The Mu2e Experiment — Searching for Charged Lepton Flavor Violation

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02/23/2023

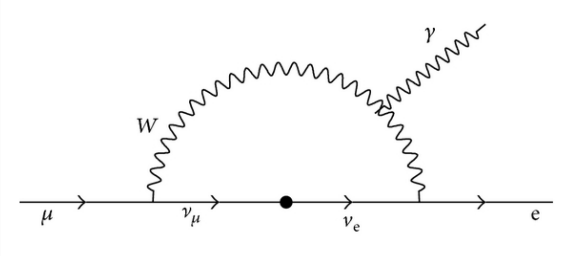
Charged Lepton Flavor Violation

Charged leptons are only fermions without observation of flavor violation

- Quarks mix (CKM)
- Neutrinos oscillate

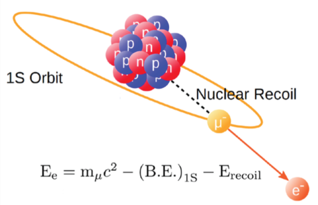
CLFV is required in νSM, but ludicrously suppressed

- $Br(\mu \to e\gamma) \propto (\frac{\Delta m_\nu}{M_W})^4 < 10^{-52}$

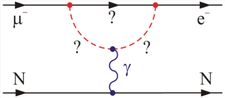


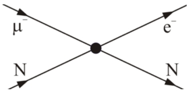
Any experimental observation would unambiguously indicate New Physics

CLFV: $\mu \to e$ conversion

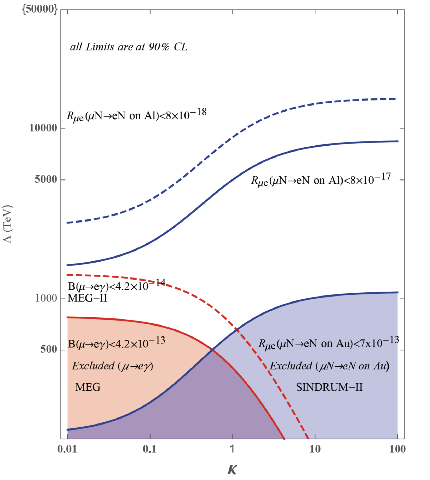


- Monoenergetic $\sim$105 MeV/c conversion-electron (CE)
- Sensitive to energy scales $\mathcal{O}(1000)$ TeV



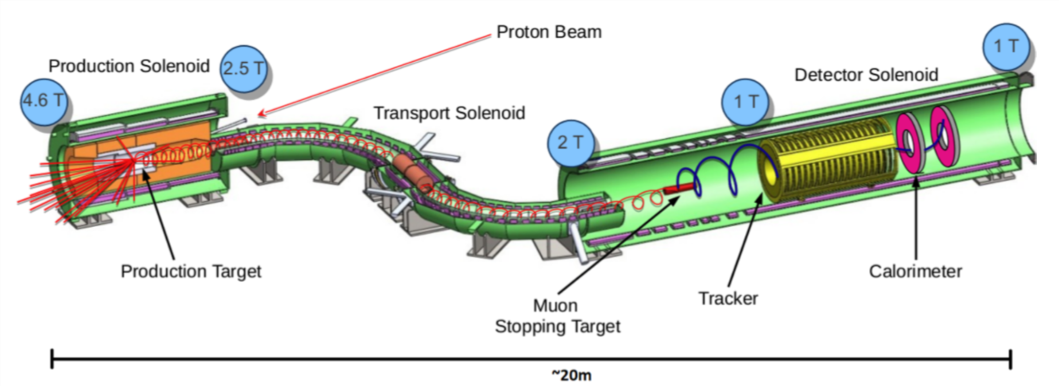


Adapted from A. de Gouvea and P. Vogel,
Progress in Particle and Nuclear Physics 71, 75–92 (2013)



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

Mu2e



Discovery potential of $R_{\mu e} = \frac{\Gamma(\mu^- + N(Z,A) \to e^- + N(Z,A))}{\Gamma(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A))} > 2 \times 10^{-16}$ (5σ)

- $R_{\mu e} < 8 \times 10^{-17}$ (90% CL)
- $\mathcal{O}(10^4)$ improvement of previous result (SINDRUM-II)

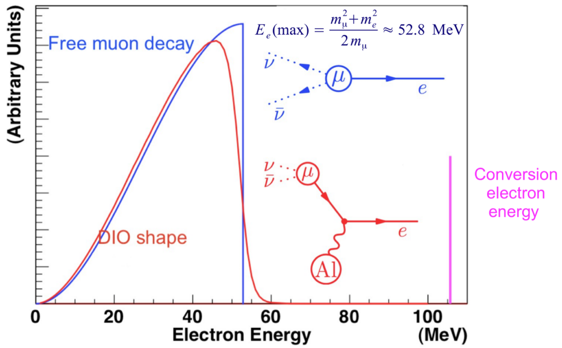
Backgrounds

Intrinsic

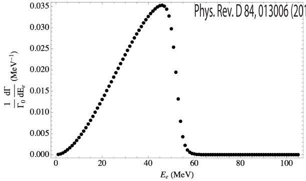
- μ Decay-in-orbit (DIO)
- Cosmic rays
- Mitigate with detector design

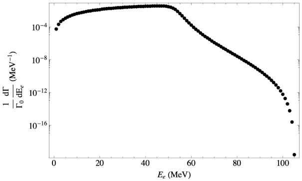
Beam-induced

- Beam electrons (decays-in-flight)
- Radiative pion capture (pions in μ-target)
- Mitigate with accelerator design and μ-target choice



Andrzej Czarnecki, Xavier Garcia i Tormo, and William J. Marciano
Phys. Rev. D 84, 013006 (2011)

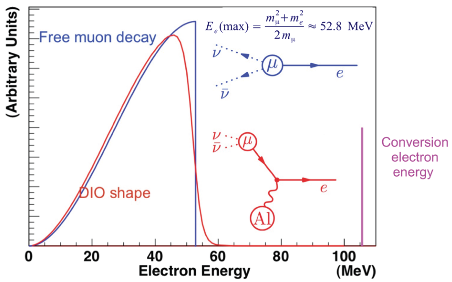


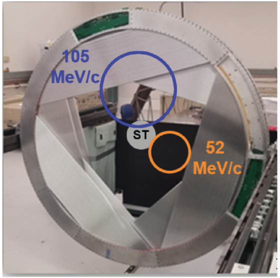


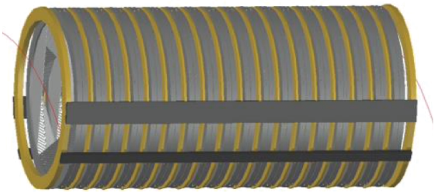
Tracker

Annular disks of straw tubes

- Inner hole (38 cm) reduces flux of high-intensity, low-momentum particles
- 20k mylar straws (15 μm)
- 1 atm 80:20 Ar:CO_2 at 1450 V
- $\sim$ 100 keV/c momentum resolution to separate signal from DIO tail



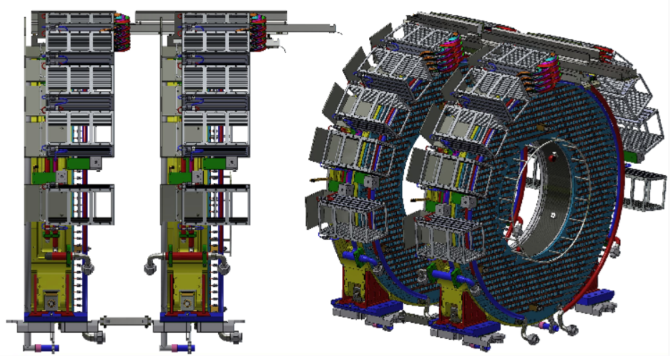




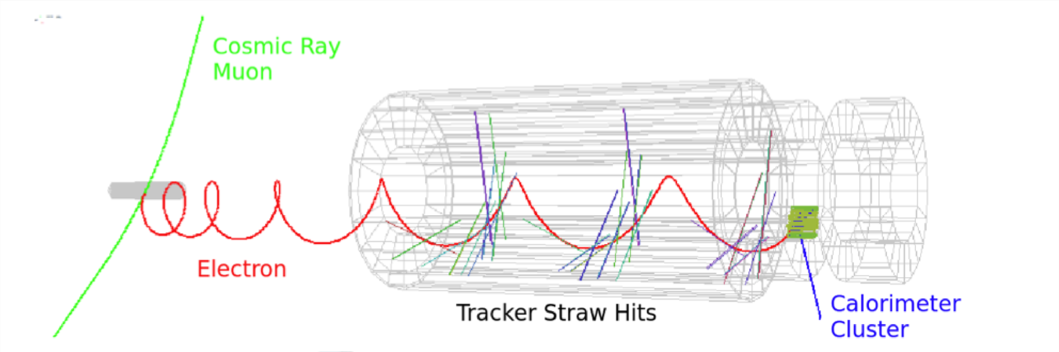
Calorimeter

2 annular disks of 674 undoped CsI crystals

- Provides E/p (along with tracker)
- $\sigma_E/E = \mathcal{O}(10\%)$
- $\sigma_t < 500$ ps
- $\sigma_{x,y} \leq 1$ cm
- $\tau < 40$ ns

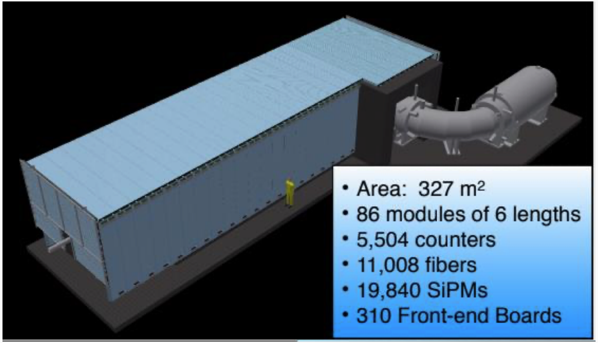


Cosmic ray background

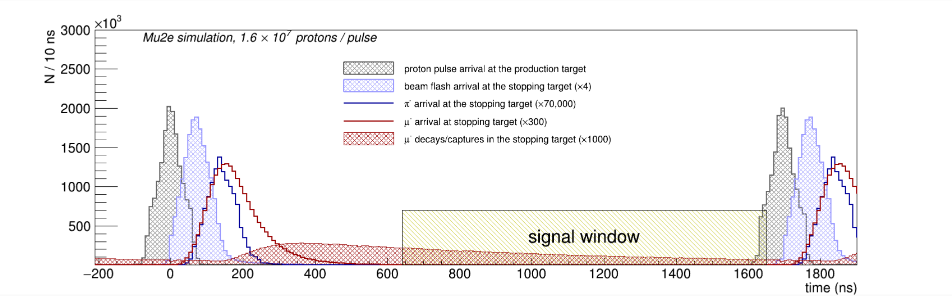


Cosmic Ray Veto

- Expect base rate of ~1 CE-like event / day from cosmic rays
- Need 99.99% veto efficiency
- Solution: 4 layers of extruded polystyrene scintillators surrounding entire detector area
    - Veto events with triple coincidence



Beam backgrounds: pulsed beam and aluminum target

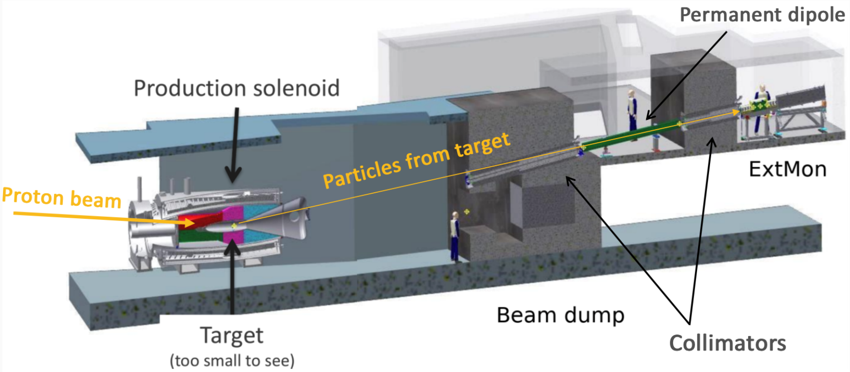


- $\sim$200 ns pulses of $\sim 10^7$ protons at 8 GeV/c, spaced at $\sim$1700 ns
- Muonic aluminum lifetime of 864 ns
- Strategy: Extract muon beam onto Al target, wait for prompt backgrounds to decay, search for CLFV signal

Extinction Monitor

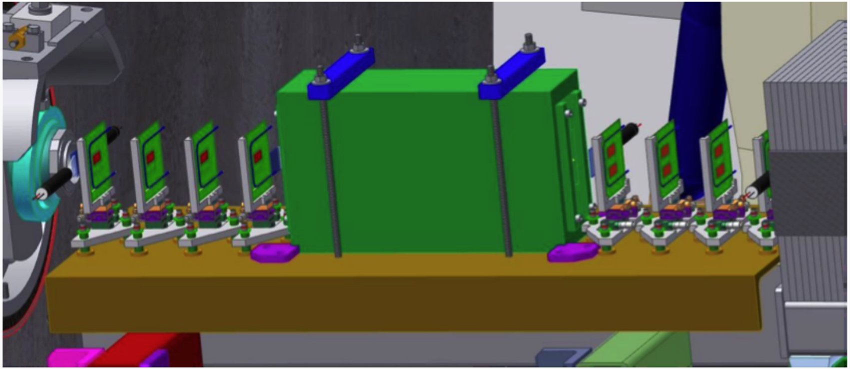
How do we know the signal window is free of residual beam?

- Measure beam extinction as ratio of out-of-time beam to in-time beam
  - Must achieve extinction level of 10^{-10} or better



Extinction Monitor

- Track target-scattered protons using ATLAS silicon pixel sensors and FE-I4b readout chips
- 8 pixel planes and a permanent dipole magnet
  - Detect $\sim$4 GeV/c protons and deflect low-energy secondary particles



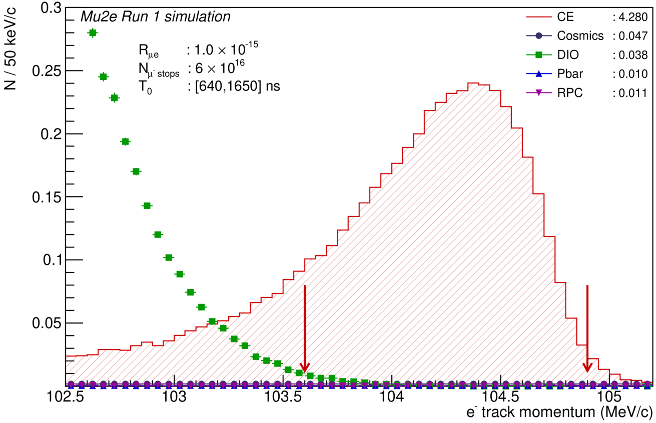
Simulating first physics run (mid-2020s)

Recently completed MC campaign to estimate Run 1 sensitivity

- arxiv:2210.11380

Discovery potential at $R_{\mu e} > 1 \times 10^{-15}$ (5σ)

- $R_{\mu e} < 6 \times 10^{-16}$ (90% CL)
- 10^3 improvement over SINDRUM-II



Summary

Searches for CLFV provide excellent opportunity to probe New Physics

Mu2e will search for CLFV in $\mu \to e$ conversion and improve previous results by $\mathcal{O}(10^4)$ by the end of the decade

Mu2e is currently under construction and performing system integration tests

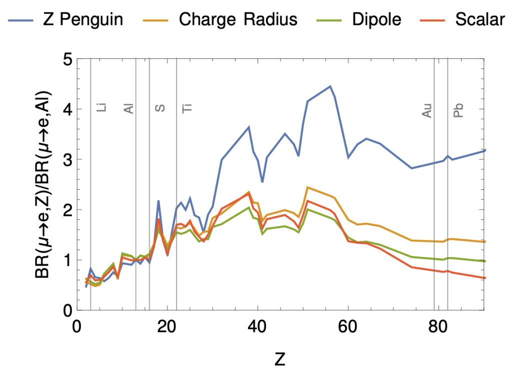
Commissioning underway, Run 1 expected during the middle of this decade

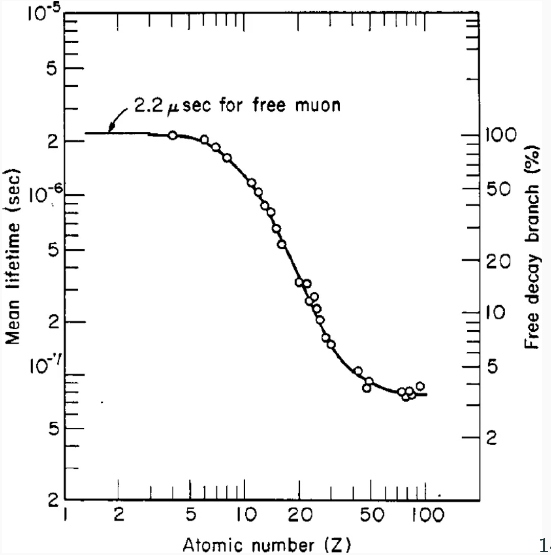
Similar schedule expected for COMET (J-PARC)

Should be an exciting few years!

Backup

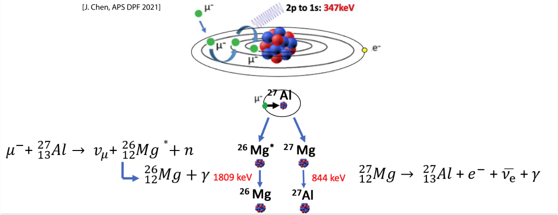
Physics reach and μ-lifetime vs Z

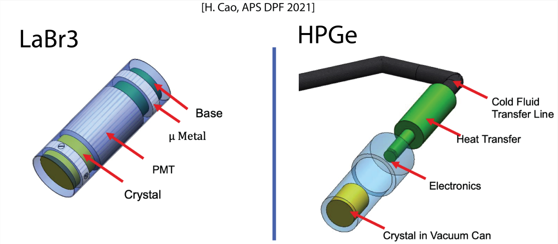




Stopping target monitor

- Need to measure denominator of $R_{\mu e}$
  - Measure rate of muonic atoms to $\mathcal{O}(10\%)$
- System of HPGe and LaBr detectors downstream of Mu2e detect γ spectrum

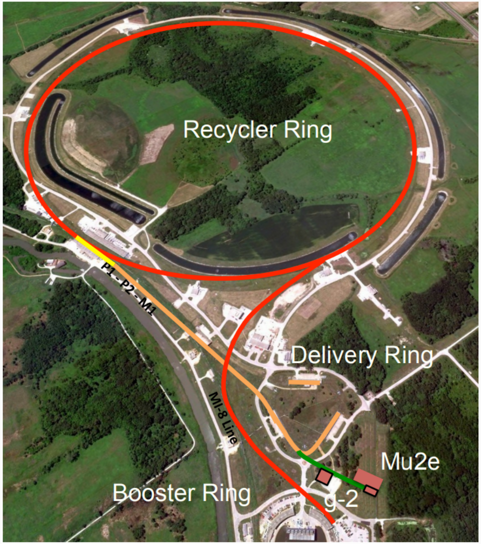




Challenge 1: μ^- beam from FNAL protons

Resonant extraction @ FNAL:

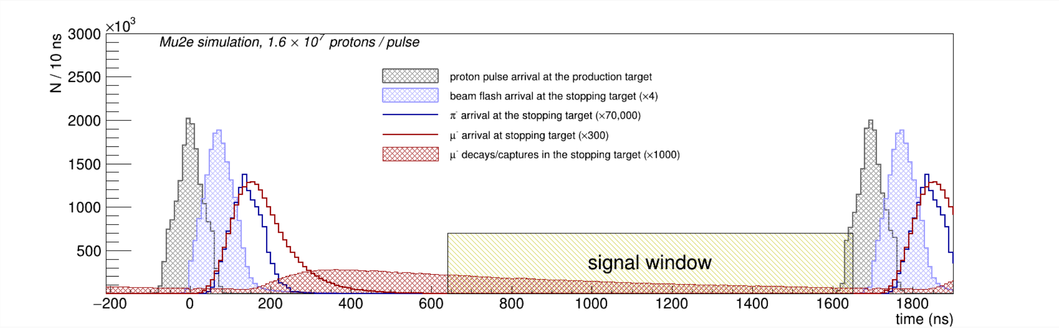
- $\sim 4 \times 10^7$ protons @ 8 GeV
- ~ 1 mm gaussian beam radius
- 250 ns pulses
- 1.7 μs pulse period
- At 2.5 MHz



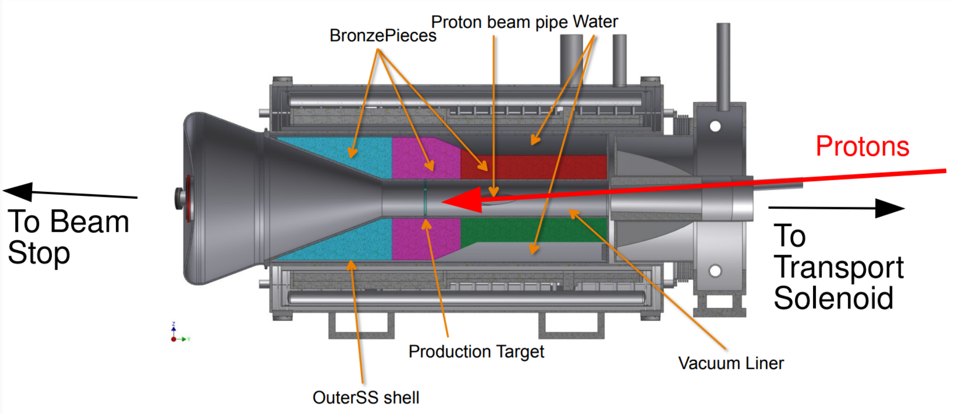
Challenge 2: Ideal Mu2e conditions

Mu2e needs:

- High yield of *stoppable* muons ⇒ low momentum μ^- beam
- Minimal beam-induced backgrounds (i.e. radiative pion capture)
- Low radiation environment



Production Solenoid (PS)



Compact, high-Z pion-production target in high B-field with backwards extraction

Production Target

LaO_2-doped Tungsten, core EDMed from single rod

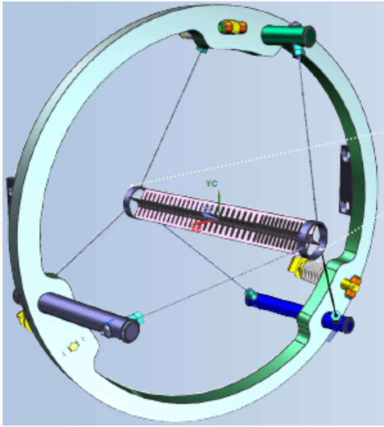
Longitudinally segmented cylinder
⇒ stress management

Longitudinal fins
⇒ thermal and structural management

1mm tungsten spokes

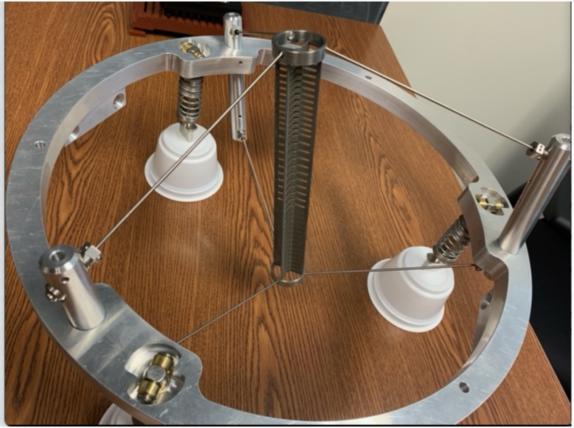
~700 W power absorbtion ⇒ ~1500 K

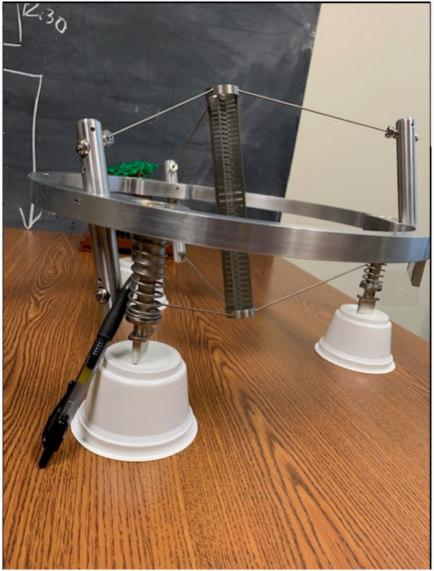
- Radiatively cooled



Expect target lifetime of ~1 year: ⇒ replace during summer shutdowns

Production Target





Future work and remaining questions

First target is in-hand

- Mu2e Run 1 scheduled for $\sim$2026 ($\leq$ 1 year long, $\sim$0.5x beam intensity)

First-of-its-kind target: fully simulation-driven optimization and stress analysis

- Designed with nominal beam intensity @ 1 year: $\Rightarrow$ Run 1 should not be a concern
- Target failure and replacement outside of shutdown window slows experiment

What can we test and how?

- Are expected performance degradations (e.g. thermal stresses, oxidation, creep) within tolerances?

Can we setup Mu2e target testing at FNAL?

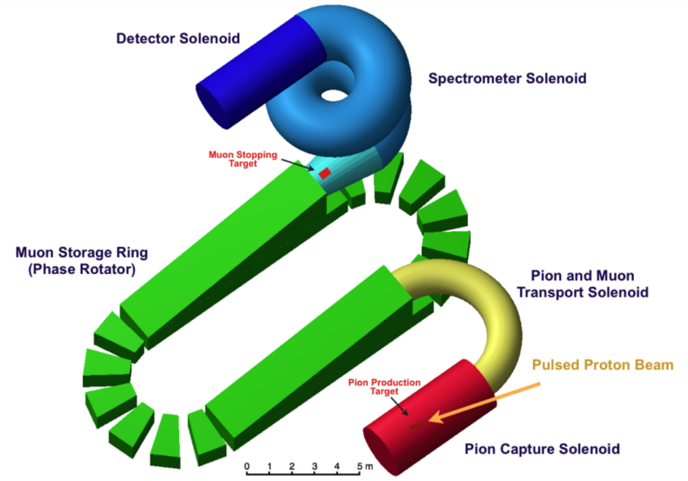
PIP-II upgrade

TABLE III. Mu2e and Mu2e-II Proton beam parameters

Parameter	Mu2e	Mu2e-II	Comment
Proton source	Slow extraction from DR	PIP-II Linac	
Proton kinetic energy	8 GeV	0.8 GeV	
Beam Power for expt.	8 kW	100 kW	Mu2e-II can be increased
Protons/s	6.25×10^{12}	7.8×10^{14}	
Pulse Cycle Length	1.693 μs	1.693 μs	variable for Mu2e-II
Proton rms emittance	2.7	0.25	mm-mrad, normalized
Proton geometric emittance	0.29	0.16	mm-mrad, unnormalized
Proton Energy Spread (σ_E)	20 MeV	0.275 MeV	
$\delta p/p$	2.25×10^{-3}	2.2×10^{-4}	
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}	
Stopped μ per cycle		1.2×10^{5}	

Mu2e-II whitepaper: arvix:2203.07569

$\mu \to e$ at the Advanced Muon Facility (proposed)



AMF whitepaper: arvix:2203.08278