Mu2e-II: Status and Perspectives

Mu2e

PIP-II

J. Miller (Boston University)

On behalf of Mu2e and Mu2e-II

What is Mu2e?

- Search for the occurrence of neutrinoless muon to electron conversion in the near field of a nucleus

$$R_{\mu e} = \frac{\Gamma(\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al)}{\Gamma(\mu^- + {}^{27}_{13}Al \rightarrow capture)}$$

  - An example of charged lepton flavor violation
- Goal $R_{\mu e}\ (90\%\ \mathrm{CL}) < 8\times10^{-17}$ $R_{\mu e}(5\sigma) = 2\times10^{-16}\ (5\sigma)$
  - x10000 improvement on current best experimental limit
  - SM prediction (estimate based on neutrino oscillation rate) is undetectably tiny, O(10^{-50})
  - Detection of a signal would be a definitive sign of new physics
- Timescale
  - Now under construction at Fermilab
  - Uses ~8 kW of 8 GeV protons originating in the Booster
  - Run 1: in 2026 – world-best goal x1000 improvement on current limit before shutdown
  - Run 2: 3-4 years running after LBNF/PIP-II shutdown, x10000 improvement

What is Mu2e-II?

- An upgrade to the current Mu2e experiment that
  - Uses ~100 kW of PIP-II 800 MeV protons
  - Leverages as much of Mu2e investment as reasonably possible
  - Achieves an order of magnitude improvement in sensitivity over Mu2e (i.e. probes $R_{\mu e}$ (90% CL) ~ 6 x 10^{-18} level, extends Λ_{NP} reach by x2)
- Timescale
  - Could start a few years after end of Mu2e with conceptual design work starting now
  - (4+1) y of data taking at full intensity
  - Could take data on 2035-2040 timescale
  - R&D on critical items is needed now
    - The most critical item is developing a production target that can withstand the radiation and heat loads

Outline

- Science Motivation
- Muon Beamline
- Proton Beam Lines
- Detectors
- Sensitivity Estimates
- Summary

Science Motivation

Science Motivation

- CLFV is a deep & unique probe of New Physics (NP) parameter space
  - Next generation experiments planned in Europe, Asia, and Americas
    - This program is essential in our attempt to understand LFV- we do not know the mechanism for neutrino oscillations nor do we know why we have never seen charged lepton flavor violation
  - Probes complementary regions of NP space relative to rest of HEP program
  - Measured rates provide model discrimination

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu\to eee)}{\mathrm{BR}(\mu\to e\gamma)}$	$\frac{\mathrm{CR}(\mu N\to eN)}{\mathrm{BR}(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6\times 10^{-3}$	$10^{-3}-10^{-2}$
Type-I seesaw	Loop*	Loop*	$3\times 10^{-3}-0.3$	$0.1-10$
Type-II seesaw	Tree	Loop	$(0.1-3)\times 10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop†	Loop* †	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05-0.5$	$2-20$

from L. Calibbi and G. Signorelli, Riv. Nuovo Cimento, 41 (2018) 71

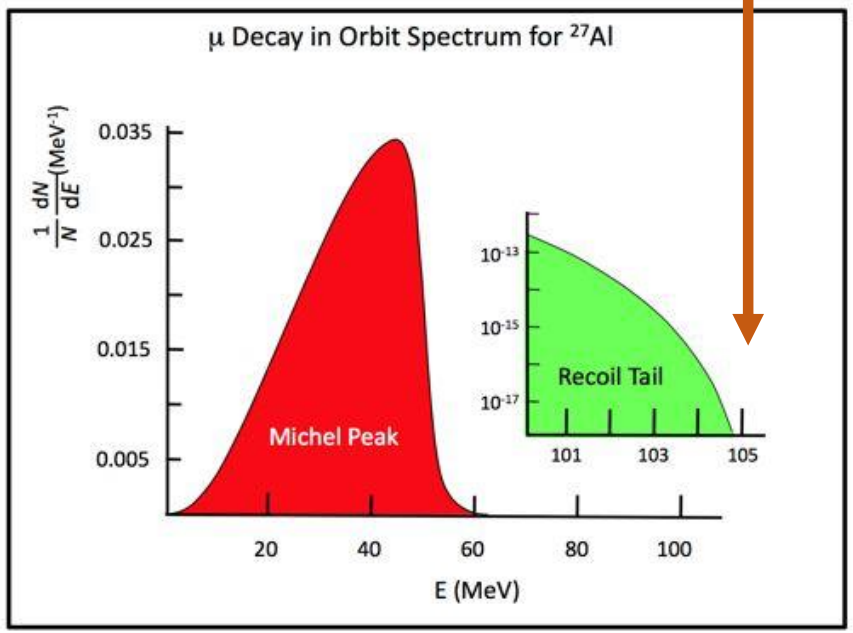
arXiv:1709.00294v2[hep-ph]

TABLE VII. – *Pattern of the relative predictions for the $\mu \to e$ processes as predicted in several models (see the text for details). It is indicated whether the dominant contributions to $\mu \to eee$ and $\mu \to e$ conversion are at the tree or at the loop level; Loop* indicates that there are contributions that dominate over the dipole one, typically giving an enhancement compared to Eq. (40, 41).* † *A tree-level contribution to this process exists but it is subdominant.*

Science Motivation

- Direct μ→e conversion is the "Golden Channel" of CLFV
  - Conversion electron energy is well above most ordinary decay electrons
    - e.g. a challenge to extend μ→eγ beyond MEG-II
  - Ultimate limit could potentially be pushed even beyond Mu2e-II to $<10^{-19}$

$$\mu N \rightarrow eN$$



Winner!
$\mu^- N \rightarrow e^- N$

Science Motivation

- Direct $\mu \rightarrow e$ conversion is the "Golden Channel" of CLFV
  - $\mu \rightarrow e$ provides likely best sensitivity to CLFV across many NP models

	s	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 4.4 E-8	10^{-9} - 10^{-10} (Belle II, LHCb)
$\tau \rightarrow \mu\mu\mu$	BR < 2.1 E-8	
$\tau \rightarrow eee$	BR < 2.7 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	NA62
$K^+ \rightarrow \pi^+e^-\mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 2.8 E-9	LHCb, Belle II
$B^+ \rightarrow K^+e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG-II)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-15} (μ3e Phase-I)
$\mu^-N \rightarrow e^-N$	$R_{\mu e}$ < 7.0 E-13	~8x10^{-17} (Mu2e, COMET Phase-II)

~6 x 10^{-18} (Mu2e-II)

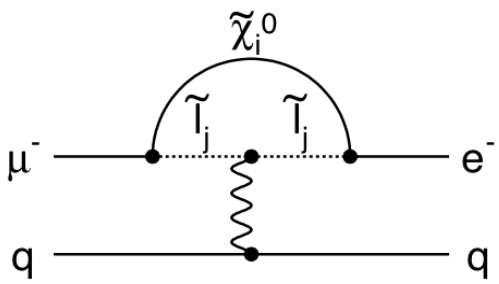
(Current Limits taken from the PDG)

Science Motivation

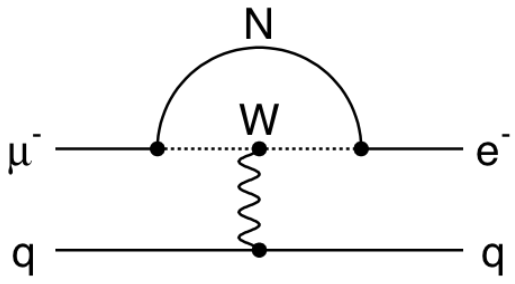
- Direct $\mu \rightarrow e$ conversion is the "Golden Channel" of CLFV
  - Sensitive to broad array of New Physics models

Mu2e comparable To $\mu \rightarrow e\gamma$

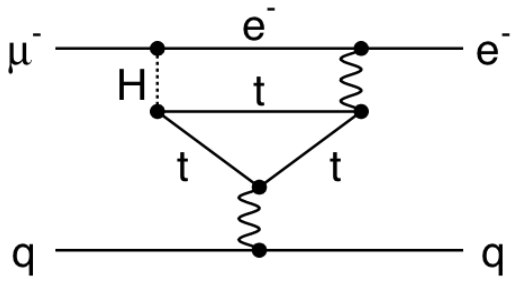
Loops



Supersymmetry



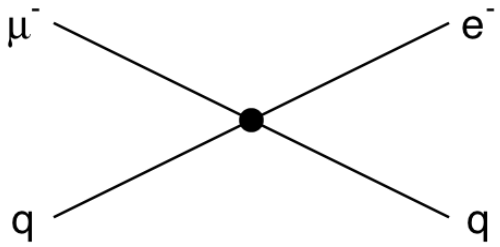
Heavy Neutrinos



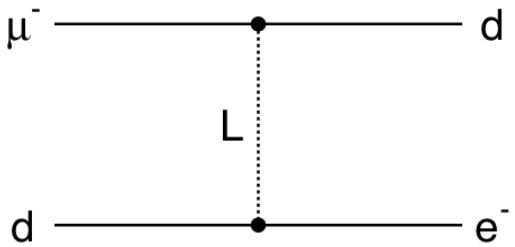
Extended higgs models

Mu2e much more sensitive vs $\mu \rightarrow e\gamma$

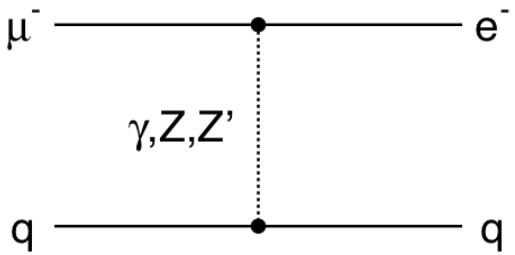
Contact Terms



Compositeness



Leptoquarks



New Heavy Bosons / Anomalous Couplings

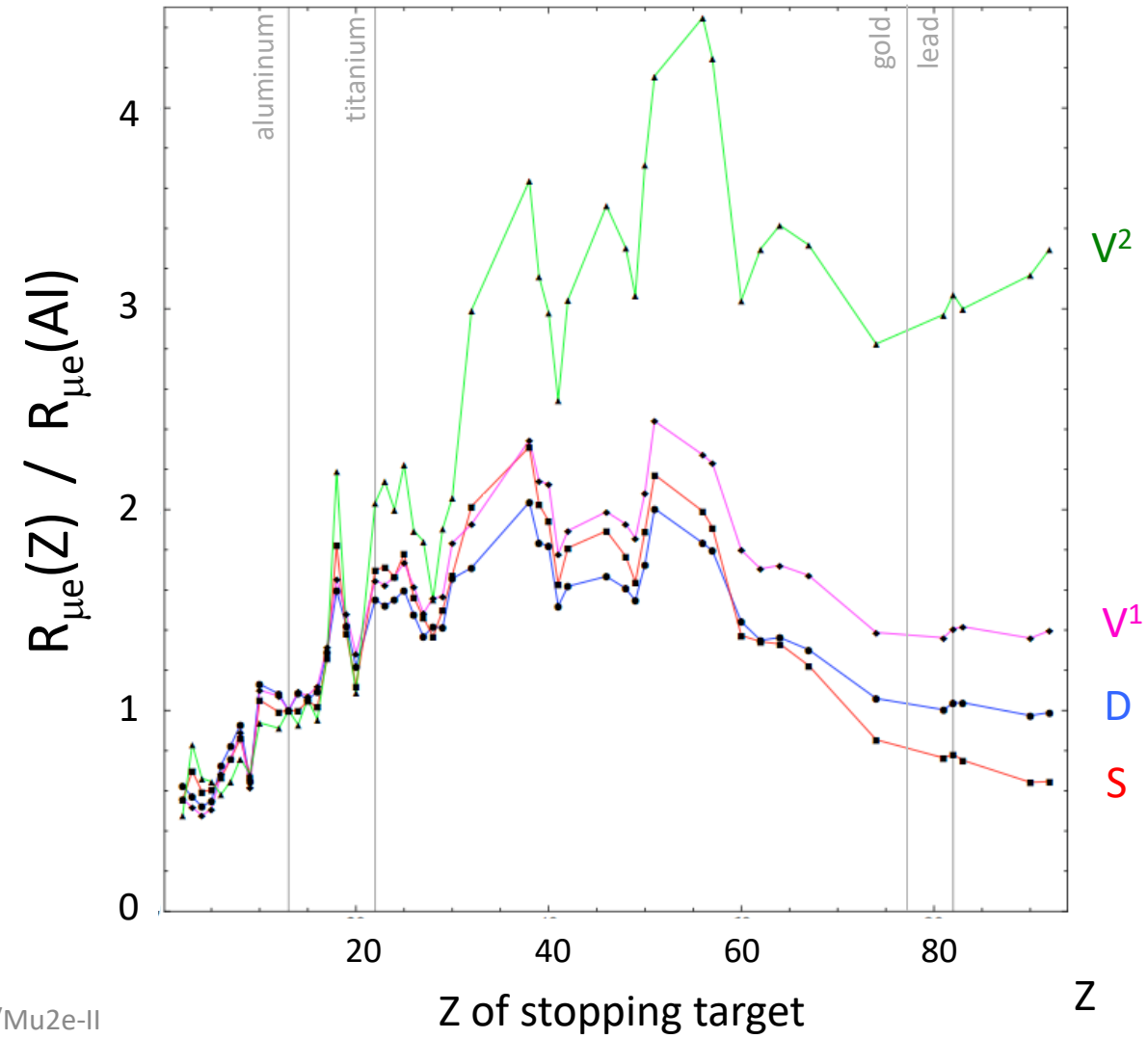
Closed caption box size

Science Motivation

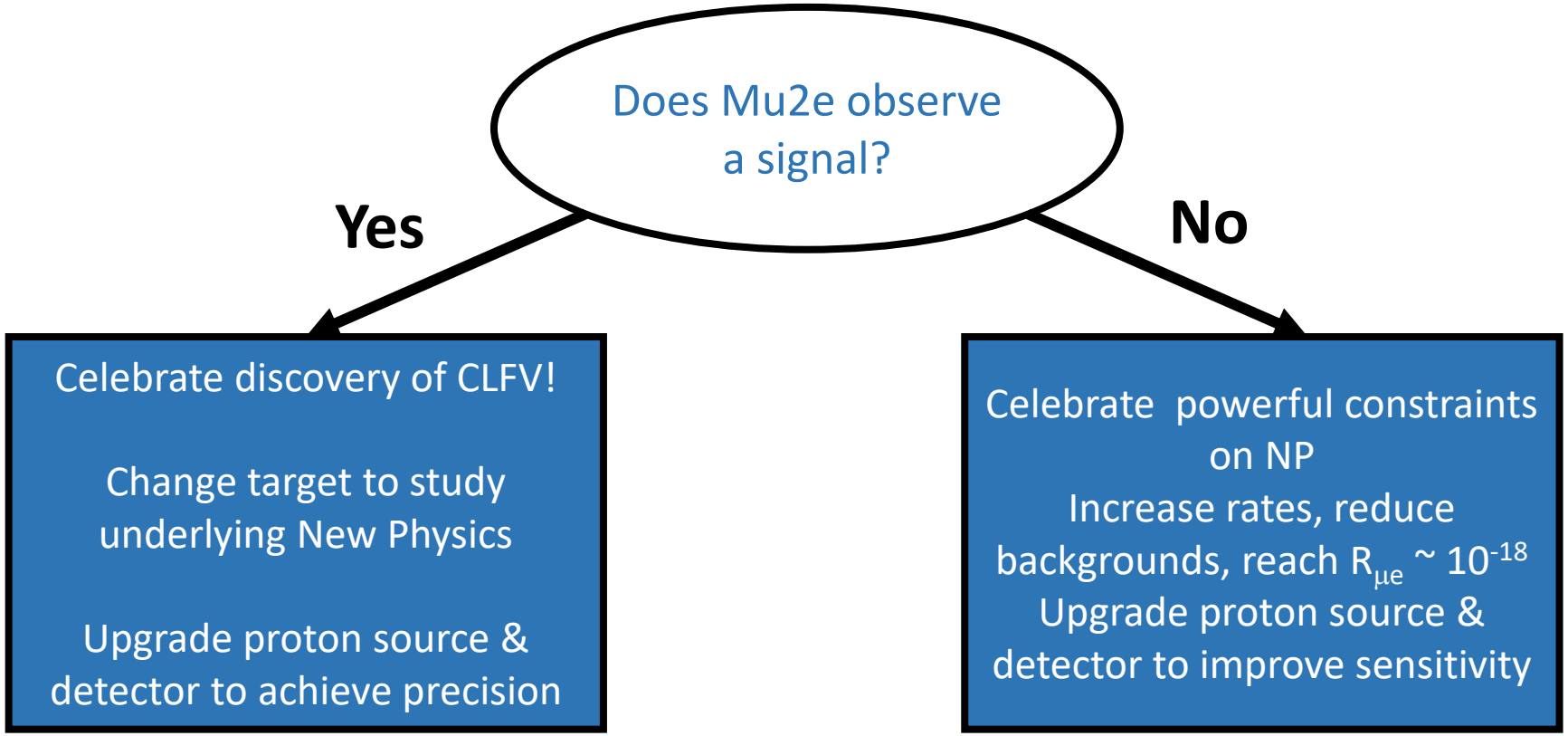
- Direct μ→e conversion is the "Golden Channel" of CLFV
  - Once an observation is made, can change stopping target to probe underlying NP operator
  - Mu2e and Mu2e-II technique has limits precluding high-Z materials due to short muonic atom lifetimes
  - Examples of muonic atom lifetimes:

Al (864 ns),), Ti((330 ns), Au(72.6 ns)

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)



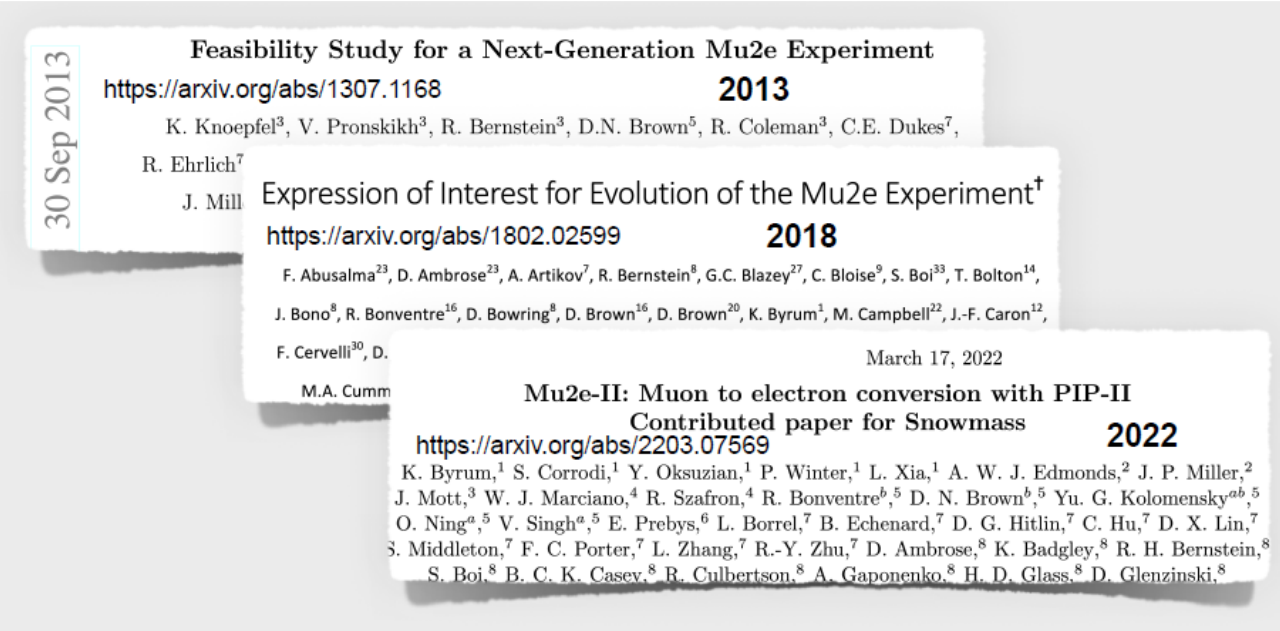
Mu2e-II Motivation



- **At conclusion of Mu2e there's a strong motivation to upgrade proton source and detector to further pursue New Physics – Mu2e-II**

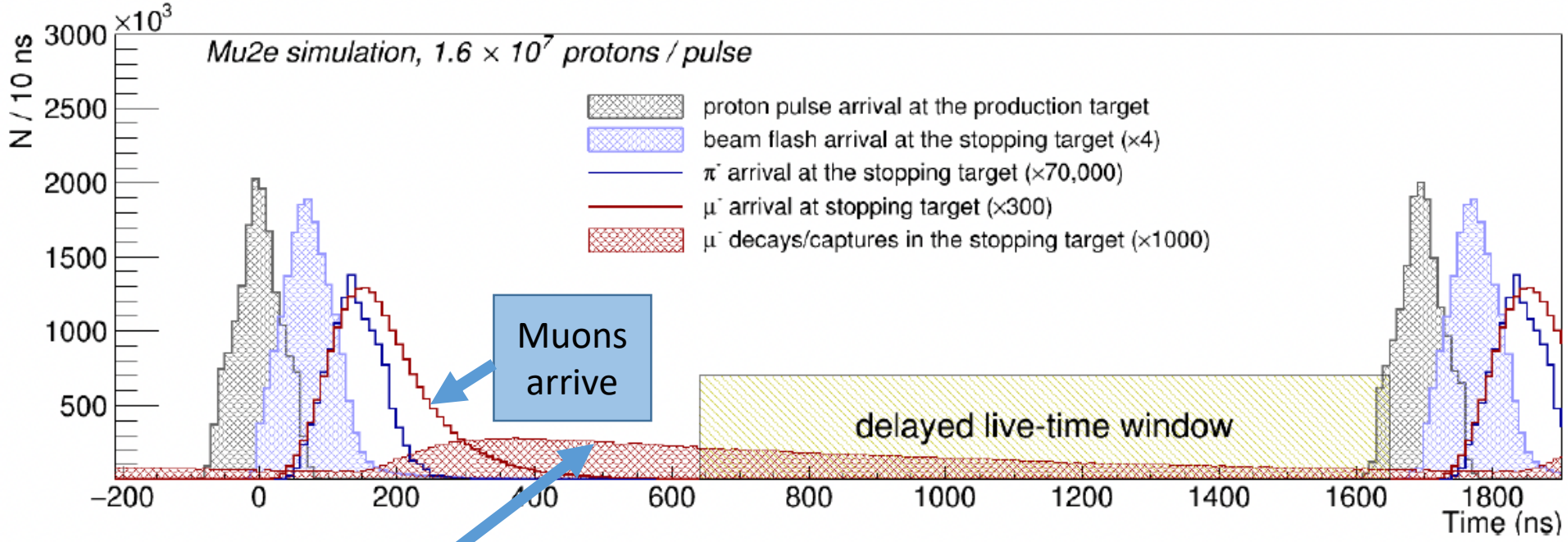
Mu2e-II Experimental Concept

- Mu2e-II Experimental concept is a natural extension of Mu2e
- Studies of feasibility started a decade ago
  - Since then multiple workshops and several study papers
- Mu2e endorsed by P5 in 2014
- Expression of Interest submitted to Fermilab PAC 2018
  - PAC recommended support for high-priority R&D items
- 2 LDRD's: production target and tracker
- 12 LOI's on Mu2e-II subsystems submitted to Snowmass21
- Snowmass22 White Paper arXiv:2203.07569
  - 108 signatories from 34 institutes and 7 countries
  - Snowmass 22 endorses the physics goal and recommends Mu2e-II as natural progression in the muon program



Muon Beamline

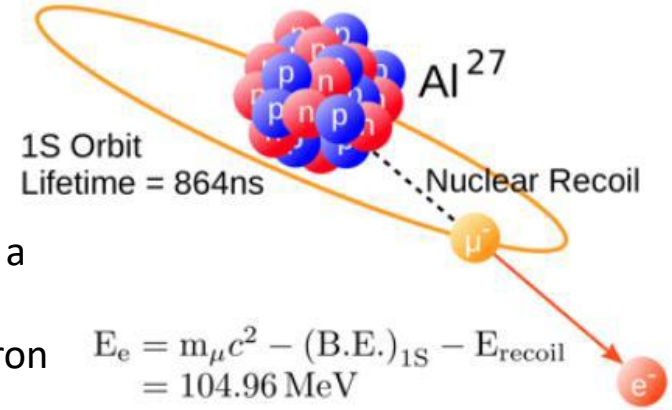
Pulsed beam to reduce background



Muonic Al atoms 864 ns life

- Pulsed proton beam
  - ~700 ns delay before beginning 1 microsec live gate
  - prompt background dies away
- Extinction factor (rate of out-of-time protons) of 10^{-10} is required for Mu2e, 10^{-11} for Mu2e-II

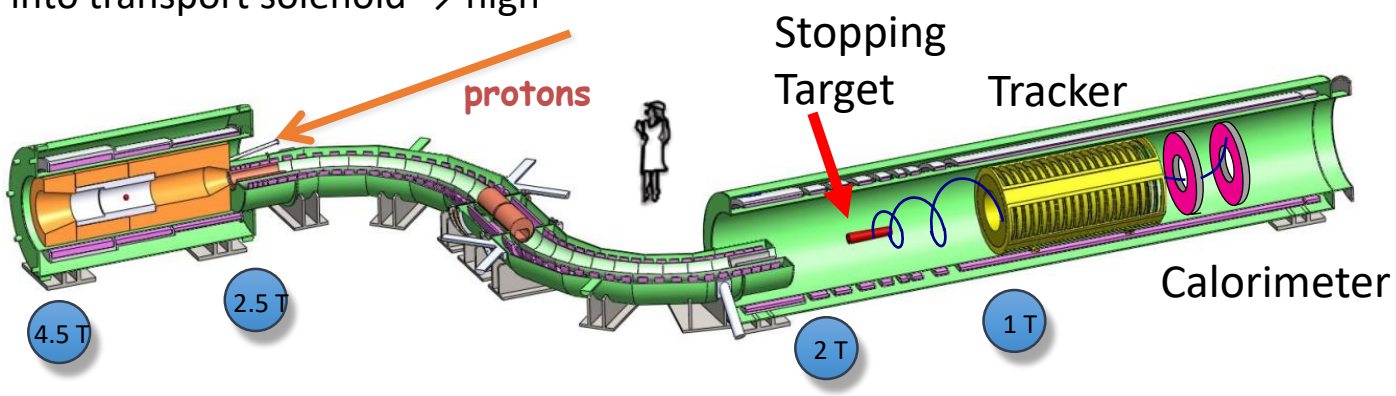
Mu2e Experimental Apparatus



Production Target / Solenoid (PS)

- Proton beam strikes target, producing pions
- Graded magnetic field contains pions/muons and collimates them into transport solenoid → high muon intensity

Muon converts in the field of a nucleus that is left intact
Signal: Mono-energetic Electron



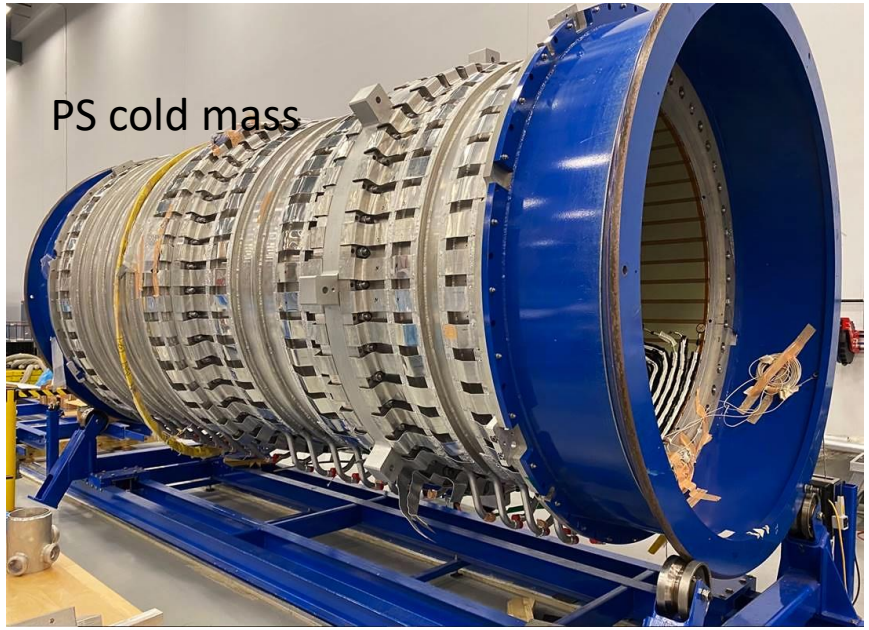
Transport Solenoid (TS)

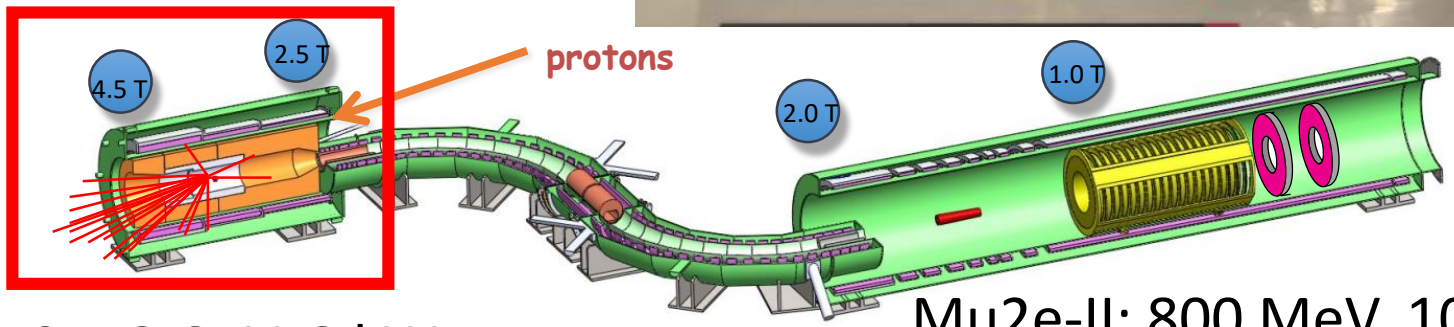
- Collimator selects low momentum, negative muons
- Antiproton absorber
- The S shape eliminates photons and neutrons at detectors

Target, Detector and Solenoid (DS)

- Stop muons on Al target
- Measure electron momentum in tracker and energy in calorimeter
- Graded field "reflects" conversion electrons emitted upstream back toward detectors, improving efficiency
- Center apertures in detectors allow copious low energy electrons from muon decays to spiral into a downstream beam dump

Production Solenoid





Mu2e: 8 GeV, 8 kW protons

- All 3 PS coils wound, assembled on cold mass
- Solenoid delivery from vendor ~Sept 2023
- Radiatively cooled W target
- Heat and radiation shield: Thick bronze shield protects superconductor, reduces backgrounds to detectors

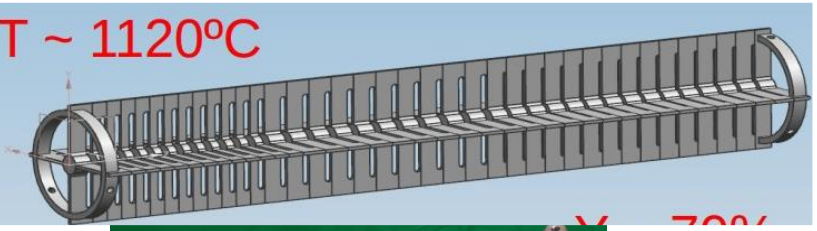
Mu2e-II: 800 MeV, 100 kW protons

- Stopped muons per watt comparable, 8 GeV vs 800 MeV
- Challenge: design a target that can handle very high heat and rad loads
- Replace bronze heat and radiation shield with tungsten shield
- Not clear if PS solenoid will need to be replaced due to radiation damage or need for a larger radius to accommodate thicker shield
- Protons curve in field, injection path must be modified
- Proton beam dump will have to be moved
- Overhead shielding must be substantially increased for rad safety

Production Targets

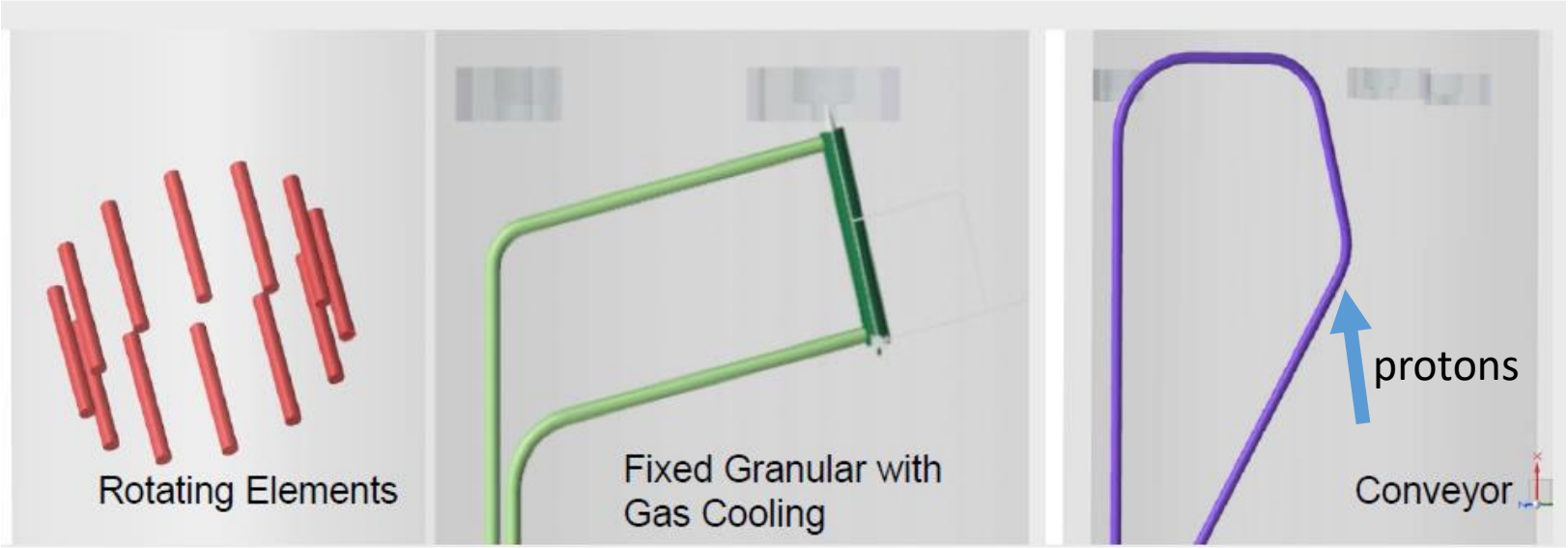
Mu2e Production Target

- Complete
- 16cm long x 6 mm diameter
- Radiatively cooled W with fins
- Supported by ‘bicycle spokes’
- Expect to replace annually with specially-designed remote handler



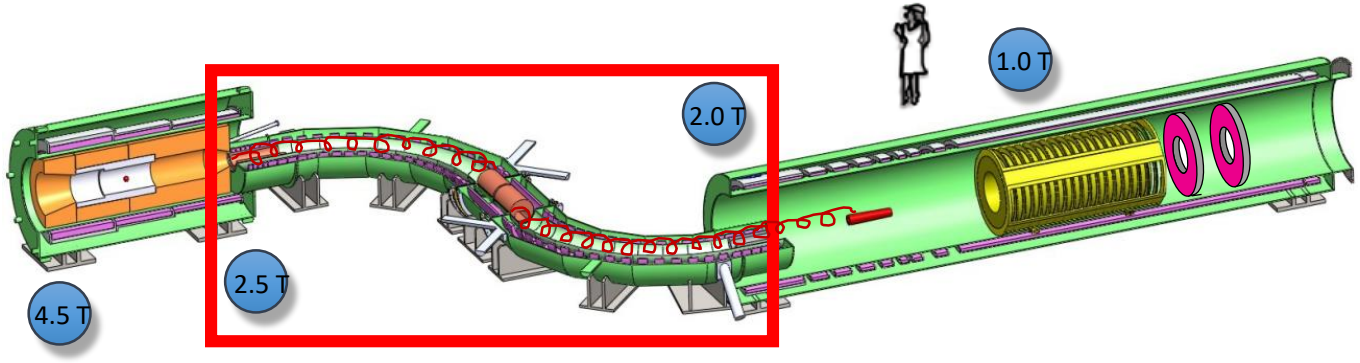
Mu2e-II Candidate targets

- Fermilab LDRD supports target investigations
- Conveyor prototype is current front-runner
- Second prototype just arrived
  - Sprocket drive with steel spheres
  - Will investigate pushing spheres with cooling helium gas flow
- Simulations ongoing of muon yield, thermal stress, radiation damage, residual activation, radiation and heat loads
- Synergy with other target groups e.g. muon collider, COMET, and AMF are being discussed, including discussion of liquid metal targets



Mu2e Transport Solenoid

Assembly at Fermilab HAB facility
Coils manufactured by Italian vendor



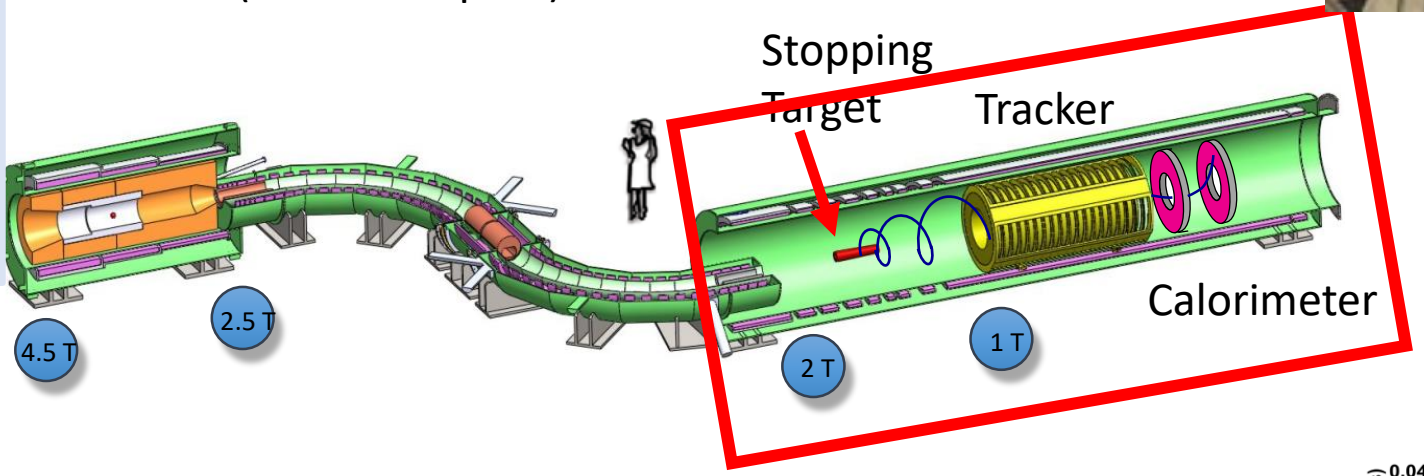
Transport Solenoid (TS)

- Delivery to Mu2e hall expected Oct 2023
- thin absorber in center can be removed - 800 MeV beam does not produce antiprotons
- No or minor changes anticipated for Mu2e-II upgrade
- Assumes upstream portion does not suffer excessive radiation damage from Mu2e operation
- For Mu2e-II: Perhaps we can reduce aperture to reduce average momentum of muons, stopping a larger fraction in a thin target and they will arrive later so more survive into live window.

Mu2e Detector Solenoid

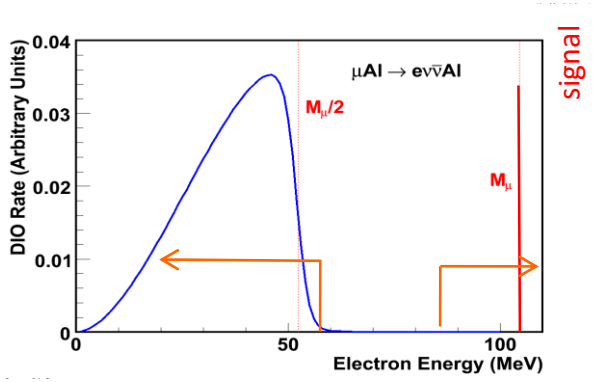
10/11 DS coils wound and epoxied
Cold mass cryo supports prepared
Delivery to Fermilab expected Feb 2024
(On critical path)

DS11 coil being wound



Mu2e Stopping Target

- Complete
- 37 Al foils, 0.1 mm thick
- 2 cm spacing,
- 43 mm diameter hole
- Each foil suspended by 3 spokes of 3 mil W wire



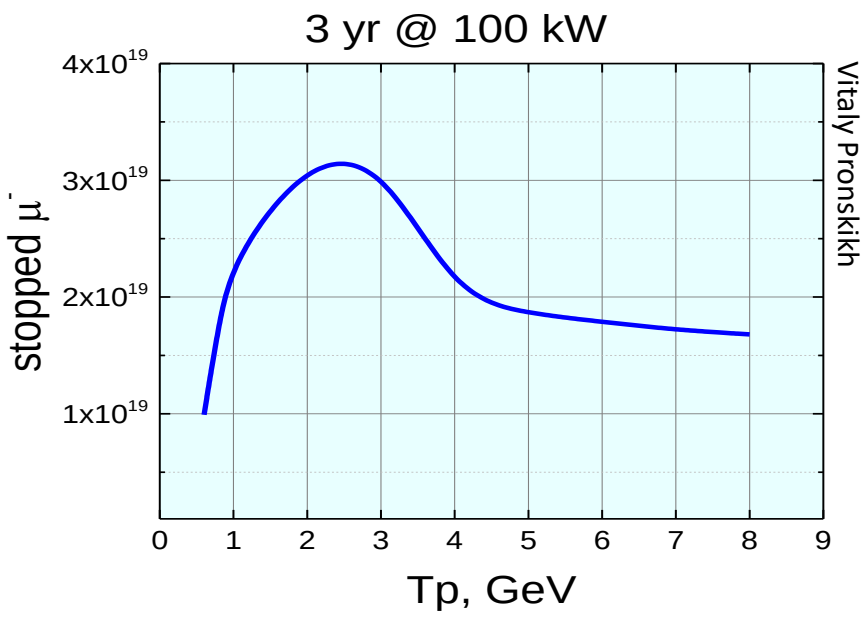
"Hollow" tracker has very small acceptance for Michels and high acceptance for high-E signal

Proton Beam Lines

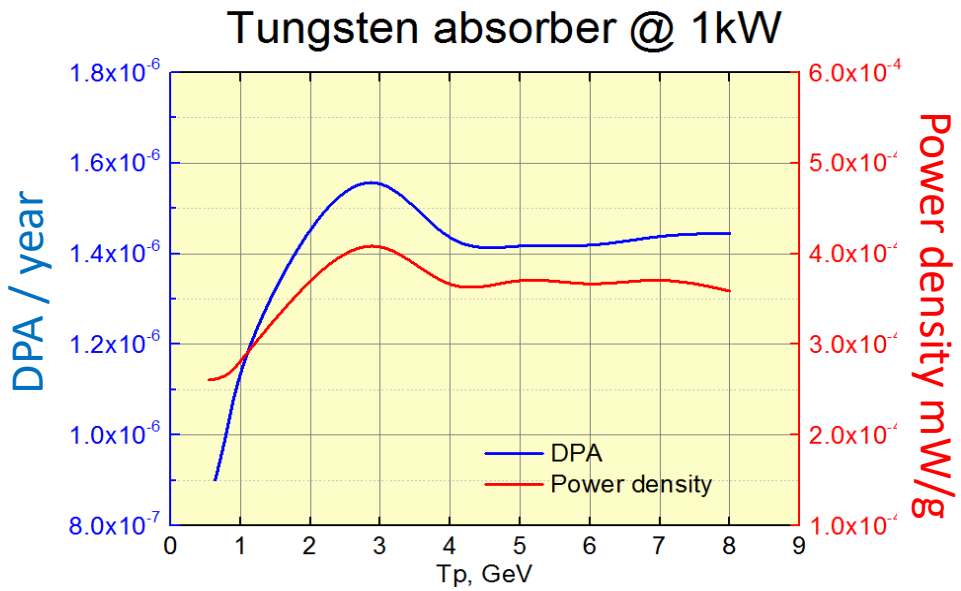
Studies of proton beam energy (arXiv:1612.08931)

(assuming no change in geometry of Heat & Radiation Shield or production target)

Muon Yield Studies



Coil Damage Studies

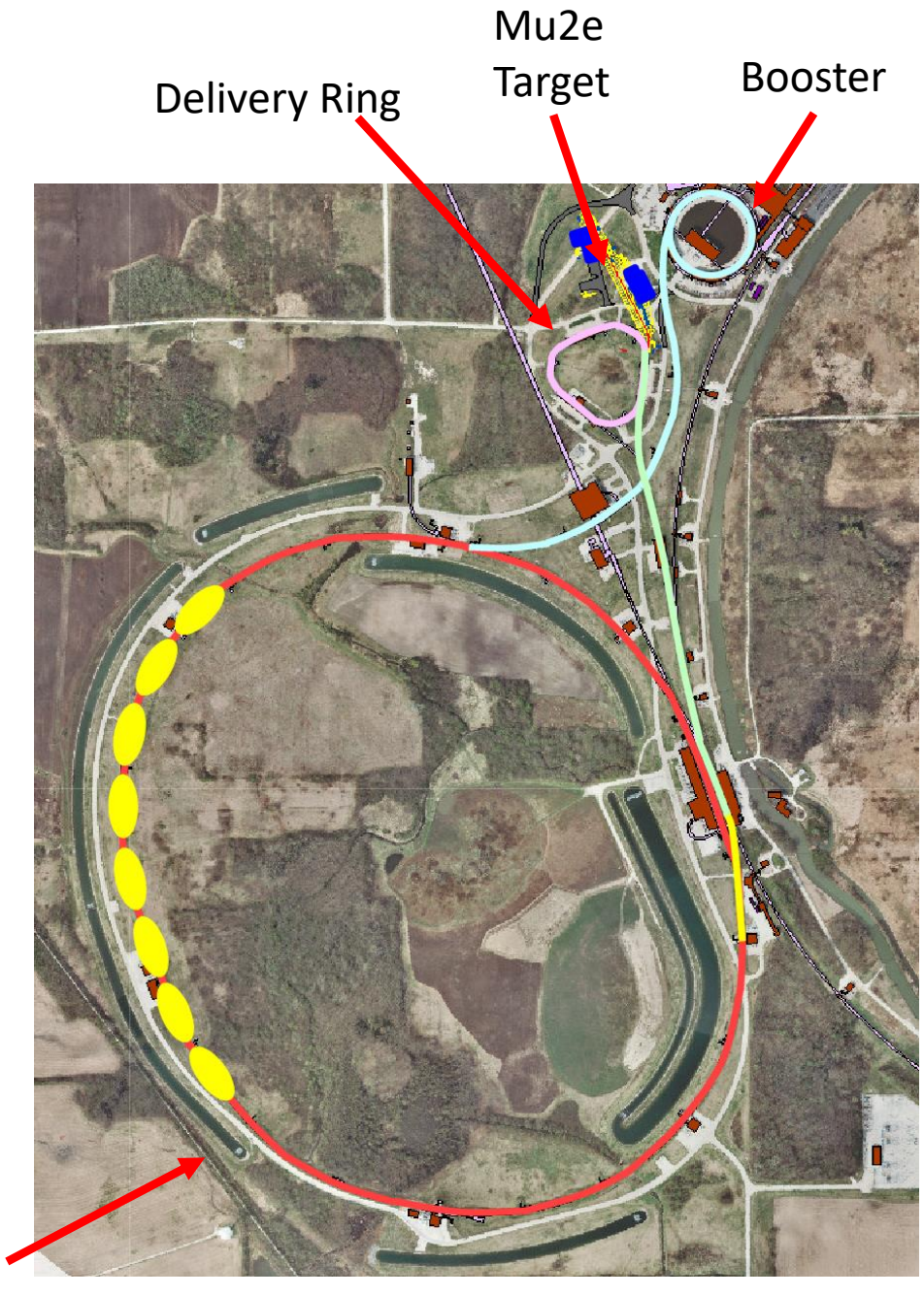


(nb. PS conductor can tolerate ~5×10^{-5} DPA/yr and ~3×10^{-2} mW/g Peak Power density)

- Muon yield at 0.8 GeV is ~same as at 8 GeV, while coil damage is ~30% smaller
- Strongly prefer an energy below pbar production threshold (E < 4 GeV) to avoid antiprotons
- 800 MeV from PIP-II is good, but higher energies, 2-3 GeV would be better
- At 2.5 GeV, per watt, we could have ~3x more muons, x~1/3power in target – but need thicker HRS
- Upgrades to shielding and PS required so that it can tolerate 100 kW

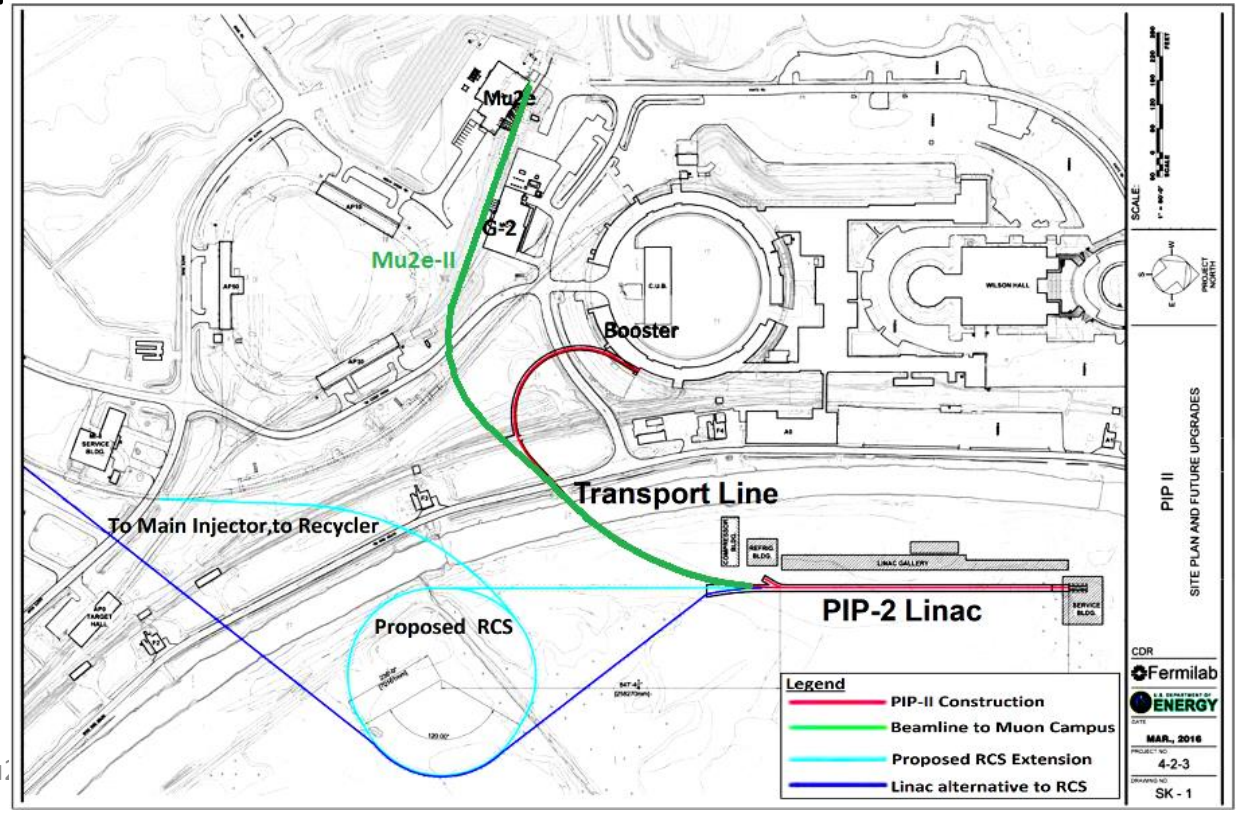
Mu2e: proton delivery

- Current beam-sharing with neutrino program
  - get 0.4 s of pulsed beam per 1.4 s Booster cycle
  - Will be adjusted as Booster cycle time decreases
- Booster→Recycler→Delivery ring (storage ring)
- Peel off small fraction of stored beam every cyclotron turn (period=1695 ns)
- Resonant extraction is challenging
  - commissioning is commencing early (now)
- Mu2e has priority muon running for current run period to develop the proton beam line and extraction
- Run 1 (2026 before LBNF/PIP-II shutdown) will use the Booster and current Linac,
- Run 2, after shutdown, use new PIP-II Linac to inject into Booster

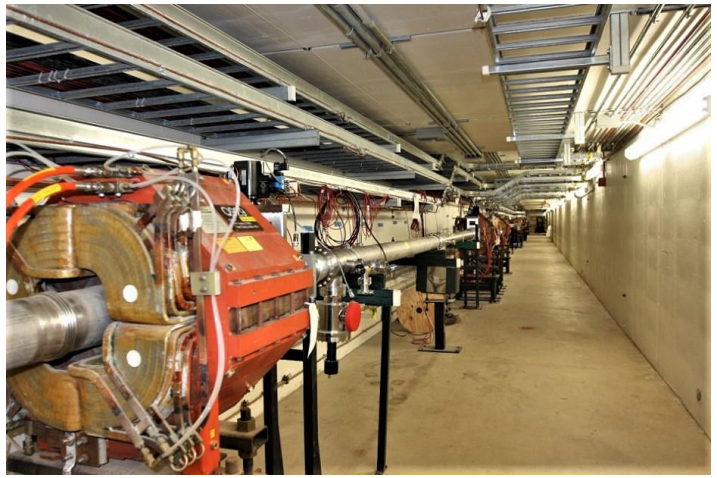


Mu2e-II beamline using PIP-II Linac protons

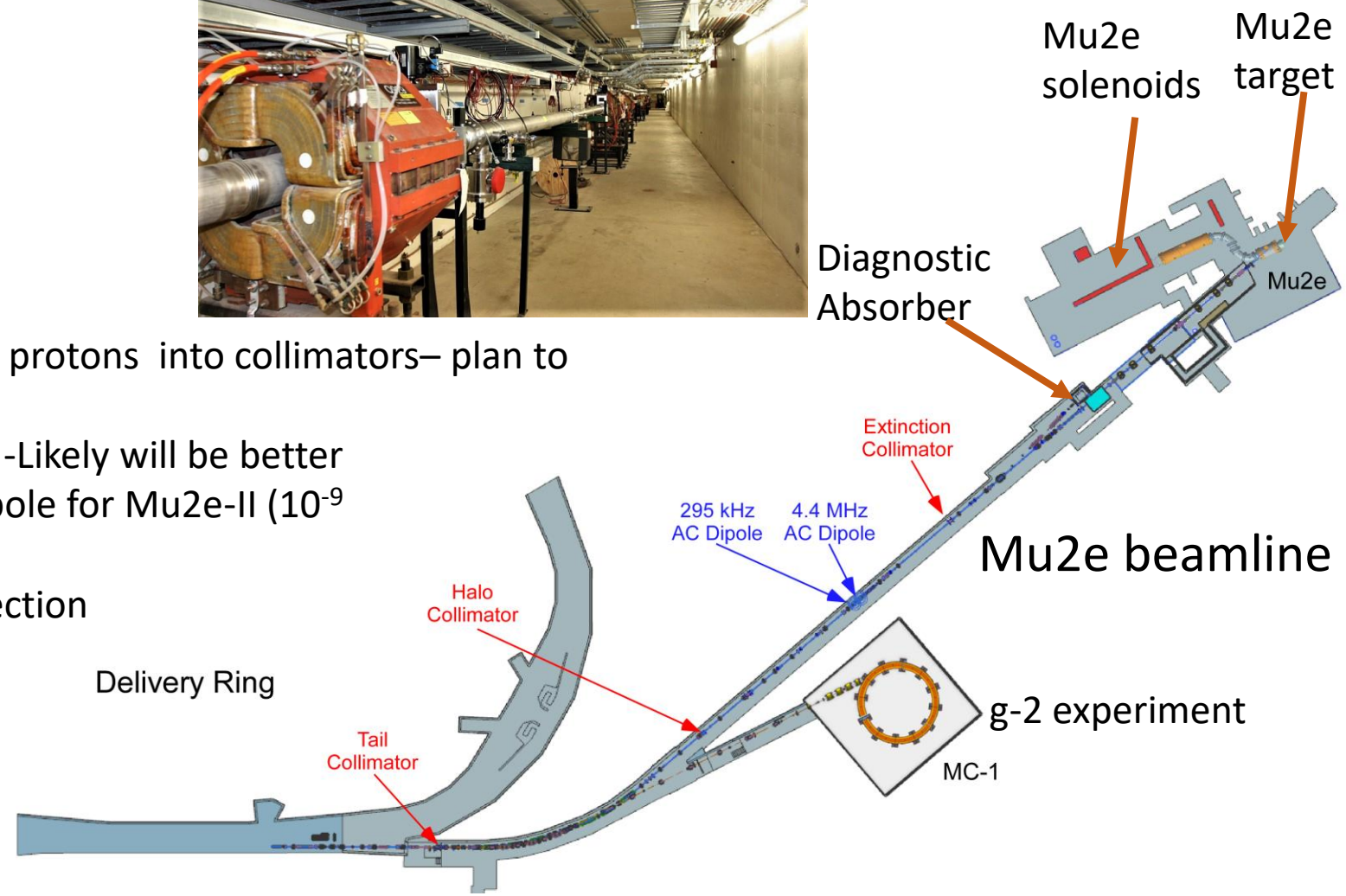
- Neutrino program will use only small fraction of potential 163 MHz pulses from PIP-II Linac
- For Mu2e-II, need to build a beam line from PIP-II Linac directly to Mu2e M4 line,
  - This eliminates Booster-Recycler-Delivery Ring and resonant extraction
  - Expect intensity particles/bunch to be significantly more stable than from Delivery Ring
  - Proton pulse will be narrower
- PIP-II has flexibility on what pulses to keep:
  - can adjust proton spacing for Z of targets
  - PIP-II may have to beef-up RF power
- Example Mu2e-II beam:10 Linac pulses produces a 62 ns wide proton pulse then skip ~270 pulses to give 1693 ns spacing
  - This gives 100 kW proton beam at 800 MeV
  - 62 ns width vs 200 ns in Mu2e is improvement
  - Spacing (1693 ns) could be adjusted according to muonic atom lifetime
  - Duty factor would be >90% vs 25% for Mu2e
  - Gives factor of 7 increase in average muon stop rate with a factor of 3 increase in instantaneous rates in detectors



Mu2e/Mu2e-II M4 Proton Line



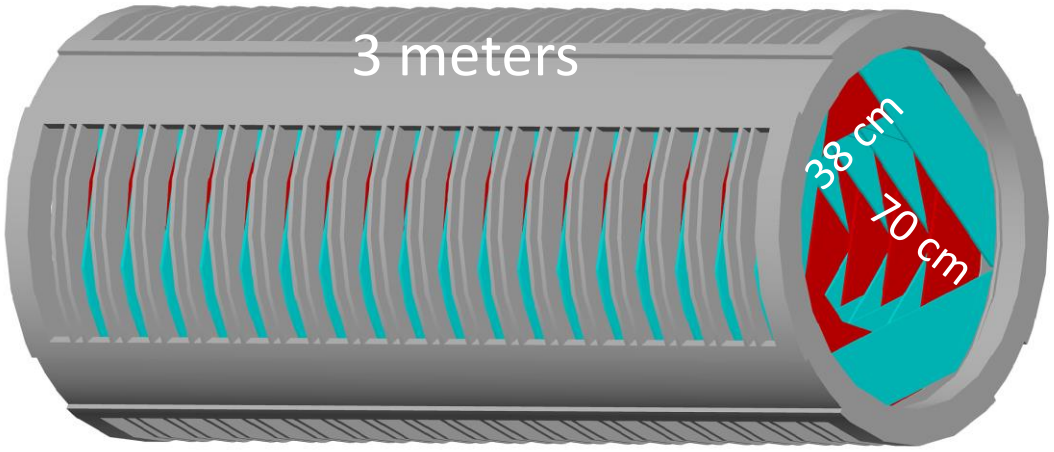
- Extinction is measure of out-of-time beam
- Mu2e-II requires extinction < 10^{-11}
  - cf Mu2e requirement < 10^{-10}
- Two factors contribute to extinction
  - intrinsic accelerator extinction
  - AC resonant dipole sweepers
- Mu2e AC dipoles sweep away out-of-time protons into collimators– plan to use also for Mu2e-II
- PIP-II Linac extinction specification is 10^{-4-} -Likely will be better
- Expect improved performance from AC dipole for Mu2e-II (10^{-9} with safety margin)
  - Lower momentum means larger deflection
  - No beam halo from Mu2e's slow extraction septum
  - Lower momentum means lower punch through at collimator



Detectors

DIO Electrons and Mu2e Tracker

- A Tracker is employed to measure the conversion electron momentum
- Electrons from muons decaying in atomic orbit (DIO) are mostly below 53 MeV
  - Central aperture in Tracker (and calorimeter) avoids copious DIO electrons with E<53 MeV, yet maintains good acceptance for the high energy conversion electrons
- But there is potential bkgnd from a high energy tail to DIO electron distribution
- Excellent resolution is required to reduce DIO background
  - Mu2e: σ~140 keV/c for 105 MeV/c electron



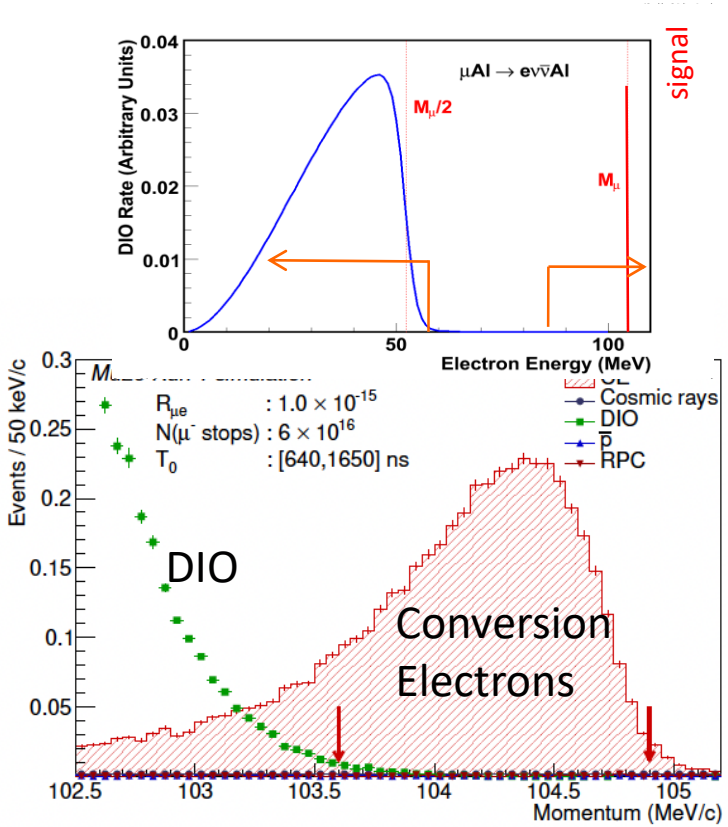
Tracker

J. Miller, Mu2e/Mu2e-II

DIO electrons arise from ordinary decays of muon in atomic orbit

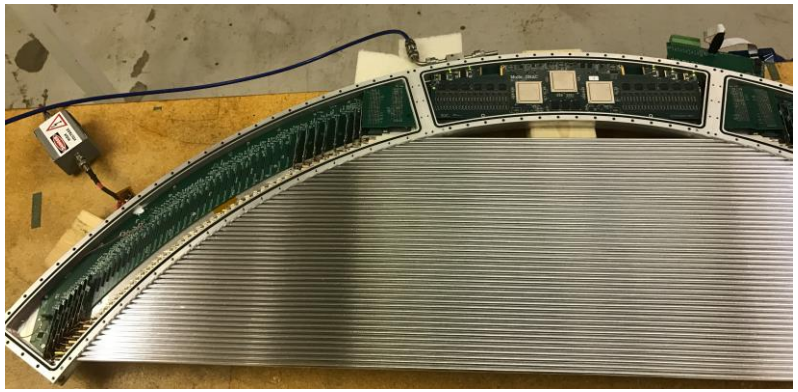
$$\mu^- +^{27}_{13} Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu +^{27}_{13} Al$$

A small high energy tail extends up to conversion electron energy

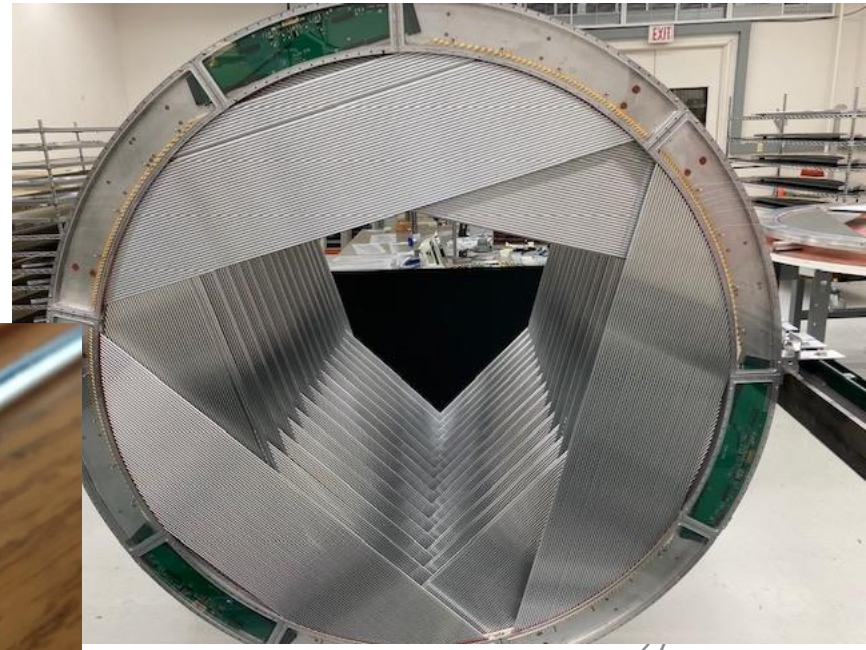


Mu2e Tracker

- 21000 straws, 96 per panel interleaved in two planes
  - Straws: 15 micron walls, 25 micron W wires
  - All 216 Panels + spares complete
  - 22 of 36 Planes assembled, to be arranged in 18 stations of pairs of planes
- Successful vertical slice tests on a plane with cosmic rays
- Electronics
  - COVID-related supply chain delays are easing
  - All FPGA's recently acquired
  - Enough electronics will be available shortly to test several stations
- Completion expected March 2025

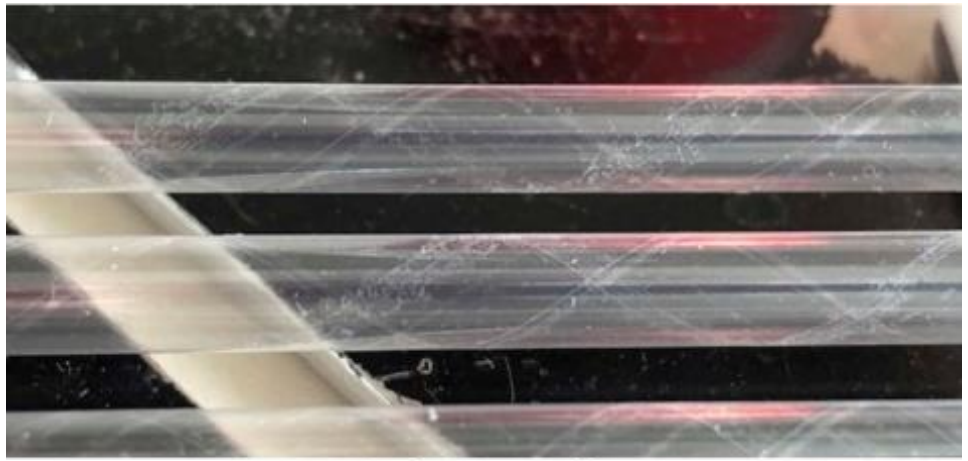


Panel w/Front-End Electronics



Mu2e-II Tracker R&D

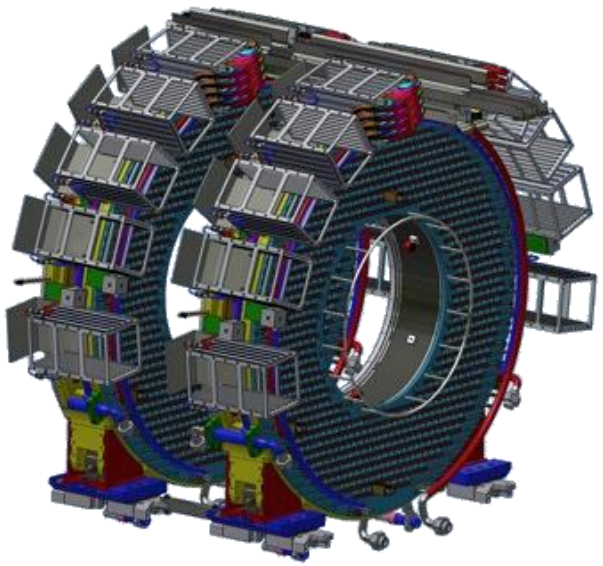
- Decay in orbit electron background increases x10
  - Improve resolution of Tracker by reducing its mass, improving analysis techniques
  - Reduce proton absorber and target thicknesses
  - Increase energy threshold for conversion electrons
- LDRD at Fermilab supporting effort to evaluate options for improved tracker
  - Reducing straw thickness, 15 microns (Mu2e) to 8, improves resolution from 140 keV to 100 keV
  - Ongoing studies of prototype straws, investigating challenges with vacuum tightness, long-term stability, and large scale production.
  - Also investigating other options such as drift chambers
- Integrated rad dose levels will be x10 that of Mu2e- ~Mrad and 10^{13} (1 MeV equiv.) n/cm^2
  - Studies of rad-hard electronics especially for Tracker
  - may require custom ASIC's
- Host of simulations related to tracker:
  - Stopping target material and geometry, proton absorber

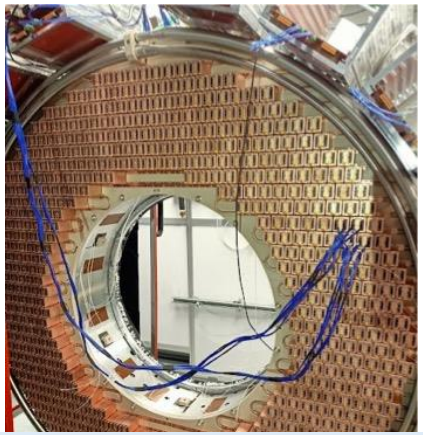


Pressurized 8 μm Mylar Straws

Mu2e Calorimeter

- 2 annular disks. Each with 674 pure CsI crystals + 1348 SiPMs
- Large Italian contribution
- FEE on SiPM pins + digital readout on crates
- Complements the tracker for μ/e PID + triggering and support on track-seeding
- Resolution requirements for 100 MeV electrons: < 10% energy, < 500 ps timing, < 1 cm position
- Assembly at Fermilab under way, installation early 2024



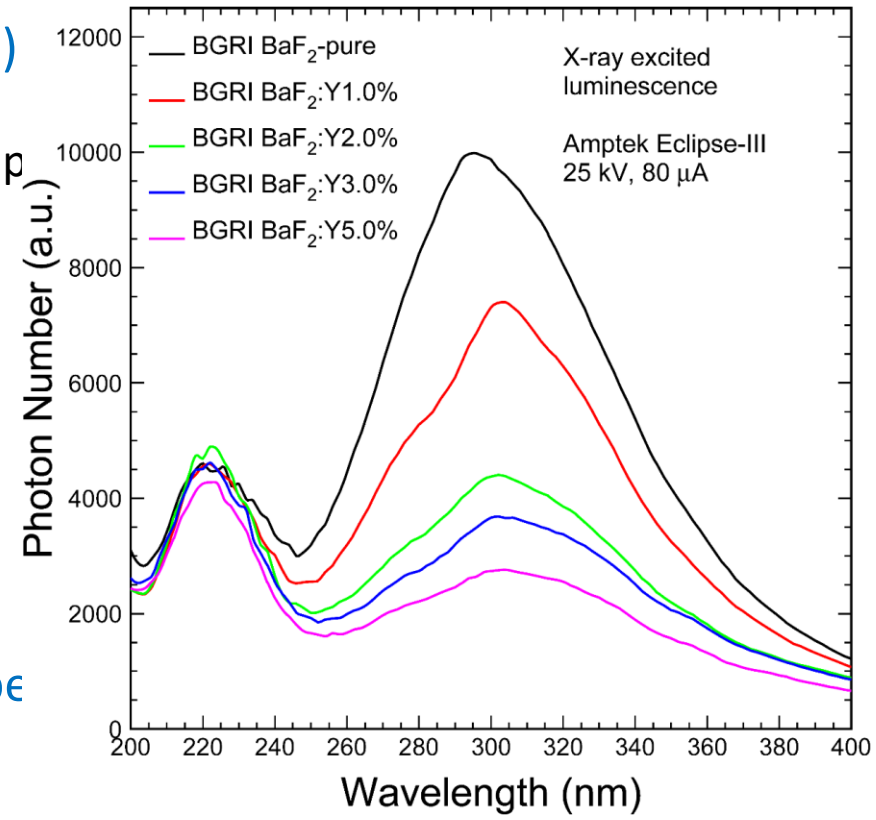


Full Disk assembled with Readout Units (SIPM/FEE)

Mu2e-II Calorimeter

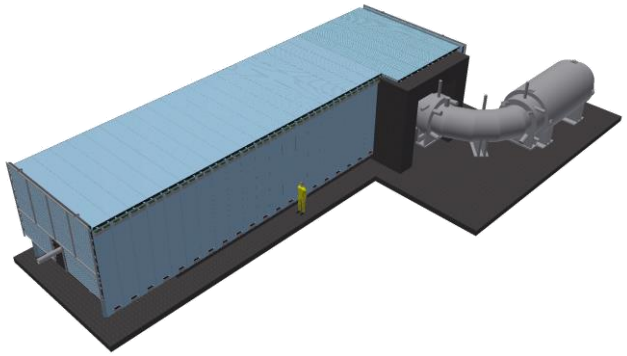
- Mu2e crystals CsI can't handle rad doses and occupancies at Mu2e-II first disk
  - ~Mrad and 10^{13} n/cm^2
- BaF_2 is an excellent crystal candidate: rad hard, has fast UV (220 nm) component
  - A large but slow solar component centered at 300 nm can cause pileup
  - Efforts to suppress:
    - Recent breakthrough work established that Y doping suppresses the slow component
    - Develop UV sensitive, solar-blind photosensors (rad resistant)
    - Apply bandpass filters with atomic layer deposition to tune wavelength response
  - Currently unfunded, R&D funds needed for Y-doped BaF_2 and for photosensor development
- Current estimates: only the front calorimeter disk of Mu2e should be replaced, Mu2e CsI is sufficient for the second disk

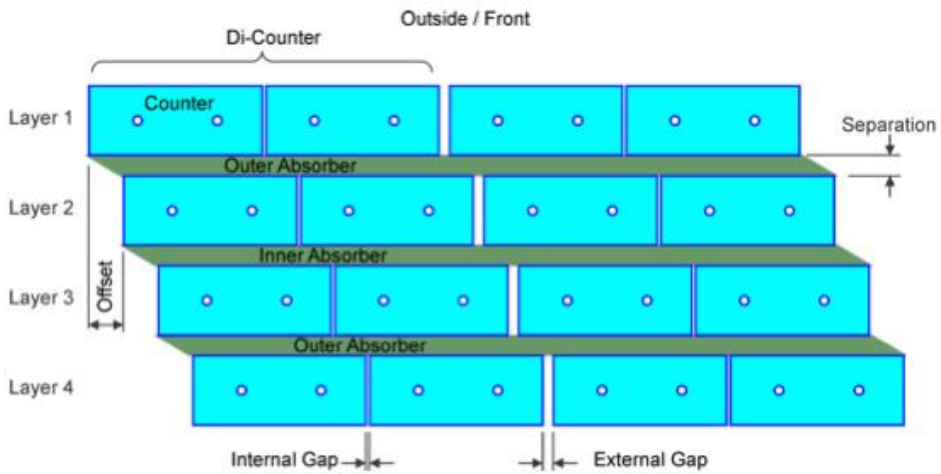
Photons produced in BaF_2 vs. wavelength for different levels of Y doping



Mu2e Status – Cosmic Ray Veto

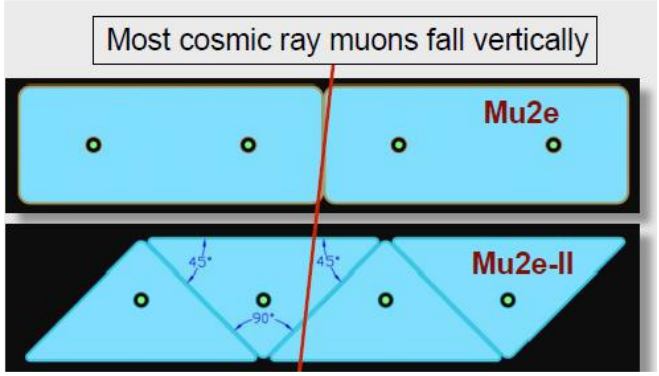
- Cosmic rays are an important source of background
- Cosmic ray veto (CRV) detector surrounds the Detector Solenoid - needs to be 99.99% efficient
- Thick concrete shield on inside to protect from secondaries following muon interactions in target
- Module
  - 4 layers extruded polystyrene scintillator counters w/ embedded wavelength-shifting fibers, SiPM readout
- Modules 96% complete
  - Composed of 16 5cmx2cm ranging 1m to 6m long
- Electronics
  - Now receiving FPGA's to complete electronics
- Will be installed after Tracker, calorimeter are inserted into vacuum and DS concret shsileidng is in place

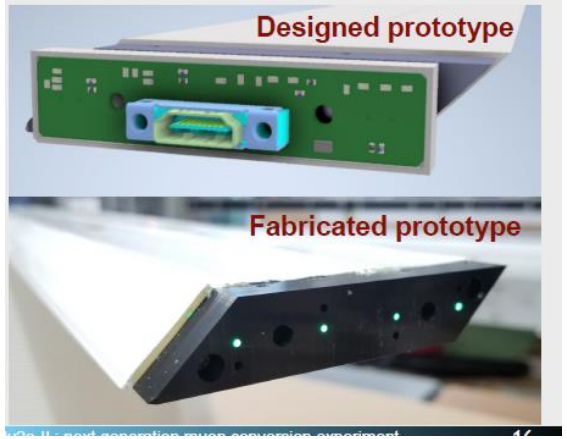




Mu2e-II Cosmic Ray Veto

- Mu2e-II will require an improved CRV
  - X3 more live time means will need x3 higher veto efficiency
  - Enhance light yield: thicker wavelength-shifting fiber, improved SiPMs, potting fiber in holes
  - Enhanced design using triangular-shaped counters, improved efficiency due to reduced gaps
    - A prototype has been designed
  - Enhanced instrumentation of geometric holes in coverage, especially at TS entrance
  - Increase shielding in key spots
    - Overhead to reduce neutrals (neutrons) in cosmic ray flux
    - To absorb cosmic rays that evade the CRV in the un-instrumented DS entrance aperture
    - Between the DS and the production and stopping targets to reduce noise hit rates in CRV





Mu2e-II Background and Sensitivity vs Mu2e

- Mu2e-II simulation with reduced straw wall thickness: 8 micron vs Mu2e 15 microns, improved CRV
  - Simulated momentum resolution of Tracker improved from 140 keV to 100 keV
- Improved CRV
- Same Al target as Mu2e, assume BaF_2 crystals in calorimeter disks
- Assumes 28 carbon spheres (0.75 cm radius) as pion production target
- CE energy acceptance window is reduced from 1.05 MeV → 0.85 MeV to reduce DIO background
- Assuming 5 years of data collection gives X10 improvement in sensitivity with <0.5 background counts

Results	Mu2e	Mu2e-II (5-year)	Required improvement
Backgrounds			
Decay In Orbit	0.144	0.263	Improved tracker resolution
Cosmics	0.209	0.171	Improved veto and enhanced shielding
Radiative Pion Capture	0.025	0.033	Improved extinction $< 10^{-11}$
Radiative Muon Capture	< 0.004	< 0.02	
Antiprotons	0.040	0.000	Beam energy below $\overline{p}$ threshold
Others	< 0.004	< 0.017	
Total	0.41	0.47	
N(muon stops)	6.7×10^{18}	5.5×10^{19}	
SES	3.01×10^{-17}	3.25×10^{-18}	
$R_{\mu e}$(90% CL)	6.01×10^{-17}	6.39×10^{-18}	
$R_{\mu e}$(discovery)	1.89×10^{-16}	2.34×10^{-17}	

Mu2e-II Experimental Challenges

Challenges for Mu2e-II apparatus are known:

- Solenoids & collimators: heat & radiation loads
- Target station: convectively cooled production target, HRS, remote handling, proton beam dump, radiation safety
- Tracker: lower mass, increased radiation dose, beam flash
- Calorimeter: background rates, light yield & SiPM performance vs rad dose
- Cosmic Ray Veto: accidental rates, scintillator & SiPM aging
- TDAQ: increased rates and occupancies
- Electronics : radiation tolerance (~3 Mrad, $10^{12} – 10^{13}$ $n_{1MeV\text{-}eq}/cm^2$)
  - Following efforts at CERN to ID rad-hard electronics components
  - ASICs may be required
- Beam monitors : rates (STM), sensitivity & feasibility (ExtMon)
- Detector Shielding needs to be beefed up: accidental rates in CRV, tracker, calorimeter
- Timely execution of Mu2e
- Advancing PIP-II beam line (RF kicker, tunnel to Mu2e-II,
- →R&D support Is needed to move Mu2e-II forward, beginning now for critical items (target, tracker, calorimeter, CRV, beamlines, shielding)

Summary Mu2e

Mu2e will produce x10000 improved sensitivity to muon to electron conversion by mid-2030

- **Strong endorsement from P5(2014)**
- **Important component of the Fermilab program into the next decade**
- **Major step forward in the search for charged lepton flavor violation**
  - Provides one of the deepest probes of NP related to CLFV
- **Run 1 will occur in 2026 before LBNF/PIP-II shutdown**
  - Goal: 10% of total data set and x1000 improvement in sensitivity over present experimental limit
- **Run 2 after LBNF shutdown expects to reach final x10000 goal in 3-4 years of running**

Summary Mu2e-II

Mu2e-II offers compelling science beyond Mu2e

- **Provides in most NP scenarios the deepest probe of CLFV for currently planned experiments**
- **Offers additional insights into New Physics parameter space, independent of Mu2e outcome**
  - If Mu2e discovery: Mu2e-II achieves precision to explore underlying NP operators
  - If Mu2e limits: Mu2e-II extends sensitivity of $R_{\mu e}$ another order of magnitude, energy scale of NP by factor 2

Mu2e-II can be an important part of FNAL program in ~2030s

- **Science goals can be achieved utilizing an upgraded Mu2e and additions to the PIP-II complex**
  - Experimental concept established using detailed simulation and full sensitivity estimate
  - PIP-II capable of providing required proton beam (in fact it is ideally suited for this)
  - Leverages significant investment in Mu2e and Fermilab Muon Campus
- Natufral step in longer term AMF program

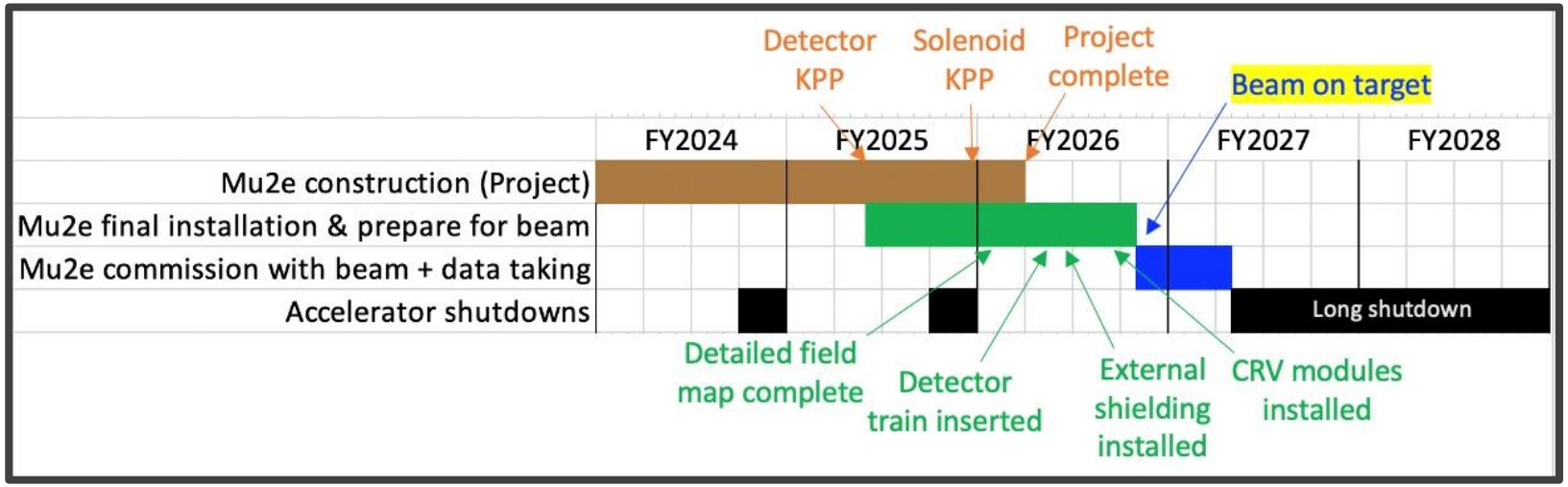
END

Fermilab's long shutdown and Mu2e

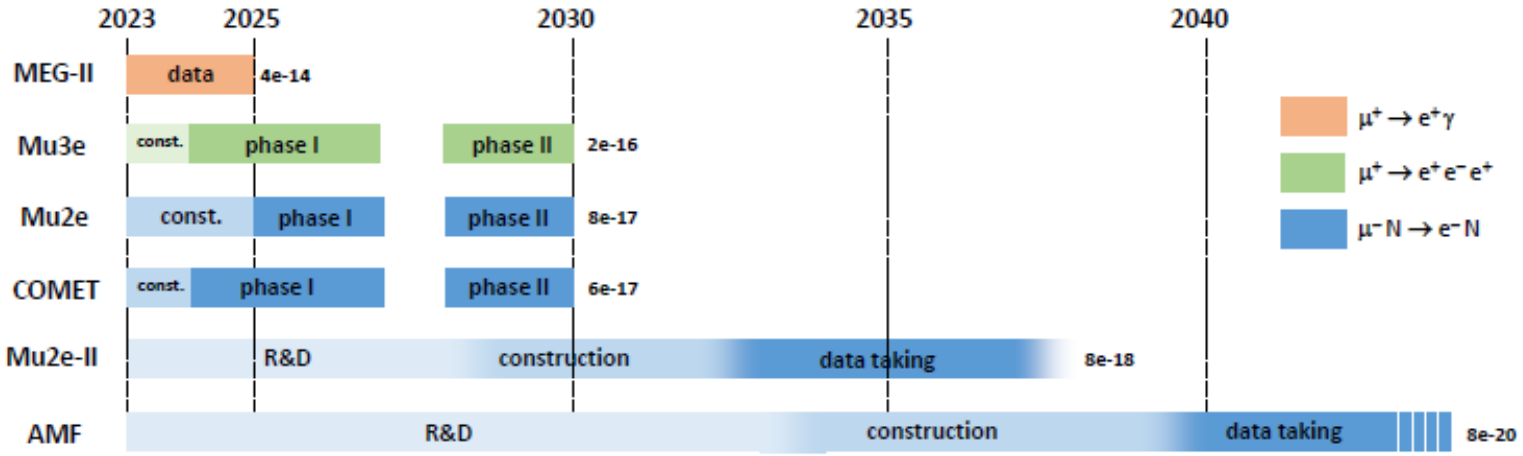
- The DOE, Fermilab, and the Collaboration all agree it is a high priority to get Mu2e a decent sized physics quality data set before the long shutdown.
- The current shutdown schedule was set in 2020 based on the Mu2e, PIP-II, and LBNF/DUNE schedules.
- All three stakeholders believe they can achieve their goals given the current shutdown schedule.
- If the Mu2e solenoid delivery schedule slips to the point where Mu2e no longer believes they can get physics data before the shutdown, Mu2e will ask Fermilab and the other stake holders to revisit the shutdown schedule

Schedules

- Mu2e



- Charged Lepton Flavor Tests



Project Cost and Schedule Benchmarks

- Mu2e
  - Project is 85% complete.
  - Mu2e TPC: $315.7M
  - Mu2e Project is fully funded as of March 2023
  - Contingency > 40% on work to go
  - Run 1 2026
  - Run 2 2029-2033
- Mu2e-II Project cost estimate ~$150M Current year dollars

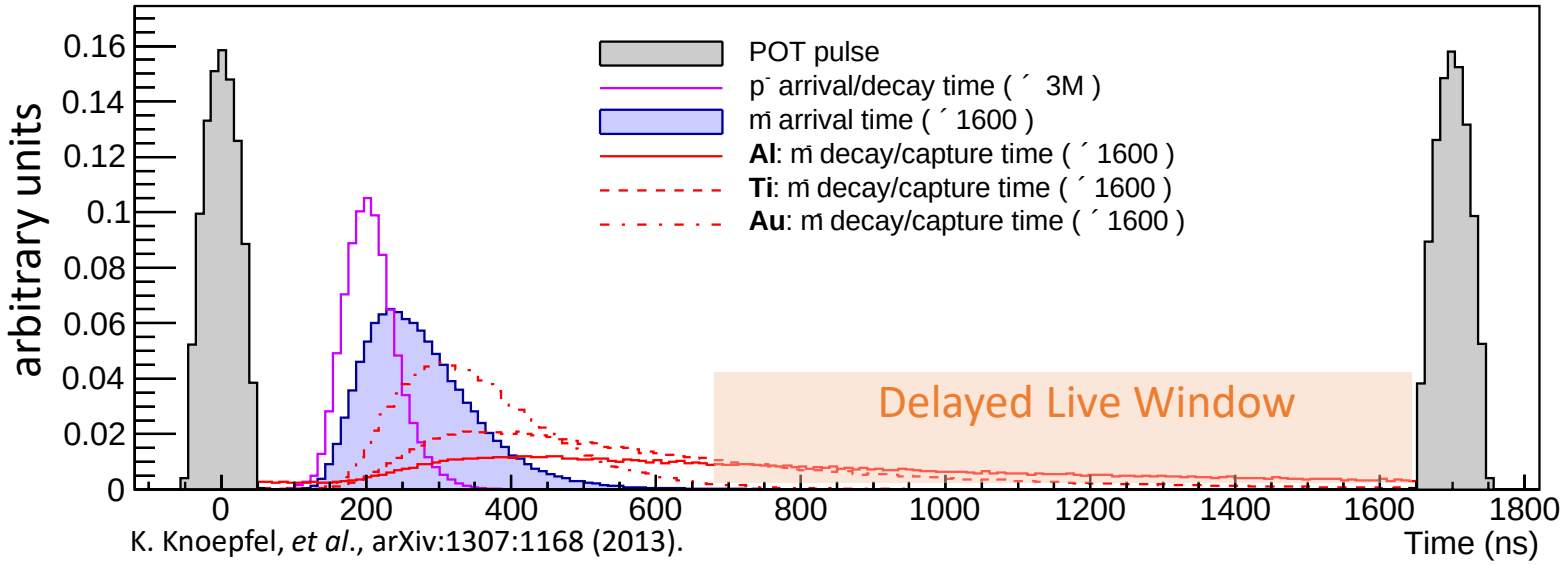
- Schedule: R&D design continues, data-taking ~second half of 2030 ‘s

International Contributions to Mu2e

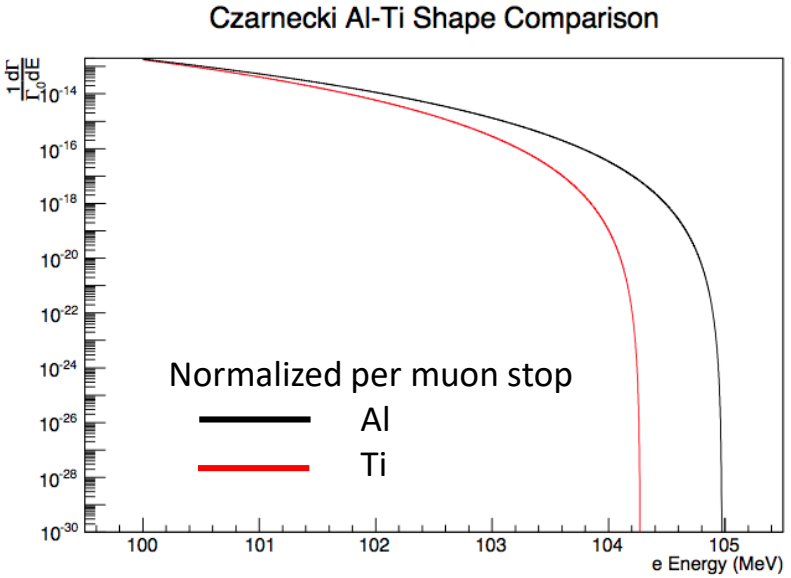
- UK contributions
  Production Target R&D
  Stopping Target Monitor - Germanium detectors plus readout/integration with TDAQ (detector delivered, readout/integration in progress), FPGA programming and front-end firmware, Labor associated with these activities

  Italy contribution
  Transport solenoid coil fabrication oversight
  Shared calorimeter CsI crystal procurement
  All calorimeter photosensors
  Front-end and back-end electronics
  Back-end electronics and power
  Calorimeter mechanical structure and cooling manifolds
  Laser calibration system
  Prototyping and QA/QC including radiation, B-field tests, etc.
  Labor associated with these activities
- HZDR Dresden
  - Background rates, and radiation dose calculations for all elements of the experiment
  - Led multiple beam tests of calorimeter and stopping target monitor detectors
- Russia
  - Simulations, detector R&D for Mu2e-II, calorimeter electronics QC/QA

Feasibility of Mu2e-II Experimental Concept



K. Knoepfel, *et al.*, arXiv:1307:1168 (2013).



Element ($^A_Z N$)	Density (ρ_N)	Decay fraction (f_N)	Lifetime (τ_N)
$^{27}_{13}$Al	2.70 g/cm^3	0.39	864 ns
$^{46-50}_{22}$Ti	4.51 g/cm^3	0.15	329 ns

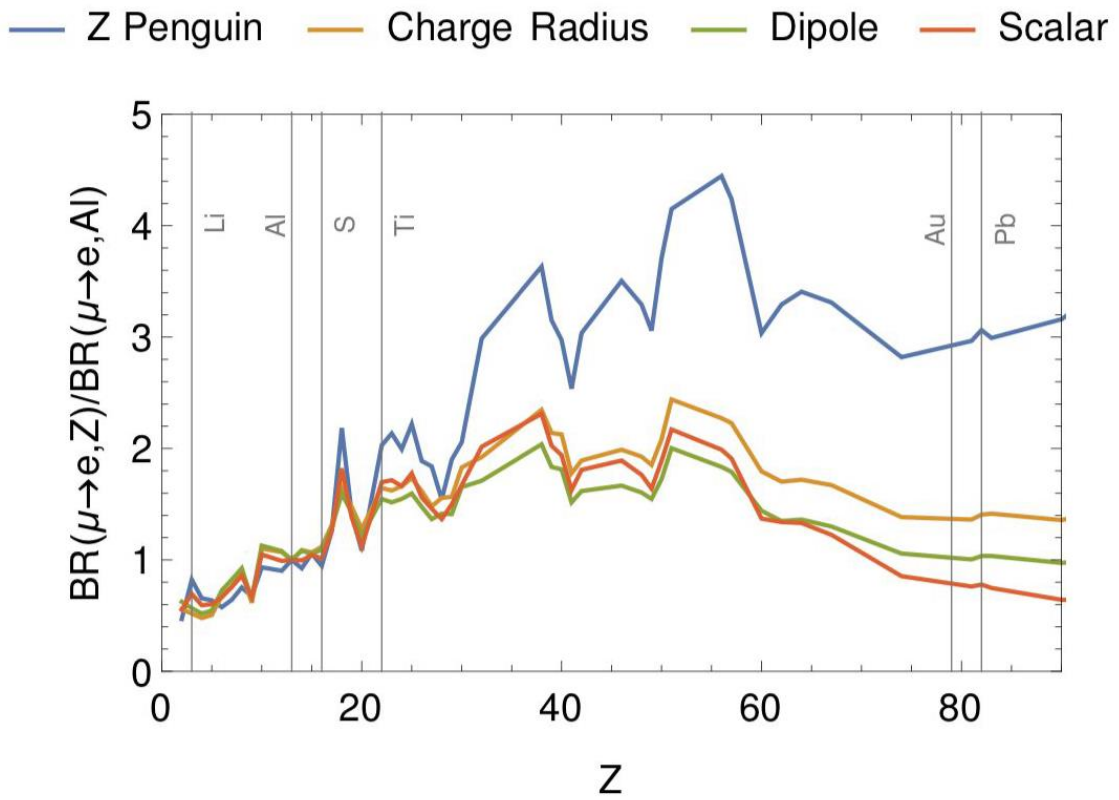
A. Czarnecki, X. Garcia I Tormo, & W.J. Marciano, PRD 84 (2011) 013006.

- Aluminum & Titanium stopping targets investigated
  - Accounted for differences in density, decay fraction, end-point energy, DIO spectrum
- **Total background can be kept ~1 event**
  - **Discovery sensitivity continues to scale linearly with single-event-sensitivity**

Stopping Target

Mu2e Stopping Target

- Complete
- 37 Al foils, 0.1 mm thick
- 2 cm spacing,
- 43 mm diameter hole
- Suspended by 3 spokes of 3 mil W wire

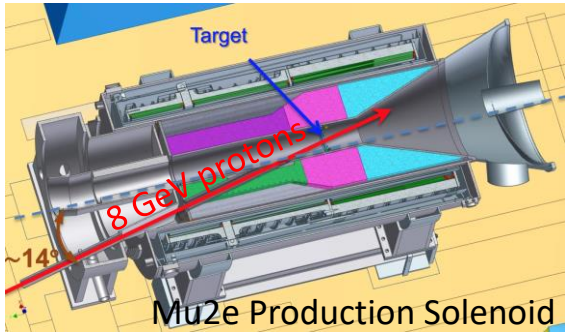


Mu2e-II: On-going studies of other target materials

- Theory: examine sensitivities to structure of LFV operators
- Simulate experimental sensitivity for various target thicknesses and geometries
- Potential low-Z candidates: Li, Al, Ti, V
- High-Z targets have short lifetimes and do not survive into the delayed measurment window

Required R&D – Beam delivery

- Main issue: need to steer 0.8 GeV beam to hit the production target
- Internal studies (mu2e-doc-db-16205, 16328) have found solutions
  - Require modifications to various components of target station region
  - Exact solution will depend on details of production target & solenoid
  - Now beginning studies of stripping & secondary extinction options



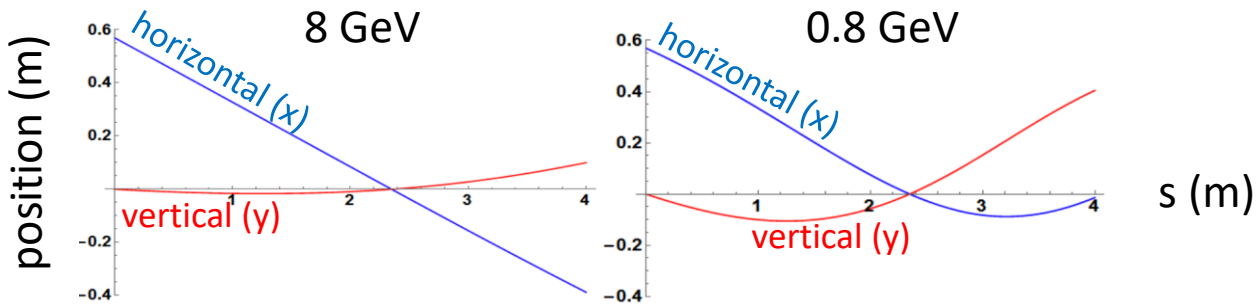


FIGURE 6. x-y coordinates through PS for 8 GeV protons (left) and 0.8 GeV protons (right). Target is at =2.35m

TABLE 1. Trajectories for 8 GeV and 800 MeV protons. (target at s=2.35m)

Position	8 GeV (x, y)	8 GeV (x', y')	800 MeV (x,y)	800 MeV (x', y')
s=0 entrance	0.57, 0.0 m	-13.6 º, -1.4º	0.57, 0.0	-11.4, -8.3º
s=2.35 target	0.0, 0.0 m	-13.6º, 1.8º	0.0, 0.0	-9.6º, 10.9 º
s=4m exit	-0.39, 0.08 m	-12.7º, 5.1 º	-0.01, 0.40	10.2 º,11.4 º

Table & Figures from Dave Neuffer

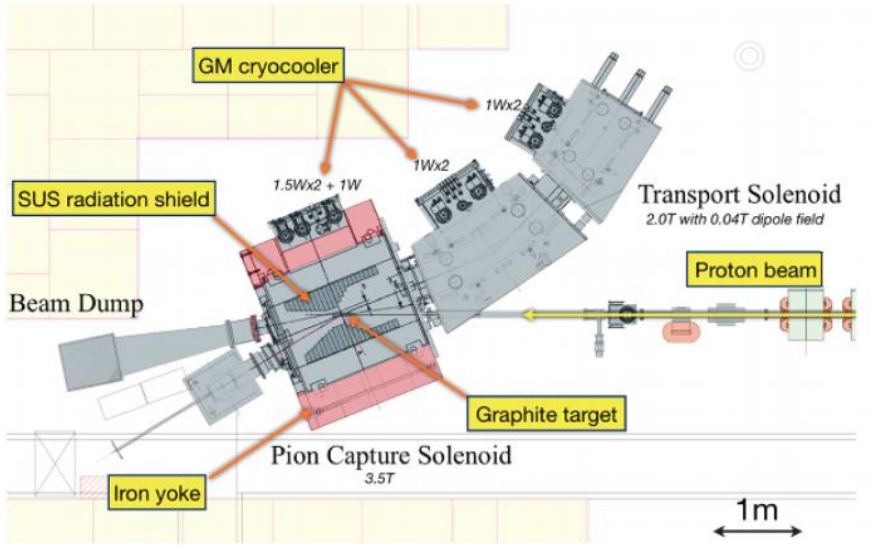
To Further Define Mu2e-II Scope:

- Complete Task Force work and then identify resources to pursue the TF recommendations (e.g. for target R&D)
- Measure extinction from chopper using PIP2-IT (e.g. via LDRD)
- Develop conceptual design for beam line – extinction, final focus to target
- Develop conceptual design for production solenoid + heat & radiation shield

- Based on the above can then
  - Estimate Heat & radiation loads on collimators, proton beam stop, muon beam stop, detector materials
  - Estimate Detector occupancies and the effect on backgrounds and sensitivity
  - Estimate Required radiation tolerance of electronics components
  - Understand the radiation safety needs
  - Develop plans

- In parallel, initiate high priority detector R&D

Demonstration of technique



- MuSIC facility at RCNP (Japan) measured stop-μ rate (S. Cook, et al., J. Phys. Conf. **408** (2013) 012079)
  - 1 nA of 392 MeV proton
  - 3.5 T solenoid with graphite production target
  - 8.5×10^5 stop-μ / W / s
  - Agrees with simulation estimates <30%

Mu2e-II: Muon to electron conversion with PIP-II
Contributed paper for Snowmass

K. Byrum,[1] S. Corrodi,[1] Y. Oksuzian,[1] P. Winter,[1] L. Xia,[1] A. W. J. Edmonds,[2] J. P. Miller,[2] J. Mott,[3] W. J. Marciano,[4] R. Szafron,[4] R. Bonventre[b],[5] D. N. Brown[b],[5] Yu. G. Kolomensky[ab],[5] O. Ning[a],[5] V. Singh[a],[5] E. Prebys,[6] L. Borrel,[7] B. Echenard,[7] D. G. Hitlin,[7] C. Hu,[7] D. X. Lin,[7] S. Middleton,[7] F. C. Porter,[7] L. Zhang,[7] R.-Y. Zhu,[7] D. Ambrose,[8] K. Badgley,[8] R. H. Bernstein,[8] S. Boi,[8] B. C. K. Casey,[8] R. Culbertson,[8] A. Gaponenko,[8] H. D. Glass,[8] D. Glenzinski,[8] L. Goodenough,[8] A. Hocker,[8] M. Kargiantoulakis,[8] V. Kashikhin,[8] B. Kiburg,[8] R. K. Kutschke,[8] P. A. Murat,[8] D. Neuffer,[8] V. S. Pronskikh,[8] D. Pushka,[8] G. Rakness,[8] T. Strauss,[8] M. Yucel,[8] C. Bloise,[9] E. Diociaiuti,[9] S. Giovannella,[9] F. Happacher,[9] S. Miscetti,[9] I. Sarra,[9] M. Martini,[10] A. Ferrari,[11] S. E. Müller,[11] R. Rachamin,[11] E. Barlas-Yucel,[12] A. Artikov,[13] N. Atanov,[13] Yu. I. Davydov,[13] v. Glagolev,[13] I. I. Vasilyev,[13] D. N. Brown,[14] Y. Uesaka,[15] S. P. Denisov,[16] V. Evdokimov,[16] A. V. Kozelov,[16] A. V. Popov,[16] I. A. Vasilyev,[16] G. Tassielli,[17] T. Teubner,[18] R. T. Chislett,[19] G. G. Hesketh,[19] M. Lancaster,[20] M. Campbell,[21] K. Ciampa,[22] K. Heller,[22] B. Messerly,[22] M. A. C. Cummings,[23] L. Calibbi,[24] G. C. Blazey,[25] M. J. Syphers,[25] V. Zutshi,[25] C. Kampa,[26] M. MacKenzie,[26] S. Di Falco,[27] S. Donati,[27] A. Gioiosa,[27] V. Giusti,[27] L. Morescalchi,[27] D. Pasciuto,[27] E. Pedreschi,[27] F. Spinella,[27] M. T. Hedges,[28] M. Jones,[28] Z. Y. You,[29] A. M. Zanetti,[30] E. V. Valetov,[31] E. C. Dukes,[32] R. Ehrlich,[32] R. C. Group,[32] J. Heeck,[32] P. Q. Hung,[32] S. M. Demers,[33] G. Pezzullo,[33] K. R. Lynch,[34] and J. L. Popp[34]

[1] *Argonne National Laboratory, Lemont, Illinois 60439, USA*
[2] *Boston University, Boston, Massachusetts 02215, USA*
[3] *Boston University, Boston, Massachusetts 02215, USA; Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[4] *Brookhaven National Laboratory, Upton, New York 11973 USA*
[5] *University of California[a], Lawrence Berkeley National Laboratory[b], Berkeley, California 94720, USA*
[6] *University of California, Davis, California 95616, USA*
[7] *California Institute of Technology, Pasadena, California 91125, USA*
[8] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[9] *Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy*
[10] *Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy; Università degli Studi Guglielmo Marconi, 00193, Rome, Italy*
[11] *Helmholtz-Zentrum Dresden-Rossendorf, Dresden 01328, Germany*
[12] *University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[13] *Joint Institute for Nuclear Research, 141980, Dubna, Russia*
[14] *Western Kentucky University, Bowling Green, Kentucky 42101, USA*
[15] *Kyushu Sangyo University, Fukuoka 813-8503, Japan*
[16] *NRC Kurchatov Institute, IHEP, 142281, Protvino, Moscow region, Russia*
[17] *INFN Sezione di Lecce, Leece I-73100, Italy*
[18] *Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 3BX, UK*
[19] *University College London, London WC1E 6BT, UK*
[20] *University of Manchester, Manchester, M13 9PL, UK*
[21] *University of Michigan, Ann Arbor, Michigan 48109, USA*
[22] *University of Minnesota, Minneapolis, Minnesota 55455, USA*
[23] *Muons, Inc., Batavia, Illinois 60510, USA*
[24] *School of Physics, Nankai University, Tianjin 300071, China*
[25] *Northern Illinois University, DeKalb, Illinois 60115, USA*
[26] *Northwestern University, Evanston, Illinois 60208, USA*
[27] *INFN Sezione di Pisa; Università di Pisa, I-56127 Pisa, Italy*
[28] *Purdue University, West Lafayette, Indiana, 47907, USA*
[29] *Sun Yat-Sen University, Guangzhou, 510275, China*
[30] *INFN Sezione di Trieste, I-34127 Trieste, Italy*
[31] *Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China; Michigan State University, East Lansing, Michigan 48824, USA*
[32] *University of Virginia, Charlottesville, Virginia 22904, USA*
[33] *Yale University, New Haven, Connecticut, 06520, USA*
[34] *York College and the Graduate Center, The City University of New York, New York, New York 11451, USA*

An observation of Charged Lepton Flavor Violation (CLFV) would be unambiguous evidence for physics beyond the Standard Model. The Mu2e and COMET experiments, under construction, are

Mu2e-II vs. Mu2e proton beamlines

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}	
Stopped muons per second	9.9×10^{9}	7.1×10^{10}	

Expression of Interest – Mu2e-II

Expression of Interest for Evolution of the Mu2e Experiment†

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06 February 2018

Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

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- **130 Signatories, 36 Institutions, 6 Countries**

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"The PAC recommends the Mu2e-II proponents to identify the most relevant and urgent R&D items for the detector. The PAC endorses the Mu2e-II request of dedicated R&D funding and encourages them to engage the Laboratory and funding agencies into identifying the required resources".