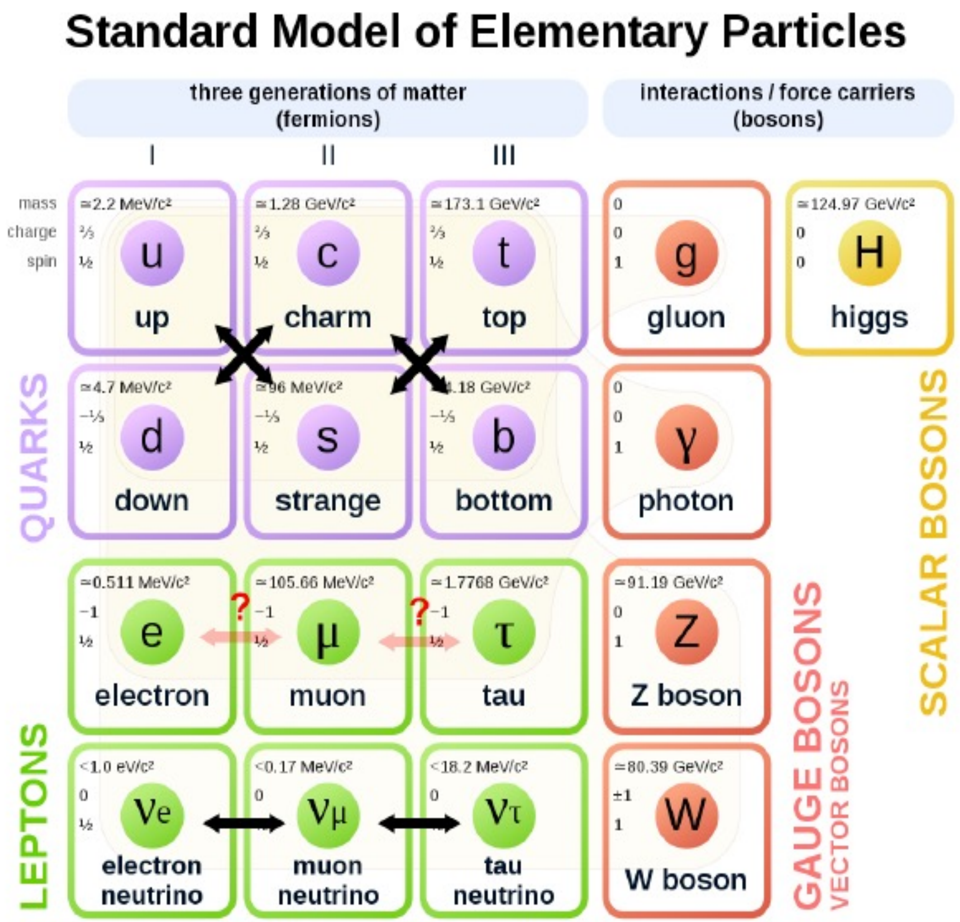
The Mu2e Experiment

Motivations, Design and Current Status

Sophie Charlotte Middleton

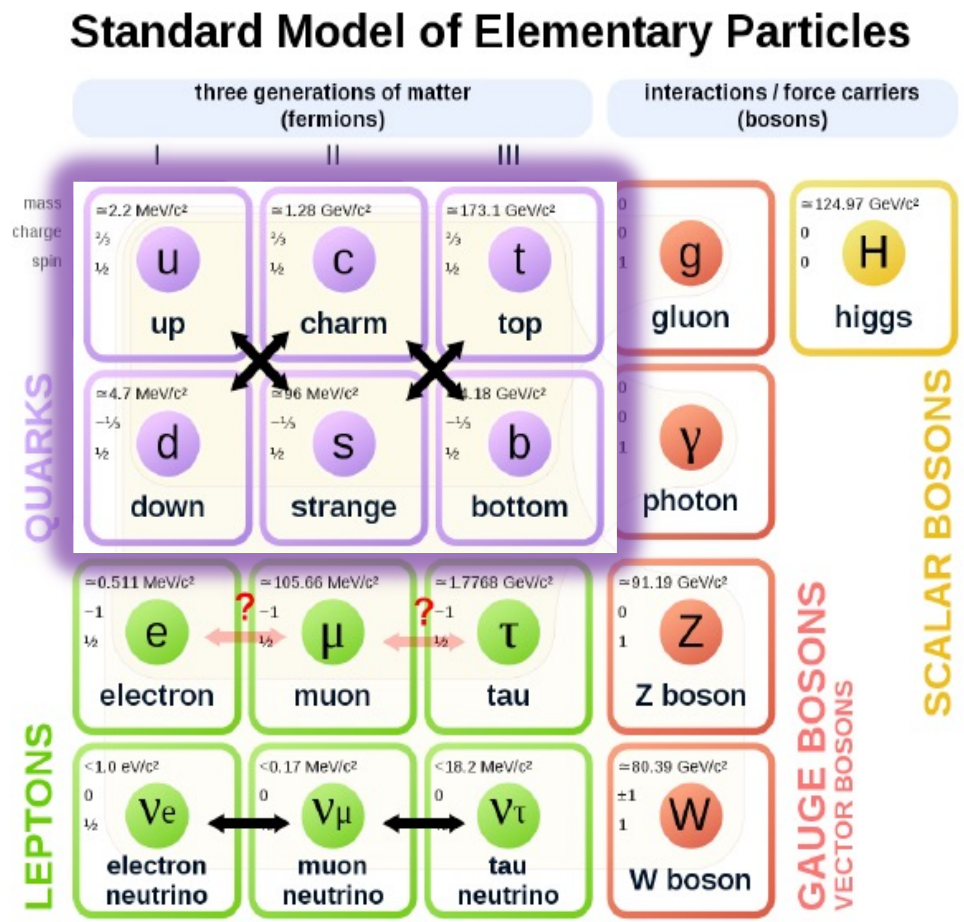
Caltech

Flavor Physics



- Flavor is not conserved

Flavor Physics: Quarks



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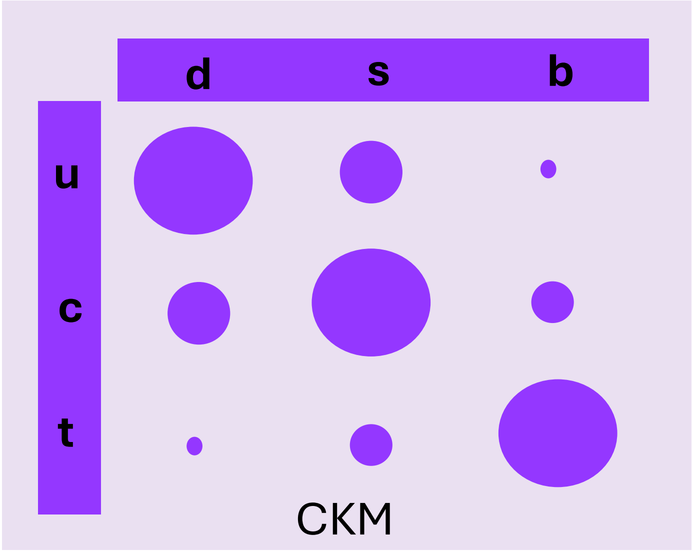
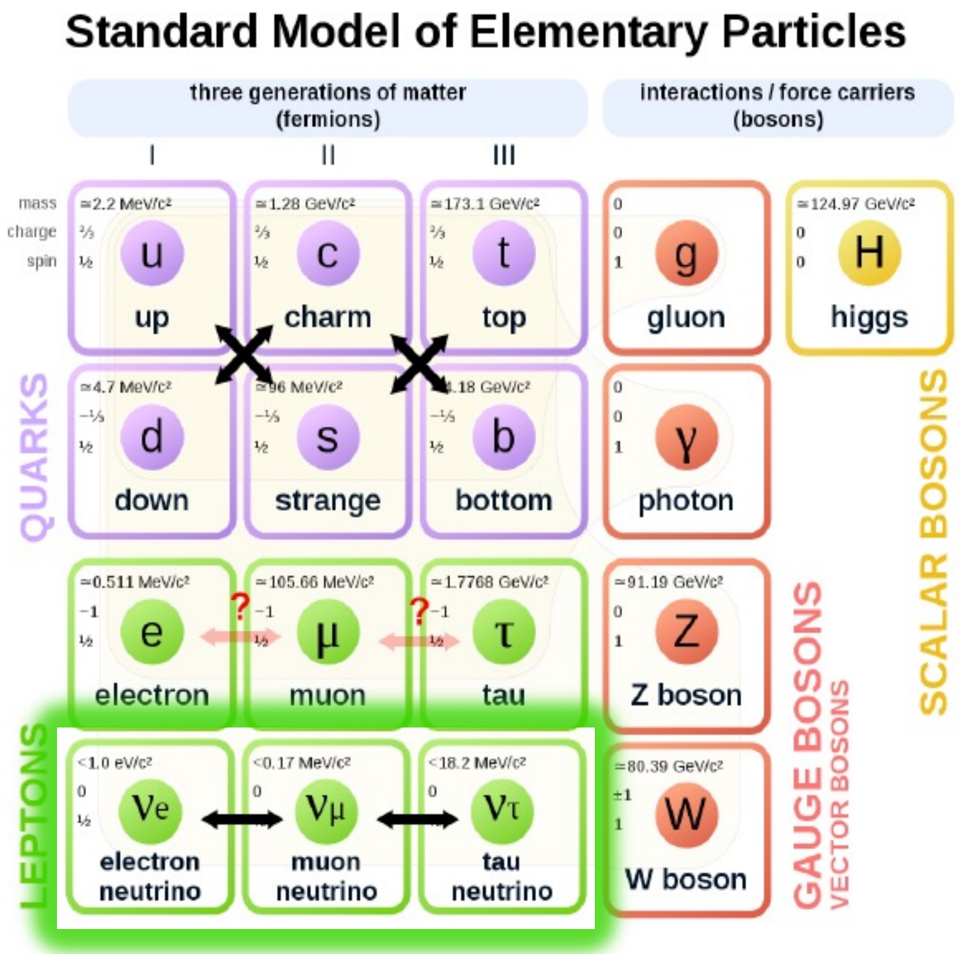
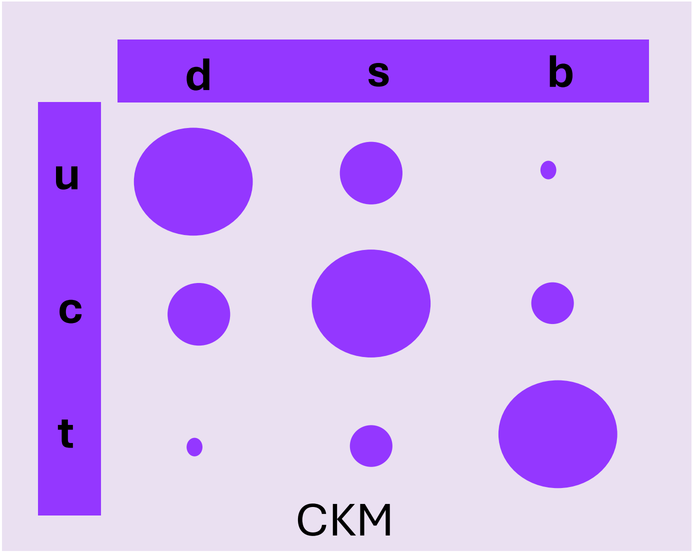


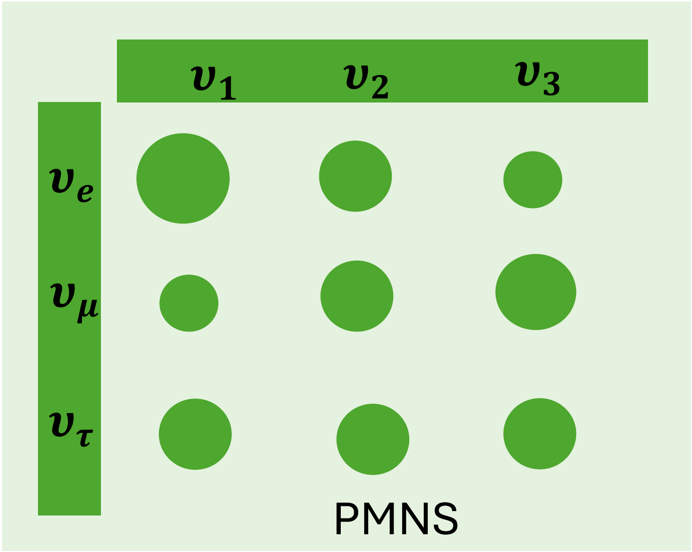
*size of circle proportional to size of term

Flavor Physics: Neutrinos



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





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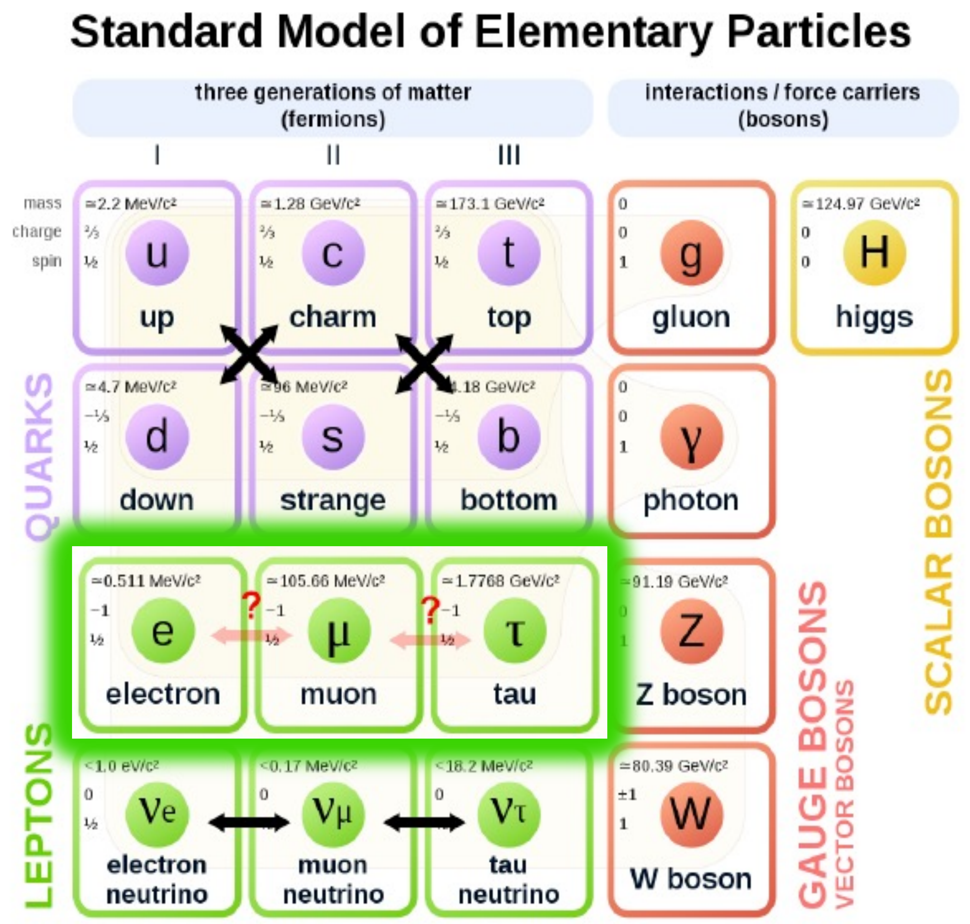
Flavor Physics: Charged Leptons?

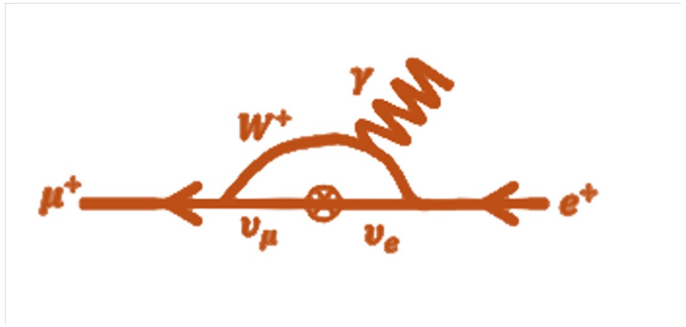


- Do charged leptons exhibit flavor violation?
  - If so, at what rate?
  - What would that imply about New Physics?
- **These are the fundamental questions Mu2e is aiming to answer!**
  - Mu2e, based at Fermilab, is searching for muon to electron conversion within a nuclear (aluminum) field
  - Mu2e is part of global program searching for charged lepton flavor violations in both muon and tau channel.

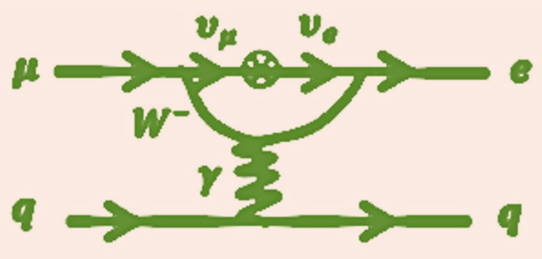
Charged Lepton Flavor Violation (CLFV)

- 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:

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54},$$

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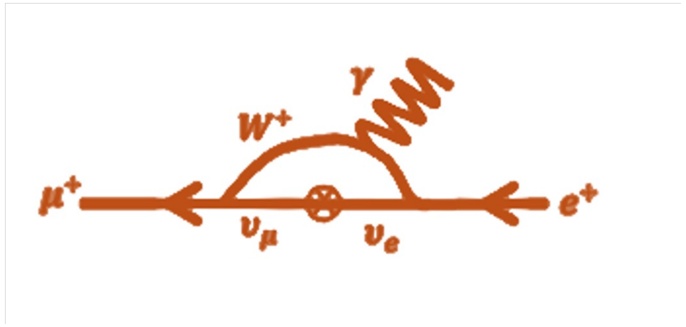

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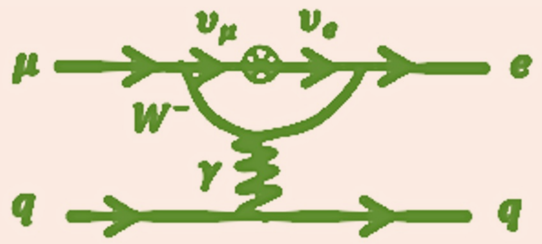

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- ...but many Beyond Standard Model (BSM) theories (e.g. SO(10) SUSY, scalar leptoquarks, seesaw models) predict enhanced rates of CLFV just below current limits $O(10^{-13})$.

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

Current Experimental Searches for CLFV

- There is a global program of experiments currently coming online and which seek to observe 3 types of muon CLFV:

Mode	Current Upper Limit (at 90% CL)	Projected Limit (at 90% CL)	Upcoming Experiment/s
$\mu^+ \to e^+\gamma$	1.5×10^{-13}	4×10^{-14}	MEG II
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	5×10^{-15} 10^{-16}	Mu3e Phase-I Mu3e Phase-II
$\mu^- N \to e^- N$	7×10^{-13} (SINDRUM-II, 2006)	8×10^{-15} 8×10^{-17}	COMET (phase-I) Mu2e

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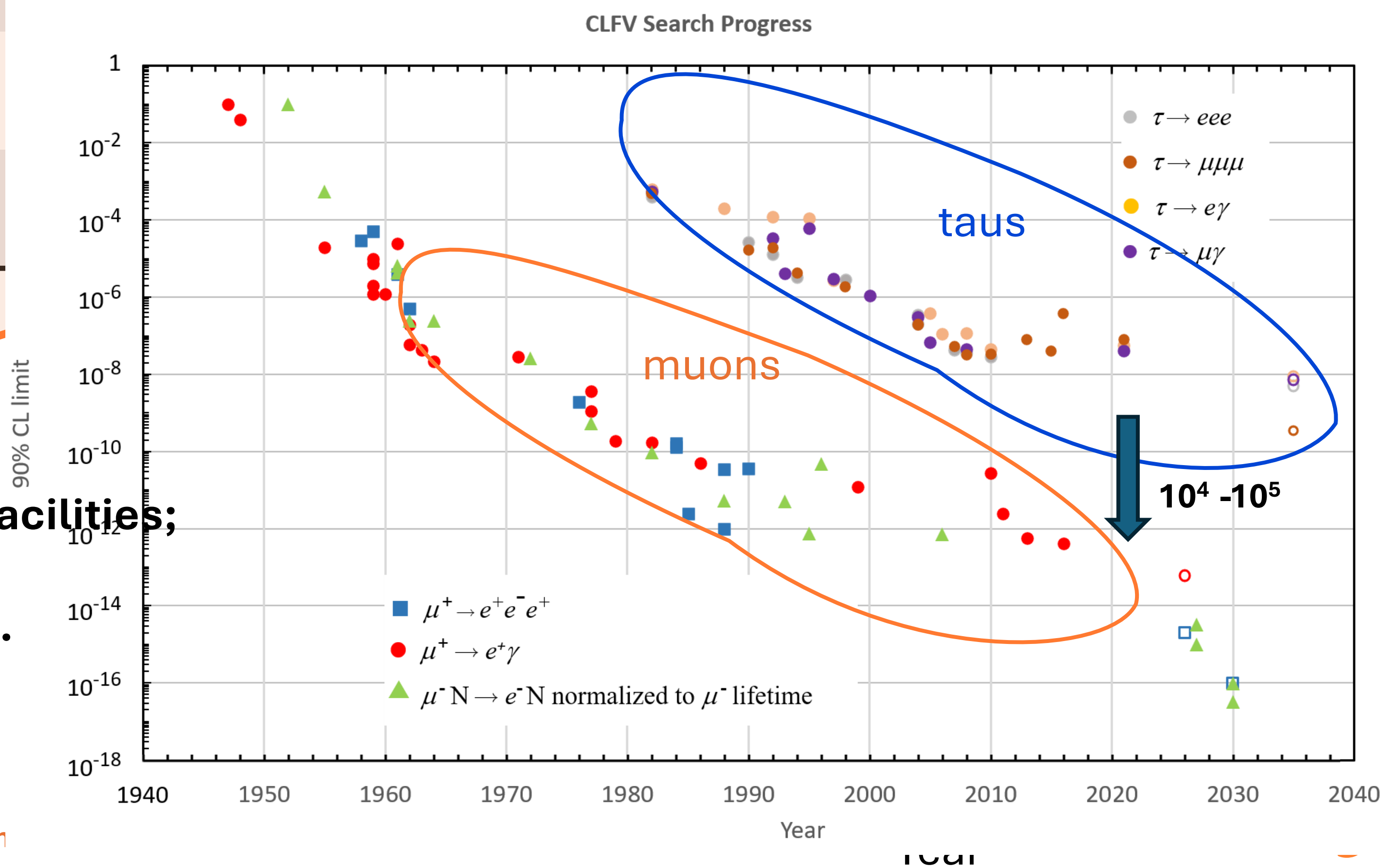
Muon has experimental advantages:

- can create intense muon beams in existing facilities;
- long (microsecond) lifetime;
- reducible, well understood SM backgrounds.



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

Need to stop $O(10^{18})$ and have << 1 background event to achieve this ambitious goal.

Effective Physics Reach

- Can think of physics possibilities in terms of Effective Field Theories;
- 90+ operators describe these processes;
- *Eur.Phys.J.C* 82 (2022) 9, 836 reduced to 6 terms for $\mu \rightarrow e\gamma, \mu \rightarrow eee$, and spin-independent $\mu N \rightarrow eN$;
- Effective lagrangian shows the complementarity between these three channels:

$$\delta\mathcal{L} = \frac{1}{\Lambda^2_{LFV}}\Big[C_D(m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re) + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Re) + C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big] \quad (2.1)$$

Λ = Effective Mass Reach, **D** = dipole, **V** = vector, **S** = scalar

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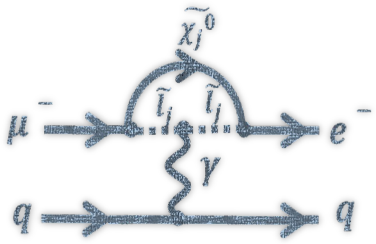
Effective Physics Reach

Photonic Term:
Mediating $\mu \to e\gamma$
Contributing to $\mu \to eee$ and $\mu N \to eN$
at loop level



SO(10) SUSY

Rate ~ 10^{-15}

$$\delta\mathcal{L} = \frac{1}{\Lambda^2_{LFV}}\Big[C_D(m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re)$$
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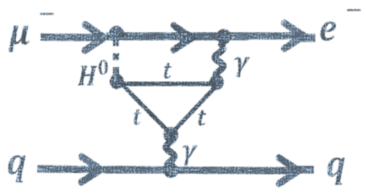
2 Higgs Doublets



$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$

Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8 \times 10^{-13}$

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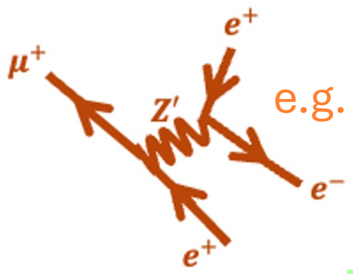
Effective Physics Reach



e.g. New boson

“Contact” Scalar
$\mu \to eee$

Leptonic “Contact” term
i.e. 4 Fermion Term
$\mu \to eee$ at leading order.
Heavily suppressed in $\mu \to e\gamma$

$$\delta\mathcal{L} = \frac{1}{\Lambda^2_{LFV}}\Big[C_D(m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re)$$
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“Contact” Vector
$\mu \to eee$

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Effective Physics Reach

quark "Contact" term

i.e. 4 Fermion Term

$\mu N \rightarrow eN$ at leading order.

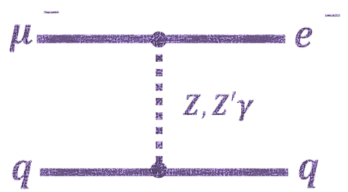
Heavily suppressed in $\mu \rightarrow e\gamma$

$$\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2}\Big[C_D(m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re) + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Re) + C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big] \quad (2.1)$$

Au and Al are prototypical "heavy" and "light" targets

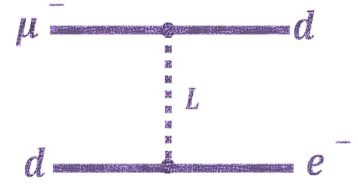
New Bosons

$M_{Z'} = 3000\ TeV/c^2$



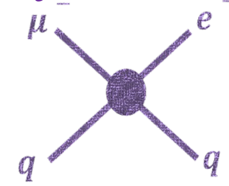
Leptoquarks

$M_{LQ} = 3000(\lambda_{\mu d}\lambda_{ed})^{\frac{1}{2}}\ TeV/c^2$



Compositeness

$\Lambda_c \sim 3000\ TeV$



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

Mu2e is sensitive to effective masses up to 10,000 TeV!!!

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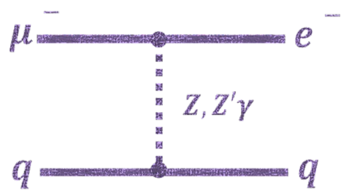

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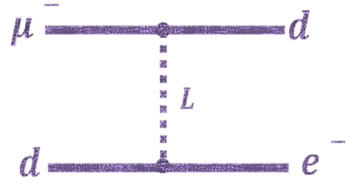

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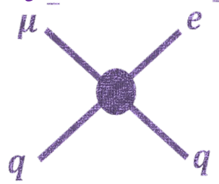

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Design

How can we improve on SINDRUM-II?

- Mu2e addresses issues of SINDRUM-II by following the proposal: Sov. J. Nucl. Phys. 49(2), 384.

Current limit = 7 x 10^{-13} @ 90% C.L
(SINDRUM-II, 2006)

SINDRUM-II limited by:

- Prompt pion backgrounds;
- Muon stopping rate (10^7 muons/s).

Mu2e:

- Eliminate pion induced backgrounds:
  - **pulsed proton beam & delayed "gate window"**
- Intense muon beam produced from protons on target. Collected and transported using three superconducting solenoids
  - **10^{10} muons/s.**

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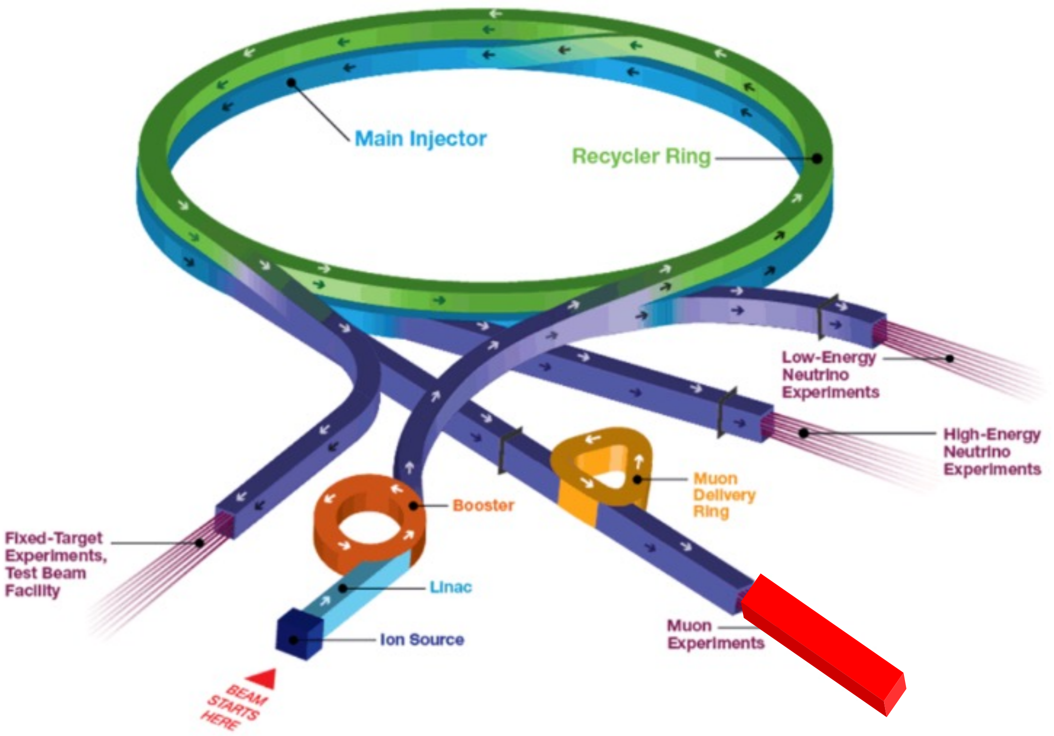
Beamline: Proton Beam

1. 400 MeV protons from the LINAC are injected into the **Booster Ring** where they are accelerated to 8 GeV and grouped into batches.
2. Each 67 ms, a booster batch is sent to the **Recycler Ring** and re-bunched into four bunches of 1e12 protons each
   - Eight 67ms buckets for Mu2e (only 2 filled), 12 for other experiments
3. Eight Mu2e bunches are sent to **Delivery Ring** from which they are resonantly extracted each 1.695 μs to create the proton pulses directed to **Mu2e beam line** (4e7 protons/pulse)



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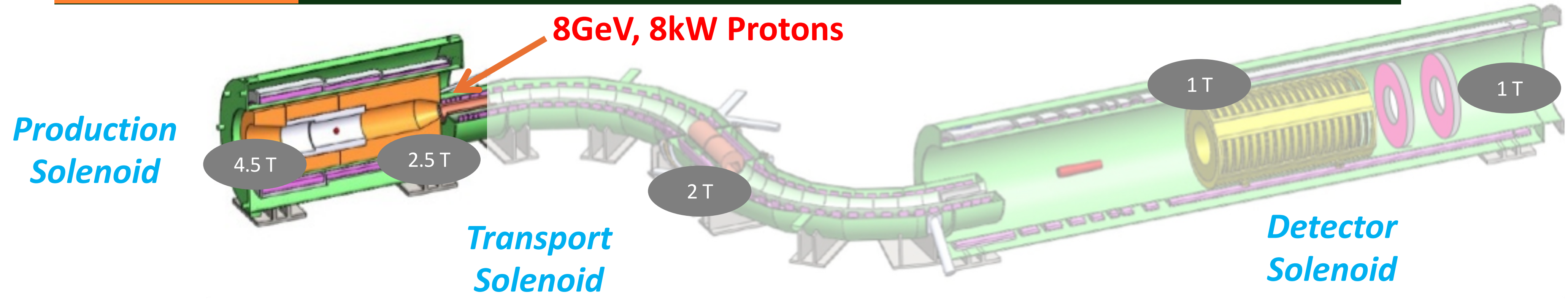
$N\mu^- \rightarrow Ne^-$: The Mu2e Experiment



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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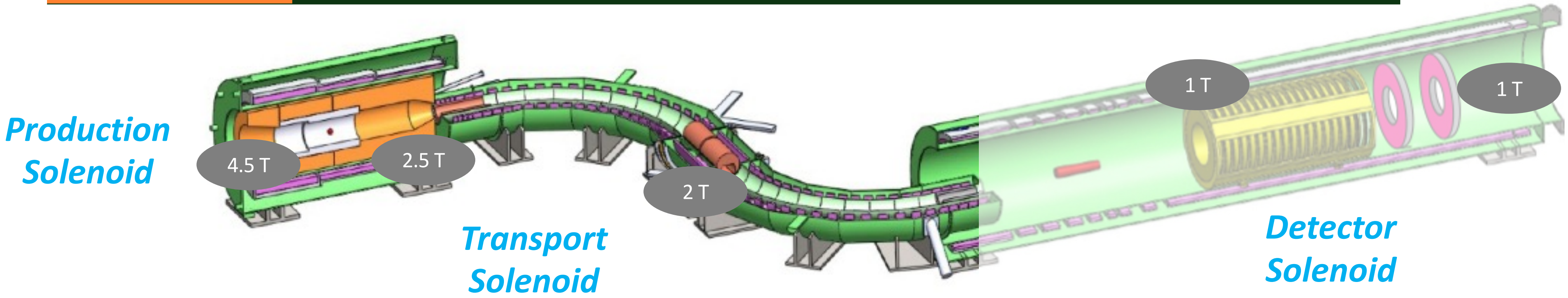

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Transport Solenoid:
- "S" shape removes line of sight backgrounds.
- Collimators select low momentum, negative muons.

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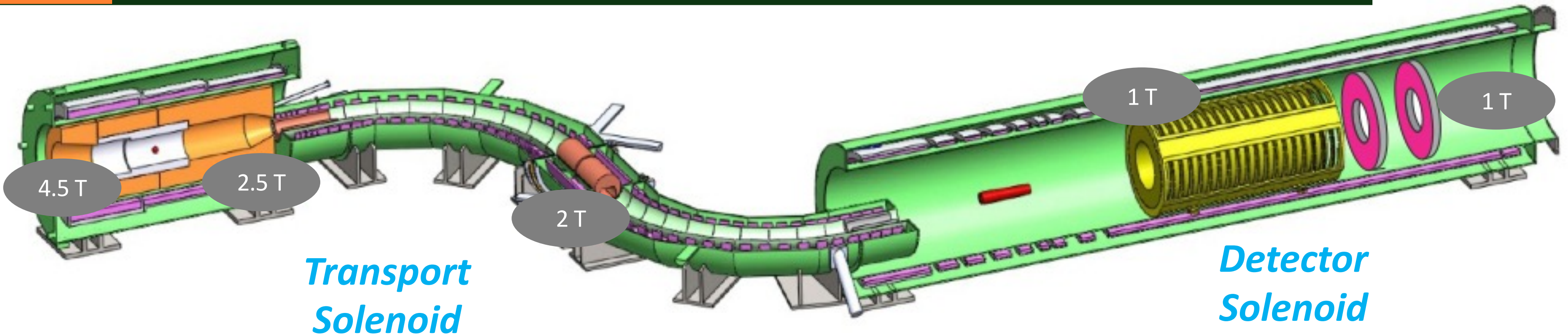

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Detector Solenoid:
- Thin aluminum foil target captures the muons.
- Possible signal electrons are detected by a tracker and a calorimeter.
- Cosmic ray veto covers the whole detector solenoid and half the transport solenoid.

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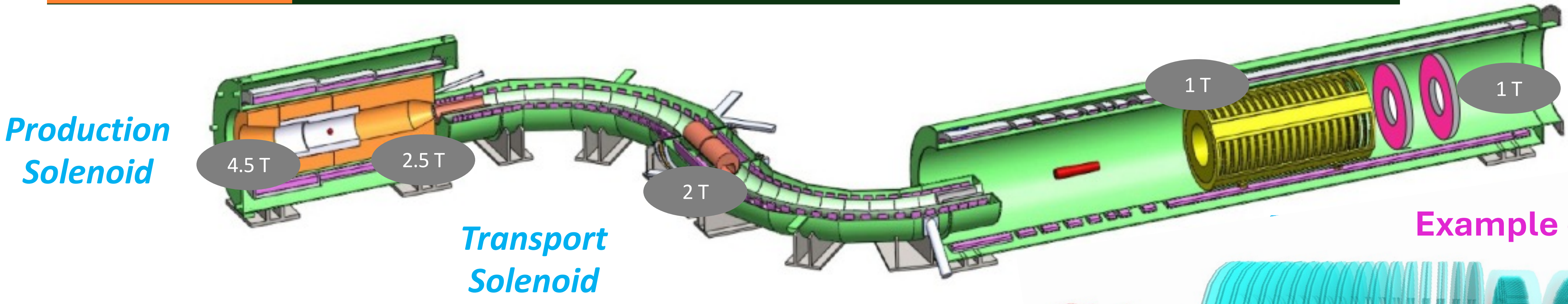
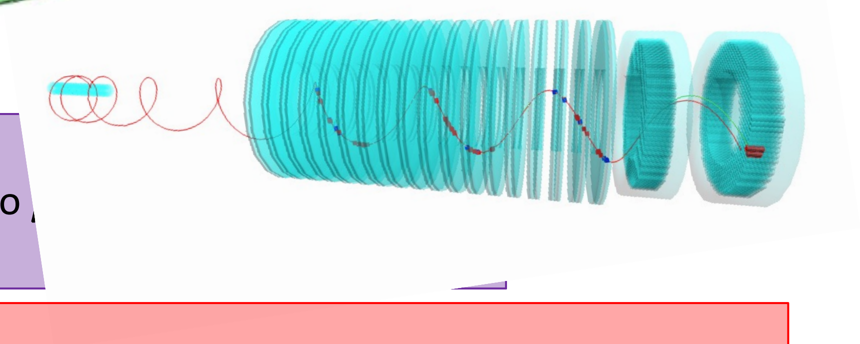


Example conversion signal



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

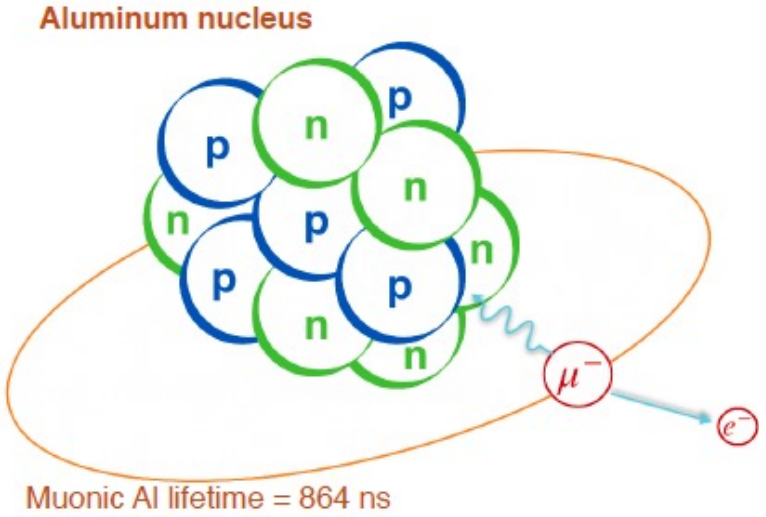
- There are 2 (maybe 3) things that can happen when the muon enters the atomic orbit of aluminum
  1. ***39 % - Decay :*** $\mu + N \rightarrow e + \bar{\upsilon}_e + \upsilon_\mu$ ***(SM, Background)***
  2. ***61 % - Capture :*** $\mu + N \rightarrow \upsilon_\mu + N'$ ***(SM, Normalization)***
     - The $\mu \rightarrow e$ conversion rate is measured as a ratio to the muon capture rate on the same nucleus:

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

  3. ***< 7 x 10^{-13} - Conversion :*** $\mu + N \rightarrow e + N$ ***(BSM, Signal):***
     - Signal is monoenergetic electron (at first order) consistent with:

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

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



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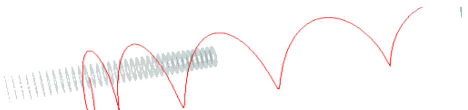
Made using Mu2eEventDisplay

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

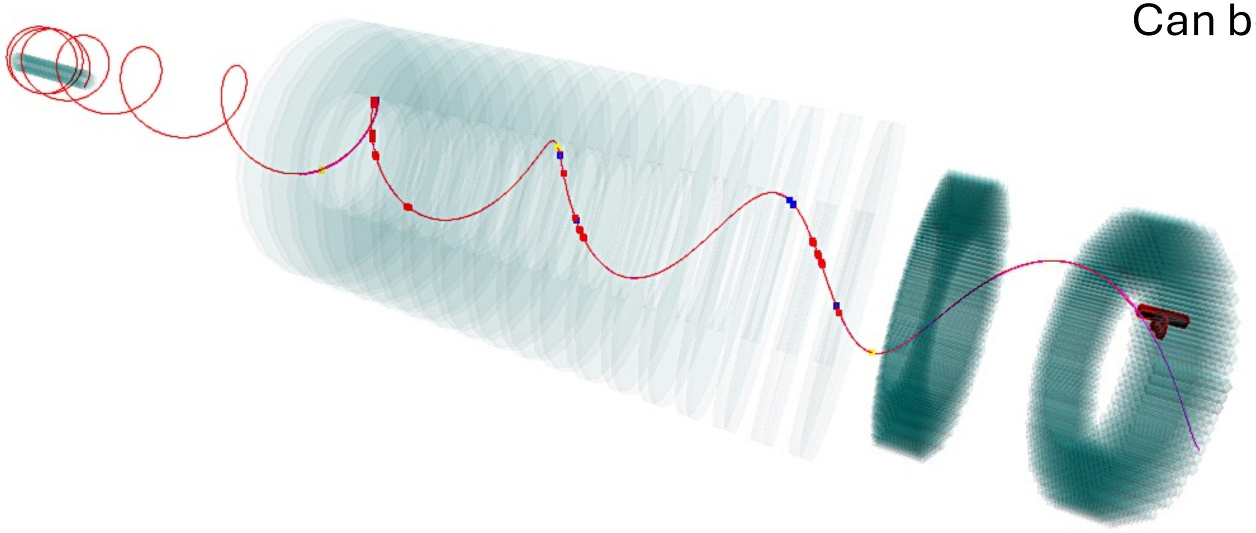
- Monoenergetic electron emanating from thin foil target with pile-up noise:



Stopping target:
37 Al thin (105μm) foils

Straw tracker:
18 stations, hollow center.

Calorimeter:
Crystals hit are combined to clusters.
Can be used to seed track (opt).



Field:
Graded between target and tracker, to reflect backwards going tracks.

Constant in tracker region.

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

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

Type	Source	Mitigation	Yield (for 1 year running)*
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 thin signal region of 103.6 < p < 104.9 MeV/c and 640 < t < 1650 ns

Detailed simulation presented in:
Universe 2023, 9, 54.

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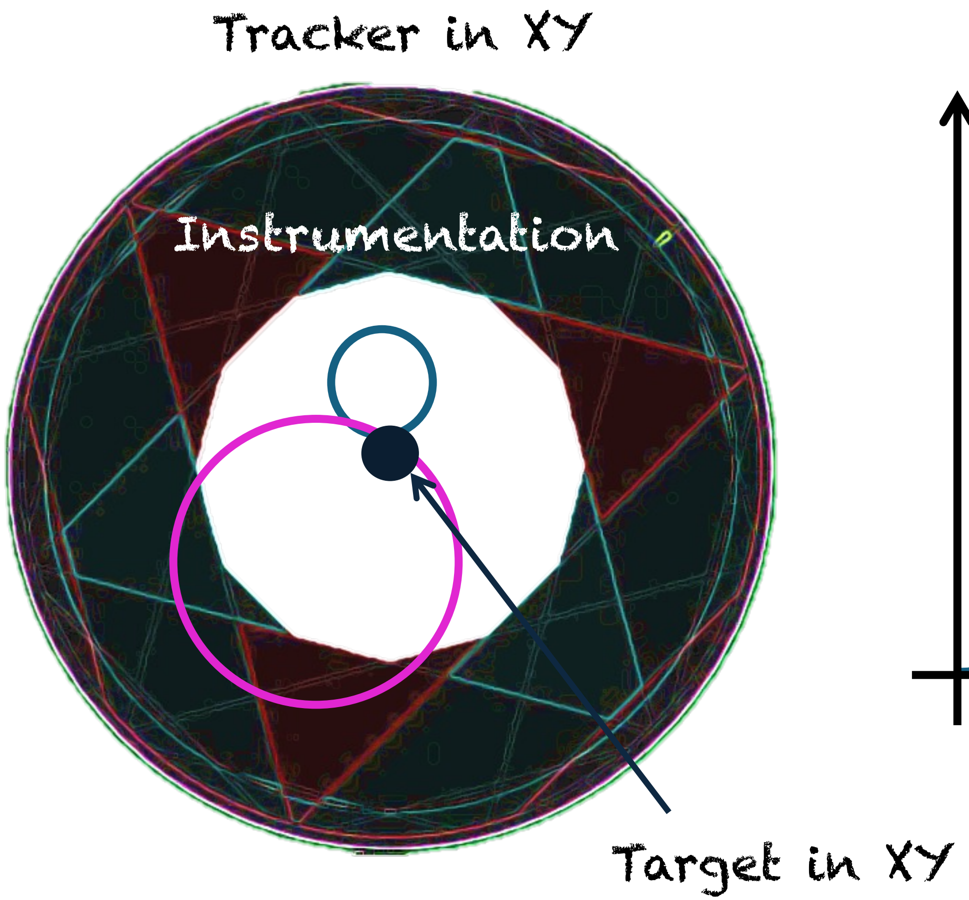
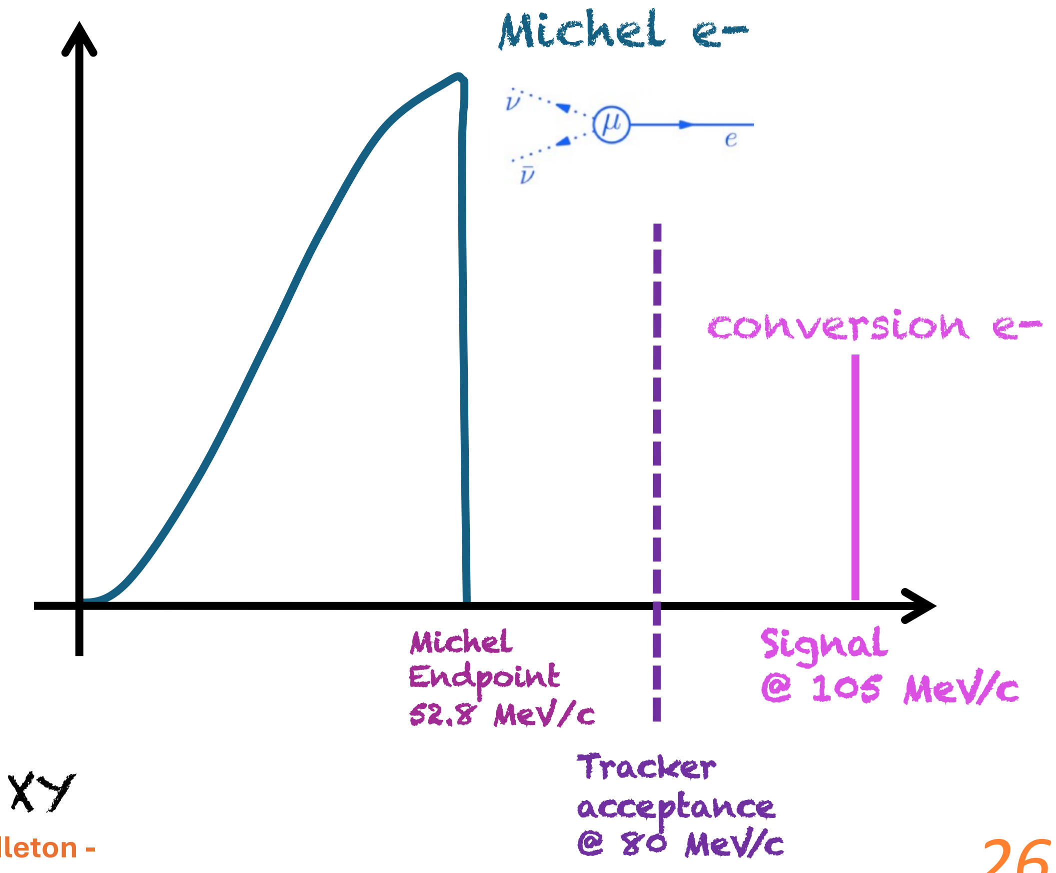
Decay in Orbit (DIO) Backgrounds

- Annular tracker: removes all Michel peak electrons.

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



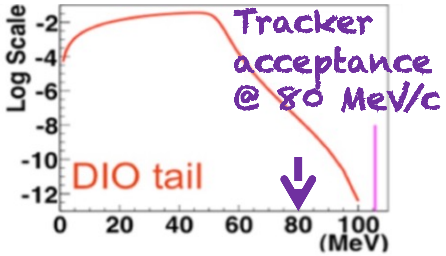


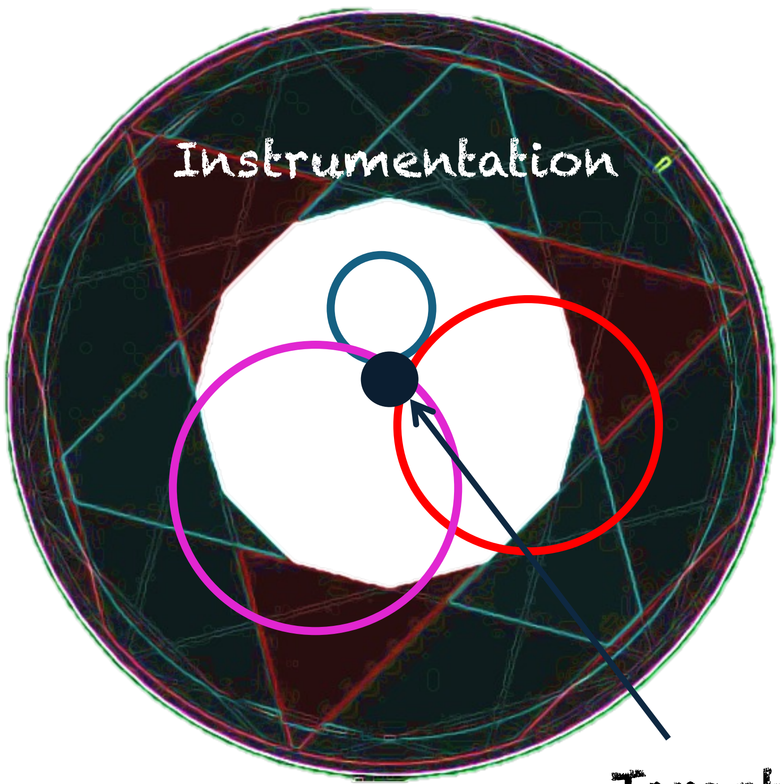
Decay in Orbit (DIO) Backgrounds

- Annular tracker: removes 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.

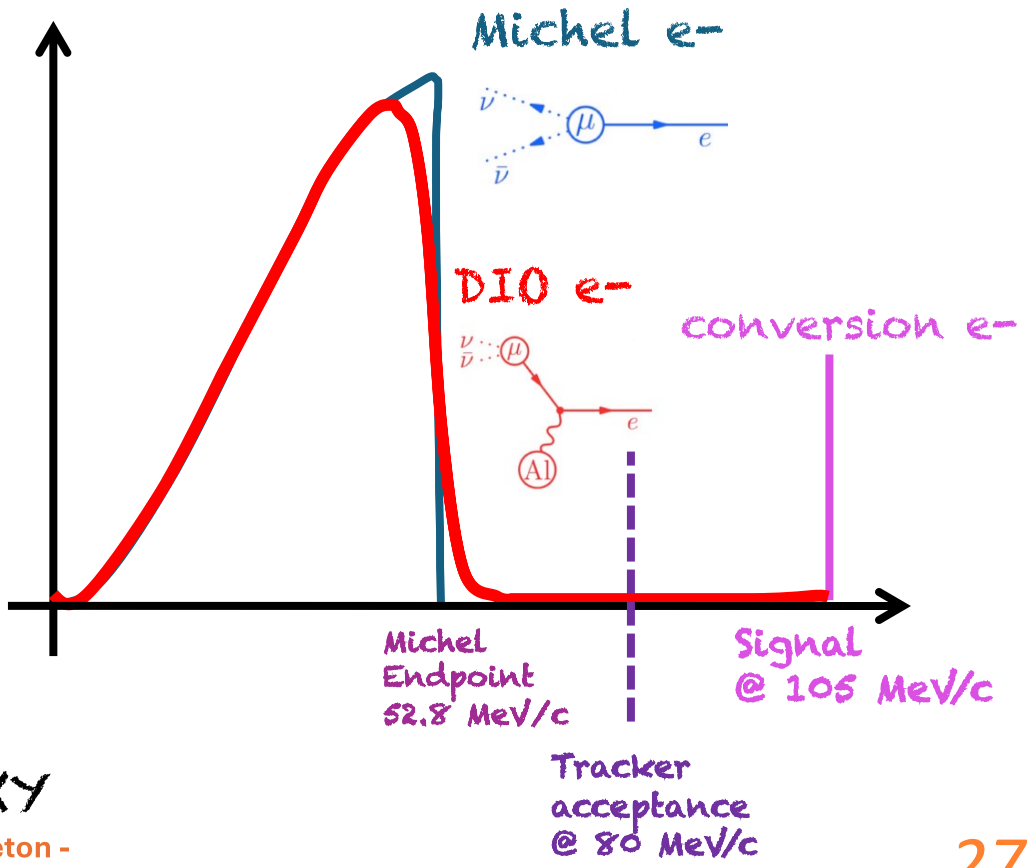
Tracker in XY

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





Target in XY



Achieving Momentum Resolution

Hardware:

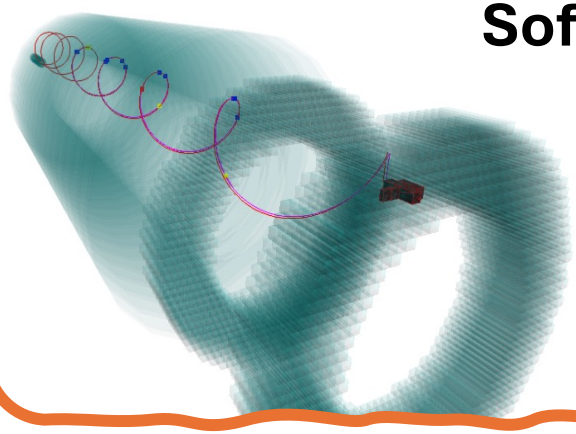
- High-resolution (< 200 keV/c) achieved using:
  - low mass straws of 15 μm thickness filled with 80:20 Ar:CO_2 operating in vacuum, double-end readout;
  - High-angle stereo angle overlaps include extra hit position information.

Software:

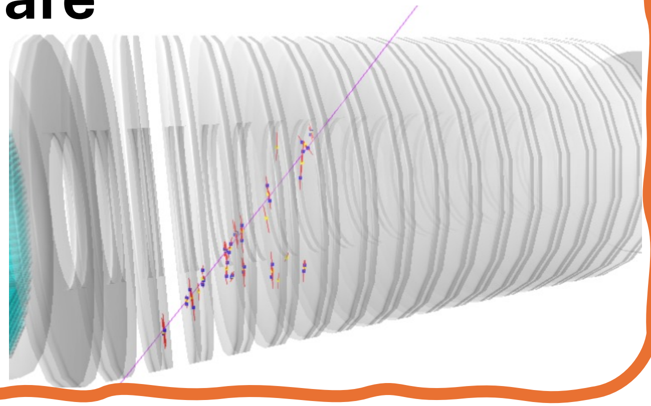
- Sophisticated algorithms to reconstruct tracks and identify momentum.
- Alignment of all subcomponents characterized using cosmics.

Software

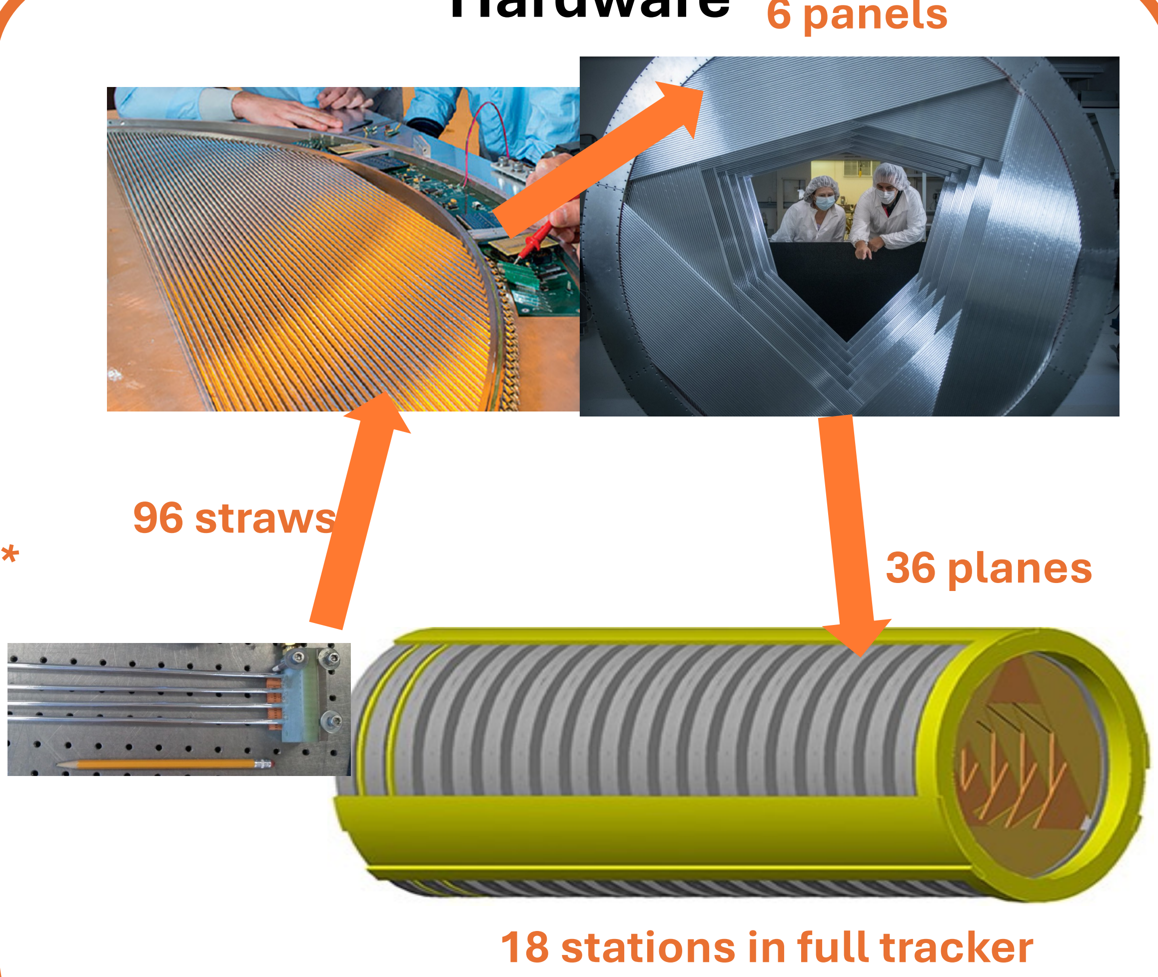
Loop Helix (signal)



*"straight" cosmic for alignment**



Hardware



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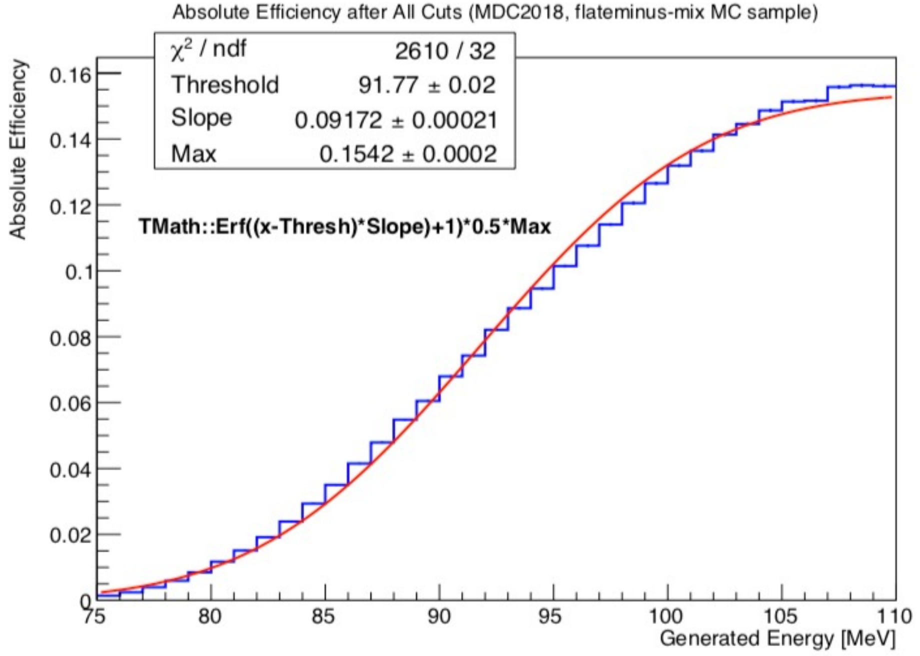
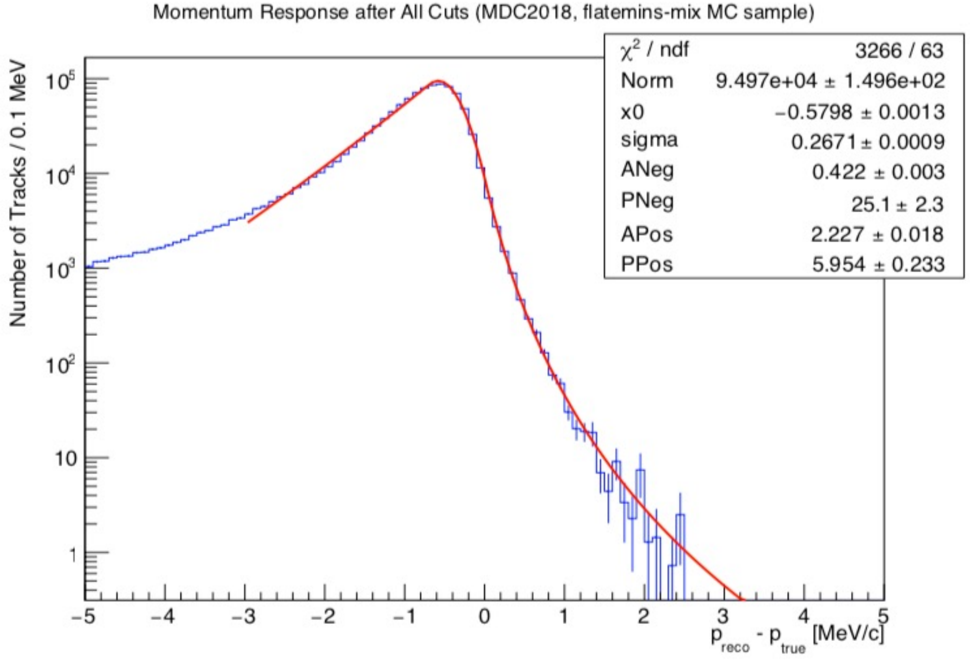
* I wrote our cosmic reconstruction and alignment algorithms

The Straw Tracker: achieving resolution

Absolute Efficiency
(as function of generated energy)



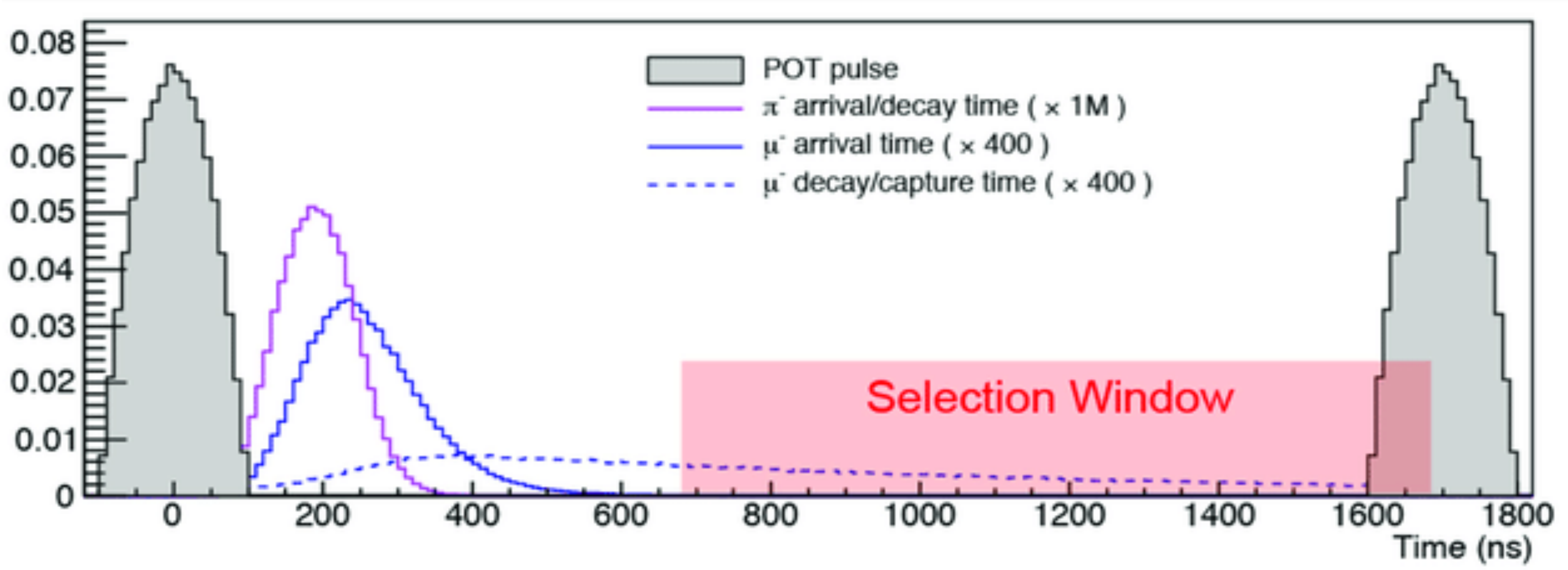
Response
(i.e. resolution and energy loss)



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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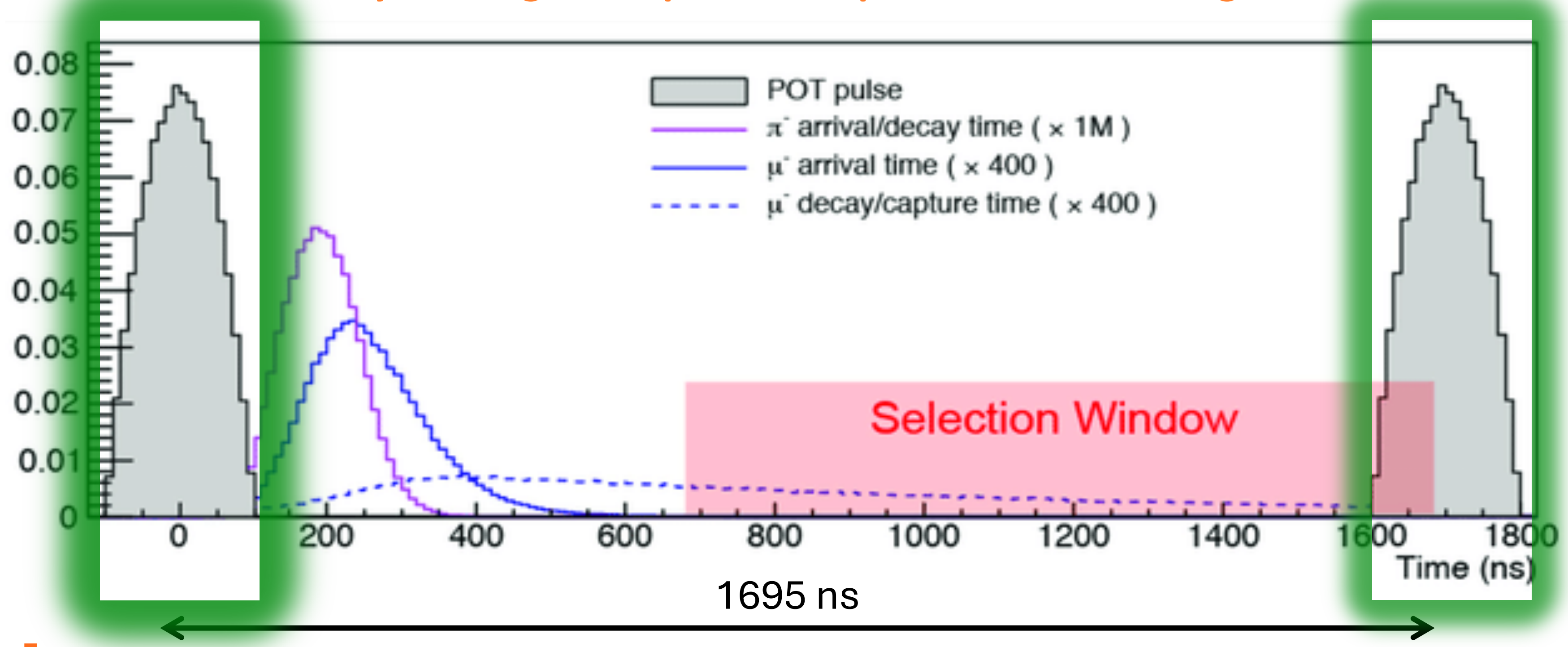

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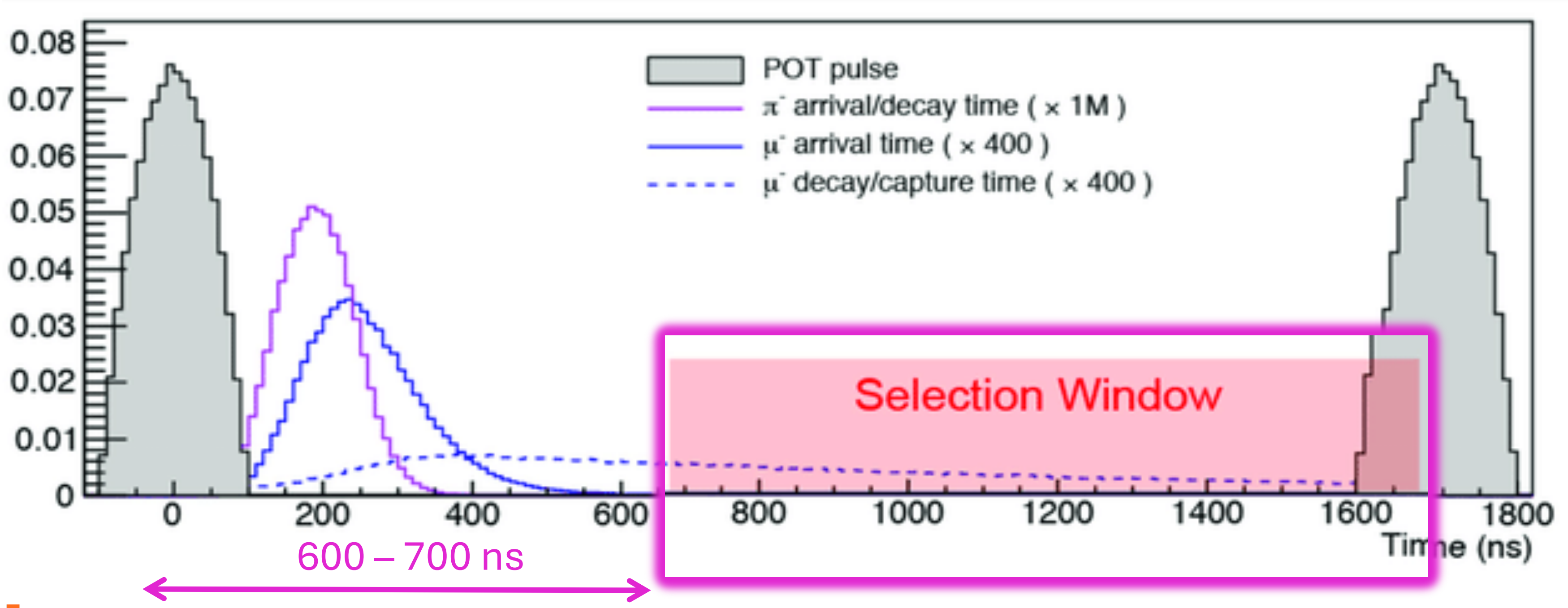

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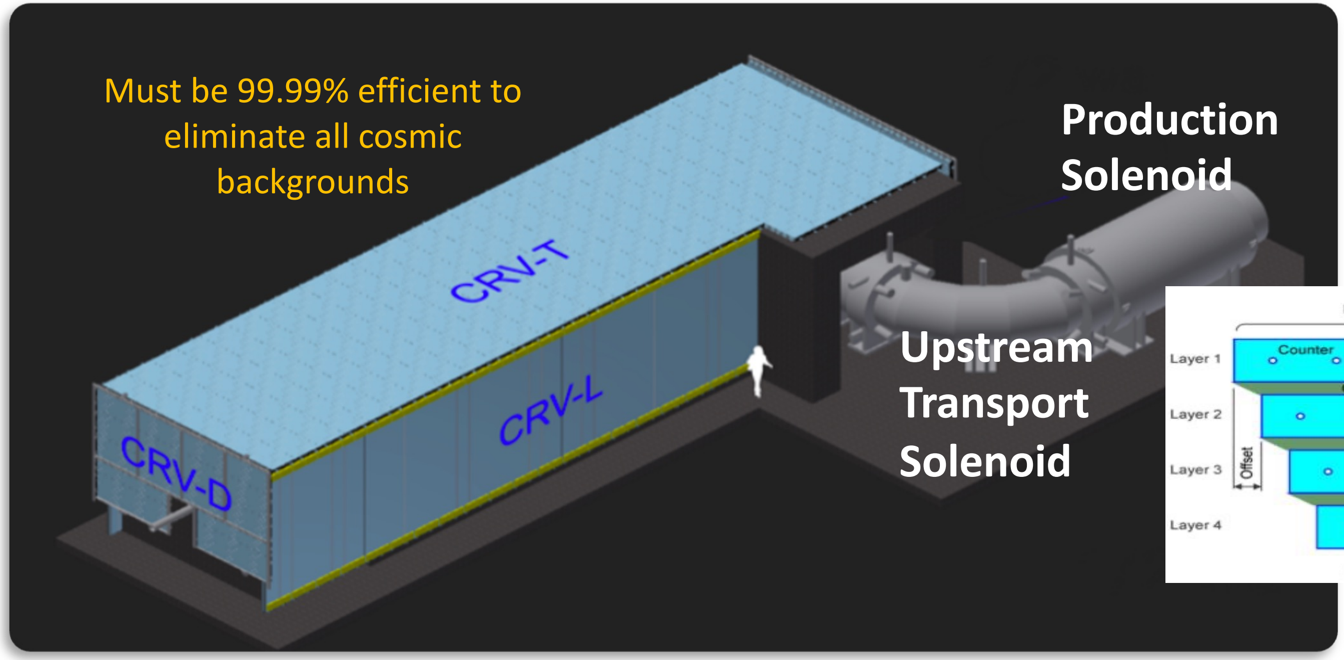
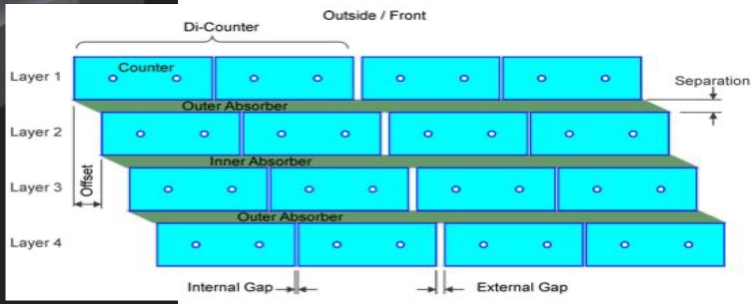
Cosmic Induced Backgrounds

- 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.

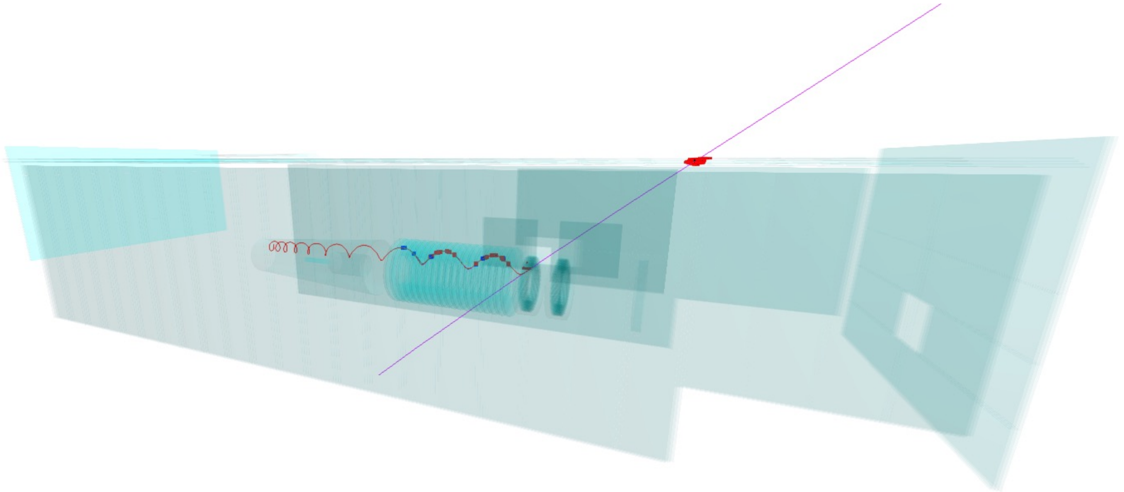
Active Cosmic Ray Veto system is key to eliminating cosmic induced backgrounds.

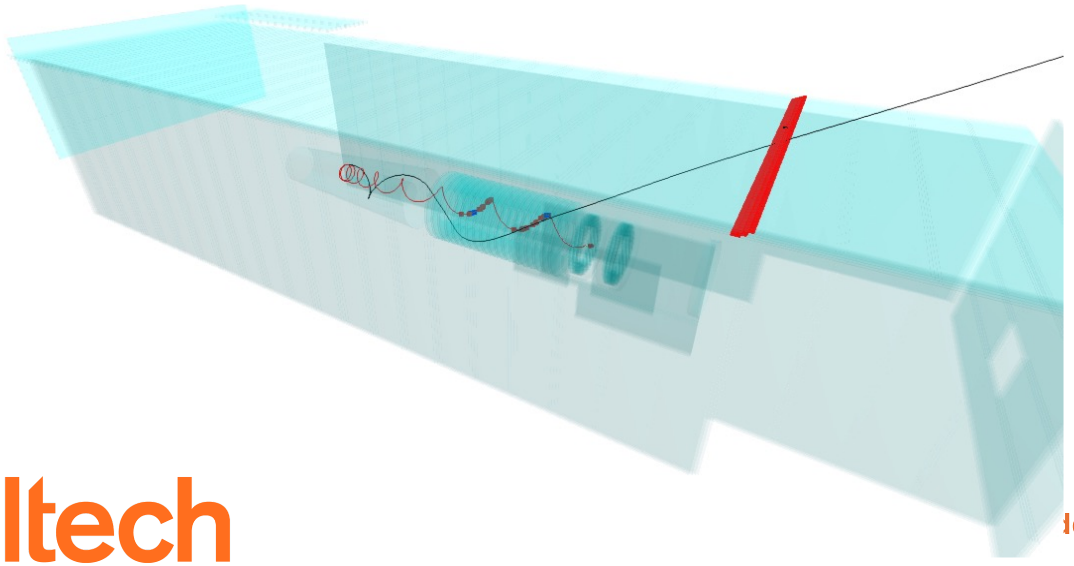




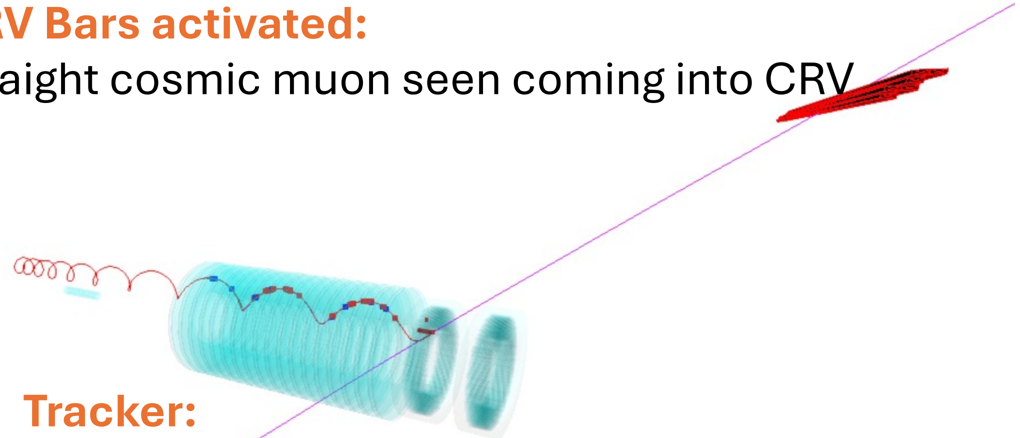
Cosmic Induced Background Examples

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

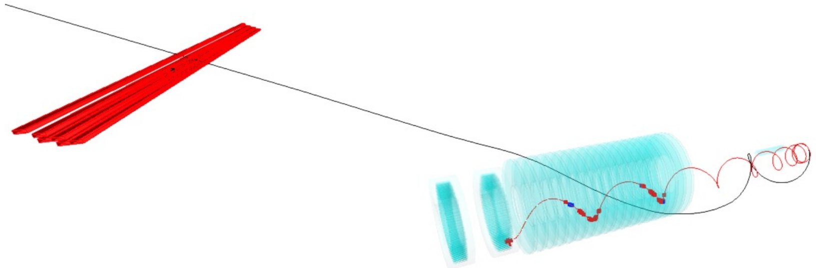




CRV Bars activated:
Straight cosmic muon seen coming into CRV



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

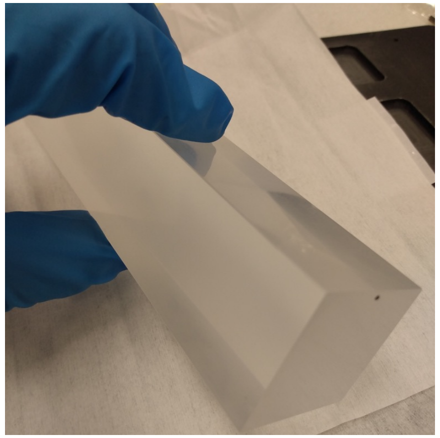


The Electromagnetic Calorimeter

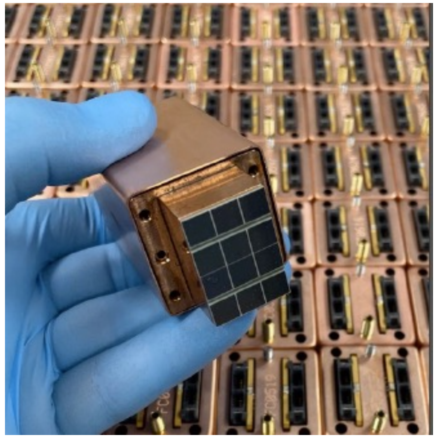
- The calorimeter is vital for reaching our physics goals:
  - particle identification – providing ~ 99% PID efficiency,
  - fast online trigger filter – quick time response,
  - accurate timing information for background rejection,
  - seeds track reconstruction – improving efficiency by 10 %

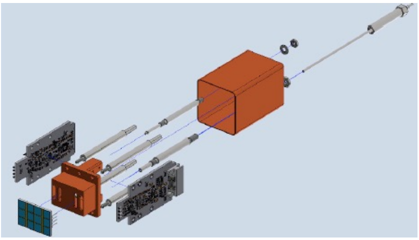
- Performance Goals:
  - Time resolution < 0.5 ns;
  - Energy resolution < 10%;
  - Position resolution < 1 cm.

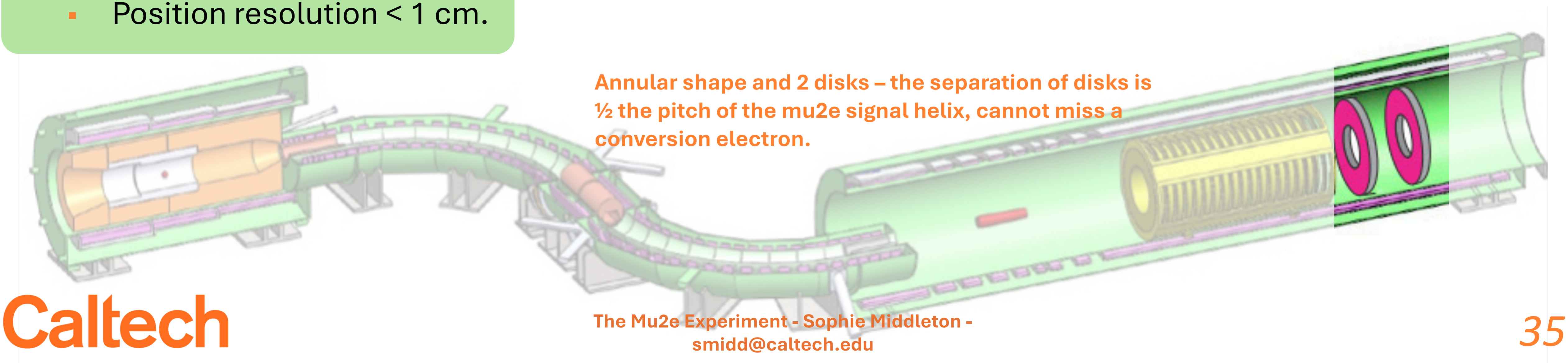
CsI crystal



2 SiPM and FEE



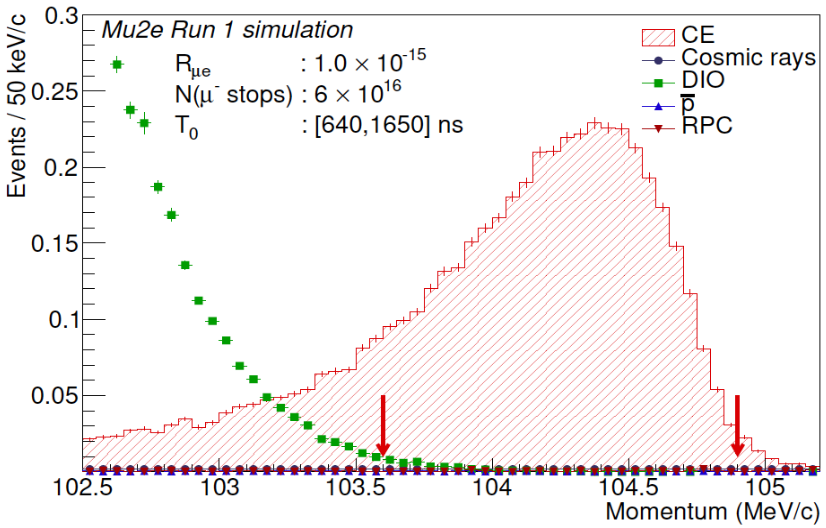


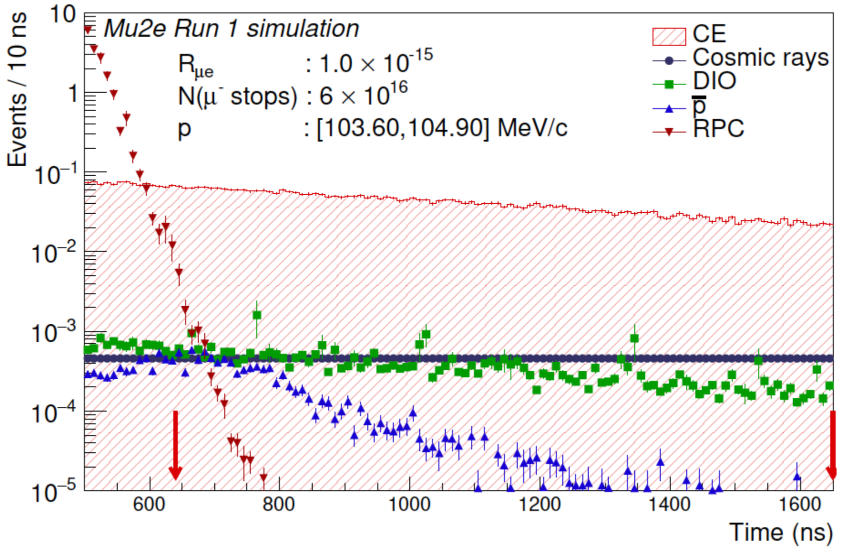


Annular shape and 2 disks – the separation of disks is ½ the pitch of the mu2e signal helix, cannot miss a conversion electron.

Physics analysis

- Mu2e physics analysis takes place in 2D:
  - **Momentum:** key to removing muon decay background;
  - **Time:** key to removing pion backgrounds.
- Work on-going by the collaboration to provide robust physics analysis infrastructure, ready for timely Run-I result!





Detailed simulation presented in:
Universe 2023, 9, 54.

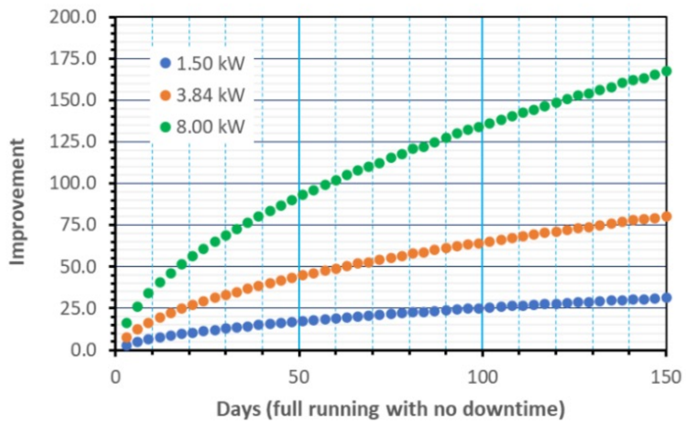
Physics Data-taking Plans

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

2026 Cosmic Ray Run:
- Field-off cosmic ray data within 3 major detector systems;
- Cross-calibrate and align detectors
- Fully commission infrastructure;
- Field-on cosmic data-taking follows.

2027 Physics Run-I:
- A few months run;
- Measure in-situ backgrounds;
- Understand beam/pile-up;
- **50-100 x improvement on current limit!**

2029 Physics Run-II:
- 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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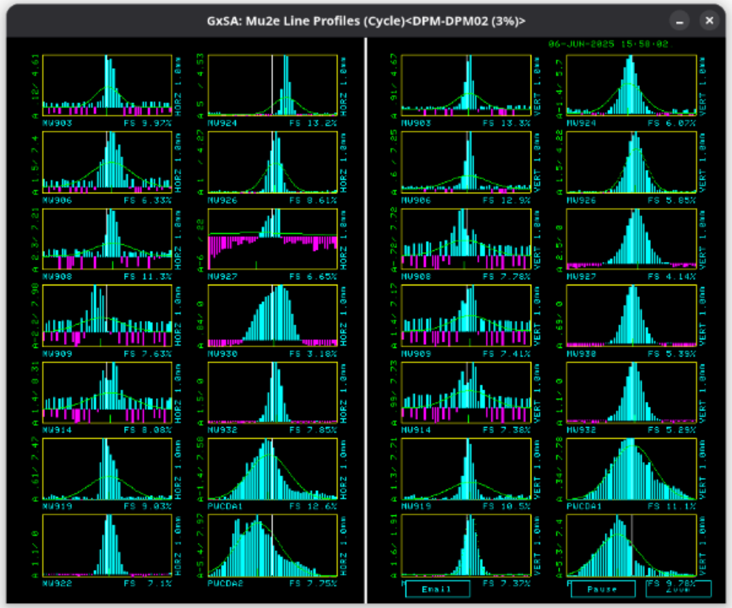
Status Update of Hardware

Beamline Commissioning

Extinction monitor installed in MC-2

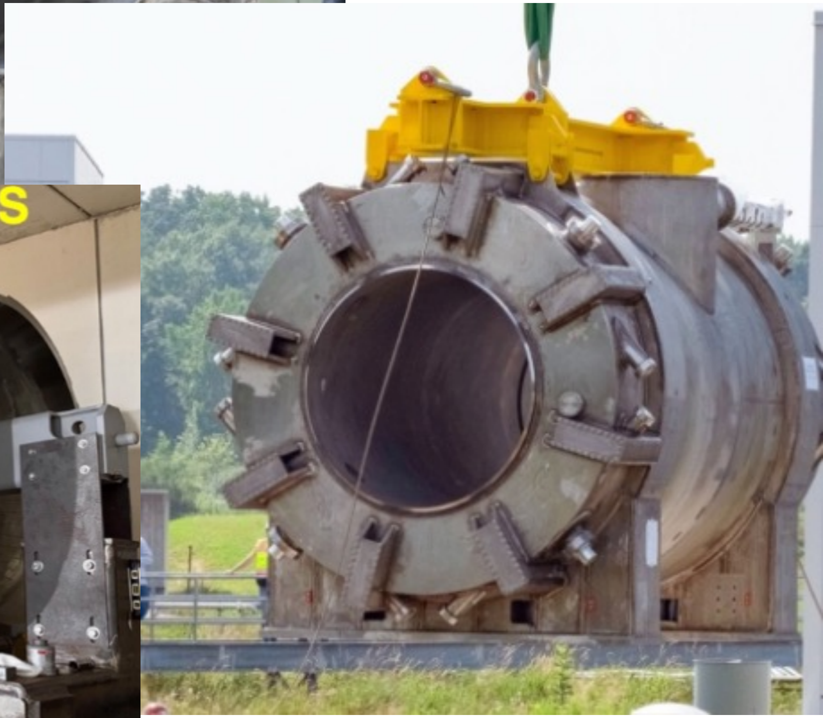
First observation of clear beam profiles in M4

- In 2024 – blind except the 2 locations of PWC monitors
- Now, we have a stable signal in all the monitors
- Steering the beam: profiles show beam well centered



Status: Solenoids

- **Production Solenoid:**
  - Installed in the Mu2e hall in July 2025.
  - Heat and radiation shield is installed.



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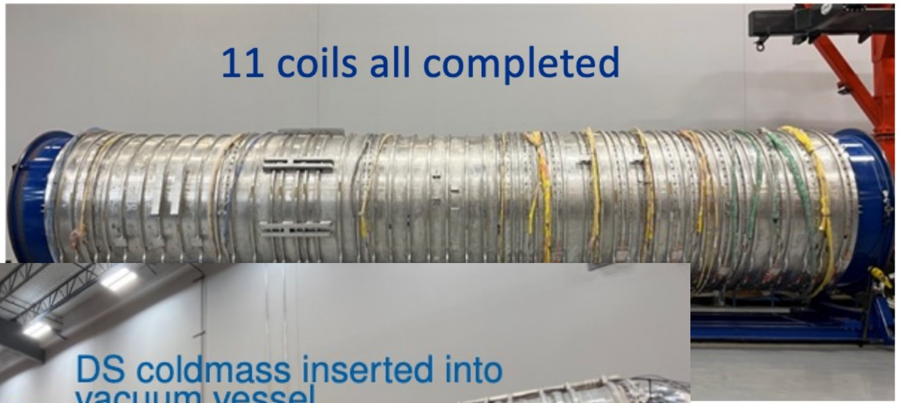
Status: Solenoids

- **Transport Solenoid:**
  - S-shaped Transport Solenoid has arrived at FNAL on 12/23 (upstream part) and 2/24 (downstream part).
  - Installed in final position in Mu2e hall
  - Rotating collimator installed and tested
  - Upstream and downstream part welded together
  - Installation of Anti-Proton absorber blade planned
  - Cryogenic system connection in progress

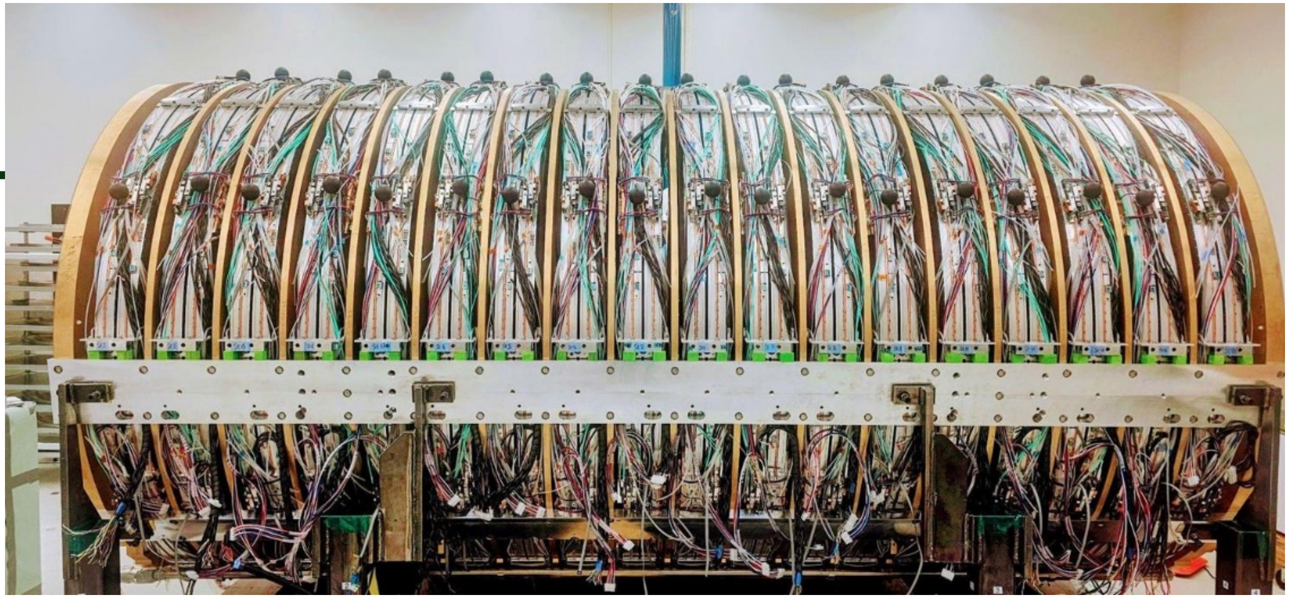
Status: Solenoids

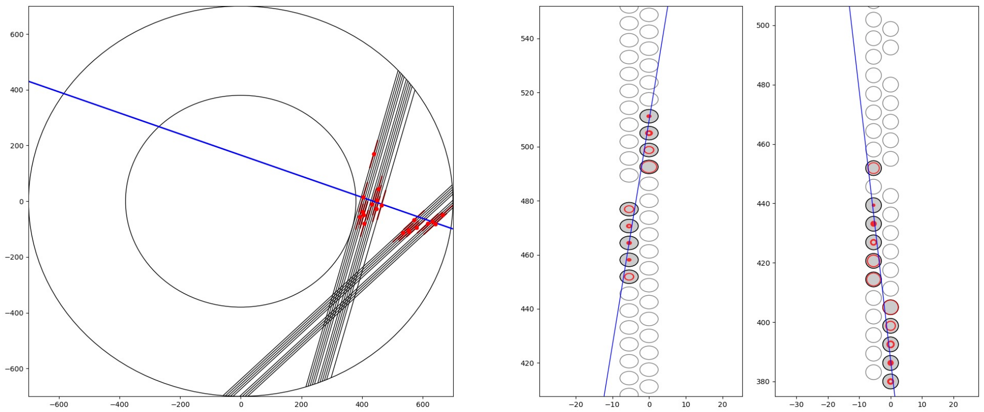
- **Detector Solenoid:**
  - All 11 coils assembled into cold mass.
  - Dry run of insertion of cold mass into vacuum vessel completed.
  - Expected delivery date to FNAL: Spring 2026.

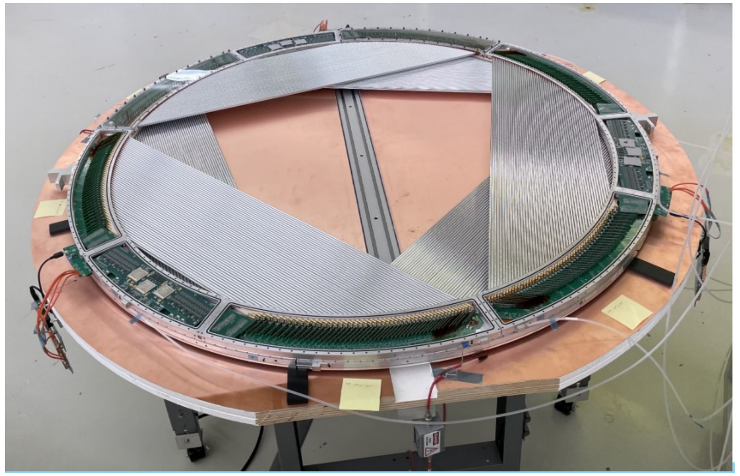


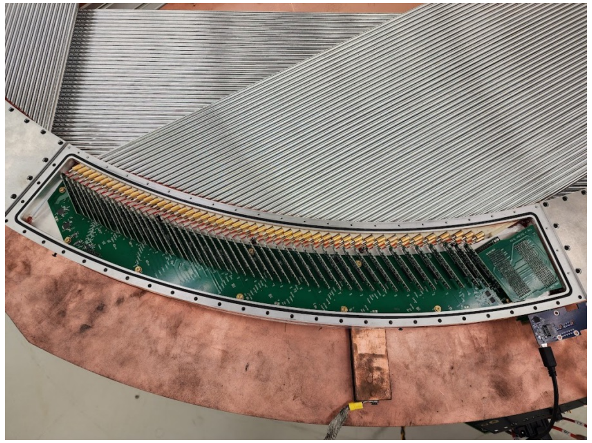
Tracker

- Installed in Mu2e Hall in November 2025!
- Commissioning on-going.
- Cosmic ray tests carried out with a single plane and full readout system for 4 years.



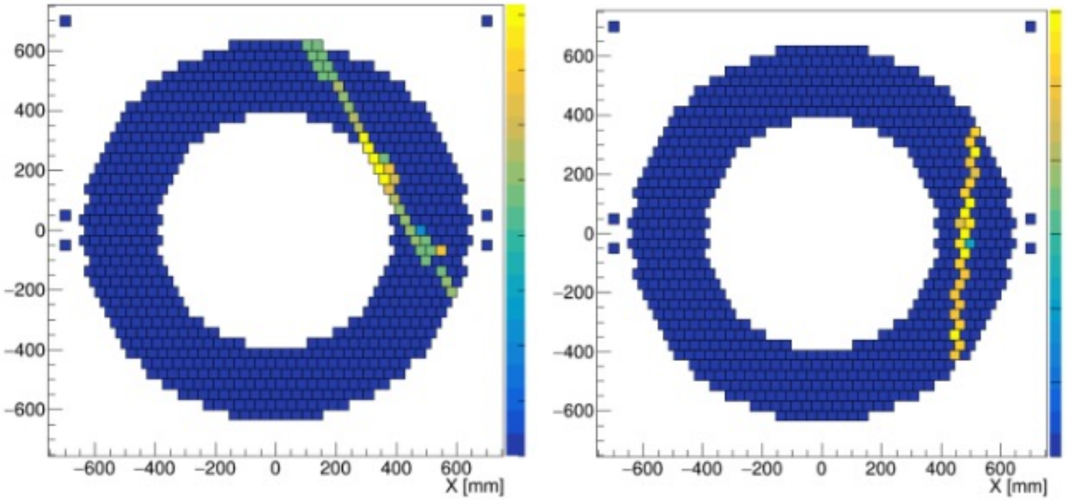


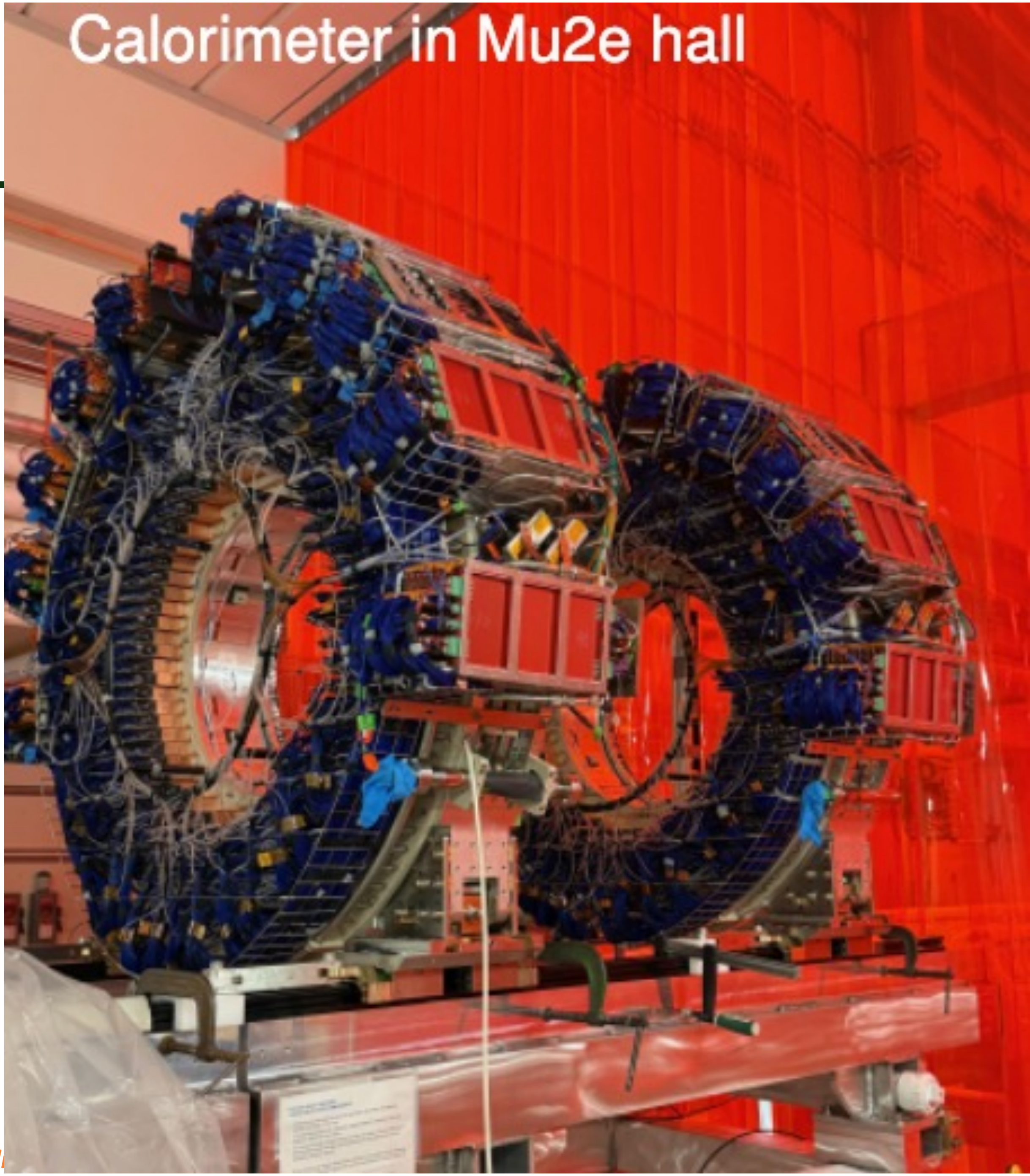




Calorimeter

- Cosmic data being taken across disks since 2024;
- Installed in Mu2e Hall July 2025;
- Commissioning on-going!





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
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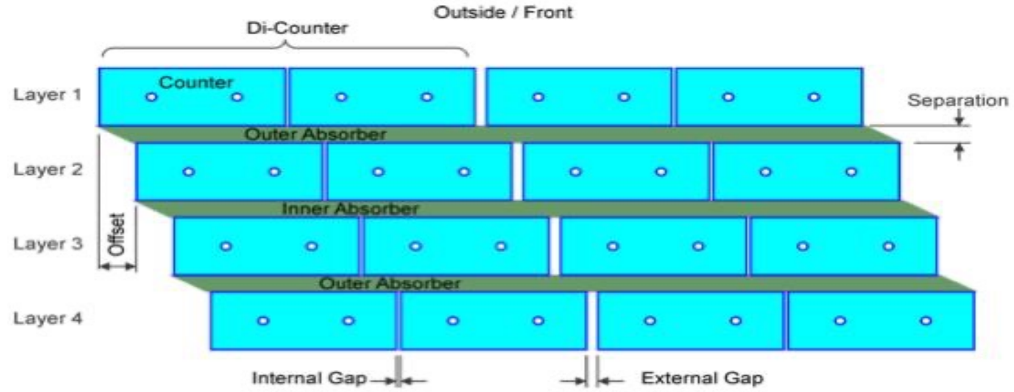
Cosmic Ray Veto System

- All 5344 di-counters produced.
- All modules produced.
- Cosmic ray tests underway at Fermilab.
- 8 modules installed in Mu2e Hall ready for cosmic ray run in 2026!



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UNIVERSITY of VIRGINIA
Argonne NATIONAL LABORATORY
Northern Illinois University
KANSAS STATE UNIVERSITY
MICHIGAN

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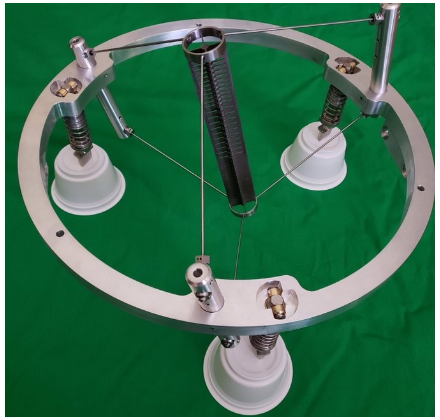
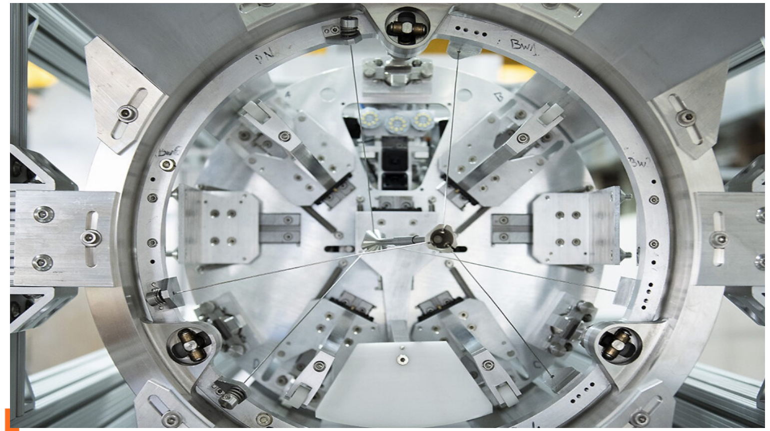
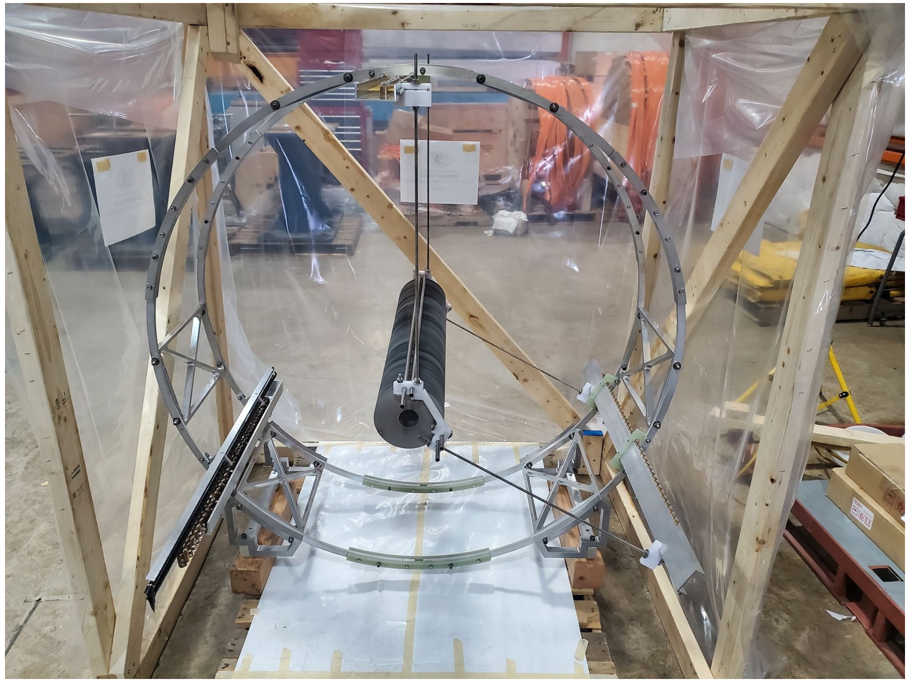
Targets

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.



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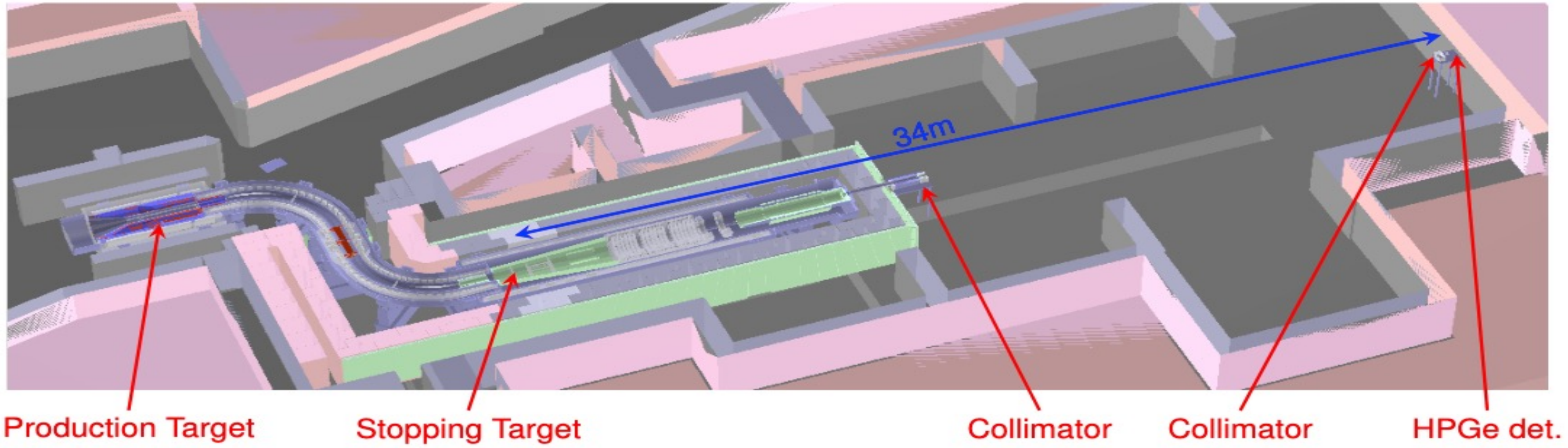
Stopping Target Monitor

High-purity Germanium detector to determine overall muon-capture rate on Al to the level of 10%



- Measure X- and γ-rays from muonic Aluminum
  - - 347 keV 2p-1s X-ray (80% of muon stops)
  - - 844 keV delayed γ-ray (5% of muon stops)
  - - 1809 keV γ-ray (30% of muon stops)

- line-of-sight view of Muon Stopping Target
- behind tungsten collimator with 1 cm2 holes

- It was decided to accompany the HPGe detector with a LaBr3 detector (worse energy resolution, but can take higher rates)

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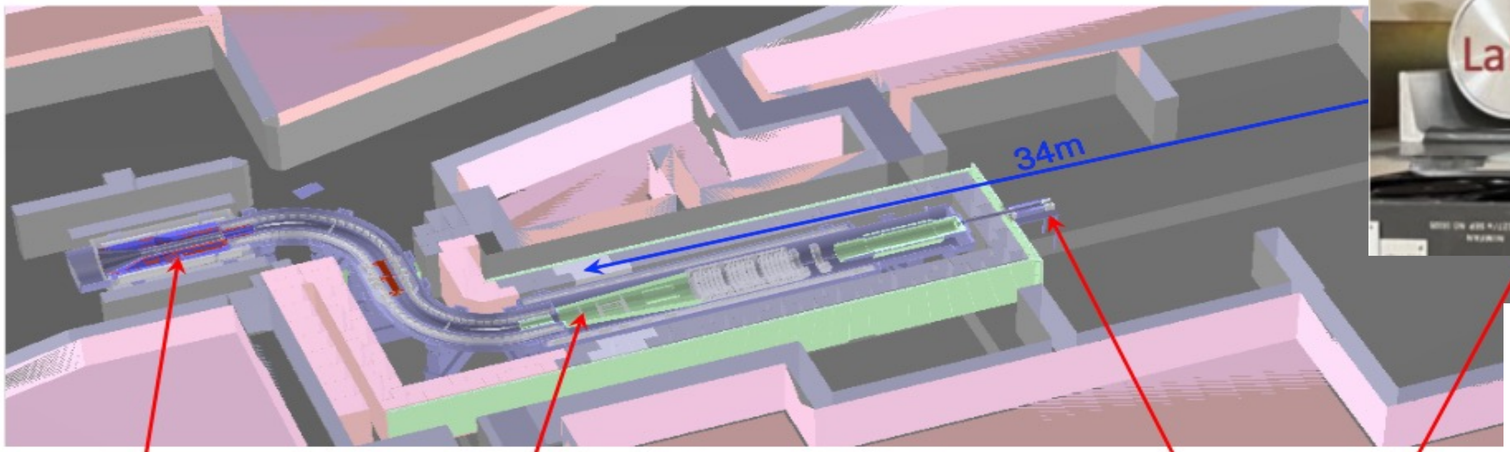
Stopping Target Monitor

High-purity Germanium detector to determine overall muon-capture rate on



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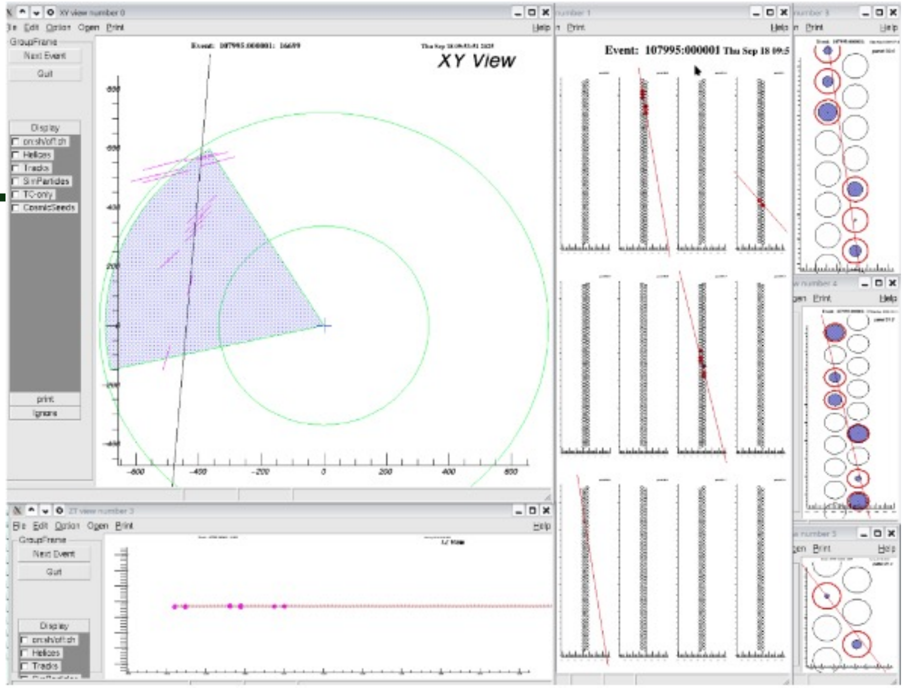
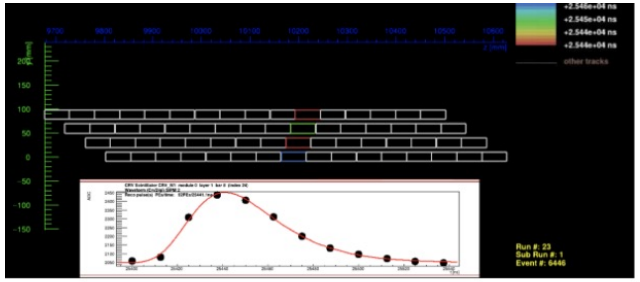
  - - 1809 keV γ-ray (30% of muon stops)

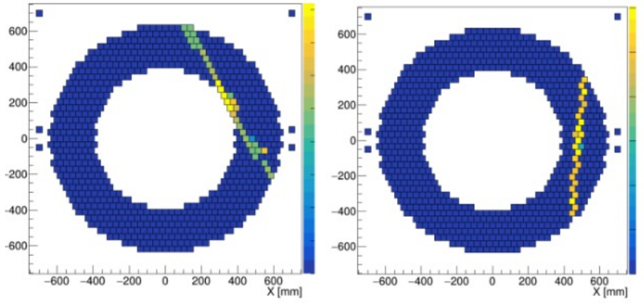
- line-of-sight view of Mu
- behind tungsten collima

- It was decided to accompany the HPGe detector with a LaBr3 detector (worse energy resolution, but can take higher rates)

Key Project Milestone - 2026







Preparations for Analysis

Mu2e: From Data to Discovery

Software based trigger system:
Optimized for 105 MeV/c electron from target

Track Reconstruction:
Utilize sophisticated algorithms to reconstruct full track measuring momentum and arrival time

Apply optimized signal selection criteria. Utilising AI/ML to enhance purity.

Characterize all backgrounds in wider 95-120 MeV/c region using control regions and dedicated studies.

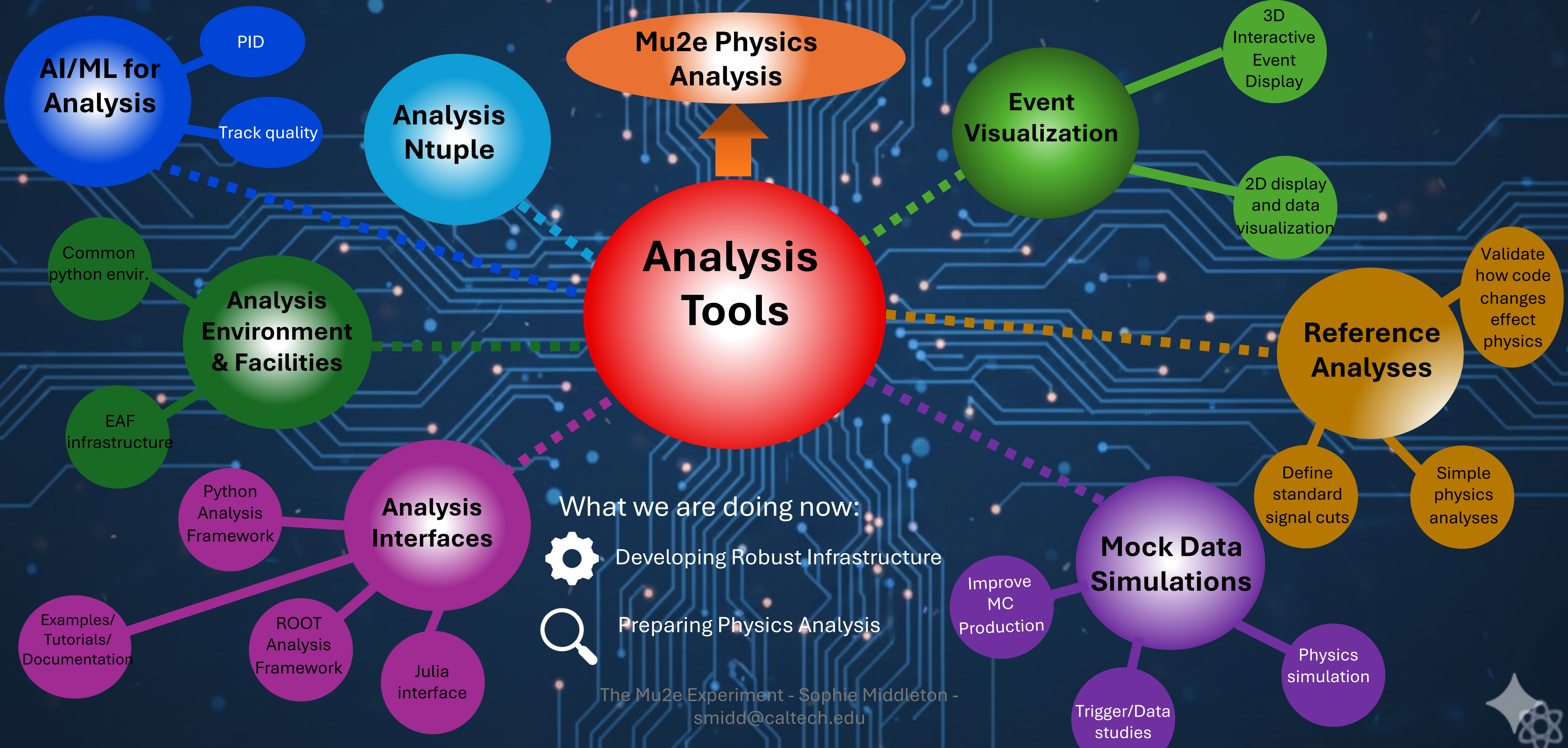
Characterize all uncertainties in dedicated studies.

Search for signal over background using maximum likelihood fit

Utilize statistical tools **to infer signal significance** of new limit

Mu2e Physics Analysis: The Integrated Analysis Tools Ecosystem

In addition to preparing the hardware, devising robust infrastructure is key to timely physics



Analysis Tools for Mu2e

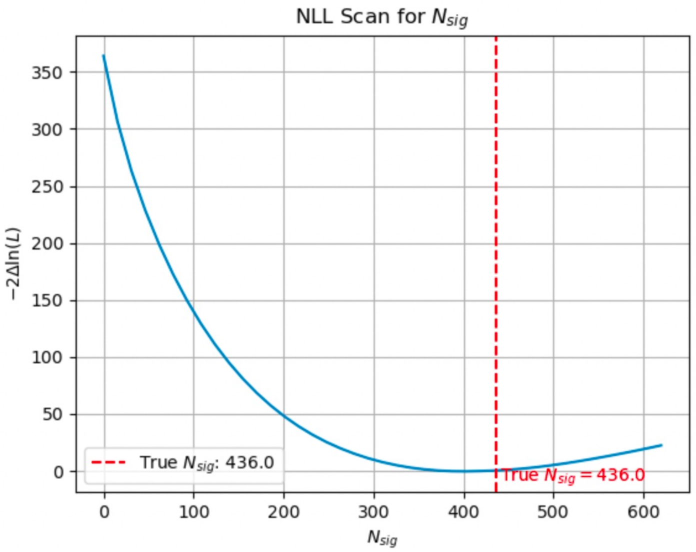
- The ultimate purpose of the analysis infrastructure is to reduce the time between **the data arriving (muons in target)** and **the physics results**.

- **1. Robust Data Pipeline with Optimal Ntupling validated through development of Mock Data:**
    - **Ntupling:** Raw data from the detector is massive and complex. Must extract only the essential variables into a flat, row-column format. This makes the data small enough to analyze on a laptop or a dedicated cluster.
    - **Mock Data (Monte Carlo):** We cannot understand the real data without "fake" data. We use massive supercomputing resources to simulate the detector's response to known physics. This allows us to predict what the background and/or signal should look like before we ever "open the box" on the real experiment.
    - **Reference Analyses:** Simple physics analyses are deployed for code validation within automated nightly checks. Ensure upgrades in code do not effect physics potential.
- **2. Well-tested and Robust Infrastructure for Processing and Performing Analysis:**
    - **Analysis Facilities (AFs):** These are specialized data centers (like those at Fermilab or CERN) that provide high-throughput computing. They often utilize "Columnar Analysis," which allows a physicist to process millions of particle events in seconds by looking at entire columns of data at once.
    - **Custom Frameworks:** Every experiment (like Mu2e or CMS) builds its own software framework to perform analysis tasks and provide verified results unified between all analysis teams.
- **3. Modern Visualization Tools to Investigate Interesting Events:**
    - **Event Displays:** These are 3D interfaces that show the actual paths of particles through the detector layers. They are essential for "sanity checks"—ensuring that the tracks the computer is finding actually make physical sense within the detector geometry.
- **4. AI/ML Interfaces to Maximize Physics Potential of the Experiment**
    - **Integration:** Neural networks can be used to assure excellent particle identification and to check track quality at analysis level. Upon code updates the AI/ML algorithms must be retrained and differences in performance understood.

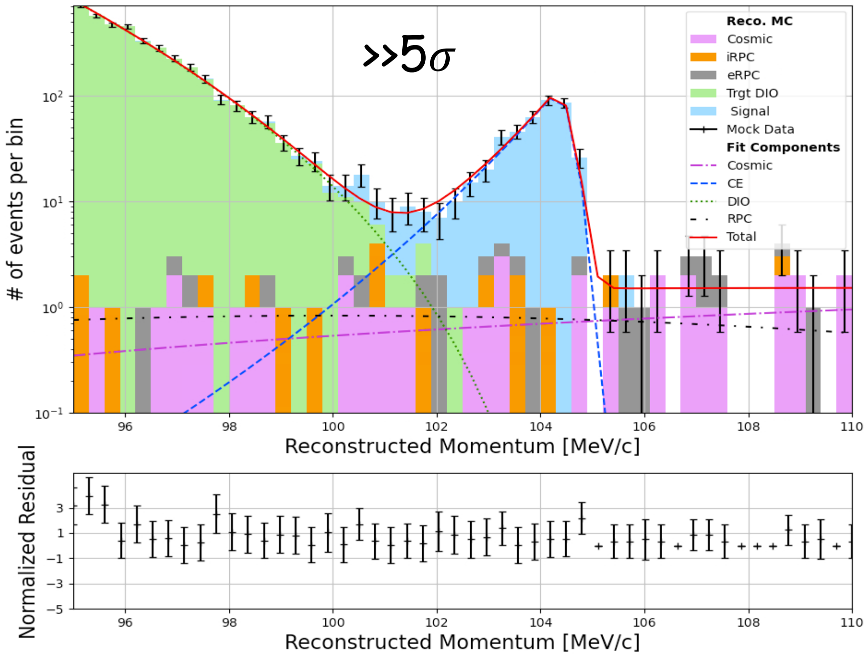
Some example fits (momentum and time)

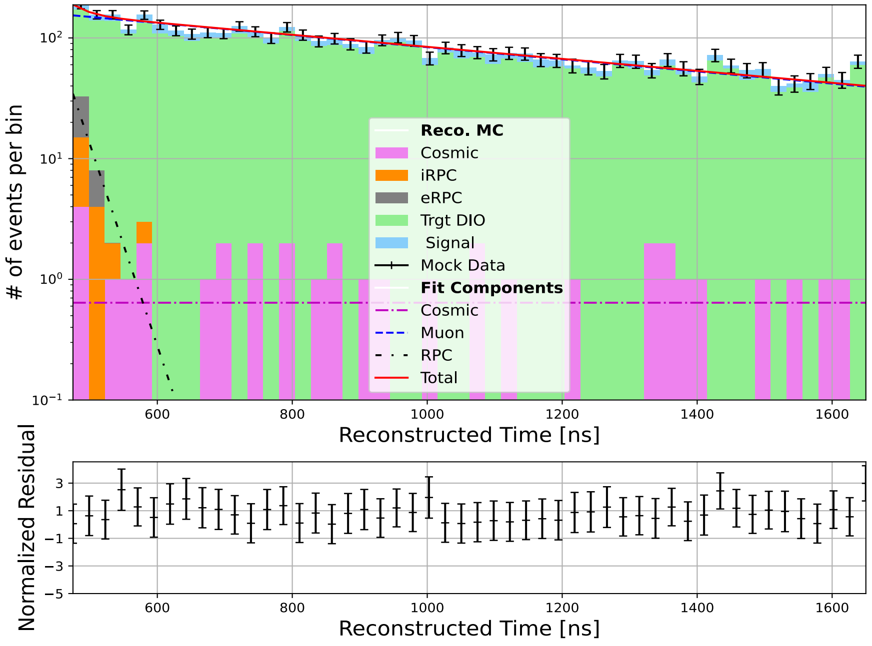
95 < p < 110 MeV/c
475 < t < 1650 ns

MDS2c + 1e-13 + 1 month live @ ½ intensity



$N_{sig} = 430$





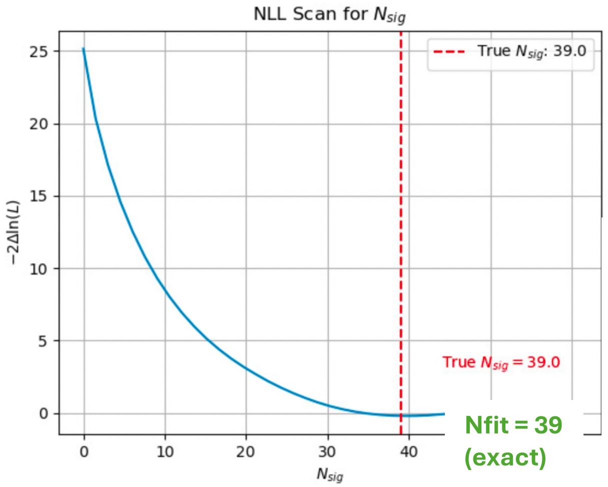
Interesting features:

- Signal rate chosen to be 1/7th current limit (favorable)
- With 1 month of ½ intensity data we see over 400 events, even with 2% efficiency
- Method clearly identifies the signal which is extremely significant in this case.

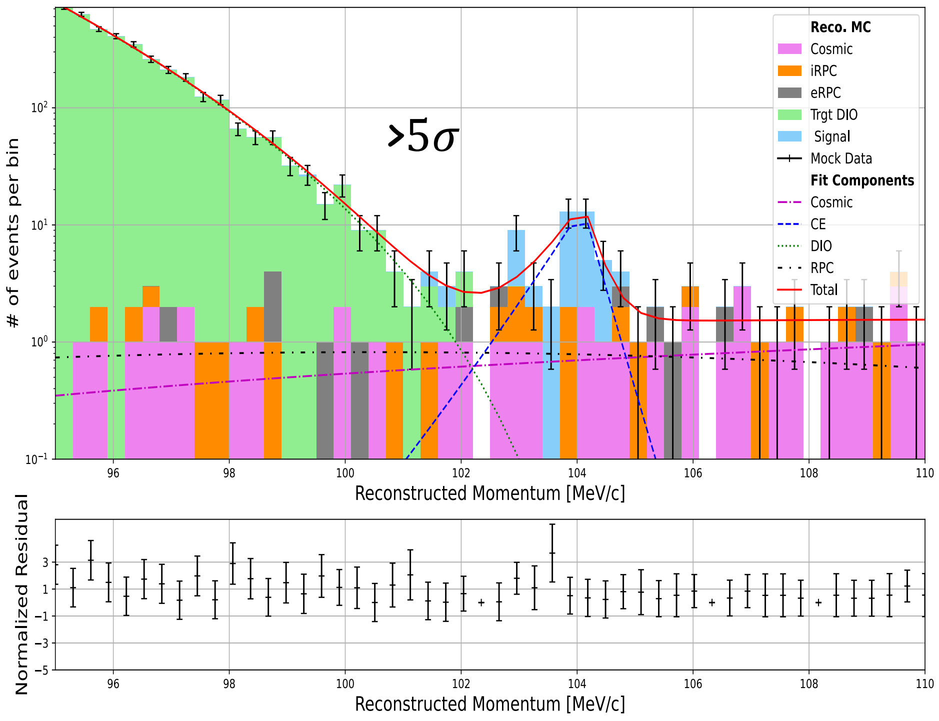
Some example fits (momentum and time)

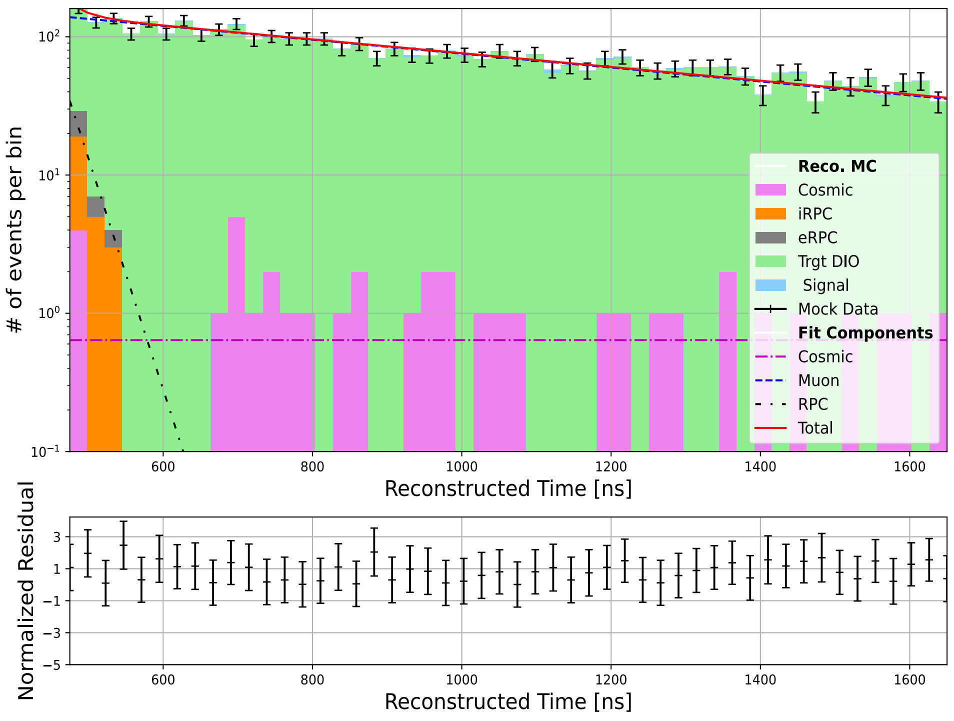
95 < p < 110 MeV/c
475 < t < 1650 ns

MDS2c + 1e-14 + 1 month live @ ½ intensity



Nfit = 39
(exact)





Interesting features:

- Signal rate chosen to be 1/70th current limit (favorable)
- With 1 month of ½ intensity data we see around 40 events are present after all cuts.
- The peak is sparser but methodology still identifies correct number of signal events
- **Further developments on-going!**

Looking Ahead

What comes next?

Current generation takes data

Signal in one or more experiments

Nice papers, exciting times!

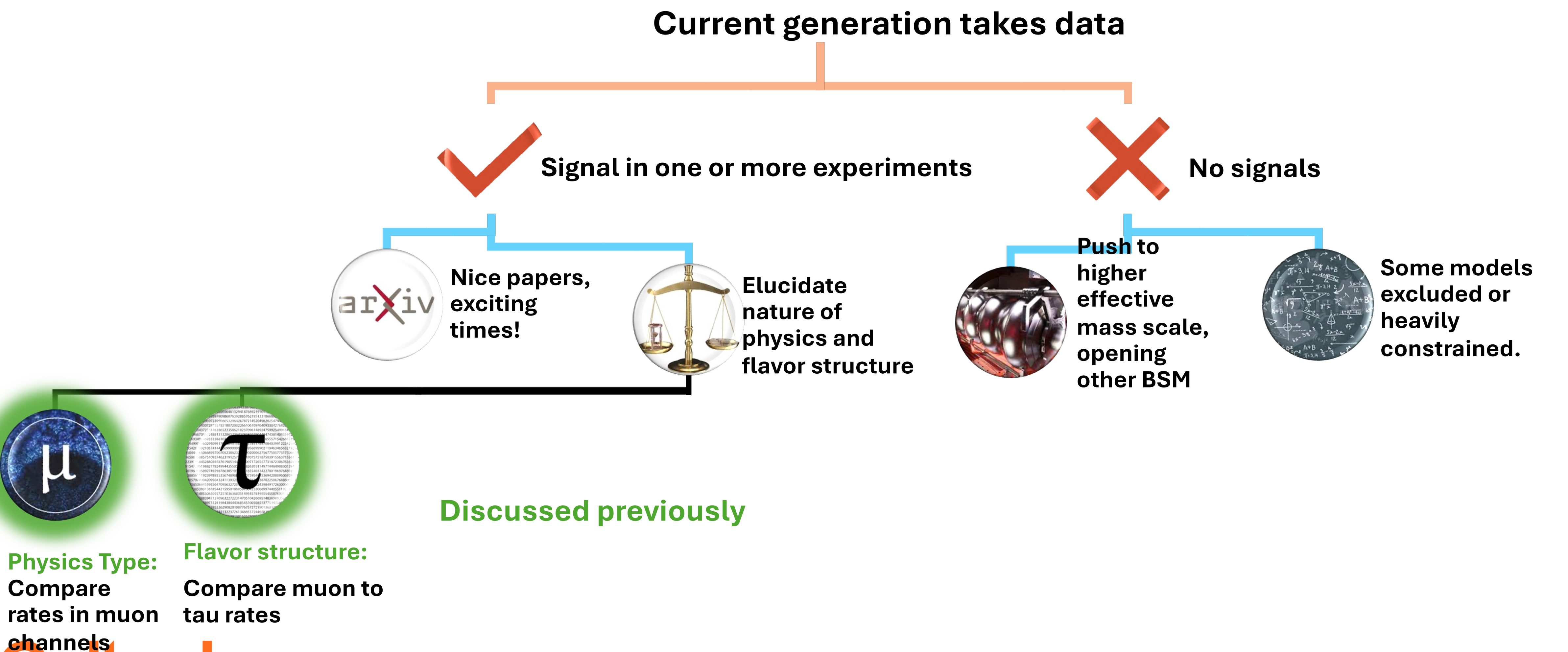
Elucidate nature of physics and flavor structure

No signals

Push to higher effective mass scale, opening other BSM

Some models excluded or heavily constrained.

What comes next?



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	$\mu^+ \rightarrow e^+ e^+ e^-$	$\mu^- N \rightarrow e^- N$	$\frac{BR(\mu^+ \rightarrow e^+ e^+ e^-)}{BR(\mu^+ \rightarrow e^+ \gamma)}$	$\frac{BR(\mu^- N \rightarrow e^- N)}{BR(\mu^+ \rightarrow e^+ \gamma)}$
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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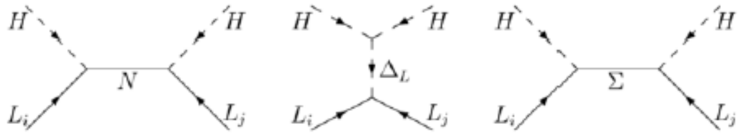
For example:

- 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!**



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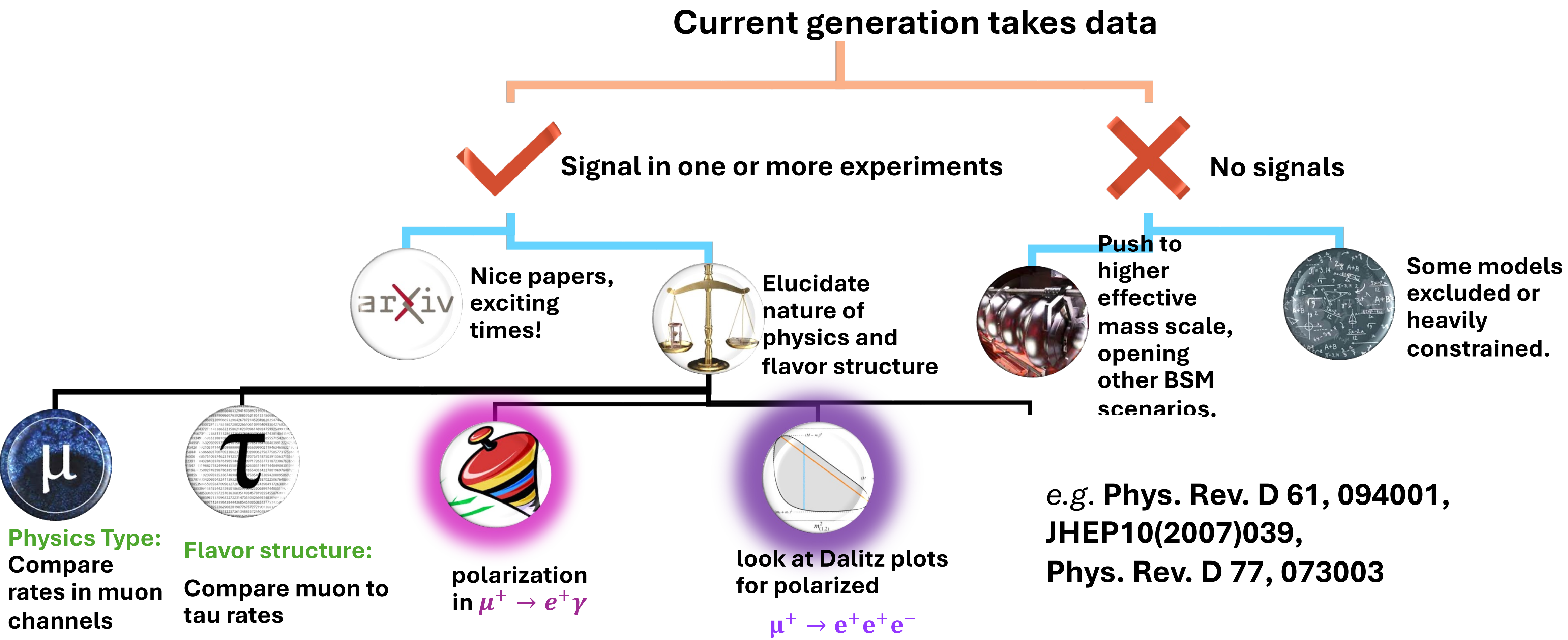
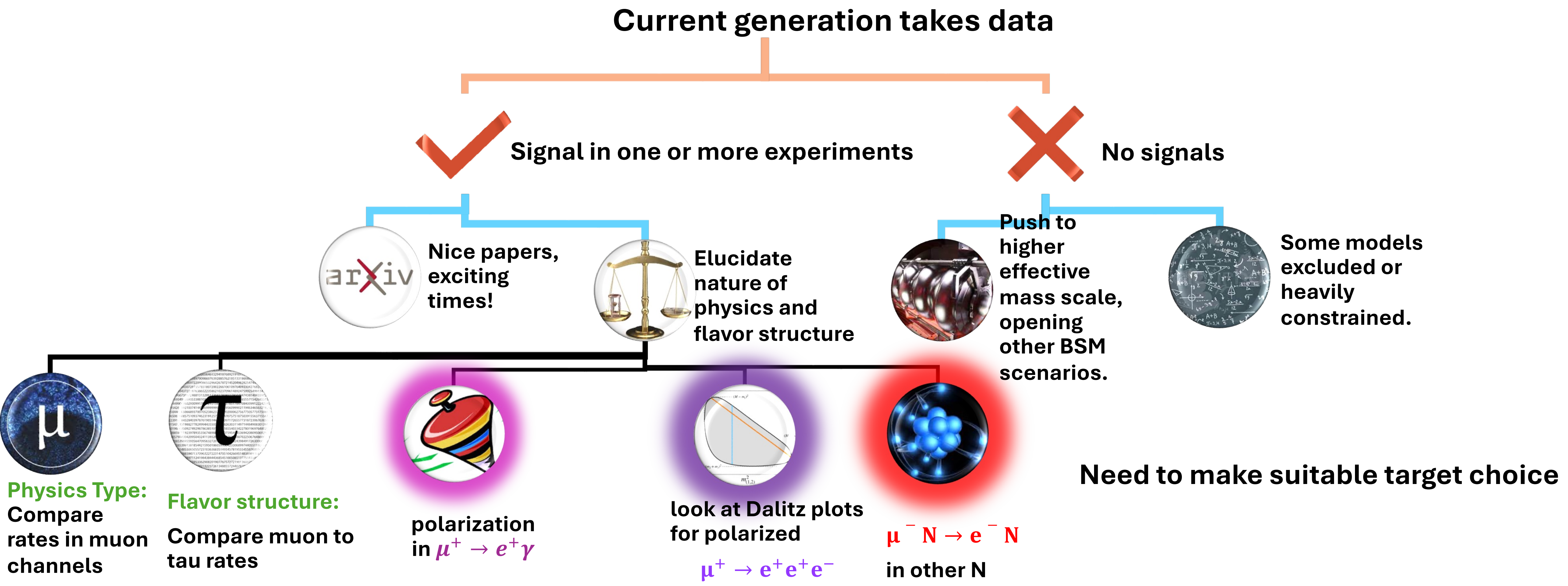
What comes next?



What comes next?



Elucidating a signal

As we are sensitive to lots of BSM scenarios – how will we know what we've seen?

$$\Gamma_{conv} = 2G_F^2 \left| A_R^* D + \tilde{g}_{LS}^{(p)} S^{(p)} + \tilde{g}_{LS}^{(n)} S^{(n)} + \tilde{g}_{LV}^{(p)} V^{(p)} + \tilde{g}_{LV}^{(n)} V^{(n)} \right|^2 + 2G_F^2 \left| A_L^* D + \tilde{g}_{RS}^{(p)} S^{(p)} + \tilde{g}_{RS}^{(n)} S^{(n)} + \tilde{g}_{RV}^{(p)} V^{(p)} + \tilde{g}_{RV}^{(n)} V^{(n)} \right|^2$$

D = dipole
S=Scalar
V=Vector

$$D = \frac{4}{\sqrt{2}} m_\mu \int_0^\infty (-E(r)) \left(g_e^- f_\mu^- + f_e^- g_\mu^- \right) r^2 dr$$

$$S^{(p)} = \frac{1}{2\sqrt{2}} \int_0^\infty Z \rho^{(p)}(r) \left(g_e^- g_\mu^- - f_e^- f_\mu^- \right) r^2 dr$$

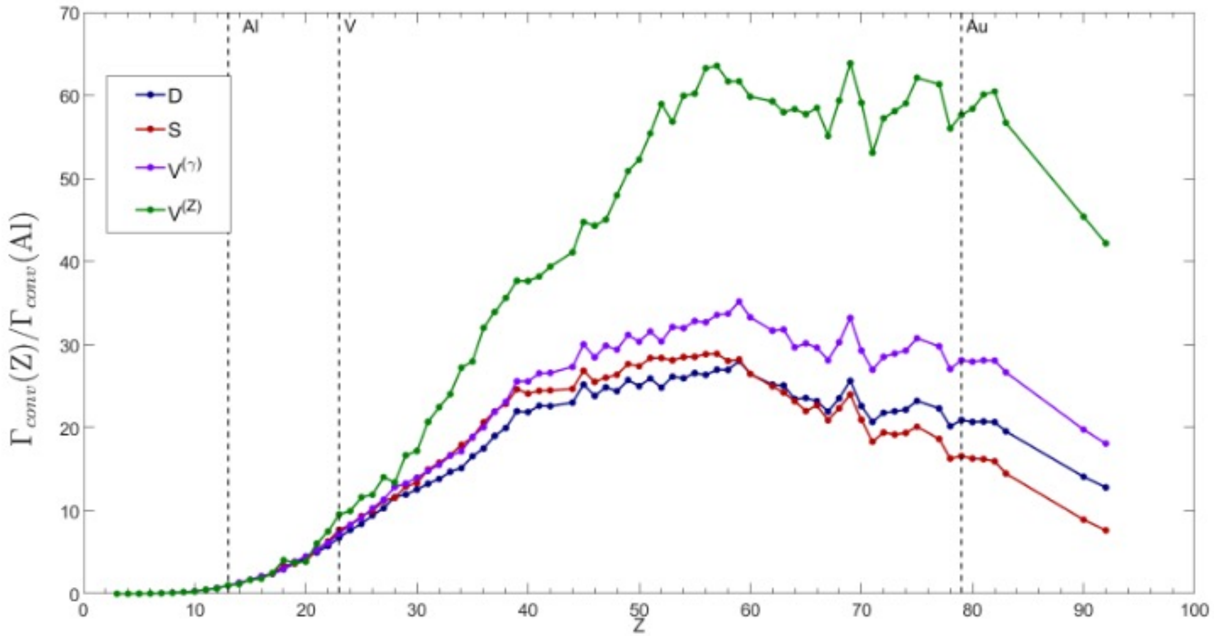
$$S^{(n)} = \frac{1}{2\sqrt{2}} \int_0^\infty (A-Z) \rho^{(n)}(r) \left(g_e^- g_\mu^- - f_e^- f_\mu^- \right) r^2 dr$$

$$V^{(p)} = \frac{1}{2\sqrt{2}} \int_0^\infty Z \rho^{(p)}(r) \left(g_e^- g_\mu^- + f_e^- f_\mu^- \right) r^2 dr$$

$$V^{(n)} = \frac{1}{2\sqrt{2}} \int_0^\infty (A-Z) \rho^{(n)}(r) \left(g_e^- g_\mu^- + f_e^- f_\mu^- \right) r^2 dr$$

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

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



V (γ) describes scenarios where the transition charge radius operator gives the dominant contribution to the CL Lagrangian, and V (Z) describes the case where the dominant operator is assumed to be an effective Z-penguin

Borrel, Hitlin, Middleton
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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.
- R&D on-going.
- Perfect for exploring other targets, but could achieve sensitivity of 10^{-18} in event of no Mu2e signal.

Advanced Muon Facility (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.**

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Summary

- Mu2e will search for the CLFV in muon to electron conversion with a 90% CL upper limit of < 8 x 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 2026, commissioning with beam in 2027 and physics data taking follows.**
- Looking further ahead the proposed Mu2e-II and AMF (https://arxiv.org/pdf/2501.15664) experiments will help elucidate any signal and push to higher mass scales.

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

Thank you for listening!

Any Questions?

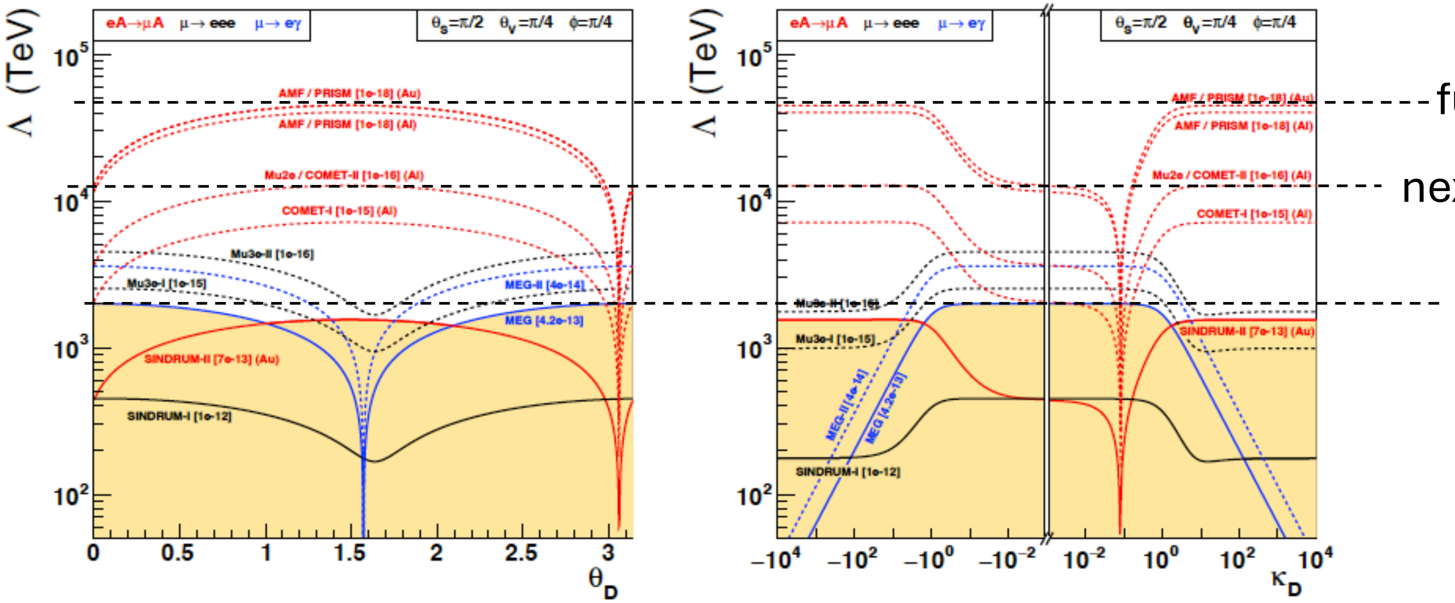
Additional Material

Effective Physics Reach

$\vec{C} \cdot \vec{e}_D$	$\vert\vec{e}_D\vert \cos\theta_D$
$\vec{C} \cdot \vec{e}_S$	$\vert\vec{e}_S\vert \sin\theta_D \cos\theta_S$
$\vec{C} \cdot \vec{e}_{VL}$	$\vert\vec{e}'_{VL}\vert \sin\theta_D \sin\theta_S \cos\theta_V$
$\vec{C} \cdot \vec{e}_{VR}$	$\vert\vec{e}'_{VR}\vert \sin\theta_D \sin\theta_S \cos\theta_V$
$\vec{C} \cdot \vec{e}_{Alight}$	$\vert\vec{e}_{Alight}\vert \sin\theta_D \sin\theta_S \sin\theta_V \sin\phi$
$\vec{C} \cdot \vec{e}_{Aheavy\perp}$	$\vert\vec{e}_{Aheavy\perp}\vert \sin\theta_D \sin\theta_S \sin\theta_V \cos\phi$

Current physics reach at O(10^3) TeV, Projections of upto O(10^4) TeV in next generation.

Parameterize coefficient space with spherical coordinates *lets you express constraints on all three processes simultaneously.*



$$\kappa_D = \text{cotan}(\theta_D - \pi/2)$$

where angle θ_D , parametrizes relative magnitude of dipole and four-fermion coefficients.

High magnitude κ_D = contact-like, closer to zero is dipole-like

Λ = effective mass reach

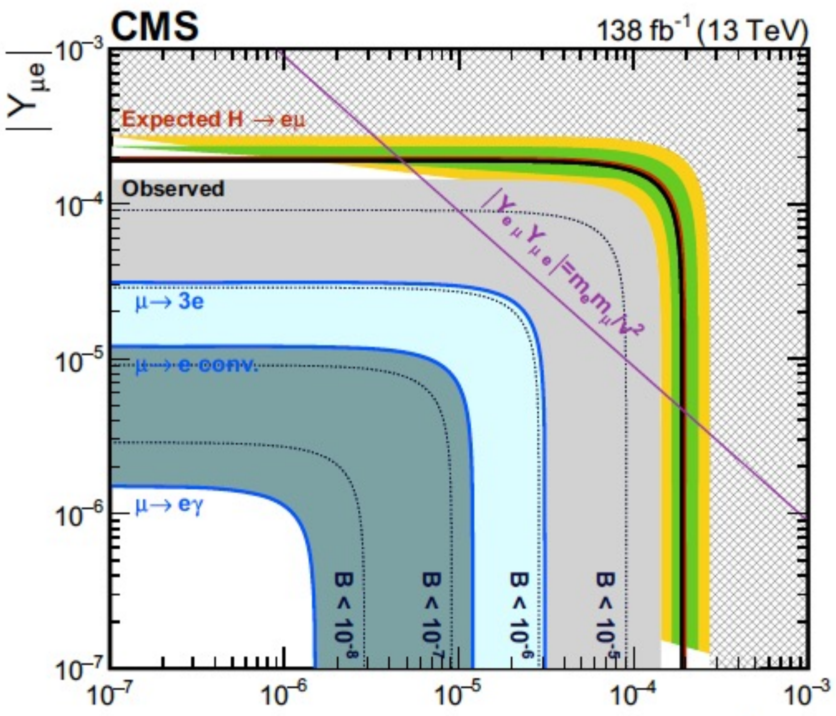
***Eur.Phys.J.C* 82 (2022) 9, 836**

Davidson & Echenard

Note: plots are a slice in multi-dimensional space, several other plots shown in paper for different slices

Complementarity with collider searches for LFV

$$\Gamma(H \to e\mu) = \frac{m_H}{8\pi}(|Y_{e\mu}|^2 + |Y_{\mu e}|^2).$$



Phys. Rev. D 108, 072004 (2023)

- Higgs LFV decays arise in many frameworks of New Physics at the electroweak scale such as **two Higgs doublet models, extra dimensions, or models of compositeness**.
- The $\mu \to e\gamma$ and $\mu \to 3e$ channels provide constraints but conversion searches such as Mu2e provide tightest projected constraints
- Current $\mu \to e$ conversion implies:

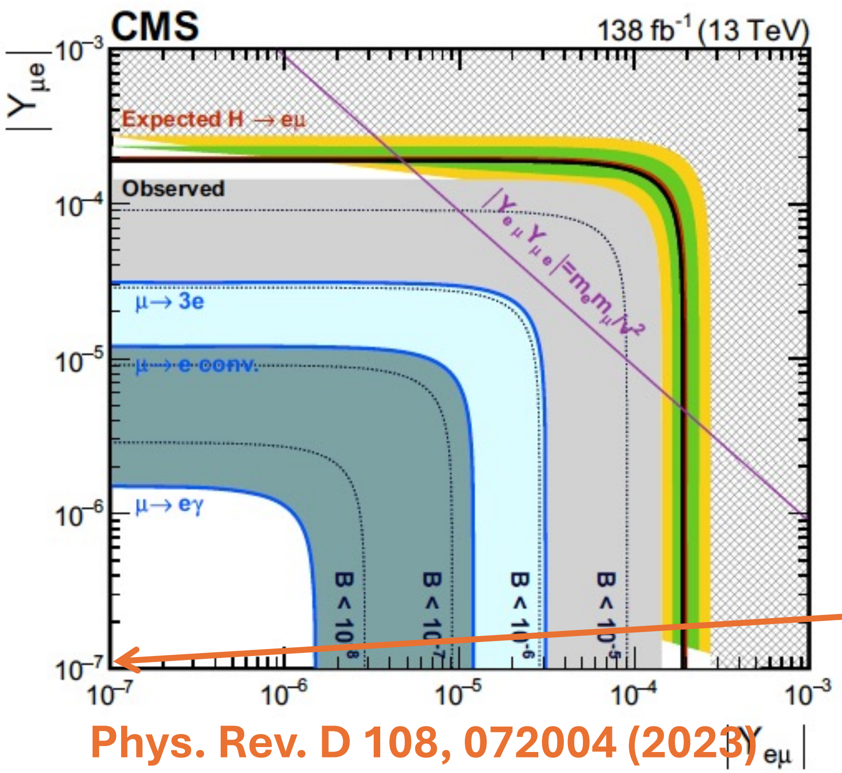
$$\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} < 4.6 \times 10^{-5}$$

- Mu2e is expected to be sensitive to:

$$\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} \sim O(10^{-7})$$

where $|Y_{\mu e}|$ and $|Y_{e\mu}|$ are off-diagnol flavor-violating Yukawa couplings for a 125 GeV Higgs boson i.e. $H \to \mu e$.

Complementarity with collider searches for LFV



Phys. Rev. D 108, 072004 (2023)

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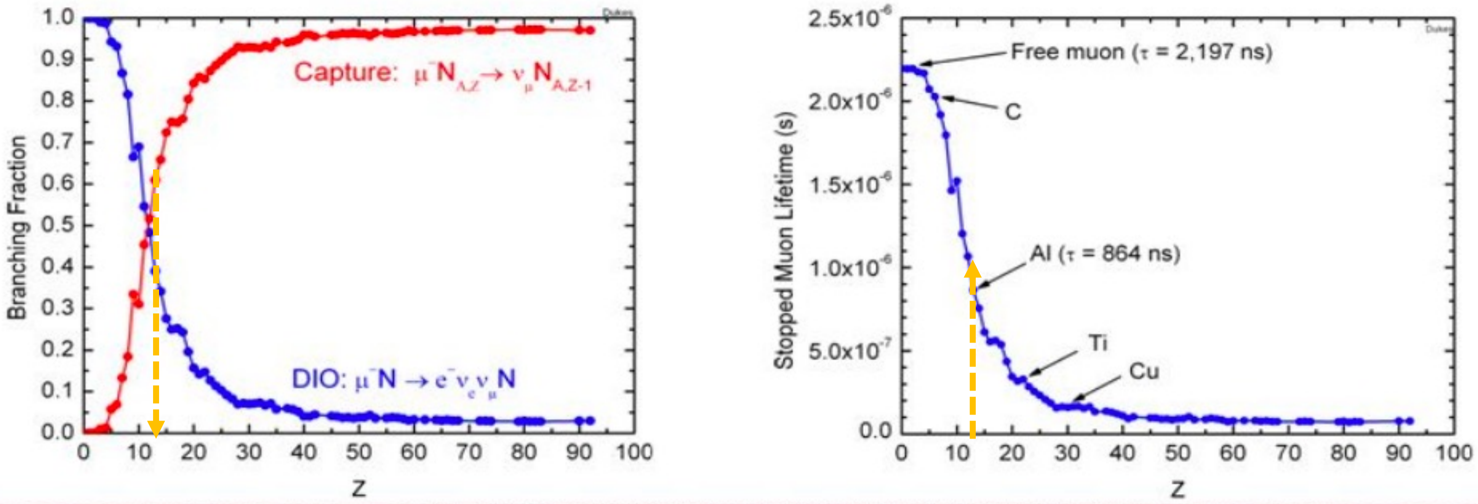
Mu2e: Why Al?

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.

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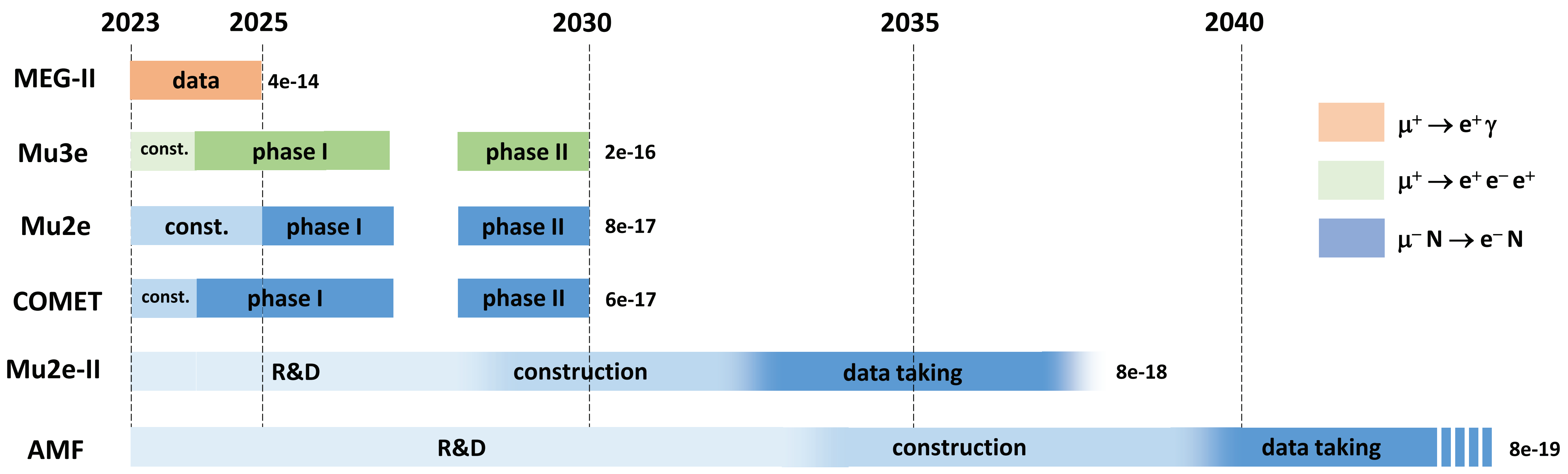
Timelines



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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.