FERMILAB-SLIDES-19-081-FESS

The Mu2e: The Muon to Electron Conversion Experiment

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From The University of Manchester

At the Fermilab Users Meeting

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OUTLINE

- What are we looking for?
- Experimental Method Employed by Mu2e.
- Hardware and Infrastructure.
- Current Status of Hardware.
- Looking Further ahead.
- Questions?

Motivation

- Mu2e is an experimental search for the coherent, neutrinoless conversion of a muon to an electron in the presence of an Aluminium nucleus

$$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z,N) \rightarrow e^- + A(Z,N))}{\Gamma(\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N))} < 7 \times 10^{-13} (90\% CL)$$

(W. Bertl, et al. (SINDRUM-II) Eur.Phys.J. C47, 337 (2006))

- Mu2e will use the Fermilab accelerator complex to improve the sensitivity by 10^4 on current limit.
- Mu2e aims to achieve a limit of $R_{\mu e} < 8\times10^{-17}$ (90% CL).
- Measure a signal with Single Event Sensitivity of $\approx 3\times10^{-17}$, discovery at 2×10^{-16} (5σ).

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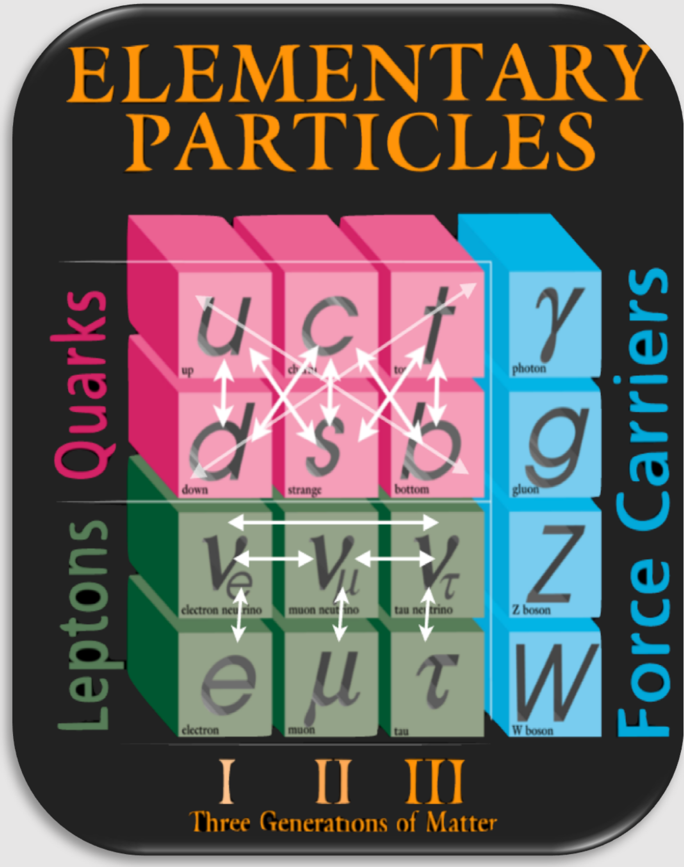
Flavor Violation

- The Quarks commit Flavor Violation
  - Mixing strengths are parameterized by CKM matrix.
- ν oscillations →Lepton Flavour Violation (LFV)
  - Mixing strengths parameterised by the PMNS matrix.



What about Charged Leptons?

- LFV - Rate constrained by mixing parameters & neutrino masses
- Neutrino Oscillations give rise to CLFV!
- Other sources of CLFV are model-dependent :
  - → Can vary over many orders of magnitude.
  - → Relative rates of different CLFV processes is important.

→ CLFV depends on mechanism behind neutrino masses and lepton mixing.

*CLFV=Charged Lepton Flavor Violation

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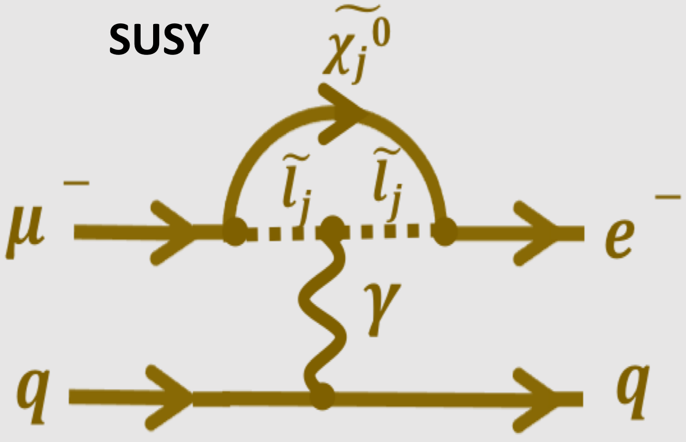
New Physics (NP) Scenarios

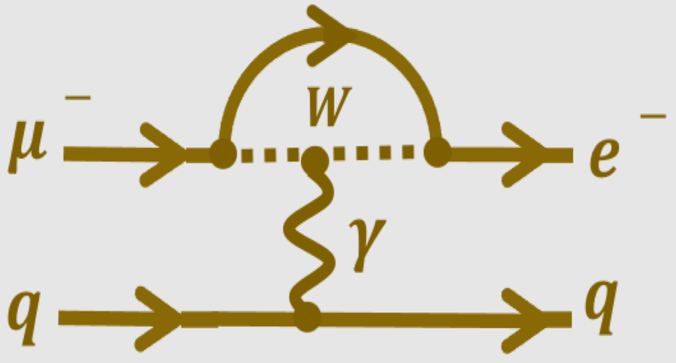
Multitude of possible new physics contributions to $\mu N \rightarrow e N$ which predict $R_{\mu e}$ $O(10^{-15})$ or higher:

Loop "Photonic"

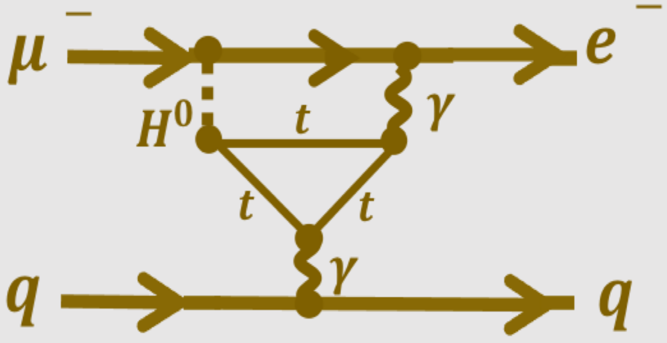
SUSY



Heavy Neutrinos

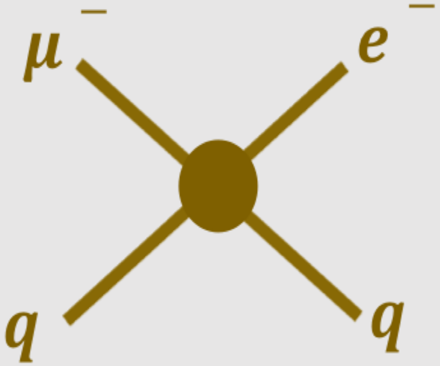


2 Higgs Doublets

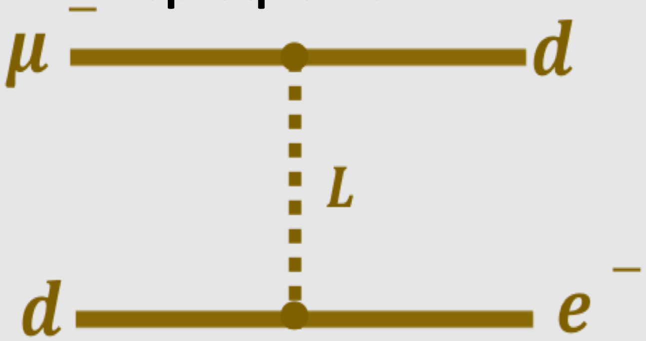


"Contact"

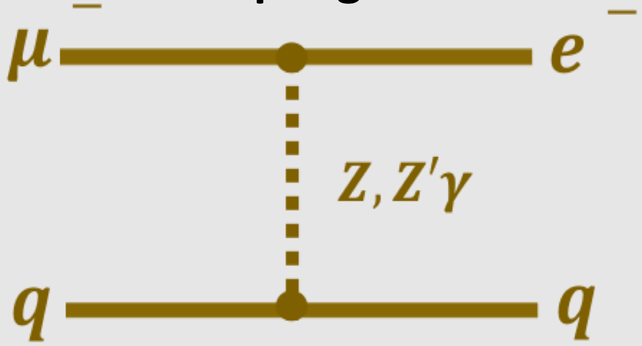
Compositeness



Leptoquarks



Anomalous Couplings

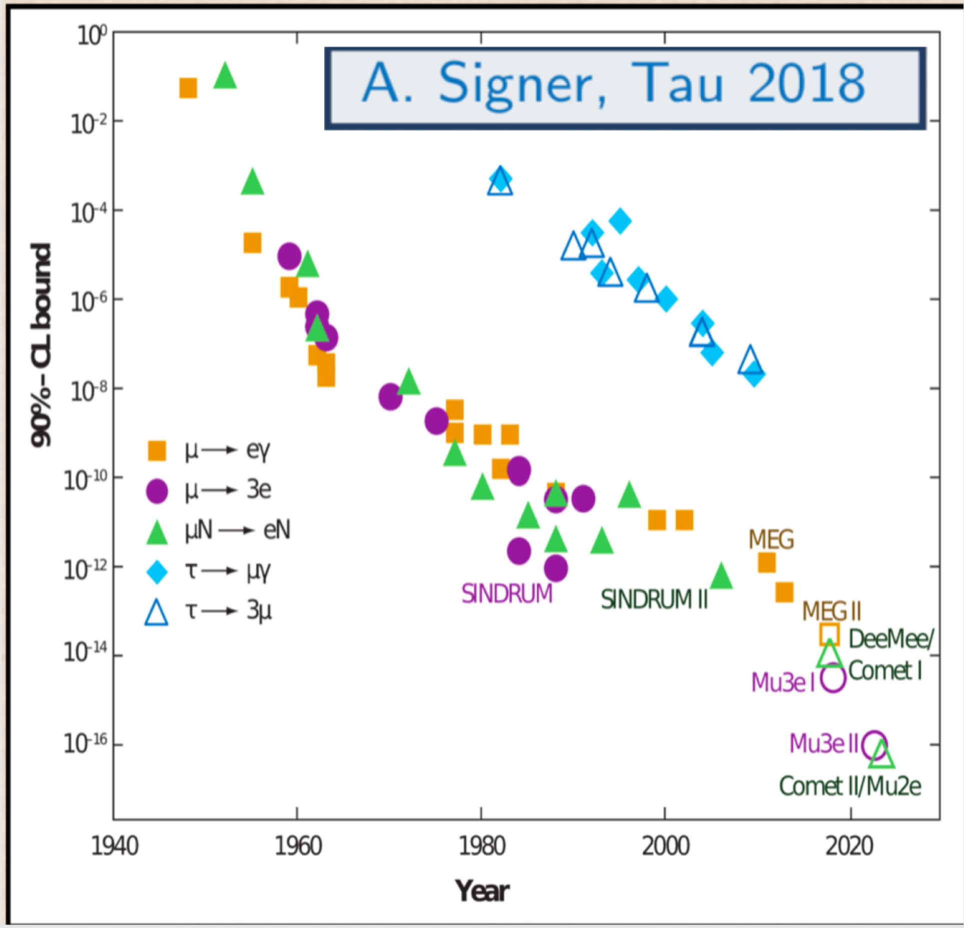


Theory Reviews: Y. Kuno, Y. Okada, 2001; M. Raidal et al., 2008
A. de Gouvêa, P. Vogel, 2013

CLFV with Muon Experiments

- **To elucidate the mechanism responsible for NP–must look at relative rates of CLFV for many processes.**
- **Intense muon beams put muon sector at forefront.**
- **3 muon CLFV channels with complementary sensitivity to NP effects:**

Mode	Current Limit (at 90% CL)	Future Limit	Future Experiment/s
$\mu^{\pm} \rightarrow e^{\pm}\gamma$	5.7 x 10^{-13} [1]	4 x 10^{-14}	MEG II[4]
$\mu^{-} N \rightarrow e^{-} N$	7 x 10^{-13} [2]	10^{-15} / 10^{-17}	COMET [5] Phase 1/ Mu2e[6]
$\mu^{+} \rightarrow e^{+}e^{+}e^{-}$	~10^{-12} [3]	10^{-15} ~ 10^{-16}	Mu3e[7]



[1] J. Adam *et al.* (EG Collaboration), Phys. Rev. Lett. **110**, 20 (2013).
[2] W. Bertl *et al.* (SINDRUM-II Collaboration), Eur. Phys. J. **C47,** 337 (2006).
[3] U. Bellgardt *et al.*, (SINDRUM Collaboration), Nucl. Phys. **B299**, 1 (1988).
[4] A.M. Baldini *et al.*, "MEG Upgrade Proposal", arXiv:1301.7225v2 [physics.ins-1.det].
[5] Y. Kuno *et al.*, "COMET Proposal" (2007)
[6] Mu2e TDR, arXiv:1501.05241
[7] Nuclear Physics B - Proceedings Supplements Volumes 248–250, March–May 2014, Pages 35-40
[8] Marciano, W. J., T. Mori, and J. M. Roney (2008)

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Model Independent Effective Lagrangian

✧ **Estimate sensitivity CLFV process in model independent manner by adding 2 different LFV effective operators to the SM Lagrangian:**

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

"Photonic"

$\mu^\pm \rightarrow e^\pm\gamma$, $\mu \rightarrow eee$

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

"Contact"

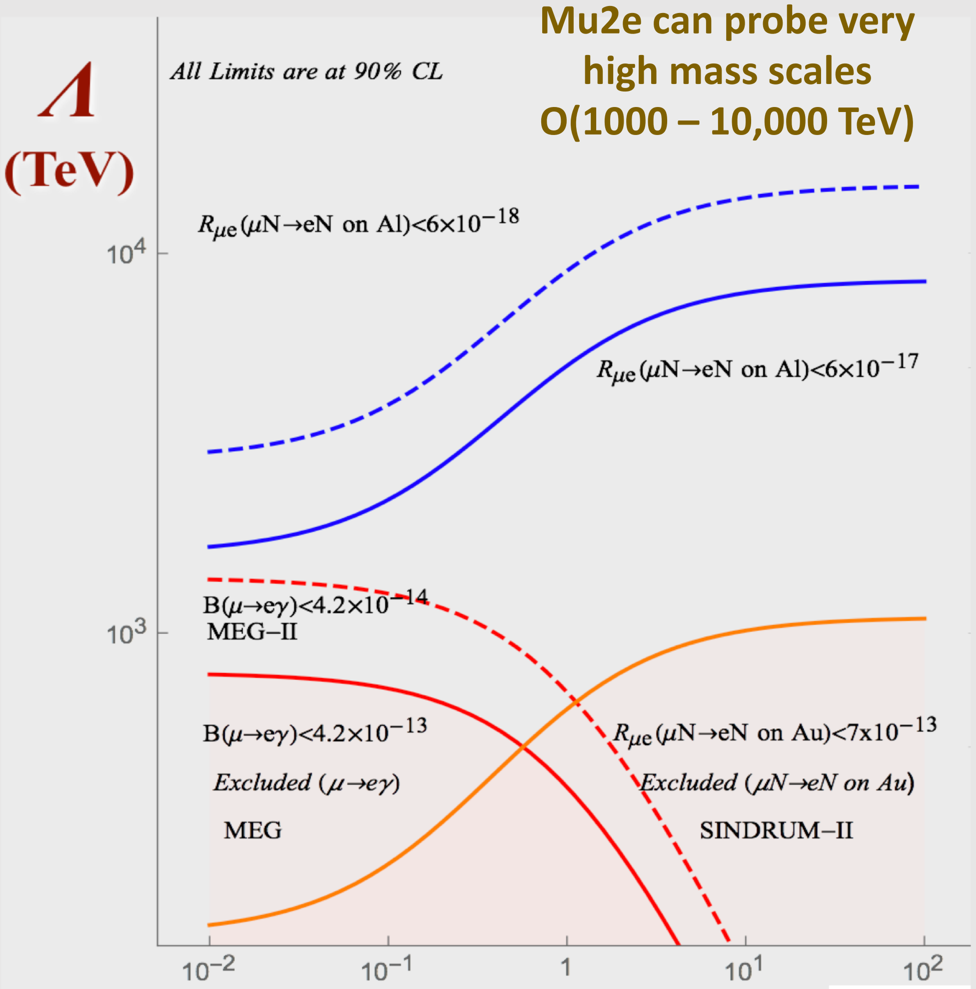
Only $\mu^+ \rightarrow e^+e^+e^-$

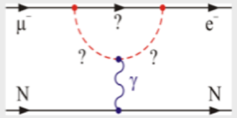
And $\mu^- N \rightarrow e^- N$

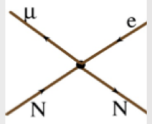
Λ= the effective mass scale of NP,

κ = controls the relative contribution of the two terms

e.g SUSY $\kappa = 0$







*From Bob Bernstein

For more detailed theoretical understanding: Eur. Phys. J C75 (2015) no.12, 579

How to Improve From SINDRUM-II?

- The SINDRUM-II results was limited by 2 main factors:
  - Backgrounds from prompt pions,
  - The muon stopping rate (~$10^7\mu$/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 -3 year run equates to 10^{18} stopped muons.
  - Use superconducting solenoids – For efficient muon collection and transport to stopping target.

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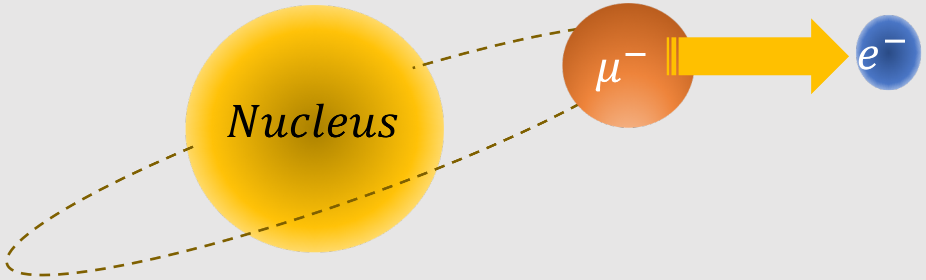
The Signal

1. Low momentum (-) muons are captured in the Al target's atomic orbit and quickly (~fs) cascades to 1s state.

2. The Signal:
   - $t_{\mu Al}$ = 864 ns – important for discriminating backgrounds .
   - Monoenergetic electron consistent with $E_e = m_\mu - E_{recoil} - E_{1S\ B.E}$, For Al: E_e=104.97 MeV.
   - Nucleus coherently recoils off outgoing electron; it does not break-up!

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



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The Backgrounds

Design choices ensure Mu2e is to almost background free

- **Intrinsic :**
  - Scale with number of stopped muons.
- **Late arriving :**
  - Scale with number of late protons/extinction performance

Type	Source	Mitigation	Yield
Intrinsic	Decay in Orbit (DIO)	Tracker Resolution	0.144 ± 0.028 (stat) ± 0.11 (sys)
Late Arriving	Pion Capture	Beam Structure	0.021 (stat) $\pm 0.001 \pm 0.002$ (sys)
	Pion Decay in Flight	-	0.001(stat) $\pm < 0.001$ (sys)
Other	Anti-proton	Thin windows	0.04 ± 0.022 (stat) ± 0.020 (sys)
	Cosmic Rays	Veto System	0.209 ± 0.0022 (stat) ± 0.055 (sys)

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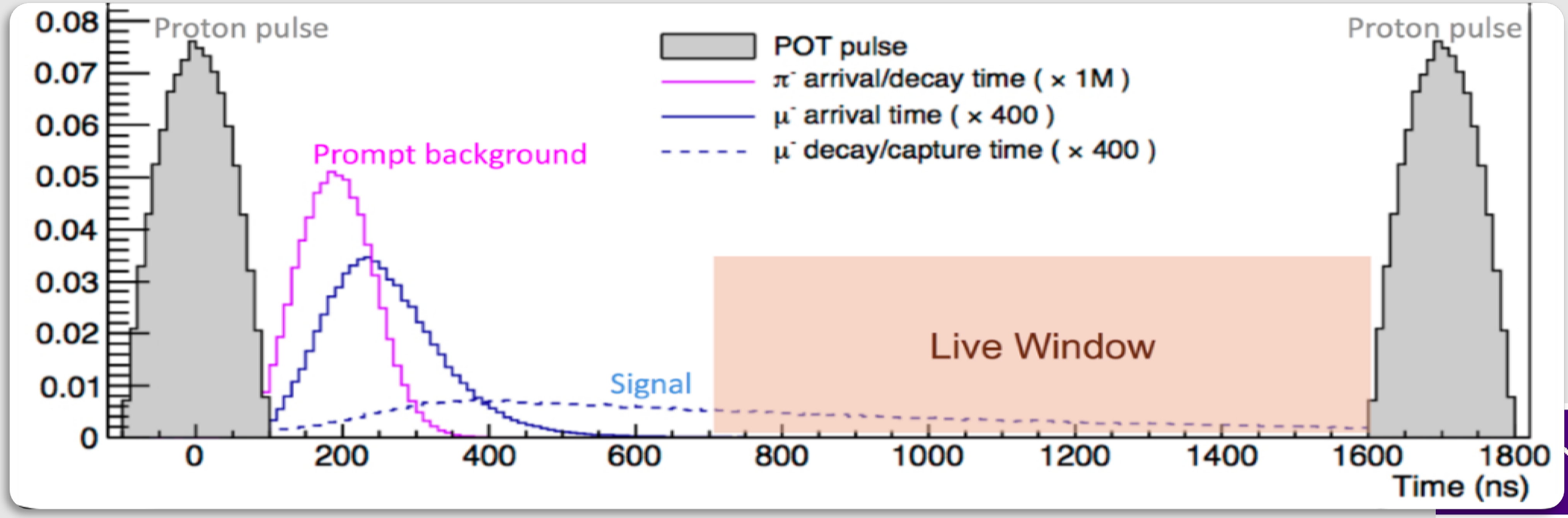
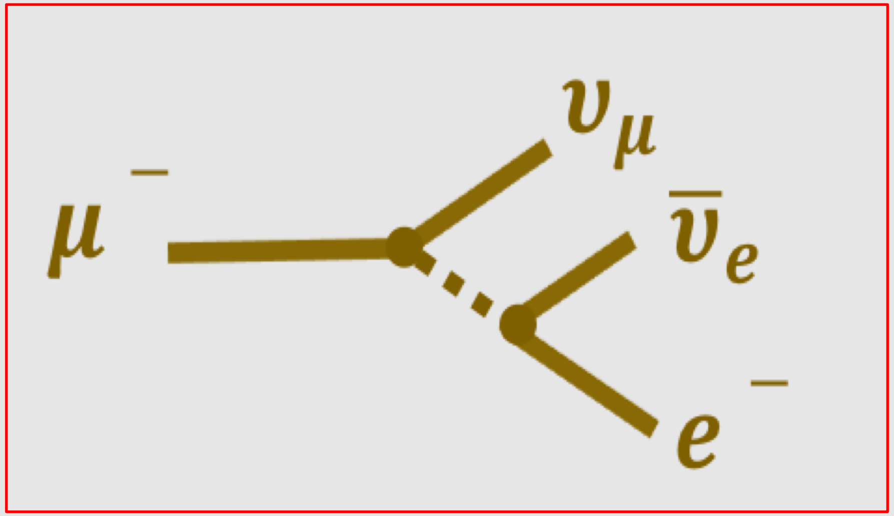
Mu2e Pulsed Proton Beam

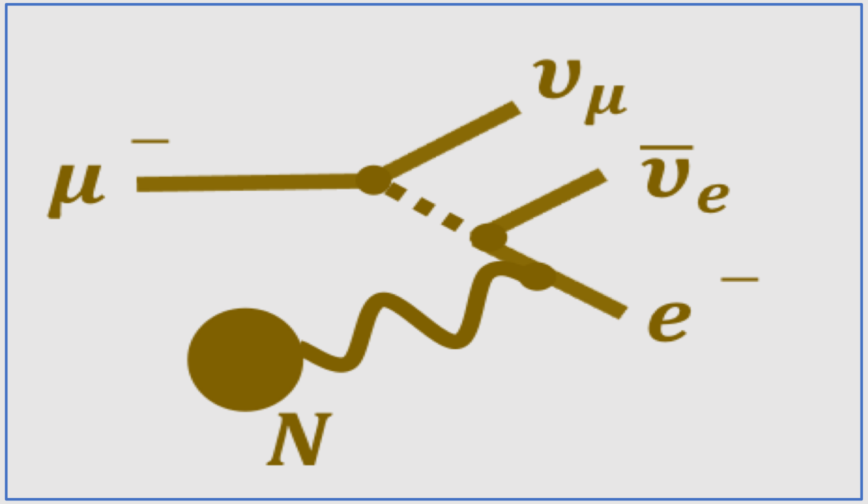
- Mu2e uses a pulsed beam with a long interval between pulses.
- Search window begins 700ns in–this suppresses prompt backgrounds e.g. pion background reduced by $>10^{-11}$.
- Must eliminate protons that arrive late. These can give rise to additional pion backgrounds in delayed live window.
- AC Dipole in beamline helps ensure $< 10^{-10}$. Extinction monitor measures.



The Importance of Tracker Resolution

- In 39% of stopped muons will decay in orbit (DIO).
- This is a 3 body decay. In free decay maximum electron energy is far below our signal energy (104.97 MeV) .
- The free decay spectrum is distorted by the presence of the nucleus.





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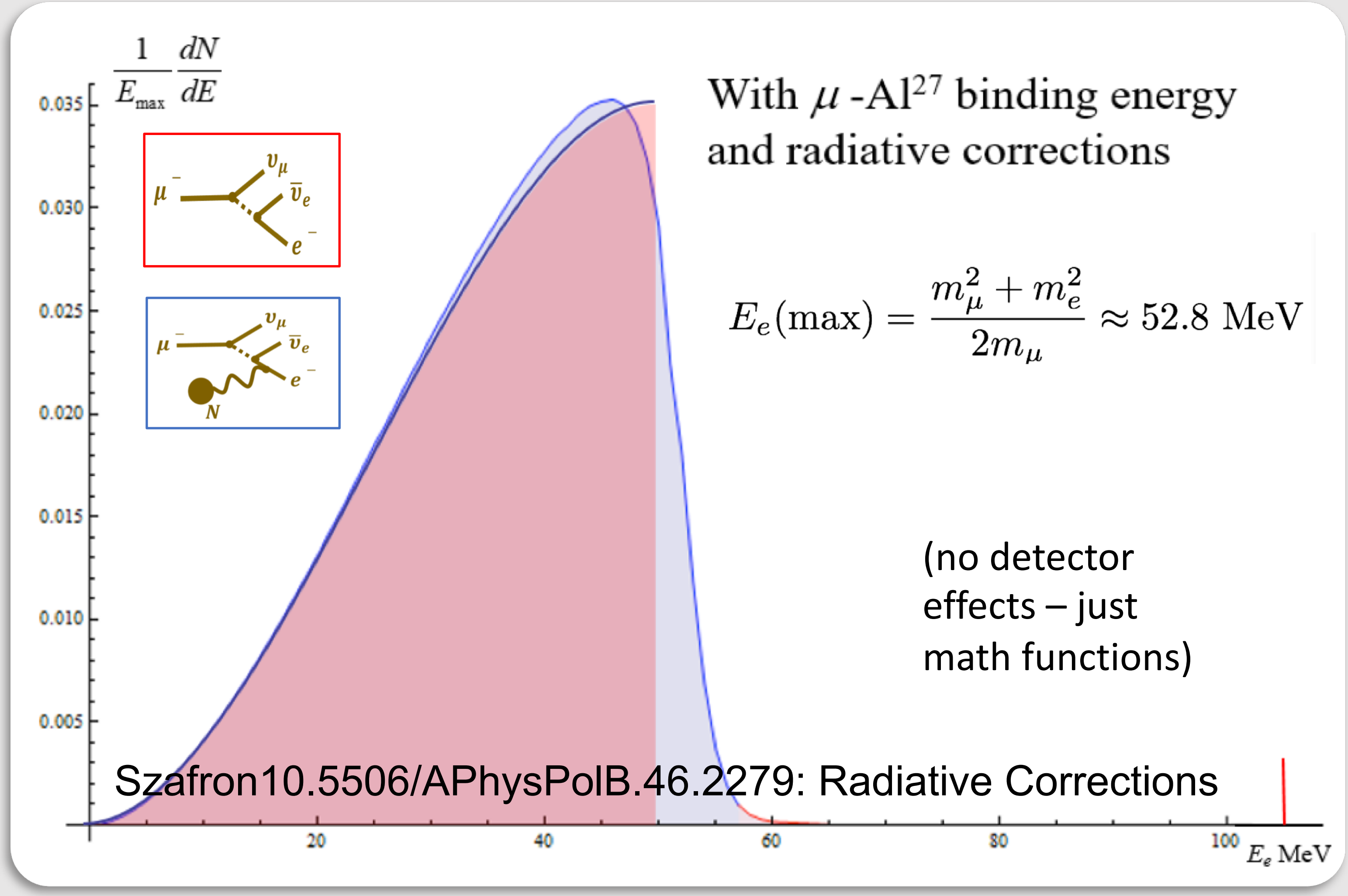
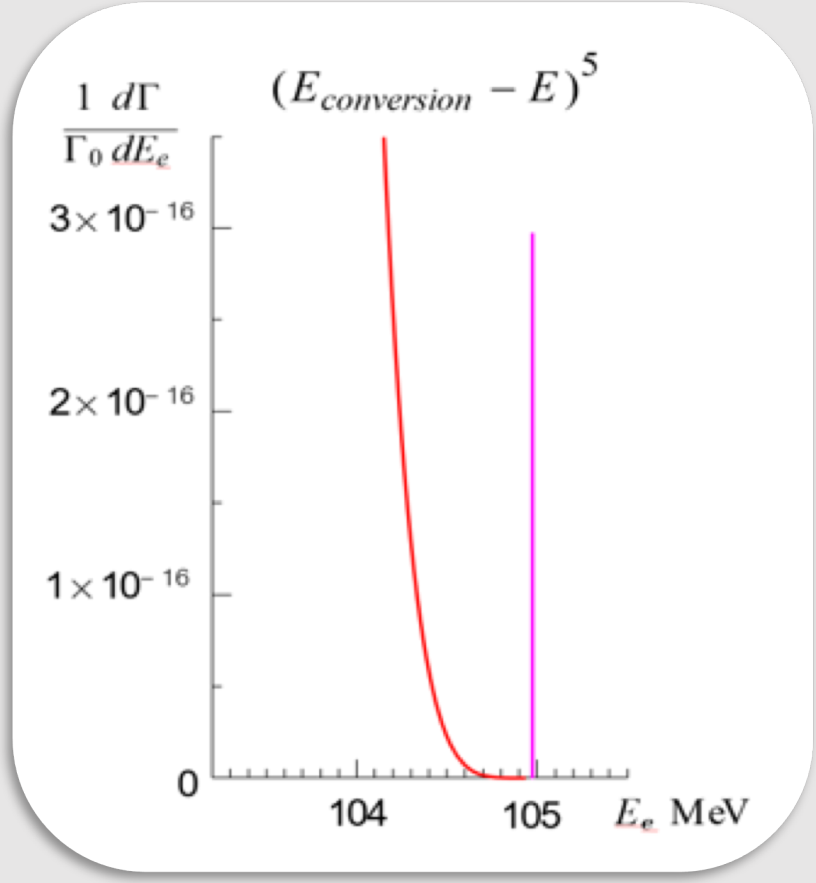
The Importance of Tracker Resolution

- Mu2e requires excellent tracker resolution of <200 keV/c to suppress DIO background.



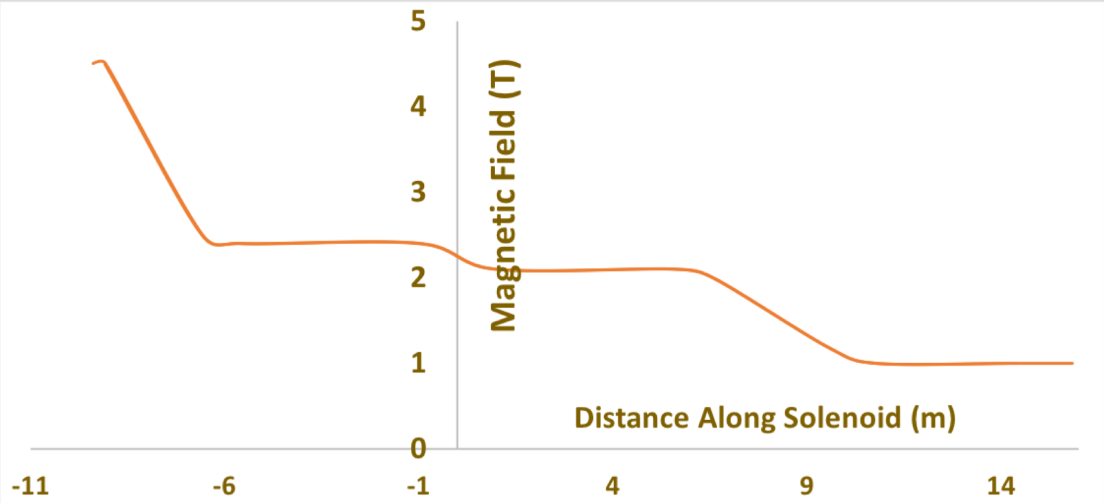


Summary

- In order to reach design sensitivity Mu2e will use:
  - Low mass straw tracker provides excellent momentum resolution <200 keV/c on electrons.
  - Pulsed proton beam with:
    - Narrow proton pulses (< +/-125 ns) .
    - Very few out-of-time protons (< 10^{-10}) .
- Anti-proton backgrounds reduced by thin anti-proton windows in beamline.
- Passive and active shielding means high cosmic ray veto efficiency (>99.99%).

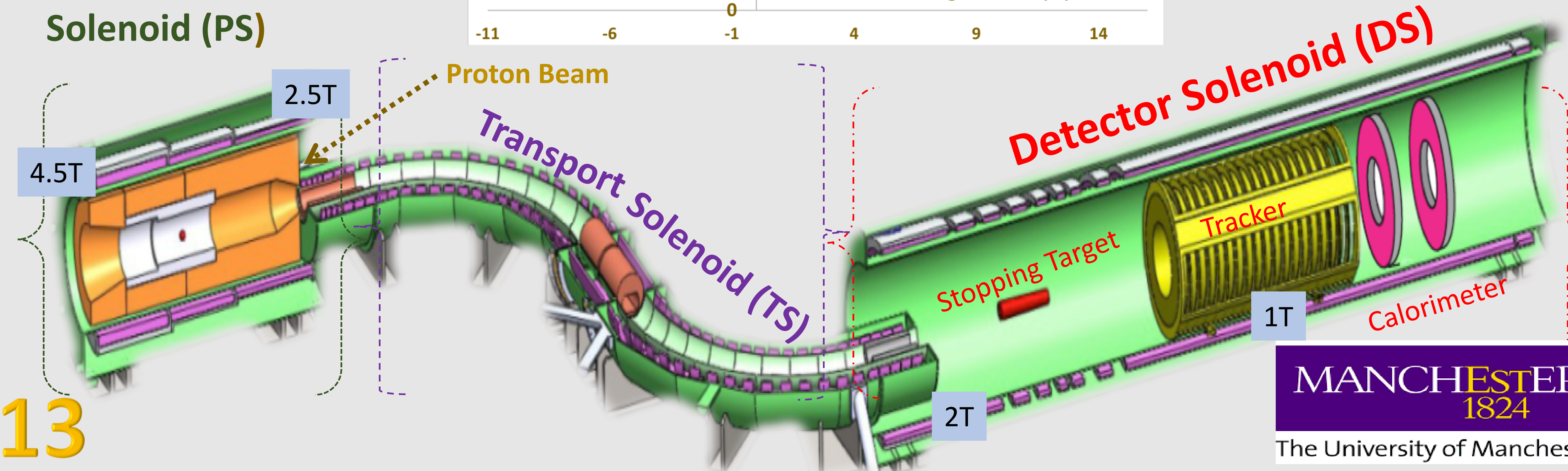
The Mu2e Solenoids

25 m in total



Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons .

Production Solenoid (PS)



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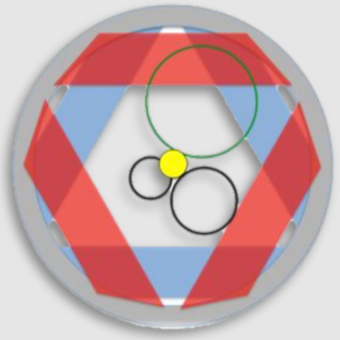
The Tracker: Purpose

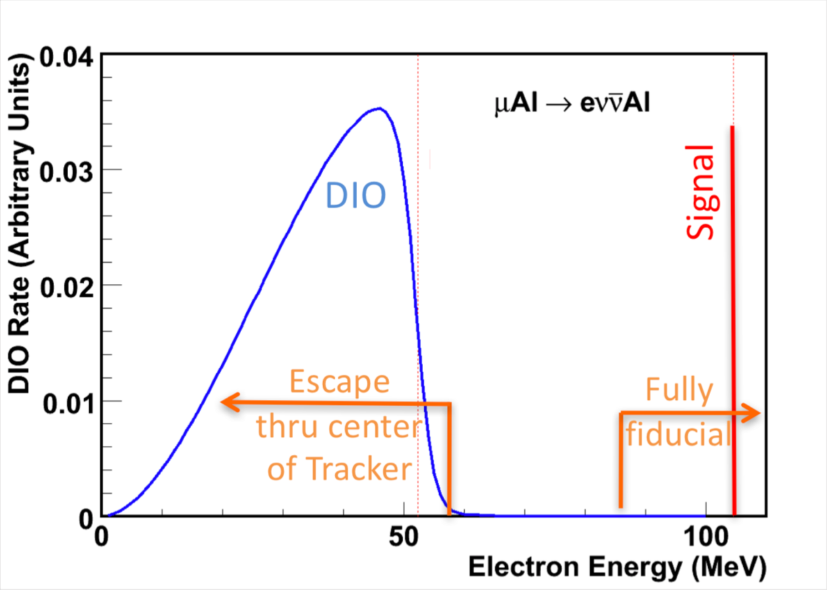
- A low mass, annular, highly segmented detector is used to:

1. Minimizes scattering and energy loss :
   - Entire Detector Solenoid held under vacuum (~10^{-4} torr).
   - Ultra low mass tracker .
2. Minimizes Background Tracker - excludes low momentum electrons via hollow centre:
   - Inner 38 cm instrumented .
   - Reduces need to reject ~ 10^{18} to ~10^{5} .
   - Blind to >99% of DIO spectrum .
3. Handle high rates and provide high-precision momentum measurements :
   - Highly segmented design.

Transverse Plane



Signal
DIO



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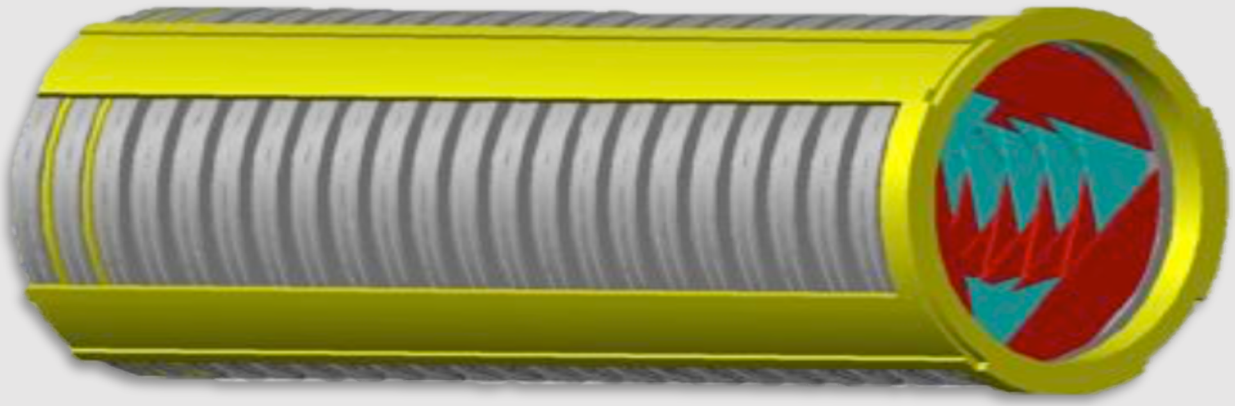
The Tracker: Design

- Tracker is constructed from self-supporting panels of low mass straws tubes detectors
- 18 stations, 2 planes per station, 6 panels per plane, 96 straws per panel.
- Straw drift tubes aligned transverse to the axis of the Detector Solenoid.
  - 1m, 5 mm diameter straw
  - Walls: 12 mm Mylar + 3 mm epoxy
  - 25 mm Au-plated W sense wire
  - 33 – 117 cm in length
  - 80:20 Ar:CO_2 with HV < 1500 V

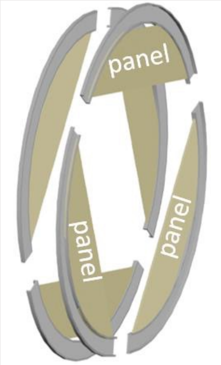
The Straws:

The Tracker:

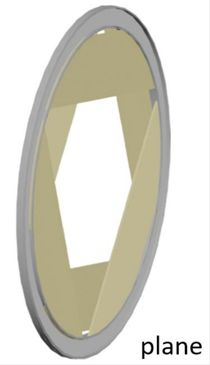
~ 3m, 1 T field



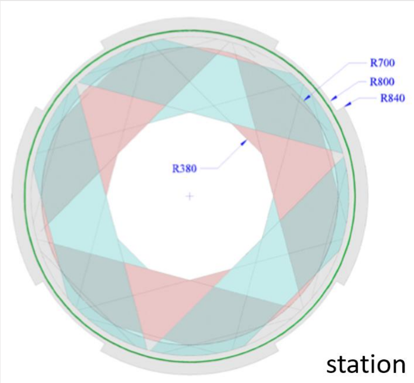
Panels



Plane

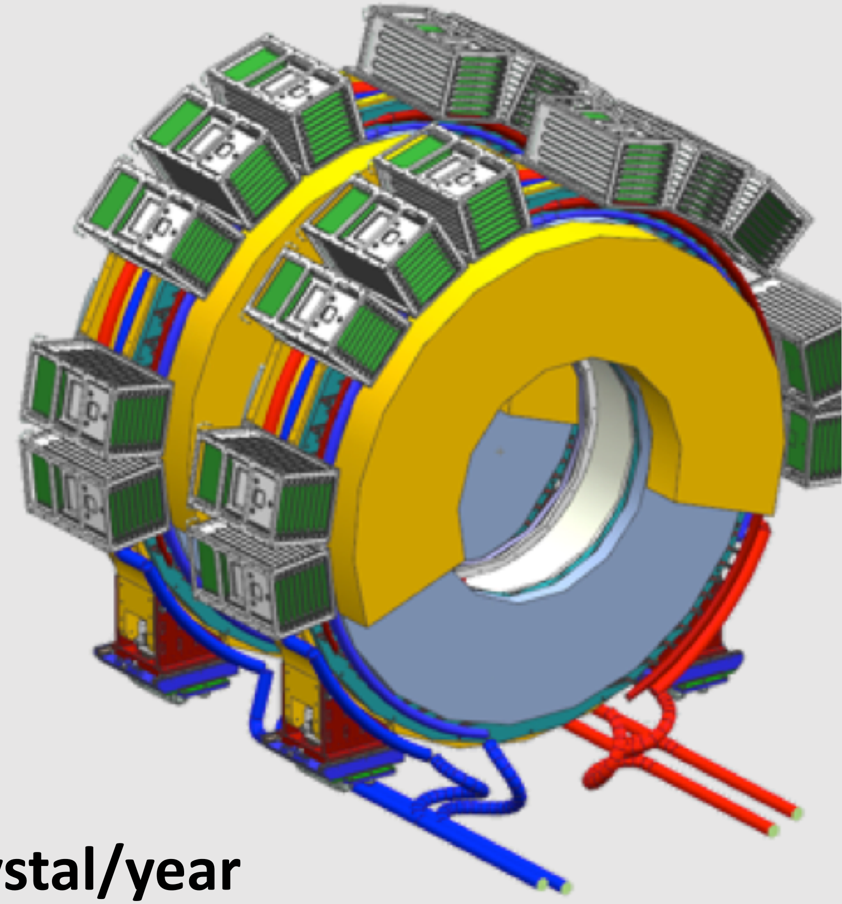


Station



The Calorimeter: Purpose

- The calorimeter is vital for providing:
  - Particle identification,
  - Fast online trigger filter,
  - Accurate timing information for background rejection
  - Seed for track reconstruction.
- The calorimeter must:
  - Have a large acceptance.
  - Provide time resolution < 0.5 ns,
  - Energy resolution < 10%;
  - Position resolution of 1 cm.
  - Function in region with radiation exposure up to 20Gy/crystal/year and with neutron flux 10^{11} /cm^2



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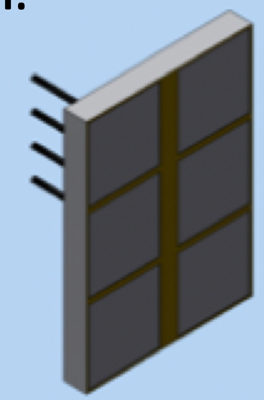
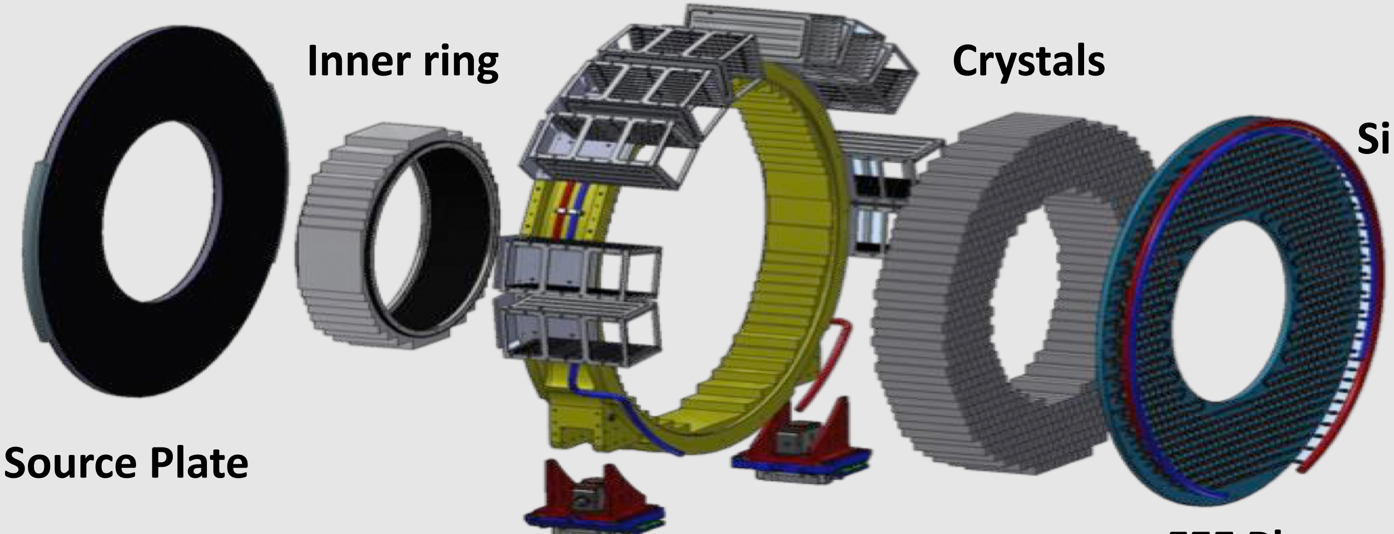
The Calorimeter: Design

- Mu2e calorimeter uses 2 annular, disks with radius 37-66 cm.
- 674 undoped CsI(34 x 34 x 200) mm^3 square crystals in each disk.
- Separated by 70 cm - distance chosen so if signal electron goes down through centre it hits the next disk.
- Redundant readout - Each crystal 2 UV-extended SiPMs.
- 1 FEE/SiPM - SiPM holders with front end electronics (FEE) are inserted into the backplane.

Crystals:

SiPM:





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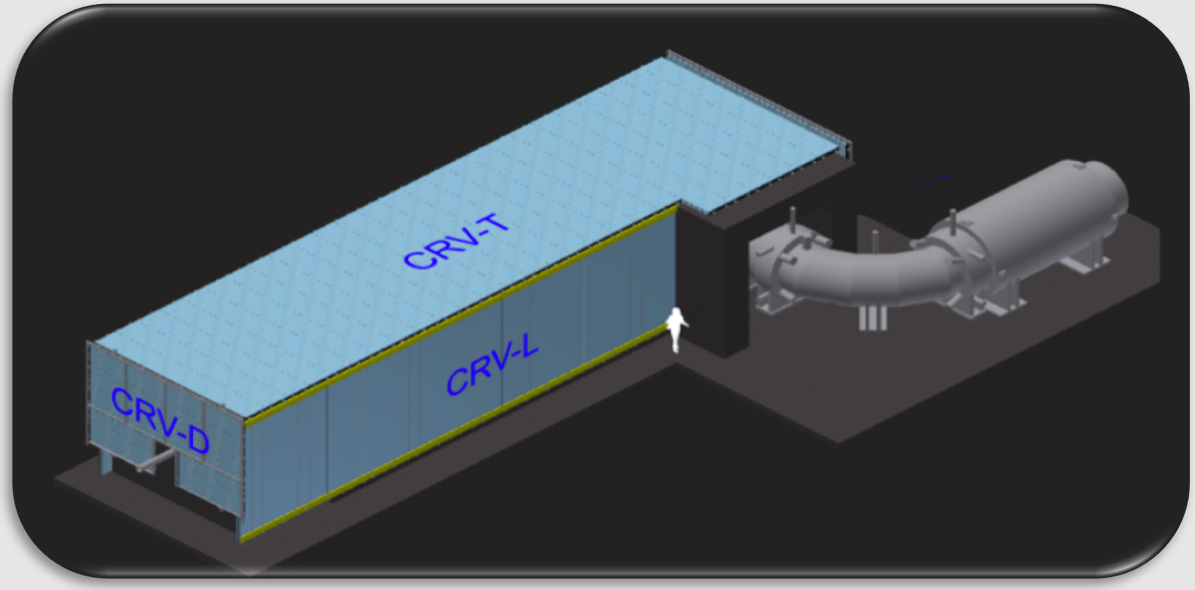
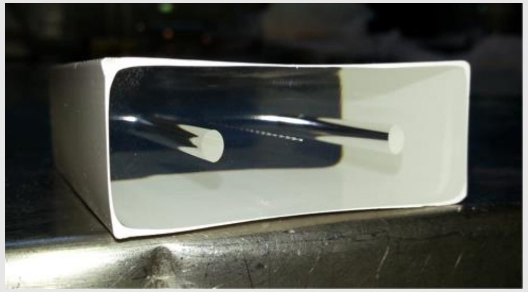
The Cosmic Ray Veto

Each day, ~1 conversion-like electron is produced by cosmic rays

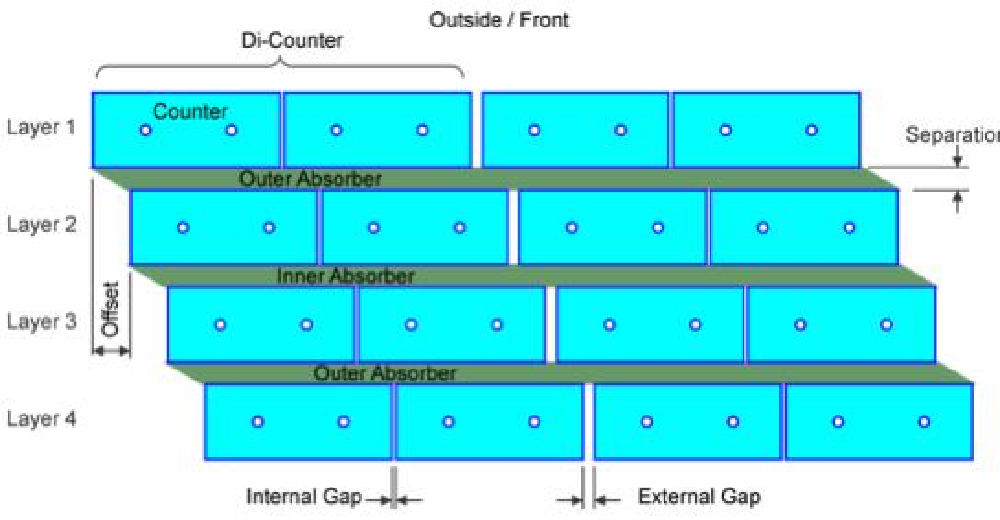
Cosmic Ray Veto will prevent cosmic muons faking a signal:

- 4 layers of extruded polystyrene scintillator counter.
- Surrounds the top and sides of DS and the downstream end of the Transport Solenoid.
- Suppresses the spurious detection of conversion-like particles initiated by cosmic-ray muons.
- 99.99% efficiency requirement!



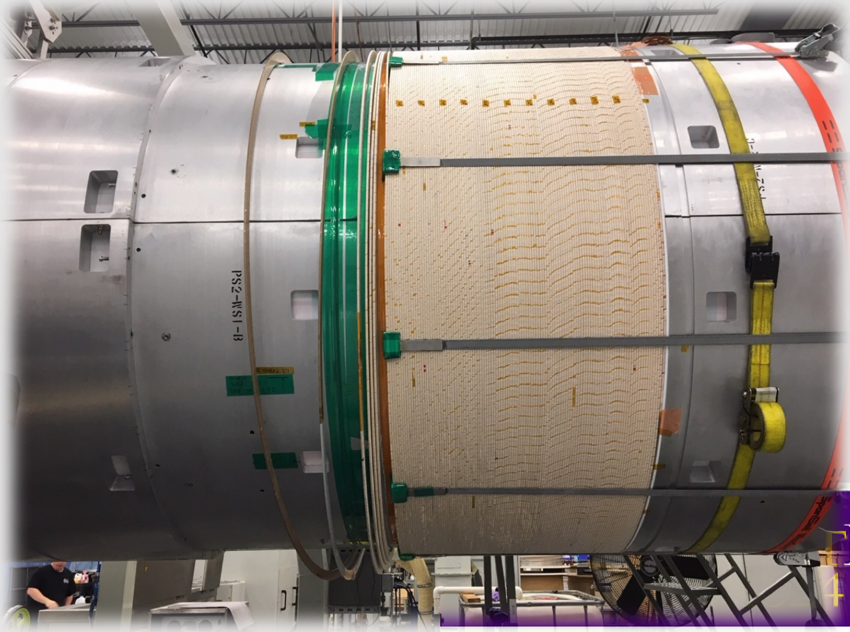


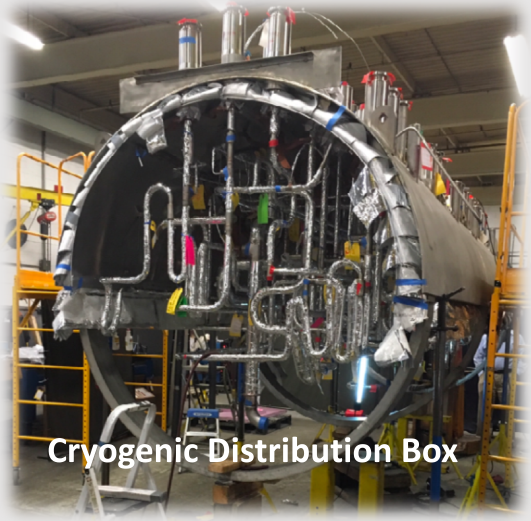
Each panel is composed of 5 x 2 x 450 cm^3 scintillator bars:



The Solenoids

- Production & Detector Solenoids built at General Atomics (GA):
  - Completed winding the first of the three PS coils.
  - Now winding first of the 11 DS coils as the PS coil goes through its finishing operations (potting, machining, insertion into its housing shell).
- Transport solenoid built at ASG & Shipped to Fermilab
  - ASG, has delivered 25% of the 27 TS coil modules.




Cryogenic Distribution Box


TS Coil Module prototype at Fermilab

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The Tracker

- Prototype panels complete, ramping-up production line.
- Full-sized pre-production panels assembled and tested.
- Multiple panels have been assembled into a prototype station.
- Final straw production is currently underway.
- FEE Readout QA taking place at LBNL/Berkeley, this summer.

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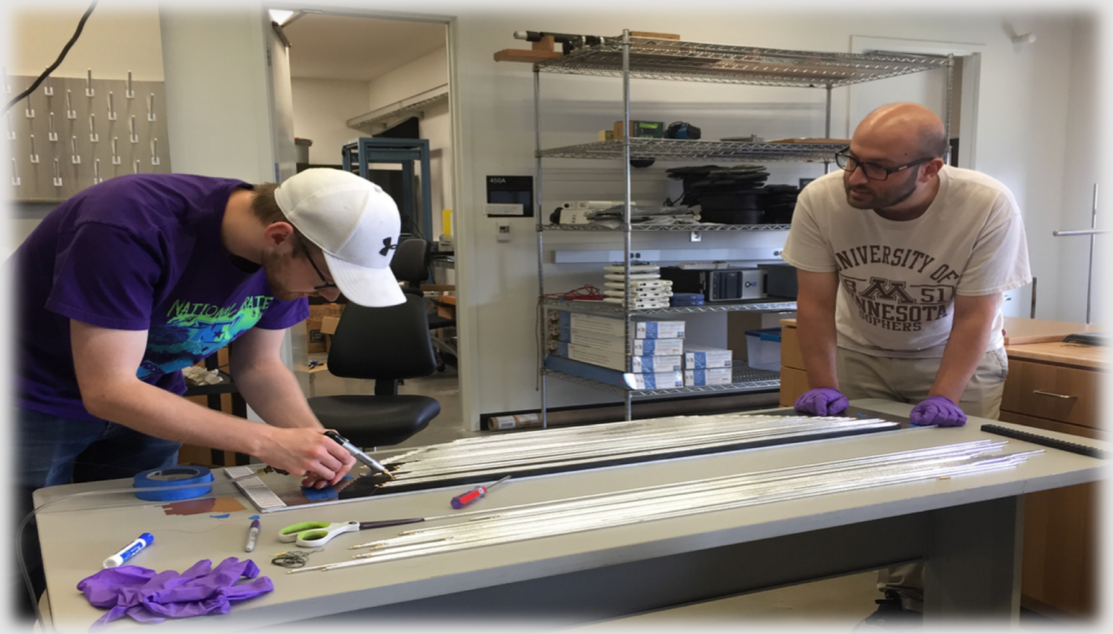

Fermilab

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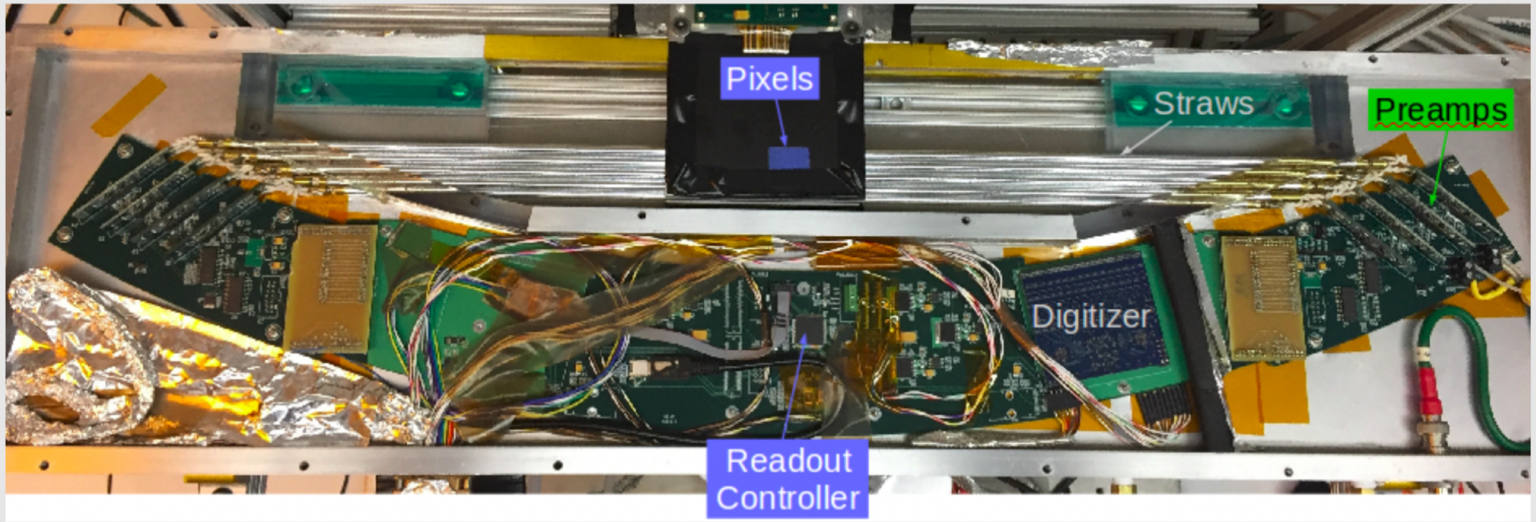
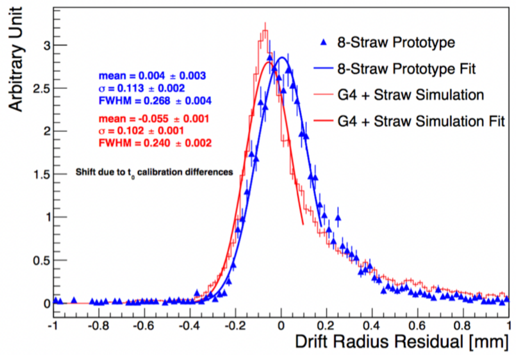
The Tracker

8 channel prototype



Measured gain, crosstalk, resolution...

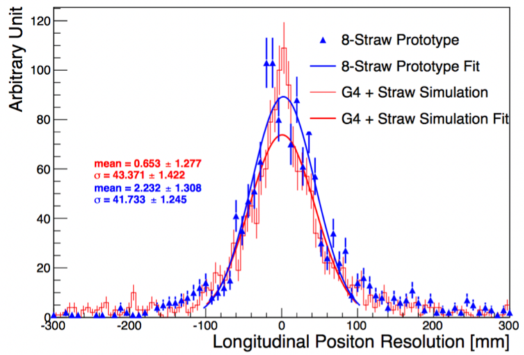
- Use Cosmic Rays.
- Use information gained to update MC.
- Measured performance and resolutions.
- Performance met requirements!



Transverse Resolution
(Data vs MC)

$\sigma_{data} = 0.113 \pm 0.002$ mm

$\sigma_{MC} = 0.102 \pm 0.001$ mm



Longitudinal Resolution
(Data vs MC)

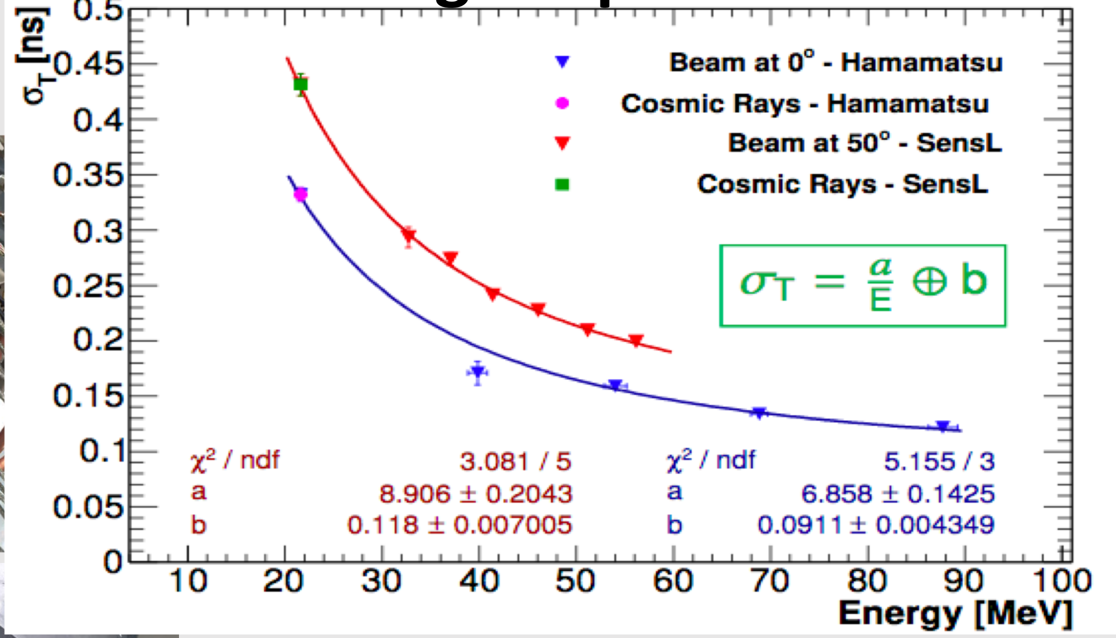
$\sigma_{data} = 42 \pm 1$ mm

$\sigma_{MC} = 43 \pm 1$ mm

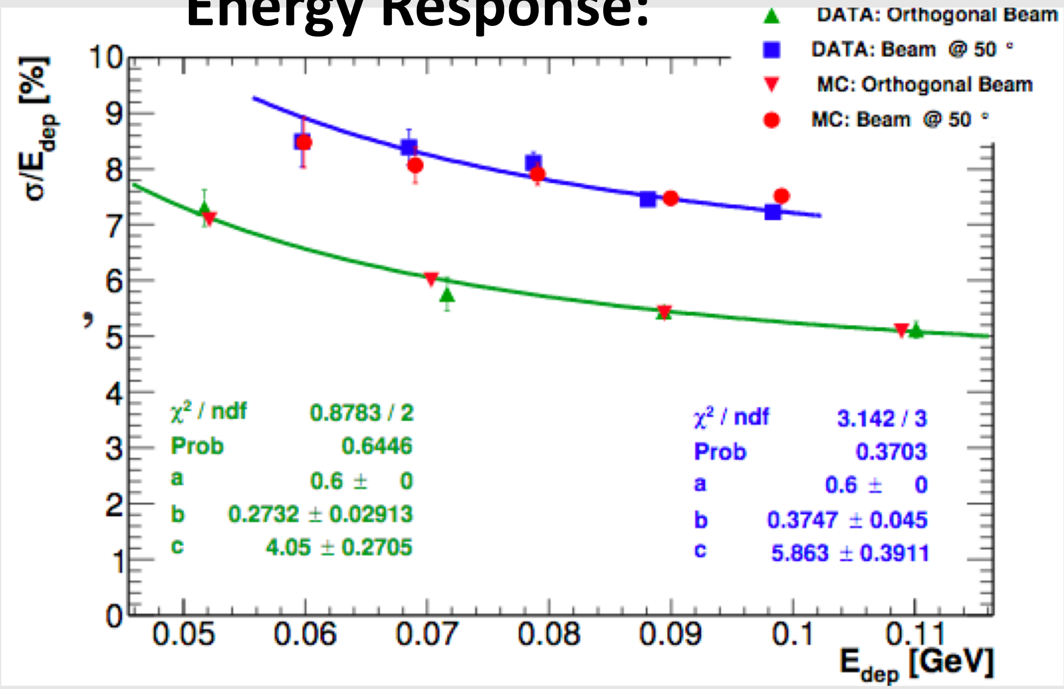
The Calorimeter

- R&D and Prototyping successfully completed.
- Crystal and SiPM fabrication has begun.
- 67% of crystals, 100% SiPMs.

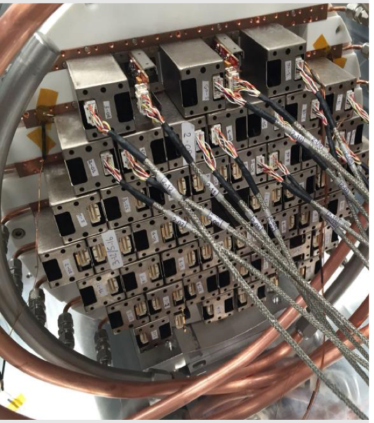
Timing Response:



Energy Response:



Typical time resolution
E_{beam} @ 100 MeV
σ_{T1} ~ 130 ps



- Test beam with e^- with E = 60-120 MeV .
- Good agreement between MC/Data!
- Meets energy and timing performance requirements!

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The Cosmic Ray Veto

- Di-counter production started June 2018.
- 1/3 of production is now done.
- Modules will be built at University of Virginia at a rate of 1-2 per week and shipped to FNAL -begins this summer (2019).

6 crates scintillator (4.7m) arriving:

Modules built @ University of Virginia

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What happens if we see a signal?

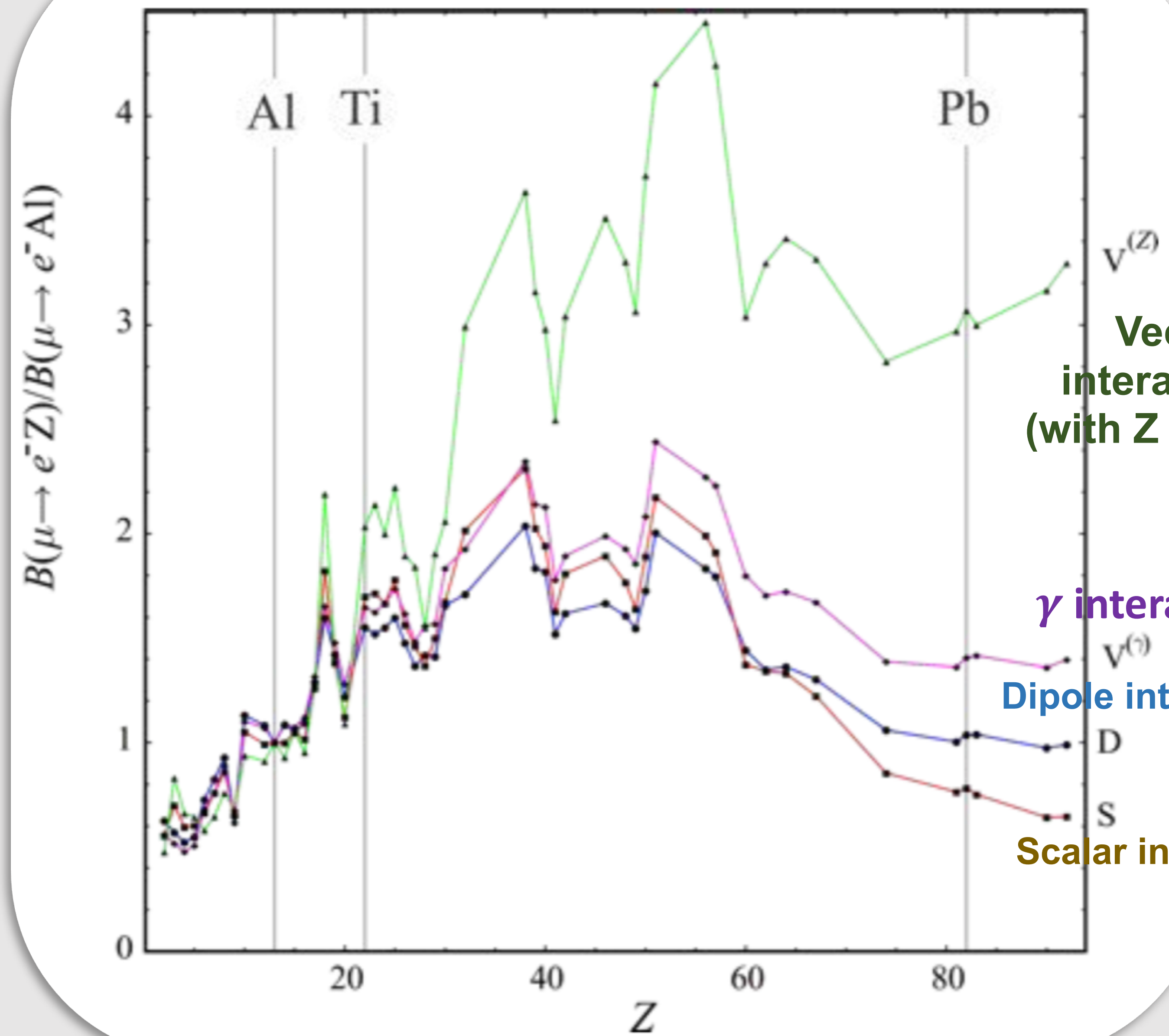
V. Cirigliano, S. Davidson, YK, Phys. Lett. B 771 (2017) 242
S. Davidson, YK, A. Saporta, Eur. Phys. J. C78 (2018) 109

If we do see a signal at Mu2e in Al:

- **Various operator coefficients add coherently in the amplitude.**
- **Weighted by nucleus-dependent functions.**

➔ Requires measurements of R in other target materials!

5% measurement on Al/Ti needed to see split



Vector interactions (with Z bosons)

γ interactions

Dipole interaction

Scalar interaction

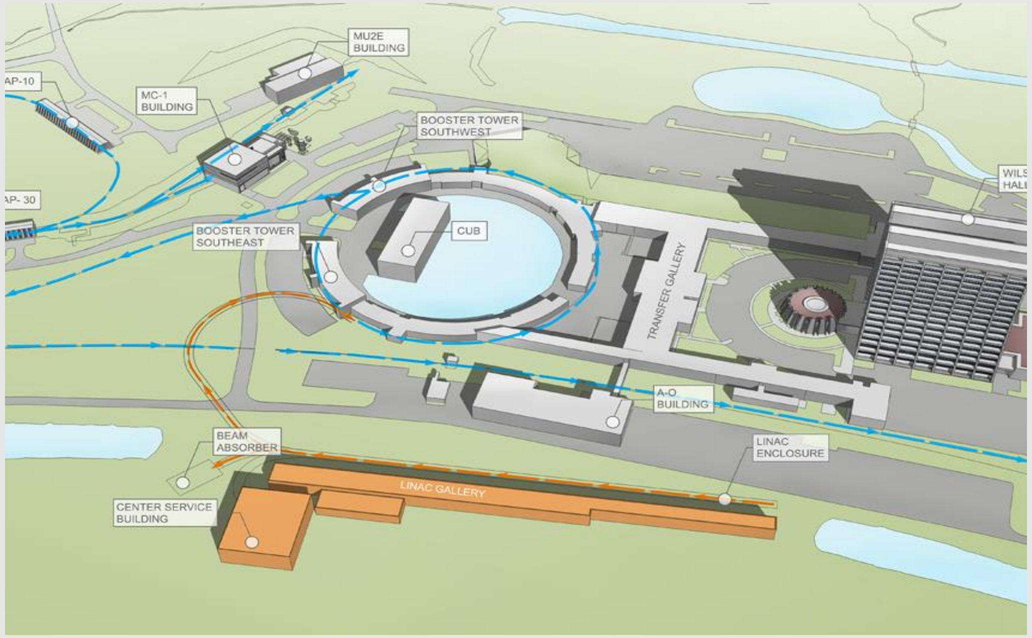
Mu2e II

- Use ~100 kW of PIP-II protons at 800 MeV to achieve an x10 improvement in sensitivity.

- If there is no signal at Mu2e:
  - We could extend our sensitivity to find a signal or set new limits.

- If Mu2e does see something:
  - Mu2e-II would improve statistical significance, different target materials to narrow down the NP processes.

- Mu2e-II could begin taking data around 2030.



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Summary

- The Mu2e Experiment is a search for CLFV based at Fermilab looking for signal of coherent, neutrinoless conversion of muon to electron in nucleus. Aims:
  - To Improve sensitivity on relative rate to reach $R_{\mu e} < 8 \times 10^{-17}$
  - With SES ~ 3×10^{-17}
  - And 5σ discovery at 2×10^{-16}.

- Will constrain New Physics models up to a scale of 10^4 TeV.

- Lots of activity currently underway at both FNAL and at our many collaborating institutions.

- Commissioning will begin in the next year with physics data taking expected by 2022.

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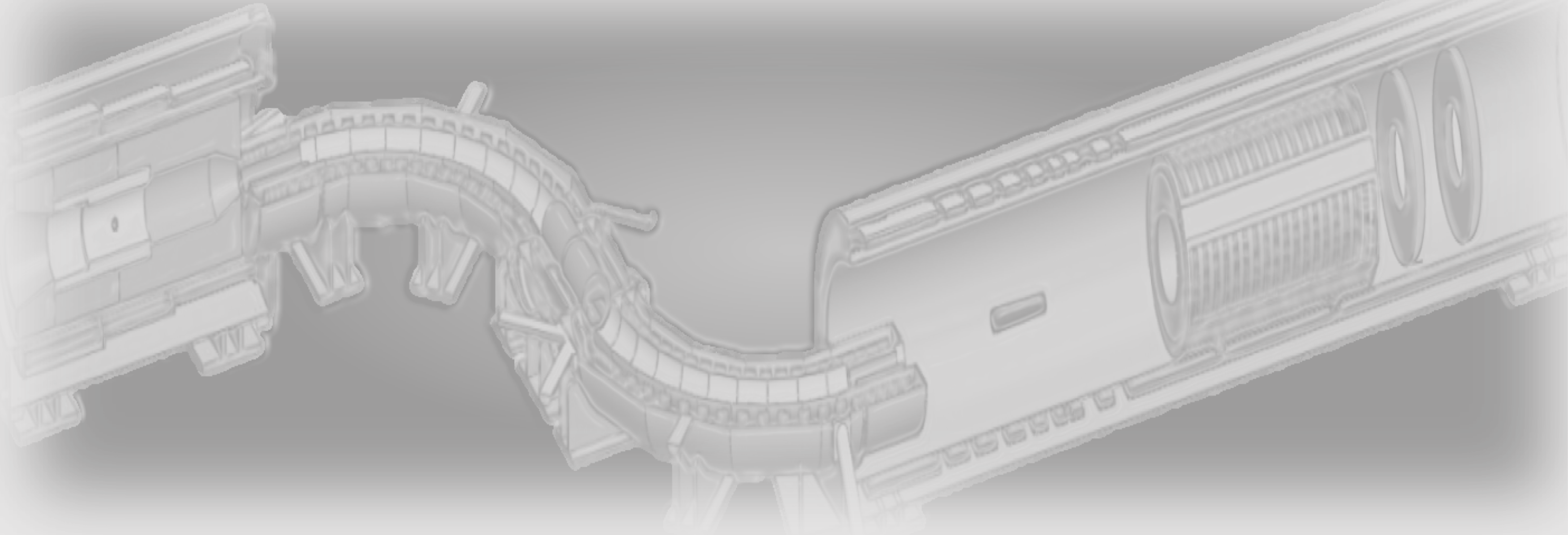

Thank You For Listening!

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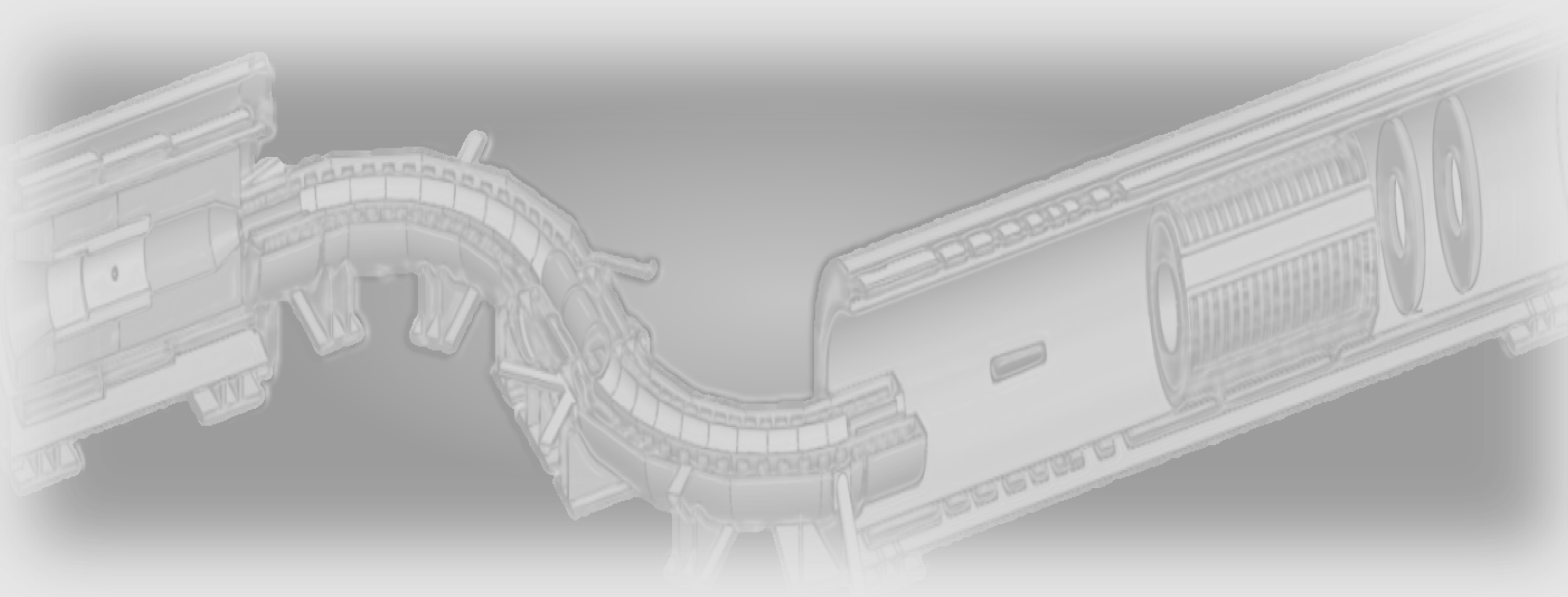

Back-Up

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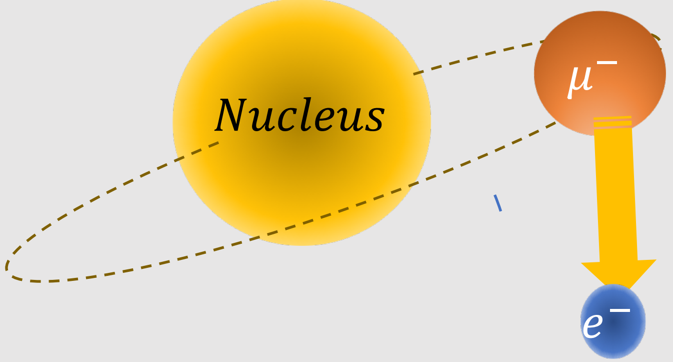
CLFV In the Standard Model

- In Minimal Extension to SM possible in loop diagrams due to neutrino oscillations:

$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

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



=> An observation is unambiguous evidence of New Physics!

- Broad array of New Physics models predict rates observable at next generation CLFV experiments - New Physics models predict rates in 10^{-14} – 10^{16} region.
- Mu2e sees 40 conversions at 10^{-15}.

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Discovery Sensitivity

★★★ = Discovery Sensitivity

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

- **Mu2e has discovery sensitivity across the board.**
- **Relative Rates however will be model dependent.**

*arXiv:0909.1333[hep-ph]

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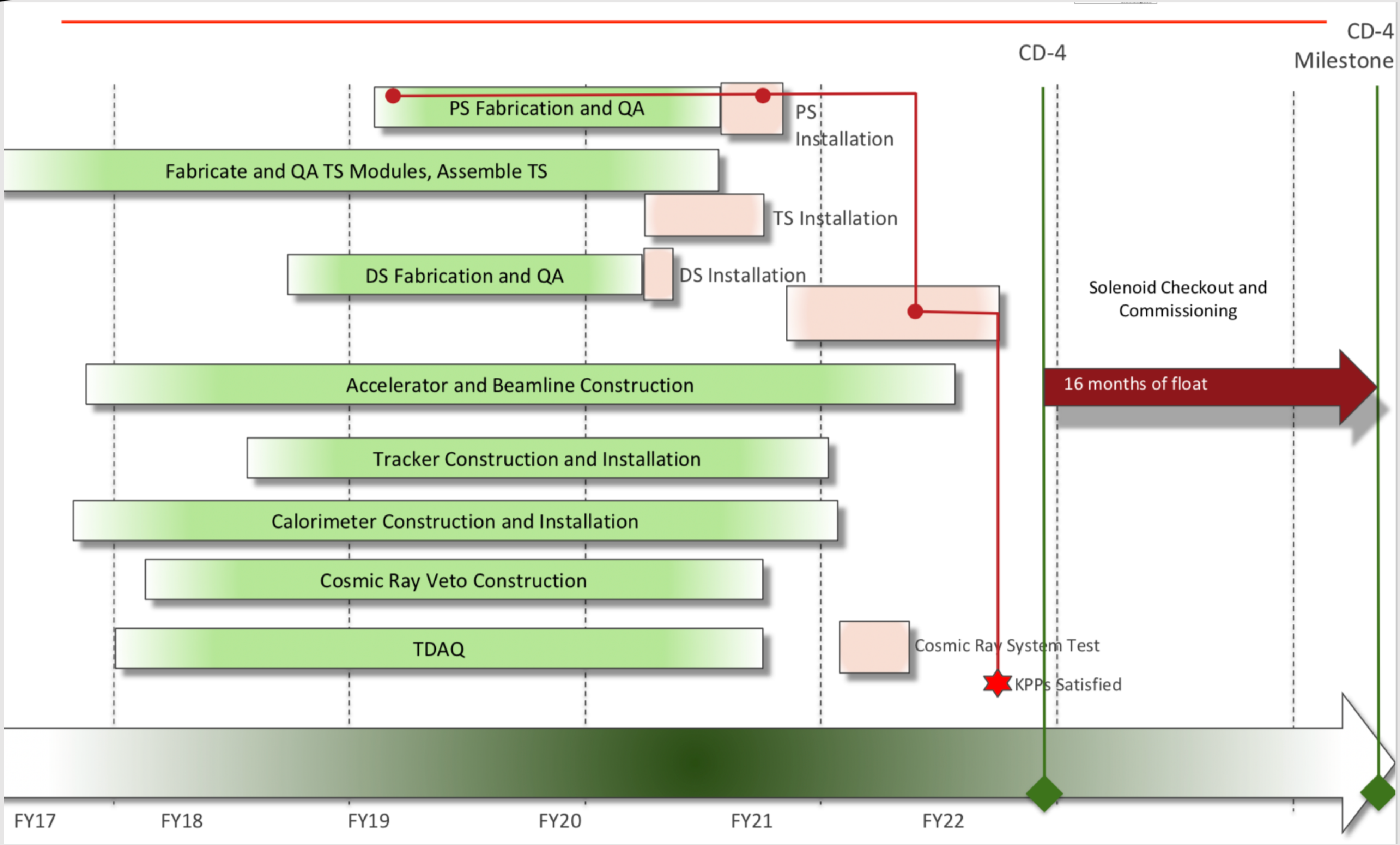
Schedule



CD-4
CD-4
Milestone
PS Fabrication and QA
PS
Installation
Fabricate and QA TS Modules, Assemble TS
TS Installation
DS Fabrication and QA
DS Installation
Solenoid Checkout and Commissioning
Accelerator and Beamline Construction
16 months of float
Tracker Construction and Installation
Calorimeter Construction and Installation
Cosmic Ray Veto Construction
TDAQ
Cosmic Ray System Test
KPPs Satisfied
FY17
FY18
FY19
FY20
FY21
FY22

CLFV Experiments Timeline

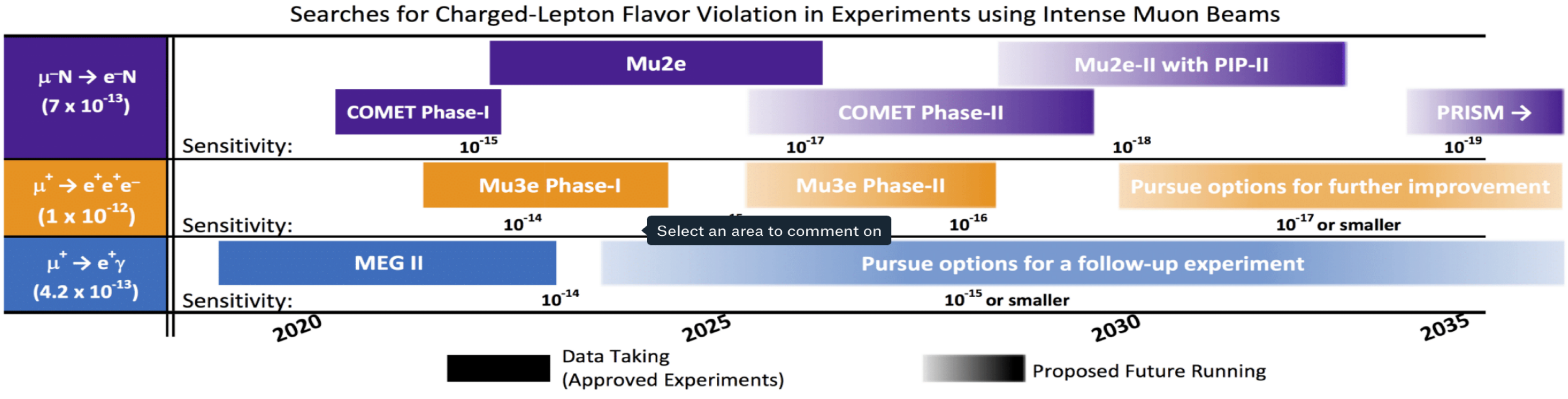


Figure 1: *Planned data taking schedules for current experiments that search for charged-lepton flavor violating $\mu \rightarrow e$ transitions. Also shown are possible schedules for future proposed upgrades to these experiments. The current best limits for each process are shown on the left in parentheses, while expected future sensitivities are indicated by order of magnitude along the bottom of each row.*

*Y. Kuno

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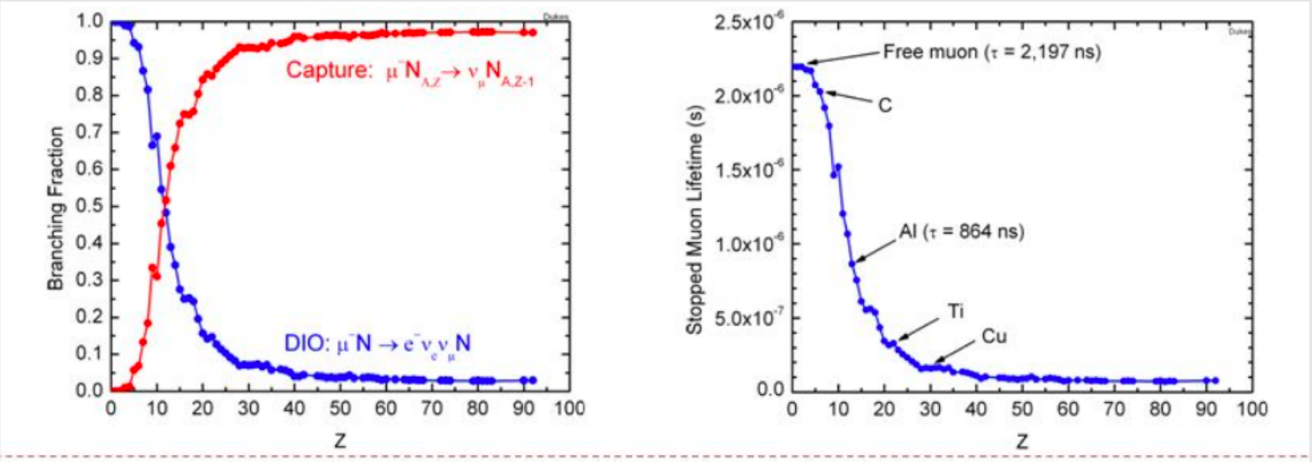
Why Aluminium?

- Must be chemically stable and available in the required size, shape, and thickness.
- Conversion energy such that only tiny fraction of photons produced by muon radiative capture.
- Muon lifetime long compared to transit time of prompt backgrounds.
- Conversion rate increases with atomic number, reaching maximum at Se and Sb, then drops. Lifetime of muonic atoms decreases with increasing atomic number.

➔Al (or Ti) best choices



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

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Where do the muons come from?

- Mu2e uses 8kW of 8 GeV protons from the Booster.
- 2 batches of 4 x 1012Protons, transported from Booster via MI-8 beamline to the Recycler Ring
- Circulate and re-bunched by a 2.5 MHz RF system.
- Reformatted bunches are kicked into the P1 line and transported to the Delivery Ring
- They are slow extracted to the Mu2e detector through a new external beamline

Where will our muons come from?

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The Mu2e Collaboration

Argonne National Laboratory • Boston University Brookhaven National Laboratory Lawrence Berkeley National Laboratory and University of California, Berkeley • University of California, Davis • University of California, Irvine • California Institute of Technology • City University of New York • Joint Institute for Nuclear Research, Dubna • Duke University • Fermi National Accelerator Laboratory • Laboratori Nazionali di Frascati • INFN Genova • HelmholtzZentrum Dresden- Rossendorf • University of Houston • Institute for High Energy Physics, Protvino • Kansas State University • INFN Lecce and Università del Salento • Lewis University • University of Liverpool • University College London • University of Louisville • University of Manchester • Laboratori Nazionali di Frascati and Università Marconi Roma • University of Minnesota • Institute for Nuclear Research, Moscow • Muons Inc. • Northern Illinois University • Northwestern University • Novosibirsk State University/Budker Institute of Nuclear Physics • INFN Pisa • Purdue University • University of South Alabama • Sun Yat Sen University • University of Virginia • University of Washington • Yale University

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Extinction System

- Must have out-of-time : in-time proton ratio < 10^{-10}
- 2 steps:
  1. The technique for generating the required bunch structure in the Recycler Ring y leads to a high level of extinction. Fast "kicker" which transfers the proton beam from the Recycler to the Delivery Ring preserves extinction. Extinction of 10^{-5} is expected as the proton beam is extracted and delivered.
  2. The beam line from the Delivery Ring to the production target has a set of AC oscillating dipoles that sweep out-of-time protons into a system of collimators. This should achieve an additional extinction of 10^{-7} or better.

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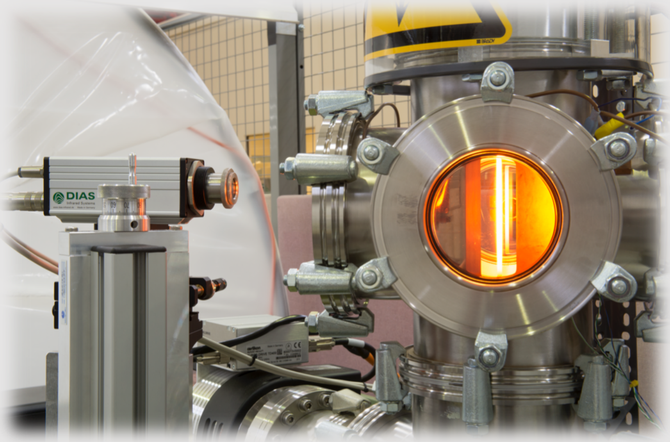
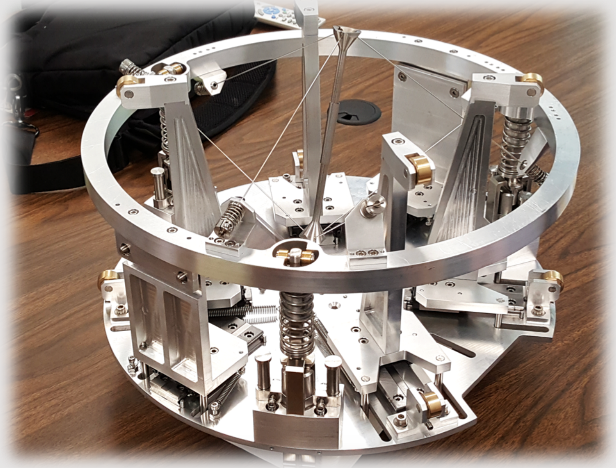
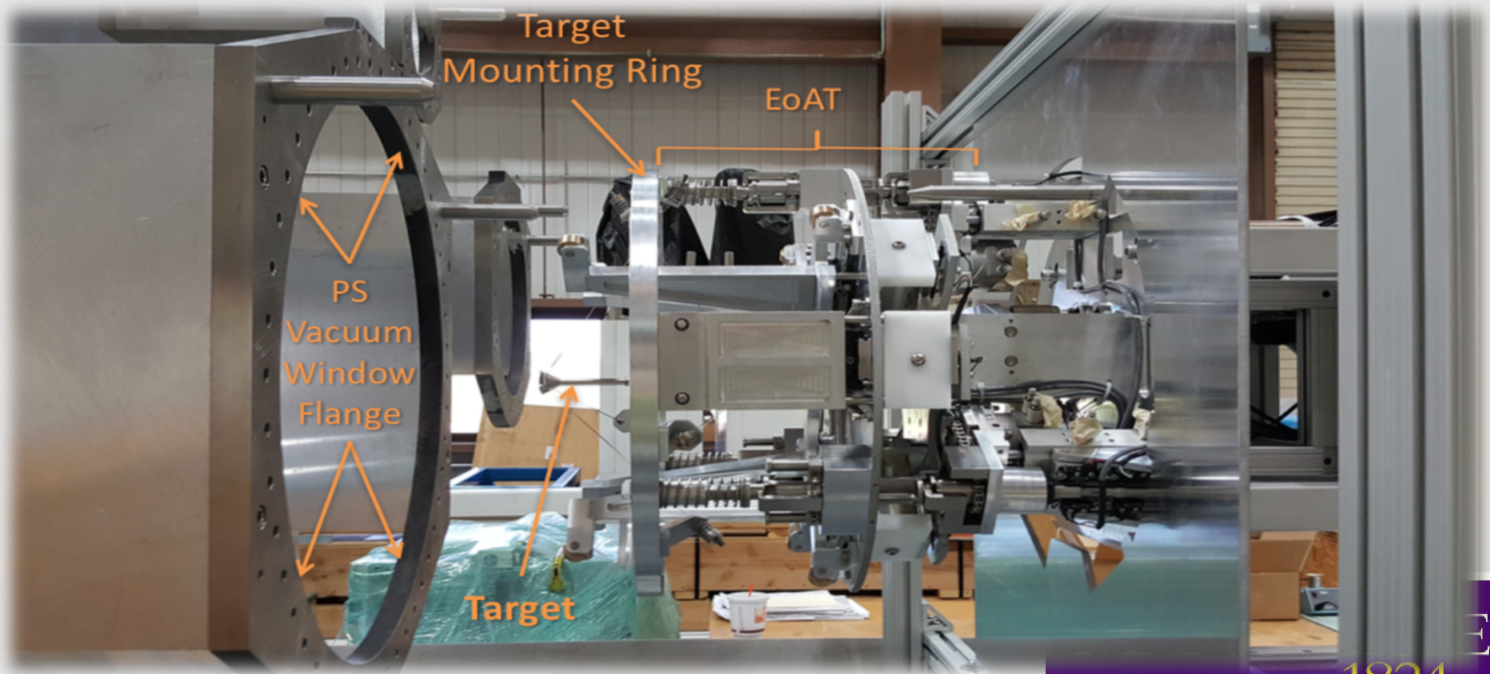
Production Target





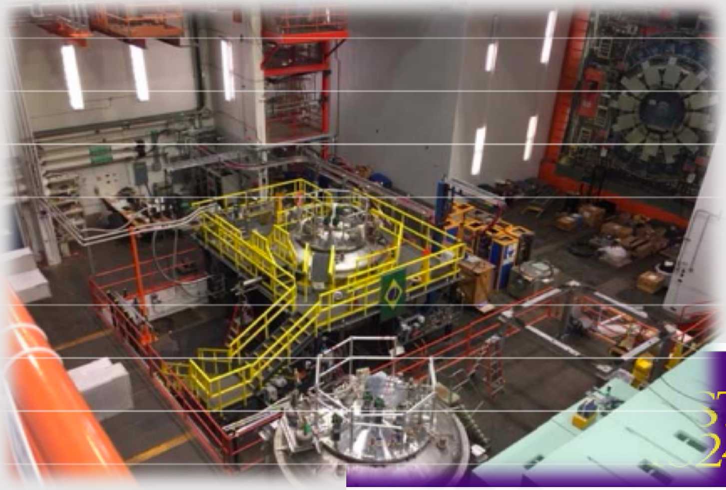


- Tungsten rod in frame
- Fabrication in progress

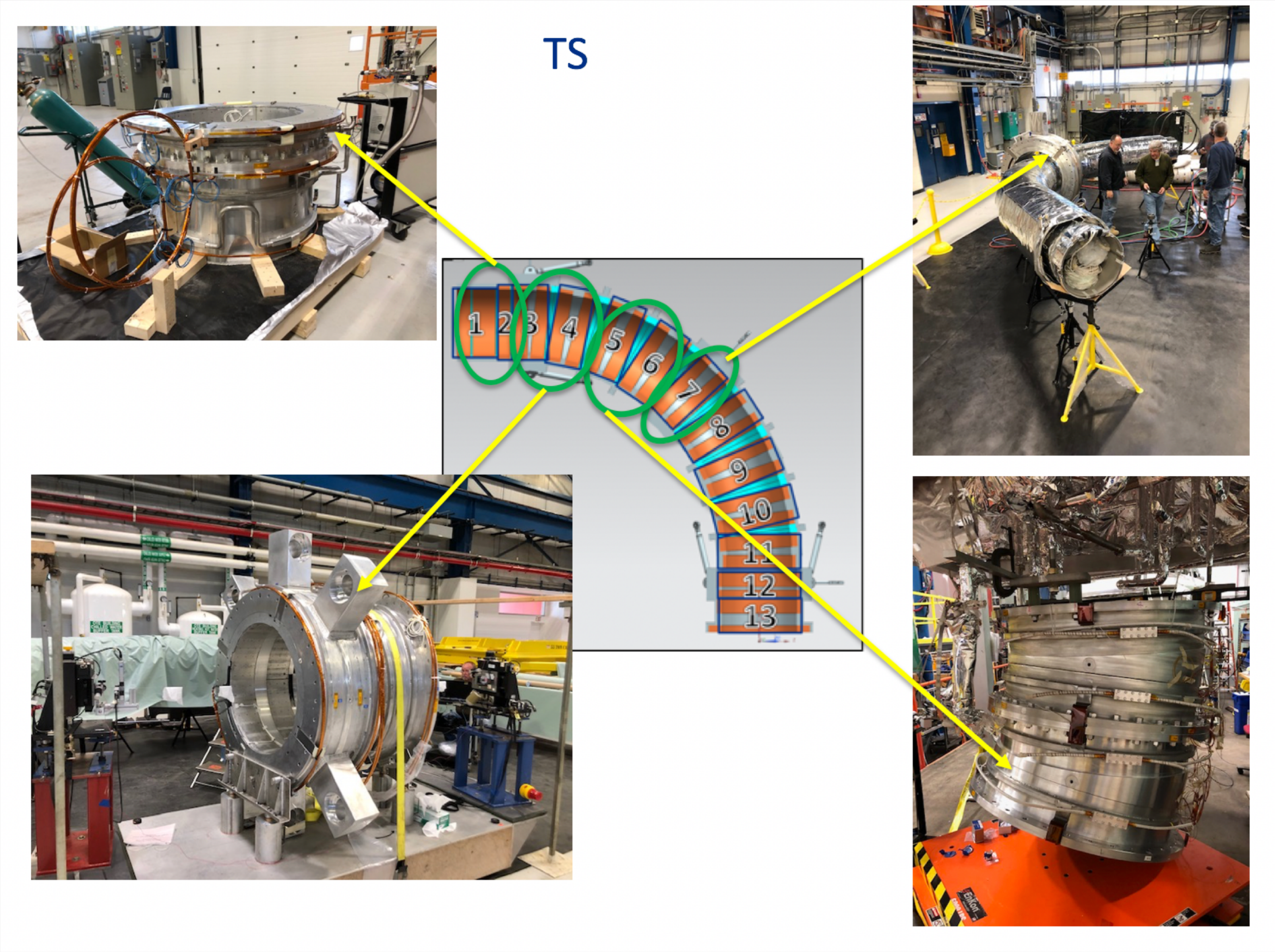
The Transport Solenoid

- Built at ASG & Shipped to Fermilab
  - Successful R&D and prototype campaign completed.
  - Vendor, ASG, has delivered 25% of the 27 TS coil modules.
  - 100% of the 52 TS coils wound at cold mass vendor.
  - Good progress made with the fabrication of the coils' housing shells
  - FNAL solenoid test facility operational.
  - The first of the coil modules has been installed around the magnet bore at assembly site.
  - Fabrication of the outer TS cryostat is underway.


TS coils at ASG



The Transport Solenoid



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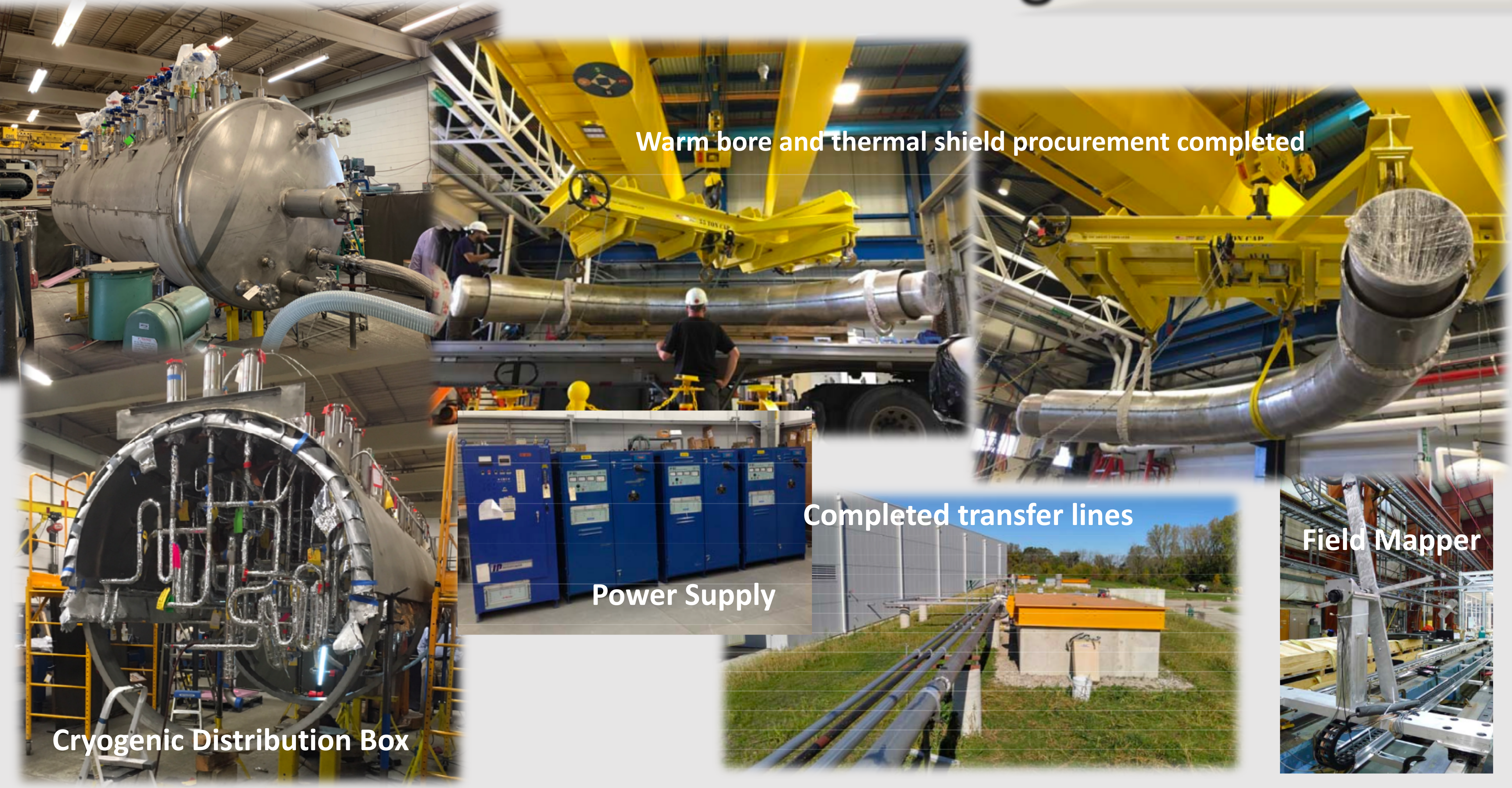
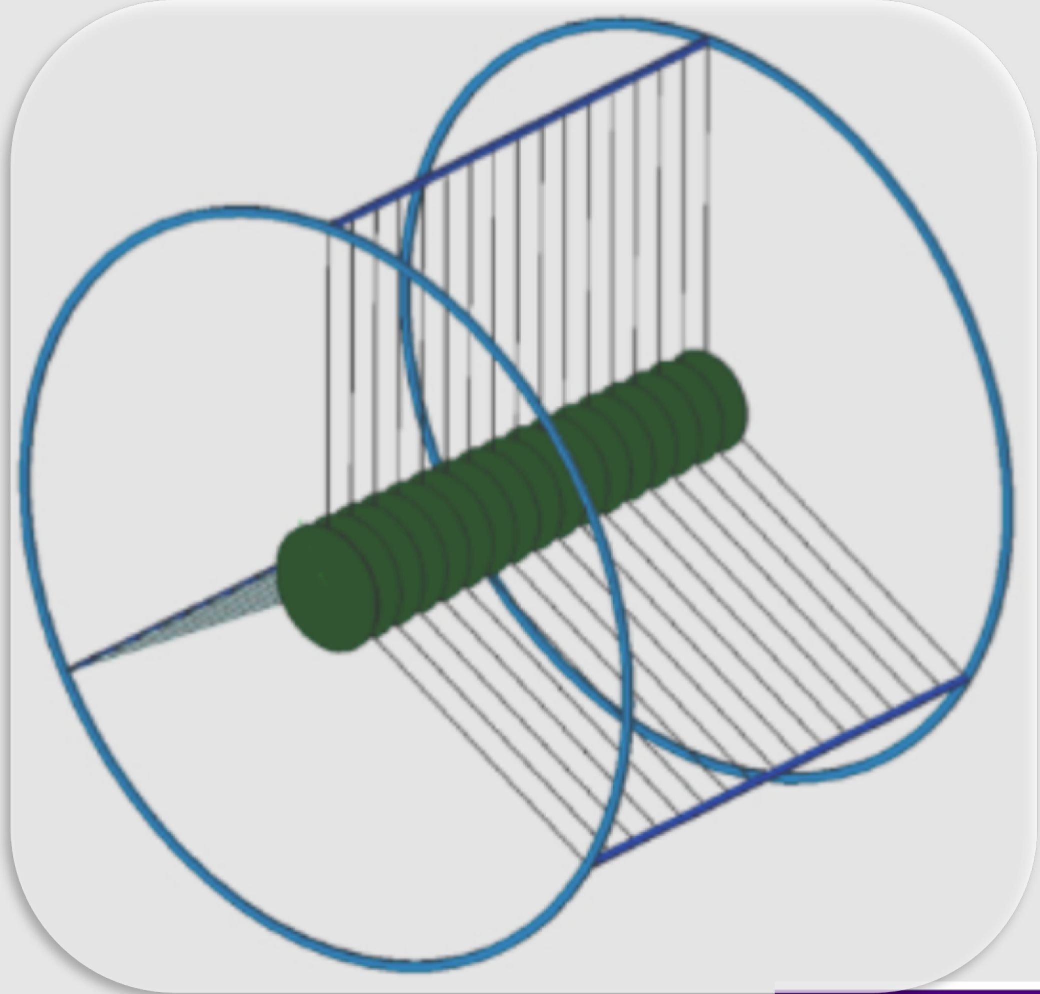
Recent Solenoid Progress at FNAL



Stopping Target

- Design still being finalized
- Target must be massive to stop significant number of muons
- Target must not distort momentum measurement
- Use Combination of lower energy muons and a thin foil Al target help alleviate corruption



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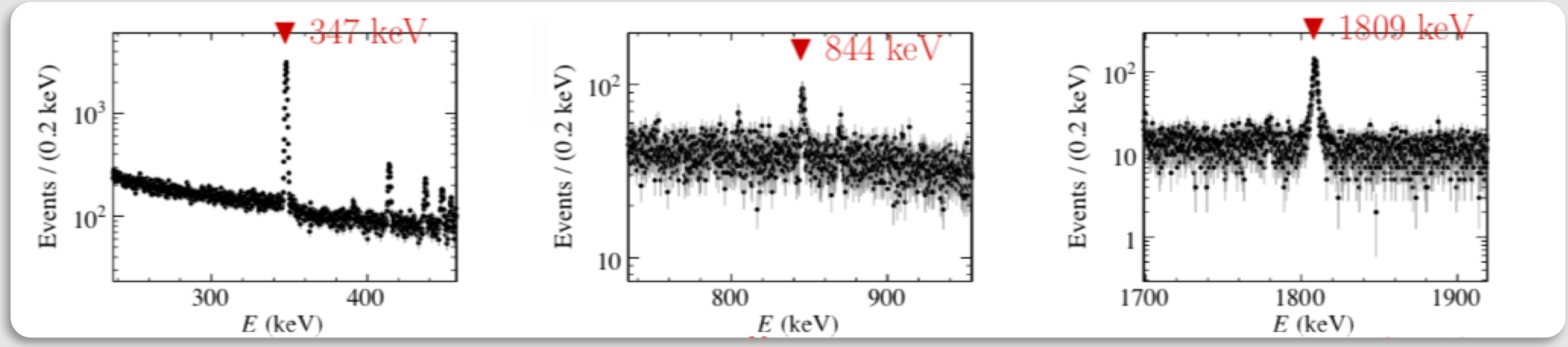
The Stopping Target Monitor (STM)

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



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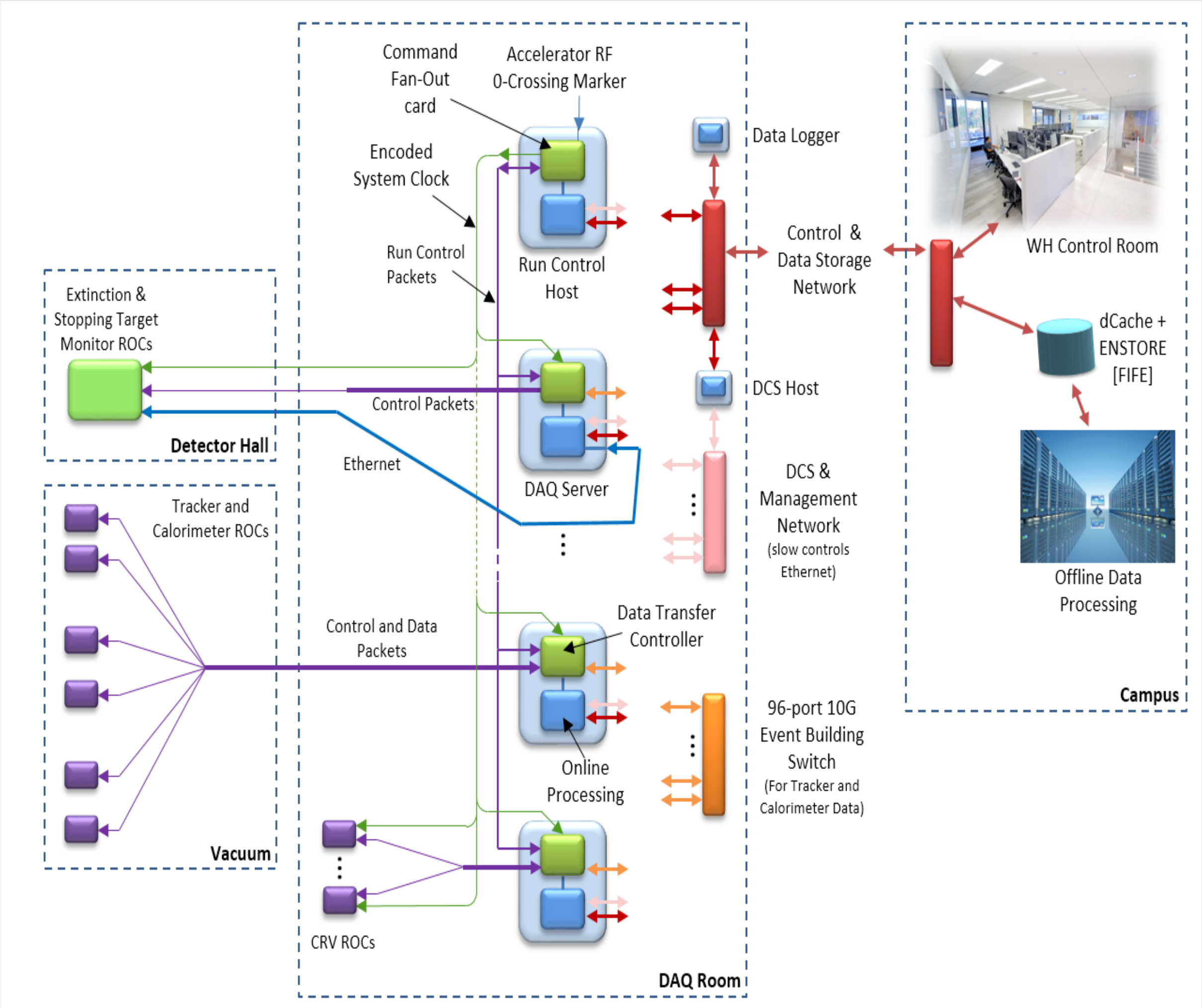
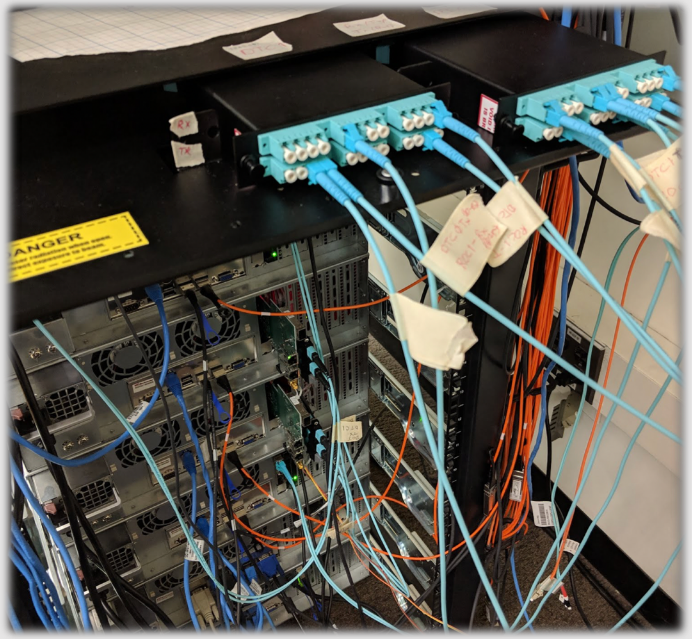
The DAQ: Purpose

- The DAQ system must provide readout and control for all detector subsystems.
- Trigger processing is handled entirely in software.
- This allows use of commercial computing hardware.
- Filtering can be designed in offline environment and can then be run in online trigger environment.



The DAQ: Status



- Lots of progress over the last year:
  - Test stand set up at the Feynman Computing Centre at FNAL
  - Need to synchronize all the sub-detectors
  - A joint platform (OTSDAQ) has been set up to allow compatibility between trackers, calorimeter and STM interfaces.

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Comparing other channels?

- **Relative rates important in determining new physics:**

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

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

arXiv:1709.00294v2[hep-ph]

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Constraining NP with CLFV

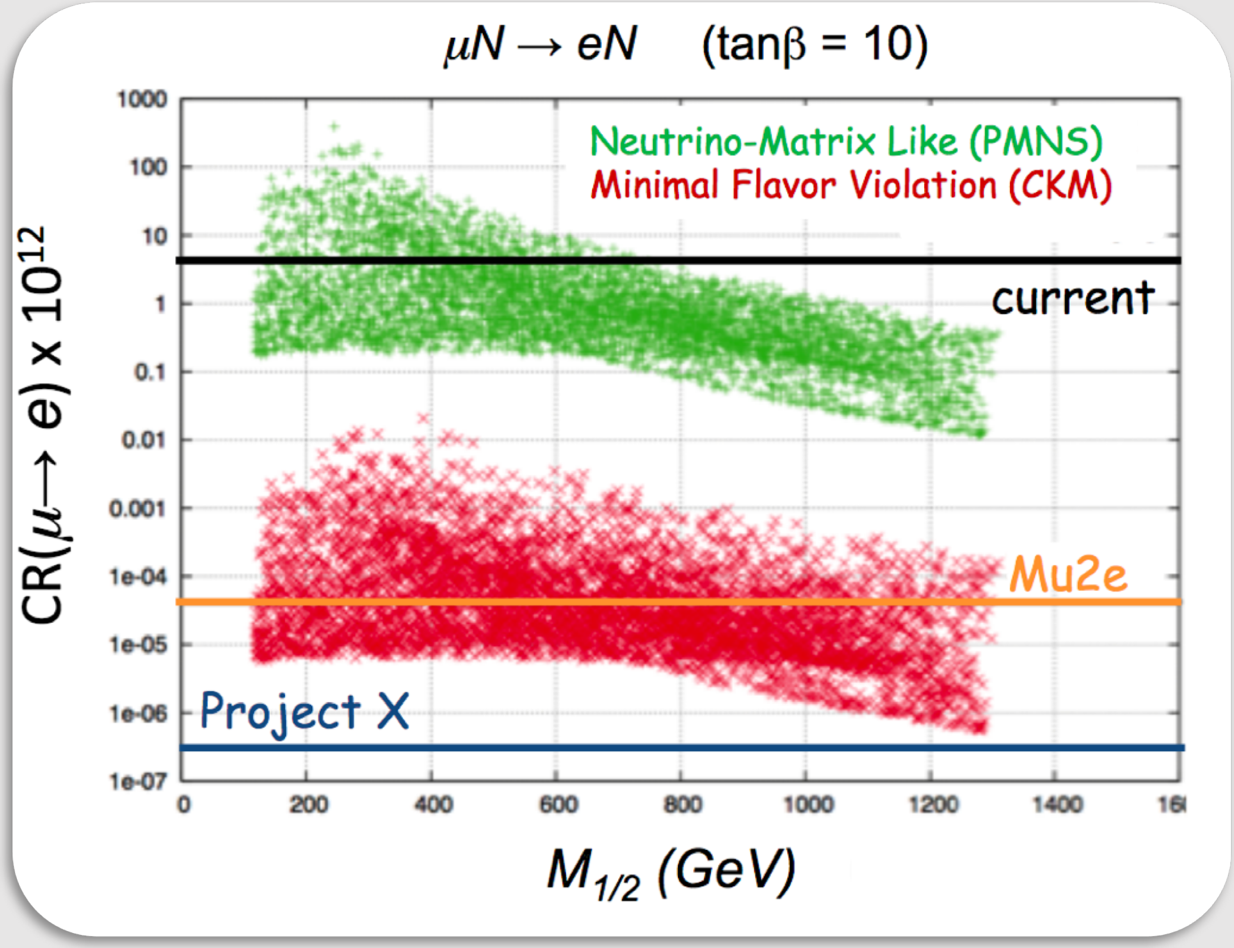
SUSY SO(10) GUT:

Interesting Overviews:

Calibbi L, Signorelli G. Charged lepton flavour violation: anexperimental and theoretical introduction. Riv Nuovo Cim.(2018) 41:71.

Gouvêa A, Vogel P. Lepton flavor and number conservation, and physics beyond the standard model.arXiv:1303.4097 (2013)

Marciano WJ, Mori T, Roney JM. Charged lepton flavour violation experiments. Annu. Rev. Nucl. Part. Sci. (2008)



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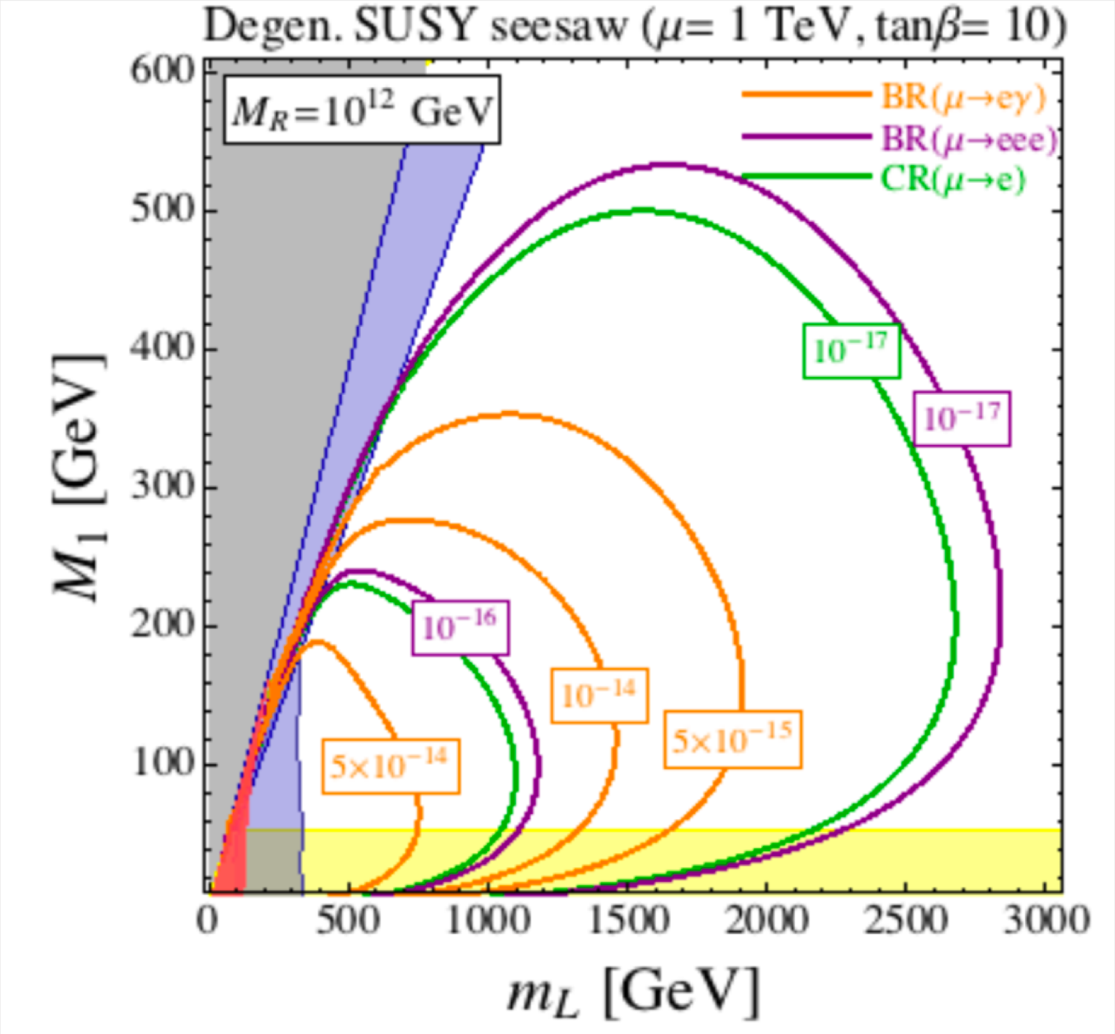
Constraining NP with CLFV



SUSY

L. Calibbi, G. Signorelli Riv. Nuov. Cim41 (2018) 71.

Lepto quarks - A. Crivellin, et al., PRD 97 (2018) 015019.

Z' - A. Falkowski, M. Nardeccia, R. Ziegler, JHEP 11 (2015) 173.

Others - P.Q. Hung, et al arXiv:1701.01761[hep-ph]

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Constraining NP with CLFV

Scalar Leptoquarks

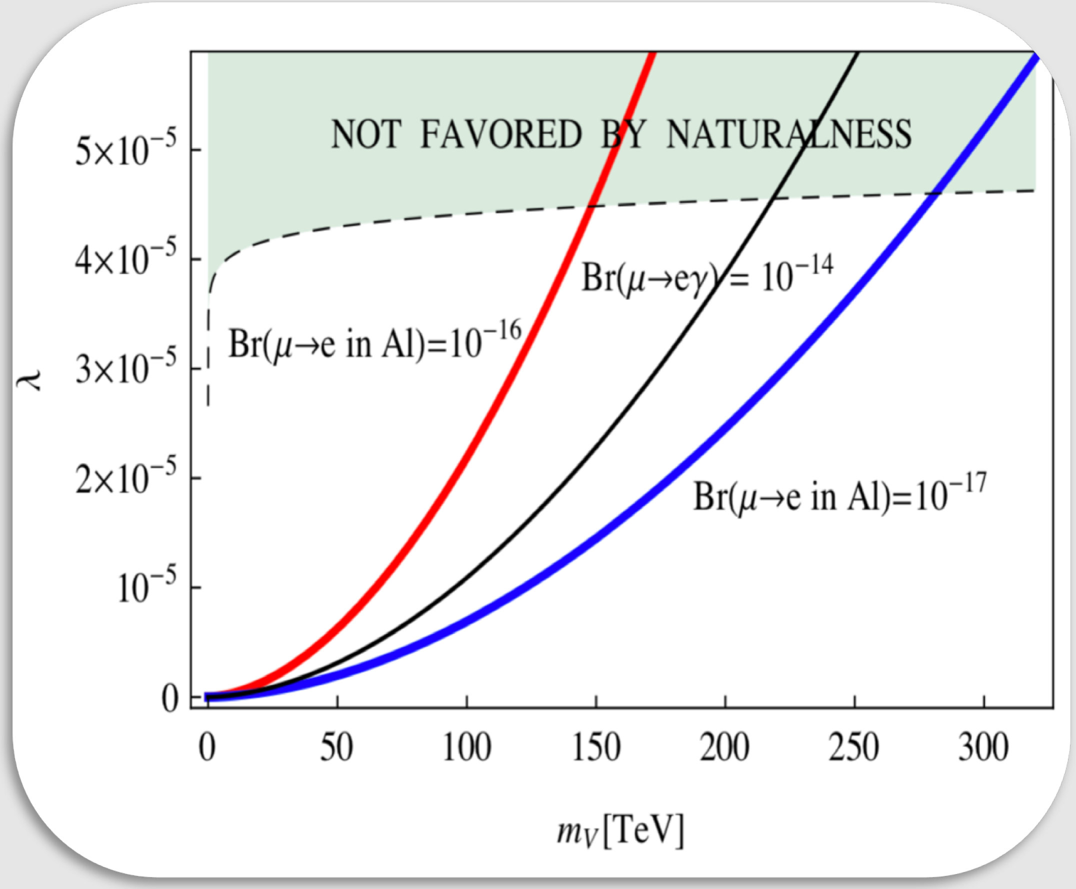

Figure shows the reach in the new coupling λ for a range of scalar leptoquark masses for the μ → e conversion rate for two values of the Br(μ → e conversion in Al) relevant for the Mu2e experiment.

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