The muon-to-electron conversion process and the Mu2e experiment at Fermilab

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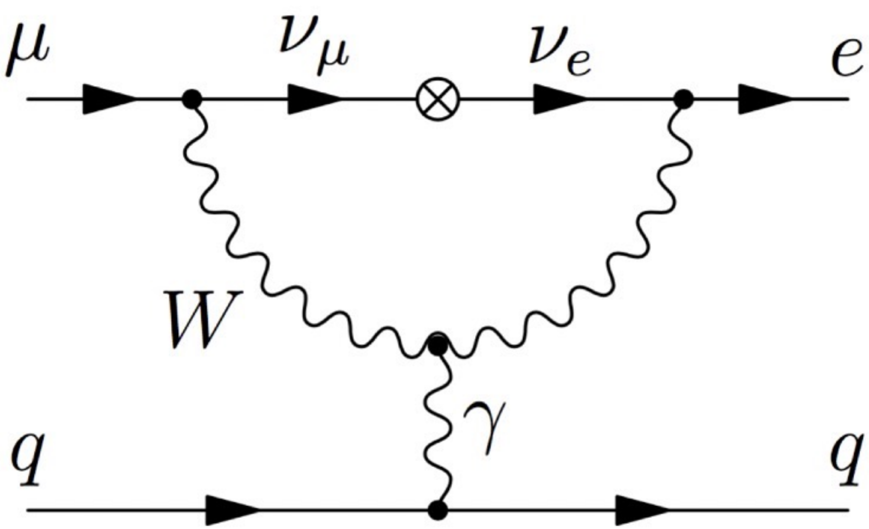
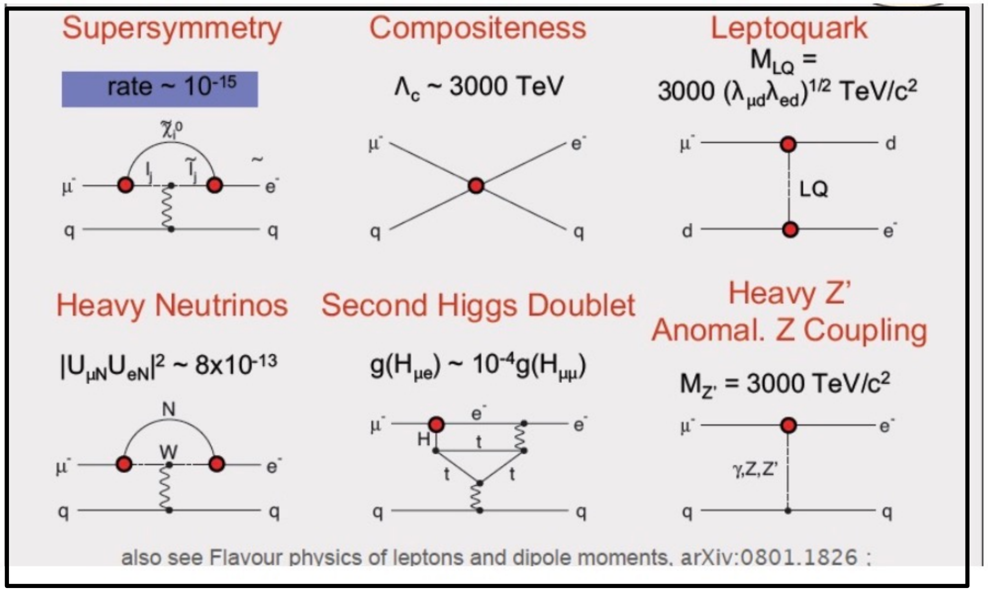
CLFV in the Standard Model

- CLFV processes are forbidden in the Standard Model (SM)
- μ conversion in the SM is introduced by the neutrino masses and mixing at a negligible level (~10^{-52})



- Many SM extensions enhance the rate through mixing in the high energy sector of the theory (with other particles in the loop).

New Physics and μ→e



- According to many theroretical models, μ → e provides a *** (3-star) discovery potential
- It is certainly worth pursuing.

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

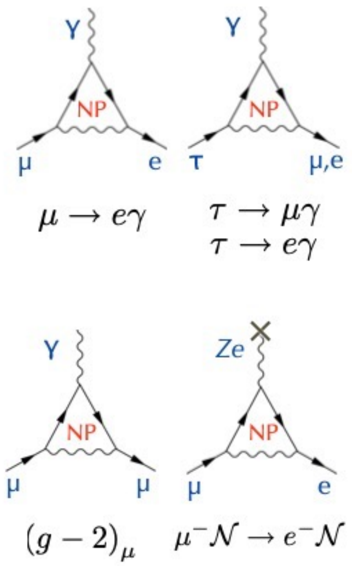
W.Altmanshofer at al. arxiv 0909.1333v2

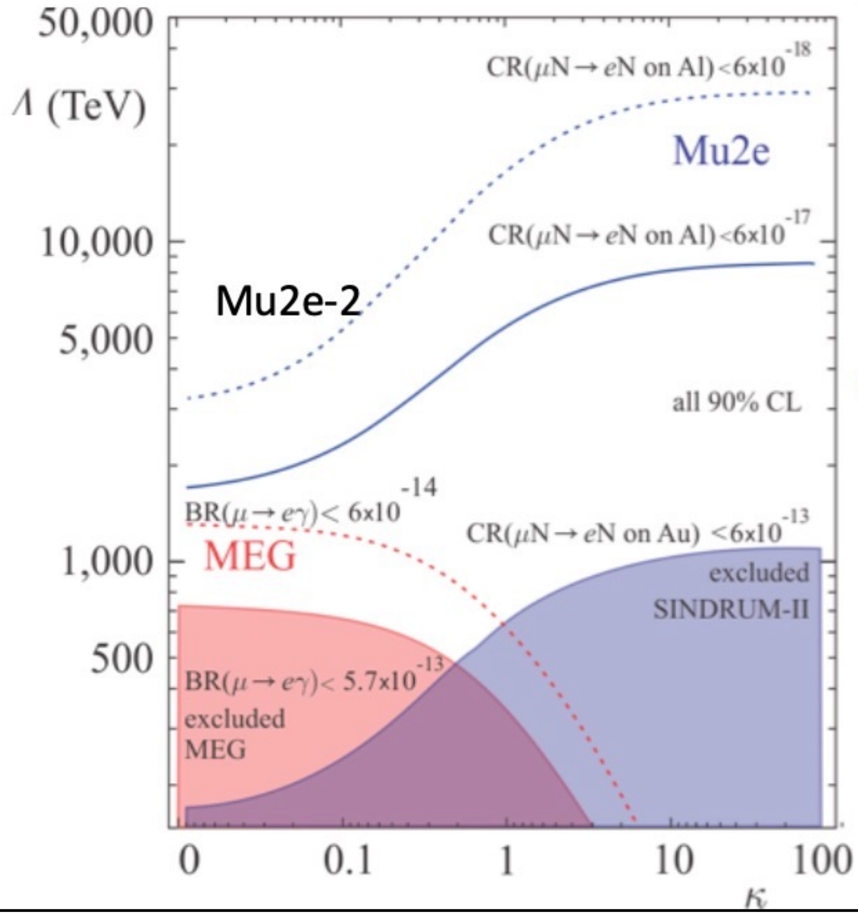
Mu2e vs MEG/MEG upgrade

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

LOOP TERM

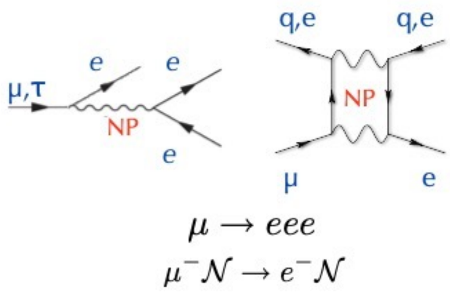
$\kappa \ll 1$





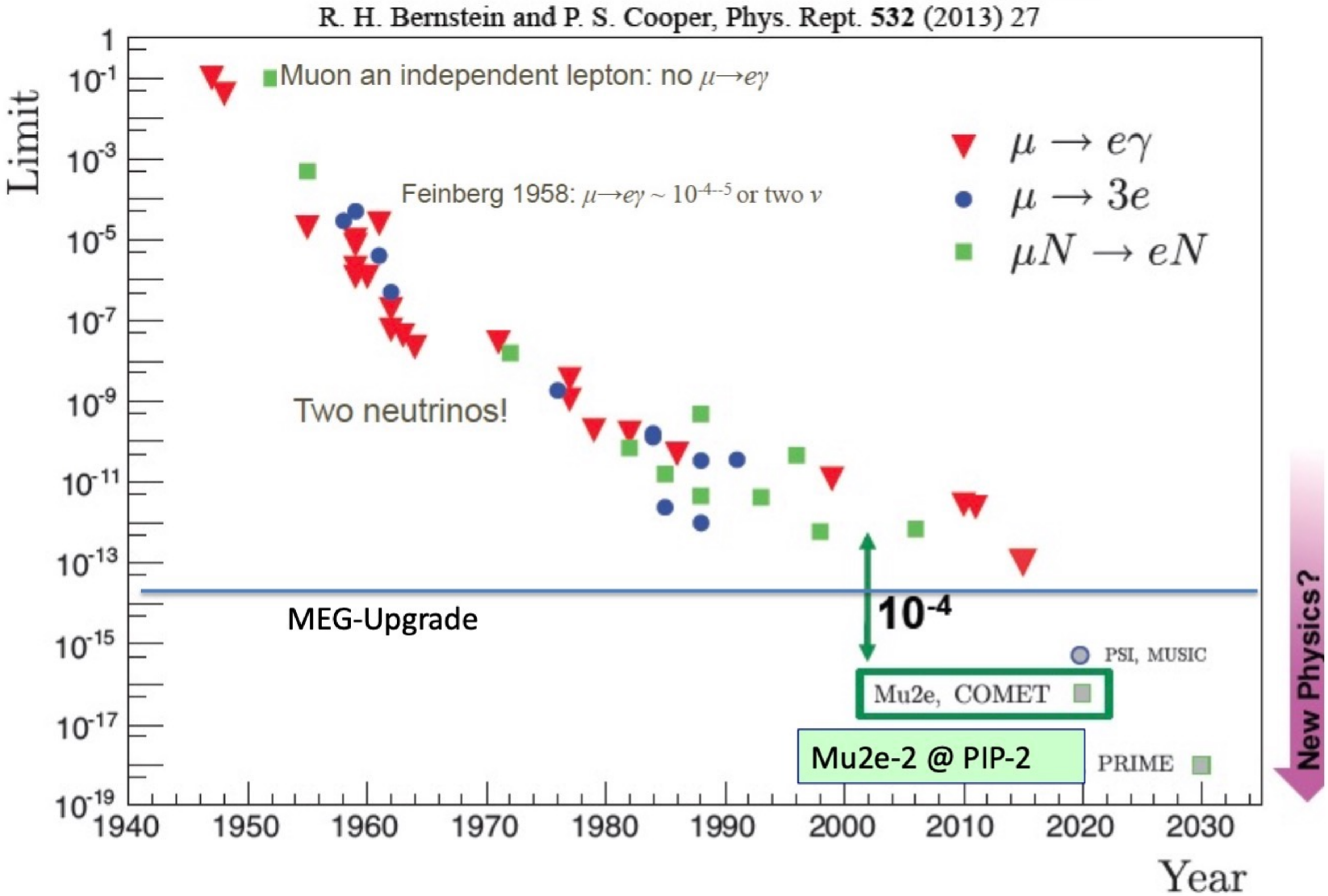
CONTACT TERM

$\kappa \gg 1$



- Sensitivity to different processes makes the μ → eγ, μ → eee, μN → eN searches complementary.

History of μ → e search

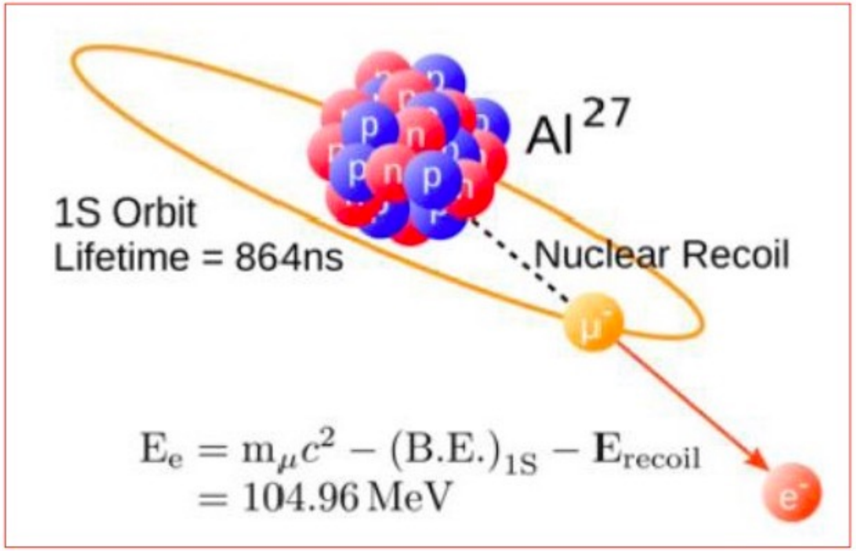


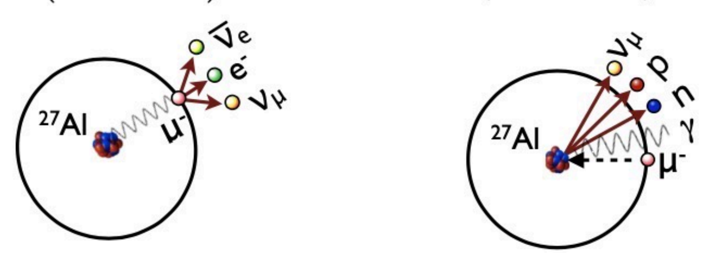
The Mu2e experiment at Fermilab

Search for Charged Lepton Flavor Violation (CLFV) through the coherent conversion:

$$\mu^- + Al \rightarrow e^- + Al$$

- Low momentum μ^- beam (< 100 MeV/c)
- High intensity pulsed rate
  - 10^{10} μ^-/s stopped on Al target
- Stopped μ^- captured in atomic orbits
  - Cascade in the 1s state (fs)





Background

Normalization

Mu2e goal: improve by a factor 10^4 the world's best sensitivity (SINDRUM II*) on:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N \rightarrow e^- + N)}{\Gamma(\mu^- + N \rightarrow \text{all captures})}$$

down to a Single Event Sensitivity of 3×10^{-17}. SM prediction < $10^{-49} - 10^{-52}$, any observation would be a clear evidence of New Physics.

*W. Bertl et al., Eur. Phys. J. C47, 337 (2006)

Main Backgrounds

- **Intrinsic** (*scales with the stopped* μ)
  - Muon decay in orbit (DIO)

  $$\mu^- + Al \to e^- + \bar{\nu}_e + \nu_\mu + Al$$

  - Radiative μ capture (RMC)

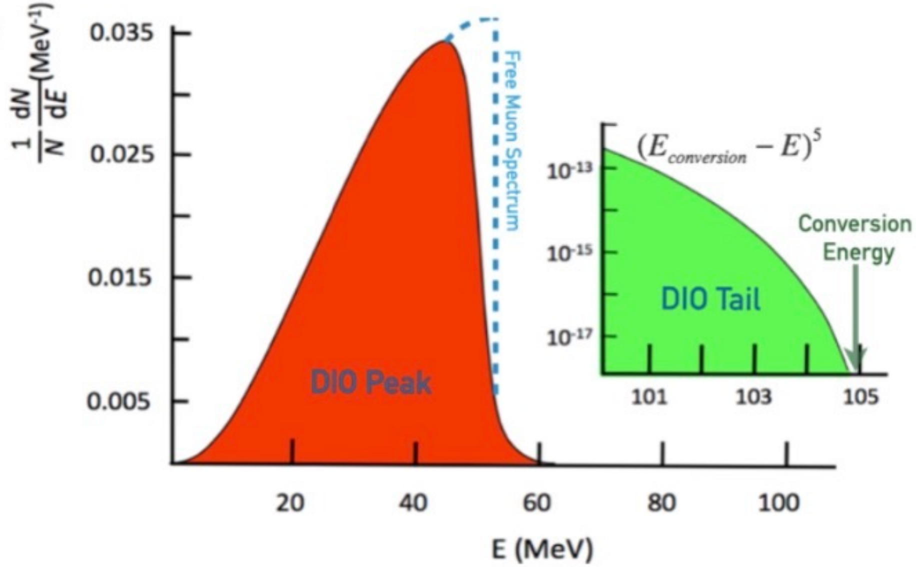
  $$\mu^- + Al \to \nu_\mu + \gamma + Mg$$

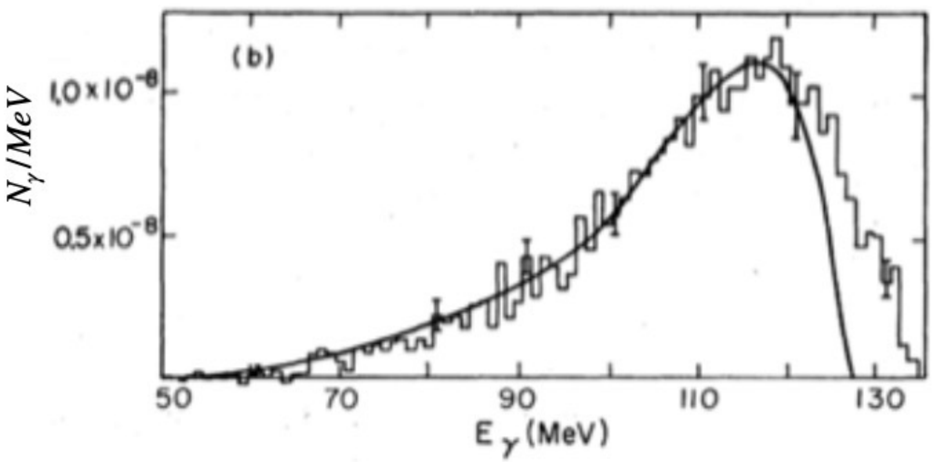
- **Cosmic Rays**

- **Late arriving from prompt processes** (*scales with number of late protons*)
  - Radiative π capture (RPC)

  $$\pi^- N \to \gamma N^*, \gamma \to e^+ e^-$$
  $$\pi^- N \to e^+ e^- N^*$$

- **Antiproton annihilation**





Main Backgrounds

- **Intrinsic** (*scales with the stopp… *)
  - Muon decay in orbi…

  $\mu^- + Al$ … Al

  - Radiat… μ capture (RMC)

  $\mu^- + Al \rightarrow \nu_\mu + \gamma + Mg$

High Performance Detectors (Tracker+Calorimeter)

- **Cosmic Ra…**

Cosmic Ray Veto

- **Late arriving from prompt processes** (*scales with number of* … *protons*)
  - Radiative π … (RPC)

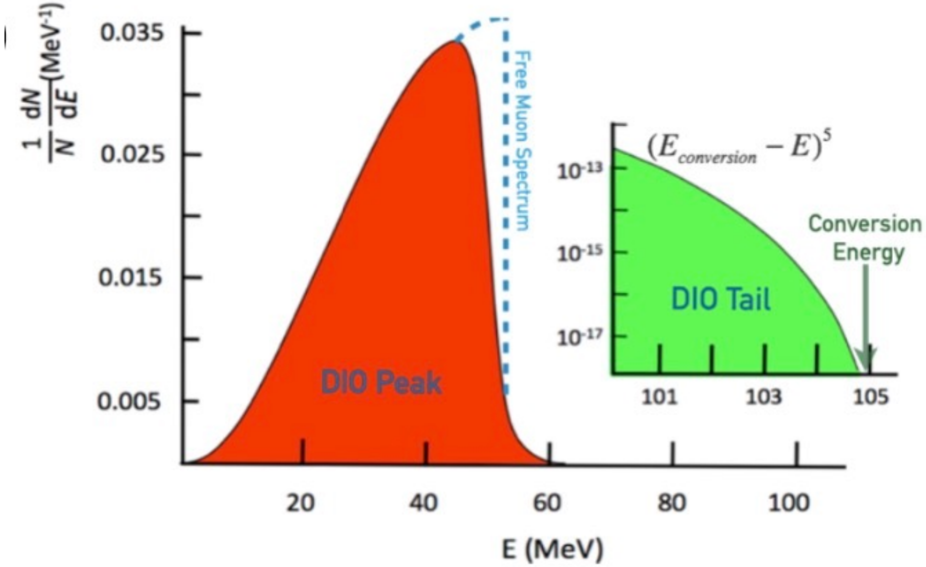
  $\pi^- N \rightarrow$ … $, \gamma \rightarrow e^+ e^-$

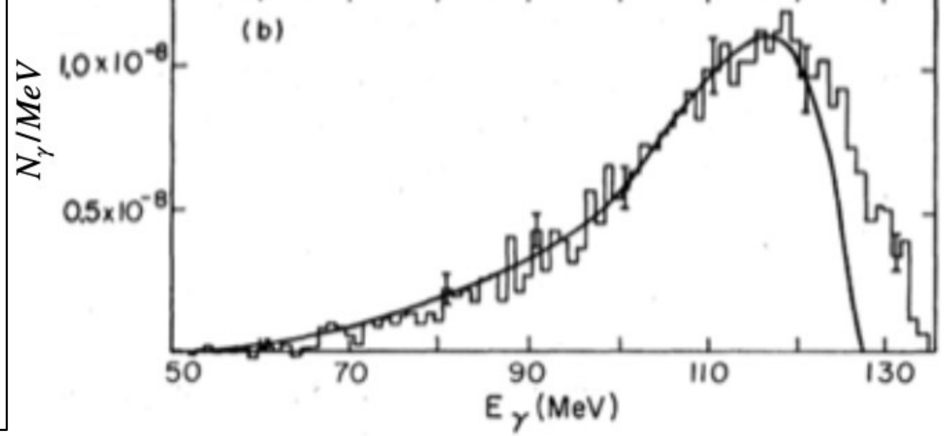
  $\pi^- N \rightarrow e^+ e^- N^*$

Pulsed Proton Beam

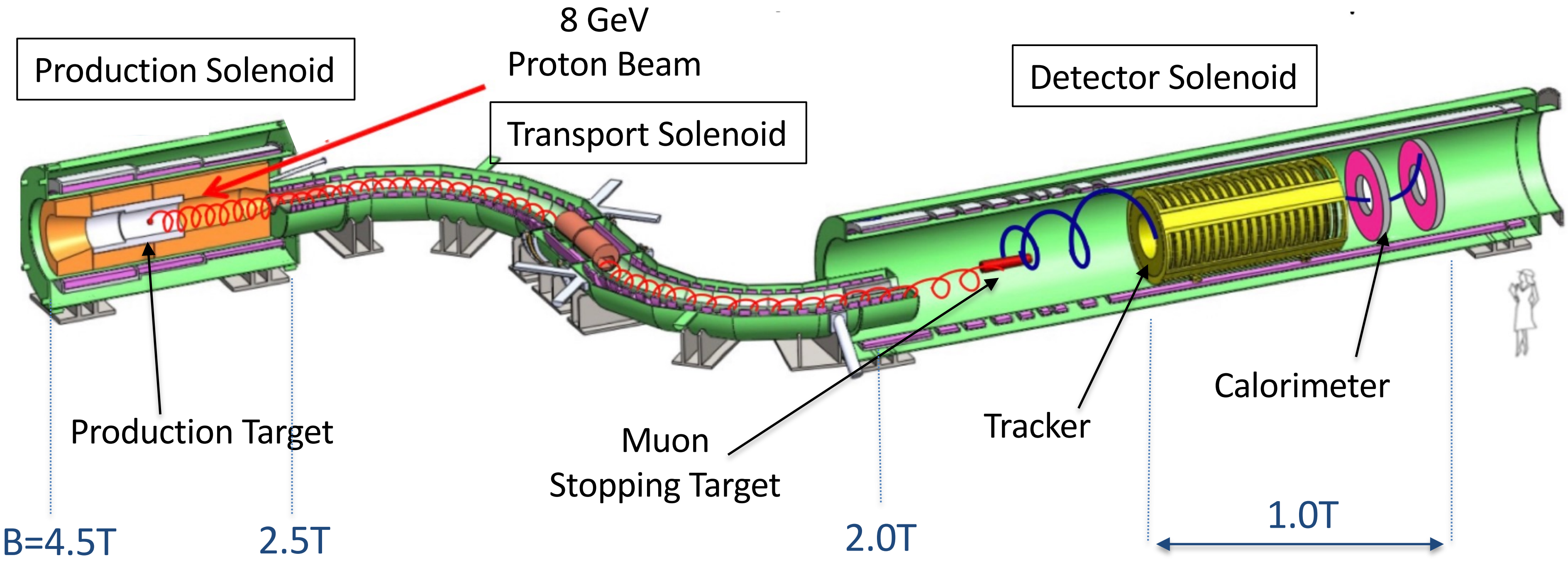
- **Antiproton anni…**

Antiproton Absorber





The muon beamline



Production Solenoid:

8 GeV protons strike tungsten target producing mostly pions

Graded B field reflects low momentum particles downstream

Transport Solenoid:

Select low momentum negative muons (+antiproton absorber)

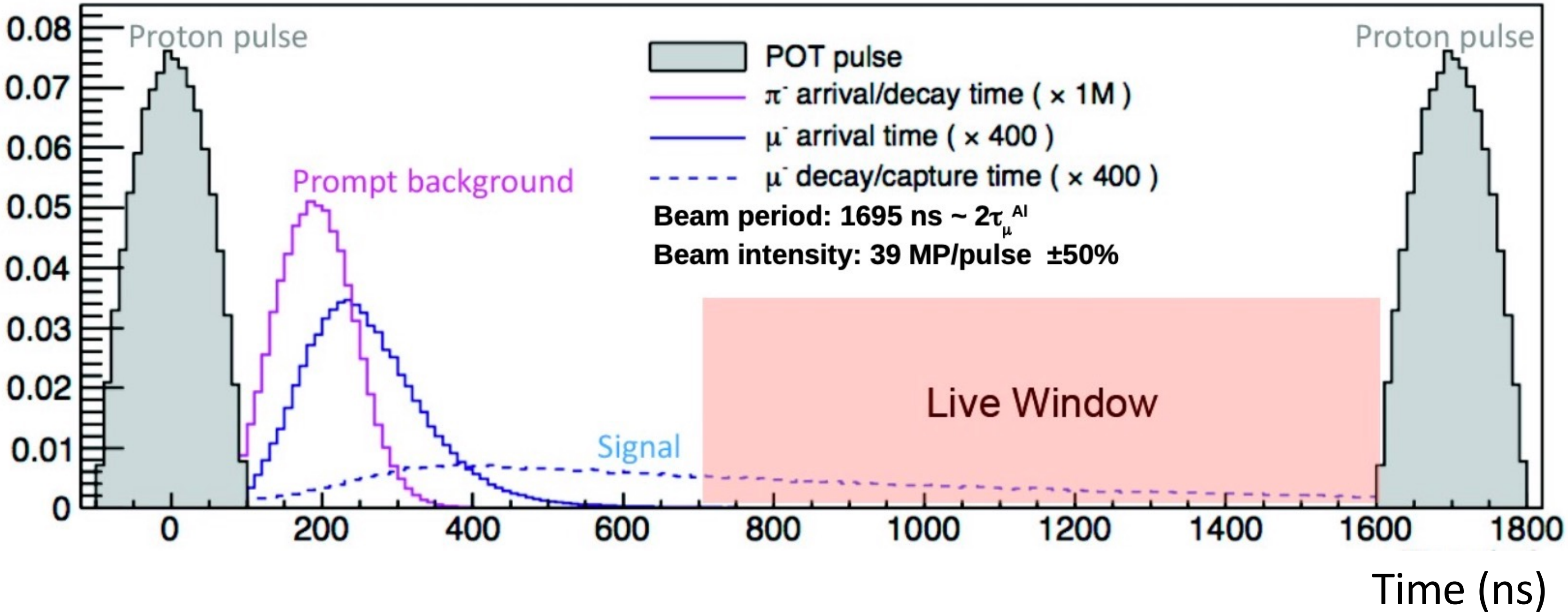
Detector Solenoid:

Capture muons on Al target, absorber reduces proton background

Graded B field focuses electrons in tracker fiducial volume

Tracker/Calorimeter measure particles momentum/energy.

The proton beam structure

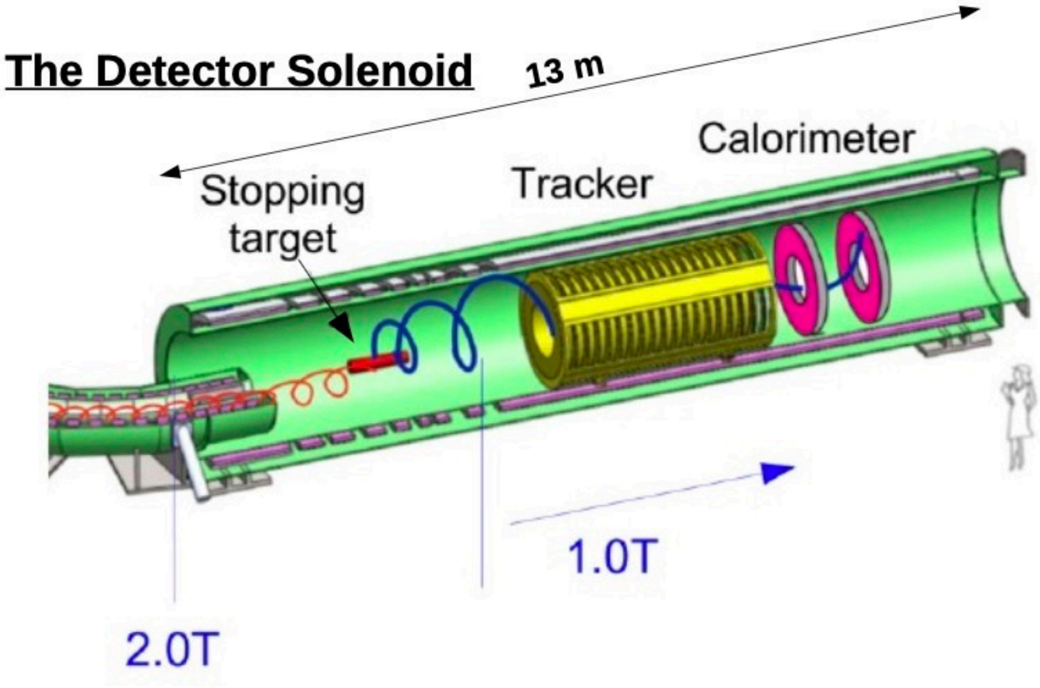


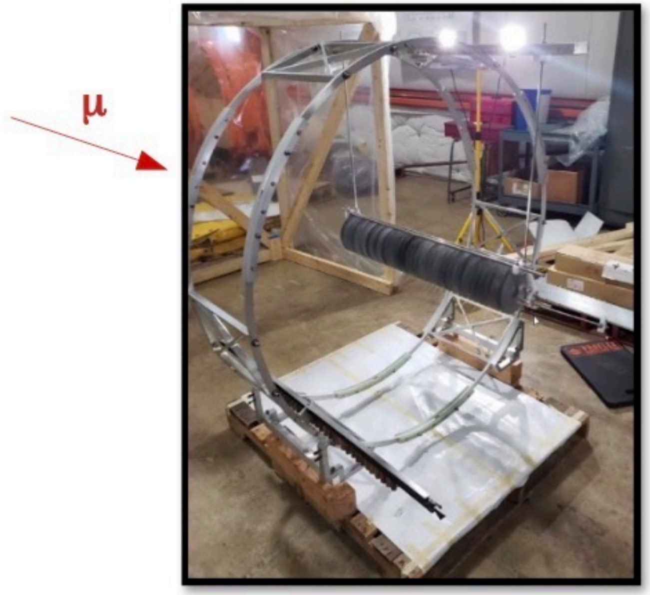
Minimize prompt backgrounds

Narrow Pulsed Proton Beam Structure + Excellent Extinction Factor (< 10^{-10})

- Muonic atom lifetime (τ = 864 ns) >> prompt backgrounds
- Analysis (Live) Window starts 700 ns after the proton pulse

The detector region





Al stopping target
37 foils 100 um thick
75 mm radius
21 mm central hole radius

- Design of the Mu2e detectors optimized for the CE observation (acceptance improved by magnetic field gradient)
- Minimum amount of material before momentum measurement (employed a segmented Al target and a light straw tube-tracker)
- Tracker and Calorimeter present a hole in the central part to get rid of low momentum particles (p < 60 MeV).

The Mu2e detectors

Aluminum target

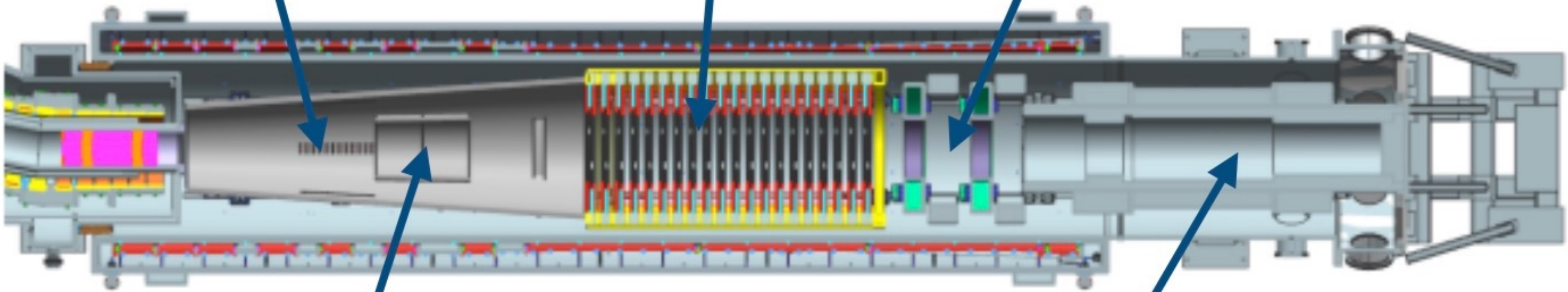
34 Al foils; the material choice is a compromise between the μ life time and E_{ce}

Calorimeter

2 disks of CsI crystals; used for Particle Identification; σ_E<10%

Tracker

~20k straw tubes; low mass detector with high performances (σ <200 keV/c)



Proton absorber

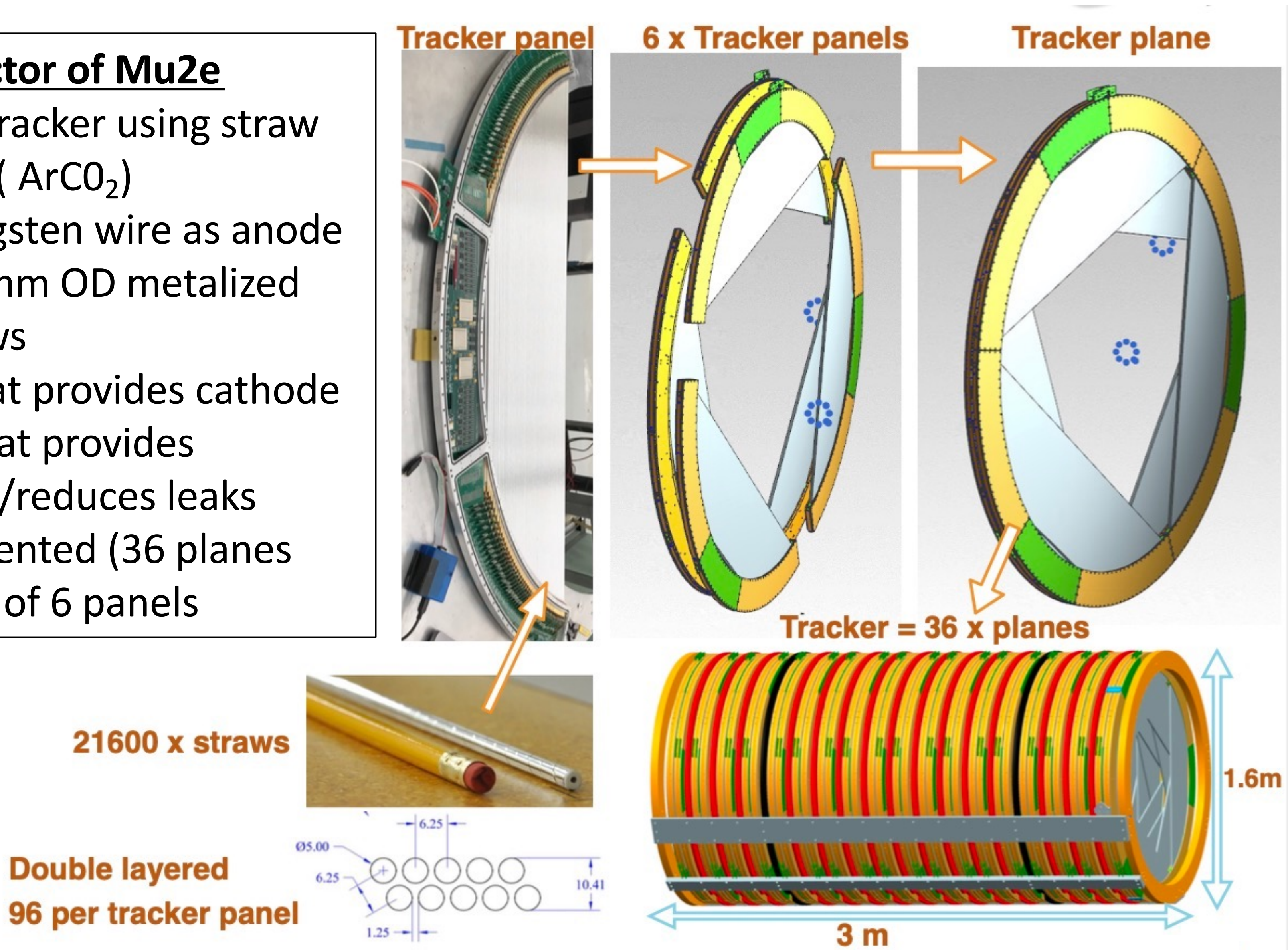
made of high-density polyethylene; designed in order to reduce proton flux on the tracker and minimize energy loss

Muon Beam Stop

several concentric cylindrical structures of stainless steel and high density polyethylene; absorbs beam particles at the end of DS

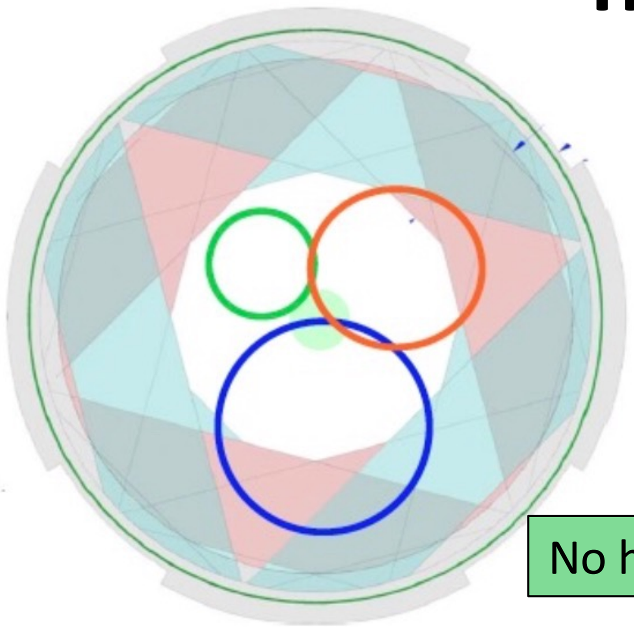
The Mu2e Tracker

- **<u>Main detector of Mu2e</u>**
- Low mass tracker using straw drift tubes ($ArC0_2$)
- 25 μm Tungsten wire as anode
- 21600 x 5 mm OD metalized Mylar straws
  - Inner coat provides cathode
  - Outer coat provides shielding/reduces leaks
- Highly semented (36 planes each made of 6 panels



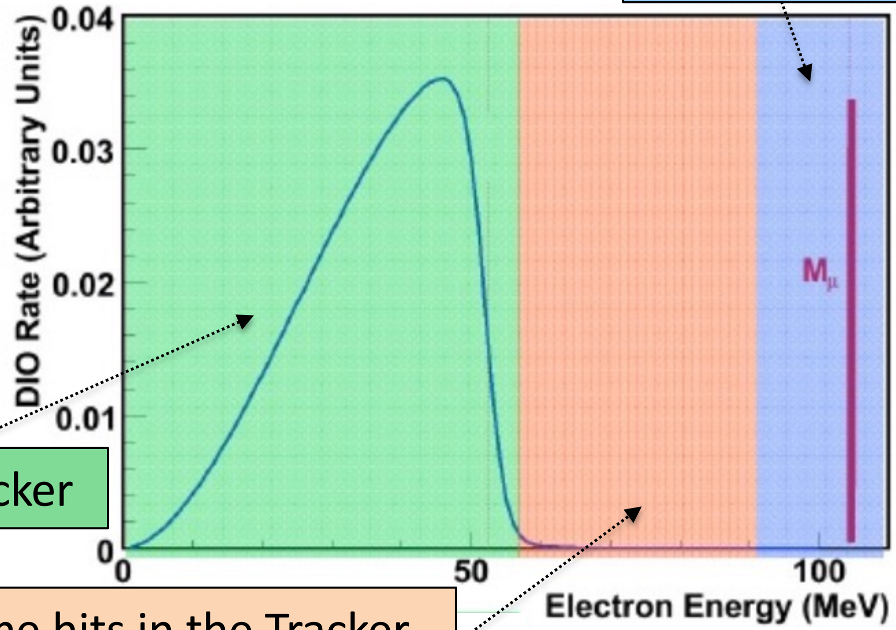
M. Yucel: Detector (Poster)
D. R. Varier: Software (Poster)

Tracking Pattern Idea



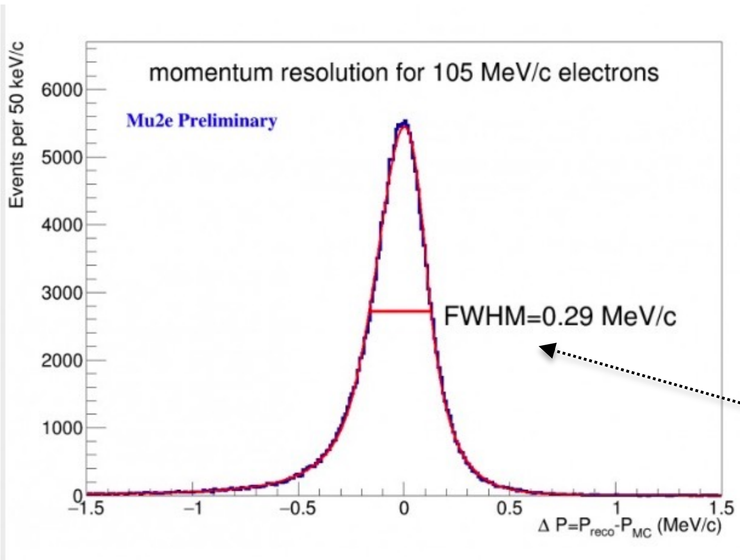
Beam's eye view of the Tracker

Reconstructed Tracks

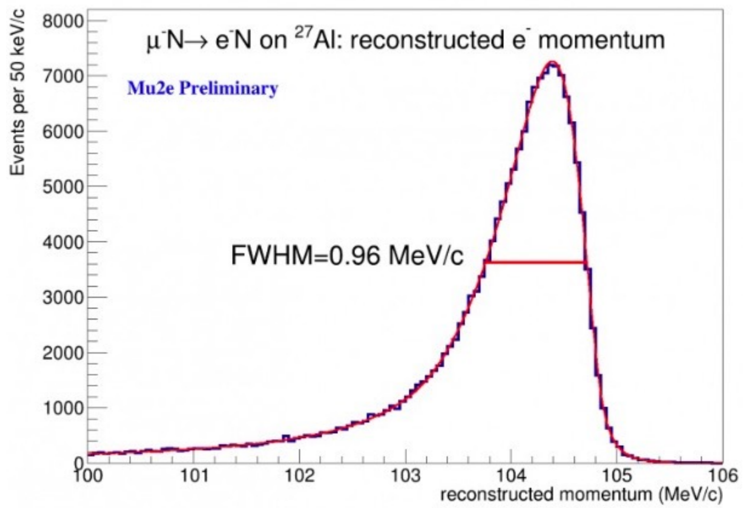


No hits in the Tracker

Some hits in the Tracker
Cannot reconstruct tracks

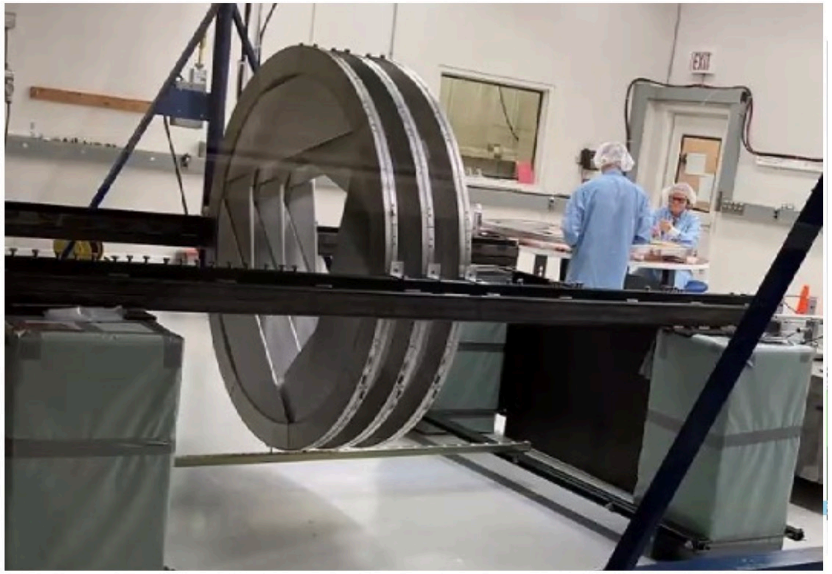


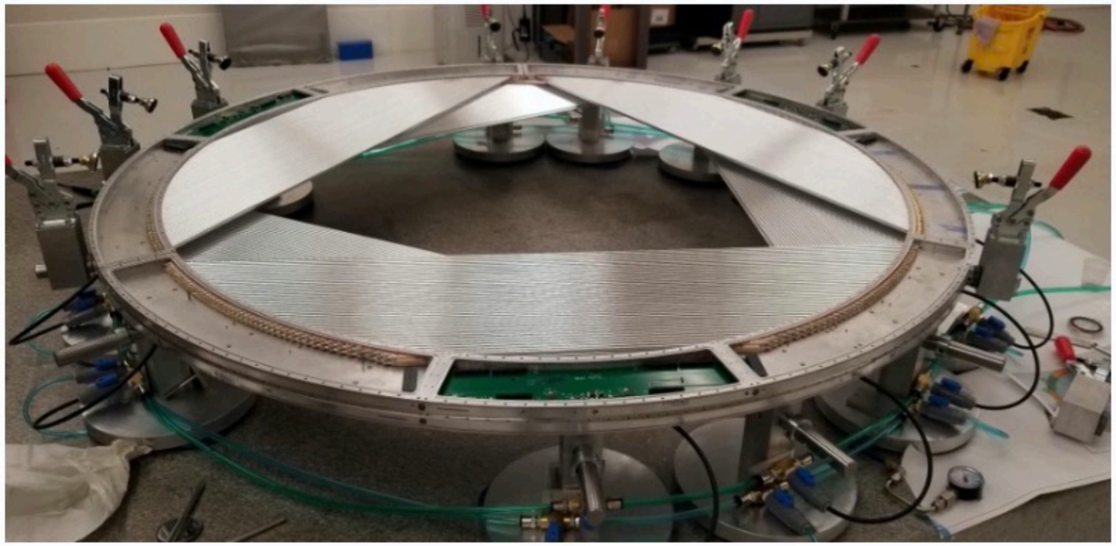
Performance from full detector simulation

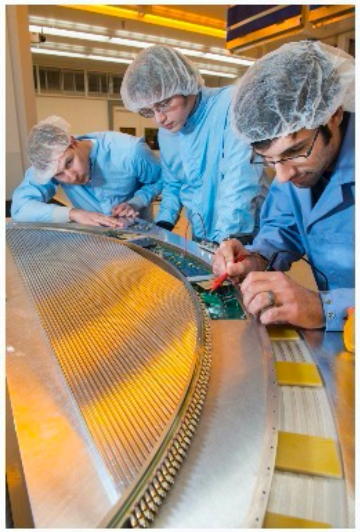


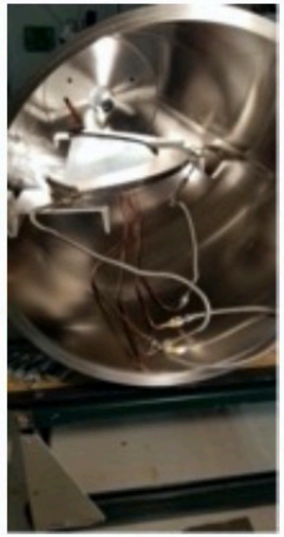
Status of Construction: Tracker

- Panels produced at the University of Minnesota
  - 100% straws manufactured
  - 55% panels fabricated and QC-ed
- Planes production progressing well at Fermilab
- Vertical Slice Test progressing well (long data runs with full optical readout)



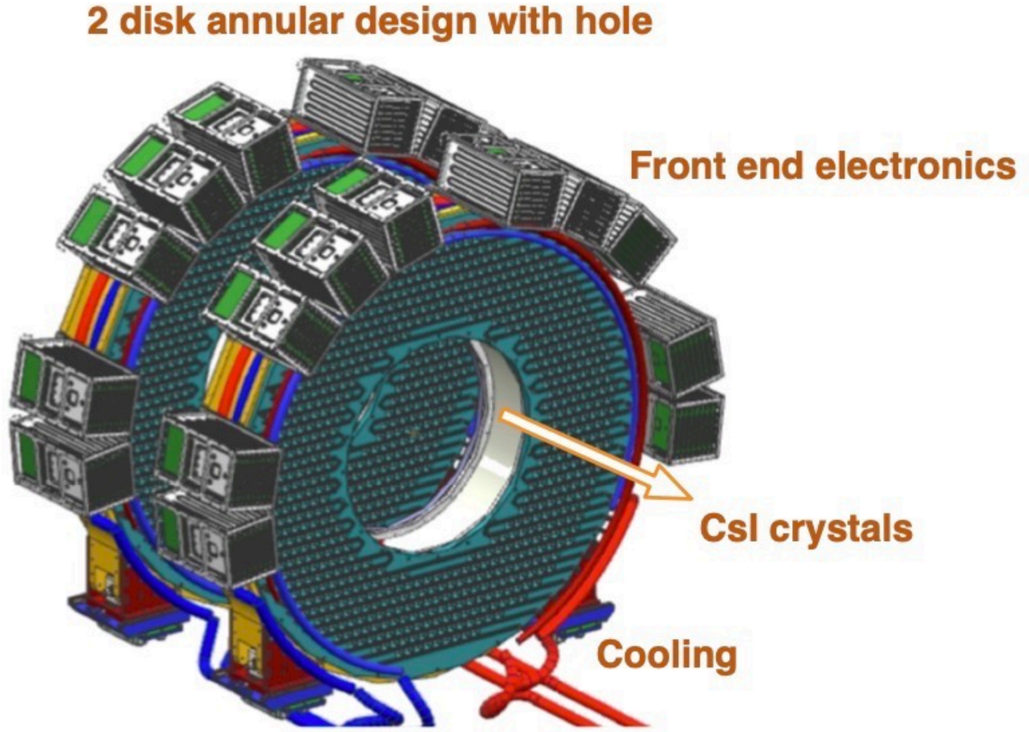


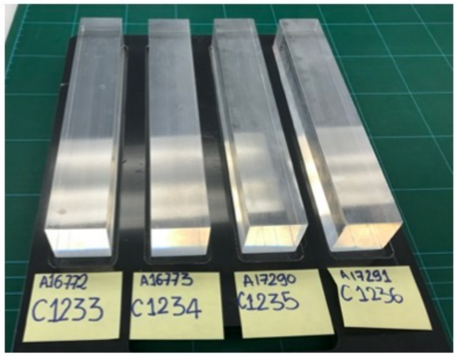


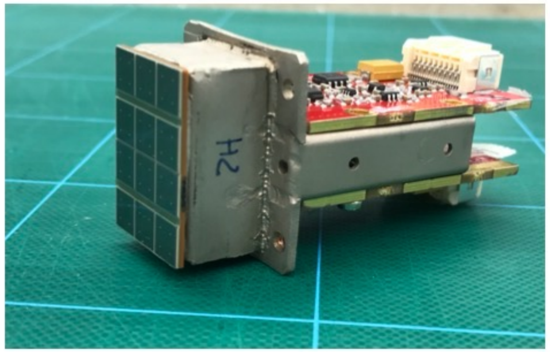


The Mu2e EM Calorimeter

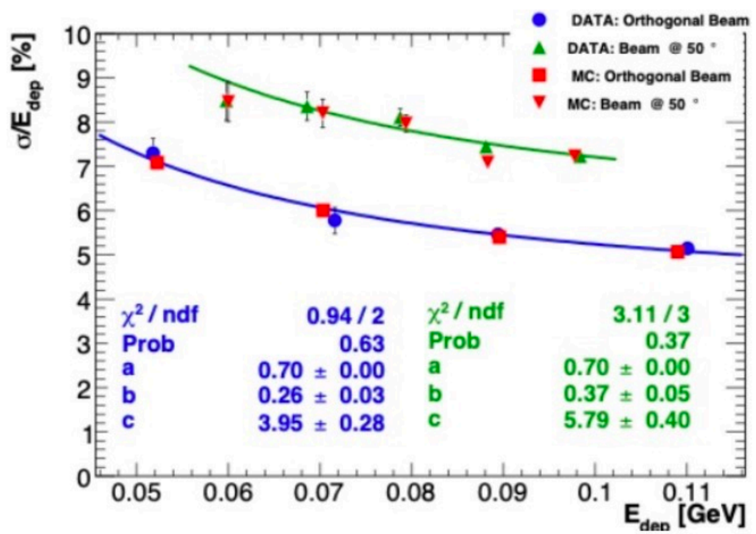
- **<u>Geometry (acceptance optimized)</u>**
  - 2 disks spaced by 70 cm
  - Inner radius: 37 cm
  - Outer radius: 66 cm
- **<u>Active Material</u>**
  - Pure CsI crystals
  - 674 crystals/disk
  - 3.4x3.4x20 cm3
- **<u>PhotoSensors</u>**
  - Array of 6 SiPMs
  - 2 arrays/crystal
  - 14x20 mm2 each
- **<u>Readout electronics</u>**
  - Preamplifiers on sensors back
  - Voltage control and Waveform Digitizers in crates around disks
- **<u>Calibration/Monitoring system</u>**
  - Fluorinert liquid in front of each disk
  - Laser and electronic pulses

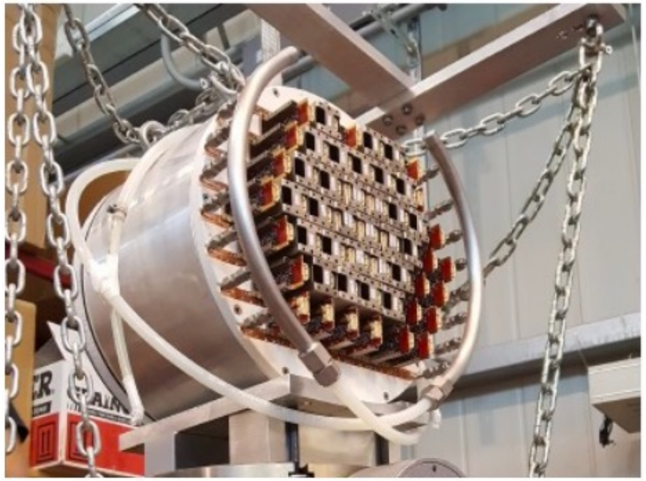




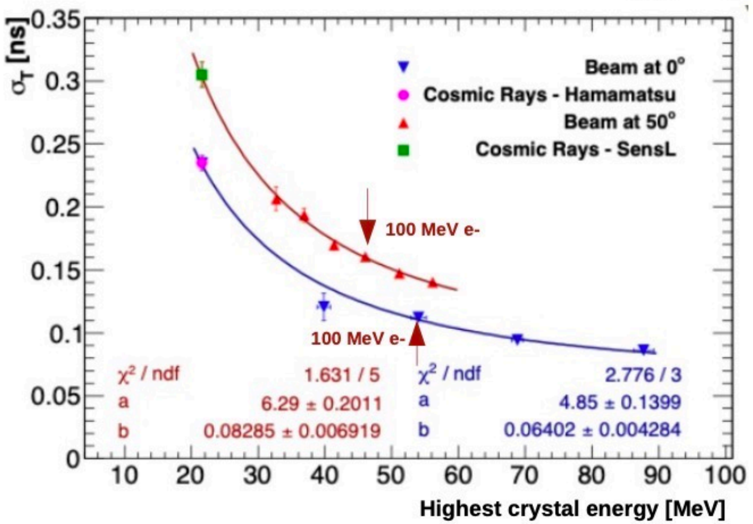


Status of Construction: EM Calorimeter





Test on a 51 crystal prototype (electrons and muons)



Measured prototype performance

σ(E)/E = 5.4% (0° angle) - 7.3% (50° angle)

σ(t) 160 ps (0° angle) – 230 ps (50° angle)

Status of Construction

100% crystals & SiPM produced

100 % Front End Electronics produced

Almost 100 % Mechanical parts produced

Digital electronics ready for production

Ready to begin assembly at Fermilab.

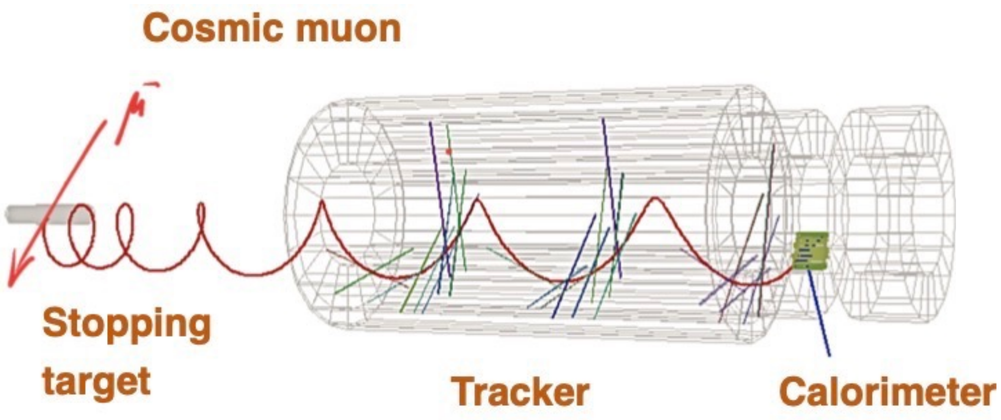
F. Happacher: Calorimeter (Poster)

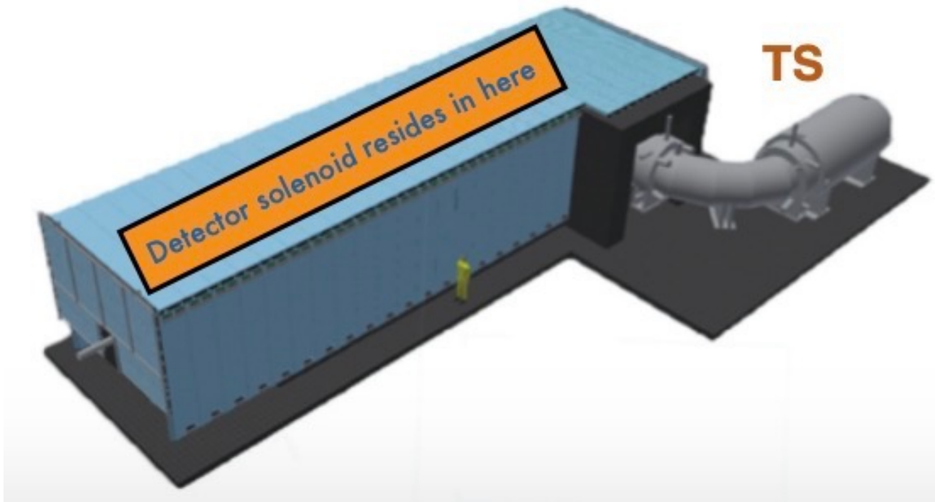
D. Pasciuto: Mechanics (Poster)

L. Morescalchi: Electronics (Talk)

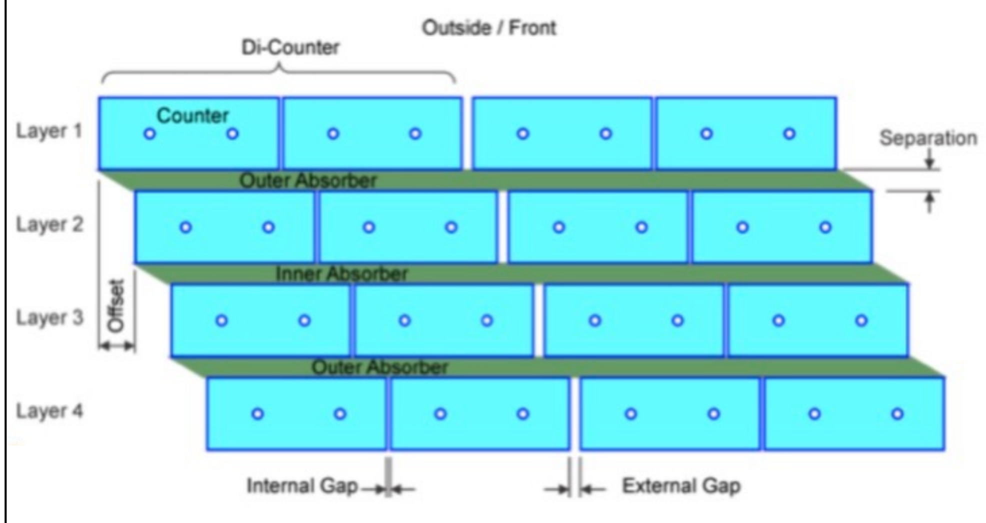
A. Gioiosa: TDAQ (Poster)

The Mu2e Cosmic Ray Veto





- **<u>About 1 cosmic event/day emulating a 105 MeV electron</u>**
- CRV covers 100% DS + part of TS
- 337 m^2 surface area
- Polystyrene scintillators coated with TiO_2 sandwiched between Al absorbers
- 4 overlapping scintillator layers
  - 3 layer coincidence veto
- Readout through WLS fibers & SiPMs on both ends
- 99.99% muon veto efficiency.

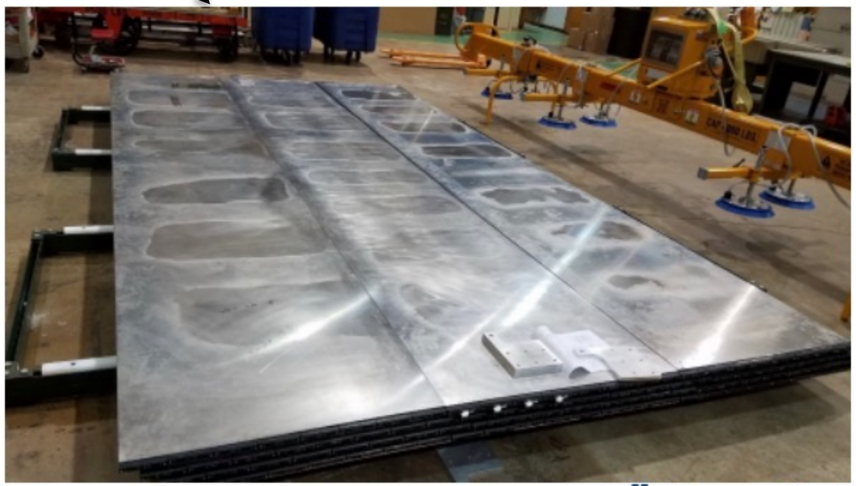


Status of Construction: Cosmic Ray Veto

4 layer modules produced at the U. of Virginia

Vertical Modules

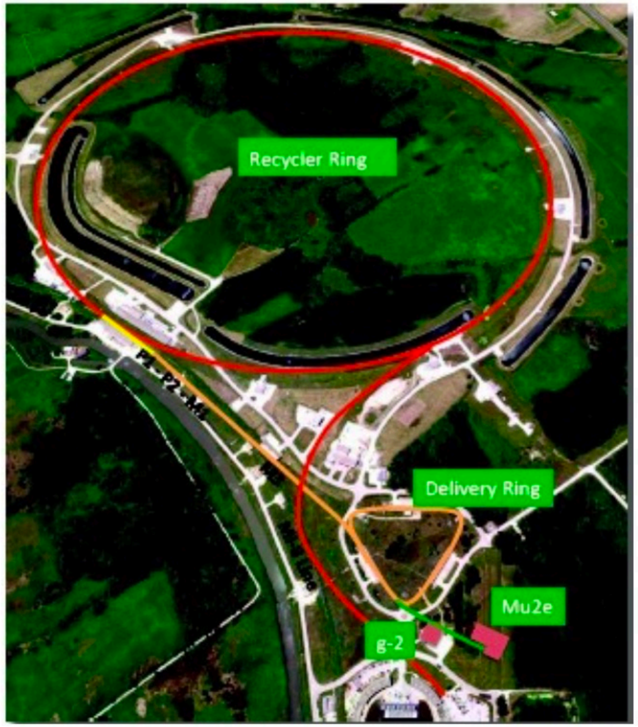
Horizontal Modules

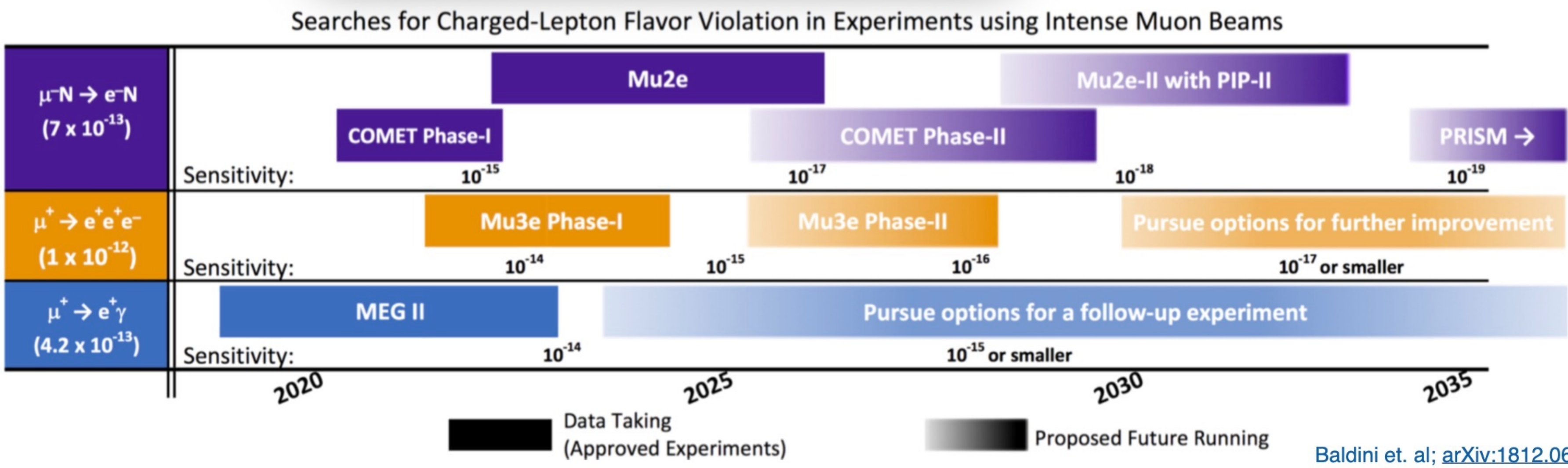


- 100% SiPM tested
- 67% modules produced
- Vertical Slice Test progressing well

Mu2e schedule (compared to other muon searches)

- **Late 2024:** first beam on target
- **2025-2026:** Mu2e Run 1
  - Half beam intensity → x1000 improvement over SINDRUM-II
- **End of 2026:** PIP-II/LBNF shutdown
- **Early 2029:** resume data taking
  - Full beam intensity → x10000 improvement over SINDRUM-II





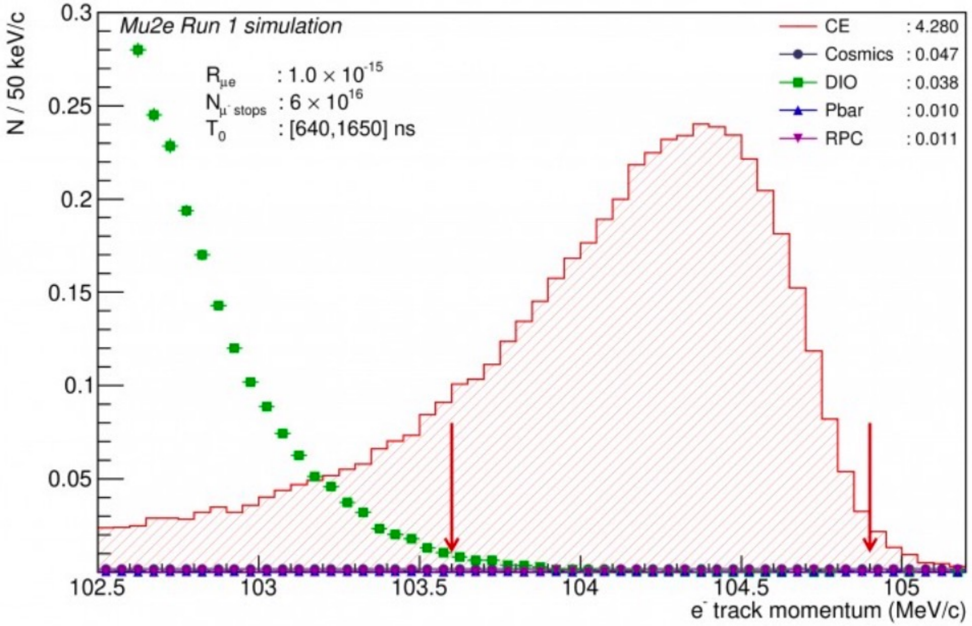
Baldini et. al; arXiv:1812.06540v1

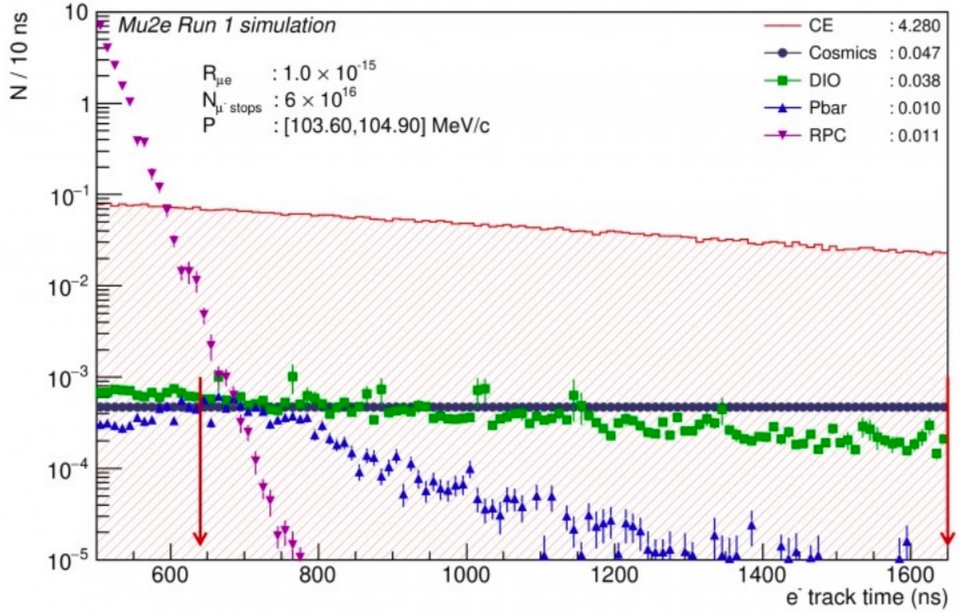
Mu2e Run 1 Background Expectation

Channel	Mu2e Run 1 Background Expectation
Cosmics	$0.048 \pm 0.010\ (\text{stat}) \pm 0.010(\text{syst})$
DIO	$0.038 \pm 0.002\ (\text{stat})^{+0.026}_{-0.016}\ (\text{syst})$
Antiprotons	$0.010 \pm 0.003\ (\text{stat})\ ^{+0.010}_{-0.004}\ (\text{syst})$
RPC in-time	$0.011 \pm 0.002\ (\text{stat})\ ^{+0.001}_{-0.002}\ (\text{syst})$
RPC out-of-time	negligibly small
RMC	negligibly small
Beam electrons	negligibly small
Total	$0.107 \pm 0.032\ (\text{stat}\oplus\text{syst})$

Main background: Cosmics passing through small regions of the Transport Solenoid that cannot be covered by the Cosmic Ray Veto and produce delta rays that mimic the Conversion Electron signal.

Estimate of Backgrounds (Run 1)





Decays in Orbit (DIO):

Spectrum falls As $(E_{max}\text{-}E)^5$ close to the end point → Suppressed with momentum cuts

Antiprotons:

Suppressed with passive absorbers

Radiative Pion Captures (RPC):

(Generate $\gamma \rightarrow e^+e^-$ mimicking CE signal) → Suppressed with time cuts.

Selection cuts (momentum and time) optimized for best sensitivity:

Expected Mu2e Run 1 90% CL limit (0 event observed): $R_{\mu e} = 5.9 \times 10^{-16}$ (x1000 better than SINDRUM II)

Conclusions

- **Mu2e is a discovery experiment:** will search for the CLFV neutrinoless coherent muon-to-electron conversion in a nucleus field.
- **Construction of the beamline and detectors is progressing well:** prototypes tests confirm detectors performance expected from full simulation.
- **2022 - early 2024:** complete detectors assembly and commissioning.
- **Late 2024:** first beam on target.
- **Mu2e Run 1 (2025-2026):** begin data taking at half beam intensity → improve SINDRUM II limit by x1000.
- **End of 2026:** PIP-II/LBNF shutdown for neutrino beams upgrade.
- **Early 2029:** resume data taking at full beam intensity → improve SINDRUM II limit x10000.
- **Mu2e will search also for LFV:** $\mu^- N(A, Z) \rightarrow e^+ N(A, Z\text{-}2)$ → improve SINDRUM II limit by x1000.
- **Mu2e-II (long term plans):** achieve x10 sensitivity over Mu2e using higher intensity and lower energy proton beam.

The Mu2e Collaboration

> 220 scientists from 38 institutions

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