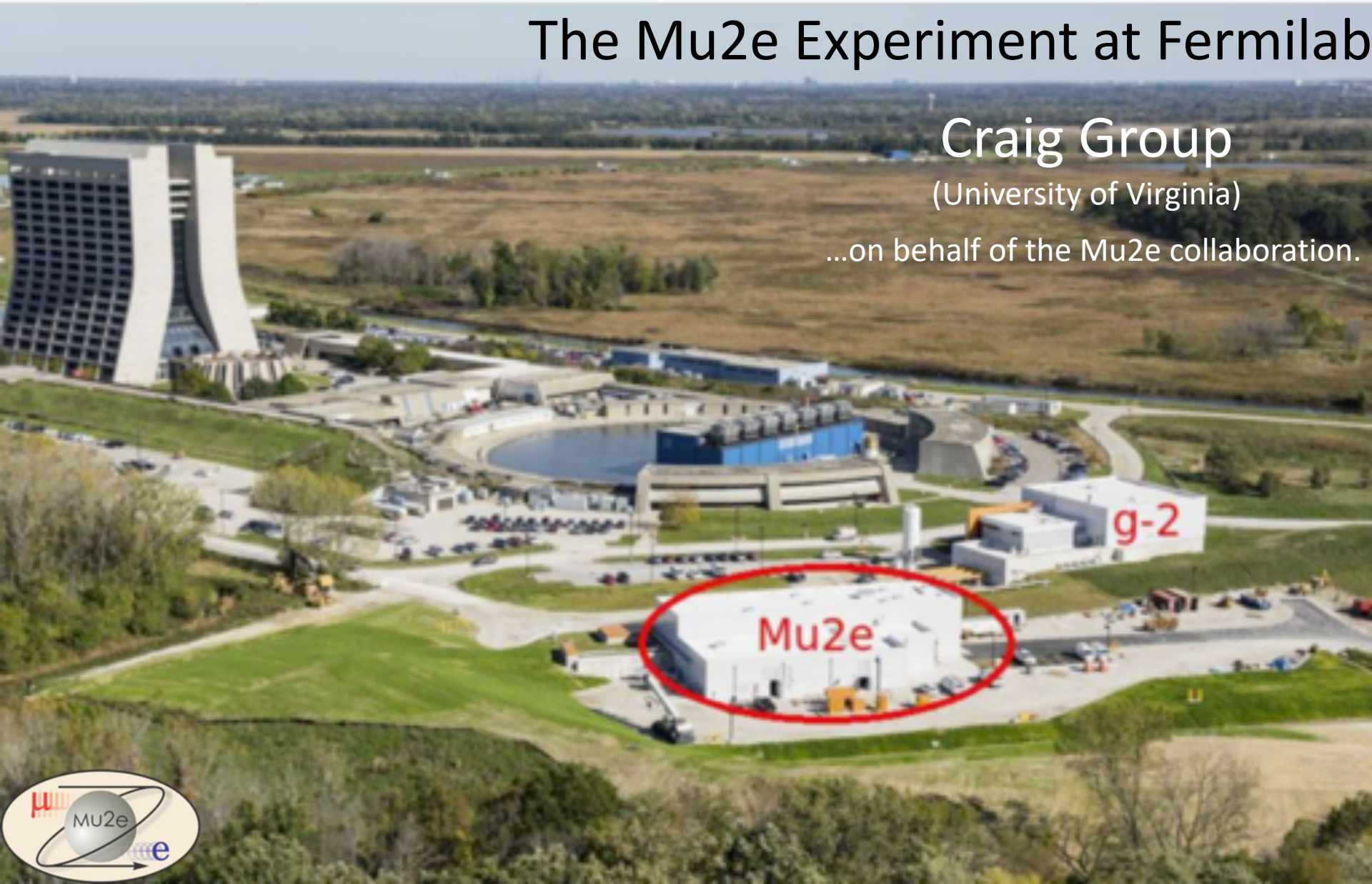
NuFact 2022

The Mu2e Experiment at Fermilab

Craig Group
(University of Virginia)
…on behalf of the Mu2e collaboration.



Where is the new physics?

We know the Standard Model is not complete.

So, where is the rest of the physics we need to complete it?

Where is the new physics?

We don't know!

What is a muon?

What is a muon?

A surprise!

Discovered (by mistake in 1936) while looking for the mediator of the strong nuclear force in cosmic rays…

What is a muon?

- Pontecorvo (1947) suggested that the muon may have been some kind of "isomer" of the electron.
  - If so, he suggested you would see the decay $\mu \rightarrow e\,\gamma$.
  - He and Hincks performed the first search for $\mu \rightarrow e\,\gamma$ in 1948.

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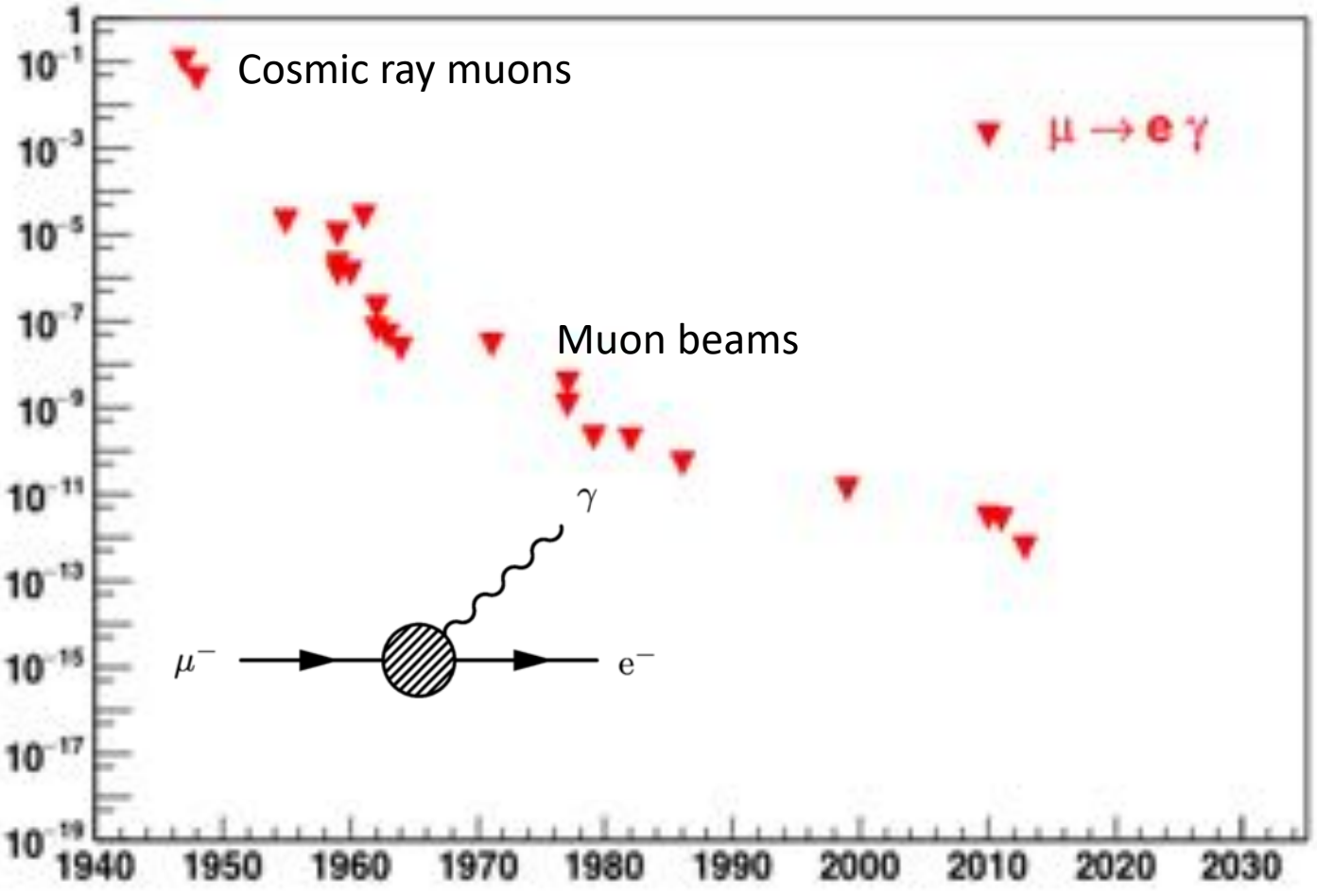
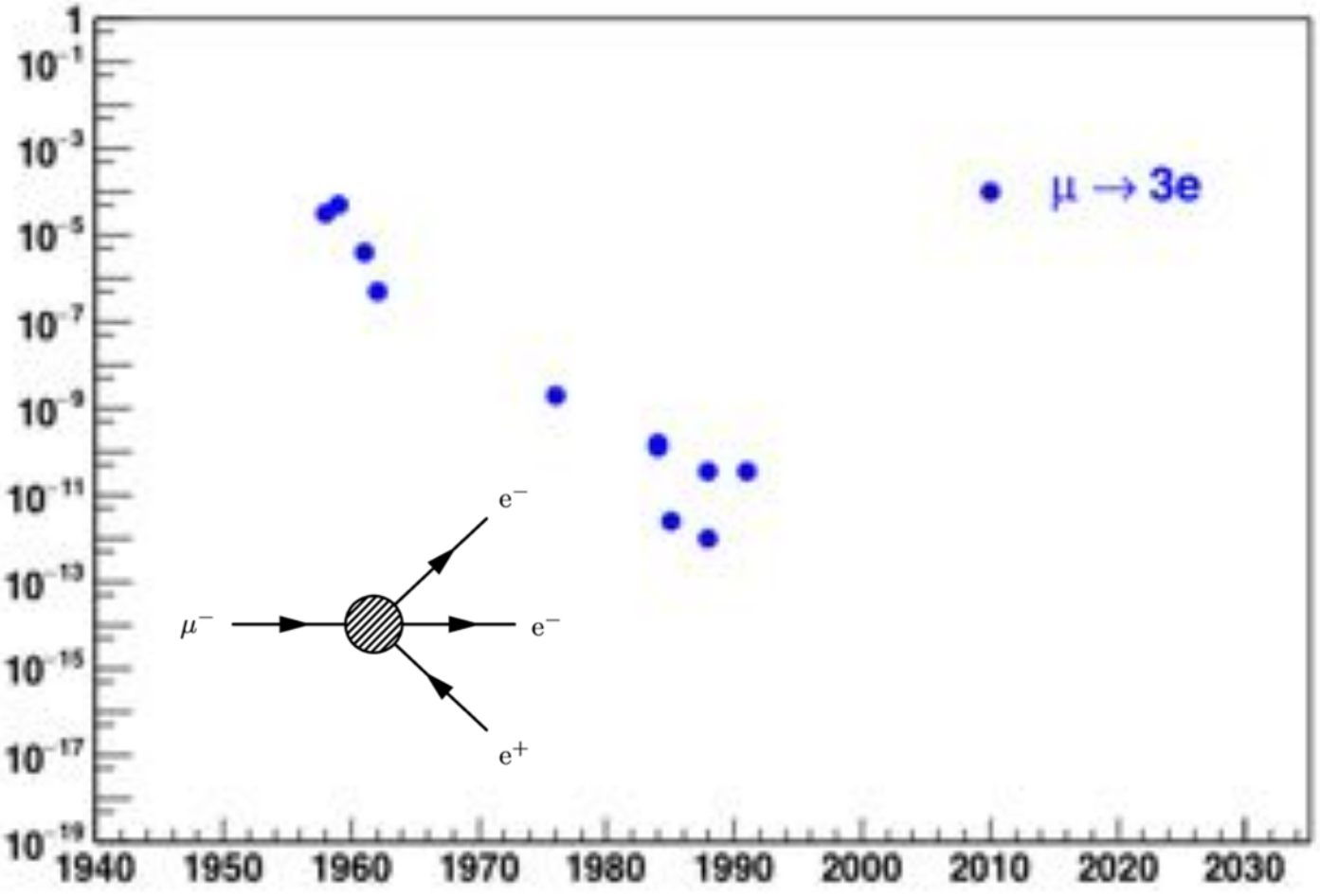
The birth of charge lepton flavor conservation!

History of CLFV Searches



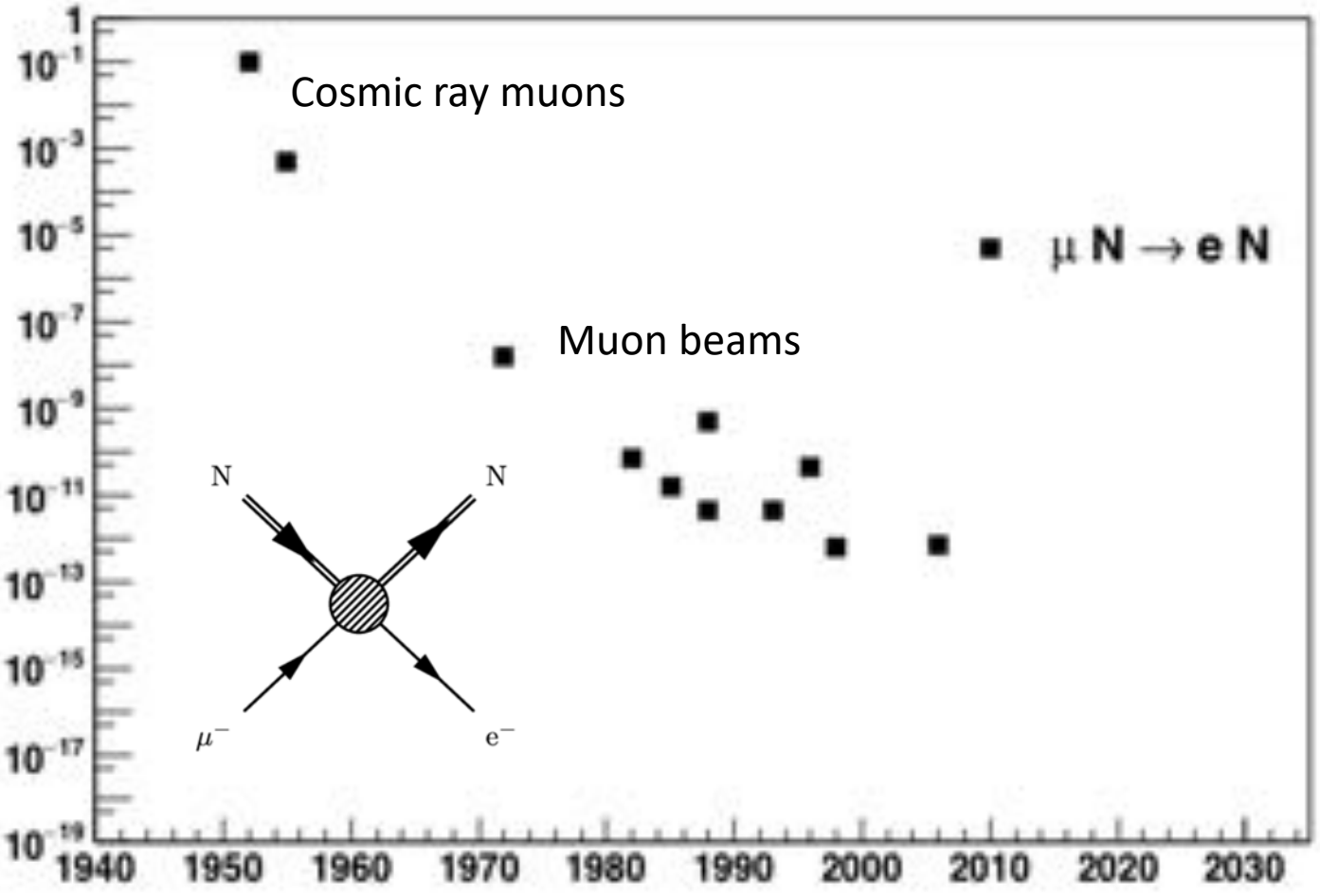
MEGA, MEG (PSI), and others…

History of CLFV Searches



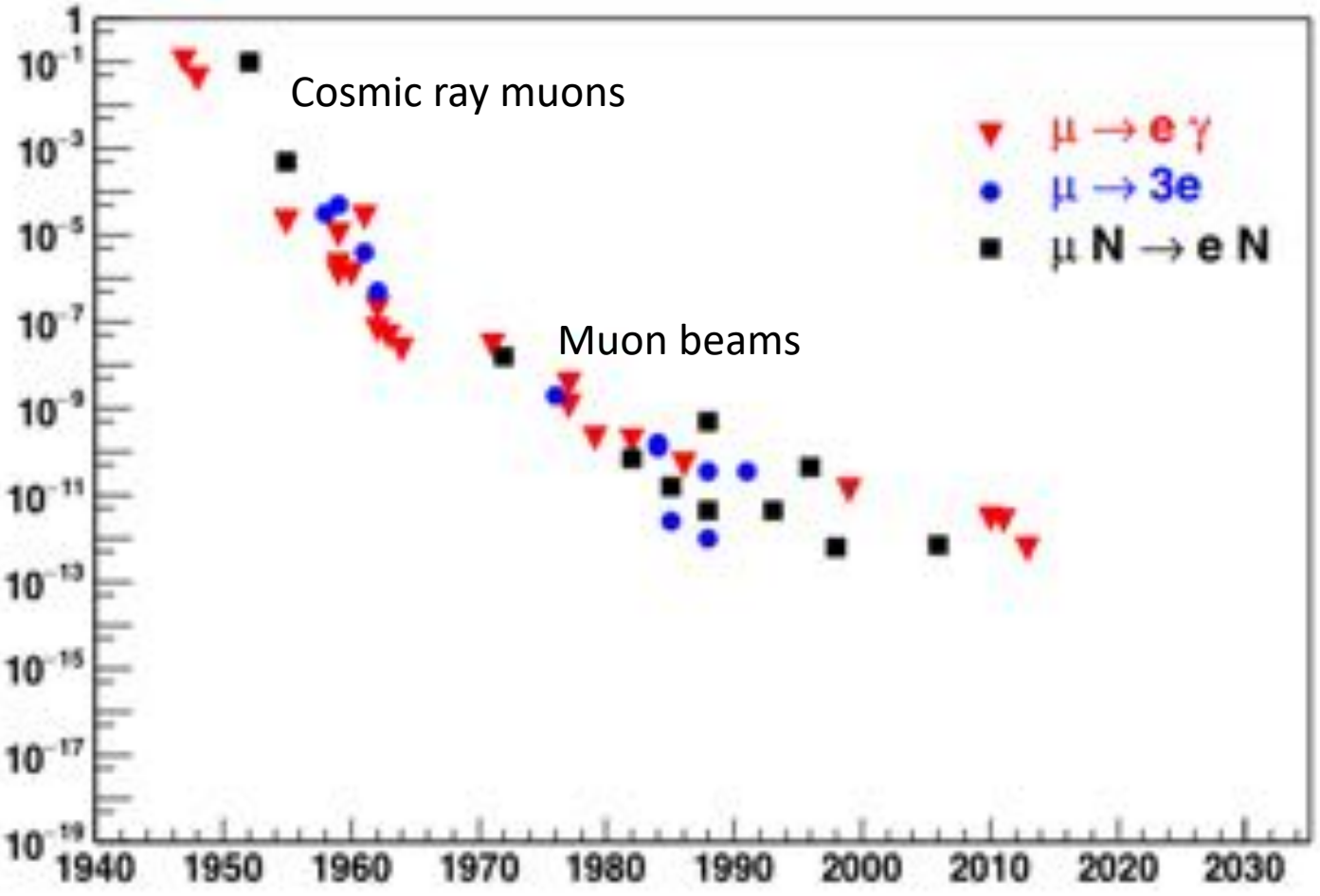
Mu3e, PSI

History of CLFV Searches



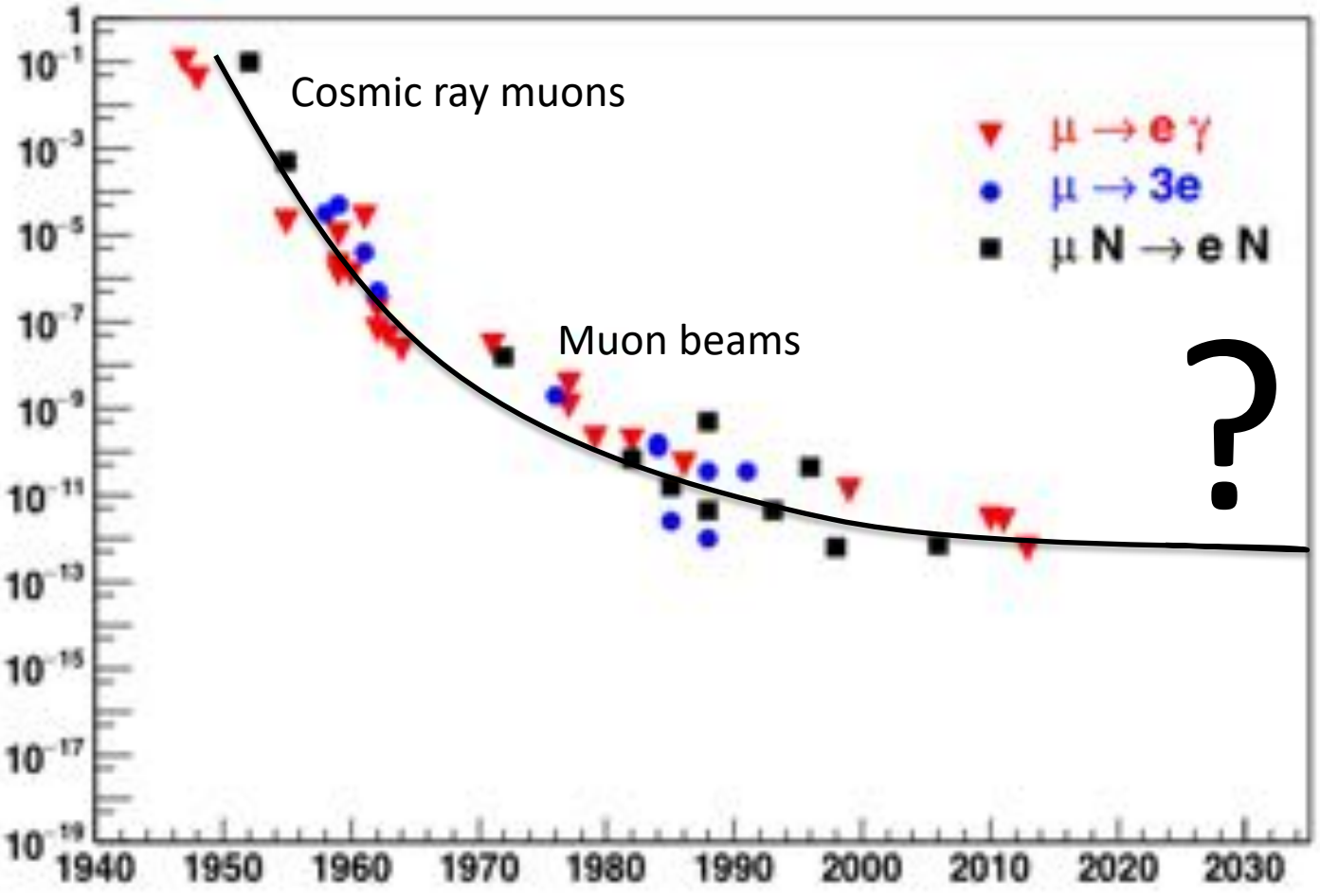
Mu2e, SINDRUM II, COMET, DeeMe, and others…

History of CLFV Searches



We did not observe CLFV so far - why don't we just give up and do something else?

Future of CLFV Searches?



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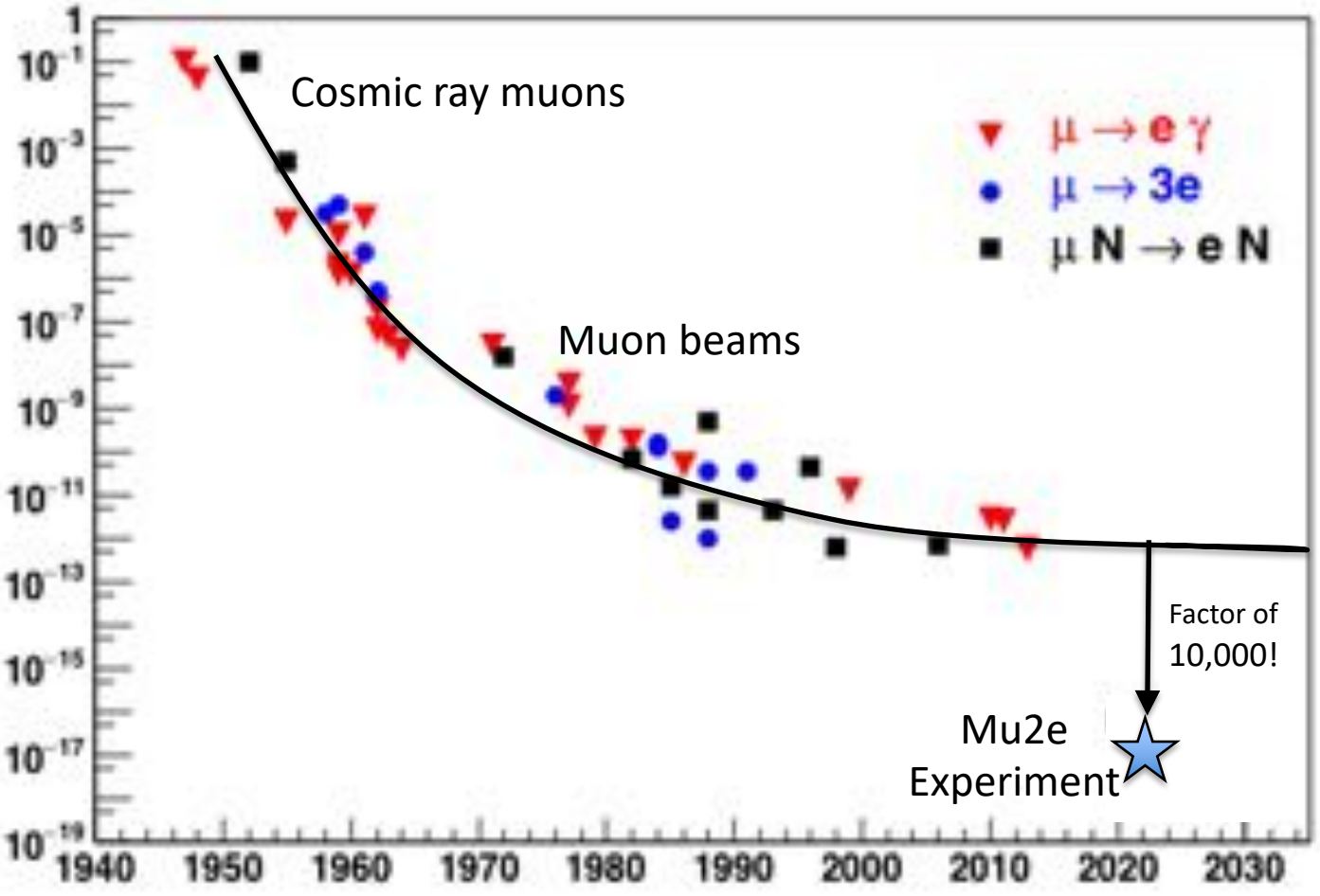
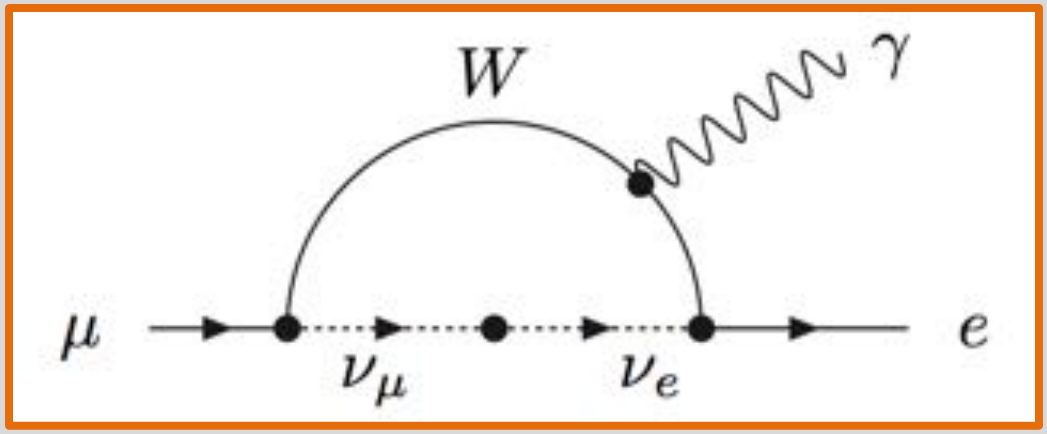
Future of CLFV Searches!!!



Future CLFV experiments like Mu2e expect huge gains in sensitivity!

Charged Lepton Flavor Violation (CLFV)

- Neutrinos have mass
- Individual lepton numbers are not conserved
- Therefore, Lepton Flavor Violation occurs in Charged Leptons

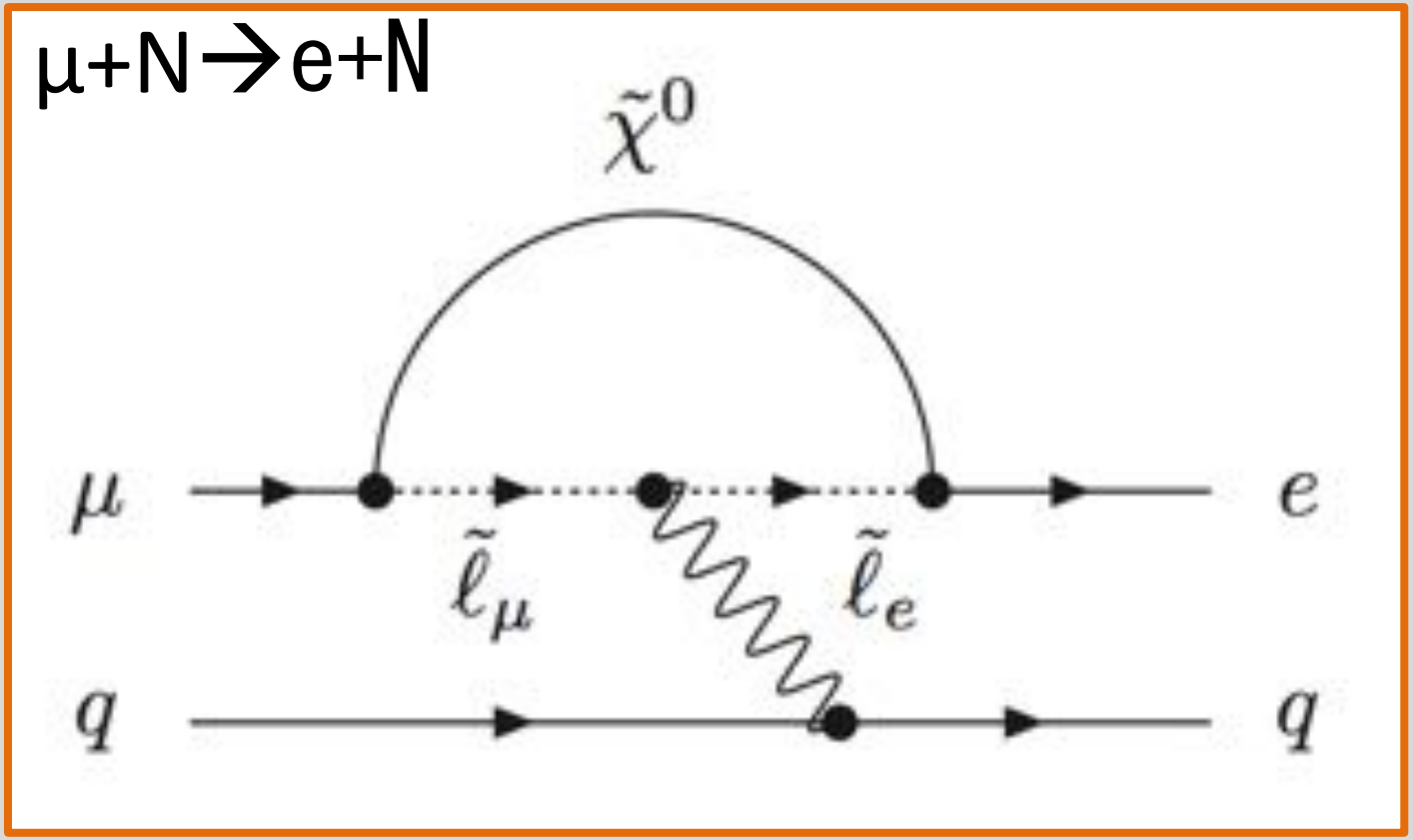


NO SM PHYSICS BACKGROUND! Observation is unambiguous sign of new physics!

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

Searching for CLFV with muon-to-electron conversion

Conversion in the presence of a nucleus (N):

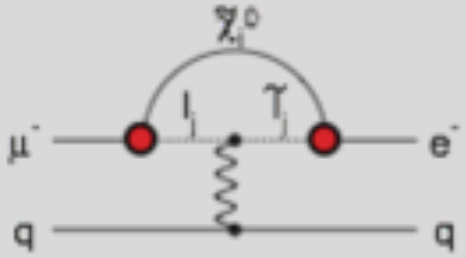


Experiments: Mu2e, SINDRUM II, COMET, and others…

"New physics" may also provide CLFV signal at higher rate!

Supersymmetry

rate ~ 10^{-15}

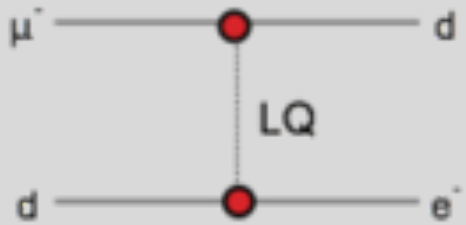


Compositeness

Λ_c ~ 3000 TeV

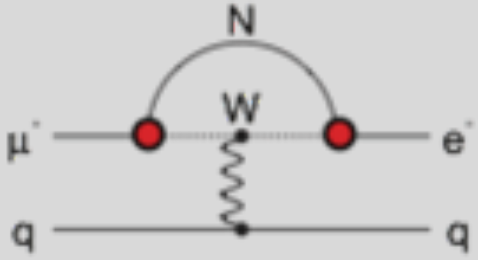
Leptoquark

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



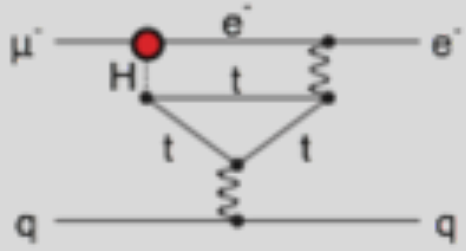
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



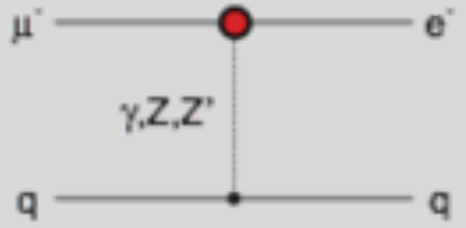
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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



Marciano, Mori, and Roney , Ann. Rev. Nucl. Sci. 58

Mu2e

Mu2e is a DOE experiment to take place at Fermilab that is about 90% constructed.

- Goal: Search for $\mu^- N \rightarrow e^- N$
  - Measure ratio:

$$R_{\mu e} = \frac{\Gamma[\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)]}{\Gamma[\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N+1)]}$$

  - Run 1 (2025-2026) sensitivity to R at 90% C.L. of $6.6*10^{-16}$

→3 orders of magnitude better than current limits

-- $R_{\mu e} < 7 \times 10^{-13}$ @ 90% CL (on Au)

-- SINDRUM II (W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006))

→Need ~10^{17} stopped muons!

-- ~10^{29} protons on target (3 year run)

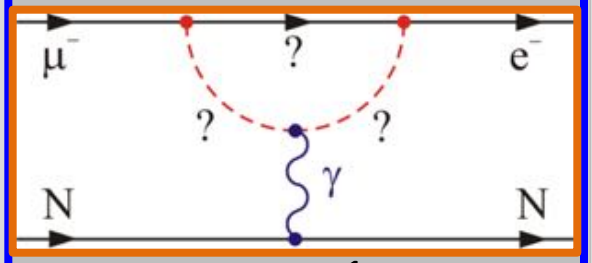
→Need to keep background small and well understood

CLFV in $\mu^+ \rightarrow e^+\gamma$ and $\mu^- N \rightarrow e^- N$

Model-independent effective CLFV Lagrangian

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

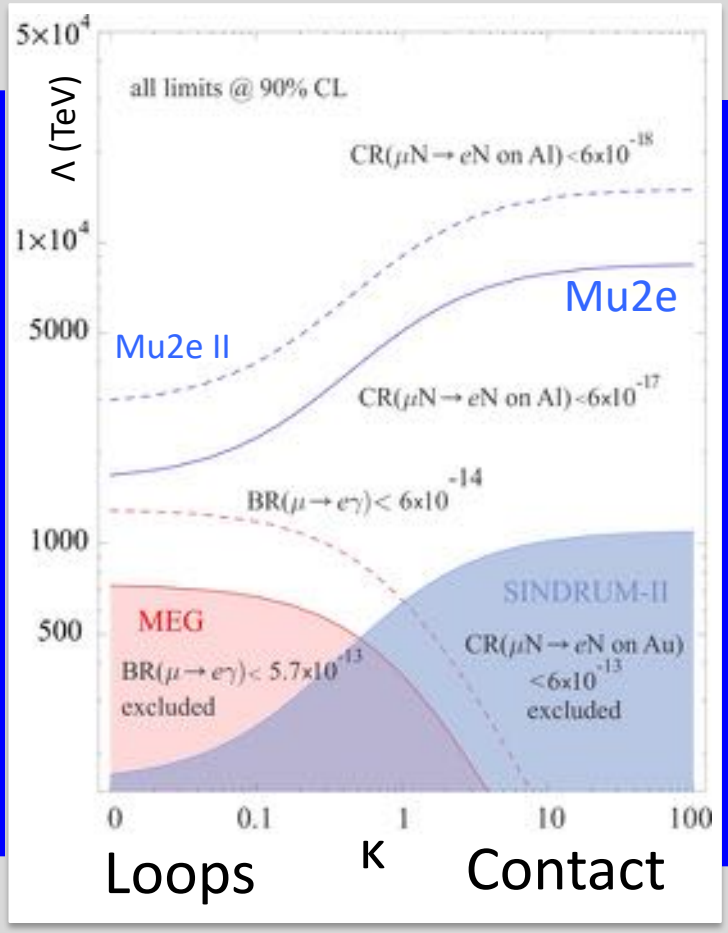
Loops



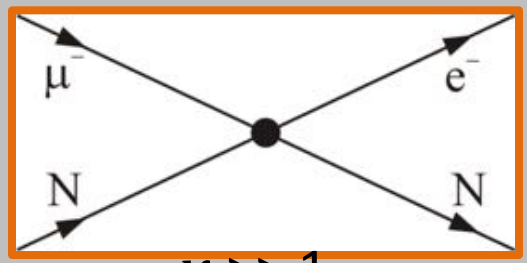
$\kappa << 1$

magnetic moment type operator

$\mu \rightarrow e\gamma$ rate ~300X $\mu N \rightarrow eN$ rate



Contact Interactions



$\kappa >> 1$

four-fermion interaction

$\mu N \rightarrow eN$ rate >> $\mu \rightarrow e\gamma$ rate

A. de Gouvea and P. Vogel
Prog.Part.Nucl.Phys. 71 (2013) 75-92

CLFV in $\mu^+ \rightarrow e^+\gamma$ and $\mu^- N \rightarrow e^- N$

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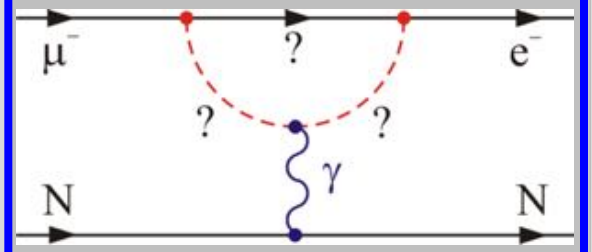
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \sum$$

Mu2e is most sensitive over the full range of κ!

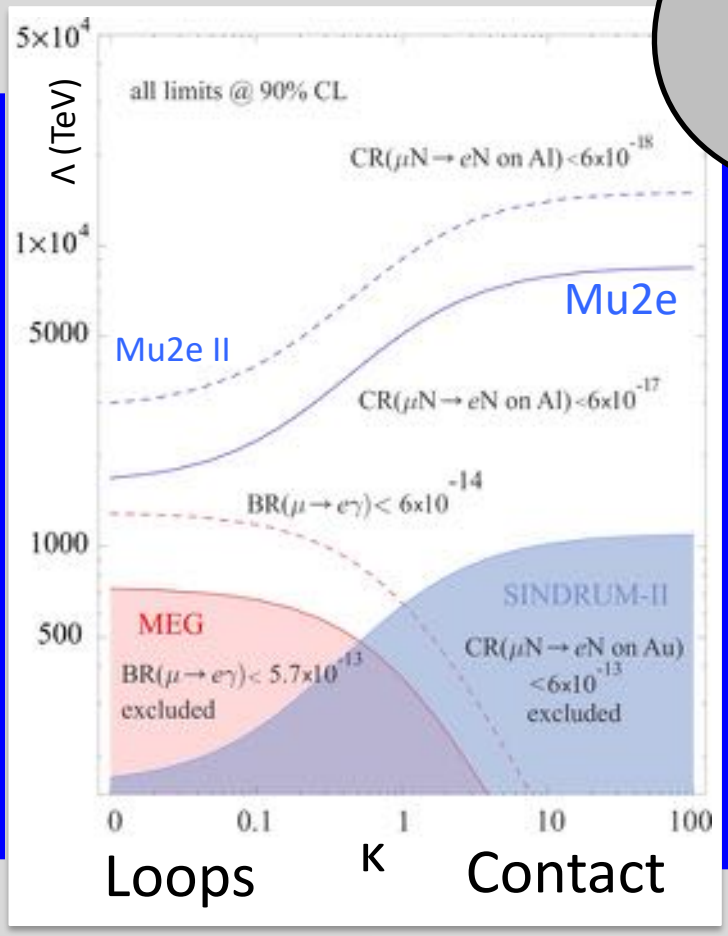
Loops



κ << 1

magnetic moment type operator

μ→ eγ rate ~300X μN → eN rate



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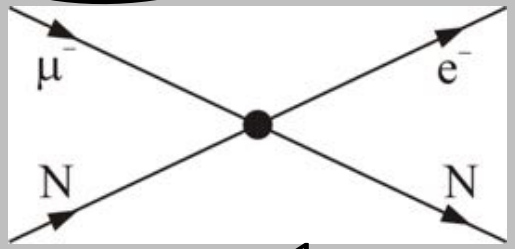

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four-fermion interaction

μN→ eN rate >> μ→ eγ rate

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Mu2e Discovery Potential

Provides information about flavor structure of new physics even if it is not easily accessible at the LHC.

A null Mu2e result at the proposed sensitivity will severely constrain new physics models.

Discovery potential is high -- CLFV is predicted at observable rates for Mu2e in many models of new physics.

Mu2e can probe mass scales up to 10^4 TeV.

Experimental Signature

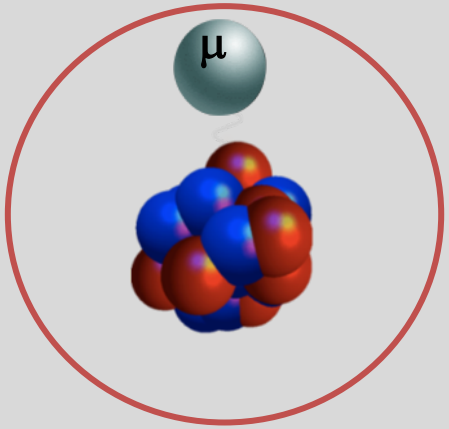
$$\mu^- N \rightarrow e^- N$$

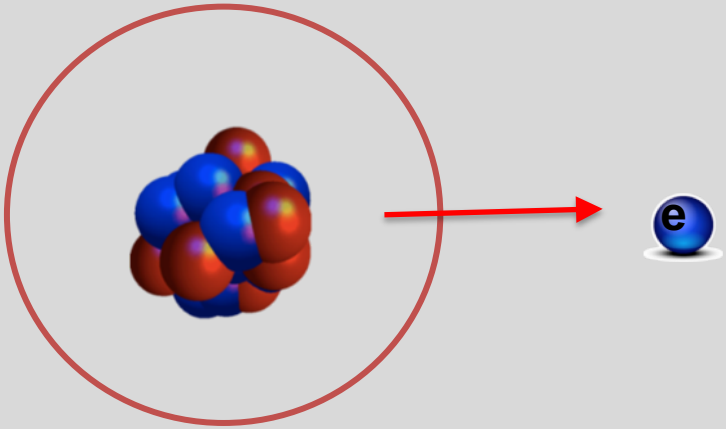
- A single monoenergetic electron
- If N = Al, E_e = 105. MeV

  (Electron E depends on Z)

$$\begin{aligned} E_{\mu e} &= m_\mu c^2 - E_b - E_{\text{recoil}} \\ &= 104.973 \text{ MeV} \quad (\text{for Al}) \end{aligned}$$

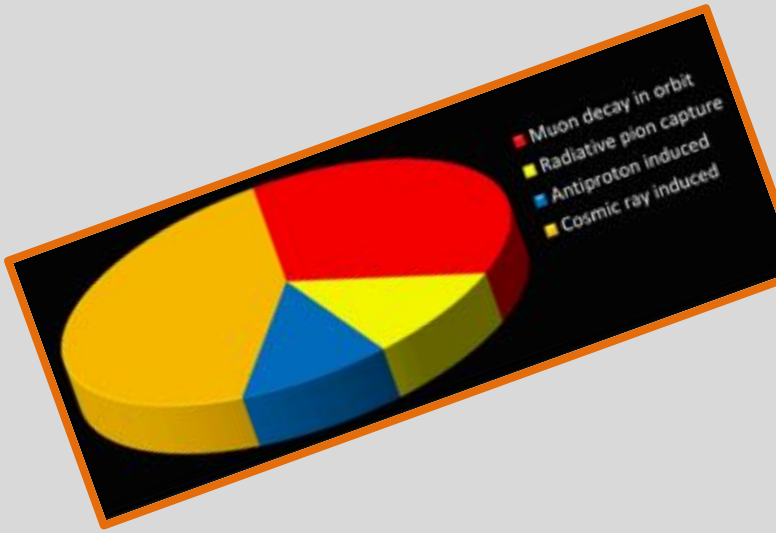
- Nucleus coherently recoils off outgoing electron, no breakup





Background Processes

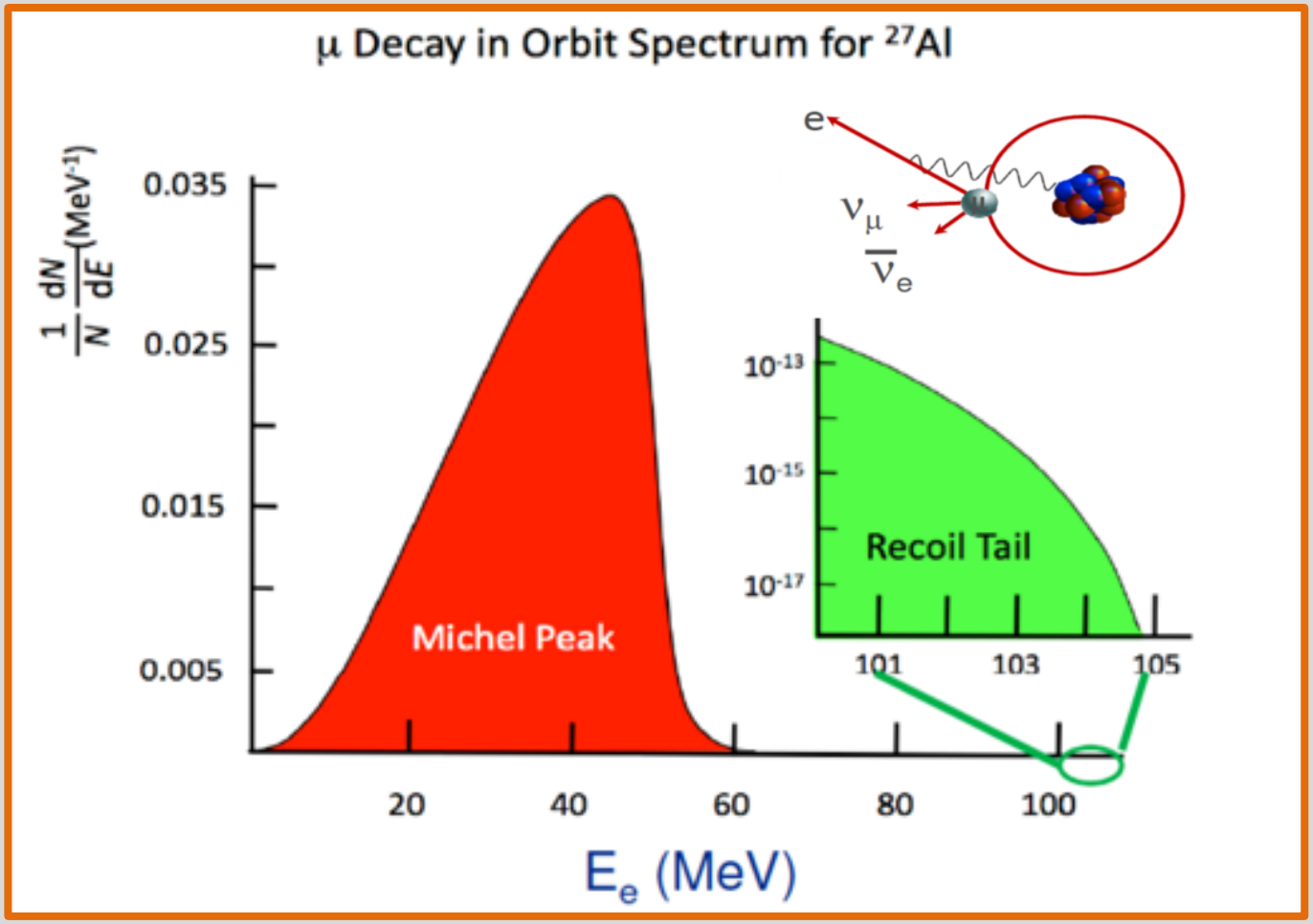
- Signal is a single ~105 MeV e-.
- Major backgrounds:
  - Intrinsic (~40%) – scale with number of stopped muons
    - Muon decay in Coulomb orbit (DIO is ~40% of total background)
    - Radiative muon capture (photon can convert asymmetrically)
  - Late arriving (~10%) – scale with number of late protons
    - Radiative pion capture
    - Muon/pion decay in flight
  - Miscellaneous (~50%):
    - Antiprotons and other late arriving particles
    - Cosmic-ray-induced (largest - ~45%)



These can all be controlled
and none produce a sharp peak at 105 MeV!

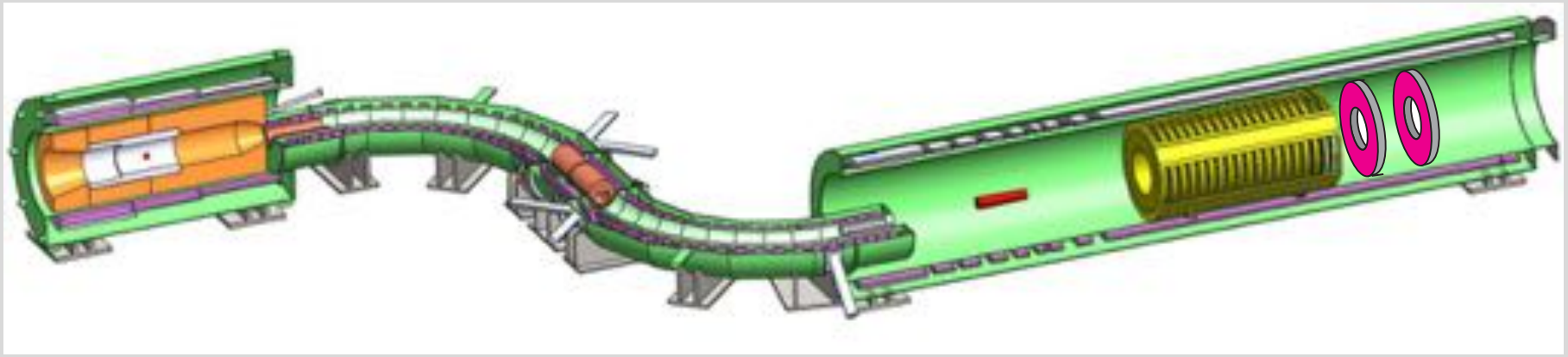
Background Processes

DIO is a large component of the background.



The Mu2e Experiment

Production Solenoid Transport Solenoid Detector Solenoid



(about 25 meters end-to-end)

The Mu2e Experiment

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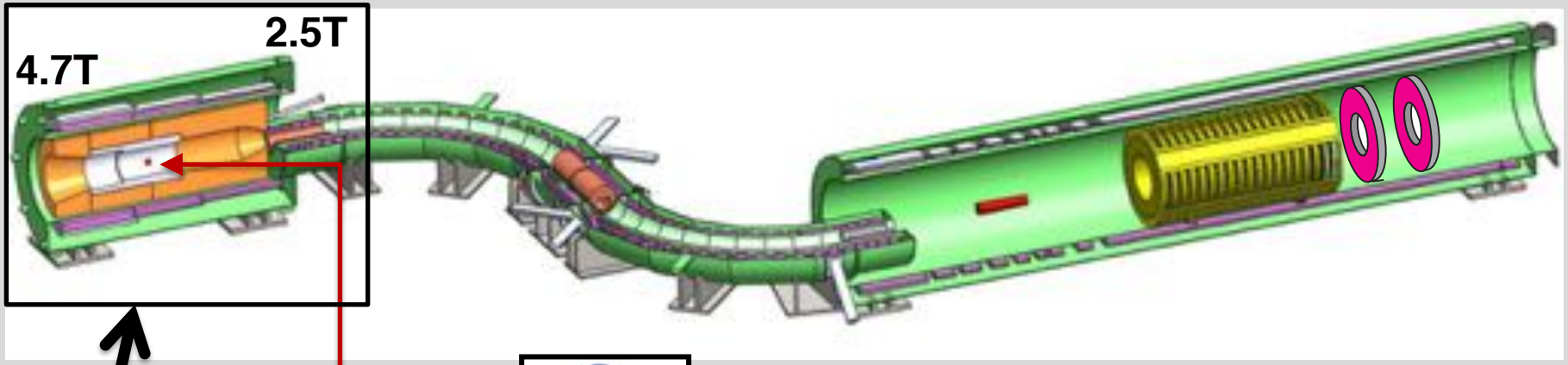
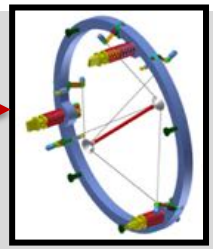




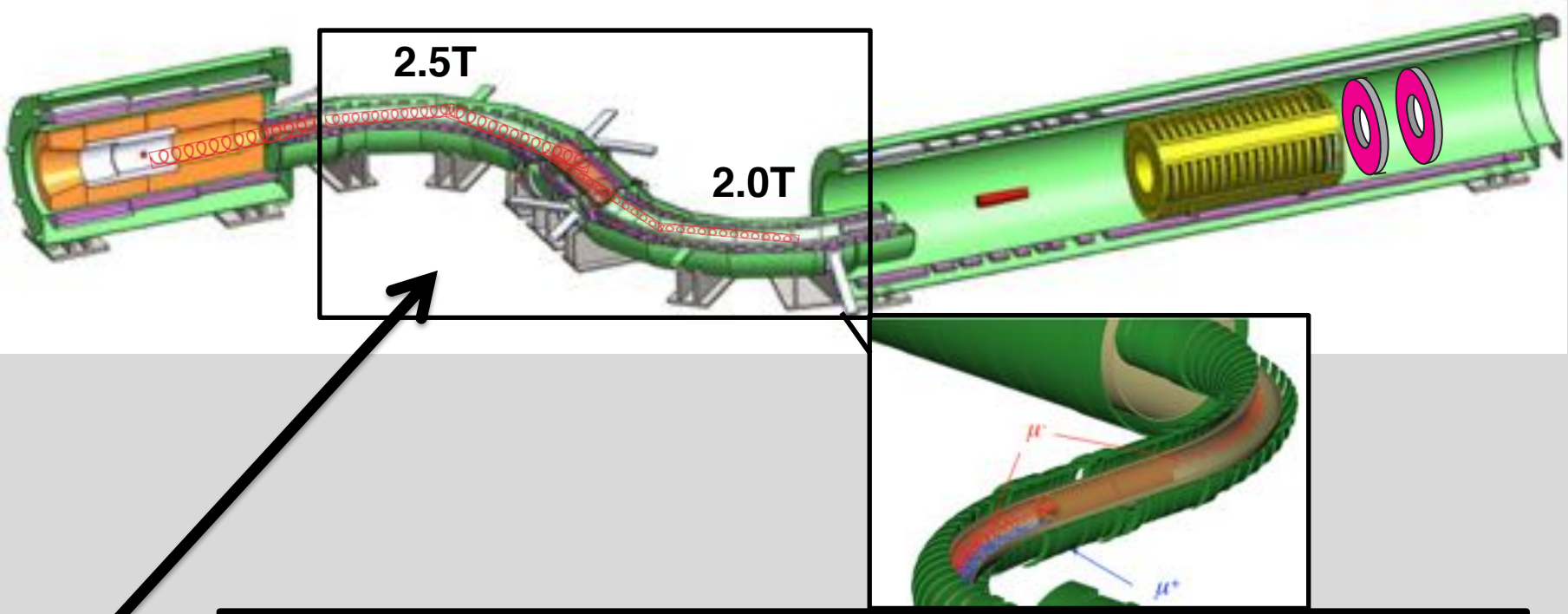
Production Target
(Tungsten, size of a pencil)

1)

- 8 GeV proton beam hits Production Target in Production Solenoid.
- Pions captured and pushed towards Transport Solenoid by graded field.
- Pions decay to muons.

The Mu2e Experiment

Production Solenoid **Transport Solenoid** Detector Solenoid

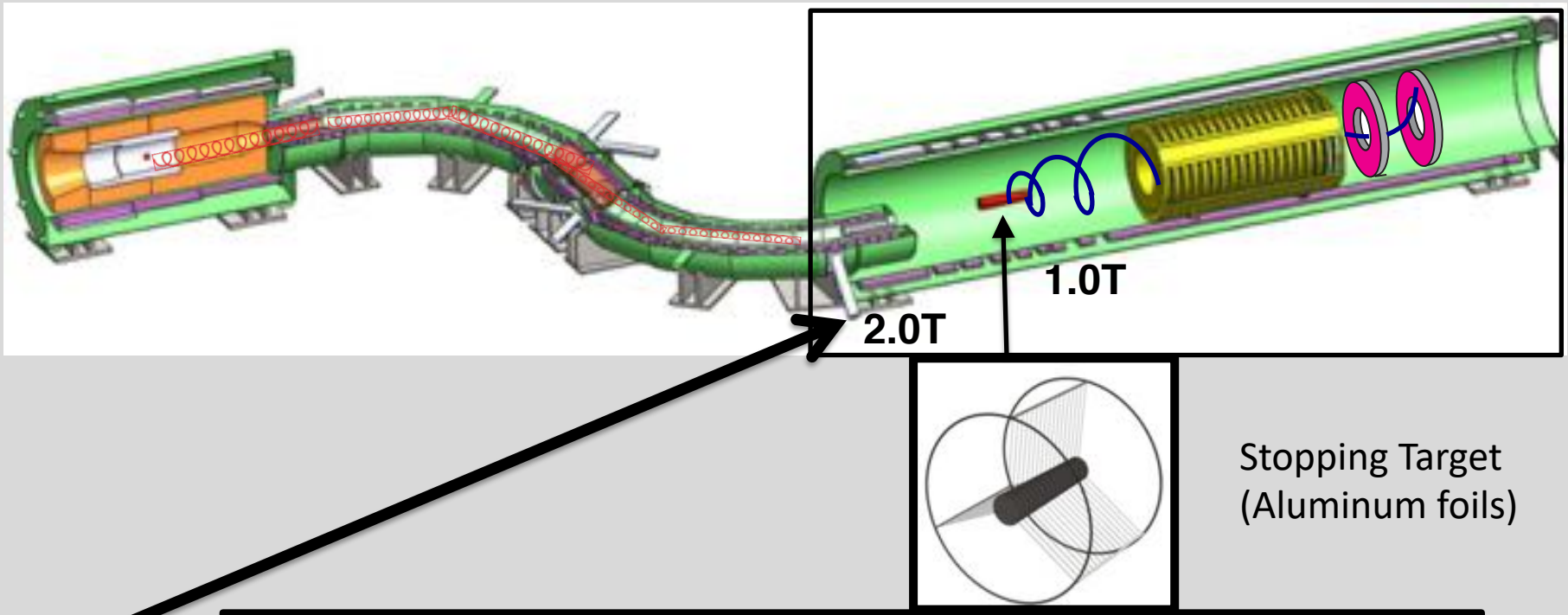


2)

- Transport solenoid performs sign and momentum selection.
- Collimators eliminate high energy negative particles, positive particles, and line-of-sight neutrals.

The Mu2e Experiment

Production Solenoid Transport Solenoid **Detector Solenoid**



Stopping Target
(Aluminum foils)

3)

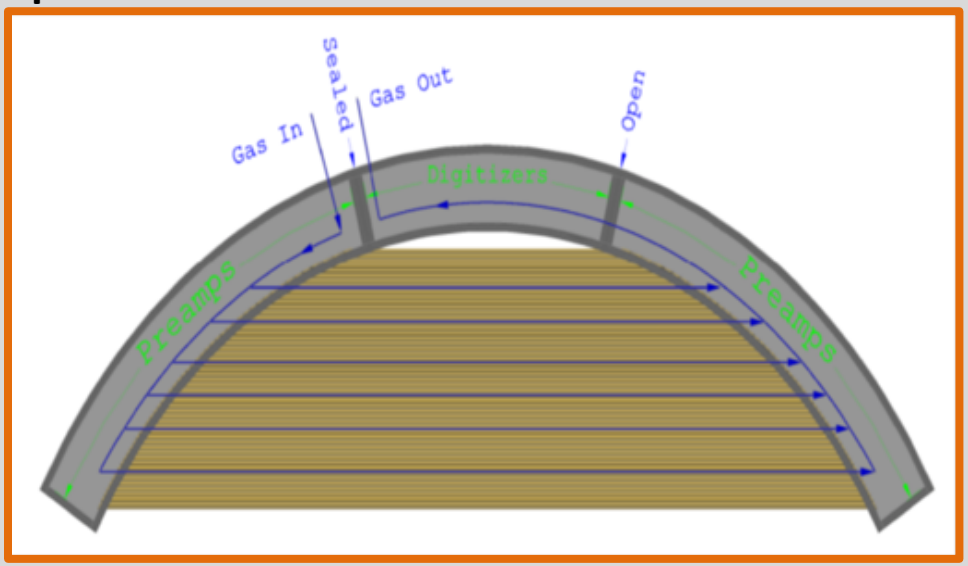
- Muons captured in stopping target foils.
- Conversion electron trajectory measured in tracker, validated in calorimeter.
- Cosmic Ray Veto surrounds Detector Solenoid.

The Mu2e Tracker

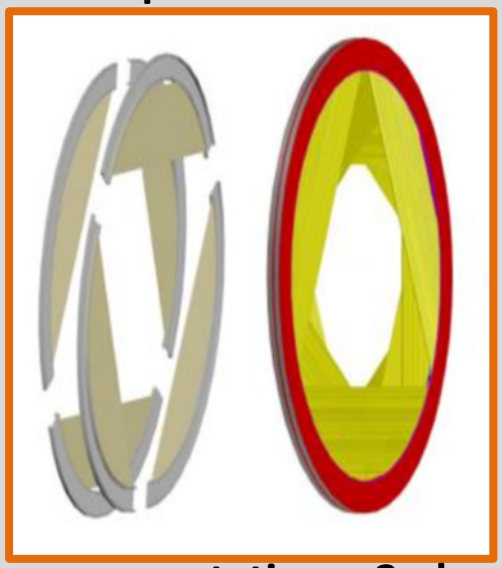
straw tube

- 5 mm diameter straw, spiral wound
- Al, Au-coated, 15 µm Mylar
- 334 – 1174 mm active length
- 80/20 Ar/CO2 with HV < 1500 V
- 100 µm hit resolution

panel = 96 straw tubes



plane = 6 panels



station = 2 planes

The Mu2e Tracker

straw tube

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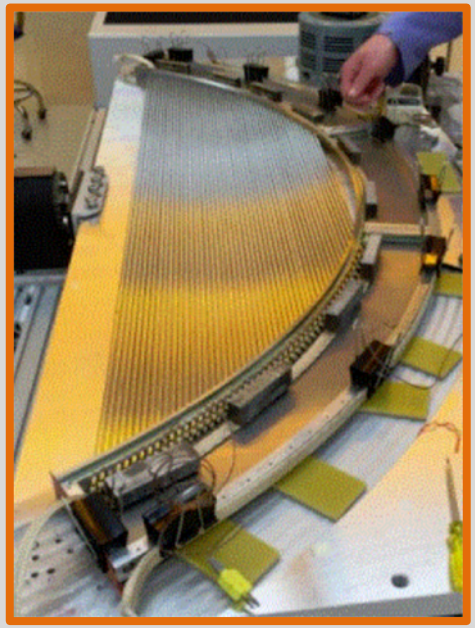
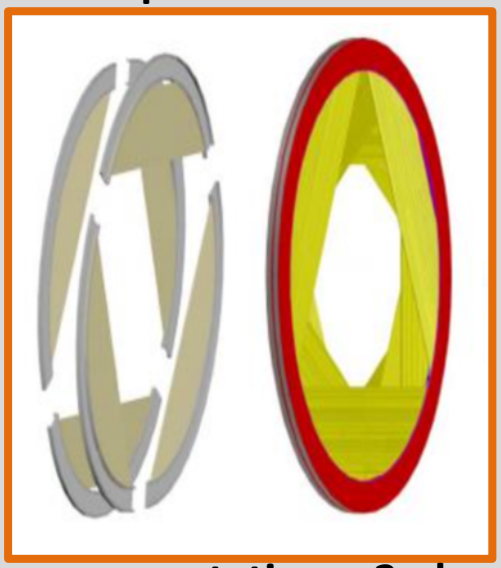
- 334 – 1174 mm active length
- 80/20 Ar/CO2 with HV < 1500 V
- 100 μm hit resolution

panel = 96 straw tubes



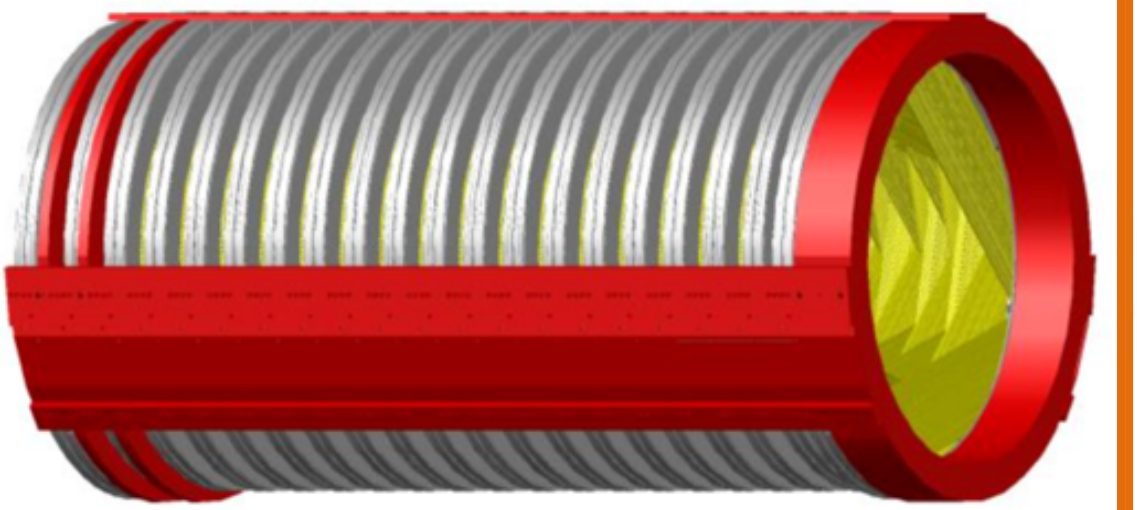
plane = 6 panels

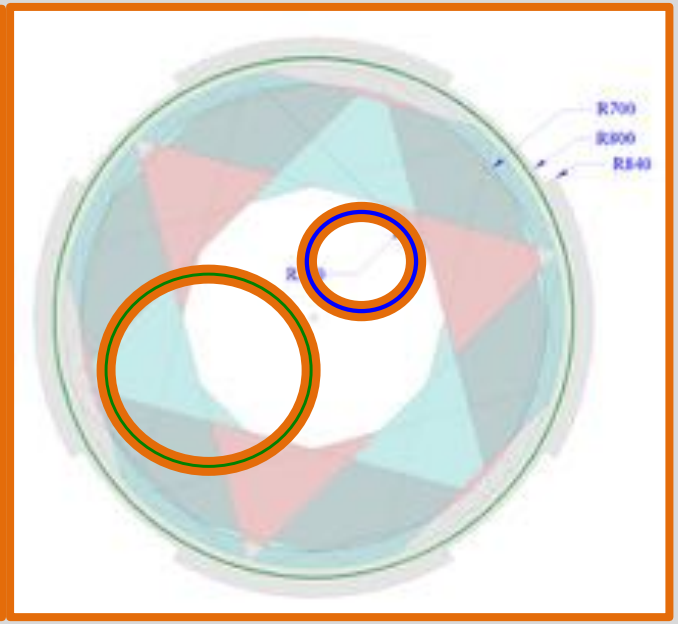


station = 2 planes

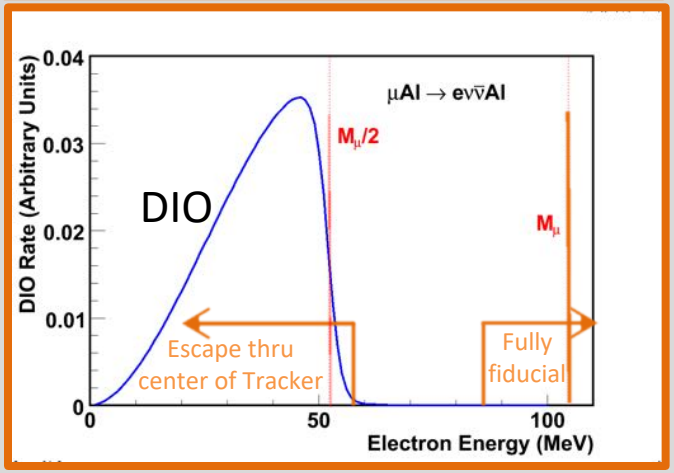
The Mu2e Tracker

detector= 18 stations (3m cylinder)





- Detector is in vacuum and inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum
- Active tracking region from 38 cm to 70 cm
- Services and structure beyond 70 cm



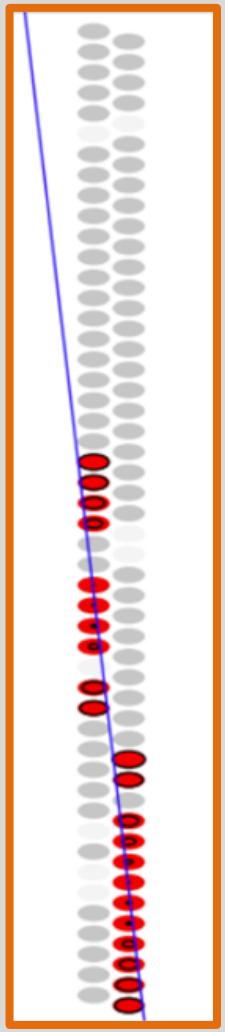
The Mu2e Tracker Status

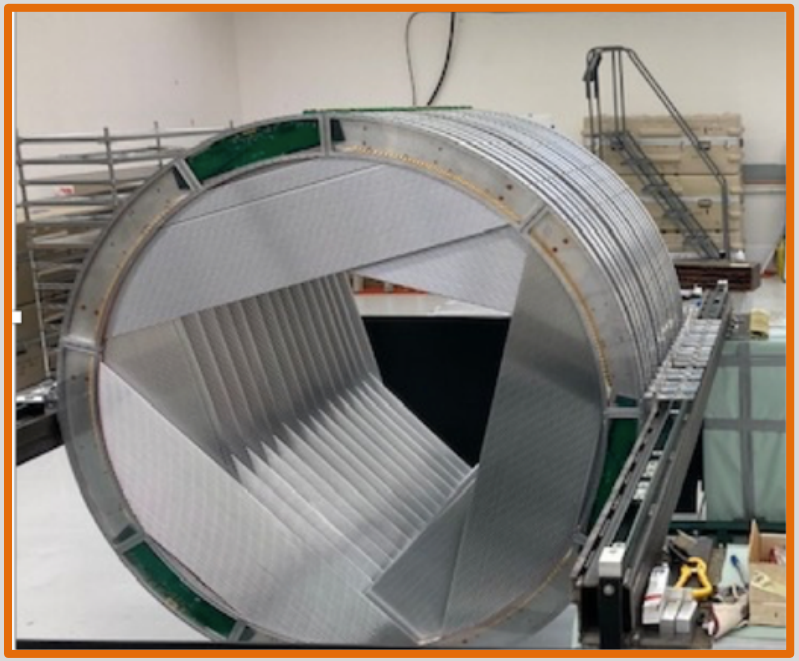
All straws produced.

167 / 216 panels produced.

16 / 36 planes are built.

Cosmic ray tests with a single plane!





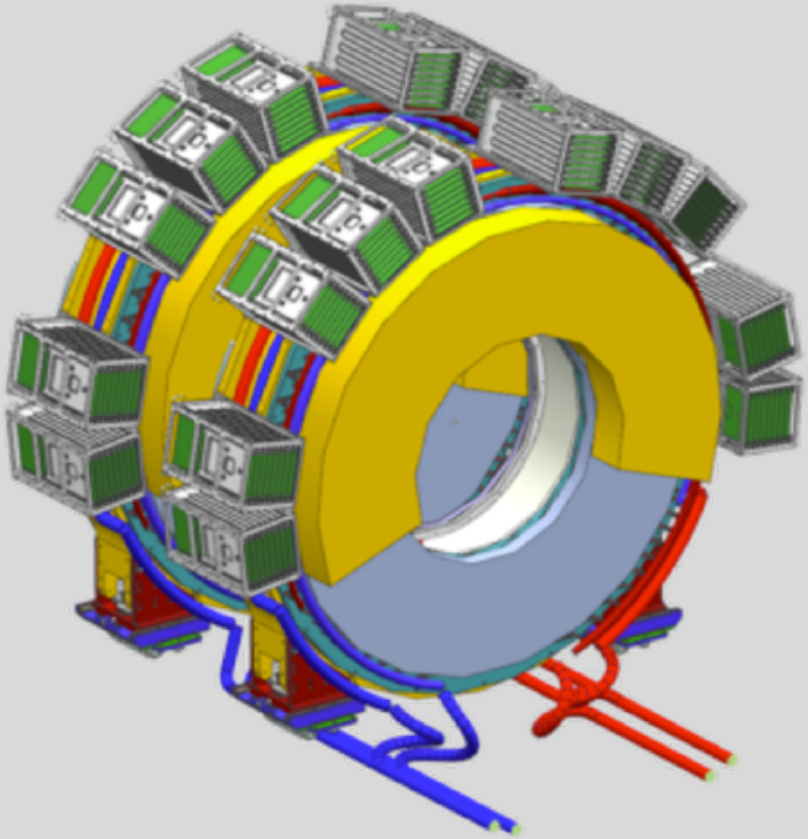
The Mu2e Calorimeter

- Role of calorimeter
  - Particle ID (e vs μ)
  - Cosmic ray rejection
  - Fast/energy - trigger
- Crystal calorimeter
  - Compact
  - Radiation hard
  - Good timing (<1 ns) and energy resolution (5%)
- Will employ 2 disks

  (radius = 36-70 cm)

  ~700 undoped CsI crystals

  Photo-sensors - SiPMs



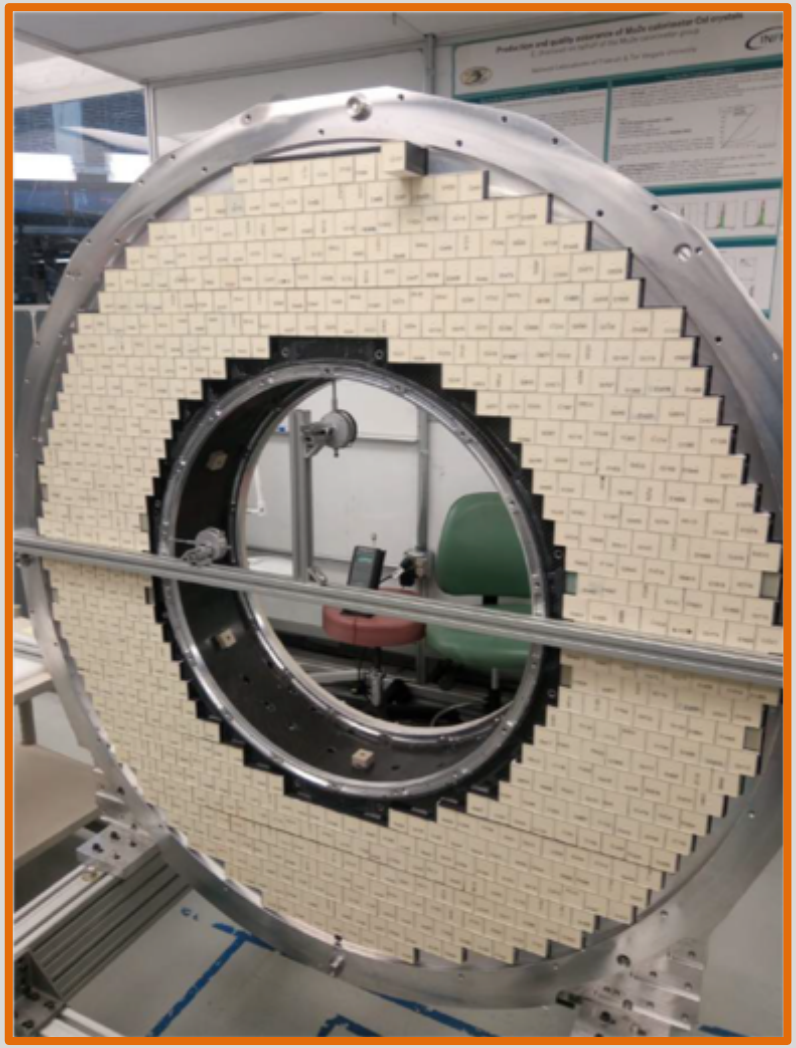
(20 x 3.4 x 3.4 cm3)

Mu2e Calorimeter Status

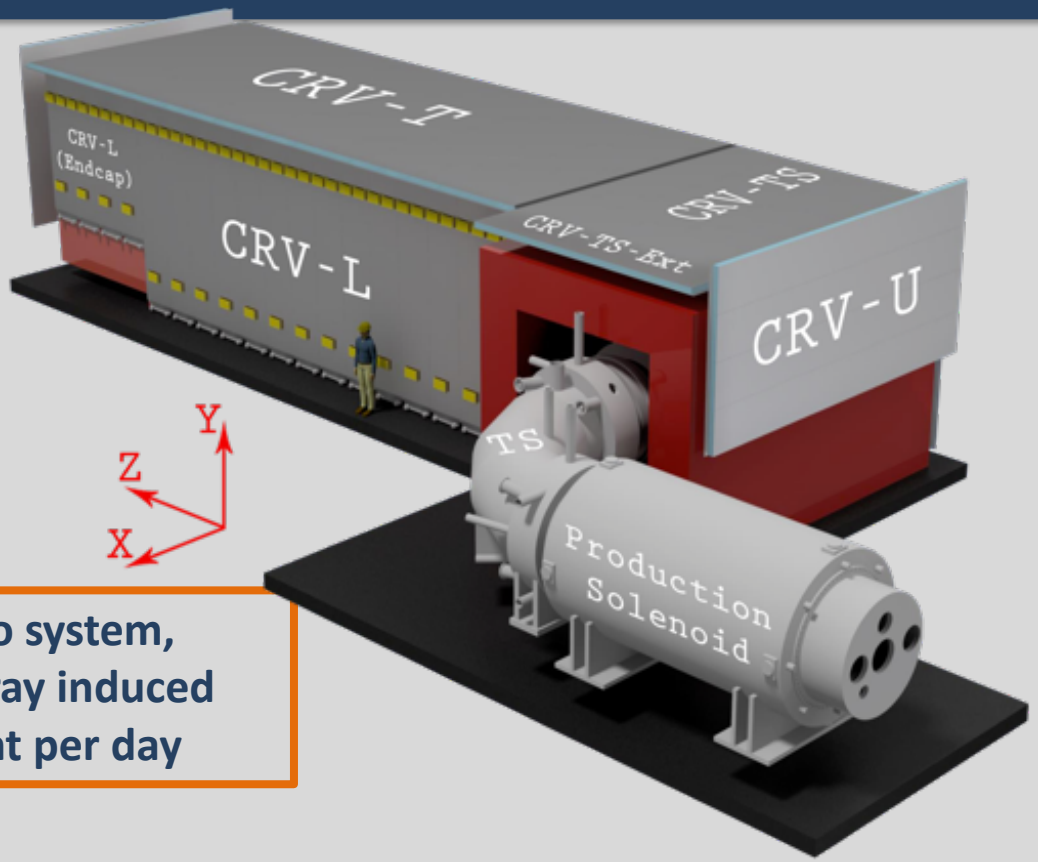
All crystals, SiPMs, and FEEs produced.

All mechanical parts in hand to build the first disk.
→ Finished stacking crystals!

Cosmic ray test underway with subset of crystals.



Mu2e Cosmic-Ray Veto

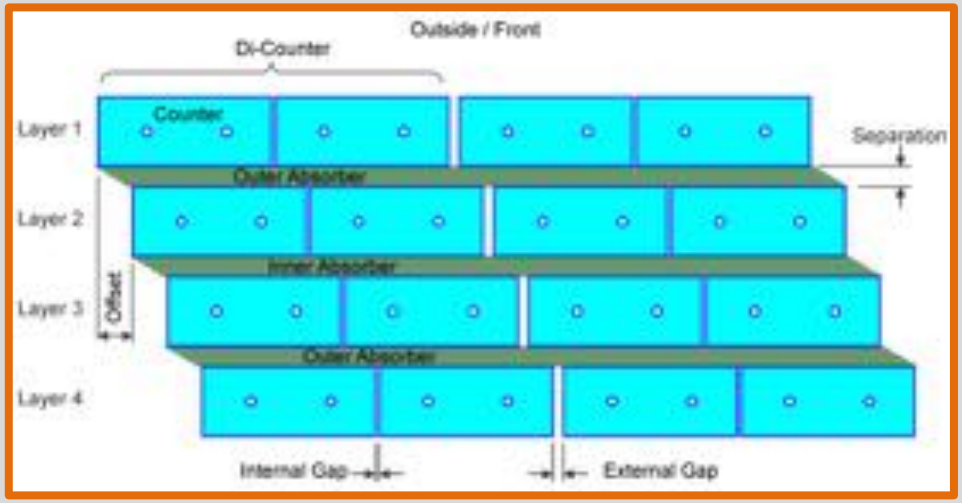


Without the veto system, expect ~1 cosmic-ray induced background event per day

Cosmic ray muons can generate background events via decay, scattering, or material interactions.

Veto system covers entire DS and half TS.

Mu2e Cosmic-Ray Veto



Will use 4 overlapping layers of scintillator bars separated by ~ 10 mm absorber

- Each bar is 5 x 2 x (300 - 660) cm^3
- 2 wavelength shifting fibers / bar
- Read-out both ends of each fiber with SiPM
- Have achieved > 99.4% (per layer) in test beam

The Mu2e CRV Status

2500 / 2700 di-counters produced.

68 / 83 modules produced.

Cosmic ray tests underway at Fermilab.

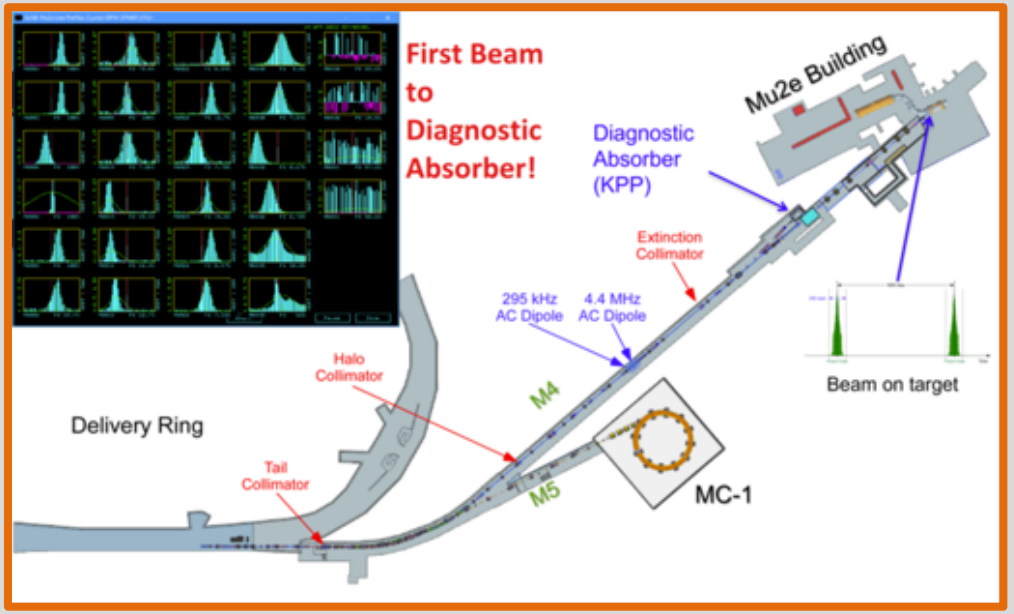
CRV Summer 2022

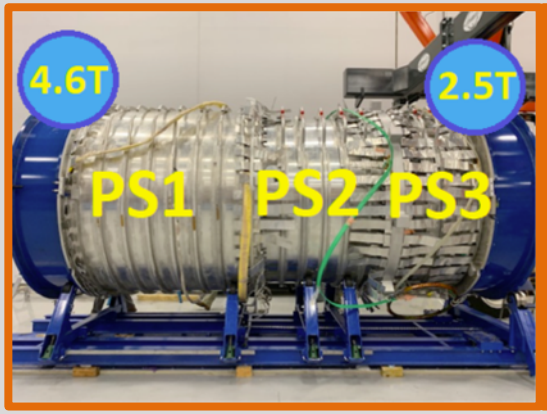
Other Recent Achivements…

Accelerator:
- Recently delivered protons to diagnostic absorber (just upstream of production target).

Solenoids:
- All coils for PS and TS are fabricated.
- Cold mass fabricated for TS.
- Everything else under construction.

Targets:
- Production and stopping targets assembled.





Sensitivity Goal

Current limits: $R_{\mu e} = \frac{\mu^- Au \rightarrow e^- Au}{\mu^- Au \rightarrow \text{capture}} < 7\text{x}10^{-13}$ (SINDRUM II)

Mu2e goal: $R_{\mu e} = \frac{\mu^- Al \rightarrow e^- Al}{\mu^- Al \rightarrow \text{capture}} < 6\text{x}10^{-17}$ (90% c.l.)

X10000 improvement over current best limit!

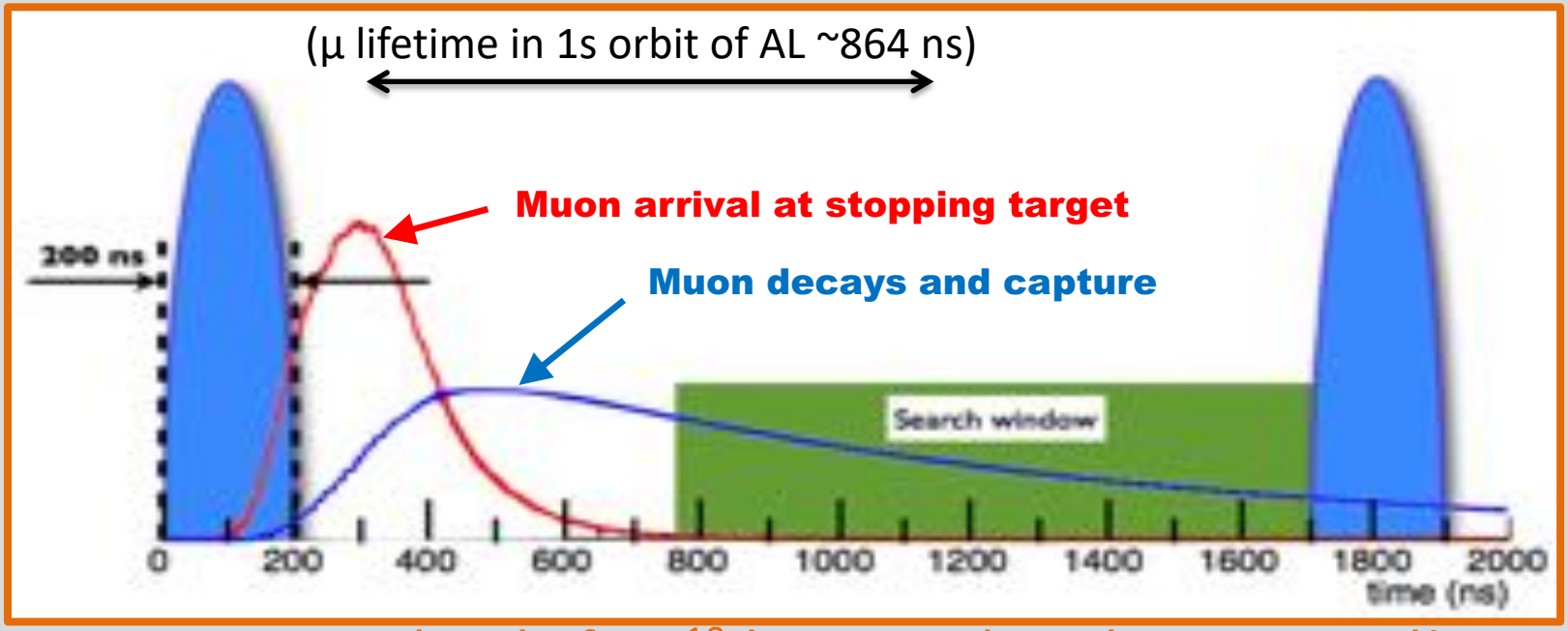
How???

- Improved efficiency for producing and stopping muons
  - Production target in gradient field* (magnetic mirror)
  - Mu2e will stop ~10 billion muons per second!
  - Expect to stop ~20 muons per 10,000 proton on target.
- Reduced backgrounds and detector occupancy due to pulsed beam
- Keep backgrounds small!

* Djilkibaev, Lobashev *et al.*

How to get 4 orders of magnitude

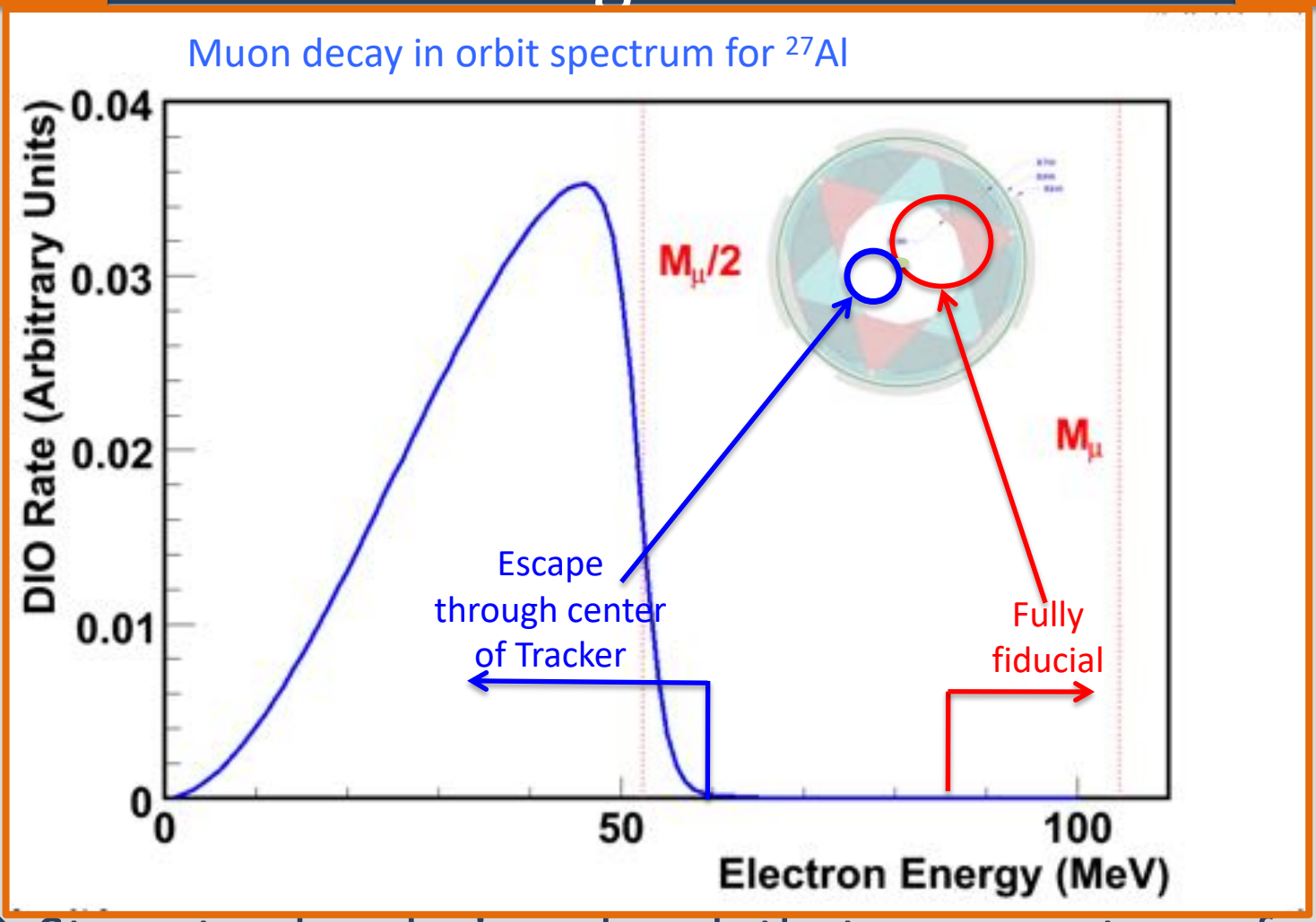
- We have the best accelerator setup in the world for this measurement! Ideal pulse spacing…
- Pulsed beam:
  - beam on target – produce and stop muons (detector blinded)
  - observe stopped muon decays



Extinction level of 10^{-10} between bunches is crucial!

(Removes 'prompt' backgrounds!)

How to get 4 orders of magnitude



→ Straw tracker designed such that no acceptance for lower-energy electrons from muon decay in orbit.

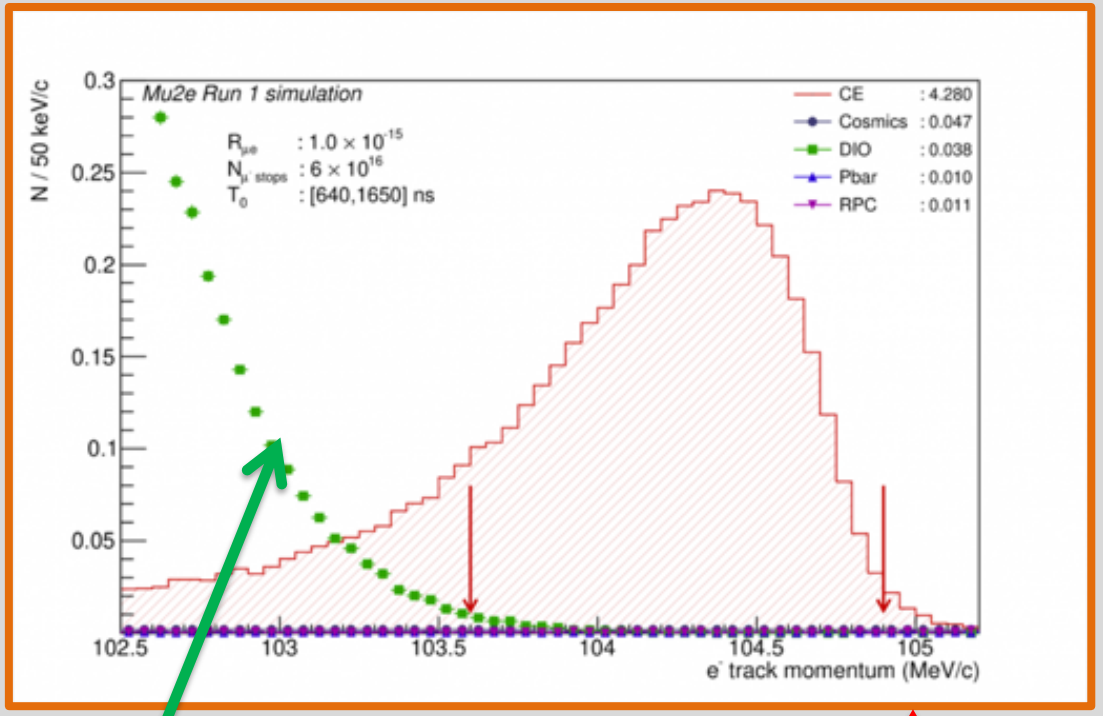
Run 1 Sensitivity Estimate

Recently completed a sensitivity estimate for Run 1:

- 5σ discovery R = 1.1 x 10^{-15}
- 90% CL R < 5.9 x 10^{-16}
- 1000x better than SINDRUM-II
- Paper to be submitted to Universe

Total background:

- 0.11 +- 0.03 (stat.+syst.) events
- cosmics = 0.05 +- 0.01 events
- DIO = 0.04 +- 0.02 events



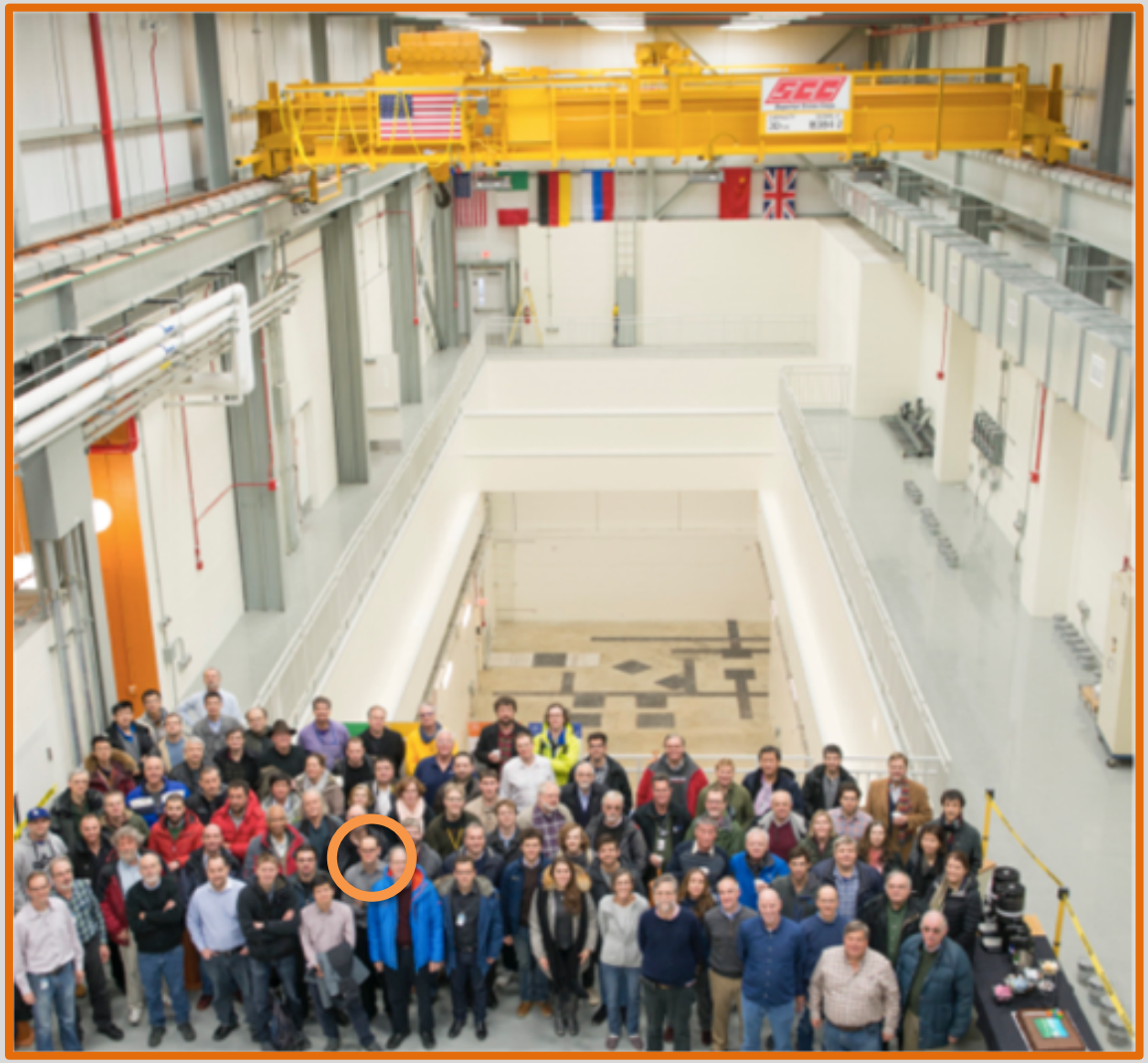
Long DIO tail due to nuclear recoil

Conversion momentum shifted due to material interactions

Mu2e Timeline

- Detector commissioning through late 2024.
- Take Run 1 data in 2025 and 2026 until LBNF/PIP-II shutdown.
- x1000 improvement over SINDRUM-II.
- Resume data collection in 2029 after long shutdown.

The Mu2e Collaboration



~160 People, 32 Institutions, 4 Countries

Additional information

- Technical Design Report

arXiv.org > physics > arXiv:1501.05241

- Experiment web site

http://mu2e.fnal.gov

Summary

- Muon physics may well reveal a sign of exotic physics!
- In Run 1, Mu2e will improve sensitivity by 3 orders-of-magnitude relative to past CLFV searches.
- Mu2e will provide complementary information relative to the LHC and is sensitive to mass scales many orders of magnitude higher than can be directly probed at colliders.
- Much recent progress, and hoping for a discovery in 2026!

Thank you

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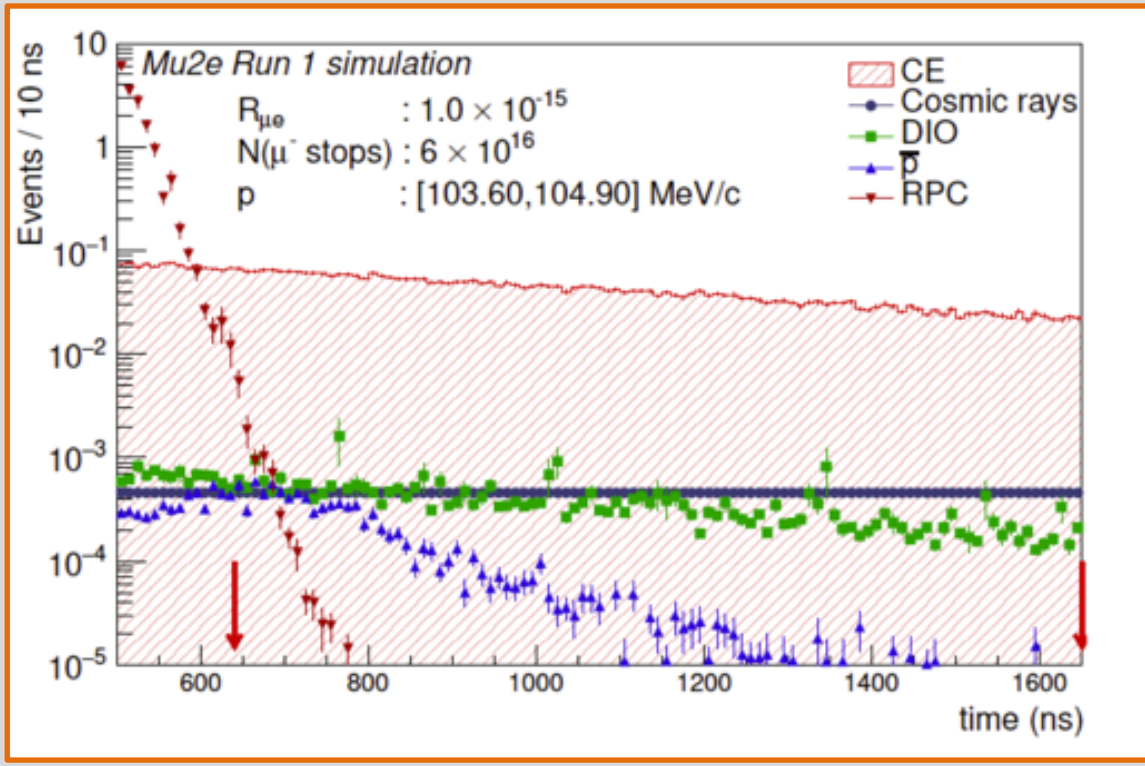


Backgrounds

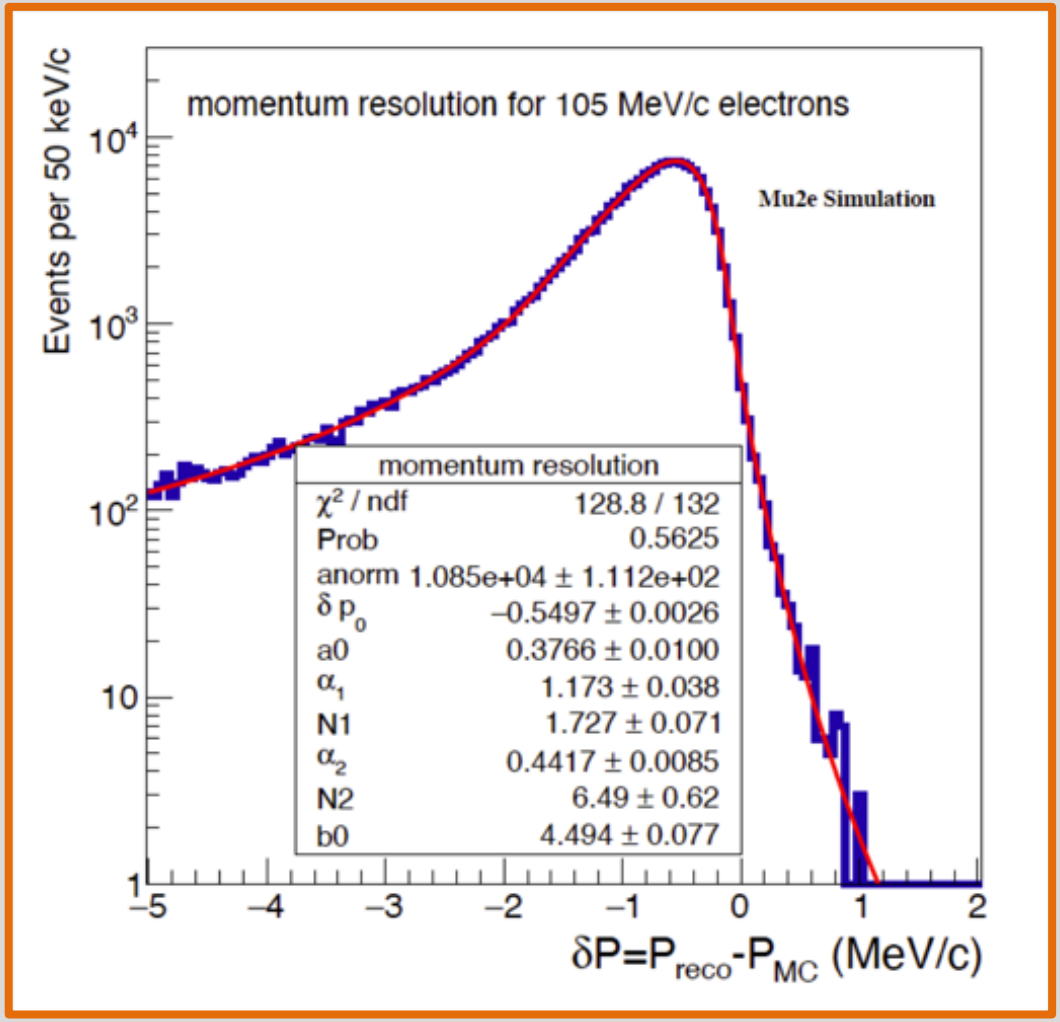
- Background counts expected with 6×10^{16} stopped muons.

Table 8. Background summary and SES using the optimized signal momentum and time window, $103.60 < p < 104.90$ MeV/c and $640 < T_0 < 1650$ ns.

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmics	$0.046 \pm 0.010\ (\text{stat}) \pm 0.009\ (\text{syst})$
DIO	$0.038 \pm 0.002\ (\text{stat})\ ^{+0.025}_{-0.015}\ (\text{syst})$
Antiprotons	$0.010 \pm 0.003\ (\text{stat}) \pm 0.010\ (\text{syst})$
RPC in-time	$0.010 \pm 0.002\ (\text{stat})\ ^{+0.001}_{-0.003}\ (\text{syst})$
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1\ (\text{stat})\ ^{+0.1}_{-0.3}\ (\text{syst})) \times 10^{-3}$
RMC	$< 2.4 \times 10^{-3}$
Decays in flight	$< 2 \times 10^{-3}$
Beam electrons	$< 1 \times 10^{-3}$
Total	0.105 ± 0.032

Tracker Performance

- Meets all physics requirements
- Total efficiency 9.2%
  - mostly acceptance
- Resolution ~120 keV
- Robust against rate increases
- Low end is energy loss (lowers efficiency)
- High end tail smears DIO into signal region



Why this Experiment

It can happen in **many** New Physics scenarios

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

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.

arXiv:0909.1333