The Mu2e Experiment:
A Search for Charged Lepton Flavor Violation

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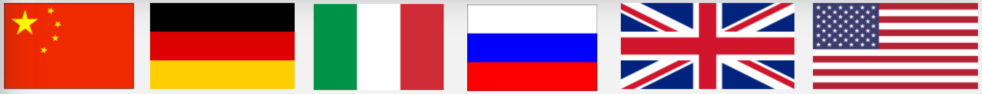
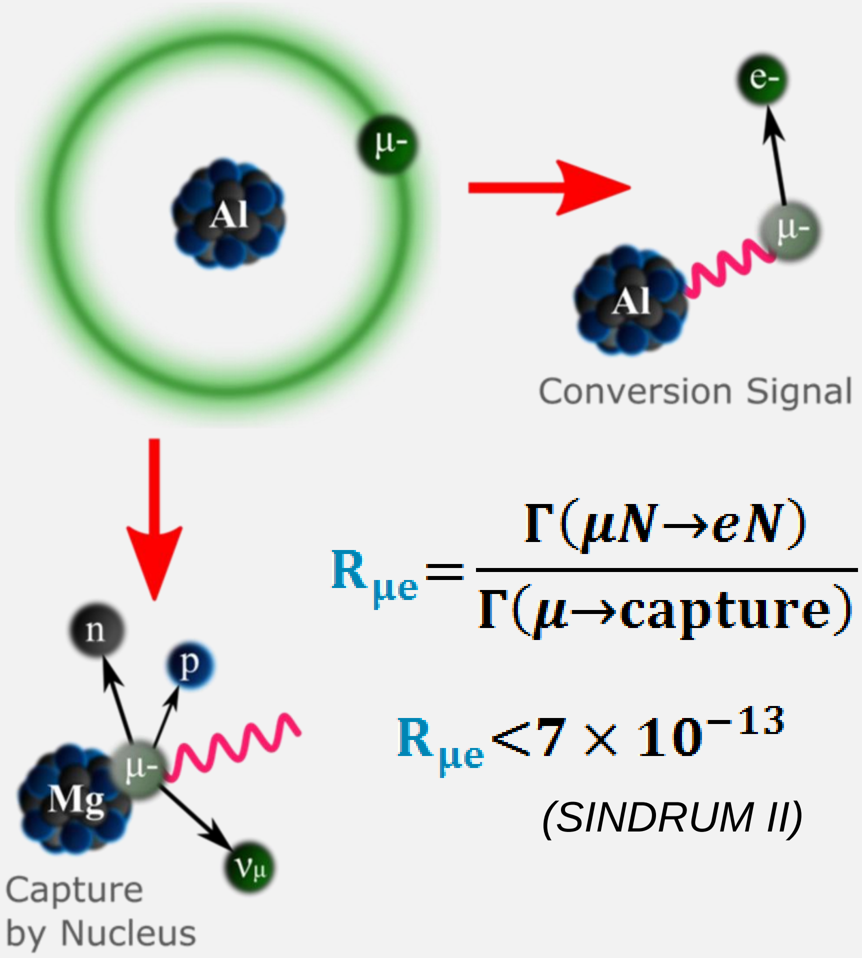
The Mu2e Experiment at Fermilab

- **Based at Fermilab's Muon Campus**
  - **8GeV primary protons from Booster Synchrotron**
- **Over 200 collaborators from 38 institutions**



Mu2e Measurement Concept

- **Signal: electron from coherent, neutrinoless muon conversion in the Coulomb field of an aluminum nucleus (μN→eN)**
- **Muon orbits in K-shell w/radius 20fm**
  - **Wavefunction overlap with nucleus**
  - **Average lifetime 864ns**
- **Dominant transition modes are weak interaction processes**
  - **Muon decay in orbit (DIO)**
  - **Muon capture by the nucleus**
- **Goal: measure $R_{\mu e}$, ratio of conversion rate to capture rate**
- **Not detected by previous experiments**
  - **Search history 1952-2006**
  - **Current upper limit from SINDRUM II**
- **Mu2e will extend sensitivity by 4 orders of magnitude**

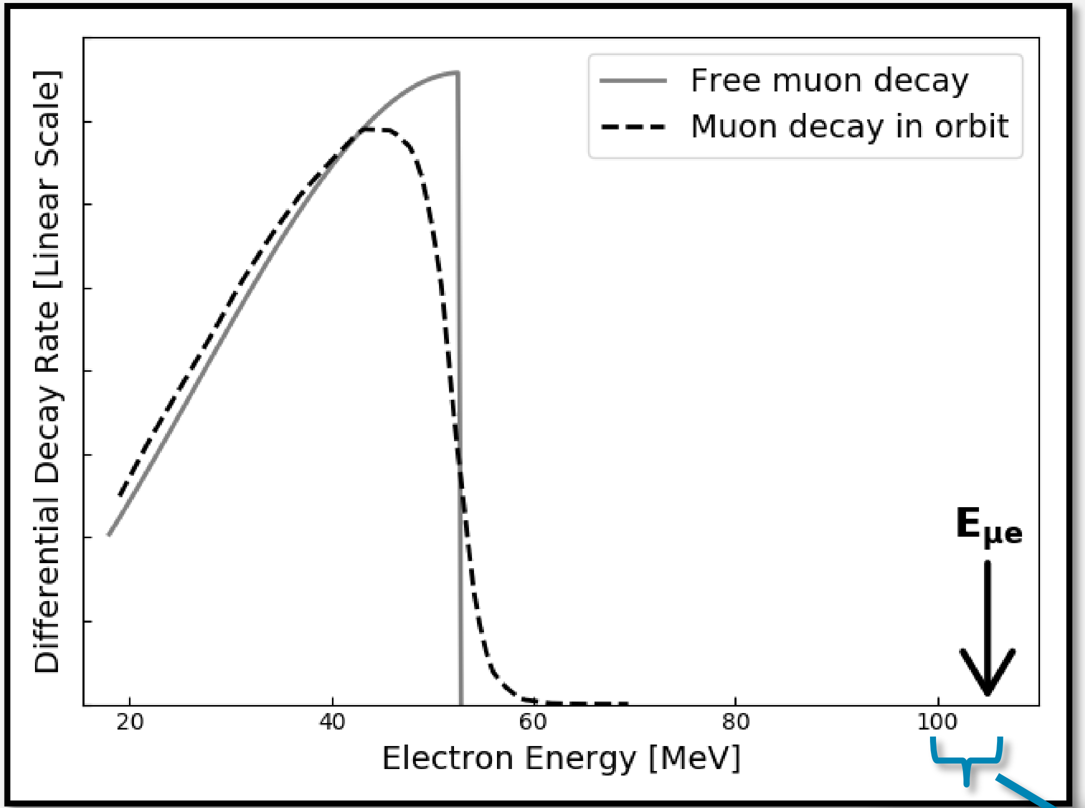


$$R_{\mu e} = \frac{\Gamma(\mu N \rightarrow e N)}{\Gamma(\mu \rightarrow \text{capture})}$$

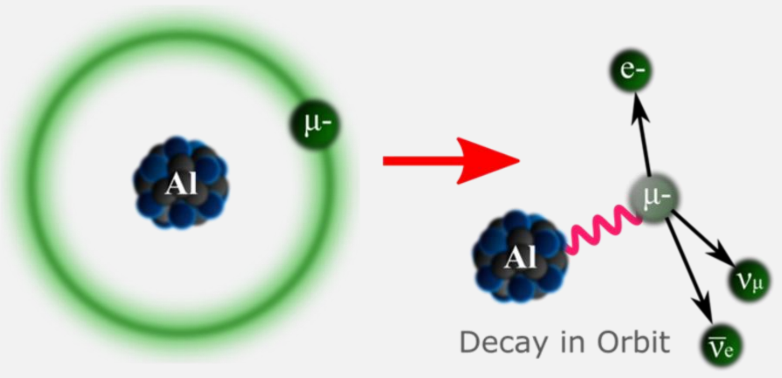
$$R_{\mu e} < 7 \times 10^{-13}$$

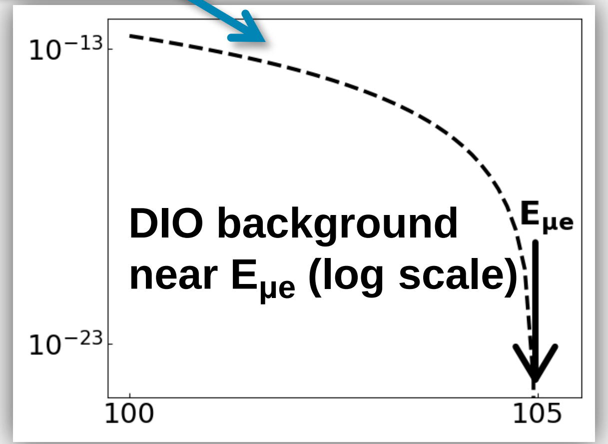
(SINDRUM II)

Conversion Electron vs. Muon Decay Spectra



- Signal electron from μN→eN
  - Kinetic energy close to muon rest mass: $E_{\mu e}$~105MeV
- Free muon decay spectrum
  - Cutoff at $m_\mu/2$
  - Conserve momentum with neutrinos
- Muon decay in orbit (DIO)
  - Momentum exchange with nucleus → high energy tail
  - Background near signal energy: $\propto(E_{\mu e}-E)^5$ expected

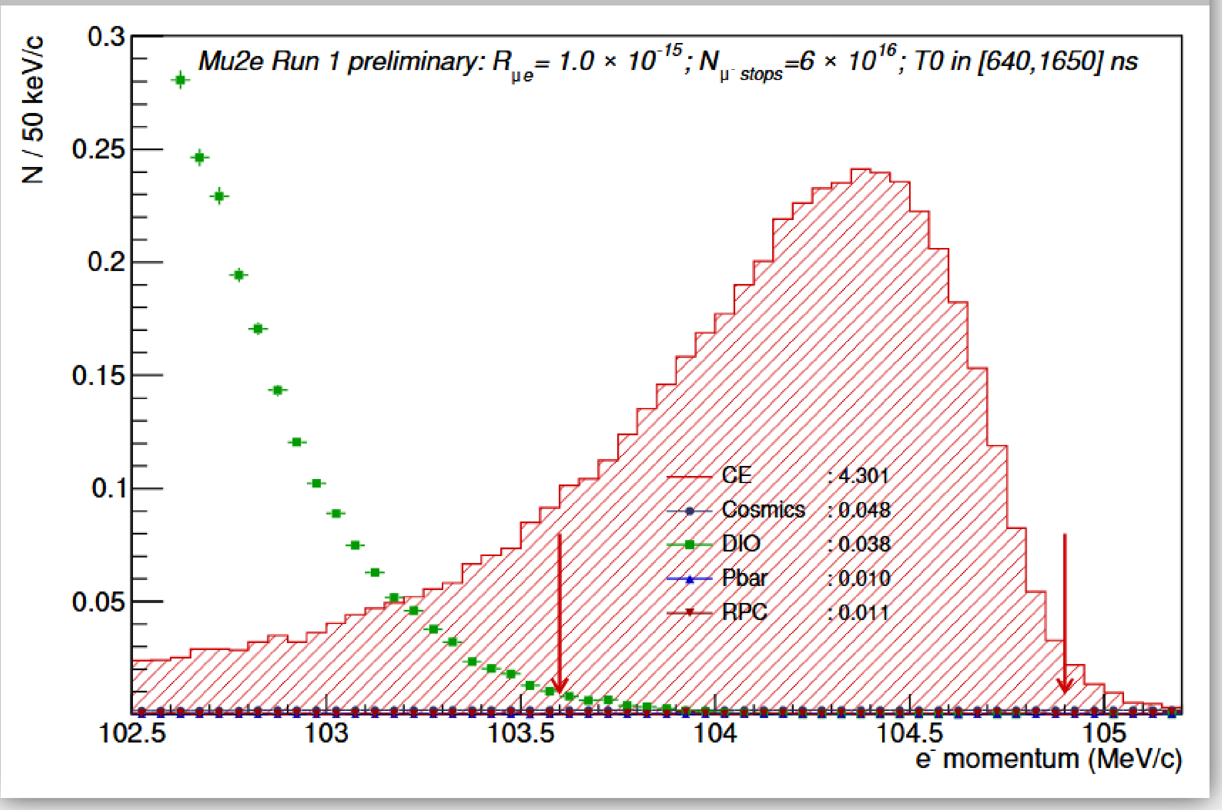




Mu2e Projected Sensitivity (Run 1)

- **Ideal conversion electron is mono-energetic, but real electrons interact with detector materials**
  - **Must minimize energy loss that shifts signal peak (red) into region with higher DIO background (green)**

Simulated Conversion Events and Backgrounds



- **Two stages of data taking: before and after Fermilab's planned LBNF/PIP-II shutdown**

Run 1 Simulation

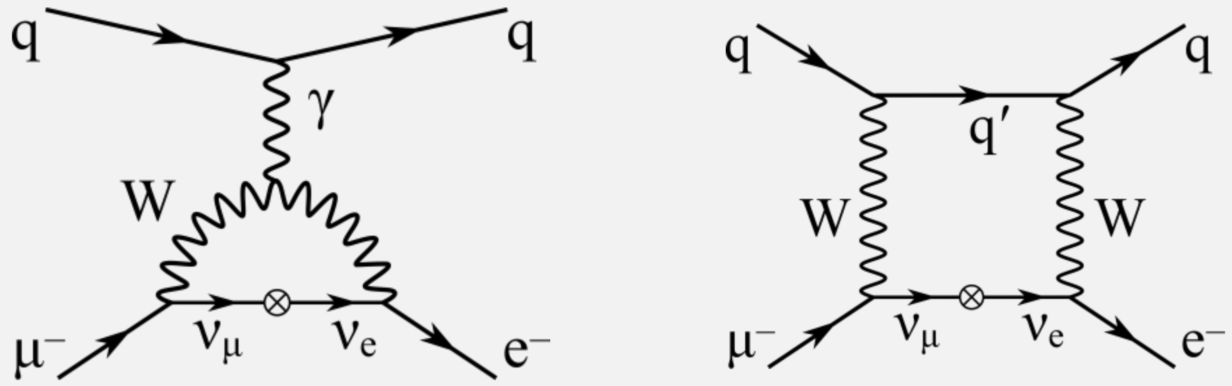
Overall expected background of 0.1 event

For a conversion ratio as low as $R_{\mu e}=10^{-15}$:

- **5 signal events**
- **5σ discovery of charged lepton flavor violation**

- **Further x10 sensitivity improvement with Run 2**

No Standard Model Backgrounds



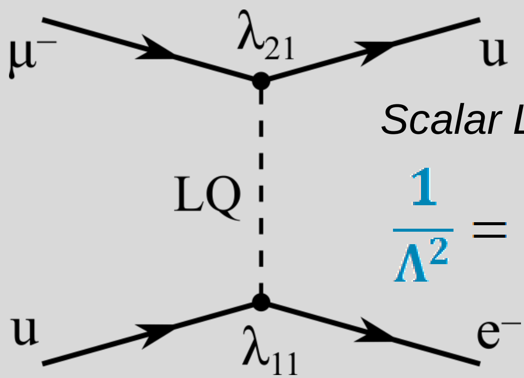
- **Using known physics processes, the only mechanism for charged lepton flavor violation (CLFV) requires neutrino oscillation**
- **Suppressed to unobservable levels by discrepancy in energy scale with W boson mass:**
  Rate ~ $|\Delta m_\nu^2|^2/M_W^4$ **< 10^{-49} to 10^{-52}**
- **Mu2e signal would thus be direct evidence of new physics with flavor violating effects**

Charged Lepton Flavor Violation and New Physics

- **CLFV rate enhancements expected in theories of new physics**
- **Muon to electron conversion sensitive to effective mass Λ, a combination of new particle masses, couplings, and mixing**
- **Probes parameter spaces of two effective operator types:**

Four-fermion interactions

- **Leptoquarks, supersymmetry with R-parity violation, anarchic warped extra dimensions, etc.**

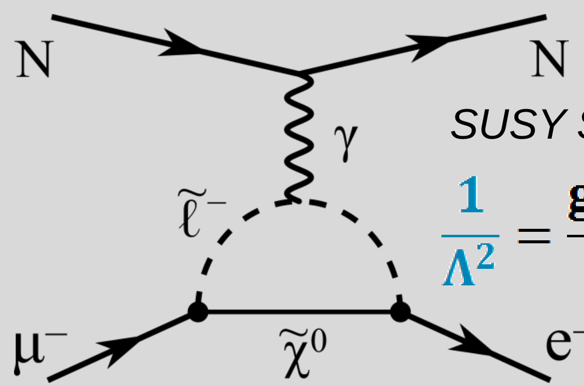


Scalar Leptoquark

$$\frac{1}{\Lambda^2} = \frac{\lambda_{21}\lambda_{11}}{M_{LQ}^2}$$

Dipole loop operators

- **Supersymmetric type I seesaw mechanism, etc.**

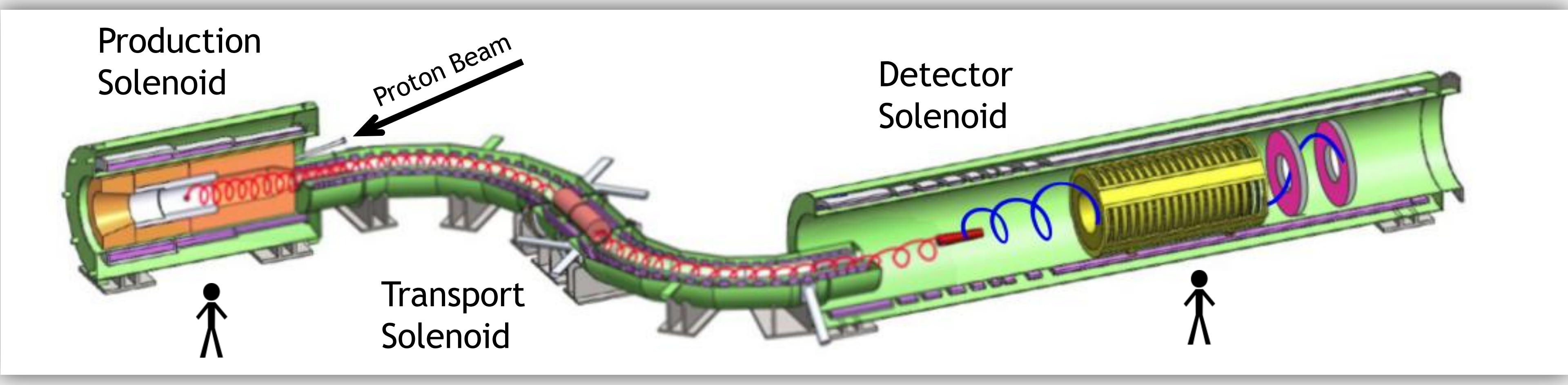


SUSY Seesaw

$$\frac{1}{\Lambda^2} = \frac{g_{SUSY}^2 (\Delta m_{\tilde{L}}^2)_{\mu e}}{M_{SUSY}^4}$$

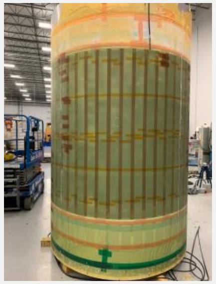
- **Mu2e is an indirect search for virtual particle effects**
  - **Complementary with direct searches and other CLFV channel searches**
  - **Can probe effective masses at 10^3–10^4 TeV**

The Mu2e Experimental Apparatus

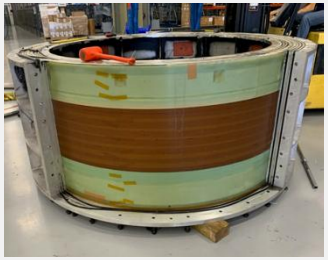


- **Pulsed proton beam incident on tungsten target produces pions**

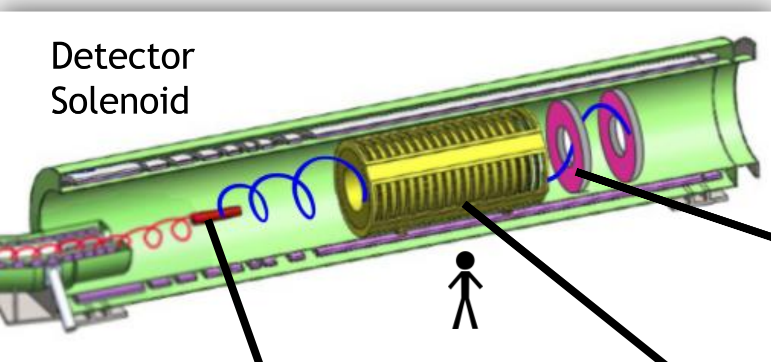
1. **Production solenoid**
   - **Magnetic field traps charged particles**
   - **Gradient 4.6-2.5T directs them downstream**
2. **Transport solenoid**
   - **Pions decay into muons**
   - **Filter beam and select low momentum (40MeV/c) muons**
3. **Detector solenoid**
   - **Muons stopped and electron tracks measured**



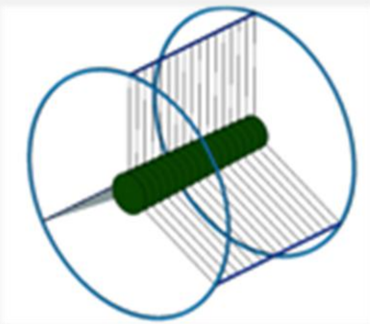
Three superconducting solenoids

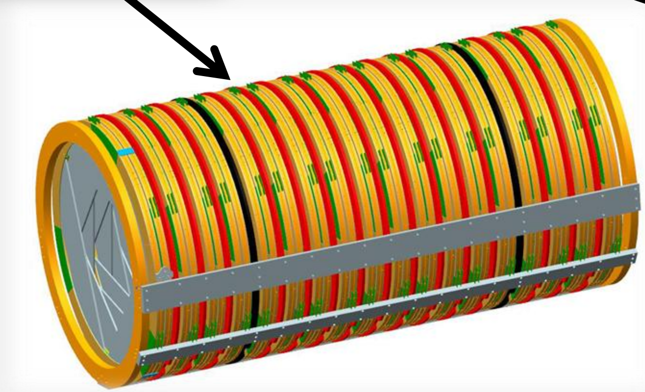


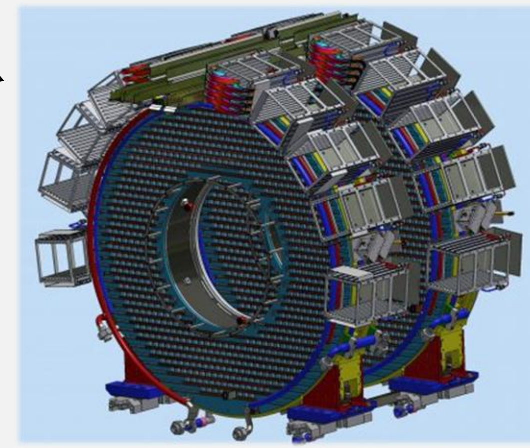
Mu2e Detector Systems



- Detector environment challenges
  – Operate in vacuum, 1T magnetic field
  – High event and radiation rates







Stopping target
- Muons brought to rest, orbit aluminum nuclei
- 100μm thick foils
- Minimize dE/dx as electrons exit

Tracker
- Over 20,000 drift cell straws
- Get electron momentum from radius of helical track in magnetic field

Calorimeter
- CsI scintillating crystals read out by silicon photomultipliers
- Electron identification, trigger, track seeding

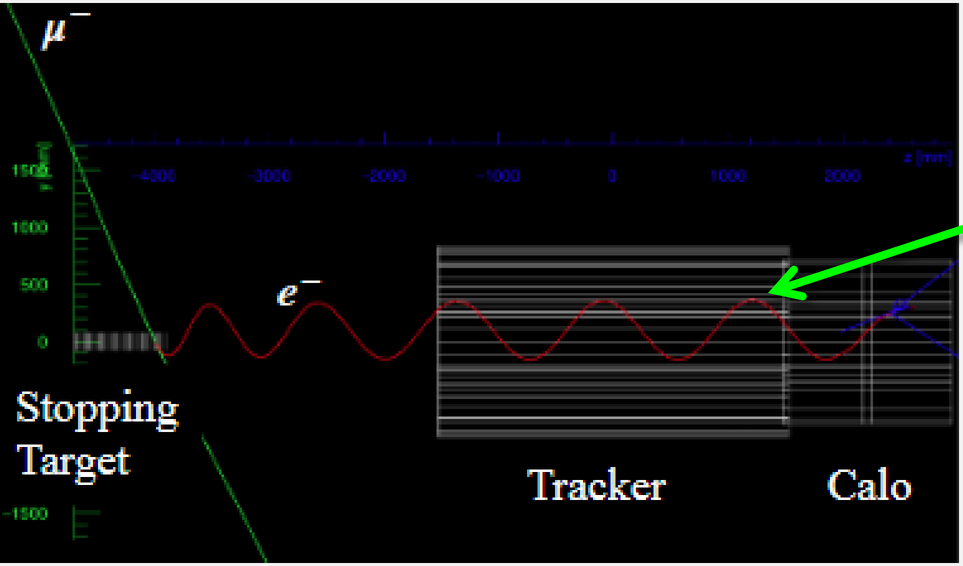
Background Mitigation Strategies

- **Beam-related backgrounds can occur late enough to coincide with signal search window**

  Electrons from radiative pion capture → ***Delay detection window***
  → ***Proton extinction between pulses***

- **Intrinsic background processes scale with muon beam intensity**

  Electrons in high energy tail of decay in orbit spectrum → ***High resolution in tracker***

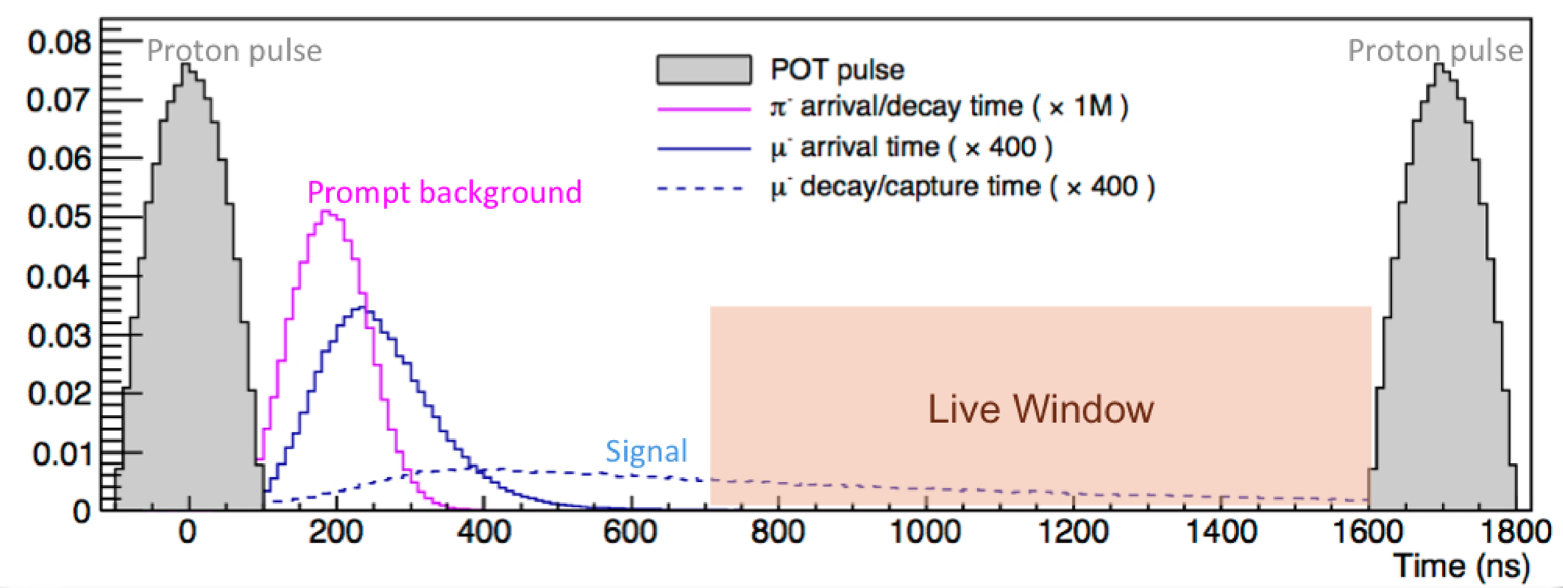


- **Cosmic ray background scales with detector run time**

  Can produce electrons that match signal trajectories
  → ***Identify and veto with active shielding***

Overall expected background for Run 1 is 0.1 event

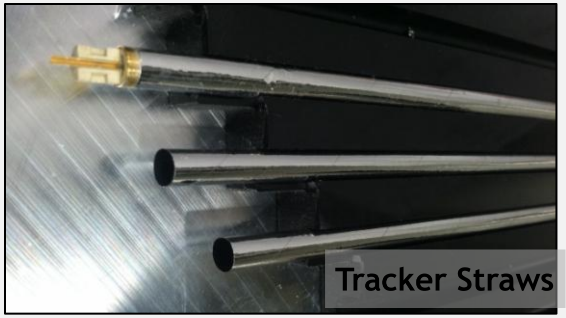
Pulsed Proton Beam and Extinction

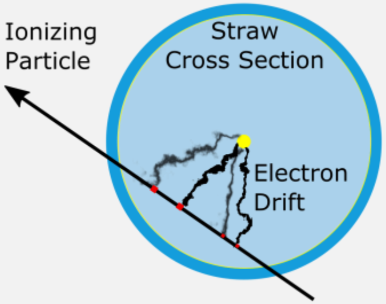


- **Beam structure from Muon Delivery Ring: proton pulses 1.7μs apart**
- **Delayed measurement window**
  - **Radiative pion capture backgrounds dissipate, while muons orbit target nuclei**
- **Factor of 10^{-10} proton extinction needed between pulses to suppress late pions**
  - **Deflect out-of-time beam with magnet, block with collimator**
  - **Monitor via sampling of particles from production target**

Low Mass Straw Tracker

- **Tracker must determine electron trajectories using minimal material**
  - **Minimize multiple scattering**
  - **Avoid signal energy loss, overlap with higher DIO background**
- **Mu2e solution: straw tracker**
  - **Over 20,000 metalized Mylar straws, 15μm walls**
  - **Supported only at ends and surrounded by vacuum**

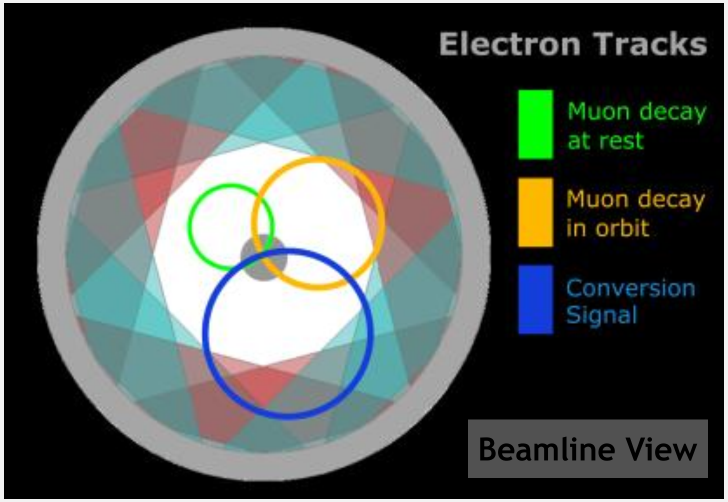




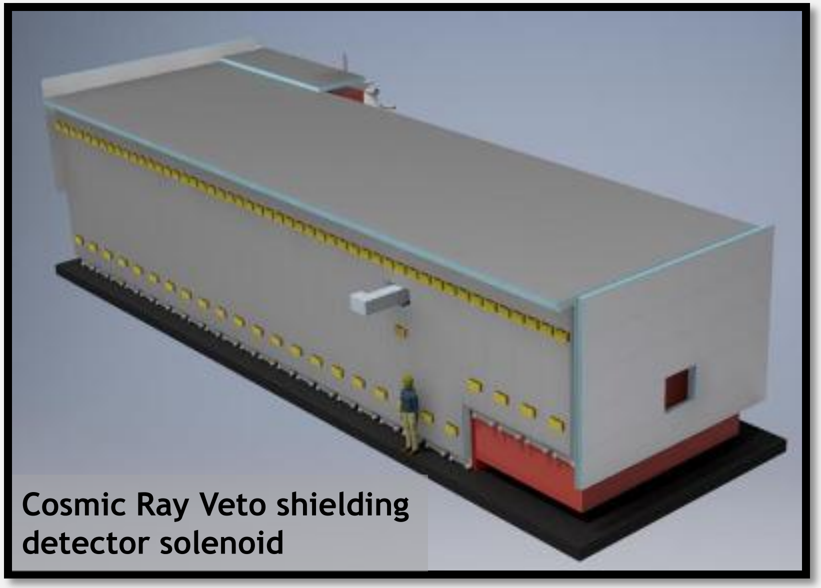
- **High energy electrons ionize Ar:CO_2 gas in the straws**
- **Secondary electrons drift to 25μm sense wire for readout at both ends**
- **Electron trajectories reconstructed from hits in straws**

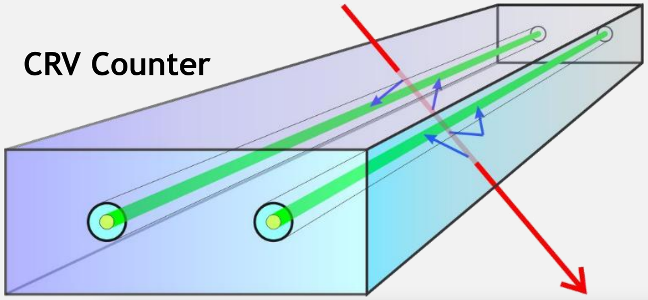
Must maintain efficiency at high hit rates

- **Highly segmented active detector volume**
- **Low energy particles pass through central hole**



Cosmic Ray Veto (CRV)

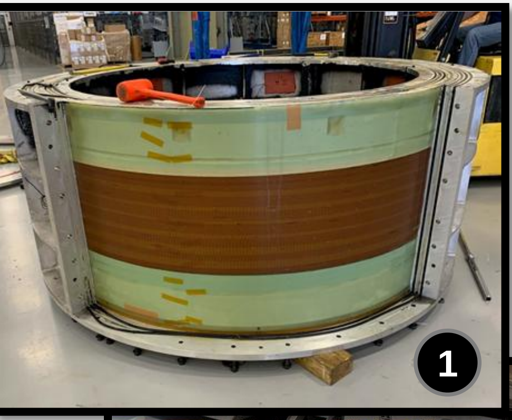

Cosmic Ray Veto shielding detector solenoid

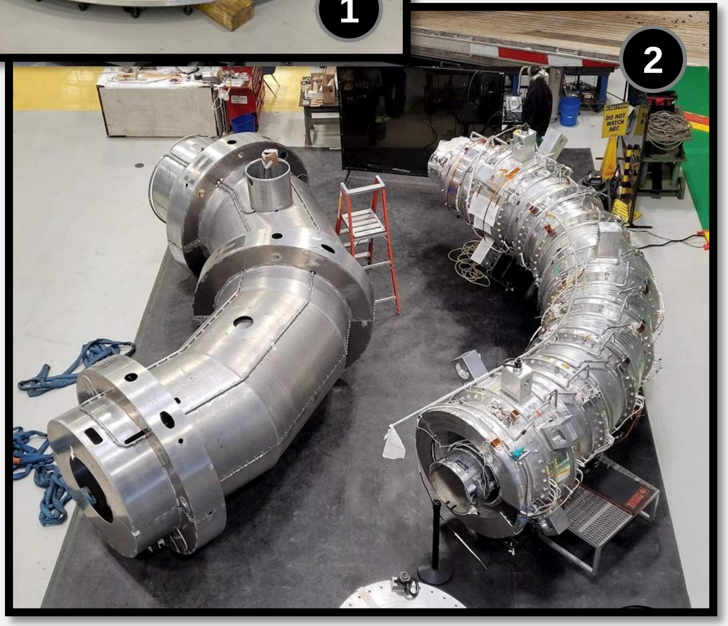



CRV Modules

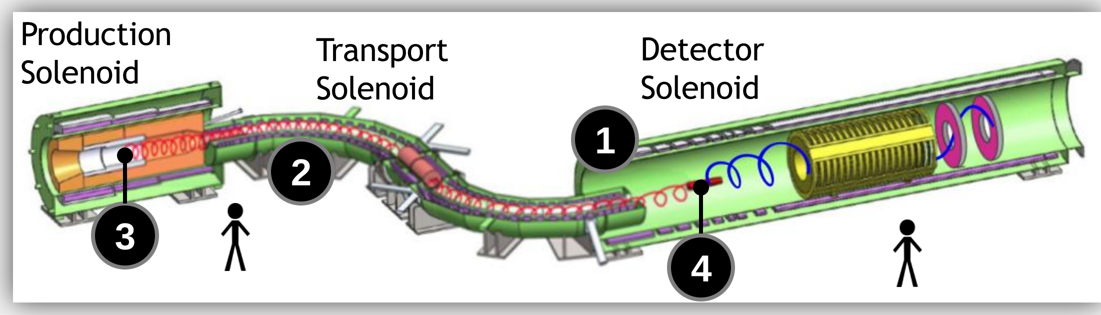
- Cosmic ray muons can produce electrons with energy and trajectory matching conversion signal
  - Rate of 1 background event per day without shielding
  - Must reduce by 99.99% to get <1 event over full run time
- Mu2e solution: surround detectors with active shielding
  - Cosmic Ray Veto has 4 layers of scintillator counters with wavelength shifting fibers, read out with silicon photomultipliers
  - Cosmic ray tracks through CRV identified in offline analysis, associated electron events in detectors are vetoed

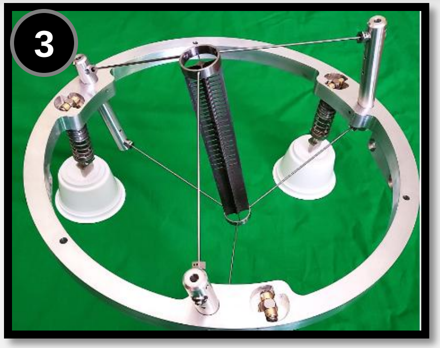
Mu2e Current Status



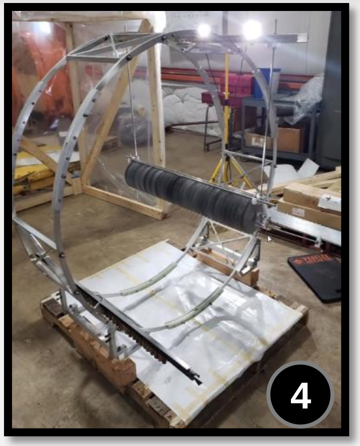


Solenoid fabrication and testing



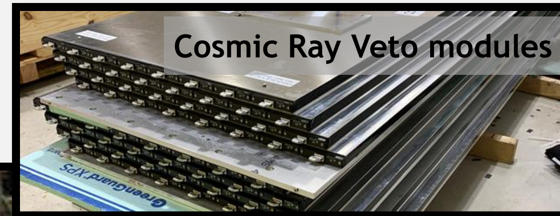


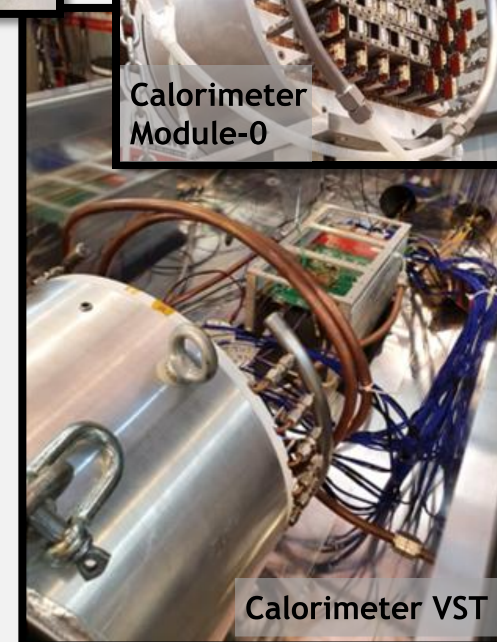
Proton and stopping targets assembled



- Simulation of realistic data for Mock Data Challenge
- New estimates of backgrounds from Sensitivity Update 2020 campaign (slide 6)

Mu2e Current Status

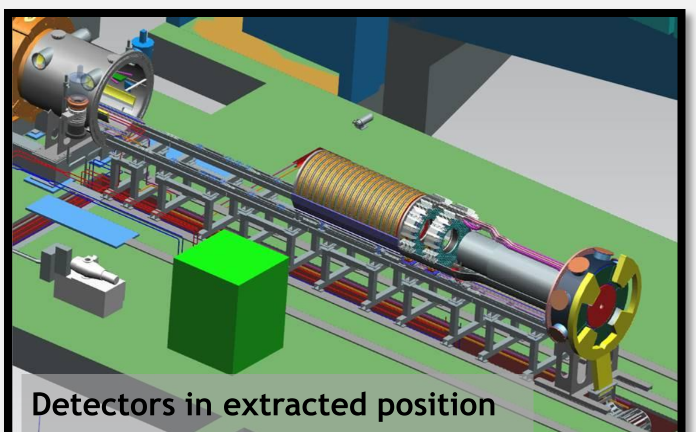




Detector vertical slice tests

- Prove operations and data collection

Integration of detector systems and preparation for installation



Planning underway for Mu2e-II

- Re-use major components from Mu2e
- Upgrade detectors to improve resolution and handle higher rates
- Better than 10^{-18} sensitivity to $\mu N \rightarrow eN$

Summary and Outlook

- **Mu2e has the potential to discover charged lepton flavor violation in neutrinoless muon to electron conversion**
  - **Previously unobserved process that would be direct evidence for new physics**
  - **Mu2e measurement sensitive to new particles with effective masses up to thousands of TeV**
- **Run 1 data taking planned for 2025-2026, additional data taking after LBNF/PIP-II shutdown**
- **Ultimately set conversion ratio limit $R_{\mu e}<8\times10^{-17}$ (90%CL), four orders of magnitude beyond current limit**

Mu2e Talks at DPF

Mu2e Detectors

5. D. Pasciuto (Calorimeter)
30. A. Gioiosa (Data acquisition)
37. S. Roberts (Cosmic Ray Veto)
38. R. Group (Cosmic Ray Veto)
280. Y. Wu (Tracker)

Cosmic Ray Studies

146. M. Devilbiss (Event reconstruction)
322. M. Srivastav (Muon identification)
354. Y. Oksuzian (Background simulation)

Simulation Studies

70. D. R. Varier (Background rejection)
221. S. Huang (Familon search)
323. X. Shi (Calibration)

Mu2e Targets and Monitoring

104. J. Chen (Stopping Target Monitor)
134. H. Cao (Stopping Target Monitor)
166. H. Casler (Pion production)

Mu2e-II

213. V. Pronskikh (Pion production)
306. E. Dukes (Cosmic Ray Veto)
311. G. F. Tassielli (Tracker)

AlCap – Muon Capture Studies

51. A. Edmonds (First results)
76. N. Tran (Photon emission)

https://indico.cern.ch/event/1034469/contributions/

More Information on Mu2e and Mu2e-II

- **Mu2e public results**

  https://mu2e.fnal.gov/public/hep/results/index.shtml

- **Mu2e proposal (2008) and technical design report (2014)**
  - **https://www.fnal.gov/directorate/program_planning/Nov2008PACPublic/Mu2e_Proposal.pdf**
  - **https://arxiv.org/abs/1501.05241**

- **Mu2e-II Snowmass 2022 letter of interest**

  https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_Frank_Porter-106.pdf

Additional Resources

- **A. Grossheim *et al*. [TWIST Collaboration], Decay of negative muons bound in ^{27}Al. Phys. Rev. D 80, 052012 (2009).**
- **A. Czarnecki, X. Garcia i Tormo, and W. J. Marciano, Muon decay in orbit: Spectrum of high-energy electrons. Phys. Rev. D 84, 013006 (2011).**
- **W. Bertl *et al*. [SINDRUM II Collaboration], A search for μ–e conversion in muonic gold. Eur. Phys. J. C 47, 337 (2006).**