Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

The Mu2e Experiment at Fermilab

Jason Bono
Rice University
February 12, 2016

RICE®

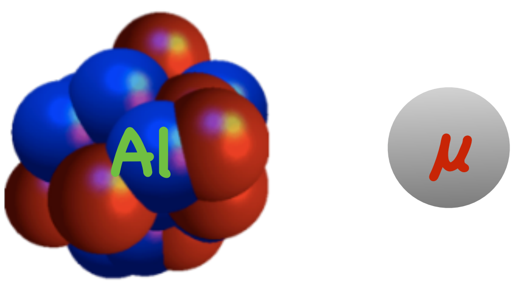
The Mu2e Experiment at a Glance

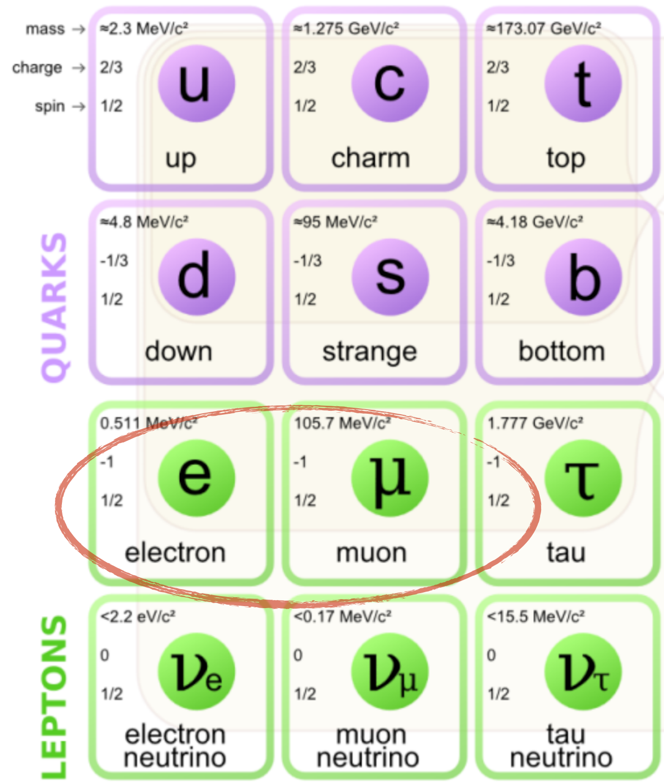
The Mu2e experiment will search for the neutrinoless **conversion** of a muon into an electron within the vicinity of a nucleus, $\mu N \rightarrow eN$.

The Mu2e Experiment at a Glance

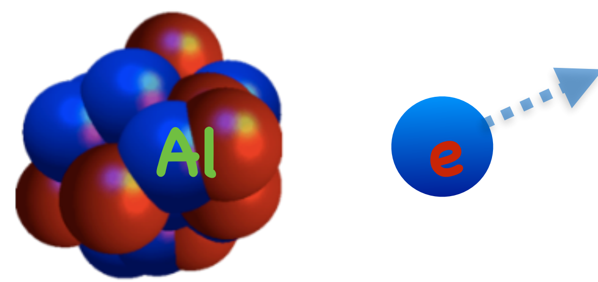
- Recall that the muon and electron are elementary particles known as a leptons
- Aside from leptons, there are also quarks
- The quarks and leptons seem to come in three generations
- The muon can be thought of as a heavy twin to the electron, and the tau heavier still. This is commonly referred to as "generation"

Initial state





Final state



Fermilab

The Mu2e Experiment at a Glance

An empirically founded law called **Lepton Flavor Conservation** says that the total number of leptons in a generation (flavor) can not change.

So, we assign quantum numbers such as "electron number," "muon number," and "tau number" to keep track.

E.g electrons and electron-neutrinos carry $N_e = 1$, anti-muons and anti-muon-neutrinos carry $N_\mu = -1$ and so on...

Disclaimer: The exact language regarding flavor conservation is cumbersome for historical reasons. I've chosen simpler words...

The Mu2e Experiment at a Glance

The law of **Lepton Flavor Conservation** is at the heart of the Mu2e experiment

The Mu2e Experiment at a Glance

The law of **Lepton Flavor Conservation** is at the heart of the Mu2e experiment

$\mu N \rightarrow eN$ would break it

The Mu2e Experiment at a Glance

The law of **Lepton Flavor Conservation** is at the heart of the Mu2e experiment

$\mu N \rightarrow eN$ would break it

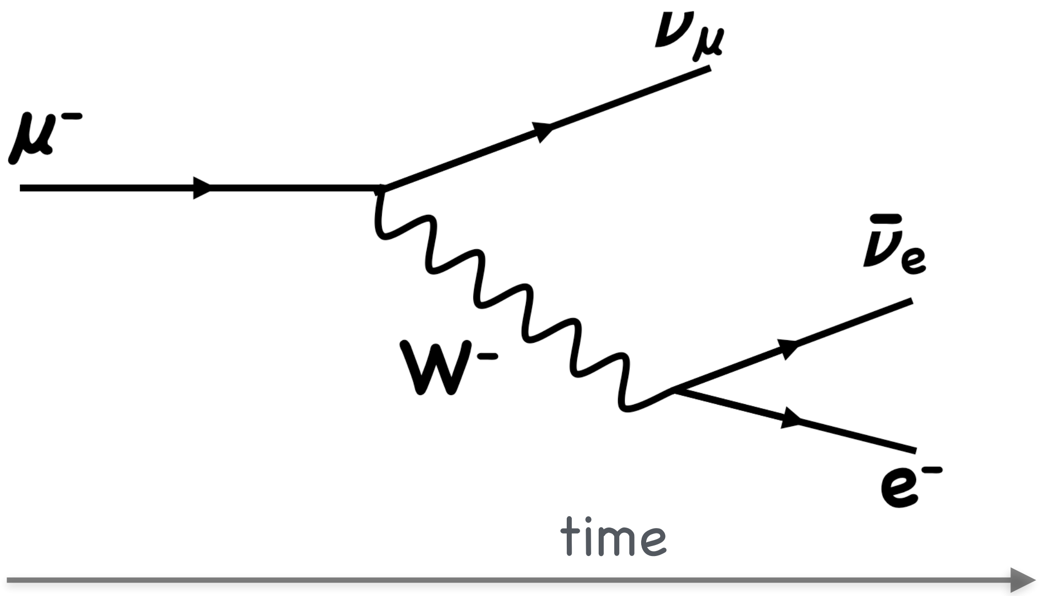
In the law books, this is known as

charged lepton flavor violation

Something that has never been observed!

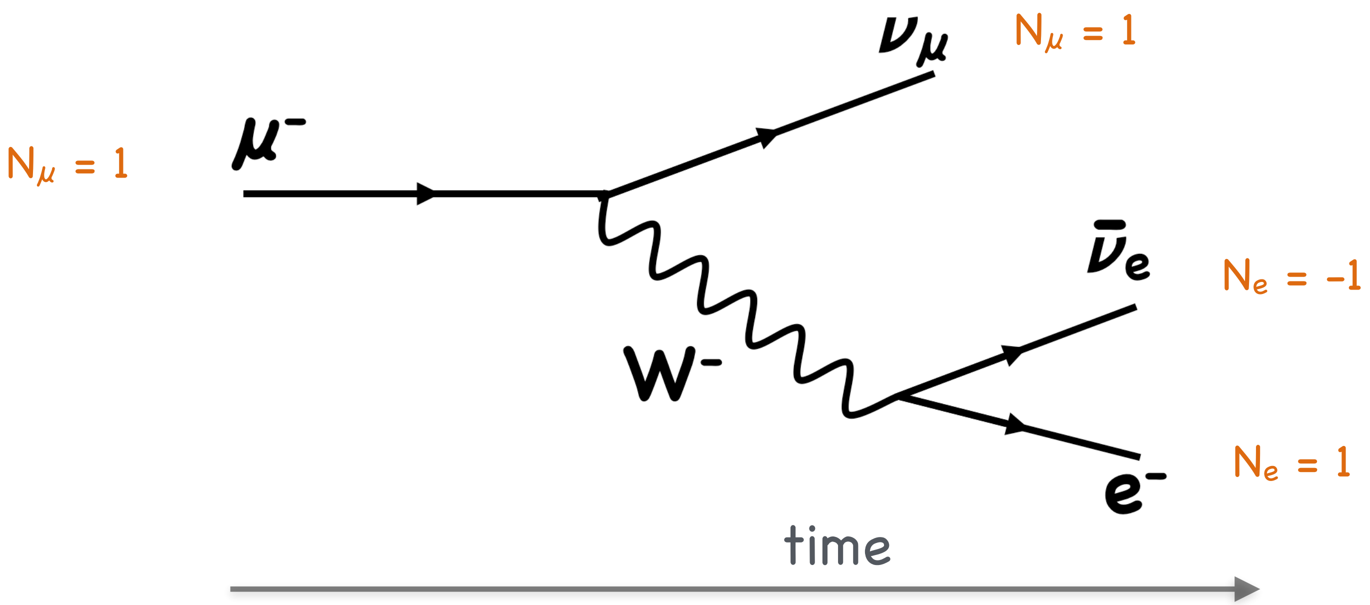
What About Ordinary Muon Decay?

A free muon will typically undergo what is known as the "Michel Decay" ~2.2 μs after creation



What About Ordinary Muon Decay?

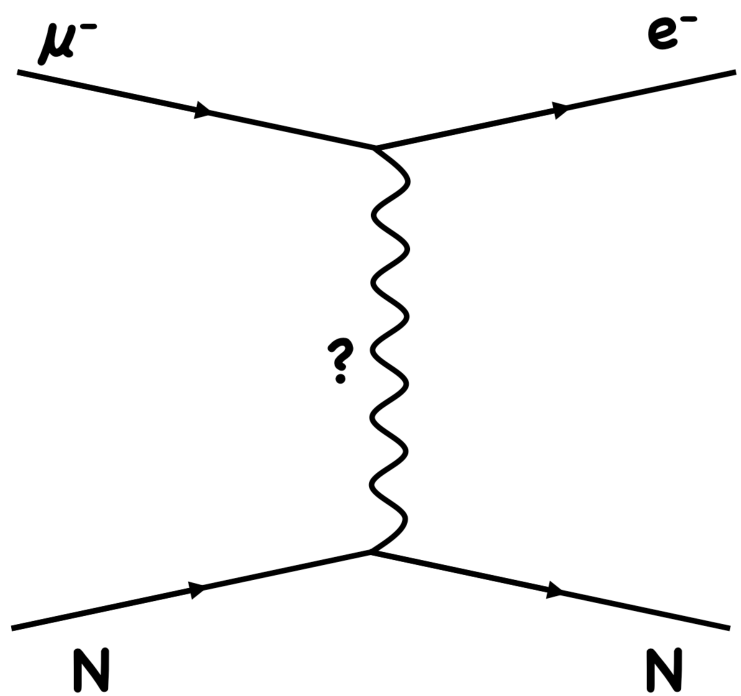
A free muon will typically undergo what is known as the "Michel Decay" ~2.2 μs after creation



This decay conserves electron number (Ne=0) and muon number ($N\mu$ = 1)

The Mu2e Experiment at a Glance

But mu2e wants to see if this can happen:



? = New Physics

N_e = 0
N_μ = 1

Charged Lepton Flavor Violation

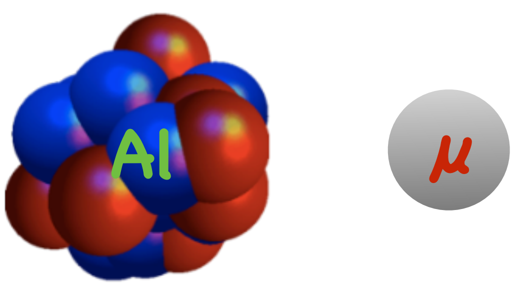
N_e = 1
N_μ = 0

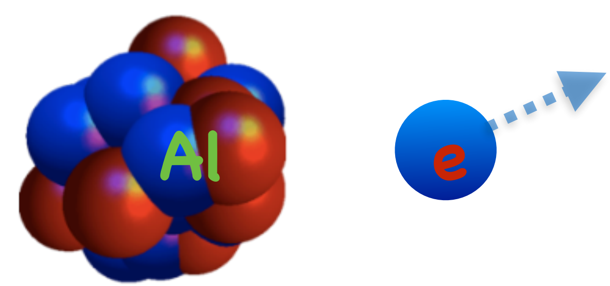
The Mu2e Experiment at a Glance

- The $\mu N \rightarrow eN$ conversion violates charged lepton flavor conservation (CLFV)
- CLFV is not just empirically forbidden, it's **forbidden** in the **Standard Model** of particle physics. More on this later…
- Although, there is no fundamental reason (i.e. corresponding symmetry) for this law
- However, despite nearly **eight decades of searching** since the discovery of the muon, no one has ever observed a flavor violating reaction for charged leptons

The Mu2e Experiment at a Glance

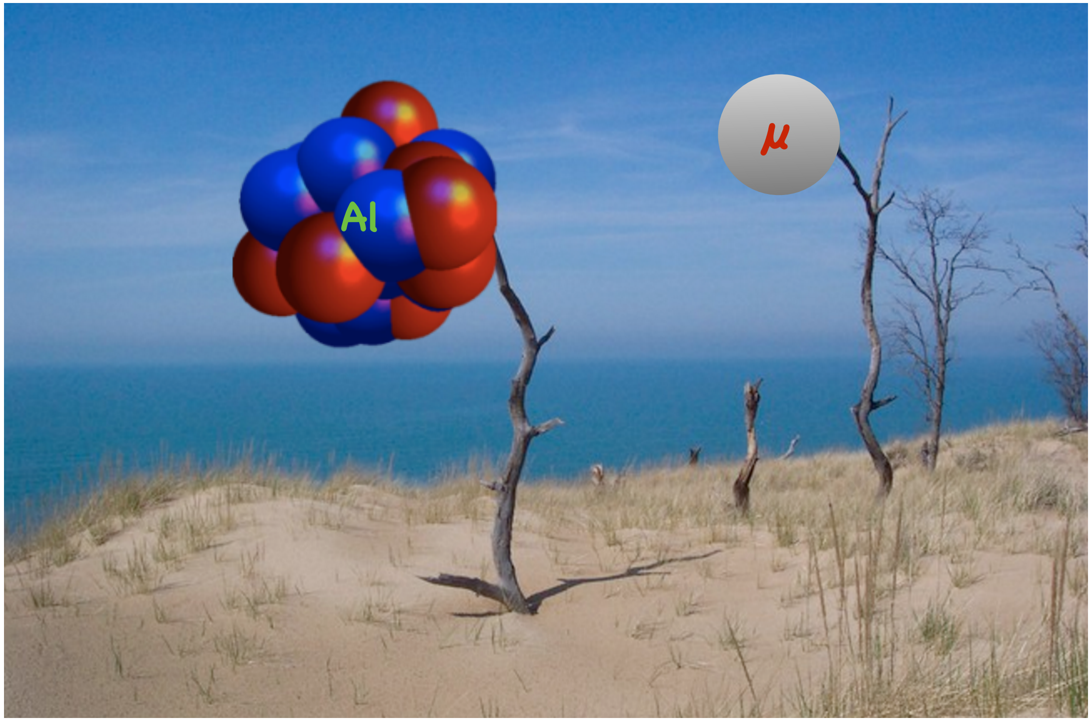
The goal of Mu2e is to **discover CLFV** and **New Physics** by expanding the current best sensitivity limit by a **factor of 10,000**





The Mu2e Experiment at a Glance

- Mu2e will achieve its goal by producing a **quintillion muonic atoms** and looking for the signature of their conversion, a mono-energetic signal of electrons with the rest energy of a muon (around 105 MeV)
- One quintillion = **10^{18}**
- That's about the number of grains of sand on all the world's beaches…



The Mu2e Experiment at a Glance

A signal would be **unambiguous evidence of physics beyond the Standard Model,** something that has also been elusive thus far!

The Mu2e Experiment at a Glance

"Beyond the Standard Model physics" includes **new** fundamental interactions, charges or quantum numbers, degrees of freedom (e.g. extra dimensions) and symmetries!

The Mu2e Experiment at a Glance

- Most extensions to the standard model include new mechanisms for CLFV processes that yield **measurable** rates
  - » In fact, the non-observation of CLFV has already imposed strong restrictions on possible new physics phenomena

- Many of the **leading extensions** to the standard model predict rates for $\mu N \rightarrow eN$ conversion to be **within Mu2e's discovery sensitivity** but out of reach of all previous experiments!

The Mu2e Experiment at a Glance

So, Mu2e will have **unprecedented sensitivity** to a multitude of **New Physics** phenomena with mass scales up to **10,000 TeV**, which is far beyond the mass scales that are accessible at the LHC or future colliders

The Mu2e Experiment at a Glance

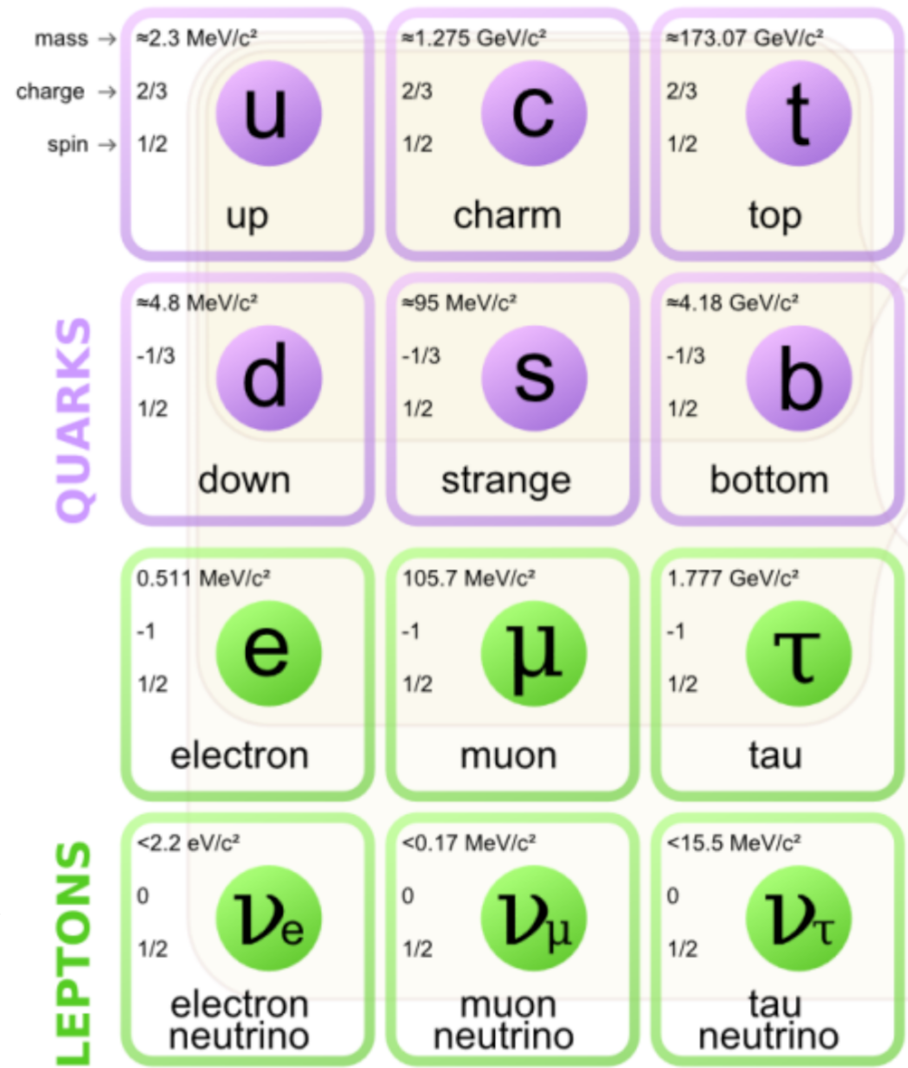
If the experimentalist's goal is to prove as many theorists wrong as possible, Mu2e is positioned to be successful, **regardless** of the outcome!

Outline of Topics

1. The Standard Model (SM) of particle physics
   - What is it?
   - What are its shortcomings?
   - Looking beyond the SM for "New Physics"
2. Charged Lepton Flavor Violation (CLFV)
   - Why search for CLFV?
   - Why $\mu N \rightarrow eN$?
   - Mu2e's place in the history of CLFV searches
3. A closer look at Mu2e
   - What exactly are we measuring?
   - What are the backgrounds?
   - Mu2e experimental design

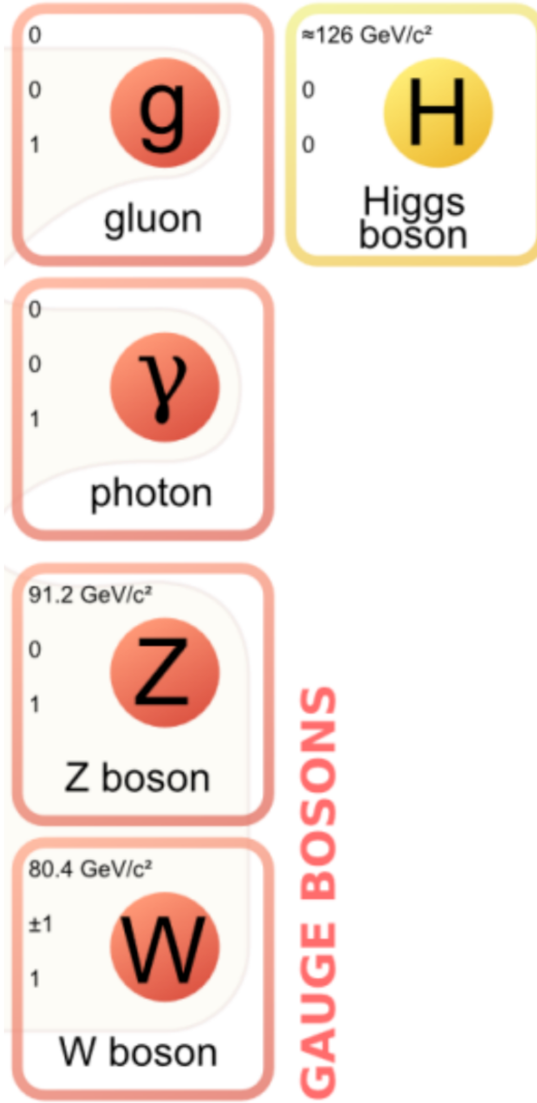
The Standard Model of Particle Physics

- The SM incorporates our current understanding of **particles** and **forces**, excluding gravity
- Within the SM framework, all matter is ultimately composed of **quarks** and **leptons,** which together form a family of **12** spin-1/2 **fermions**
- Each particle is endowed with intrinsic properties such as **mass**, **electric charge**, **color charge**, **spin**, **baryon number**, **lepton number** and **flavor** which determine their dynamical behavior

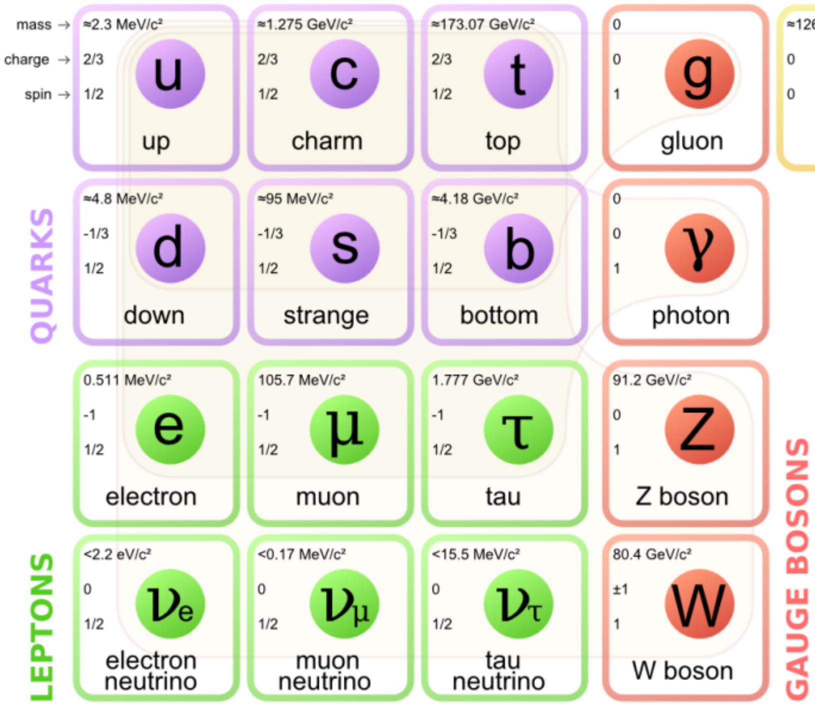


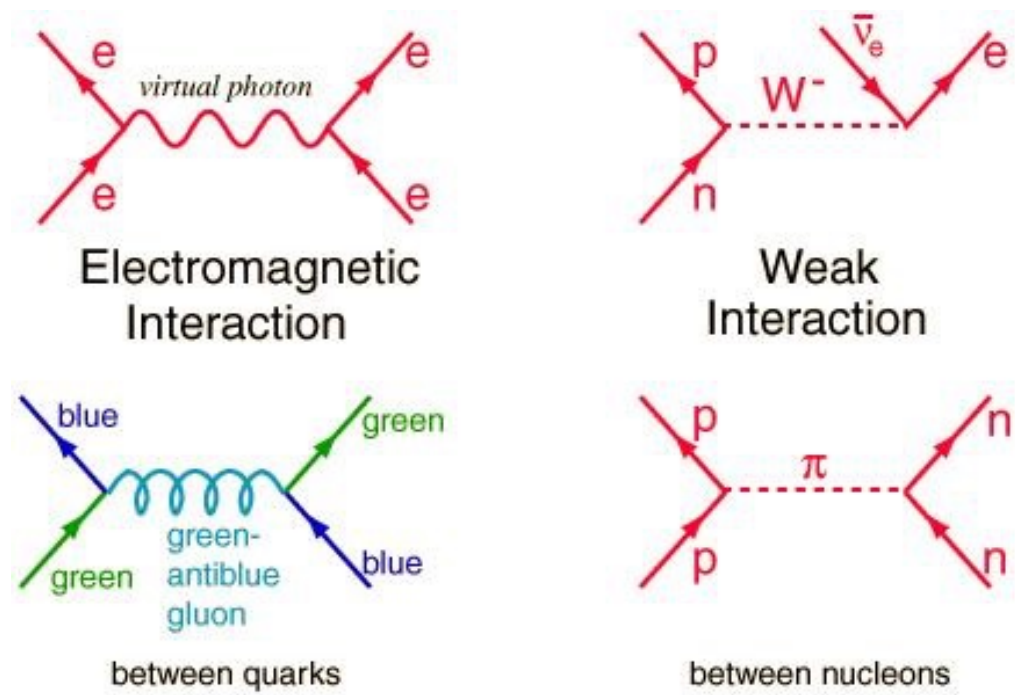
The Standard Model of Particle Physics

- The dynamics of quarks and leptons arises from a few **fundamental interactions** (forces) which are mediated by spin-1 **gauge bosons**:
  - gluons (strong force)
  - photon (electromagnetic force)
  - W/Z bosons (weak force)
- Bosons & fermions acquire a mass via the Higgs mechanism
- The gluon & photon remain massless
- We don't understand neutrino mass generation!



The Standard Model of Particle Physics





Strong Interaction

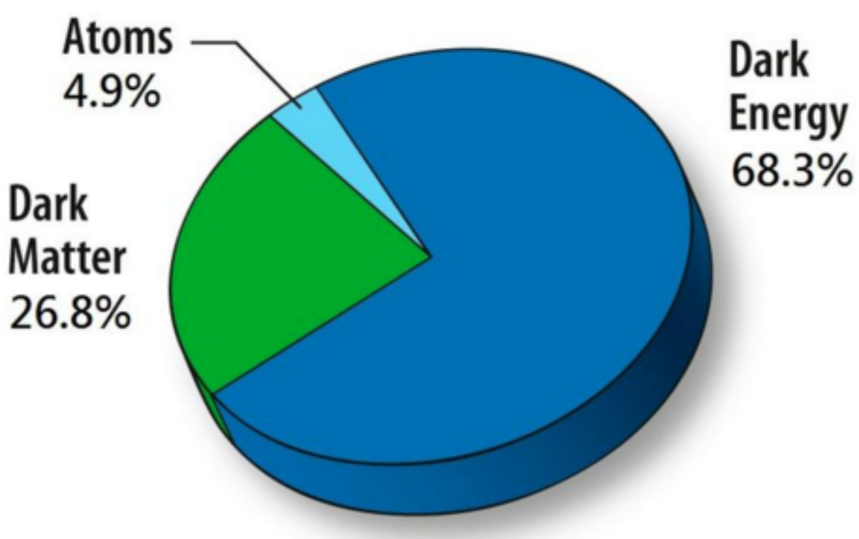
Problems With the Standard Model

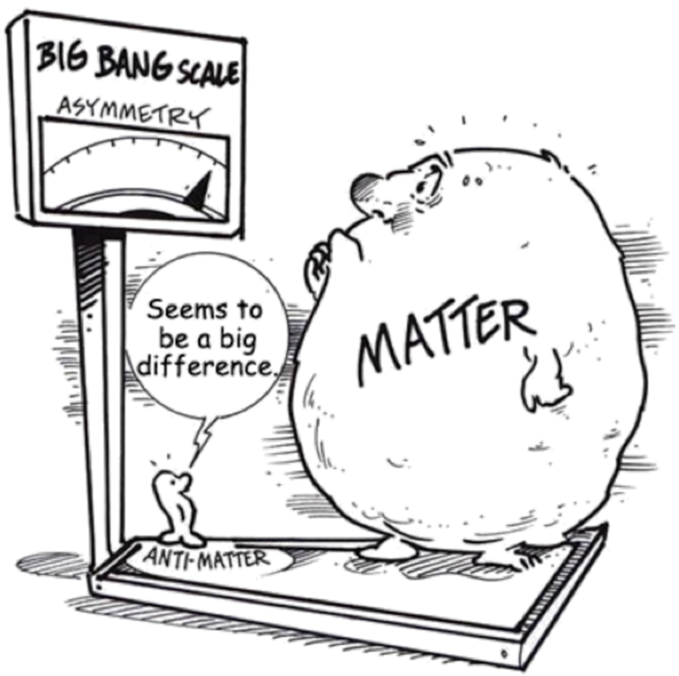
- To the extent we have been able to probe thus far, the SM describes the basic structure of matter and forces with remarkable precision
- However, the SM leaves some **big questions** unanswered
  - There are "aesthetic" problems **within** the SM itself
  - There are **cosmological observations** that the SM should, but can't explain

Problems With the Standard Model

The SM fails to explain:

- Gravity
- The prevalence of matter over anti-matter
- Dark matter
- The acceleration of cosmic expansion (dark energy)





Aesthetic Problems Within Standard Model

Aesthetic problems with the SM relate to questions including:

- Why are there so many fundamental particles?
- Why do they have different masses?
- Why three generations?
- Why so many fundamental constants?
- etc…

These types of problems don't prove that a theory is incorrect, but nevertheless suggest that a piece of the story is missing.

There is something deeper going on…

Looking Beyond The Standard Model

Despite the aforementioned discomforts with the SM and decades of searching, we have never seen an unambiguous signal of physics beyond (it's very successful).

Experimentally speaking, how are we looking to move beyond the SM? The same way we put it together!

1. Direct searches at colliders
   - Compelling, but these can only probe mass scales up to a few TeV
   - The Higgs was the last "sure bet", the energy scale of the next discovery is unknown

2. Indirect searches that probe quantum effects
   - These use low energy, intense sources with ultra-sensitive detectors and have the advantage of probing mass scales far greater than those accessible at colliders

3. Astrophysical searches
   - These use sources of astrophysical origin to study elementary particles

These efforts are complementary and we need all three!

Looking Beyond The Standard Model

Despite the aforementioned discomforts with the SM and decades of searching, we have never seen an unambiguous signal of physics beyond (it's very successful).

Experimentally speaking, how are we looking to move beyond the SM? The same way we put it together!

1. Direct searches at colliders
   - Compelling, but these can only probe mass scales up to a few TeV
   - The Higgs was the last "sure bet", the energy scale of the next discovery is unknown
2. Indirect searches that probe quantum effects
   - These use low energy, intense sources with ultra-sensitive detectors and have the advantage of probing mass scales far greater than those accessible at colliders
3. Astrophysical searches
   - These use sources of astrophysical origin to study elementary particles

These efforts are complementary and we need all three!

Outline of Topics

1. ~~The Standard Model (SM) of particle physics~~
    - ~~What is it?~~
    - ~~What's the matter with it?~~
    - ~~Looking beyond the SM for "New Physics"~~
2. Charged Lepton Flavor Violation (CLFV)
    - Why search for CLFV?
    - Why $\mu N \rightarrow eN$?
    - Mu2e's place in the history of CLFV searches
3. A closer look at Mu2e
    - What exactly are we measuring?
    - What are the backgrounds?
    - Mu2e experimental design

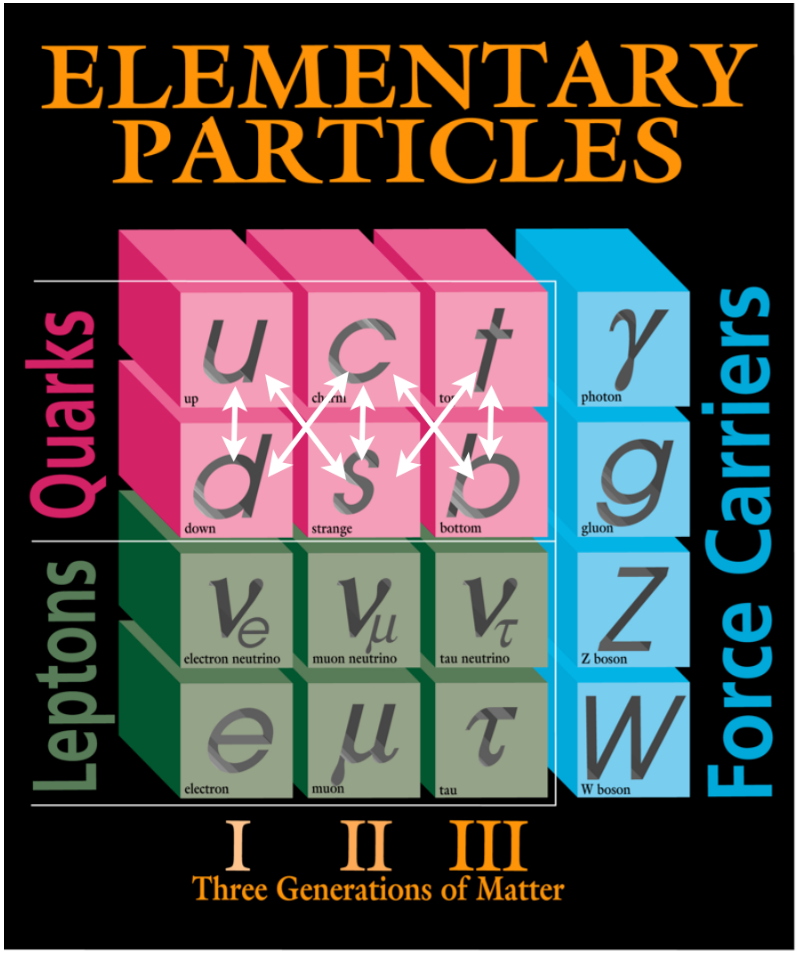
The Muon

Ever since the 1937 discovery of the muon by Anderson and Neddermeyer, physicists have been trying to understand its deeper relation to the electron. Rabi summed it nicely…

Image Credit:
Roni Harnik

Flavor Violation

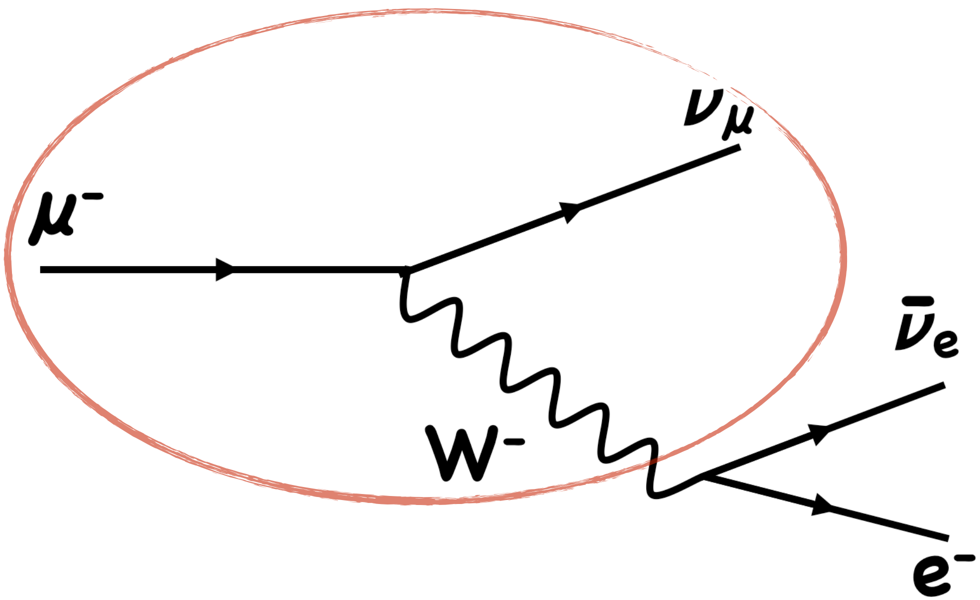
- As it turns out, flavor violation happens among the quarks
  - » They change type (mix) via the W boson

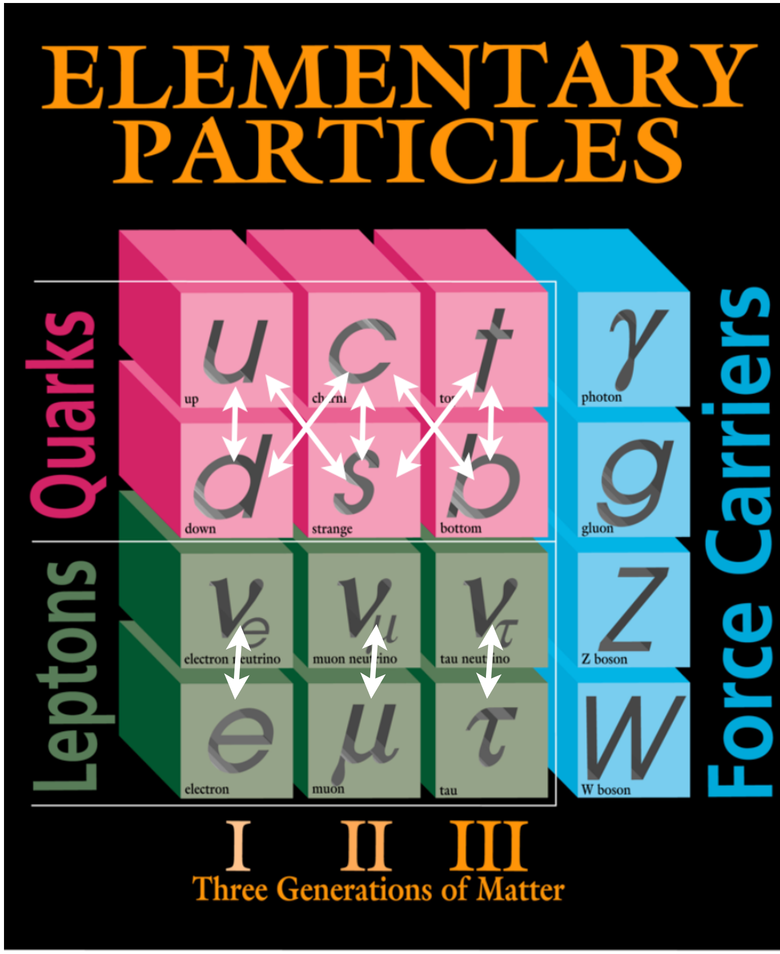


Fermilab 95-759

Flavor Violation

- As it turns out, flavor violation happens among the quarks
  - » They change type (mix) via the W boson
- Neutrinos can change into their charged partners (and vice versa)

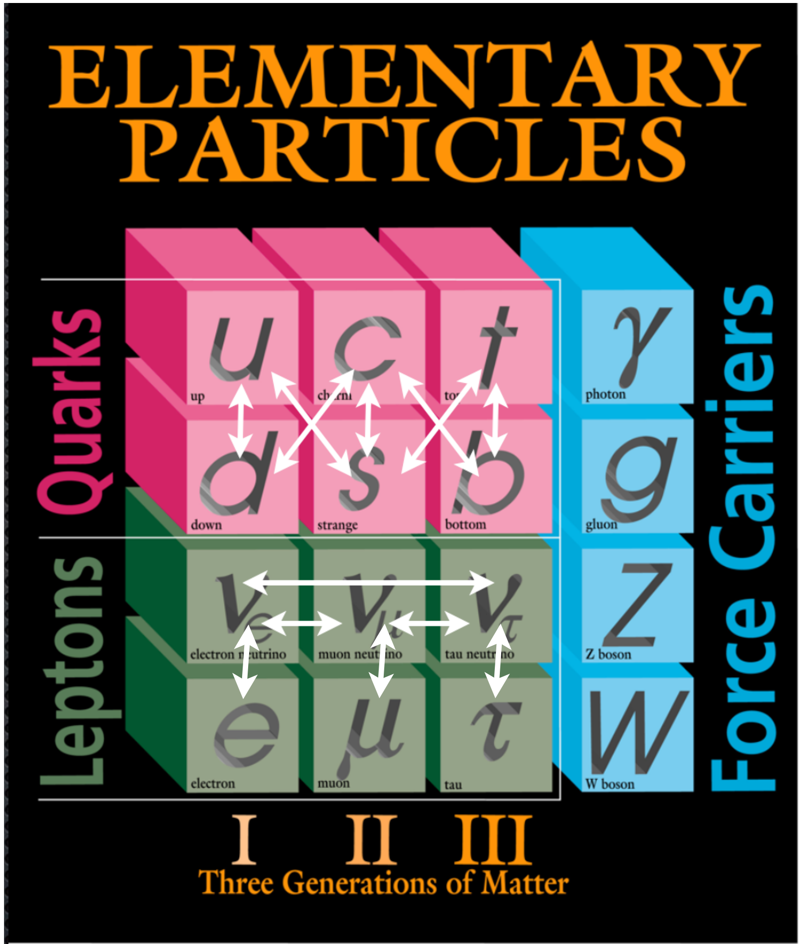




Fermilab 95-759

Flavor Violation

- As it turns out, flavor violation happens among the quarks
  - » They change type (mix) via the W boson
- Neutrinos can change into their charged partners (and vice versa)
- And the neutrinos also mix!



Fermilab 95-759

Rabi's question is as relevant as ever!

What is happening with the **charged** leptons?

CLFV in the Standard Model

A clarification

Neutrinos are massless in the SM and Strictly speaking, Lepton Flavor Violation is forbidden

However…

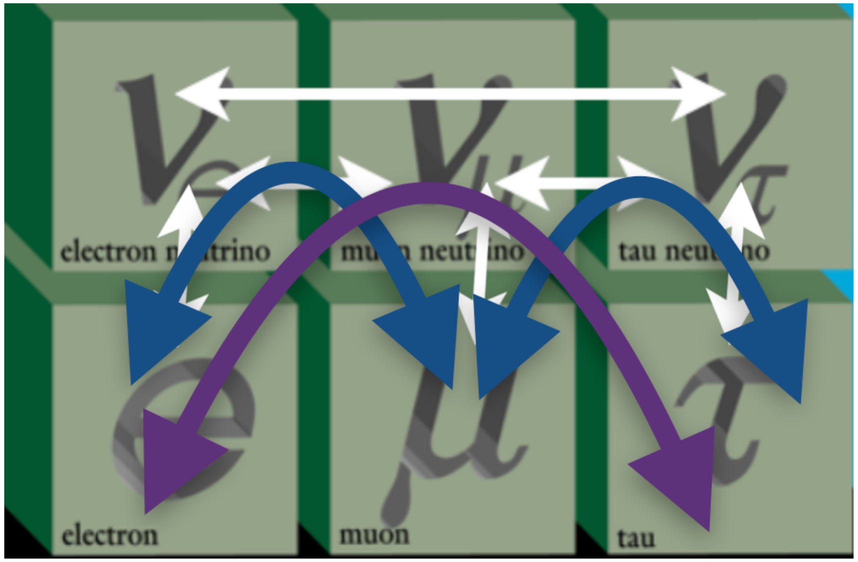
CLFV in the Standard Model

The observation of neutrino oscillations implies they have mass, which the SM can include with minimal extension

But it also implies…

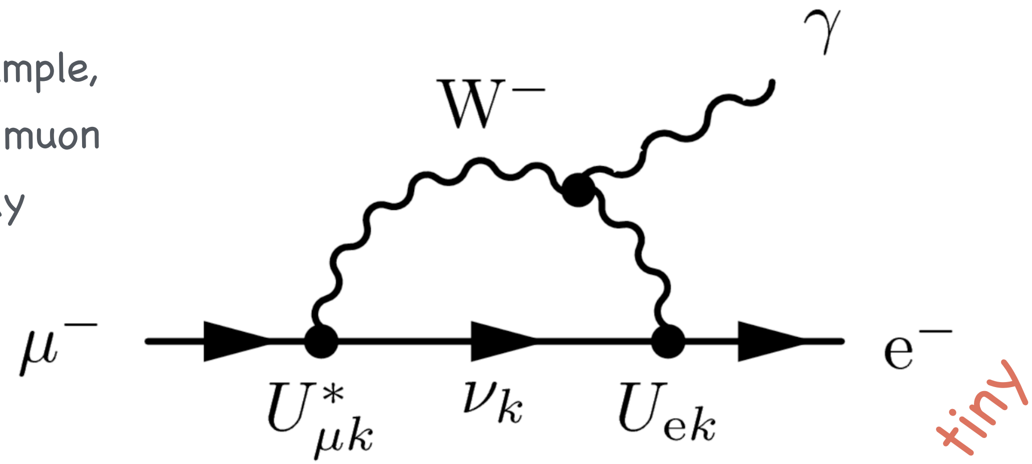
CLFV in the Standard Model

CLFV Must Occur!



CLFV in the Standard Model

CLFV example, radiative muon decay



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

tiny

- The bad news: We will never observe this
- The good news: We will never observe this!
  - Any signal is unambiguous evidence of physics beyond the SM!
    - » Provided experimental backgrounds are accounted for

Searches for CLFV

- Searches for CLFV are motivated by Rabi's question and by the prospects of discovering (or excluding) new physics phenomena
- Because muons are relatively easy to produce and have a long lifetime (as opposed to the τ), rare muon processes offer the best combination of New Physics reach and experimental sensitivity

Searches for CLFV

- Searches for CLFV are motivated by Rabi's question and by the prospects of discovering (or excluding) new physics phenomena

- Because muons are relatively easy to produce and have a long lifetime (as opposed to the τ), rare muon processes offer the best combination of New Physics reach and experimental sensitivity

$$\mu^{\pm} \rightarrow e^{\pm}\gamma$$

MEG @ PSI

$$\mu^{-} A(Z,N) \rightarrow e^{-} A(Z,N)$$

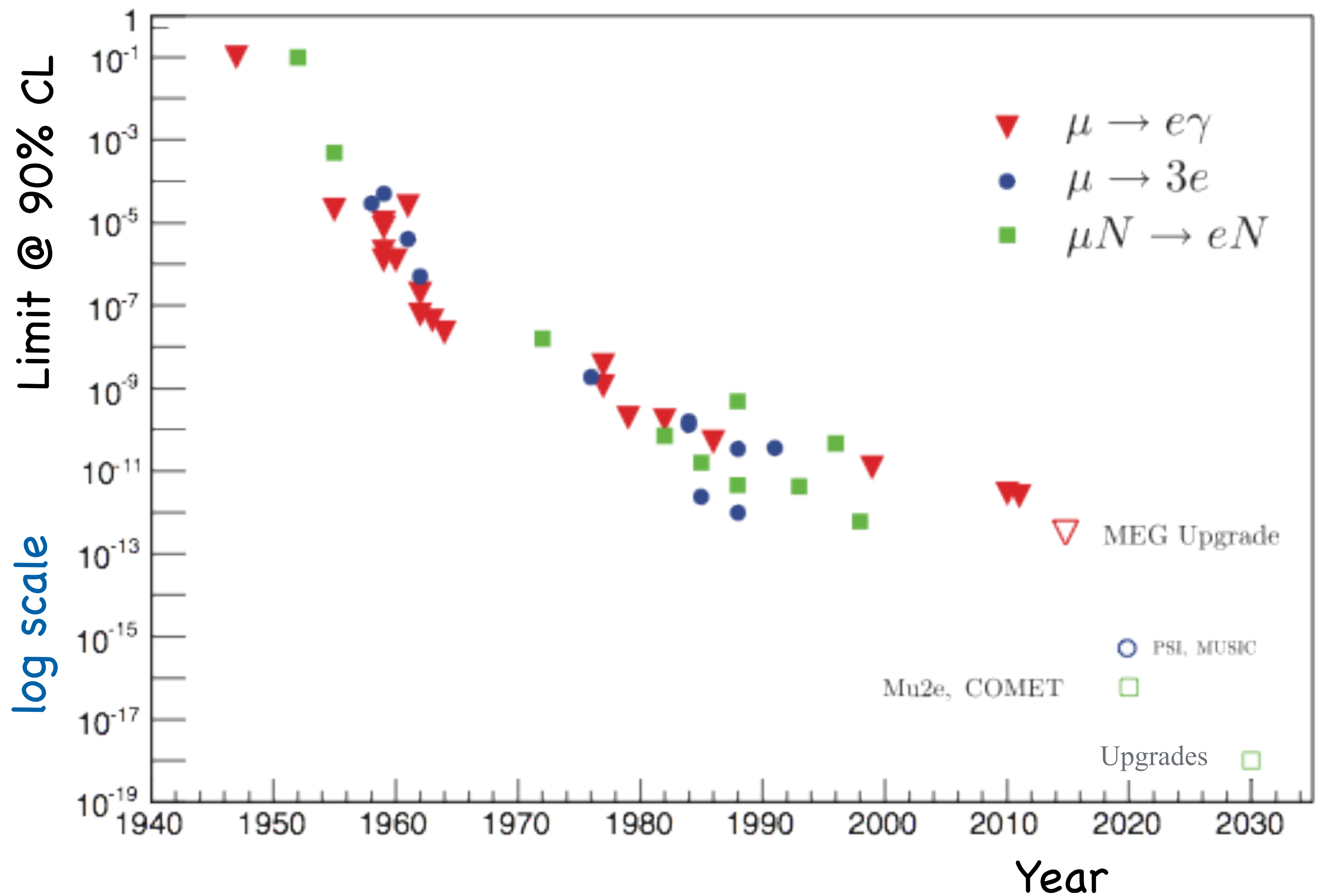
Mu2e @ Fermilab,

COMET @ JPARC

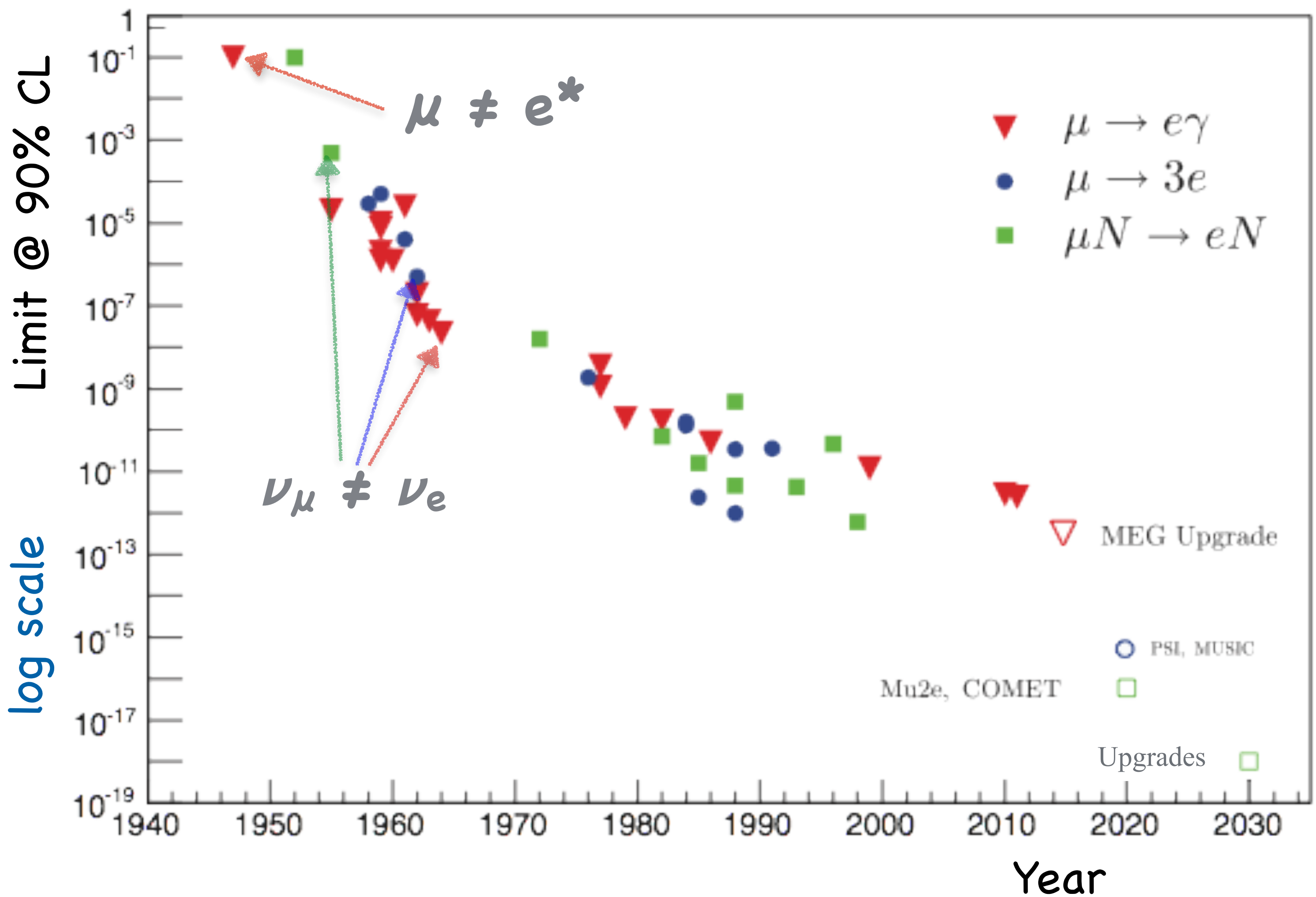
$$\mu^{\pm} \rightarrow e^{\pm}e^{+}e^{-}$$

Mu3e @ PSI

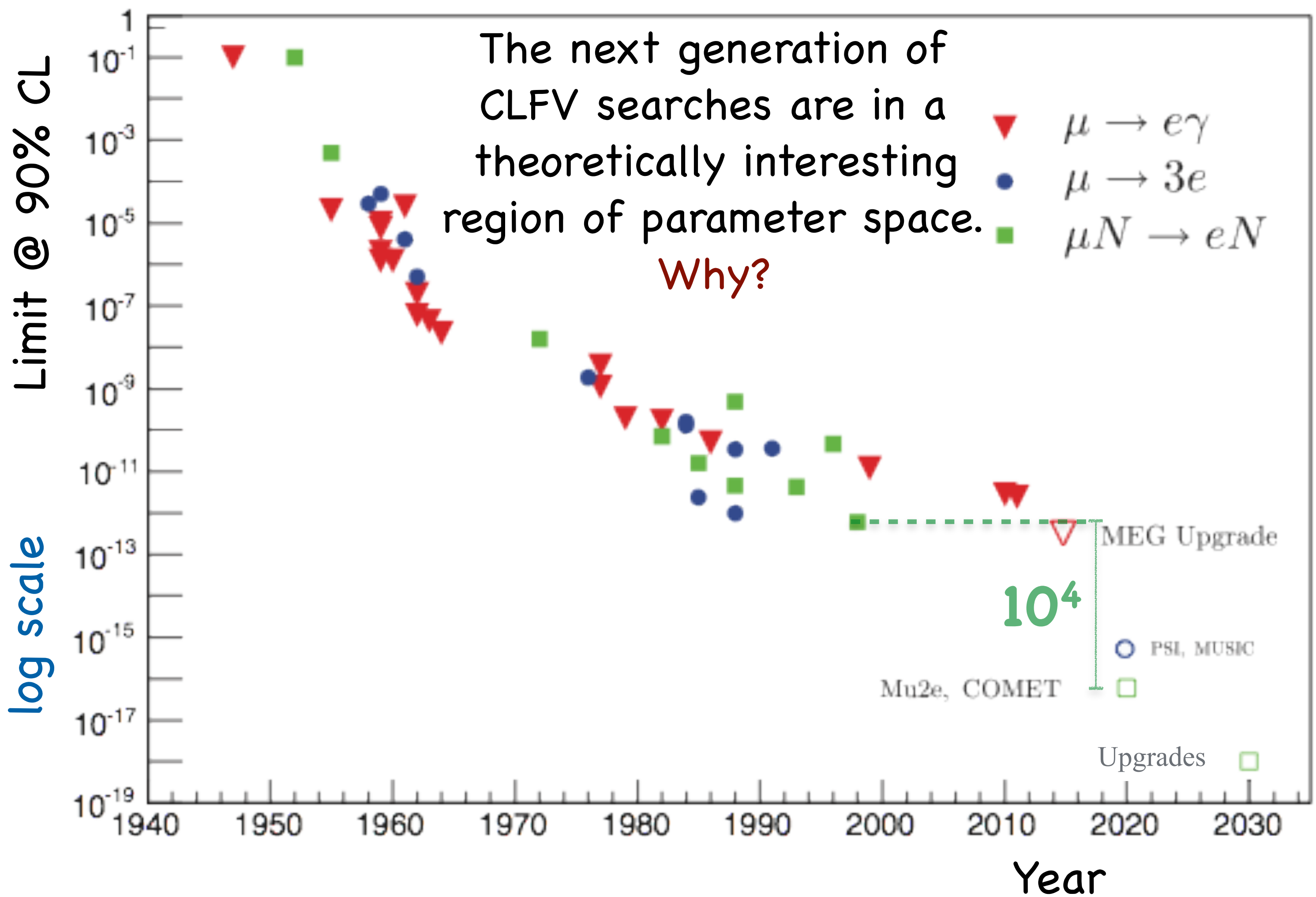
The Muon CLFV Search Landscape



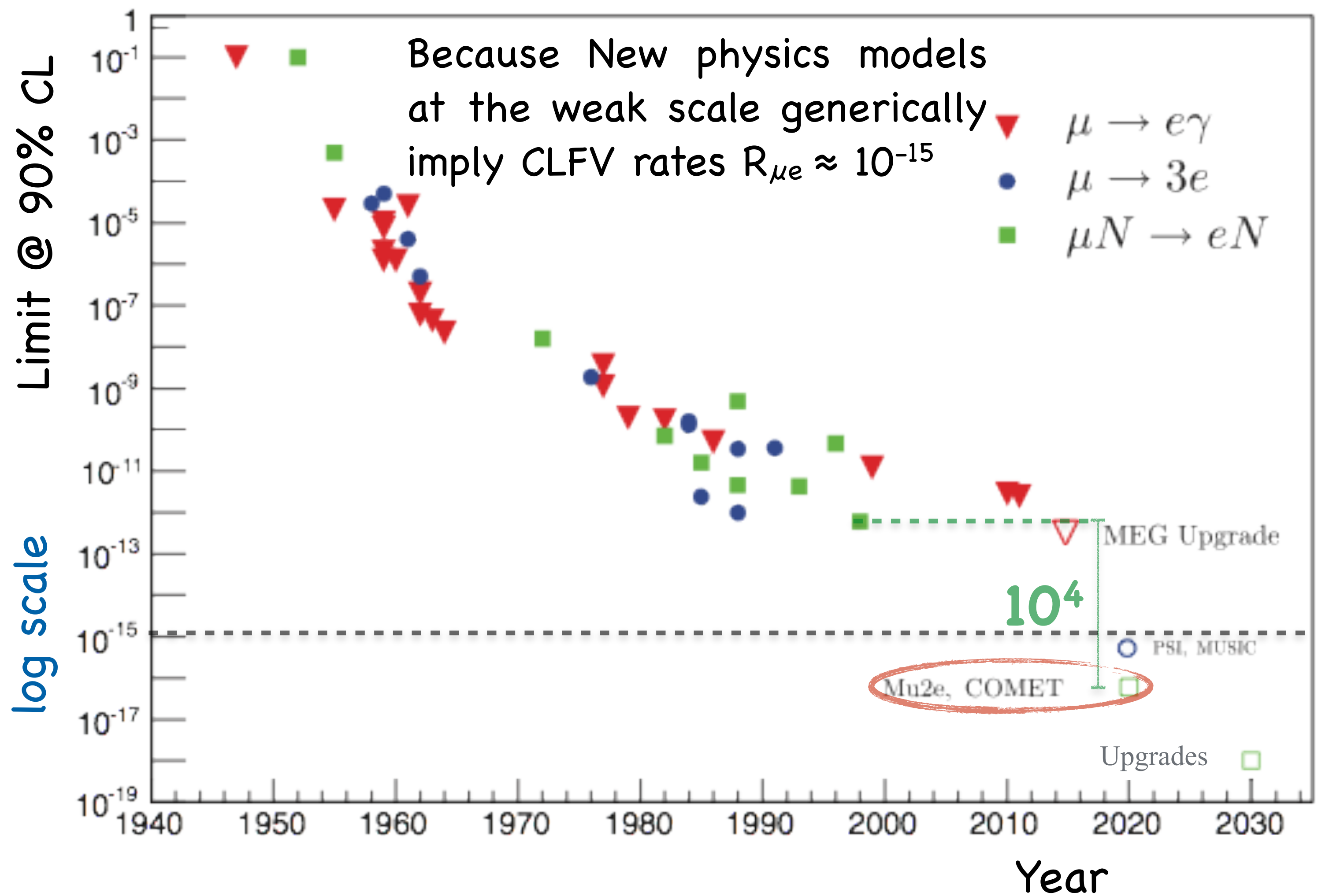
The Muon CLFV Search Landscape



The Muon CLFV Search Landscape



The Muon CLFV Search Landscape



Why $\mu N \rightarrow eN$?

While the next generation of CLFV experiments all have **reach**, $\mu N \rightarrow eN$ has the largest **breadth**…

Why $\mu N \rightarrow eN$?

To illustrate this, one can express a CLFV process in a model independent way by writing a generic flavor-violating effective operator with two terms, where their relative strengths are parameterized by a dimensionless factor (κ)

Why $\mu N \rightarrow eN$?

To illustrate this, one can express a CLFV process in a model independent way by writing a generic flavor-violating effective operator with two terms, where their relative strengths are parameterized by a dimensionless factor (κ)

For experts!

Why $\mu N \rightarrow eN$?

Generic parametrization of CLFV process

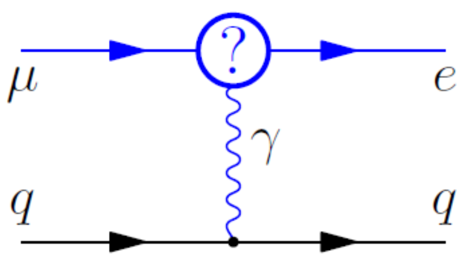
$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Λ: effective mass scale of New Physics

κ: relative contribution of the contact term

"Electromagnetic" (Loop)

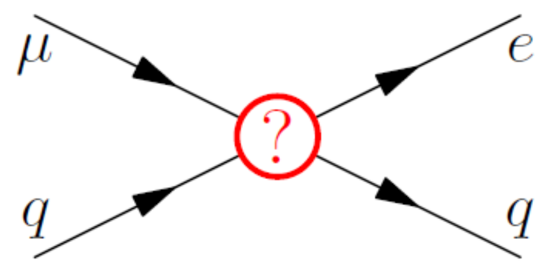
$\kappa=0$



Contributes to $\mu \rightarrow e\gamma$

"Contact"

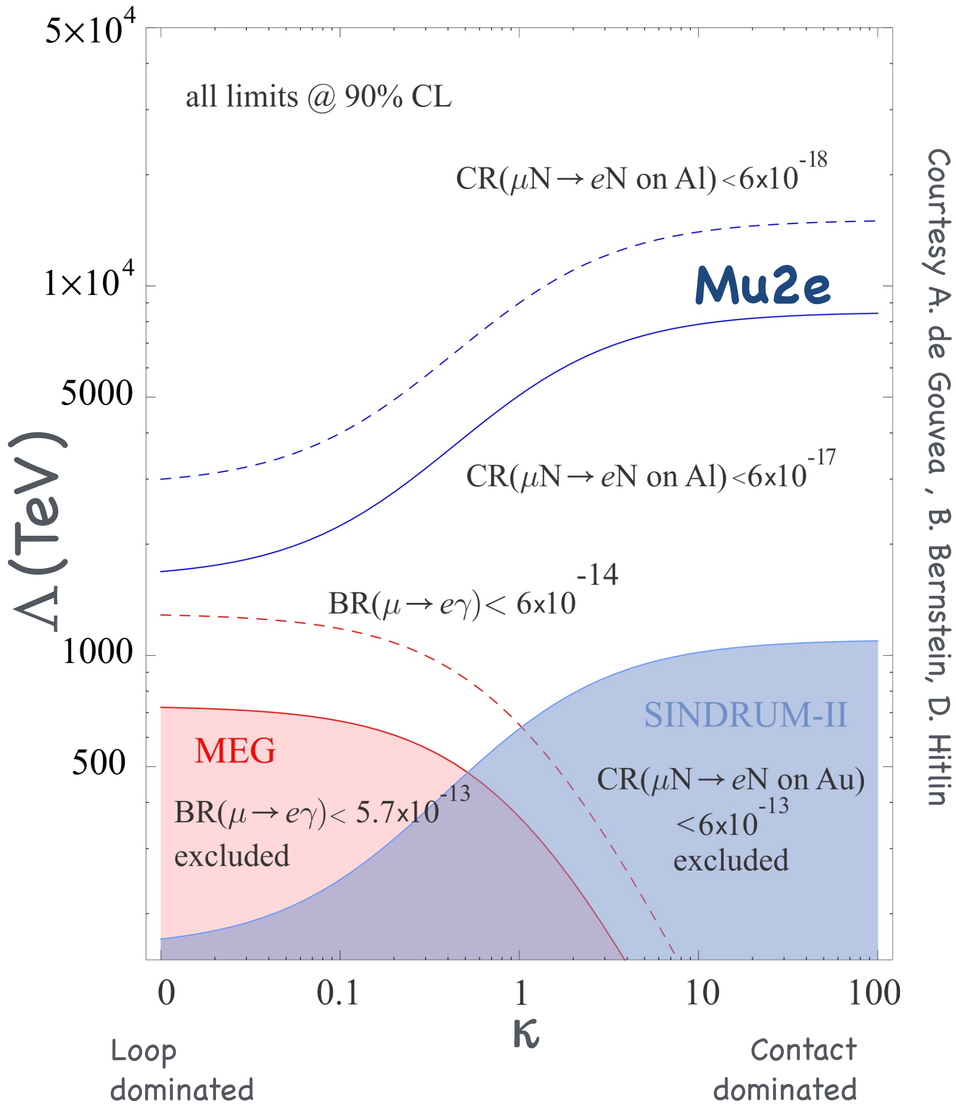
$\kappa=\infty$

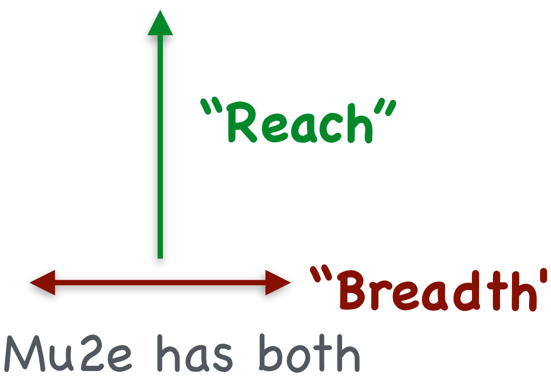


Does not contribute to $\mu \rightarrow e\gamma$

New Physics models predict various values of κ

Why μN → eN?





- Factor of 10 in Λ
  - 10^4 increase in sensitivity
- Covers all values of kappa

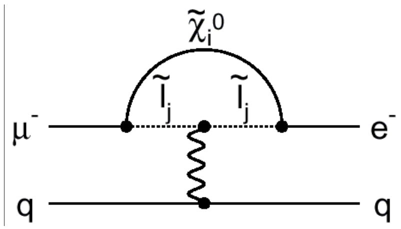
Why $\mu N \rightarrow eN$?

What are some specific examples of New Physics models to which mu2e has sensitivity?

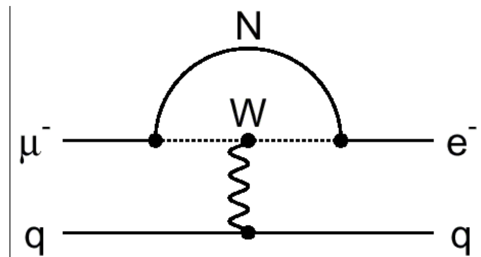
Physics Sensitivity

μN→eN is induced in a wide array of New Physics models

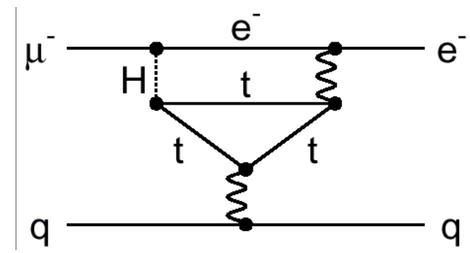
Loops



Supersymmetry

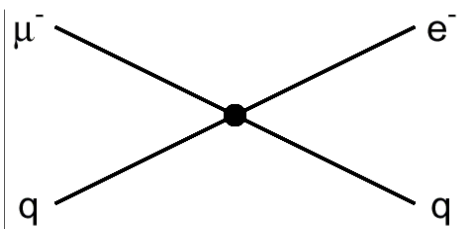


Heavy neutrino

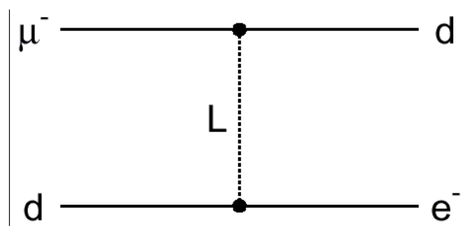


Two Higgs doublet

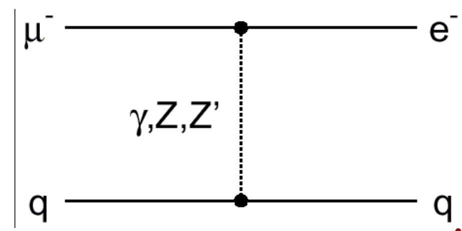
Contact Interactions



Compositeness



Leptoquarks



New heavy bosons / anomalous coupling

With a predicted branching ratio of around 10^{-15}

i.e. within the sensitivity of mu2e!

Outline of Topics

1. ~~The Standard Model (SM) of particle physics~~
   - ~~What is it?~~
   - ~~What's the matter with it?~~
   - ~~Looking beyond the SM for "New Physics"~~
2. ~~Charged Lepton Flavor Violation (CLFV)~~
   - ~~Why search for CLFV?~~
   - ~~Why $\mu N \longrightarrow eN$?~~
   - ~~Mu2e's place in the history of CLFV searches~~
3. A closer look at Mu2e
   - What exactly are we measuring?
   - What are the backgrounds?
   - Mu2e experimental design

What Will We Measure?

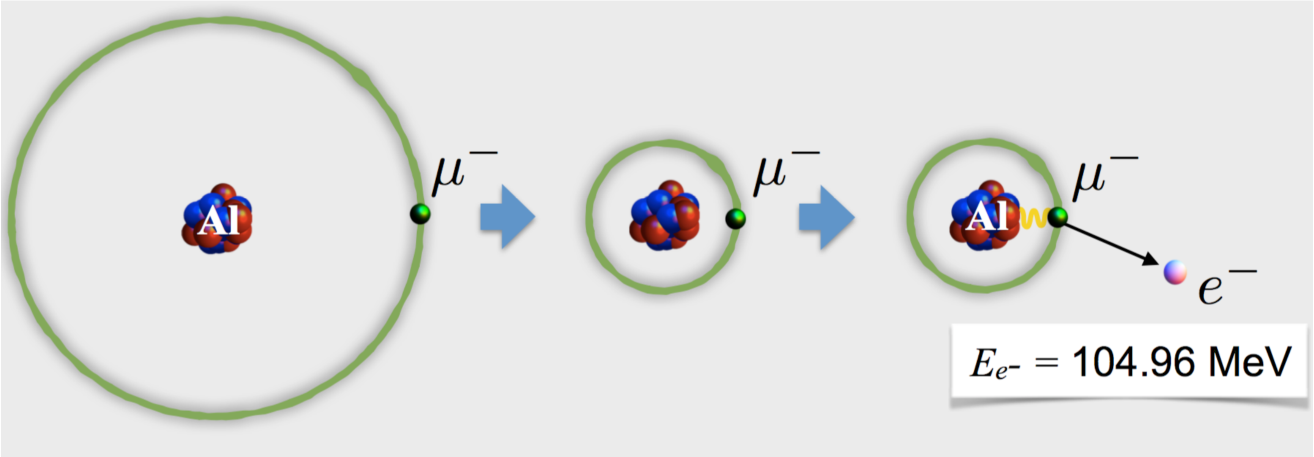
Mu2e will measure the ratio of $\mu \rightarrow e$ conversions to the number of muon captures by Al nuclei:

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

What We Will Measure: Numerator

Mu2e will measure the ratio of $\mu \to e$ conversions to the number of muon captures by Al nuclei:

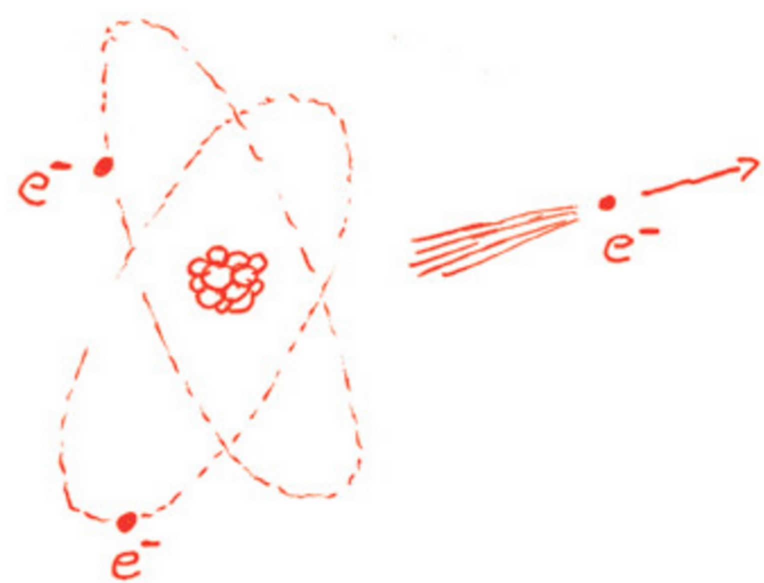
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$



For Al, the conversion signature is a **mono-energetic** signal @ **104.96 MeV**

What We Will Measure: Numerator

Why is the conversion electron mono-energetic?



What We Will Measure: Numerator

Why is the conversion electron mono-energetic?

Think of the conversion as two-body decay

Parent

1 Muonic Atom

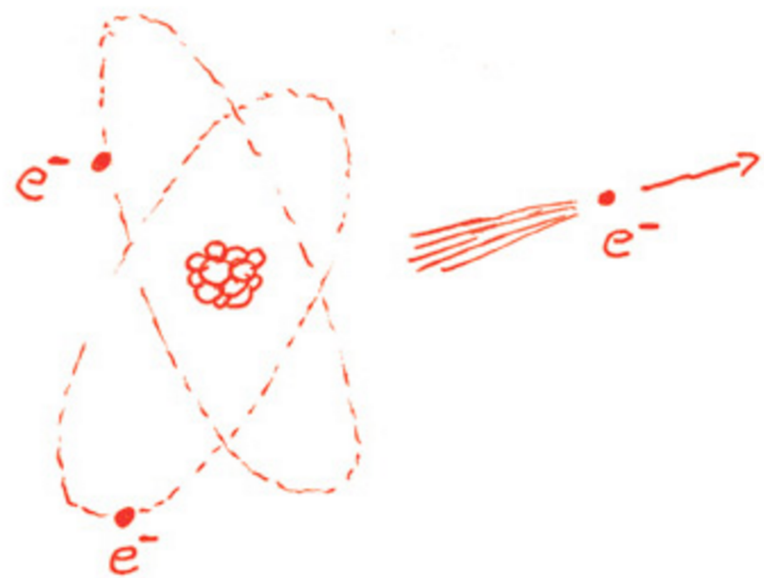
2 Daughters:

1 Atom + 1 Electron

What We Will Measure: Numerator

Why is the conversion electron mono-energetic?

Think of the conversion as two-body decay



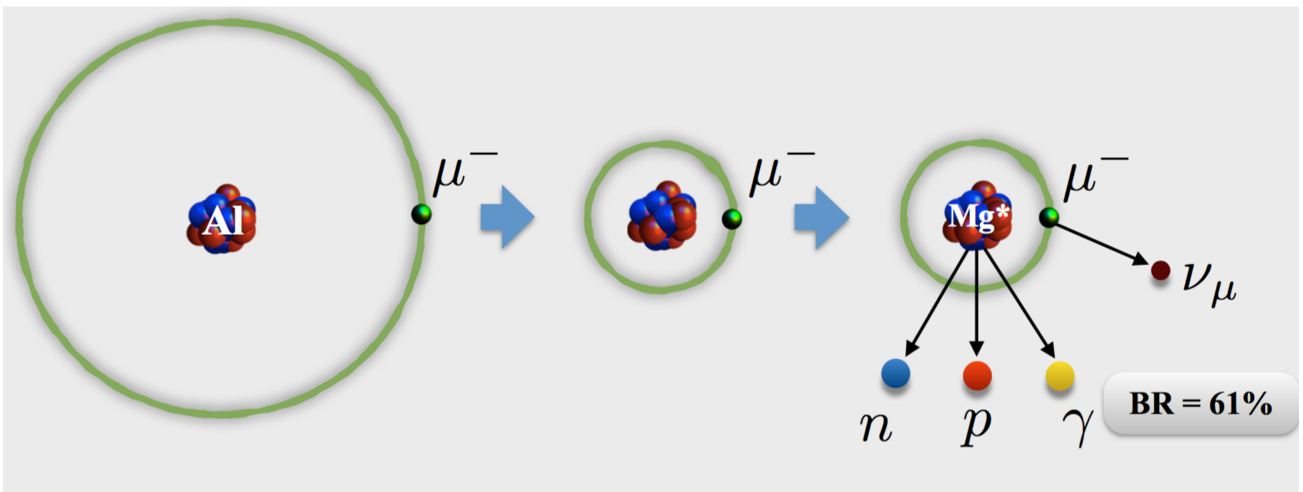
The atom and the electron gain net zero momentum, so the (much) lighter electron gets (nearly) all of the released energy!

$$E_e = m_\mu c^2 - E_b - E_{recoil} = \underline{104.96\ \text{MeV}}$$

What We Will Measure: Denominator

Mu2e will measure the ratio of $\mu \rightarrow e$ conversions to the number of muon captures by Al nuclei:

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



Once trapped, 61% of the muons will descend to the muonic ground state and be subsequently captured by the nucleus

Mu2e Sensitivity

- Mu2e is sensitive to $R_{\mu e} > 6 \times 10^{-17}$ @ 90%CL
- Previous experiments rule out $R_{\mu e} > 7 \times 10^{-13}$ @ 90%CL
- New physics at the weak scale generically implies conversion rates of $R_{\mu e} \sim 10^{-15}$

Mu2e Sensitivity

- Mu2e is sensitive to $R_{\mu e} > 6 \times 10^{-17}$ @ 90%CL
- Previous experiments rule out $R_{\mu e} > 7 \times 10^{-13}$ @ 90%CL
- New physics at the weak scale generically implies conversion rates of $R_{\mu e} \sim 10^{-15}$

If $R_{\mu e} = 10^{-15}$
will see ~ 50 events

If $R_{\mu e} = 3 \times 10^{-17}$
will see 1 event

Mu2e Sensitivity

- Mu2e is sensitive to $R_{\mu e} > 6 \times 10^{-17}$ @ 90%CL
- Previous experiments rule out $R_{\mu e} > 7 \times 10^{-13}$ @ 90%CL
- New physics at the weak scale generically implies conversion rates of $R_{\mu e} \sim 10^{-15}$

If $R_{\mu e} = 10^{-15}$
will see ~ 50 events

If $R_{\mu e} = 3 \times 10^{-17}$
will see 1 event

Sounds great… in the absences of backgrounds!

What Backgrounds Are Present?

Some backgrounds are "obvious," while a few others have been brought to light from past experiments

e.g. cosmic rays in 1988 TRIUMF conversion experiment

What other backgrounds are present?

We will not discuss these in detail…

- Intrinsic processes that scale with beam intensity e.g. decay-in-orbit
  - » Minimize multiple scattering, maximize momentum resolution
- Prompt processes e.g. radiative pion capture
  - » Delayed search window
- Delayed processes from slowly moving particles e.g. as antiprotons
  - » Absorbers, collimators and strict magnetic field requirements
- Processes initiated by cosmic rays
  - » Cosmic ray veto system
- Reconstruction errors

The ability to eliminate background is what give mu2e its unprecedented physics reach

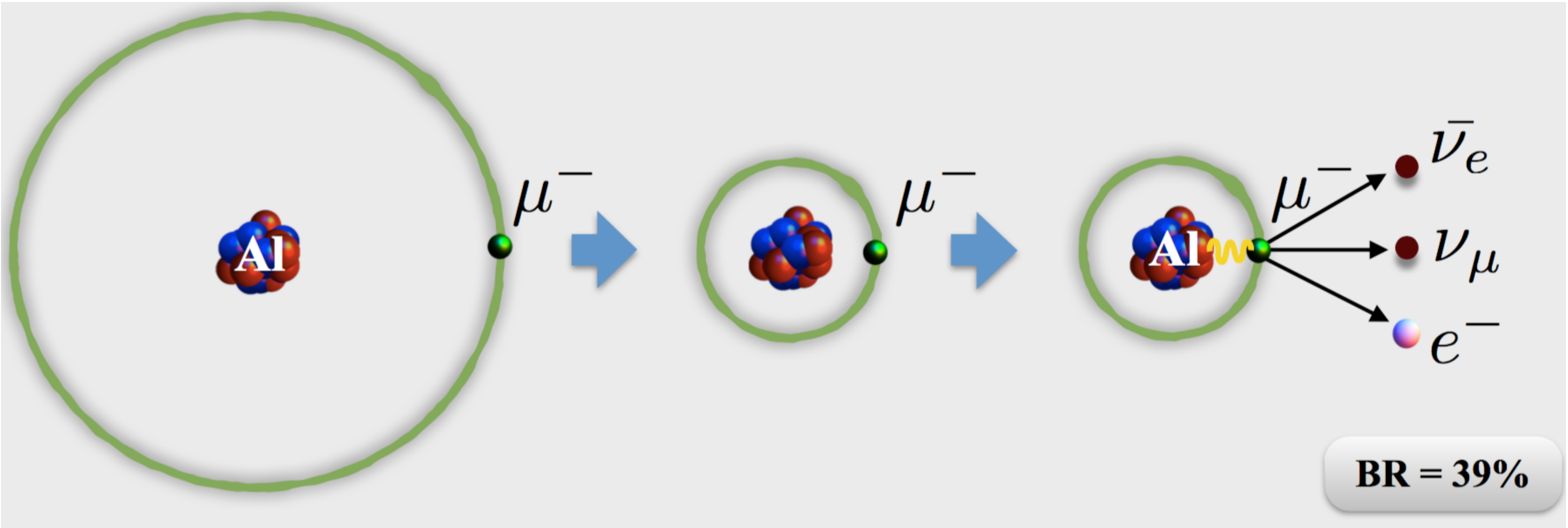
What other backgrounds are present?

We will not discuss these in detail…

- Intrinsic processes that scale with beam intensity e.g. decay-in-orbit
  - » Minimize multiple scattering, maximize momentum resolution
- Prompt processes e.g. radiative pion capture
  - » Delayed search window
- Delayed processes from slowly moving particles e.g. as antiprotons
  - » Absorbers, collimators and strict magnetic field requirements
- Processes initiated by cosmic rays
  - » Cosmic ray veto system
- Reconstruction errors

The ability to eliminate background is what give mu2e its unprecedented physics reach

Dominant Background: Decay In Orbit

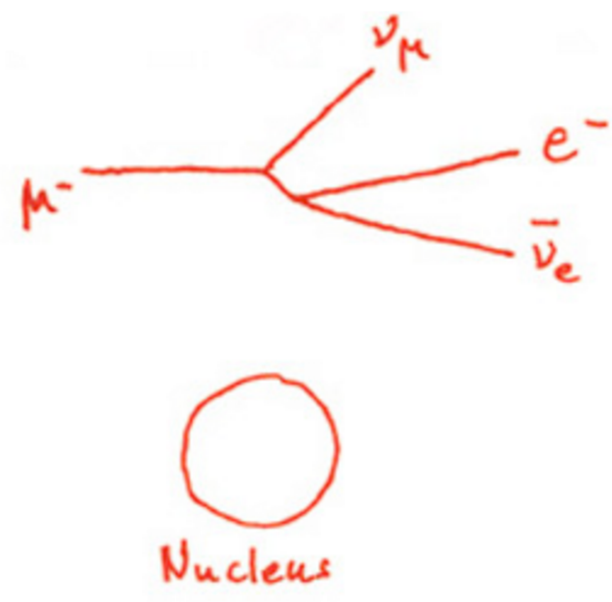


The other 39% of stopped muons will "decay in orbit" before the nuclear capture occurs.

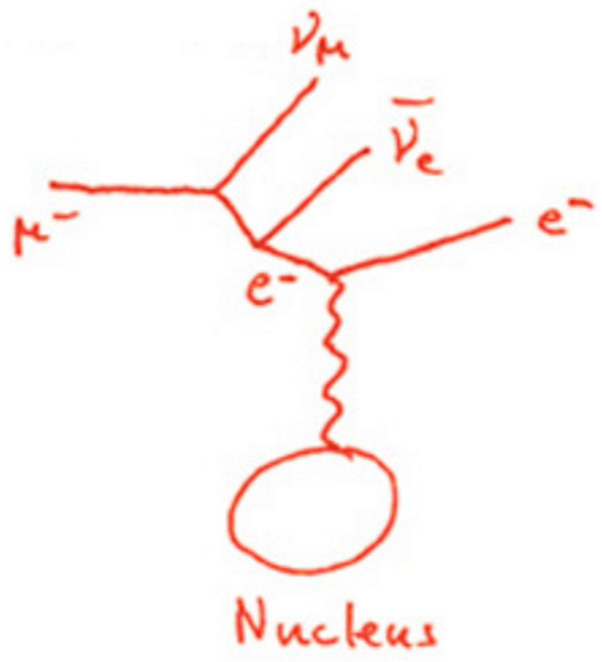
This three body decay is similar to the "Michel Decay." The energy spectrum of the daughter electron will be referred to as the decay-in-orbit spectrum

Dominant Background: Decay In Orbit

Ordinary Michel Decay

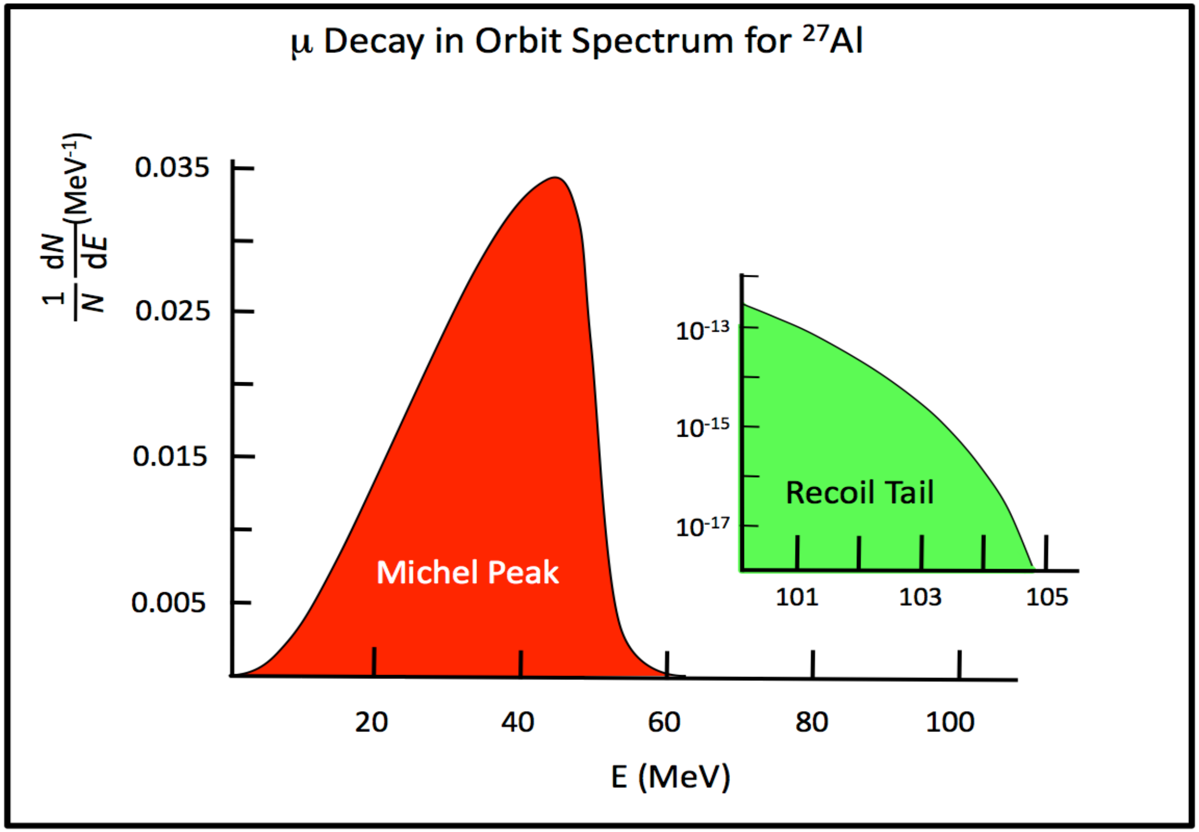


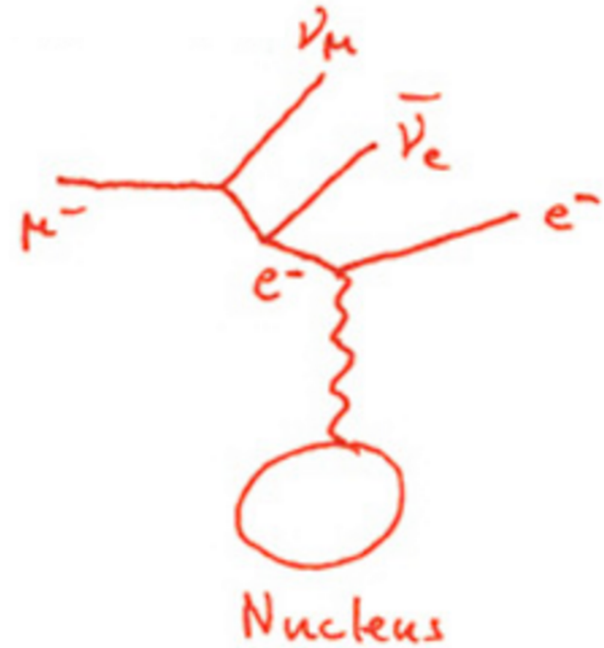
Decay-in-orbit



Interaction with the nucleus changes the electron energy spectrum

Dominant Background: Decay In Orbit



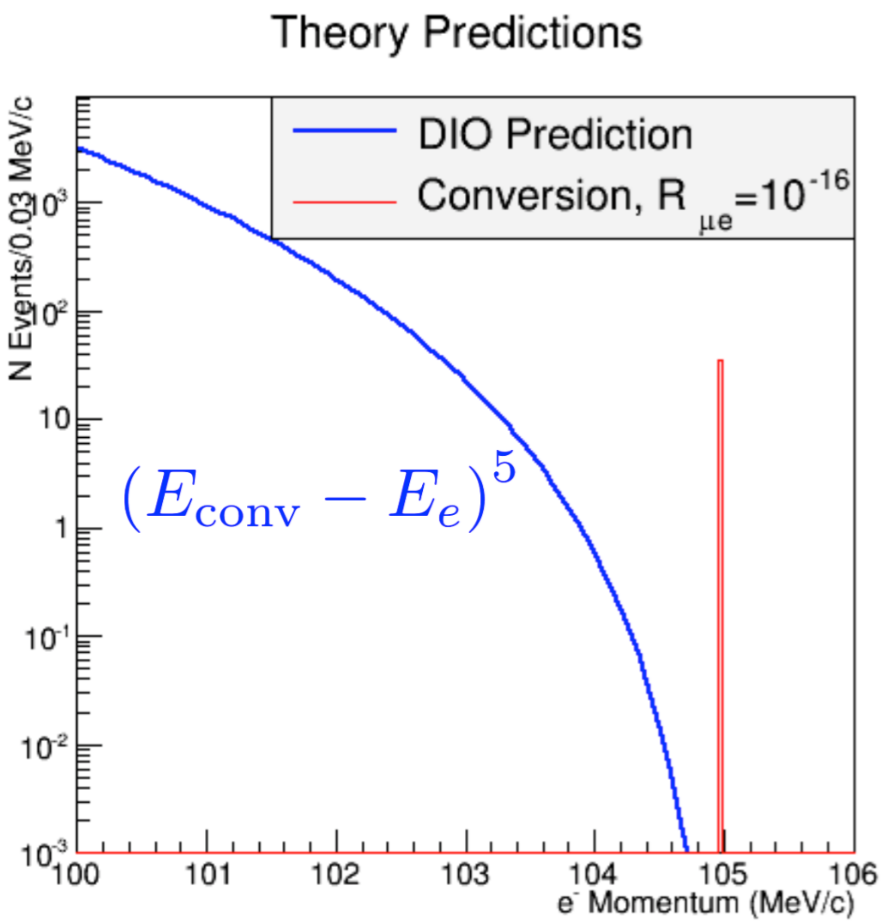


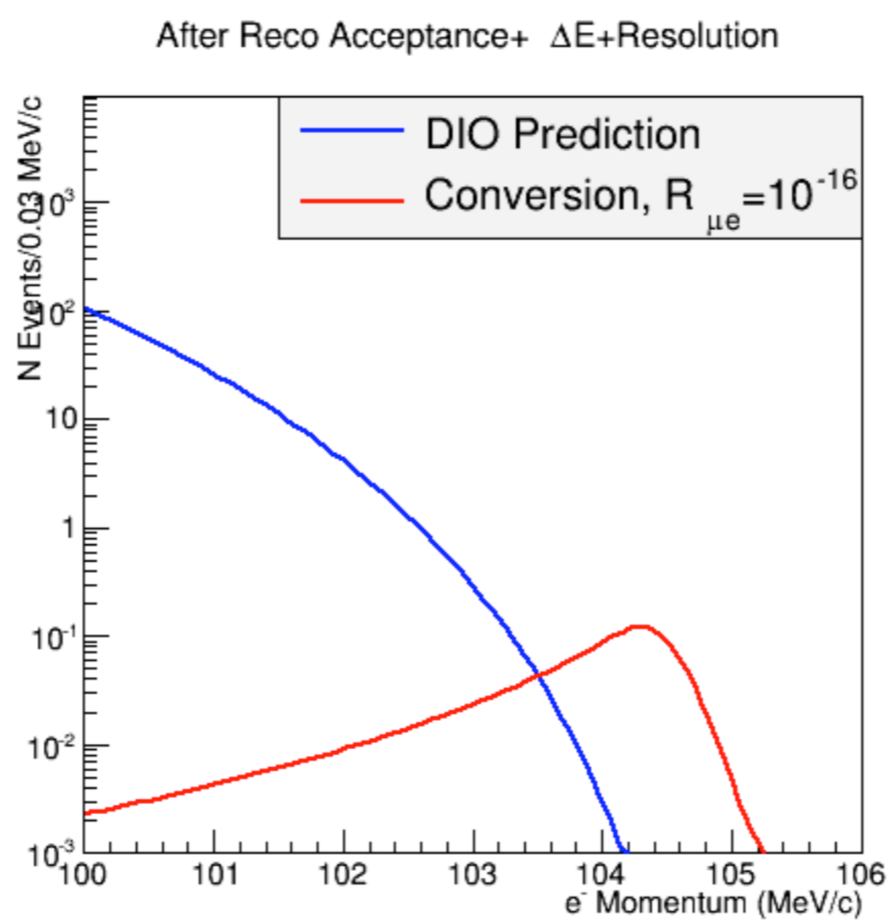
The Michel spectrum for a free muon has a cutoff at 53 MeV

However, a bound muon can interact with the nucleus smearing the spectrum out to 104.96 MeV

This accounts for ~55% of the total background

Dominant Background: Decay In Orbit





Electron momentum resolution is a big driver of the experiment design

Need precise measurements and to minimize multiple scattering!

Prompt Background: Radiative Pion Capture

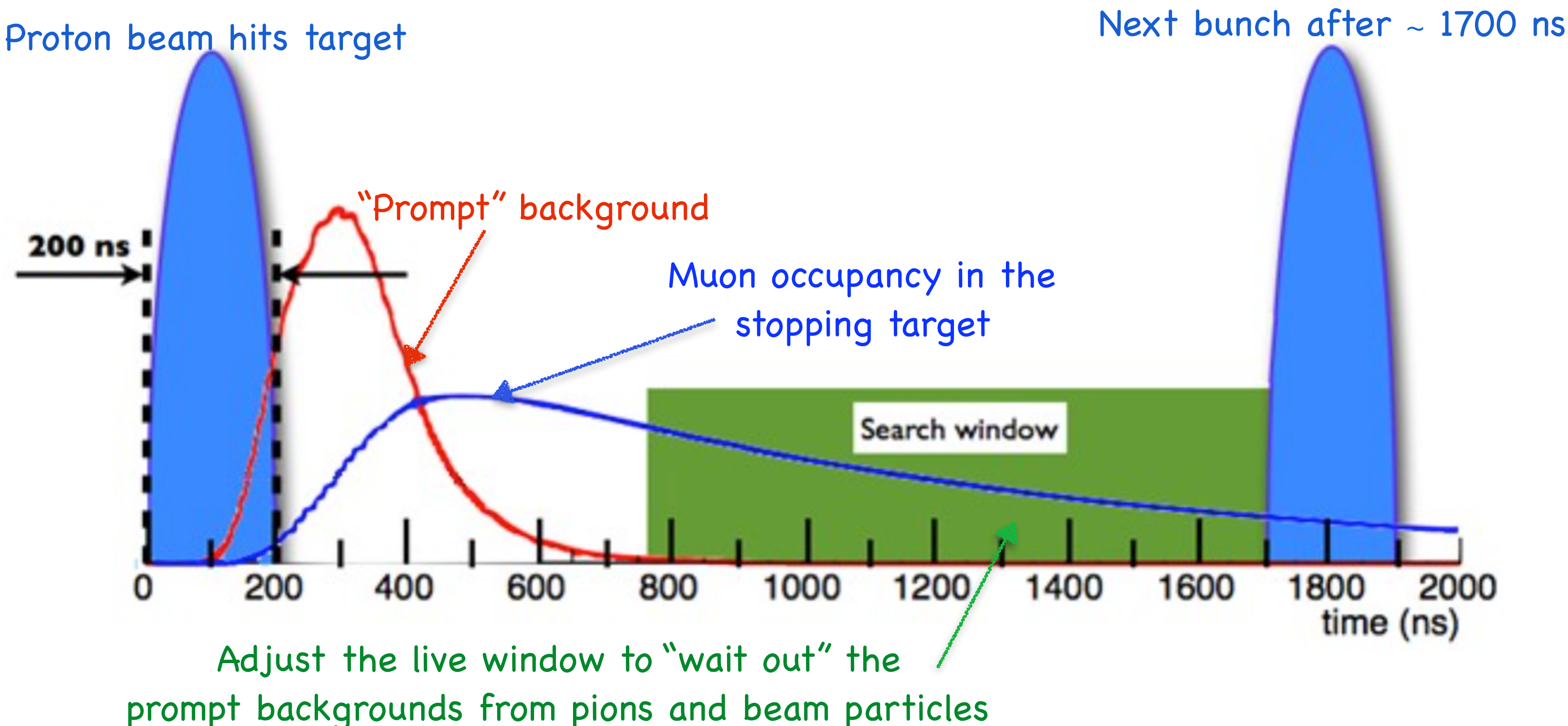
- The muon beam is naturally contaminated with pions since the muons themselves come from pion decay.
- Some pions are stopped on the Al target (or other material in the detector) and ~2% of these produce a photon or e-ē pair
- Sometimes the produced electron can be at the conversion energy

$$\pi^{-}N \rightarrow e\bar{e}N^{*}$$

- But, the pion lifetime is around 26 ns, while the muon lifetime in Al is 864 ns

Prompt Background

Use a pulsed muon beam with a long interval between bunches and delay the search window!



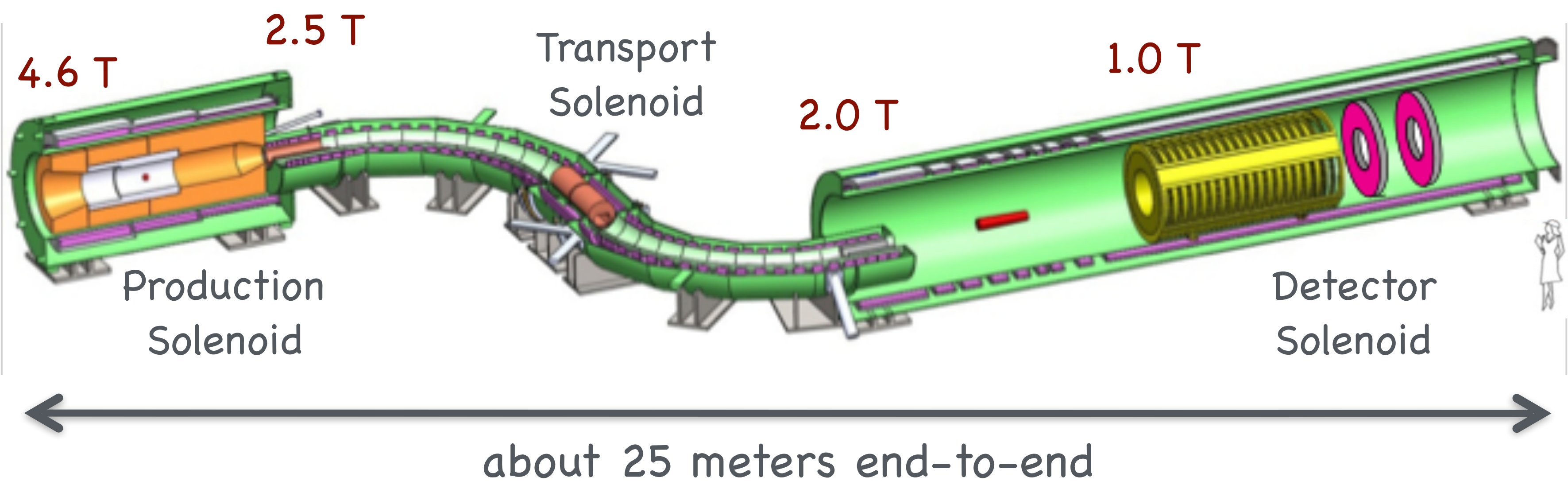
Total Background

Table 3.4 A summary of the estimated background yields using the selection criteria of Section 3.5.3. The total run time and corresponding number of protons on target are provided in Table 3.1. An extinction of 10^{-10}, a cosmic ray inefficiency of 10^{-4}, and particle-identification with a muon-rejection of 200 is used. 'Intrinsic' backgrounds are those that scale with the number of stopped muons, 'Late Arriving' backgrounds are those with a strong dependemce on the extinction, and 'Miscellaneous' backgrounds are those that don't fall into the previous two categories.

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.20 ± 0.09
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	< 0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm < 0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.096 ± 0.020
	Total	0.37 ± 0.10

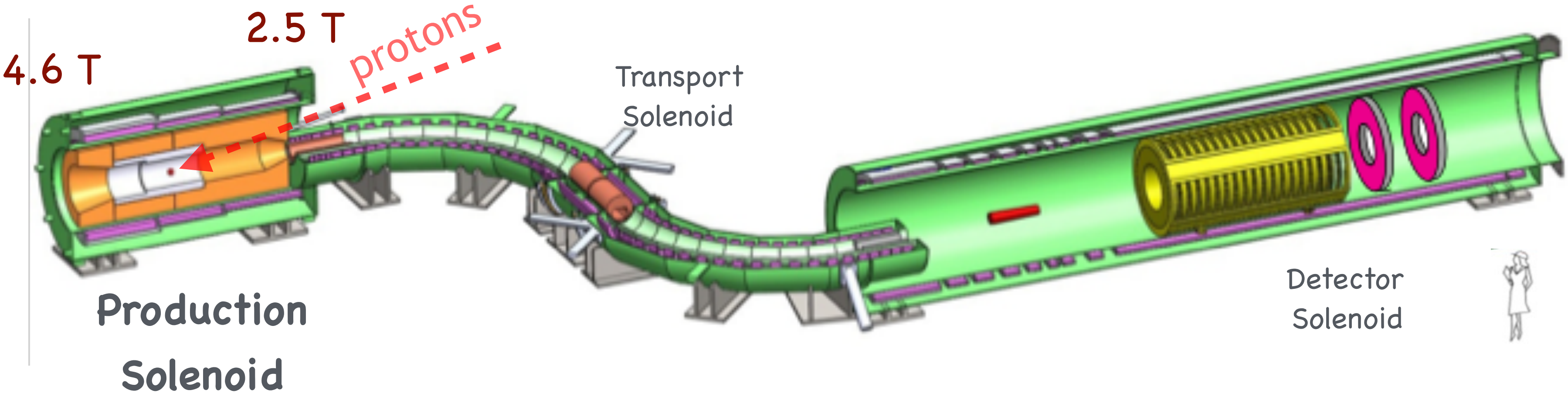
Mu2e Design at a Glance

Mu2e consists of 3 solenoid systems



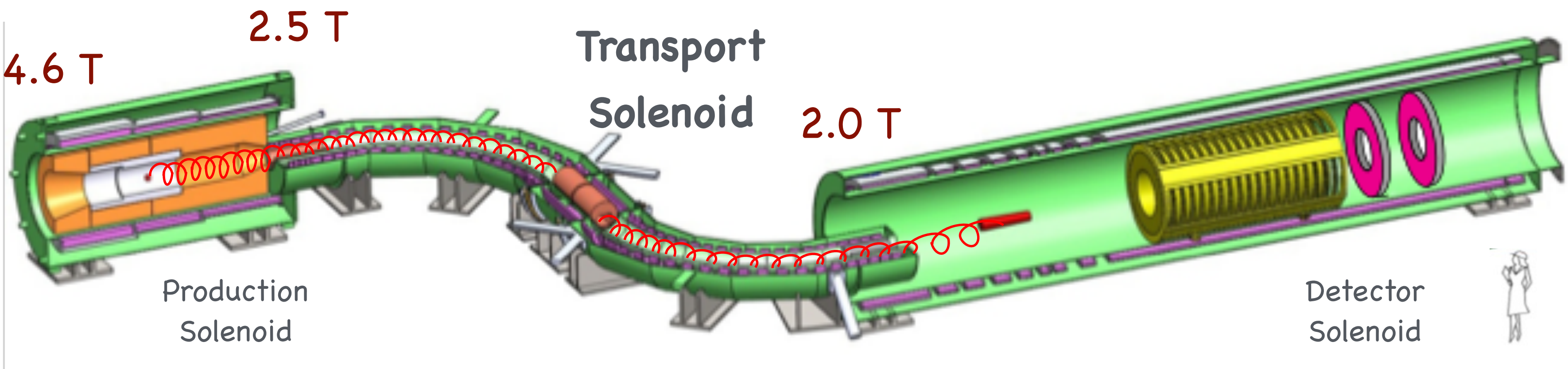
- The solenoids use a graded magnetic field to suppress background and increase yield
- The earth's field, for comparison, is 0.0006 T

Mu2e Design at a Glance: Production Solenoid



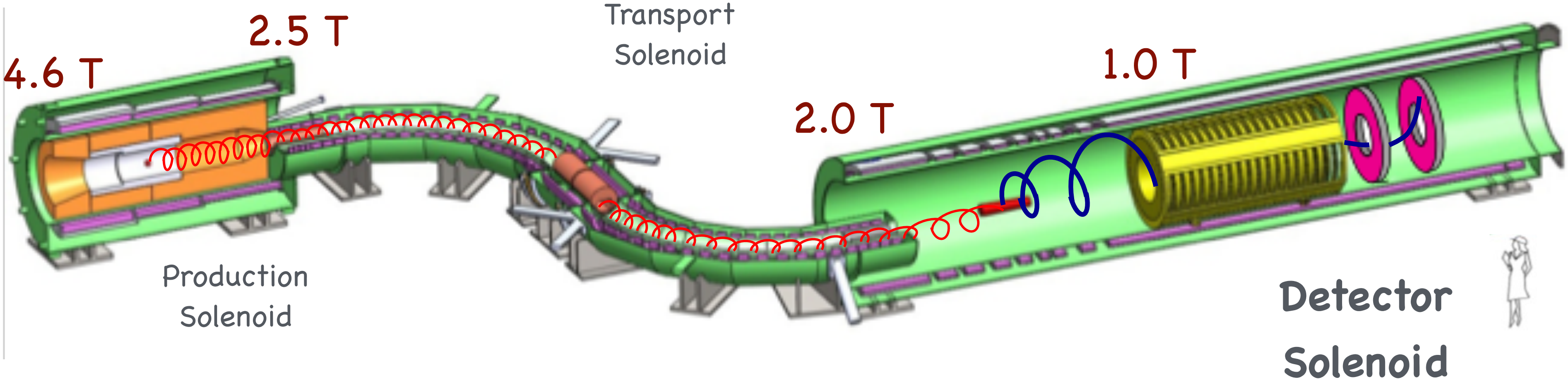
- Every second 7×10^{12} protons at 8 GeV enter into the Production Solenoid which is held at high vacuum (10^{-5} Torr)
- The protons interact with a tungsten target (about the size of a pencil) to produce negative pions that decay into negative muons
- The magnetic field in the production solenoid spirals the pions & muons into the transport solenoid. Pions moving away from the Transport Solenoid are "reflected" magnetically by the graded field

Mu2e Design at a Glance: Transport Solenoid



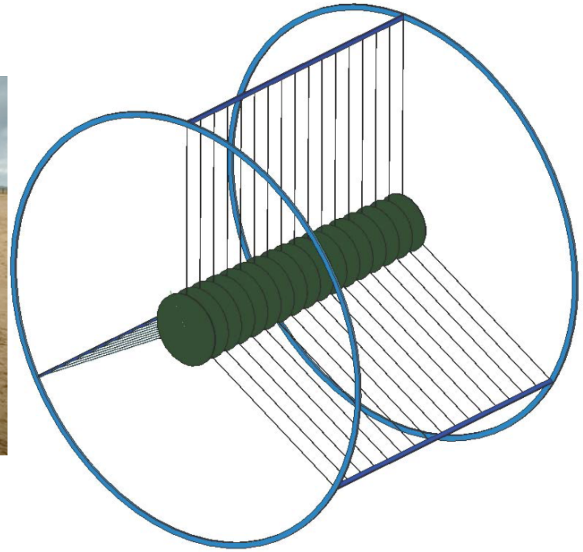
- The Transport Solenoid transmits low energy, negatively charged muons to the detector solenoid and greatly reduces the background particles
- The charge and momentum are selected through the S-shape design, collimators, and a set of field requirements (e.g. a negative axial gradient in the straight sections)
- Every second 2.6×10^{12} negative muons are transmitted to the Detector Solenoid

Mu2e Design at a Glance: Detector Solenoid



- **Upstream** in the Detector Solenoid sits the **aluminum stopping target**
- The stopping target is the ultimate destination for the muon beam

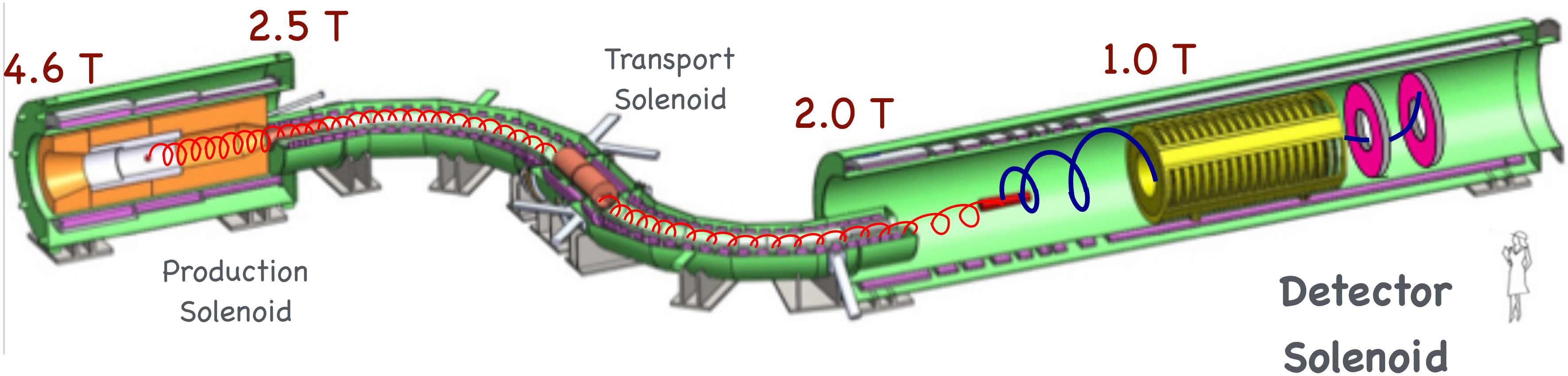
Mu2e Design: Stopping Target



- The Muon Stopping Target consists of a series of thin **aluminum** discs supported by fine tungsten wire
- Every second 1.3 x 10^{12} muons are stopped
- Once stopped they fall to their ground state orbitals and are captured or decay… this is where the muon to electron conversion may occur!

After 3 years of running 10^{18} muons will be stopped!

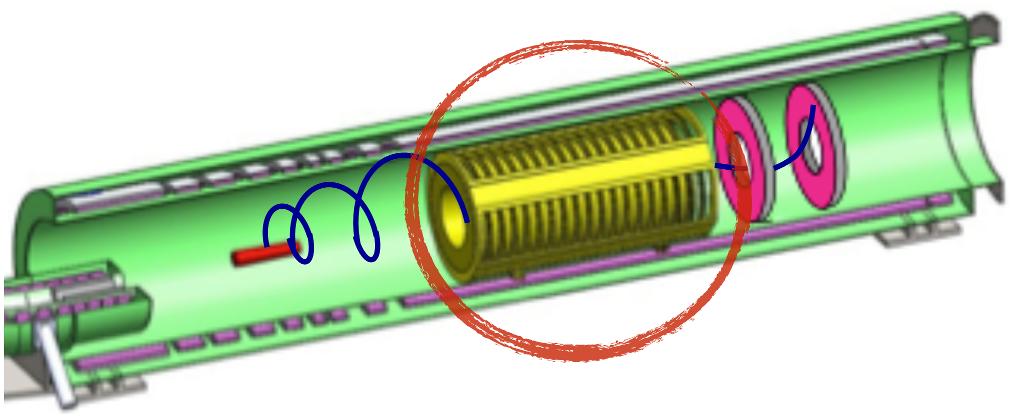
Mu2e Design at a Glance: Detector Solenoid



- **Downstream** in the detector solenoid are the **Physics Detectors** to which the conversion electrons emanating from the target are guided
- The Physics Detectors are designed to be "blind" to most of the lower momentum decay electrons
- The graded field reflects backward going electrons returning them toward the Physics Detectors

Mu2e Design at a Glance: Tracker

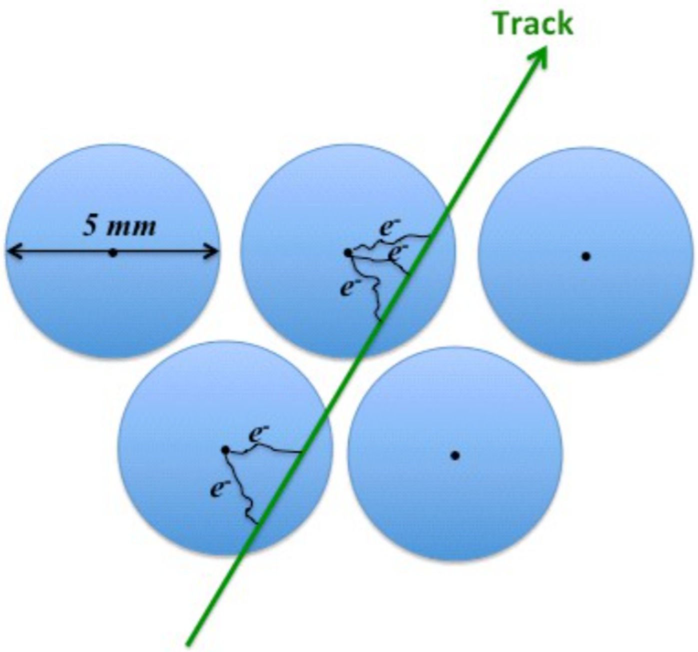
- The Mu2e Tracker is a low mass array of ~20,000 straw drift tubes aligned along the transverse axis of the Detector Solenoid and held in vacuum
- Its job is to measure the trajectory of electrons in order to determine their momenta
- No one has ever built such a low mass detector that operates in vacuum



Mu2e Design at a Glance: Tracker

How does it work?

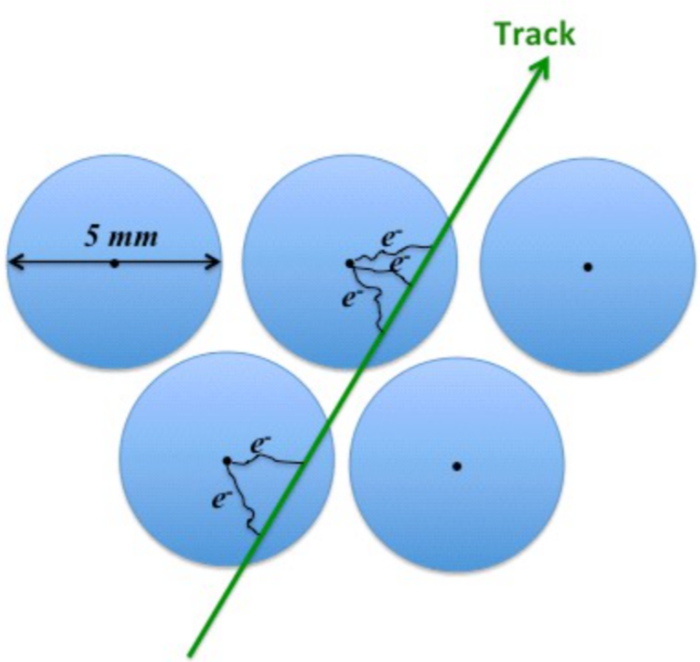
- A charged particle passes through the straws (filled with Argon/CO2), leaving a trail of ions and electrons in its wake
- The straw is at ground, and a sense wire at the center is at ~1450V
- The electrons then drift toward the sense wire and induce a current that is extracted with electronics



Mu2e Design at a Glance: Tracker

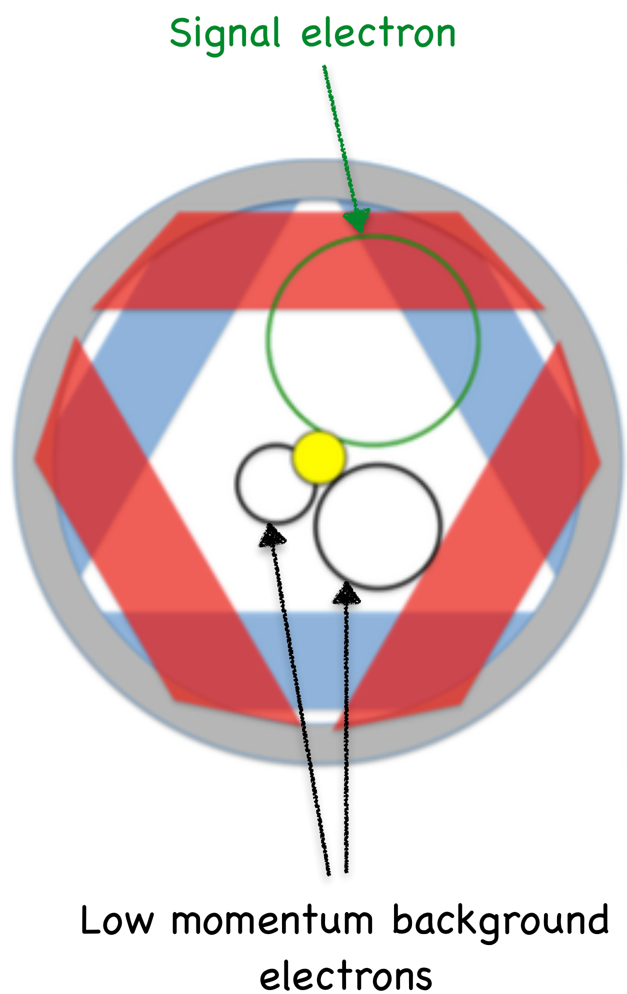
Why straw tubes?

- Low mass
- Can reliably operate in vacuum



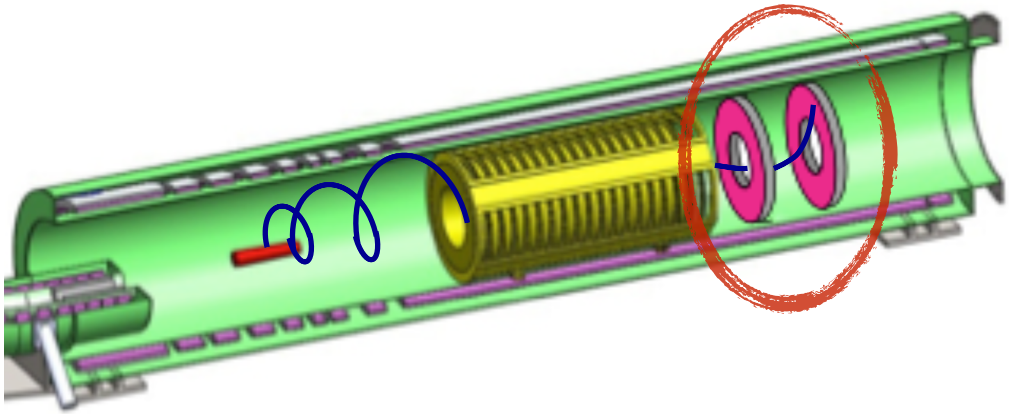
Tracker: Basic Performance Requirements

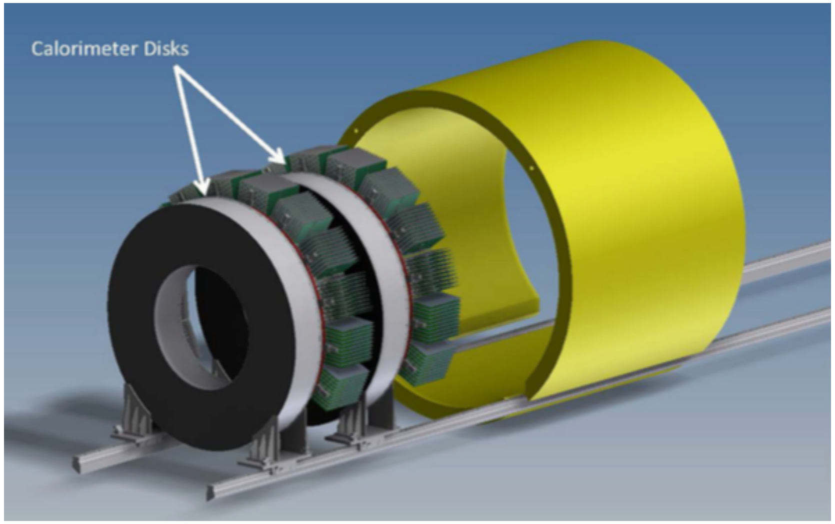
- Minimize energy loss and multiple scattering
  - » Low mass straw tube design
- Momentum resolution $\sigma < 0.2\%$ @ 105 MeV/c
- Precision alignment
- Blind to low momentum (decay-in-orbit) background
  - » Hole in center of tracker
    - – Recall that **p** = q(**B**.**r**)
- Operate in vacuum (10^{-4} torr)



Mu2e Design at a Glance: Calorimeter

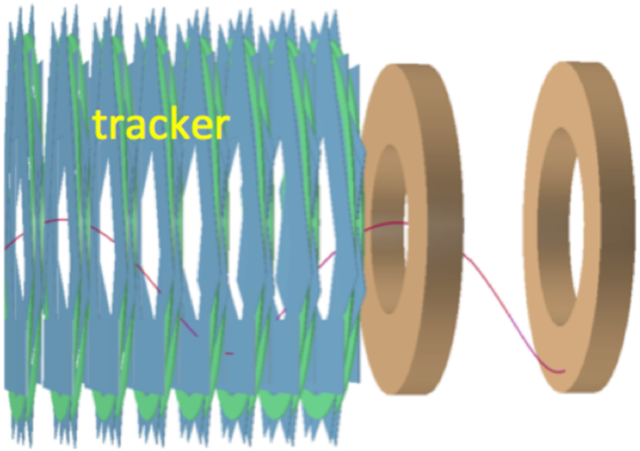
- The Mu2e Calorimeter's job is particle identification, to confirm that we really are looking at electrons, and to cross check the measurements taken by the Tracker.

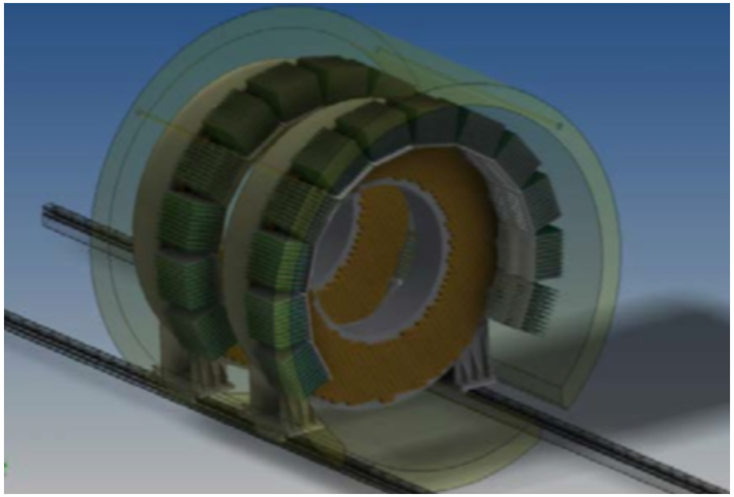




Calorimeter: Basic Performance Requirements

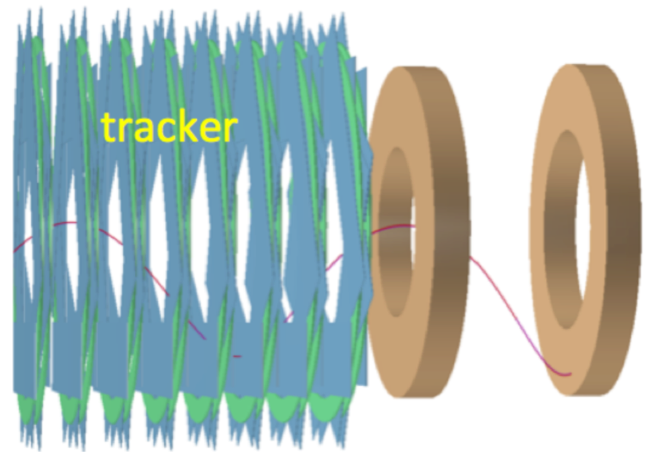
- Distinguish muons from electrons
- Operate in 1T field and in vacuum
- Under 500 ps timing resolution and ~5% energy resolution @100 MeV
- Position resolution of ~1cm
- Almost full acceptance for conversion electron signal

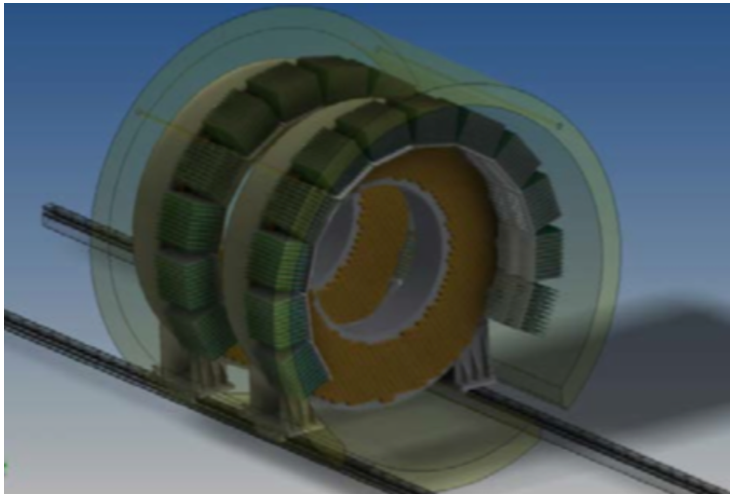




Calorimeter: Basic Design

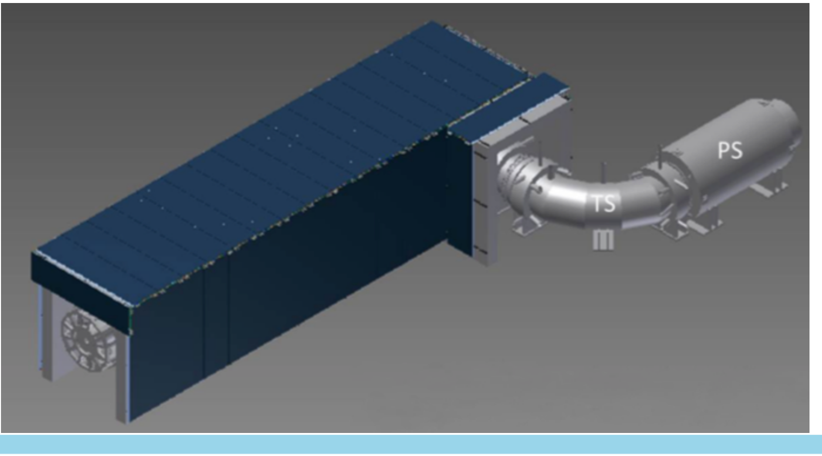
- Two annuli with inner radius 35.1 cm and outer radius 66 cm
- Disks separated by 70 cm (1/2 wavelength)
- ~800 pure Cesium Iodide crystals per disk
- Two 9x9 mm^2 avalanche photodiodes per crystal





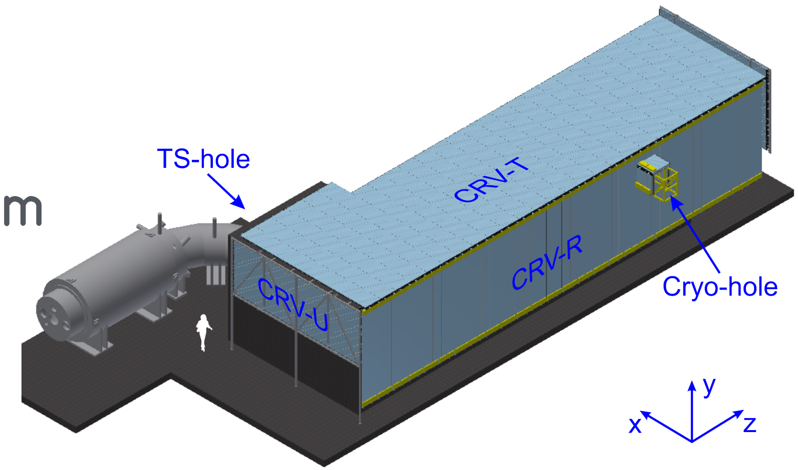
Mu2e Design: Cosmic Ray Veto (CRV)

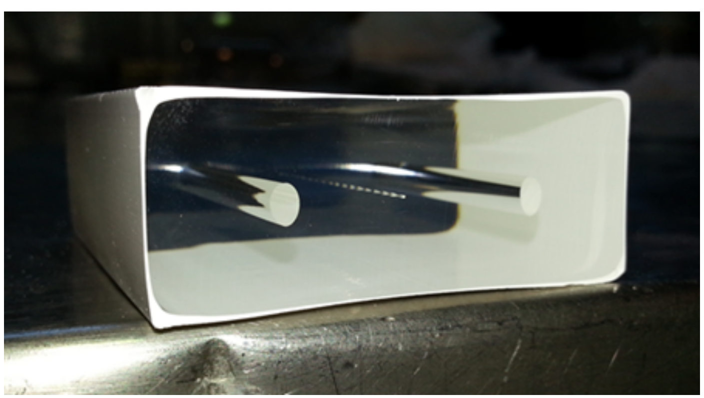
- Cosmic Ray Veto System's job is to **suppress** the **spurious** detection of conversion-like particles initiated by **cosmic-ray** muons that appear to originate in the stopping target
- Without the CRV Such background events would occur at the rate of about **one event per day**
- The CRV will cover half of the transport solenoid, and the entire detector solenoid

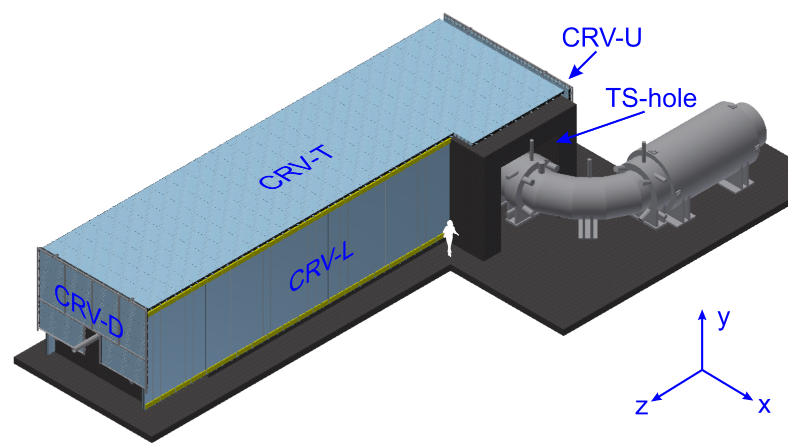


Cosmic Ray Veto: Basic Design

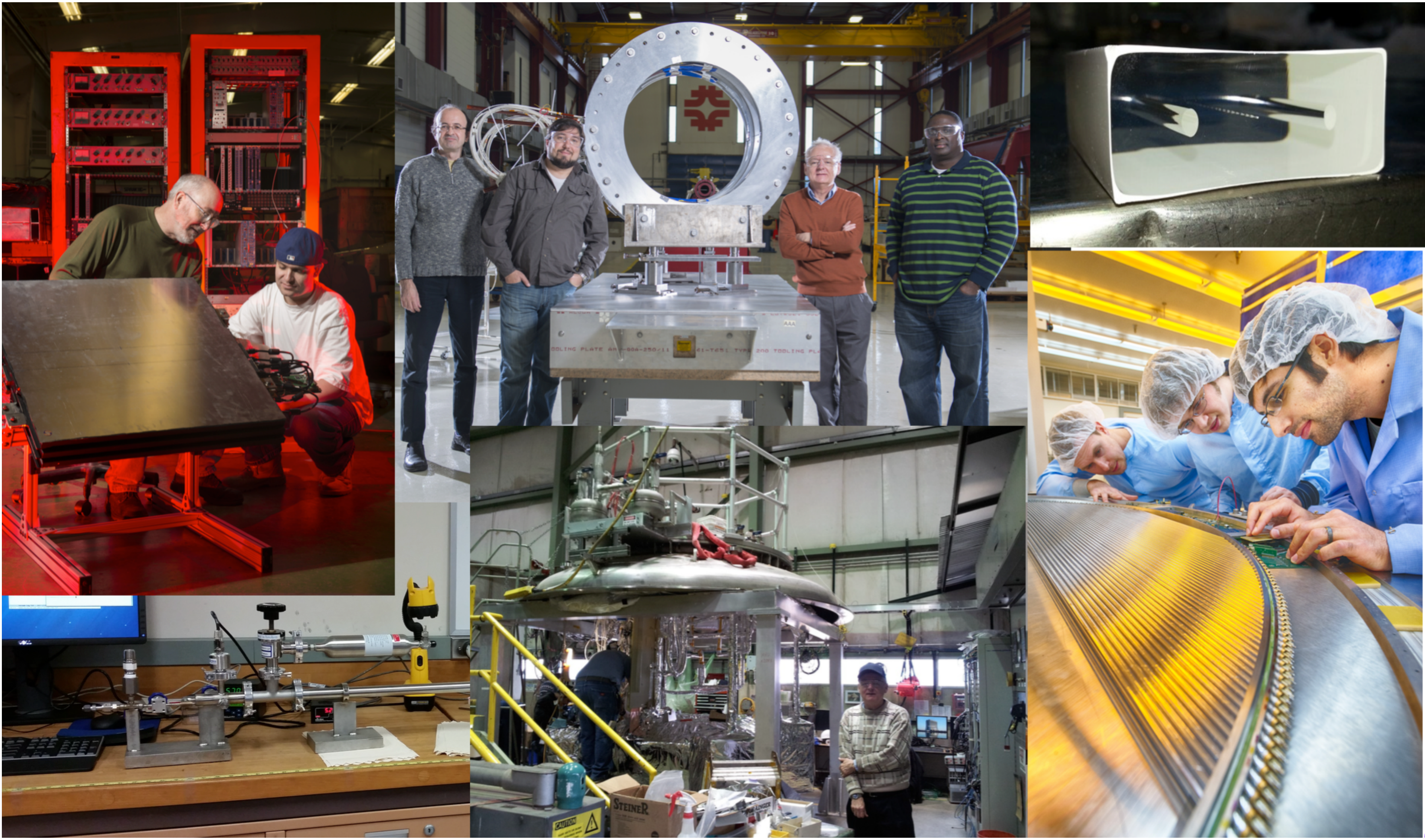
- Four layers of extruded polystyrene scintillator counters.
- Total of ~5000 counters of width ~5 cm
- Each counter has two embedded wavelength shifting fibers
- Read out with SiPMs, ~20,000 in total







Active R&D Program



Ground Breaking: April 2015

The Collaboration

Data Collection

Data collection is set to start in 2021

Three years worth of data will be collected

Outline of Topics

1. The Standard Model (SM) of particle physics
   - What is it?
   - What's the matter with it?
   - Looking beyond the SM for "New Physics"
2. Charged Lepton Flavor Violation
   - Why search for CLFV?
   - Why $\mu N \to eN$?
   - Mu2e's place in the history of CLFV searches
3. A closer look at Mu2e
   - What exactly are we measuring?
   - What are the backgrounds?
   - Mu2e experimental design

The Future: Next Generation Experiment

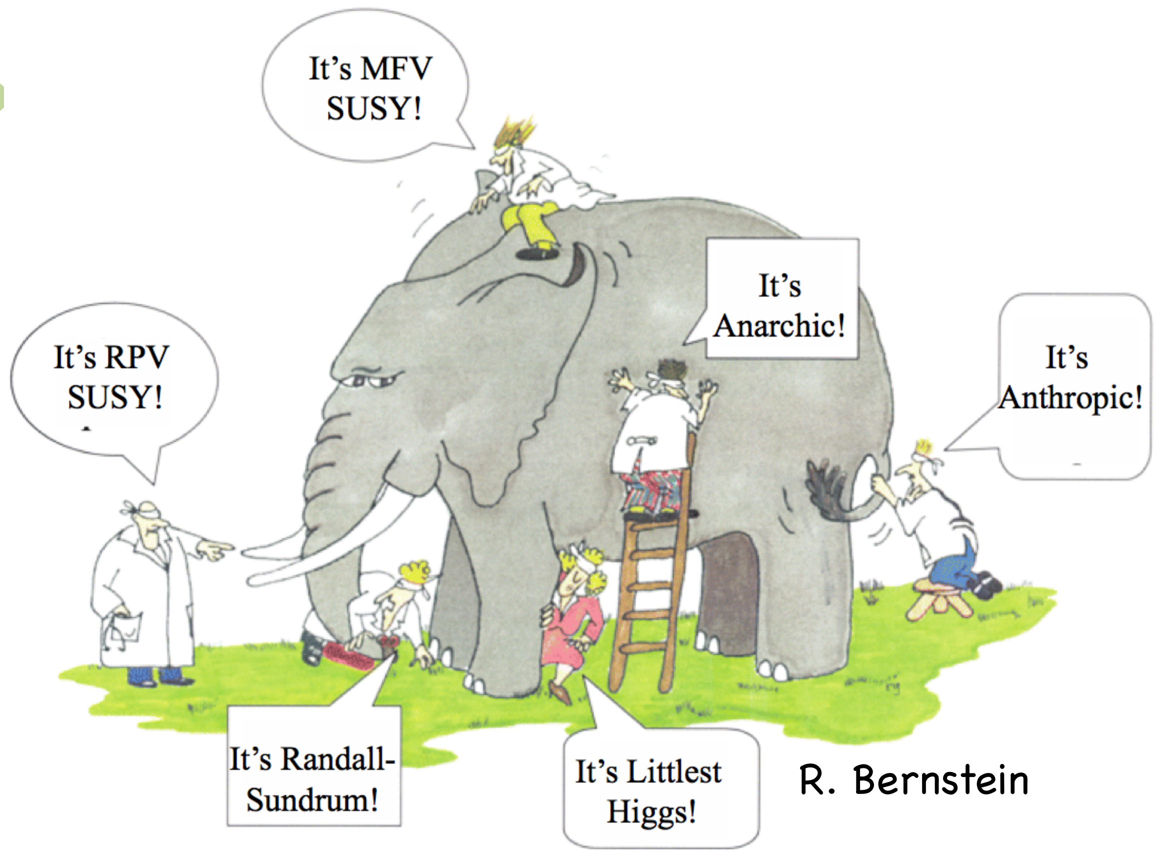
If a signal is seen, we will study the underlying New Physics using different target materials

Mu2e signal ?

Yes

Precision measurement if necessary

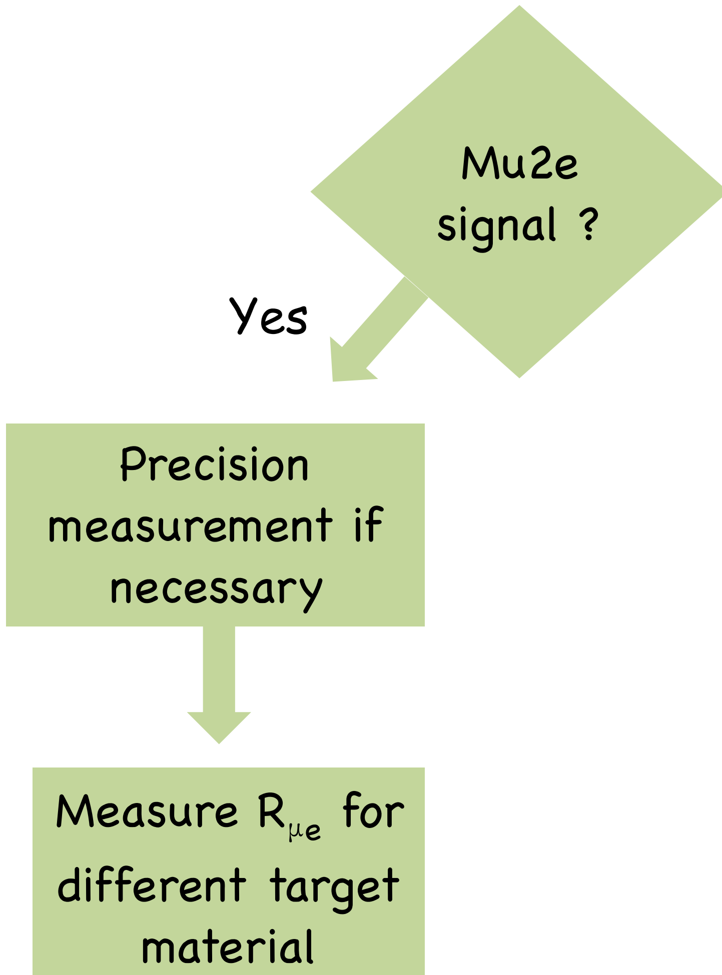
Measure $R_{\mu e}$ for different target material



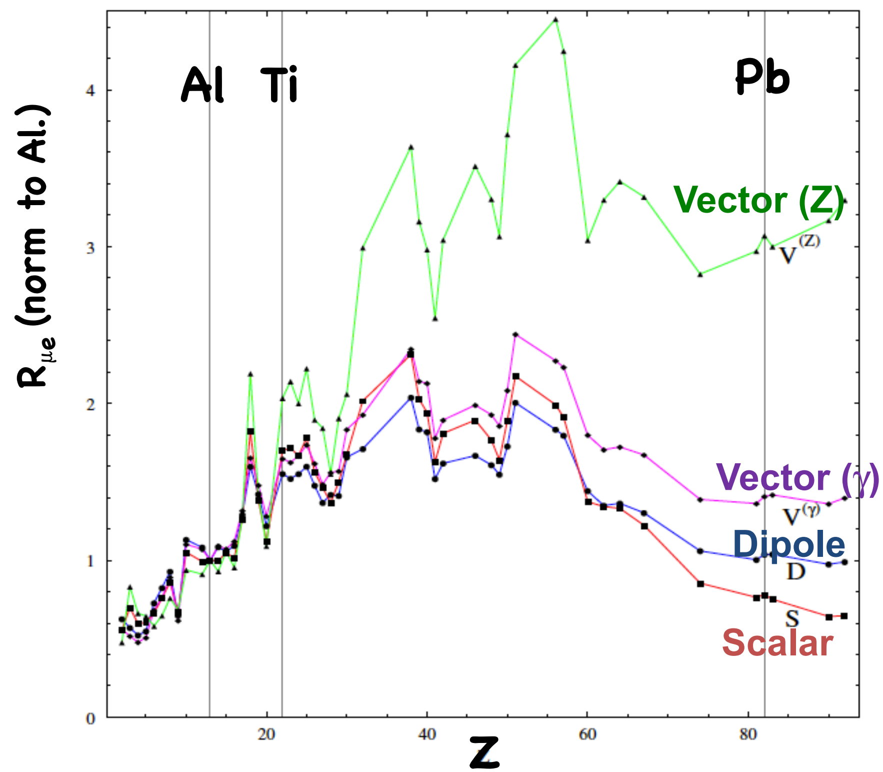
R. Bernstein

The Future: Next Generation Experiment

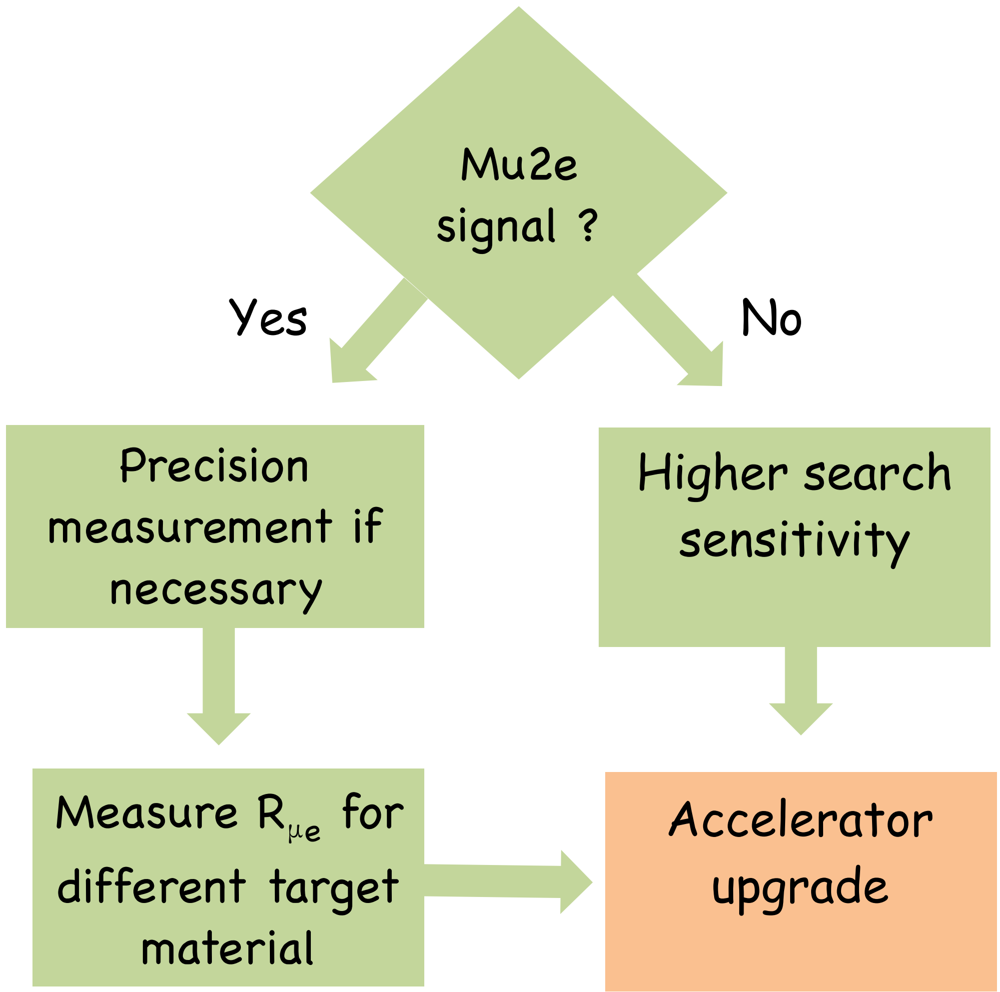
If a signal is seen, we will study the underlying New Physics using different target materials



Cirigliano, *et al*, PRD **80**, 013002 (2009)



The Future: Next Generation Experiment



A next generation Mu2e experiment is well motivated in all scenarios

We will study the underlying New Physics if a signal is seen

or

Improve the experimental sensitivity

Either way, we will need to Upgrade the accelerator to get more protons!

To read about the upgraded Mu2e experiment, see arXiv:1307.1168

Summary

- Mu2e will search for the neutrinoless conversion of a muon into an electron within the vicinity of a nucleus, $\mu N \rightarrow eN$
- Mu2e will have unprecedented sensitivity to a plethora of New Physics phenomena with mass scales up to 10,000 TeV, which is far beyond the mass scales that are accessible at the LHC or future colliders
- The goal of Mu2e is to discover charged lepton flavor violation, thereby providing unambiguous evidence of physics beyond the Standard Model
- If no signal is found, mu2e will increase the current sensitivity limit on $R_{\mu e}$ by a factor of 10,000 and exclude a vast collection of New Physics models
- Under any outcome, a next-generation Mu2e experiment is well motivated
- Construction is underway with data collection scheduled for 2021

Concluding Remarks

High Energy Physics is at a crossroads

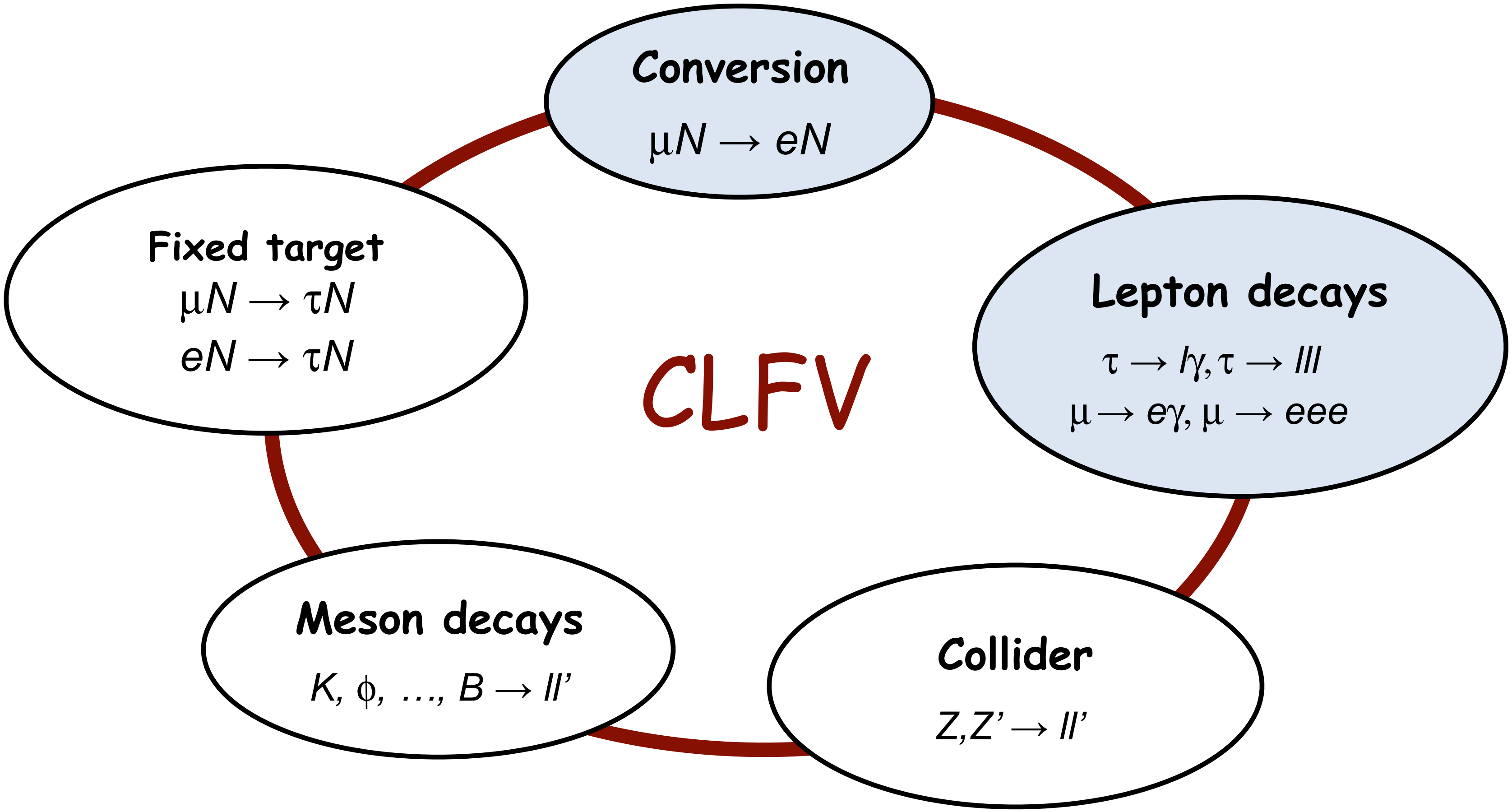
- We know that the Standard Model is incomplete
- There are many ideas about what a more complete model might look like
- But we don't know which is the right one…

Concluding Remarks

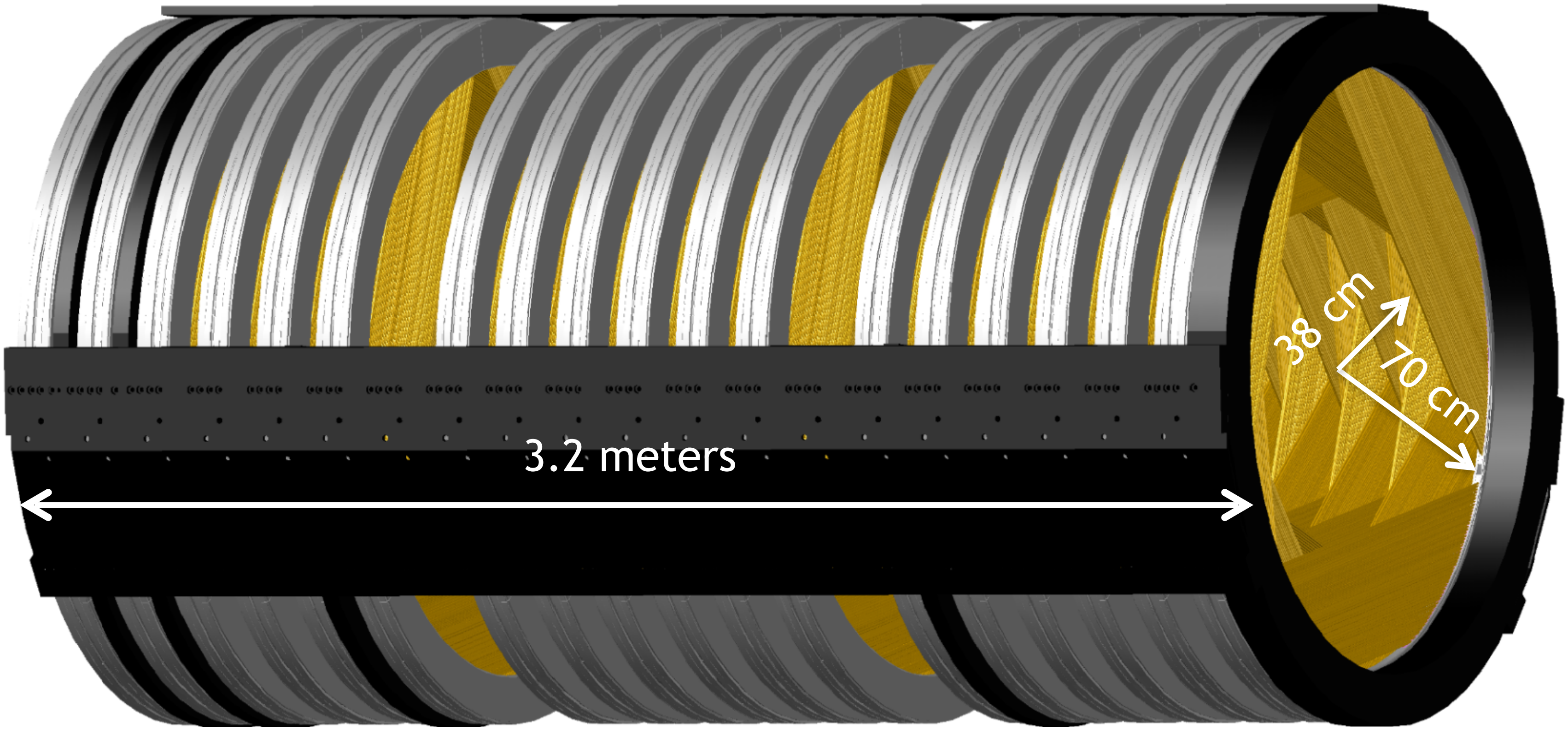
Fermilab's Mu2e experiment is designed to discover which direction is the right one


Questions?
http://mu2e.fnal.gov/
jbono@fnal.gov

Current and Proposed Searches for CLFV

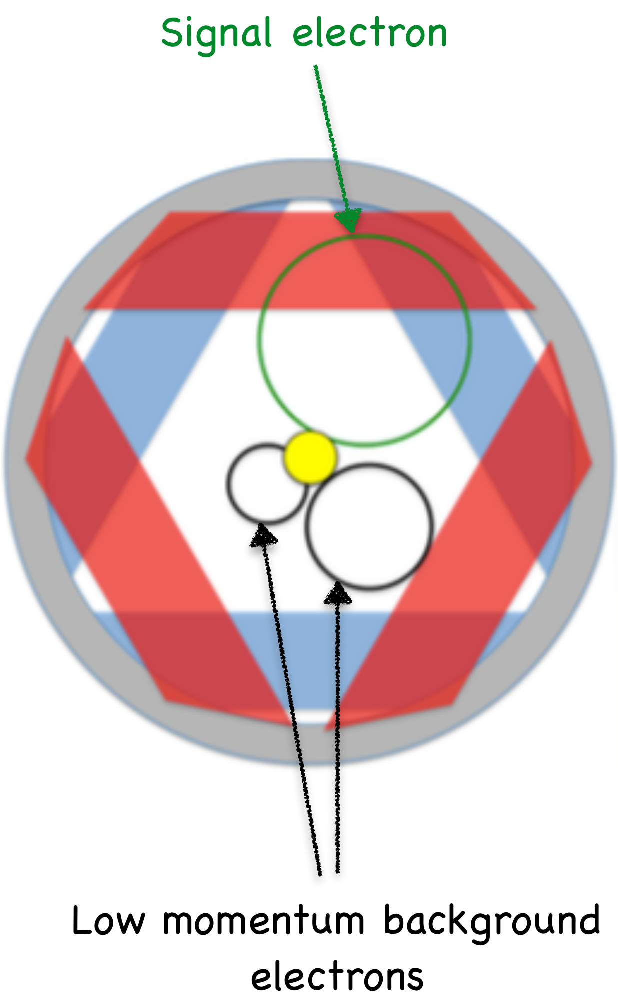


Tracker: Basic Design



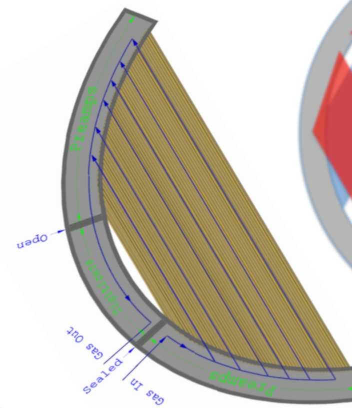
Tracker: Basic Performance Requirements

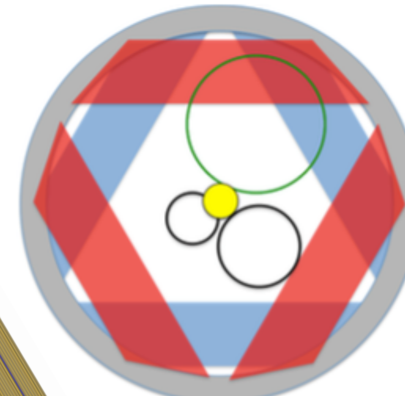
- Minimize energy loss and multiple scattering
  - Low mass straw tube design
- Momentum resolution σ < 180 KeV/c @ 105 MeV/c
- Precision alignment
  - 75 μm wire position accuracy relative to detector coordinates
- Blind to low momentum (decay-in-orbit) background
  - Hole in center of tracker
- Operate in vacuum (10^{-4} torr)
  - Combined outgassing (after 6 days) and leak rate less than 7 ccm
- Reliable
  - Operate for 1 year without access
  - Negligible risk of catastrophic failure
  - 10 year lifetime

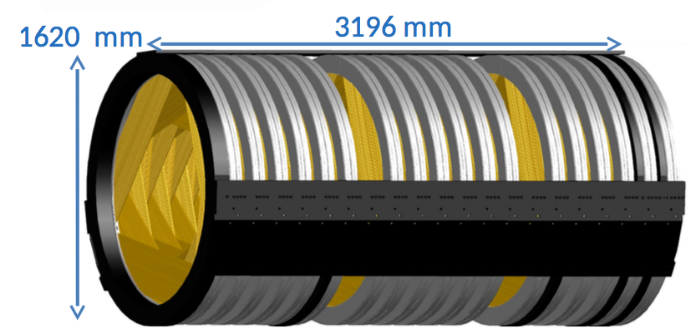


Tracker: Basic Design

- 5 mm diameter mylar straws
  - Filled with Ar/CO2 80:20
  - 15 μm wall thickness
  - Al: 500 Å inside and out. Au: 200 Å inside
- 25 μm gold plated tungsten wire
  - Operate at ~1450 V
- 96 straws per panel, 6 panels per plane
  - 30 degree rotations for stereo output
  - Tracking region: 380 < r < 700 mm
- 2 planes per station, 18 stations total

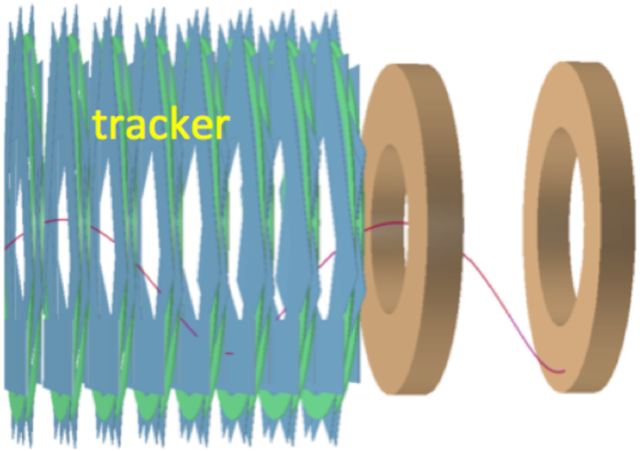


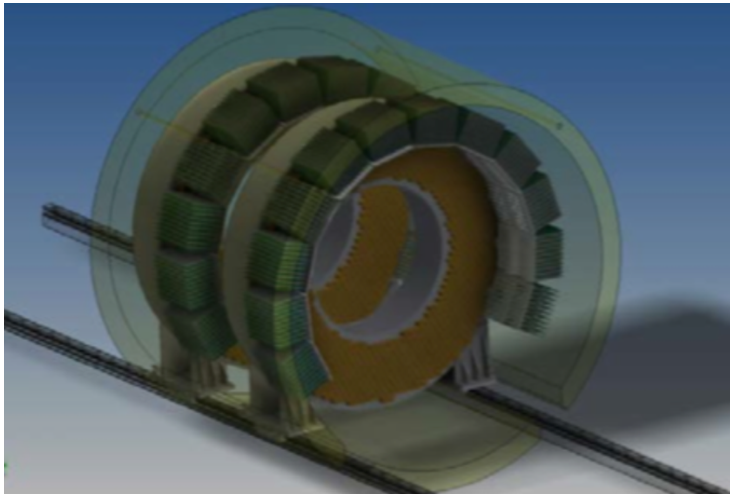




Calorimeter: Basic Performance Requirements

- Provide particle identification for distinguishing muons from electrons
- Seed for track recognition algorithm to improve track-finding efficiency
- Provide a tracker independent trigger to reduce data rates
- Operate in 1T field and in vacuum (10^{-4} Torr)
- Radiation hard up to 100 krad, 10^{12} n/cm^2
- Under 500 ps timing res and ~5% energy res @100 MeV
- Position resolution of ~1cm
- Almost full acceptance for conversion electron signal

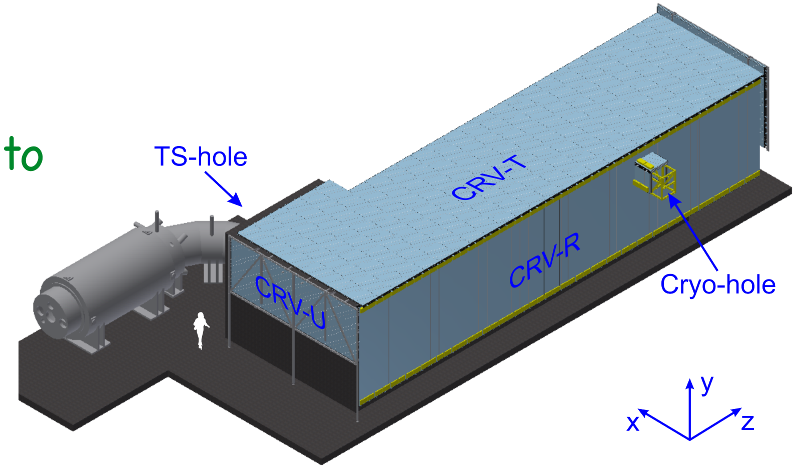




Cosmic Ray Veto: Basic Performance Requirements

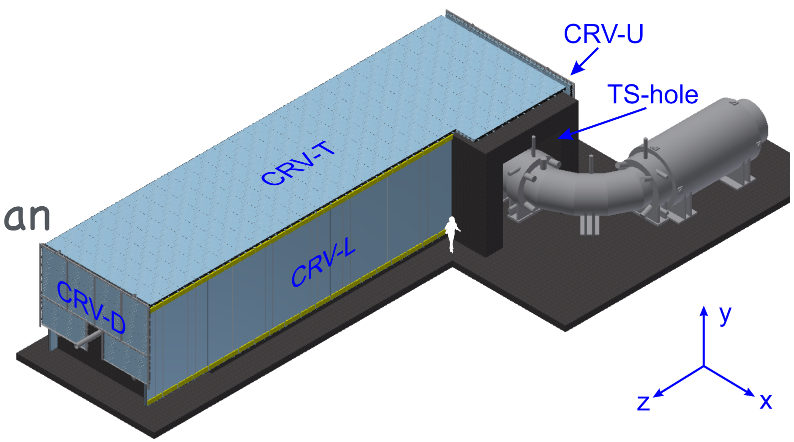
Fundamental

- Reduce the conversion-like cosmic background to less than 0.10 events over the course of the entire run at a 90% confidence level
- Provide a cosmic-ray trigger primitive to the data acquisition system (DAQ)
- Produce less than 10% dead time
- Use less than 20% of the DAQ bandwidth



Derived

- Exhibit excellent efficiency for identifying cosmic-ray muons: inefficiency must be less than 1×10^{-4}
- 5 ns timing resolution
- Large area: must cover the entire detector
- Gaps must be small and few
- Ability to handle high rates



Flavor Violation in Supersymmetric Models

★ Vanishingly small effects

★★ Moderate, but visible effects

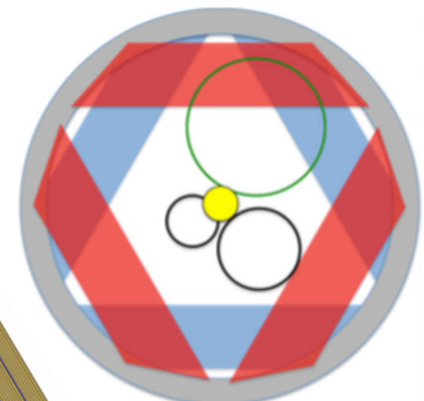
★★★ Large effects

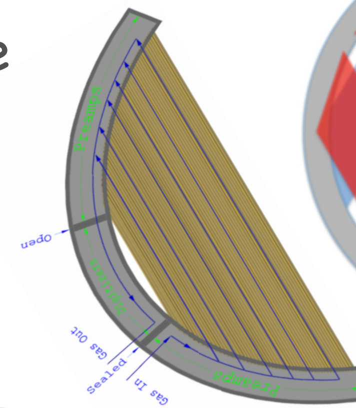
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★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

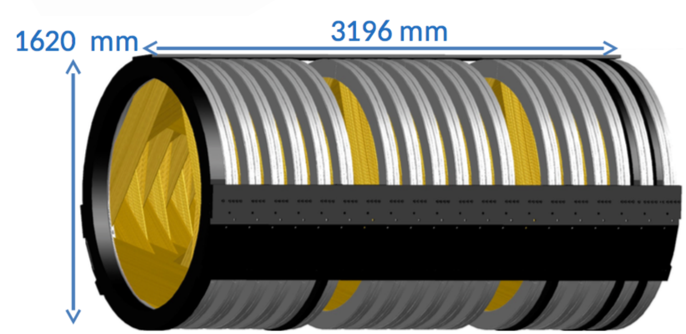
Altmannshofer, Buras, *et al*,
Nucl.Phys.B830:17-94, 2010

Tracker: Basic Design

- 5 mm diameter metalized mylar straws
  - Filled with Ar/CO2 80:20
- 25 μm gold plated tungsten wire
  - Held at ~1450 V
- 96 straws per panel, 6 panels per plane
- 2 planes per station, 18 stations total







Mu2e Support

*"The existence of new particles that are too heavy to be produced directly at high-energy colliders can be inferred by looking for quantum influences in lower energy phenomena… Some **notable** examples are a **revolutionary** increase in sensitivity for the transition of a muon to an electron in the presence of a nucleus **Mu2e** (Fermilab)…"*

- 2014, Report of the Particle Physics Project Prioritization Panel (P5)

Mu2e Support

"The existence of new particles that are too heavy to be produced directly at high-energy colliders can be inferred by looking for quantum influences in lower energy phenomena… Some notable examples are a ***revolutionary*** *increase in sensitivity for the transition of a muon to an electron in the presence of a nucleus Mu2e (Fermilab)…"*

- 2014, Report of the Particle Physics Project Prioritization Panel (P5)

"The science of Mu2e is Critical to the DOE OHEP mission and is Ready to Construct."

- 2013, P5 (Highest endorsement)

"Mu2e should be pursued in all budget scenarios considered by the panel"

- 2008, P5 (Strong support)