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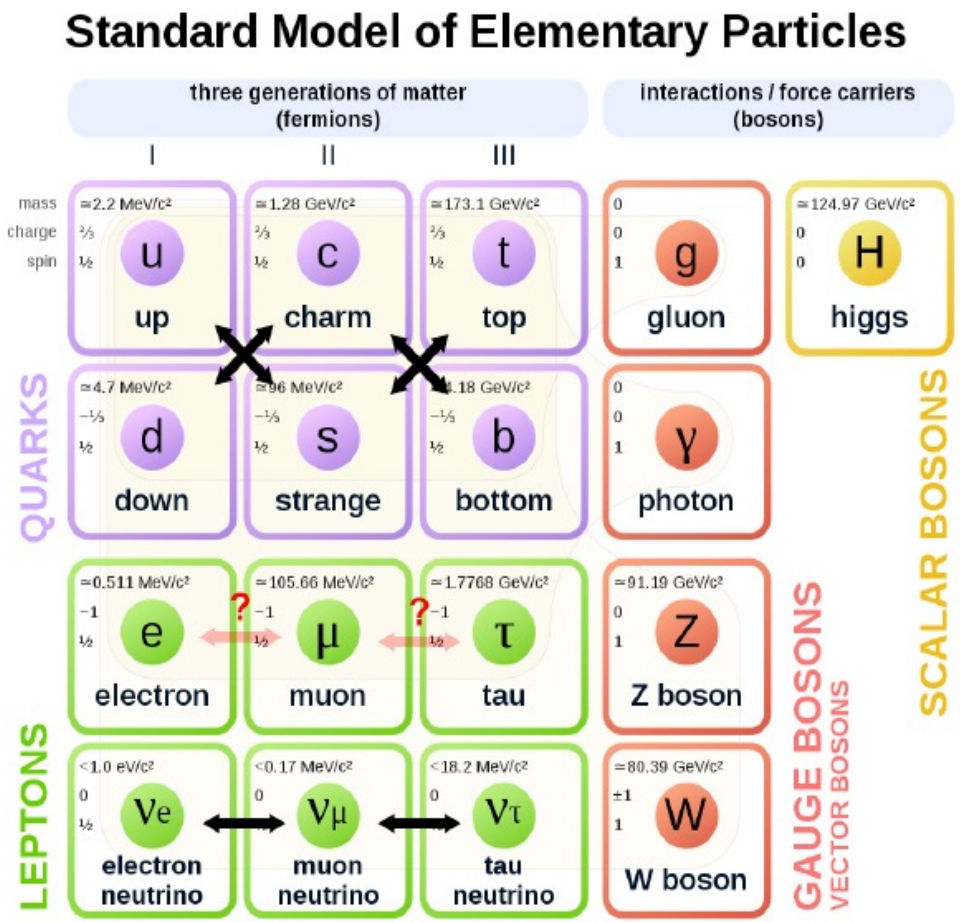
Mu2e: A Search for Charged Lepton Flavor Violation at FNAL

Design and Current Status

Sophie Charlotte Middleton

on behalf of the Mu2e experiment

Flavor Physics



- Flavor is not conserved in:
  - quarks (via quark mixing);
  - neutrinos (via neutrino oscillations)

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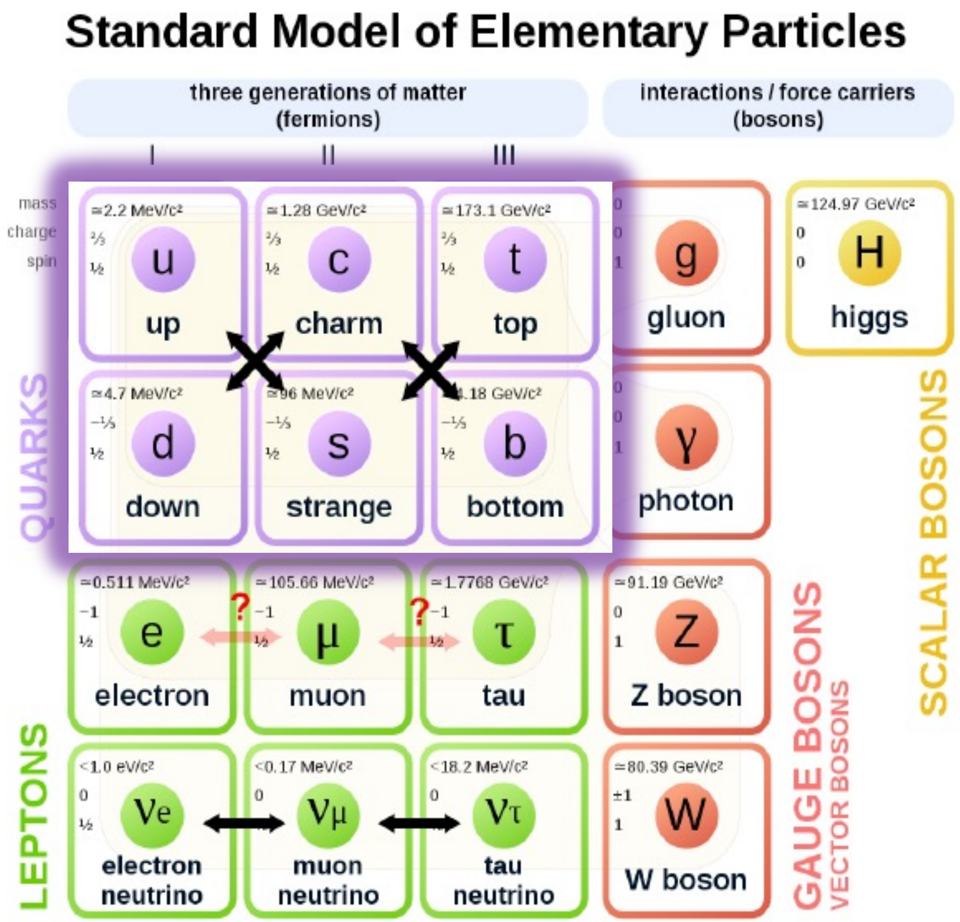

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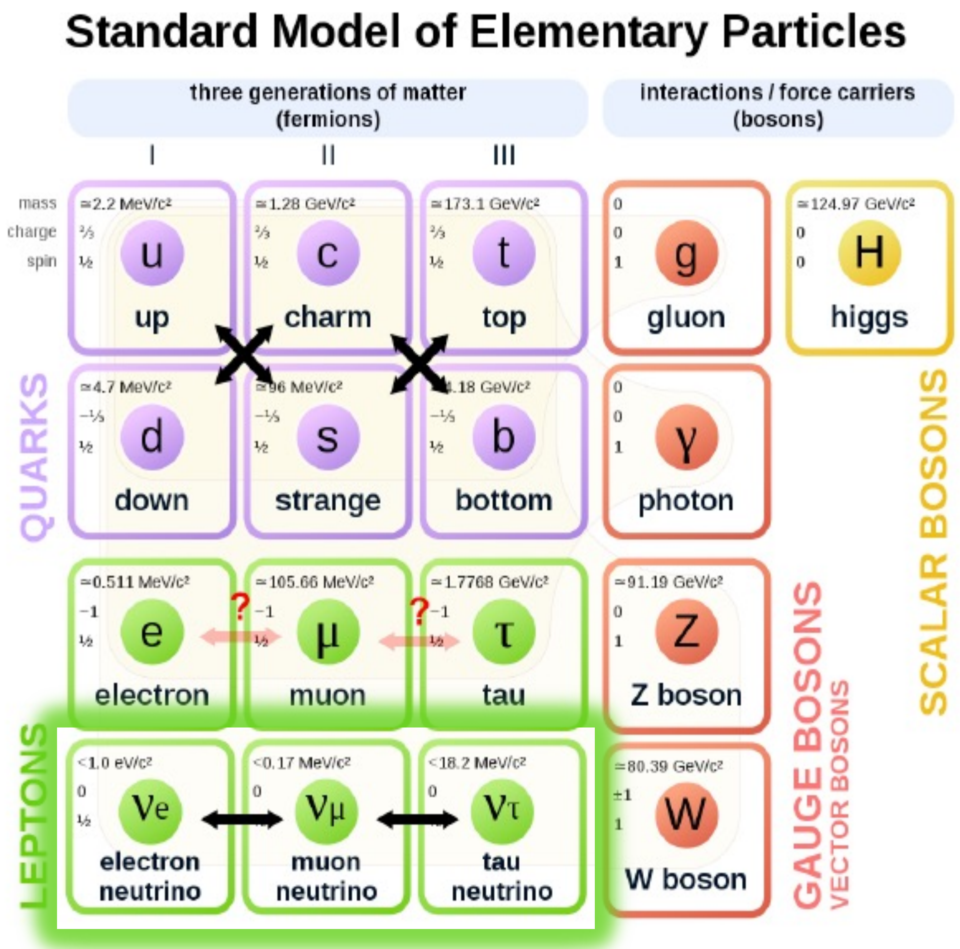

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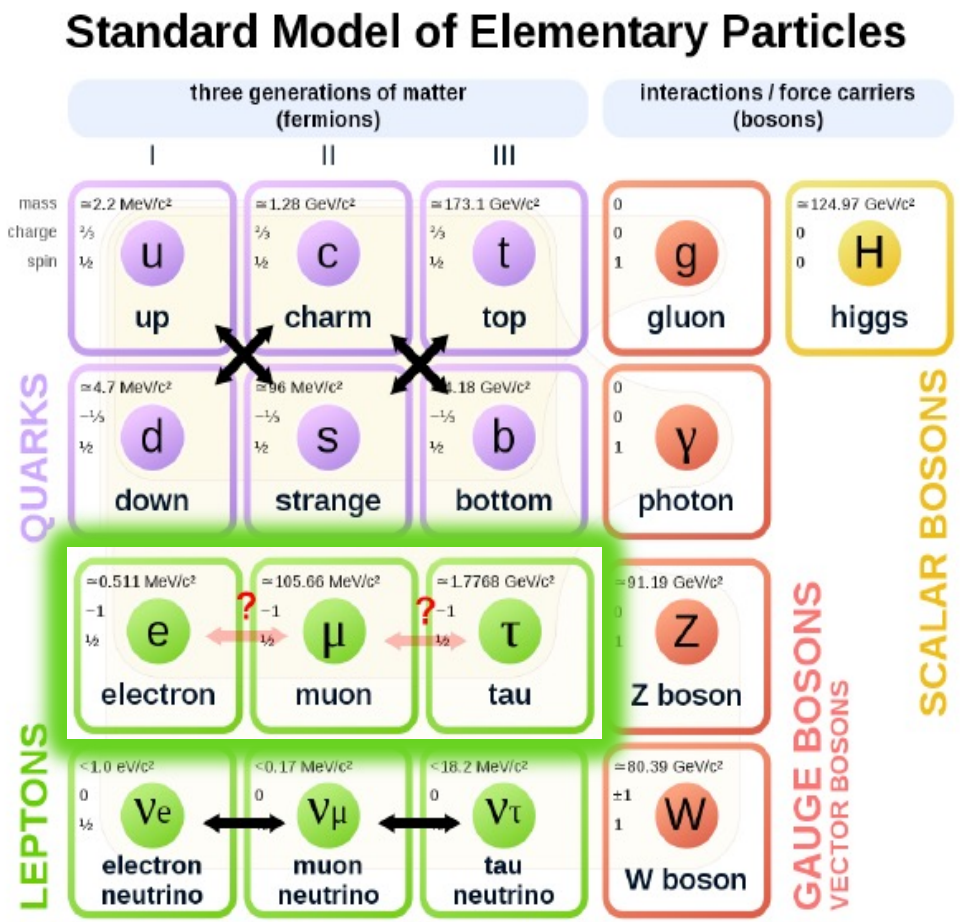
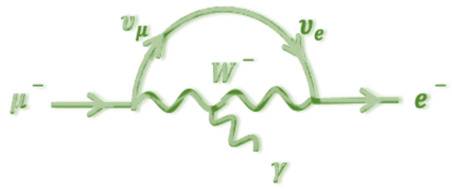
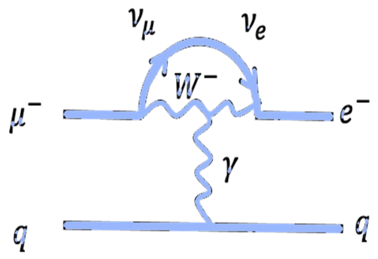


- Flavor is not conserved in:
  - quarks (via quark mixing);
  - neutrinos (via neutrino oscillations)
- **What about Charged Lepton Flavor Violation?**

Charged Lepton Flavor Violation (CLFV)

- The minimal extension of the Standard Model, including masses of neutrinos, allows for CLFV at loop level, mediated by W bosons.





No outgoing neutrinos!

- Rates heavily suppressed by GIM suppression and are far below any conceivable experiment could measure:

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left(\frac{1}{4}\right) sin^2 2\theta_{13} sin^2\theta_{23} \left|\frac{\Delta m^2_{13}}{M^2_W}\right|^2$$

$$B(\mu \to e\gamma) \sim \vartheta(10^{-54})$$

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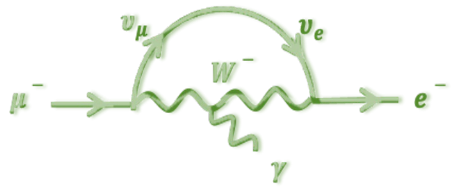

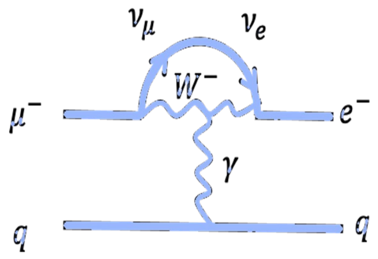

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- ...but many Beyond Standard Model (BSM) theories (e.g. SO(10) SUSY, scalar leptoquarks, seesaw models) predict enhanced rates of CLFV just below current limits O(10^{-13}).

Mu2e is an indirect search for New Physics which offers a deep probe of many well-motivated BSM theories.

Current Experimental Searches for CLFV

- **Mu2e is an important part of a world-wide search for CLFV.**
- Muons are a very powerful probe thanks to the availability of very intense beams and their relatively long lifetime.

Mode	Current Upper Limit (at 90% CL)	Projected Limit (at 90% CL)	Upcoming Experiment/s
$\mu^+ \rightarrow e^+\gamma$	**4.2 x 10^{-13}**	**4 x 10^{-14}**	**MEG II**
$\mu^+ \rightarrow e^+e^+e^-$	**~10^{-12}**	**10^{-15} ~ 10^{-16}**	**Mu3e**
$\mu^- N \rightarrow e^- N$	**7 x 10^{-13} (SINDRUM-II, 2006)**	**10^{-15} 10^{-16} 10^{-17}**	**COMET Phase-I Mu2e Run-I Mu2e Run-II/ COMET Phase-II**

- Synergies with tau CLFV searches. Comparing different lepton CLFV elucidates source of flavor violation.
- Need to explore the entire CLFV-sector like with quark and neutrino searches.

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- Synergies with tau CLFV searches. Comparing different lepton CLFV elucidates source of flavor violation.
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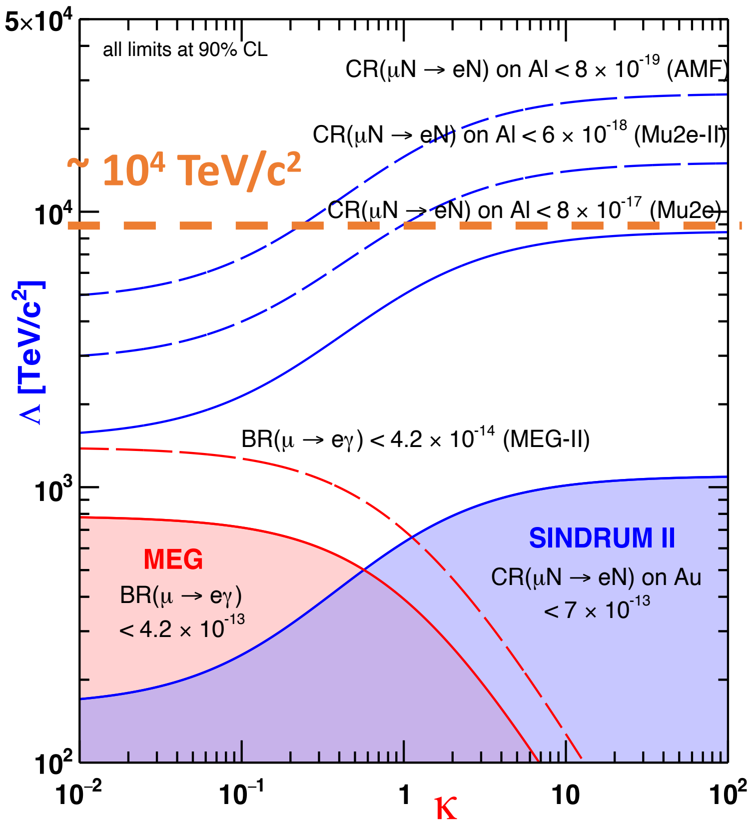
Effective Physics Reach

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

"Photonic" "Contact"

* Mu2e-II and AMF are proposed future experiments/facilities.



Λ : Effective mass scale of New Physics (NP),

κ : Determines relative sizes of contributions and to what extent NP is photonic ($\kappa \ll 1$) or 4-fermion ($\kappa \gg 1$)

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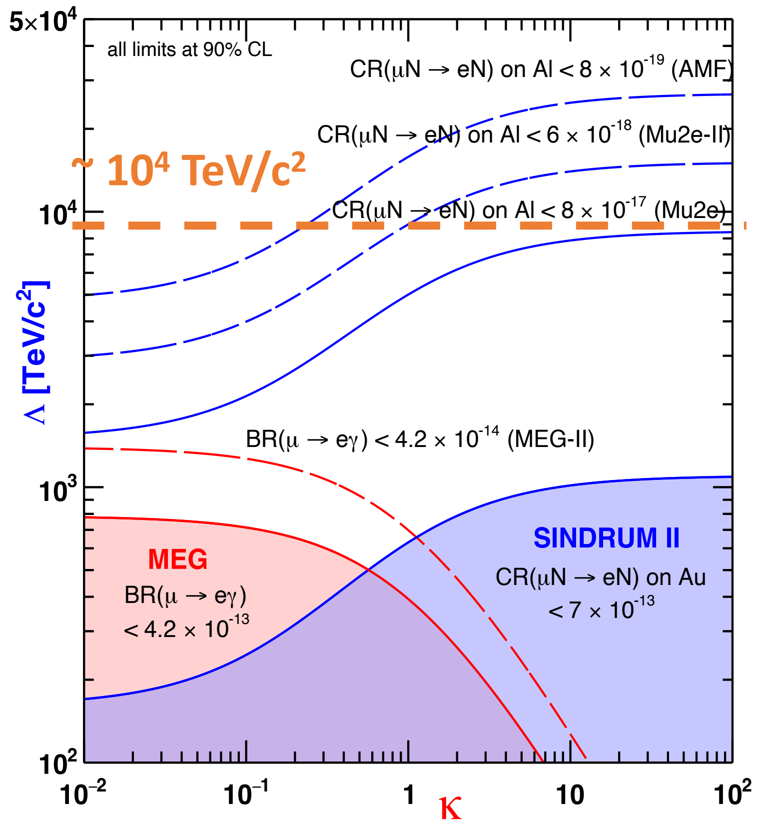

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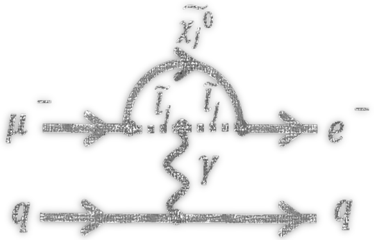
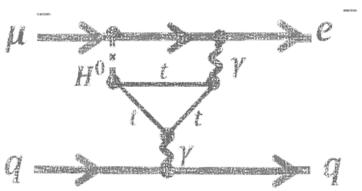


SO(10) SUSY

2 Higgs Doublets



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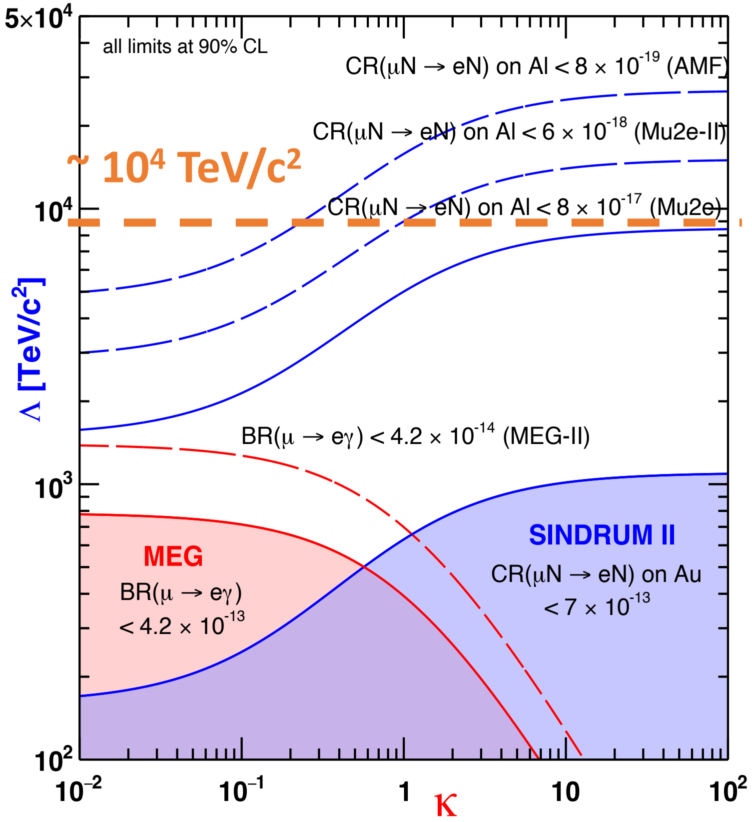

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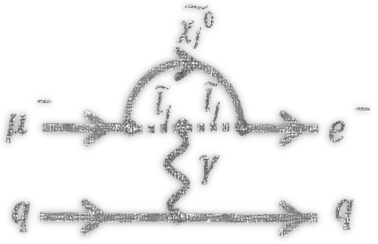

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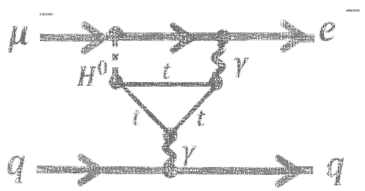

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i.e. 4 Fermion Term

$\mu^- N \to e^- N$ at leading order.

Heavily suppressed in $\mu^+ \to e^+\gamma$

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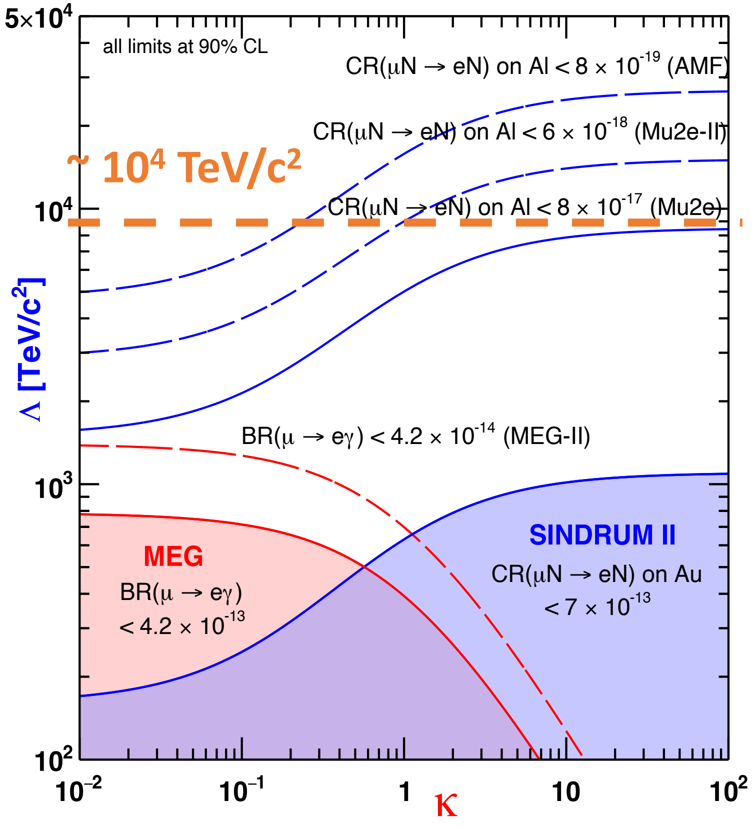

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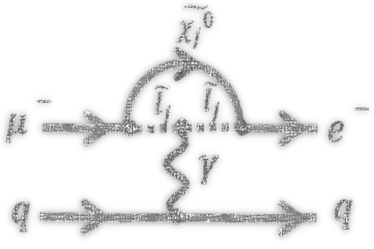

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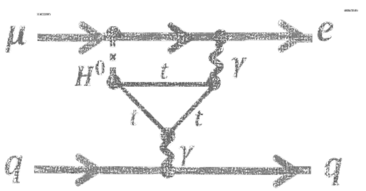

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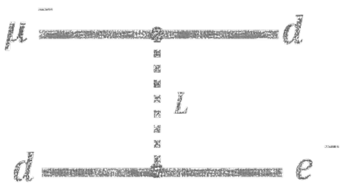
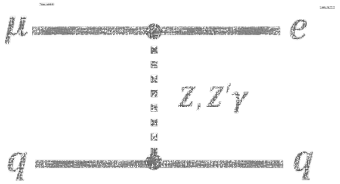
Leptoquarks



New Bosons



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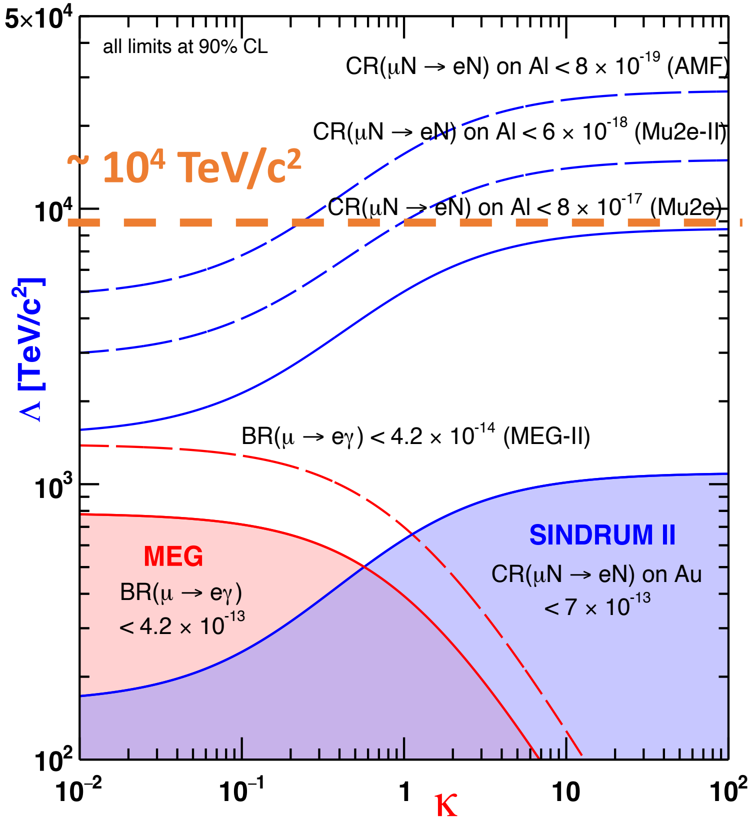

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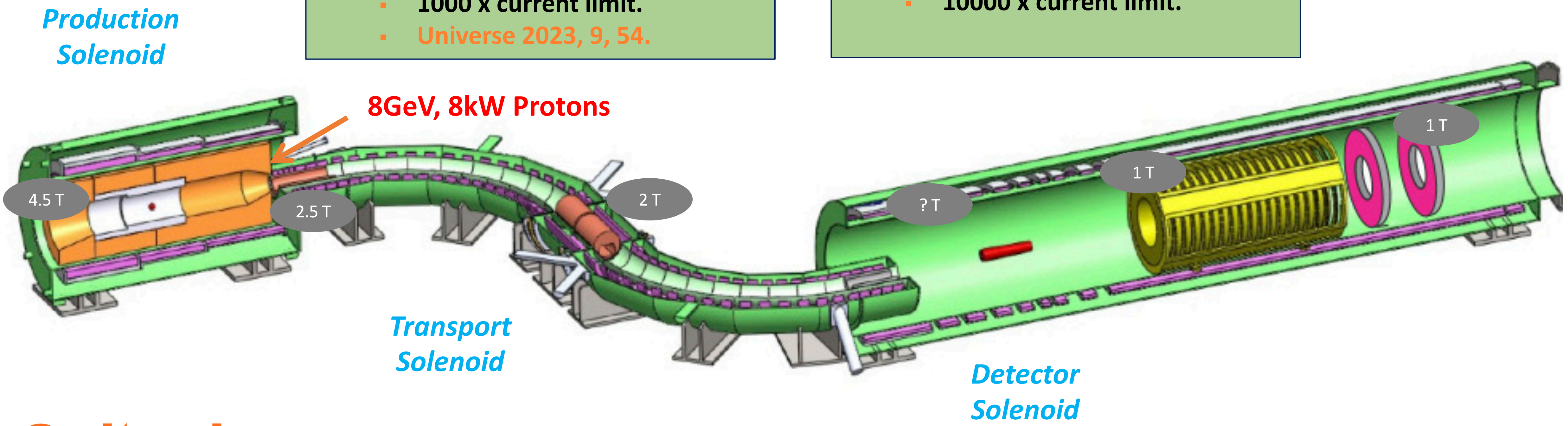
$N\mu^{-} \rightarrow Ne^{-}$: The Mu2e Experiment

- **The Mu2e experiment will search for this process in Al and improve on this limit by four orders of magnitude!**
- Need to stop O(10^{18}) and have << 1 background event

2026 – 27 Run-I:
- 1 x 10^{-15} 5σ discovery,
- Single-Event-Sensitivity = 2 x 10^{-16}
- U.L : 6 x 10^{-16} (90% C.L.)
  - **1000 x current limit.**
  - **Universe 2023, 9, 54.**

Total (Run-I + Run-II) end-goal (2033):
- 2 x 10^{-16} 5σ discovery,
- Single-Event-Sensitivity = 3 x 10^{-17}
- U.L : 8 x 10^{-17} (90% C.L.)
  - **10000 x current limit.**



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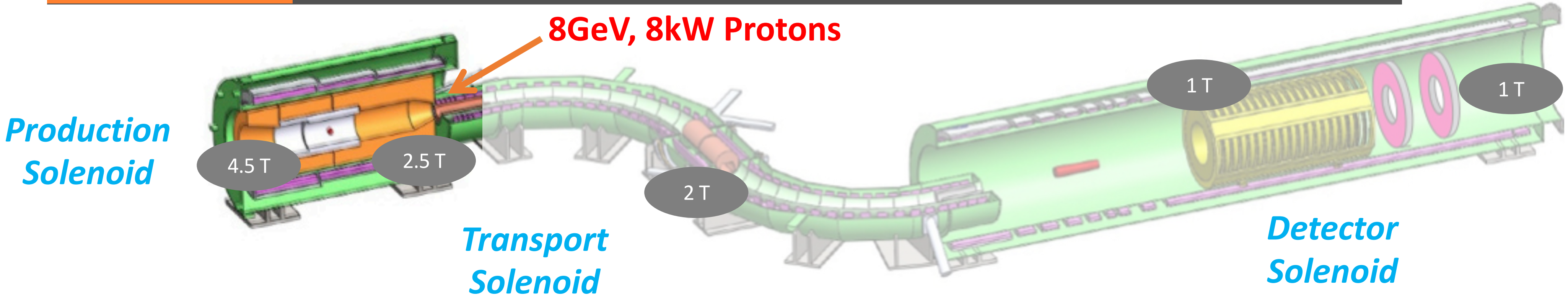

Production Solenoid:

- Pulsed 8 GeV Protons enter, hit Production Target. π produced, decay to μ.
- Graded magnetic field reflects muons to transport solenoid.

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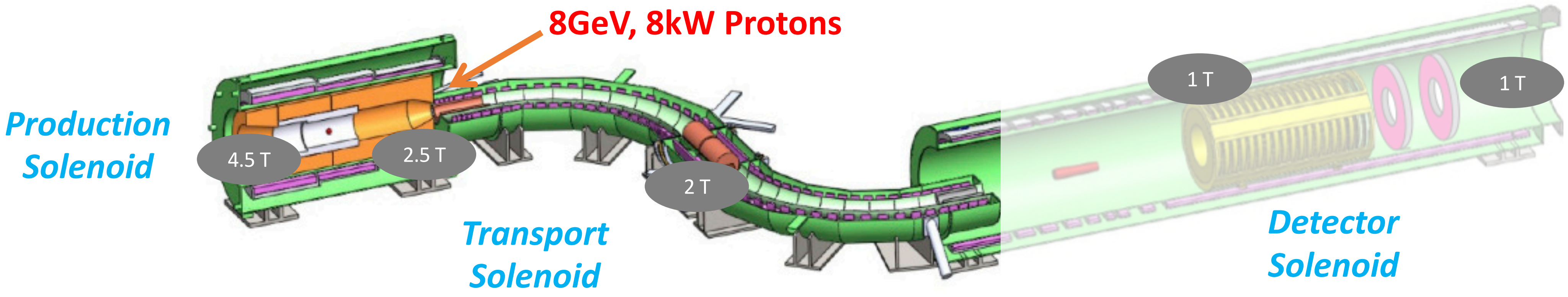

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- “S” shape removes line of sight backgrounds.
- Collimators select low momentum, negative muons.

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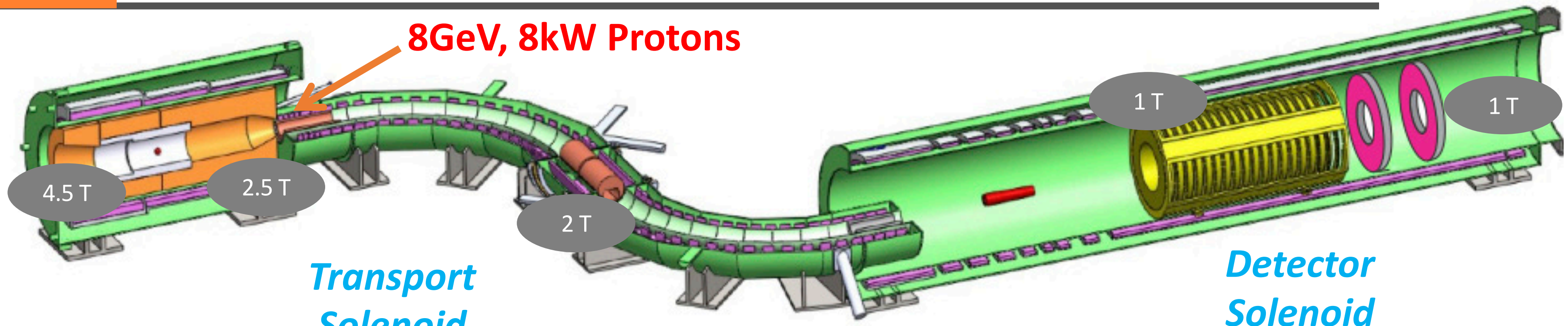

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Detector Solenoid:

- Thin aluminum foil target captures the muons.
- Possible signal electrons are detected by a tracker and a calorimeter.
- Cosmic ray veto covers the whole detector solenoid and half the transport solenoid.

$N\mu^- \rightarrow Ne^-$: Signal

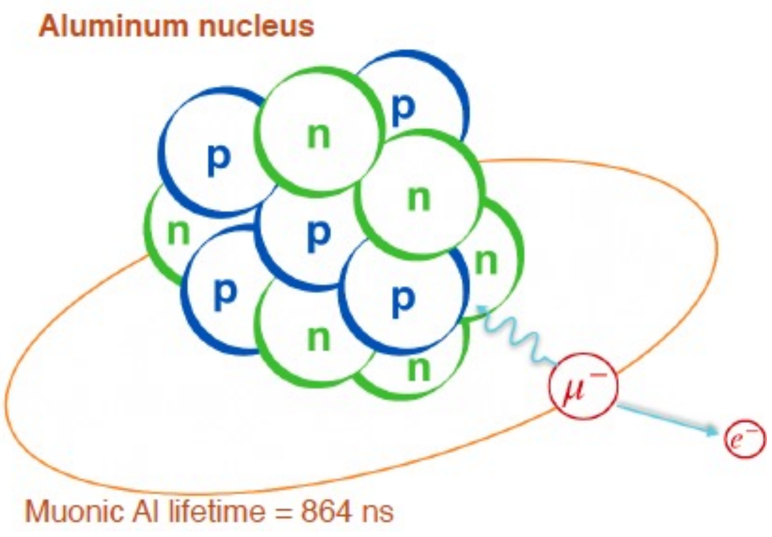
- The $\mu \rightarrow e$ conversion rate is measured as a ratio to the muon capture rate on the same nucleus:

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

- Low momentum (-) muons are captured in the target atomic orbit and quickly (~fs) cascades to 1s state.
- In aluminum:
  - *39 % - Decay :* $\mu + N \rightarrow e + \bar{\upsilon}_e + \upsilon_\mu$ *(Background)*
  - *61 % - Capture :* $\mu + N \rightarrow \upsilon_\mu + N'$ *(Normalization)*
  - *< 7 x 10^-13 - Conversion :* $\mu + N \rightarrow e + N$ *(Signal)*
- Signal is monoenergetic electron consistent with:

$$E_e = m_\mu - E_{recoil} - E_{1S\,B.E}$$, **e.g For Al: E_e = 104.97 MeV.**

  - Coherent = nucleus stays intact.
  - Will be smeared by scattering and energy losses



$N\mu^- \to Ne^-$: Removing Backgrounds

Beam delivery and detector systems optimized for high intensity, pure muon beam – must be "background free":

Type	Source	Mitigation	Yield (for Run-I only)*
Intrinsic	Decay in Orbit (DIO)	Tracker Design/ Resolution	$0.038 \pm 0.002\ (\text{stat})^{+0.025}_{-0.015}$ (sys)
Beam Backgrounds	Pion Capture	Beam Structure/ Extinction	(in time) $0.010 \pm 0.002\ (\text{stat})^{+0.001}_{-0.003}$ (sys) (out time) ($1.2 \pm 0.001\ (\text{stat})^{+0.1}_{-0.3}$ (sys)) x 10^{-3}
Cosmic Induced	Cosmic Rays	Active Veto System	0.046 ± 0.010(stat) ± 0.009 (sys)

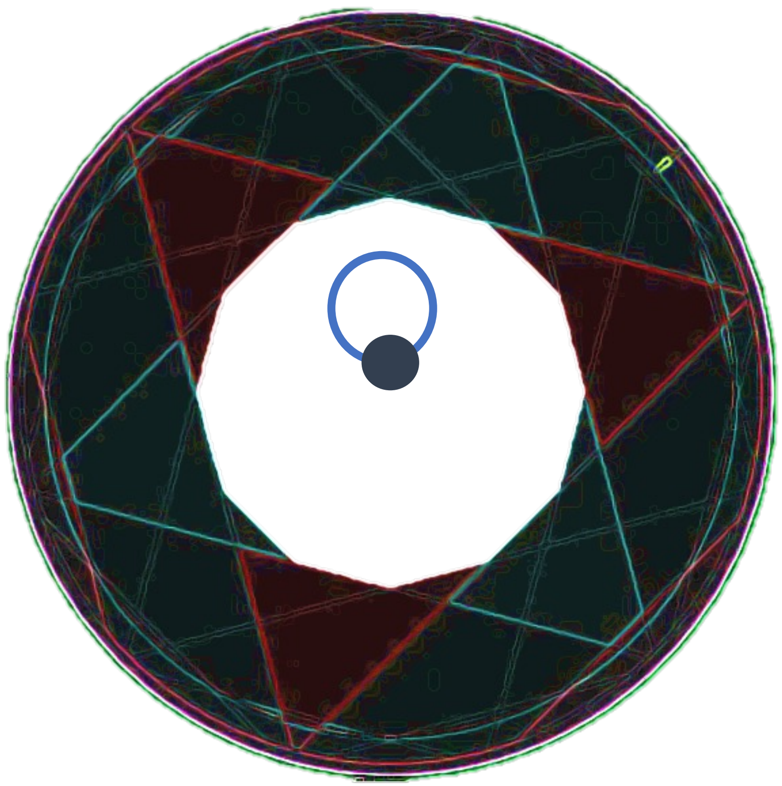
* assumes signal region of 103.6 < p < 104.9 MeV/c and 640 < t < 1650 ns

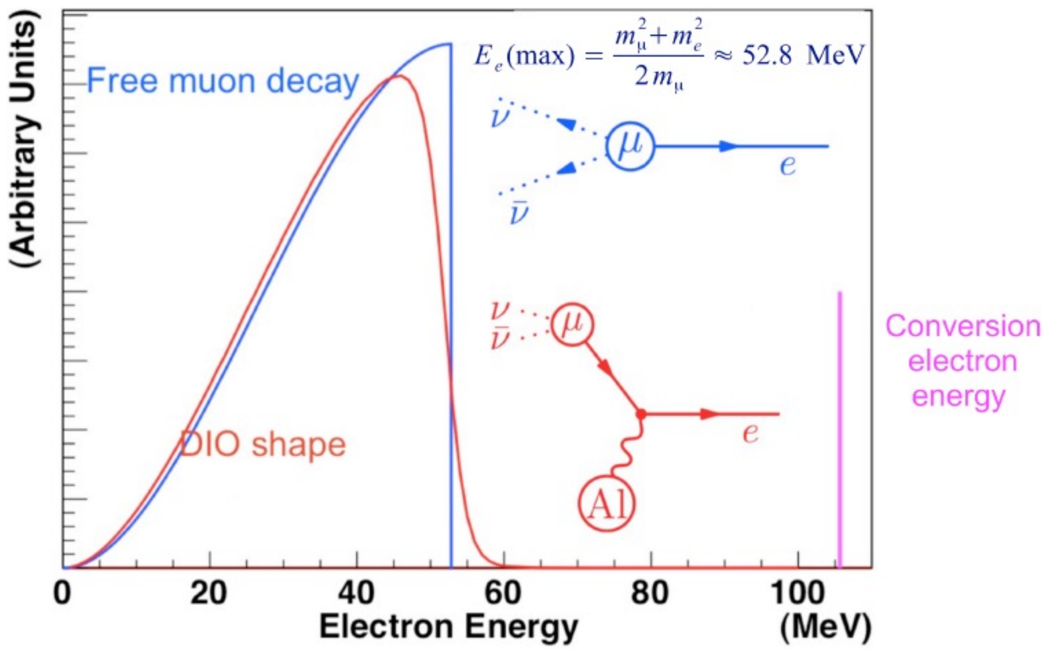
Run-I Sensitivity of Mu2e:
Universe 2023, 9, 54.

Decay in Orbit (DIO) Backgrounds

- Annular tracker: Removes > 97% of DIO (all Michel peak electrons).

- Michel Electron (< 52MeV/c)



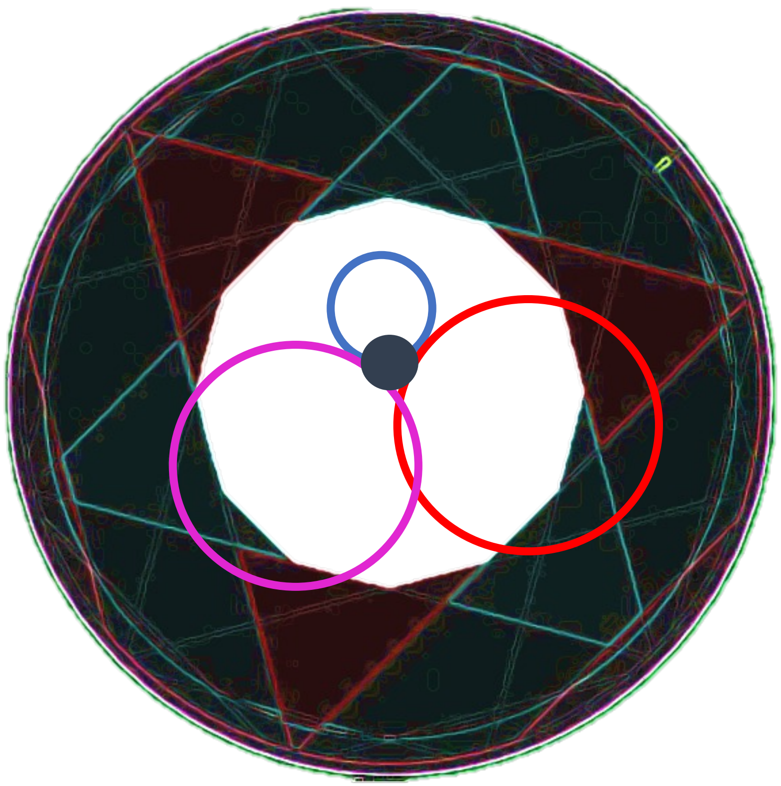


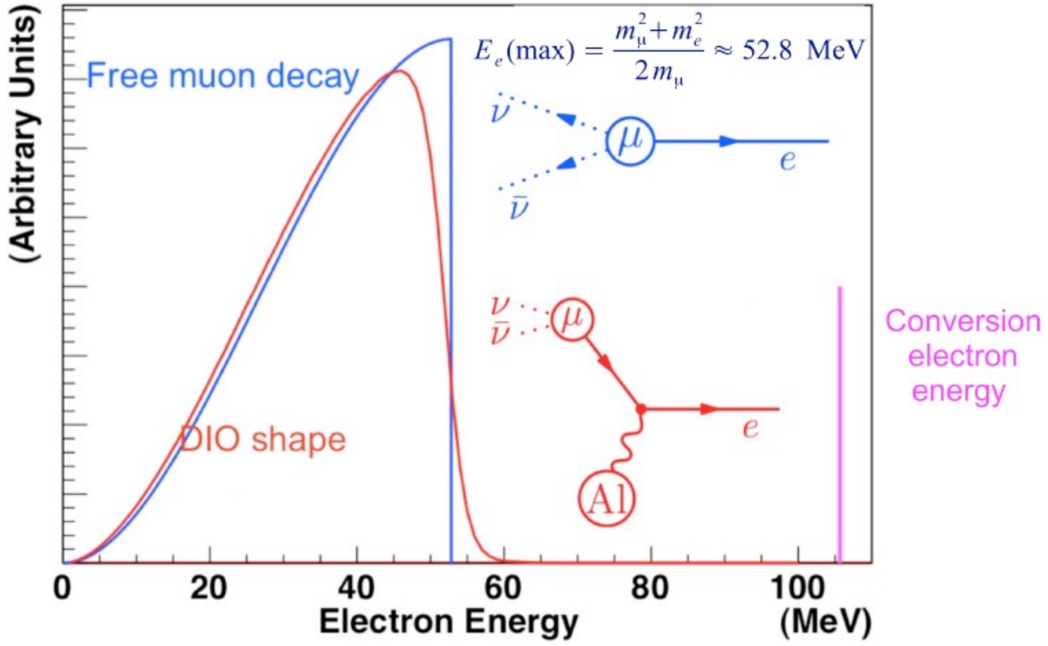
Cartoon of DIO Energy Spectrum
(see Szafron, Czarnecki PhysRevD.94.051301 + others)

Decay in Orbit (DIO) Backgrounds

- Annular tracker: Removes > 97% of DIO (all Michel peak electrons).
- However, when decay happens in orbit, exchange of momentum produces recoil tail close to signal region (105 MeV/c).
- To remove remaining backgrounds necessitates < 200 keV/c momentum resolution.

- Michel Electron (< 52MeV/c)
- Problematic Tail (>100MeV/c)
- Signal (105MeV/c)





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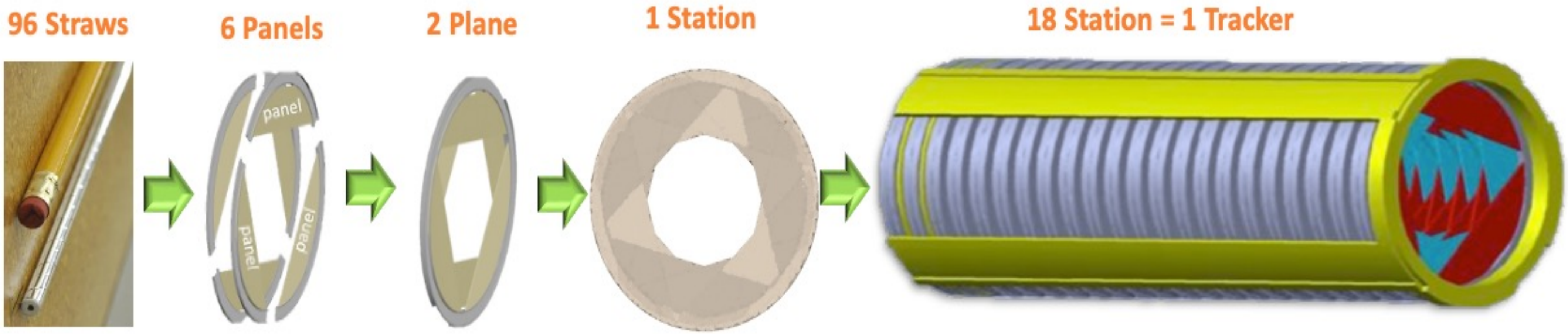
Decay in Orbit Backgrounds

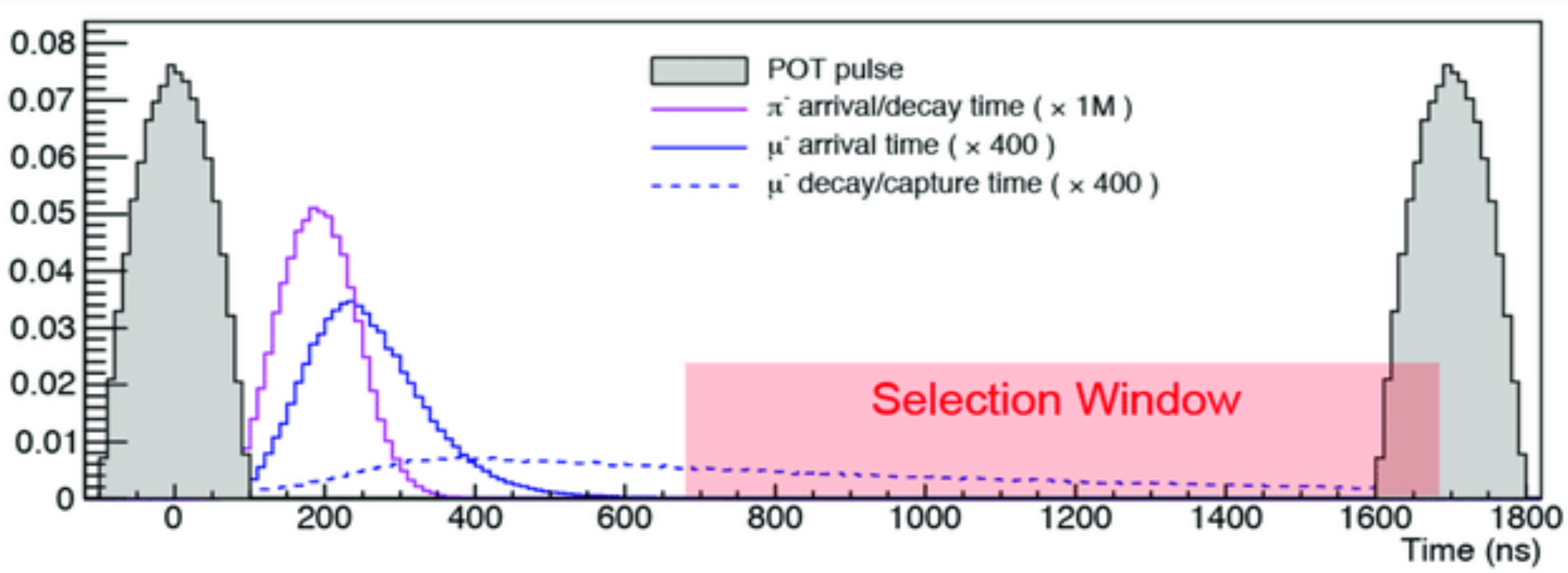
- Need a high-resolution momentum measurement to distinguish tail DIO from signal:
  - Minimize energy loss by operating in vacuum and using low mass straws of 15 μm diameter filled with 80:20 Ar:CO_2 ;
  - Include extra hit position information with high-angle stereo overlaps and readout on both ends of straw.



Radiative Pion Capture Backgrounds

- Radiative pion capture backgrounds: $\pi^- + N(A, Z) \rightarrow \gamma^{(*)} + N(A, Z-1)$ followed by $\gamma^{(*)} \rightarrow e^+ + e^-$.
- Pion lifetime 26 ns at rest. Pulsed proton beam (250 ns wide, pulses 1695 ns apart) → wait out pion decay.
- In addition, upstream extinction removes out-of-time protons.

Delayed live-gate helps remove pion and beam backgrounds.



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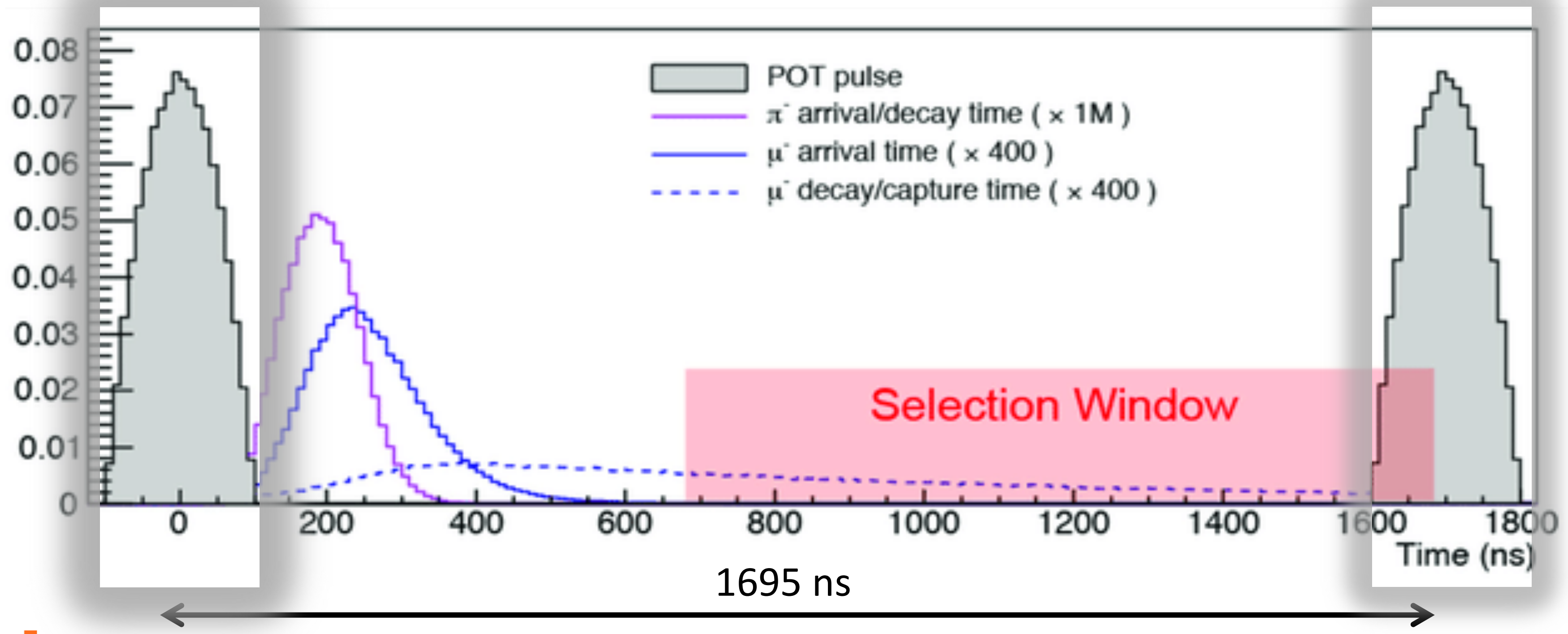

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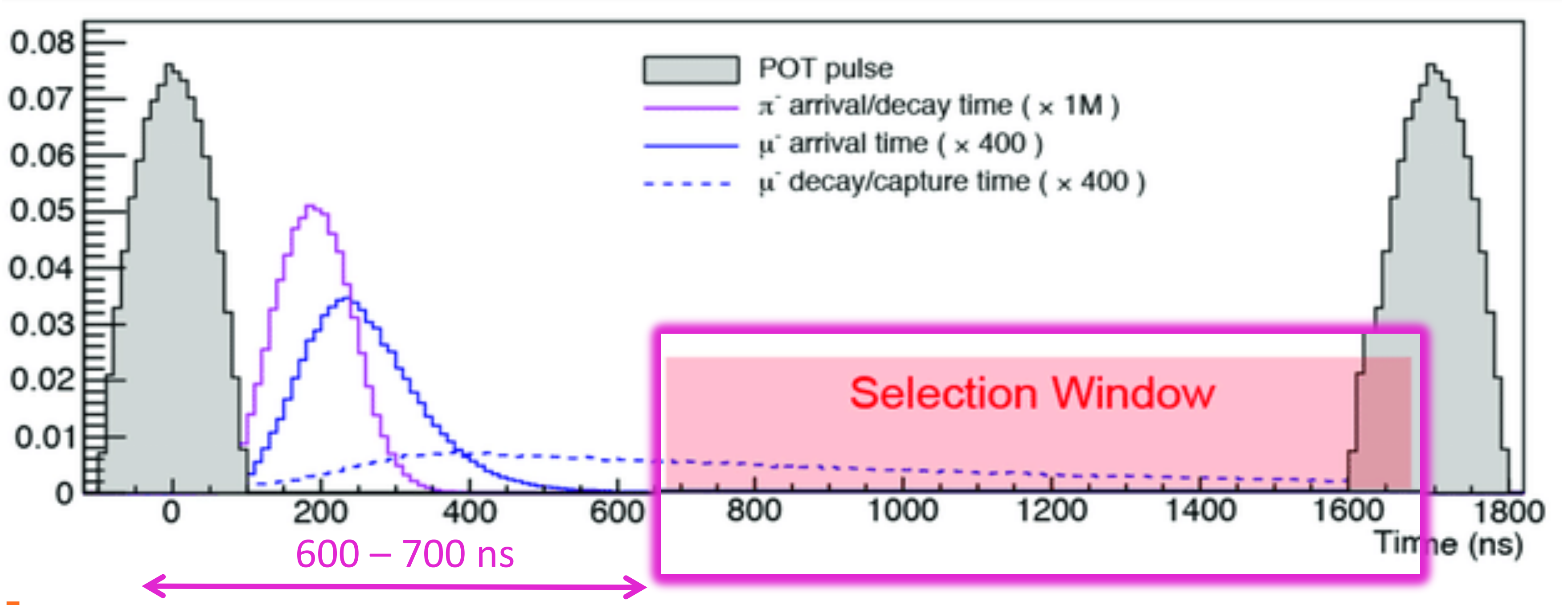
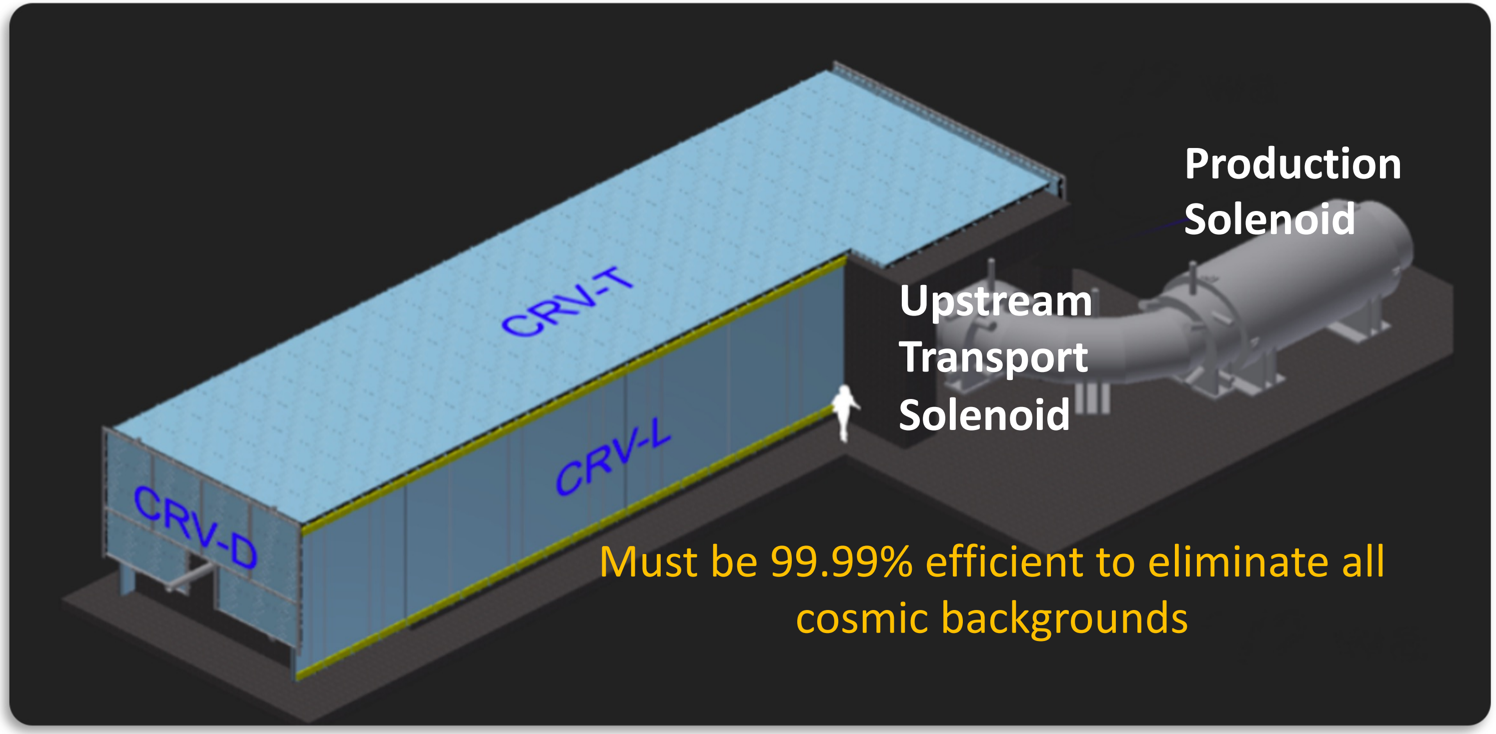


Cosmic Induced Backgrounds

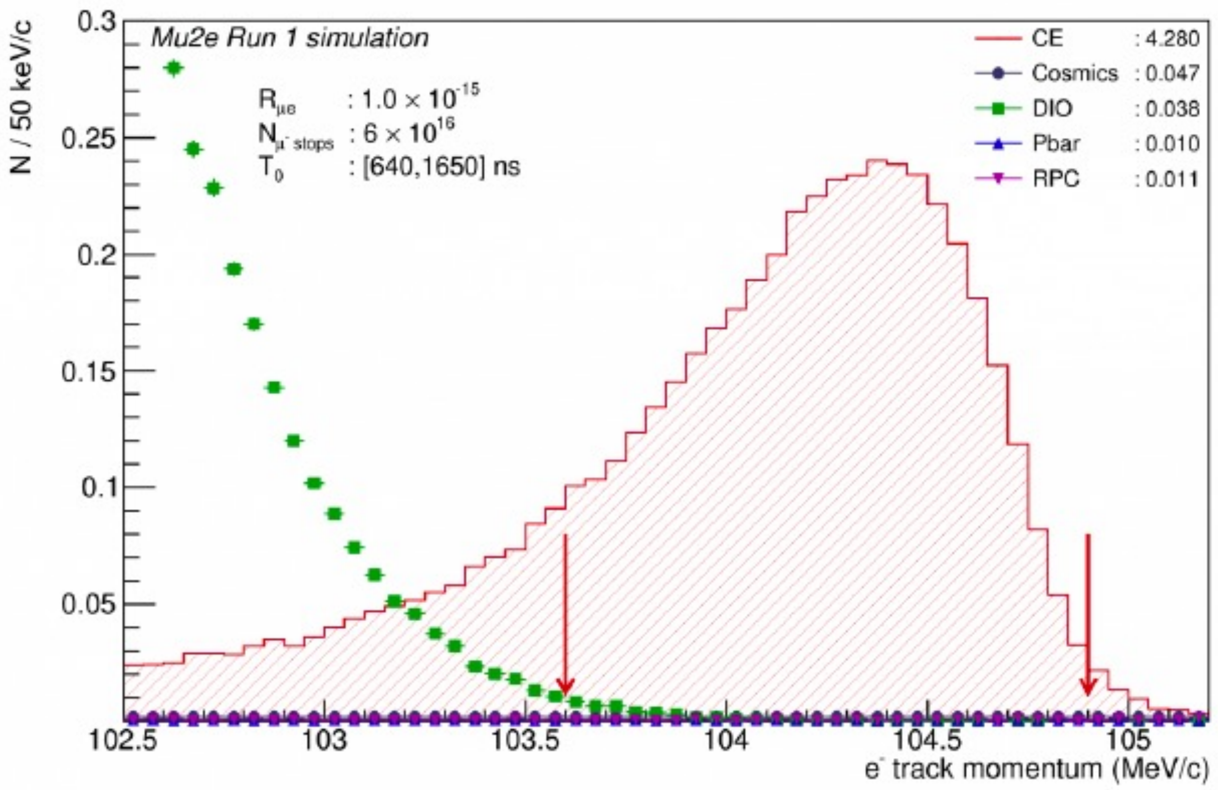
- Cosmic-ray muons can initiate 105 MeV particles that appear to emanate from the stopping target.
- Remove using active veto (CRV) + overburden and shielding concrete surrounding the Detector Solenoid.

Active Cosmic Ray Veto system is key to eliminating cosmic induced backgrounds.



Signal & Backgrounds

Expected signal ($R_{\mu e} = 10^{-15}$) and DIO spectra from Run_I simulation (~10% of final dataset, includes resolution and energy loss effects):



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Universe 2023, 9, 54.

Status Update

Update on current status of experimental aparatus

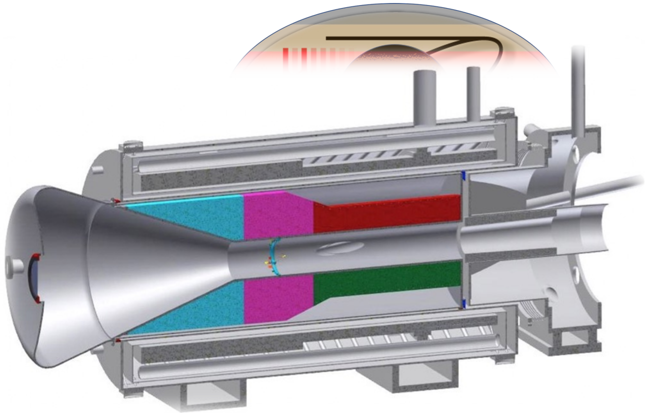
Solenoids

- Production Solenoid:
  - Consists of 3 coils, all wound at vendor.
  - Undergoing final assembly.
  - Arrives at Fermilab in Fall 2023.


PS cold mass – inner shield dry run insertion


PS outer cryostat components fit-up.

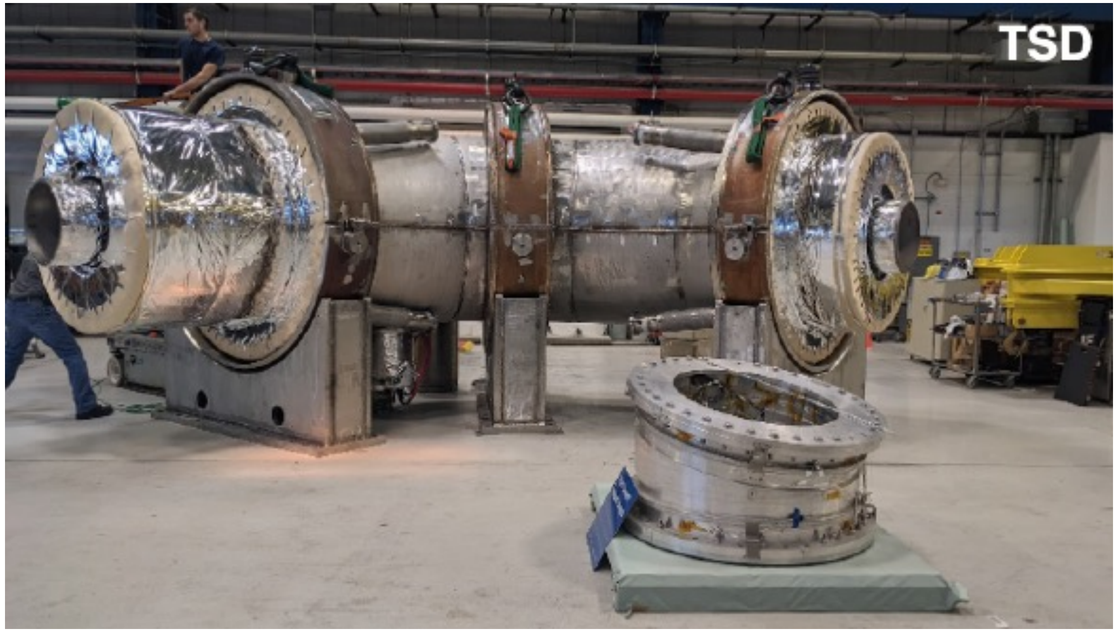

PS wires being routed to chimney area


Heat & Radiation Shield

Caltech

Solenoids

- Transport Solenoid:
  - Assembly being completed on-site (located in HAB).
  - Moved to Mu2e Hall in Fall 2023.

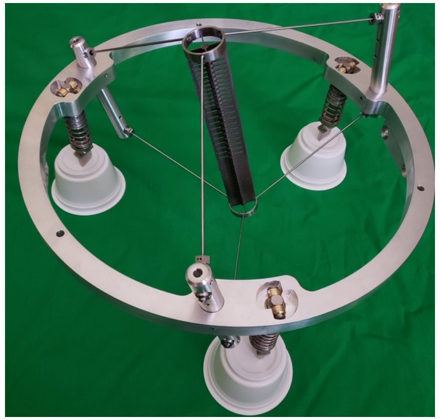


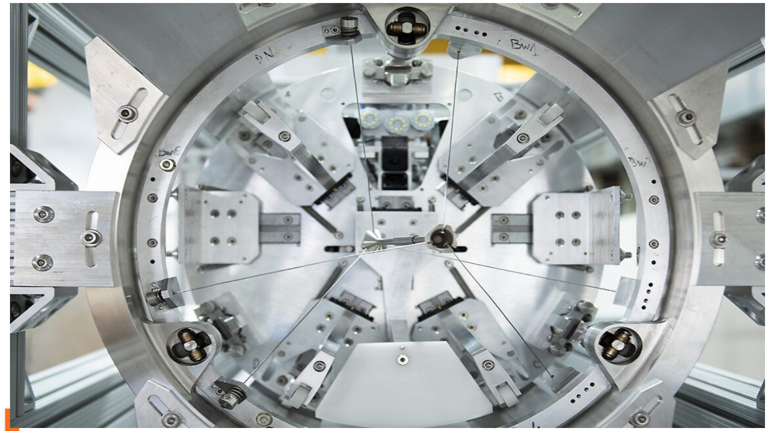
Solenoids

- Detector Solenoid:
  - All coils fabricated at vendor.
  - Cold mass cryo. supports prepared
  - Delivery to Fermilab expected early 2024.

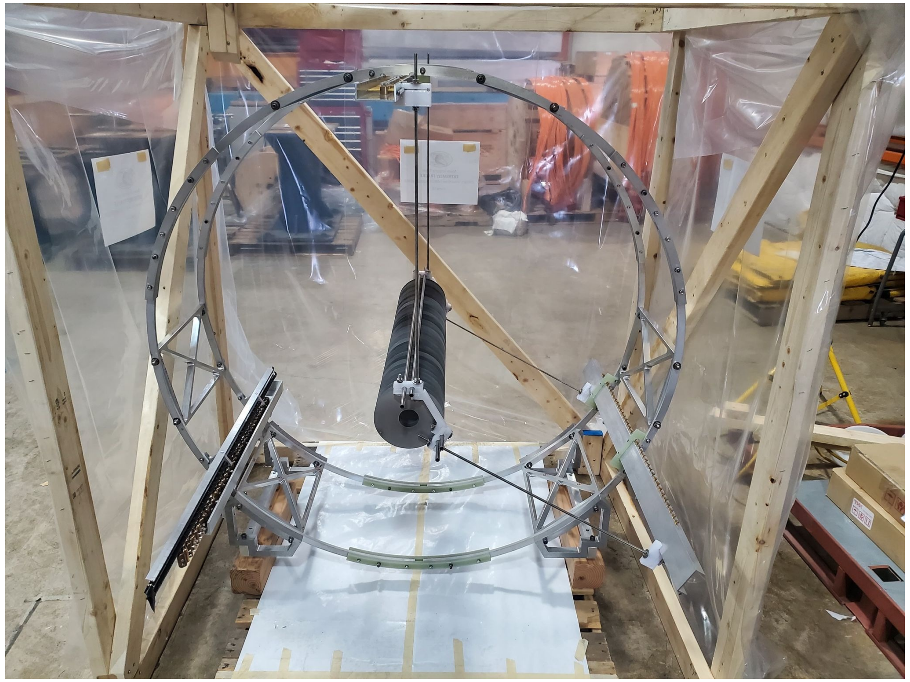
Targets

Production target: resides in Production Solenoid, stops 8 GeV protons, produces pions.



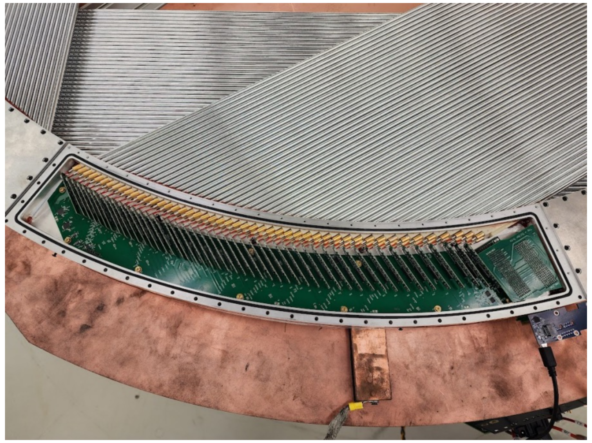


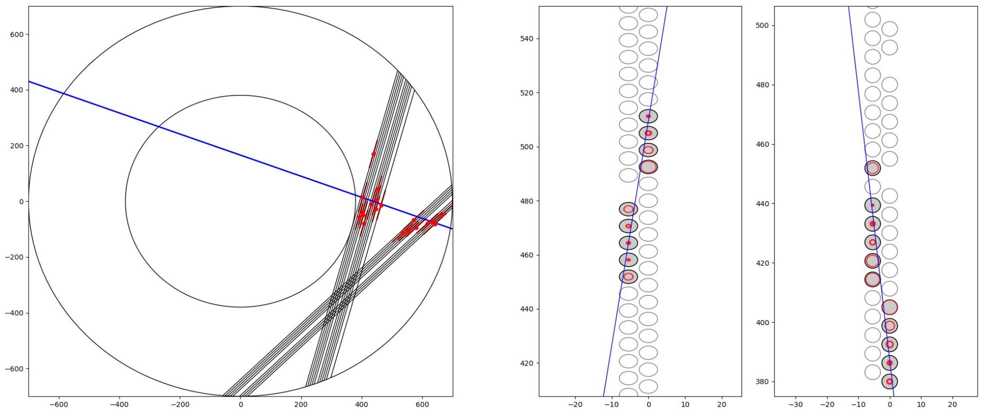
Muon Stopping target: resides in Detector Solenoid, stops muons, potentially produces signal conversion electrons.

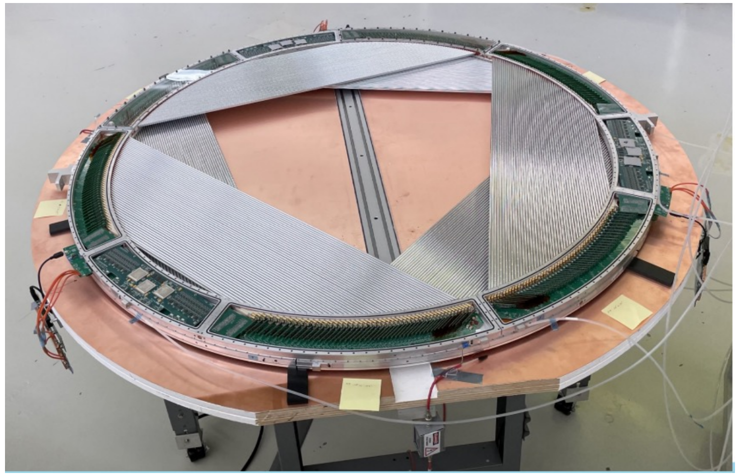


Tracker

- All 20736 straws produced.
- All 216 panels produced. Now working through QC.
- 25 / 36 planes are built.
- Cosmic ray tests carried out with a single plane and full readout system for 3 years.







Calorimeter

Calorimeter is vital for providing:

- **Particle identification,**
- **Fast online trigger filter,**
- **Seed for track reconstruction.**

Design:

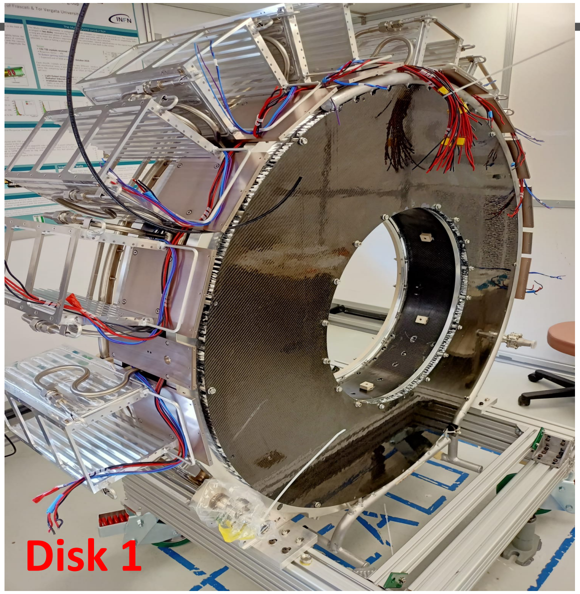
- 2 x 674 CsI crystals in 2 disks, each coupled to 2 SiPMs.

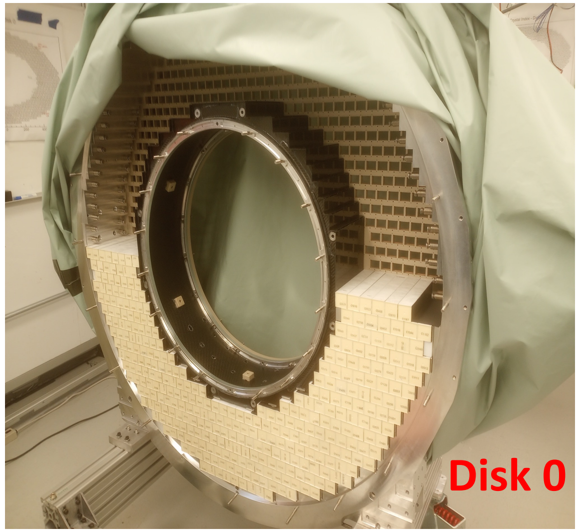
First disk (Disk – 1):

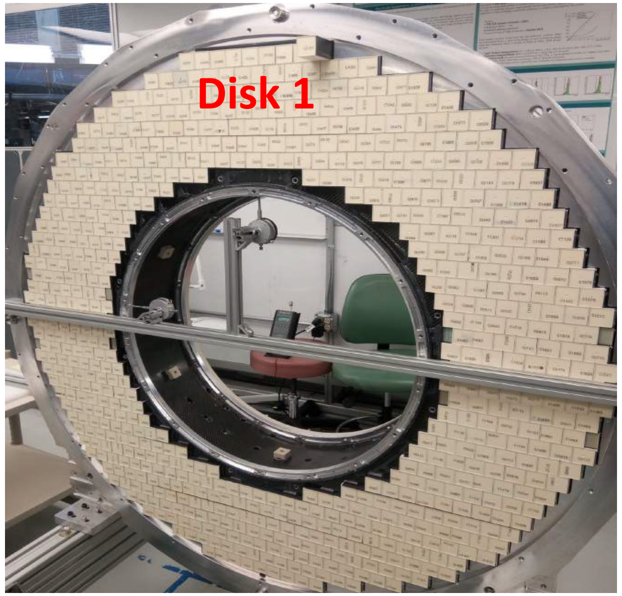
- Has crystals and SiPMs installed (2022).
- 450 ROU's installed.

Second disk (Disk – 0):

- Being assembled this summer (2023).

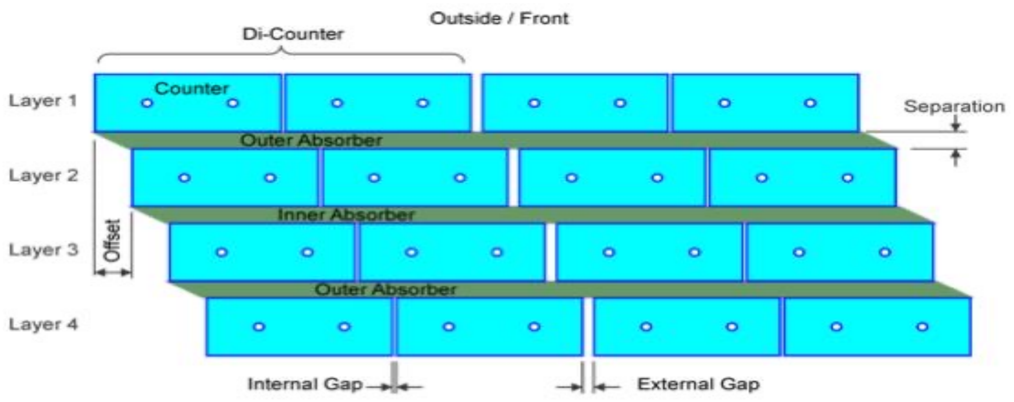






Cosmic Ray Veto System

- All 5344 di-counters produced.
- 81 / 83 modules produced.
- Cosmic ray tests underway at Wideband.



Summary

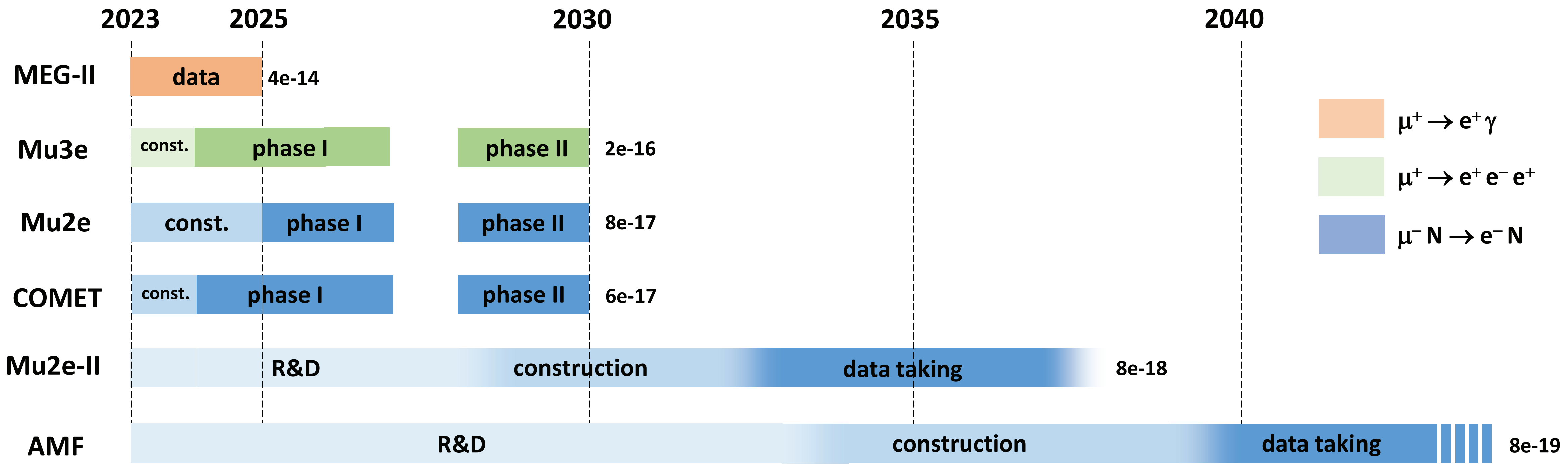
- Mu2e will search for the CLFV in muon to electron conversion with a 90% CL upper limit of $< 8 \times 10^{-17}$.
- Muon CLFV channels offer deep indirect probes into BSM. Discovery potential over a wide range of BSM models.
- Mu2e commissioning with cosmics begins in 2024, commissioning with beam in 2025 and physics data taking begins in 2026.
- Looking further ahead the proposed Mu2e-II and AMF experiments will help elucidate any signal and push to higher mass scales.

Plenty of opportunities for postdocs and new collaborators to commission a new experiment! https://mu2e.fnal.gov/

Thank you for listening!

Any Questions?

Timelines



2023
2025
2030
2035
2040
MEG-II
data
4e-14
Mu3e
const.
phase I
phase II
2e-16
Mu2e
const.
phase I
phase II
8e-17
COMET
const.
phase I
phase II
6e-17
Mu2e-II
R&D
construction
data taking
8e-18
AMF
R&D
construction
data taking
8e-19
$\mu^+ \to e^+ \gamma$
$\mu^+ \to e^+ e^- e^+$
$\mu^- N \to e^- N$

Additional Material

Things I couldn't fit into this talk…

Complementarity amongst channels

- All three channels are sensitive to many new physics models → discovery sensitivity across the board.
- Relative Rates however will be model dependent and can be used to elucidate the underlying physics.

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{BR(\mu\to eee)}{BR(\mu\to e\gamma)}$	$\frac{CR(\mu N\to eN)}{BR(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6\times10^{-3}$	$10^{-3}-10^{-2}$
Type-I seesaw	Loop*	Loop*	$3\times10^{-3}-0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1-3)\times10^{3}$	$\mathcal{O}(10^{-2})$
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*	$0.05-0.5$	$2-20$

arXiv:1709.00294v2[hep-ph]

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

- In seesaw models CLFV rates aren't suppressed by smallness of neutrino mass.
- Different seesaw models given very different predicted rates of CLFV.
- **Measuring CLFV can help us understand neutrino mass origin!**

Synergies with neutrino physics: Nuclear Physics B (Proc. Suppl.) 248–250 (2014) 13–19

Possibilities

Outcomes of current era of CLFV searches

Signal in Mu2e and/or MEG-II and/or Mu3e

- Nice papers, exciting times!

- Make further measurements.

- Elucidate nature of physics and flavor structure by comparing rates in different channels.

No signals

- Push to higher effective mass scale, opening other BSM scenarios.

- Some models excluded or heavily constrained.

$N\mu^- \rightarrow Ne^-$: Complementarity in Target Materials

Kitano et al 2002: arXiv:hep-ph/0203110v4

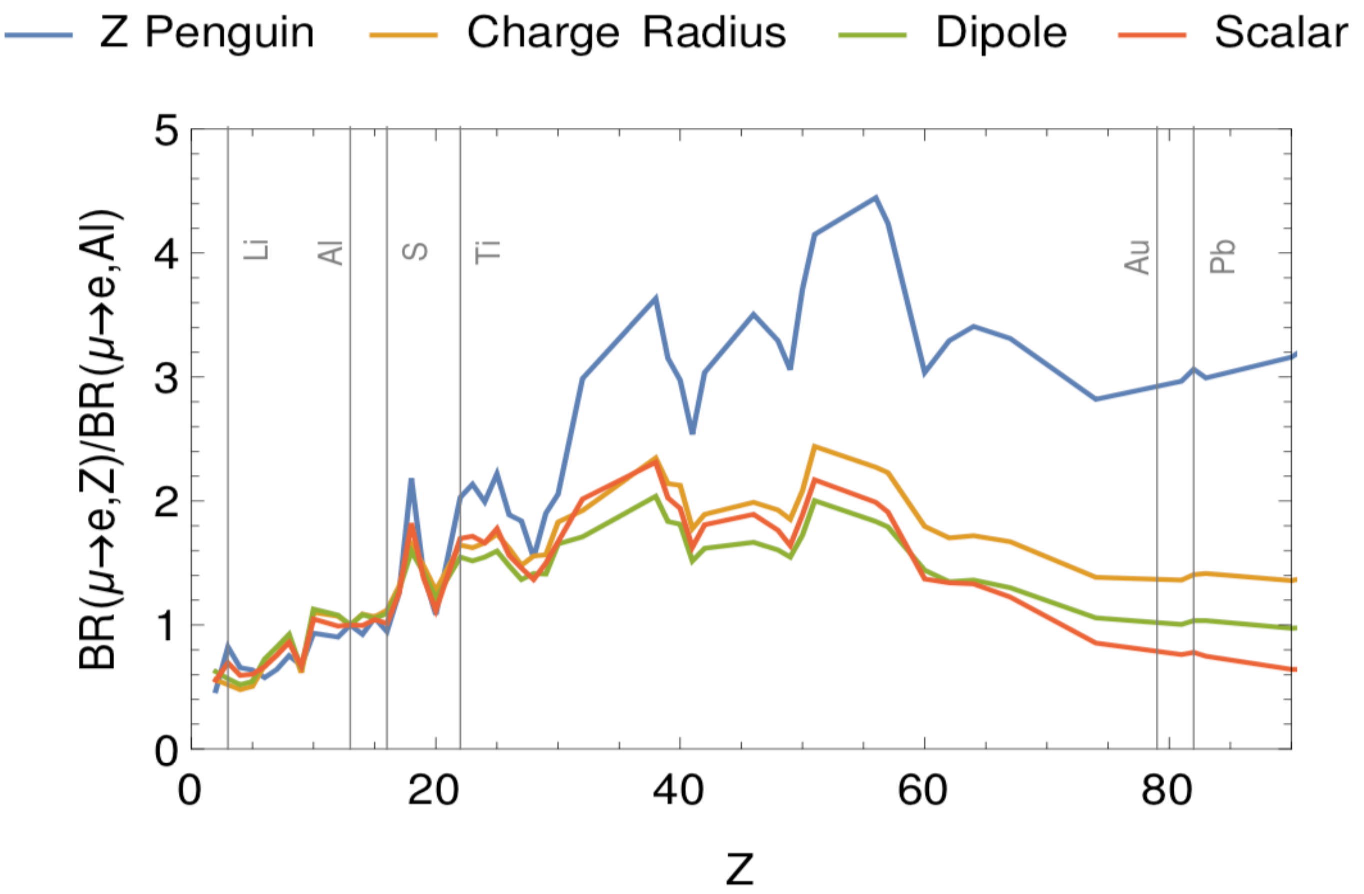
$$BR(\mu \rightarrow e) \propto |DC_{DL} + S^p C^p_{S,L} + V^p C^p_{V,R} + S^n C^n_{S,L} + V^n C^n_{V,R}|^2 + (L \leftrightarrow R)$$

Overlap with nucleus probes form factors and reveals the nature of the interaction.

→ can elucidate type of physics through looking at relative conversion rate.

	S	D	V^1	V^2
$\frac{B(\mu\to e,\mathrm{Ti})}{B(\mu\to e,\mathrm{Al})}$	$1.70 \pm 0.005_y$	1.55	1.65	2.0
$\frac{B(\mu\to e,\mathrm{Pb})}{B(\mu\to e,\mathrm{Al})}$	$0.69 \pm 0.02_{\rho_n}$	1.04	1.41	$2.67 \pm 0.06_{\rho_n}$

y = nuclear scalar form factor, ρ_n = nuclear neutron density



Higher Z target provides most splitting!

Next Generation Searches

Proposed multi-decade muon CLFV at Fermilab which would utilize PIP-II and ACE 2GeV ring:

Mu2e-II [see: arXiv: 2203.07569 [hep-ex]] (mid-2030s):

- ***Similar design to Mu2e, reuses much of the hardware but requires new production target and detector systems.***
- Uses pulsed beam as necessary to remove pion backgrounds.
- Lots or R&D on-going including 2 LDRD proposals: tracker and production target.

AMF [see: arXiv: 2203.08278 [hep-ex]] (mid 2040s):

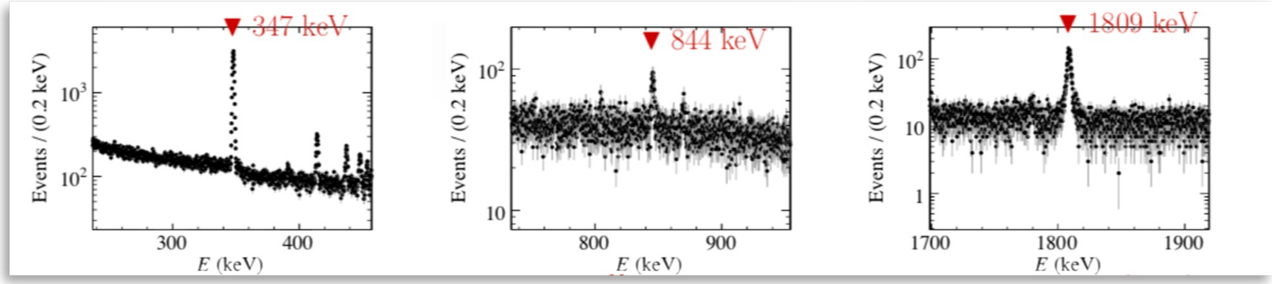
- ***A multi purpose muon facility which would search for all three muon CLFV channels at Fermilab.***
- Would utilize a fixed field alternating (FFA) gradient synchrotron which would provide:
  - Monoenergetic beam of central momentum 20-40 MeV/c: thin target, minimizing material effects, retaining momentum resolution.
  - Pure muon beam: don't need the pulsed beam and delayed signal window.
    - Can utilize a high Z material to elucidate physics if signal at Mu2e/COMET or Mu2e-II.
    - Has smaller decay branching fraction.
- R&D required and lots of opportunities to get involved.

Stopping Target Monitor (STM)

- Need an accurate measure of total number of stopped muons in the target (within 10%) .
- Placed far downstream of target (~34 m).
- STM uses HPGe and $LaBr_3$ detectors to measure X/γ-rays produced by stopped muons in Al target:
  1. Prompt X-ray emitted from muonic atoms at 347keV;
  2. Delayed gamma ray at 844keV;
  3. Semi-prompt gamma ray at 1.809MeV

$$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z,N) \to e^- + A(Z,N))}{\Gamma(all - captures)}$$

Normalization = from X -rays emitted when muon stops in Al.



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