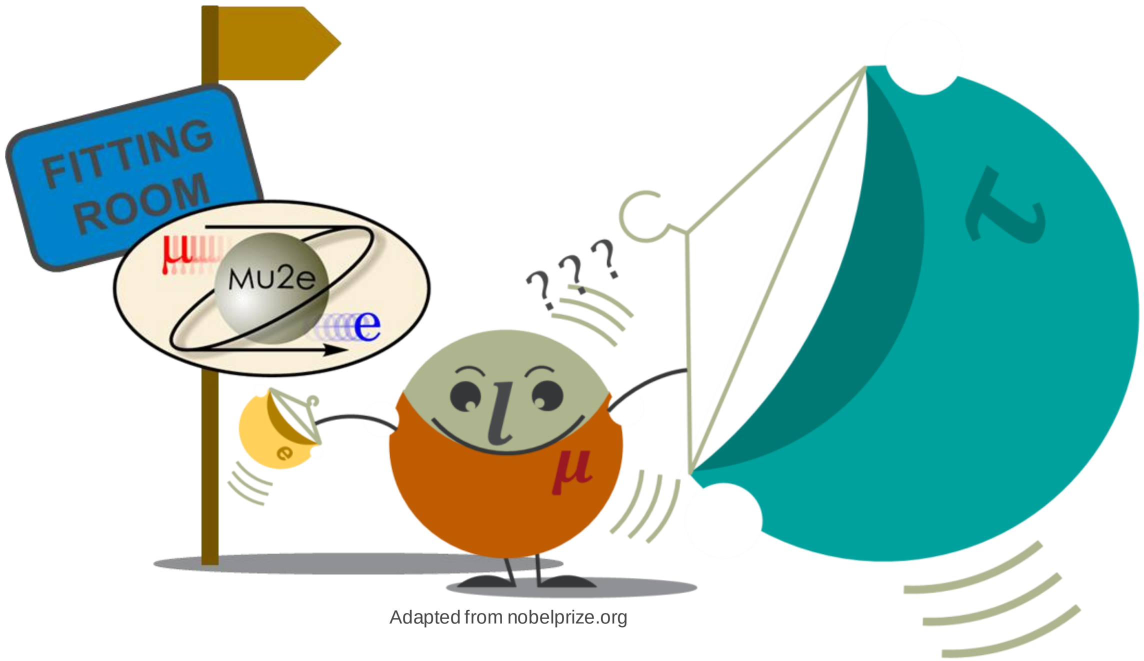
# THE MU2E EXPERIMENT: A CHARGED LEPTON FLAVOR VIOLATION (CLFV) SEARCH



Adapted from nobelprize.org

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***On behalf of the Mu2e Collaboration***

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# CONTENTS

# CHARGED LEPTON FLAVOR VIOLATION (CLFV)

- What symmetries do new physics beyond the Standard Model (SM) have?
- Noether's theorem links continuous symmetries of local Lagrangian to conservation laws, e.g.:
  - Charge conservation
    ⬄ QED gauge symmetry
  - Lepton family number conservation
    ⬄ Accidental symmetry in (vanilla) SM;
    - Family number not conserved in the quark sector,
    - Neutrino oscillation (Neutral LFV) tells us lepton flavor is not a fundamental symmetry
- Charged lepton flavor violation:
  transition involving $e$, $\mu$, and $\tau$ that does not conserve lepton family number
  - A wide range of CLFV processes, none has been observed so far
  - Discovery of any CLFV process means new physics

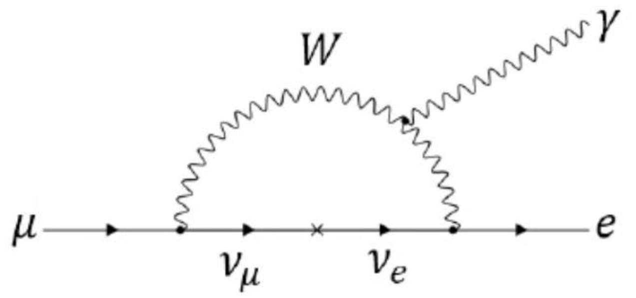
$$\begin{array}{lccccc} & \mu^+ & \rightarrow & e^+ & + & \gamma \\ L_e: & 0 & \rightarrow & -1 & + & 0 \\ L_\mu: & -1 & \rightarrow & 0 & + & 0 \end{array}$$

CLFV Examples:

- Neutrinoless muon conversions, e.g.,
  $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^-e^+$, $\mu^- N \rightarrow e^- N$
- Similar neutrinoless auon decays
  $\tau \rightarrow e, \mu + X$
- Decays in $K/B$ meson systems, e.g.,
  $K_L^0 \rightarrow e^\pm\mu^\mp$, $B^+ \rightarrow K^+e^-\mu^+$
- Di-leptonic $Z/H$ boson decays, e.g.,
  $Z \rightarrow e^\pm\mu^\mp$

# CLFV IN (EXTENDED) SM

- NLFV leads directly to CLFV, but it is never observed
  - Occur through loop diagrams
  - Rates proportional to $\left(\Delta m_{ij}^2 / M_W^2\right)^2$
  - Severely suppressed in SM
- SM Branching ratios of $\mu \to e\gamma$ and $\mu N \to eN$ are both $< 10^{-50}$
  - Not measurable
- But thinking on the bright side, CLFV searches are very “clean” and have effectively no SM backgrounds!

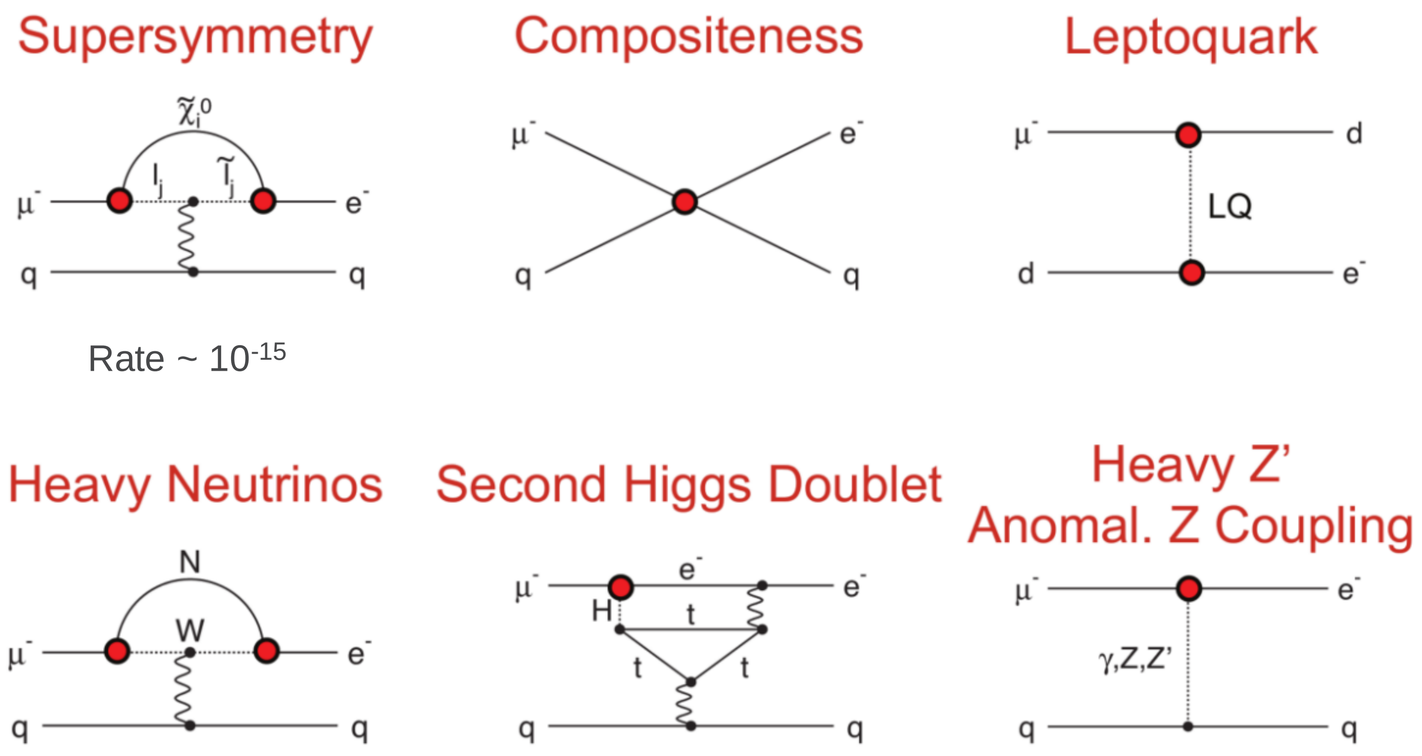



$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} V_{\mu i}^* V_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2$$

$$= \frac{3\alpha}{32\pi} \left(\frac{1}{4}\right) \sin^2 2\theta_{13} \sin^2 \theta_{23} \left| \frac{\Delta m_{13}^2}{M_W^2} \right|^2$$

# CLFV BEYOND SM

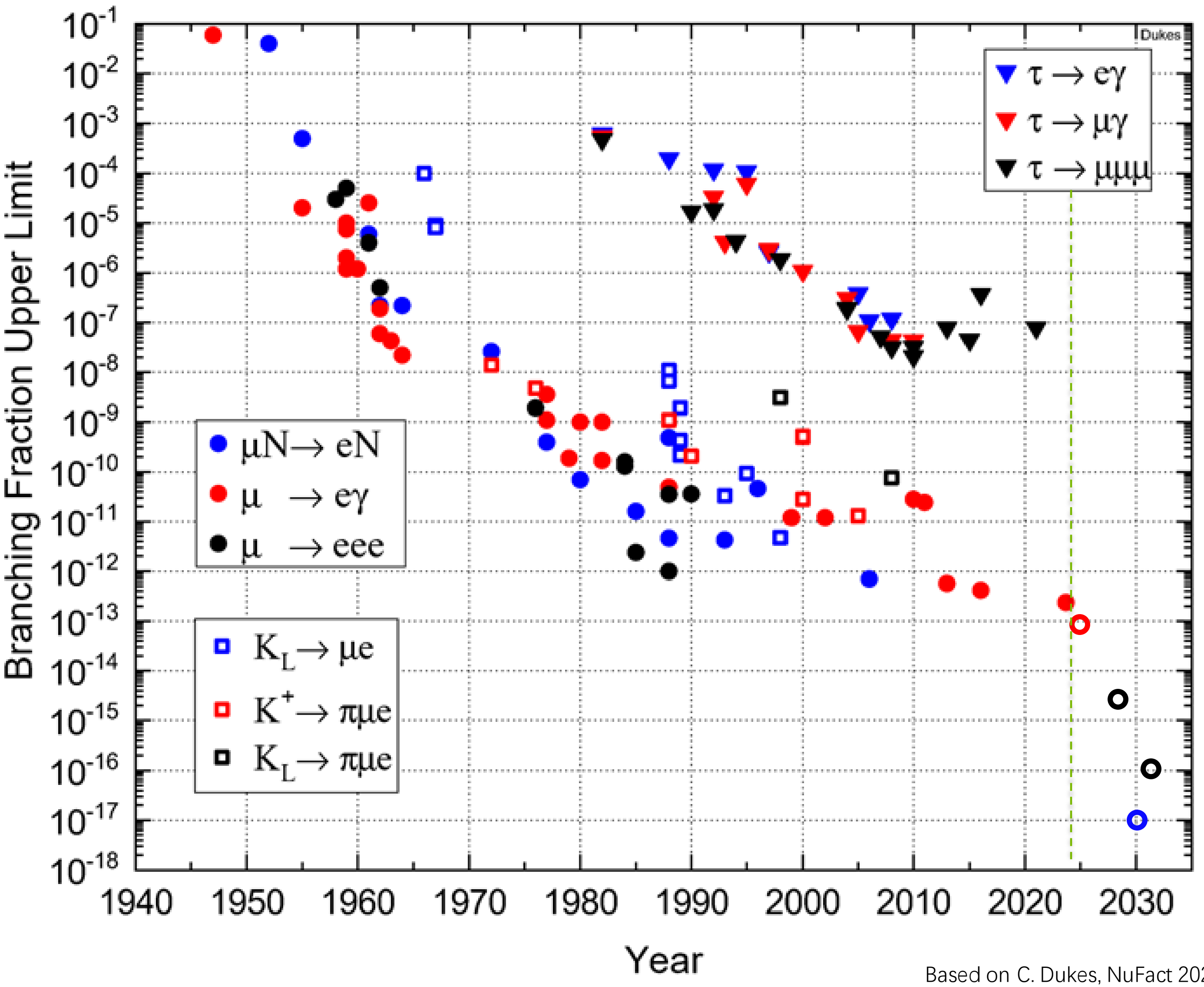
- Many Beyond Standard Model (BSM) theories predict contributions to CLFV processes at rates much higher than SM
- Any CLFV observed means discovery of new physics!
- Rare decay searches are typical intensity frontier efforts:
  - Model independent:
    don't know exactly what's happening, need to infer from multiple experiments, can constrain parameter spaces for multiple theories, have great vetoing power
  - Probing into high effective mass scales
- Great way to point the direction




Some example Feynman diagrams of BSM processes that contributes to $\mu N \to eN$

Figure adapted from W. J. Marciano;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58 (2008);
M. Raidal et al, Eur.Phys.J.C57:13-182, (2008)

# CLFV RARE DECAY SEARCHES




Based on C. Dukes, NuFact 2021

- There is a long history of CLFV rare decay searches
- B-meson decays not shown in plot; current PDG values of 90% CL:
  $BR(B^+ \to K^+ e^- \mu^+) < 6.4 \times 10^{-9}$
  $BR\left(B^0 \to e\mu\right) < 1.0 \times 10^{-9}$
- Among the several methods of detecting CLFV, muon rare decay experiments provide smallest branching ratio limits
  - Relatively easy to produce
  - Relatively long-lived
  - Cleanest process, no irreducible backgrounds
  - Need to cross-check with other channels to sort out the underlying physics

# MUON RARE DECAY SEARCHES

| Process | Current upper limit of BR (90% CL) | Sensitivity of current efforts |
|---|---|---|
| $\mu \to e\gamma$ | $< 3.1 \times 10^{-13}$ (MEG, MEG II 2021) | $10^{-14}$ (MEG II) |
| $\mu \to e\bar{e}e$ | $< 1.0 \times 10^{-12}$ (SINDRUM) | $10^{-16}$ (Mu3e) |
| $\mu N \to eN$ | $< 7 \times 10^{-13}$ (SINDRUM II on *Au*) | $10^{-17}$ (COMET, Mu2e) |

R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update; K. Afanaciev et al., arXiv:2310.12614; B. Echenard, CLFV-2023.

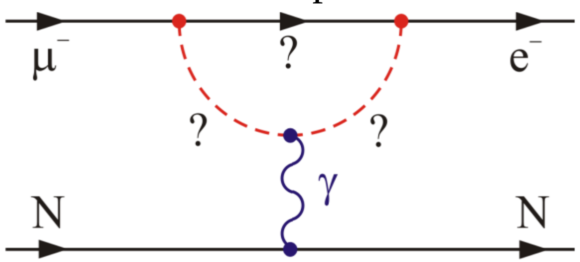
- New experiments in the next decade aim to improve the current limit by up to $10^4$
- Relative rates among different muon rare decay channels can provide insights to underlying models:
  - For a simple demonstration, the following page discusses a less-general, incomplete effective CLFV toy Lagrangian that emits “lepton-only” 4-fermion operators.
  - More general and “proper” EFT for CLFV using more complex parametrization, see arXiv:1801.04709 or arXiv: 2204.00564.

# EFFECTIVE CLFV LAGRANGIAN

- Model-independent effective CLFV toy Lagrangian:

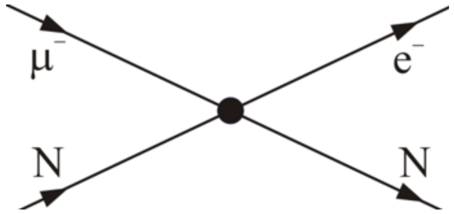
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right) + h.c.$$

Loops

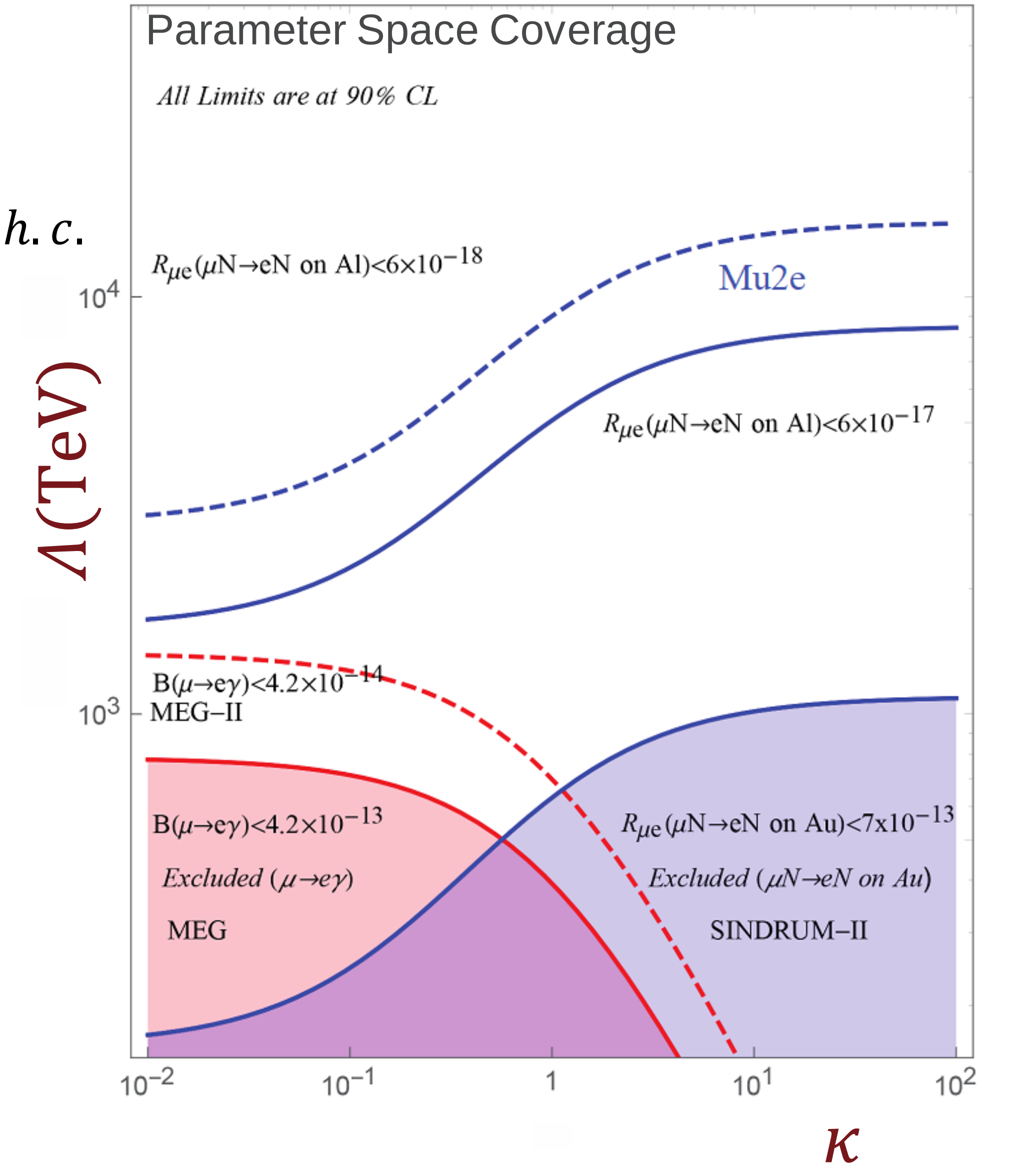



magnetic moment type operator,
e.g., SUSY and heavy neutrinos
dominates when $\kappa \ll 1$;
$\mu \to e\gamma$ rate $\gg$ $\mu N \to eN$ rate;
$\mu \to eee$ also on the tree level

Contact Interactions




four-fermion interaction,
e.g., new particles (Z', leptoquark) at high mass scale
dominates when $\kappa \gg 1$;
$\mu N \to eN$ on the tree level

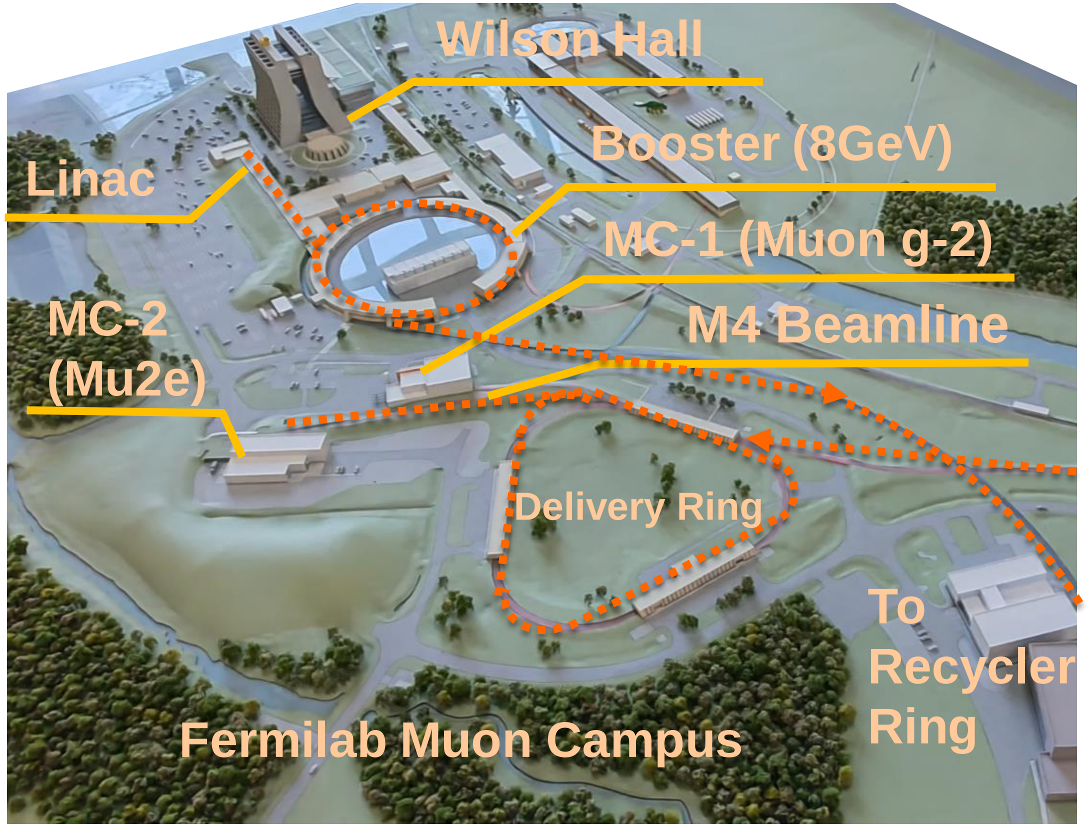



Courtesy of R. H. Bernstein. Adapted from A. de Gouvea, P. Vogl, Prog. Part. Nucl. Phys. 71 (2013) 75

- Relative rates dependent on the underlying physics, and different decay channels are complementary to each other to probe across the parameter space
- Can reach high effective mass scale!

# THE MU2E EXPERIMENT AT FERMILAB

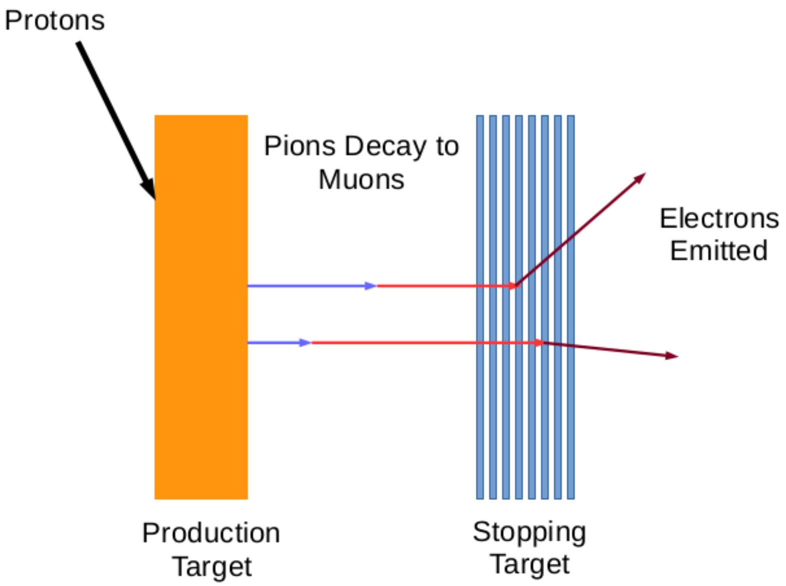
- Searches for neutrinoless muon-to-electron conversion in the presence of nucleus $\mu N \rightarrow eN$
- Aims at a 4-order-of-magnitude improvement in $R_{\mu e}$ compared to SINDRUM-II, expected limit of $R_{\mu e} < 8 \times 10^{-17}$ @ 90% CL
- Mu2e uses the 8 GeV pulsed proton beam:
  - Re-bunched in the recycler ring
  - Transported to the delivery ring
  - Extracted through resonant extraction (a.k.a., slow extraction)

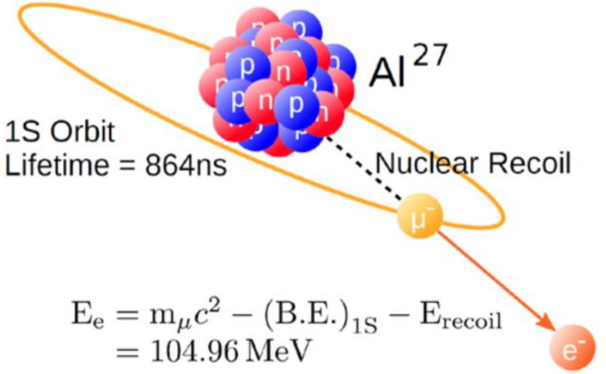


# MU2E EXPERIMENT CONCEPT

- Produce a muon beam using a proton beam:
  - Proton beam hitting a production target produces pions
  - Pions decay to muons ($\pi^- \rightarrow \mu^- \bar{\nu}_\mu$)
- Low momentum muons captured in a stopping target
  - Instantaneously (~ $10^{-13}$ s) cascade to 1s state
  - Muonic X-ray emission spectrum gives estimation of number of muons captured
- Muons in muonic atom decay after a certain lifetime:
  - Muon nuclear capture (~61% in Al): $\mu N \rightarrow \nu_\mu N'^*$
  - Muon decay-in-orbit (DIO, ~39% in Al): $\mu N \rightarrow eN\nu_\mu \bar{\nu}_e$
  - $\mu N \rightarrow eN$ conversion: signature of a single monoenergetic electron of ~105 MeV
- Measure ratio of conversions to muon nuclear capture

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



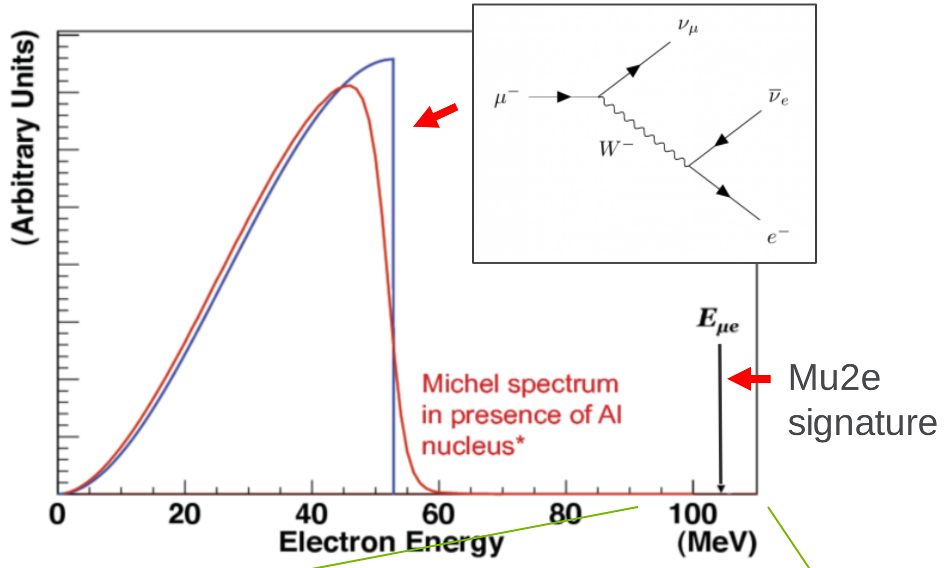



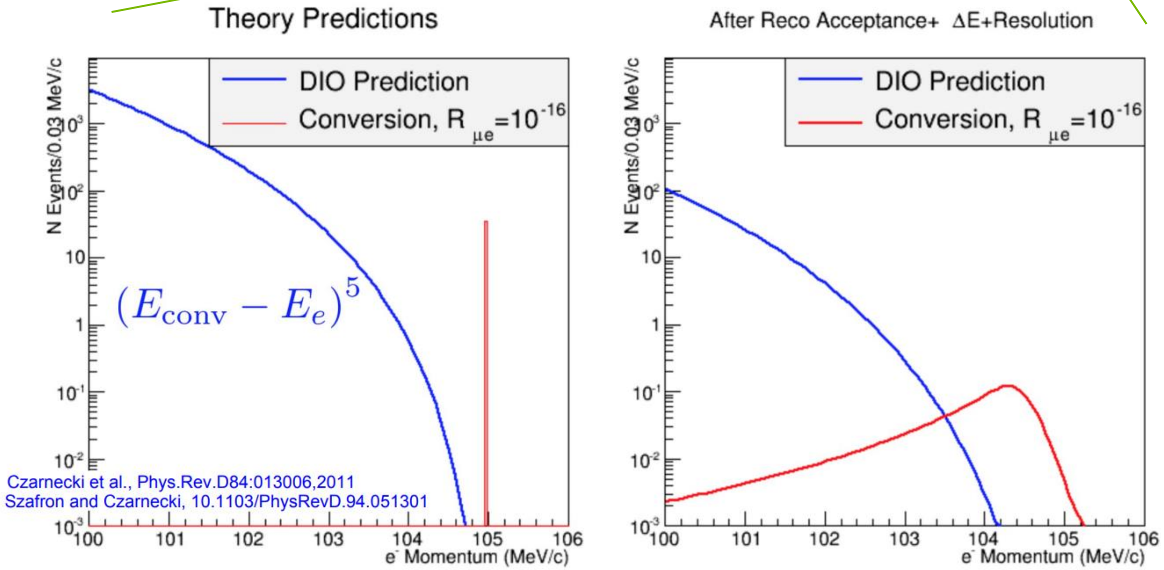
# $\mu N \to eN$ SEARCH BACKGROUNDS

Anything producing 105 MeV electrons can be background

- Muon decay-in-orbit (DIO):
  - Free muon decay has maximum energy of $E_{max} = (m_\mu^2 + m_e^2)/2m_\mu \approx 52.8$ MeV
  - Presence of nucleus distorts the DIO spectrum shape

  Reconstruction uncertainties and detector energy loss smears out the monoenergetic peak
- Primary beam related backgrounds: Leading background in SINDRUM-II
  - Radiative pion capture (RPC, $\pi^- N \to \gamma N'$, $\gamma \to e^+e^-$; $\pi^- N \to e^+e^- N$), pion/muon decay-in-flight, delayed beam electrons, etc.
- Cosmic rays interacting with detector materials
- Antiproton induced backgrounds
  - Annihilation, various interactions with detector materials
- Accidental reconstruction errors from conventional processes




With resolution effects

# BACKGROUND MITIGATION IN MU2E

Anything producing 105 MeV electrons can be background

- Muon decay-in-orbit (DIO):
  - Free muon decay has maximum energy of $E_{max} = (m_\mu^2 + m_e^2)/2m_\mu \approx 52.8$ MeV
  - Presence of nucleus distorts the DIO spectrum shape

  Reconstruction uncertainties and detector energy loss smears out the monoenergetic peak
- Primary beam related backgrounds:
  - Radiative pion capture (RPC, $\pi^- N \to \gamma N'$, $\gamma \to e^+ e^-$; $\pi^- N \to e^+ e^- N$), pion/muon decay-in-flight, delayed beam electrons, etc.
- Cosmic rays interacting with detector materials
- Antiproton induced backgrounds
  - Annihilation, various interactions with detector materials
- Accidental reconstruction errors from conventional processes

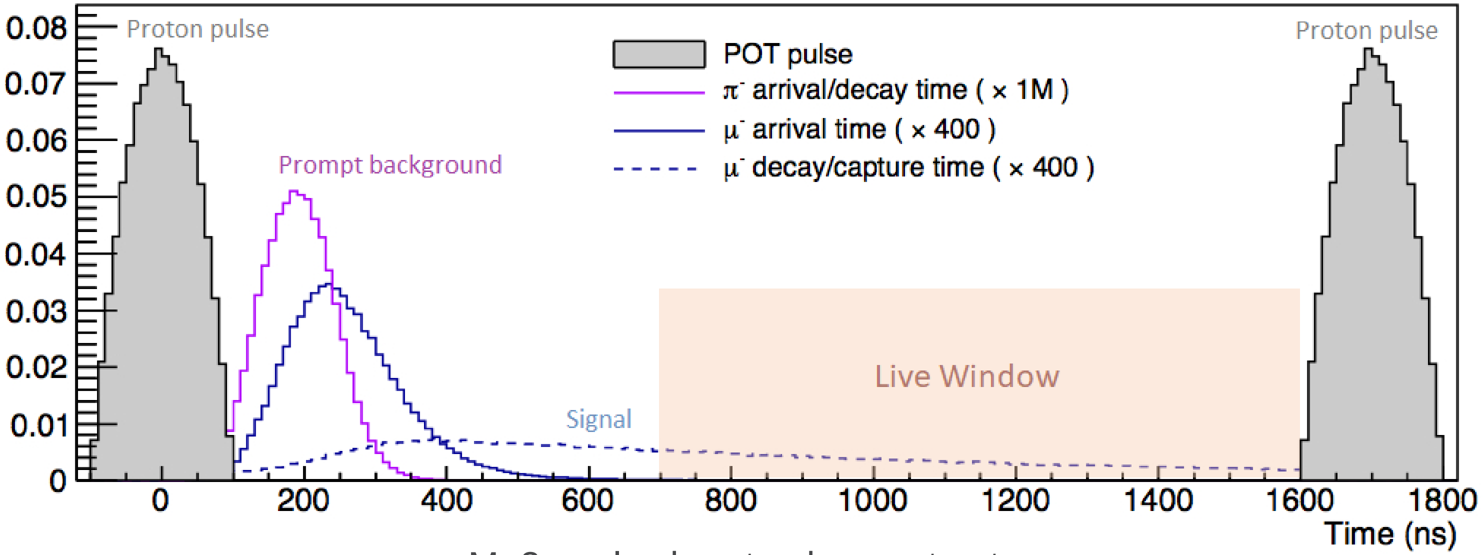
**Mitigations:**

- ✔ **Improved detector design, good momentum resolution**
- ✔ **Pulsed proton beam**
- ✔ **Active veto**
- ✔ **Absorber in muon beamline**
- ✔ **Proton absorbers around the stopping target, improved reconstruction**

# PULSED PROTON BEAM

- Mu2e uses a pulsed proton beam to mitigate backgrounds associated with the primary beam
  - Each pulse: 1695 ns (~2 $\tau_{\mu}^{\mathrm{Al}}$), $3.9 \times 10^{7}$ protons ($\pm$50%)
  - 900 ns live window starting from 700 ns
  - Inter-bunch extinction ratio (fraction out of bunch) < $10^{-10}$

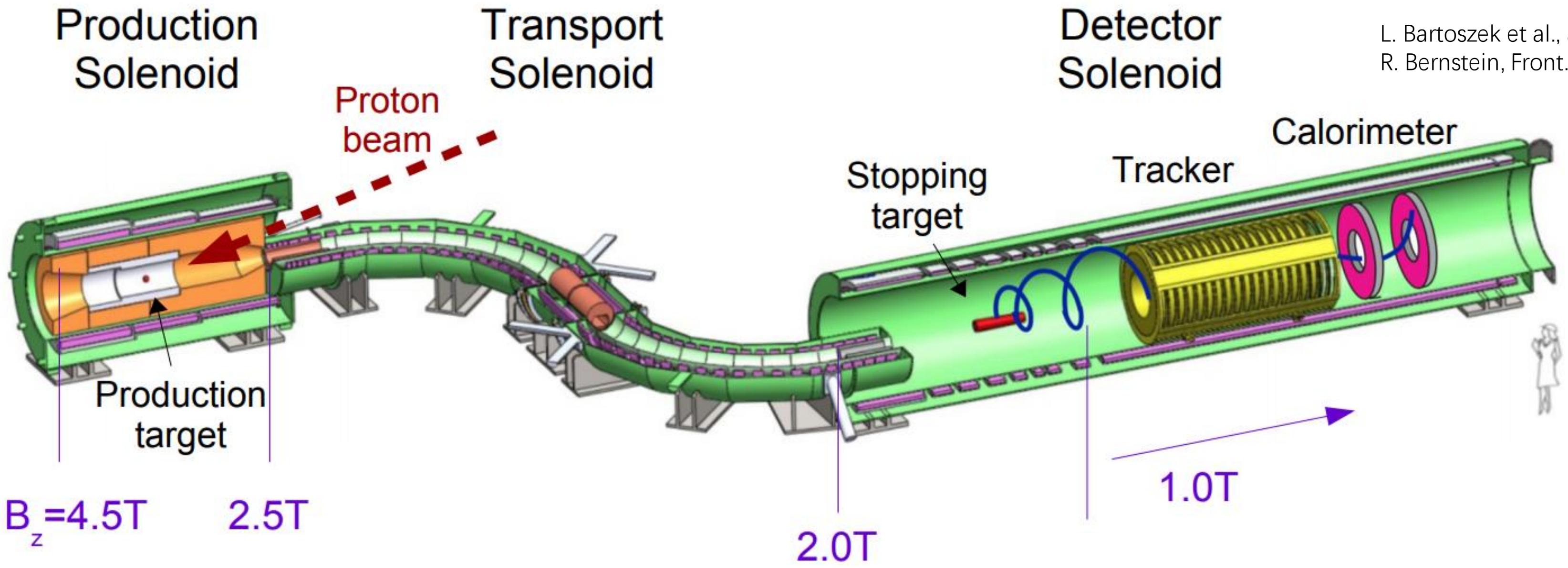
By R. E. Ray




Mu2e pulsed proton beam structure

# MU2E EXPERIMENT SETUP

- Production solenoid (PS)
  - Contains tungsten production target
  - Gradient magnetic field sweeps pions/muons to transport solenoid
- Transport solenoid (TS)
  - S-shaped; collimator in the middle selects sign and momentum
  - Absorbers to remove antiprotons
- Detector solenoid (DS)
  - Al muon stopping target
  - Proton absorber to reduce accidental events
  - Straw tube tracker provides momentum measurement, electromagnetic calorimeter differentiates particles through energy deposition
- Searching for 105 MeV electrons, with a 180 keV/c momentum resolution

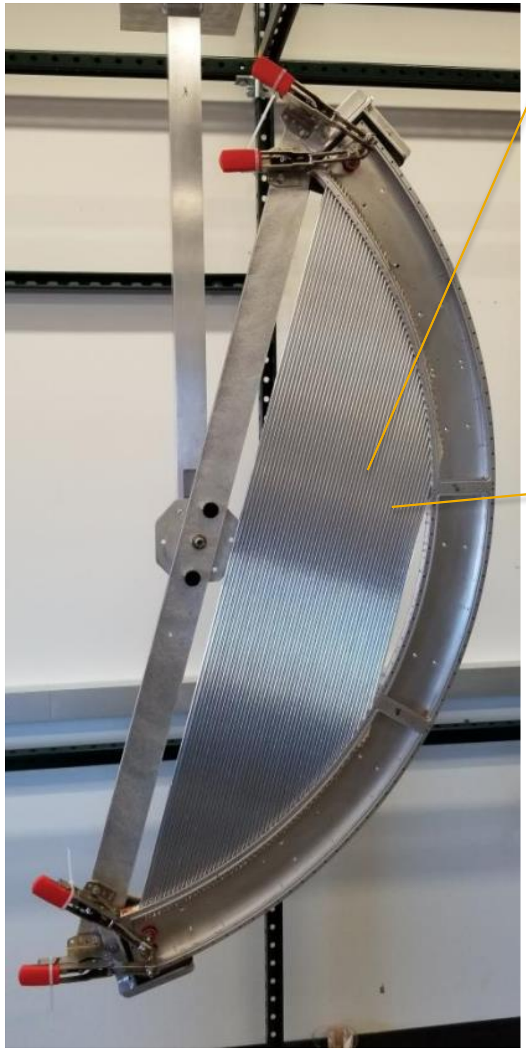



L. Bartoszek et al., arXic:1501.05241;
R. Bernstein, Front. Phyis. 7, 1 (2019)

A schematic view of the Mu2e experiment (not including the Cosmic Ray Veto)

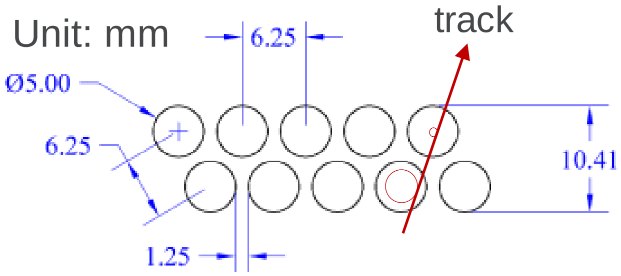
# STRAW TUBE TRACKER

- Gas drift tube ("straw tube") as detecting element
  - Gaseous ionization detector in proportional mode
  - Low mass budget to minimize particle scattering, thus lowering track reconstruction uncertainties: 15 μm-thick metallized mylar wall, thinnest straw wall in a straw tube tracker to date
  - 5 mm diameter with ⌀ 25 μm gold-plated tungsten wire at center
  - 80%/20% Ar/$CO_2$, 1 atm within the gas volume, vacuum outside
  - High voltage ~1450 V
  - Read out from both ends
- A panel consists of 96 straws of various lengths arranged in two staggered layers



A tracker panel

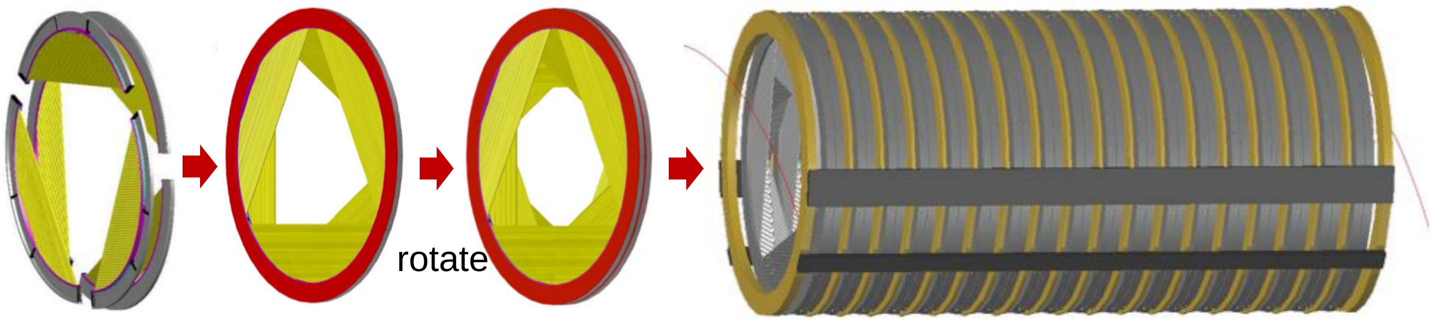
Straw tube (with termination) compared to a pencil

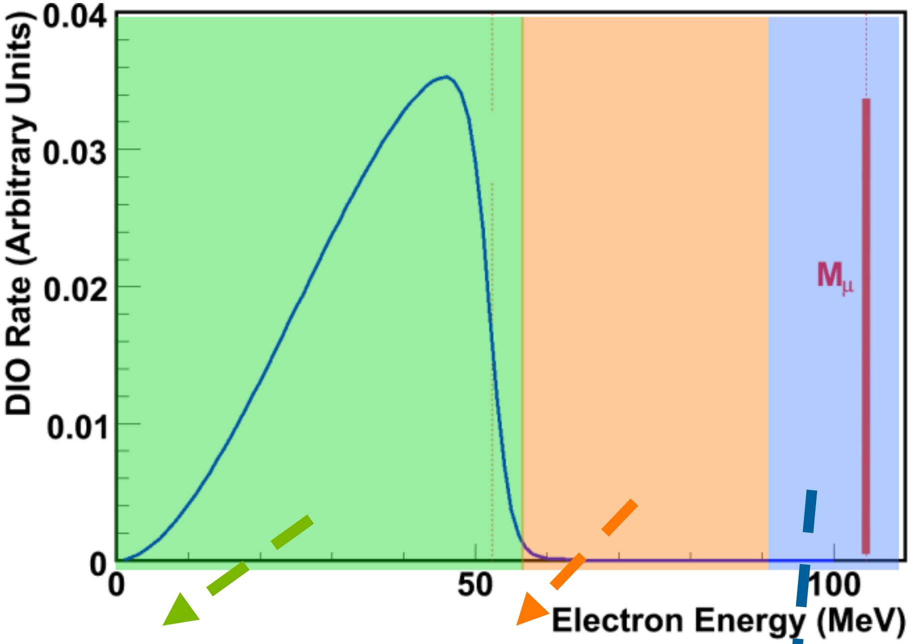



Spatial arrangement of straw tubes

# STRAW TUBE TRACKER

- Full Tracker made of 216 tracker panels
  ⌀ 1.7 m, 3.2m long
- Straws only in active region of 380 mm < $r$ < 700 mm
- Central part purposefully not instrumented
- Annular detectors specifically designed to reduce backgrounds
  – Blind to muon beam and associated activity
  – Blind to all but ~100k of the lower energy Michel electrons, significantly reduce muon DIO background

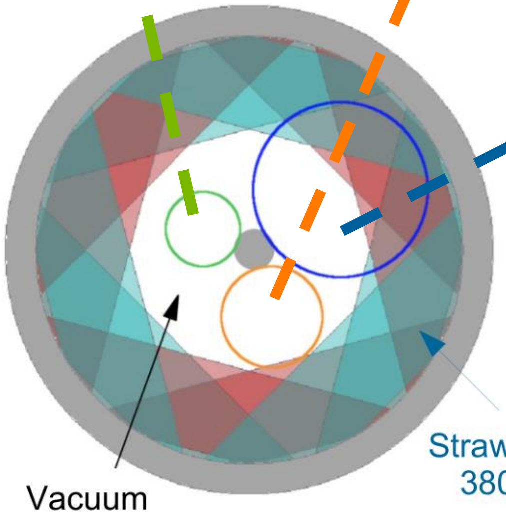



No hits

Some hits, Tracks not reconstructable

Reconstructable tracks

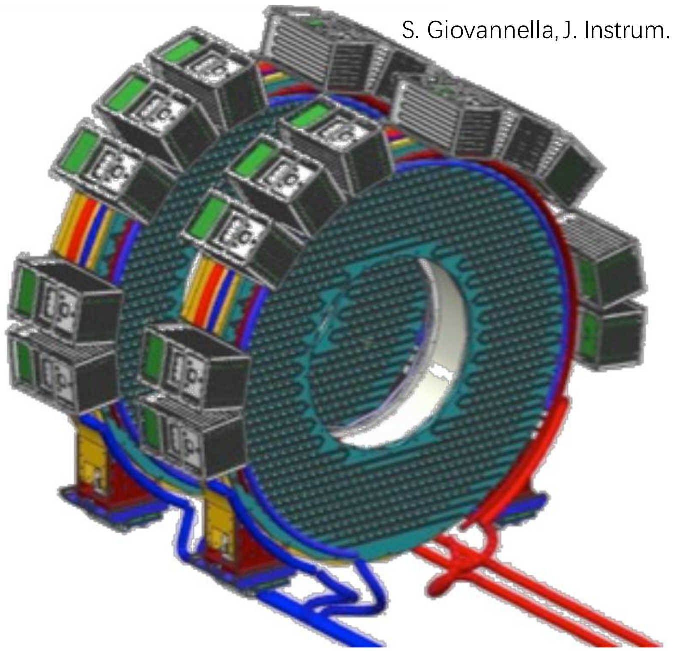



Beam's-eye view of Tracker with helical tracks of electrons with different momenta

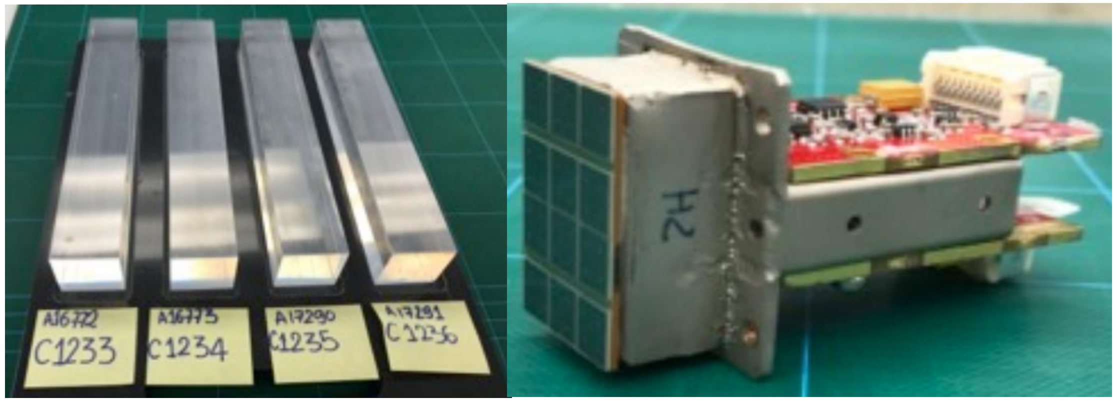
# CALORIMETER

- 2 annular disks separated by 70 cm (half “wavelength” of helix) to maximize detection probability
- 674 undoped CsI crystals per disk:
  - $34 \times 34 \times 200\ \mathrm{mm}^3$
  - Read out using arrays of 12 SiPMs per crystal
  - Works in vacuum and 1T magnetic field
  - Radiation hard up to 100 krad, $10^{12}\ \mathrm{n/cm^2/yr}$
  - Resolution: 0.5 ns in time, 10% in energy, 1 cm in position
- Multiple functions:
  - Distinguish between conversion electron and cosmic muon with same momentum
  - Seed for track pattern recognition
  - Provide triggers independent of the Tracker

S. Giovannella, J. Instrum. 15(06), C06022



CAD view of Mu2e calorimeter instrumented with electronics

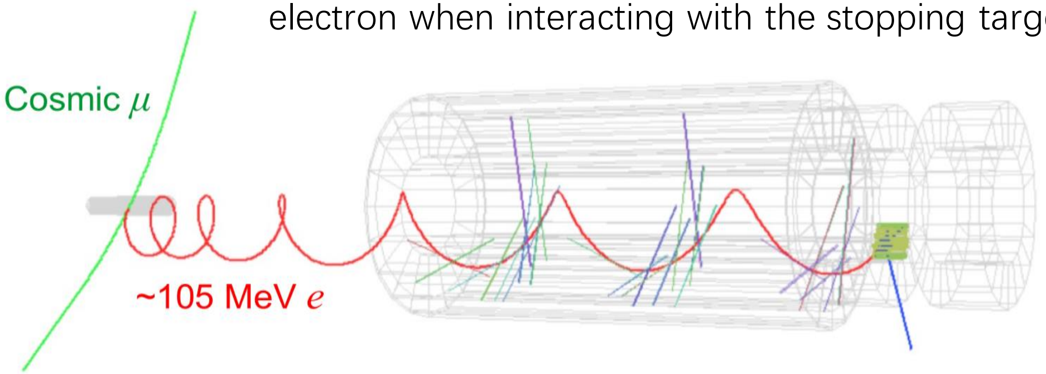


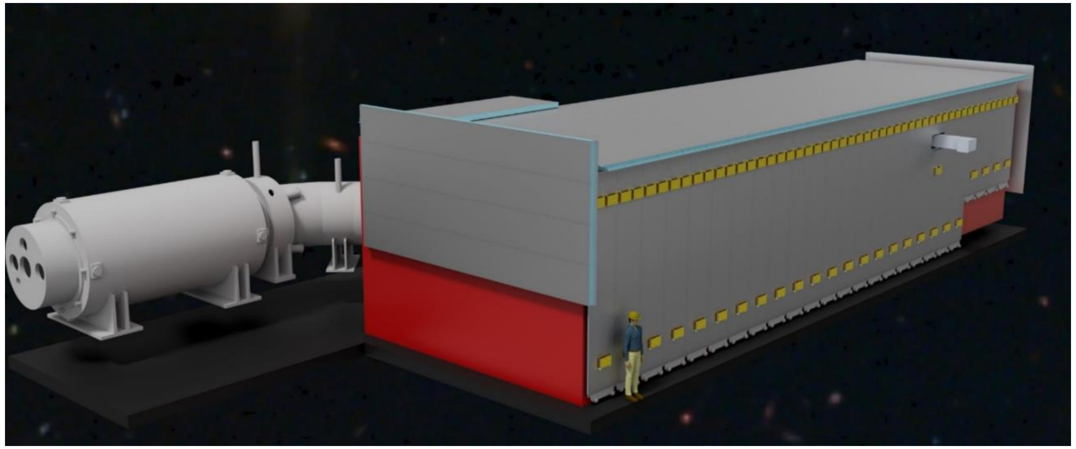

Calorimeter crystals (left) and SiPMs with Front End Electronics (right)

# COSMIC RAY VETO (CRV)

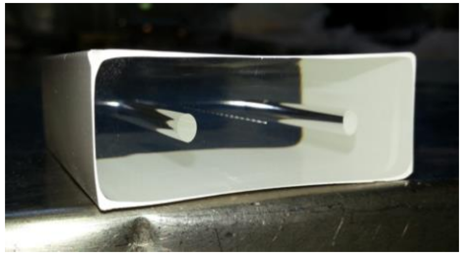
- Vetoes cosmic ray muons that produce conversion-like backgrounds (~once/day)
- Covers entire Detector Solenoid (DS) and half of the Transport Solenoid (TS)
- 4 overlapping layers of extruded polystyrene scintillator bars, separated by ~ 10 mm absorber
  - 2 wavelength shifting (WLS) fibers per bar
  - Silicon photomultiplier (SiPM) readout, most modules on both ends
  - 125 ns veto when 3/4 layers hit (localized in space and time)
- High efficiency (>99.99%) veto, help to reduce total background over the entire experiment to <0.5 event (about half is cosmic background, still the main background of Mu2e)

Simulated cosmic event that produces 105 MeV electron when interacting with the stopping target.

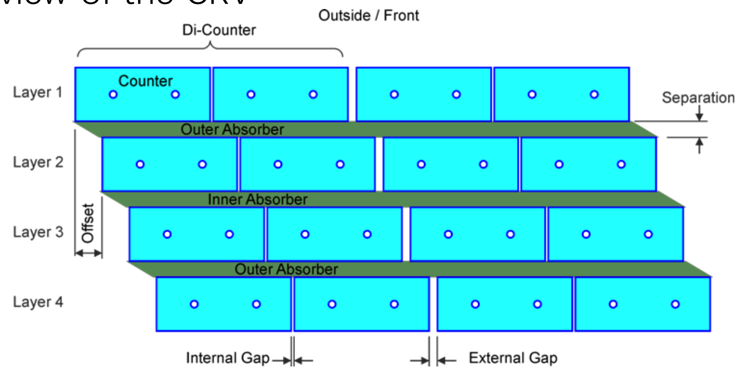


overview of the CRV



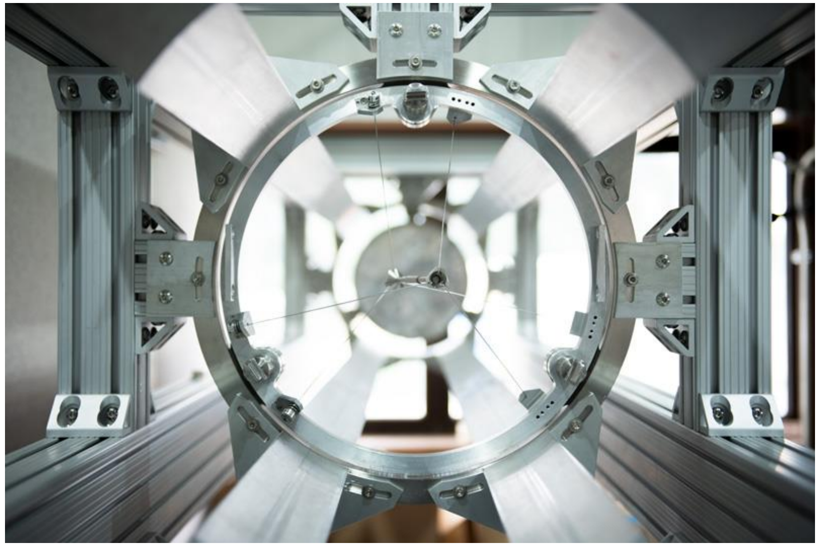
Extruded plastic scintillator bar



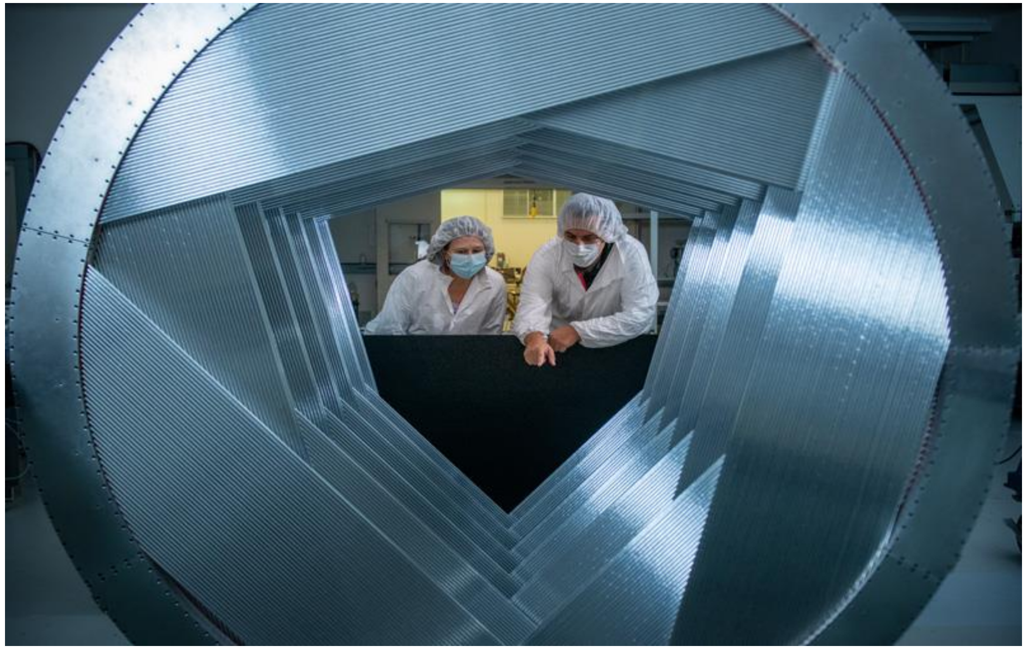

Cross-sectional module geometry

# MU2E STATUS

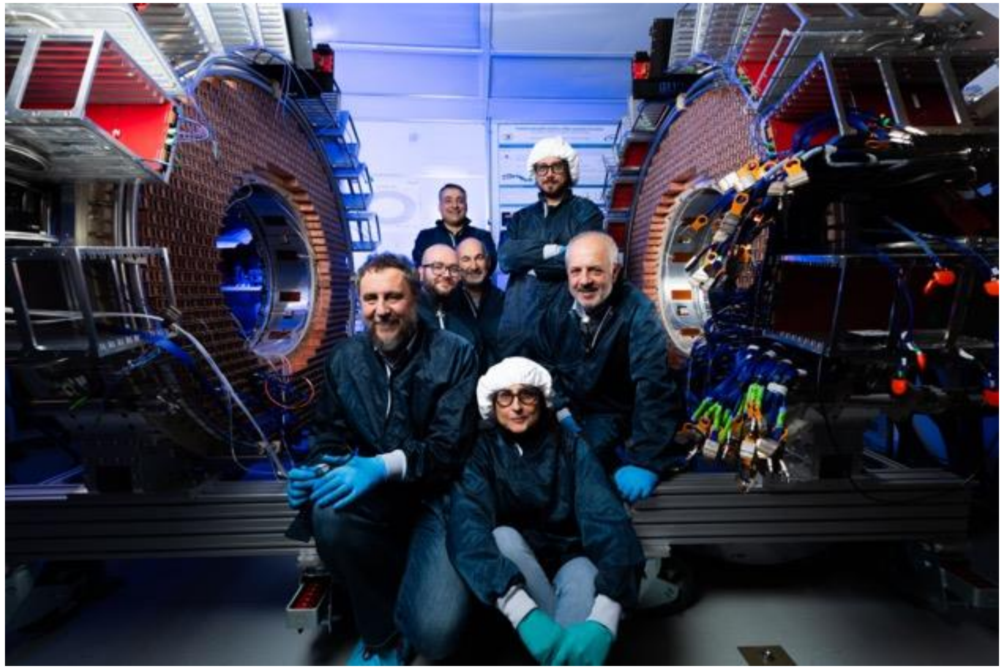
- Almost all Mu2e detector components have finished production and arrived at Fermilab
- Experiment is moving towards installation and commissioning
- DAQ under active development and test



Production target and robot



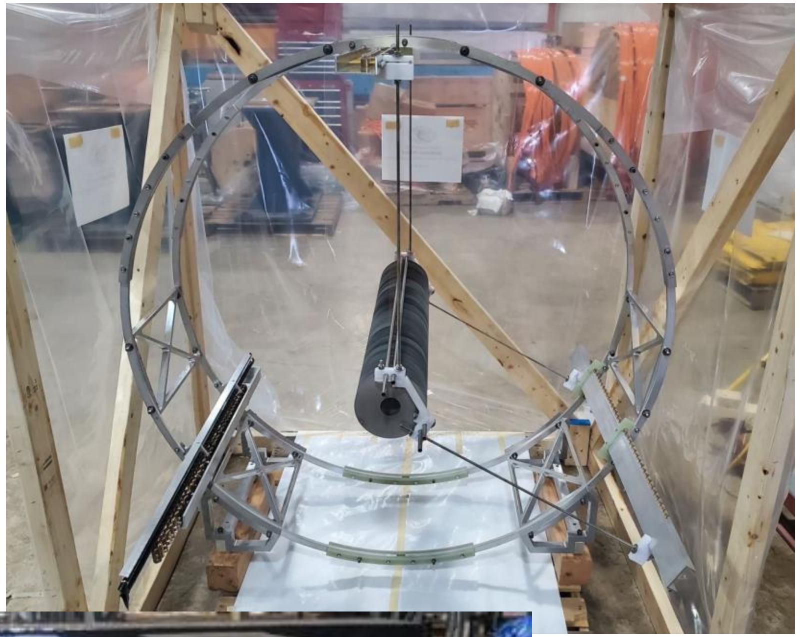
Tracker planes



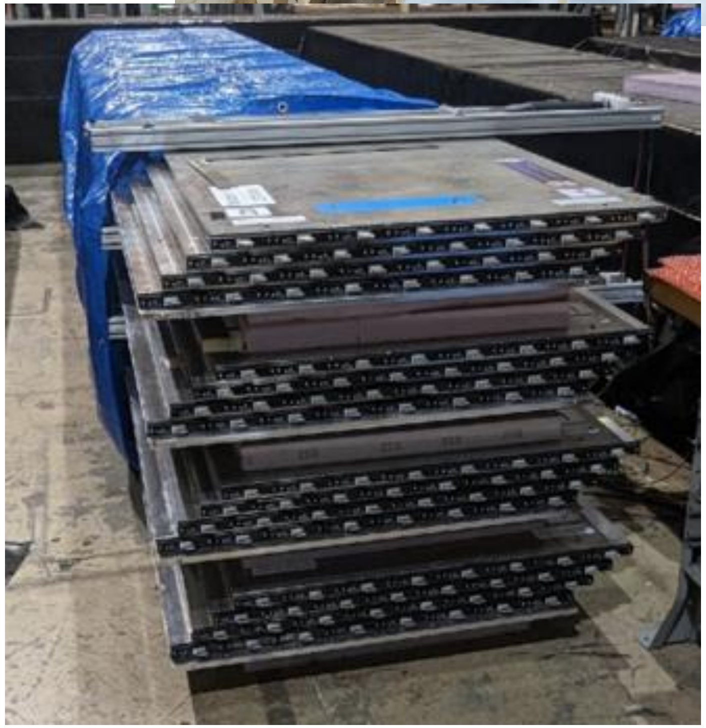
Calorimeter disks

# MU2E STATUS

Stopping target



CRV Installation Test



A Stack of production CRV modules used for cosmic studies

# MU2E STATUS

- Upstream and downstream transport solenoids were moved into the detector hall respectively in Dec. and in Feb.
- Production solenoid arriving in the next few months

TSu en route to MC-2


TSu lowered to pit

Mechanical interconnect between TSu and TSd being worked on and welded

# MU2E STATUS

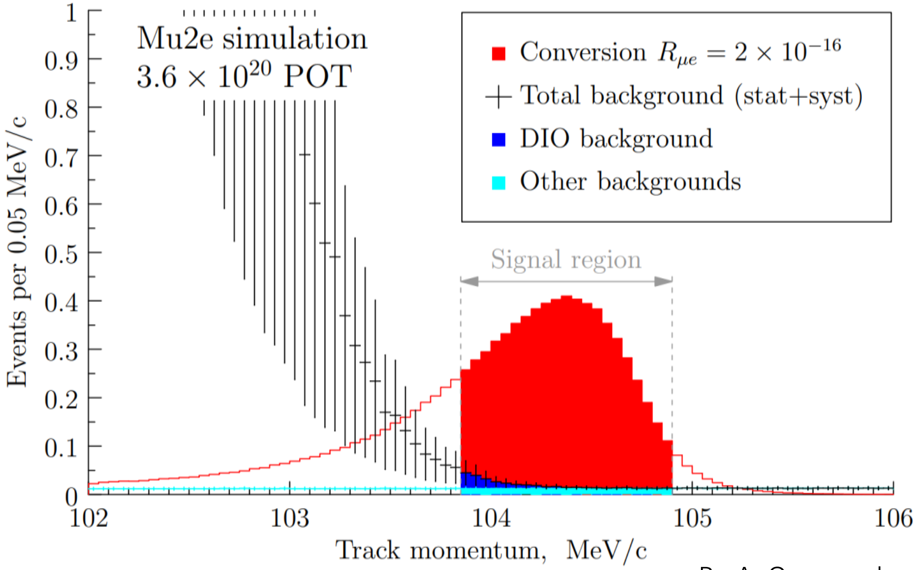
| Other recent and near future milestones | | |
|---|---|---|
| Beam slow extraction demonstrated | Jul. 23’ | |
| First LHe delivered | Aug. 23’ | LHe production inherited from g-2 |
| Calorimeter delivery | Aug. 24’ | |
| Tracker delivery | Oct. 24’ | |
| Detector solenoid delivery | Early 25’ | |

- Expect about a year-long cosmic ray run, starting in 2025, that should be enough to completely determine initial calibrations for all systems and get everything production ready

# MU2E SCHEDULE

- Physics Run I: expected to start in Jan. 2027 and continue until the beginning of the PIP-II/LBNF Long Shutdown at Fermilab
  - ~$10^3$ improvement over SINDRUM-II
- Full data set by mid-2030s, expected $R_{\mu e} < 8 \times 10^{-17}$ @ 90% CL, 4 orders of magnitude improvement to the current limit
- 2023 P5 Report recommended continued support for Mu2e in the next decade

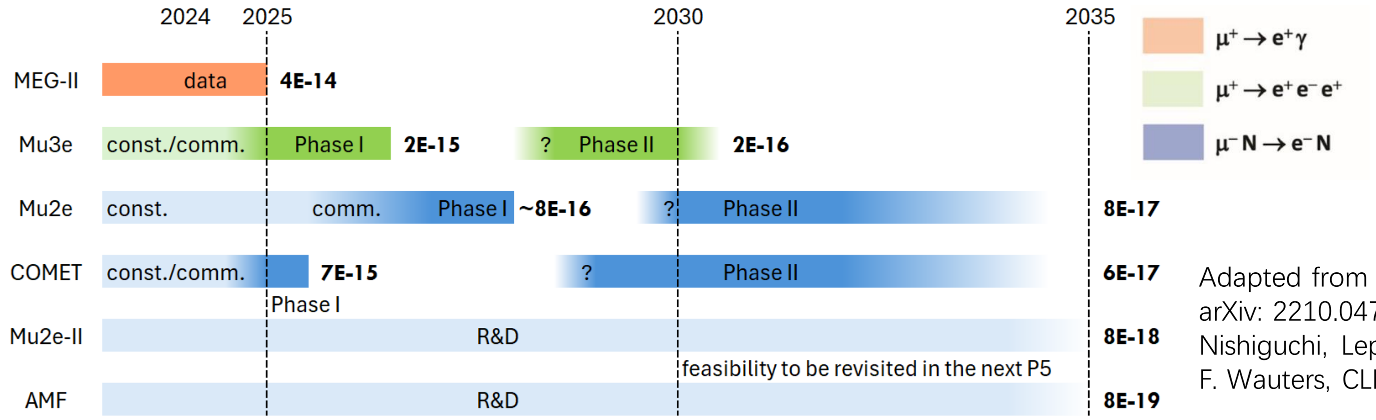
Simulated Mu2e signal and background




By A. Gaponenko

- Discovery reach (5$\sigma$): $R_{\mu e} \geq 2 \times 10^{-16}$
- Exclusion power (90% CL): $R_{\mu e} \geq 8 \times 10^{-17}$

Muon-based CLFV rare decay experiments, expected timeline, and expected 90% CL exclusion power.



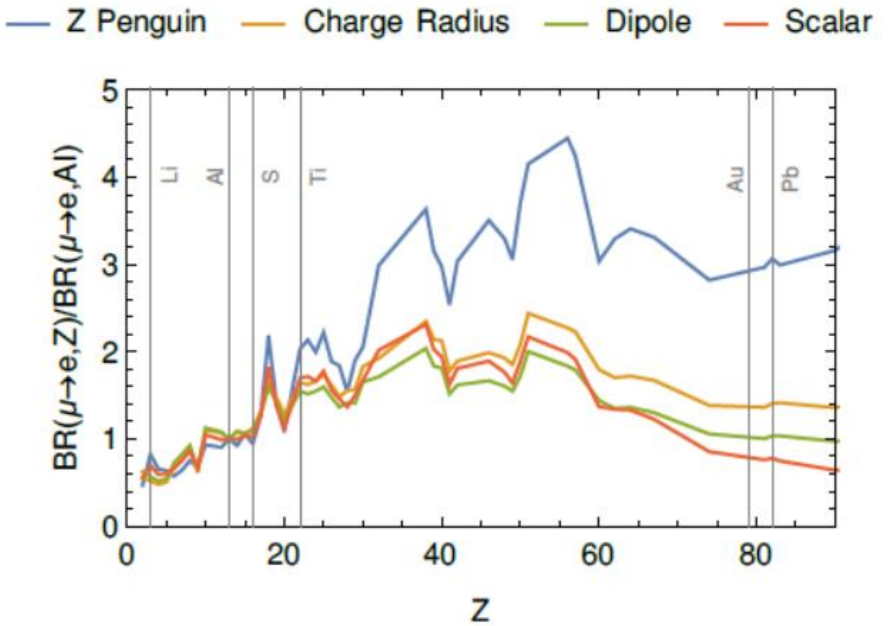

Adapted from M. Artuso et al., arXiv: 2210.04765;
Nishiguchi, Lepton Photon 2023;
F. Wauters, CLFV 2023

# WHAT'S NEXT: MU2E-II EXPERIMENT

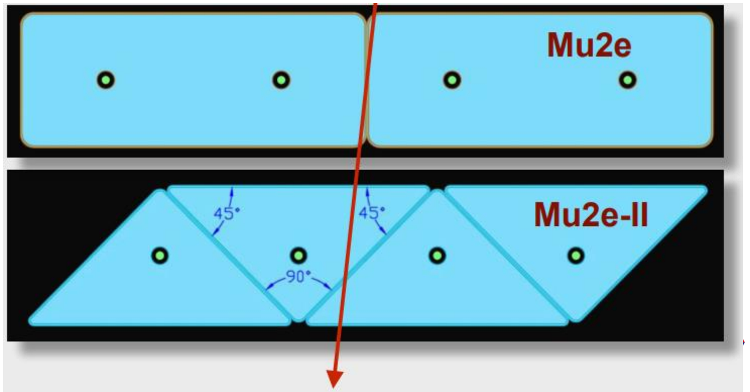
- Mu2e-II is current being contemplated as a continuation of Mu2e (Snowmass LOI arXiv:2203.07569)
- Plan to use the PIP-II beam line at Fermilab
- Want to squeeze for another 10x SES
- Depending on what we see …
  - If we do see any signal with Mu2e:
    We will switch to a stopping target made of some different material (e.g., Ti) and try to understand the nature of the underlying physics
  - If we do not see any signal with Mu2e:
    We continue the search, excluding a larger region in the parameter space
- High beam intensity requires upgrades to production target, most of the detectors, and DAQ. The 2023 P5 report endorsed funding R&D efforts into these extremely challenging problems under all budget scenarios.

based on
R. Kitano et al Phys. Rev. D 66 (2002) 096002
V. Cirigliano et al., Phys. Rev. D 80 (2009) 013002.

Z dependence $\mu \rightarrow e$ of conversion rates




Example Mu2e-II R&D for CRV. Scintillator with triangular cross sections can help improve veto efficiency as most cosmic ray muons fall almost vertically



# SUMMARY

- Charged Lepton Flavor Violation provides a powerful and model independent tool of finding new physics.
- Muon CLFV decay experiments, due to their lack of SM backgrounds, provide the best limits of CLFV searches to date.
- The Mu2e experiments aims to measure $\mu N \rightarrow eN$ with an expected limit of $R_{\mu e} < 8 \times 10^{-17}$ @ 90% CL, improving the previous limit by 4 orders of magnitude.
- Detector production is concluding, installation and commissioning efforts are ramping up. We are expecting a one-year run starting in Jan. 2027 for first 10% of data

***This is an exciting time to work on Mu2e!***

# THANK YOU!

# BACKUP SLIDES

# THEORY DIFFERENTIATING POWER OF CLFV PROCESSES

W. Altmannshofer et al, Nucl.Phys B.830:17-94, (2010)

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

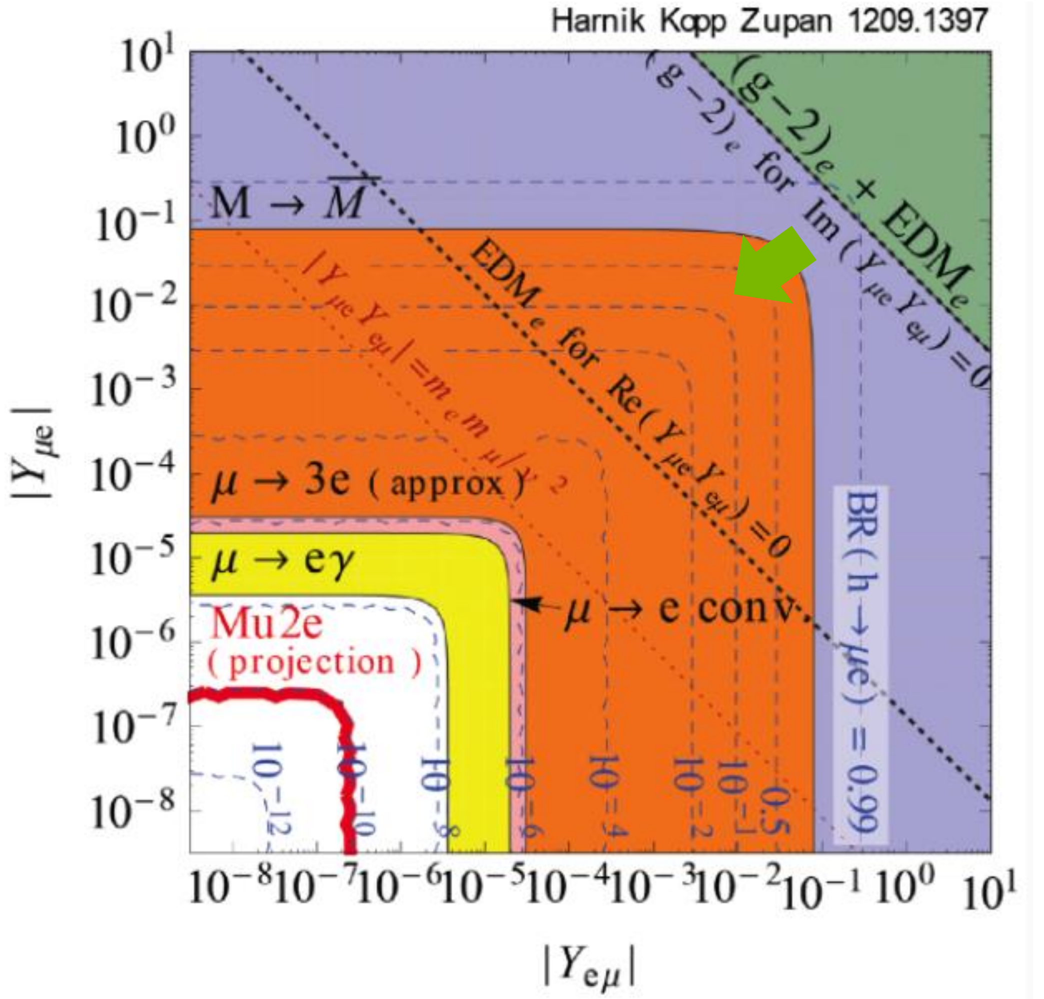
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

# CLFV IN COLLIDER EXPERIMENTS

M. Ardu, CLFV2023

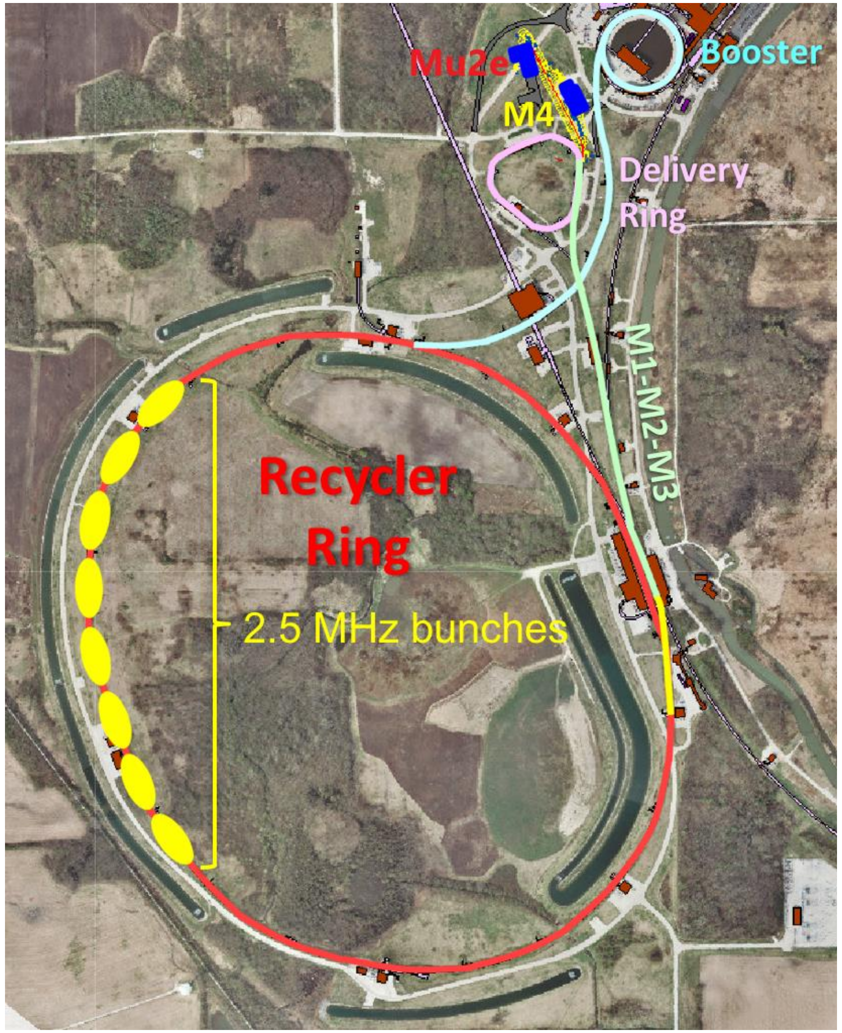
| | | |
|---|---|---|
| $h \to e^{\pm}\mu^{\mp}$ | $< 6.1 \times 10^{-5}$ | Atlas |
| $h \to e^{\pm}\tau^{\mp}$ | $< 2.2 \times 10^{-3}$ | CMS |
| $h \to \tau^{\pm}\mu^{\mp}$ | $< 1.5 \times 10^{-3}$ | CMS |
| $Z \to e^{\pm}\mu^{\mp}$ | $< 7.5 \times 10^{-7}$ | Atlas |
| $Z \to l^{\pm}\tau^{\mp}$ | $< 10^{-7}$ | Atlas |

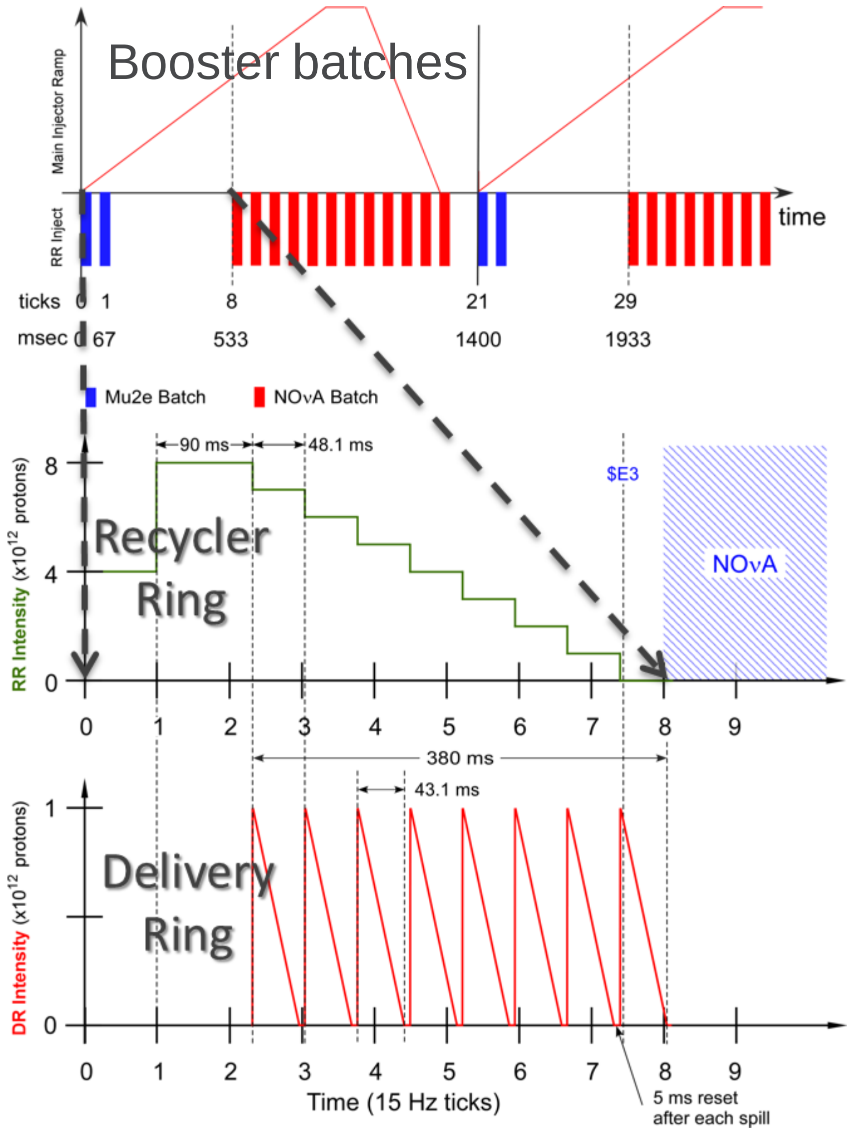
- Additional Higgs doublets / neutral gauge bosons
- Probing of off-diagonal Yukawa coupling term $Y_{l_1 l_2}$
- Muon experiments much better sensitivity in $e\mu$ mode, but energy too low for $\tau$; complimentary to collider experiments



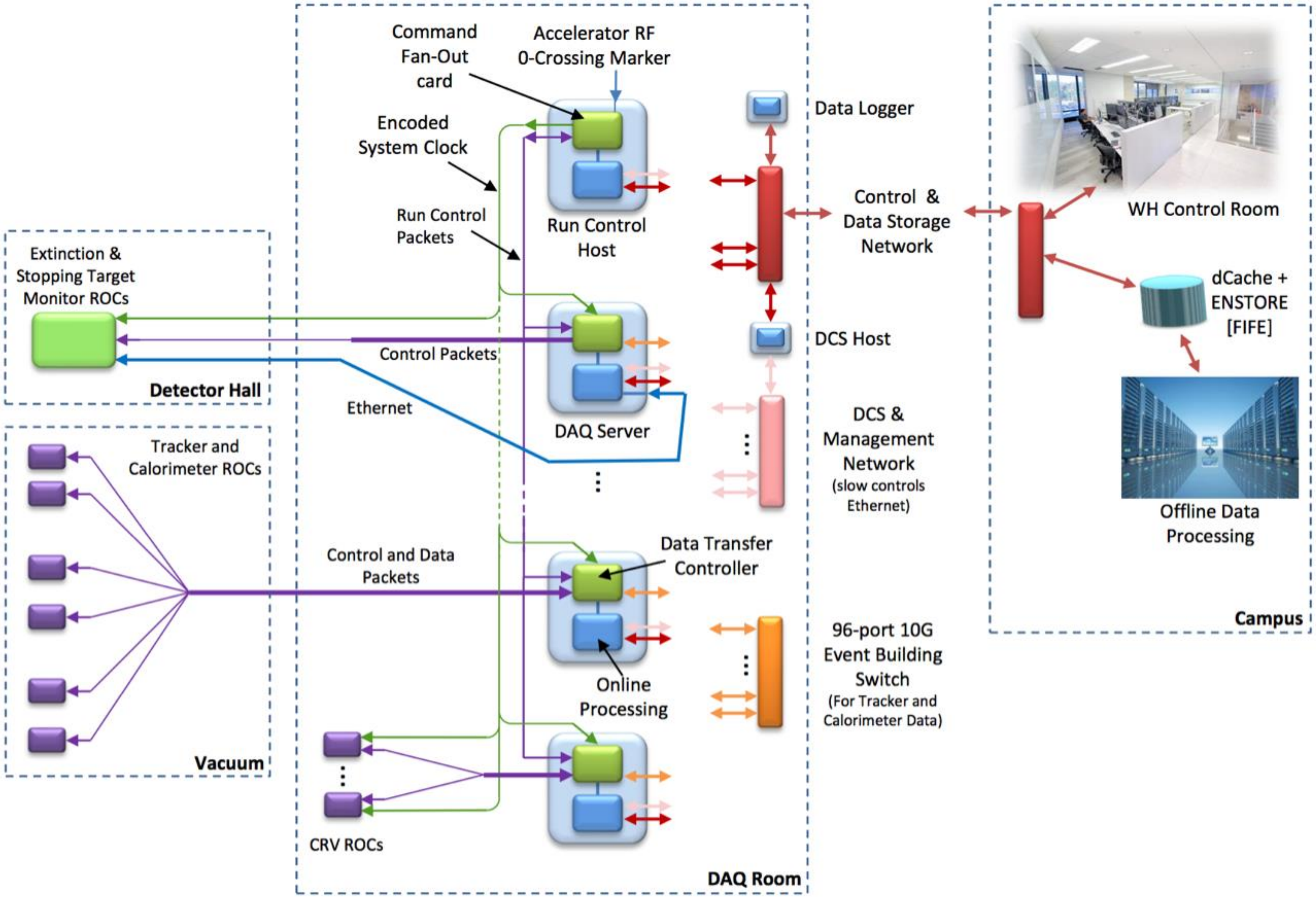

Harnik, Kopp, and Zupan, J. High Energ. Phys. (03) 2013: 26

# MU2E BEAM STRUCTURE IN ACCELERATOR SUPER-CYCLE



# MU2E DAQ SYSTEM

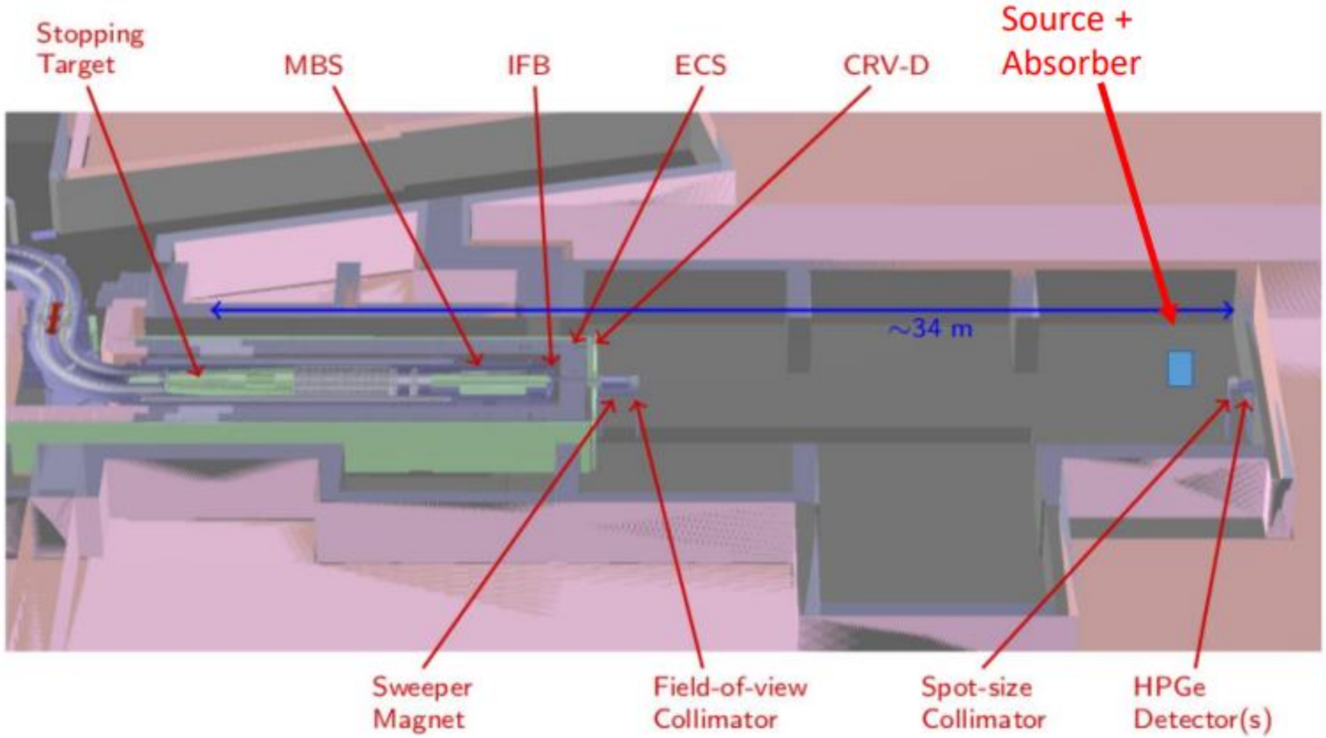


# STOPPING TARGET MONITOR

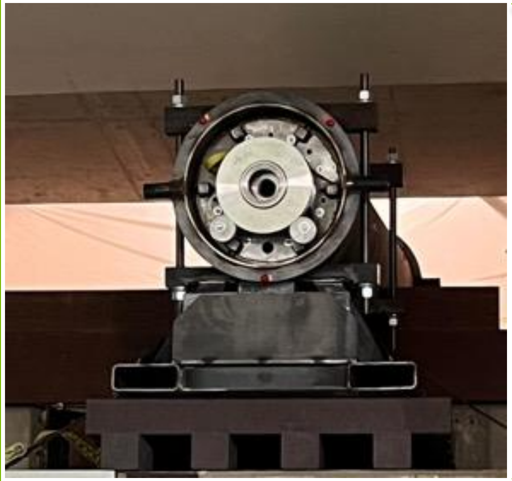

Stopping target monitors

Muonic X-ray emission spectrum measured by LaBr3+HPGe detectors to estimate number of muons captured.

- 10% uncertainty in number of stopped muons over the entire experiment; timing to few x 10 ns
- AlCap experiment (COMET-Mu2e collaboration) measured photon spectra from muons stopping on Al, at low rates.
- ELBE experiment tested HPGe performance in pulsed brem beam, closely replicating Mu2e conditions

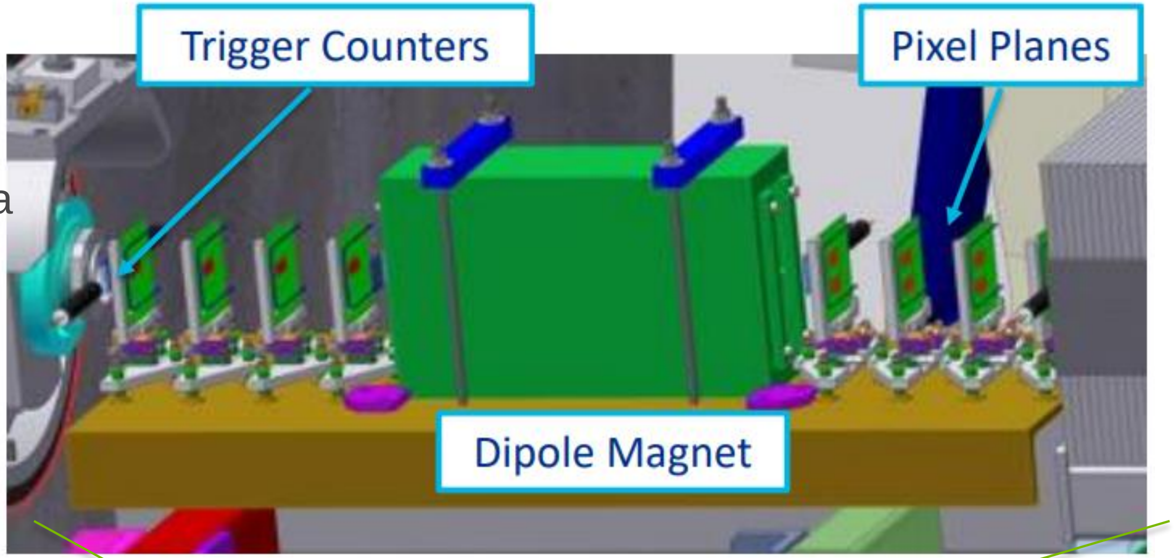


# EXTINCTION MONITOR

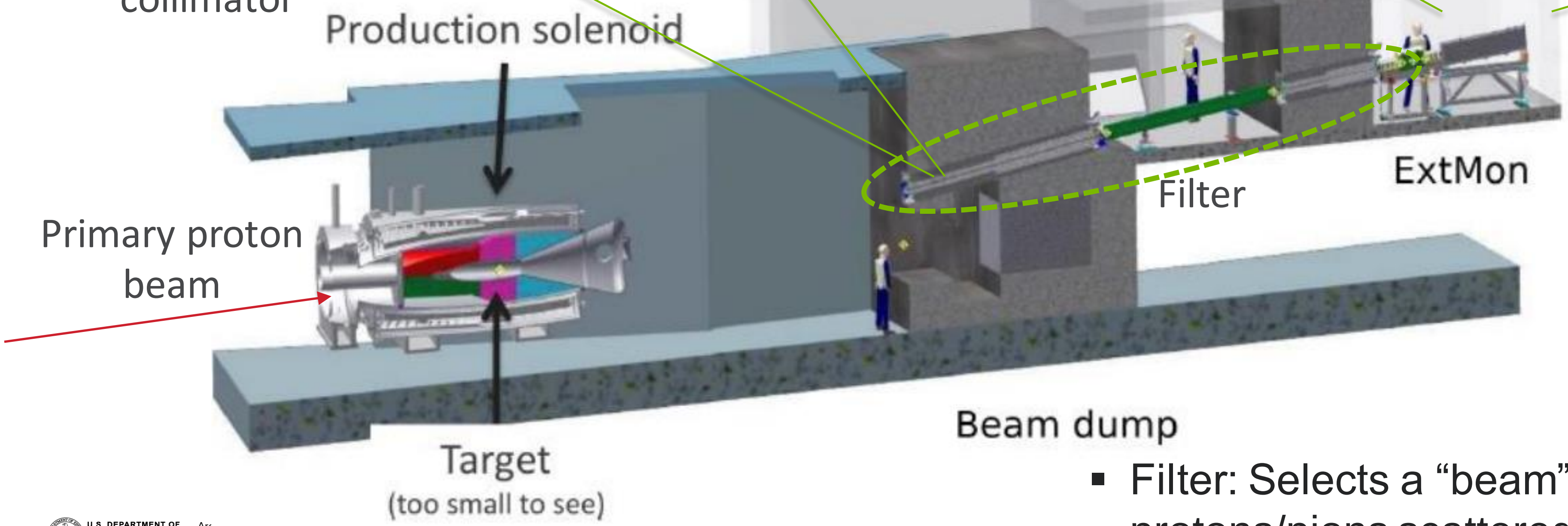


Extinction Monitor collimator

Trigger scintillators: Provide a between-bunch trigger signal for the pixels and high-resolution arrival times for inter-bunch tracks




Mini spectrometer based on ATLAS pixel chips




Pixel Tracker: Detect and reconstruct tracks during and between beam pulses. Provides the basic measurement

Permanent Dipole: Eliminates electrons from muon decays and also provides a rough momentum measurement

- Filter: Selects a “beam” of ~4 GeV/c protons/pions scattered off the target

# MU2E BACKGROUNDS SUMMARY

* Simulation results for $3.6\times10^{20}$ POT

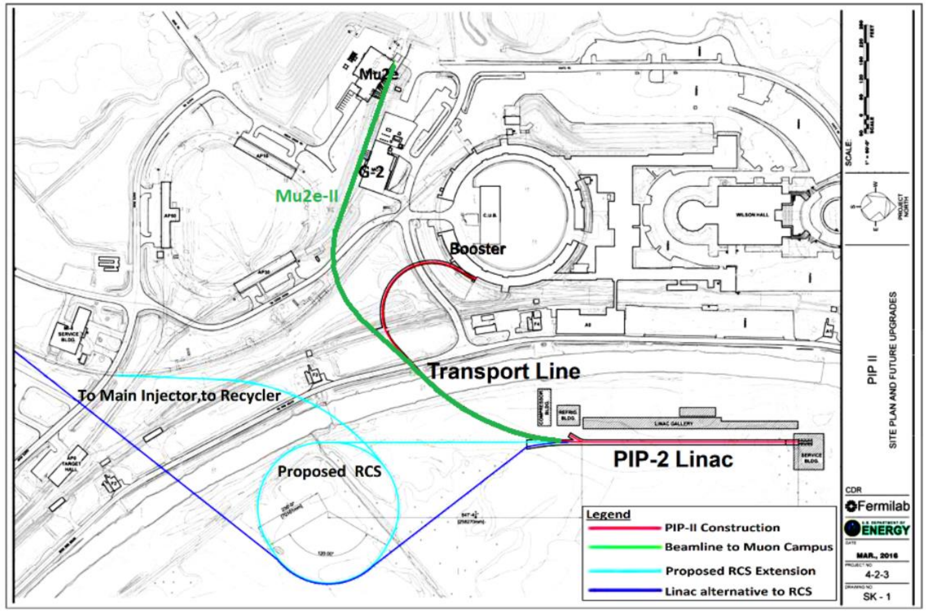
| Process | Expected event yield |
| --- | --- |
| Cosmic rays | $0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$ |
| DIO | $0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$ |
| Antiprotons | $0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$ |
| Pion capture | $0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$ |
| Muon DIF | $< 0.003$ |
| Pion DIF | $0.001 \pm < 0.001$ |
| Beam electrons | $(2.1 \pm 1.0) \times 10^{-4}$ |
| RMC | $0.000^{+0.004}_{-0.000}$ |
| Total | $0.41 \pm 0.13(\text{stat+syst})$ |

# PIP-II FOR MU2E-II

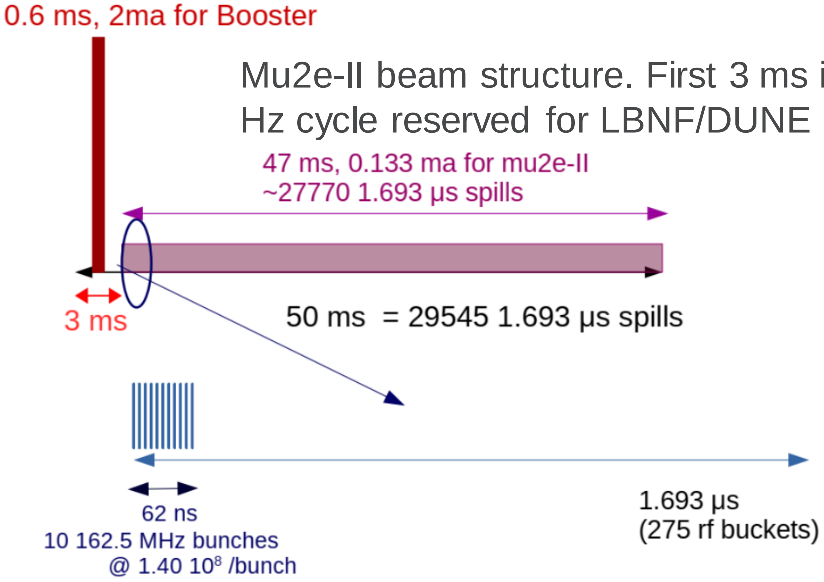
The Proton Improvement Plan-II (PIP-II) is an enhancement plan for Fermilab's accelerator complex

- Under construction until ~2028
- Contains a Linac to deliver 800 MeV $H^-$ beam
  - Lower than anti-proton production threshold
- Up to ~2 mA; peak current up to 10 mA for less than a few microseconds
- Chopper system to create arbitrary pattern of filled / empty buckets at 162.5 MHz
- Can deliver beam to multiple users within a 20 Hz cycle
- Mu2e-II can use this higher intensity proton beam
  - 10 filled buckets (62 ns long) followed by 265 empty buckets form 1.693 μs Mu2e-II spill
  - Estimates $5.5 \times 10^{19}$ stopped muons over 5 years for Mu2e-II

K. Byrum et al., arXiv:2203.07569




PIP-II linac with transport lines to Booster (brown) and Mu2e-II (green) indicated.

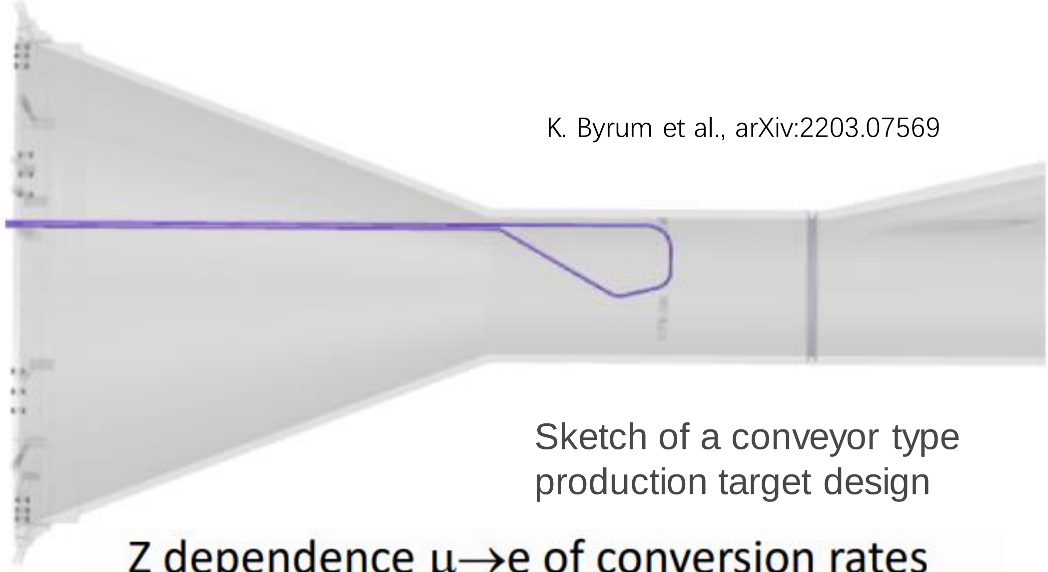



Mu2e-II beam structure. First 3 ms in each 20 Hz cycle reserved for LBNF/DUNE

# MU2E-II UPGRADES

High beam intensity requires upgrades to production target, most of the detectors, and DAQ. There are many ongoing R&D efforts. Some example below.

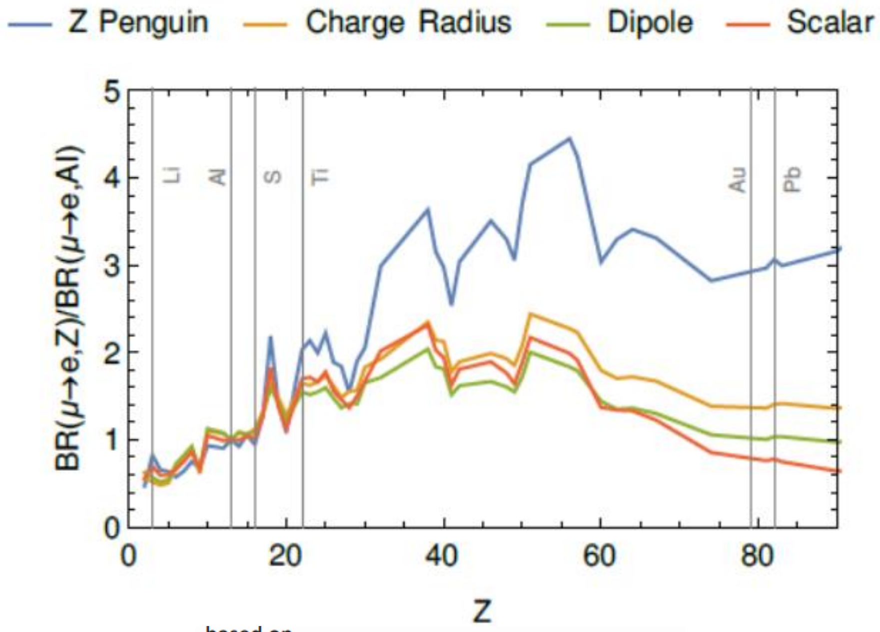
- Overall electronics upgrade to deal with higher level of radiation
- Production target upgrades to survive beam intensity
  - Rotating? Granular? Conveyor?
- In case Mu2e sees something, potentially change stopping target materials (e.g. Ti) to provide model differentiating power.
- Improving straw tracker momentum resolution
  - Mitigates ~10x intrinsic muon DIO background
  - Reduce straw thickness:
    15 μm → 8 μm, 140 keV → 100 keV
    But challenges with gas tightness and stability
  - Alternative detectors (all wires, light gas vessels, etc.) also under investigation



K. Byrum et al., arXiv:2203.07569

Sketch of a conveyor type production target design

Z dependence μ→e of conversion rates

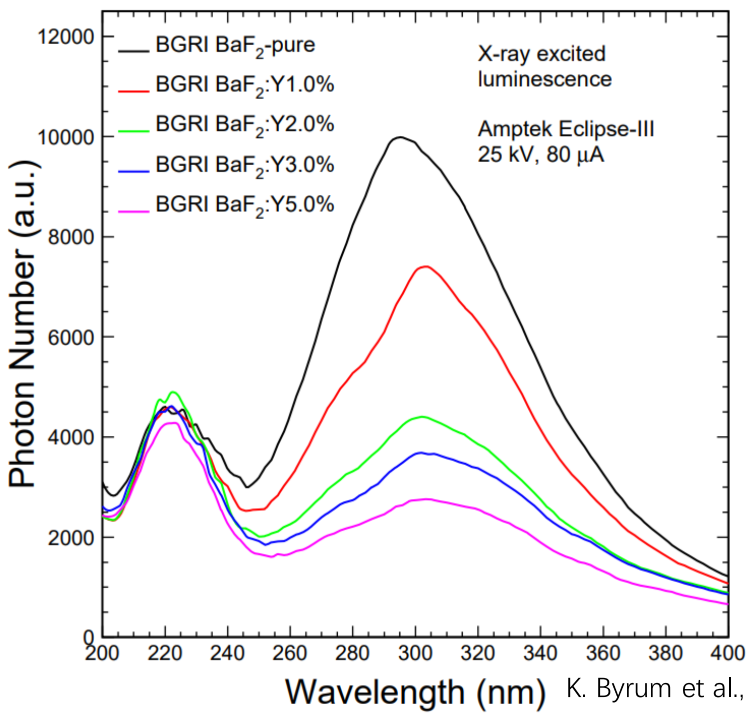



based on
R. Kitano et al Phys. Rev. D 66 (2002) 096002
V. Cirigliano et al., Phys. Rev. D 80 (2009) 013002.

# MU2E-II UPGRADES

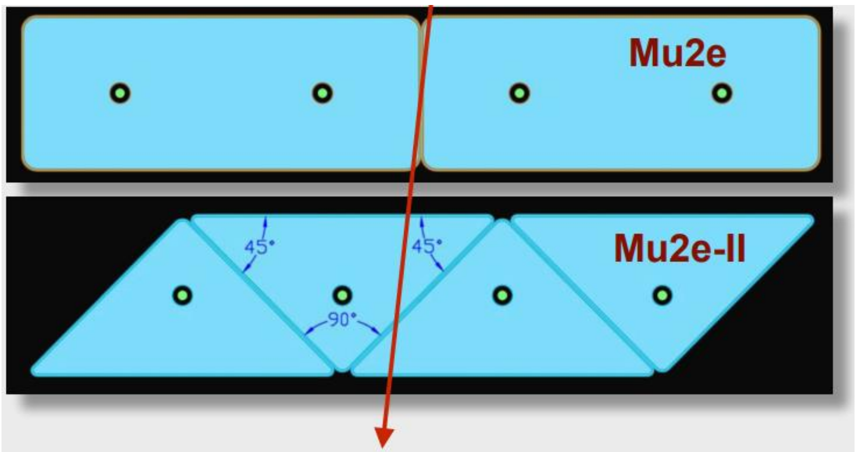
- Replacing CsI scintillators in the calorimeter
  - CsI cannot withstand the radiation dose
  - Possible candidate $BaF_2$
  - Fast component < 0.6 ns decay time in UV
  - Require suppression of slow scintillation component (~300 nm) through doping or photosensor optimization
- Optimization of CRV design with triangular-shaped plastic scintillator counters
  - Smaller chance of cosmic ray muons falling through gaps, thus higher detection efficiency
  - Better (~1 mm) positional resolution can reduce accidental events, lower dead time
  - Light yield can be further enhanced through optimizing wavelength shifting fiber size, fiber potting method, and SiPM efficiency
  - Studies conducted on a prototype showing promising results

Light yield of $BaF_2$ with different levels of yttrium doping




K. Byrum et al., arXiv:2203.07569

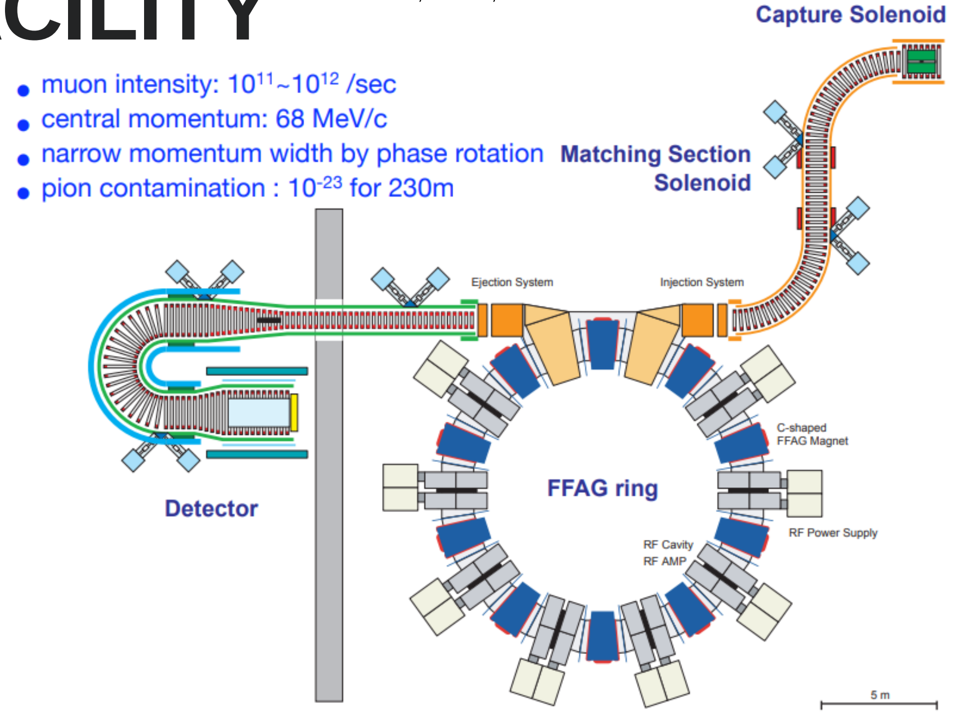
Most cosmic ray muons fall almost vertically

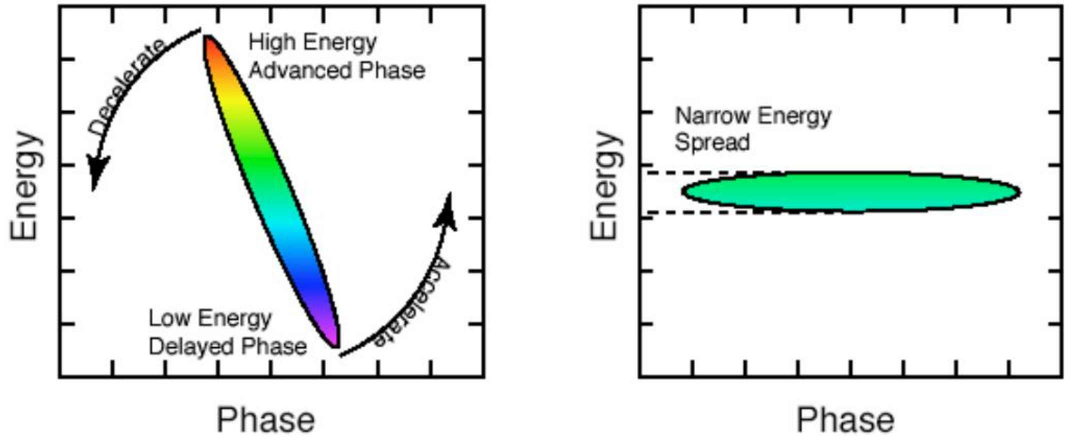


# FUTURE MUON CLFV CONCEPTS: NEXT GENERATION MUON FACILITY

A. Sato, TAU 06;
Y. Kuno, Nucl. Phys. B - Proceedings Supplements, 149, 2005, 376-378

- Phase Rotated Intense Slow Muon Source (PRISM) @ J-PARC
- Fixed Field Alternating Gradient synchrotron (FFAG) capable of handling large-size muon beam
  - Large transverse and longitudinal acceptance
- Phase rotation in the FFAG means decelerating particles with high energy and accelerating particle with low energy by high-field RF
  - Trading between energy resolution and time resolution
- Produces monochromatic muon bunches, can be directly used in muon CLFV searches

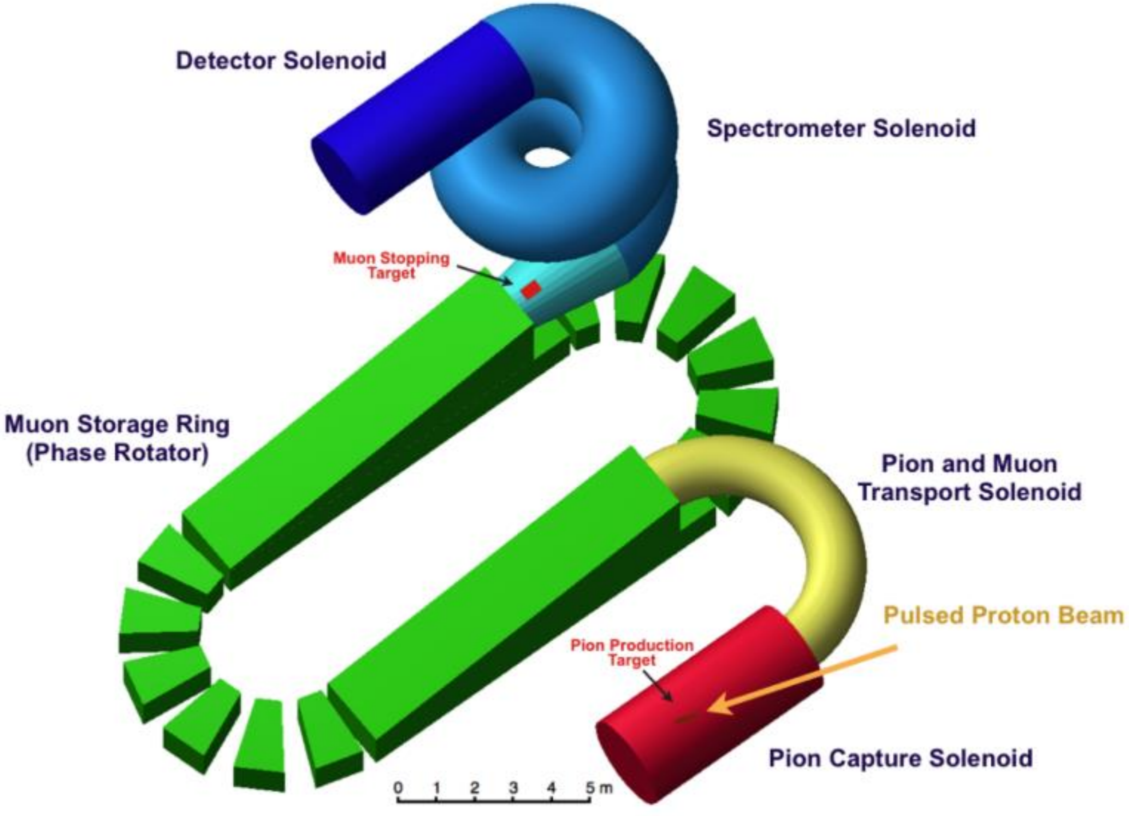


# FUTURE MUON CLFV CONCEPTS: NEXT GENERATION MUON FACILITY

M. Aoki et al., arXiv: 2203.08278

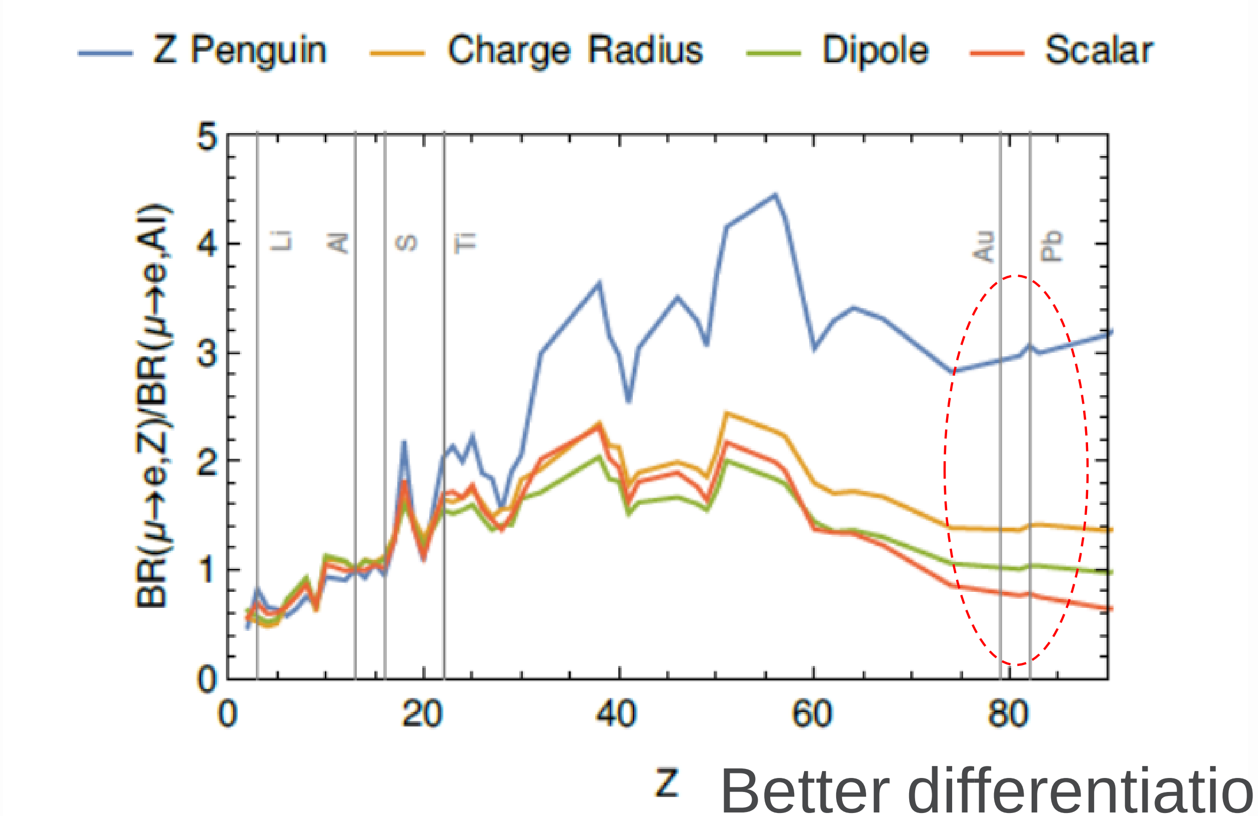
- Advanced Muon Facility (AMF) at Fermilab adapts the concept of PRISM
- Using Fermilab PIP-II beam as primary proton beam
- A racetrack geometry to separate injection and extraction systems
- Central momentum of 20-40 MeV/c, ideal for muon CLFV searches in all channels
- Expected to push current limits by 2 orders of magnitude
- Recent increase of interest in the community. Snowmass LOI arXiv:2203.08278




AMF schematic based on PRISM concept

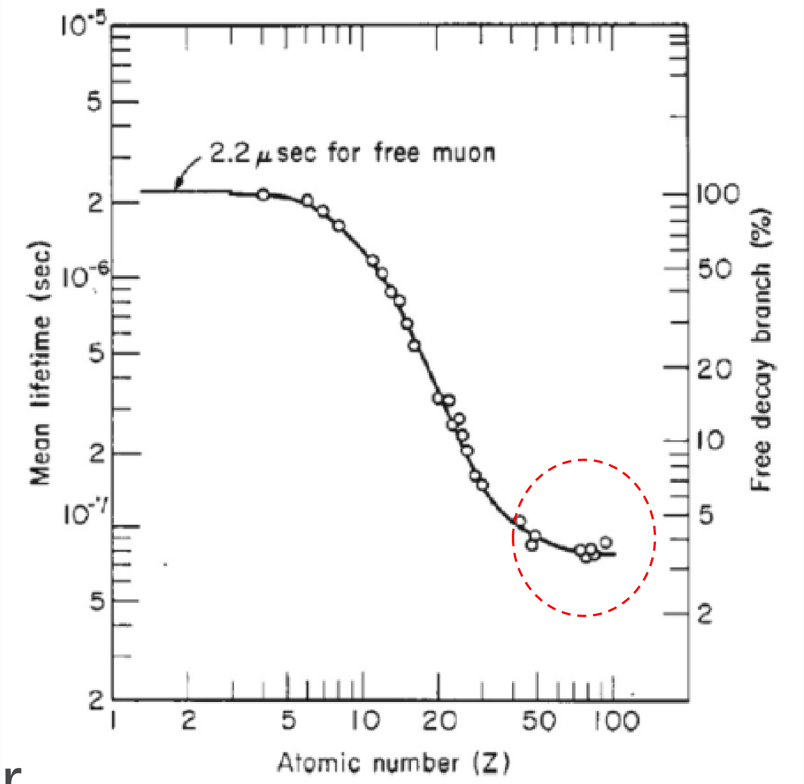
# $\mu N \rightarrow eN$ SEARCH STOPPING TARGET MATERIALS

Z dependence μ→e of conversion rates




Better differentiation power

Muonic atom lifetime




J. Heeck et al. (SNOWMASS21-RF5_RF0-TF6_TF0_Heeck-043.pdf)
based on
R. Kitano et al Phys. Rev. D 66 (2002) 096002
V. Cirigliano et al., Phys. Rev. D 80 (2009) 013002.

A. Knecht et al., EPJ. Plus (2020) 135

Short lifetime, more background using pulsed proton beam