The Mu2e Experiment

Motivations, Design and Current Status

Sophie Charlotte Middleton

on behalf of the Mu2e experiment

Caltech

ICHEP 2024 Prague
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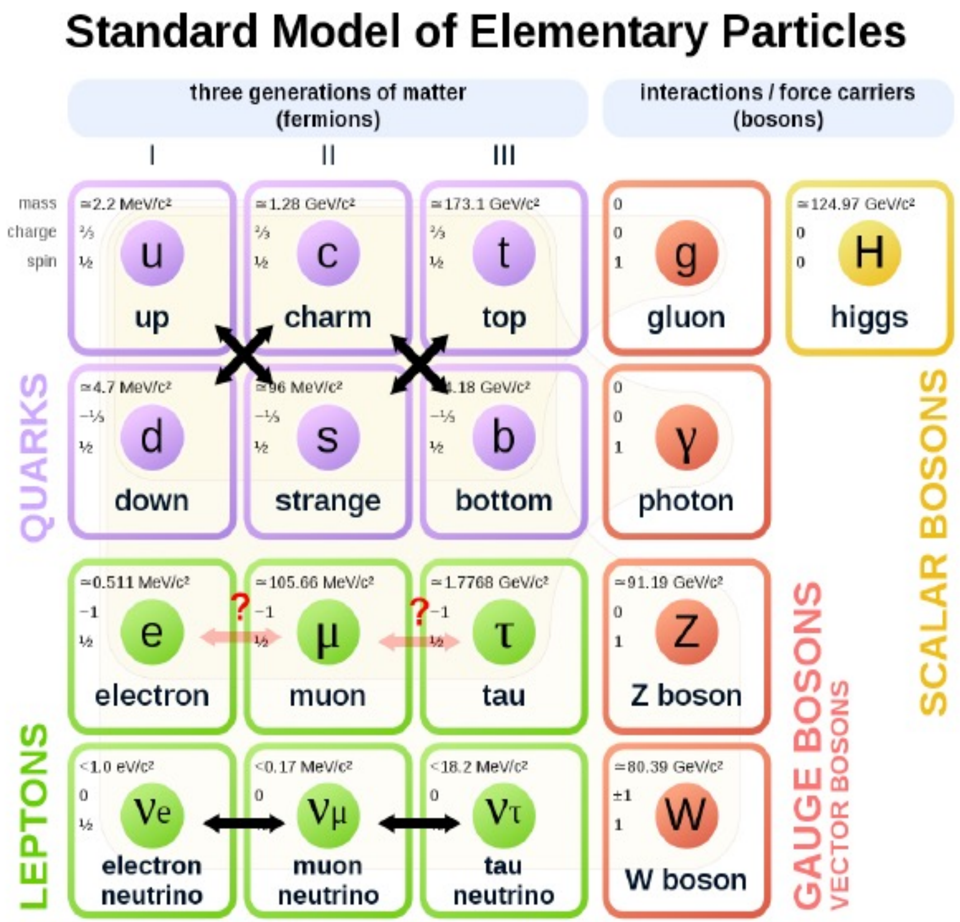
Motivations

Flavor Physics



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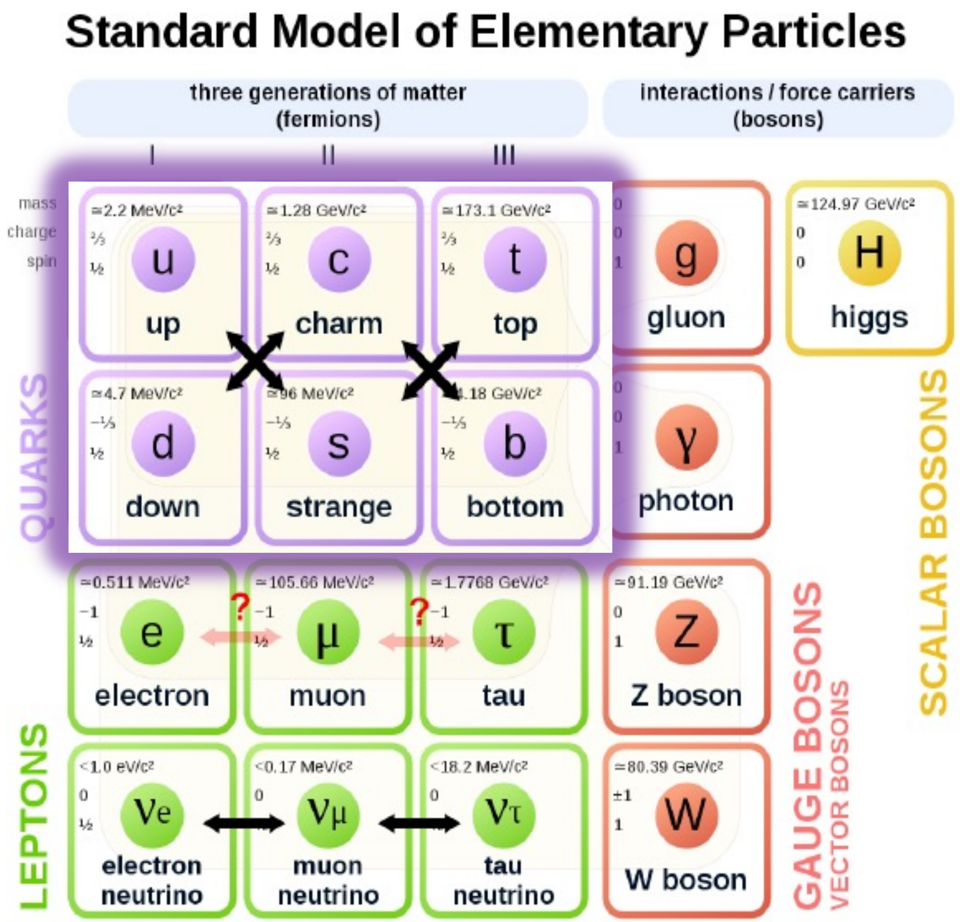
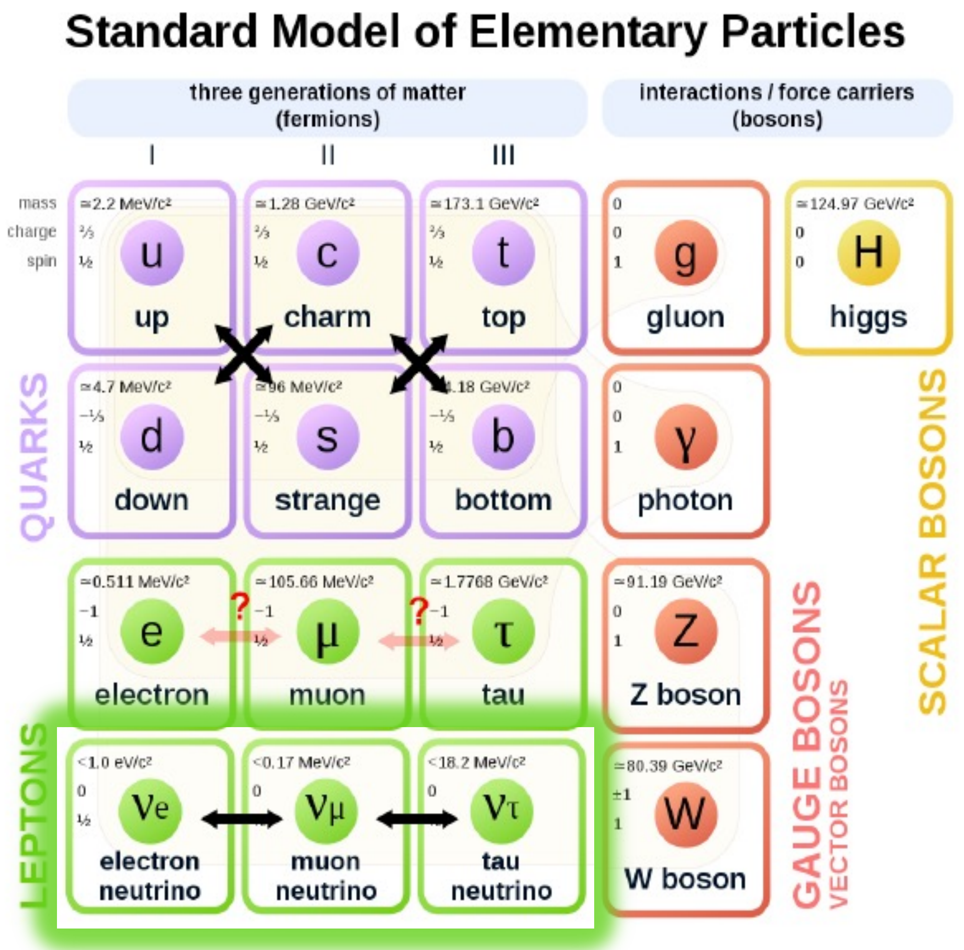


- Flavor is not conserved in:
  - quarks (via quark mixing);

Flavor Physics



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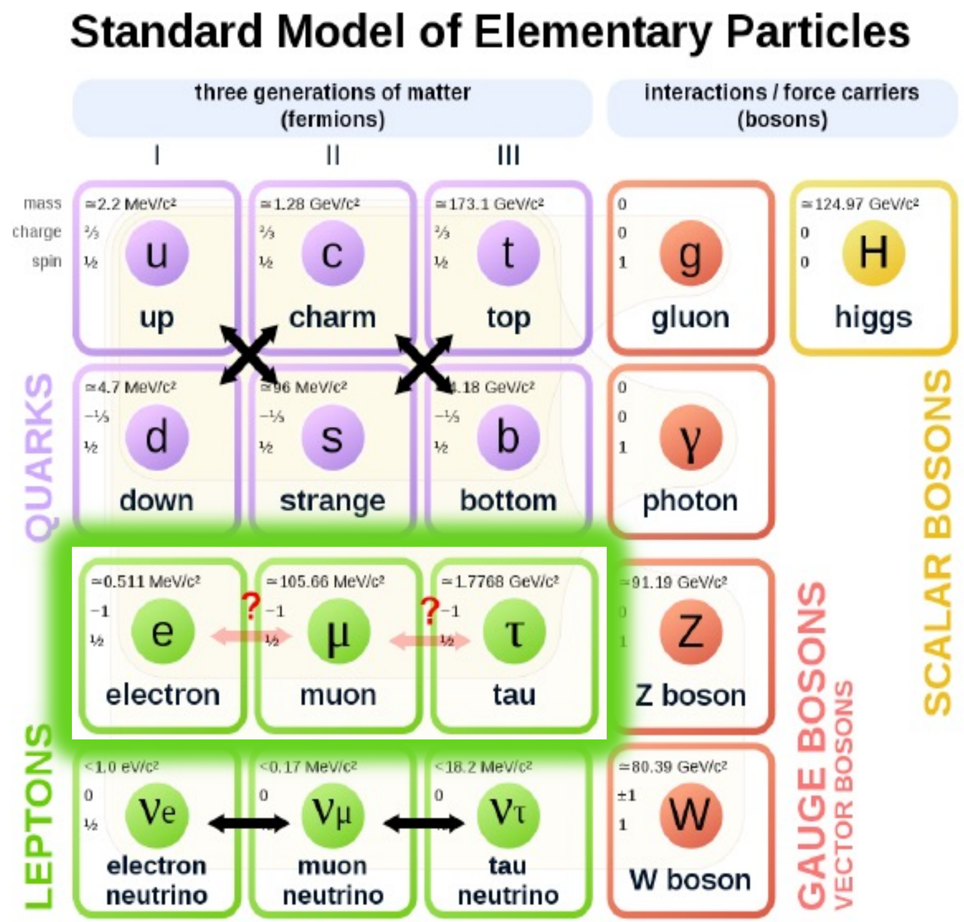
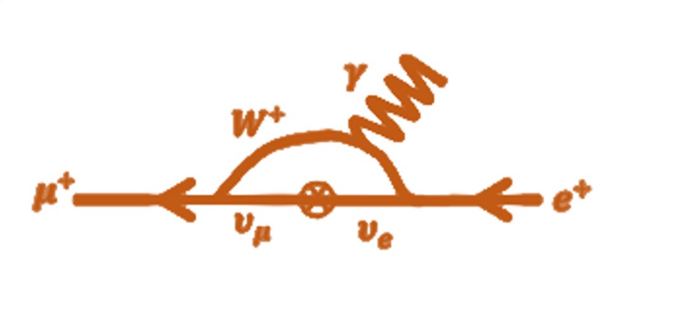


- Flavor is not conserved in:
  - quarks (via quark mixing);
  - neutrinos (via neutrino oscillations)
- **What about Charged Lepton Flavor Violation?**

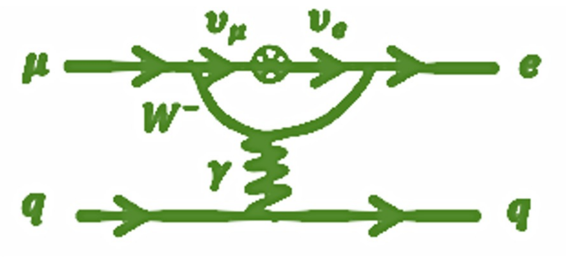
Charged Lepton Flavor Violation (CLFV)

- Adding neutral lepton flavor violation to the Standard Model, introduces CLFV at loop level, mediated by W bosons:

$\mu^+ \rightarrow e^+\gamma$



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



$\mu^+ \rightarrow e^+e^+e^-$

No outgoing neutrinos!

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

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

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

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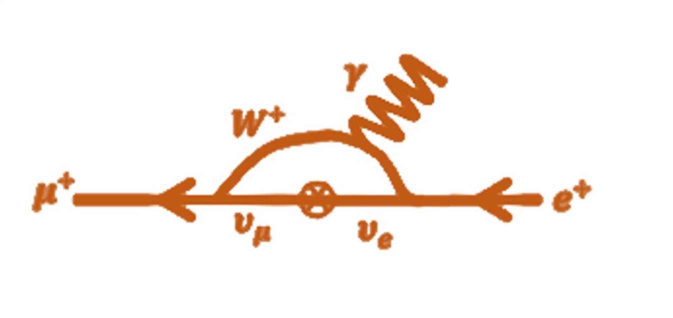

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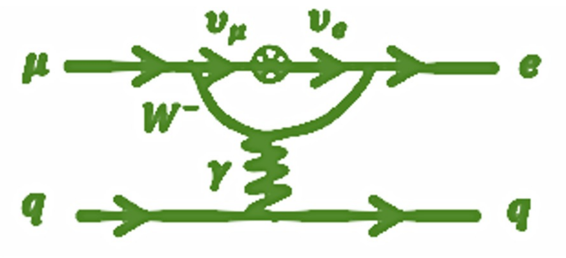

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- ...but many Beyond Standard Model (BSM) theories (e.g. SO(10) SUSY, scalar leptoquarks, seesaw models) predict enhanced rates of CLFV just below current limits O(10^{-13}).

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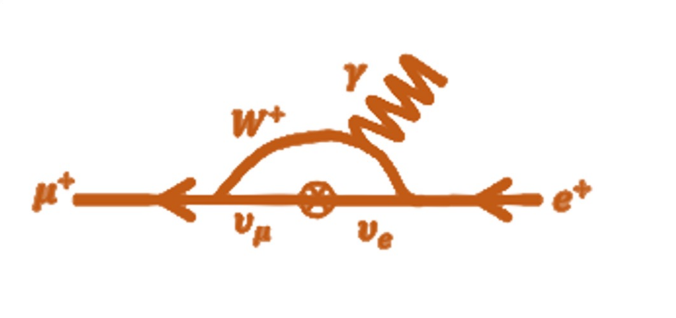

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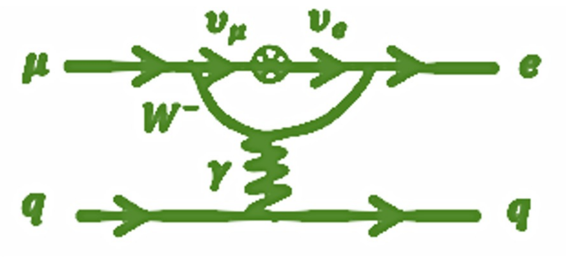

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- ...but many Beyond Standard Model (BSM) theories (e.g. SO(10) SUSY, scalar leptoquarks, seesaw models) predict enhanced rates of CLFV just below current limits O(10^{-13}).

Mu2e is an indirect search for New Physics and offers a deep probe of 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
$\mu^+ \to e^+\gamma$	4.2×10^{-13}	4×10^{-14}	MEG II
$\mu^+ \to e^+e^+e^-$	$\sim 10^{-12}$	$10^{-15} \sim 10^{-16}$	Mu3e
$\mu^- N \to e^- N$	7×10^{-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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Physics Data-taking Plans

Mu2e will search for conversion in Al and improve on current limit by four orders of magnitude:

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

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

Need to stop $O(10^{18})$ muons and have << 1 background event over entire lifetime of the experiment to achieve these numbers!

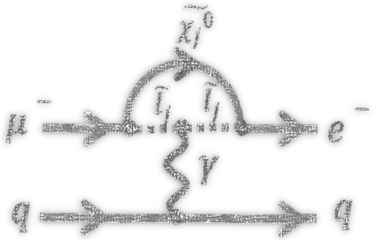
Effective Physics Reach

De Gouvea & Vogel

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

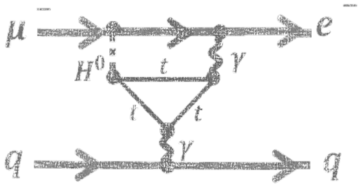
"Photonic"

i.e. Dipole Term:
$\mu^+ \to e^+\gamma, \mu^+ \to e^+e^+e^-$.
$\mu^-N \to e^-N$ at loop level



SO(10) SUSY

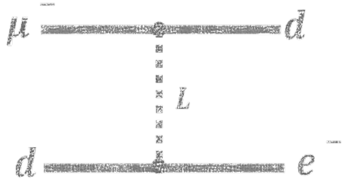
2 Higgs Doublets



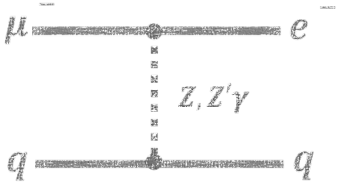
"Contact"

i.e. 4 Fermion Term
$\mu^-N \to e^-N$ at leading order.
Heavily suppressed in $\mu^+ \to e^+\gamma$

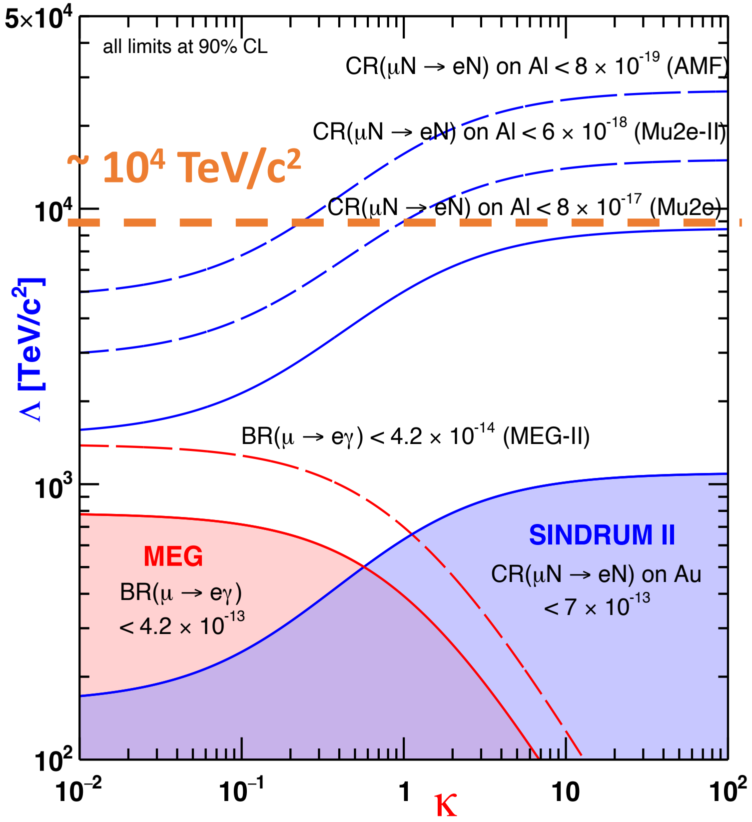
Leptoquarks



New Bosons



* 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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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	$\mu^+ \rightarrow e^+ e^+ e^-$	$\mu^- N \rightarrow e^- N$	$\frac{BR(\mu^+ \rightarrow e^+ e^+ e^-)}{BR(\mu^+ \rightarrow e^+ \gamma)}$	$\frac{BR(\mu^- N \rightarrow e^- N)}{BR(\mu^+ \rightarrow e^+ \gamma)}$
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}
Type III Seesaw	Tree	Tree	~10^{3}	10^{3}
LFV Higgs	Loop	Loop	10^{-2}	0.1
Composite Higgs	Loop	Loop	0.05-0.5	2-20

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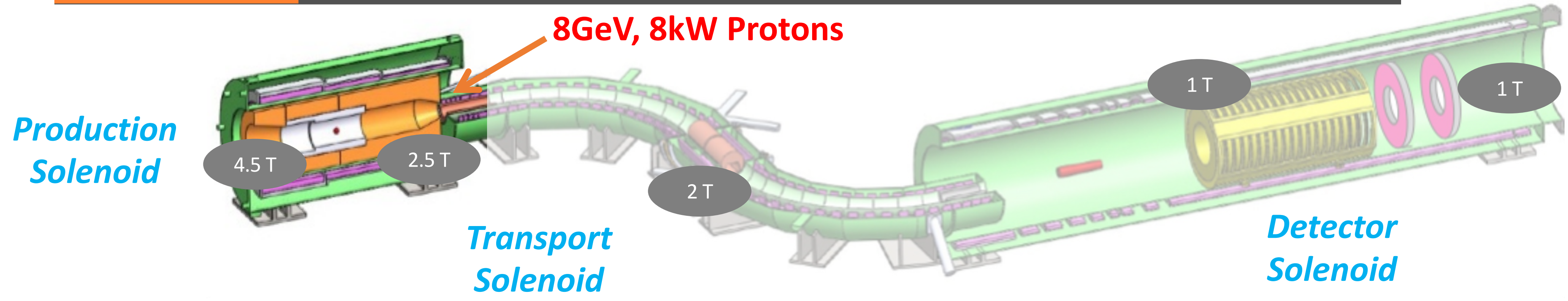
Design

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



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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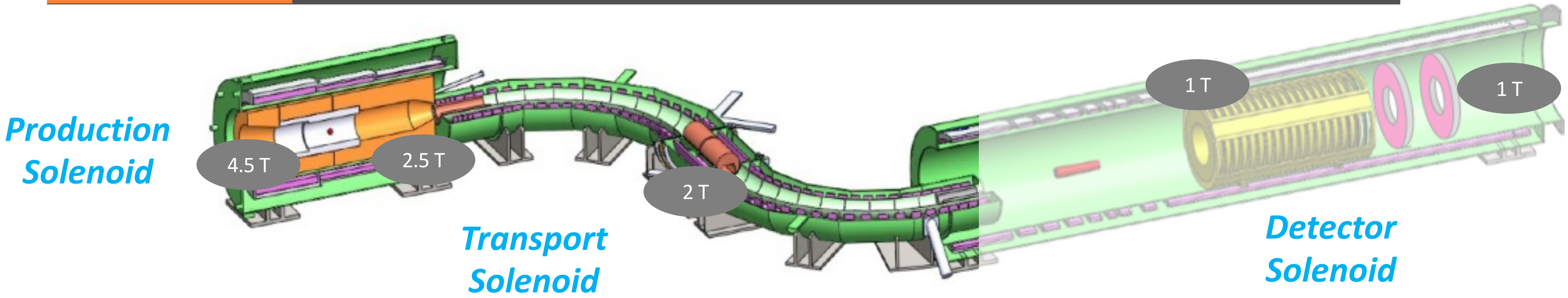

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Transport Solenoid:
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- Collimators select low momentum, negative muons.

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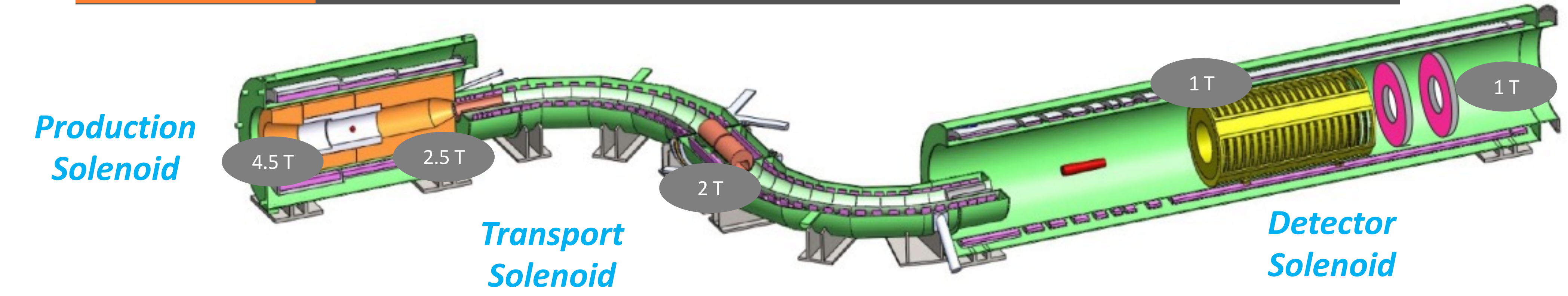

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Detector Solenoid:
- Thin aluminum foil target captures the muons.
- Possible signal electrons are detected by a tracker and a calorimeter.
- Cosmic ray veto covers the whole detector solenoid and half the transport solenoid.

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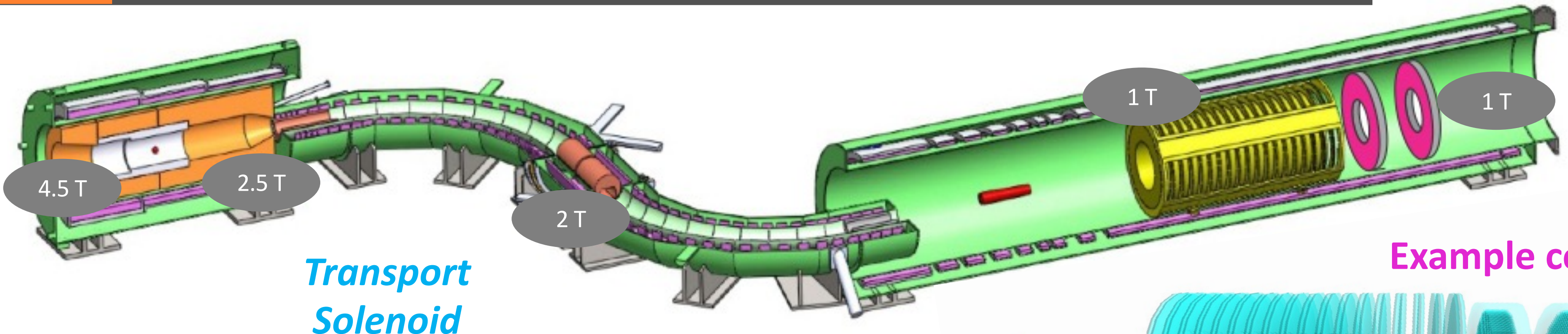
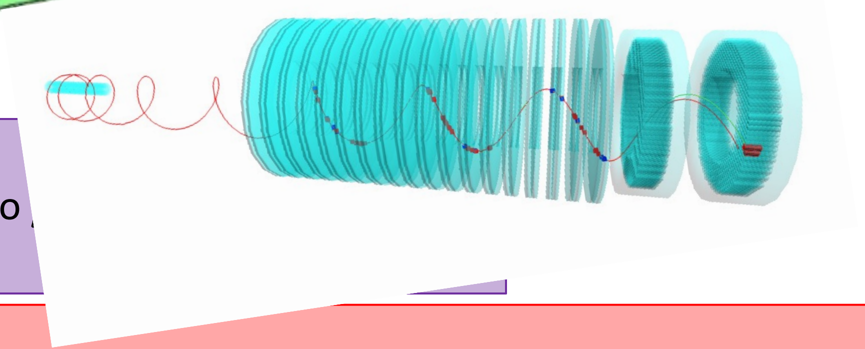


Example conversion signal



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

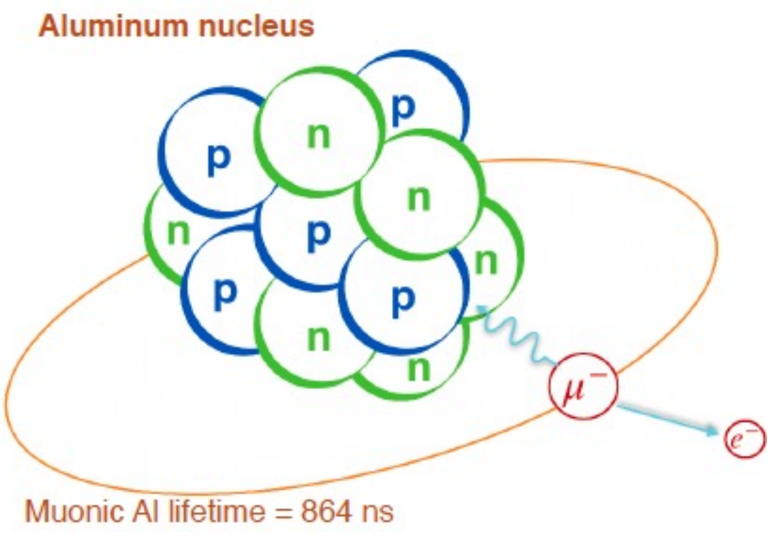
- The $\mu \rightarrow e$ conversion rate is measured as a ratio to the muon capture rate on the same nucleus:

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

- 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



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

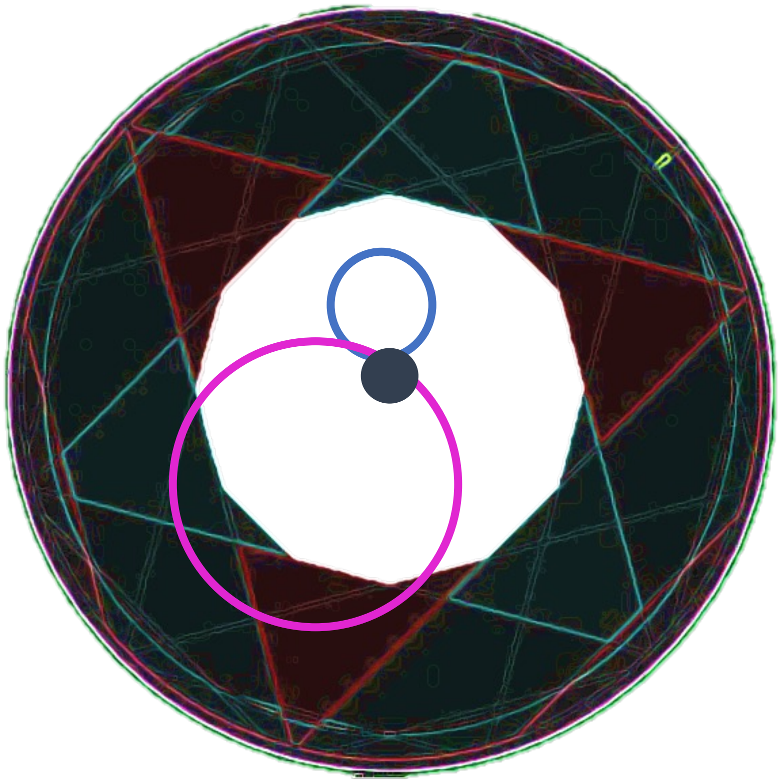
Run-I Sensitivity of Mu2e:
Universe 2023, 9, 54.

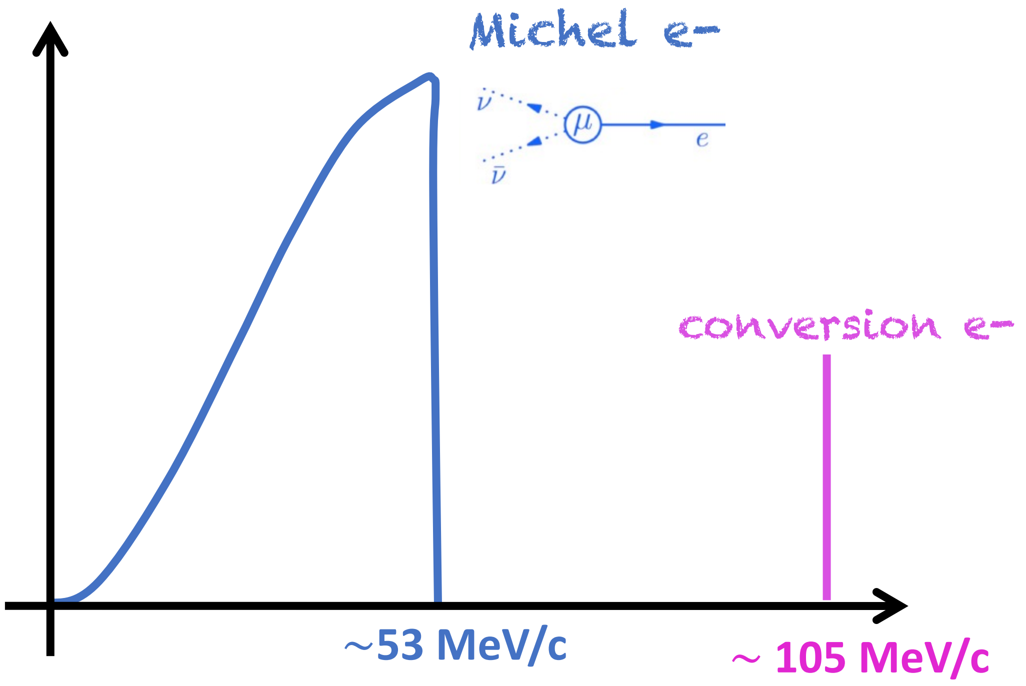
Decay in Orbit (DIO) Backgrounds

- Annular tracker: Removes most of DIO (all Michel peak electrons), analyze 10^5 instead of 10^{18} muons.

$$R = \frac{p_\perp}{qB} = 35cm$$

- Michel Electron (< 52MeV/c)
- Signal (105MeV/c)



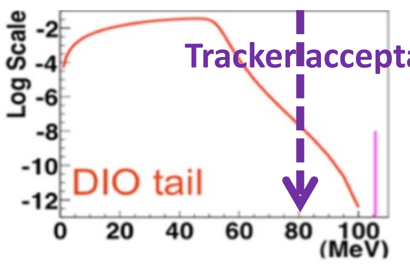


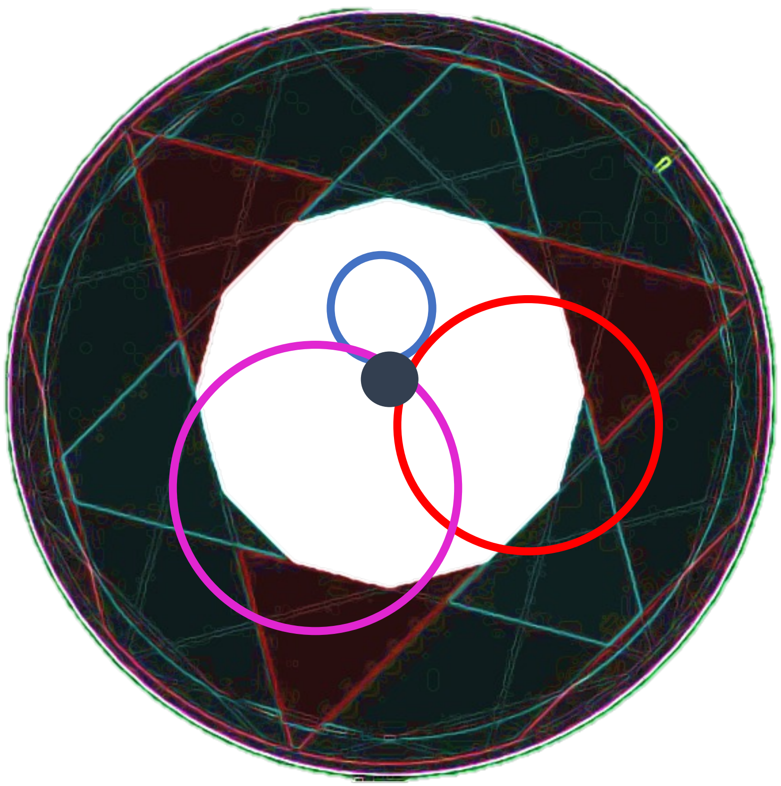
Decay in Orbit (DIO) Backgrounds

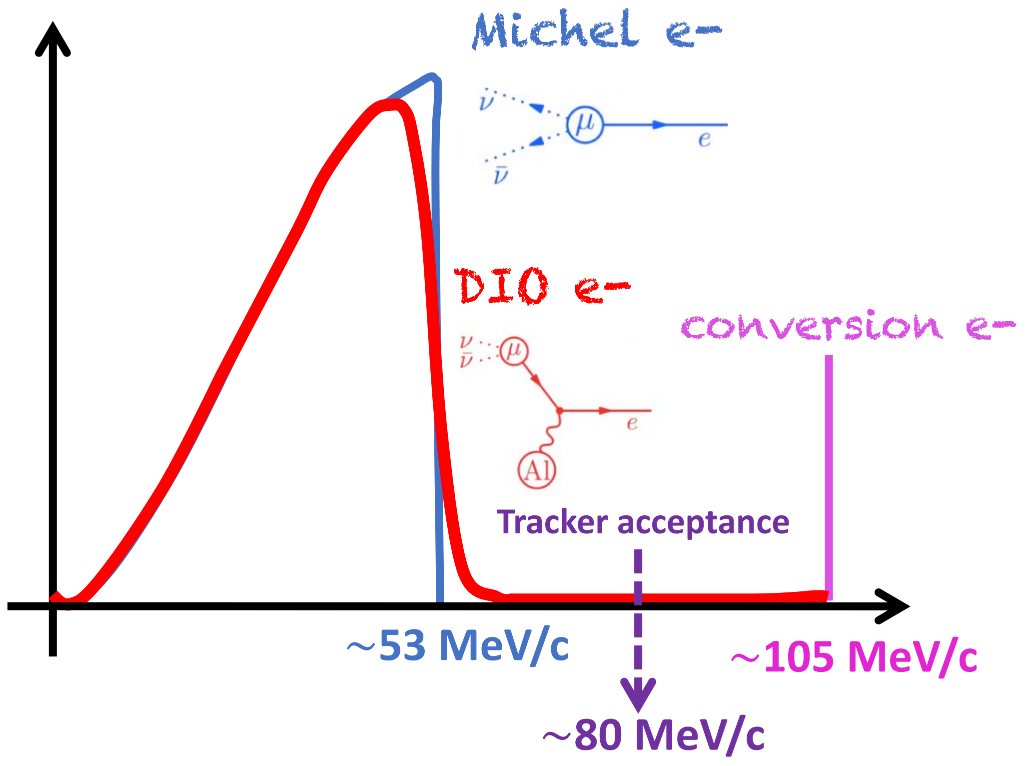
- Annular tracker: Removes most of DIO (all Michel peak electrons), analyze 10^5 instead of 10^{18} muons.
- However, when decay happens in orbit, exchange of momentum produces recoil tail close to signal region (105 MeV/c).
- To remove remaining backgrounds necessitates < 200 keV/c momentum resolution.

$$R = \frac{p_\perp}{qB} = 35cm$$

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

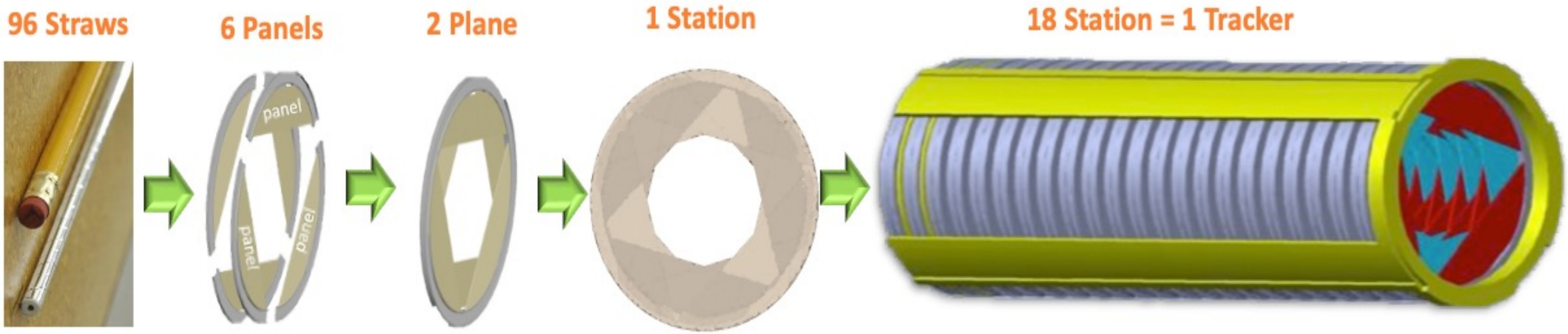






The Straw Tracker: achieving resolution

- Need a high-resolution (< 200 keV/c) momentum measurement to distinguish tail DIO from signal:
  - Minimize energy loss by operating in vacuum and using low mass straws of 15 μm thickness filled with 80:20 Ar:CO_2 ;
  - Include extra hit position information with high-angle stereo overlaps and readout on both ends of straw.



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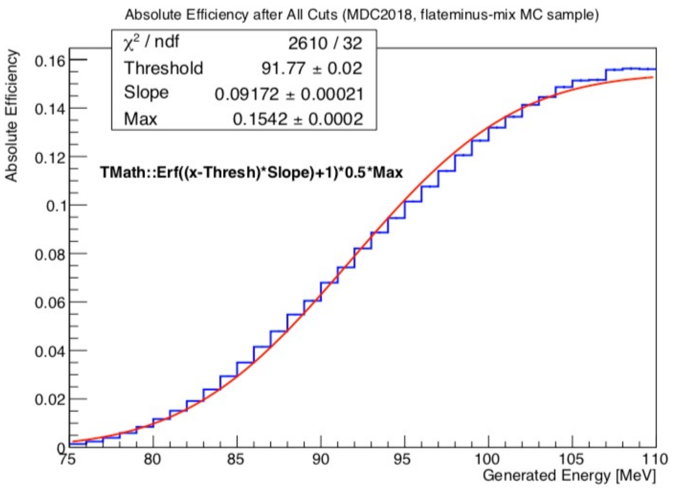
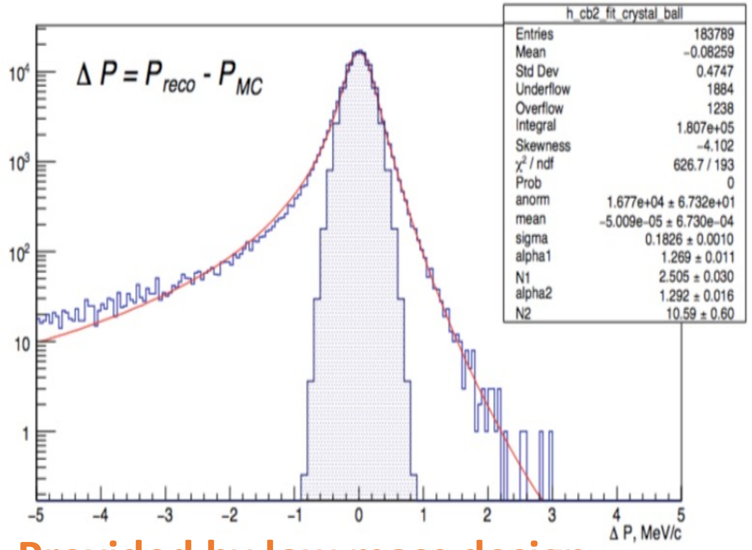
Absolute Efficiency
(as function of generated energy)



Provided by annular shape

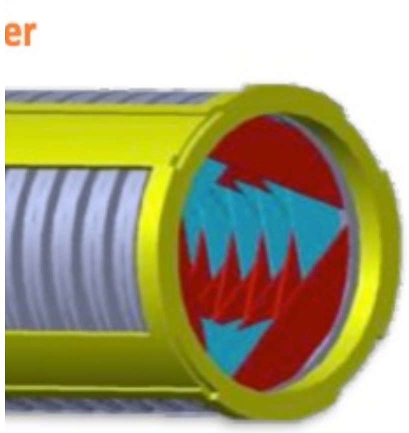
Response
(i.e. resolution and energy loss)



Provided by low mass design

Resolution (core) : 183 keV ie $\frac{\sigma(p)}{p} \sim 0.2\%$ at 100 MeV

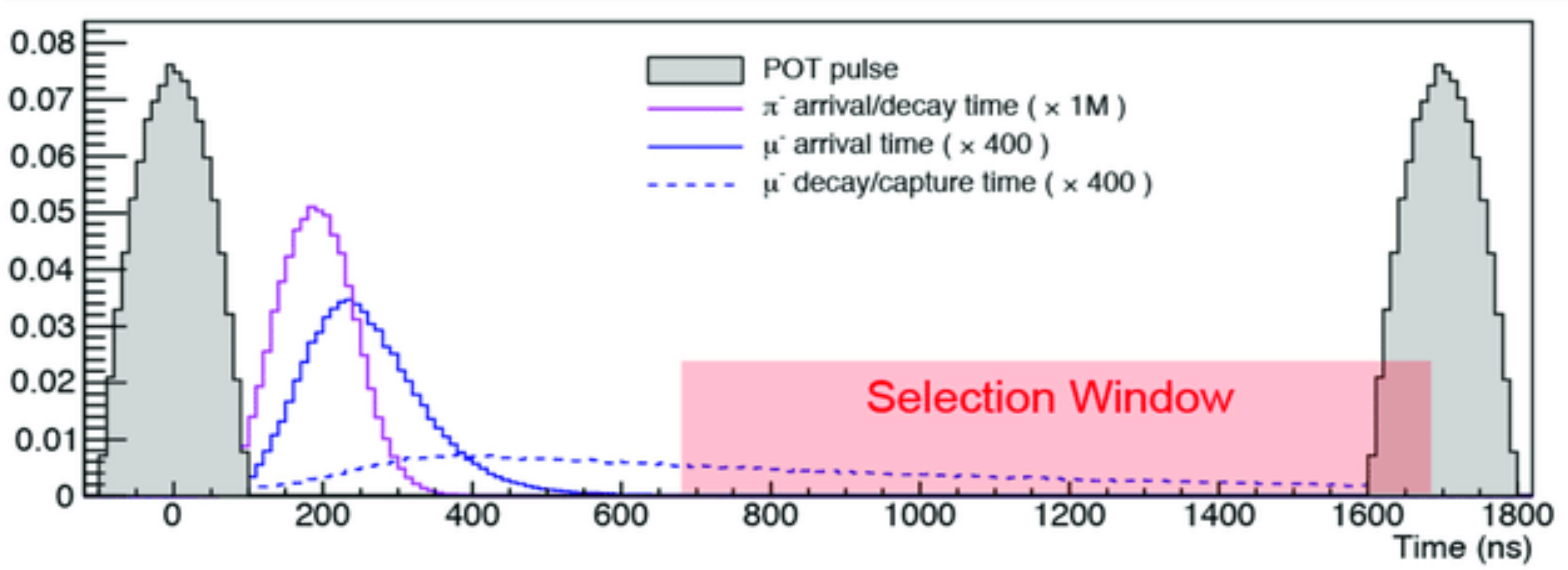
Non Gaussian tail ~ 4%



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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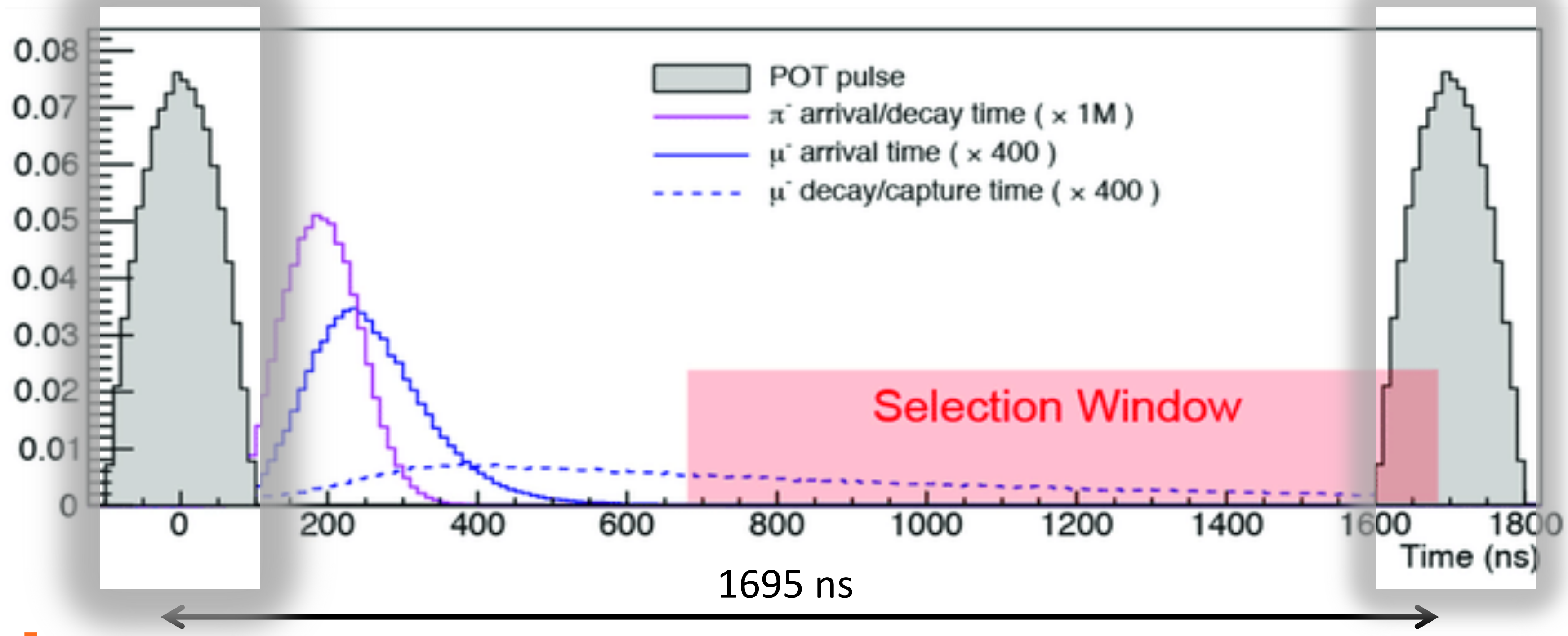

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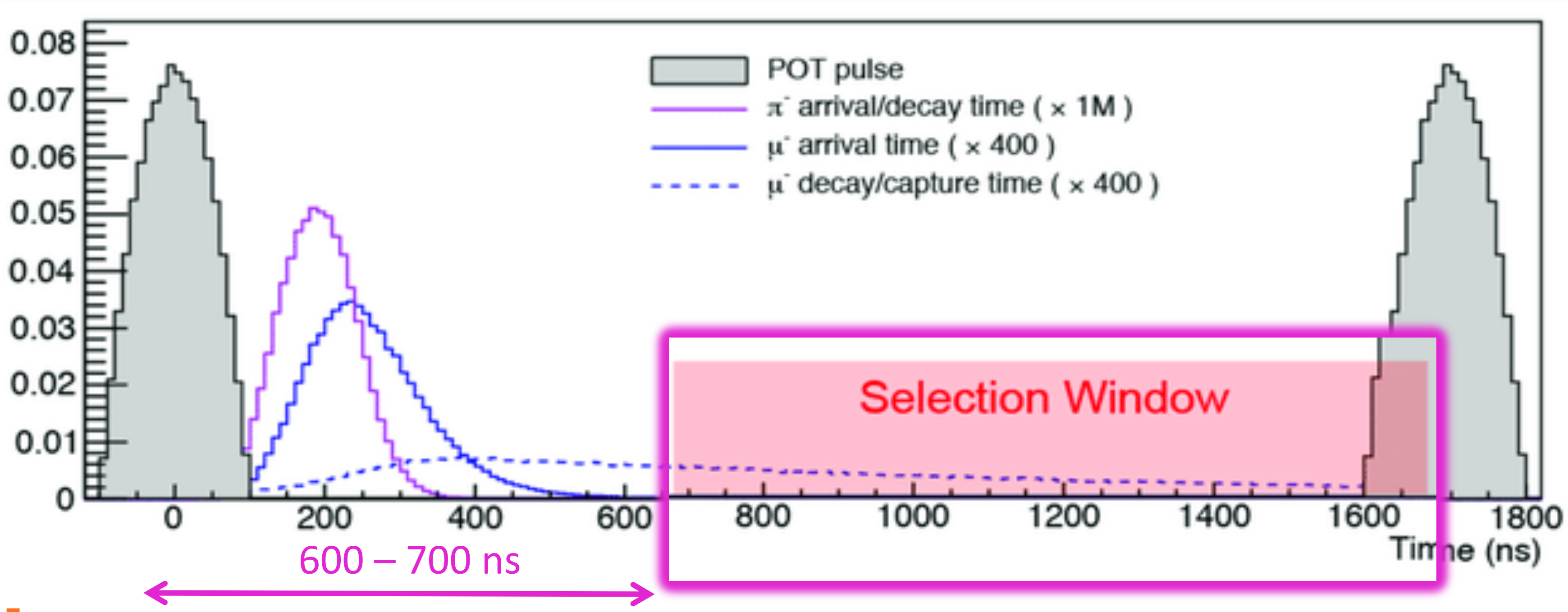
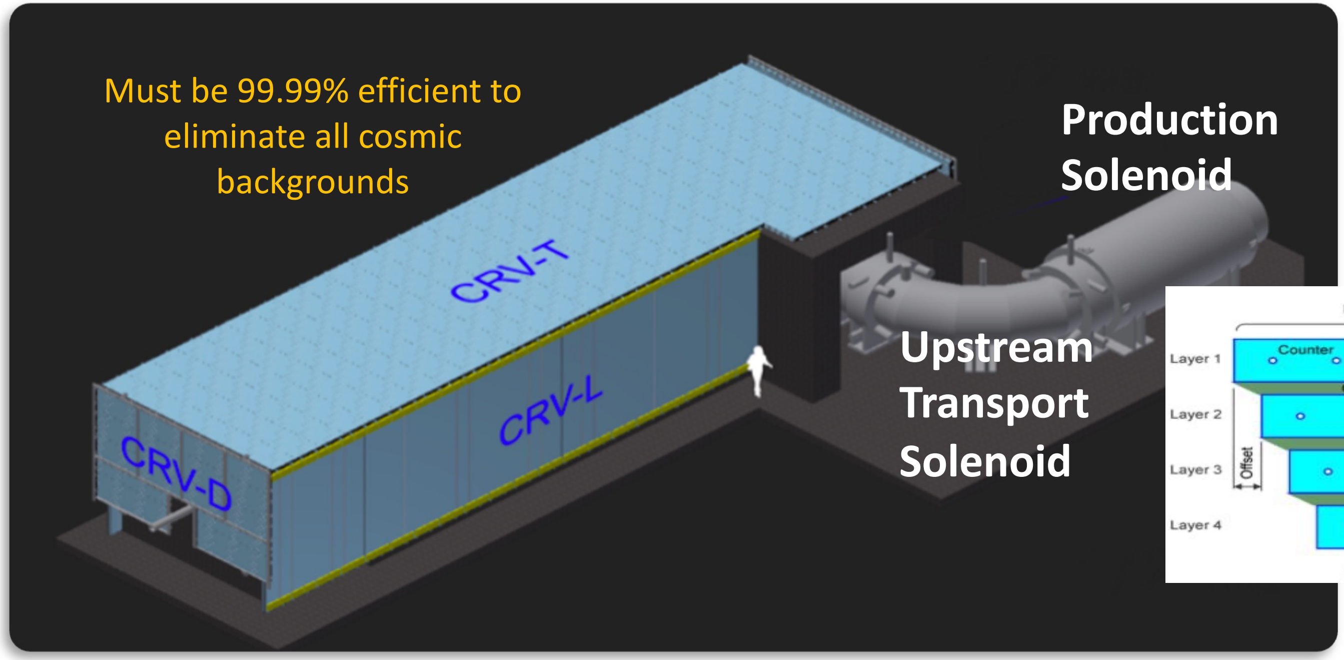
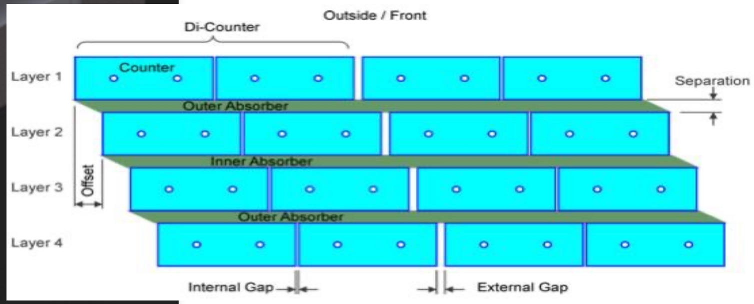


Cosmic Induced Backgrounds

- 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.

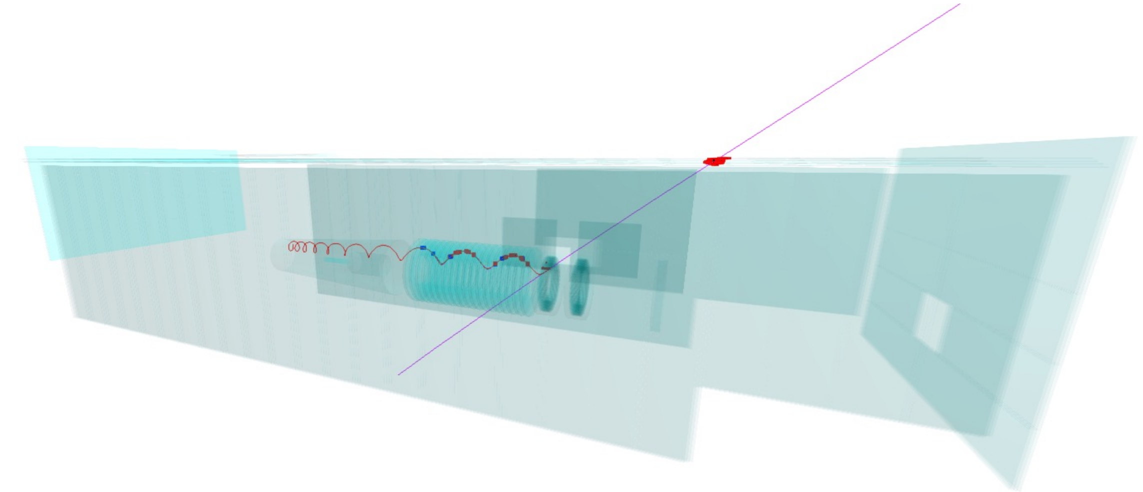
Active Cosmic Ray Veto system is key to eliminating cosmic induced backgrounds.



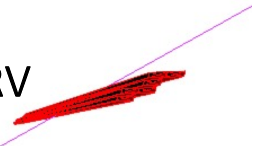


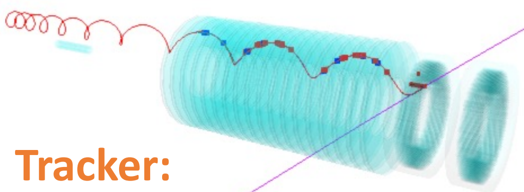
Cosmic Induced Background Examples

Example cosmic producing noise in calorimeter, the cosmic muon enters field, spirals and then produces backwards going track (potential background)

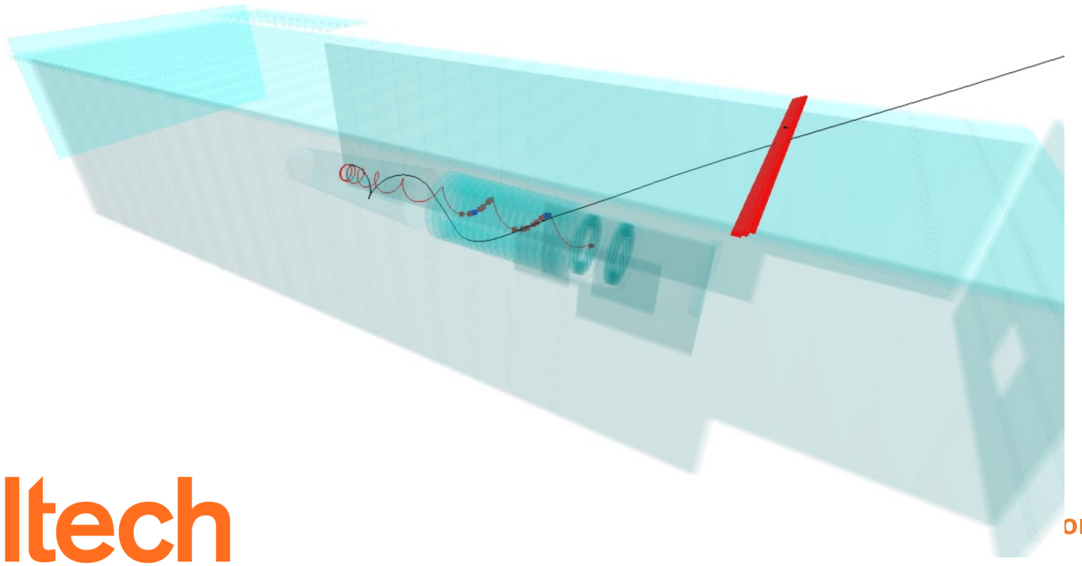


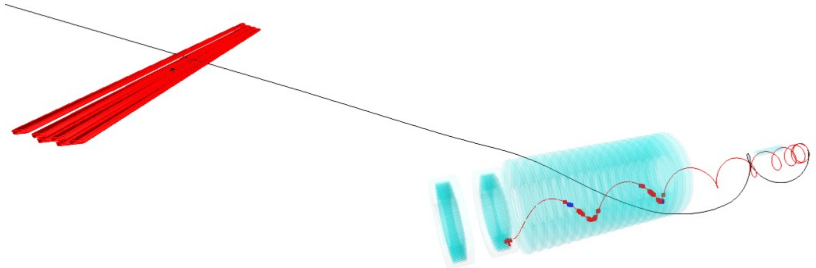
CRV Bars activated:
Straight cosmic muon seen coming into CRV





Tracker:
Cosmic particles enter tracker and secondary electrons spirals in field, going backwards toward target.





Status Update

Status: Solenoids

- **Production Solenoid:**
  - Undergoing final tests.
  - Delivery to Fermilab expected mid-2024.
- **Transport Solenoid:**
  - Installed in the Mu2e hall.
- **Detector Solenoid:**
  - Undergoing final tests.
  - Delivery to Fermilab expected mid/late-2024

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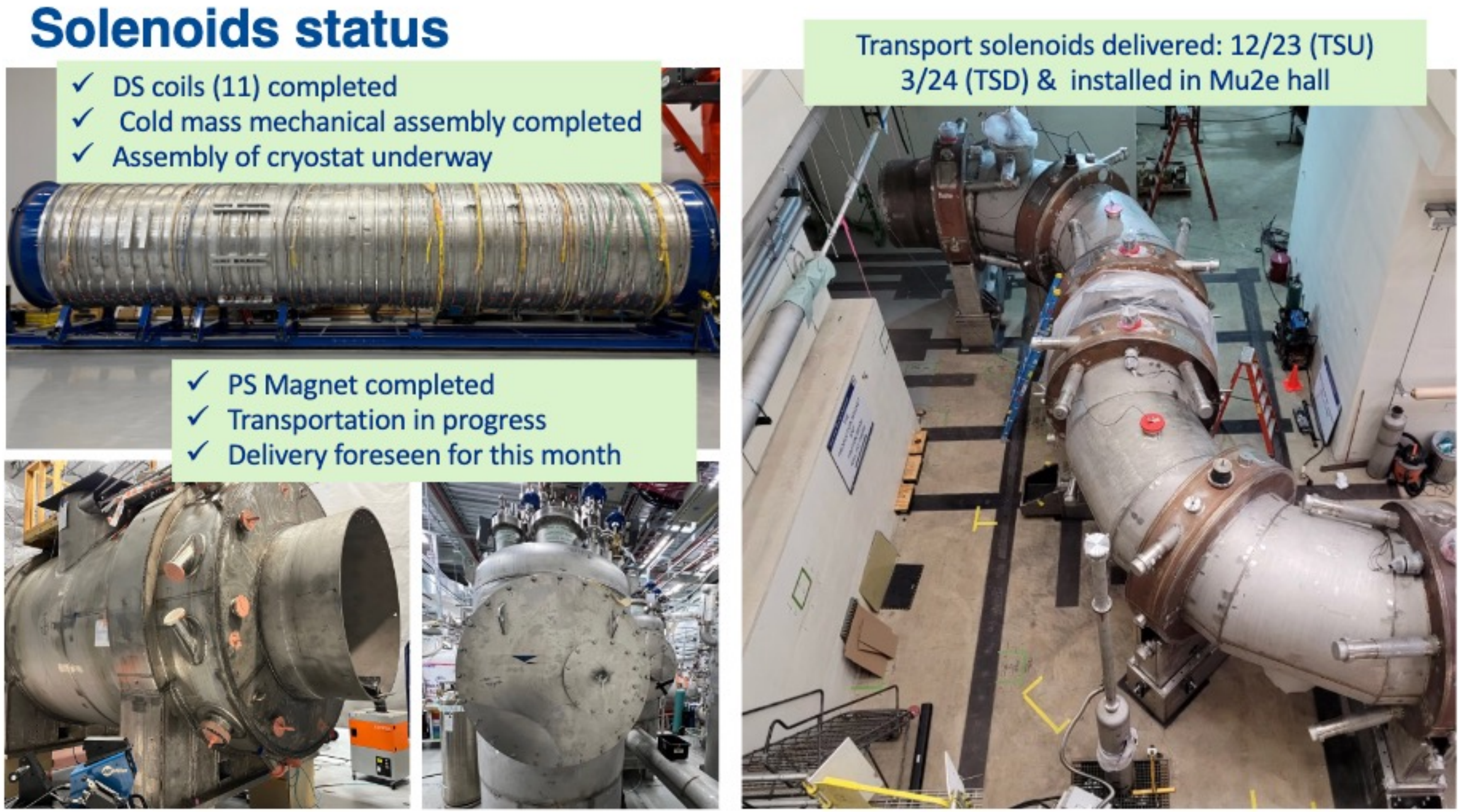
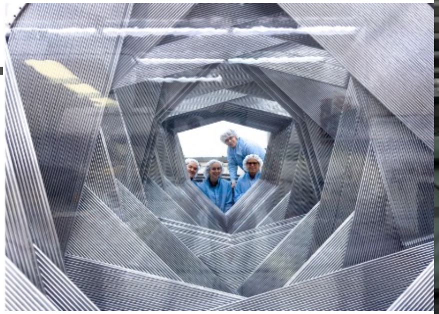
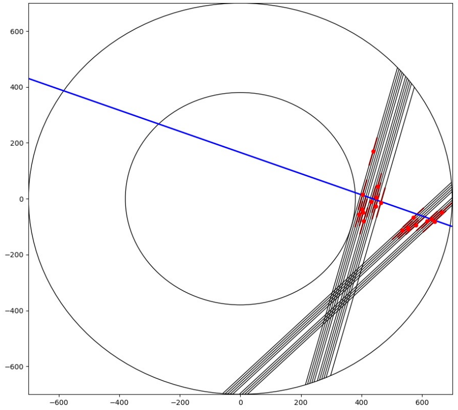
Status: Solenoids

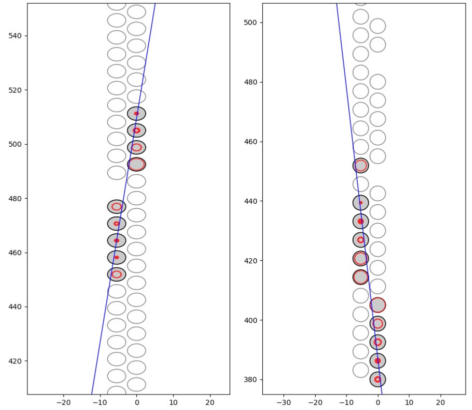


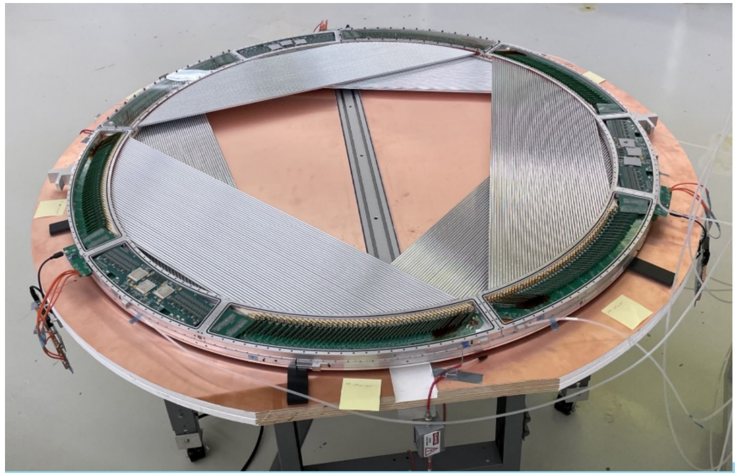
Tracker

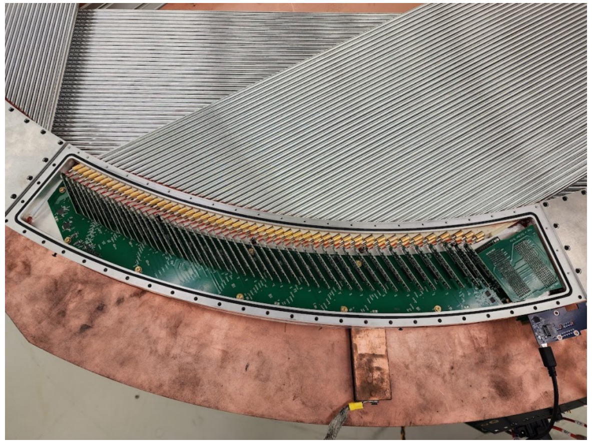


- All 20736 straws produced.
- All 216 panels produced. Now working through QC.
- 33/36 planes are built.
- Cosmic ray tests carried out with a single plane and full readout system for 3 years.









Calorimeter

Calorimeter is vital for providing:

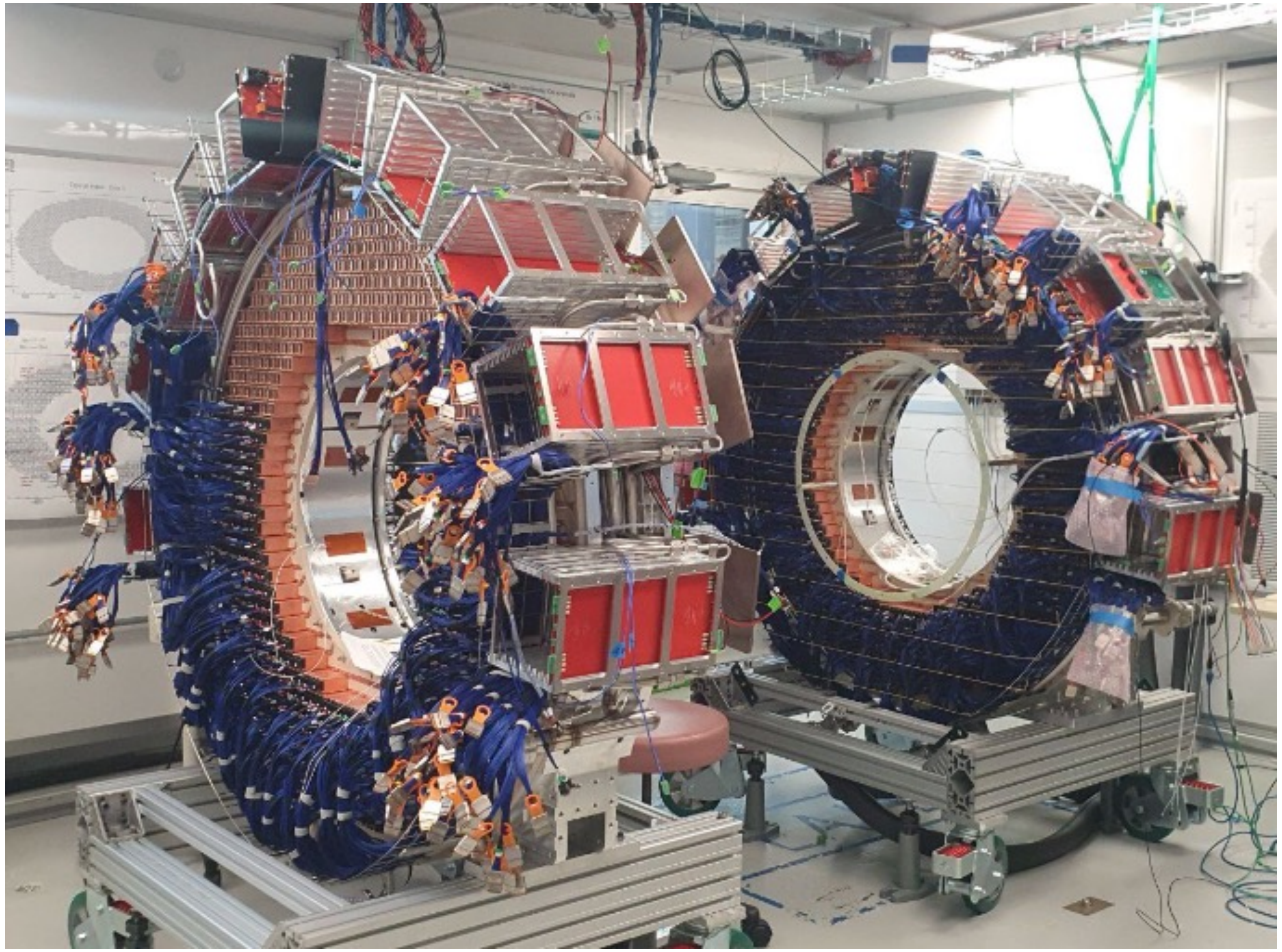
- **Particle identification,**
- **Fast online trigger filter,**
- **Seed for track reconstruction.**

Design:

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

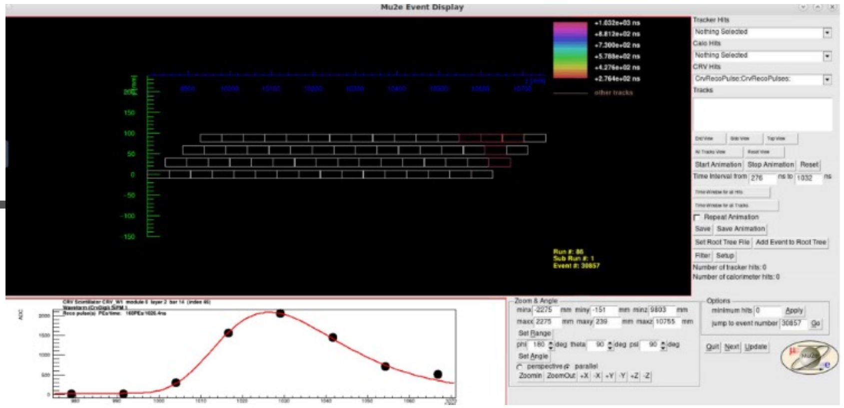
Both disks

- Have crystals and SiPMs installed.
- Final cabling underway.
- Installation in hall in Autumn 2024.

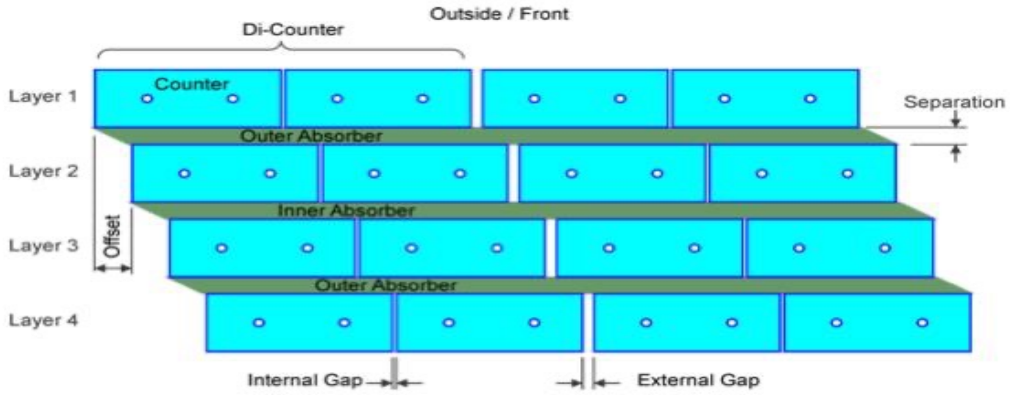


INFN TRIESTE
INFN PISA Istituto Nazionale di Fisica Nucleare Sezione di Pisa
INFN LNF Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
Caltech

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 2025, commissioning with beam in 2026 and physics data taking follows.**
- 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 new collaborators to commission a new experiment! https://mu2e.fnal.gov/

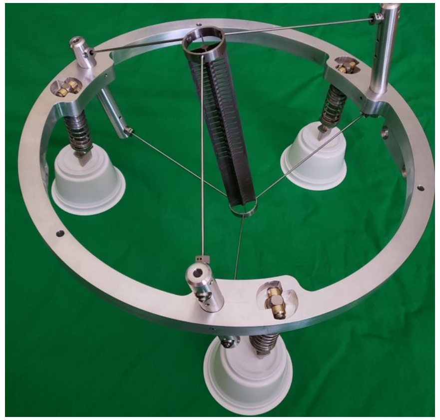
Thank you for listening!

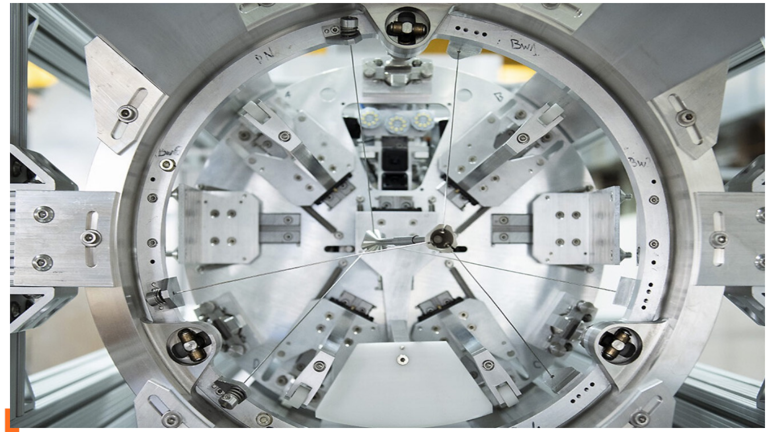
Any Questions?

Additional Material

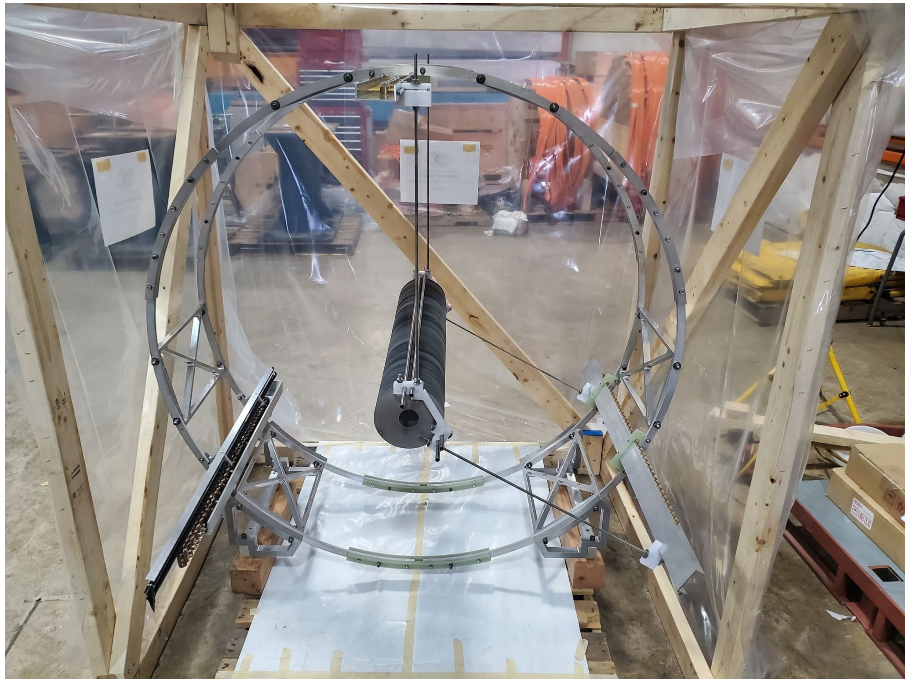
Targets

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



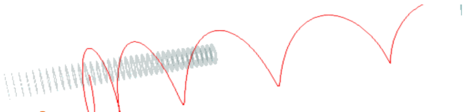


Muon Stopping target: resides in Detector Solenoid, stops muons, potentially produces signal conversion electrons.



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

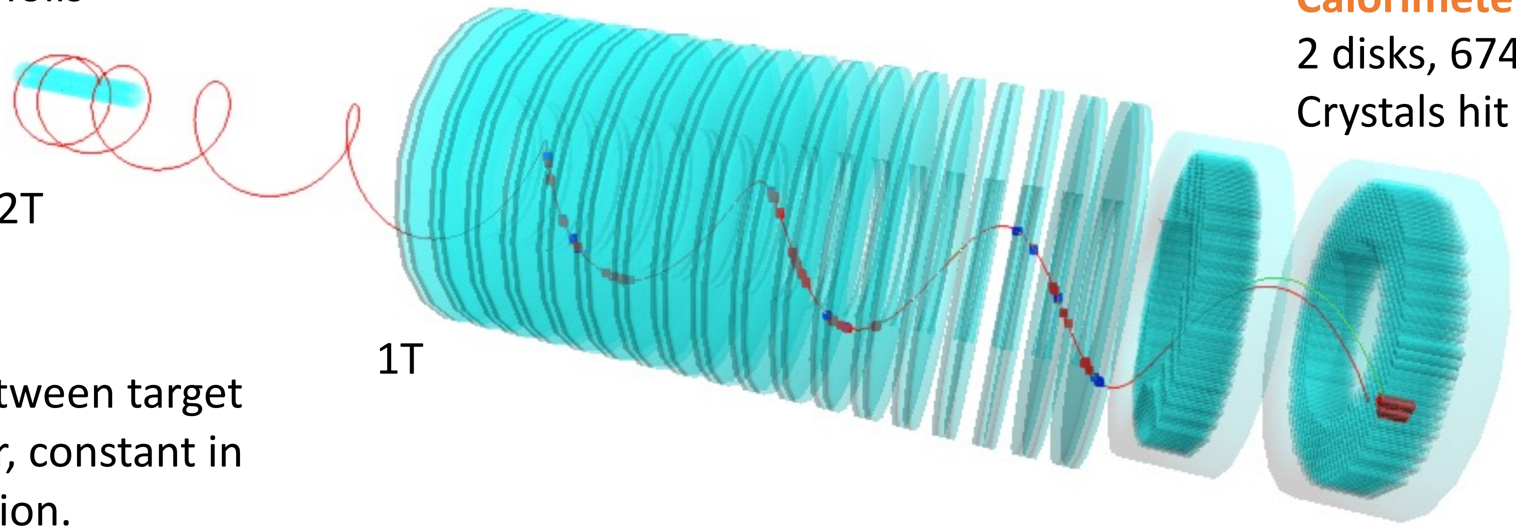
- Monoenergetic electron emanating from thin foil target with pile-up filtered out using existing Mu2e algorithms:



Stopping target:
37 Al thin (105μm) foils

Straw tracker:
18 stations, hollow center.

Calorimeter:
2 disks, 674 CsI crystals each.
Crystals hit are combined to clusters.

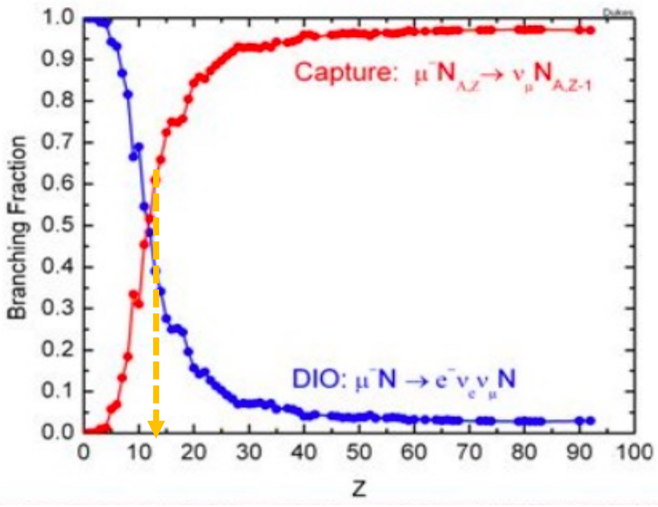


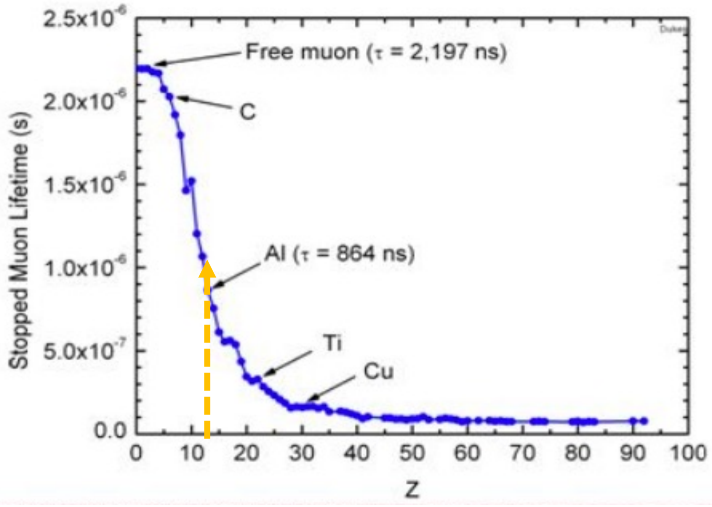
Field:
Graded between target and tracker, constant in tracker region.

Mu2e/REve display (MC true CE)

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

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

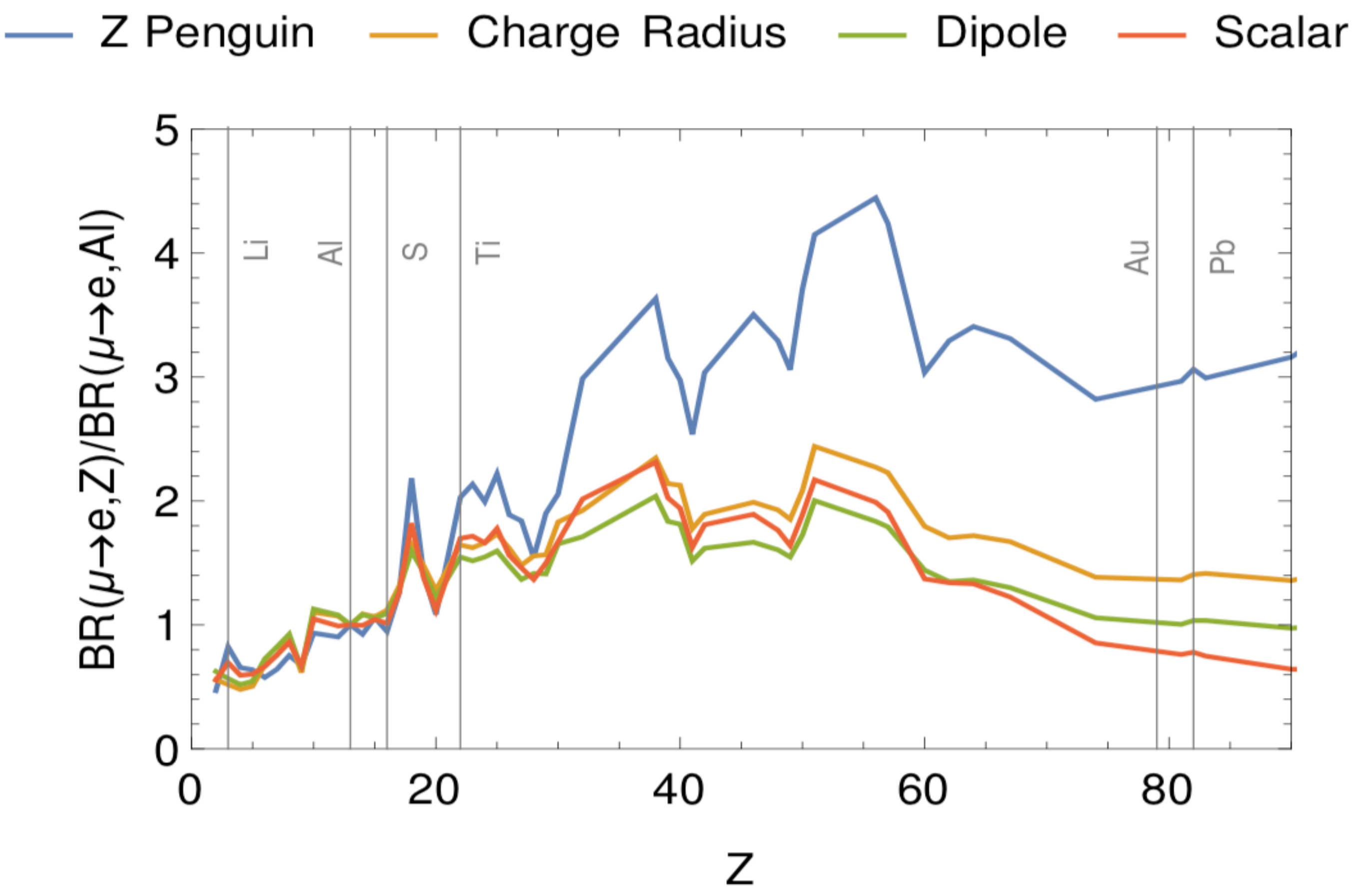
Overlap with nucleus probes form factors and reveals the nature of the interaction.

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

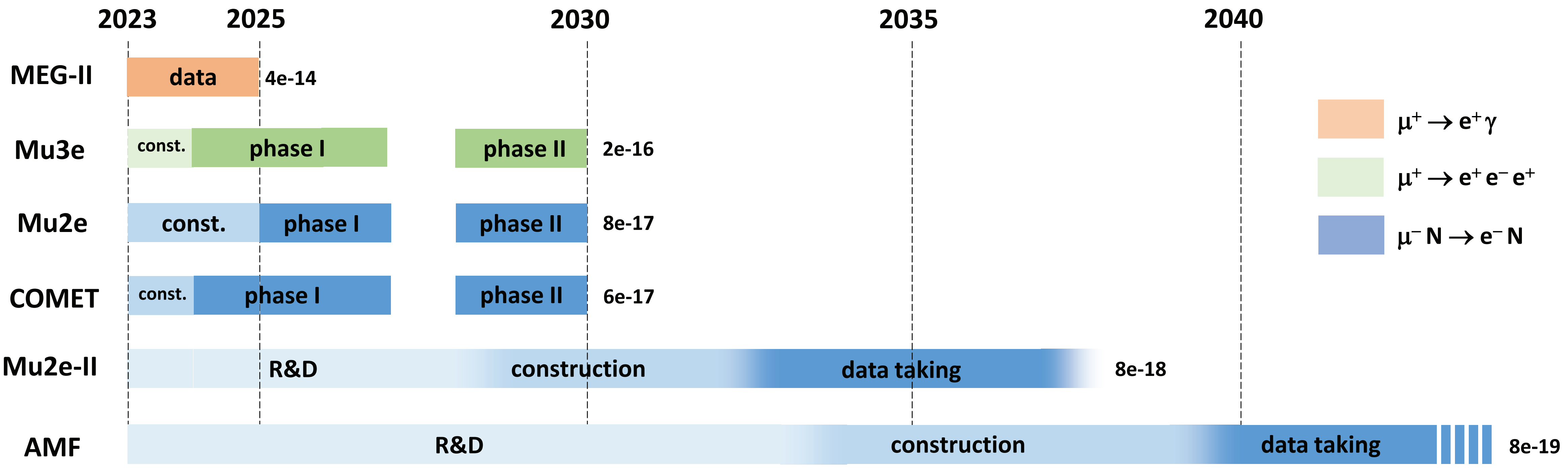
	S	D	V^1	V^2
$\frac{B(\mu\to e,Ti)}{B(\mu\to e,Al)}$	$1.70 \pm 0.005_y$	1.55	1.65	2.0
$\frac{B(\mu\to e,Pb)}{B(\mu\to e,Al)}$	$0.69 \pm 0.02_{\rho_n}$	1.04	1.41	$2.67 \pm 0.06_{\rho_n}$

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

Higher Z target provides most splitting!



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

Complementarity amongst channels

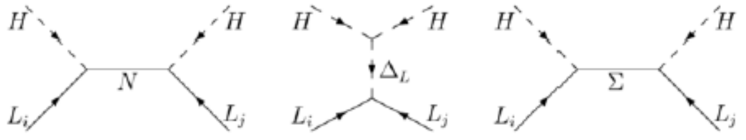
- All three channels are sensitive to many New Physics models.
- Relative Rates however will be model dependent and can be used to elucidate the underlying physics.

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}
Type III Seesaw	Tree	Tree	~10^{3}	10^{3}
LFV Higgs	Loop	Loop	10^{-2}	0.1
Composite Higgs	Loop	Loop	0.05-0.5	2-20

Nucl. Phy. B (Proc. Suppl.) 248–250 (2014) 13–19

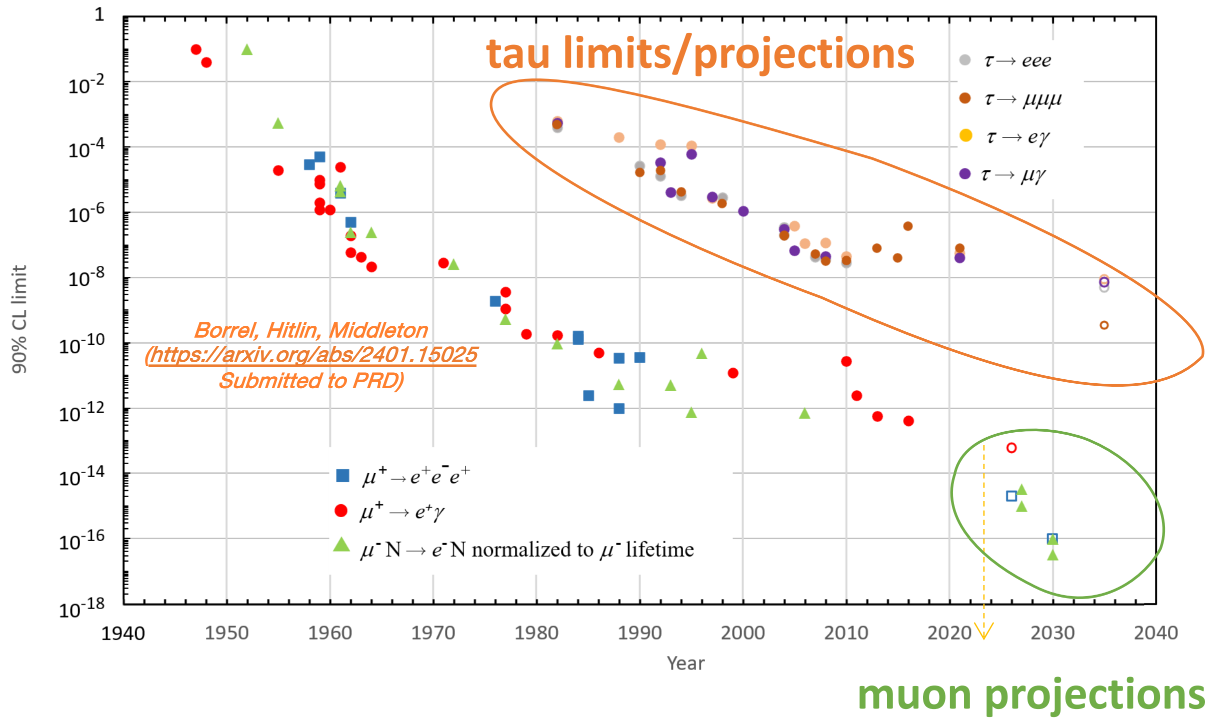
For example:

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



Complementarity with collider searches for CLFV

- 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 muon rates to tau rates.



How do we improve on SINDRUM-II?

- The SINDRUM−II results was limited by 2 main factors:
  1. Backgrounds from prompt pions,
  2. The muon stopping rate ($\sim 10^7 \mu/s$ −with a ~ 1 MW beam).
- Mu2e must address these issues to improve limit on $R_{\mu e}$.
- Following the proposal by **V. Lobashev & R. Djilkibaev (Sov. J. Nucl. Phys. 49(2), 384 (1989))** , Mu2e will:
  - Utilize a pulsed proton beam & delayed "gate window" → **Eliminates pion induced backgrounds.**
  - Use intense muon source → **10^{10} muons/s.**
  - Use superconducting solenoids → **For efficient muon collection and transport to stopping target.**

Mu2e aims to achieve 3 x 1020 POT over entire run period

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.