Experimental Searches for CLFV in the Muon Sector

Sophie Charlotte Middleton

Rare Processes and Precision Physics Frontier Meeting

May 2022

Associated Snowmass White Papers

In this talk I will summarize work presented in the following list of Contributed Papers. For more details on the specifics, please see the links below:

1. **Experimental Searches for Muon to Electron Conversion in a Nucleus: COMET, DeeMe, and Mu2e**

$\boldsymbol{\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}}$ **:** https://arxiv.org/abs/2203.07089

2. **The Mu3e Experiment**

$\boldsymbol{\mu^+ \rightarrow e^+ e^+ e^-}$**:** https://arxiv.org/abs/2204.00001

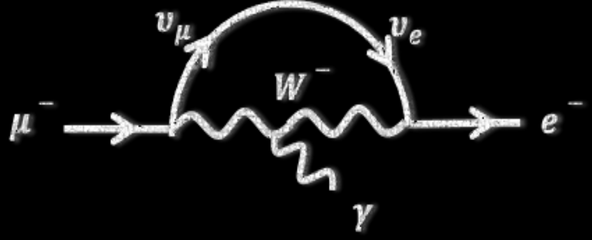
3. **Towards a New $\mu \rightarrow e\gamma$ Search with the MEG II Experiment: From Design to Commissioning**

$\boldsymbol{\mu^\pm \rightarrow e^\pm \gamma}$ **:** Not yet published

Motivations

Charged Lepton Flavor Violation (CLFV)

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



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

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

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

$$B(\mu \to e\gamma) \approx \mathcal{O}(10^{-54})$$

[1-5]

W. J. Marciano, T. Mori, and J. M. Roney, Annual Review of Nuclear and Particle Science 58 (2008) 315–341.

using best-fit values for neutrino data ($m_{\nu j}$ for the neutrino mass and U_{ij} for the element of the PMNS matrix).

If observed at next generation of CLFV experiments → this would be an unambiguous sign of physics beyond the Standard Model (BSM).

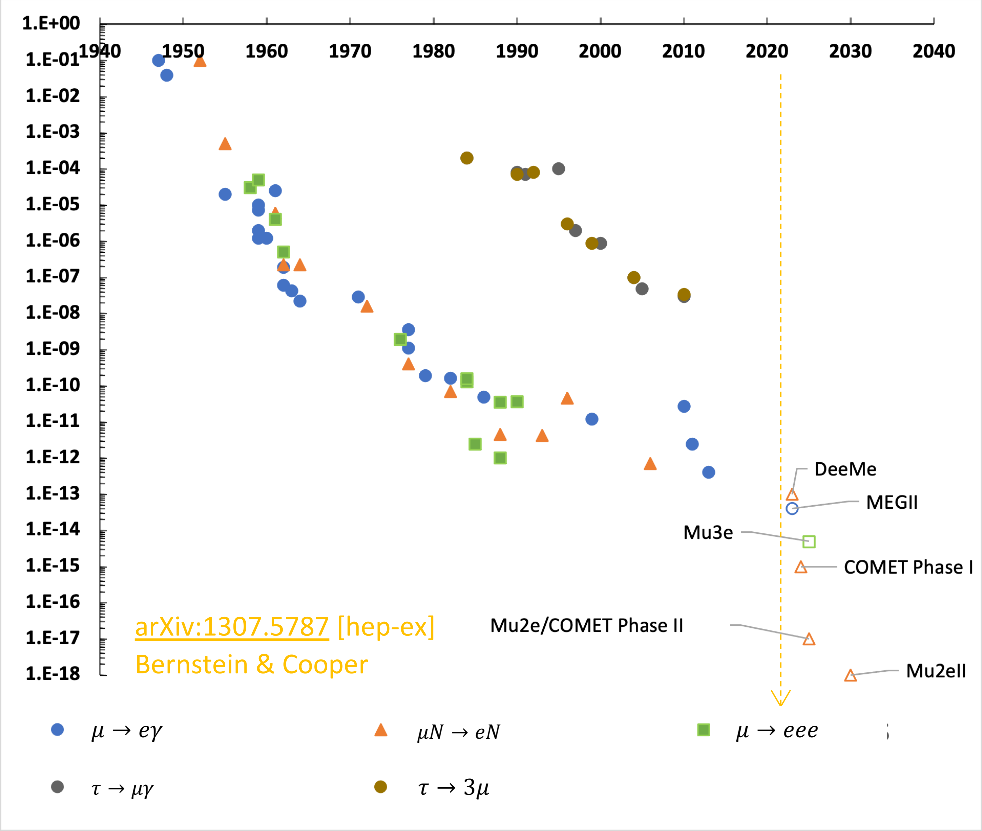
- Many well-motivated BSM theories predict CLFV in the muon sector at rates measurable in these experiments.

Experimental Searches for CLFV

$$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z,N) \to e^- + A(Z,N)}{\Gamma(all - captures)} < 7 \times 10^{-13} (90\% C.L)$$

- $\mu^+ \to e^+e^+e^-$, $\mu^-N \to e^-N$ and $\mu^\pm \to e^\pm\gamma$ searches are crucial part of global program searching for CLFV.
- Muons offer more powerful probe for CLFV compared to taus.
- To elucidate the mechanism responsible for any CLFV – must look at relative rates (if any) in different muon channels.

Mode	Current Limit (at 90% CL)	Future Proposed Limit	Future Experiment/s
$\mu^\pm \to e^\pm\gamma$	4.2×10^{-13} [6]	6×10^{-14} [7]	MEG II [10]
$\mu^- N \to e^- N$	7×10^{-13} [8]	10^{-14} 10^{-15} 10^{-17} 10^{-18}	DeeMe [11] COMET Phase-I [12] Mu2e [13] & COMET Phase-II [14] Mu2e-II [15]
$\mu^+ \to e^+e^+e^-$	$\sim 10^{-12}$ [9]	$10^{-15} \sim 10^{-16}$	Mu3e [16]



- Muon-to-electron sector provides powerful probes and complements collider searches for $\tau \to e\gamma$ or $\mu\gamma$ and $H \to e\tau$, $\mu\tau$, or μe.

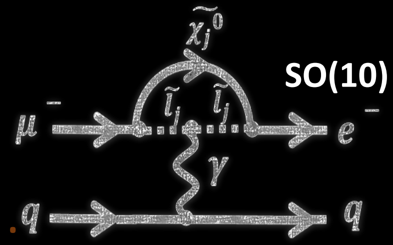
Simplistic Explanation of Physics Reach

- For the purposes of discussion we can build a Toy Lagrangian which consists of 2 terms representing 2 types of physics process:

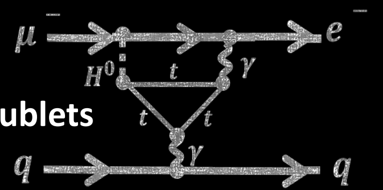
$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma_\mu q_L\right)$$

A. de Gouvêa, P. Vogel arXiv:1303.4097

i.e. Dipole terms:
$\mu^\pm \to e^\pm \gamma$, $\mu^+ \to e^+ e^+ e^-$
$\mu^- N \to e^- N$



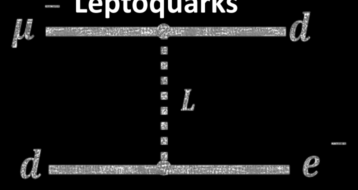
SO(10) SUSY



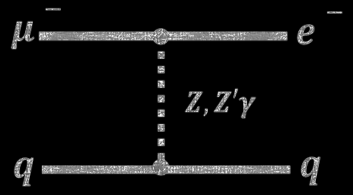
2 Higgs Doublets

i.e. 4 fermion terms
Only $\mu^+ \to e^+ e^+ e^-$
And $\mu^- N \to e^- N$

Leptoquarks

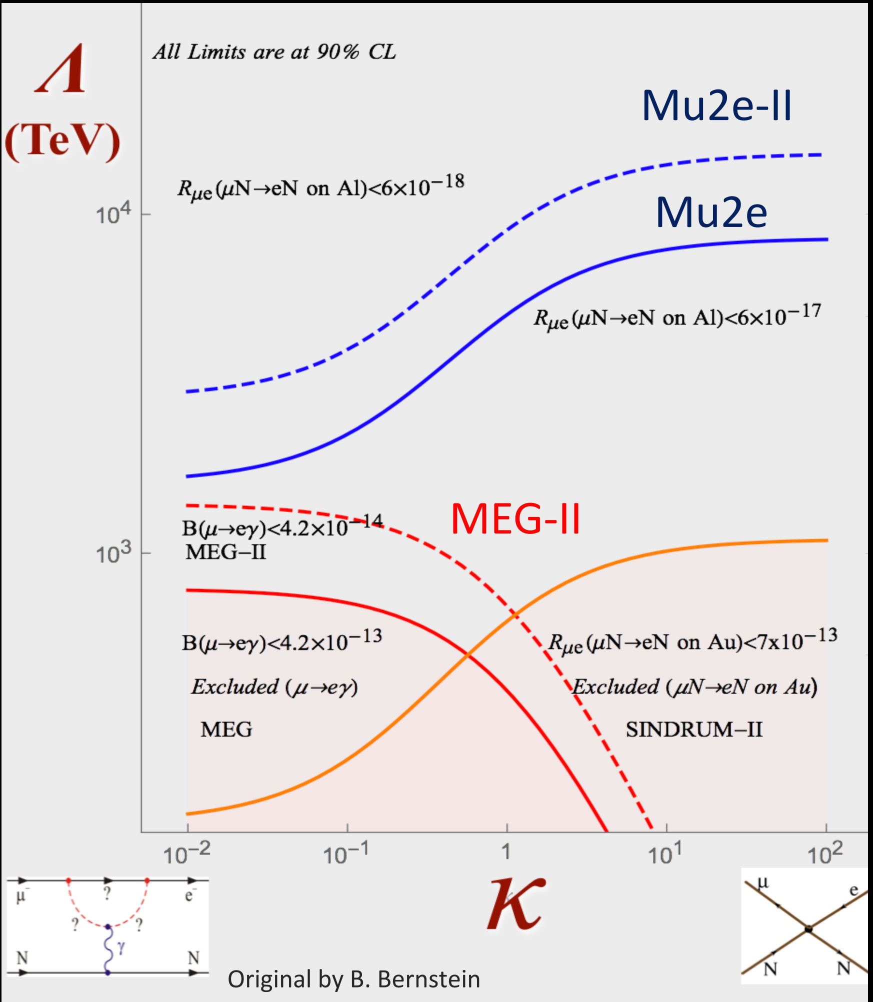


New Bosons



Λ : effective mass scale of New Physics (NP),
κ : determines to what extent NP is photonic ($\kappa \ll 1$) or 4-fermion ($\kappa \gg 1$)

For updated version of this plot see "**Reach and complementarity of $\mu \to e$ searches**" https://arxiv.org/abs/2204.00564



Original by B. Bernstein

Complementarity

AC = an abelian flavor model by Agashe and Carone
RVV2 = non-abelian Ross and collaborators (RVV)
AKM = the AKM model predicts a CKM-like RH current
FBMSSM = flavor blind MSSM
LHT = Littlest Higgs
RS = Randel-Sundrum

★★★ = Discovery Sensitivity

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

Taken from: arXiv:0909.1333[hep-ph]

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Discovery sensitivity across the board.
Relative Rates however will be model dependent.

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

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

See also: S. Davidson "Complementarity and Completeness": http://arxiv.org/abs/2010.00317v2

Muon to Electron Conversion in Nuclear Field

Signal & Backgrounds

Signal:

- Monoenergetic electron $E_e = m_\mu - E_{recoil} - E_{1S\ B.E}$, e.g 104.97 MeV in Al.
- Radiative corrections [Szafron, R. Acta Phys. Polon. B 2017, 48, 2183]

Beam delivery systems optimized for high intensity, pure muon beam – must be “background free”:

Intrinsic physics background:

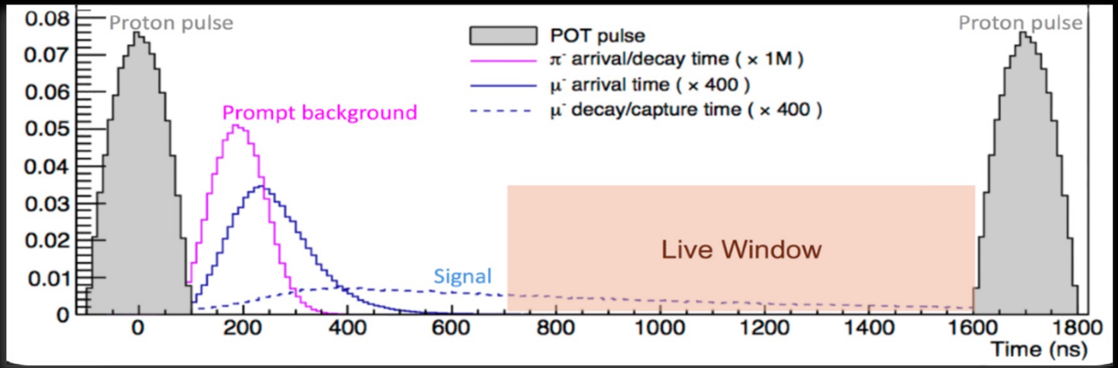
- Decay-in-orbit - tail is 5-order polynomial near endpoint reaching to signal region $\sim 105 MeV$ [Phys. Rev. D 84 (Jul, 2011)]
- Necessitates momentum resolution required to be better than $200\ KeV/c$

Beam related background:

- Pions - Mostly prompt. Can be suppressed by a delayed measurement window ($\sim$700 ns).
- Proton extinction factor required to be $< 10^{-10}$.

Cosmic ray background:

- COMET & Mu2e use active vetoes around detectors.



Mu2e

The Mu2e Experiment

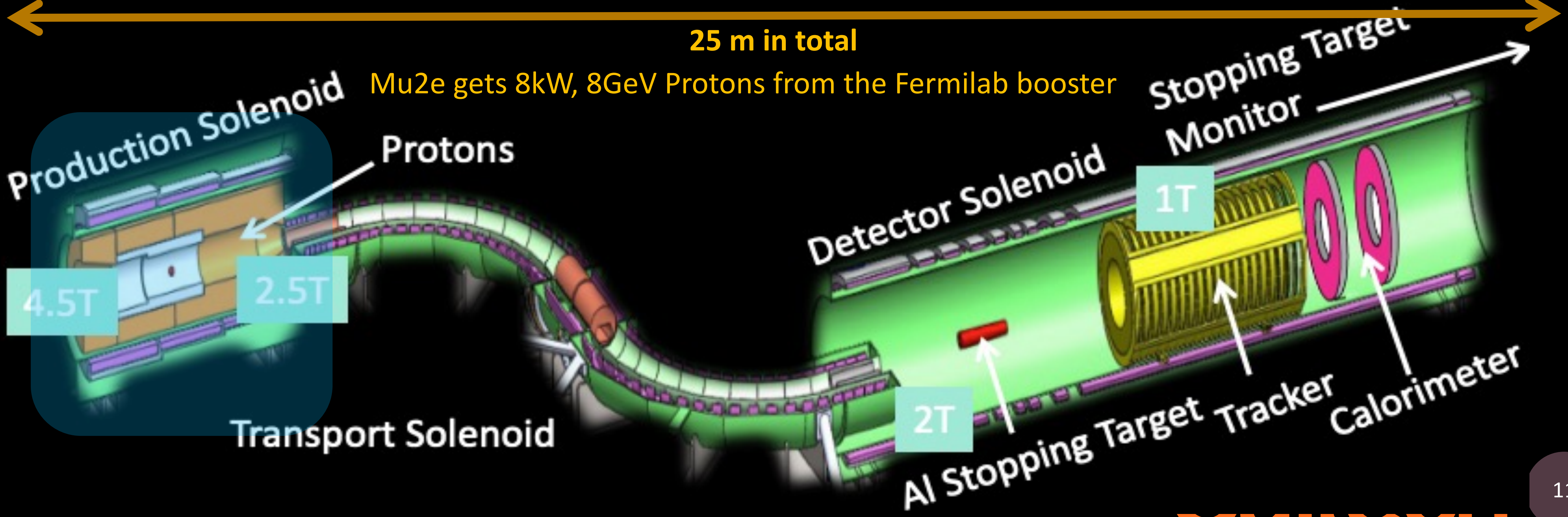
Based on concept: V. Lobashev & R. Djilkibaev (Sov. J. Nucl. Phys. 49(2), 384 (1989))

Production Solenoid:

- 8 GeV Protons enter, pions produced, decay to muons
- Graded magnetic field reflects pions/muons to transport solenoid

25 m in total

Mu2e gets 8kW, 8GeV Protons from the Fermilab booster



The Mu2e Experiment

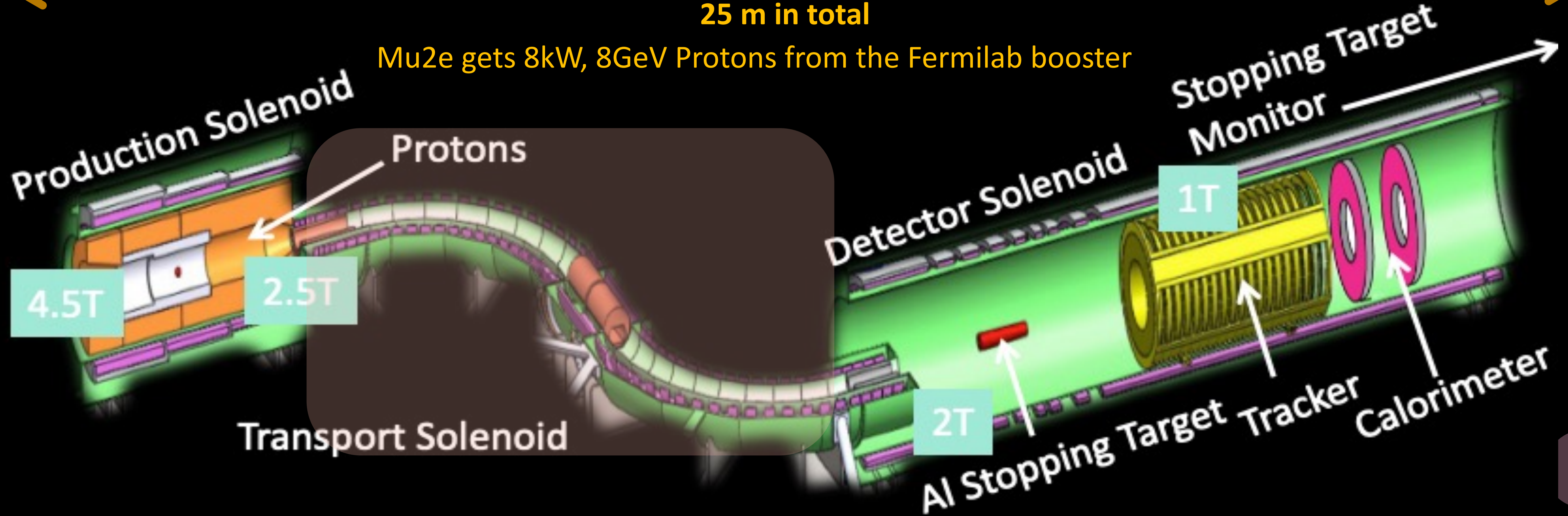
Based on concept: V. Lobashev & R. Djilkibaev (Sov. J. Nucl. Phys. 49(2), 384 (1989))

Production Solenoid:
- 8 GeV Protons enter, pions produced, decay to muons
- Graded magnetic field reflects pions/muons to transport solenoid

Transport Solenoid:
- "S" shape removes line of sight backgrounds
- Windows remove anti-protons
- Collimators help select low momentum, negative muons and "focus" on detector solenoid aperture.

25 m in total

Mu2e gets 8kW, 8GeV Protons from the Fermilab booster



The Mu2e Experiment

Based on concept: V. Lobashev & R. Djilkibaev (Sov. J. Nucl. Phys. 49(2), 384 (1989))

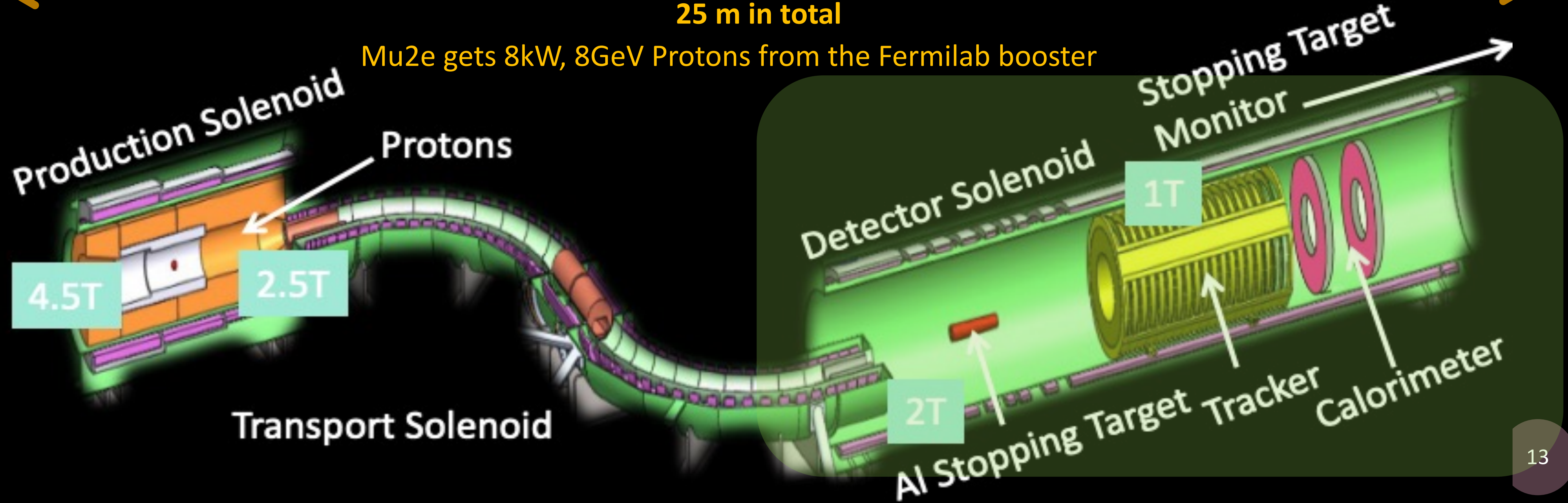
Production Solenoid:
- 8 GeV Protons enter, pions produced, decay to muons
- Graded magnetic field reflects pions/muons to transport solenoid

Transport Solenoid:
- "S" shape removes line of sight backgrounds
- Windows remove anti-protons
- Collimators help select low momentum, negative muons and "focus" on detector solenoid aperture.

Detector Solenoid:
- Al Stopping Target made of thin foils captures the muons
- Graded magnetic field "focusses" electrons on tracker
- Straw tracker and calorimeter measure momentum

25 m in total

Mu2e gets 8kW, 8GeV Protons from the Fermilab booster



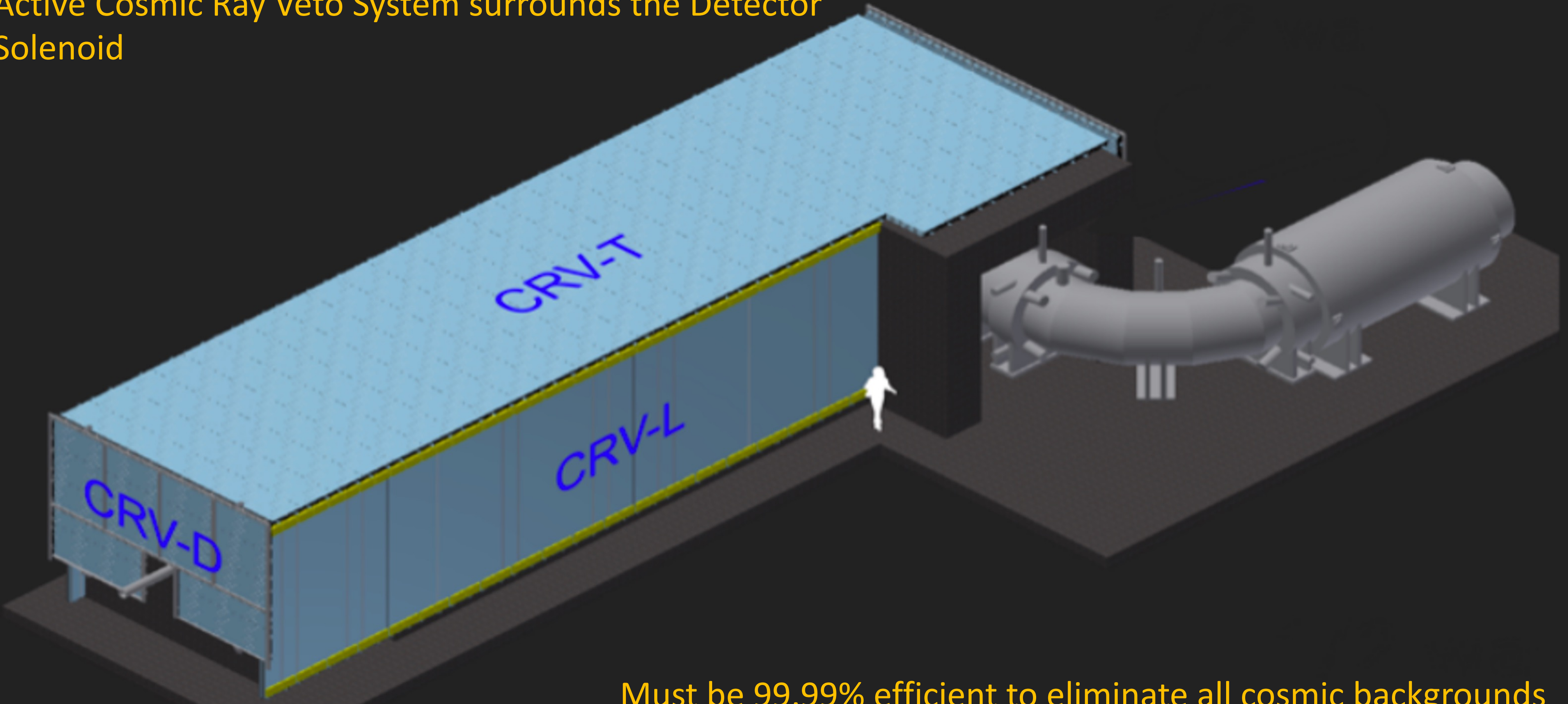
The Mu2e Experiment

Based on concept: V. Lobashev & R. Djilkibaev (Sov. J. Nucl. Phys. 49(2), 384 (1989))

Production Solenoi

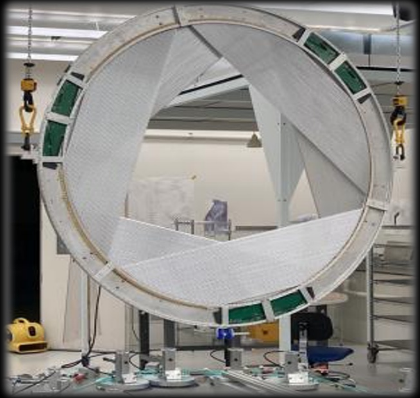
- 8 GeV Protons e
  decay to muons
- Graded magneti
  pions/muons to

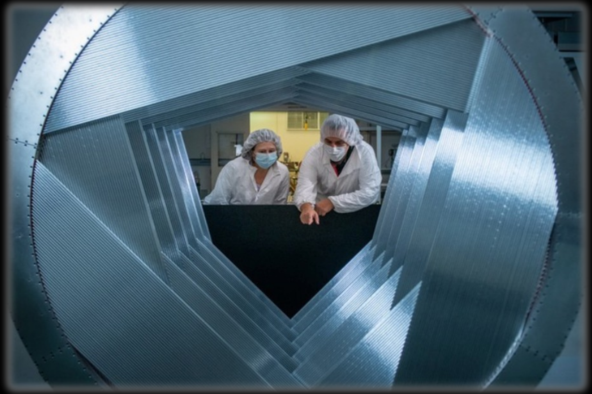
Active Cosmic Ray Veto System surrounds the Detector Solenoid



Must be 99.99% efficient to eliminate all cosmic backgrounds

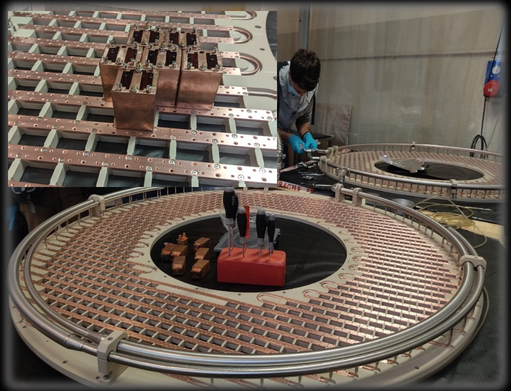
Detectors: Status

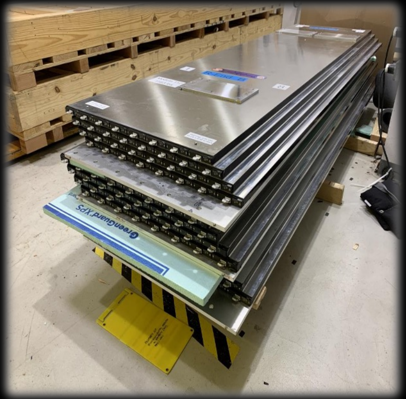




Tracker:
- → Panel construction almost complete
- → 10/36 planes so far assembled on site at FNAL
- → Electronics prototype: https://arxiv.org/abs/1710.03799 shows good resolution.

Calorimeter:
- → All crystals procured and tested.
- → Mechanical assembly underway
- → Prototype test beam results: https://www.osti.gov/pages/biblio/1523418 show meets requirements in terms of energy and time response.





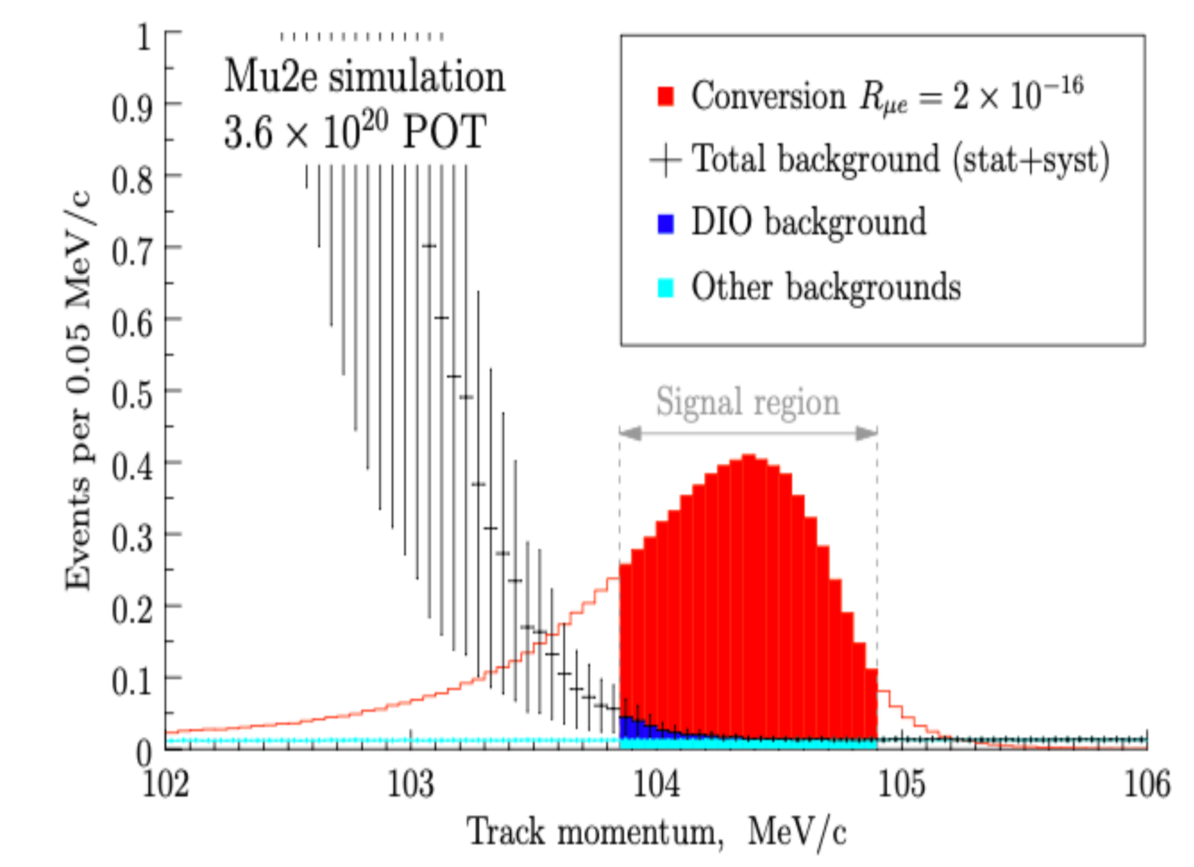
Cosmic Ray Veto System:
- →> 70% of modules fabricated at UVA

Mu2e: Projected Timeline & Physics Reach

- Detector commissioning without beam beginning in 2023;
- Commissioning with beam continuing through 2025;
- Physics running is expected to begin in late 2025:
  - Run I : 2025 – 2026 (expect $O(10^{-16})$ i.e. 3 orders of magnitude improvement on SINDRUM-II at 90% C.L.)
  - Run II : after PIP-II/LBNF 2 year long shutdown – get final amount of data to reach $O(10^{-17})$

- Design Goals:
  - Single event sensitivity (SES) of $\sim 3.01\times10^{-17}$ on the conversion rate,
  - 90% CL upper limit on $R_{\mu e}$ of 6.12×10^{-17},
  - 5σ discovery potential at $\sim 1.89 \times 10^{-16}$.

$R_{\mu e} = 2 \times 10^{-16}$

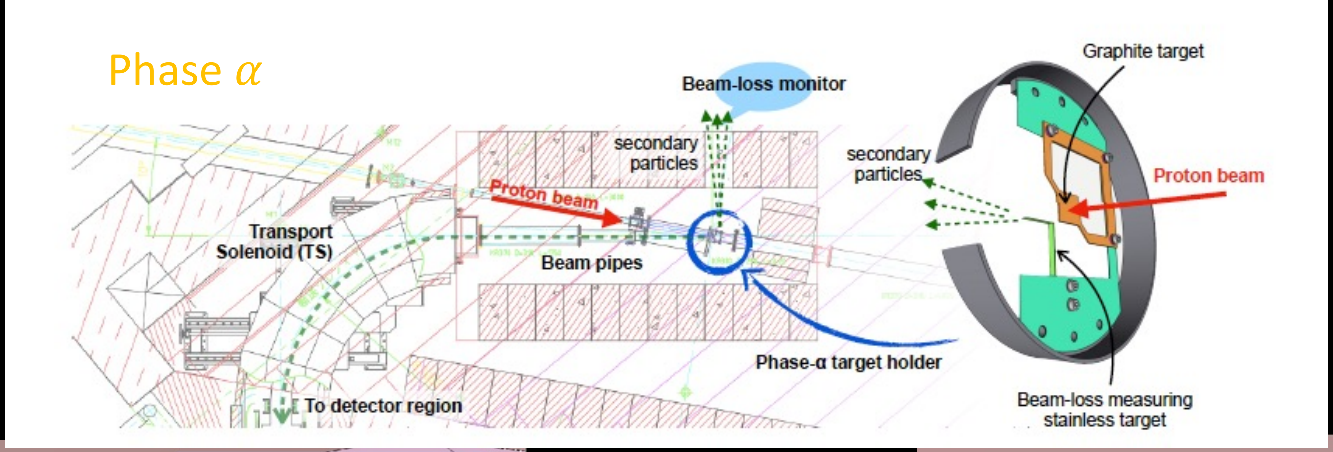


COMET

COMET: Phased Implementation

The Phase- α will:

- Monitor beam profile
- Measure muon yield
- Demonstrate charge and momentum separation in TS.

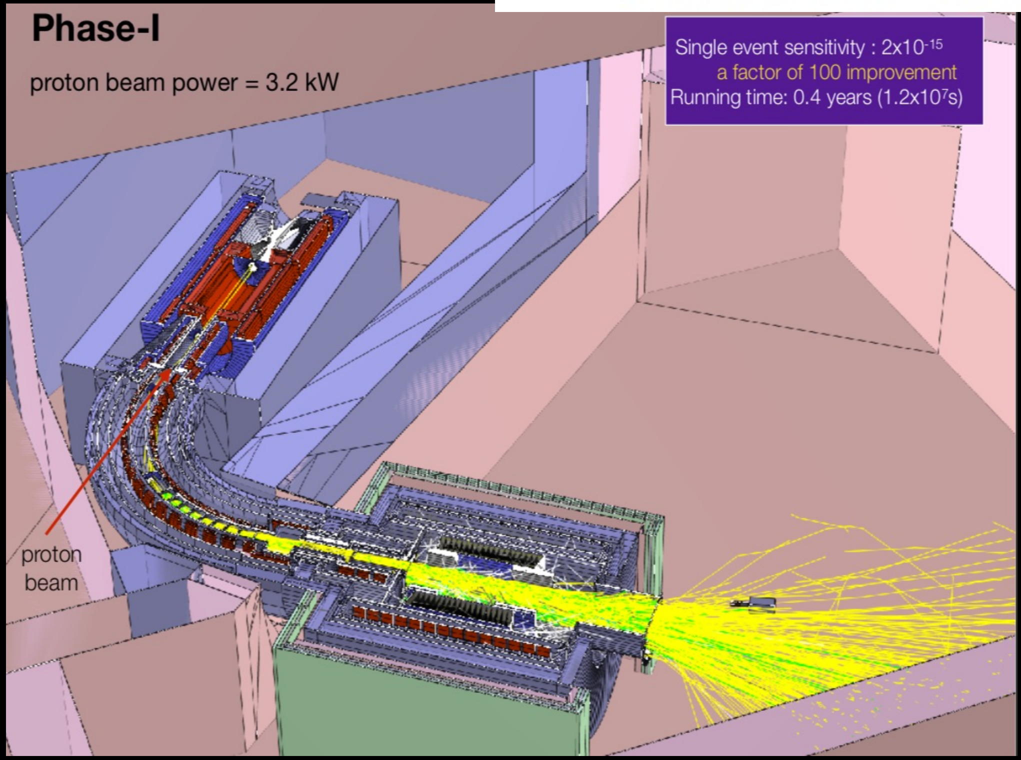


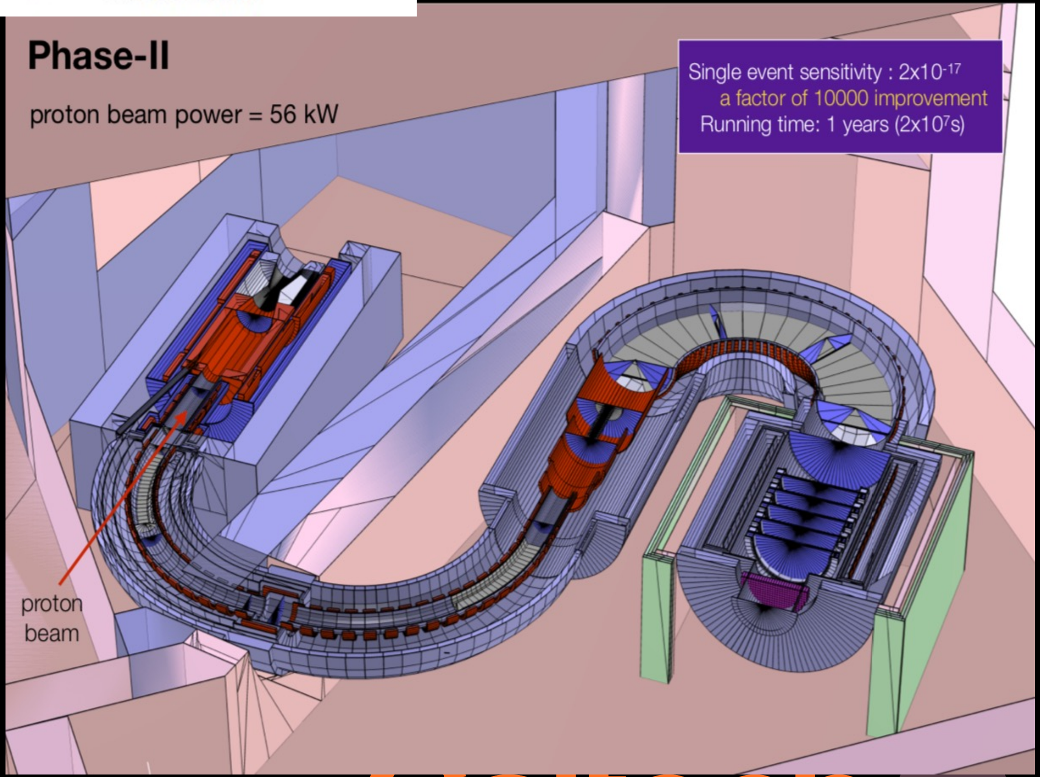
3 Phases:

Phase-α - begins in 2023

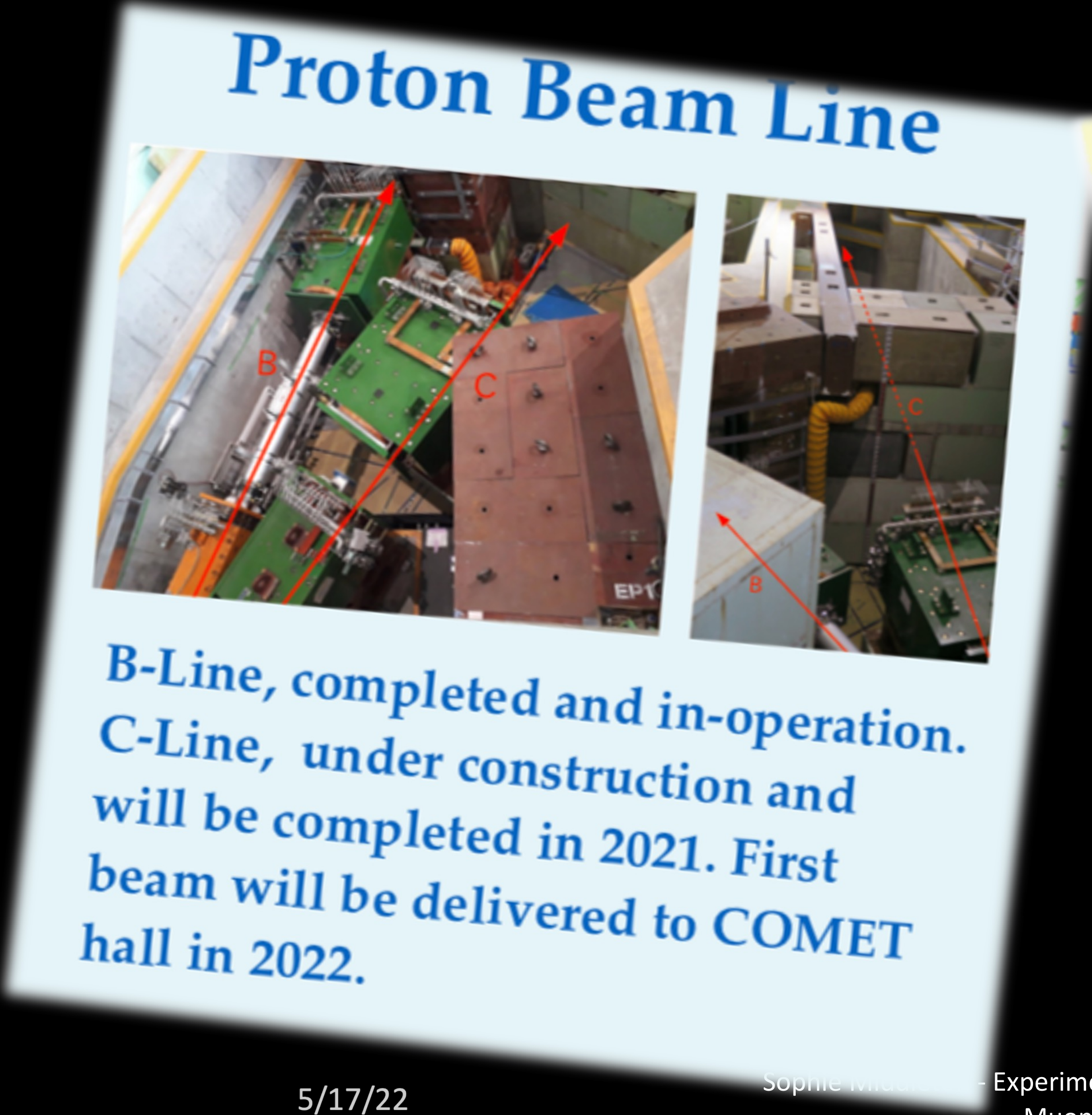
Phase I - begins in 2024

Phase II - begins in the following years.





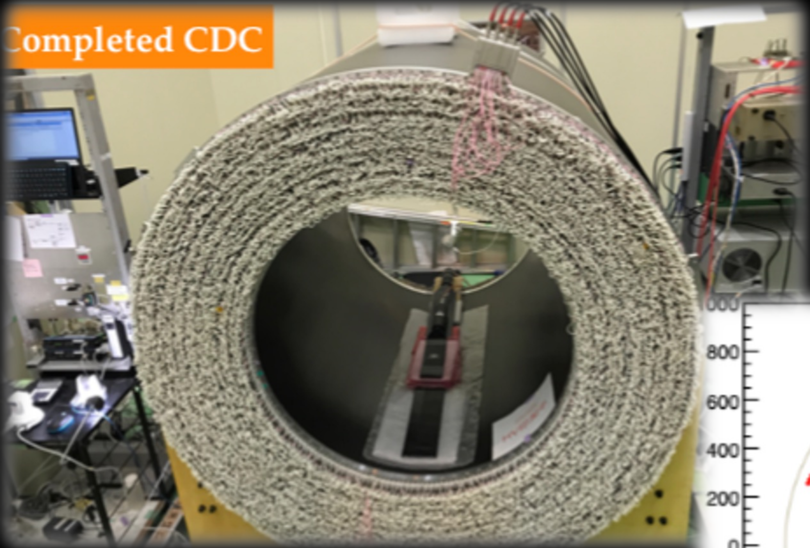
COMET: Facility Construction

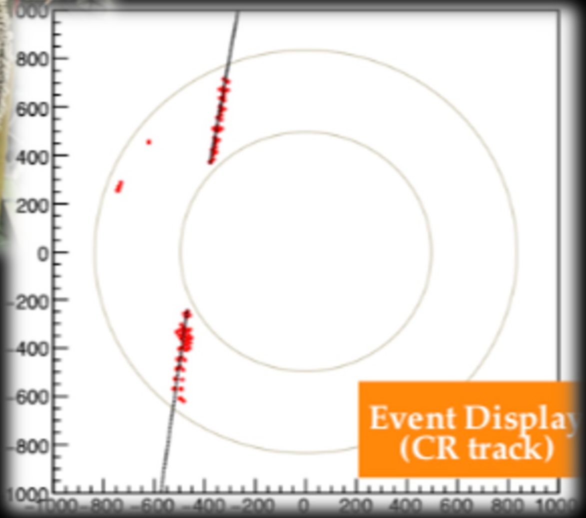


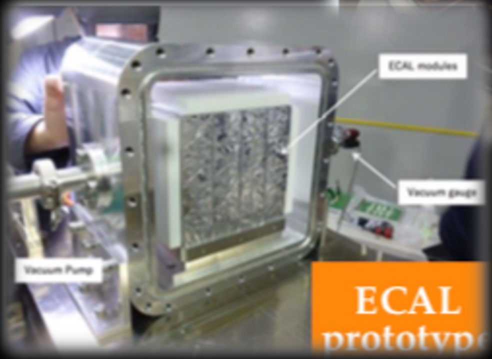
COMET: Detector Construction

- Phase-I detector the CyDet consists of Cylindrical Drift Chamber(CDC) and Trigger Hodoscope:
    - CDC: completed, commissioning underway
    - Trigger hodoscope: under development

- Phase-II detector the StrECAL will be prototyped during Phase I:
    - 5 stations in total, first is under construction
    - ECAL prototype completed
        - Assembly soon to begin



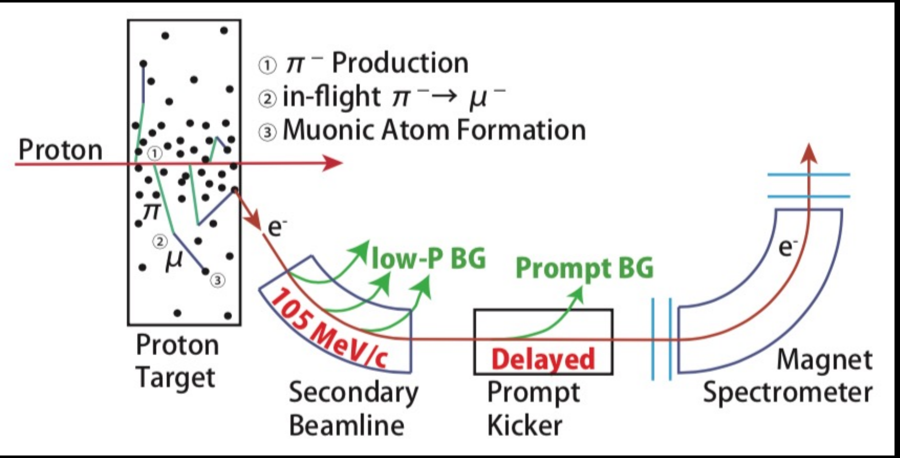


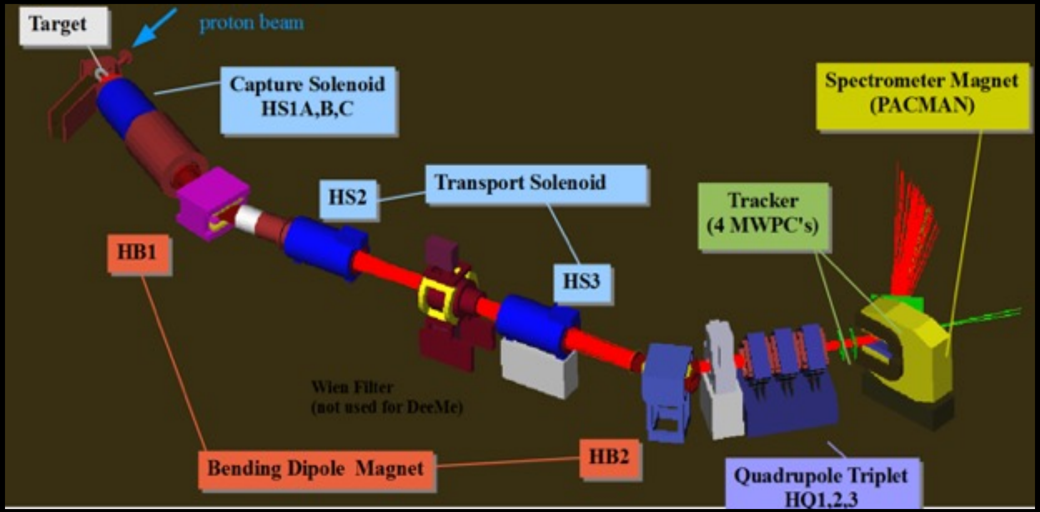


DeeMe

DeeMe

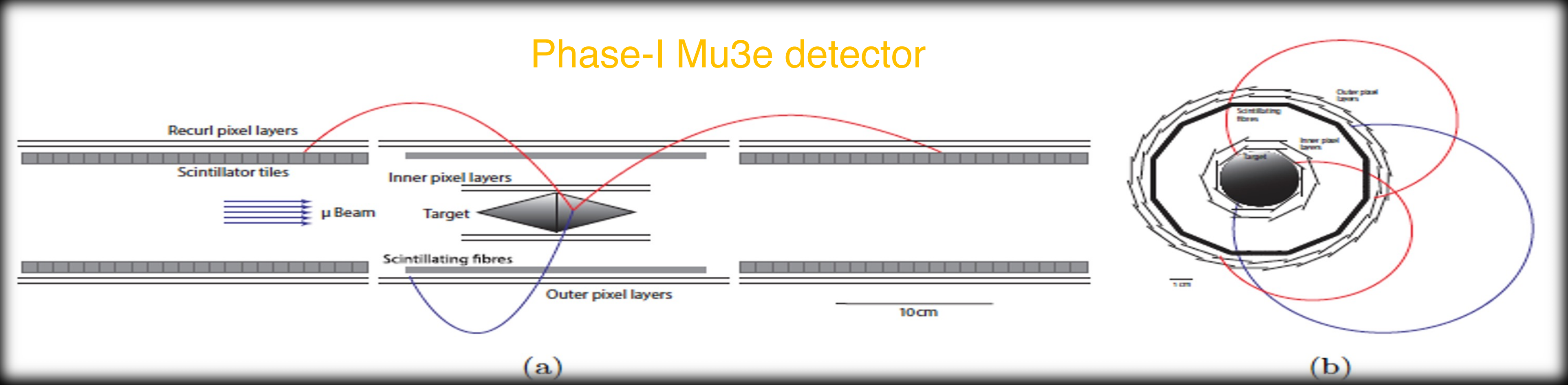
- Expected sensitivity of 1 x 10^{-13} (carbon) , 2×10^{-14}(SiC). 1 year, 1MW operation.
- Design – single production/stopping target:
  - Pulsed proton beams are injected into the target;
  - Target atoms and muons form muonic atoms.
  - Extract the decaying particles through the secondary beamline, H Line.
  - Magnetic spectrometer consists of a spectrometer electromagnet and four tracking detectors .
- The number of muonic atoms produced per proton-beam-power is 1/100 compared to Mu2e/COMET.
- Construction of detector system completed.
- Expect physics data following H-line completion in the next few years.





Mu3e

The Mu3e Experiment



Unique concept:

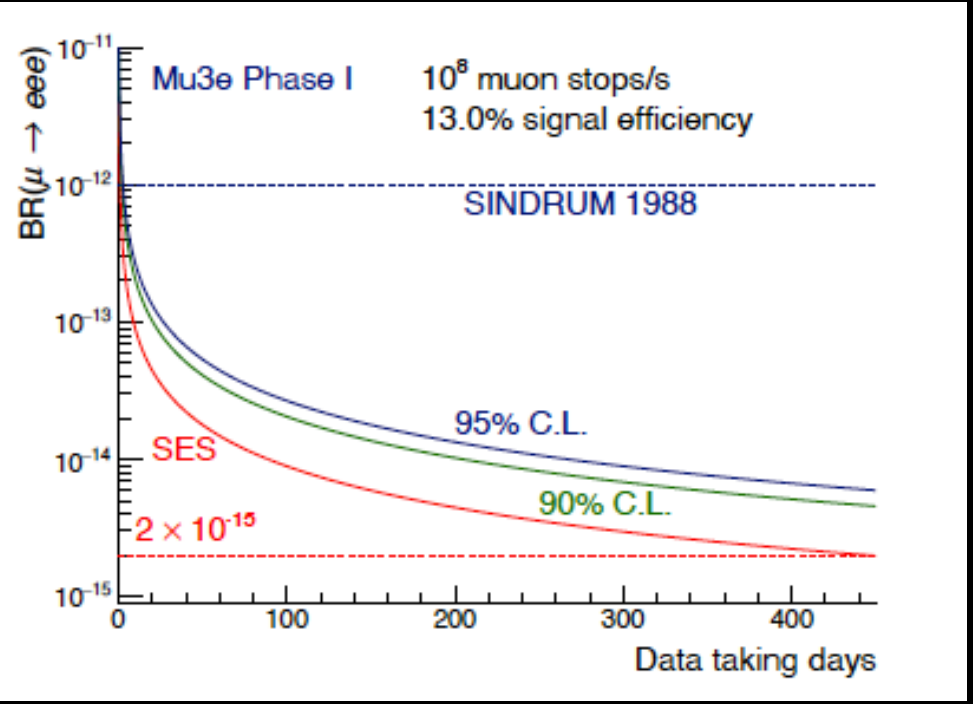
- Hollow double cone target made of thin aluminum; large target area spreads out decay vertices and reduces accidental backgrounds.
- Rest of detector geometry is optimized for momentum resolution:
  - Extremely low material budget minimizes multiple scattering.
  - 4 layers of HVMAPS silicon pixel sensors thinned to 50 μm, and scintillating fibre and tile detectors providing sub-ns timing resolution.
  - Electrons from muon decays can pass through the detector several times as they follow helical paths in the 1T solenoidal field.
    - This significantly extends the lever-arm for measurement, and hence the momentum resolution.

The Mu3e Experiment: Status & Outlook

- Several physics opportunities outlined in: https://arxiv.org/abs/2204.00001 at Mu3e including searches for dark photons, long lived particles and ALPs., in addition to CLFV!

- Phase-I:
  - Undergoing commissioning.
  - Plot shows existing limits will be superseded within days.
  - Target sensitivity reached with ~400 days with a muon stopping rate of 1×10^{8} s^{-1}.

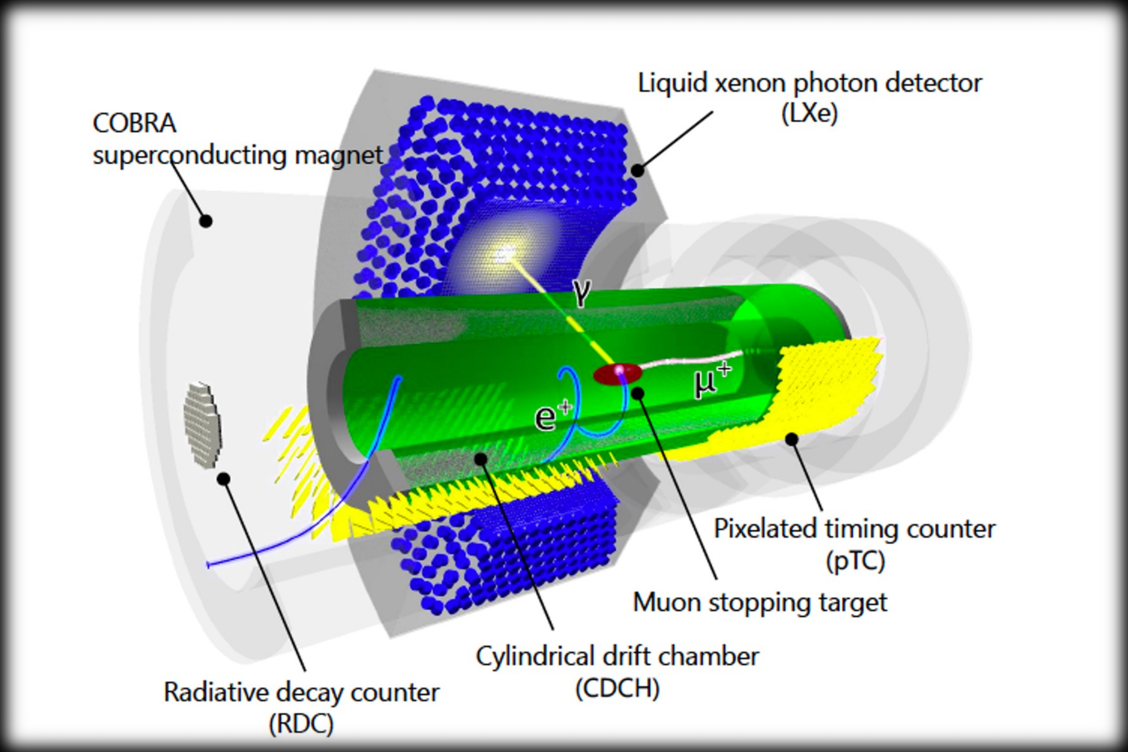
- Phase-II:
  - To reach 10^{-16} , a higher rate of muon stops is required.
  - The High Intensity Muon Beam (HiMB) currently under study at PSI would deliver a stopping rate of 2×10^{9} s^{-1}.
  - Not expected before 2028. Will require detector upgrades - currently under study.



MEG-II

The MEG-II Experiment

- Based at PSI, uses which delivers 1 x 10^8 μ^+/s.
- μ^+ stopped on thin plastic target - decay at rest to exploit the two-body kinematics.
- Target located at the center of a magnetic spectrometer used to track the candidate positron.
- LXe photon detector measures the timing, energy and the conversion position of the photon.

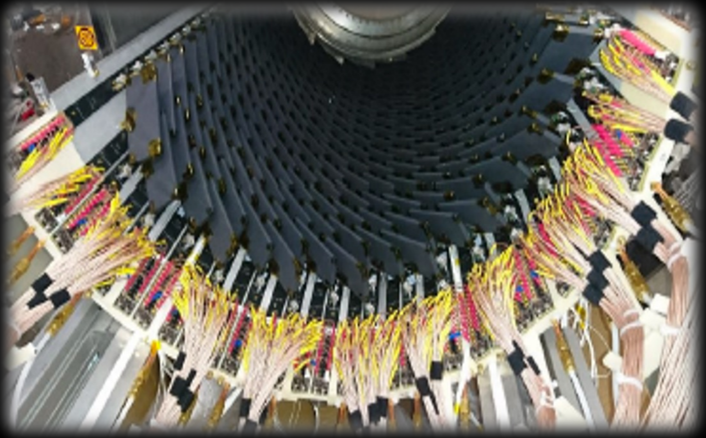


Two sources of background:

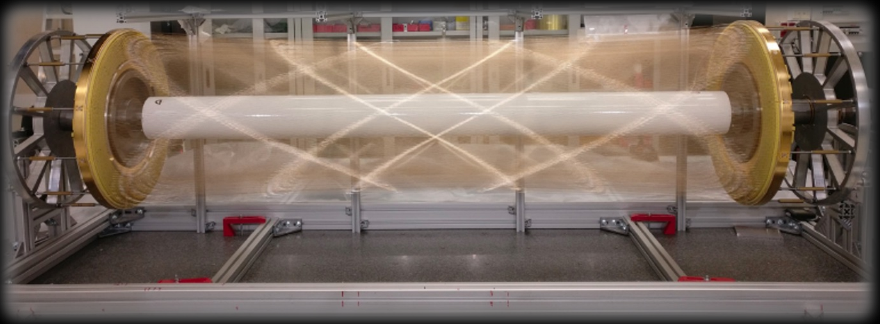
- Irreducible: Radiative muon decay ($\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$).
  Accidental: Ordinary muon decay $\mu^+ \rightarrow e^+ \nu\bar{\nu}$.

MEG-II: Current Status

Single pTC module inside the COBRA volume



The fully wired MEG II CDCH



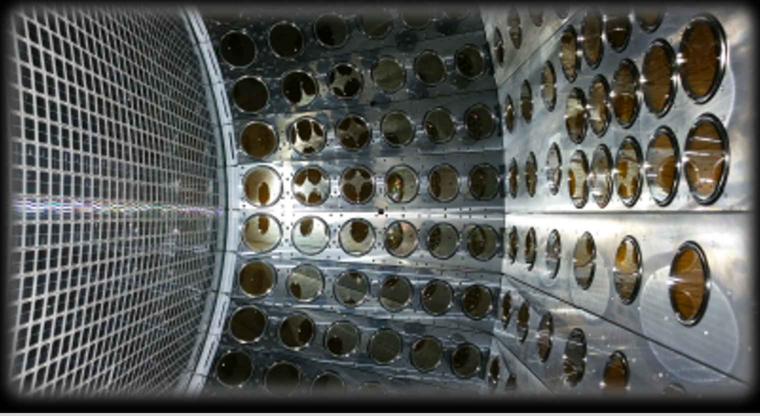


Photo-sensors mounted on inner faces

- Currently under commissioning at the PSI.
- Since 2017 each detector has undergone set of “Pre-Engineering” tests.
- This allowed estimate of the experiment sensitivity to be confirmed as 6 x 10^{-14} at 90% confidence level.
- In 2021:
  - first engineering run with the full detectors was completed.
  - complete TDAQ system was finally installed in the experimental area.

Discussion: Universe 2021, 7, 466

MEG-II: Commissioning Results

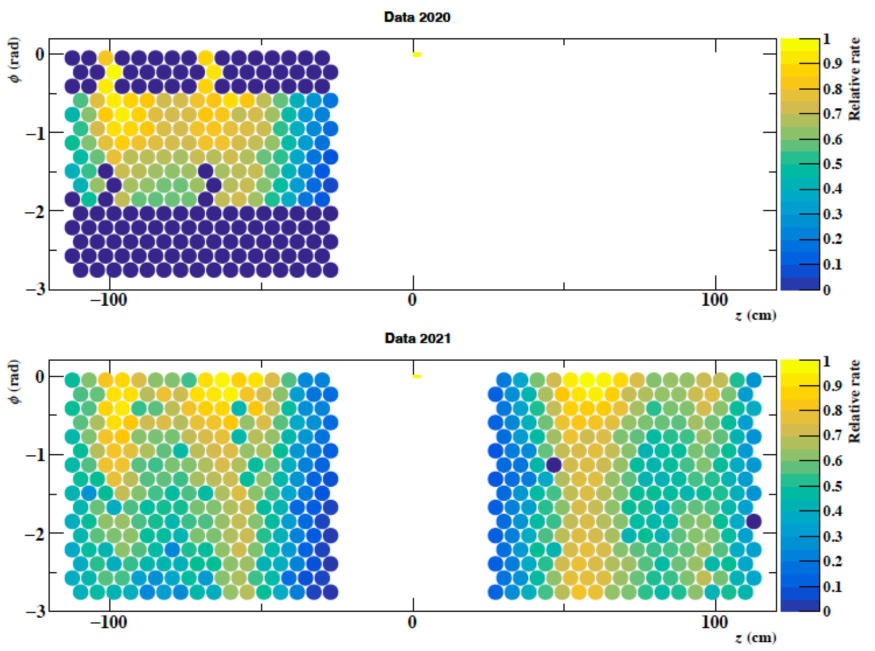


Figure 7. Relative hit rate of the pTC tiles in 2020 (top) and 2021 (bottom) runs.

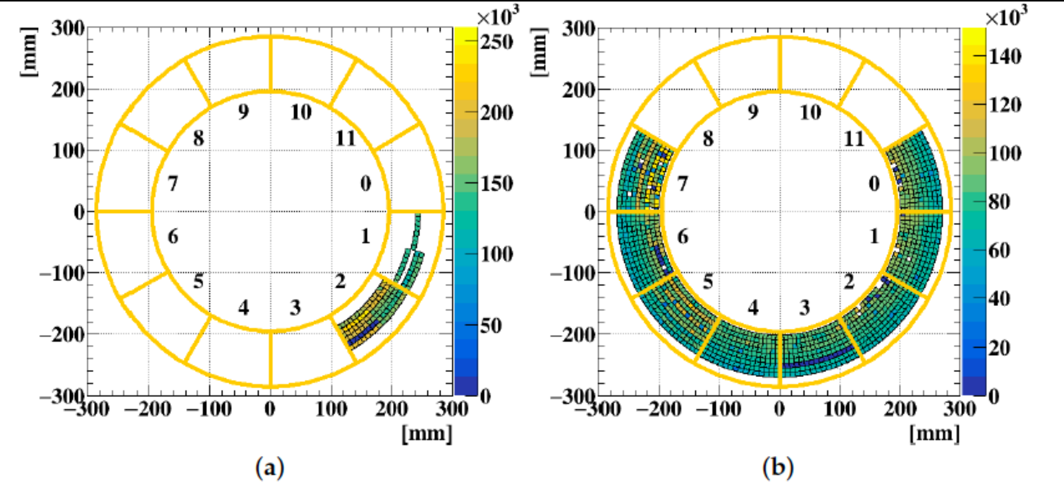


Figure 8. Occupancy plots from Michel e^+ events with a comparison between the 2020 (a) and 2021 (b) readouts.

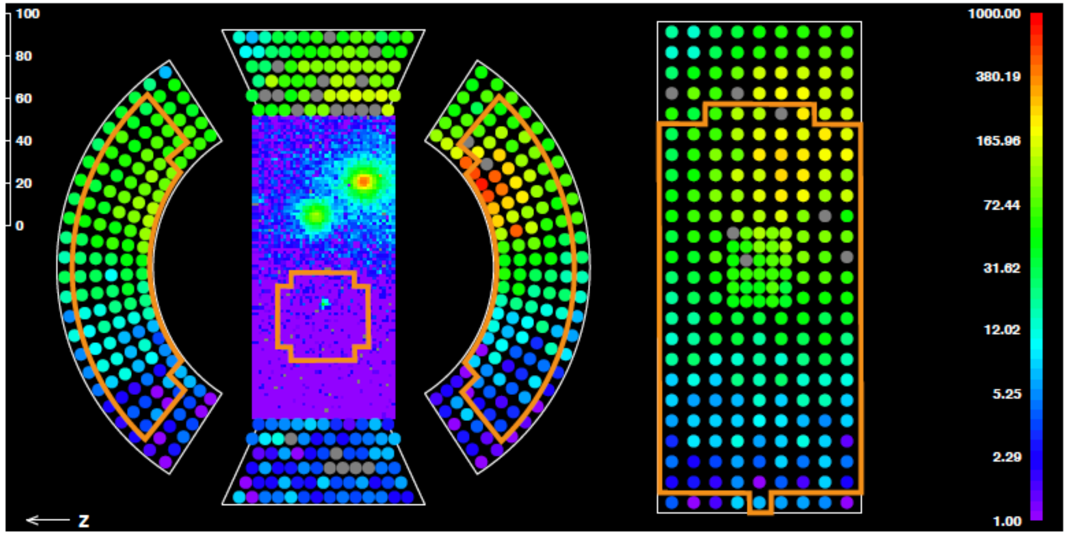


Figure 9. Gamma-ray event display with full readout. Readout region in 2020 is surrounded by orange lines.

Lots of progress during commissioning.
For details see: Universe 2021, 7, 466

Summary & Outlook

Summary

- Muon CLFV channels offer deep indirect probes into BSM. Therefore very complementary to Energy Frontier searches for New Physics.
- Mu3e, MEG-II, Mu2e, COMET and DeeMe at the forefront of active global CLFV program. They provide discovery potential over a wide range of well motivated BSM models.
- Muon-to-electron sector complements tau and Higgs collider searches such as: $\tau \rightarrow e\gamma$ or $\mu\gamma$ and $H \rightarrow e\tau, \mu\tau$, or μe.
- Expect limits on all 3 muon CLFV processes to improve by several orders of magnitude (with potential for discovery) by the end of the decade.
- Experiments also have sensitivity to other New Physics channels ($\mu^- N \rightarrow e^+ N'$, $\mu^- N \rightarrow e^- XN$, ALPs etc.…).
- These experiments will be indispensable pieces of the global search for New Physics over the next decade, it is important they are supported throughout their physics programs to complete their physics goals.

Thank You for listening!

Additional Reading and Useful Resources

CLFV in the SM:

1. S. T. Petcov, Sov. J. Nucl. Phys. **25**, 340 (1977); Yad. Fiz. **25**, 1336 (1977) [erratum].
2. S. M. Bilenky, S. T. Petcov, and B. Pontecorvo, Phys. Lett. B **67**, 309 (1977).
3. W. J. Marciano and A. I. Sanda, Phys. Lett. B **67**, 303 (1977).
4. B. W. Lee, S. Pakvasa, R. E. Shrock, and H. Sugawara, Phys. Rev. Lett. **38**, 937 (1977); **38**, 1230 (1977) [erratum].
5. W. J. Marciano, T. Mori, and J. M. Roney, Annual Review of Nuclear and Particle Science 58 (2008) 315–341.

Experiments Past and Present:

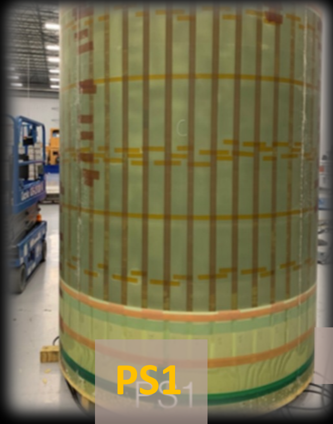
6. J. Adam *et al*. (MEG Collaboration), Phys. Rev. Lett. **110**, 20 (2013).
7. MEG-II: Universe 2021, 7, 466
8. W. Bertl *et al*. (SINDRUM-II Collaboration), Eur. Phys. J. **C47,** 337 (2006).
9. U. Bellgardt *et al*., (SINDRUM Collaboration), Nucl. Phys. **B299**, 1 (1988).
10. A.M. Baldini *et al*., “MEG Upgrade Proposal”, arXiv:1301.7225v2 [physics.ins- det].
11. DeeMe Proposal, submitted to KEK IMSS (2010).
12. COMET Phase 1: https://arxiv.org/abs/1812.09018
13. Mu2e TDR: arXiv:1501.05241
14. Y. Kuno *et al*., “COMET Proposal” (2007)
15. Mu2e-II Contributed Paper: https://arxiv.org/abs/2203.07569
16. Mu3e Experiment: Nuclear Physics B - Proceedings Supplements Volumes 248–250, March–May 2014, Pages 35-4

Overviews of CLFV and theory:

17. Bernstein & Cooper: arXiv:1307.5787 [hep-ex]
18. L. Calibbi *et al.*, Phys. Rev. D **74**, 116002 (2006), L. Calibbi *et al.,* JHEP **1211,** 40 (2012). (SUSY and CLFV)
19. J.M. Arnold *et al.*, Phys. Rev D **88**, 035009 (2013). (Scalar Leptoquarks and CLFV)
20. Nuclear Physics B (Proc. Suppl.) 248–250 (2014) 13–19 (links to see saw mechanisms and neutrino mass)
21. Lorenzo Calibbi, Giovanni Signorelli arXiv:1709.00294 (2018) (general overview)
22. Complementarity and Completeness: https://arxiv.org/abs/2010.00317v2

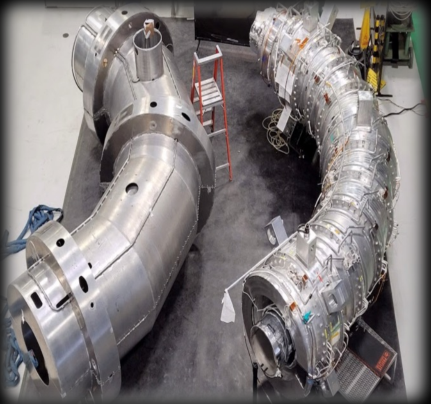
Additional Material

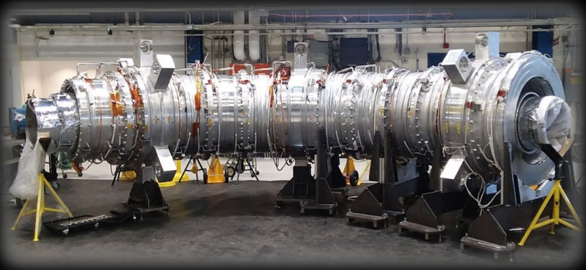
Mu2e: Solenoids Status



Production:
- → Production Target procured
- → Heat & Rad. Shield in hall
- → All coils fabricated, tests underway

Transport:
- → All coils at FNAL
- → TSu and TSd cold-masses assembled
- → Testing almost complete





Detector:
- → Many coils fabricated
- → Tests on-going
- → Stopping target procured

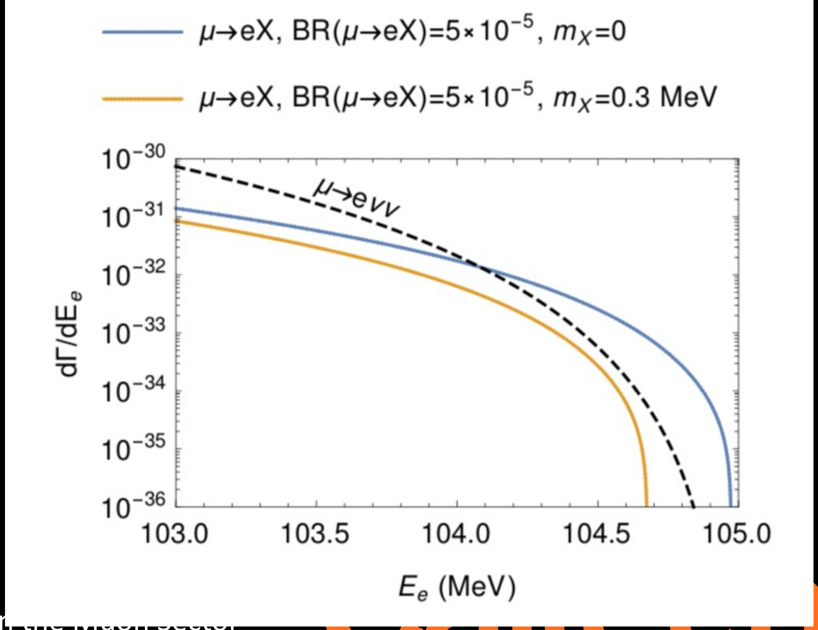
Other Physics Searches at Mu2e

$$R^{\mathrm{Ti}}_{\mu^- e^+} \equiv \frac{\Gamma(\mu^- + \mathrm{Ti} \to e^+ + \mathrm{Ca})}{\Gamma(\mu^- + \mathrm{Ti} \to \nu_\mu + \mathrm{Sc})} < \begin{cases} 1.7 \times 10^{-12} \text{ (GS, 90\% CL)} \\ 3.6 \times 10^{-11} \text{ (GDR, 90\% CL)} \end{cases}$$

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

- This conversion violates both lepton number ($\Delta L = 2$) and lepton flavor conservation and can be mediated by Majorana neutrinos through a type-1 see saw mechanism or new particle at > TeV scale.
- The Mu2e sensitivity to μ− → e+ extends beyond the current best limit: Phys Rev Lett B 412 p 334-338 [13]
- $< m_{e\mu} >$ effective Majorana neutrino mass scale sensitivity down to the MeV region, surpassing the $< m_{\mu\mu} >$ sensitivity in the kaon sector which is limited to the GeV region

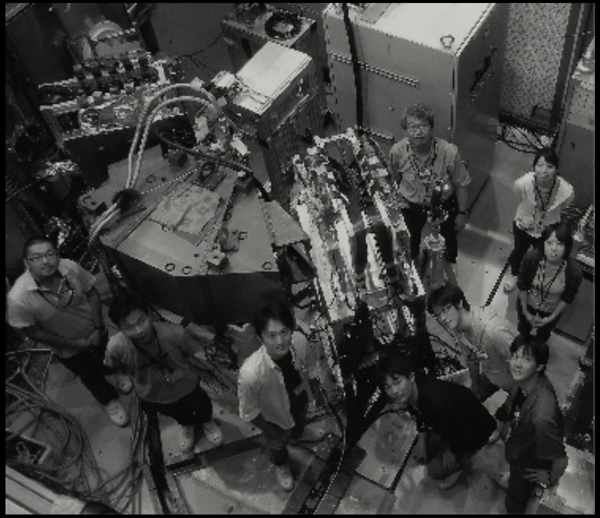
Yeo et al 2017 https://arxiv.org/abs/1705.07464



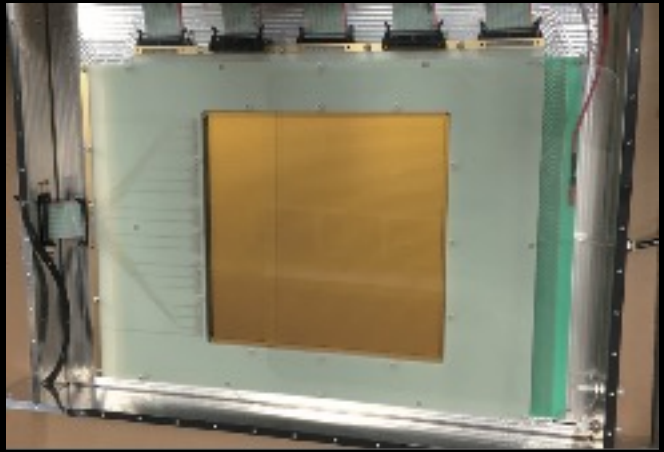
$\mu^- N \rightarrow eXN$

- Currently understanding feasibility
- Example parameterization: arXiv: 1110.2874

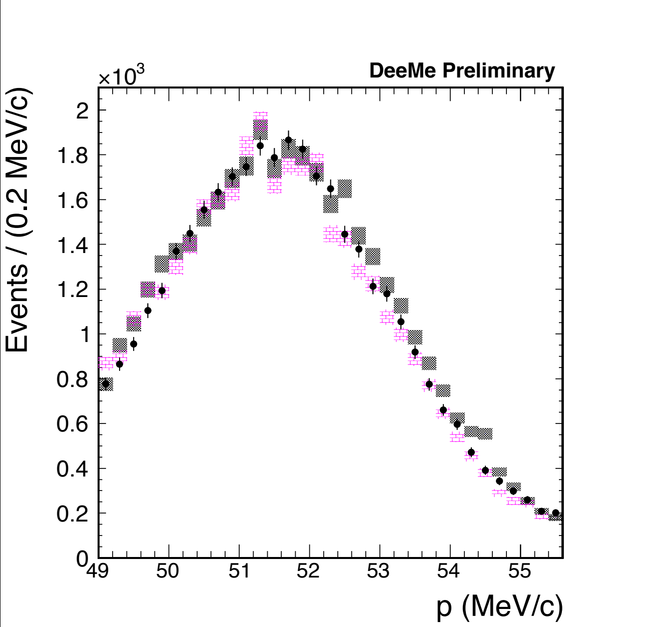
DeeMe: Status



Spectrometer setup for the DIO spectrum measurement conducted at the D2 area at MLF.



Inside of a multiwire proportional chamber used in the DeeMe experiment.

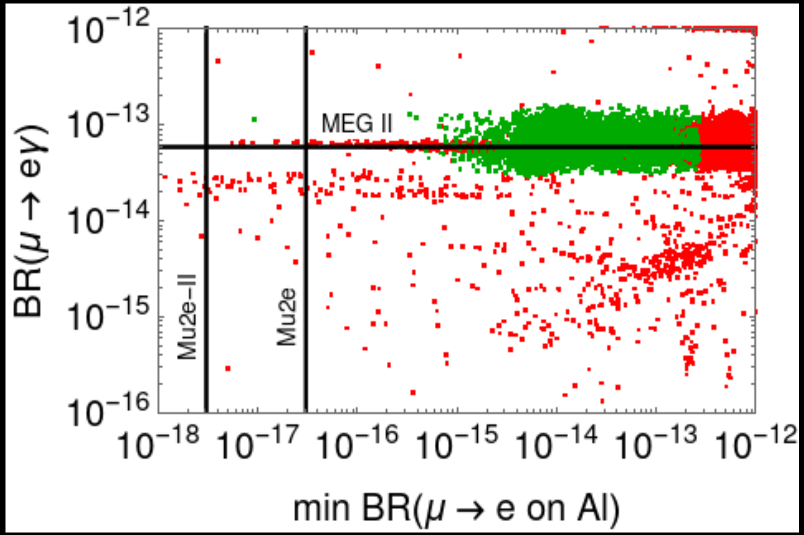


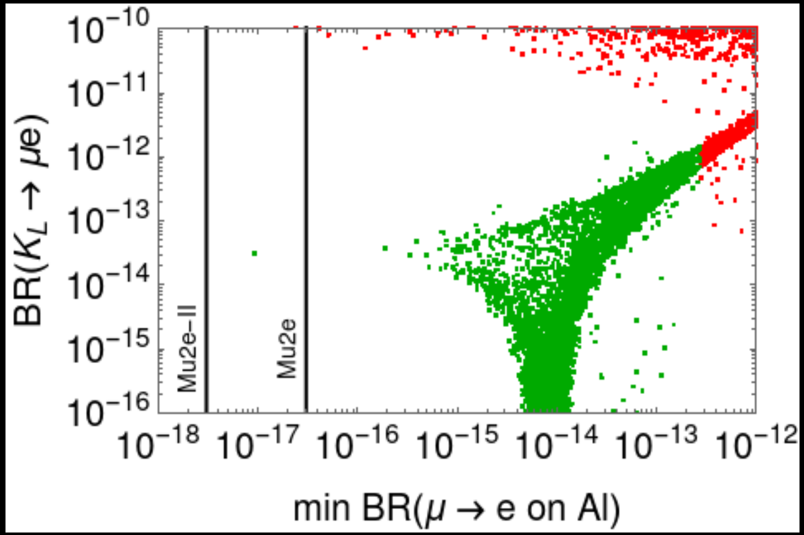
Obtained DIO momentum distributions compared to theoretical calculations

- Using an existing muon beamline at MLF, DIO spectrum measurements were made with all the MWPCs and DAQ systems in place. A graphite target was put in the D2 experimental area to stop muons.
- The H-line construction has been completed and is ready for commissioning.
- DeeMe plan to begin commissioning in April 2022 and move to the initial physics runs in June 2022.
- Expecting beam time in the latter half of 2022 with a good level of data collection in the year 2023.

Example: Leptoquarks

- Pati-Salam Leptoquarks: B-meson anomalies could be explained by two scalar leptoquarks, whose couplings enter neutrino masses as well. Type-II seesaw dominance is favored.



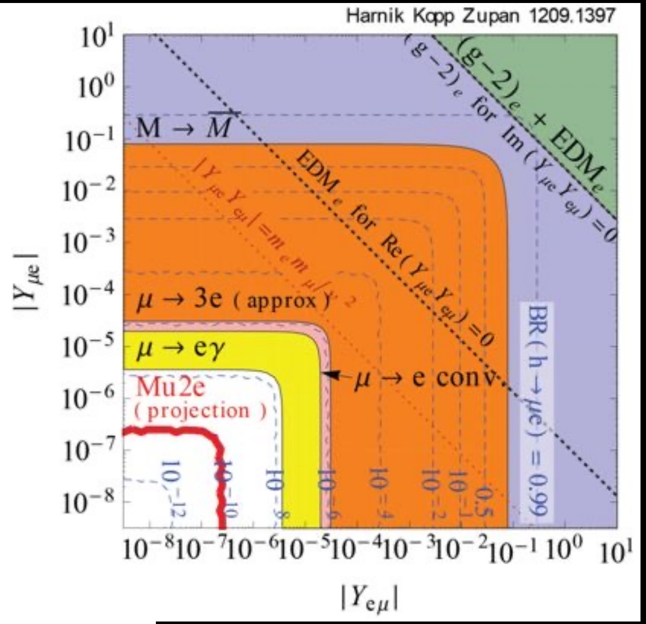


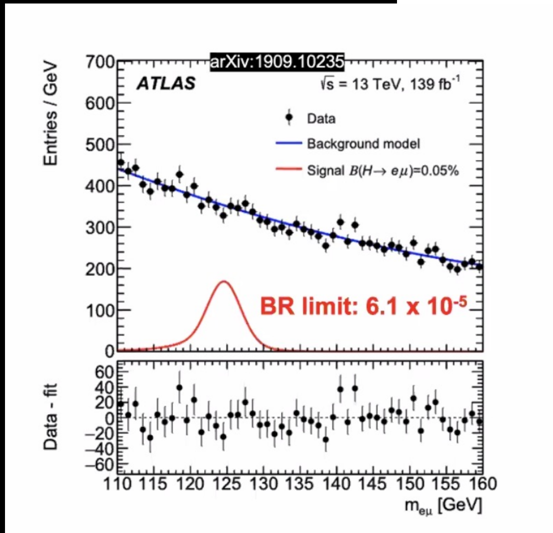
Heeck & Teresi, 1808.07492

- Flavor structure fixed by neutrino mass/mixing; scale Λ fixed to explain B-meson anomaly R(K).
- Predicts testable rates in Mu2e!
- Explain B meson anomalies through adding 2 scalar leptoquarks: Bigaran, Gargalionis, Volkas, 1906.01870 → B($\mu N \rightarrow$ eN) < 3 x 10^{-13}

Example: Constraining Flavor Violating Higgs Decays

Harnik, J. Kopp and J. Zupan, JHEP **3**, 26 (2013).





- Can also help constrain flavor violating Higgs decays.
- 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.
- 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:

$$\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} > \text{few} \times 10^{-7}.$$

- Where $|Y_{\mu e}|$ and $|Y_{e\mu}|$ are flavor-violating Yukawa couplings for a 125 GeV Higgs boson i.e. $h \to \mu e$.
- **Very strong limits on LFV Higgs decays for 1st-2nd generation**