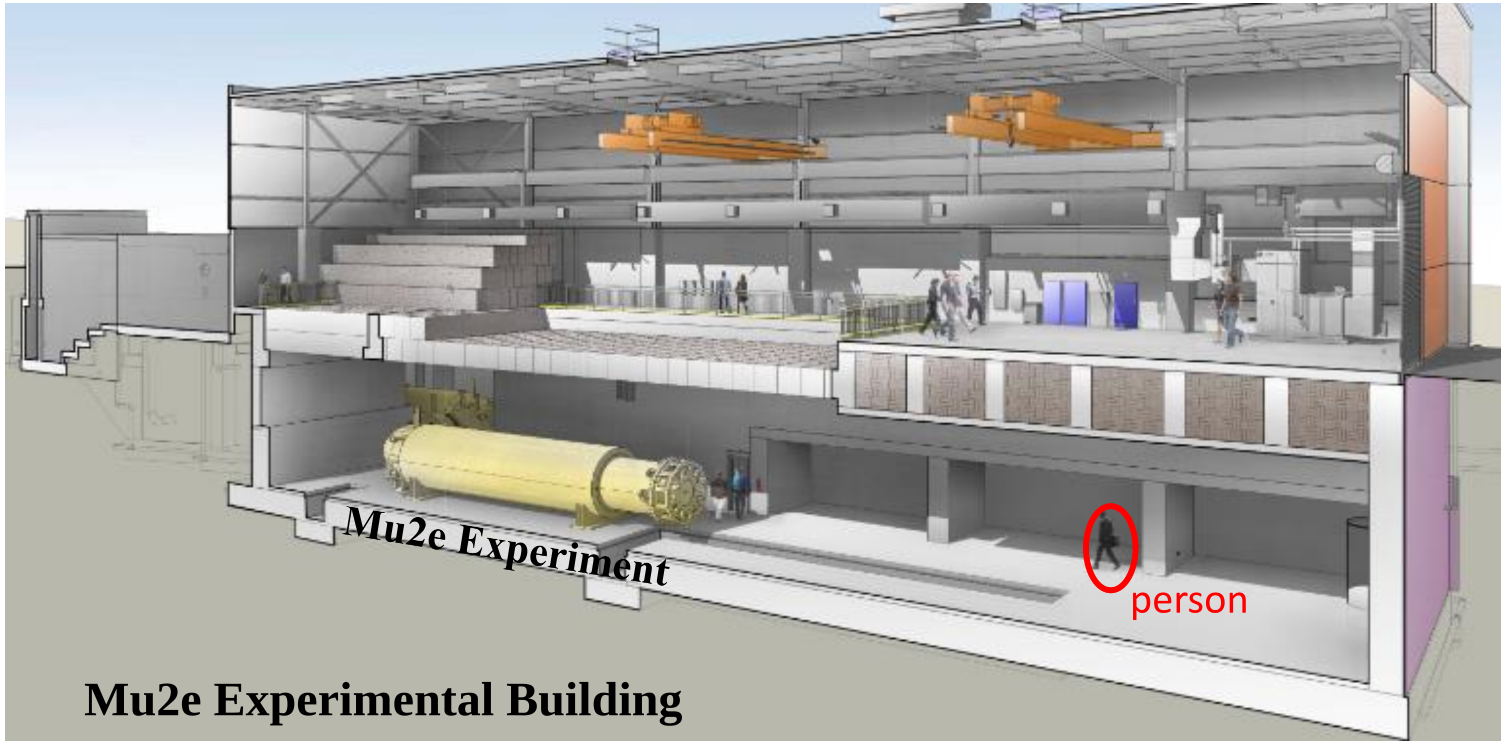
On behalf of the Mu2e collaboration

The University of Minnesota Twin Cities is built within and continues to occupy the traditional homelands of the Dakota people. It is important to acknowledge the peoples on whose land we live, learn, and work as we seek to improve and strengthen our relations with our tribal nations.

Outline

- Why? Probe of Physics Beyond the Standard Model
- What? The Mu2e Experiment
- When? Mu2e Progress and Schedule for Physics
- Who? The Mu2e Collaboration

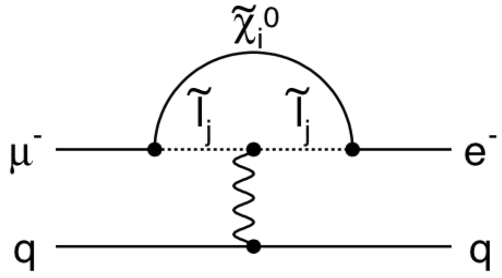
Yoshitaka Kuno
Plenary talk
for global context



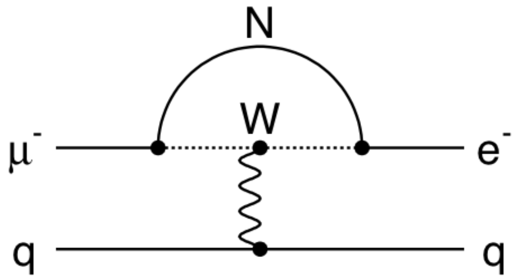
Why Broad Search for Physics Beyond the Standard Model

Direct $\mu^- \rightarrow e^-$ conversion occurs in a wide variety of New Physics models.
Mu2e accesses energies beyond the reach of current or planned colliders

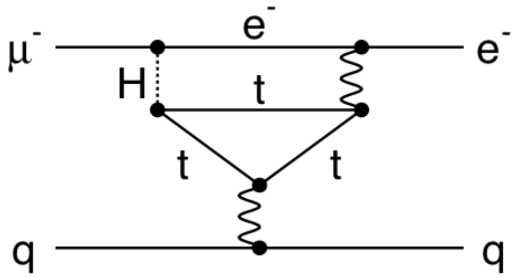
Loops



Supersymmetry

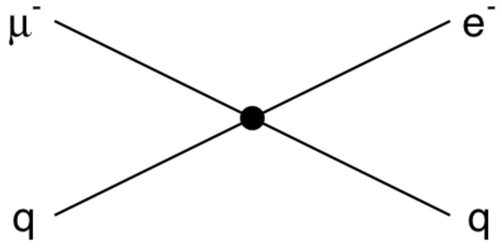


Heavy Neutrinos

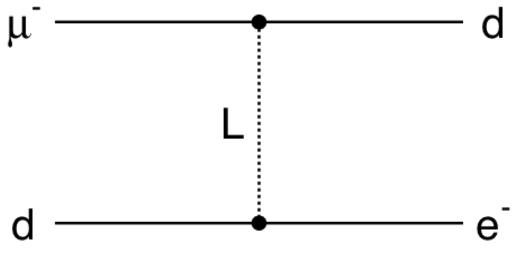


Extended Higgs Models

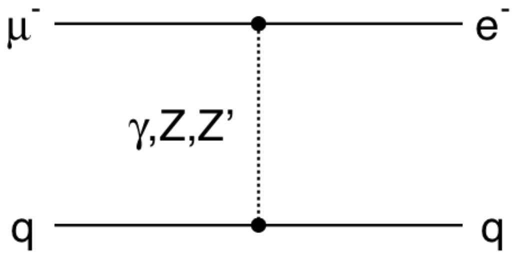
Contact Terms



Compositeness



Leptoquarks



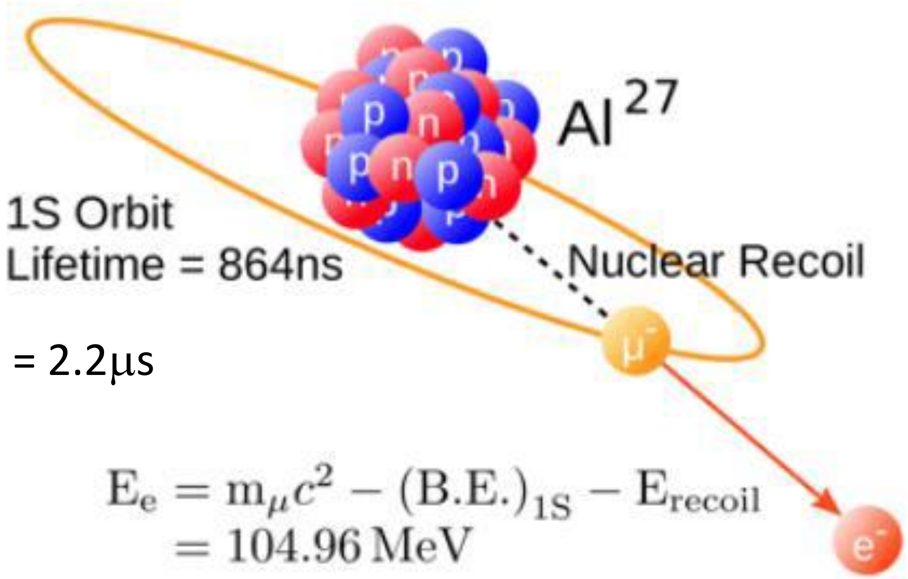
New Heavy Bosons / Anomalous Couplings

Reasonable models give motivation for CLFV at the ~10^{-16} level

Yoshitaka Kuno
Plenary talk

What

Mu2e measures the rate of $\mu^- \rightarrow e^-$ relative to muon capture in an Al nucleus.



Free μ lifetime = 2.2μs

$$R_{e\mu} = \frac{\Gamma(\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al})}{\Gamma(\mu^- + \mathrm{Al} \rightarrow \mu^- \mathrm{capture} \rightarrow \gamma + \mathrm{Al})}$$

Mu2e goal:

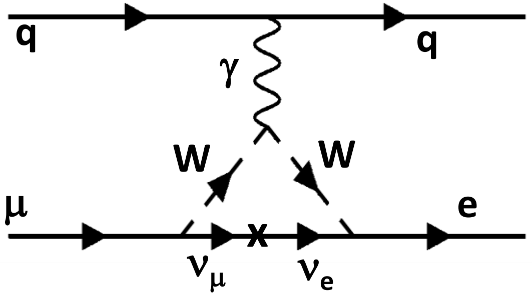
Limit: $R_{e\mu}$ (90% CL) < 6×10^{-17}

Discovery: $R_{e\mu}$ ($5\ \sigma$) = 2×10^{-16}

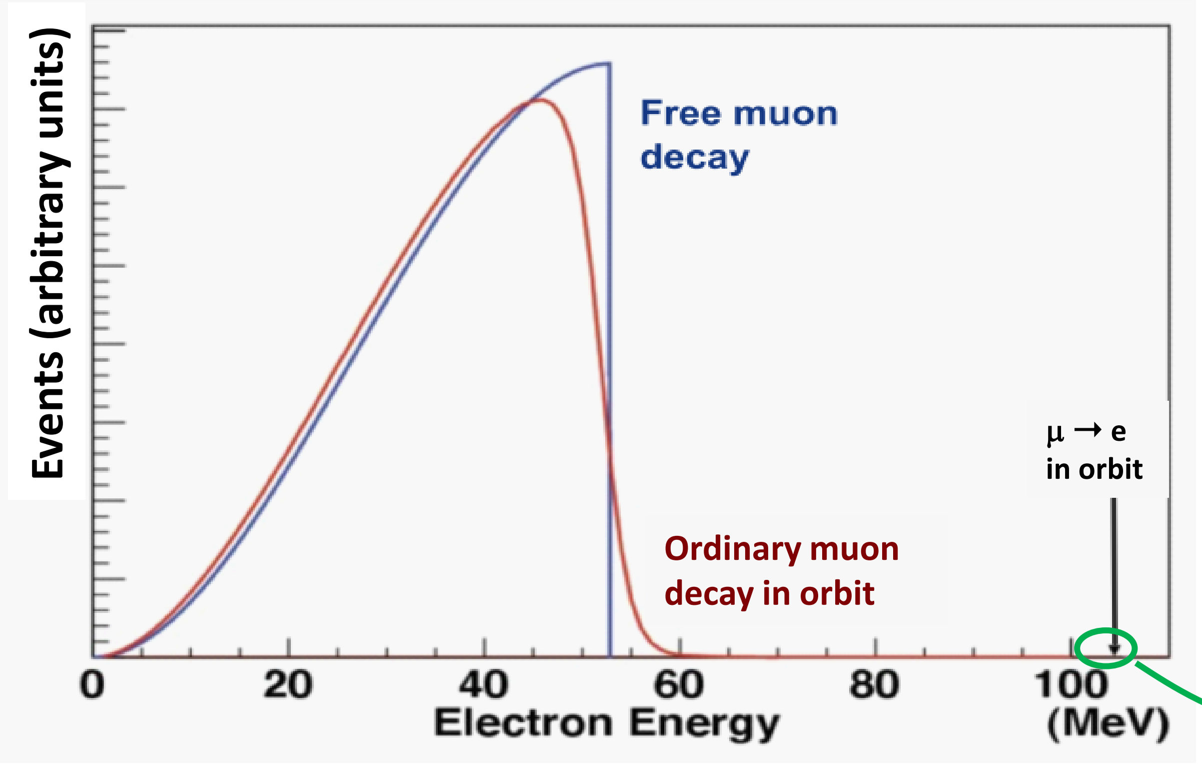
(Universe 2023, 9(1), 54)

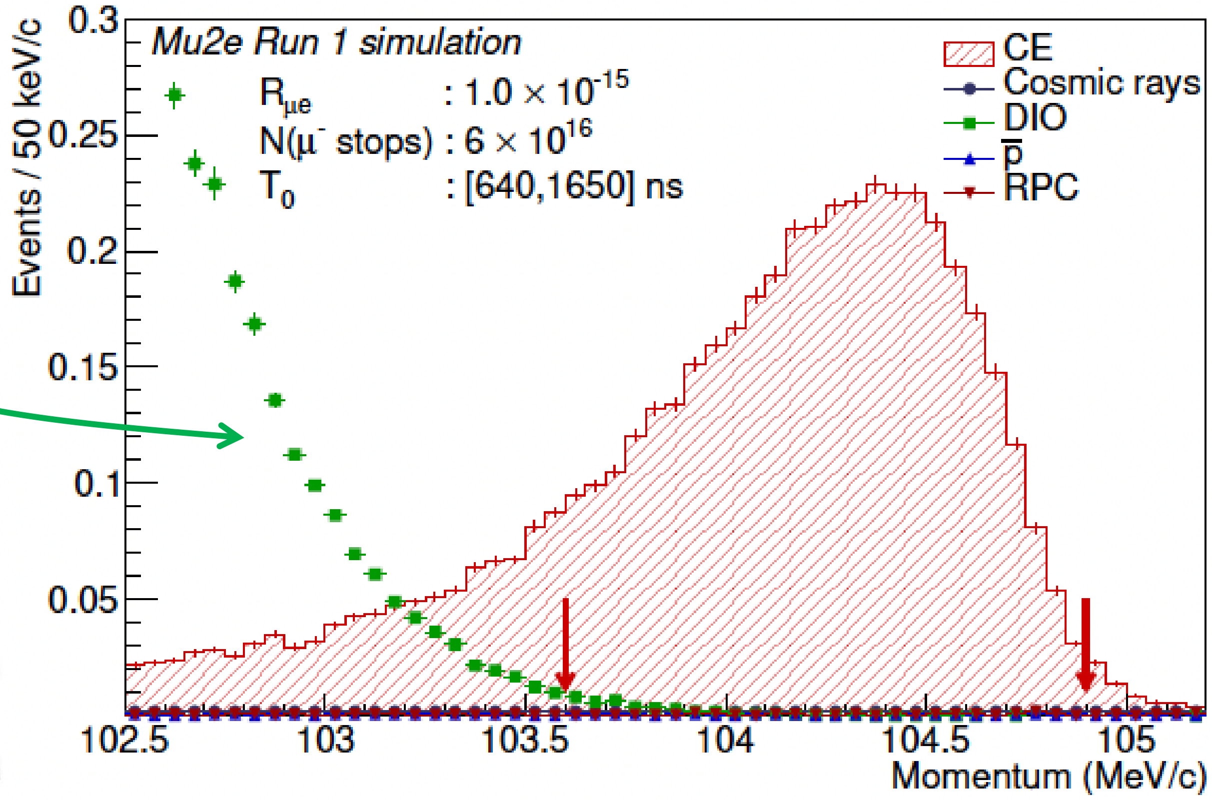
Standard Model Prediction:

$R_{e\mu} < 10^{-50}$

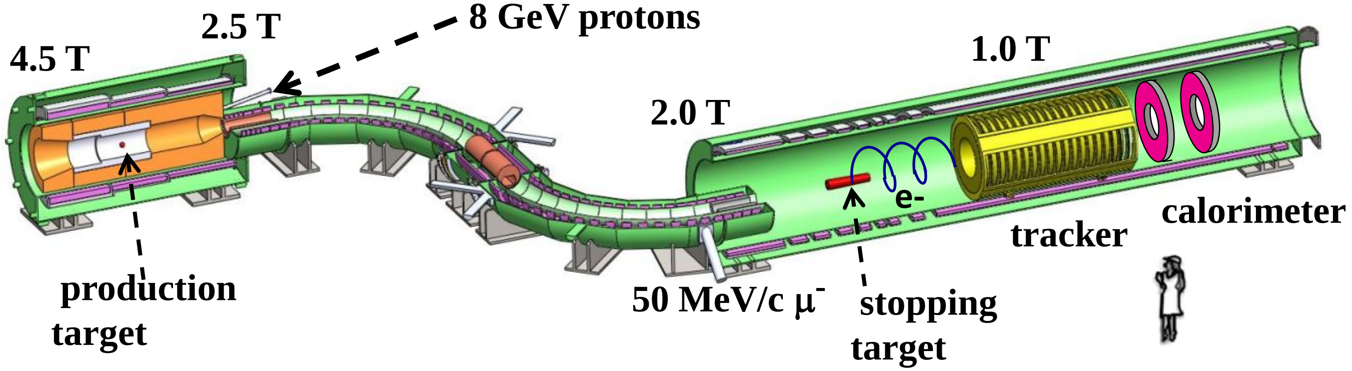


Simulation: Signal & Background



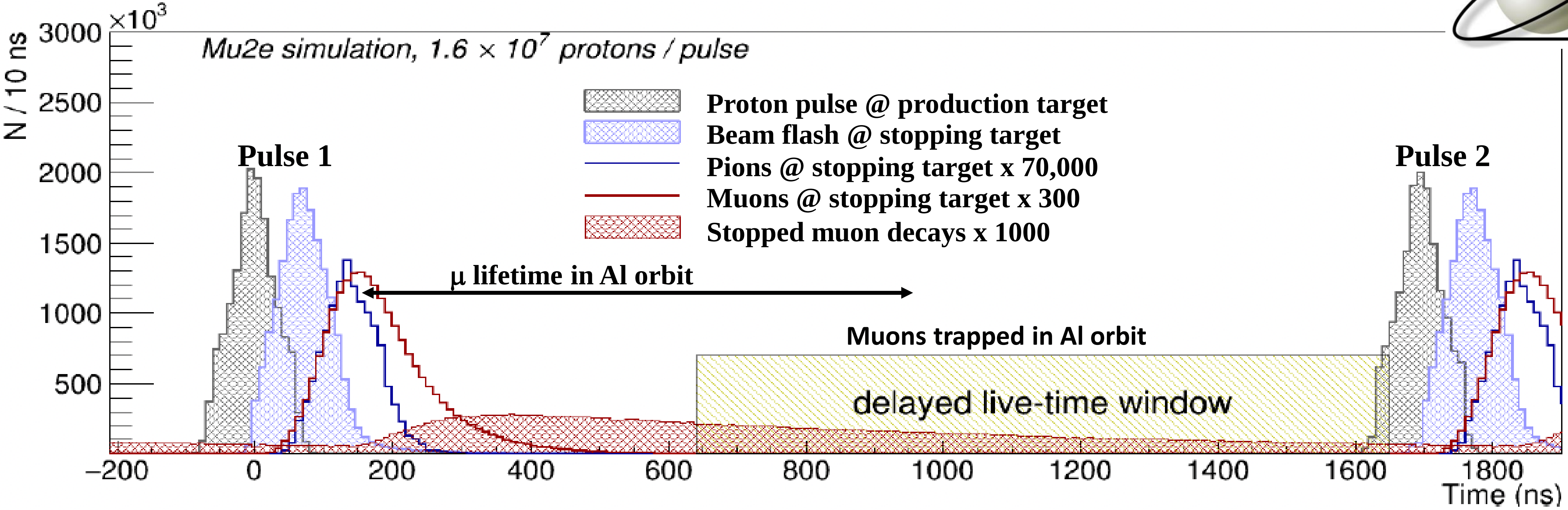


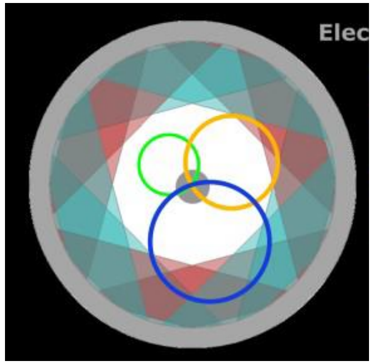
Mu2e Experiment in Vacuum & Magnetic Field



Also sensitive to $\mu^- \rightarrow e^+$

Muon Conversion Detected Between Pulsed Protons





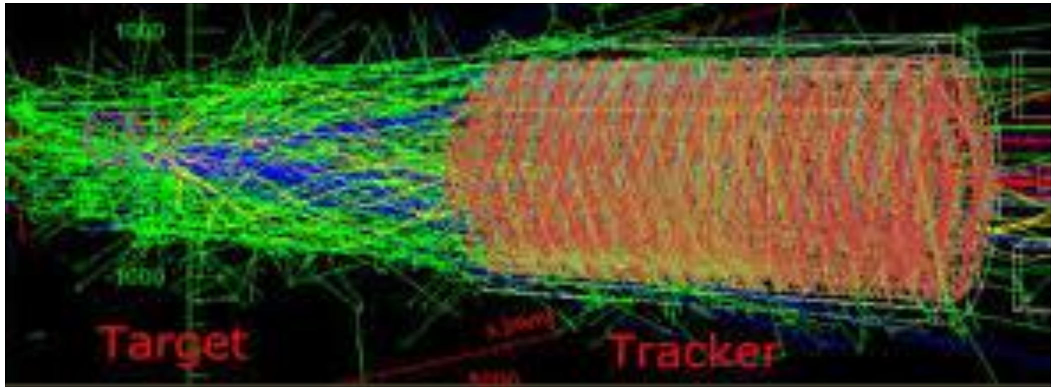
Helical trajectory though tracker

Signal electron

SM μ decay in orbit

SM μ decay at rest

Tracker occupancy during data taking during live-time

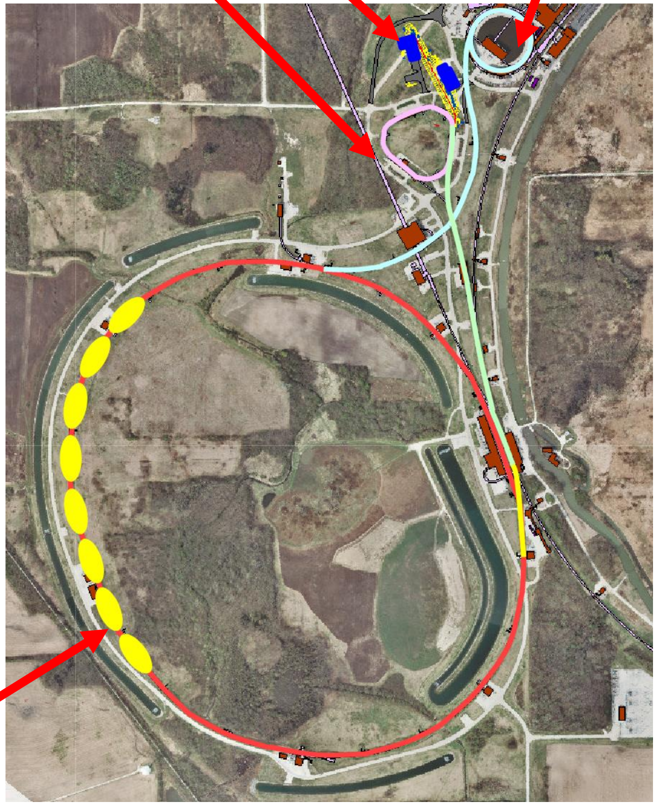


Journey of the 8 GeV, 8 KW Mu2e Pulsed Proton Beam

8 GeV protons → 50 MeV muons

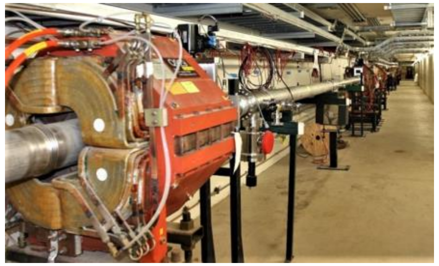
Linac → Booster → Recycler → Delivery Ring → Beamline to Muon Area → Mu2e Production Target

Delivery Ring **Mu2e Target** **Booster**

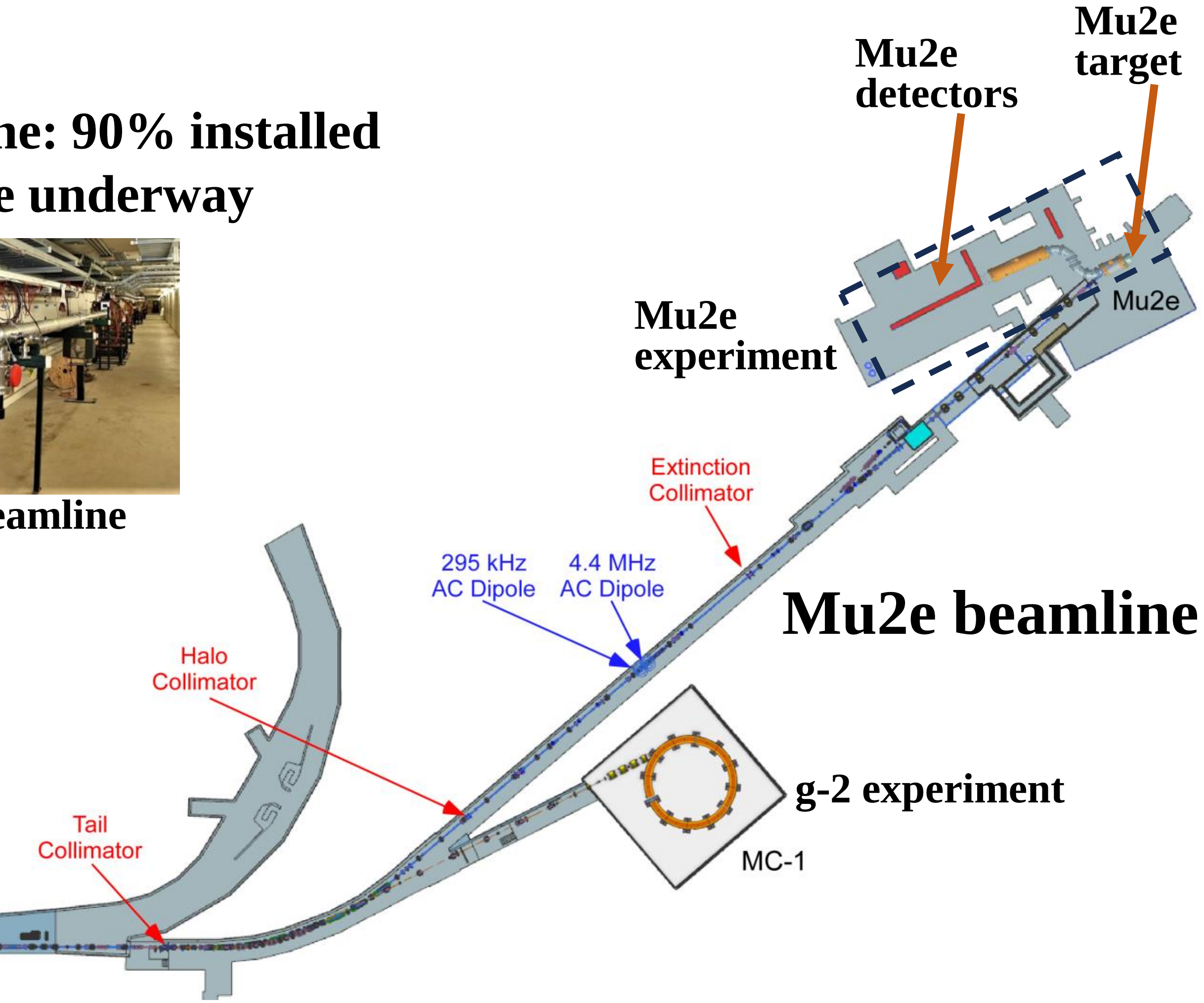


Recycler

Mu2e Beamline: 90% installed
Beam tests are underway

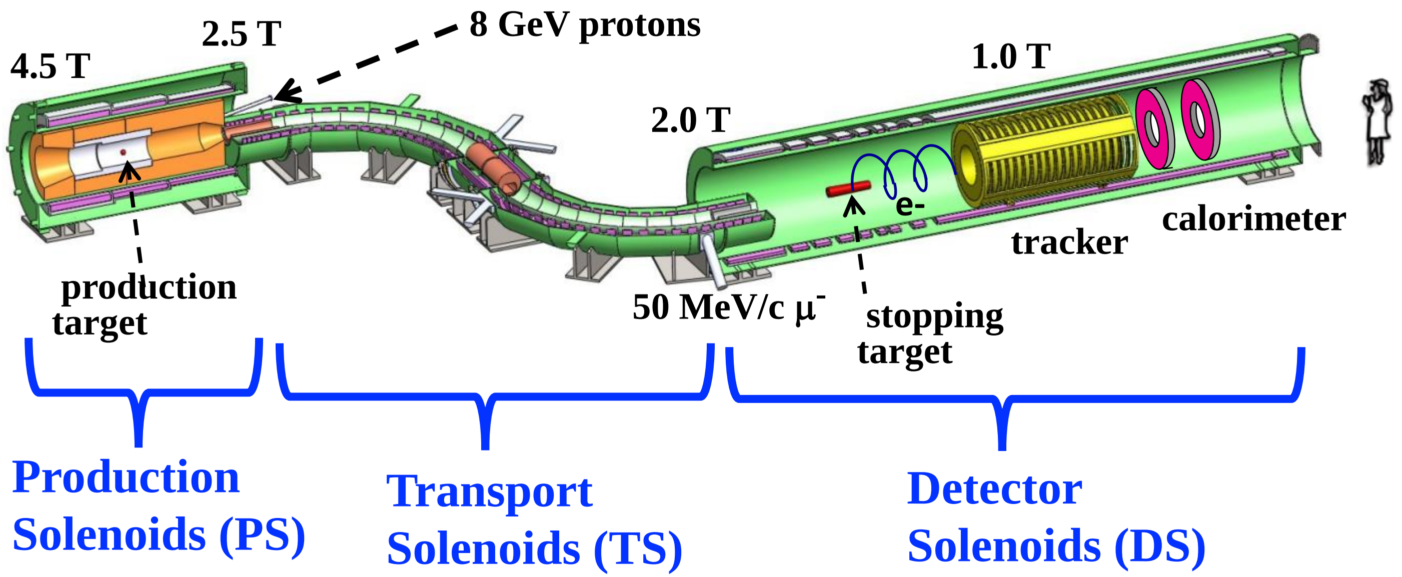


Mu2e beamline

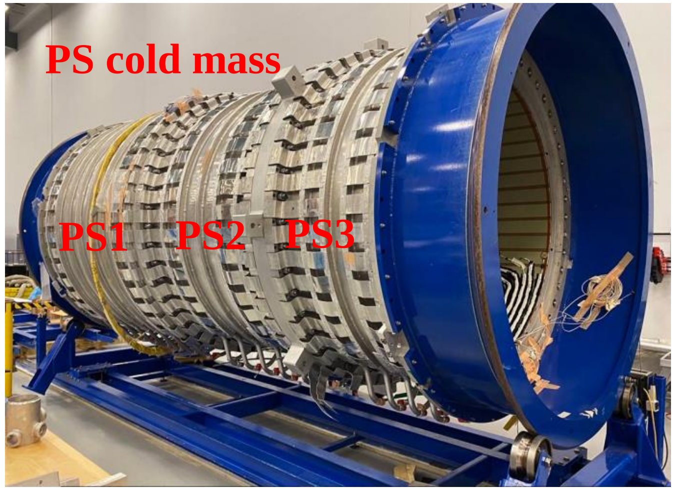


Mu2e Experiment – Superconducting Solenoids Encase the Experiment

Protons → Pions → Muons → Electrons



Solenoid installation, testing, & mapping duration to mid 2026



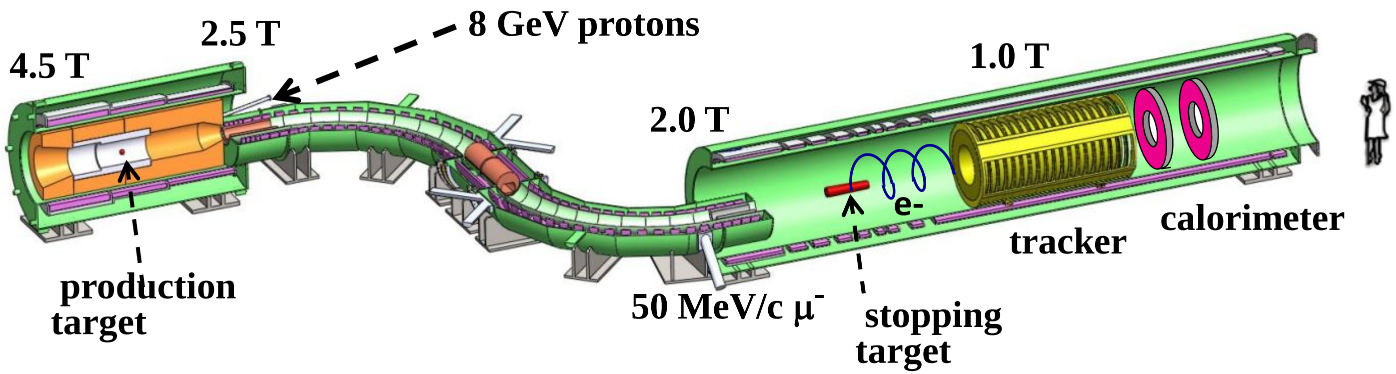
PS (3 coils) Delivery this Fall (2023)

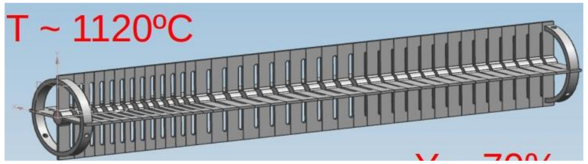
TS Completed. Ready for installation.

DS (11 coils) Delivery Summer (2024)

Solenoids have NbTi coils.

Mu2e Experiment – Targets





W Production Target

Protons → Pions

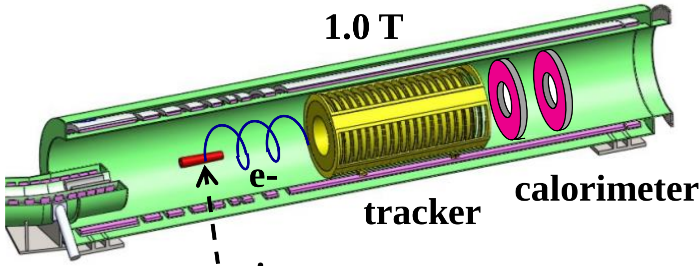
- Complete
- 22 cm long 3.2 mm diameter cylinder
- Radiatively cooled with fins

Al Stopping Target

Muons → Electrons

- Complete
- 37 Al foils, 0.1 mm thick
- 2 cm spacing, 7.5 cm radius
- 43 mm diameter hole in center

Mu2e Experiment – Electron Detectors: Tracker



Determines track curvature: momentum resolution of 140 KeV/c for 105 MeV/c electron

Most ordinary muon decays and beam flash goes through center hole of tracker

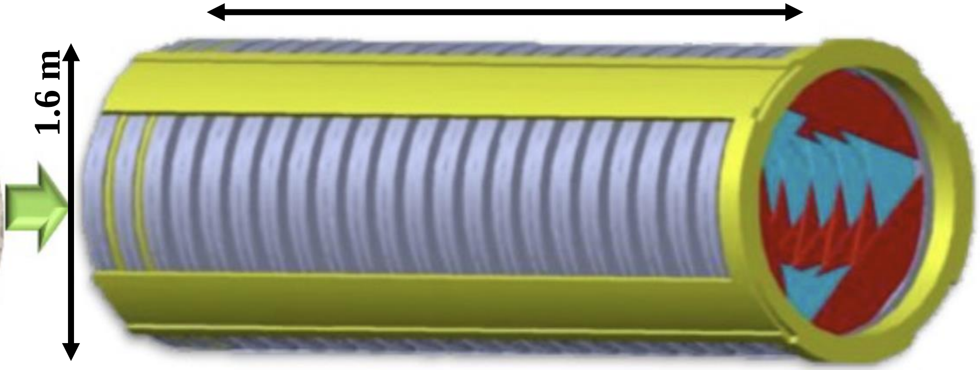
Detector elements (21,000 straw drift tubes): 15 μm wall thickness Al & gold coated Mylar with a 25 μm signal wire @ 1450V filled with 80/20 $ArCO_2$ gas.

96 straws = 1 module

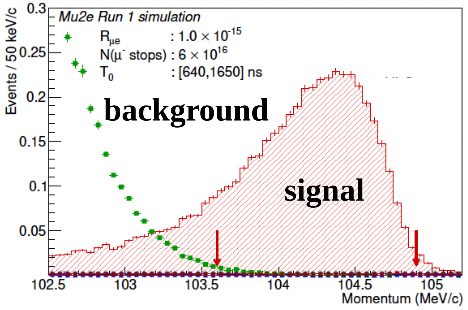
5 cm diameter

6 modules = 1 plane

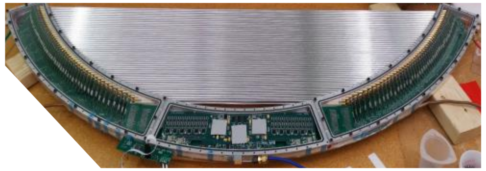
2 planes = 1 station



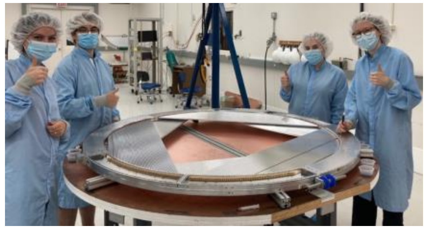
18 stations = 1 tracker (~21,000 straws)



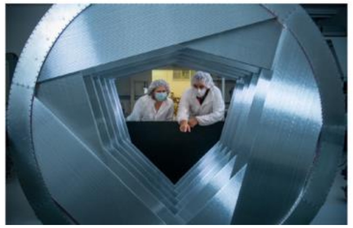
70 cm



1 module



1 plane



Planes stored for long term testing

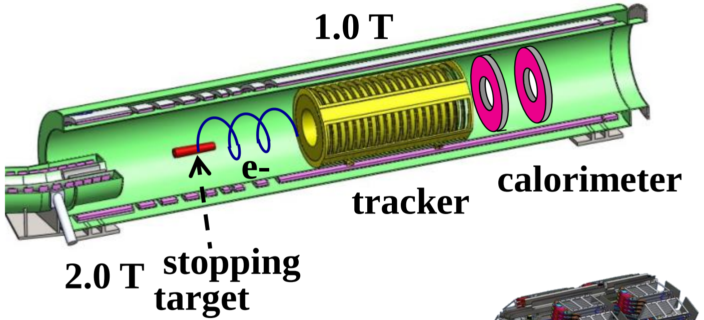
Tracker Frame

- **Straws completed**
- **Modules completed**
- **70% planes completed**
- **Frame constructed and being tested**

- **Straws read out from both ends – pulse height & time.**
- **Electronics under construction**

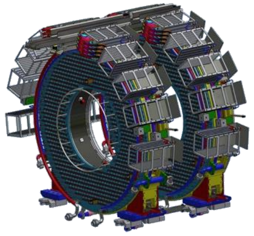
Installation of tracker completed early 2025

Mu2e Experiment – Electron Detectors: Calorimeter



2 annular rings of 1348 CsI crystals. Each crystal read out with SiPMs.

Determines time, position, and energy of electron candidate to seed tracker reconstruction.



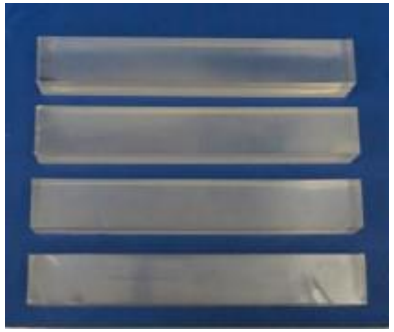
For 100 MeV electron.

$\Delta t < 500$ ps.

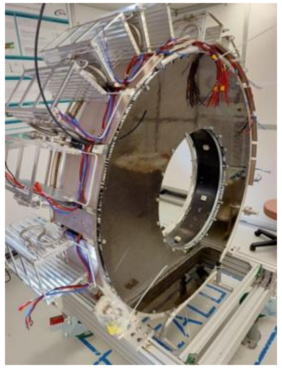
$\Delta E < 10\%$

$\Delta x < 1$ cm

674 CsI crystals = 1 ring **2 rings = calorimeter**



3.4 cm x 3.4 cm x 20 cm



Ring IR = 37.4 cm
Ring OR = 66 cm

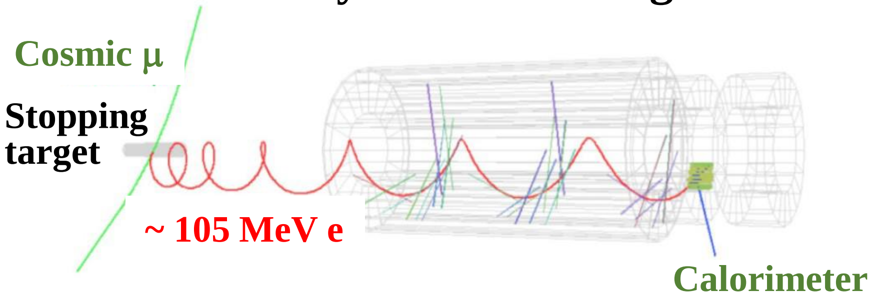
Ring separation:
70 cm

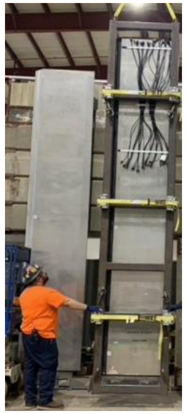
Installation of calorimeter to be completed late 2024

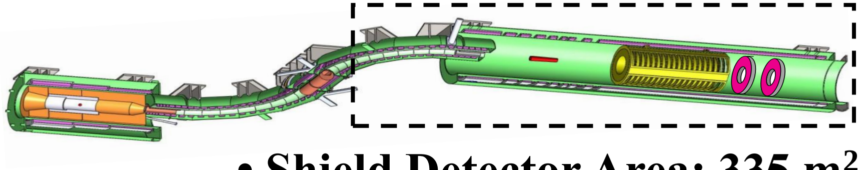
- Crystals, SiPMS, Front end electronics completed
- Ring 1 completed
- Ring 2 being finished
- Calibration systems being installed
- Digital electronics being produced.

Mu2e Experiment – Cosmic Ray Veto (CRV)

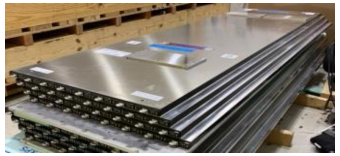
~1 cosmic/day makes a background event without CRV.





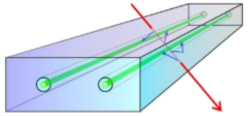


- Shield Detector Area: 335 m^2
- 5,344 plastic scintillator strips
- 10,688 wavelength shifting fibers
- 19,392 SiPMs

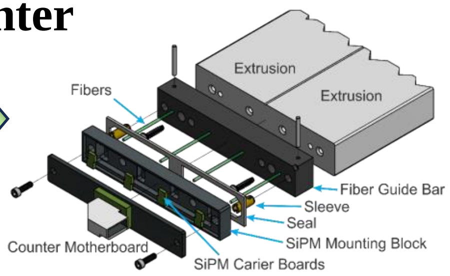


CRV has 99.99% cosmic ray tagging giving a background < half an event for the Mu2e experiment.

2 extruded plastic scintillator strips = 1 di-counter

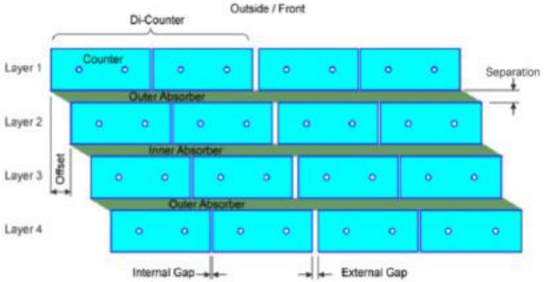


Co-extruded plastic scintillator with TiO_2 coating & 2 WLS fibers 2 cm x 5 cm x various lengths (1 m to 7 m).



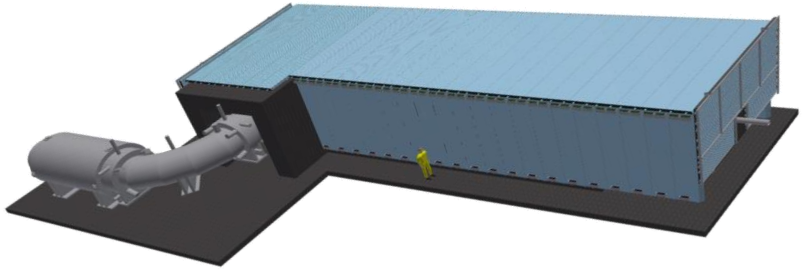
SiPM at each end of WLS fiber. Pulse height & time output.

8 di-counters = 1 module



4 layers of offset counters separated by Al sheets

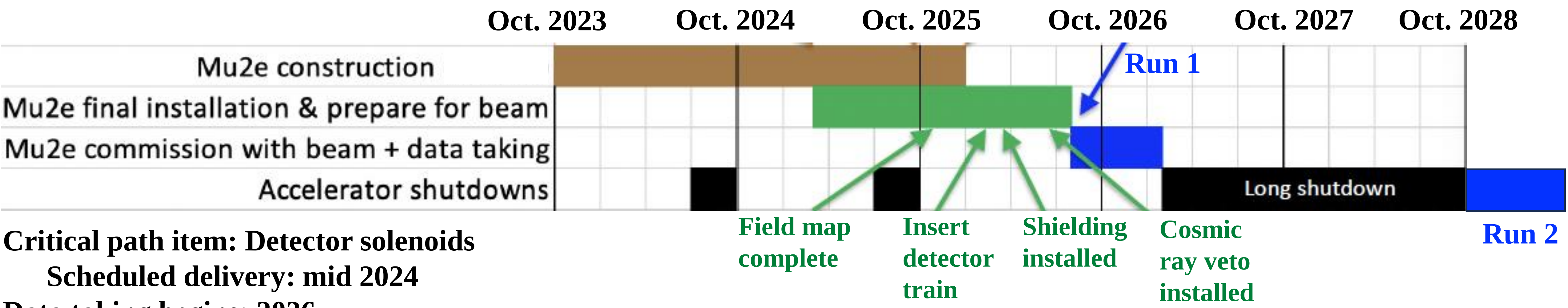
83 modules = cosmic ray veto



Installation of CRV to be completed late 2025

- 96% of modules completed.
- Mechanical installation tested.
- Final electronics being built.

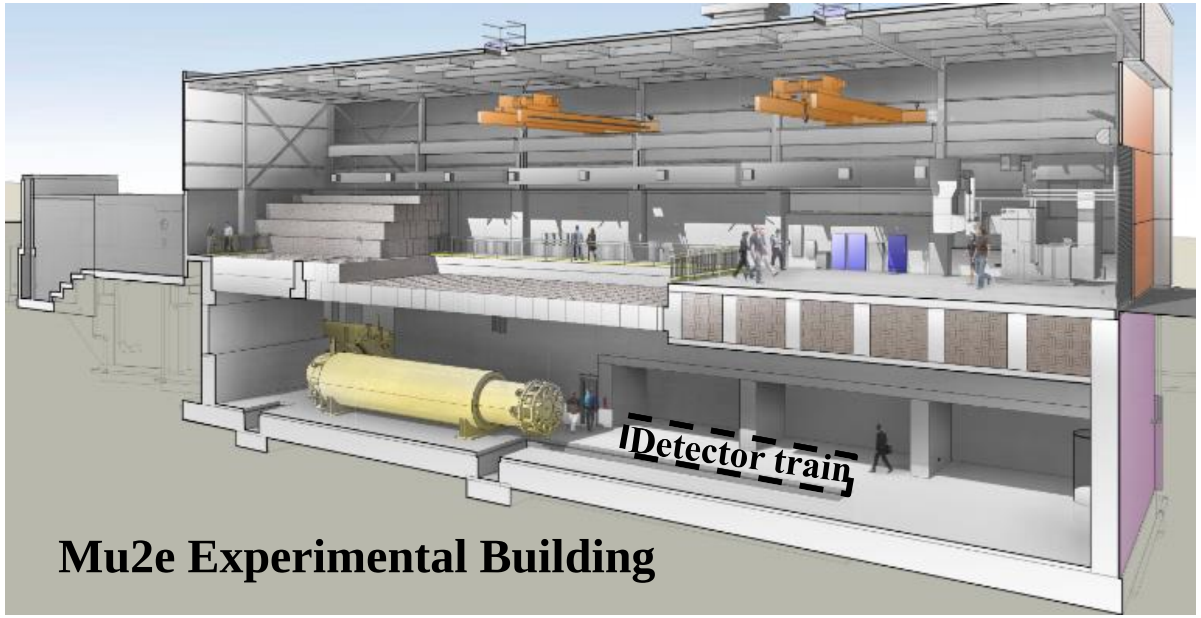
Mu2e Experiment – When

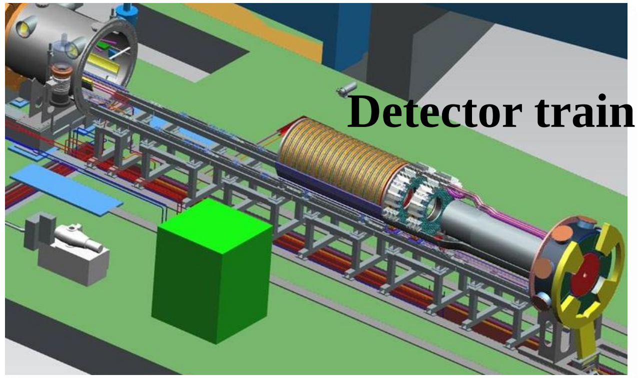


Critical path item: Detector solenoids

Scheduled delivery: mid 2024

Data taking begins: 2026





Mu2e Experiment (10^4 improvement on current knowledge)

- **Accelerator & proton beam modifications in progress: 90% in place**
- **Production & stopping target complete**
- **Muon beam solenoids complete at end of 2023**
- **Detector solenoids final delivery by mid 2024**
- **Tracker modules complete, 67% of planes assembled**
  Electronics being assembled
- **First half of calorimeter complete, 2nd half being assembled**
- **Cosmic ray veto modules 96% complete**
  Electronics being assembled

Run 1 2026: Expected single event sensitivity (SES) 2.4 x 10^{-16}

Backgrounds	Events
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

DIO: SM μ decay
RPC: Radiative p capture
RMC: Radiative μ capture

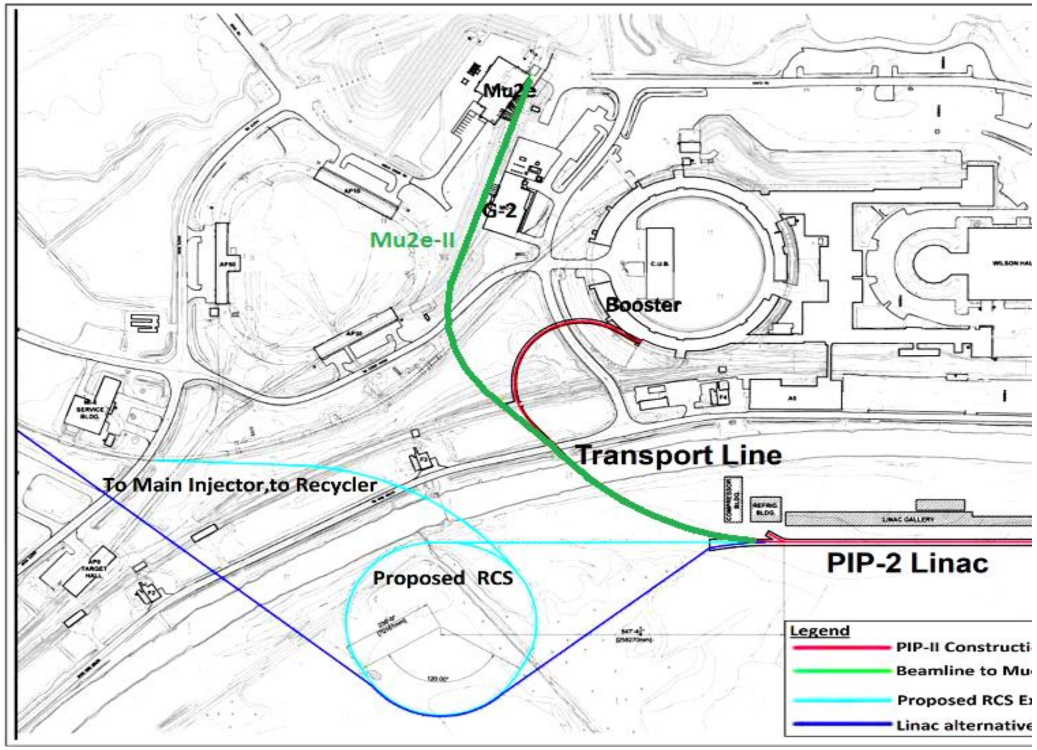
Run 2 2029: Factor of 10 improvement

Backgrounds	
Decay In Orbit	0.144
Cosmics	0.209
Radiative Pion Capture	0.025
Radiative Muon Capture	< 0.004
Antiprotons	0.040
Others	< 0.004
Total	0.41
N(muon stops)	6.7×10^{18}
SES	3.01×10^{-17}
$R_{\mu e}$(90% CL)	6.01×10^{-17}
$R_{\mu e}$(discovery)	1.89×10^{-16}

Next Step: Mu2e-II

Increase sensitivity by another order of magnitude, use different targets.

PIP-2 linac could deliver high intensity pulsed proton beam directly to the experiment.



Higher intensity requires redesign

- **Production target**
- **Tracker**
- **½ of Calorimeter**
- **Cosmic ray veto**
- **Radiation shielding**

Run > 2030

Who: Mu2e Collaboration

Over 230 Scientists from 38 Institutions

Argonne National Laboratory, Boston University, Brookhaven National Laboratory, University of California Berkeley, University of California Davis, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionale di Frascati, INFN Genova, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University Marconi Rome, University of Michigan, University of Minnesota, Institute for Nuclear Research Moscow, Muon Inc., Northern Illinois University, Northwestern University, Novosibirsk State University, INFN Pisa, Purdue University, University of South Alabama, Sun Yat-Sen University, INFN Trieste, University of Virginia, Yale University