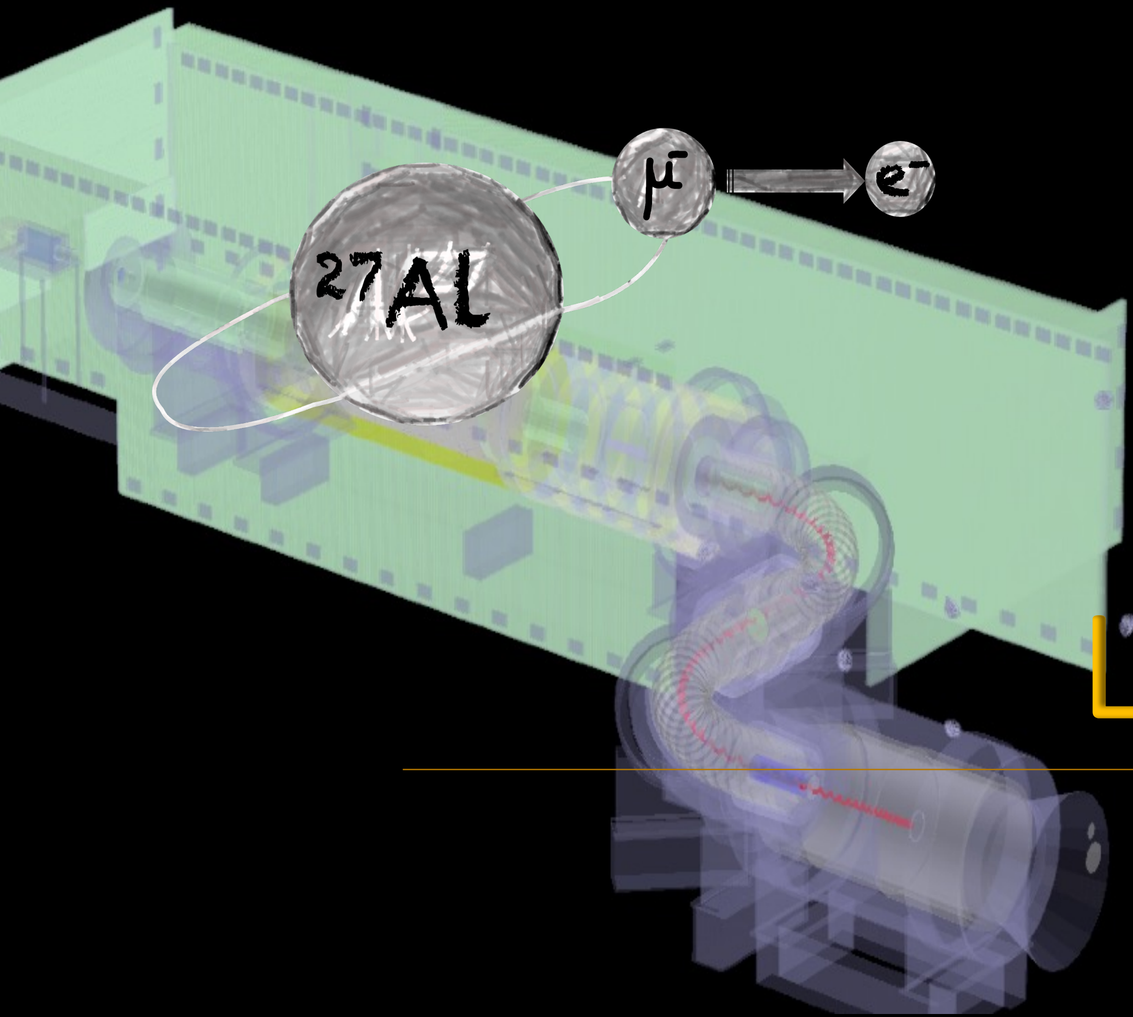

Searching for Charged Lepton Flavor Violation

Presented by ***Sophie Charlotte Middleton***

Research Associate in the High Energy Physics Group

PH242

Feb. 2022

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Caltech

About Me

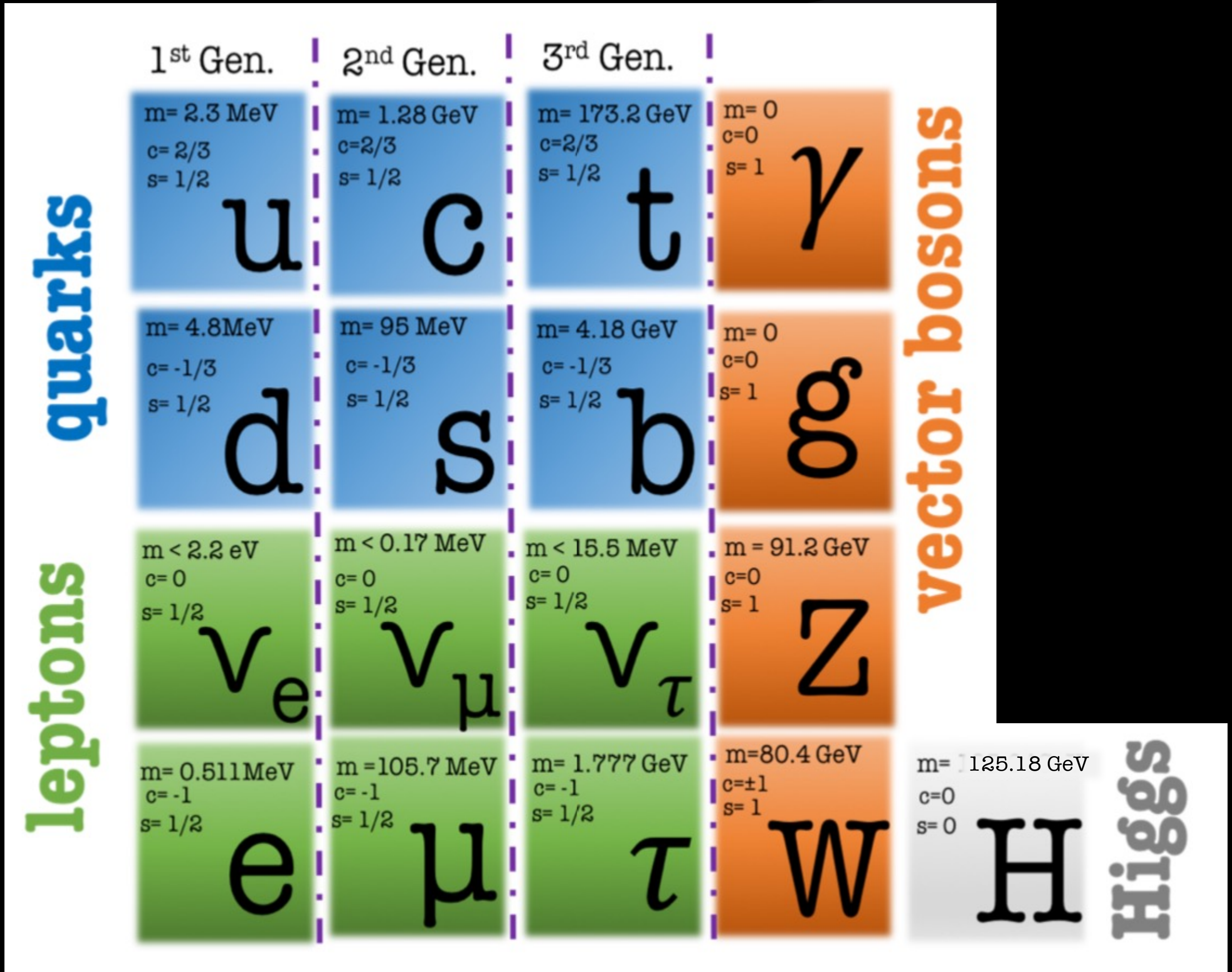
- Post-doctoral Scholar at Caltech for 2.5 years. Work in the Hitlin-Porter Group.
- We work on high-intensity searches for new physics which goes beyond the “Standard Model.”
- Previously:
  - Completed my PhD and Masters both at Imperial College London.
  - PhD research focussed on developing muon ionization cooling, a prerequisite for a future muon collider. Results: Nature 578, 53–59.

Today I will tell you about one of the collaborations we work on: Mu2e, a searching for charged lepton flavor violation based at Fermilab.

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

The Standard Model



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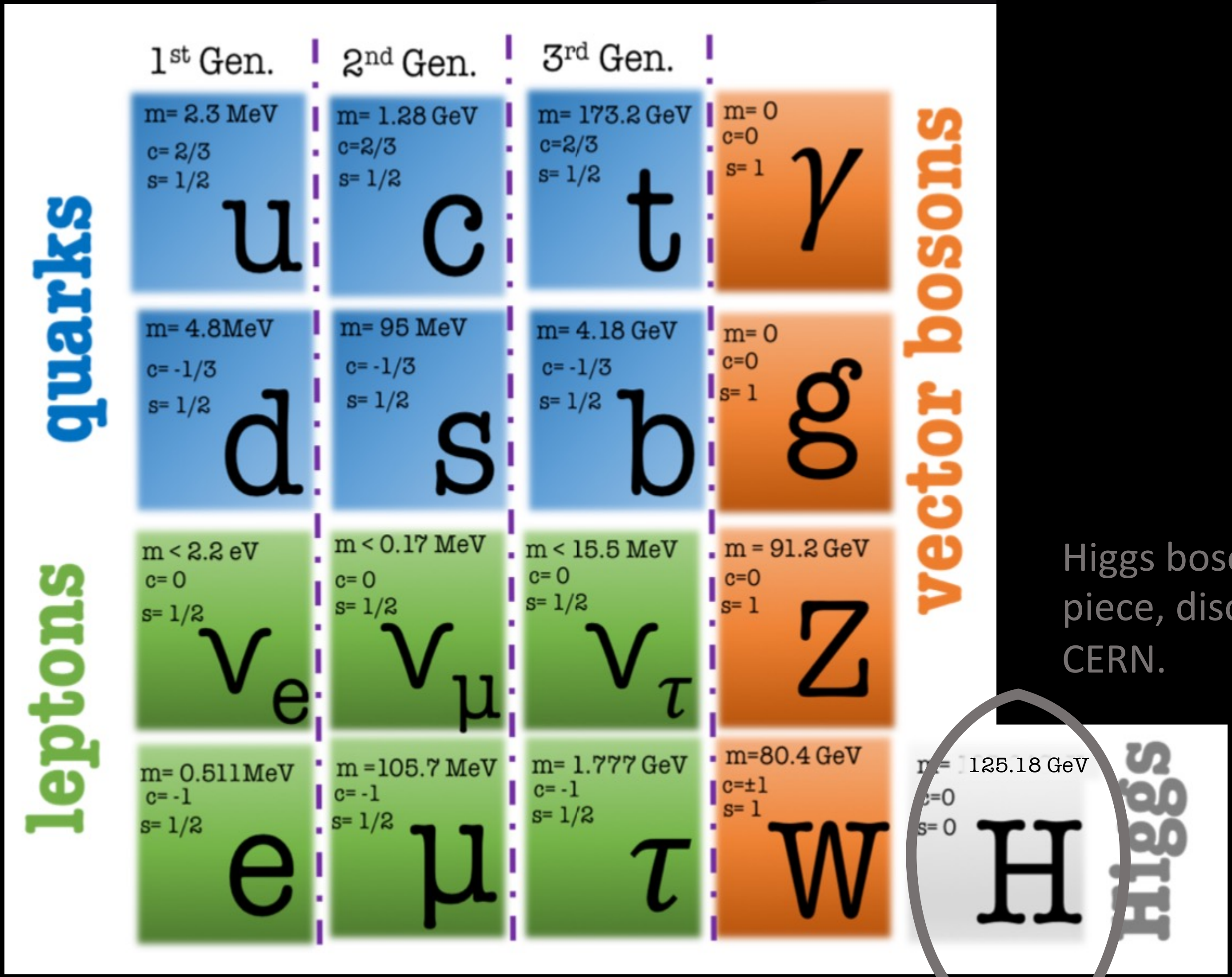
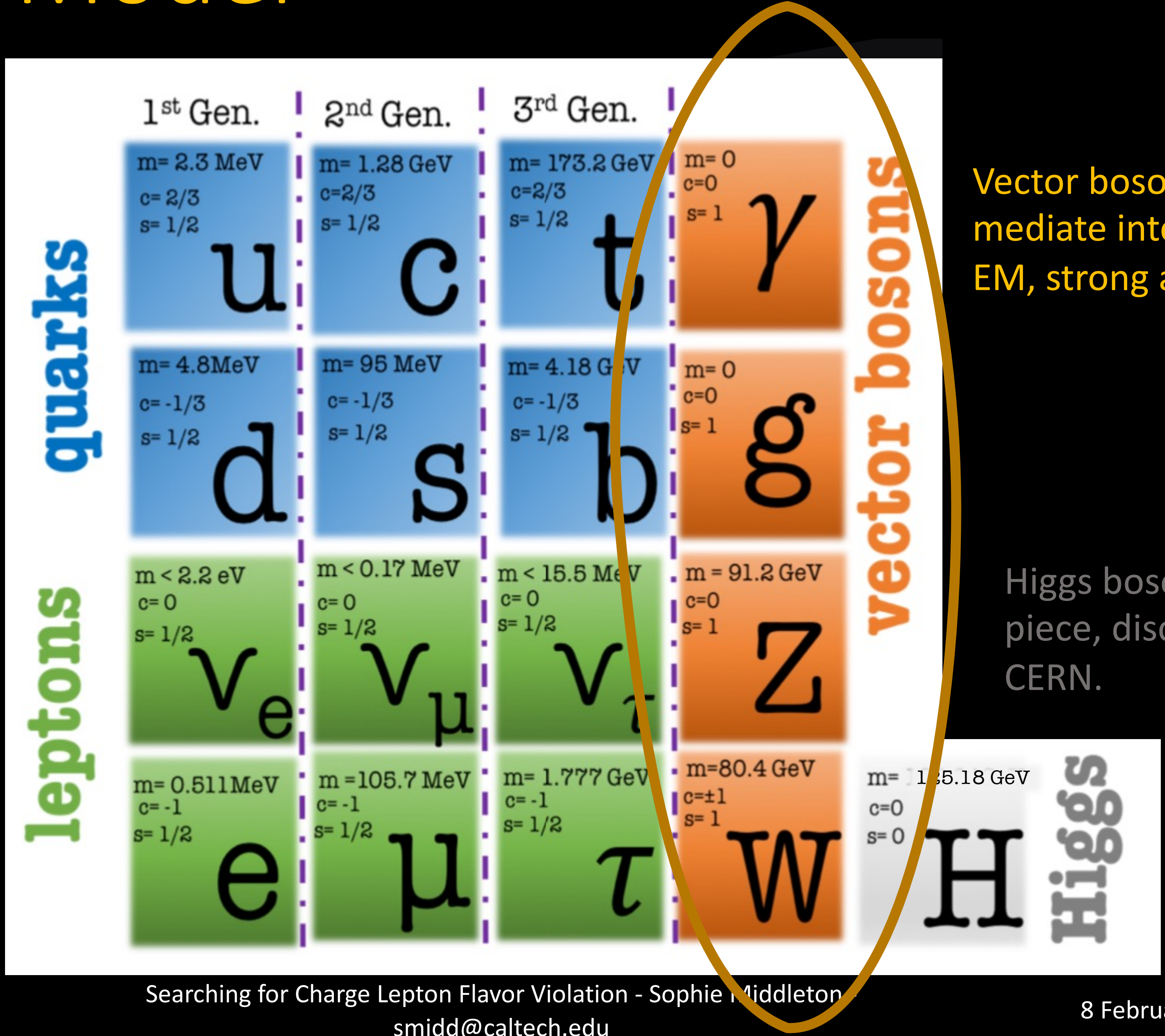


Higgs boson was the final piece, discovered in 2012 at CERN.

The Standard Model

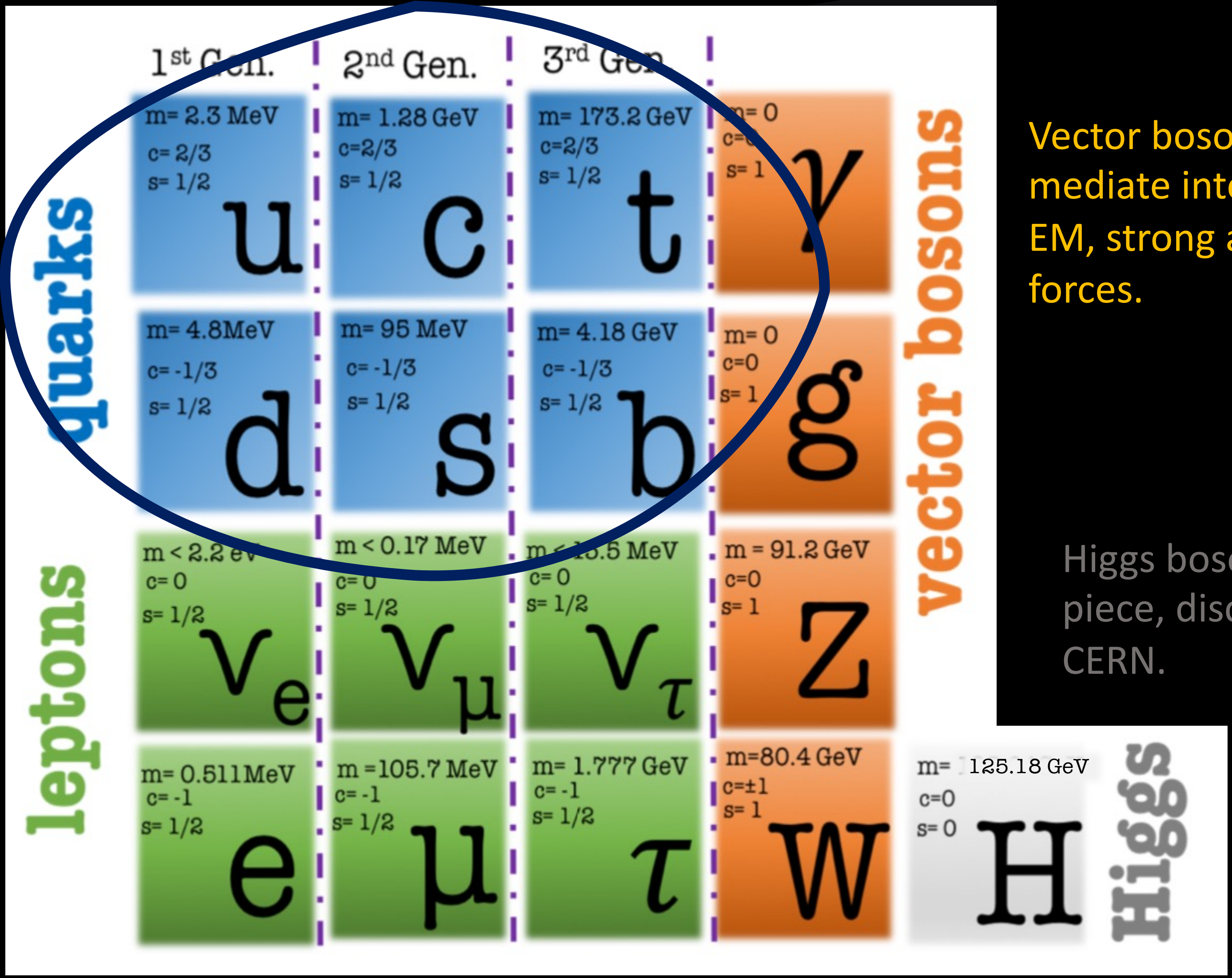


Vector bosons act to mediate interactions of the EM, strong and weak forces.

Higgs boson was the final piece, discovered in 2012 at CERN.

The Standard Model

Quarks combine to form hadrons such as protons or neutrons.



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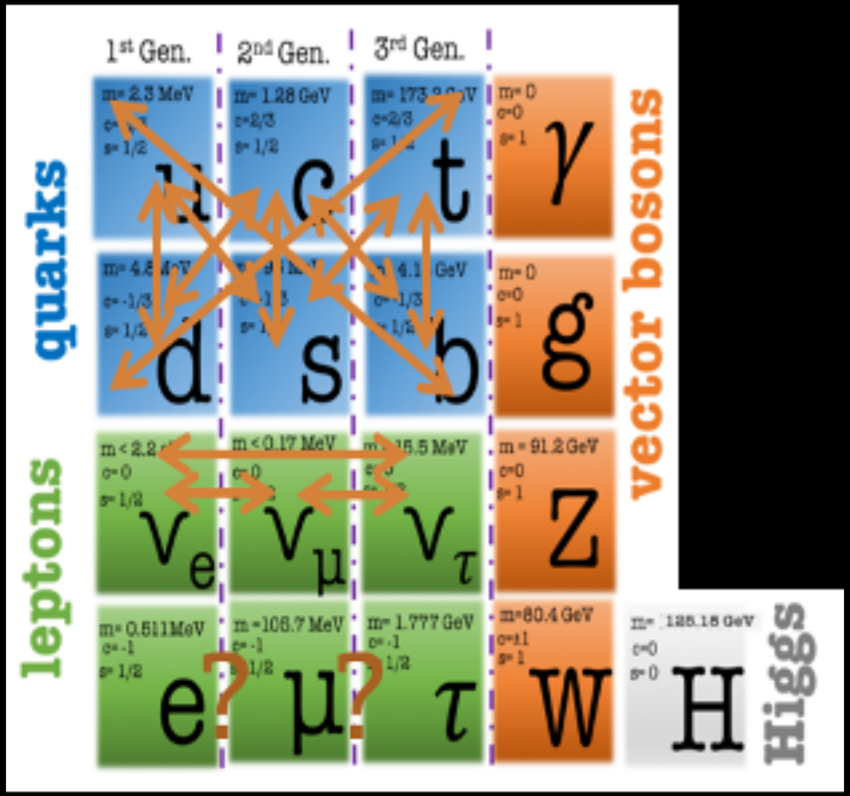
Quark Flavor Violation

- The Quarks commit Flavor Violation

  - Mixing strengths are parameterized by **Cabibbo–Kobayashi–Maskawa (**CKM) matrix:

$$(d', s', b') = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

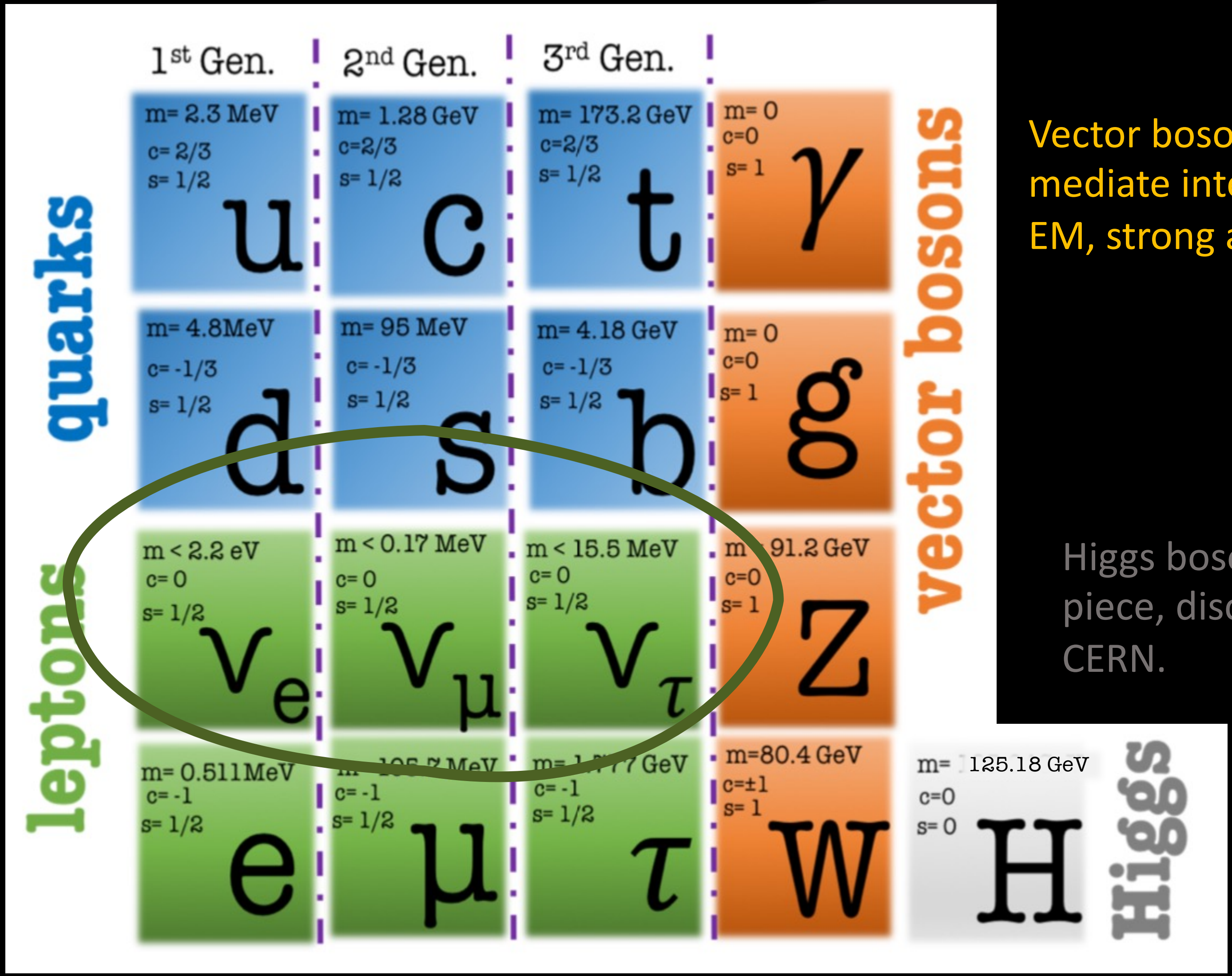
→ almost diagonal.



The Standard Model

Quarks combine to form hadrons such as protons or neutrons.

Neutrinos were long believed massless but discovery of oscillations suggest they have small mass.



Vector bosons act to mediate interactions of the EM, strong and weak forces.

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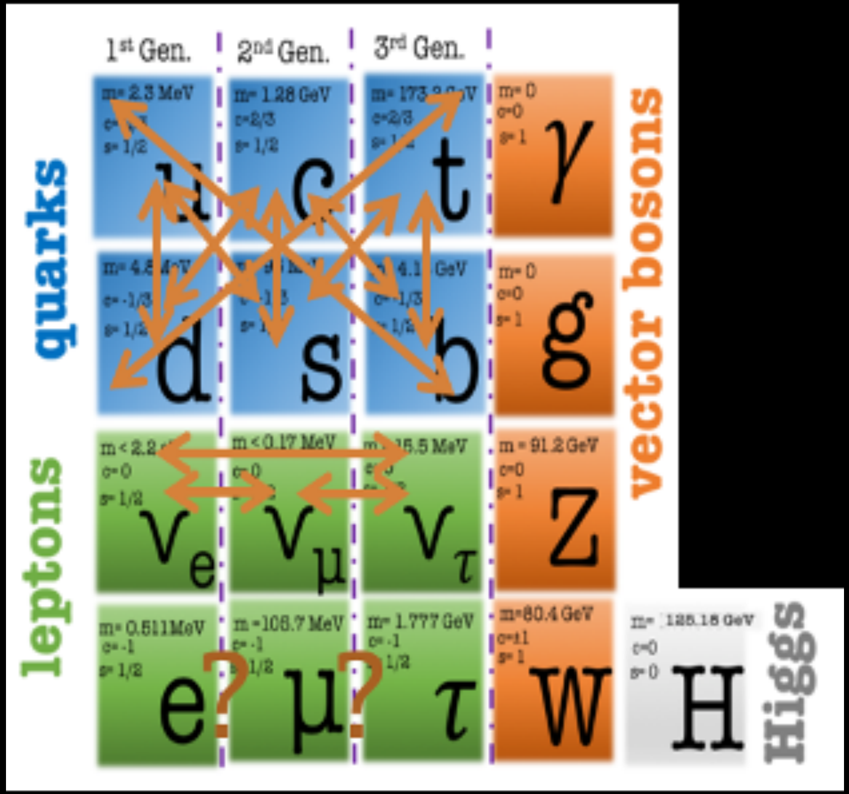
Neutral Lepton Flavor Violations

- ν oscillations → Lepton Flavour Violation (LFV)

  - Mixing strengths parameterised by the **Pontecorvo–Maki–Nakagawa–Sakata matrix (**PMNS) matrix:

$$(\nu_e, \nu_\mu, \nu_\tau) = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

→ more mixing

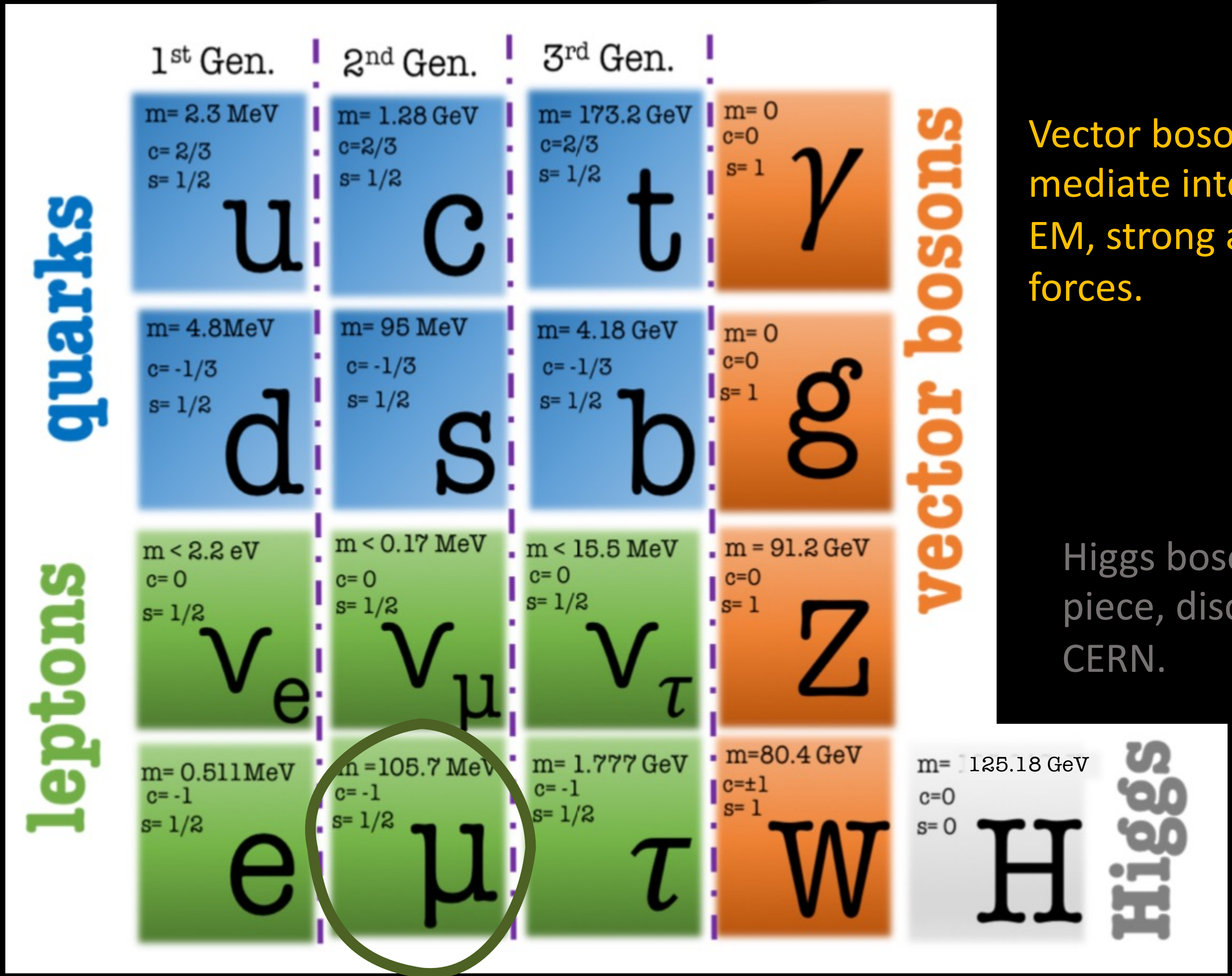


i.e. The current best fit values imply that there is much more neutrino mixing than there is mixing between the quark flavors in the CKM matrix.

The Standard Model

Quarks combine to form hadrons such as protons or neutrons.

Charged leptons exist in three generations. Muons are the second generation ….and what I have spent many years studying



Vector bosons act to mediate interactions of the EM, strong and weak forces.

Higgs boson was the final piece, discovered in 2012 at CERN.

The History of the Muon

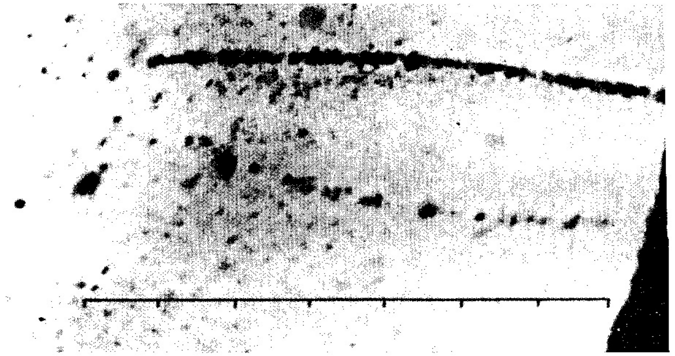
- 1897 – JJ Thompson discovers the electron.
- 1933 - Kunze published first "observation" of the muon:

  "The nature of this particle is unknown; for a proton, it does not ionize enough, and for a positive electron, the ionization is too strong"

- 1934 - Yukawa predicts a "meson" of mass $\sim 200 me$ to explain the cohesion of the nucleus.
- 1936 - 3 groups independently conclude that the penetrating particle is a new one, and of intermediate mass between the electron and proton. Neddermeyer & Anderson's Caltech group publishes first →Discovery of the the "mu-meson"
- 1937 - Observed that the "mu-meson" doesn't feel the nuclear force

  Seth H. Neddermeyer, Phys. Rev., Vol. 51, 884

- 1948 - The muon is not an excited electron – Rabi asks "who ordered that?" muon becomes understood as heavier electron and a point-like particle. Steinberger, J., 1948, Phys. Rev. 74 , 500.



"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1

Muon Properties

Muons have been very useful in helping understand the Standard Model:

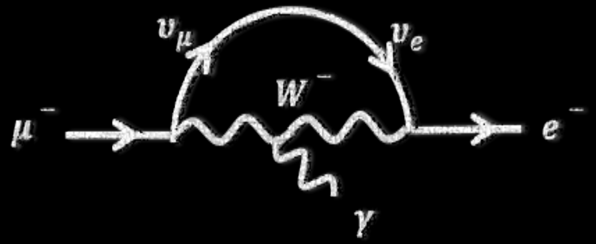
- They are charged ($q = \pm e$):
  - Contained by EM fields. So we can accelerate and focus them using magnets.
- Muons are easy to produced in well understood channels. They are naturally produced in large numbers by pion weak decay:
  - Protons on target → Pions → Muons.
- Muons decay and feel the weak but not the strong force:
  - Lifetime is long enough (2.2 μs) to study interactions but short enough to study decay.
  - Muon decay has helped us understand the weak force.
  - Pure Lepontic nature of muon decay offers analysis of V – A without CKM assumptions.

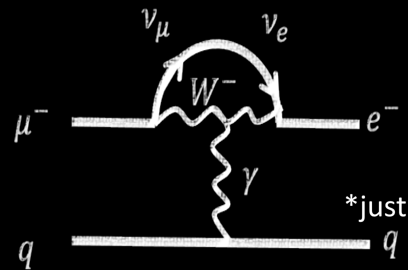
These properties also make them excellent particles to use for new physics searches:

1. High intensity beams of muons produced from pion decay can be manipulated onto a muon stopping target;
2. Much longer lifetime and clean decays mean little background to remove compared to taus which have complicated hadronic channels to cope with and a nano-second lifetime.

Charged Lepton Flavor Violation (CLFV)

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





*just one example

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

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

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

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

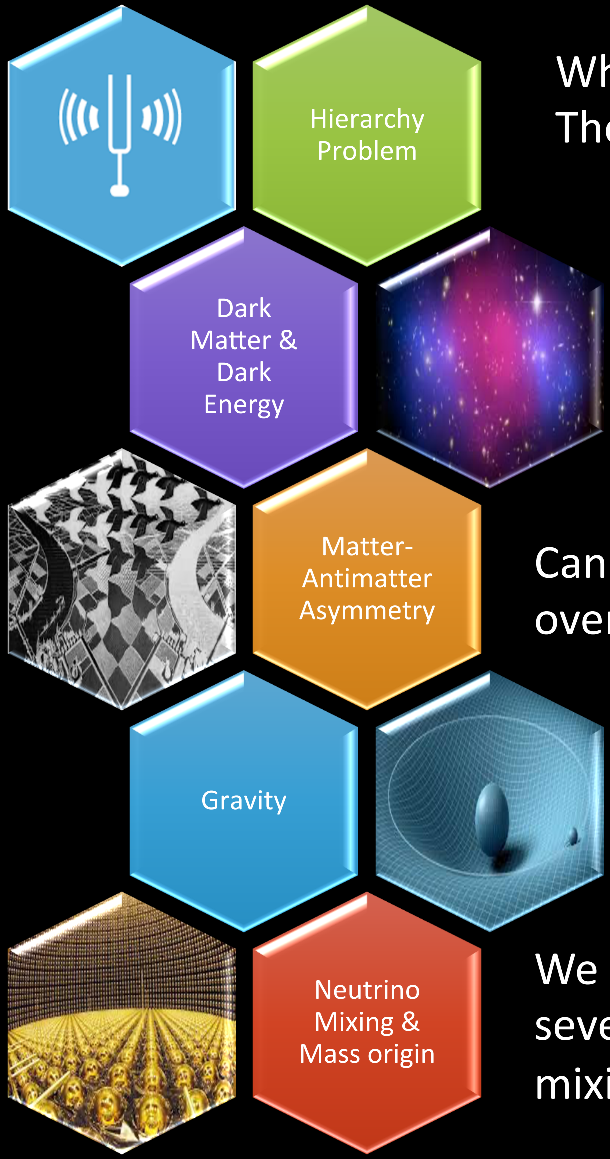
[1-4]

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 Mu2e → this would be an unambiguous sign of physics beyond the Standard Model.

Why do we need new physics?

Why is the Higgs light compared to Planck scale? There must be some fine tuning



Standard model particles are just 5% of the mass-energy content of the Universe.

Can we fully explain why matter dominates over anti-matter?

Can we unify gravity with the other forces?

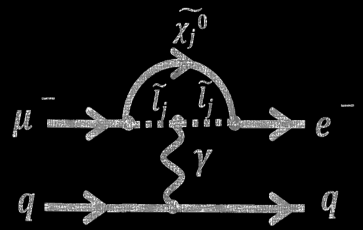
These aren't always discrete problems, and some theories can explain more than one issue e.g., SUSY provides dark matter candidate and helps resolve the hierarchy problem and neutrino experiments could find new sources of leptonic CP violation

We know neutrinos oscillate but we still have several other questions regarding neutrino mixing and the nature of neutrinos.

BSM Scenarios

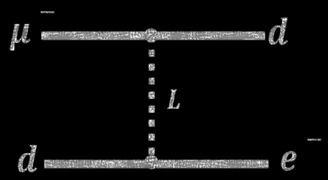
Nice overview: Lorenzo Calibbi, Giovanni Signorelli arXiv:1709.00294 (2018)

There are many well-motivated BSM theories which invoke CLFV mediated by (pseudo) scalar, (axial) vector, or tensor currents at rates close to current experimental limits i.e. $B \approx 10^{-15} - 10^{-17}$:



SO(10) SUSY : L. Calibbi *et al.*, Phys. Rev. D **74**, 116002 (2006), L. Calibbi *et al.*, JHEP **1211**, 40 (2012).

Scalar Leptoquarks: J.M. Arnold *et al.*, Phys. Rev D **88**, 035009 (2013).



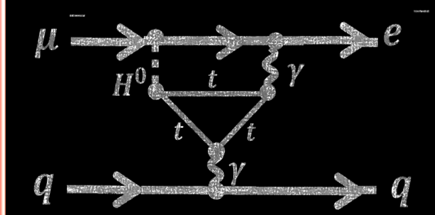
Different neutrino mass-generating Lagrangians lead to very different rates for CLFV : Nuclear Physics B (Proc. Suppl.) 248–250 (2014) 13–19

Extended Higgs/Gauge sector:

Left-Right Symmetric Models

C.-H. Lee *et al.*, Phys. ReV D **88**, 093010 (2013).

Littlest Higgs Blanke et al Phys.Polon.B41:657, 2010, arXiv:0906.5454v2 [hep-ph]



A few examples – not an exclusive list!

Important point:

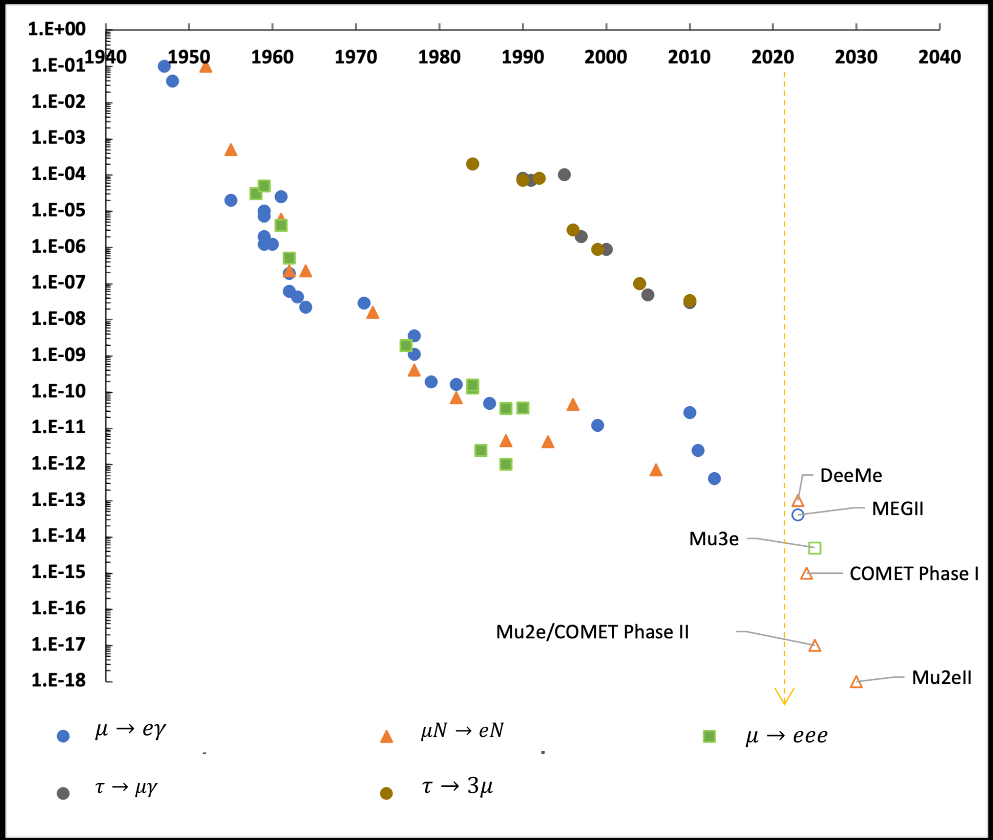
Mu2e is an indirect search for new physics, with sensitivity to lots of models. Even a null result would have huge implications!

Experimental Searches for CLFV

arXiv:1307.5787 [hep-ex]
Bernstein & Cooper

- $\mu^- N \to e^- N$ 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 x 10^{-13} [5]	4 x 10^{-14}	MEG II [8]
$\mu^- N \to e^- N$	7 x 10^{-13} [6]	10^{-15} 10^{-17} 10^{-18}	COMET Phase-I Mu2e [10] & COMET Phase-II [9] Mu2e-II
$\mu^+ \to e^+ e^+ e^-$	~10^{-12} [7]	10^{-15} ~ 10^{-16}	Mu3e



- 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.

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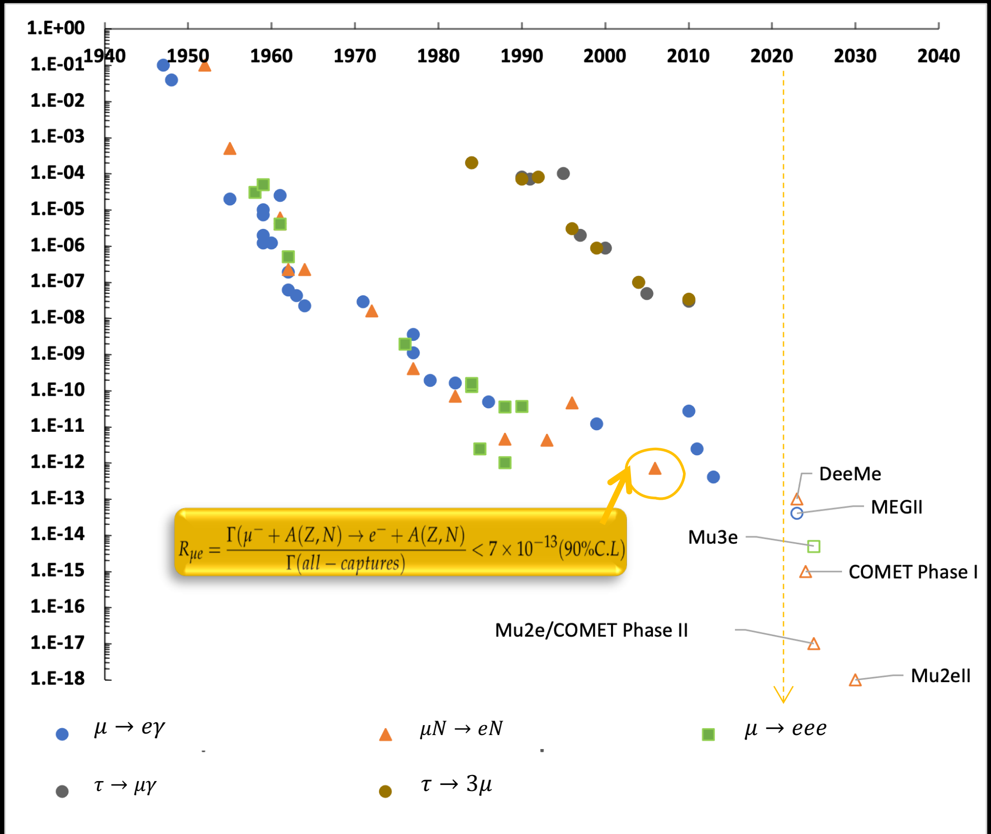

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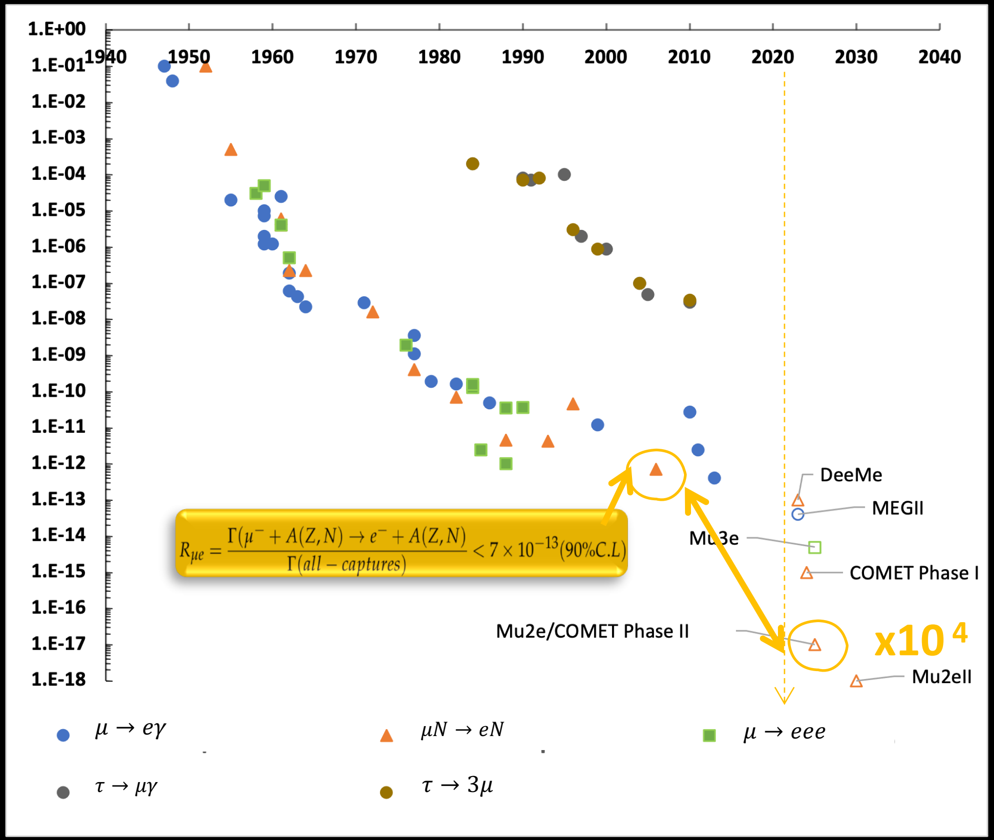

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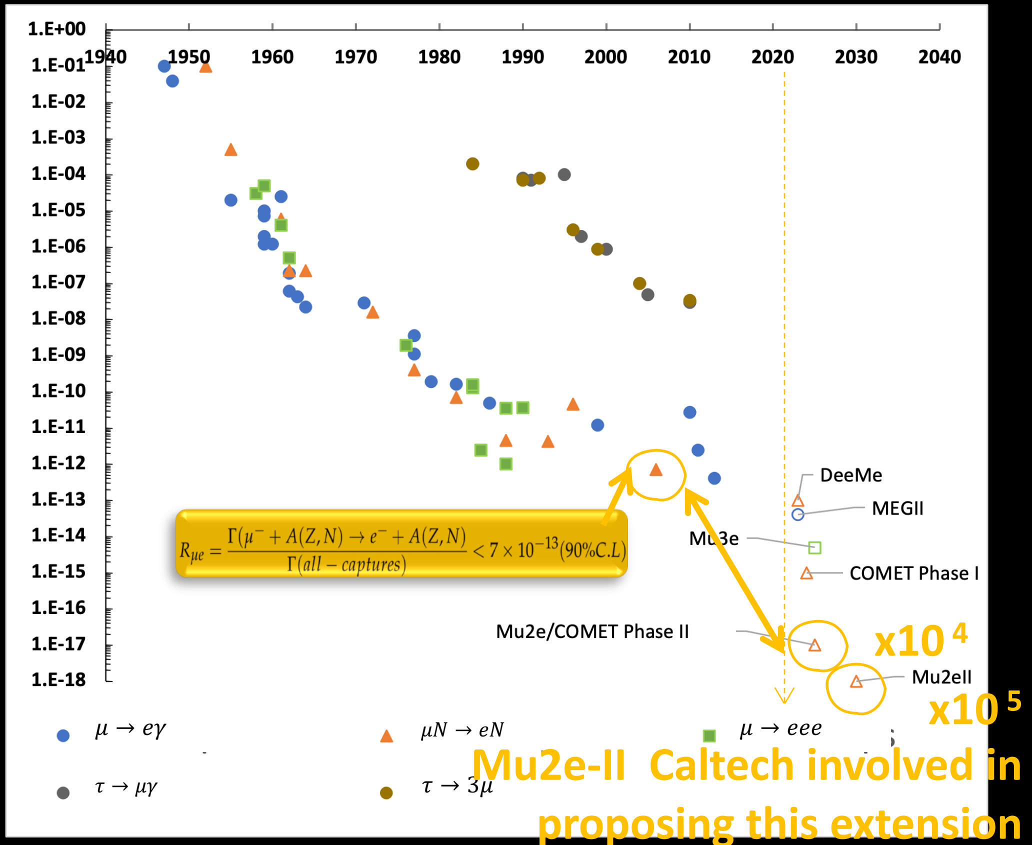

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Simplistic Explanation of Physics Reach

A. de Gouvêa, P. Vogel
arXiv:1303.4097

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

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

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

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

S
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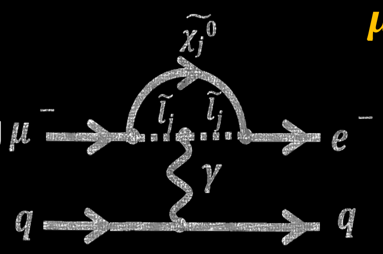
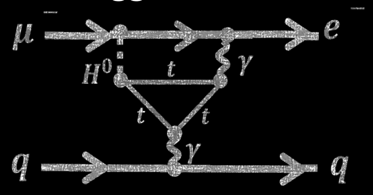
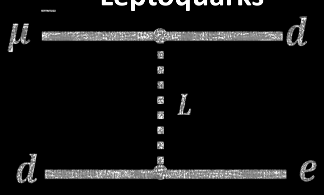
Y



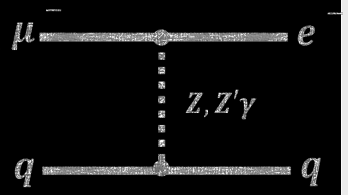
2 Higgs Doublets

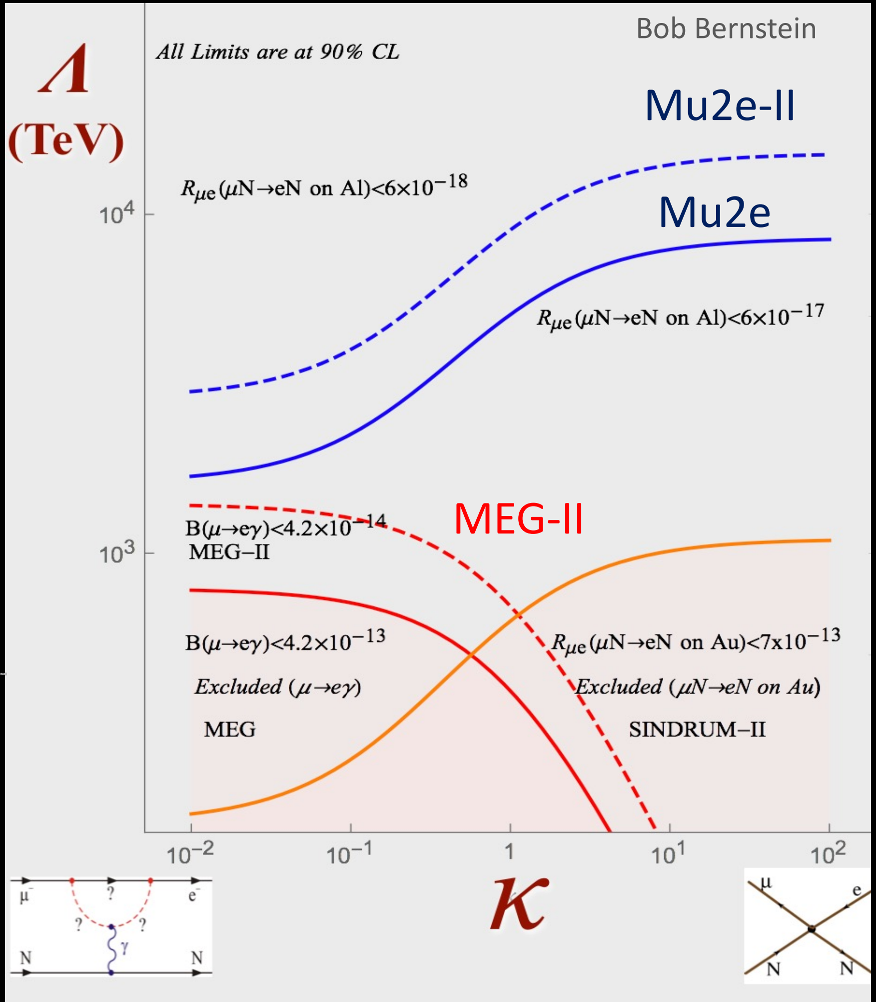


Leptoquarks



New Bosons





Λ : effective mass scale of New Physics (NP),
κ : determines to what extent NP is photonic (κ << 1) or 4-fermion (κ >> 1)

Complementarity

Taken from: arXiv:0909.1333[hep-ph]

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

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.

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$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★

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

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

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	$\approx 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop*	Loop*	$3 \times 10^{-3} - 0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^{3}$	$\mathcal{O}(10^{-2})$
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*	$0.05 - 0.5$	$2 - 20$

arXiv:1709.00294v2[hep-ph]

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

Complementarity

Taken from: arXiv:0909.1333[hep-ph]

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

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

Theory on complementarity →
http://arxiv.org/abs/2010.00317v2

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{BR(\mu \to eee)}{BR(\mu \to e\gamma)}$	$\frac{CR(\mu N \to eN)}{BR(\mu \to e\gamma)}$
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arXiv:1709.00294v2[hep-ph]

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

Complementarity in Target Materials

$$\mathrm{BR}(\mu \to e) \propto |D C_{DL} + S^p C^p_{S,L} + V^p C^p_{V,R} + S^n C^n_{S,L} + V^n C^n_{V,R}|^2 + (L \leftrightarrow R)$$

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

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

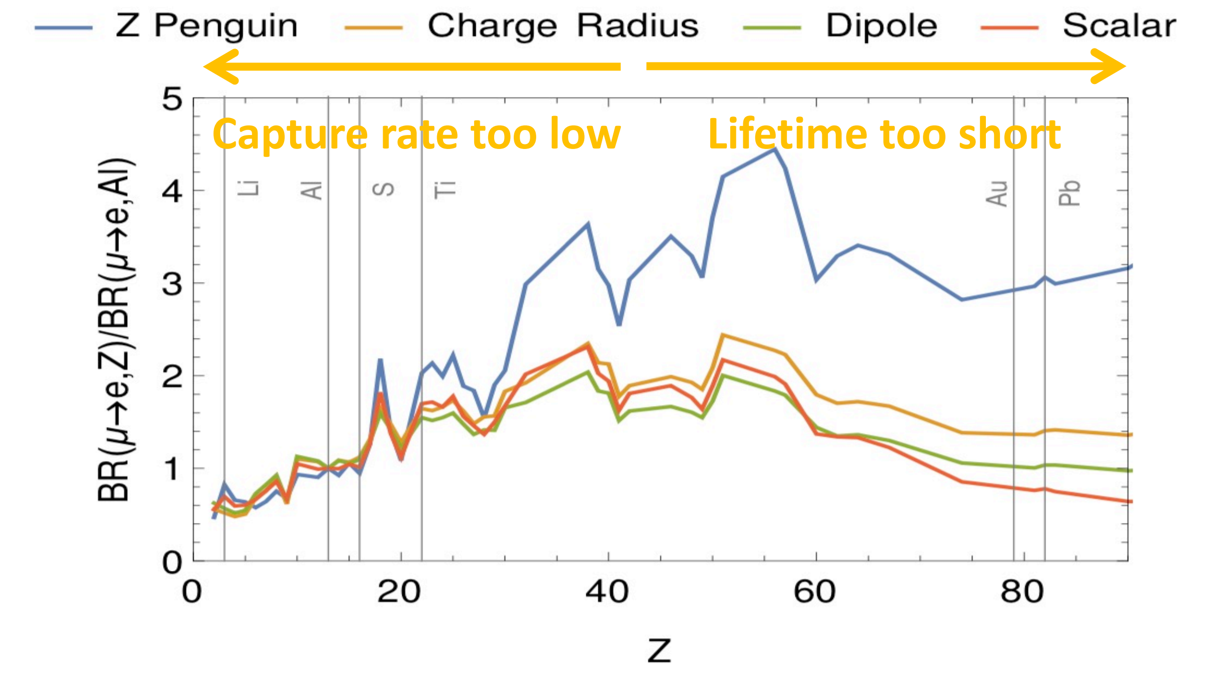
If we do see a signal in Al at Mu2e, what can we do?:

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

→ Requires measurements of conversion rate in other target materials!

- Need to choose a target which is sensitive to directions Al is "blind" to

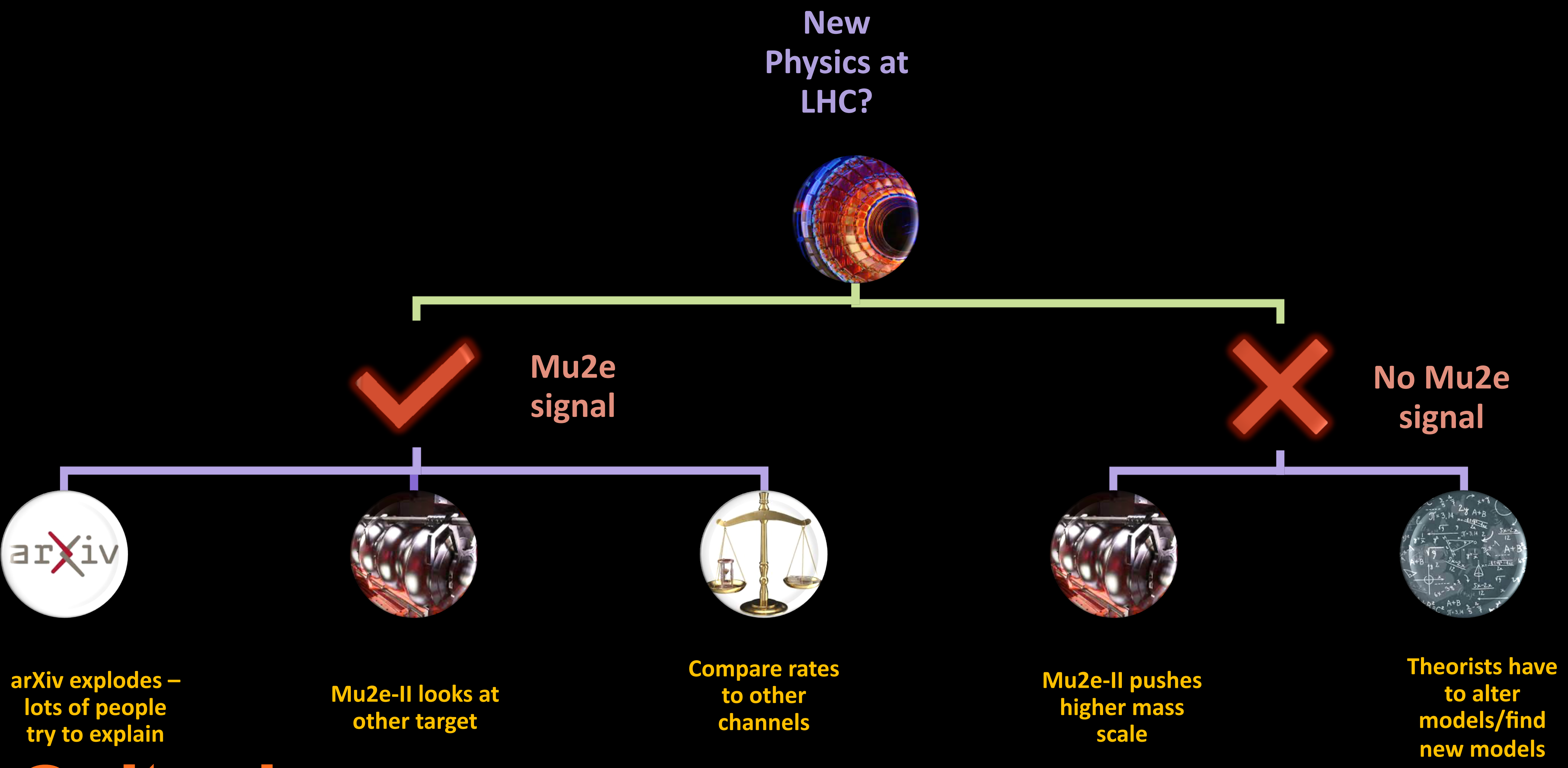
This is something we need to think about for Mu2e-II – our extended program (see final slide).

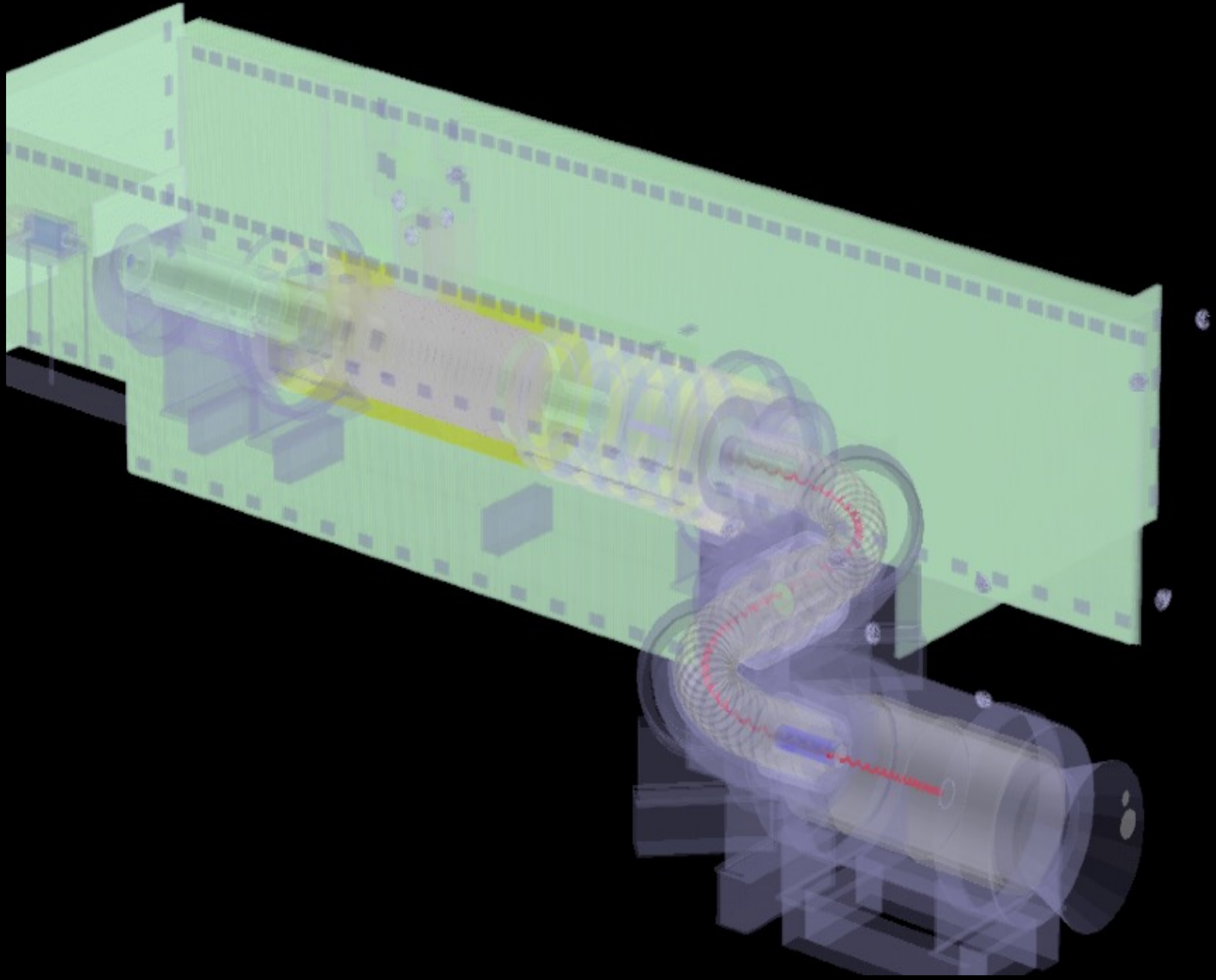


V. Cirigliano, S. Davidson, Y. Kuno, Phys. Lett. B 771 (2017) 242
S. Davidson, Y. Kuno, A. Saporta, Eur. Phys. J. C78 (2018) 109
Kitano et al 2002

Coming Soon: Borrel, Hitlin & Middleton → Caltech Group

Possibilities





Experimental Strategy

How will Mu2e try to measure this process?

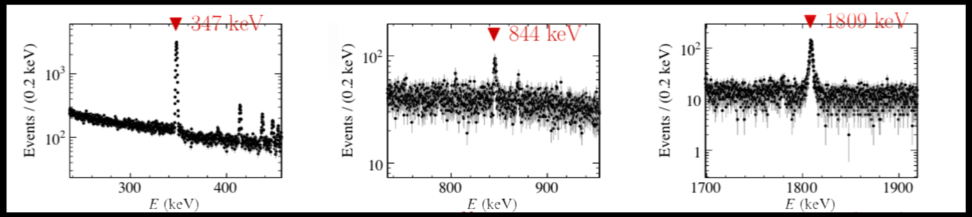
Muonic Atoms

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

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

- Low momentum (-) muons are captured in the target atomic orbit and quickly (~fs) cascades to 1s state.
- Lifetime of muonic aluminium = 864 ns

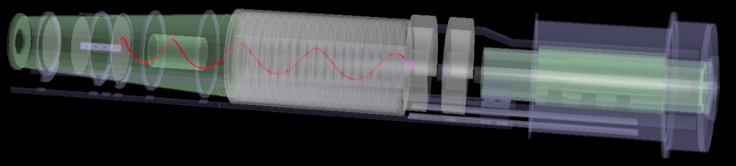
Normalization = from X -rays emitted when muon stops in Al.



- In aluminum:
  - ***39 % Decay :*** $\mu + N \rightarrow e + \bar{\upsilon}_e + \upsilon_\mu$ ***(Background)***
  - ***61 % Capture :*** $\mu + N \rightarrow \upsilon_\mu + N'$ ***(Normalization)***
  - ***The Signal :*** $\mu + N \rightarrow e + N$ ***(Conversion)***
- Signal is monoenergetic electron consistent with:

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

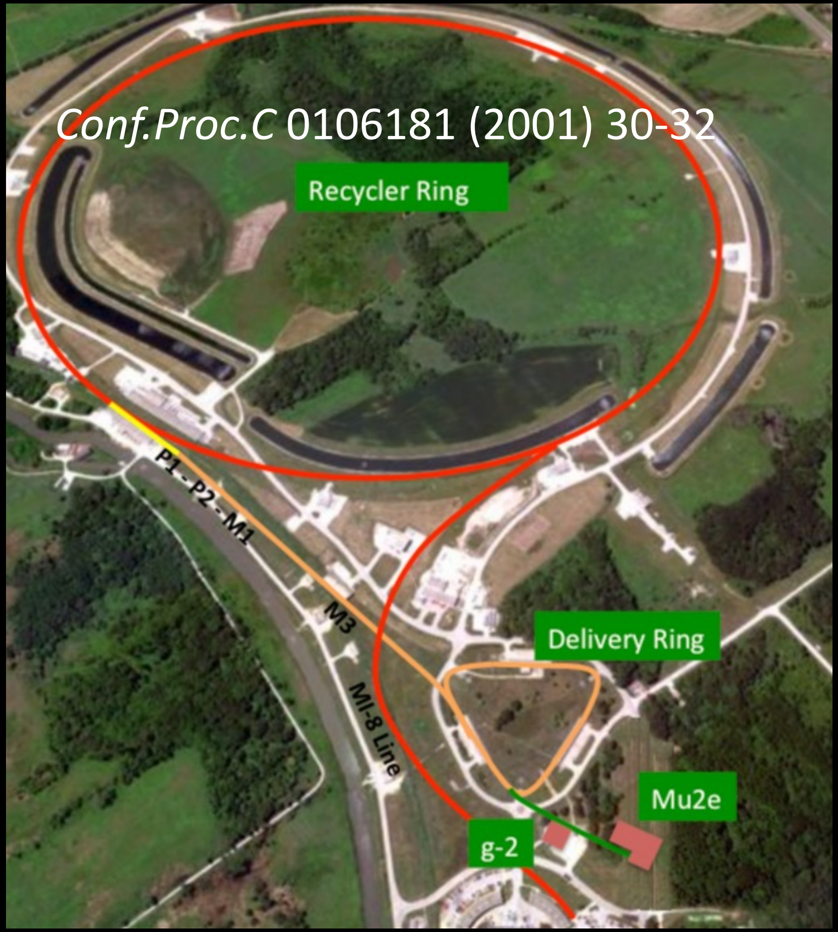
  - Will be smeared by detector and stopping target effects.
  - Nucleus coherently recoils off outgoing electron; it does not break-up!



Caltech

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

- Mu2e will acquire $\vartheta\ (10^{20})$ Protons on Target to achieve design goal



- 8GeV Protons produced in the Booster in 2 batches, each of 4 x 10^{12} protons and injected into the Recycler Ring via the MI-8 beamline;
- A new bunch formation is performed using a RF manipulation sequence and bunches are synchronously transferred to the Delivery Ring at a rate of 2.5MHz;
- A resonant extraction system injects pulses of 3.9 x 10^7 protons into the Mu2e beam-line with the pulse spacing of 1695 ns.

More info. nn RF cavities:
https://home.cern/science/engineering/accelerating-radiofrequency-cavities

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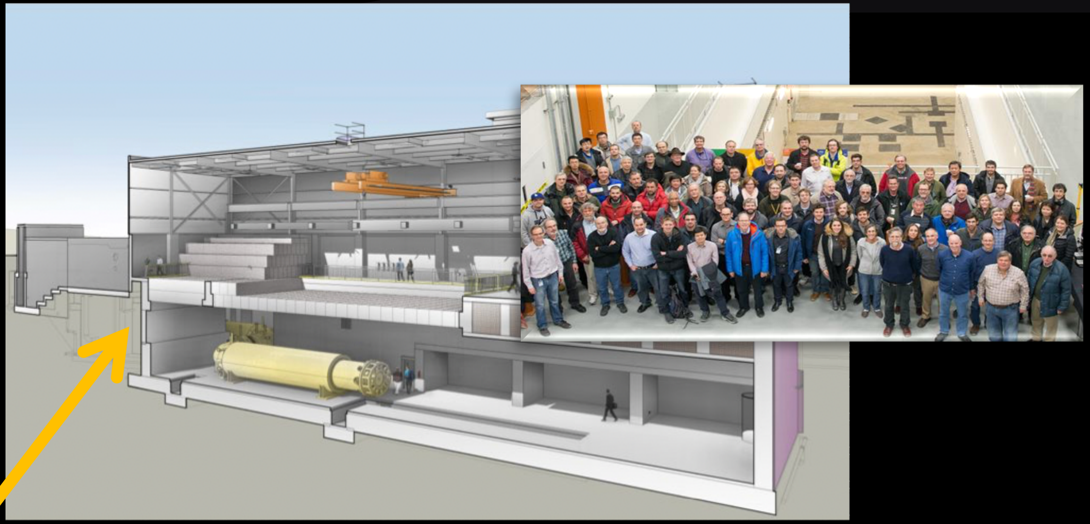
Mu2e building:



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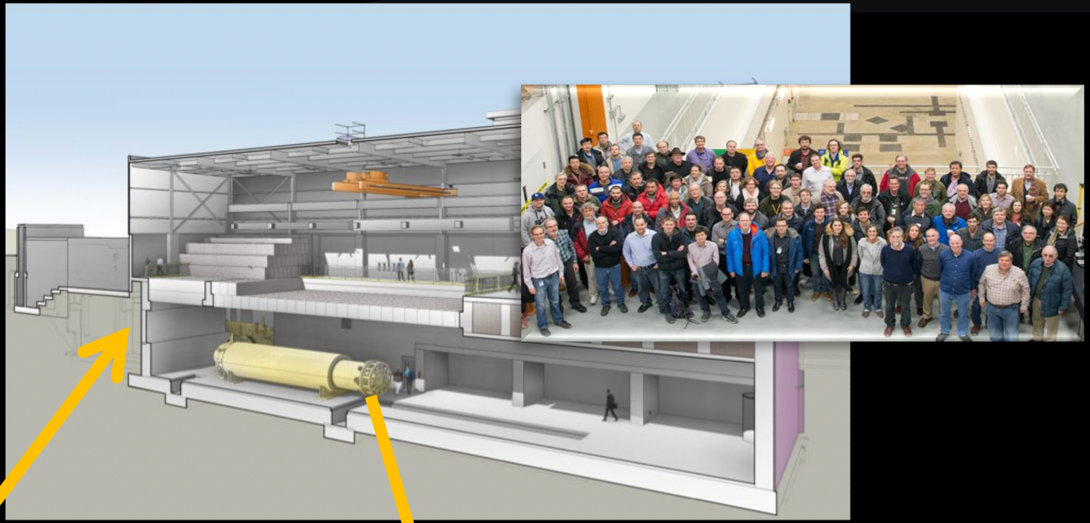
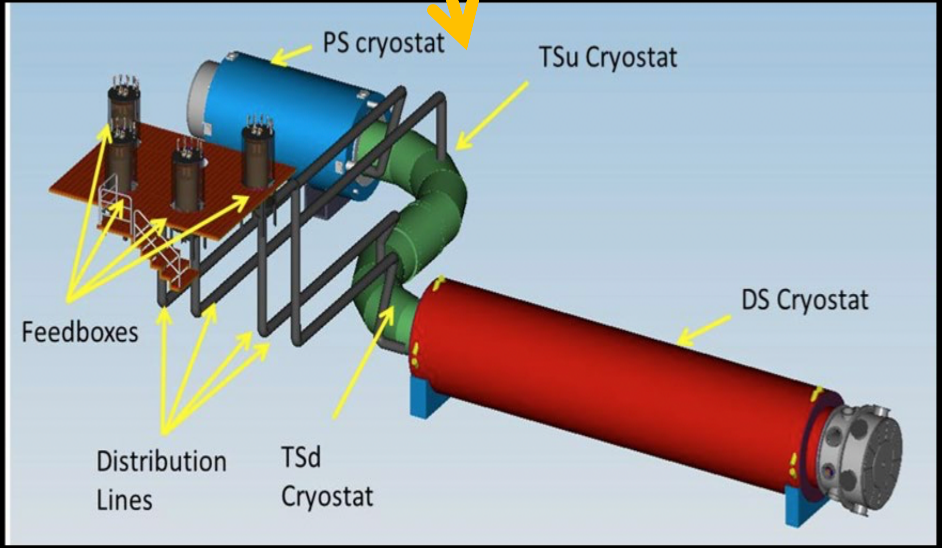


Mu2e:

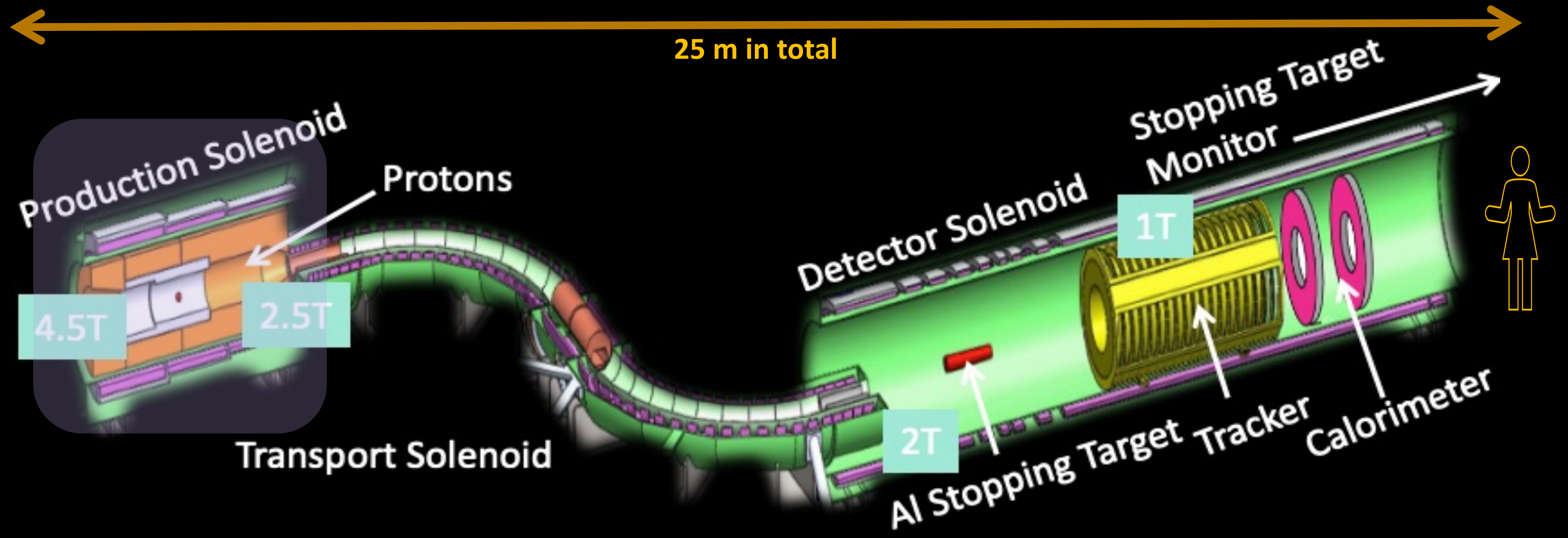


The Mu2e Experiment

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



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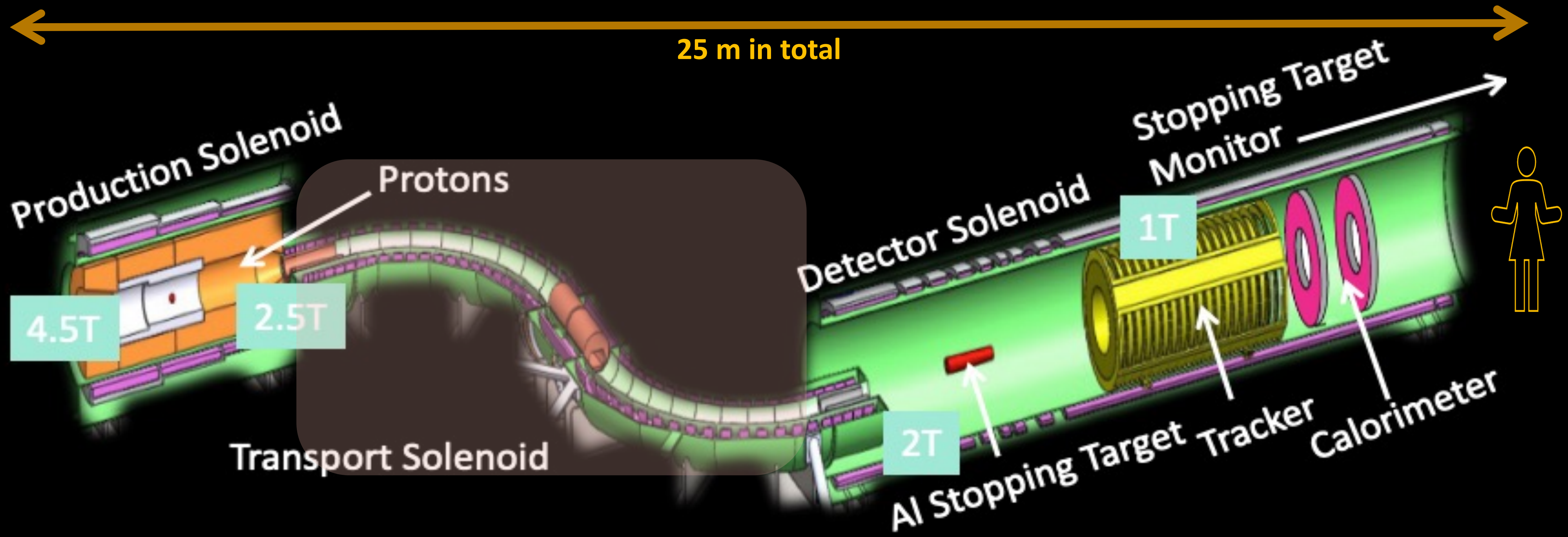
- “S” shape removes line of sight backgrounds
- Windows remove anti-protons
- Collimators help select low momentum, negative muons and “focus” on detector solenoid aperture.



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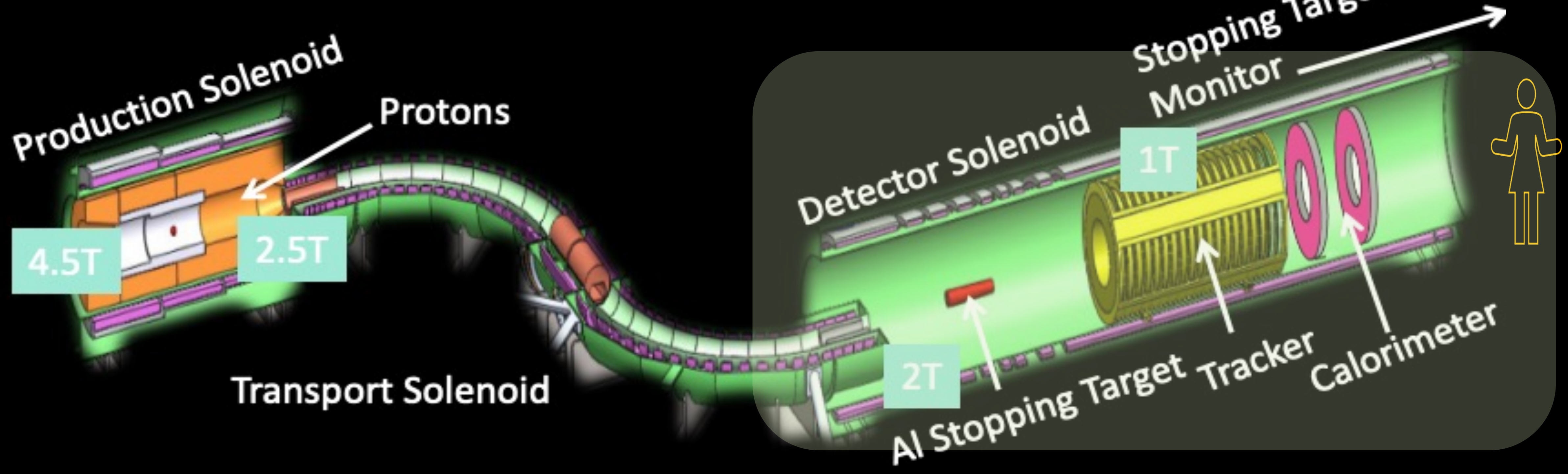
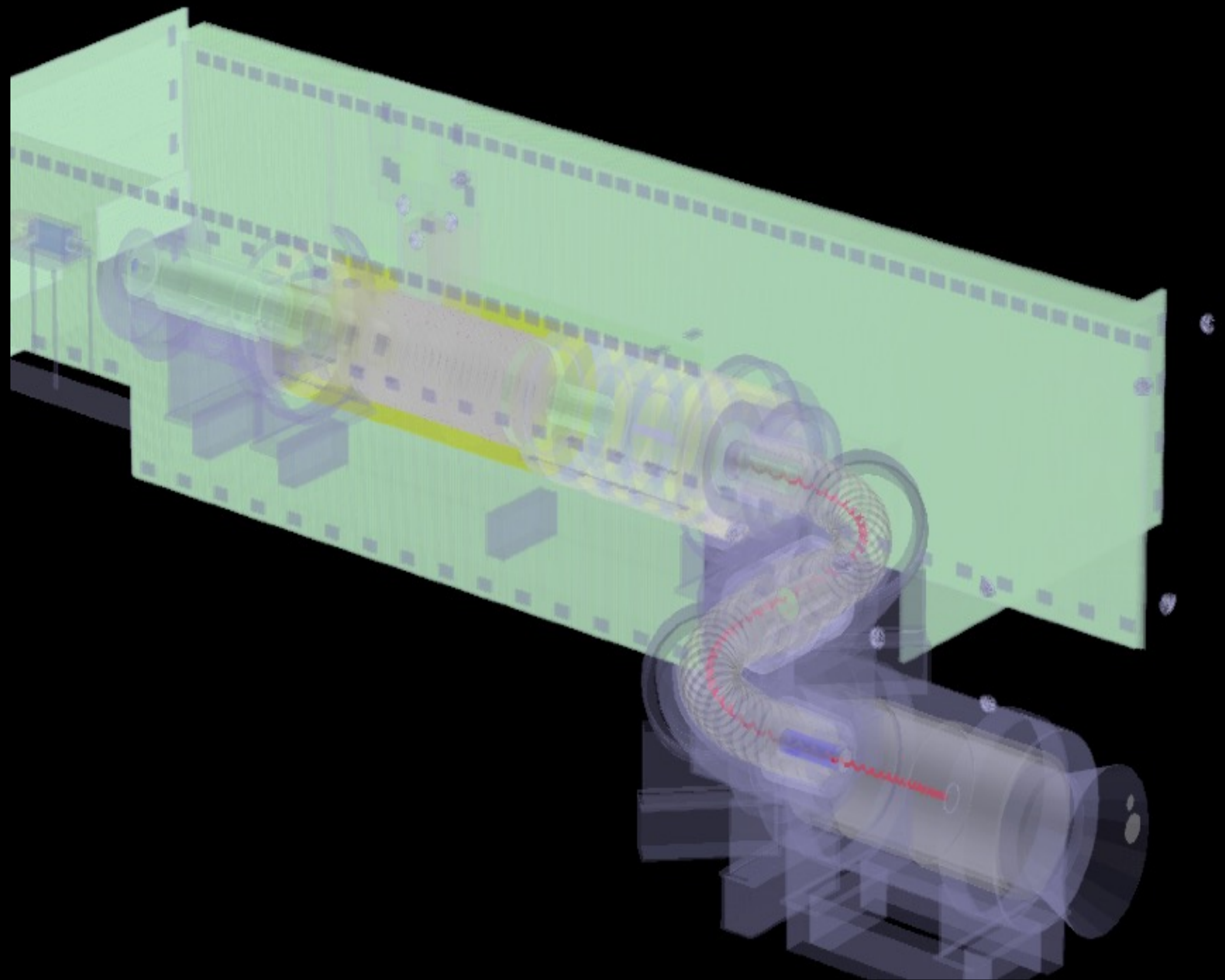
Transport Solenoid:
- “S” shape removes line of sight backgrounds
- Windows remove anti-protons
- Collimators help select low momentum, negative muons and “focus” on detector solenoid aperture.

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





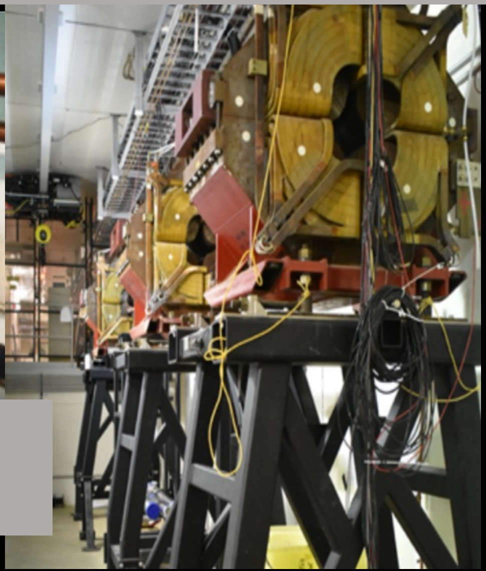
Beamline & Solenoids: Status

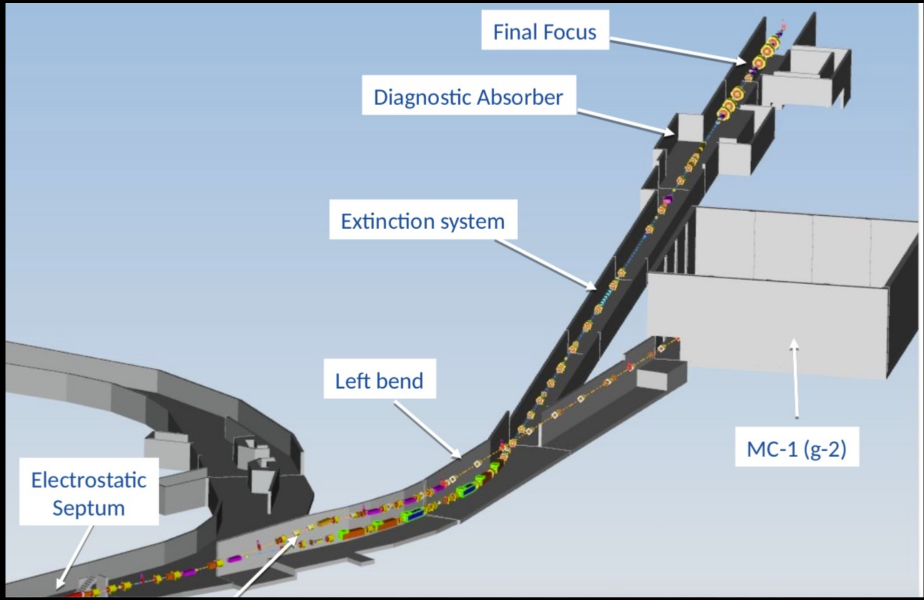
What is the current status of the beamline components?

Beamline: Status


Magnets installed along M4 beamline


Quadrupole in Delivery Ring used for resonant extraction

Final Focus magnets are in place




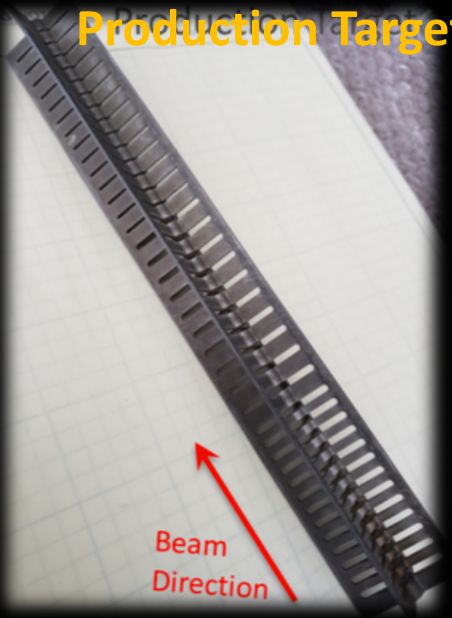
The beamline installation is almost complete:

- Vacuum System installed
- Instrumentation upstream of diagnostic absorber in progress

Production Target: Status

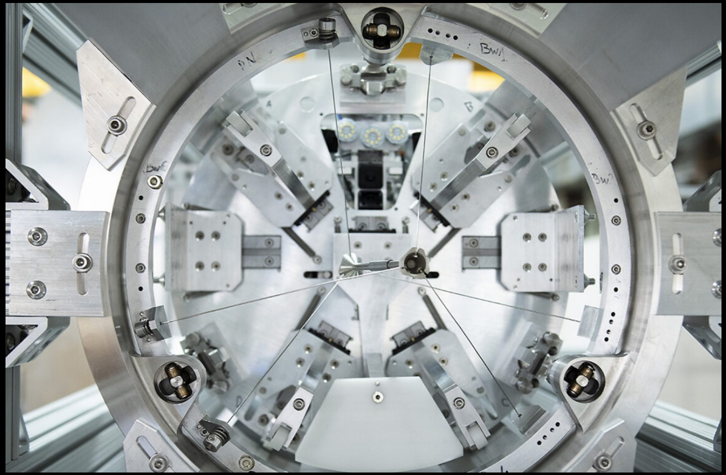
- Made of tungsten, completed in April 2021 - 10% of beam power into the target ,
- Heats up to 1700 °C (~3100 F),
- Production Solenoid must be radiatively cooled,
- Average power density ~150 MW/m^3

Production Target

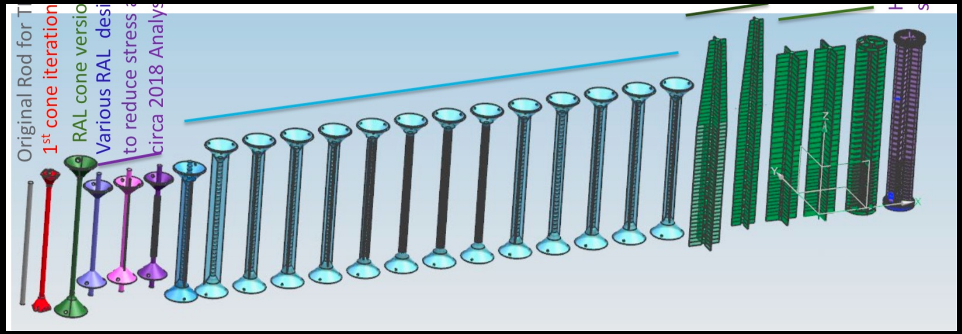


Production Target in support

Production Target & Frame



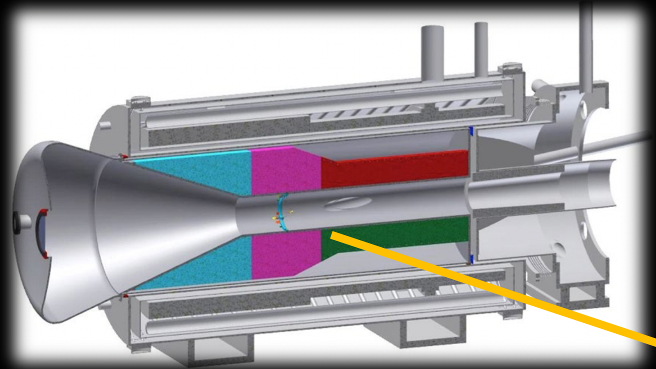
Many iterations



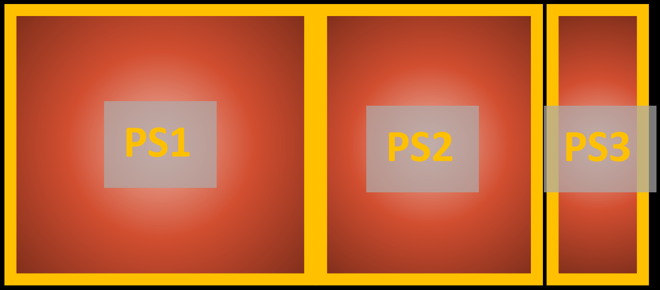
https://www.symmetrymagazine.org/article/a-robot-ballet

Nice video of robotic extraction of target

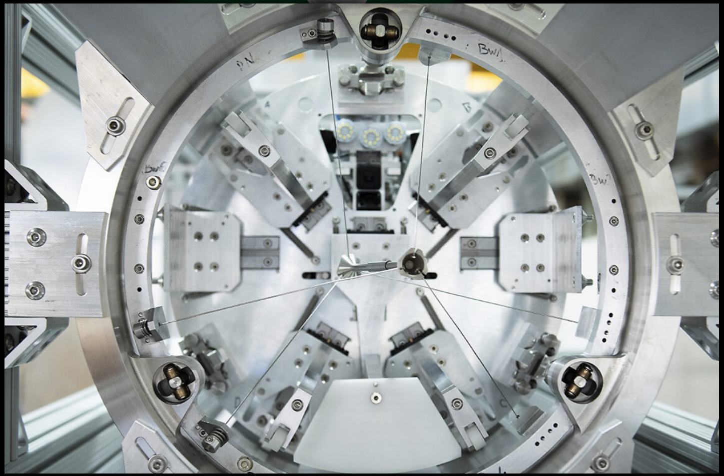
Production Solenoid: Status



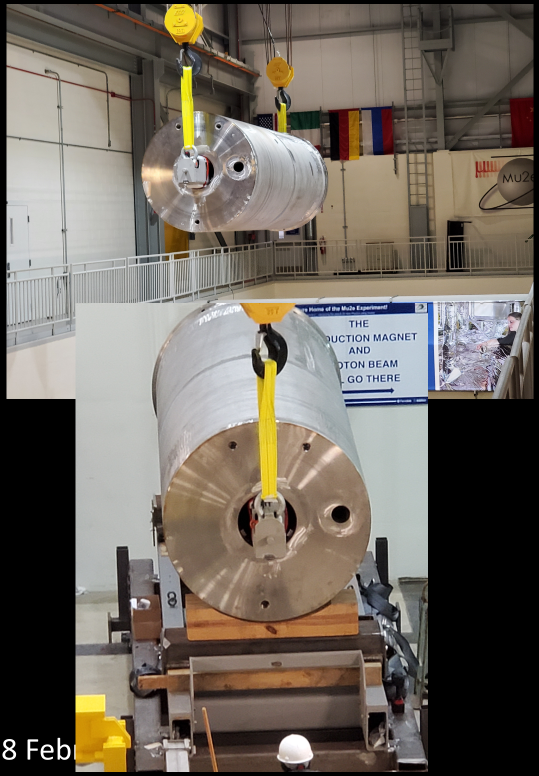
All 3 coils fabricated, under-going tests at vendor



Heat & Radiation Shield



Production Target & Frame



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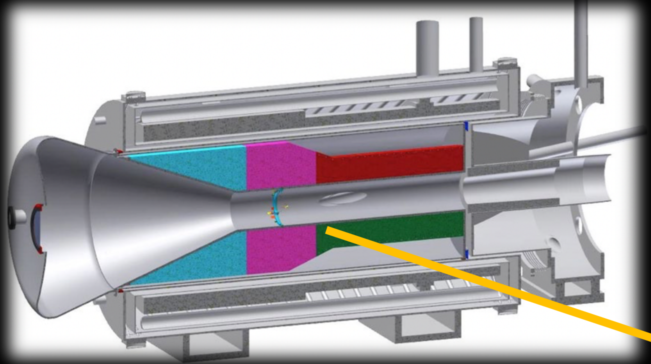
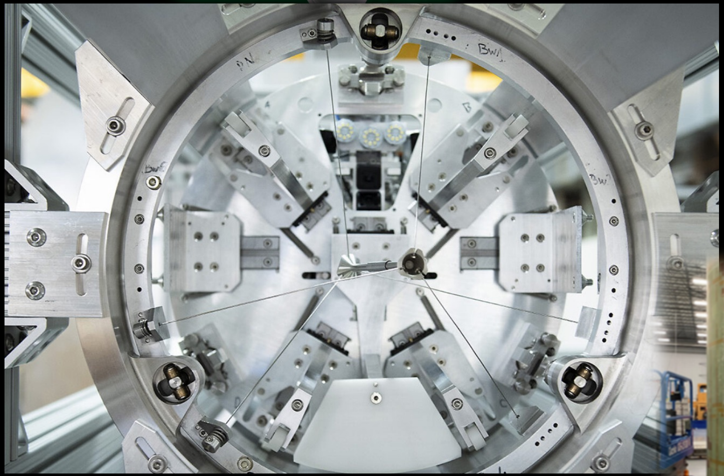
Caltech

Production Solenoid: Status



All 3 coils fabricated, under-going tests at vendor.
Cold mass assembly imminent.

Heat & Radiation Shield



Production Target & Frame

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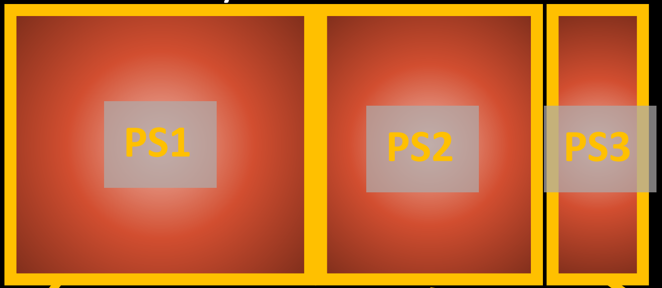
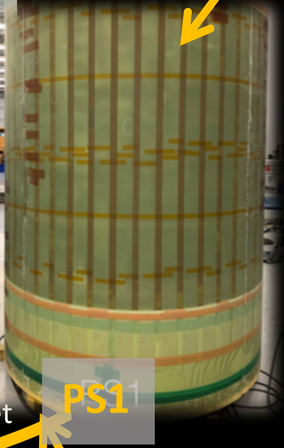
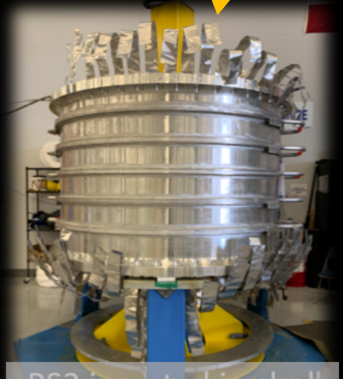
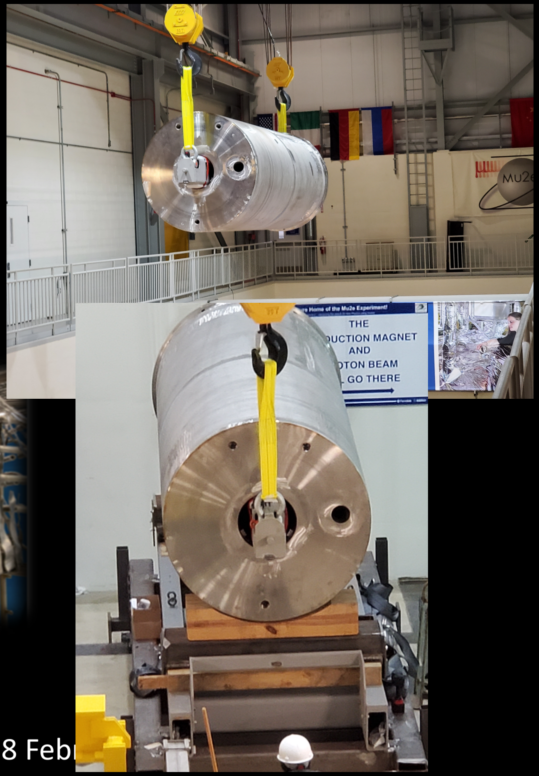






PS2 inserted into shell

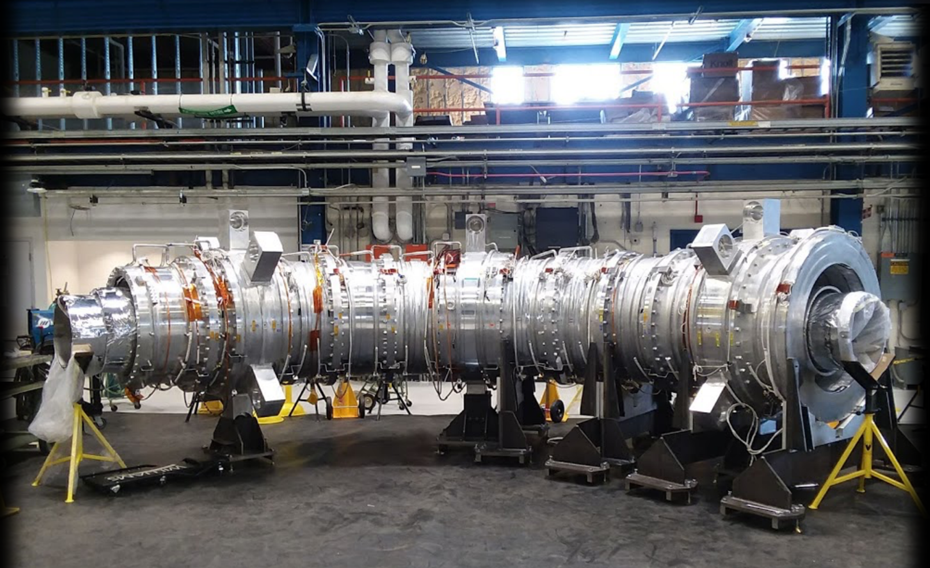


Nice video of robotic extraction of target

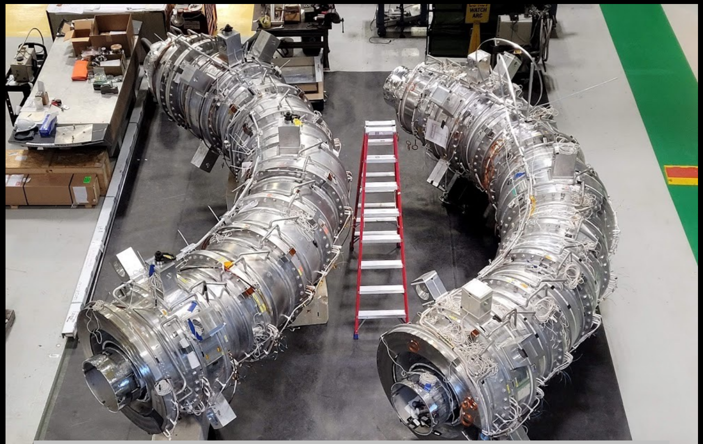
Caltech

Transport Solenoid: Status

Thermal shield shown next to TSu



TS coldmass at Fermilab awaiting final tests.



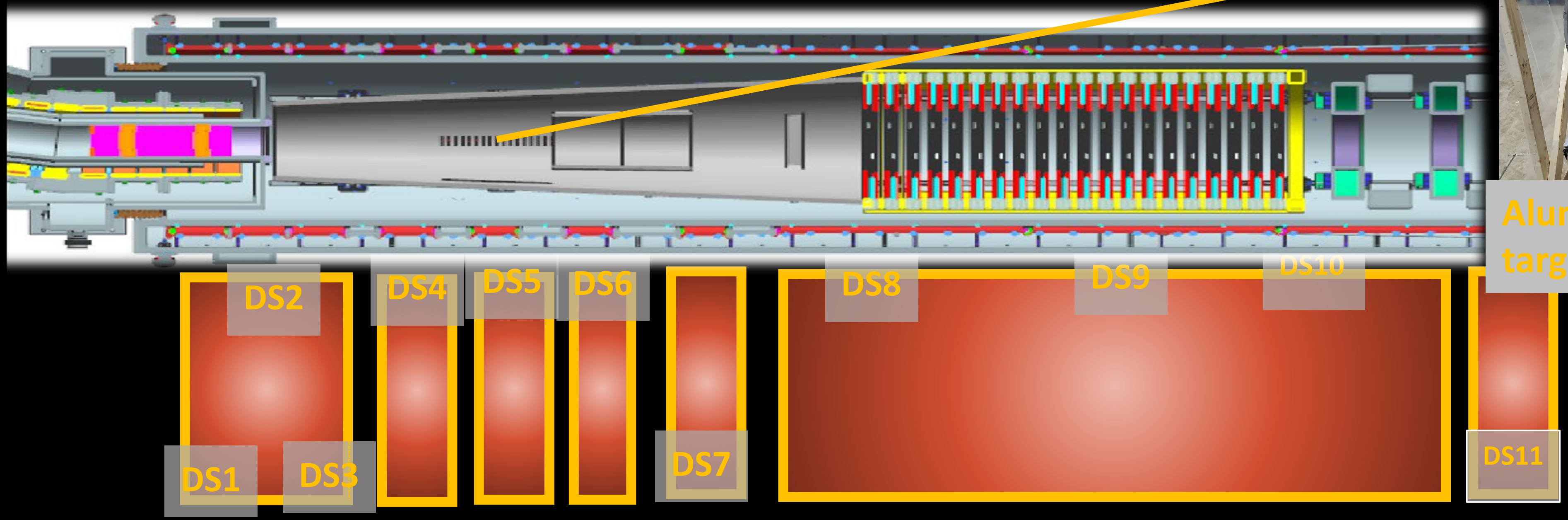
Both TSu and TSd are at FNAL

- All coils of the TS are now at Fermilab.
- TSu and TSd cold-masses assembled.
- Testing almost complete
- Outer thermal shield will be split and re-assembled around the TSu cold-mass alongside in image.

TSd vacuum vessel, awaiting leak check

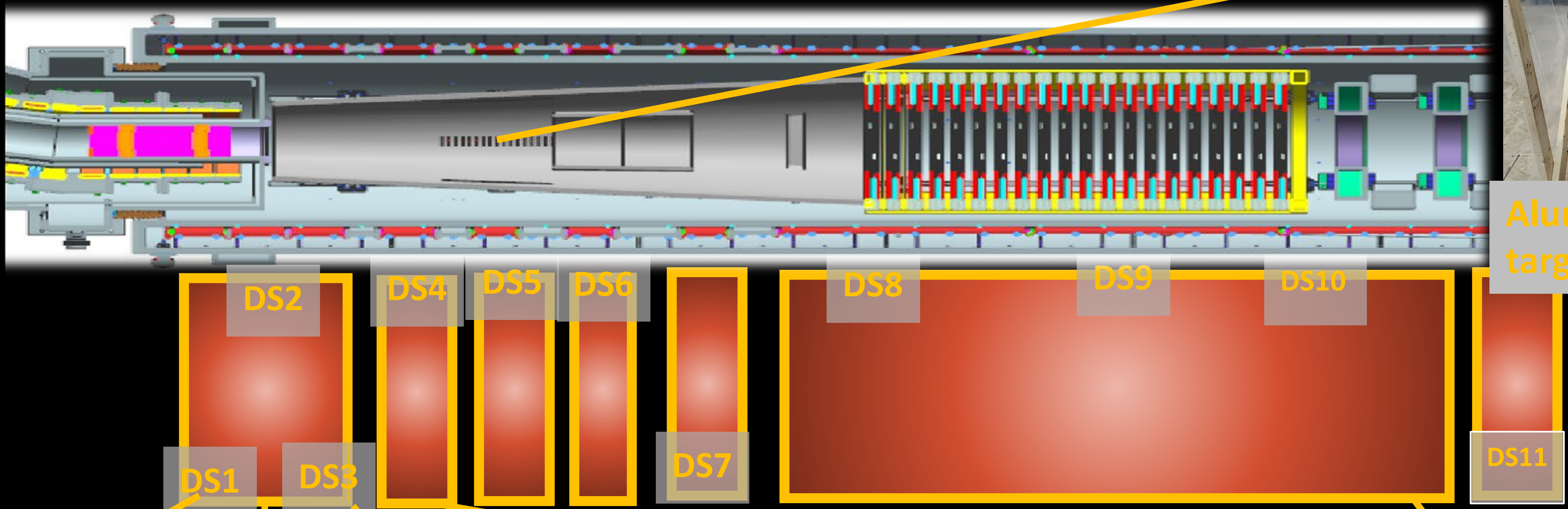
TSu vacuum vessel, leak tight

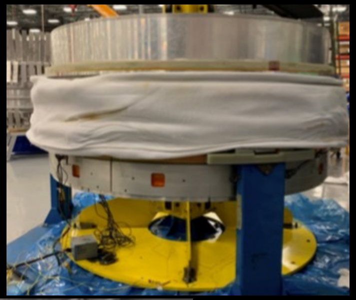
Detector Solenoid: Status

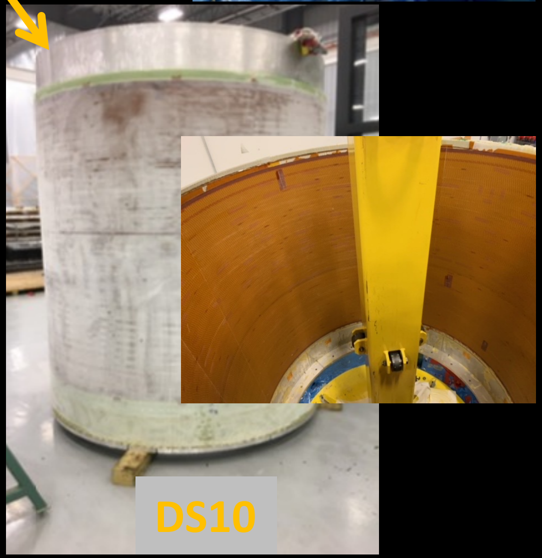


Aluminum stopping target in frame

Detector Solenoid: Status

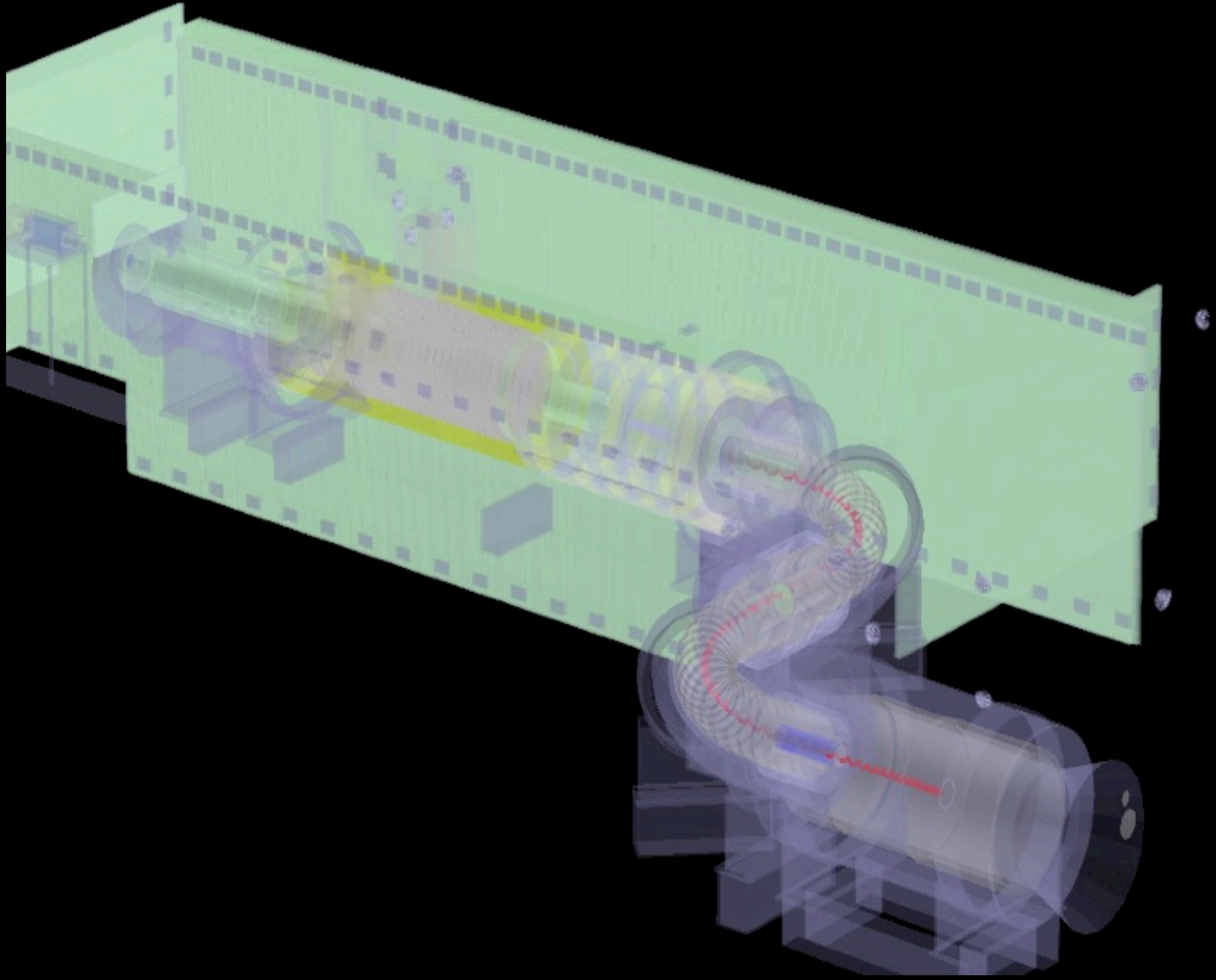






5/11 coils fabricated, tests on going
Others being wound

Caltech



“Background free” design

Understanding problematic backgrounds.
Can we design our experiment to eliminate all backgrounds?

Simulating and experiment

- In High Energy Physics we use simulations to predict expectations from experiments we are designing.
- We set up models of the geometries of our detectors, including the magnetic fields we expect.
- Models have knowledge of matter effects and other physics processes particles might undergo in the materials.
- We generate particles according to their “true” i.e. theoretical properties.
- Generated particles are passed through our models of the detector performance and efficiency so they should represent “real physics as measured in our detectors.”
- “Backgrounds” are particles which are not our conversion signal, problematic “backgrounds” are those which are similar to our “signal” as they could be confused with a signal and cause false positive result in our data.
- During experimental design we need to develop algorithms to veto backgrounds and modify our design using simulations to minimize the chances of problematic backgrounds.
- Of course, we can only predict based on previous physics results, so there’s always some uncertainty in any model we use.

Removing Backgrounds

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

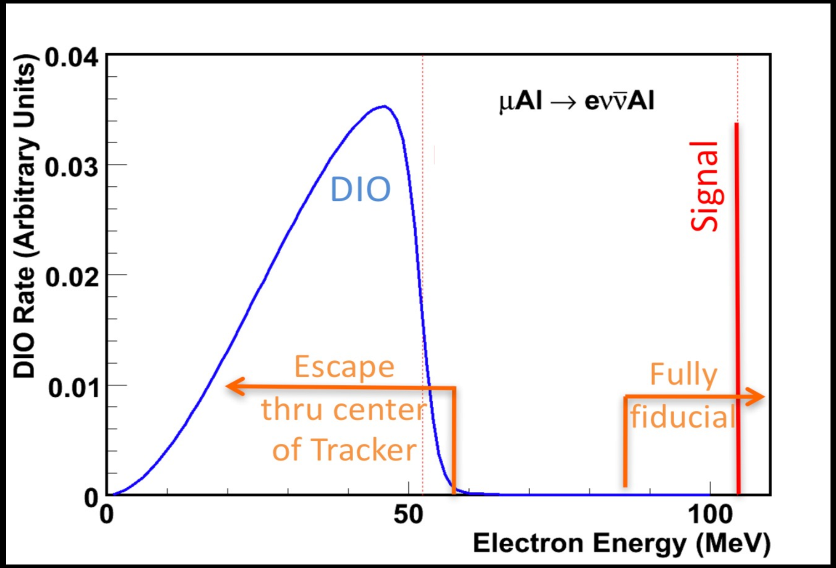
- Intrinsic :
  - Scale with number of stopped muons.
- Late arriving :
  - Scale with number of late protons/ extinction performance

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

Muon Decay-in-Orbit (DIO) Backgrounds

In Aluminium 39% of stopped muons will decay in orbit (DIO):

- Free muon decay: peak electron energy far below our signal energy (peaks 52.8 MeV).

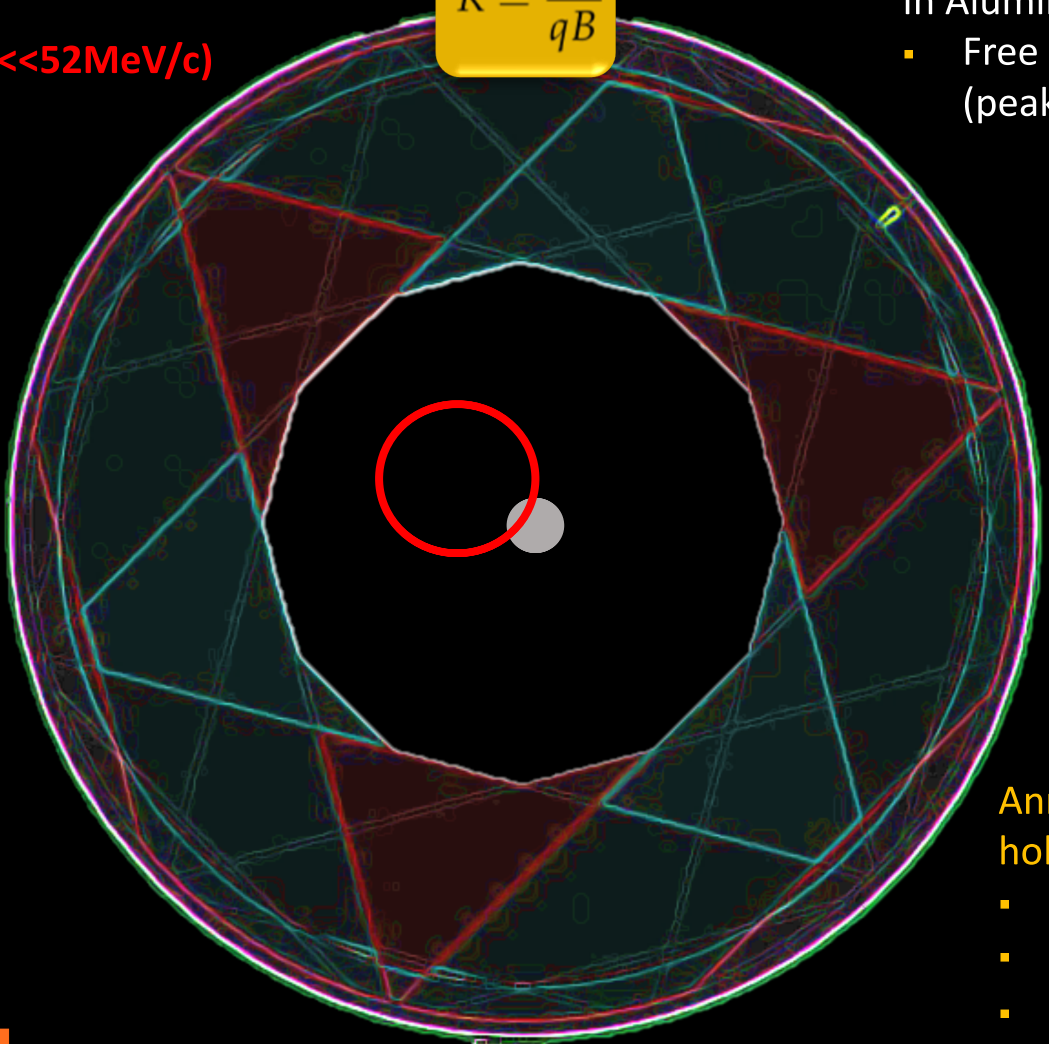


Muon Decay-in-Orbit (DIO) Backgrounds

Transverse Plane

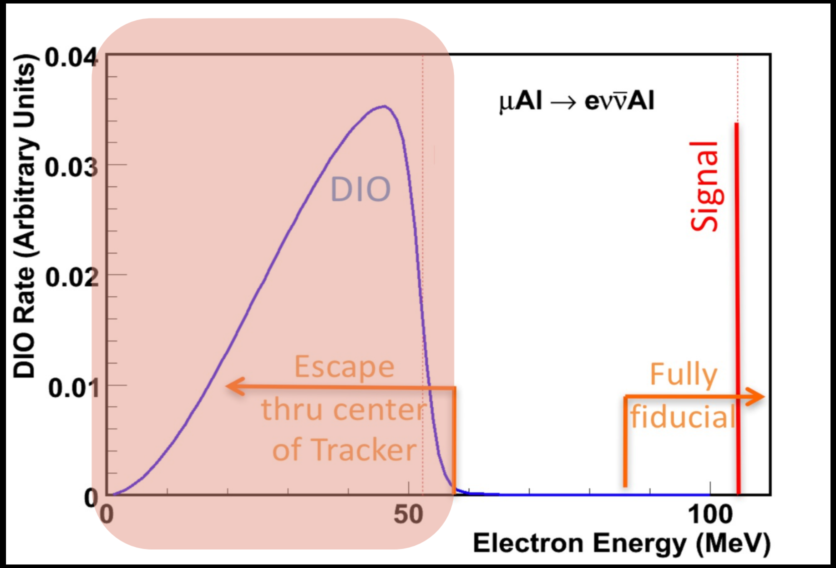
- **Michel Electron (<<52MeV/c)**

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



In Aluminium 39% of stopped muons will decay in orbit (DIO):

- Free muon decay: peak electron energy far below our signal energy (peaks 52.8 MeV).



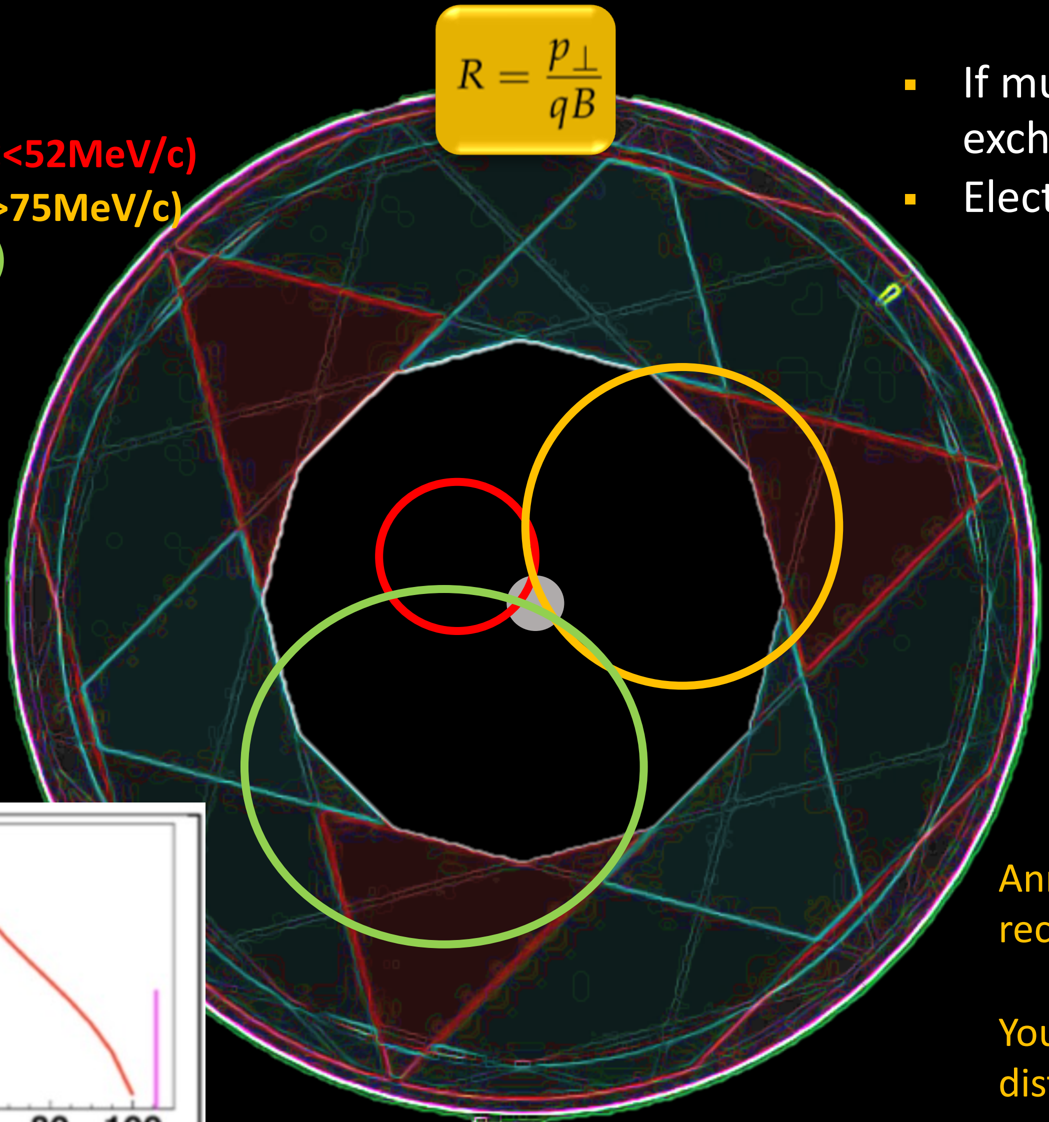
Annular Design → Excludes low momentum electrons via hollow centre:

- Inner 38 cm un-instrumented .
- Reduces need to reject $\sim 10^{18}$ to $\sim 10^{5}$.
- Blind to > 97% of DIO spectrum.

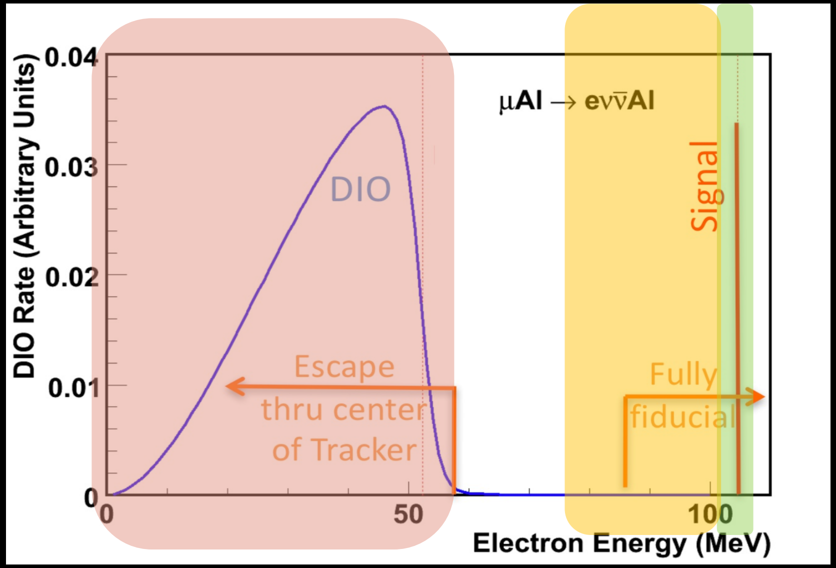
Muon Decay-in-Orbit (DIO) Backgrounds

Transverse Plane

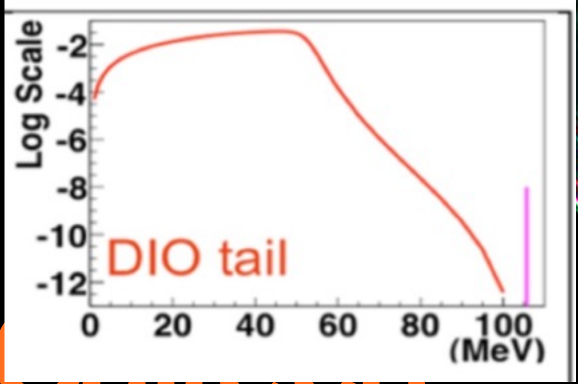
- Michel Electron (<<52MeV/c)
- Problematic Tail (>75MeV/c)
- Signal (105MeV/c)



- If muon bound in atomic orbit, the outgoing electron can exchange momentum with the nucleus.
- Electron could have energy close to signal.



Recoil tail:



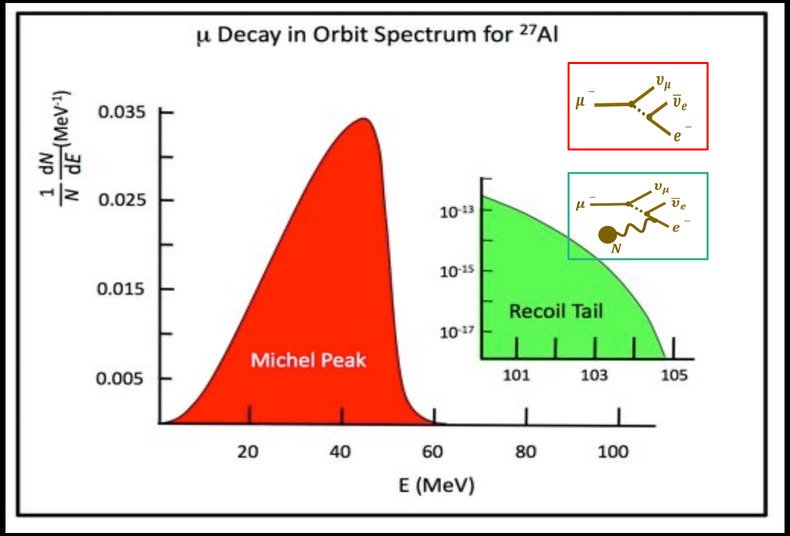
Annular Design → cannot fully exclude electrons in the recoil tail.

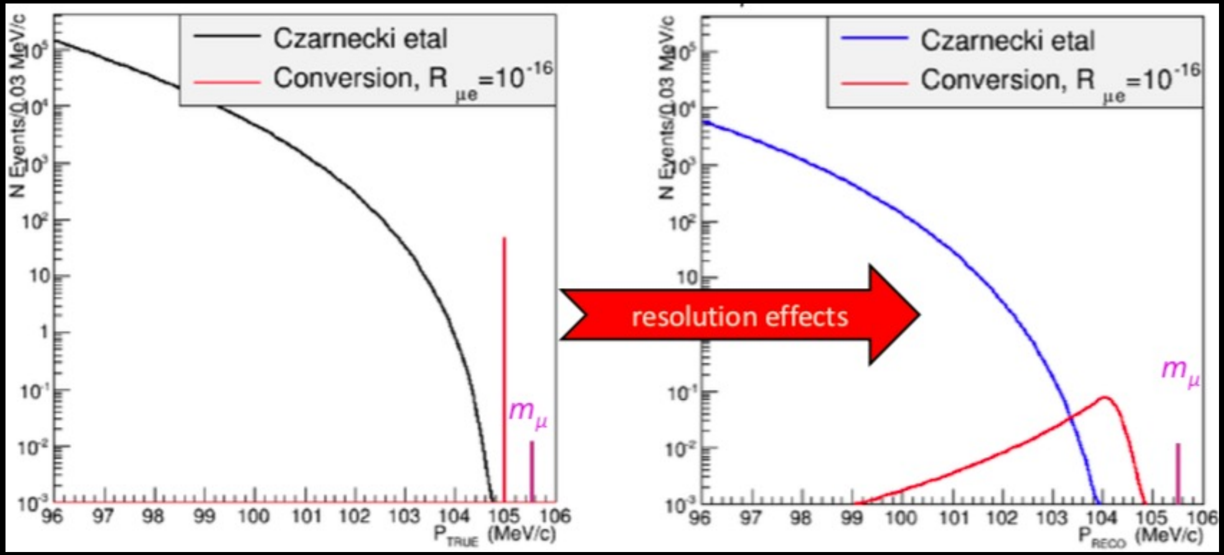
Your detector and reconstruction must be able to distinguish these from our signal

Muon Decay-in-Orbit (DIO) Backgrounds

The differential energy spectrum of DIO electron spectrum has been parameterized in A. Czarnecki et al., "Muon decay in orbit: Spectrum of high-energy electrons," Phys. Rev. D 84 (Jul, 2011) .

- Necessitates tracker resolution of better than 200 KeV/c



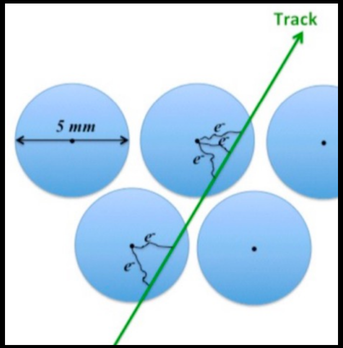


Rejecting DIO Backgrounds

To remove achieve a momentum resolution < 200 KeV/c requires optimized hardware choice and carefully crafted algorithms in our software:

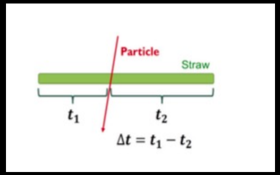
1. Hardware: Low Mass design which minimizes scattering and energy loss :
   - Entire Detector Solenoid held under vacuum ($\sim 10^{-4}$torr).
   - Ultra low mass tracker.
   - Segmented → Handle high rates and provide high-precision momentum measurements.

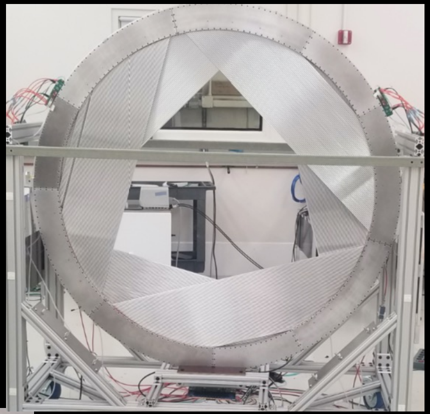
The Tracker: Design



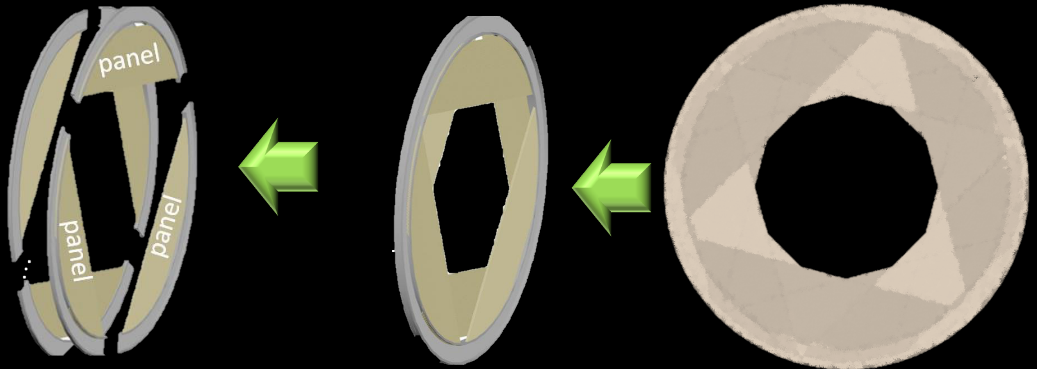
- Tracker is constructed from self-supporting panels of low mass straws tubes detectors
- 18 stations, 2 planes per station, 6 panels per plane, 96 straws per panel.
- Straw drift tubes aligned transverse to the axis of the Detector Solenoid.
  - 1m, 5 mm diameter straw
  - Walls: 12 mm Mylar + 3 mm epoxy
  - 25 mm Au-plated W sense wire
  - 33 – 117 cm in length
  - 80:20 Ar:CO_2 with HV < 1500 V
  - Straw wall thickness of 15 µm has never been done before
- Charged particles ionize gas – drift to wire – detect signals!

The Straws:

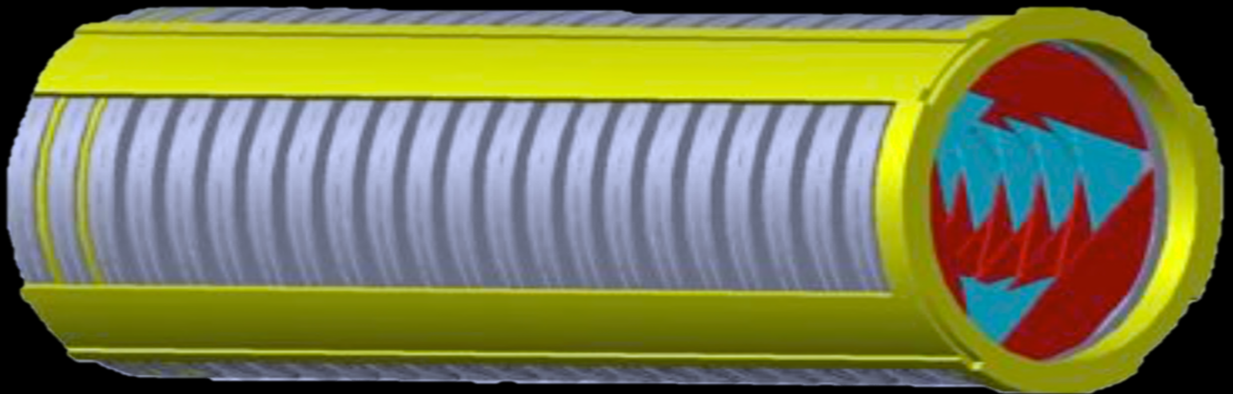




6 Panels **2 Plane** **1 Station**



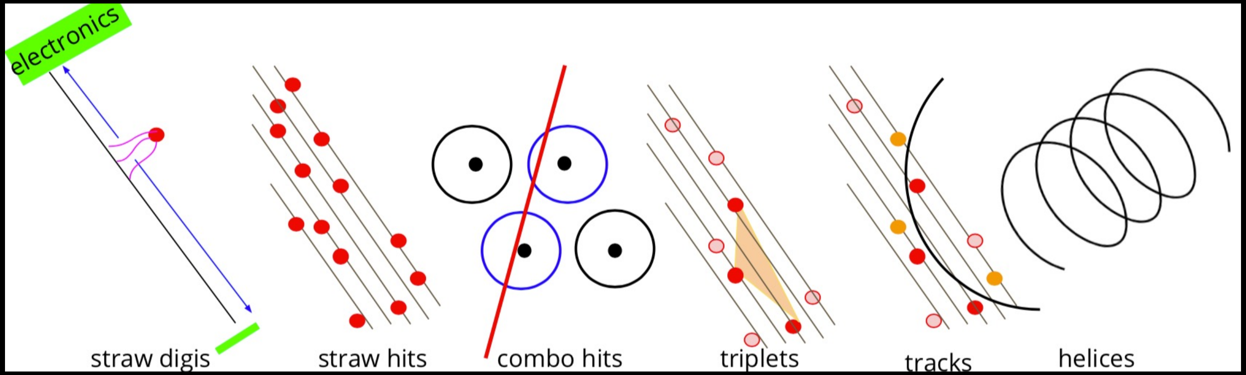
~ 3m, 1 T field



Rejecting DIO Backgrounds

To remove achieve a momentum resolution < 200 KeV/c requires optimized hardware choice and carefully crafted algorithms in our software:

1. Hardware: Low Mass design which minimizes scattering and energy loss :
   - Entire Detector Solenoid held under vacuum ($\sim 10^{-4}$torr).
   - Ultra low mass tracker.
   - Segmented → Handle high rates and provide high-precision momentum measurements.
2. Software: Sophisticated reconstruction algorithm which can turn digits to helices accurately:
   1. hit construction,
   2. time clustering,
   3. tracking via pattern recognition,
   4. refinement via Kalman fitting,
   5. background rejection via Machine Learning

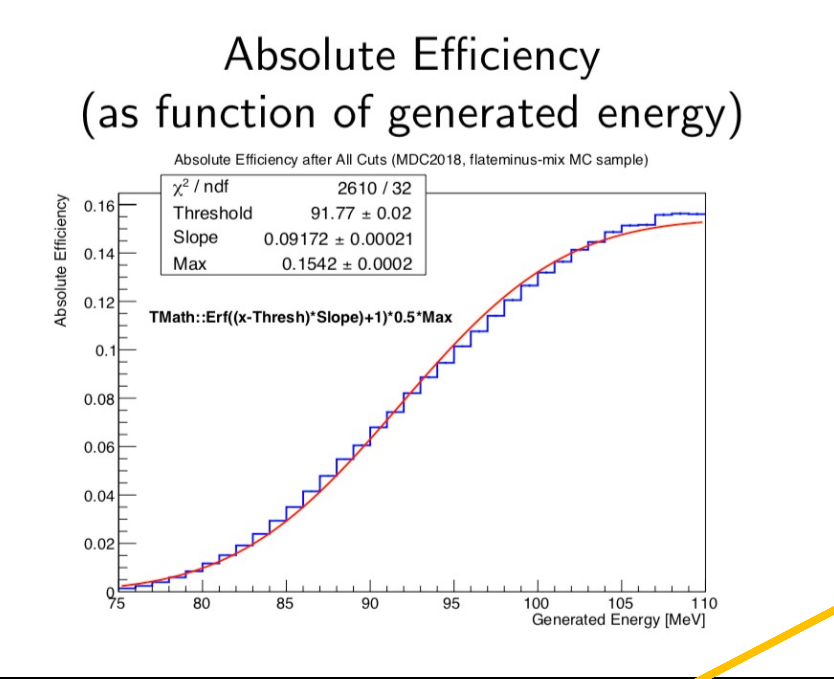


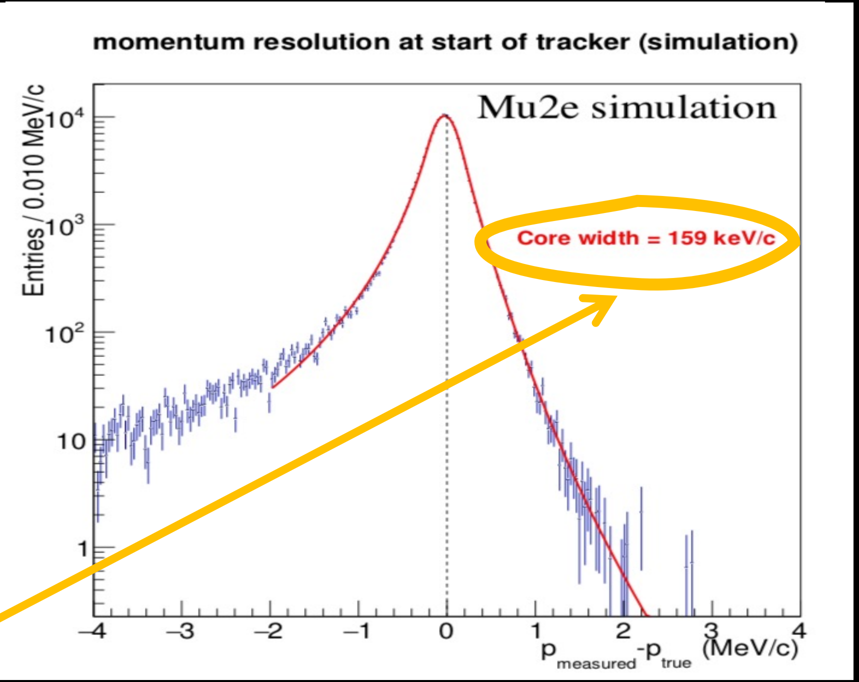
M. Devilbiss, UMich
FERMILAB-SLIDES-20-100-V

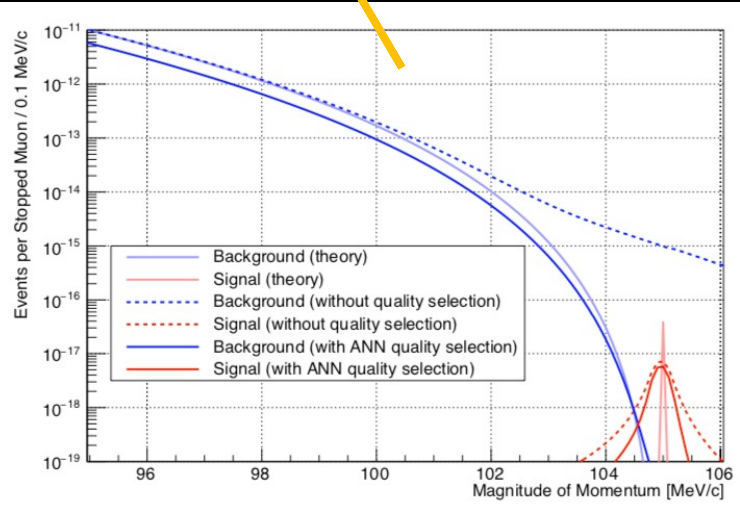
Acceptance & Response

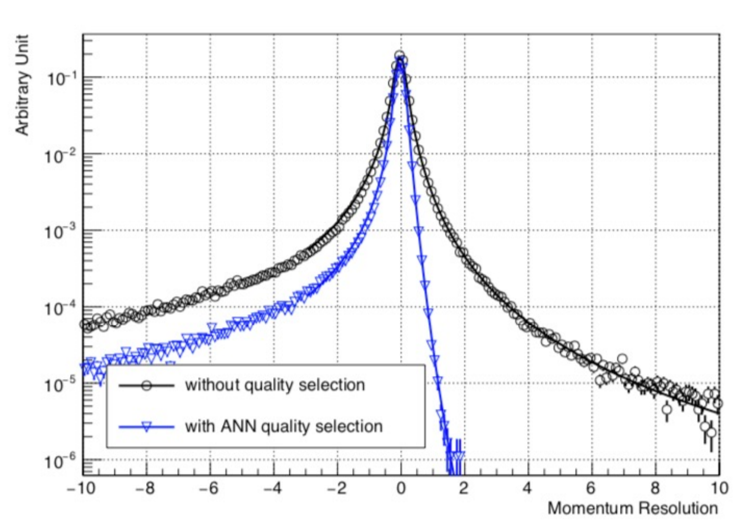
Paper documenting our Machine Learning analysis: https://arxiv.org/abs/2106.08891

- Experiment is "blind" to anything with energy < 75 MeV.
- Tracking resolution improved by use of artificial neural network trained on simulation.









Well within our requirement!

Caltech

Removing Backgrounds

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

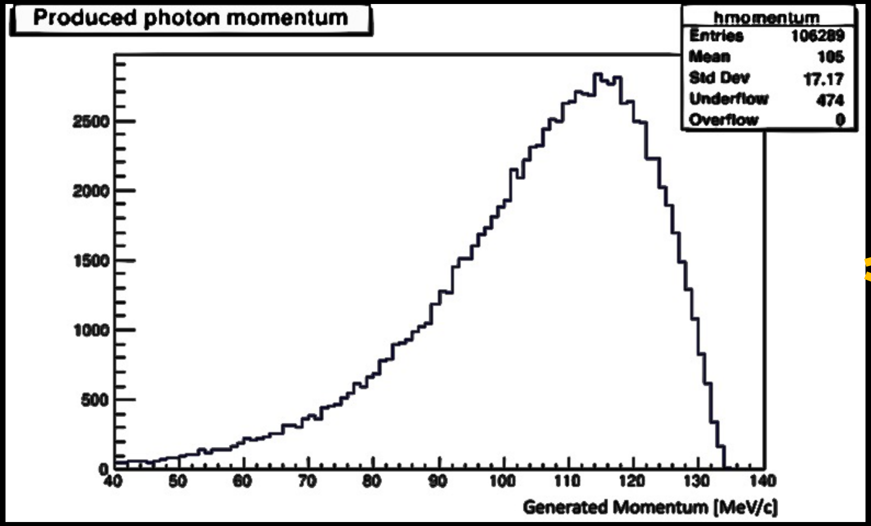
- Intrinsic :
  - Scale with number of stopped muons.
- Late arriving :
  - Scale with number of late protons/ extinction performance

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

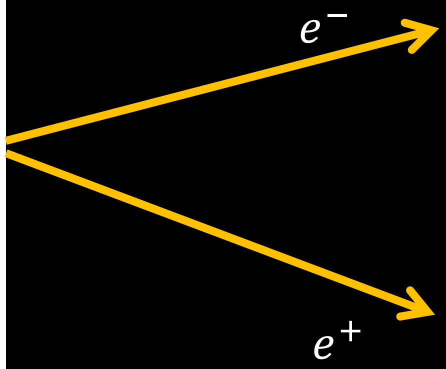
Pion Backgrounds J.A. Bistirilich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

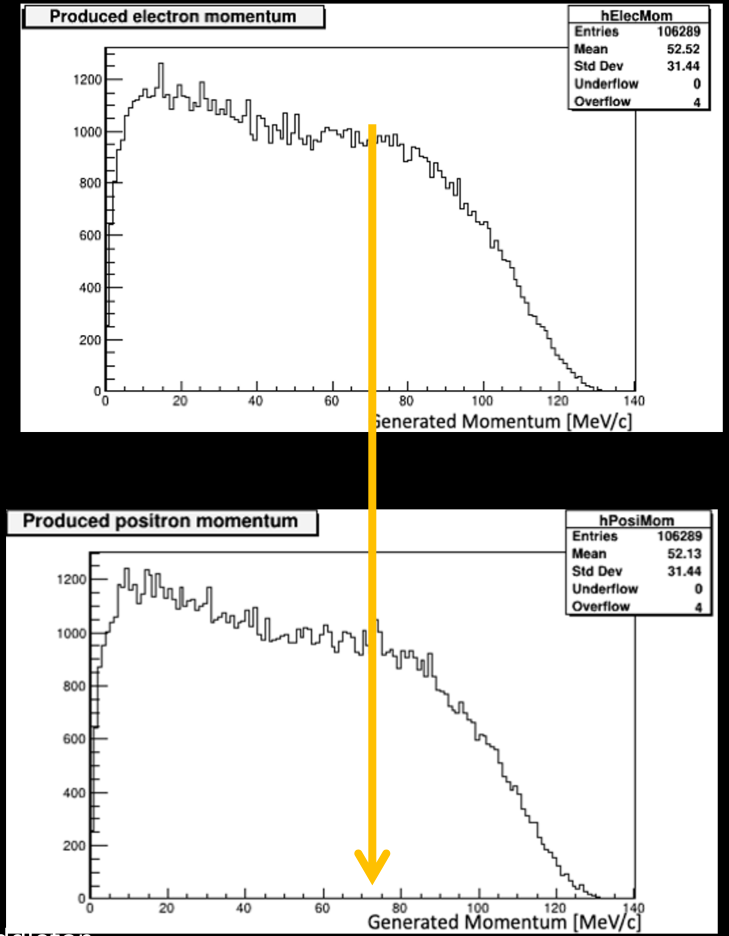
- Radiative Pion Capture occur when a pion is captured by a nucleus at our Stopping Target. The resulting photon produces an outgoing electron and positron pair. Pair production can be internal or external of atom.

The annular tracker means we are “blind” to large fraction of e-/e+ from RPC – even without time cuts!



Photon can be virtual (internal) or not (external)



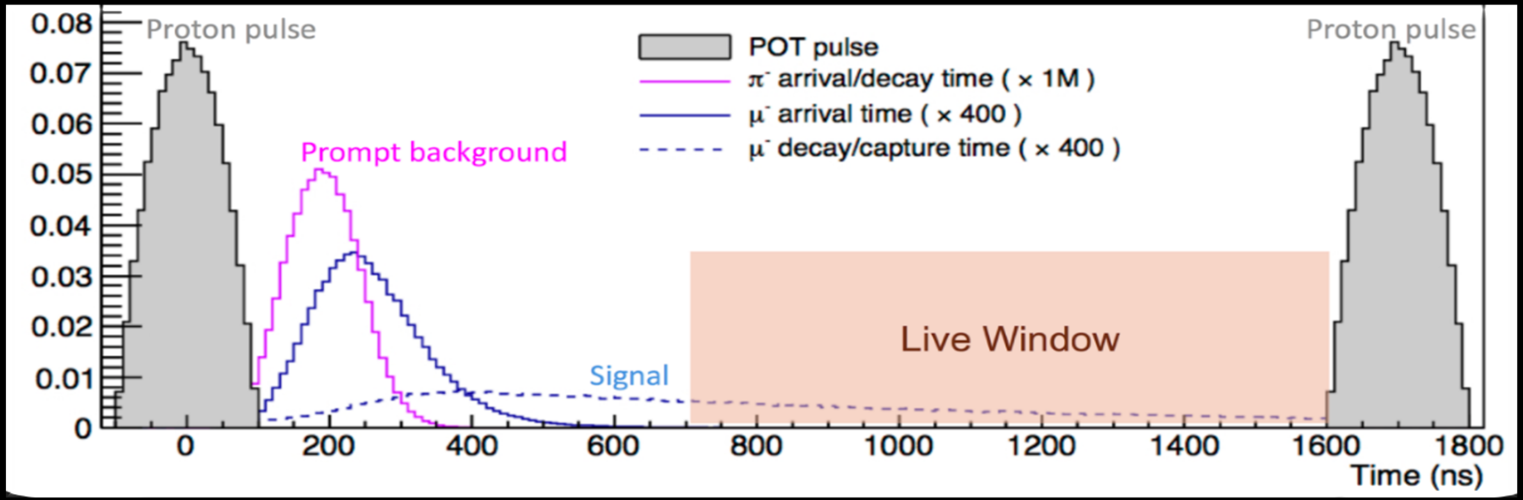


*shape templates

Pion Backgrounds

Most importantly: a delayed "livegate" is enforced:

- Pions – have a free lifetime of 26ns. They decay to produce muons (and neutrinos). Muons can further decay and produce backgrounds.
- Eliminate prompt backgrounds using a primary beam of short proton pulse. Use a delayed measurement window (~700 ns after proton pulse at target). Before this point we ignore any tracks we see in our detector systems.



- Out-of-time pions could fall inside "livegate" but are eliminated by excellent extinction in our proton beam.

Removing Backgrounds

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

Type	Source	Mitigation	Yield (over lifetime of experiment)
Intrinsic	Decay in Orbit (DIO)	Tracker Design/ Resolution	0.144 ± 0.028 (stat) $\pm$ 0.11 (sys)
Late Arriving	Pion Capture	Beam Structure /Extinction	0.021 ± 0.001 (stat) $\pm$ 0.002 (sys)
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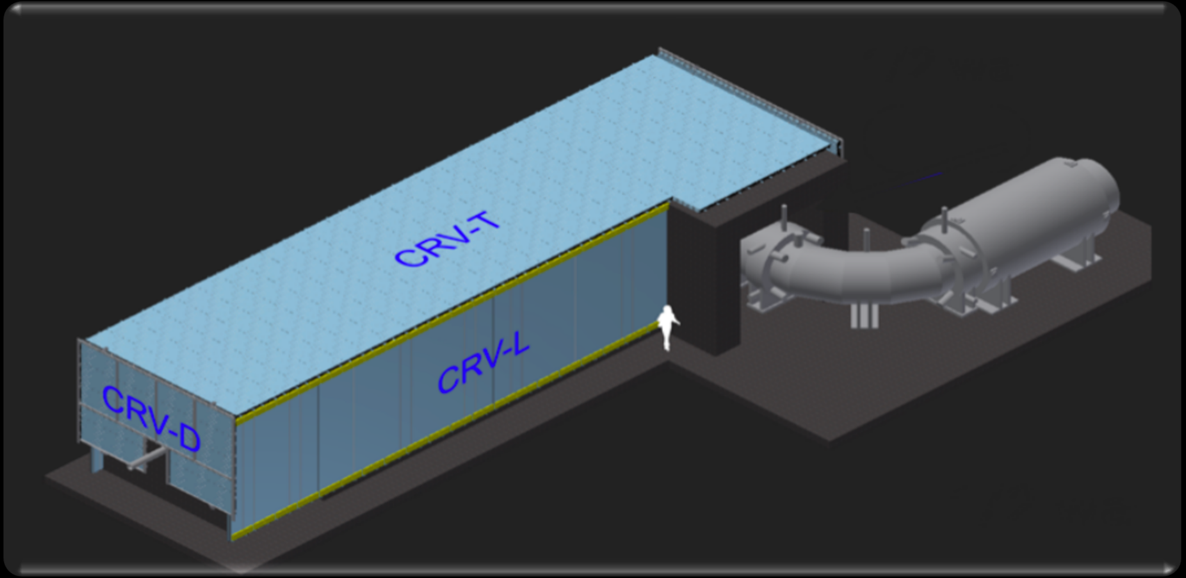
	Cosmic Rays	Active Veto System	0.209 ± 0.0022 (stat) $\pm$ 0.055 (sys)

Scales with livetime!

Cosmic Ray Backgrounds

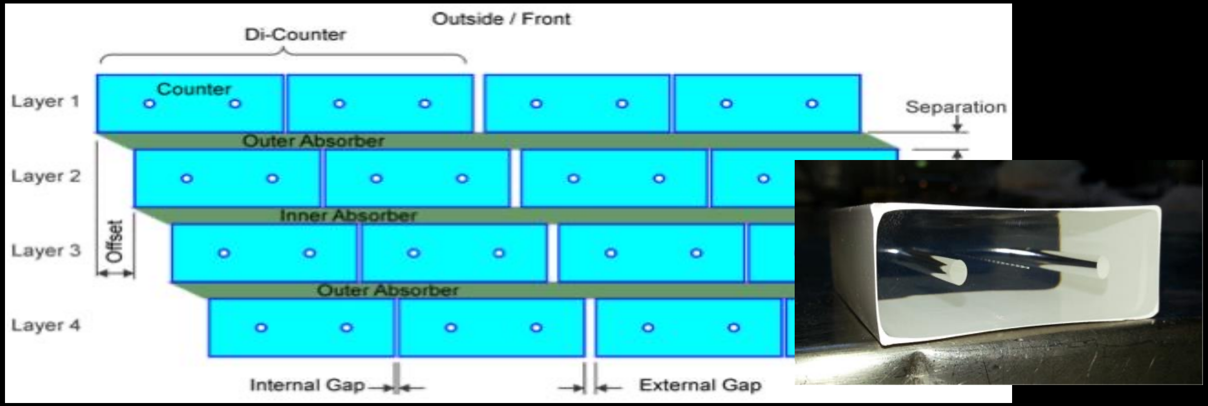
Each day, ~1 conversion-like electron is produced by cosmic rays



Cosmic Ray Veto will prevent cosmic muons faking a signal:

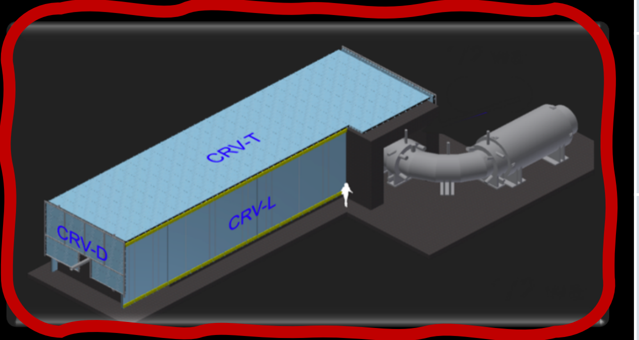
- Cosmic-ray muons can initiate 105 MeV particles that appear to emanate from the stopping target:
  - Electrons and positrons through secondary and delta-ray production in the material within the solenoids,
  - Electrons from muon decay-in-flight,
  - Muons themselves can be misidentified as electrons.
- Remove using active veto (CRV) + overburden and shielding concrete surrounding the Detector Solenoid.
- 4 layers of extruded polystyrene scintillator counter.
- Surrounds the top and sides of DS and the downstream end of the Transport Solenoid.
- Remove Cosmic-ray candidates: 99.99% efficiency requirement!

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



Removing Backgrounds

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



Active veto system surrounds detector region

Type	Source	Mitigation	Yield (over lifetime of experiment)
Intrinsic	Decay in Orbit (DIO)	Tracker Deign/ Resolution	0.144 ± 0.028 (stat) $\pm$ 0.11 (sys)
Late Arriving	Pion Capture	Beam Structure /Extinction	0.021 ± 0.001 (stat) $\pm$ 0.002 (sys)
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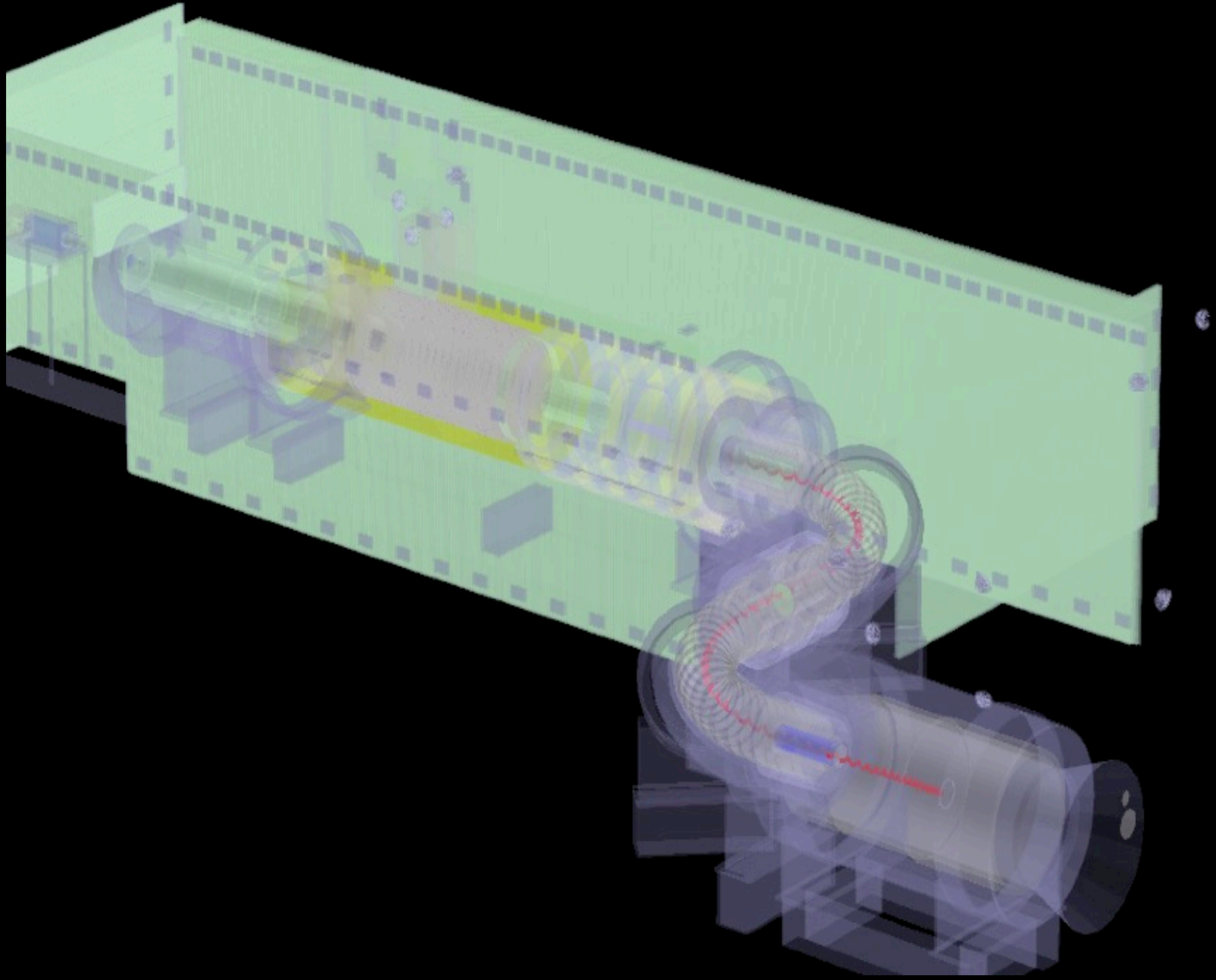
Caltech



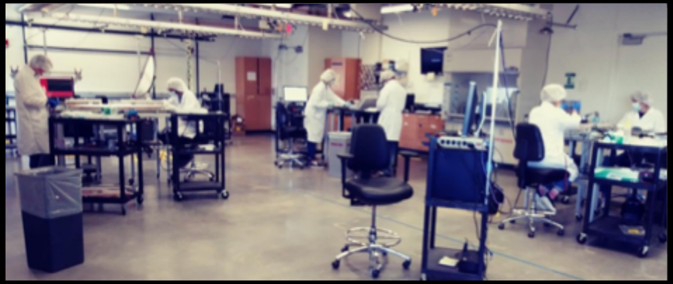
Building our Detectors

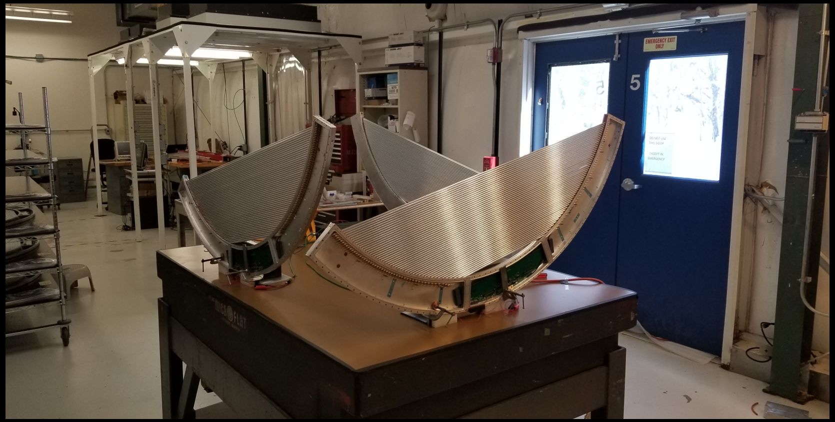
How are our detectors constructed?
Where are they constructed?
What is the current status of each system?
When will Mu2e be ready?

The Tracker: Progress

2020: Production at University of Minnesota, testing at Duke, → Over 70% of panels fabricated, testing on going

2021: Assembly at FNAL
→ 10/36 planes so far assembled on site

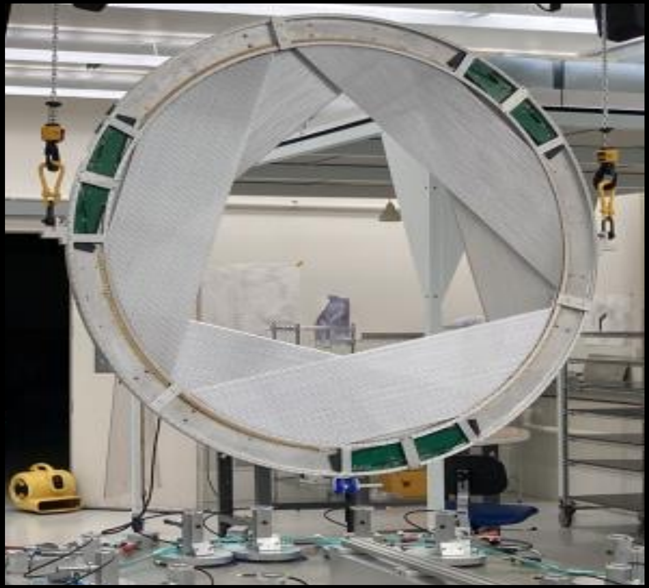


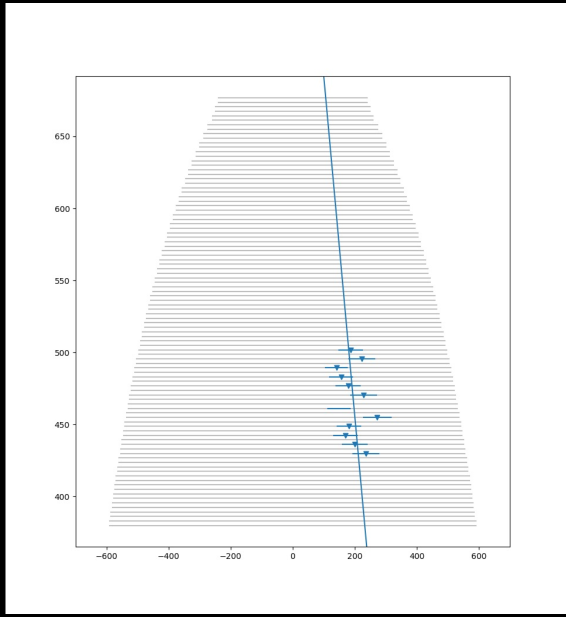


Vacuum tests at FNAL, here for single panel.

The Tracker: Progress

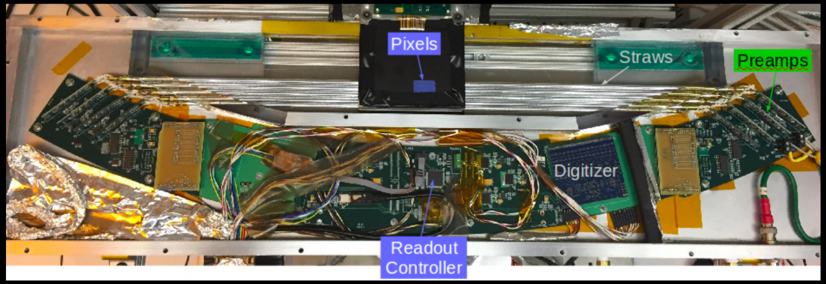
2020: Vertical Slice Test begins at FNAL



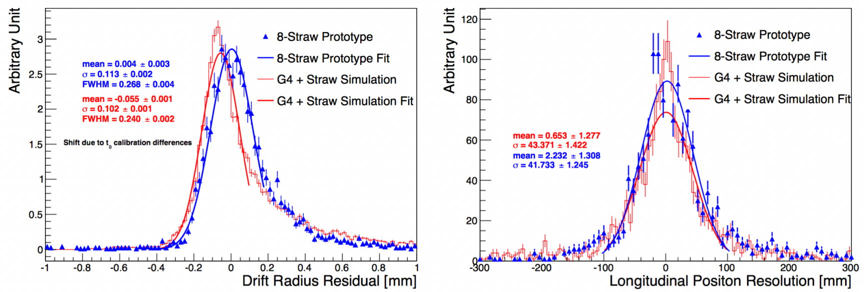


- Use Cosmic Rays.
- Use information gained to update MC.
- Measured performance and resolutions.
- First test with real data.
- I wrote algorithms for cosmic ray reconstruction in the tracker

2017-2018: Electronics prototype produced at LBNL



Measured gain, crosstalk, resolution...



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

8 channel prototype

Read about the prototype: https://arxiv.org/abs/1710.03799

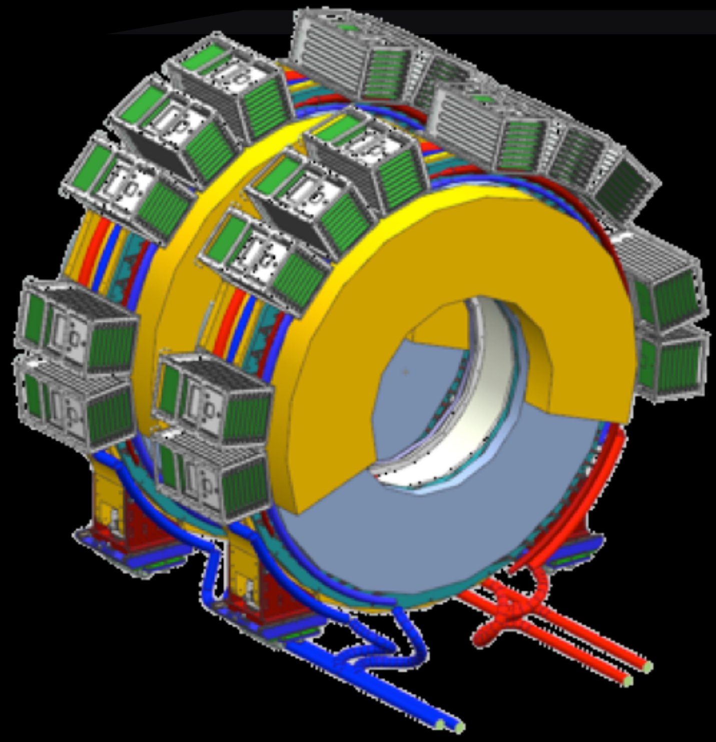
→ Good agreement between MC/Data

→ Resolution can be achieved

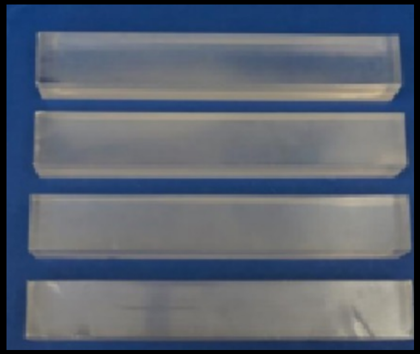
The Calorimeter: Purpose

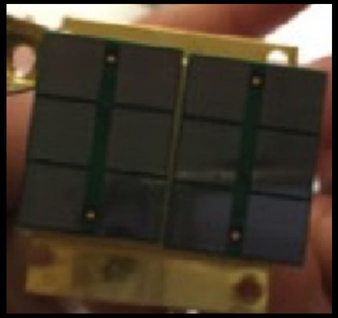
Caltech key group in Calorimetry team

- The calorimeter is vital for providing:
  - Particle identification,
  - Fast online trigger filter,
  - Accurate timing information for background rejection,
  - Seed for track reconstruction.
- The Mu2e Calorimeter must:
  - Provide time resolution < 0.5 ns;
  - Energy resolution < 10%;
  - Position resolution < 1 cm.;
  - Function in 20Gy/crystal/year + neutron flux 10^{11} /cm^2.



- Annular shape and 2 disks – the separation of disks is ½ the pitch of the mu2e signal helix, means that we cannot miss a conversion electron.
- Each disk = 674 CsI crystals
- 2 SiPMs per Crystal : UV-extended, 6 x 6mm^2.





The Calorimeter

Assembly beginning

Inner Ring

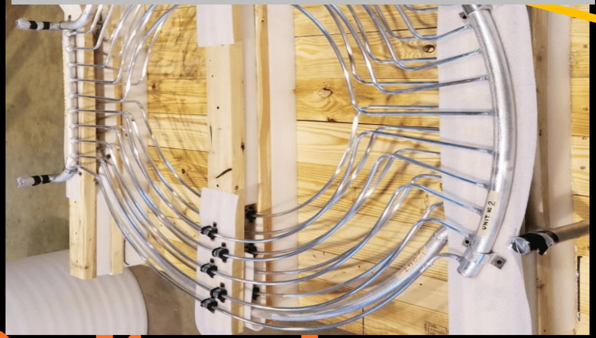
Outer Ring

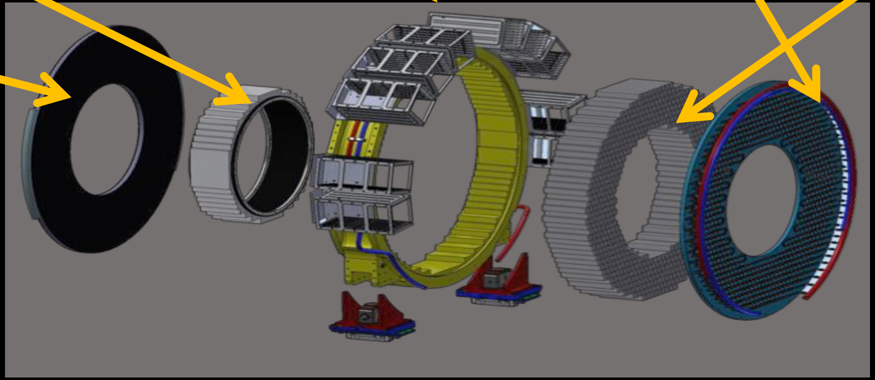
SiPMs glued into boards

FEE Board

Crystals at FNAL in sealed cupboard after QA.

Source Calibration System Caltech built!





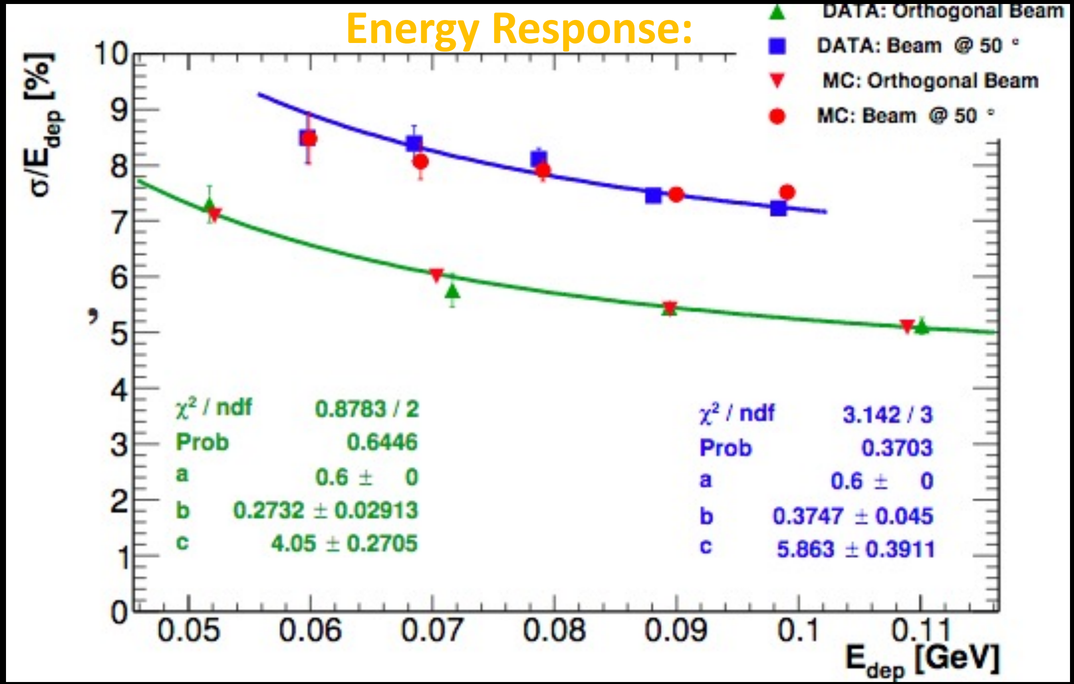
Me at FNAL – finishing crystals QA (2020)

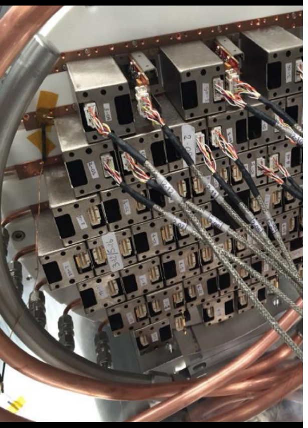
The Calorimeter: Progress

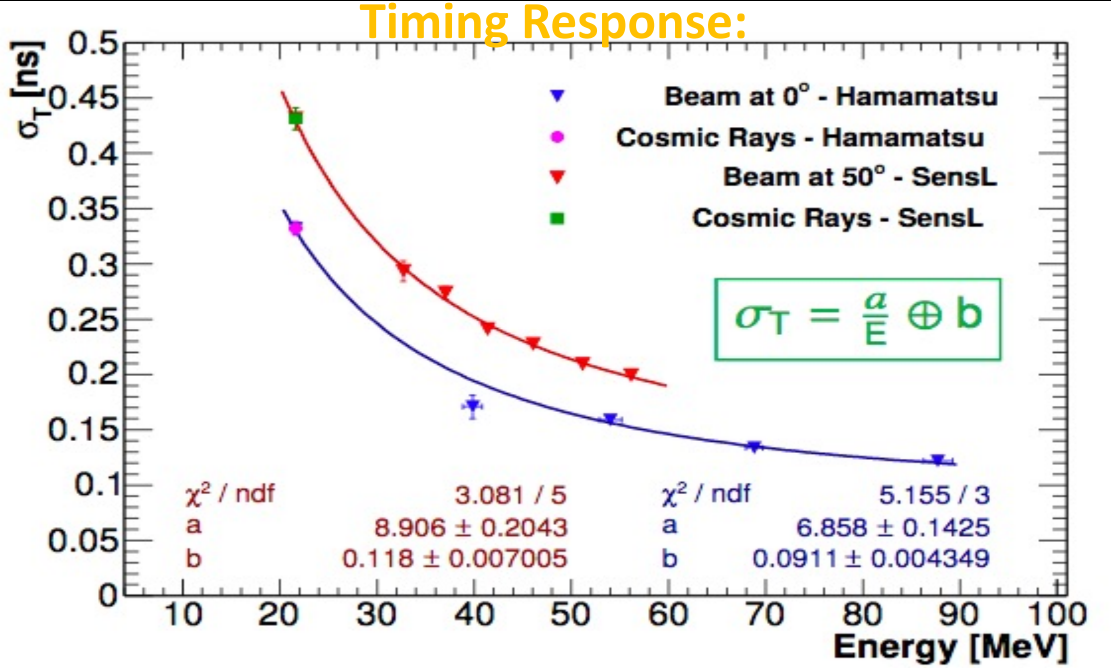
Read about the test beam results:
https://www.osti.gov/pages/biblio/1523418

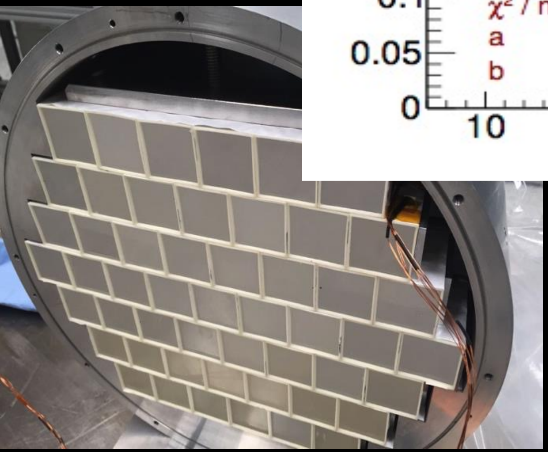
- R&D and Prototyping successfully completed.
- 51 crystals + 102 SiPM + 102 FEE boards

2018:









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

Typical time resolution
E_{beam} @ 100 MeV
$\sigma_{T1} \sim$ **130 ps**

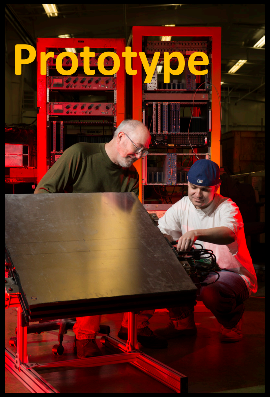
The Cosmic Ray Veto System

Modules at Fermilab

2020: Vertical Slice Test at UVA

- 70% of modules fabricated at UVA
- Electronics production underway
- Front-End-Boards produced KSU
- Vertical slice test underway

WLS



Caltech

The Stopping Target Monitor (STM)

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

2019: I set up test stands to begin DAQ development

HPGe and LaBr detectors procured

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

Test beam at ELBE this year…. results being analyzed

Mu2e: Timeline

2022
Transition to installation

2023
In situ commissioning of detectors (no beam)

2024
Commissioning with beam

2025-2026
Run 1 of data taking up to LBNF shutdown

Post shutdown (~2 years later):
Run 2 of data taking

Mu2e Data Taking

Paper being written – publication imminent. Caltech involved in simulated analysis to evaluate the current expected sensitivity of Run1.

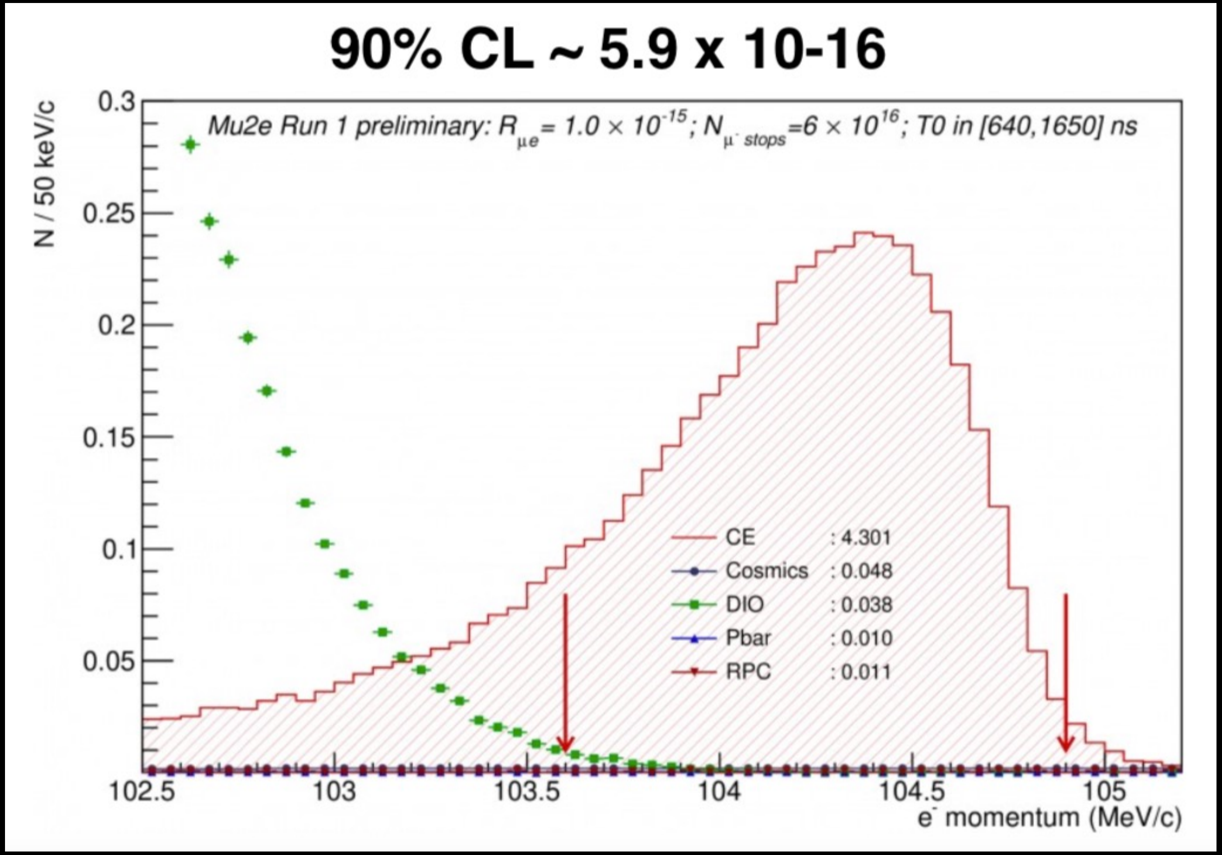
Run 1: 2025-2026:

- X 1000 improvement over SINDRUM-II 90% CL limit
- PIP-II/LBNF shutdown scheduled for end of 2026

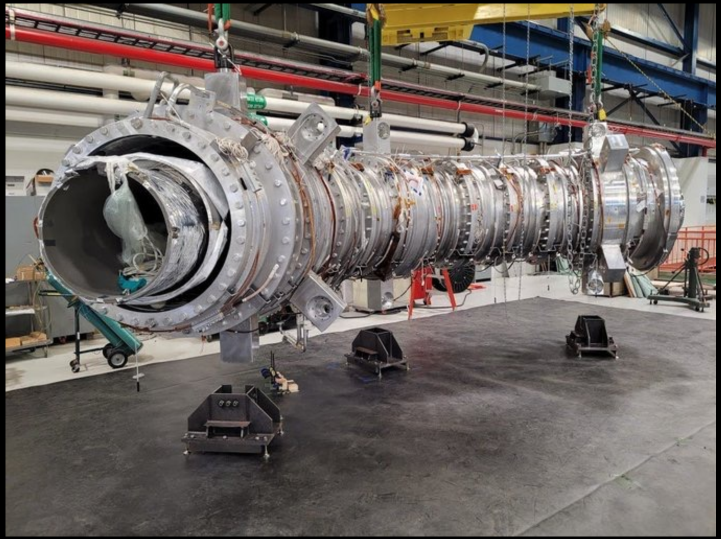
Run 2: Data-taking resumes 2 years later:

- Get the data needed for the extra X 10 improvement on SINDRUM-II

Run 1:



Follow us



Watch the experiment evolve with frequent videos and images:

https://twitter.com/Mu2eExperiment

https://www.instagram.com/mu2eexperiment/

Life in Physics

- Life in Particle Physics has many fun aspects, here are a few pictures of my times.

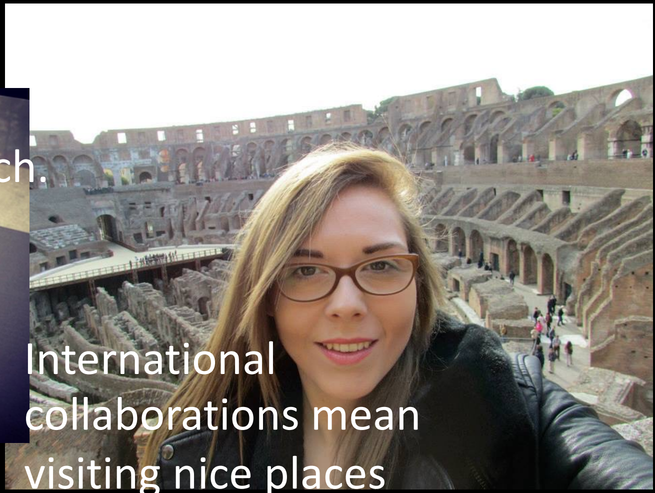

Lab in Covid Times


Fermilab near Chicago – home to many experiments.


Day/Night Data Taking Shifts


Caltech Campus Views

Cool cups and experiment merch.


International collaborations mean visiting nice places

Summary

- Muon CLFV channels offer deep indirect probes into BSM.
- Mu2e is at the forefront of active global CLFV program. 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.
- It is important to eliminate Standard Model backgrounds so the experiment is designed to be “background free”:
  - Super conducting solenoids to collect and efficiently transport low momentum muons;
  - Pulsed beam removes backgrounds from pions;
  - Low mass, annular tracker has high resolution to avoid DIO backgrounds;
  - Cosmic Ray Veto surrounds detectors to remove “fake signals” from Cosmic muons.

Thank You for listening!

Useful Resources

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2. S. M. Bilenky, S. T. Petcov, and B. Pontecorvo, Phys. Lett. B **67**, 309 (1977).
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4. B. W. Lee, S. Pakvasa, R. E. Shrock, and H. Sugawara, Phys. Rev. Lett. **38**, 937 (1977); **38**, 1230 (1977) [erratum].
5. J. Adam *et al*. (EG Collaboration), Phys. Rev. Lett. **110**, 20 (2013).
6. W. Bertl *et al*. (SINDRUM-II Collaboration), Eur. Phys. J. **C47,** 337 (2006).
7. U. Bellgardt *et al*., (SINDRUM Collaboration), Nucl. Phys. **B299**, 1 (1988).
8. A.M. Baldini *et al*., “MEG Upgrade Proposal”, arXiv:1301.7225v2 [physics.ins- det].
9. Y. Kuno *et al*., “COMET Proposal” (2007) see also https://arxiv.org/abs/1812.09018 for Phase I TDR
10. Mu2e TDR, arXiv:1501.05241
11. Nuclear Physics B - Proceedings Supplements Volumes 248–250, March–May 2014, Pages 35-4
12. A. Czarnecki et al., “Muon decay in orbit: Spectrum of high-energy electrons,” Phys. Rev. D 84 (Jul, 2011) .
13. Sindrum-II “Improved limit of Branching Fraction of mu- →e+ in Titanium”, Phys Lett B 422 (1998) 334-338 (1998)

g-2 Result: Implications for Mu2e

P. Paradisi / Nuclear Physics B (Proc. Suppl.) 248–250 (2014)

- Dipole transitions $\mu \rightarrow e\gamma$ in the leptonic sector are accounted for by means of the effective Lagrangian :

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R\sigma_{\mu\nu}A_{\ell\ell'}\ell'_L + \bar{\ell}'_L\sigma_{\mu\nu}A^{\star}_{\ell\ell'}\ell_R\right)F^{\mu\nu},$$

$$\frac{\mathrm{BR}(\ell \to \ell'\gamma)}{\mathrm{BR}(\ell \to \ell'\nu_\ell\bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right).$$

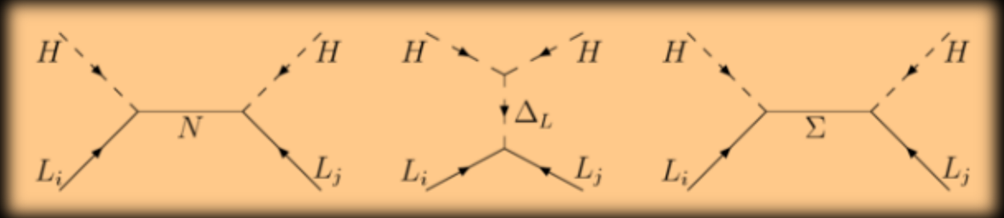
- The underlying $\mu \rightarrow e\gamma$ transition can also generate lepton flavor conserving processes like the anomalous magnetic moments (Δa_μ) as well as leptonic electric dipole moments (EDMs, d_μ).
- In terms of the effective Lagrangian can write as :

$$\Delta a_\ell = 2m_\ell^2\,\mathrm{Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\,\mathrm{Im}(A_{\ell\ell}).$$

- On general grounds, one would expect that, in concrete NP scenarios, (Δa_μ) , d_μ and BR($\mu \rightarrow e\gamma$), are correlated. In practice, their correlations depend on the unknown flavor and CP structure of the NP couplings and thus we cannot draw any firm conclusion that we would necessary see CLFV in the next generation, but this is of course a very promising result for muon physics!.

Nuclear Physics B (Proc. Suppl.) 248–250 (2014) 13–19

Example: See Saw Mechanisms



- See Saw Models can induce rates which are not suppressed by smallness of these masses.
- There are 3 ways of inducing Δ*L* = 2 Majorana neutrino masses from the tree level exchange of a heavy particle:
  - Type I exchange of right-handed neutrinos N_i,
  - Type II exchange scalar triplet Δ*L*,
  - Type II exchange of fermion triplets Σ_i.
- Knowledge of the neutrino mass matrix is not sufficient to be able to distinguish between the 3 seesaw models → CLFV can help here.

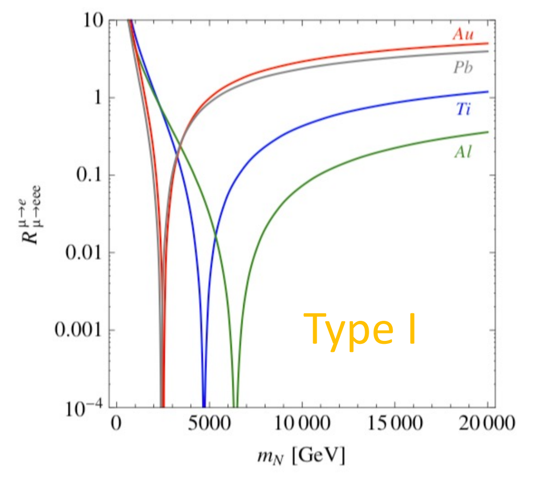


Figure 3: $R^{\mu\to e}_{\mu\to eee} = R^N_{\mu\to e}/Br(\mu\to eee)$ as a function of the right-handed neutrino mass scale m_N, for $\mu\to e$ conversion in various nuclei, from Ref. [27].

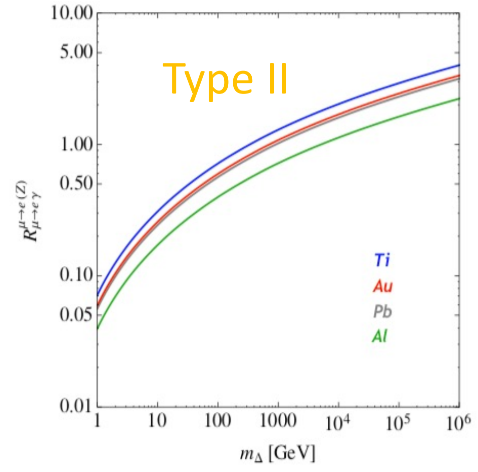


Figure 5: $R^N_{\mu\to e}/Br(\mu\to e\gamma)$ for various nuclei, as a function of m_Δ.

SUSY SO(10)

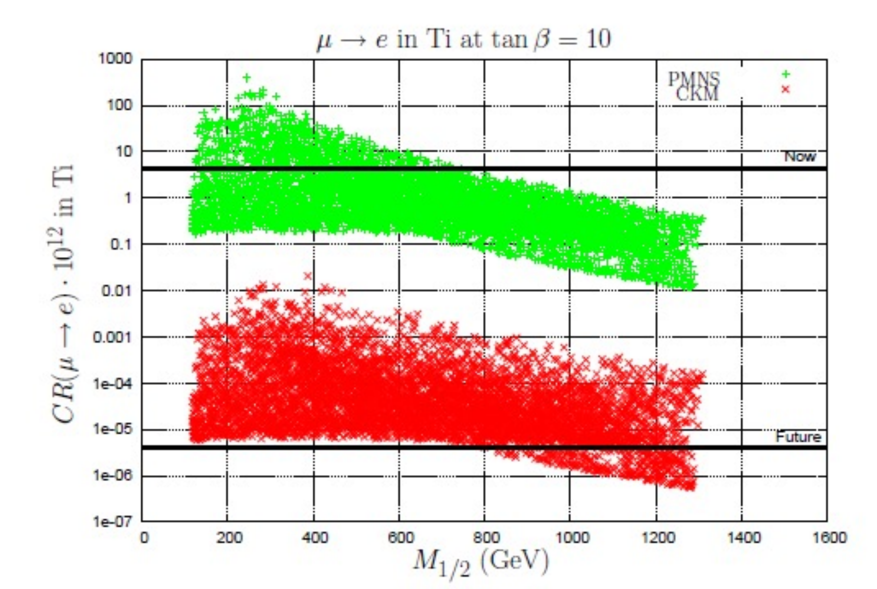
Complementary to Muon g-2 and LHC program:

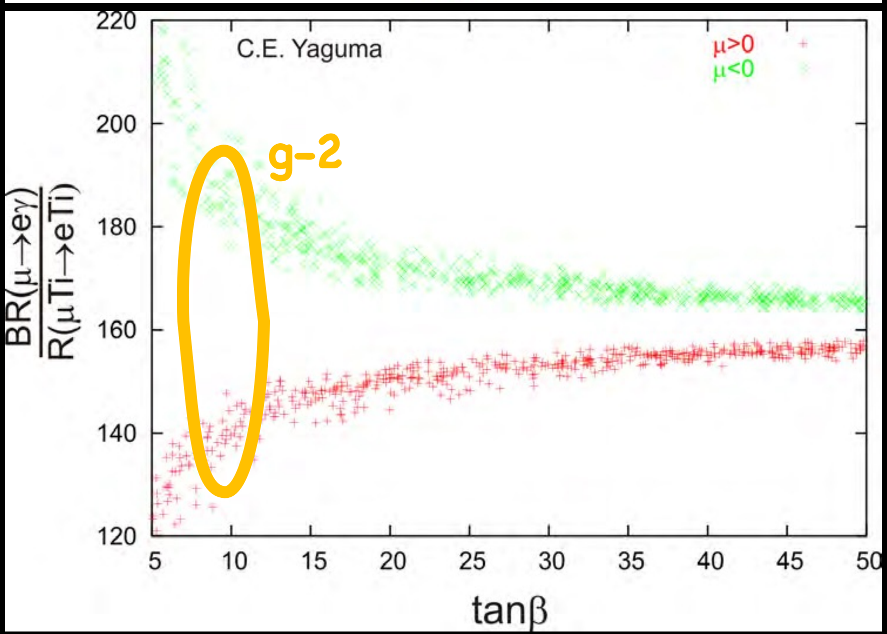
SUSY SO(10)

Consider SO(10) SUSY GUT model with very massive right-handed neutrinos. Can consider different hypothesis for the neutrino Yukawa couplings. Mu2e will be able to test all PMNS type and most CKM type SO(10).

L. Calibbi et al., JHEP 1211 (2012) 040

L. Calibbi, G. Signorelli arXiv:1709.00294





Muon g-2 results will also be helpful here.

To allow discrimination among different models

Need:

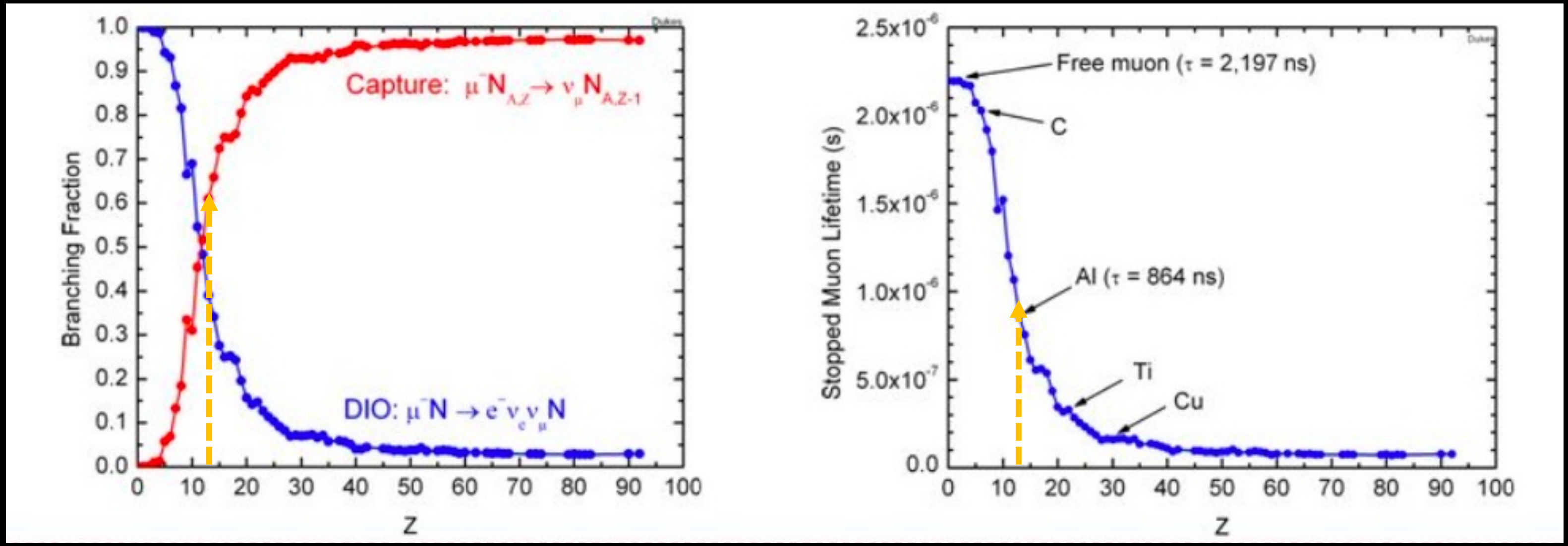
- Observation of CLFV in more than one channel, and/or
- Evidence from LHC and/or g-2

Yaguna, hep-ph/0502014v2

Endo arxiv.org/abs/1303.4256v1 (g-2 SUSY .v. LHC constraints)

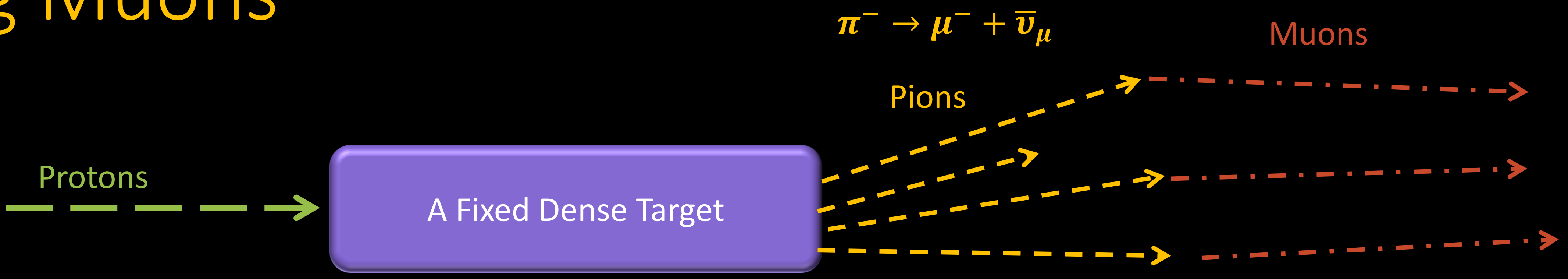
Why Aluminum?

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.

Making Muons



- Protons hit a target, produce pions:
  - $\tau_\pi = 26\ ns$ at rest
- Pions decay to produce muons (and a muon anti-neutrino).
  - $\tau_\mu = 2.2\ \mu s$ at rest
- We can use high power proton beams to produce pure, intense muon beams.

Laboratory/ Beam Line	Energy/ Power	Present Muon μ^+/μ^- Rates Hz	Future estimated μ^+/μ^- Rate Hz
PSI (CH) - LEMS - πE5 - HiMB	(590 MeV, 1.3MW, DC) " " (590 MeV, 1.3MW DC)	$4 \cdot 10^8$ $1.3 \cdot 10^8 / 10^6$	O{10^{10}/ 10^8} (μ+/-)
J-PARC (JP) - MUSE - COMET	(3 GeV, 1MW Pulsed) Reached 400kW " (8 GeV, 56kW Pulsed)	$8 \cdot 10^7 / 4 \cdot 10^6$	$2 \cdot 10^8$ (μ+) (1MW) $1 \cdot 10^7$ (μ-) (1MW) 10^{11} (μ-) 2019/2020
FNAL (FermiLab) (USA) Mu2e	(8GeV, 25kW Pulsed)		$5 \cdot 10^{10}$ (μ-) 2019/2020
RAON/RISP (Korea)	600 MeV, 400kW DC)		$7 \cdot 10^8$ (μ+)
CSNS (China)	(1.6 GeV, 100kW Pulsed)		10^8 (μ+)
TRIUMF (CA) -M20/M9B	(500 MeV, 75kW, DC)	$2 \cdot 10^6 / 1.4 \cdot 10^6$	
RAL -ISIS (UK) - RIKEN-RAL	(800 MeV, 160kW, Pulsed)	$1.5 \cdot 10^6 / 7 \cdot 10^4$	
RCNP Osaka Univ. (JP) - MUSIC	(400 MeV, 400W DC)	$7 \cdot 10^5 / 1 \cdot 10^5$ *	* scaled from 8W

Other Physics Searches at Mu2e

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

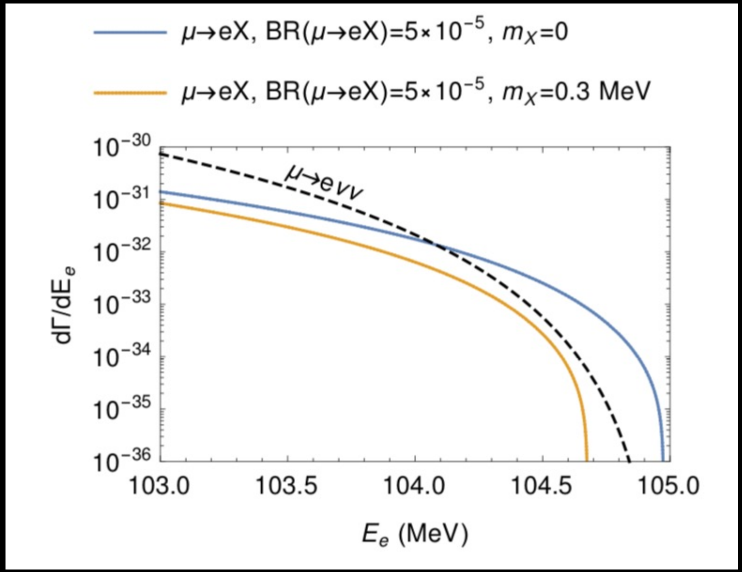
$\mu^- N \to e^+ N'$

- Also lepton number violation
- Could be mediated by Majorana neutrinos through a type-1 see saw mechanism or new particle at > TeV scale.
- The Mu2e sensitivity to $\mu^- \to e^+$ extends beyond the current best limit: Phys Rev Lett B 412 p 334-338 [13]

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

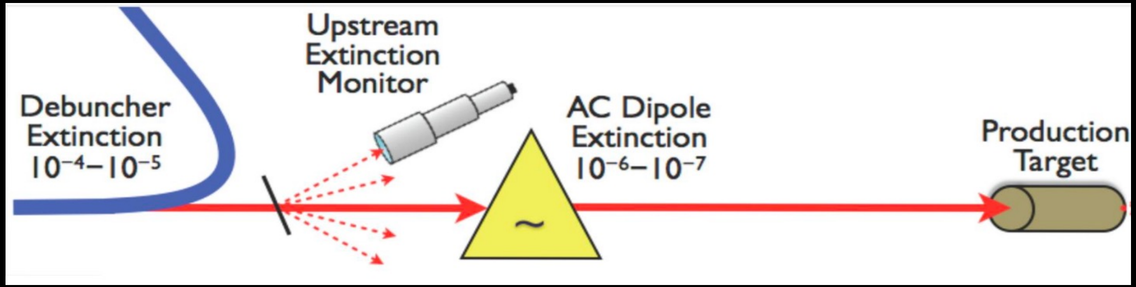
$\mu^- N \to eXN$

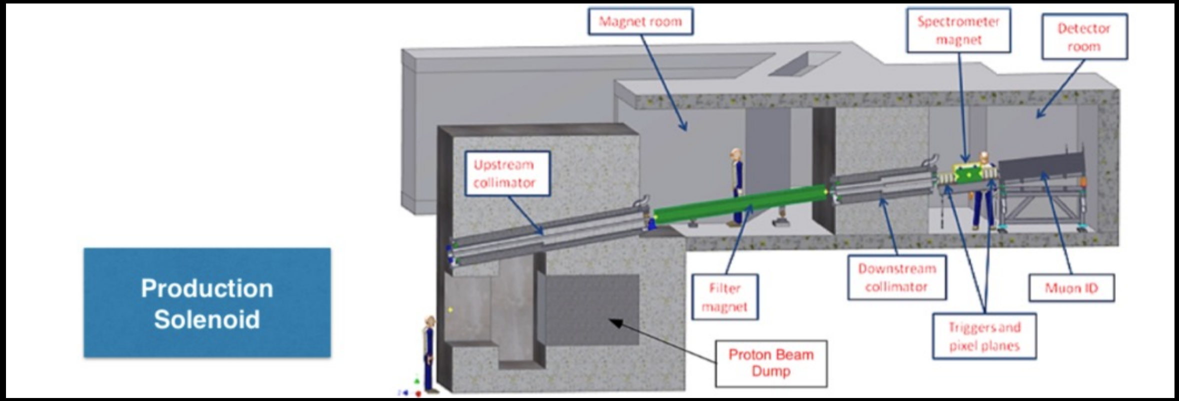
- Where X is a new light boson (or axion).
- Currently understanding feasibility
- Example parameterization: https://arxiv.org/abs/1110.2874
- 2 Caltech summer students worked with me on this last year

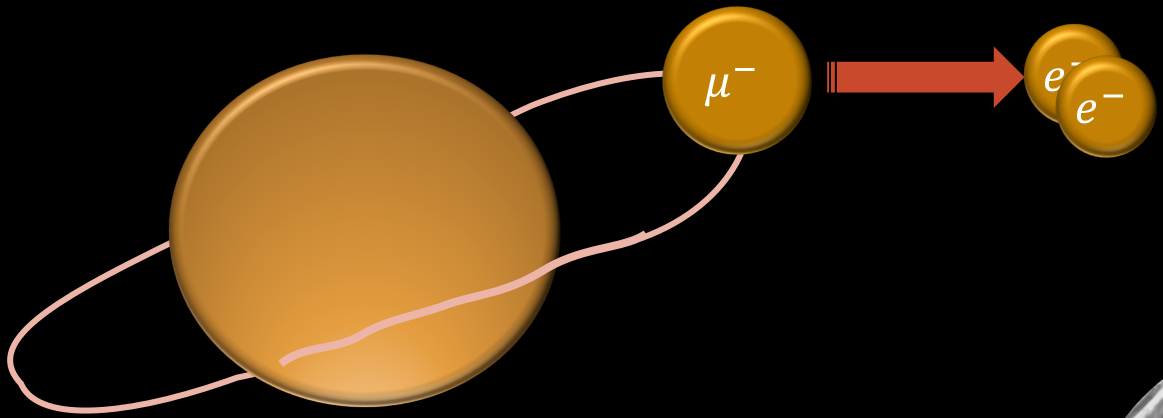


Removing out-of-time protons

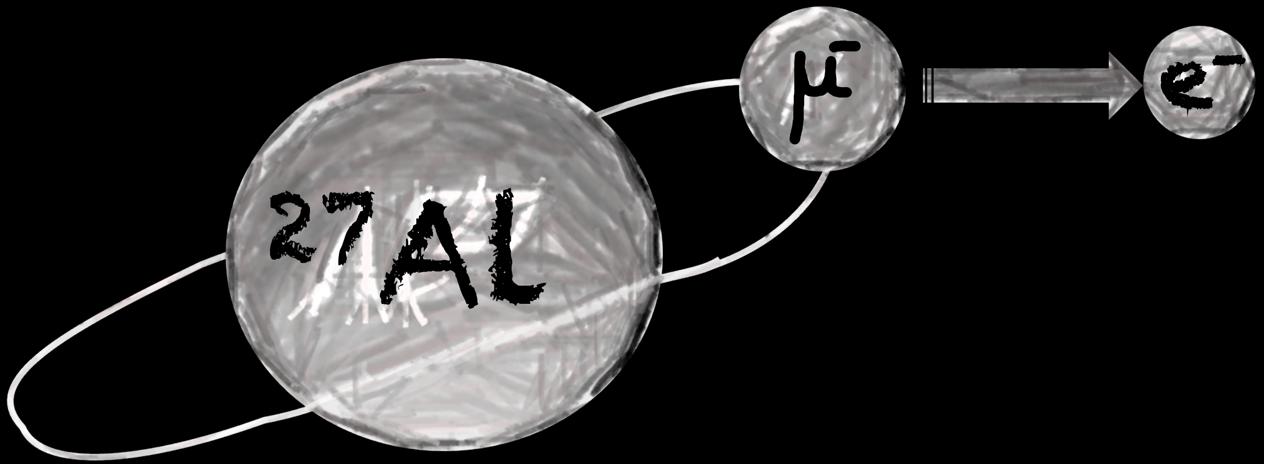
- Must have out-of-time : in-time proton ratio must be kept < 10^{-10} to remove potential backgrounds.
- 2 phase process:
  - Fast “kicker” which transfers the proton beam from the Recycler to the Delivery Ring preserves extinction. Extinction of 10^{-5} is expected as the proton beam is extracted and delivered.
  - 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.
- Extinction measured using a detector system: Si-pixel + sampling EMC .







μ^-
e^-
e^-



27AL
μ^-
e^-