The Mu2e Experiment

Motivations, Design and Current Status

Sophie Charlotte Middleton
on behalf of the Mu2e experiment

TAU 2023, Louisville Kentucky
December 2023

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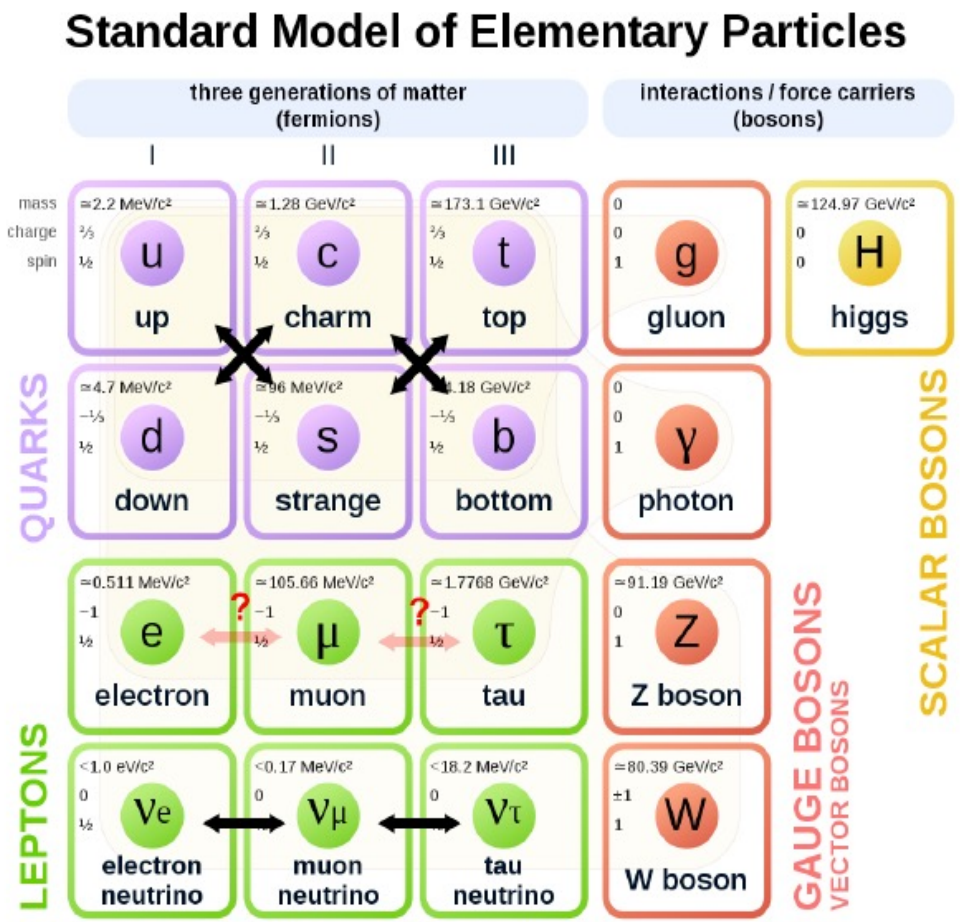
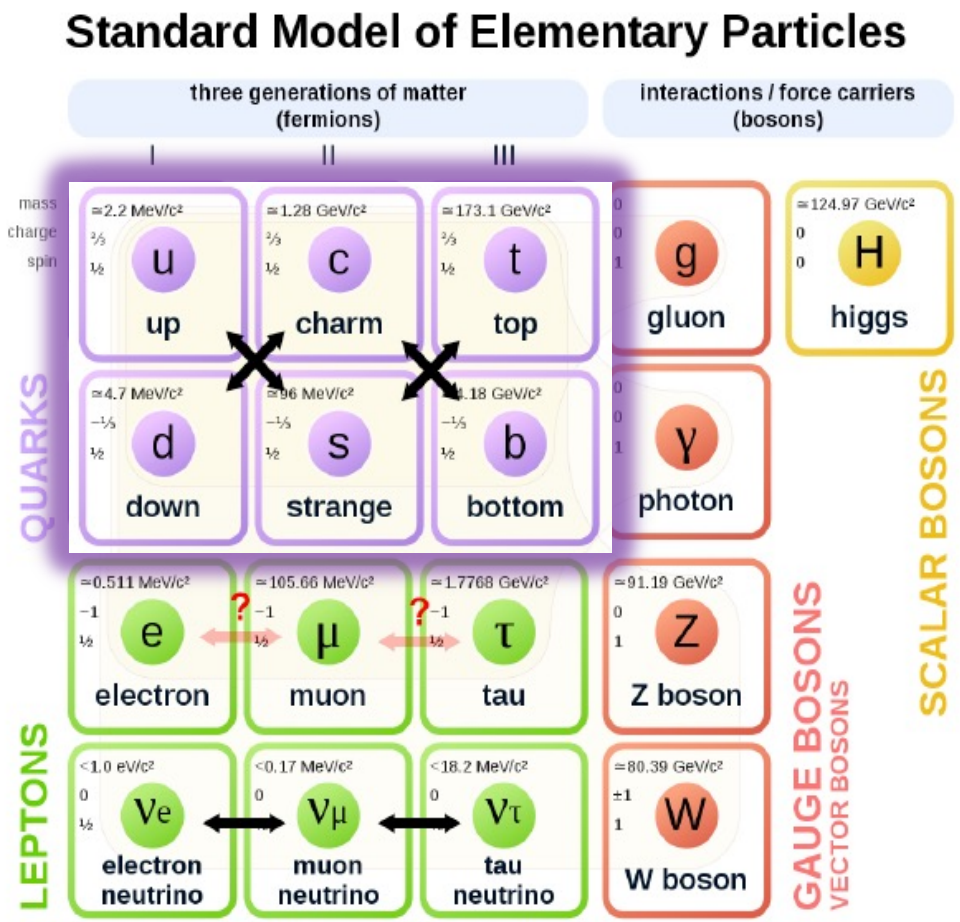
Motivations

Flavor Physics



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

Flavor Physics



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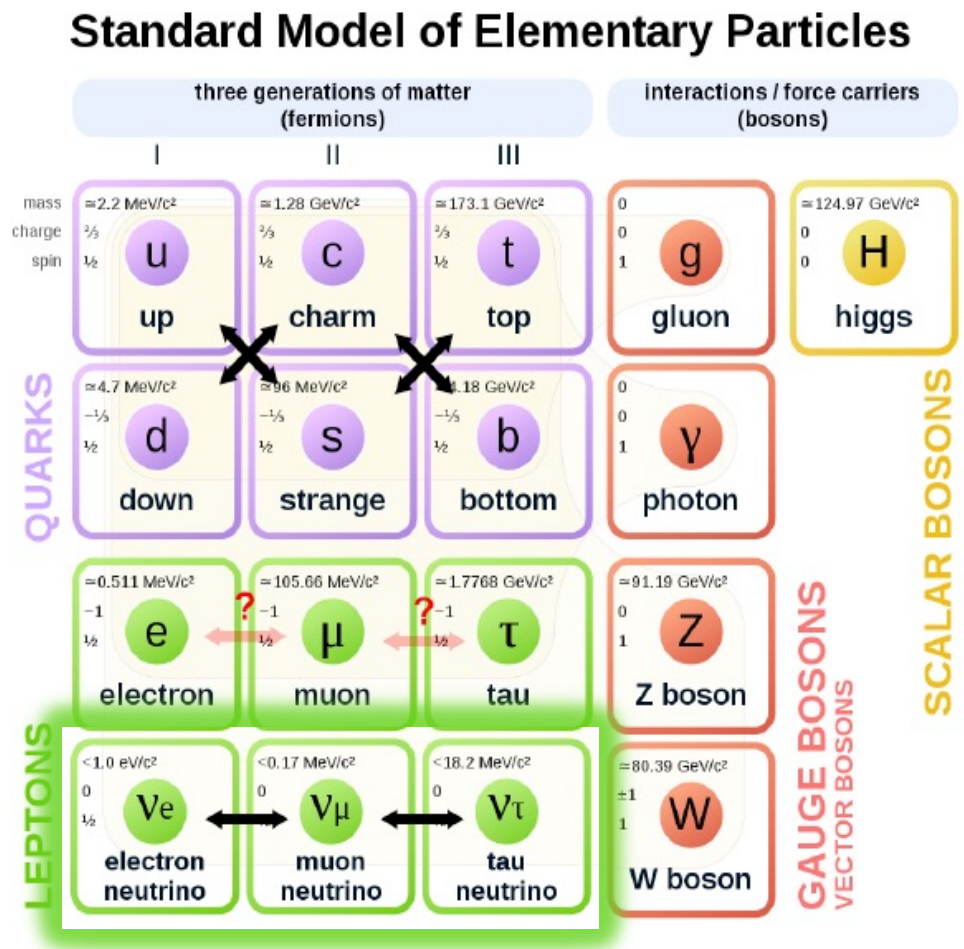

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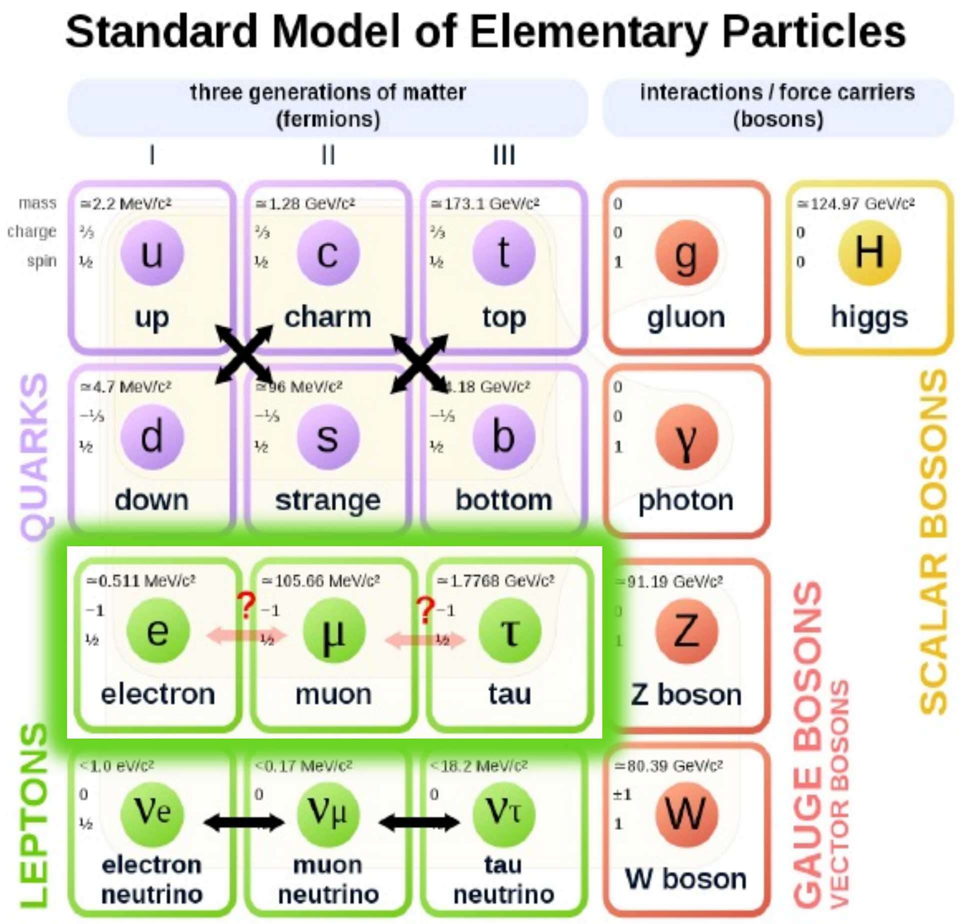
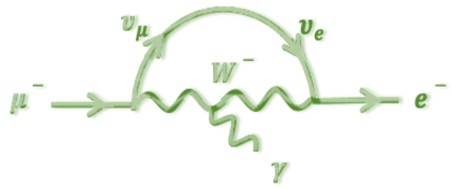
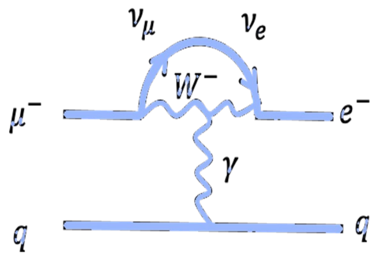


- Flavor is not conserved in:
  - quarks (via quark mixing);
  - neutrinos (via neutrino oscillations)
- **What about Charged Lepton Flavor Violation?**

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:

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

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

S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977) 340

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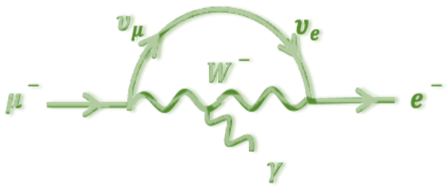

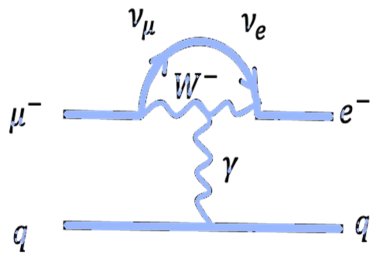

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- ...but many Beyond Standard Model (BSM) theories (e.g. SO(10) SUSY, scalar leptoquarks, seesaw models) predict enhanced rates of CLFV just below current limits O(10^{-13}).

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

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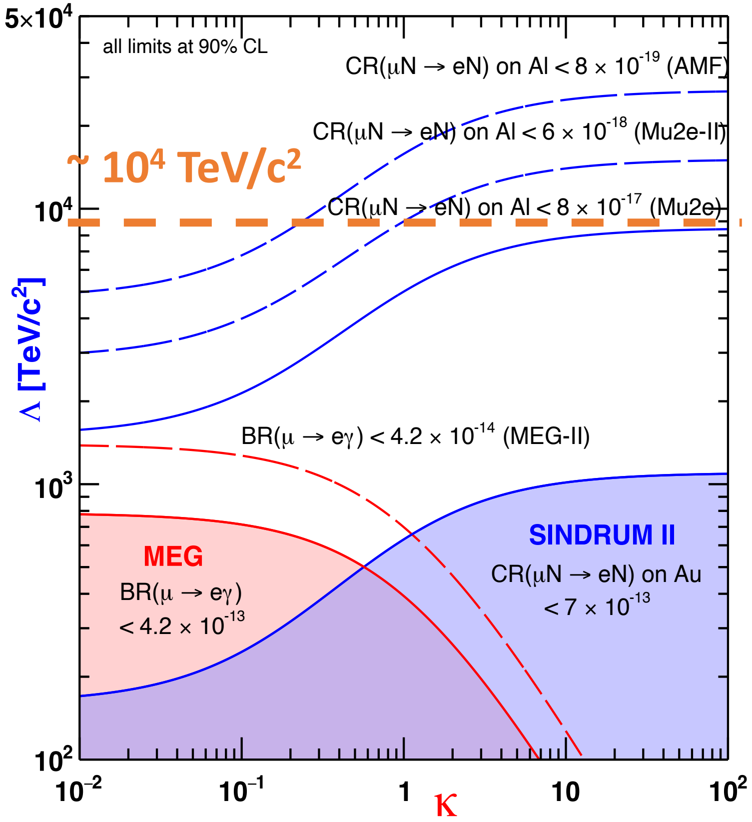
Effective Physics Reach

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

"Photonic" "Contact"

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



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$\mu^- N \to e^- N$ **at loop level**

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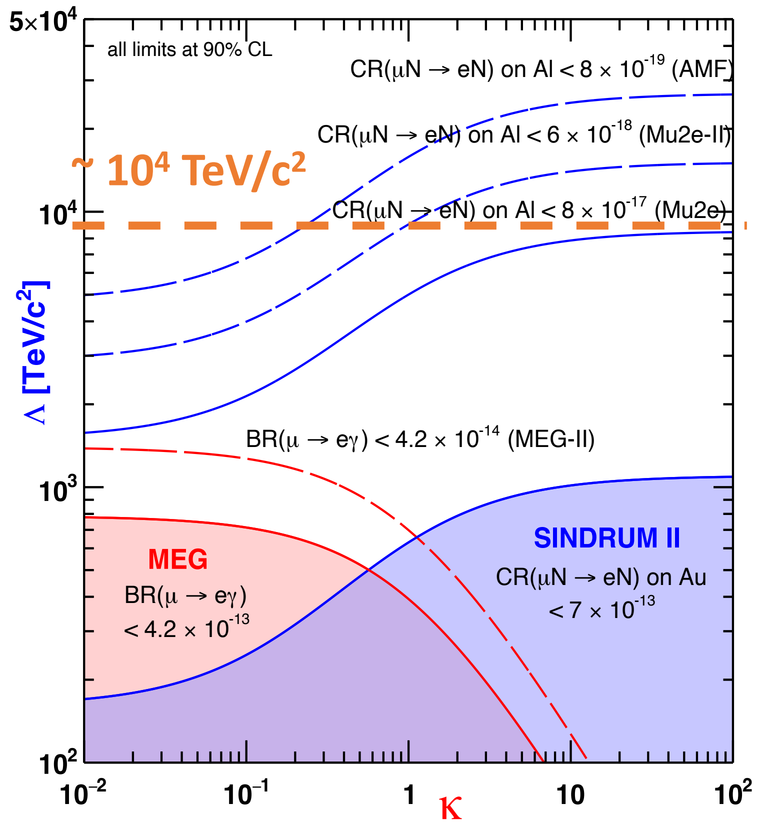

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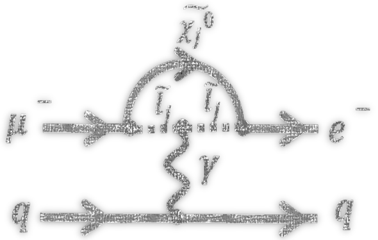
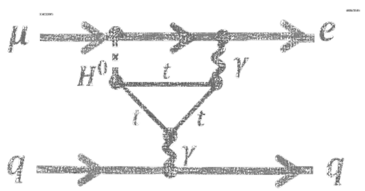


SO(10) SUSY

2 Higgs Doublets



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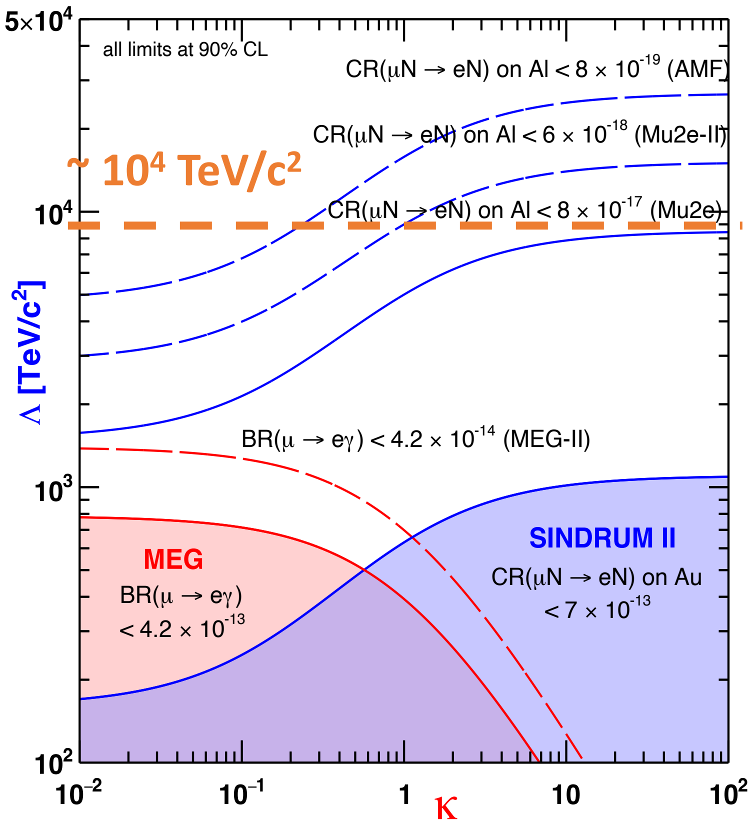

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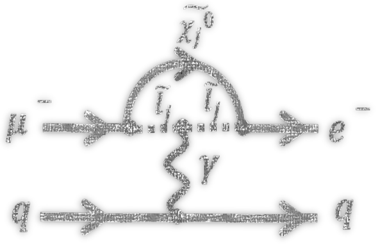

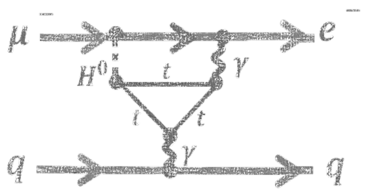

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i.e. 4 Fermion Term

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

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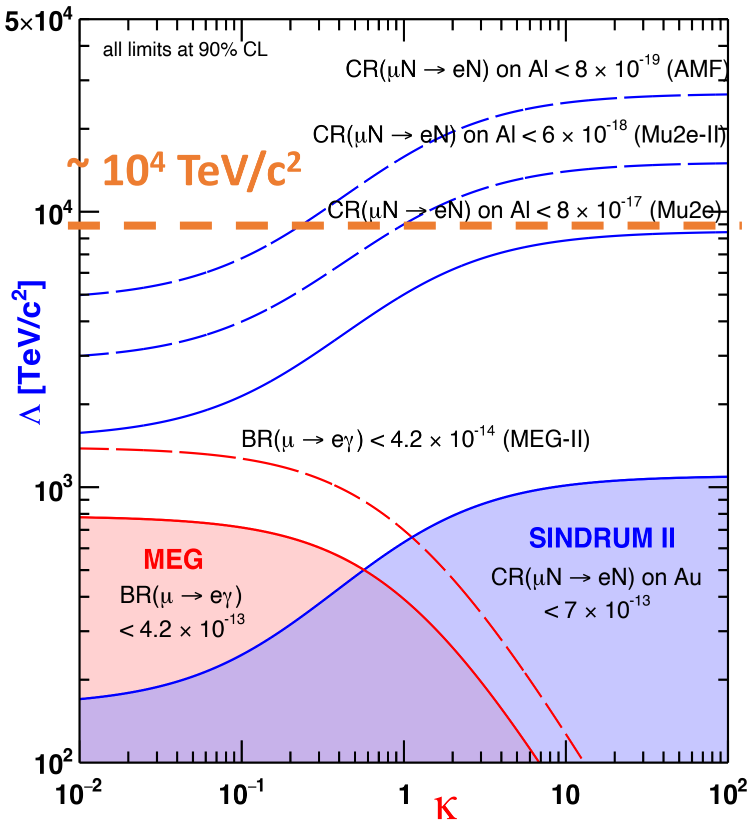

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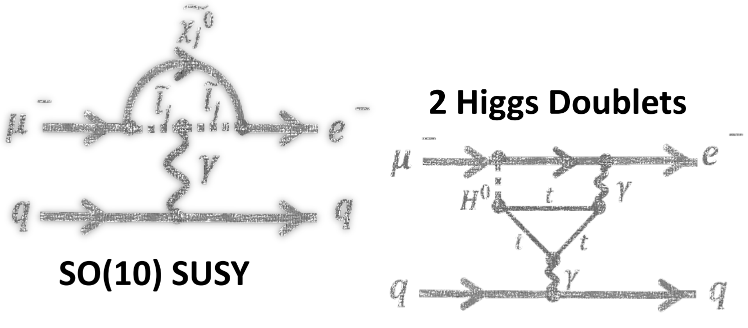

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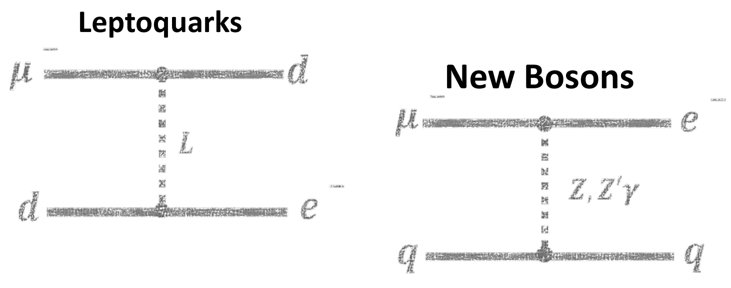

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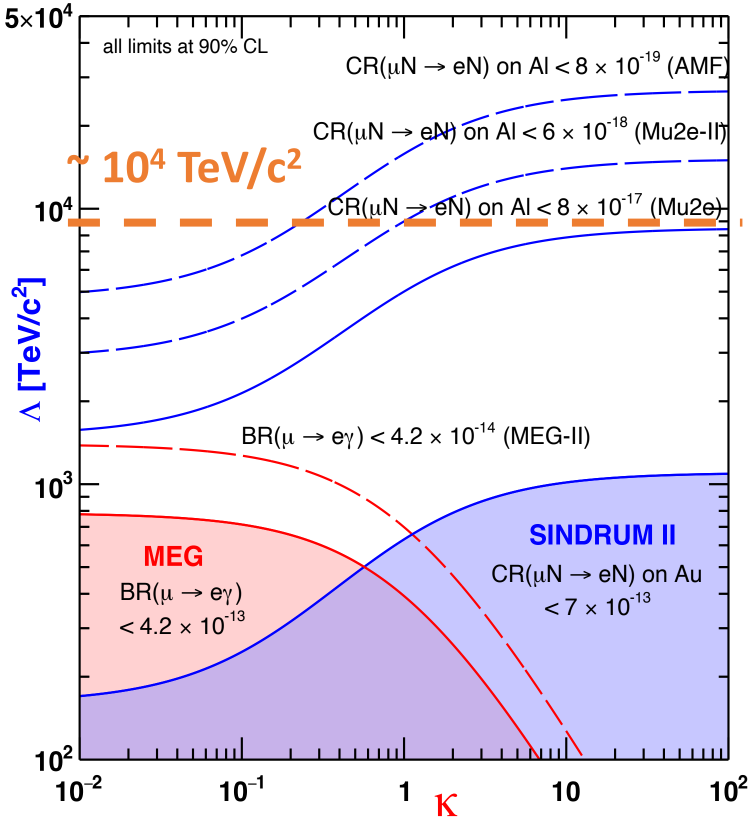

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Complementarity amongst channels

- 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.

Mode	$\mu^+ \to e^+ e^+ e^-$	$\mu^- N \to e^- N$	$\frac{BR(\mu^+ \to e^+ e^+ e^-)}{BR(\mu^+ \to e^+\gamma)}$	$\frac{BR(\mu^- N \to e^- N)}{BR(\mu^+ \to e^+\gamma)}$
MSSM	Loop	Loop	~ 6 x 10^{-3}	10^{-3} – 10^{-2}
Type I Seesaw	Loop	Loop	3 x 10^{-3} – 0.3	0.1-10
Type II Seesaw	Tree	Loop	(0.1 – 3) x 10^{3}	10^{-2}
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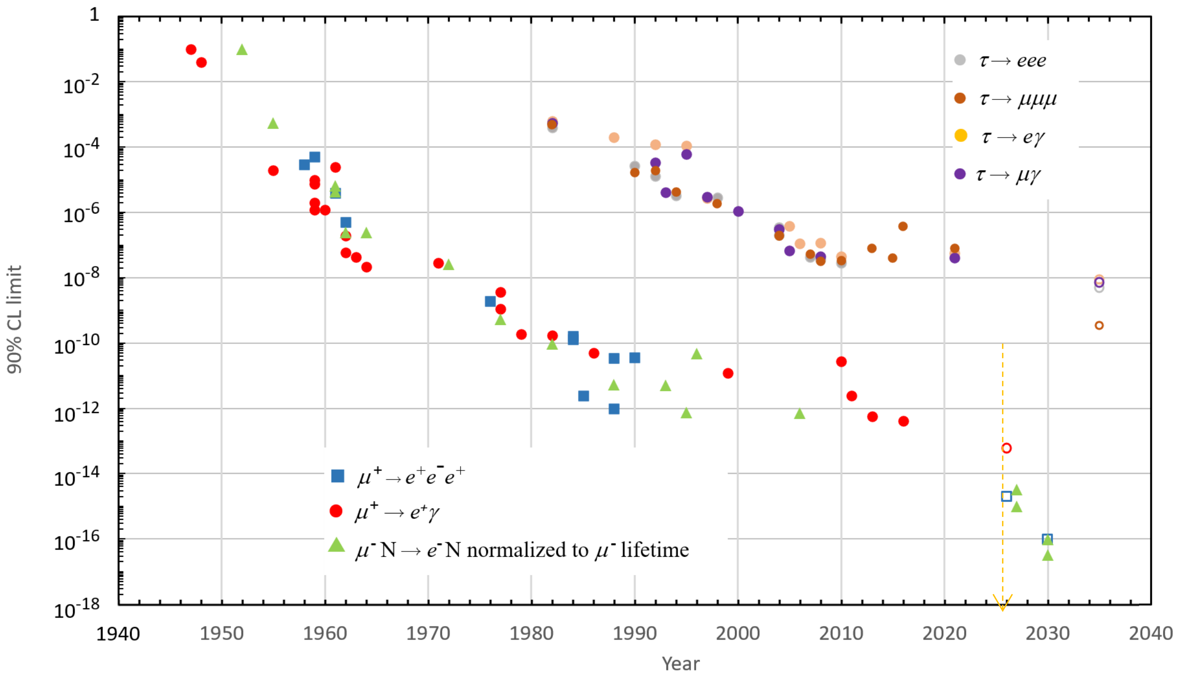
Nucl. Phy. B (Proc. Suppl.) 248–250 (2014) 13–19

- 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!**

What about taus?

- Less stringent limits in 3rd generation, but here BSM effects may be higher.
- τ LFV searches at Belle II will be extremely clean, with very little background (if any), thanks to pair production and double-tag analysis technique.
- **To determine type of mediator:**
  - **Compare muon channels to each other**
- **To determine the source of flavor violation:**
  - **Compare muons to other leptons i.e. taus**



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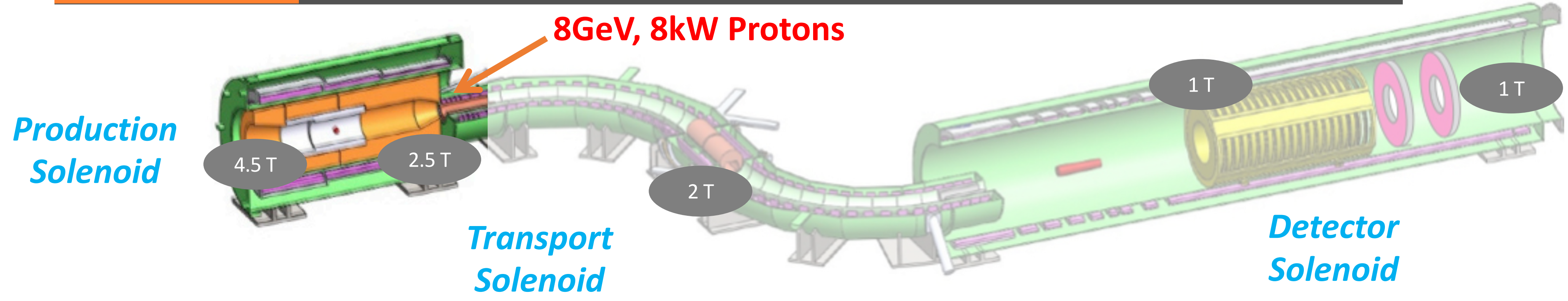
Design

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



<u>Production Solenoid:</u>

- 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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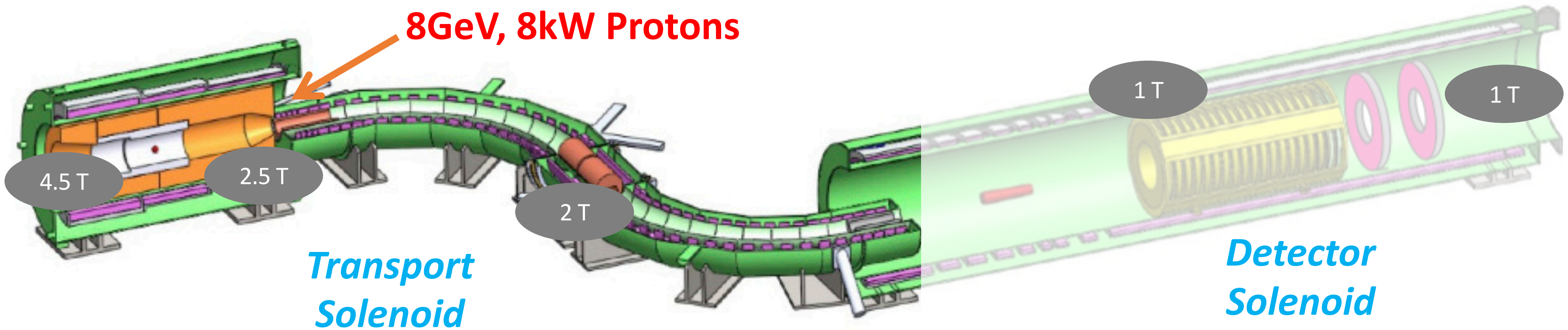

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- "S" shape removes line of sight backgrounds.
- Collimators select low momentum, negative muons.

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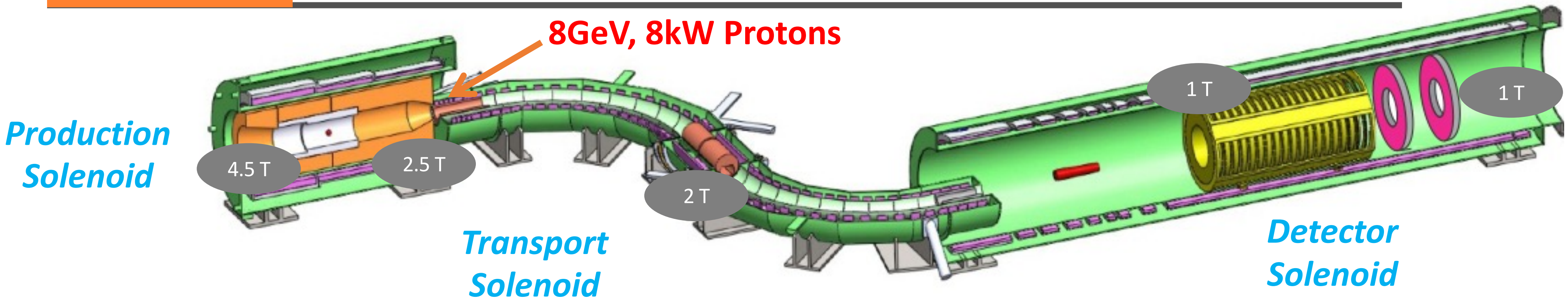

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Detector Solenoid:
- Thin aluminum foil target captures the muons.
- Possible signal electrons are detected by a tracker and a calorimeter.
- Cosmic ray veto covers the whole detector solenoid and half the transport solenoid.

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

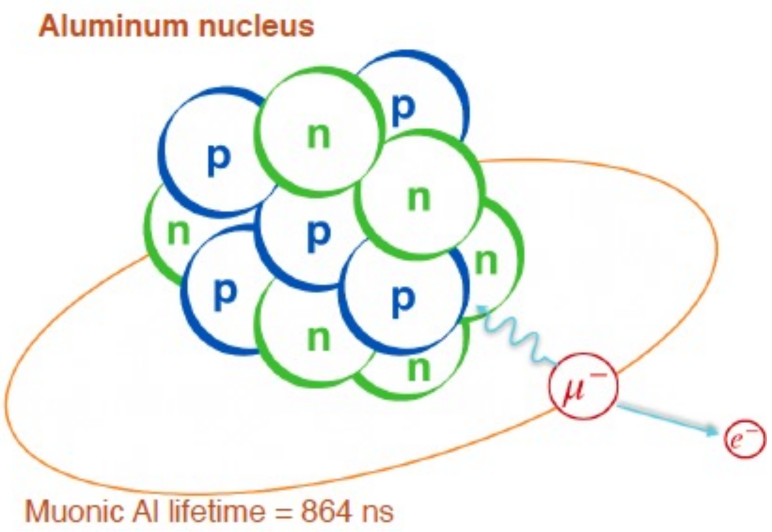
- The $\mu \rightarrow e$ conversion rate is measured as a ratio to the muon capture rate on the same nucleus:

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

- 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	$0.038 \pm 0.002\ (\mathrm{stat})^{+0.025}_{-0.015}$ (sys)
Beam Backgrounds	Pion Capture	Beam Structure/ Extinction	(in time) $0.010 \pm 0.002\ (\mathrm{stat})^{+0.001}_{-0.003}$ (sys) (out time) ($1.2 \pm 0.001\ (\mathrm{stat})^{+0.1}_{-0.3}$ (sys)) x 10^{-3}
Cosmic Induced	Cosmic Rays	Active Veto System	0.046 ± 0.010(stat) ± 0.009 (sys)

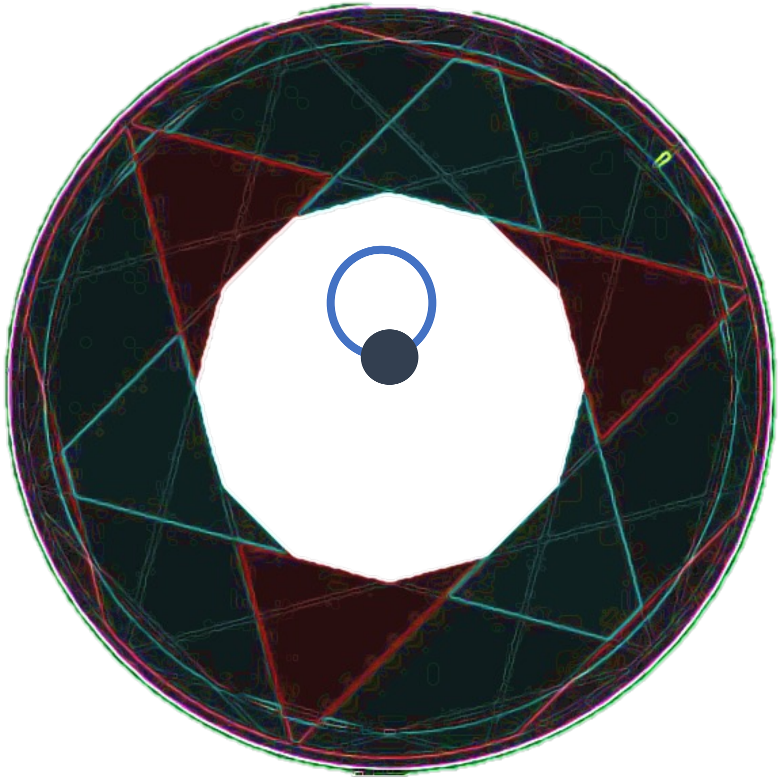
* assumes signal region of 103.6 < p < 104.9 MeV/c and 640 < t < 1650 ns

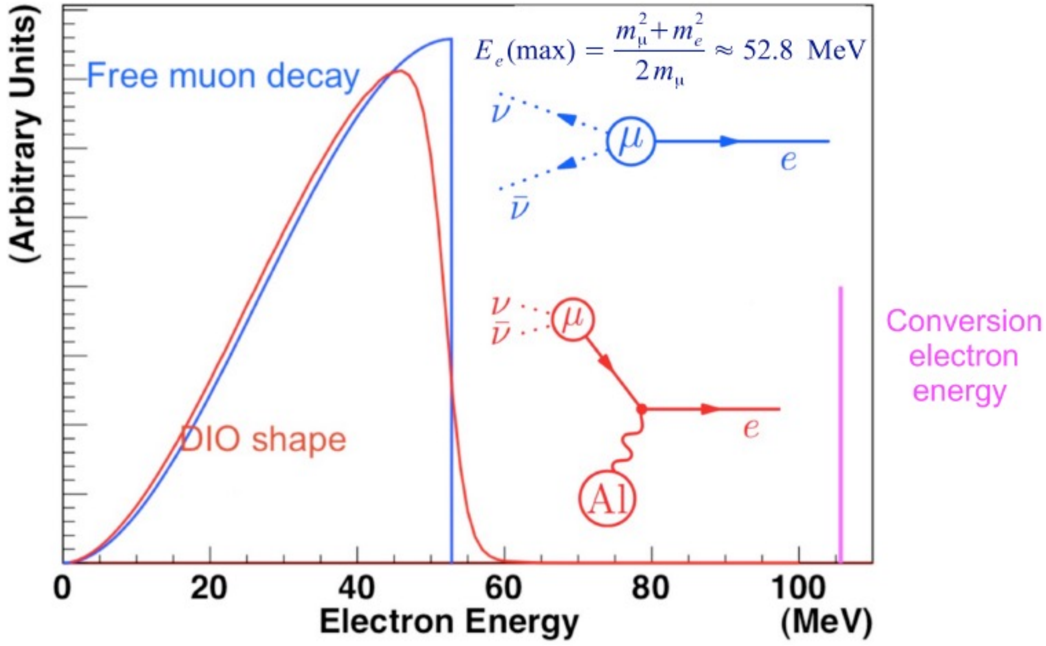
Run-I Sensitivity of Mu2e:
Universe 2023, 9, 54.

Decay in Orbit (DIO) Backgrounds

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

- Michel Electron (< 52MeV/c)



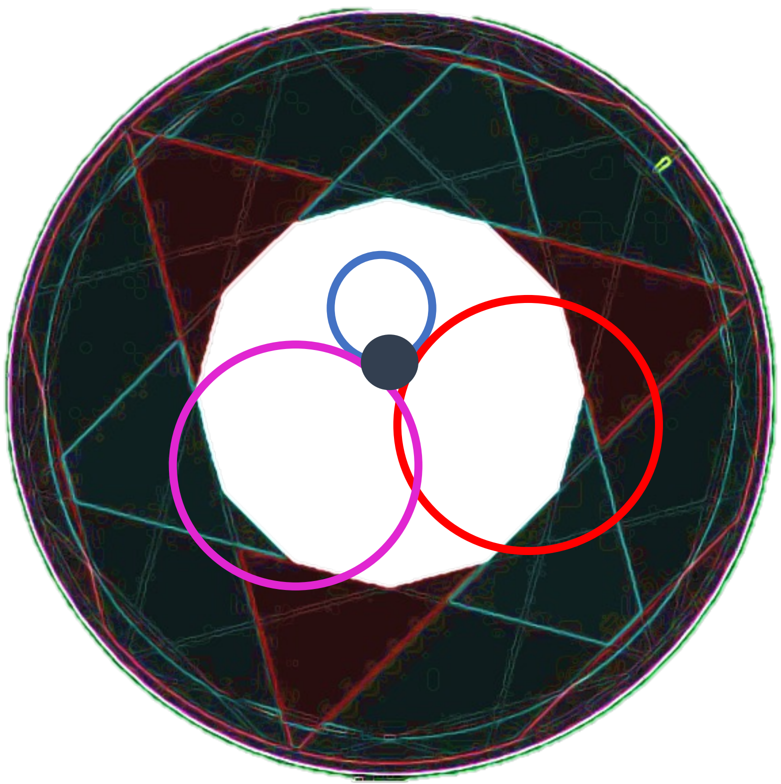


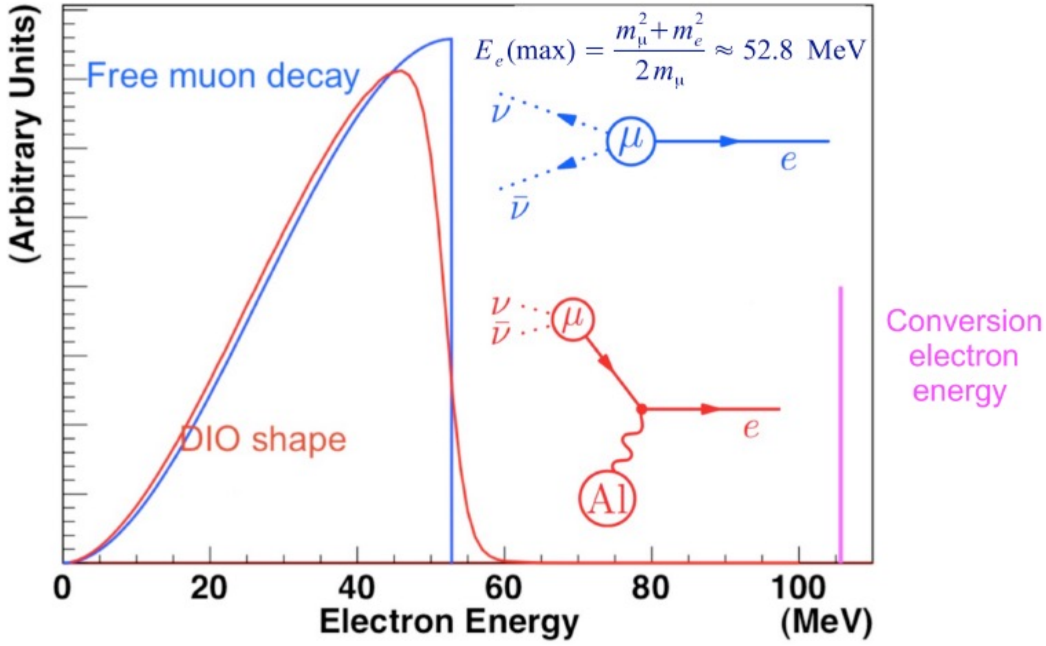
Cartoon of DIO Energy Spectrum
(see Szafron, Czarnecki PhysRevD.94.051301 + others)

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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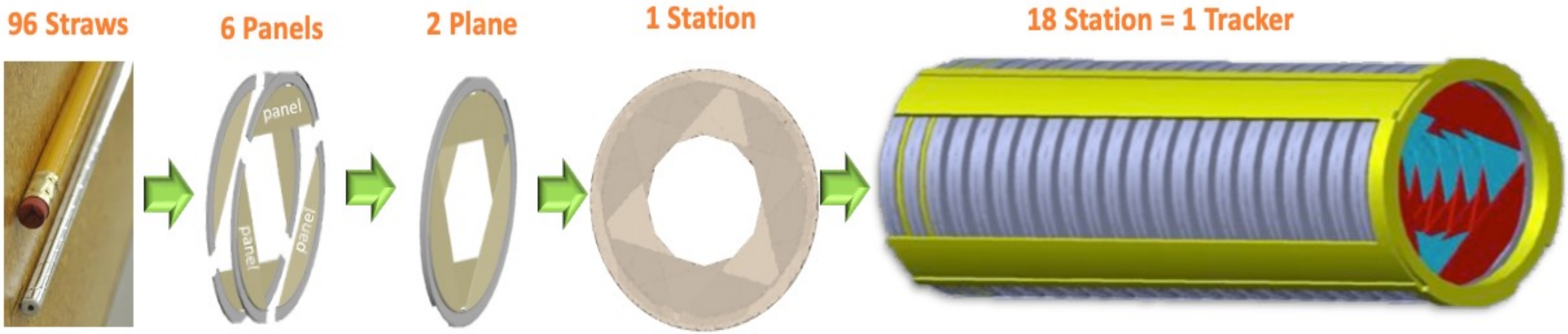
Decay in Orbit Backgrounds

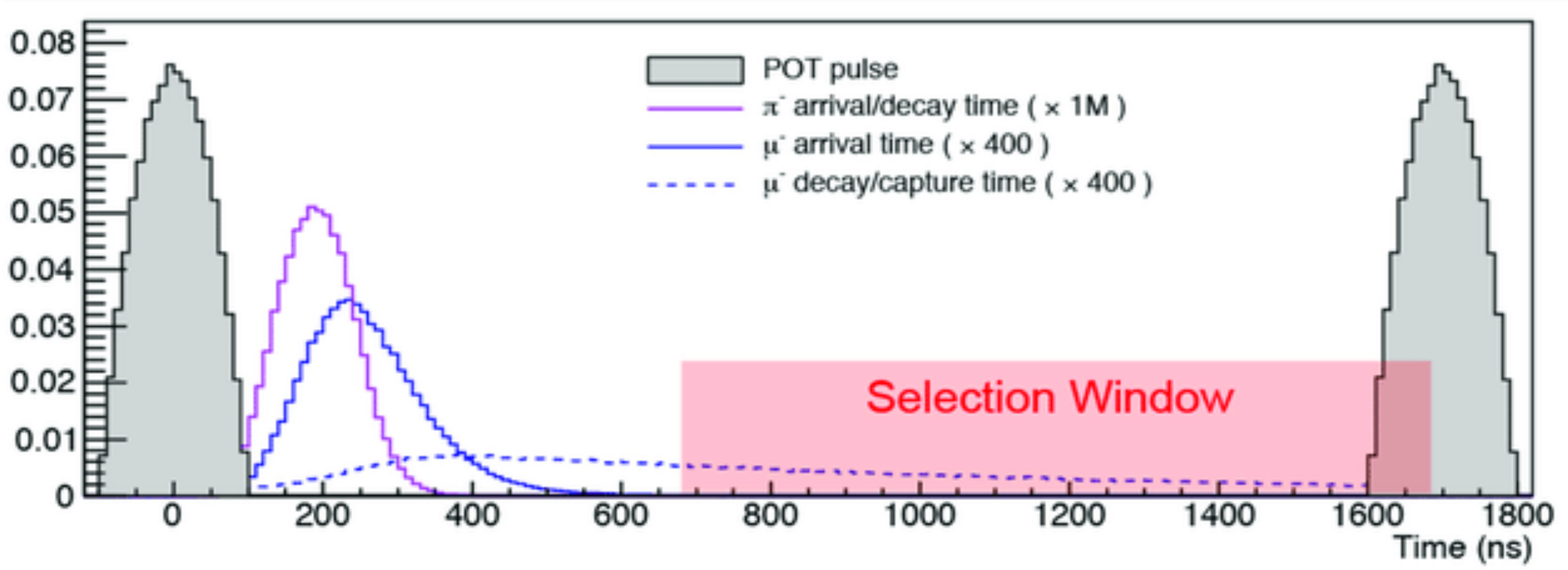
- Need a high-resolution momentum measurement to distinguish tail DIO from signal:
  - Minimize energy loss by operating in vacuum and using low mass straws of 15 μm diameter filled with 80:20 $Ar:CO_2$;
  - Include extra hit position information with high-angle stereo overlaps and readout on both ends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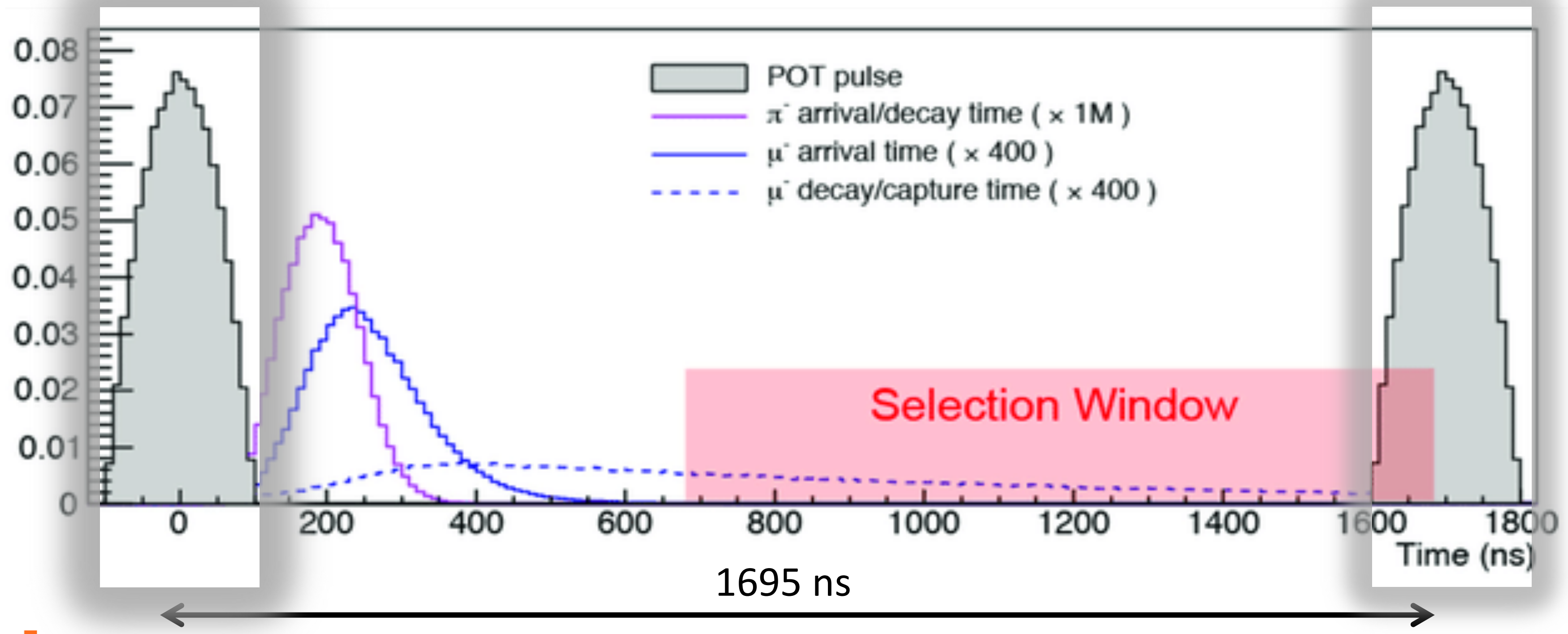

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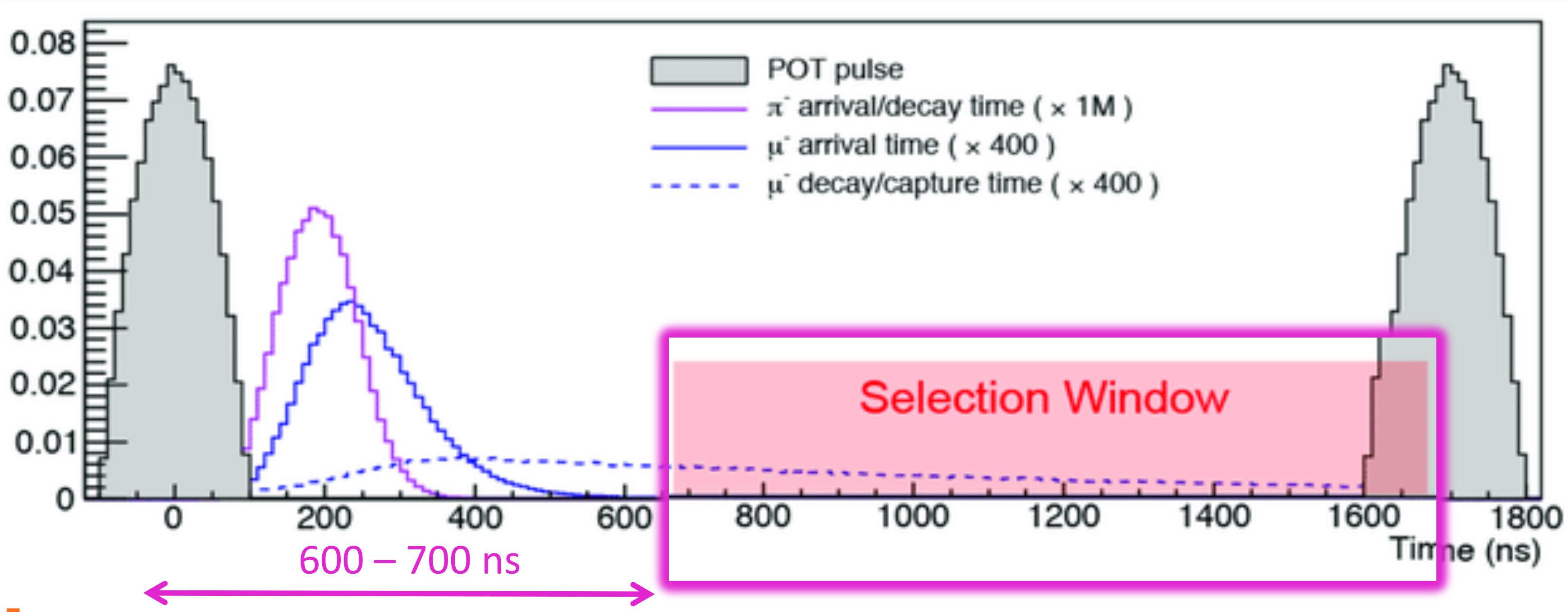
- In addition, upstream extinction removes out-of-time protons.

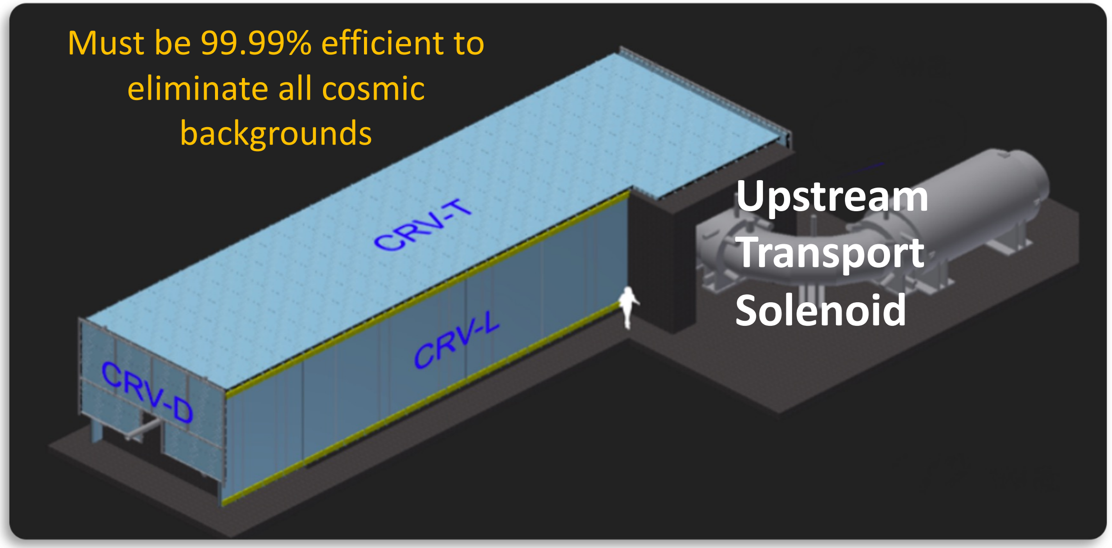
Delayed live-gate helps remove pion and beam backgrounds.



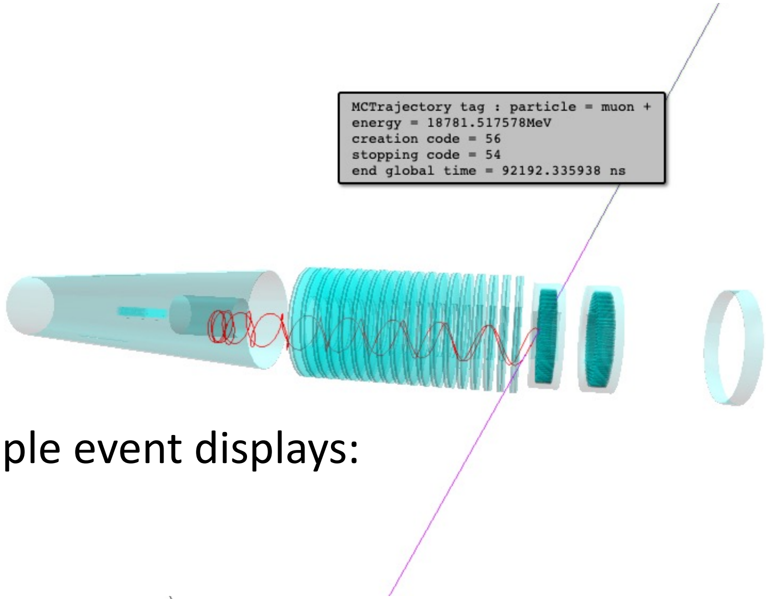
Cosmic Induced Backgrounds

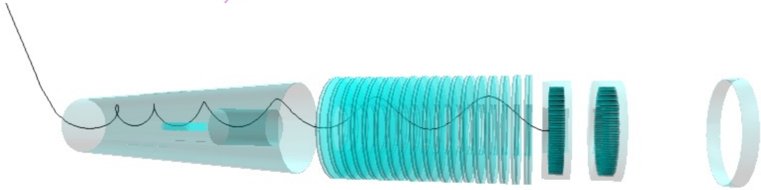
- Cosmic-ray muons can initiate 105 MeV particles that appear to emanate from the stopping target.
- Remove using active veto (CRV) + overburden and shielding concrete surrounding the Detector Solenoid.

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



Example event displays:



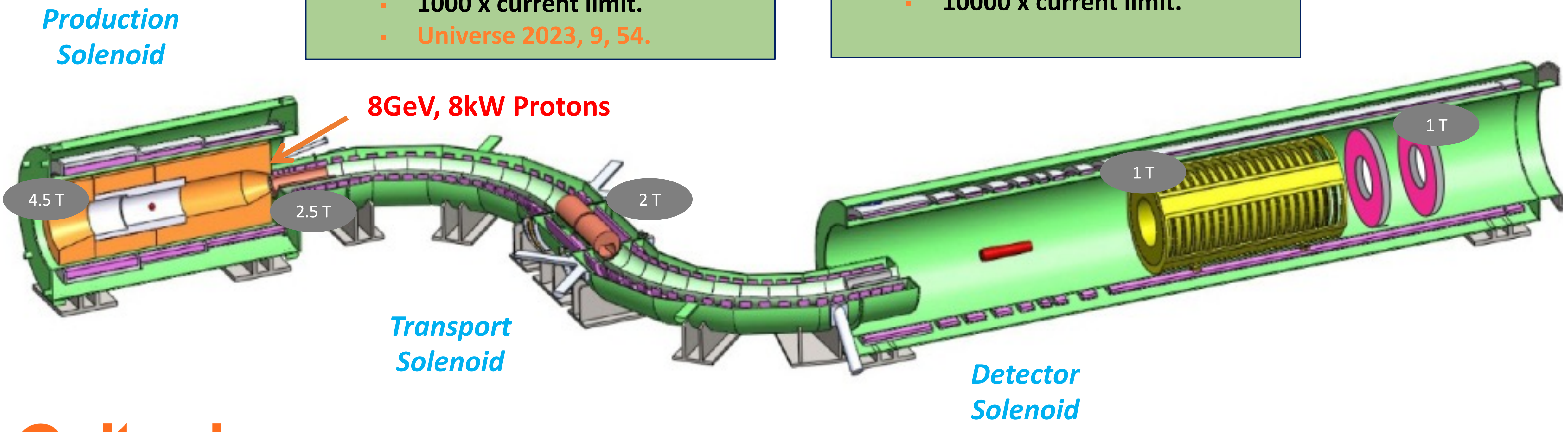


Mu2e: Data taking

- **Mu2e is approaching commissioning next year, data-taking begins in 2026:**
- 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.**

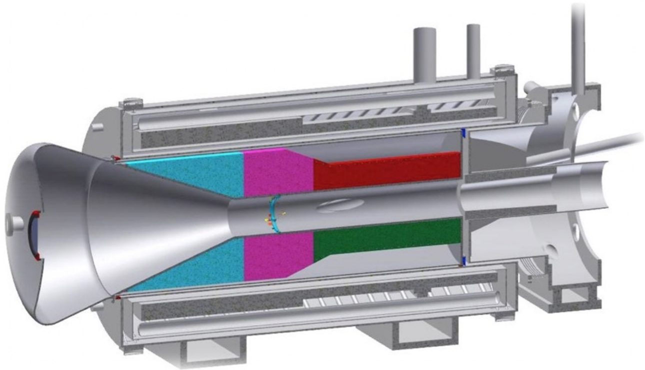
Total (Run-I + Run-II) end-goal:
- 2 x 10^{-16} 5σ discovery,
- Single-Event-Sensitivity = 3 x 10^{-17}
- U.L : 8 x 10^{-17} (90% C.L.)
  - **10000 x current limit.**



Status Update

Solenoids

- **Production Solenoid:**
  - Consists of 3 coils, all wound at vendor.
  - Undergoing final assembly.
  - Arrives at Fermilab in early 2024.



Heat & Radiation Shield

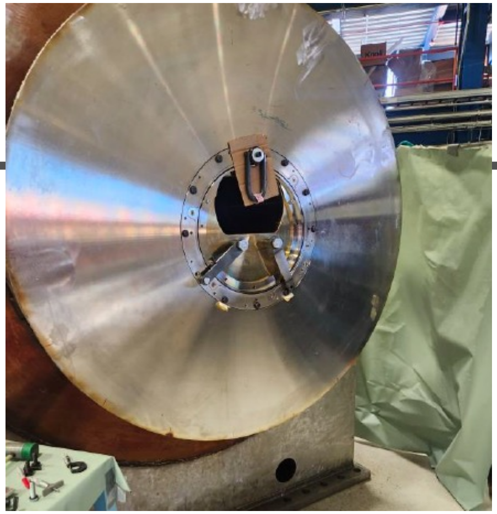
Now installing MLI around cold mass

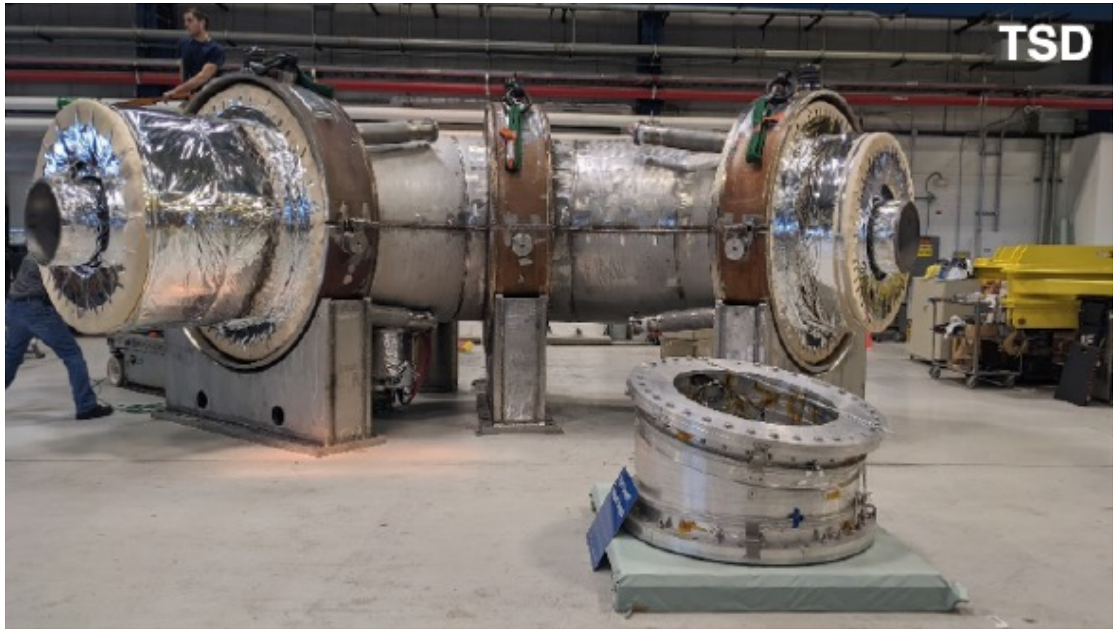
Outer thermal shield panels now installed with MLI and interconnected

Dry run from a couple months ago

Solenoids

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





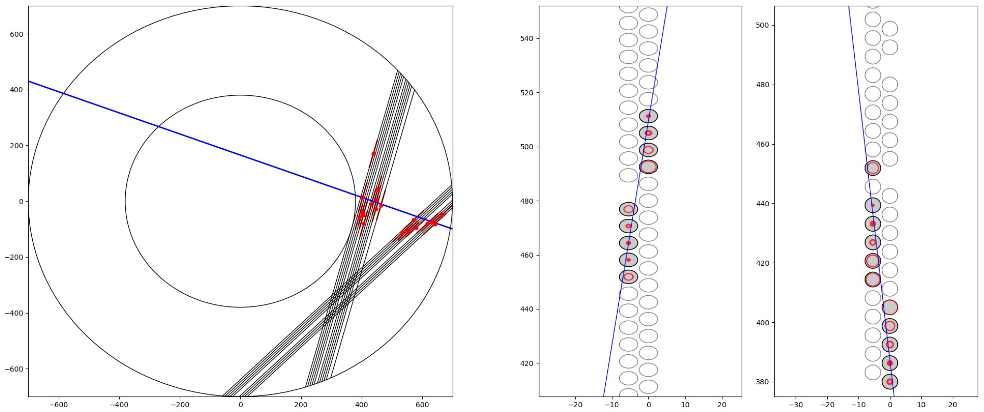
Solenoids

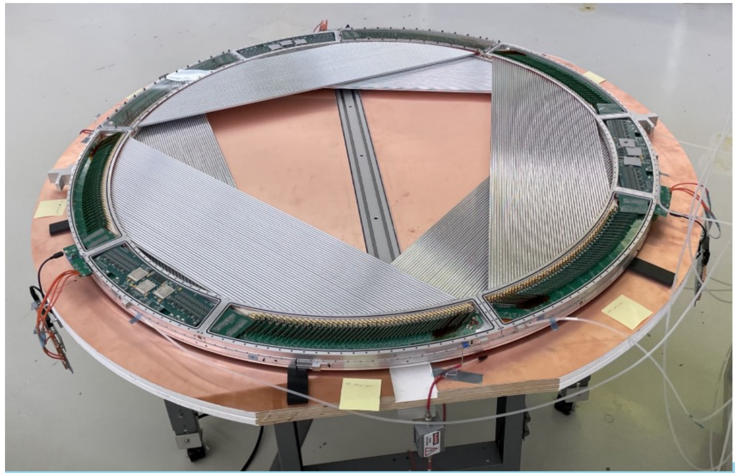
- **Detector Solenoid:**
  - All coils completed at vendor.
  - Cold mass cryo. supports prepared
  - Delivery to Fermilab expected mid-2024.

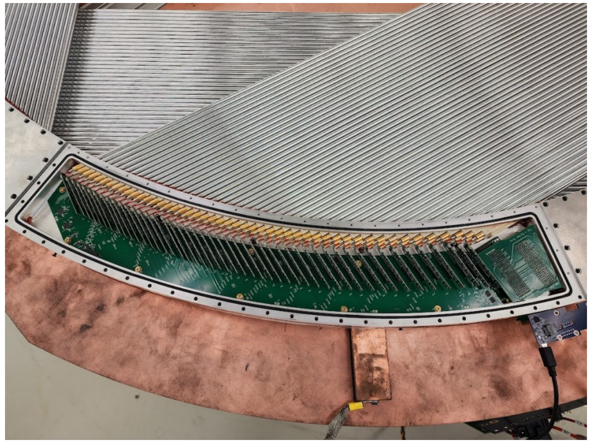
Mini cold mass: coils 1-4 bolted together

Tracker

- All 20736 straws produced.
- All 216 panels produced. Now working through QC.
- 30 / 36 planes are built.
- Cosmic ray tests carried out with a single plane and full readout system for 3 years.







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Calorimeter

Calorimeter is vital for providing:

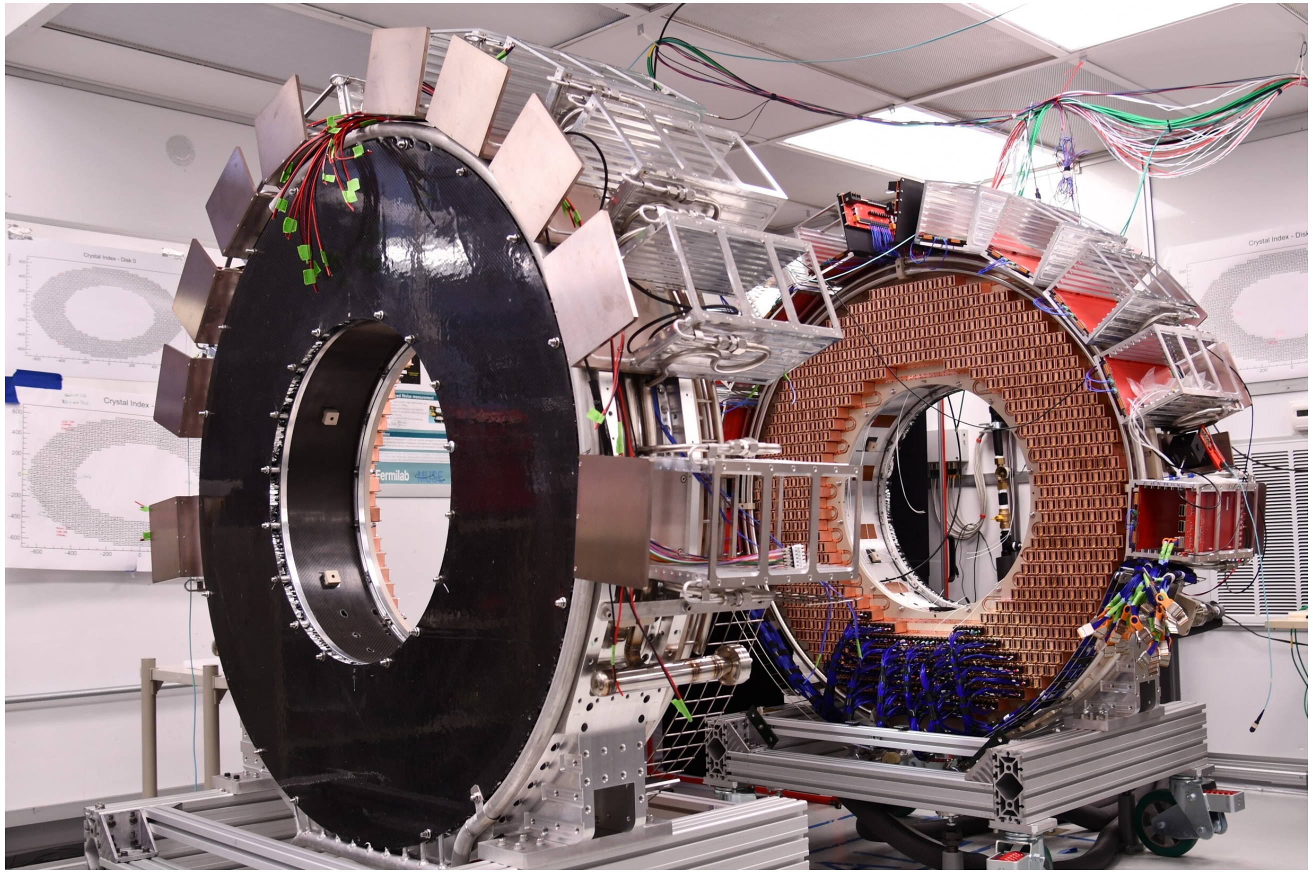
- **Particle identification,**
- **Fast online trigger filter,**
- **Seed for track reconstruction.**

Design:

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

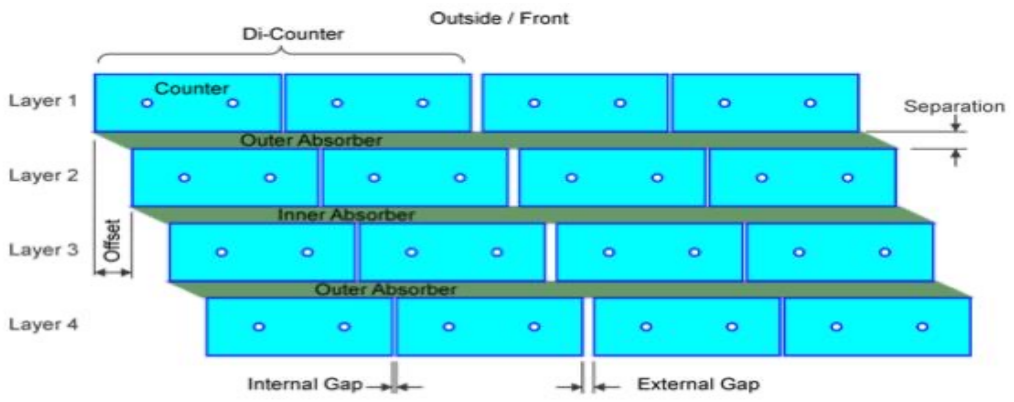
Both disks

- Have crystals and SiPMs installed.
- 450 ROU's installed.
- Cabling underway.



Cosmic Ray Veto System

- All 5344 di-counters produced.
- All modules produced.
- Cosmic ray tests underway at Fermilab.



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Summary

- Mu2e will search for the CLFV in muon to electron conversion with a 90% CL upper limit of < 8×10^{-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/

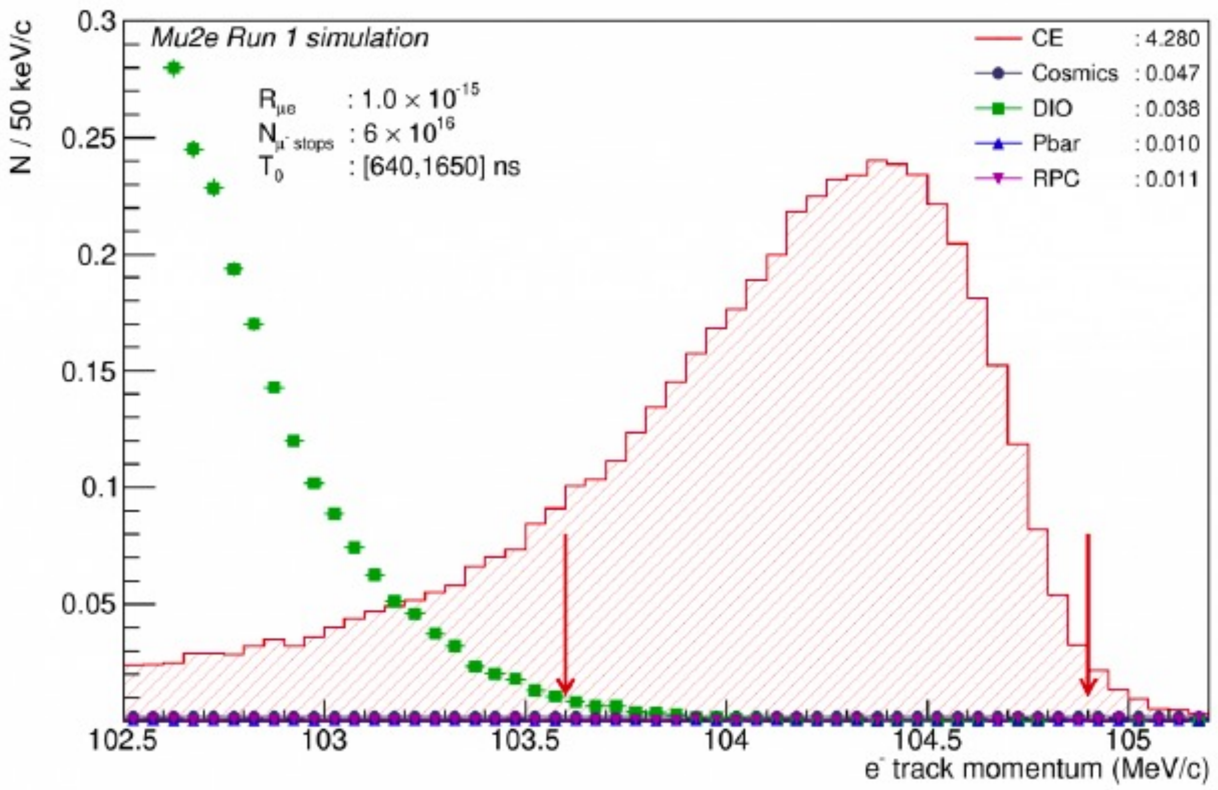
Thank you for listening!

Any Questions?

Additional Material

Signal & Backgrounds

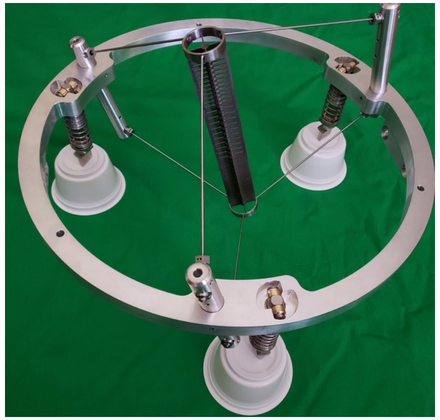
Expected signal ($R_{\mu e} = 10^{-15}$) and DIO spectra from Run_I simulation (~10% of final dataset, includes resolution and energy loss effects):

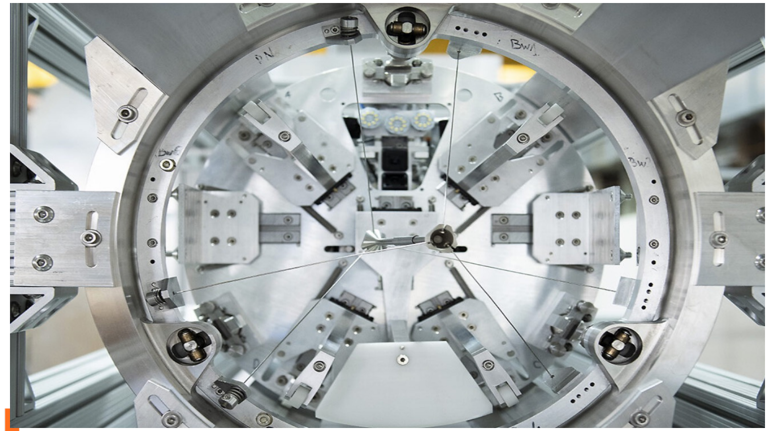


Run-I Sensitivity of Mu2e:
Universe 2023, 9, 54.

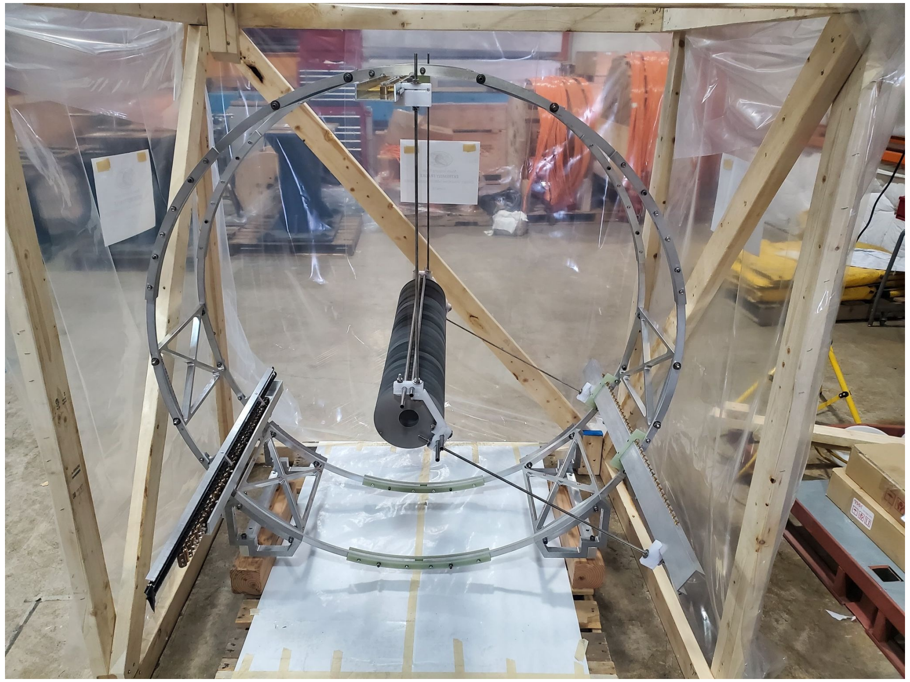
Targets

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.



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.

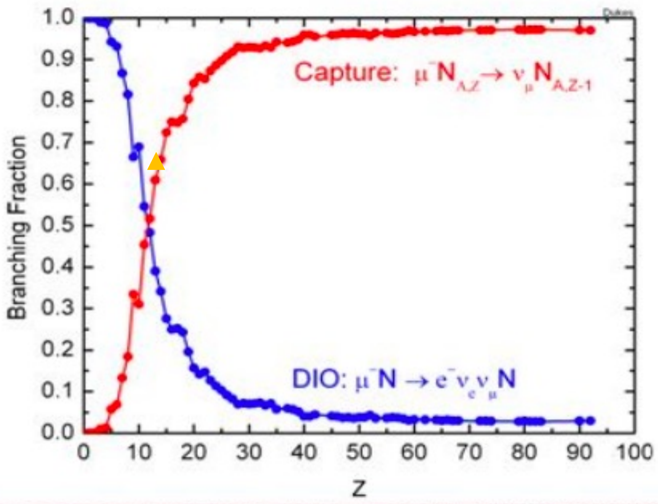
No signals

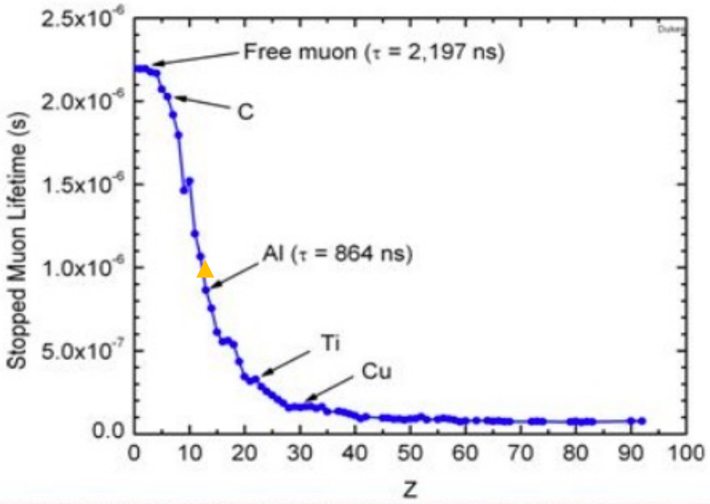
Push to higher effective mass scale, opening other BSM scenarios.

Some models excluded or heavily constrained.

Mu2e: Why Al?

Practical Advantages	Physics Advantages
Chemically Stable	Conversion energy such that only tiny fraction of photons produced by muon radiative capture.
Available in required size/shape/thickness	Muon lifetime long compared to transit time of prompt backgrounds.
Low cost	Conversion rate increases with atomic number, reaching maximum at Se and Sb, then drops. Lifetime of muonic atoms decreases with increasing atomic number.
	Lifetime of muonic atom sits in "goldilocks" region i.e. neither longer than 1700 ns pulse spacing and greater than our pionic live gate.





The lifetime of a muon in a muonic atom decreases with increasing atomic number.

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

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

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

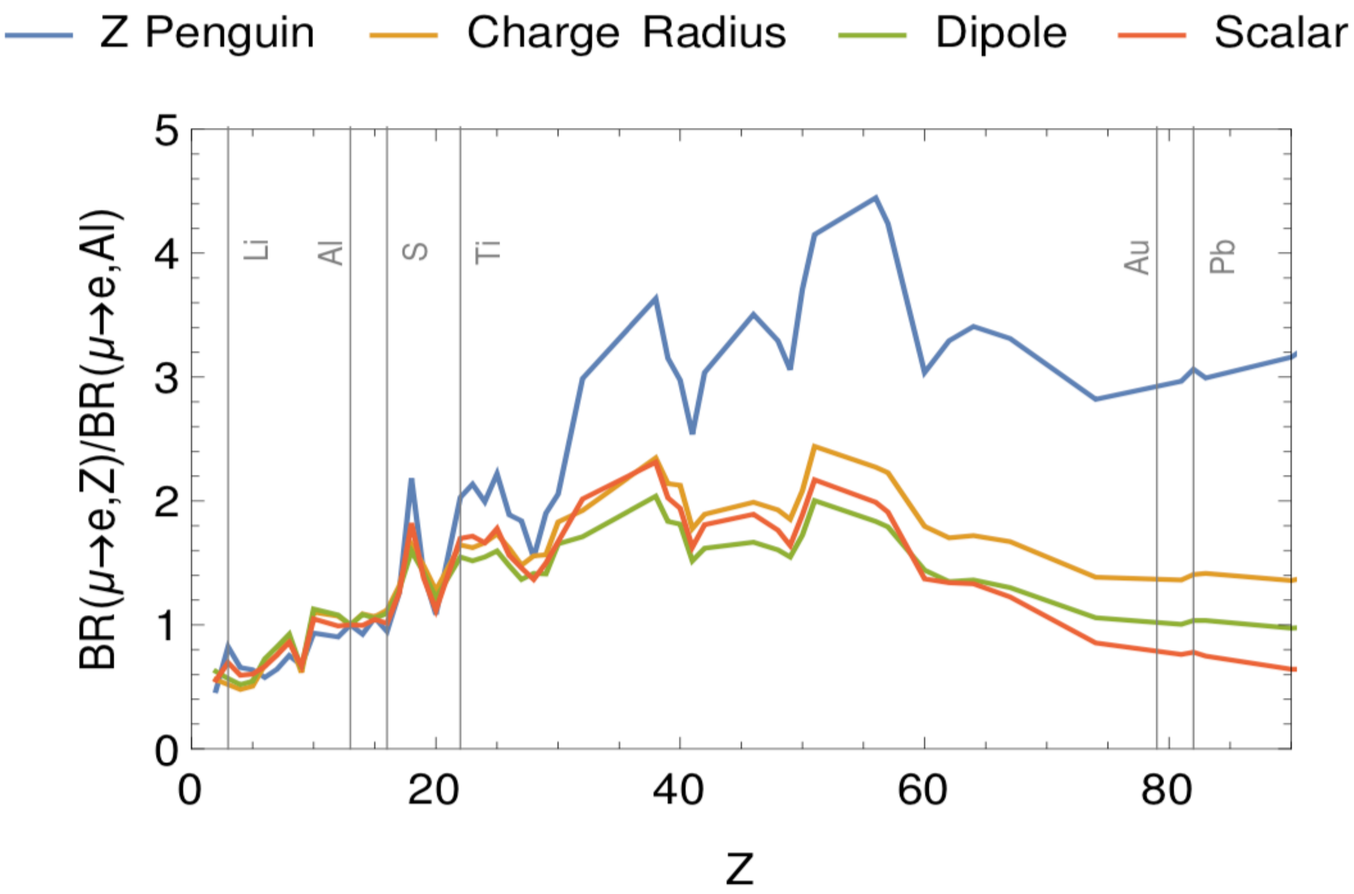
Overlap with nucleus probes form factors and reveals the nature of the interaction.

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

	S	D	V^1	V^2
$\frac{B(\mu\rightarrow e,Ti)}{B(\mu\rightarrow e,Al)}$	$1.70 \pm 0.005_y$	1.55	1.65	2.0
$\frac{B(\mu\rightarrow e,Pb)}{B(\mu\rightarrow e,Al)}$	$0.69 \pm 0.02_{\rho_n}$	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:

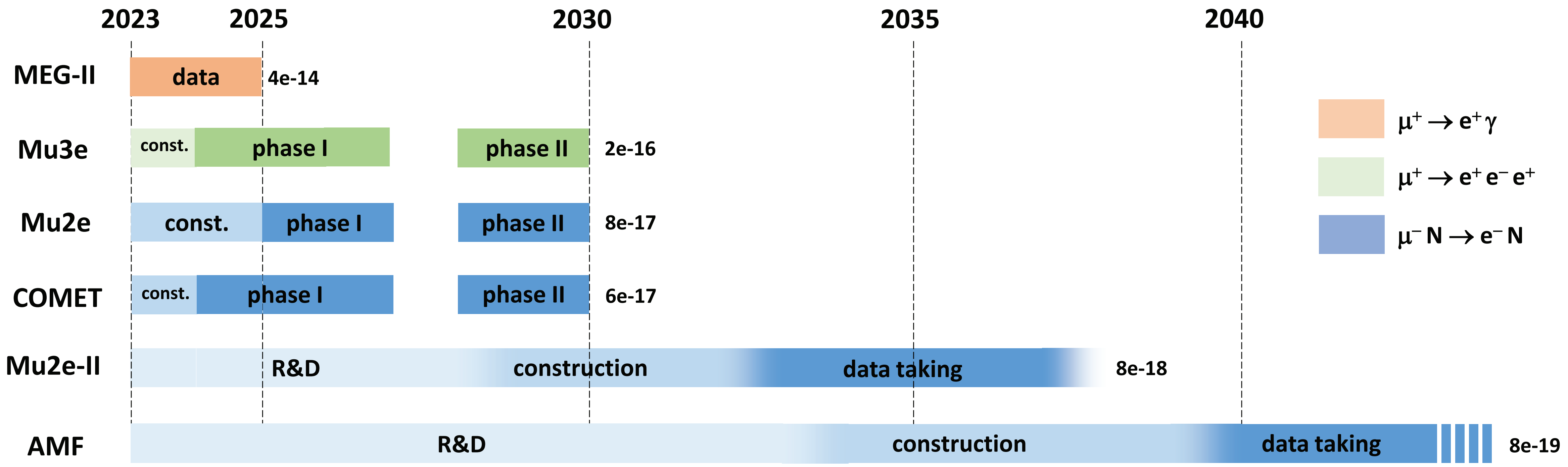
Mu2e-II [see: arXiv: 2203.07569 [hep-ex]] (mid-2030s):

- ***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.

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
$\mu^+ \to e^+ \gamma$
$\mu^+ \to e^+ e^- e^+$
$\mu^- N \to e^- N$