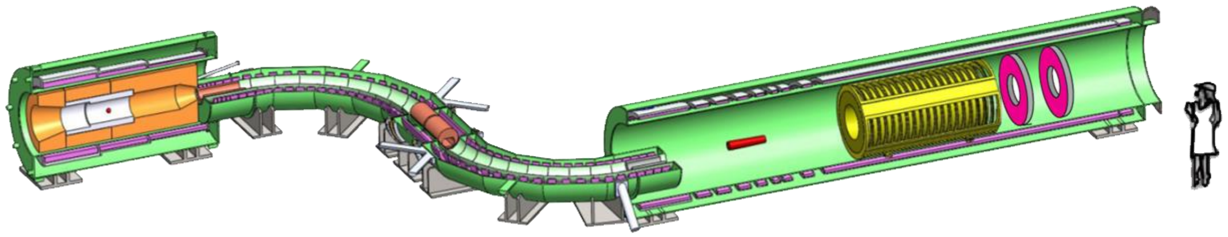
The Mu2e Experiment at Fermilab



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Workshop on Muon Physics at the Intensity and Precision Frontiers

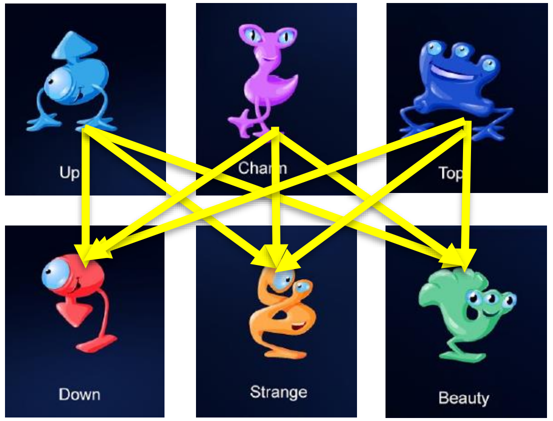
Apr. 20, 2024 Peking University, Beijing

Outline

- Charged Lepton Flavor Violation (CLFV)
- Experimental searches of CLFV
- The **Mu2e** experiment at Fermilab
- Beam and detector
- Signal and background
- Current status and schedule
- Mu2e II
- Summary

Mu2e downstream Transport Solenoid on its way to the Mu2e building
Feb. 20th, 2024

Introduction



$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

M. Kobayashi &
T. Maskawa
Nobel Prize 2008

Quark mixing

T. Kajita &
A. McDonald
Nobel Prize 2015

Neutrino mixing

$$U_{PMNS} = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\mathrm{CP}}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{13}\,c_{23} \end{pmatrix}$$

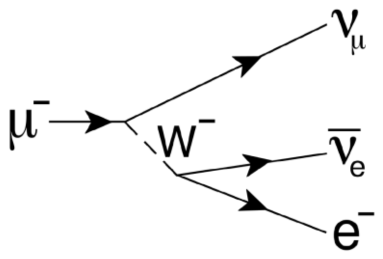
Neutrino oscillation: Uncharged Lepton Flavor Violation

$\boldsymbol{e - \mu - \tau}$: Charged Lepton Flavor Violation

Never been observed!

CLFV in the SM

- Lepton flavor is conserved in the Standard Model (SM)
- General μ decay

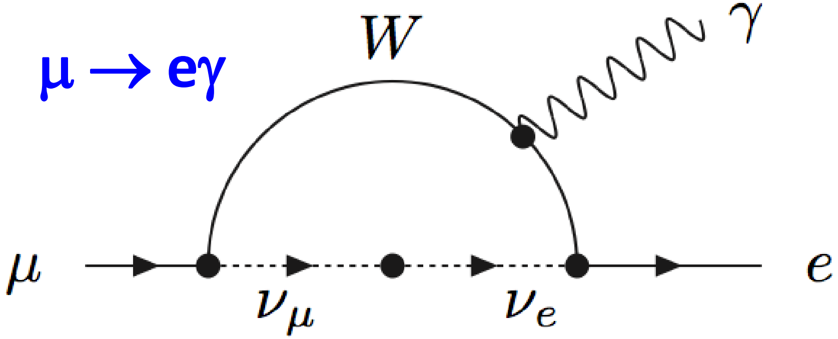


	muon		muon neutrino		electron		e^- antineutrino
equation:	μ	$\rightarrow$	ν_μ	+	e^-	+	$\bar{\nu}_e$
electron number:	0	=	0	+	1	+	-1
muon number:	1	=	1	+	0	+	0

$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

- With a minimal extension to the SM
- Considering massive neutrinos
- CLFV is allowed at loop level $\sim \mathbf{O(10^{-54})}$
- Experimentally undetectable
- Any observation of CLFV would be a clear signature of New Physics beyond the SM

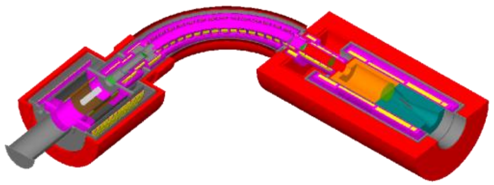
μ → eγ



Search for CLFV

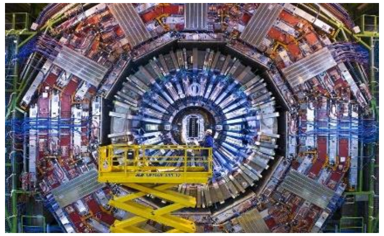
- μ transitions
  - $\mu \to e\gamma, \mu \to eee, \mu N \to eN, \mu^+ e^- \to \mu^- e^+$
- τ decays
  - $\tau \to e\gamma, \tau \to \mu\gamma, \tau \to ee\mu, \tau \to eh, \tau \to \mu h, \ldots$
- Resonance decays
  - Meson decays: $J/\psi \to e\mu, \Upsilon \to e\tau, B \to \mu\tau, \ldots$
- Heavy particles
  - Z/Higgs decays: $Z \to e\mu, H \to \mu\tau, \ldots$
  - Top decays: $t \to qll'$
  - New heavy particles: $Z' \to e\mu, \phi \to \mu\tau, \ldots$

μ beam



Low energy

Colliders



High energy

Advantages of μ beam

- μ sources has much higher intensity
  $\sim 10^8\ \mu/s$ @PSI
  $3 \times 10^{10} \sim 10^{11} \mu/s$ @Mu2e/COMET
- Produced by protons hitting target
  $\pi/K \to \mu\bar{\nu}_\mu$
- τ can only be produced at colliders
  $\sim 10^2\ \tau/s$
- The μ processes are sensitive to almost all NP models

A.J. Buras's DNA of New Physics

Models →

Observables ↓

	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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Altmannshofer, Buras, Gori, Paradisi, Straub
Nucl. Phys. B **830**, 17 (2010)

★★★ Large effects

★★ Visible, but small

★ No sizable effect

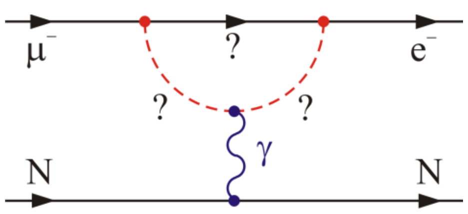
Probe New Physics

- Effective Field Theory (EFT) provides a model independent description of CLFV

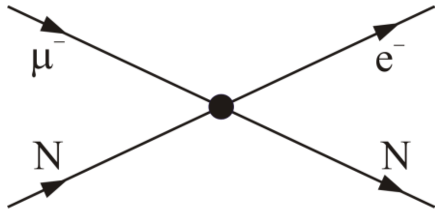
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right)$$

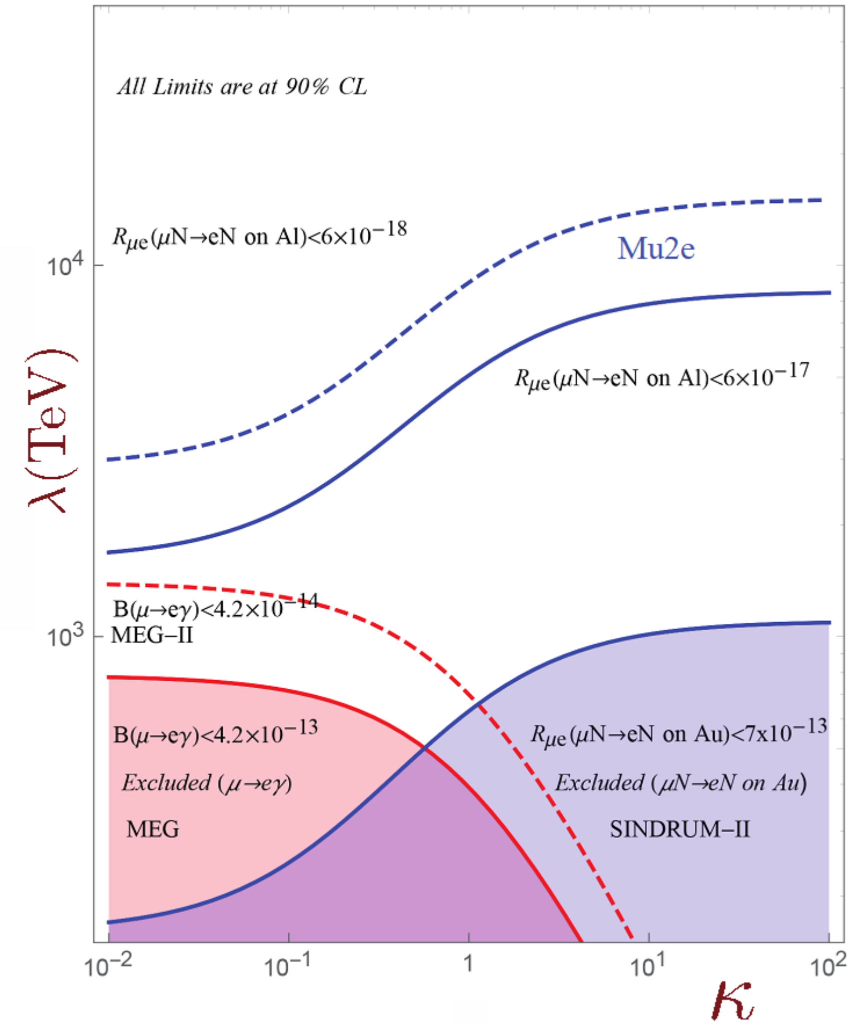
- Leading CLFV operators at dimension D=6, suppressed by $1/\Lambda_{NP}^2$
- Energy scale Λ at 2,000 ~10,000 TeV
- $\boldsymbol{\kappa_D}$ is the relative contribution of magnetic momentum term and four-fermion operator

Loops



Contact terms

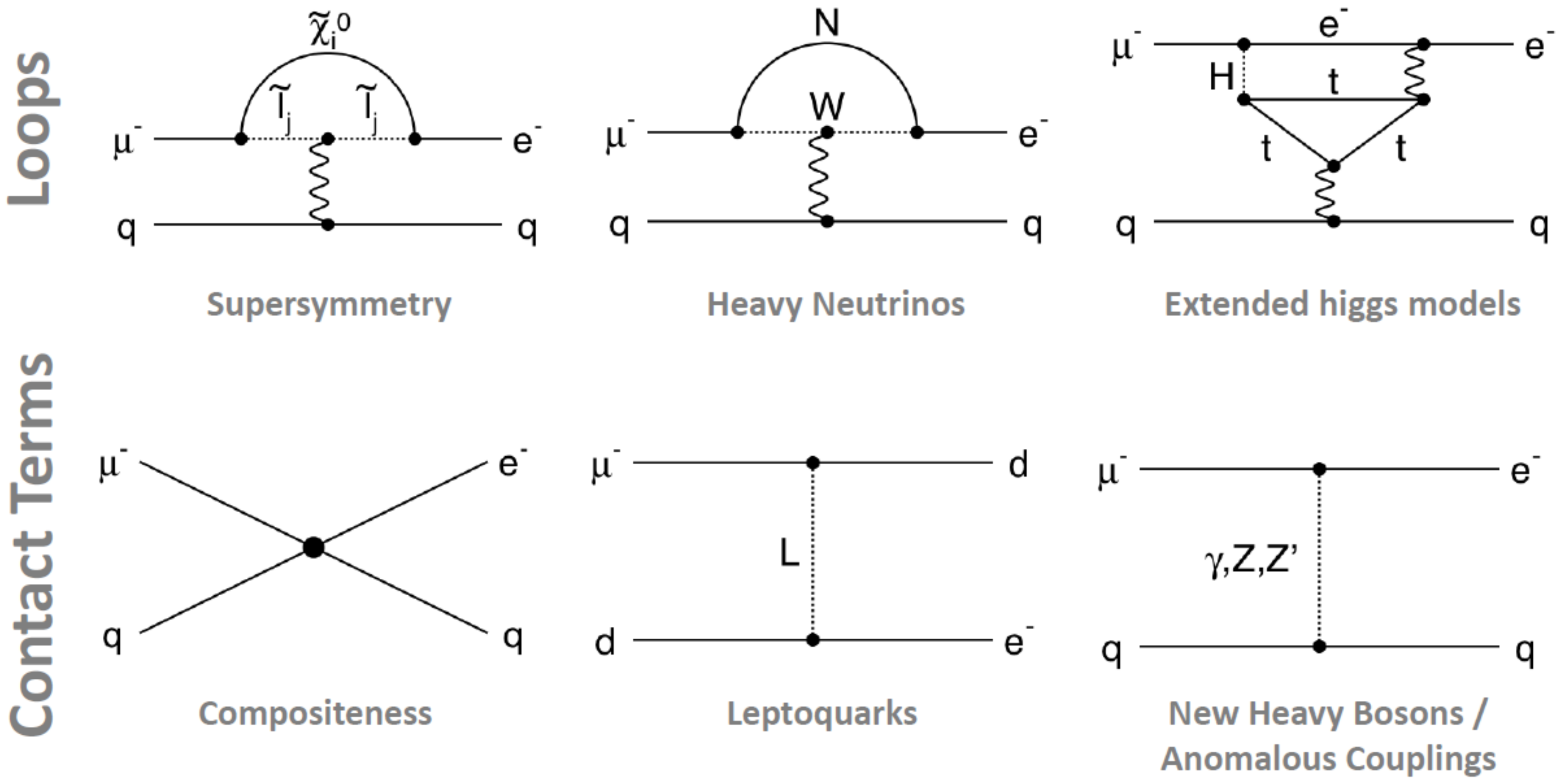




Mu2e Technical Design Report
arXiv: 1501.05241

Theoretical Models

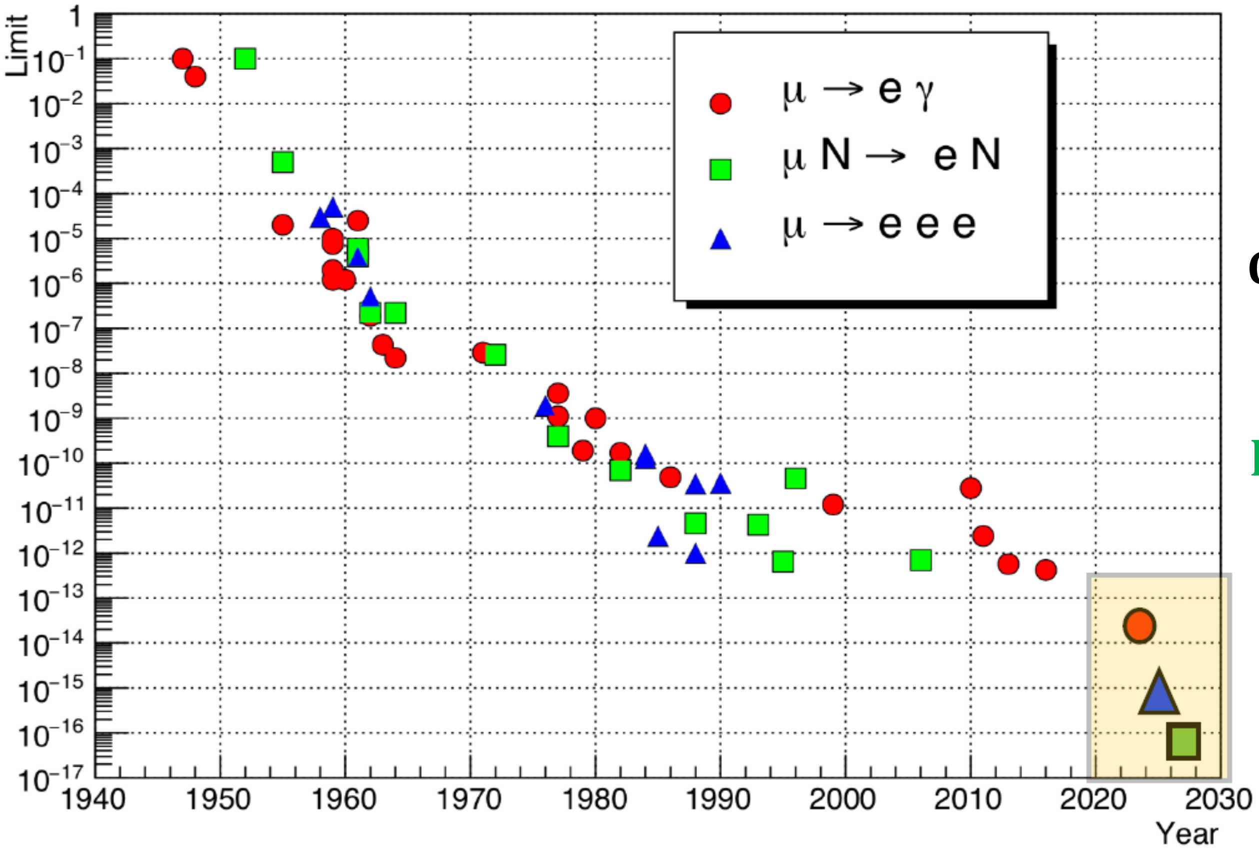
- $\mu N \to eN$ conversion is the "Golden Channel" of CLFV search, sensitive to a broad array of NP models
  - SUSY
  - Heavy neutrino
  - Higgs doublet
  - Compositeness
  - Leptoquark
  - Z prime
  - …



History & Prospect of CLFV search with μ

1947

Bruno Pontecorvo



Current Best limits @ 90% C. L.

$\mathrm{BR}(\mu \to eee) < 1.0 \times 10^{-12}$

$\mathrm{R}(\mu N \to eN@\mathrm{Au}) < 7 \times 10^{-13}$

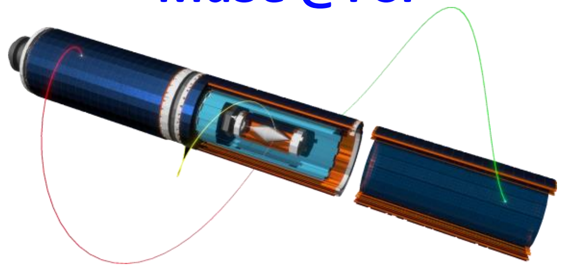
$\mathrm{BR}(\mu \to e\gamma) < 3.1 \times 10^{-13}$

arXiv:2310.12614

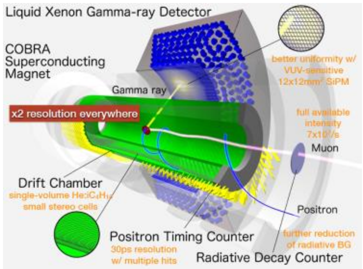
Next Generation experiments

$\boldsymbol{O(10^{-17})}$

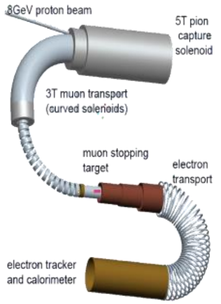
Mu3e @PSI



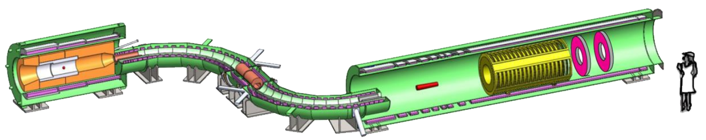
MEG II @PSI



COMET @KEK



Mu2e @FNAL



$\mu N \rightarrow eN$ Conversion

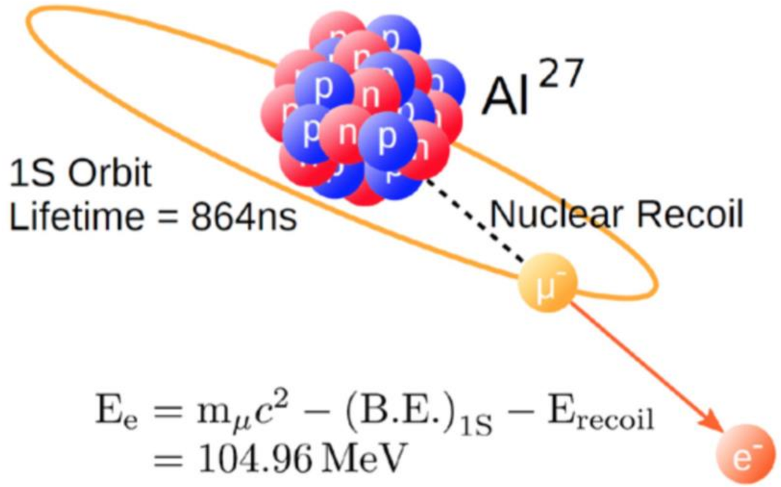
- What to measure

  The ratio of muon to electron conversions to conventional muon captures

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(Z,A) \rightarrow e^- + N(Z,A))}{\Gamma(\mu^- + N(Z,A) \rightarrow \nu_\mu + N(Z-1,A))}$$

- Signal: Neutrinoless conversion of a muon to electron in the field of a nucleus

- Experimental signature
  - Mono-energetic electron
  - $E_e = m_\mu - E_{bind} - E_{recoil}$
  - For Al, $\boldsymbol{E_e = 104.96\ MeV}$,
  - Lifetime $\boldsymbol{\tau = 864\ ns}$

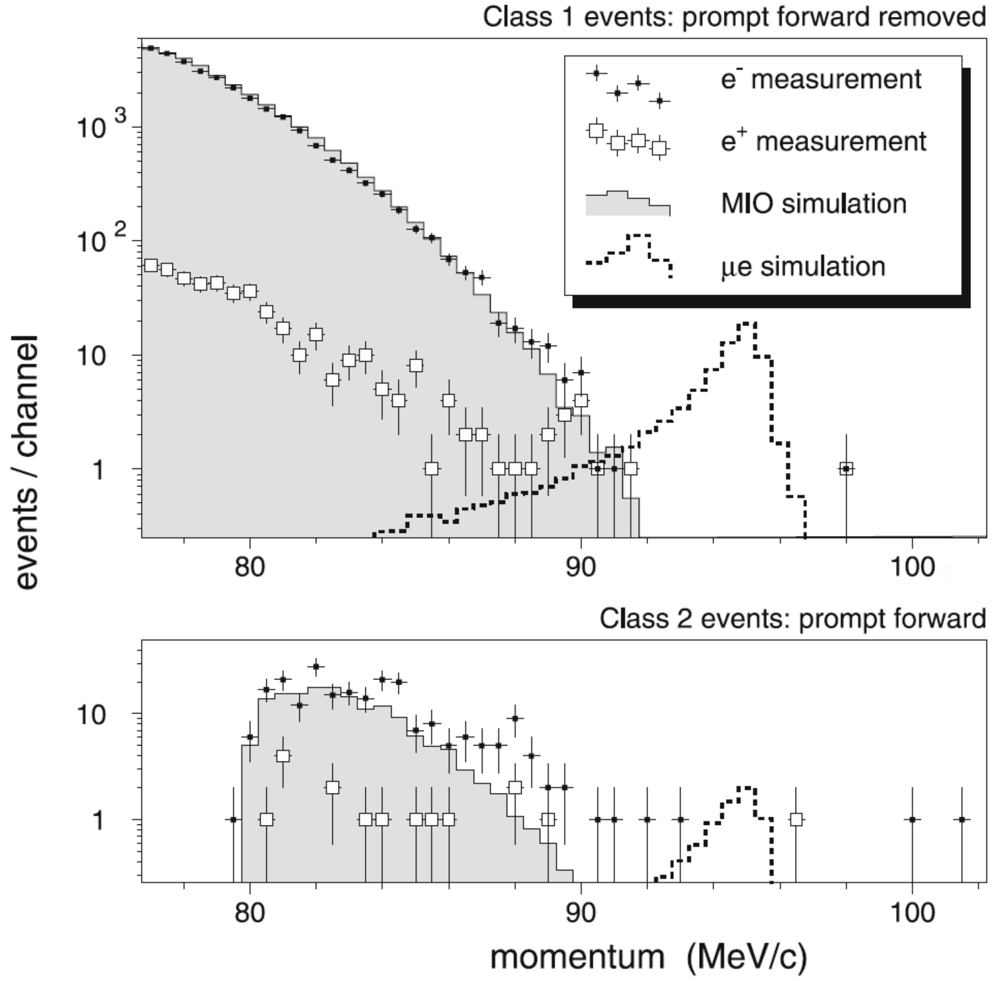


$\mu N \to eN$: Current Best Measurement

- Current best limits by SINDRUM II
  - $R_{\mu e}(Ti) < 4.3 \times 10^{-12}$ @ 90% C.L.
  - $R_{\mu e}(Au) < 7 \times 10^{-13}$ @ 90% C.L.

- Simulated signal at DIO tails

- Ti/Au target: different electron energy endpoint than Al



W. Bertl et al., *Eur. Phys. J. C* 47, 337-346 (2006)

Mu2e at Fermilab

Expected Upper Limit

$\mathbf{R_{\mu e} < 8 \times 10^{-17}}$
@ 90% C.L.

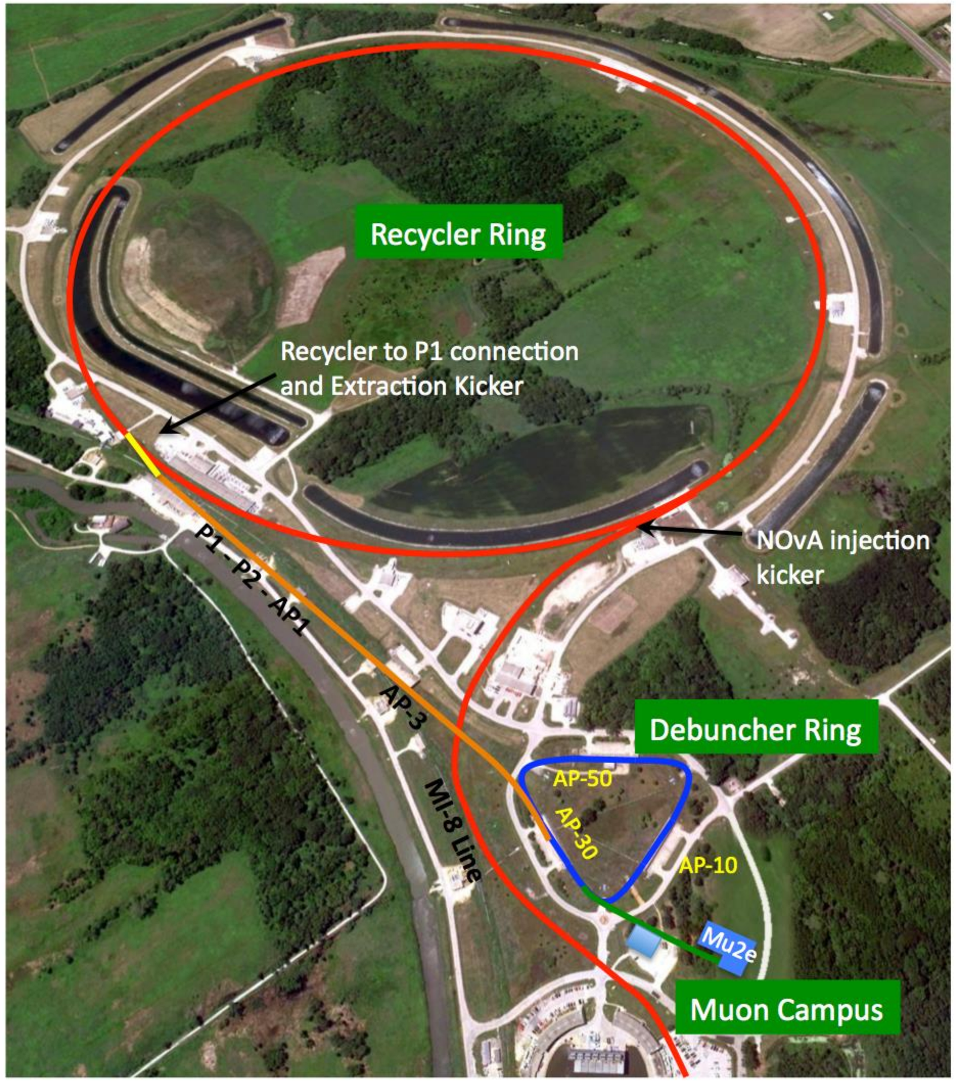
10 000 × improved
on current best limit

Mu2e Collaboration

- More than 200 scientists from 38 institutions
- Sun Yat-Sen University joined Mu2e in 2016

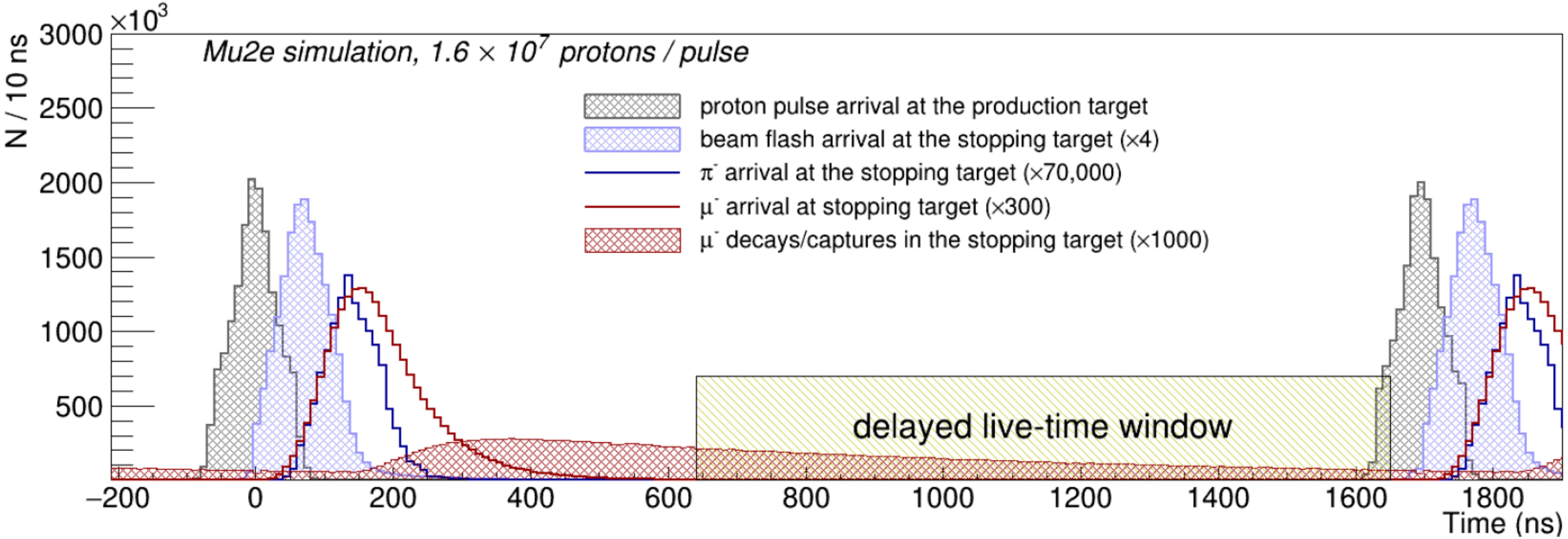
Muon Campus at Fermilab

- 8 GeV proton beams
- $3x10^7$ protons per bunch
- Bunch spacing 1.7 μs, 30% duty factor
- Run after g-2 (done), share with NOVA

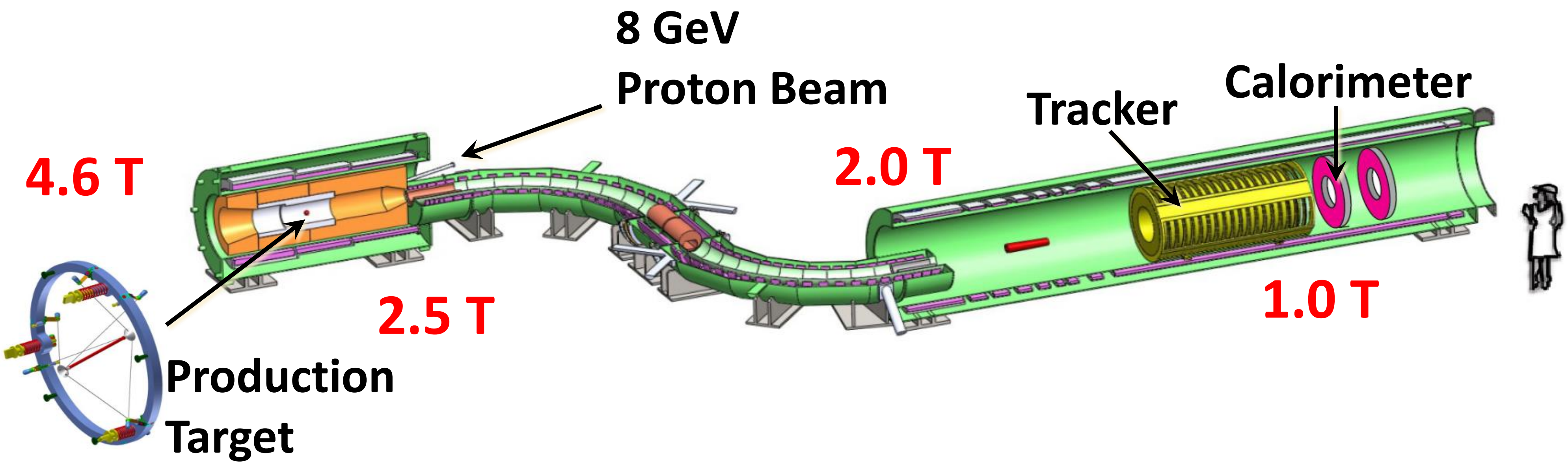


Beam Time Structure

- $4x10^7$ protons per bunch, bunch spacing 1695 ns
- 700 ns delay ($\tau_\pi = 26\ ns$) before 1 µs live gate
- Extinction factor (Out-Of-Time proton rate) < 10^{-10}



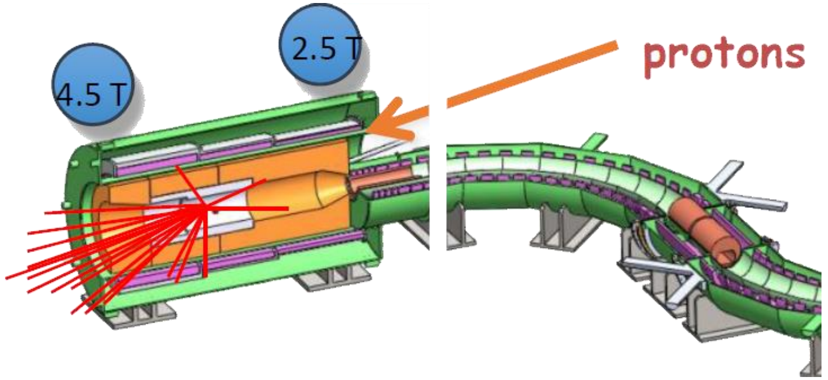
The Mu2e Apparatus

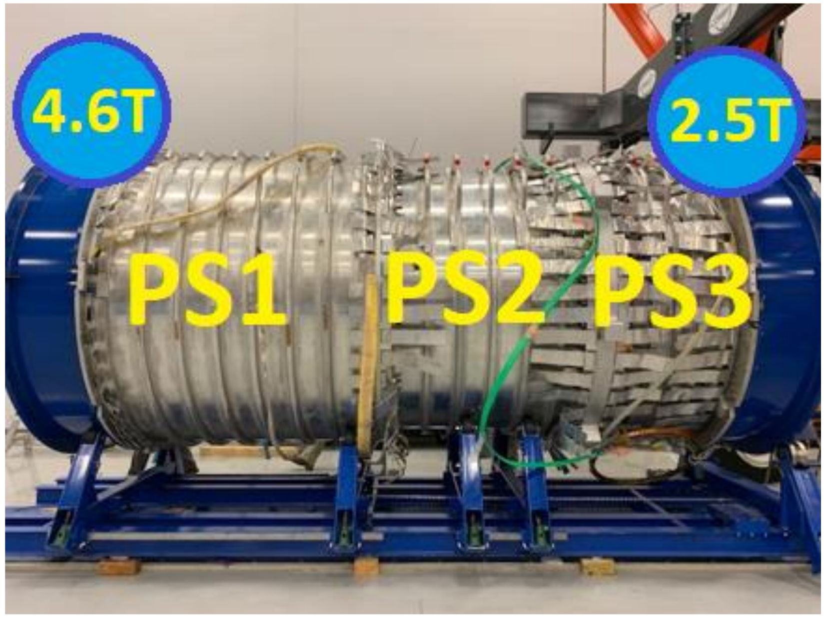


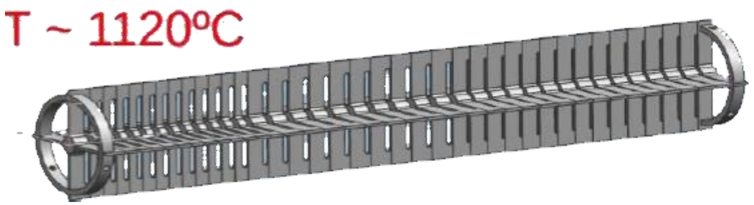
- Production Solenoid (PS)
  - 8 GeV pulsed proton beam strikes tungsten target and produces pions
  - Graded magnetic field guides pions and muons into transport solenoid
- Transport Solenoid (TS)
  - Select low momentum muons
  - Rotatable collimator selects μ^- or μ^+ beam
  - Absorbers along beamline reduce antiproton background
- Detector Solenoid (DS)
  - Aluminum target stops muons
  - Graded magnetic field collects electrons from muon decay
  - Annular tracker and calorimeter detect potential signal electrons

Production Solenoid and Target

- 8 GeV, 8 kW proton beams hitting target
- Radiative cooled Tungsten target with fins
  - 16 cm long X 6 mm diameter
  - Replaced annually with remote handler
- Heat and radiation shield
  - Thick bronze shield protects superconductor
  - Reduce backgrounds

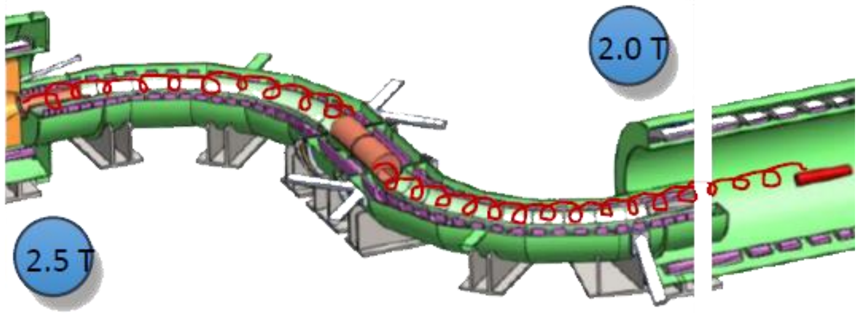


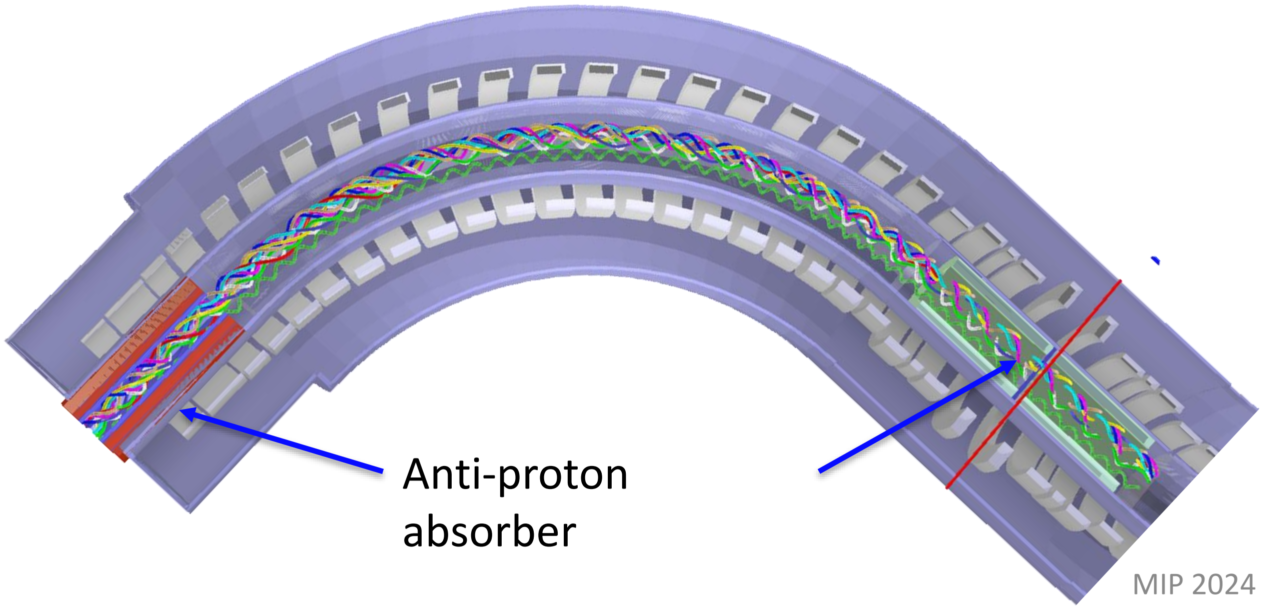




Transport Solenoid

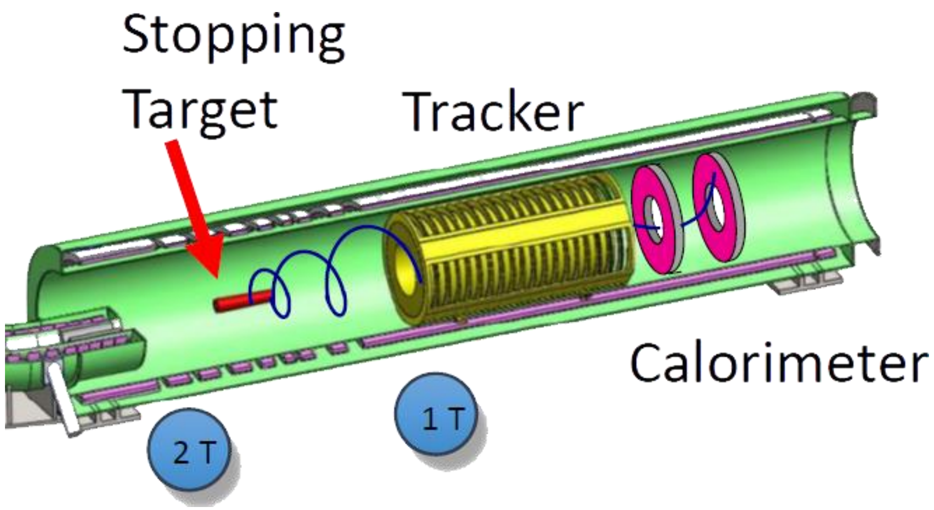
- Only very slow particles can go through TS
- The S-shape eliminates photons & neutrons
- Long flight time for π to decay
- Slow anti-protons will be absorbed
- The downstream TS at Mu2e hall on 2/20/2024

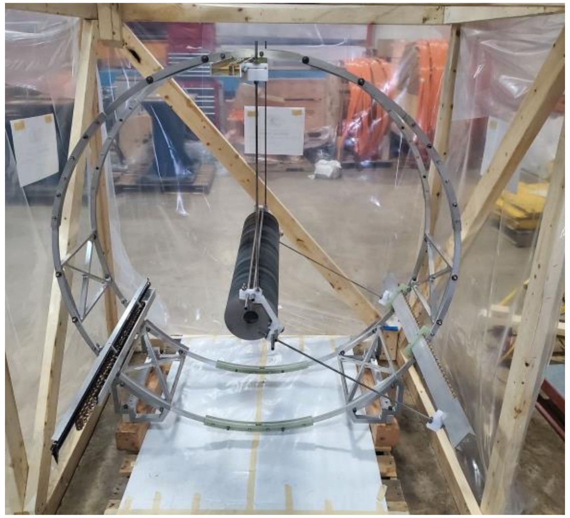


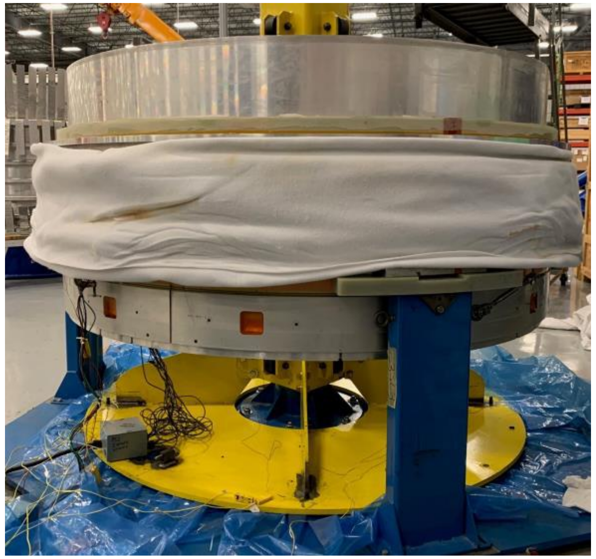


Detector Solenoid

- Stopping Target
  - Stopping μ on Al target
  - 37 Al foils, 105 µm thick, 2cm spacing
  - Central hole in target foils to permit passage of beam
  - Construction complete
- Solenoid
  - Graded field collecting conversion electrons, improving efficiency
  - Measure electron momentum and energy in tracker and calorimeter

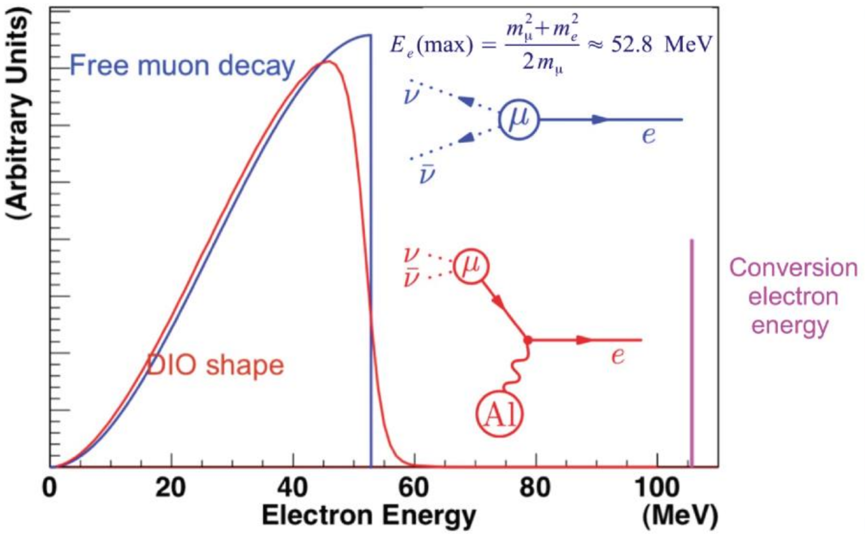


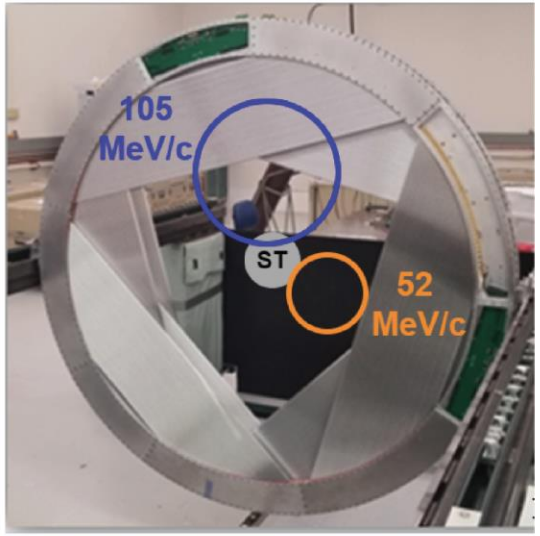


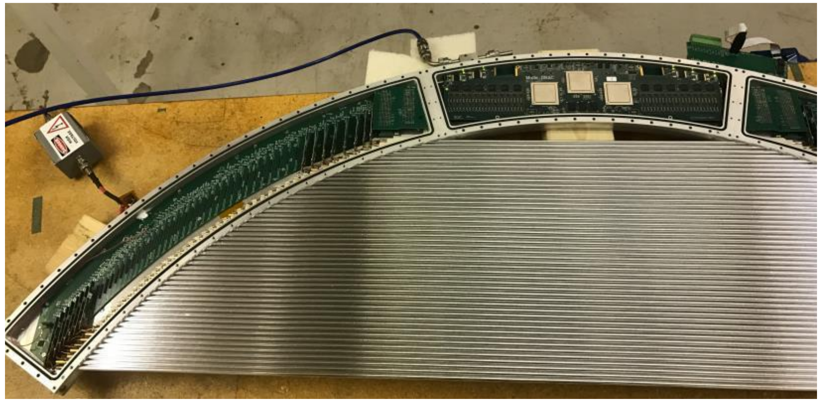


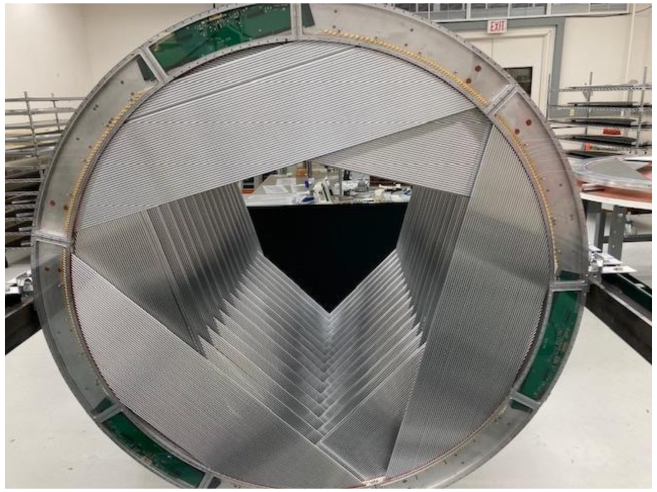
Tracker

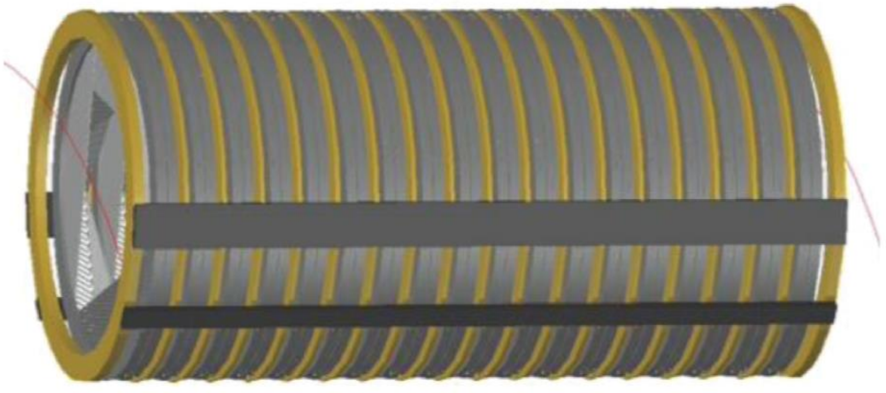
- 18 stations, 20736 straw tubes
- 5 mm diameter, 15 μm thick
- Not sensitive to backgrounds with $\mathbf{p_T < 80\ MeV}/c$
- Resolution $\boldsymbol{\sigma \sim 140\ \mathbf{keV}/c}$





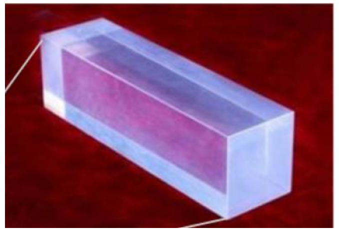


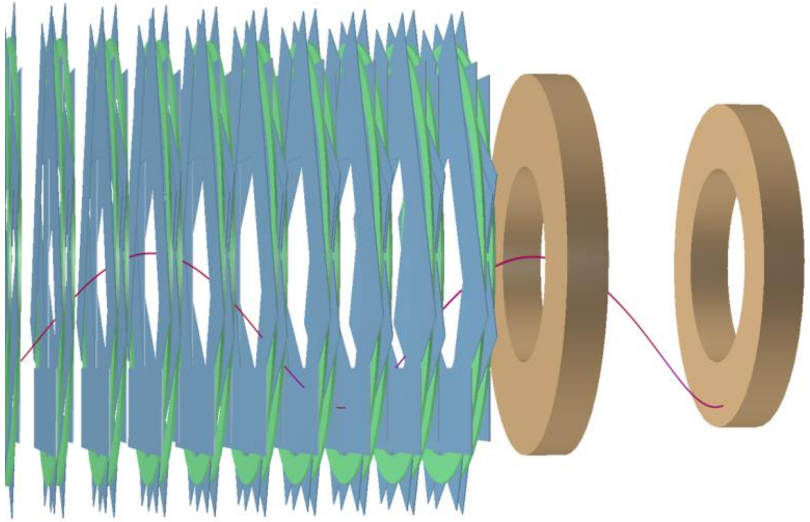


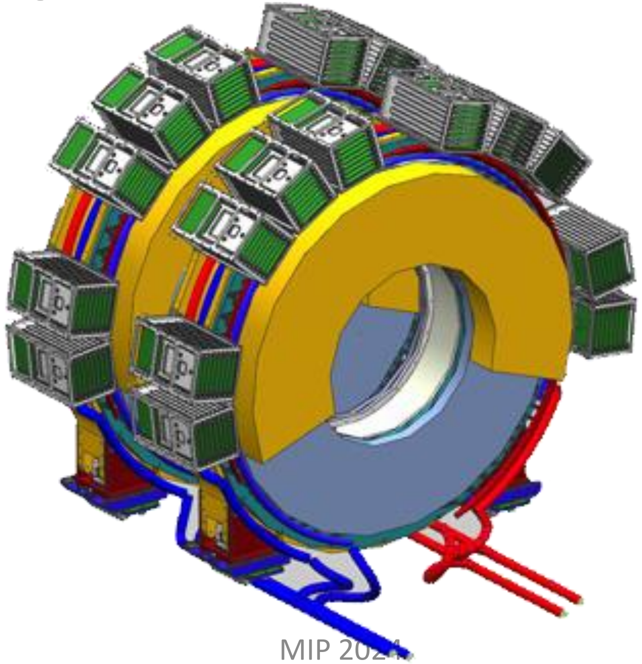


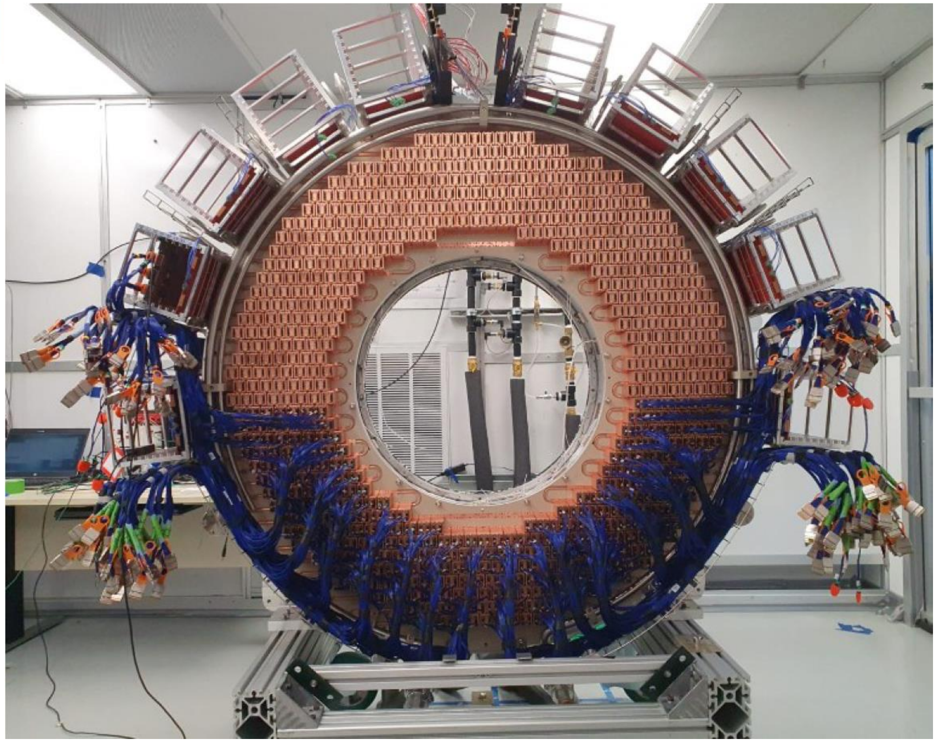
Calorimeter

- 2 annular disks, each with 674 CsI crystals + 1348 SiPMs
- Energy $\sigma < 10\%$, 500 ps timing
- Complements the tracker for μ/e PID, triggering & track seeding

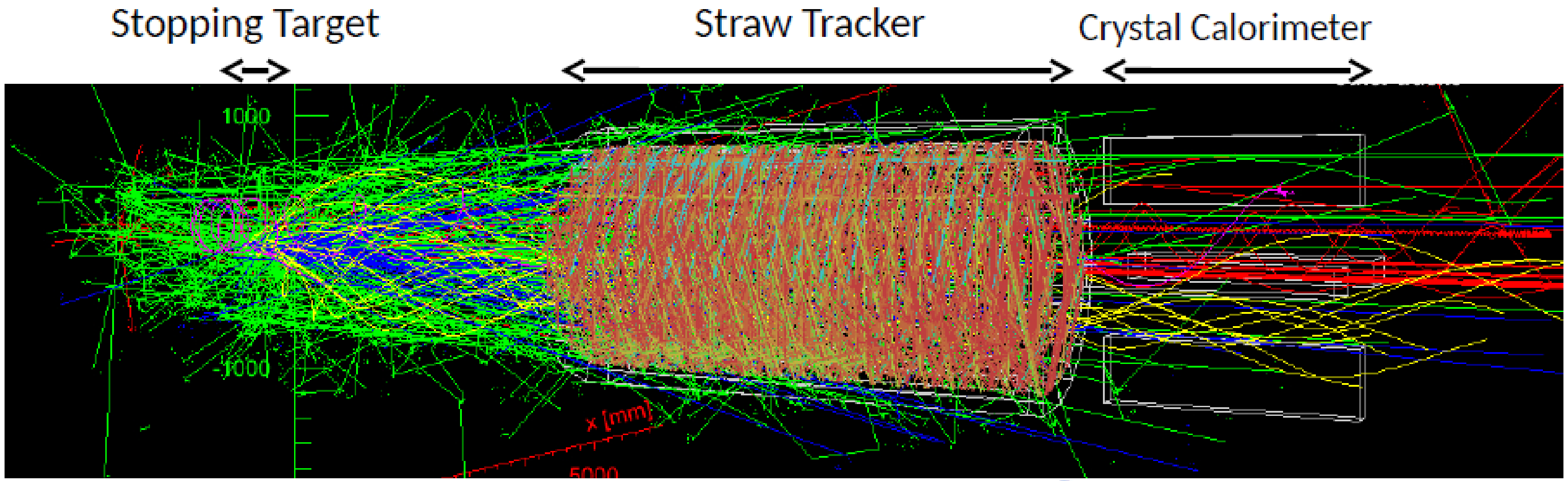


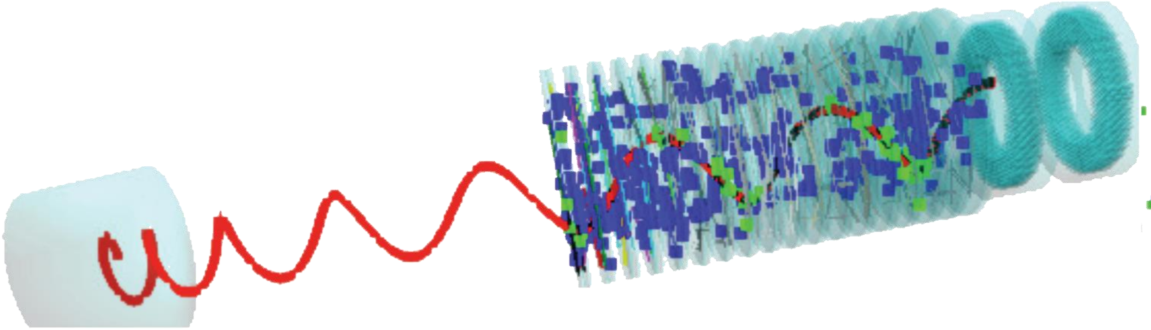




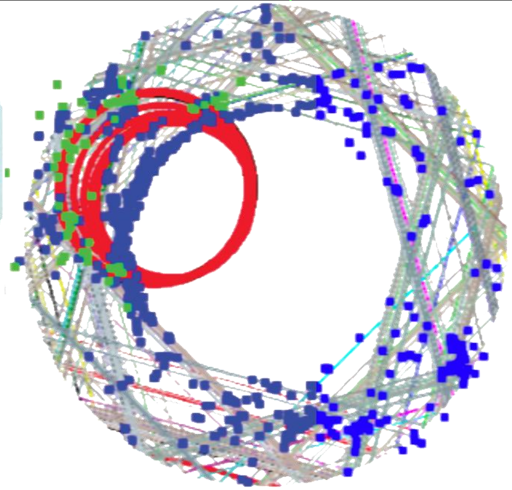


Tracks in Detector





3-D view of a simulated event
with a conversion electron track + background



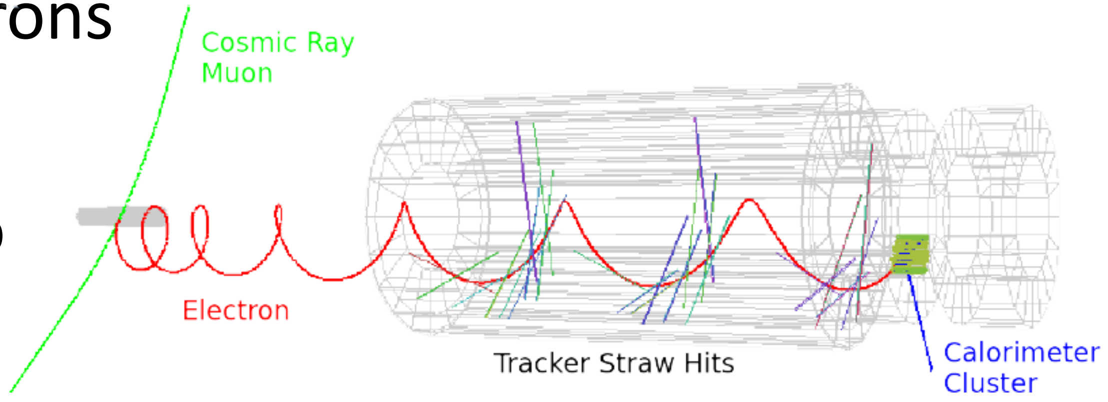
2-D XY Tracker view

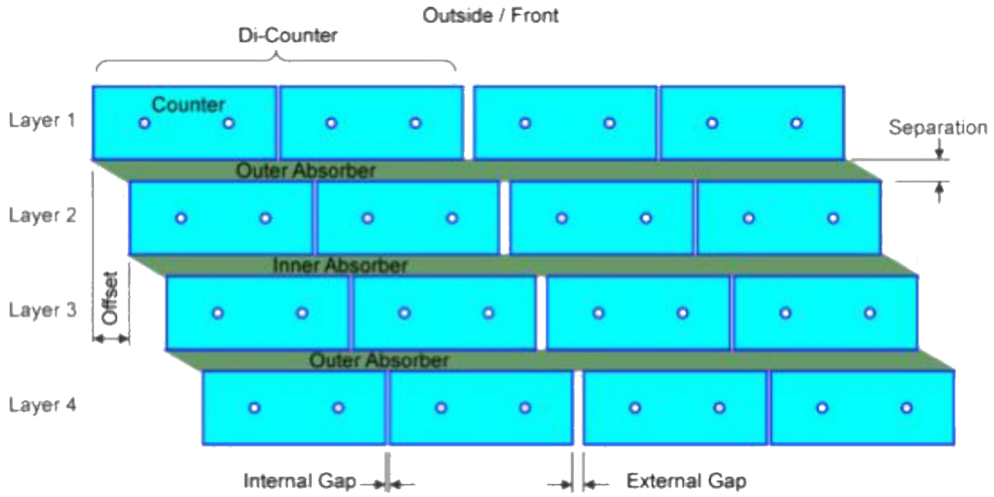
To find a signal electron near 105 MeV/c from a bunch of track candidates

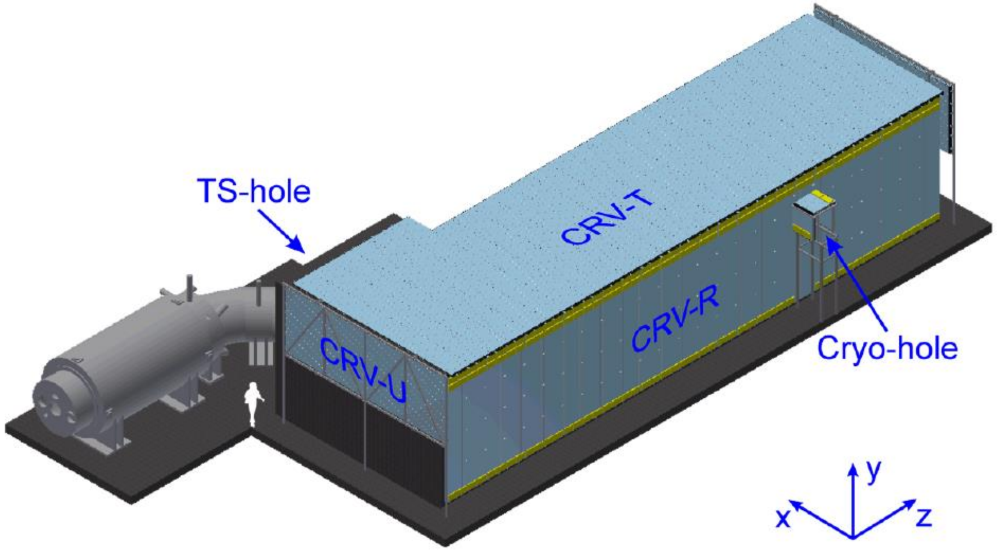
Shown in red is the CE track

Cosmic Ray Veto

- Cosmic ray can produce signal-like electrons
- Expect ~1 signal-like event per day
- Scintillators surrounding the detector, to identify cosmic rays and veto them
- Efficiency $\sim 99.99\%$

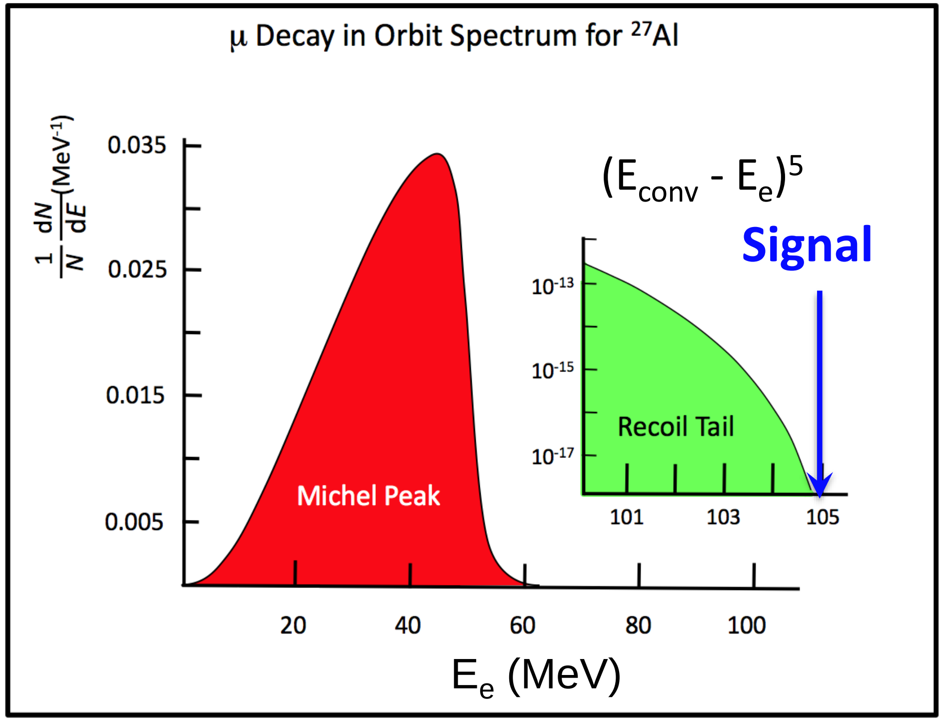






Backgrounds

- Signal
  - Conversion electrons with energy at Decay in Orbit (DIO) endpoint 104.97 MeV
- Background
  - Muon decay in orbit $\bar{m} + Al \rightarrow e^- + \overline{n}_e + u_m + Al$
  - Radiative muon capture $\bar{m} + Al \rightarrow u_m + g + Mg$
  - Radiative pion capture $p^- N \rightarrow gN^*, g \rightarrow e^+ e^-$
  - Antiprotons annihilation gamma
  - Pion/muon decay in flight
  - Electrons from beam
  - Electrons from cosmic rays



Czarnecki et al., *Phys. Rev. D 83, 013006* (2011)

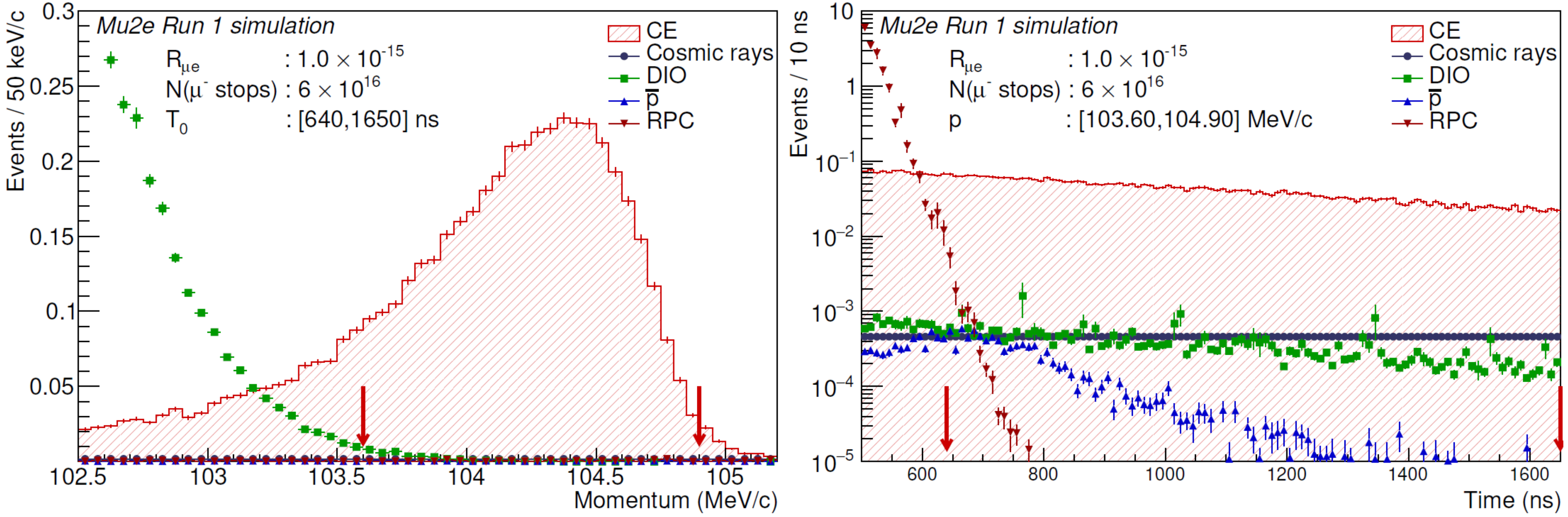
Background Summary

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	$0.046 \pm 0.010\ (\text{stat}) \pm 0.009\ (\text{syst})$
DIO	$0.038 \pm 0.002\ (\text{stat})\ ^{+0.025}_{-0.015}\ (\text{syst})$
Antiprotons	$0.010 \pm 0.003\ (\text{stat})\ \pm 0.010\ (\text{syst})$
RPC in-time	$0.010 \pm 0.002\ (\text{stat})\ ^{+0.001}_{-0.003}\ (\text{syst})$
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1\ (\text{stat})\ ^{+0.1}_{-0.3}\ (\text{syst})) \times 10^{-3}$
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 Run I Sensitivity Projections for the Neutrinoless μ→e Conversion Search in Aluminum
Universe 9, 54 (2023)

Mu2e Sensitivity

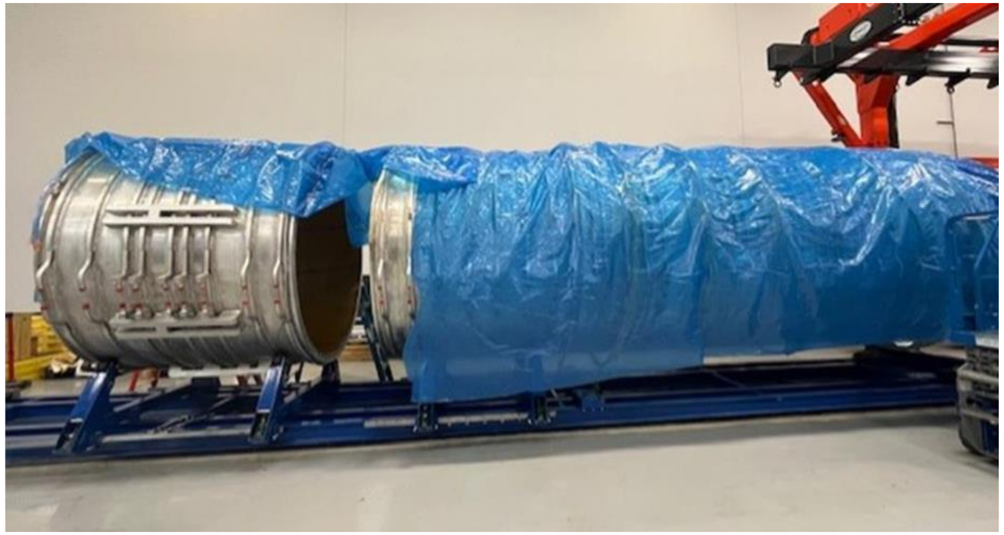
- Run 1 simulation, $R_{\mu e}(Al) < 6.2 \times 10^{-16}$ @ 90% C. L.
- For a conversion ratio of **1 x 10^{-15}** , ~5 signal events, 5σ discovery of CLFV
- Further 10X improvements with Run II



dio:10.3390/universe9010054

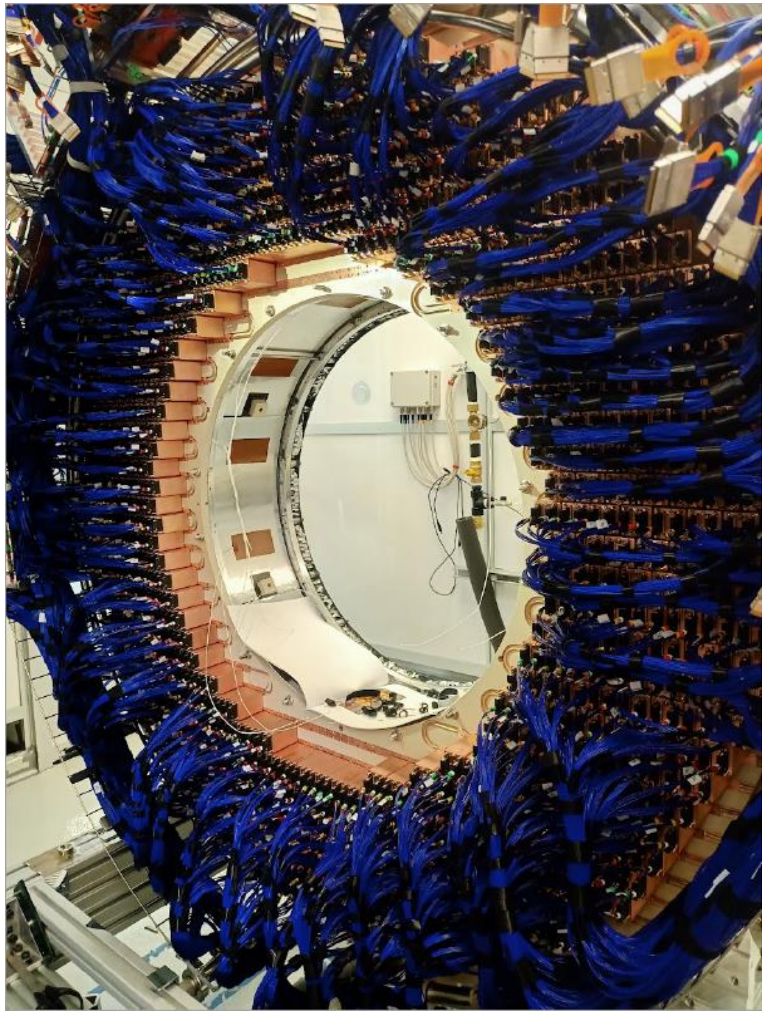
Mu2e Current Status

- Production Solenoid: Assembled cold mass inserted into cryostat
- Transport Solenoid: Upstream and downstream TS installed at Mu2e hall
- Detector Solenoid: Cold mass completed



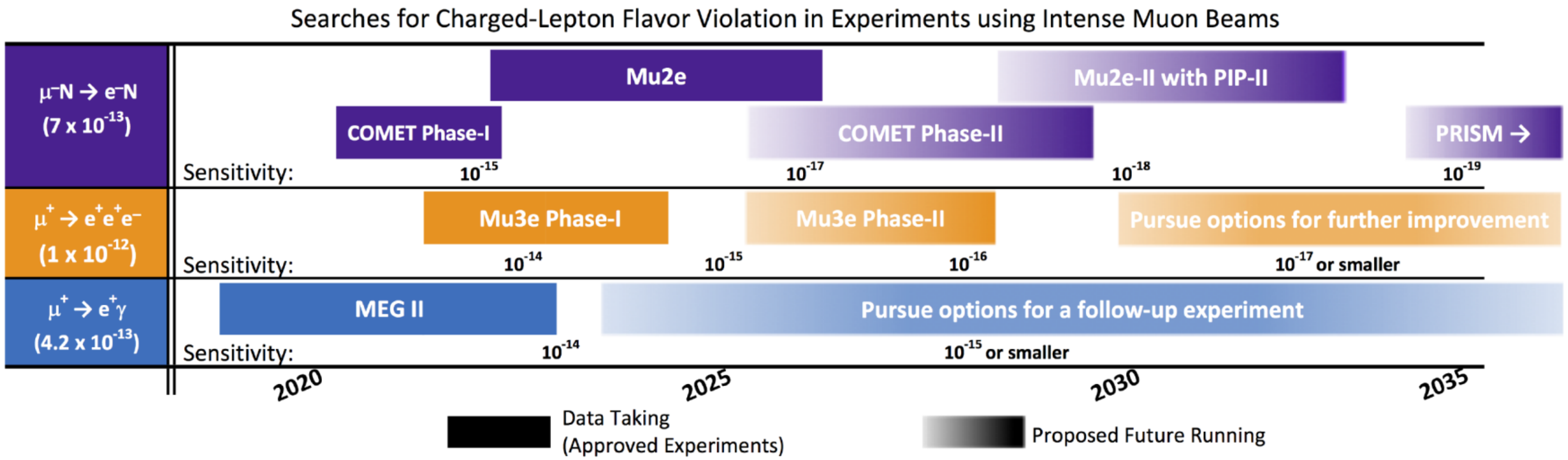
Mu2e Current Status

- Tracker: all straws and panels produced, installing electronics, leak testing
- Calorimeter: all crystals and SiPMs installed
- CRV: all modules produced, cosmic ray test



Mu2e Schedule

- Run 1: end of 2026
- X 1,000 improvement over SINDRUM-II (90% CL)
- PIP-II/LBNF shutdown scheduled in 2028
- 2023 P5 Report recommended continued support for Mu2e in next decade
- Run 2 after LBNF shutdown, expect to reach final X10,000 goal by mid-2030's



2020 European Strategy Physics input on CLFV
arXiv: 1812.06540

Mu2e-II

- An upgrade to the current Mu2e
  - Use ~100 kW of PIP-II 800 MeV protons
  - Achieves an order of magnitude improvement in sensitivity over Mu2e, with $\boldsymbol{R_{\mu e}(90\%\ \mathrm{C.L.}) \sim 6 \times 10^{-18}}$
- Challenges
  - Heat & radiation load, target station (cooling, remote handling)
  - Detector replacement (Tracker, Calorimeter, CRV)
- Timescale
  - 2~3 years after the end of Mu2e
  - Could take data on 2035-2040 timescale, R&D under development now
  - Leverages significant investment in Mu2e and Fermilab Muon Campus

Summary

- **CLFV provides unique information to search for New Physics at the intensity frontier**
- **Mu2e aims at improving the current sensitivity by X10000**
- **Run I will start in 2026, with goal of $R_{\mu e}(Al) < 6.2 \times 10^{-16}$ @90% CL**
- **Look forward to the exciting result in the next few years!**

Thank you!