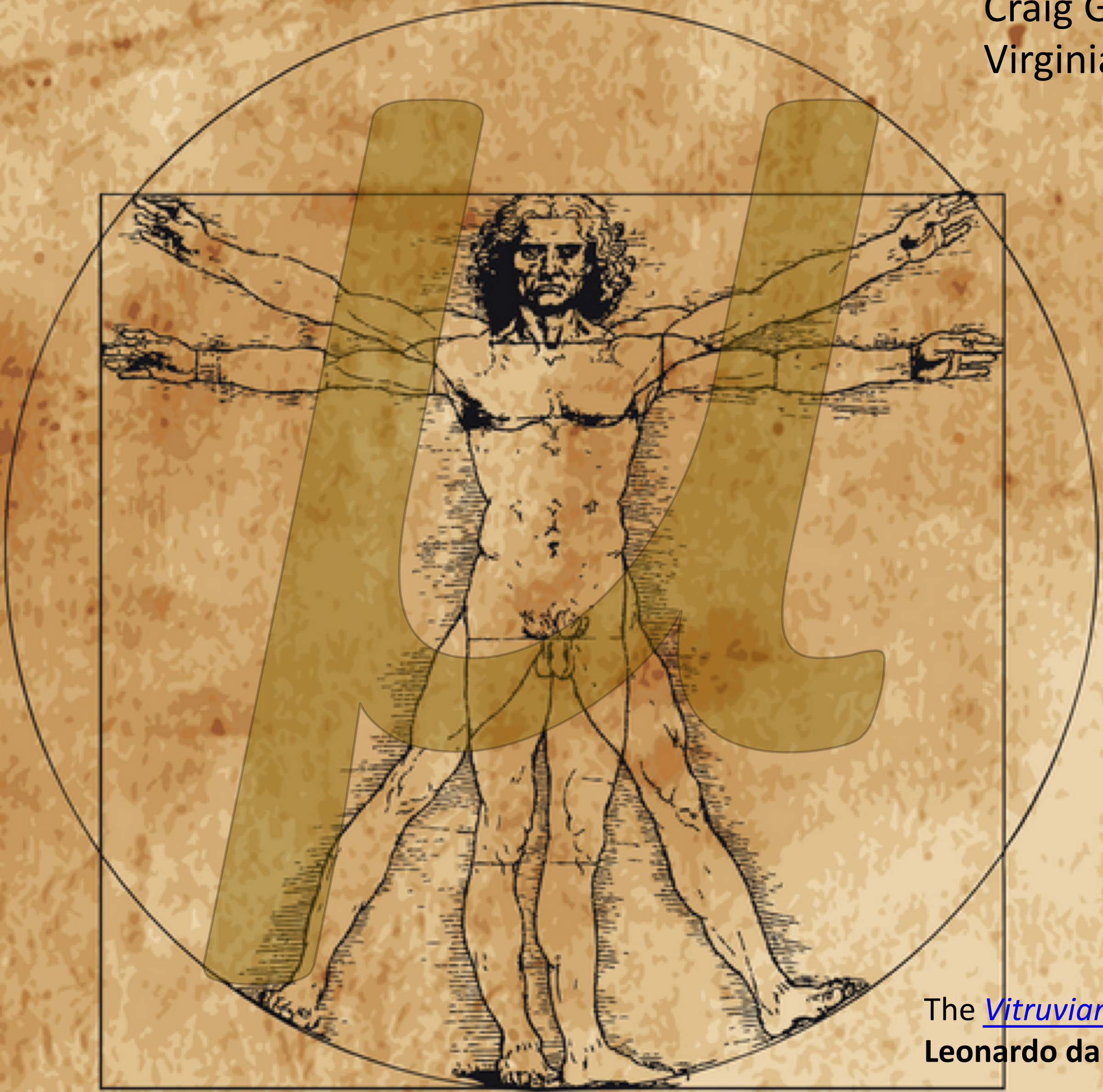
A Renaissance for Muon Physics

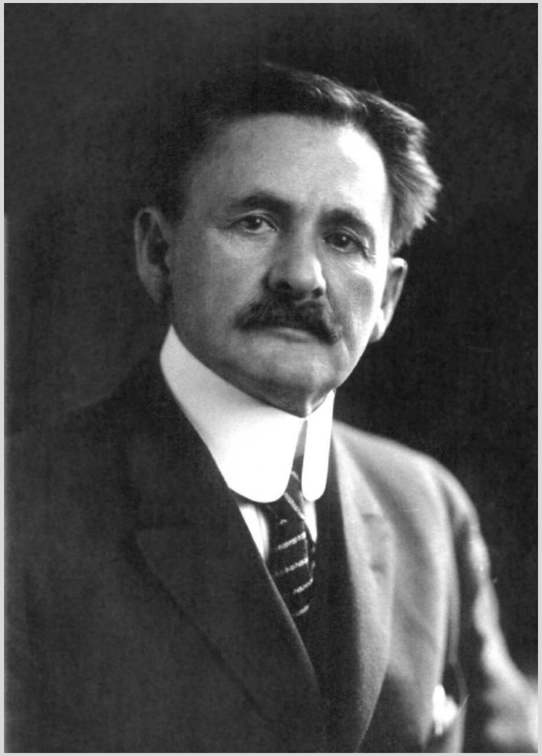
Who ordered that?

Craig Group
Virginia



The *Vitruvian Man* (c. 1485)
Leonardo da Vinci

Are we done with major discoveries?



Albert A. Michelson
~1896

“”””

While it is never safe to affirm that the future of Physical Science has no marvels in store even more astonishing than those of the past, it seems probable that **most of the grand underlying principles have been firmly established** and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice ... An eminent physicist remarked that the future truths of physical science are to be looked for in the sixth place of decimals.

“”””

1907 Nobel prize for his “optical precision instruments and the spectroscopic and metrological investigations carried out with their aid."

wikiquote.org

The birth of particle physics?

- 1897 Thompson’s study of “Cathode rays” emitted from a hot filament led to discovery of the electron.
  - q/m ratio much greater than any known ion.
  - Thompson suggested that these new particles were a fundamental part of the atom.


Sir J. J. Thomson

1906 Nobel prize ***“in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases.”***

“Classical” period of particle physics

- 1911: **Rutherford** discovered the nucleus through scattering experiments with alpha particles on a thin gold foil.
- 1914: **Bohr** model of the hydrogen atom
- Great, but the Helium nucleus (charge 2) was 4 times heavier than Hydrogen!
- 1932: **Chadwick** discovery of the neutron
- 1932: **Anderson** discovered the positron

- In parallel, the particle nature of the photon was “understood” with **Plank** (1900), **Einstein** (1905), and **Compton** (1923)

Note that Rutherford, Bohr, Chadwick, Anderson, Plank, Einstein, and Compton all won the Nobel Prize.

The picture seemed to be complete…

- So, by mid 1930’s **some physicists were even more confident that they were almost done with fundamental discoveries**!
  - After all, the nucleus, the electron, and the photon were all that were needed to describe everything. Almost…

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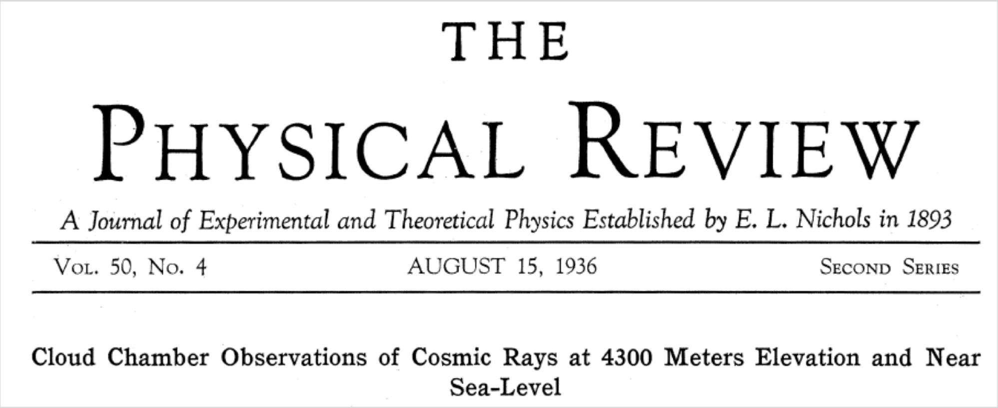
- **What force holds the nucleus together?** Protons repel one another – there must be some “strong” attractive force to overcome this!
- **Yukawa** proposed a new particle to carry the strong force, must be heavy with short lifetime to ensure that it only acted over nuclear distance scales. Estimated mass to be about 150 MeV.

A Cosmic Discovery

- In 1936 a new particle (+ and – charge) was discovered in cosmic rays (Anderson and Neddermeyer).
- This was the muon - initially called mu meson or mesotron for its middle mass between electron and proton.
- It was **initially thought to be Yukawa's particle** (mass of ~150 MeV). Mystery solved?



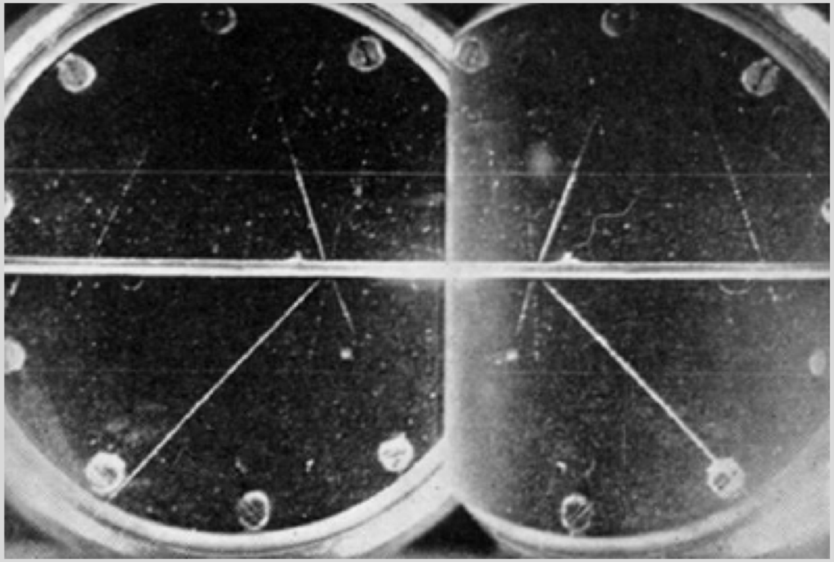
THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 50, NO. 4 AUGUST 15, 1936 SECOND SERIES

Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level



Anderson used photographs of cloud chambers to discover the positron and the muon.

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- However, it took 10 years (1947) before it was shown that these negatively charged particles **did not capture on a light nucleus** - instead decayed (Conversi, Pancini, and Piccioni).
- This meant that the strength of its interaction with the nucleus was many order's of magnitude (~10^{12}) too weak to be the Yukawa particle!
- There was intense interest in the field as summarized in a note by Fermi, Teller, and Weiskopf (1947).

→ **Not strongly interacting enough to be the Yukawa particle!**

Fermi and Anderson got Nobel Prizes but from other efforts.

Who ordered that?

- It seemed that all that was needed to fill the gap in our knowledge was the Yukawa particle.
- Yet, the muon was discovered in cosmic rays instead of the Yukawa particle.
- This was such a shock that I. Rabi famously said "Who ordered that?" (when he understood that the muon was not the expected particle responsible for the strong force.)

Isidor Isaac Rabi

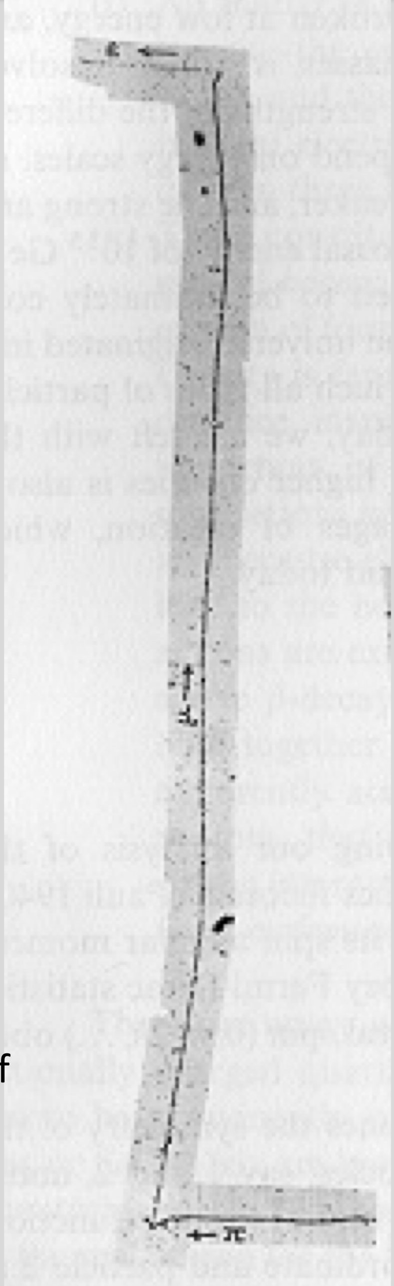
Rabi won the Nobel prize for his "*resonance method for recording the magnetic properties of atomic nuclei.*" NMR

Another Cosmic Discovery

- By doing the cosmic ray experiment on a mountain top with photographic emulsions, Powell et. al. (1950) was able to detect another particle slightly heavier than the muon.
- They observed the new particle decay into a muon.
- The constant range of the muon indicated a two-body decay.
- The 2nd particle was not unobserved.
- The observed particle was the pion - the true Yukawa particle!

But what about the muon?

→ Powell also showed that it was decaying into an electron in a 3-body decay! No other particles seen.



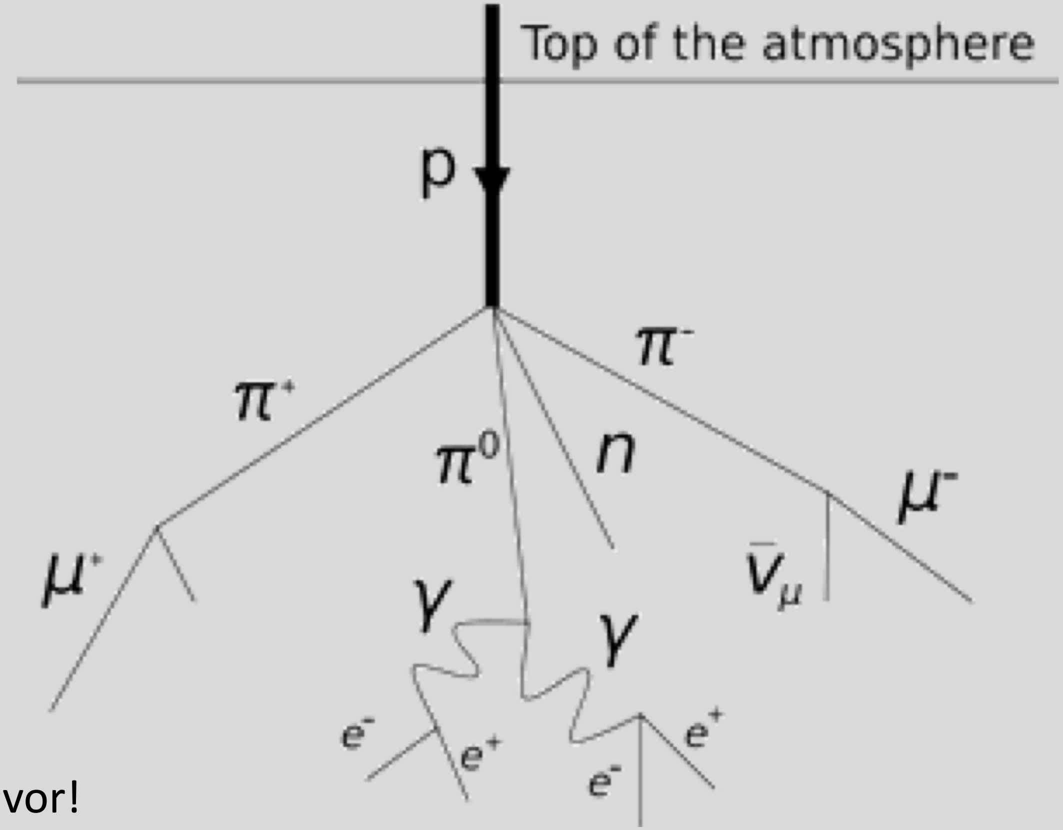
Powell won Nobel prize in 1950 for his "development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method"

Cosmic Rays – Muons and Pions

Finally, in 1950 it became clear that cosmic rays were composed of muons and pions.

$$\begin{array}{lllllll} \pi^+ & \rightarrow & \mu^+ & + & \nu_\mu & & \\ & & \downarrow & & & & \\ & & e^+ & + & \nu_e & + & \bar{\nu}_\mu \end{array}$$

Note: neutrinos not discovered until 1959.
Cowan and Reines
(predicted by Pauli in 1931 due to beta decay)



Later observed:

Decays seem to conserve lepton flavor!

- High-energy protons bombard the atmosphere from deep space - mostly from supernova.
- Pions are produced but decay quickly to muons - more remain if high on a mountain.
- Muons mostly reach ground level before decay - ~100 muons per m^2 per second.

What was a muon?

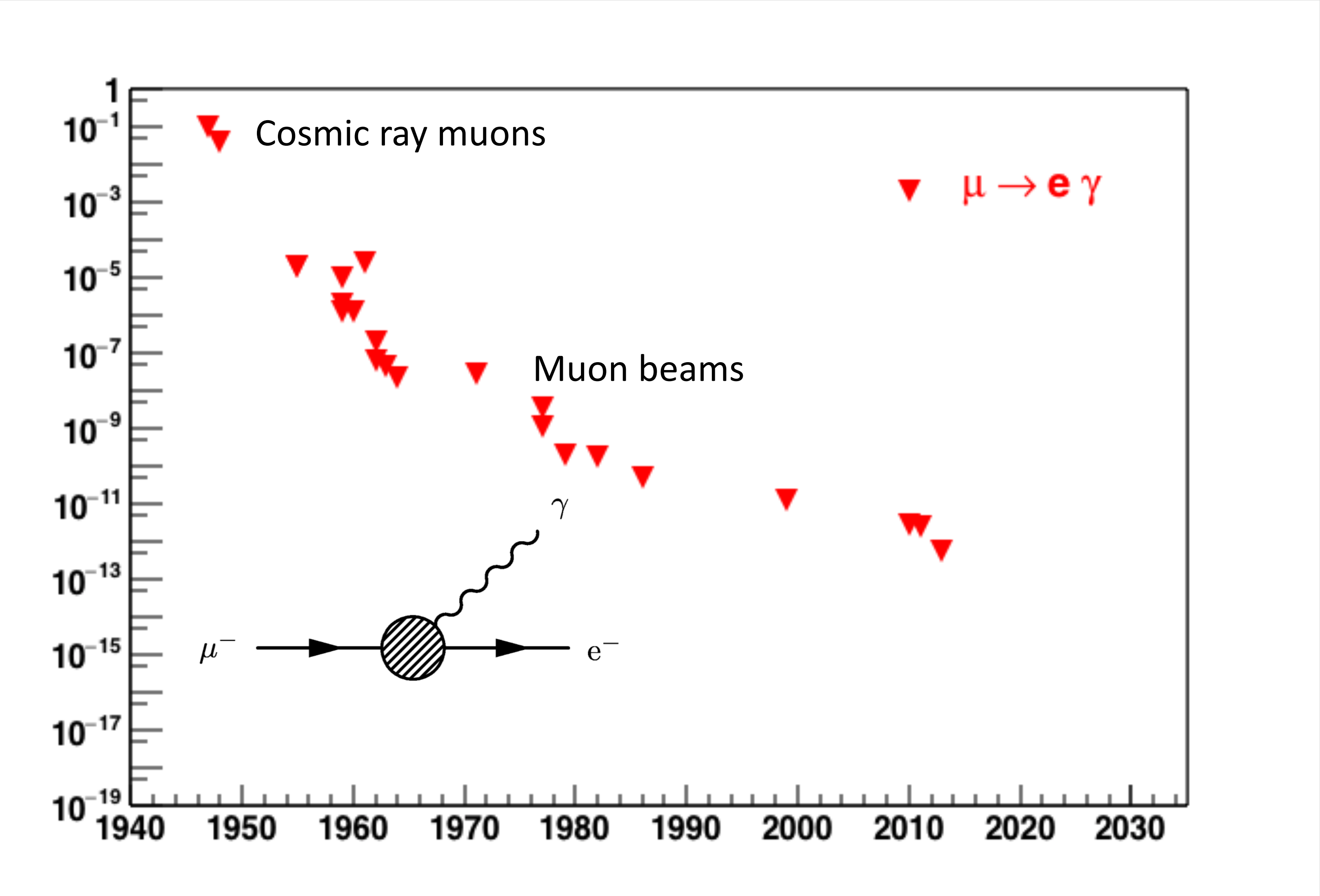
- Pontecorvo (1947) suggested that the muon may have been some kind of "isomer" of the electron.
  - If so, he suggested you would see the decay $\mu \rightarrow e\gamma$.
  - He and Hincks performed the first search for $\mu \rightarrow e\gamma$ in 1948.
- By 1950, it was clear that this decay did not occur at the percent level ($<10^{-2}$). **Lepton flavor matters!**

→The birth of charged lepton flavor conservation!

- Now we know that the two neutrino hypothesis is required to understand these decays.
- Note: the 2nd neutrino was not discovered until 1962!

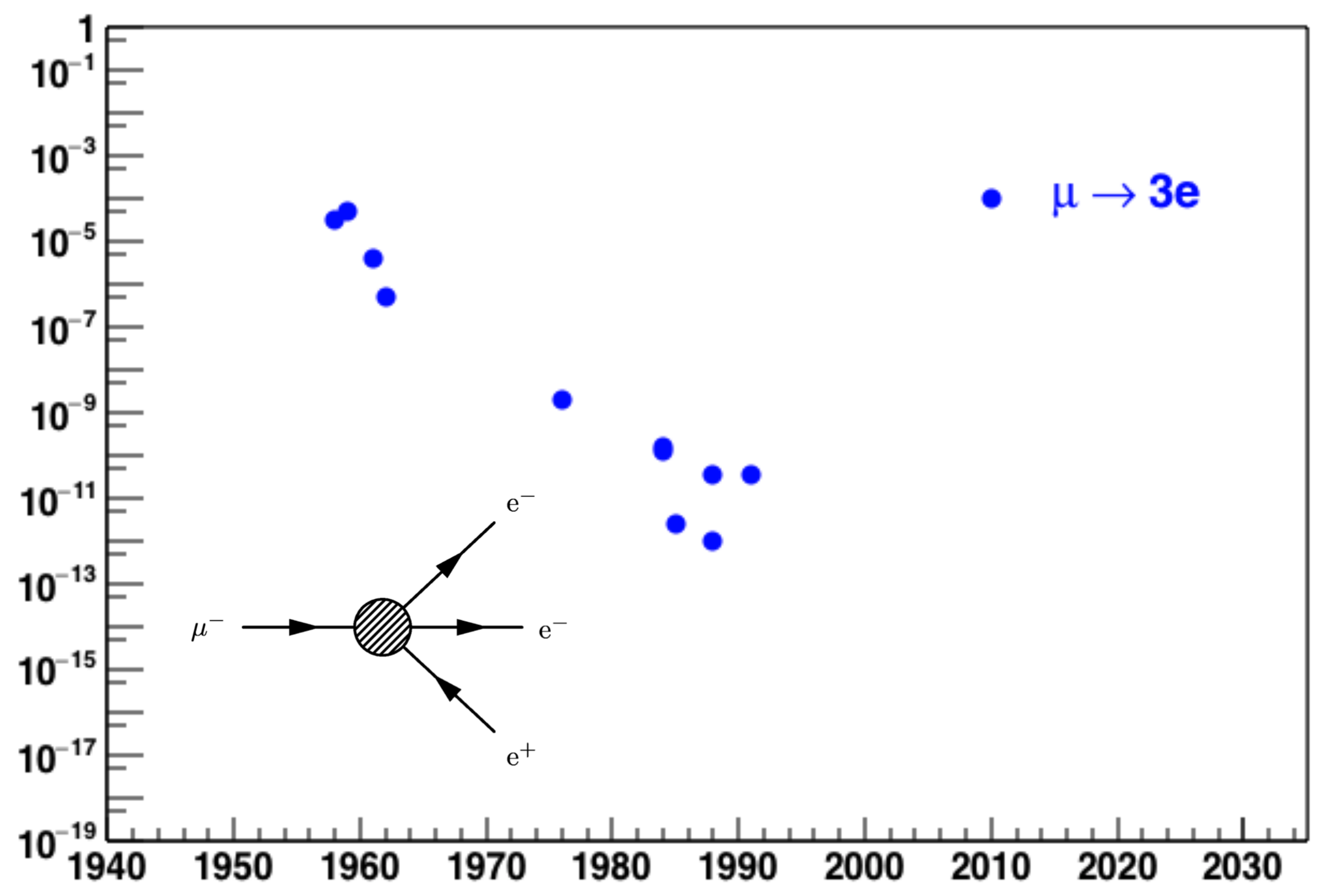
Note: The first evidence for a second generation of quarks also came in 1947.

History of CLFV Searches



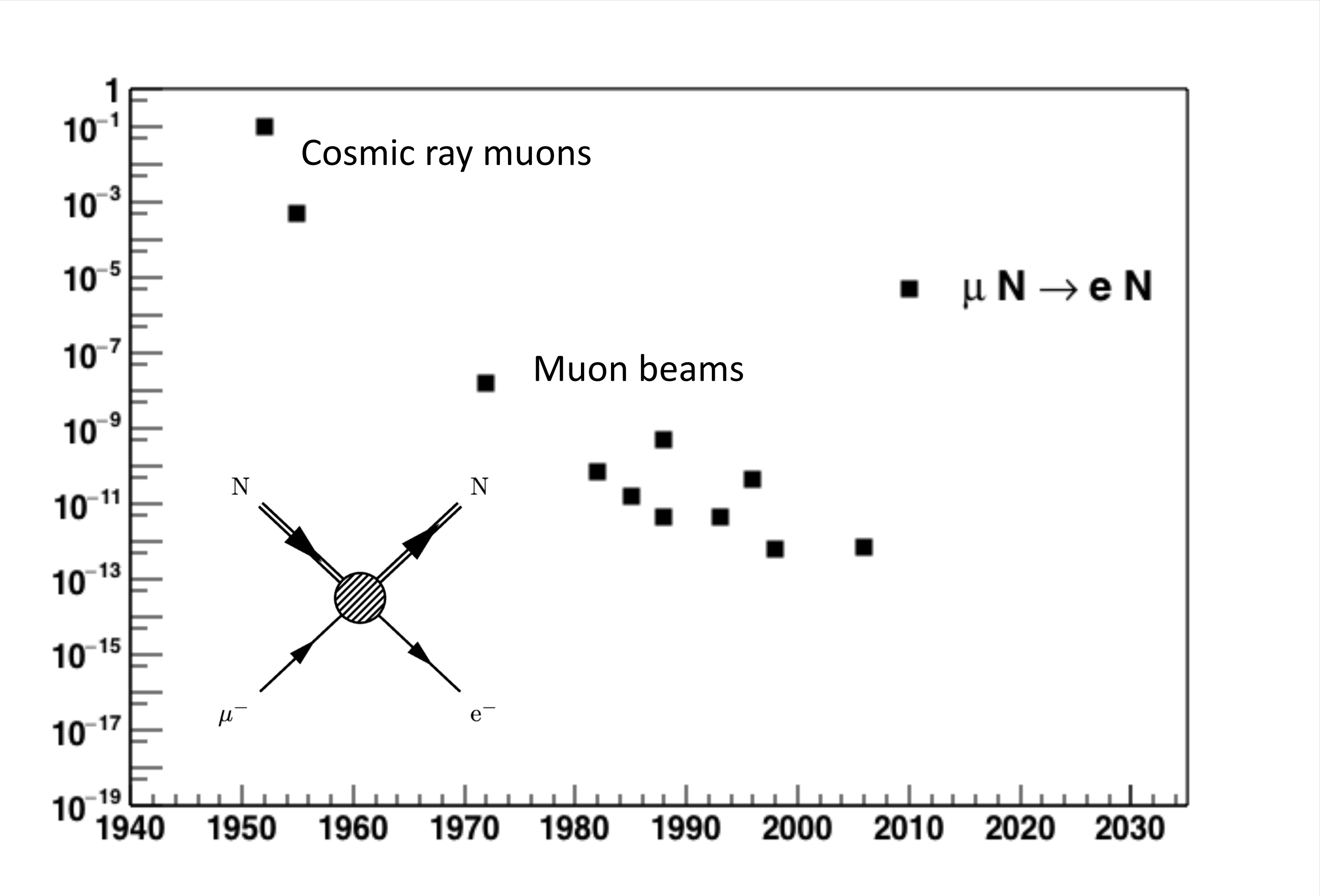
MEGA, MEG (PSI), and others…

History of CLFV Searches



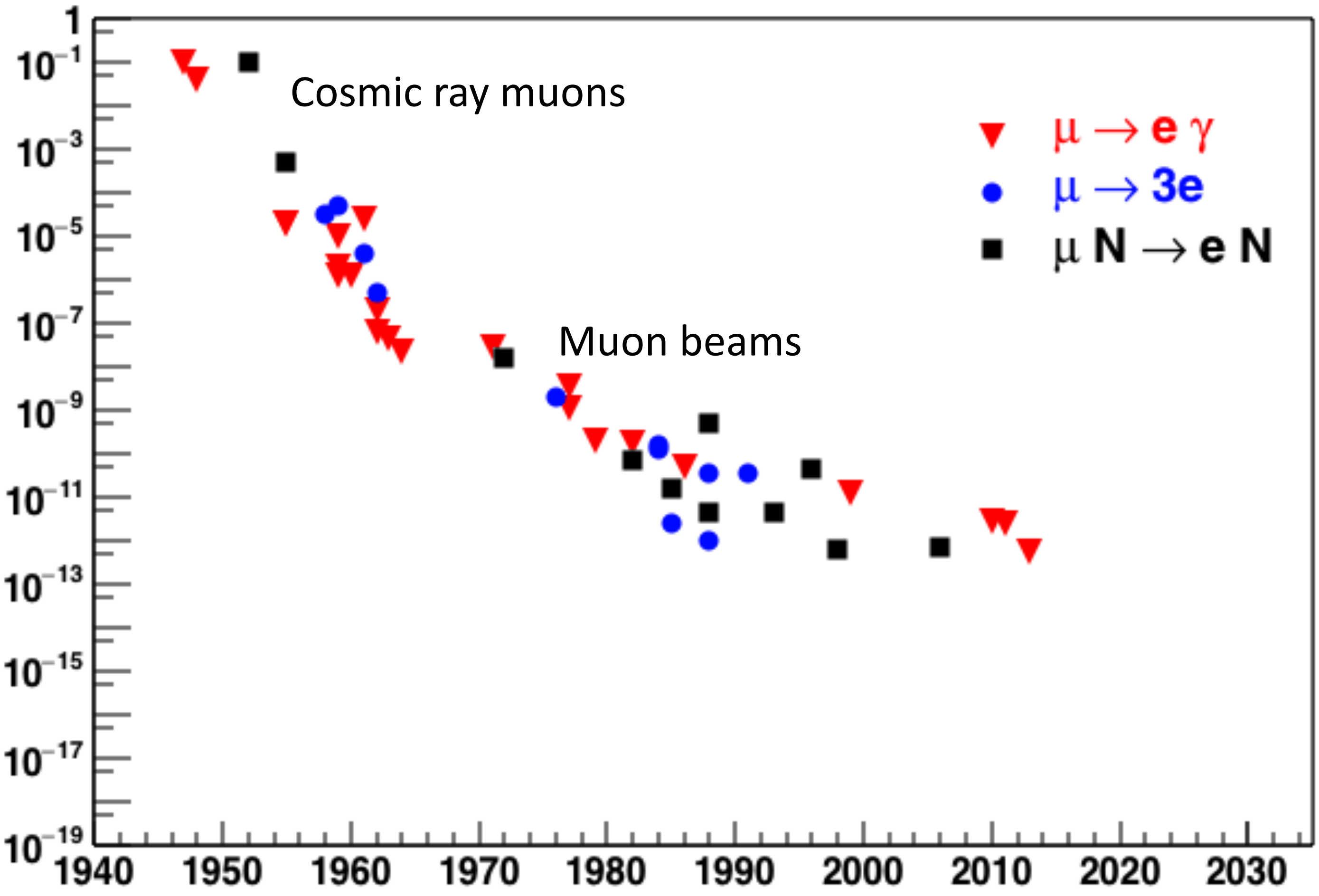
Mu3e, PSI

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?

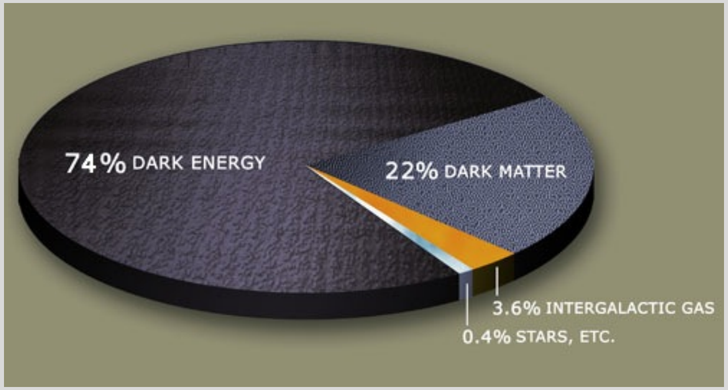
The Standard Model is Incomplete

Theory

- Quantum theory of gravity
- Origin of neutrino mass hierarchy
- Solution to hierarchy problem ⇨ supersymmetry?

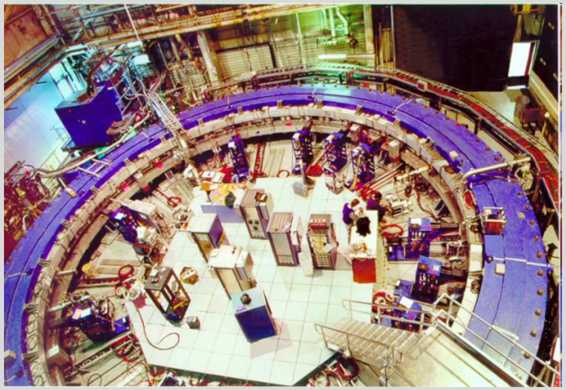
Cosmology

- Matter-antimatter asymmetry in the universe
- Dark matter
- Dark energy



Experiment

- Neutrino mass ⇨ first evidence of physics beyond the standard model?
- Only occasional hints appear: muon g-2, lepton universality, CP phases in B_s mixing, D_s decay rates, Top AFB



Where is the new physics?

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We don’t know!

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We don't know!

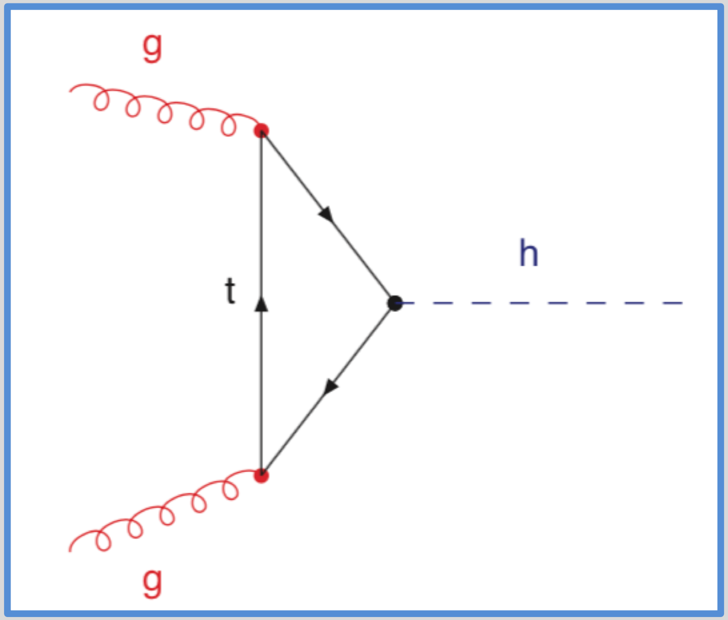
We still might find the new physics at the LHC. Maybe not.

There is no guarantee that a new accelerator 10X or 100X the LHC energy will see anything new: maybe just confirm the Standard Model at a new energy scale.

And accelerators are not cheap: a 10X the LHC energy accelerator would cost tens of billions of dollars and take several decades to realize..

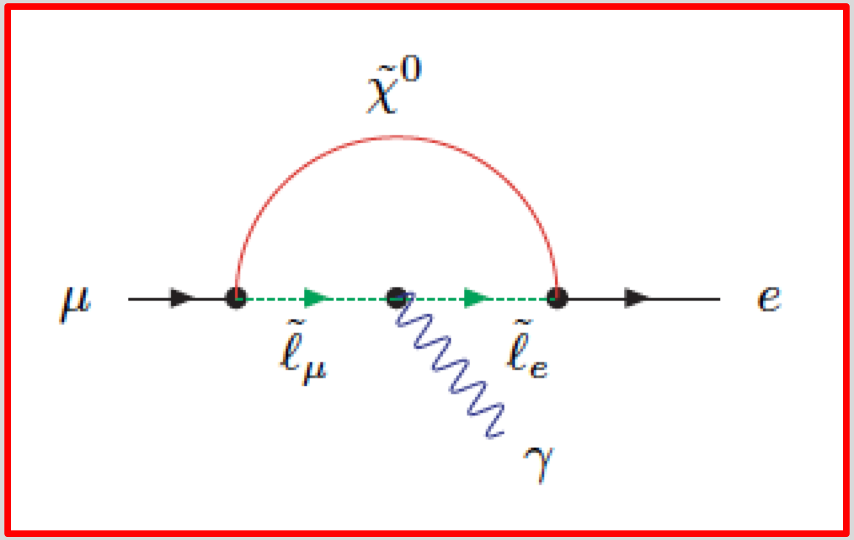
Two complimentary ways to search:

Direct Searches:
High Energy is crucial



Produce and study the heavy particles directly.

Indirect Searches:
High intensity is crucial



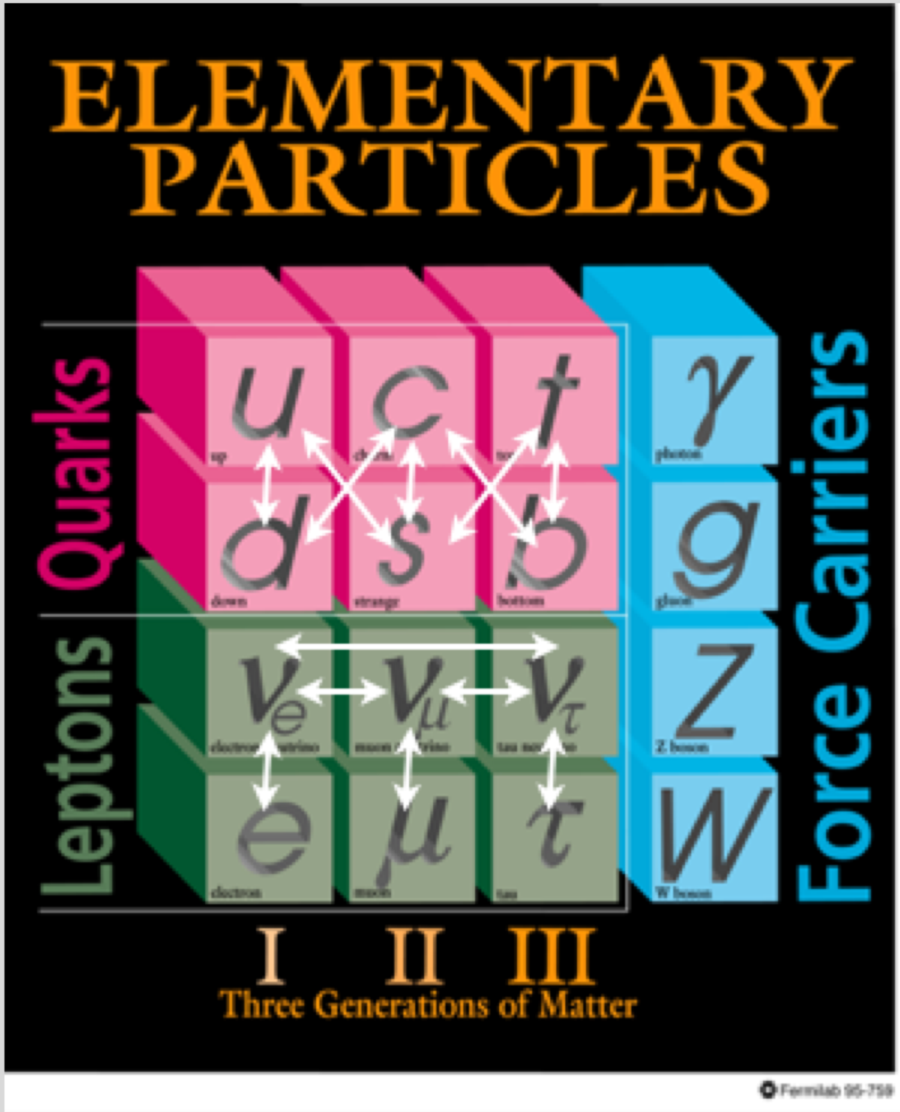
Heavy particles only contribute through loop effects.

Charged Lepton Flavor Violation (CLFV)

Quarks mix…
Neutrinos mix…

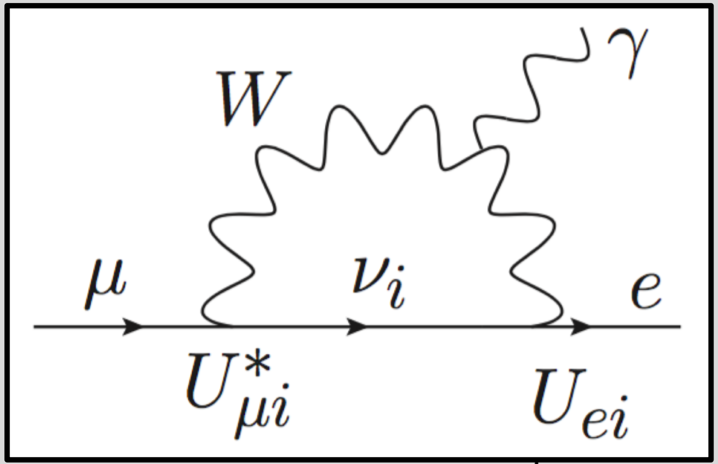
But we have not seen it in charged leptons?

Most “natural” new physics models predict we should have seen it already.



In fact, charged leptons do mix!

- Neutrinos have mass!
- Individual lepton numbers are not conserved!
- Therefore, Lepton Flavor Violation occurs in Charged Leptons! (assuming Dirac mass term)

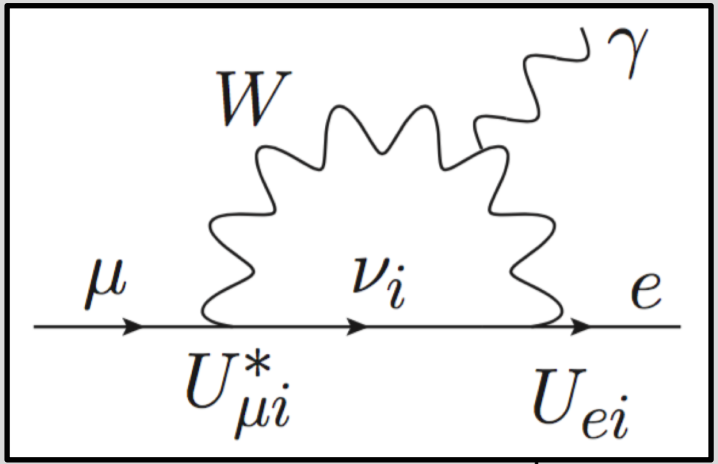


$$\mathrm{BR}(\mu \to e\gamma) \quad = \quad \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

[Petcov, ’77]

Advantage of Charged Leptons

- Neutrinos have mass!
- Individual lepton numbers are not conserved!
- Therefore, Lepton Flavor Violation occurs in Charged Leptons! (assuming Dirac mass term)



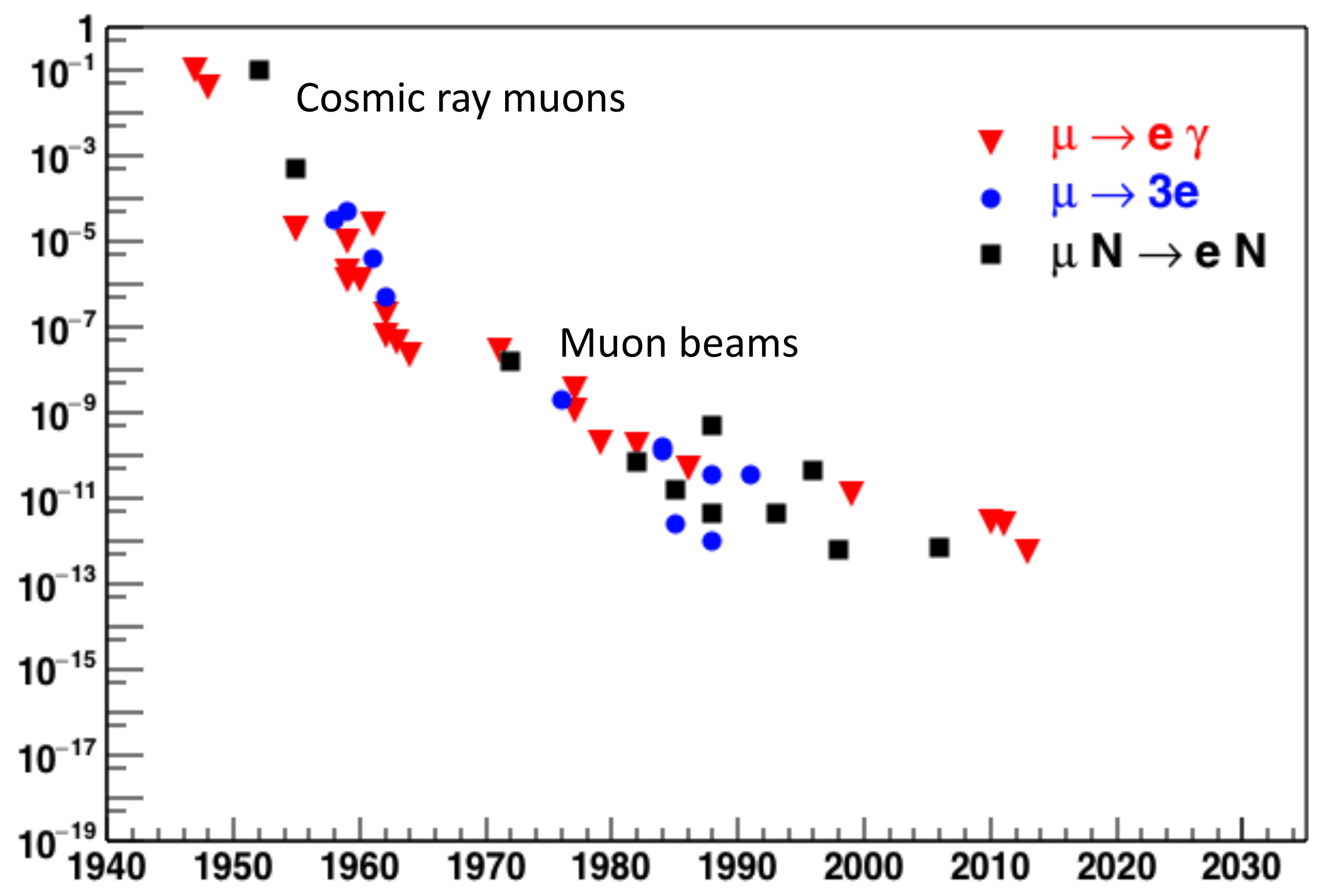
NO SM PHYSICS BACKGROUND! Observation is unambiguous sign of new physics!

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

(Too small!)

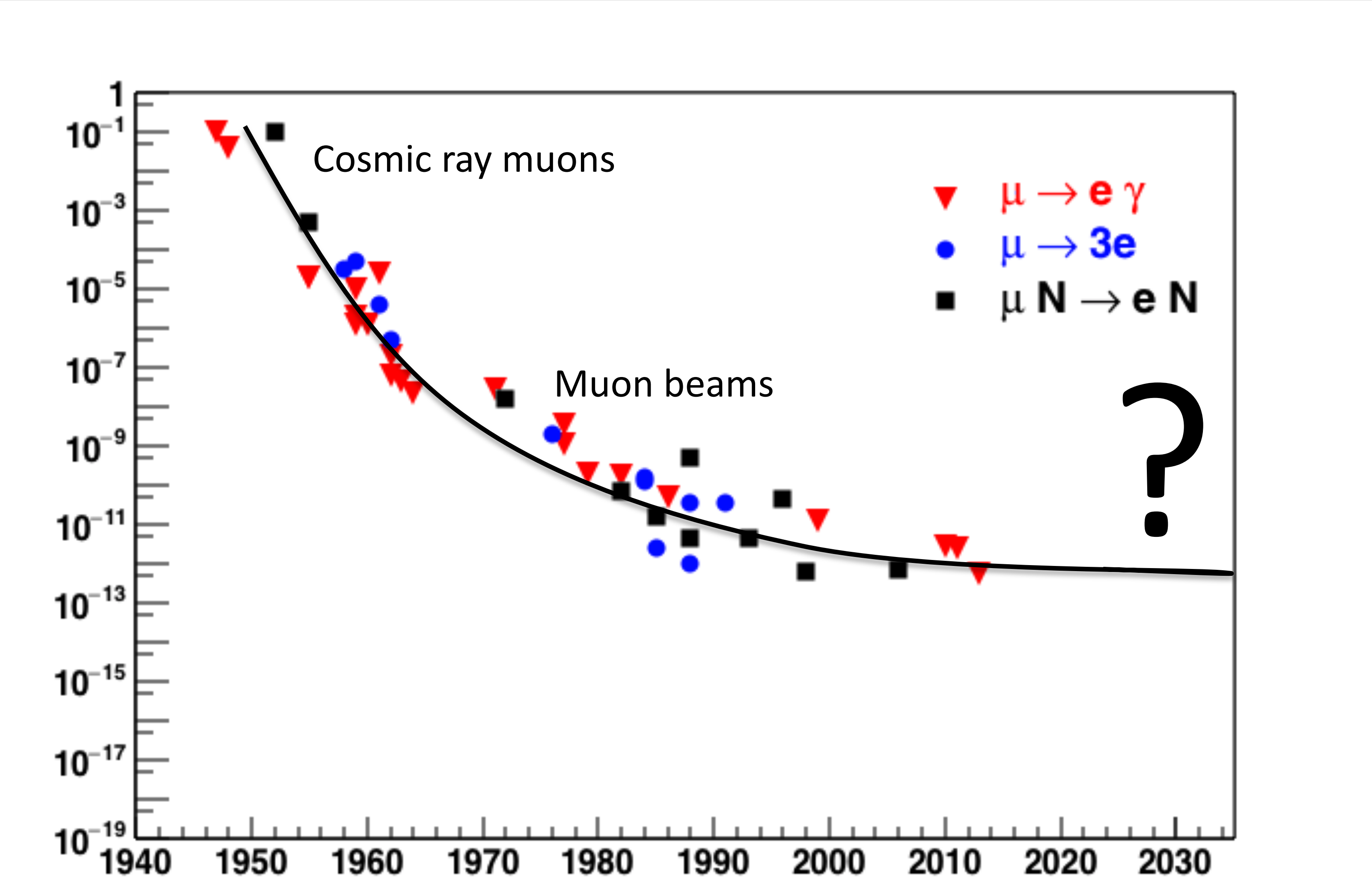
[Petcov, ’77]

History of CLFV Searches



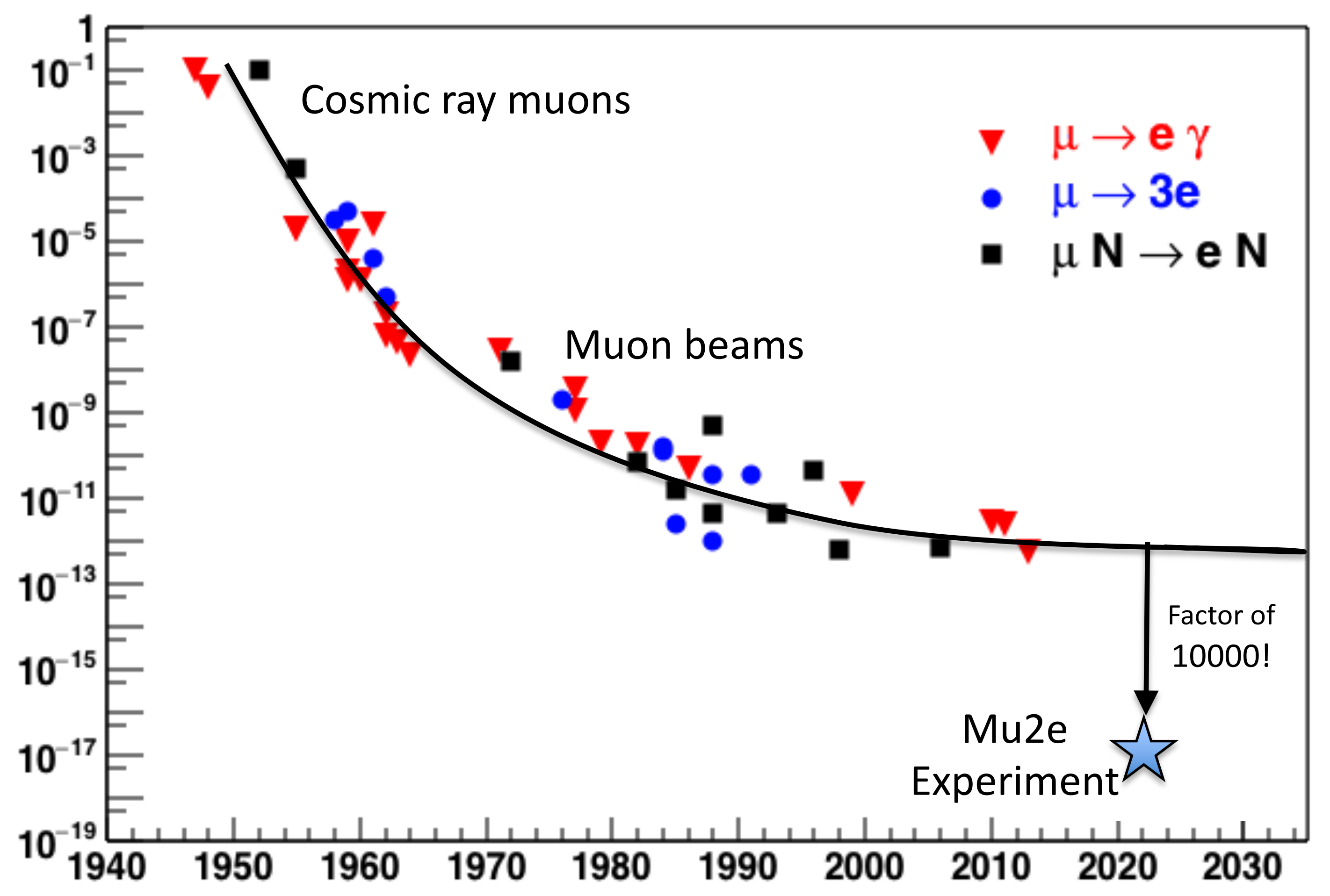
We did not observe CLFV so far - why don't we just give up and do something else?

Future of CLFV Searches?



It looks like we have run out of gains- why don't we just give up and do something else?

Future of CLFV Searches!!!

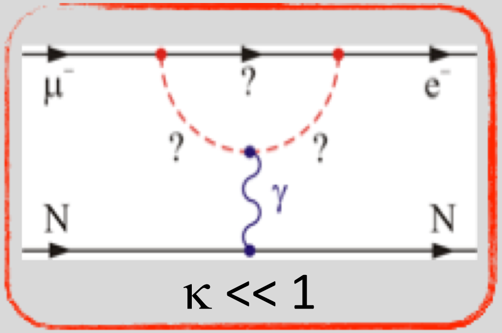


Future CLFV experiments like Mu2e expect huge gains in sensitivity!

So, why is that interesting?

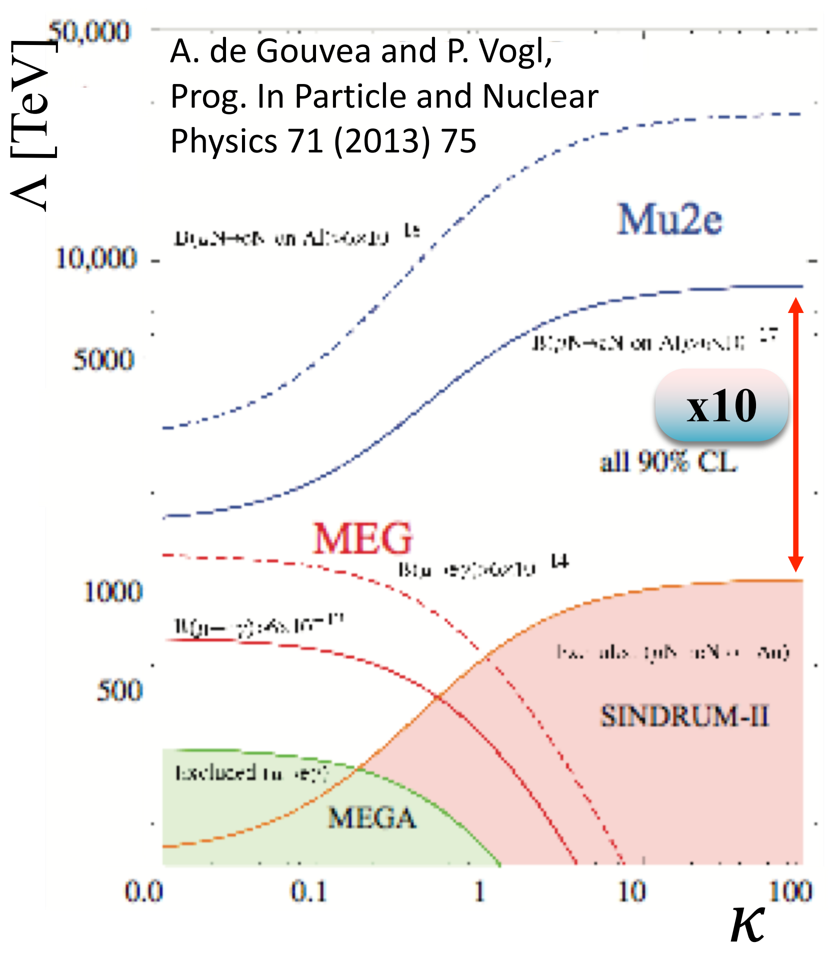
Effective CLFV Lagrangian

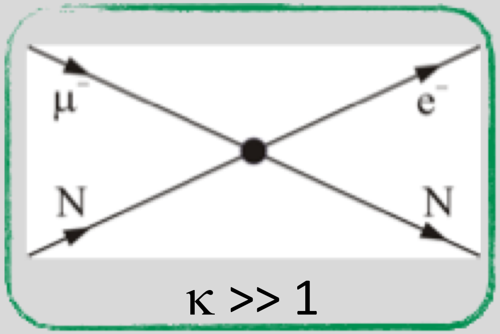
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$



Magnetic moment type operator

State	μ→eγ	μ→e
Sensitive	Yes	Yes


A. de Gouvea and P. Vogl, Prog. In Particle and Nuclear Physics 71 (2013) 75

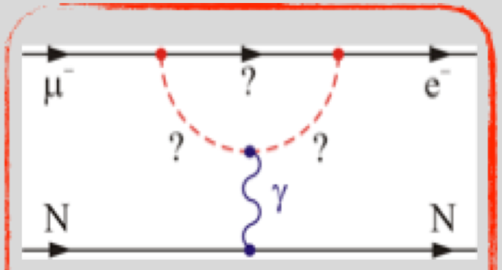


Contact term operator

State	μ→eγ	μ→e
Sensitive	No	Yes

Effective CLFV Lagrangian

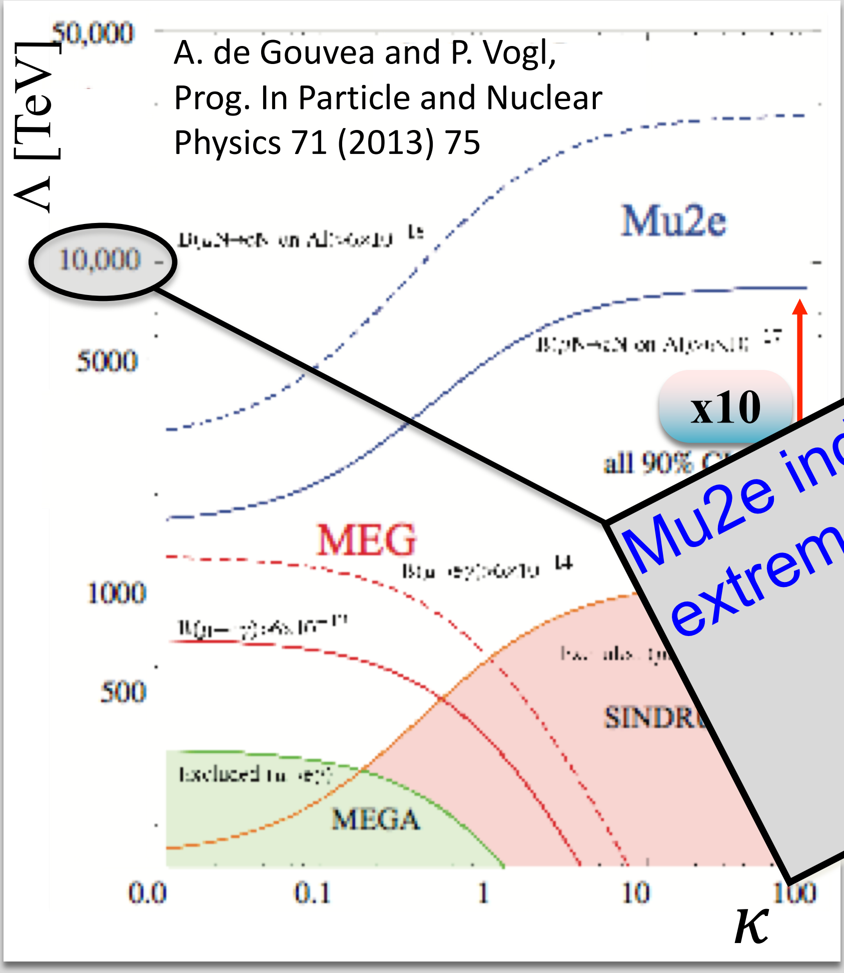
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$



κ << 1

Magnetic moment type operator

State	μ→eγ	μ→e
Sensitive	**Yes**	**Yes**



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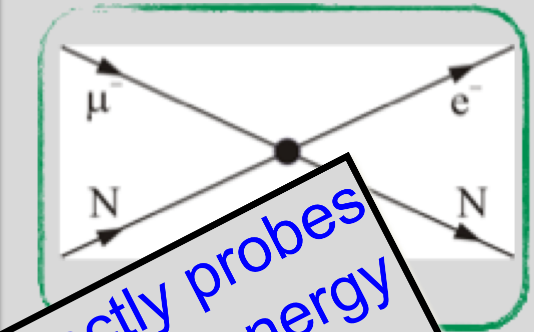


		μ→e
	No	**Yes**

Mu2e indirectly probes extremely high energy scales!

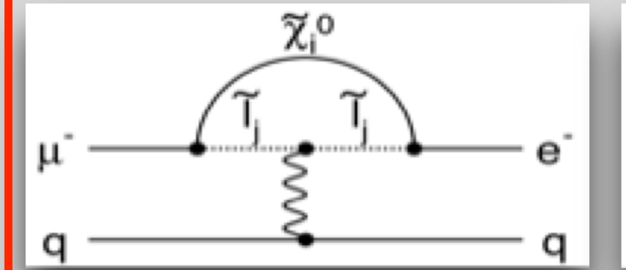
~ 1000 x LHC

Effective CLFV Lagrangian

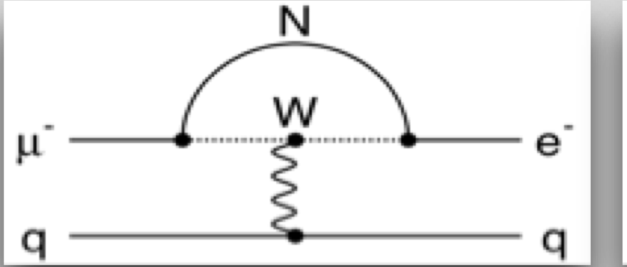
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$

Magnetic moment type operator

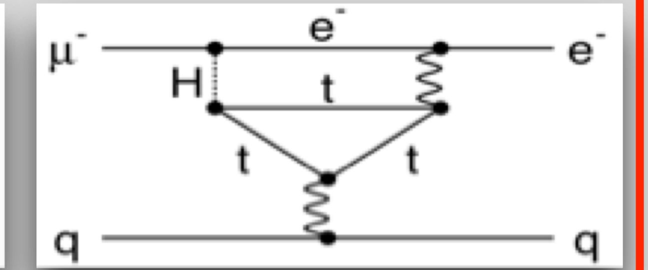
Supersymmetry



Heavy neutrinos

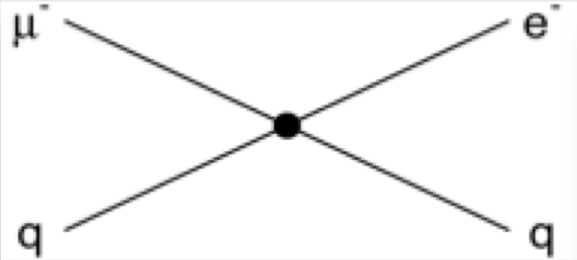


Two Higgs Doublets

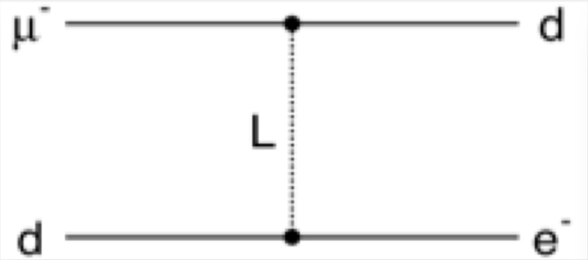


Contact term operator

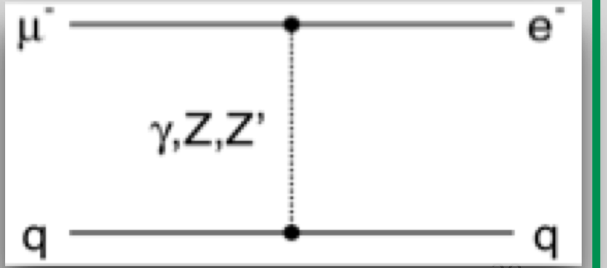
Compositeness



Leptoquarks

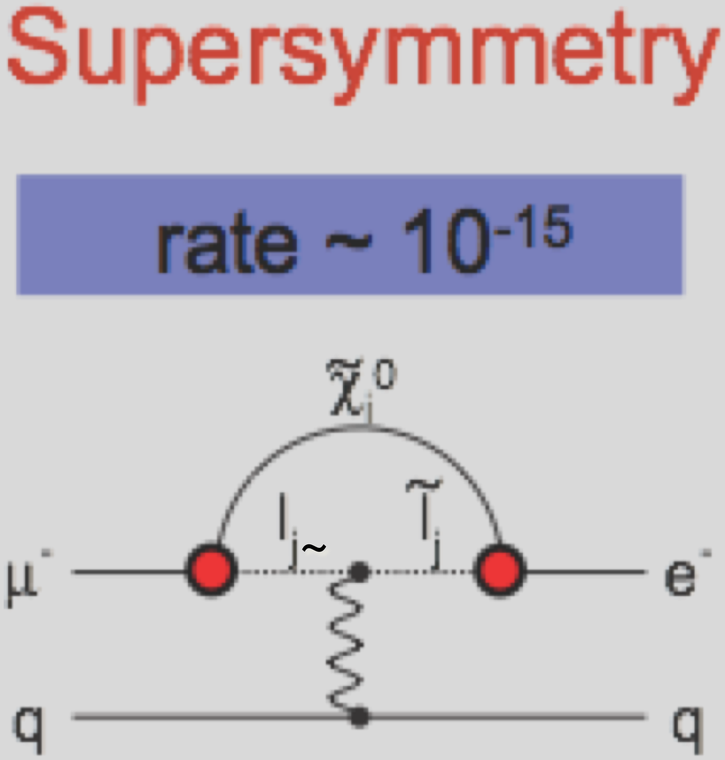


Heavy Z’



CLFV from SUSY

Access to SUSY through loops.



Supersymmetry

rate ~ 10^{-15}

In Mu2e, a signal TeV-scale discovery at LHC implies:

$$\sim \frac{\textbf{40 signal events}}{\textbf{<1 background event}}$$

Mu2e Discovery Potential

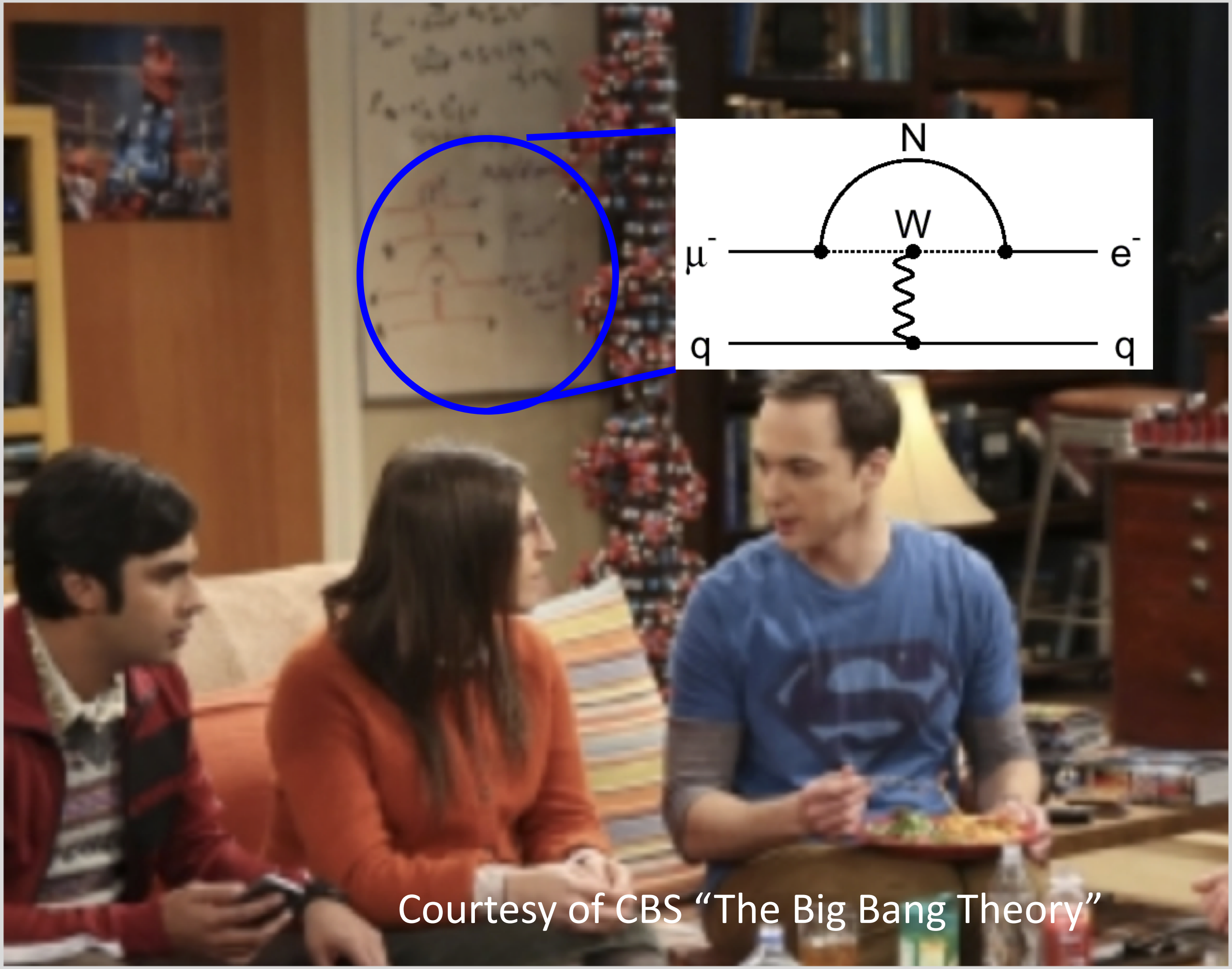
Discovery potential is high -- CLFV is predicted at observable rates for Mu2e in many models of new physics.

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

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

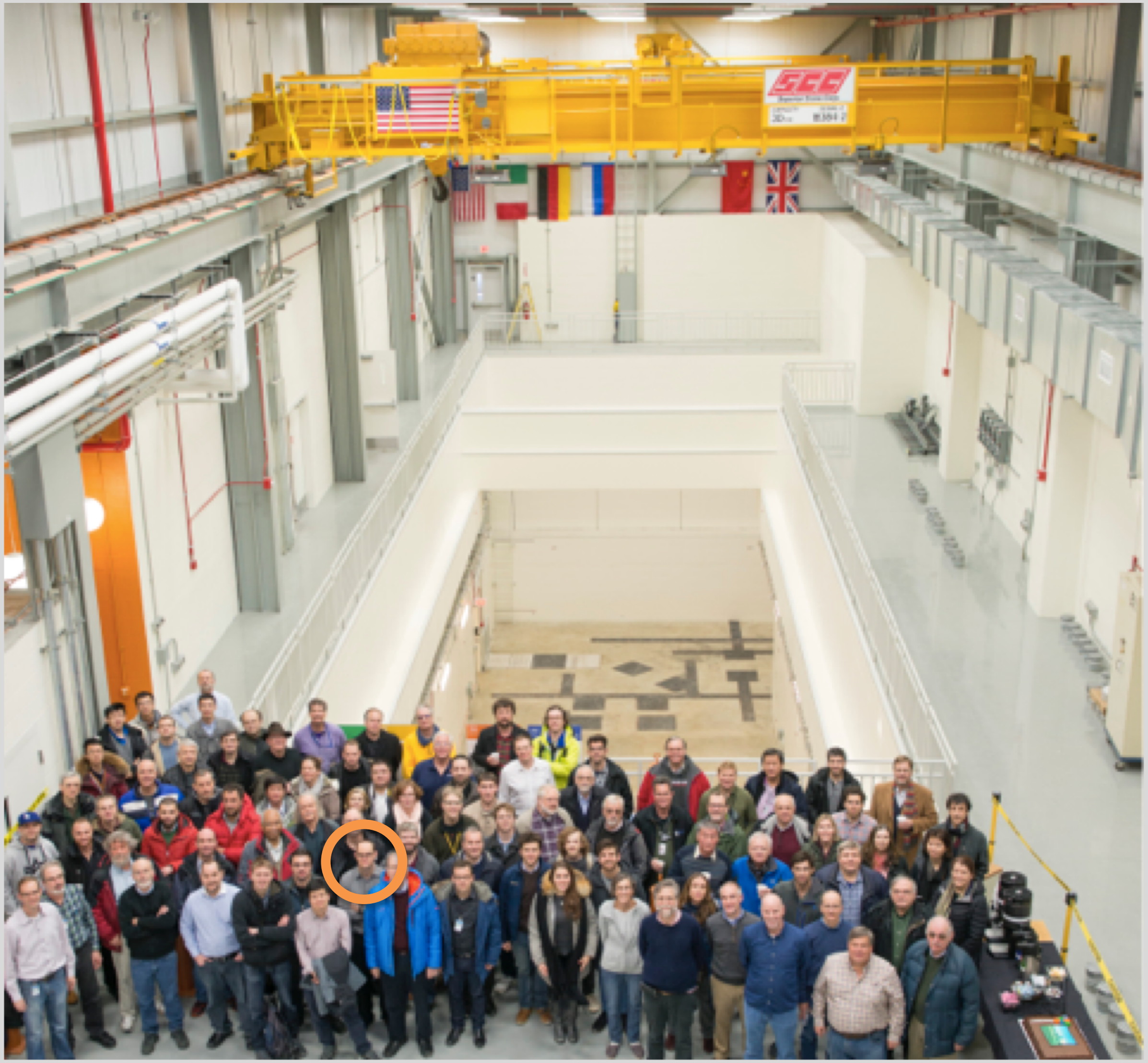
Mu2e can probe mass scales up to 10^4 TeV.

Importance of CLFV is Widely Recognized



Courtesy of CBS “The Big Bang Theory”

The Mu2e Collaboration



~160 People, 32 Institutions, 4 Countries

What will we measure?

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

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

Numerator (signal!)

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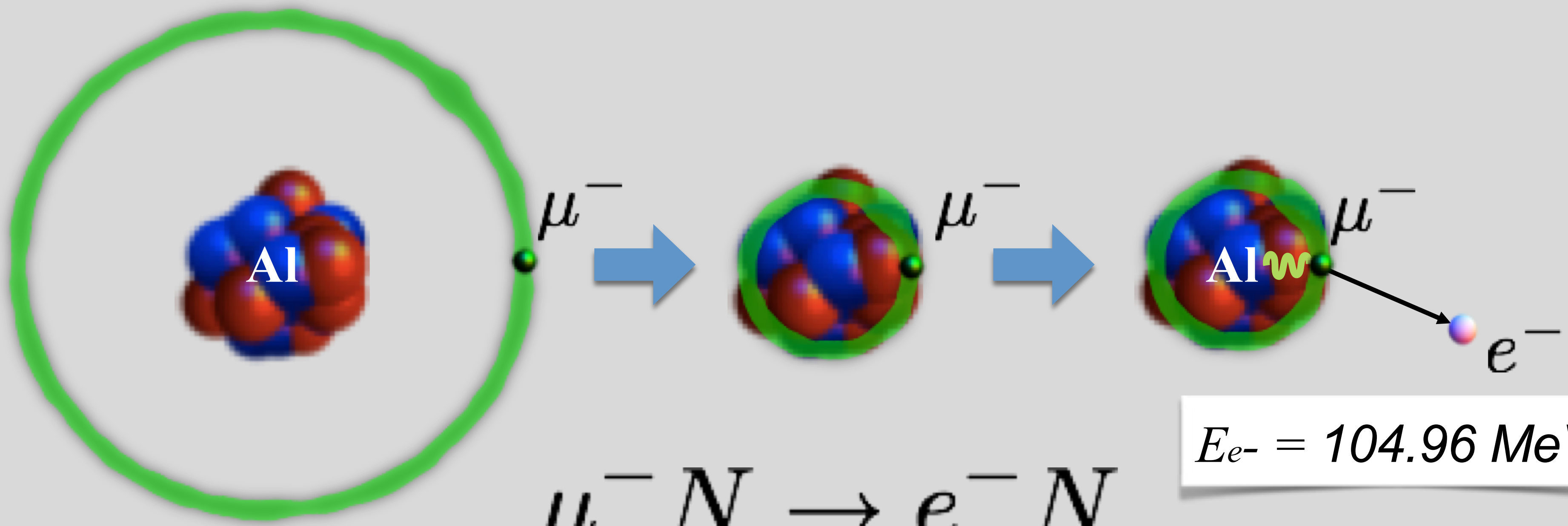

E_{e^-} = 104.96 MeV

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

Denominator

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

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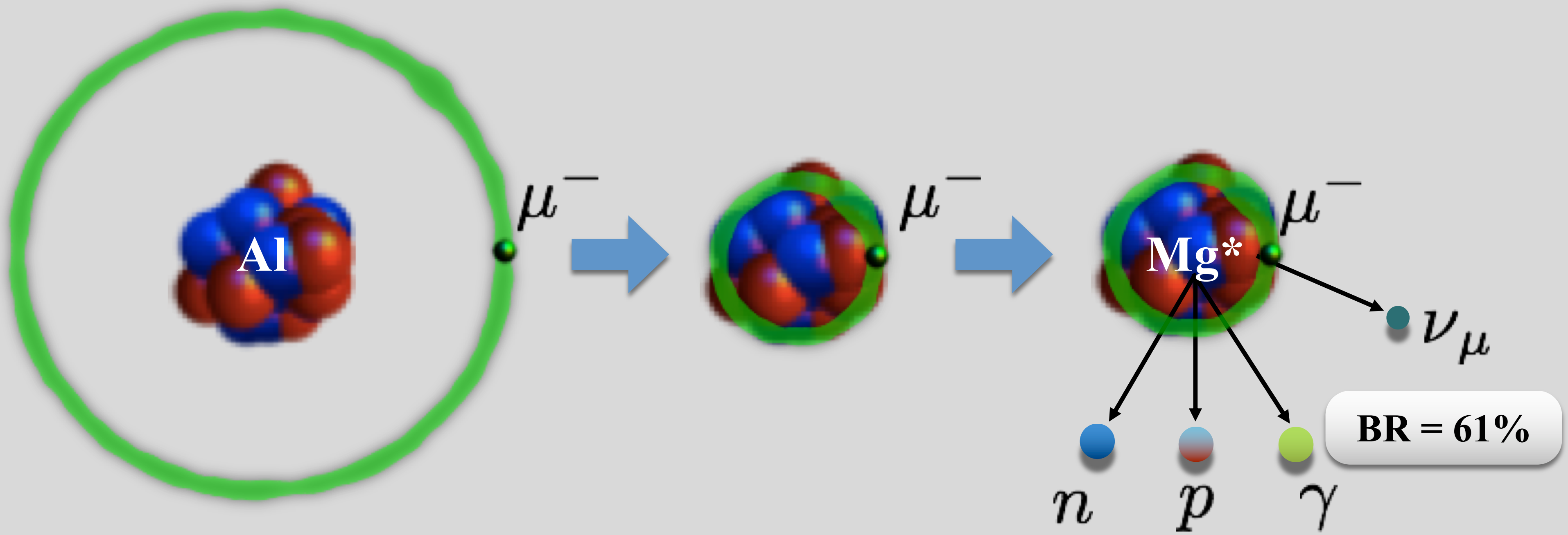
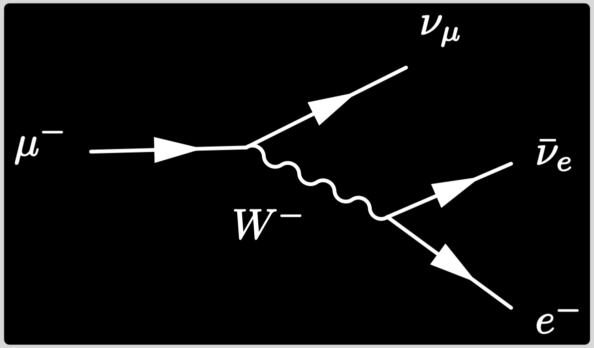
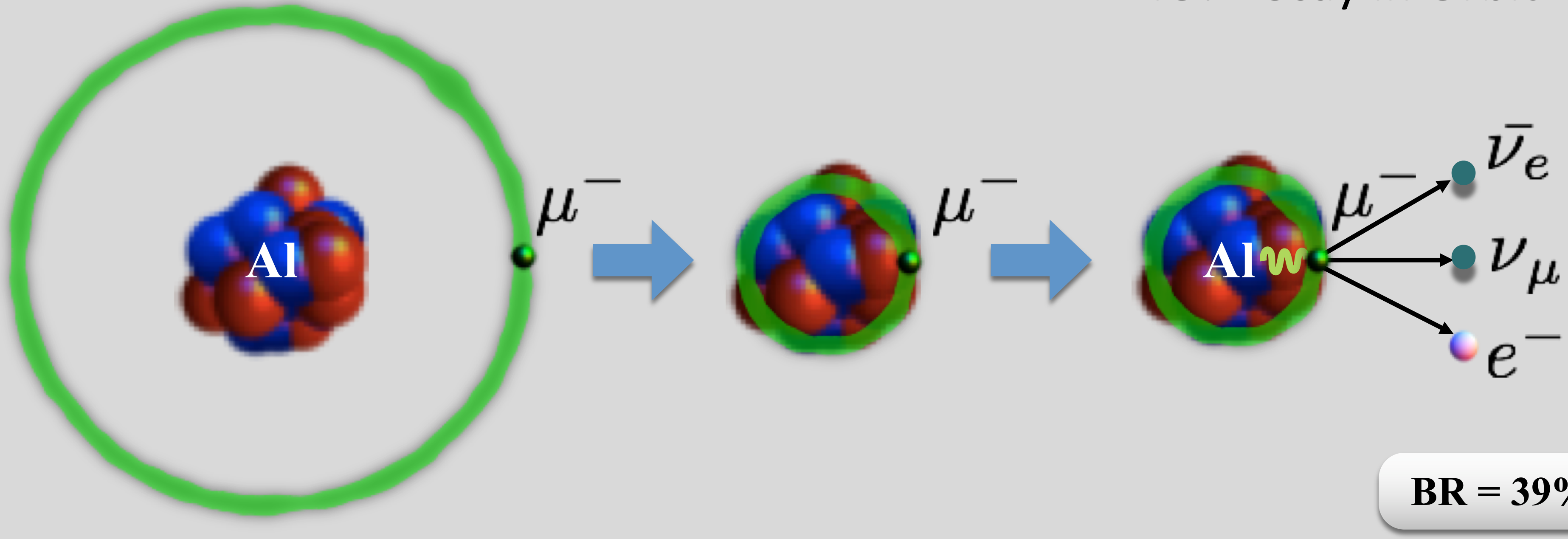


BR = 61%

Irreducible Background



DIO: Decay in Orbit



BR = 39%

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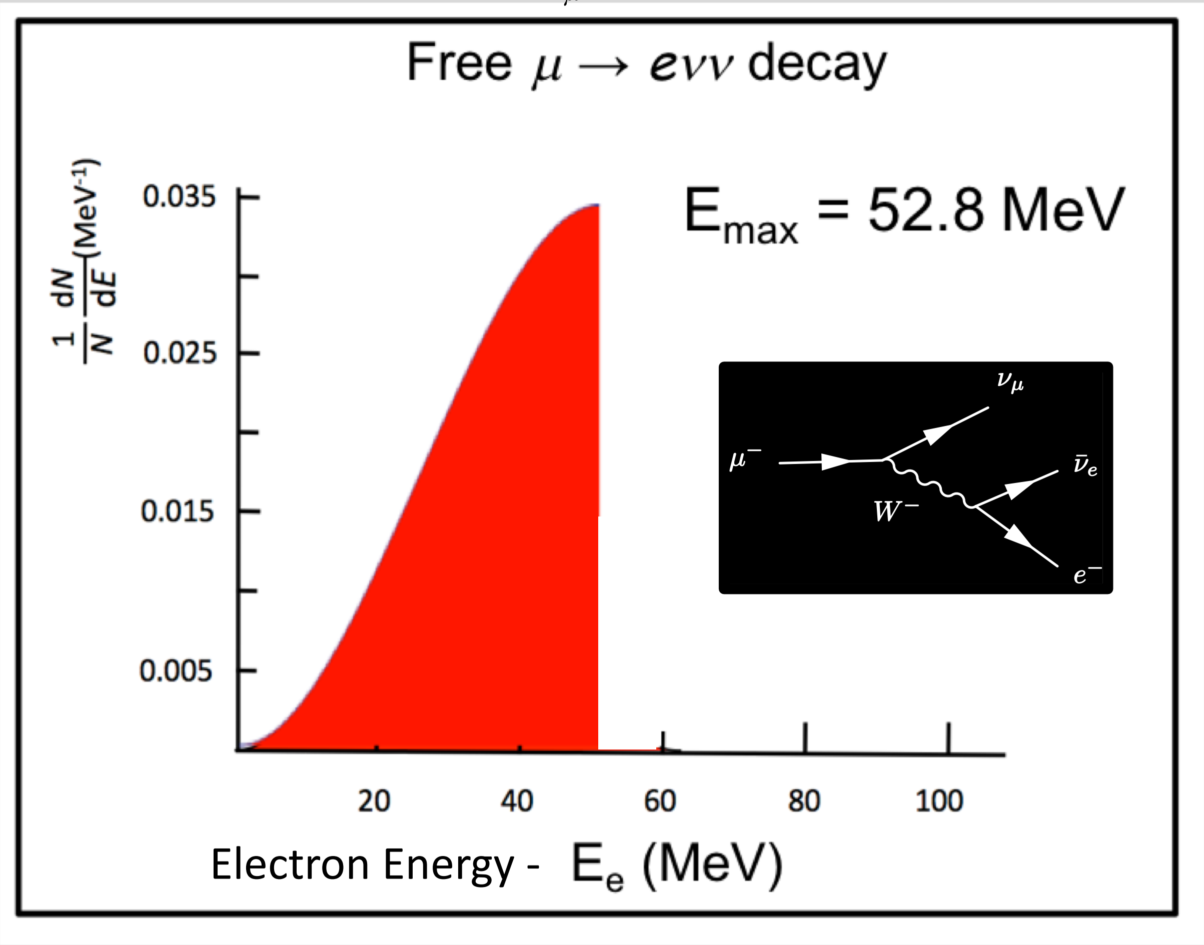
- Mu2e single event sensitivity: $R_{\mu e} = 3\times10^{-17}$
  - Expect 7 events and 5σ discovery sensitivity at $R_{\mu e} = 2\times10^{-16}$
- Expected limit: $R_{\mu e} = 8\times10^{-17}$ @ 90% CL
- Mu2e needs to stop ~10^{18} muons
  → ~4×10^{20} protons on target
- Need to keep background small and well understood
  → Total expected background ~0.4 events

Muon Decay in Orbit

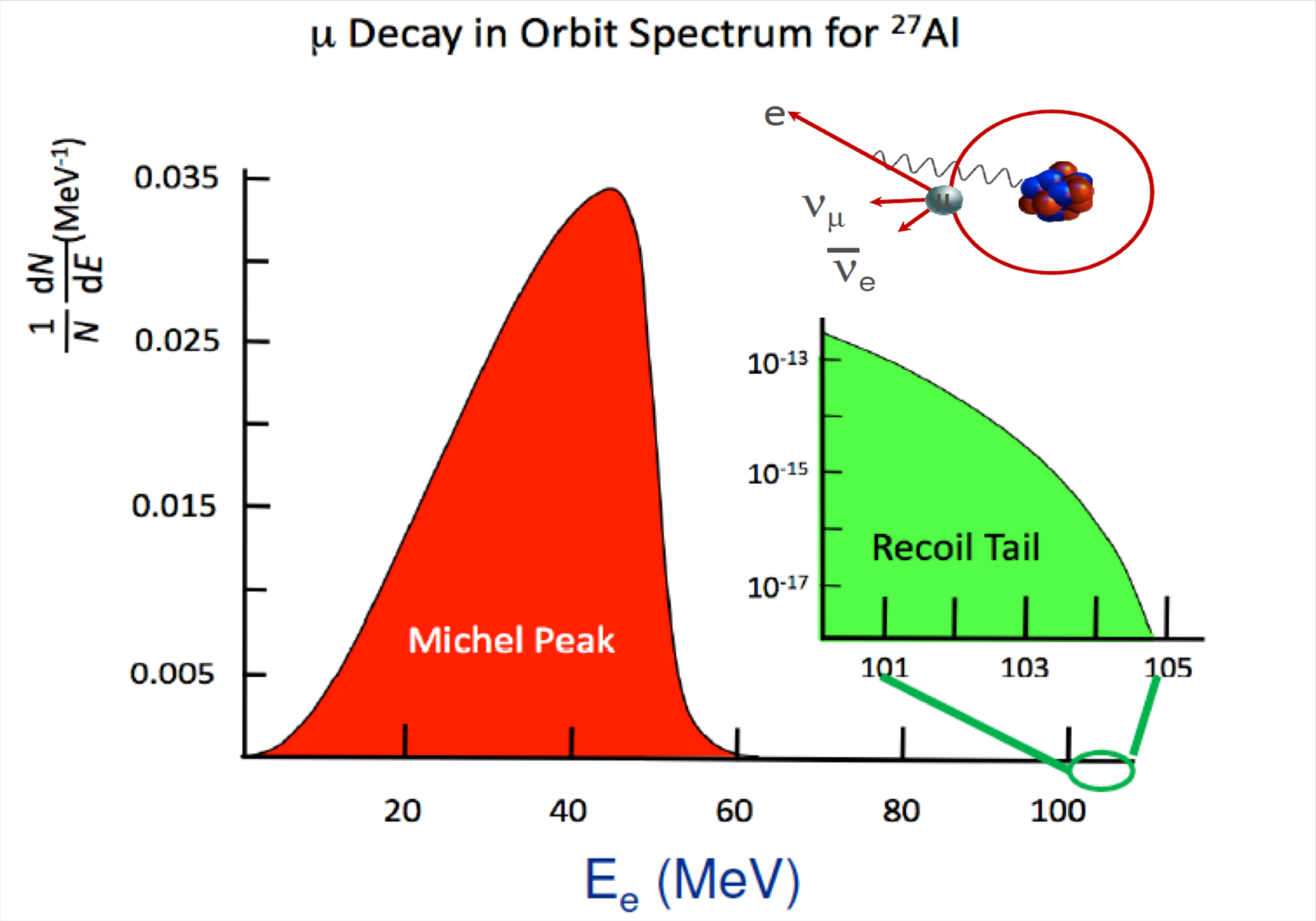
Free muon decay: end point of Michel spectrum is well below the signal energy

$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$



Muon Decay in Orbit

- However, in the nucleus, the DIO electron can be exactly at conversion energy (up to neutrino mass) if the neutrinos are at rest.



Muon Decay in Orbit

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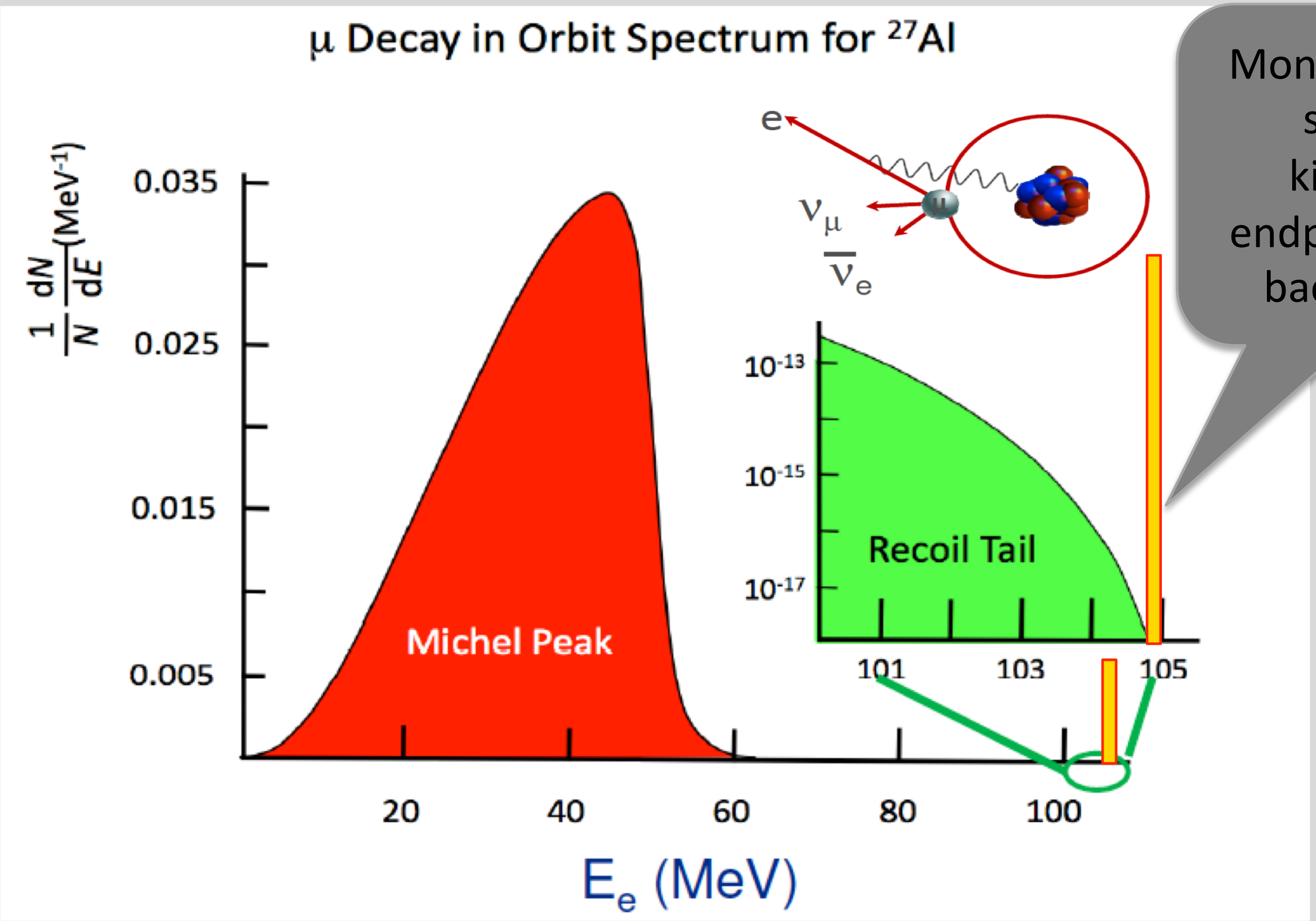


Mono-energetic signal at kinematic endpoint of DIO background.

Background Processes

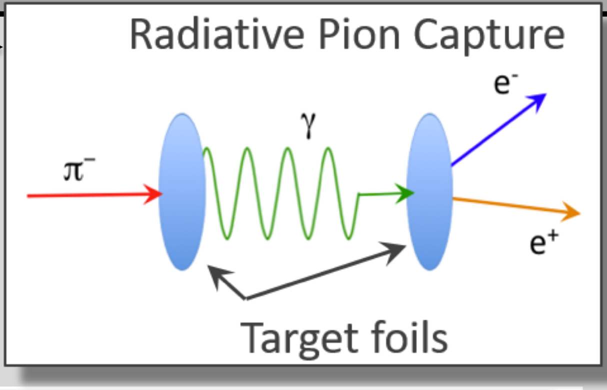
- Signal is a single ~105 MeV e-.
- Many possible sources of background events:
  - Intrinsic (~55%) – scale with number of stopped muons
    - Muon decay in Coulomb orbit (DIO is ~55% of total background)
    - Radiative muon capture (photon can convert asymmetrically)
  - Late arriving (~10%) – scale with number of late protons
    - Radiative pion capture
    - Muon/pion decay in flight
  - Miscellaneous (~35%):
    - Antiprotons and other late arriving particles
    - Cosmic-ray-induced electrons (will discuss later)

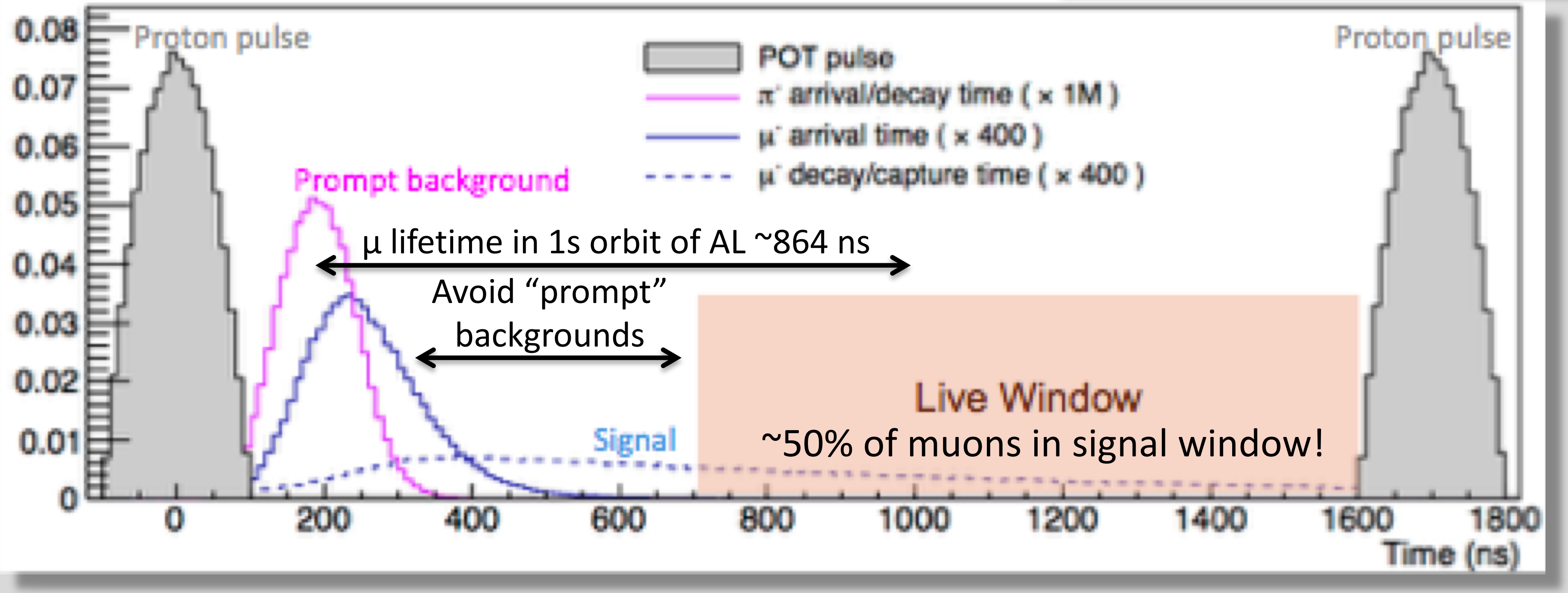
These can all be controlled

and none produce a sharp peak at 105 MeV!

Pulsed beam!

- “Prompt” background from pion capture →
- Fermilab accelerator capable of ideal pulse spacing…
- Provides major improvement of Sindrum II





μ lifetime in 1s orbit of AL ~864 ns

Avoid “prompt” backgrounds

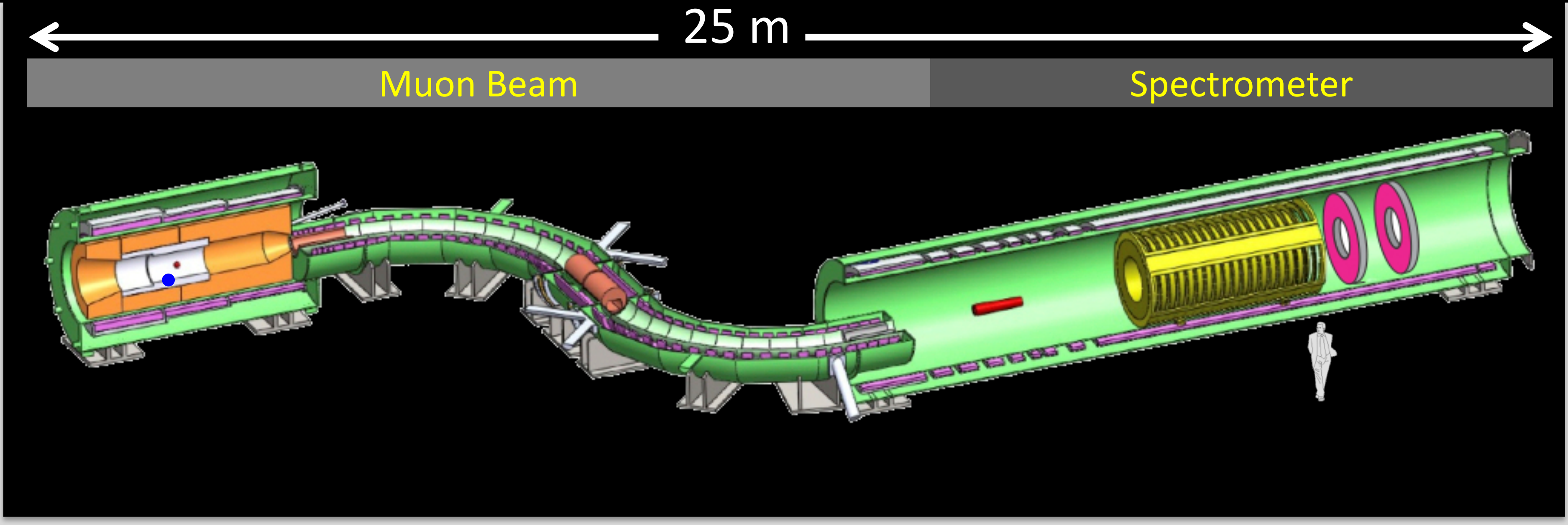
Live Window

~50% of muons in signal window!

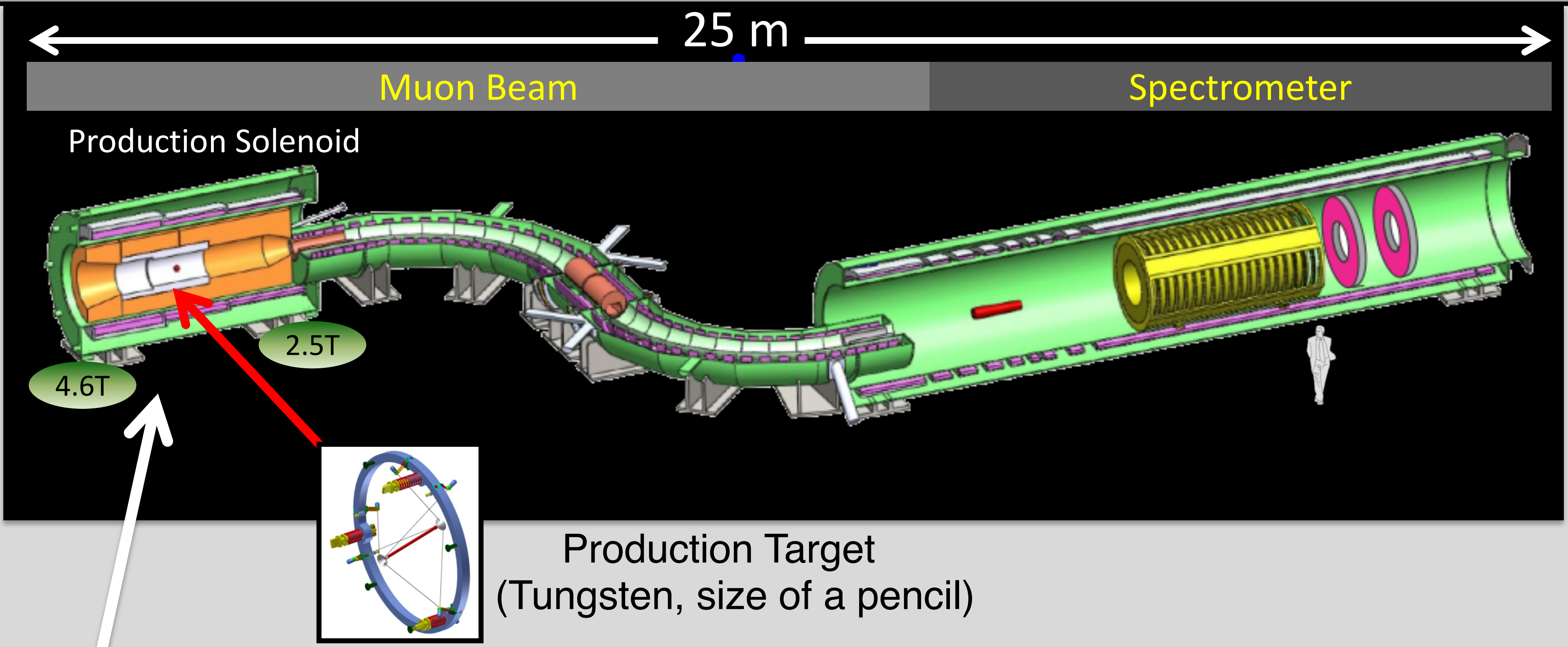
Extinction level of 10^{-10} between bunches is crucial!

(Removes ‘prompt’ backgrounds!)

The Mu2e Experiment



The Mu2e Experiment

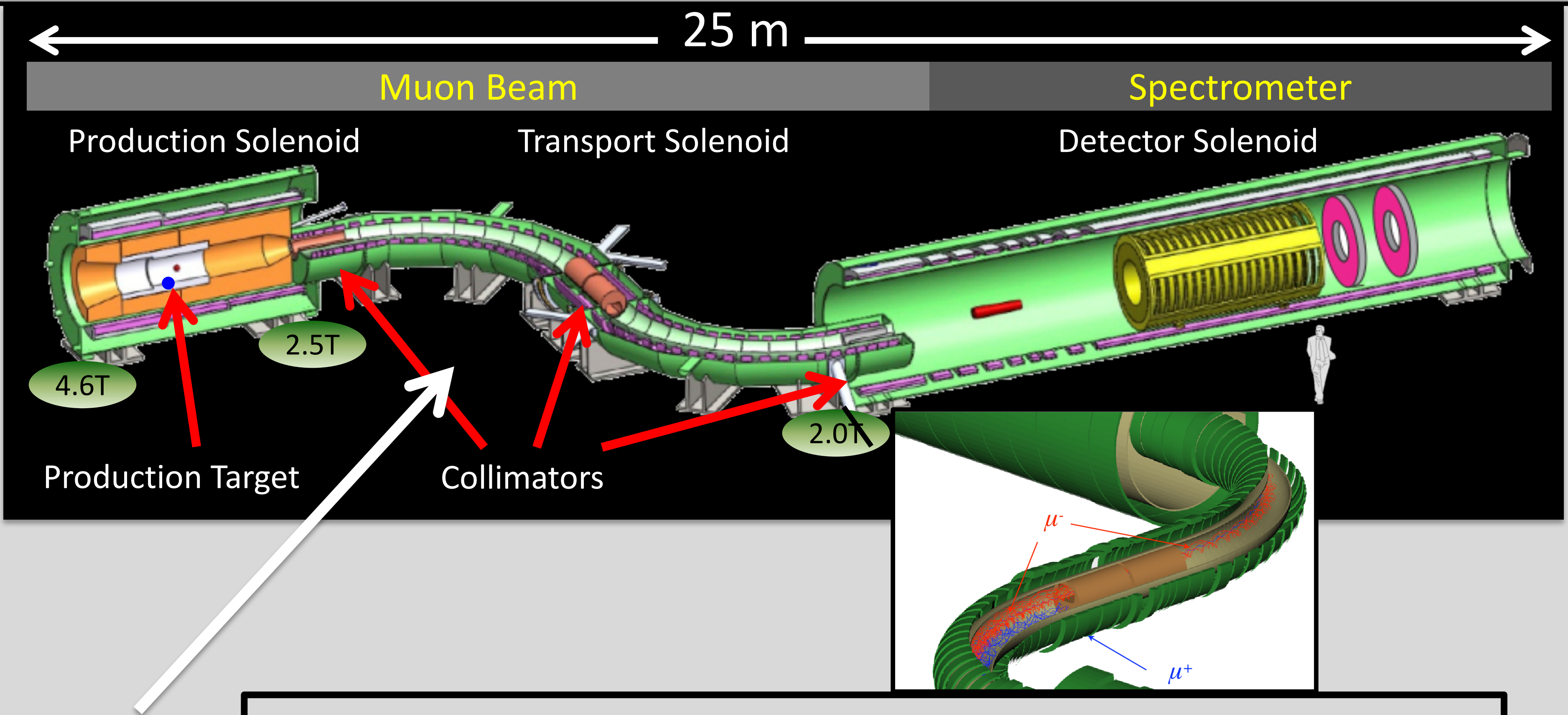


Production Target
(Tungsten, size of a pencil)

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



25 m

Muon Beam

Spectrometer

Production Solenoid

Transport Solenoid

Detector Solenoid

4.6T

2.5T

2.0T

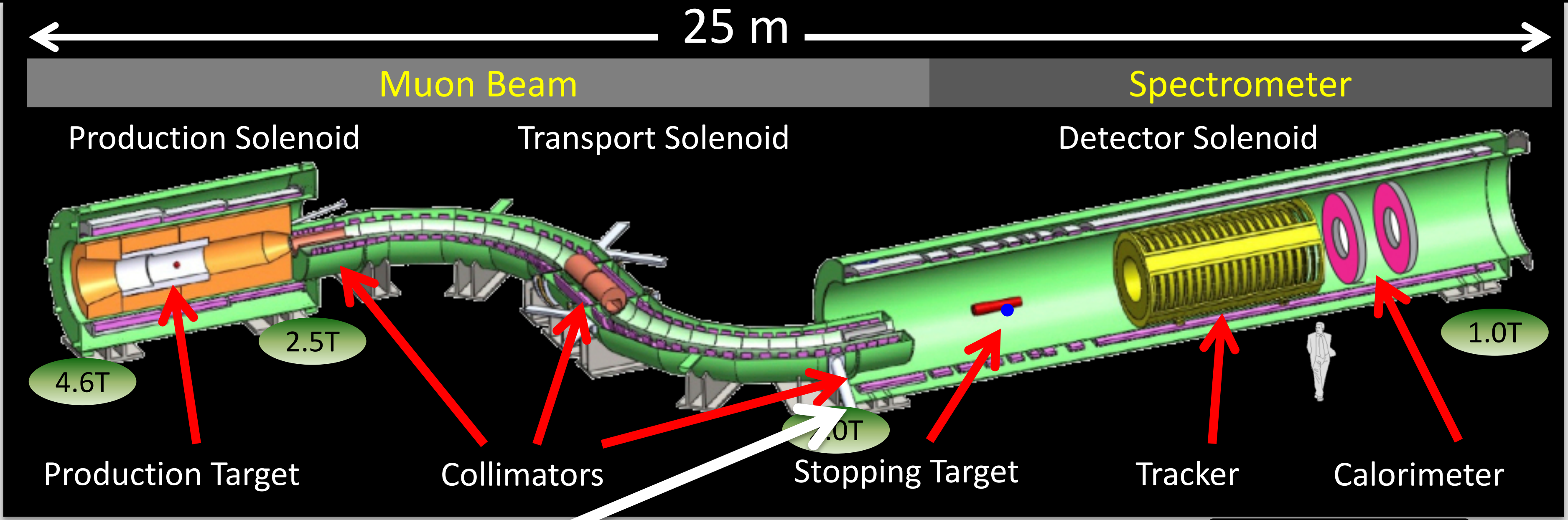
Production Target

Collimators

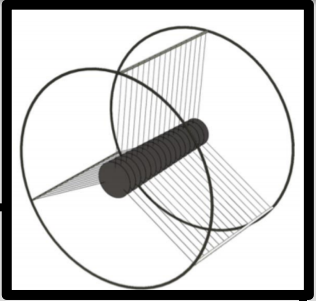
2)

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

The Mu2e Experiment



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.

Some Mu2e numbers

- Every 1 second Mu2e will
  - Send 7,000,000,000,000 protons to the Production Solenoid
  - Send 26,000,000,000 μs through the Transport Solenoid
  - Stop 13,000,000,000, μs in the Detector Solenoid
- By the time Mu2e is done…

Total number of stopped muons

1,000,000,000,000,000,000

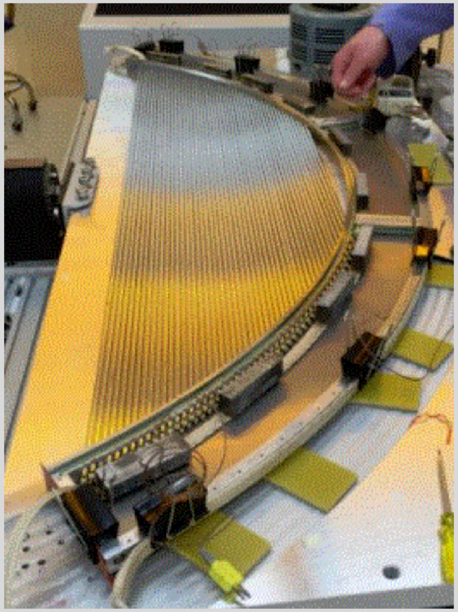
- 10^{18} is approximately the number of grains of sand on all of Earth’s beaches.
- LHC ~ 10^{16} collisions per year.

The Mu2e Tracker

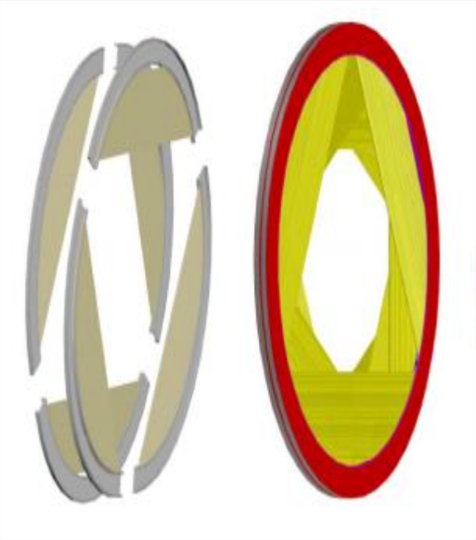
straw tube

- 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



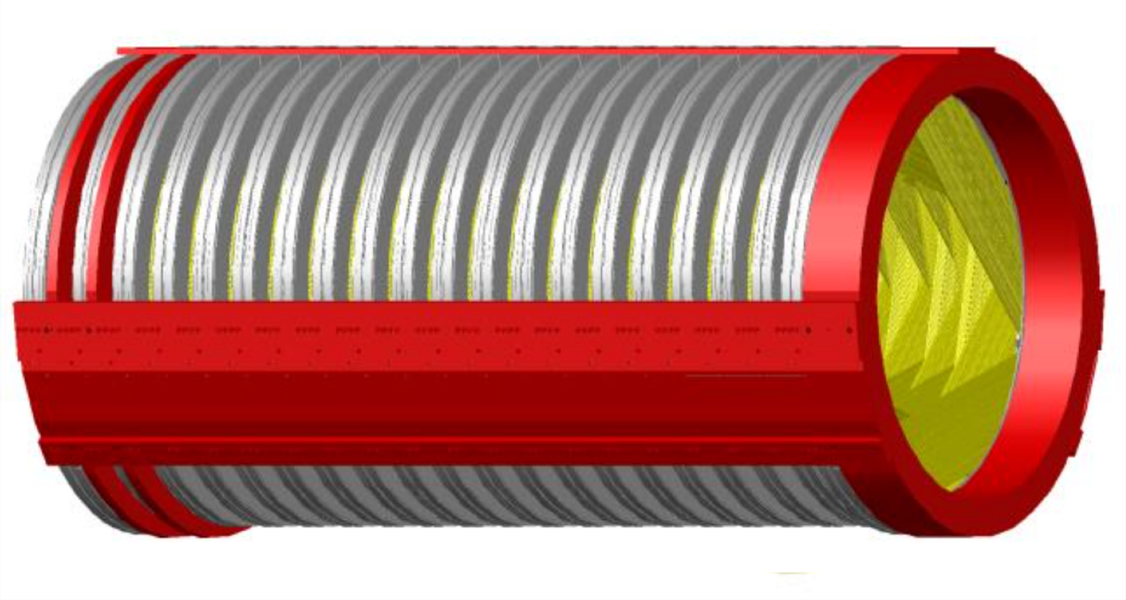
plane = 6 panels

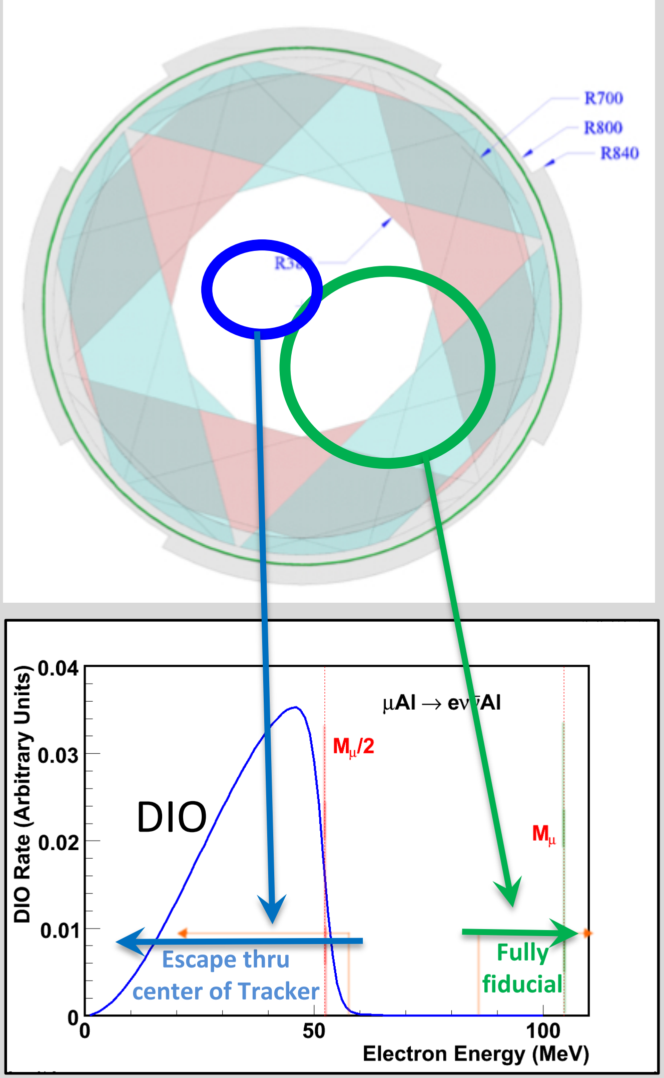


station = 2 planes

The Mu2e Tracker

detector= 18 stations (3m cylinder)



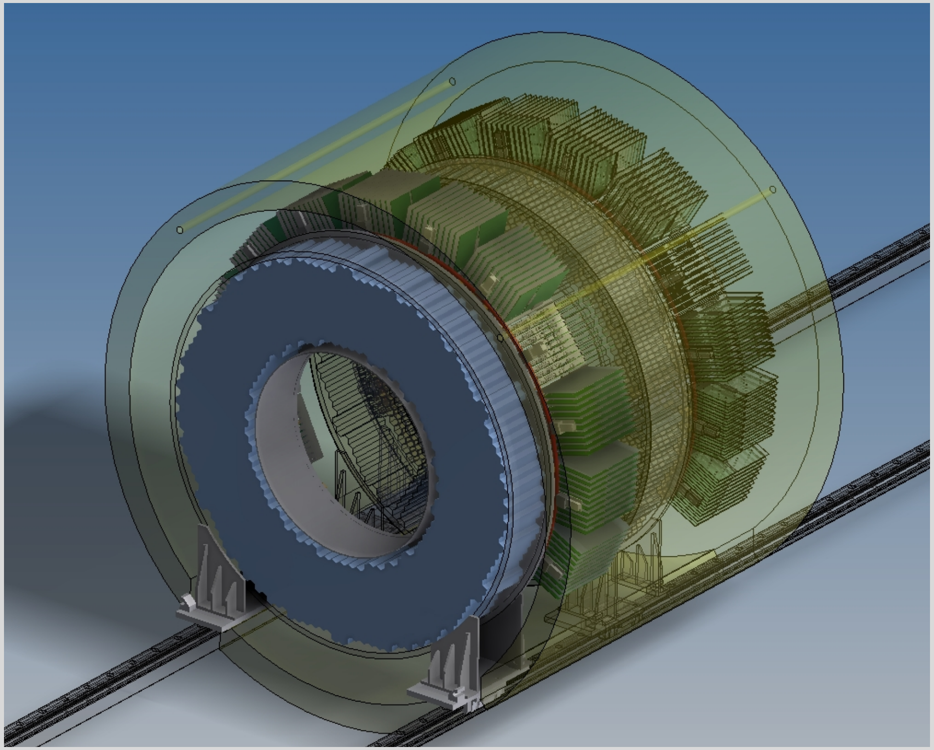


- Detector is in vacuum and inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum
- Active tracking region from 38 cm to 70 cm
- Services and structure beyond 70 cm
- Need good momentum resolution- **< 200 KeV/c** is achievable

The Mu2e Calorimeter

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

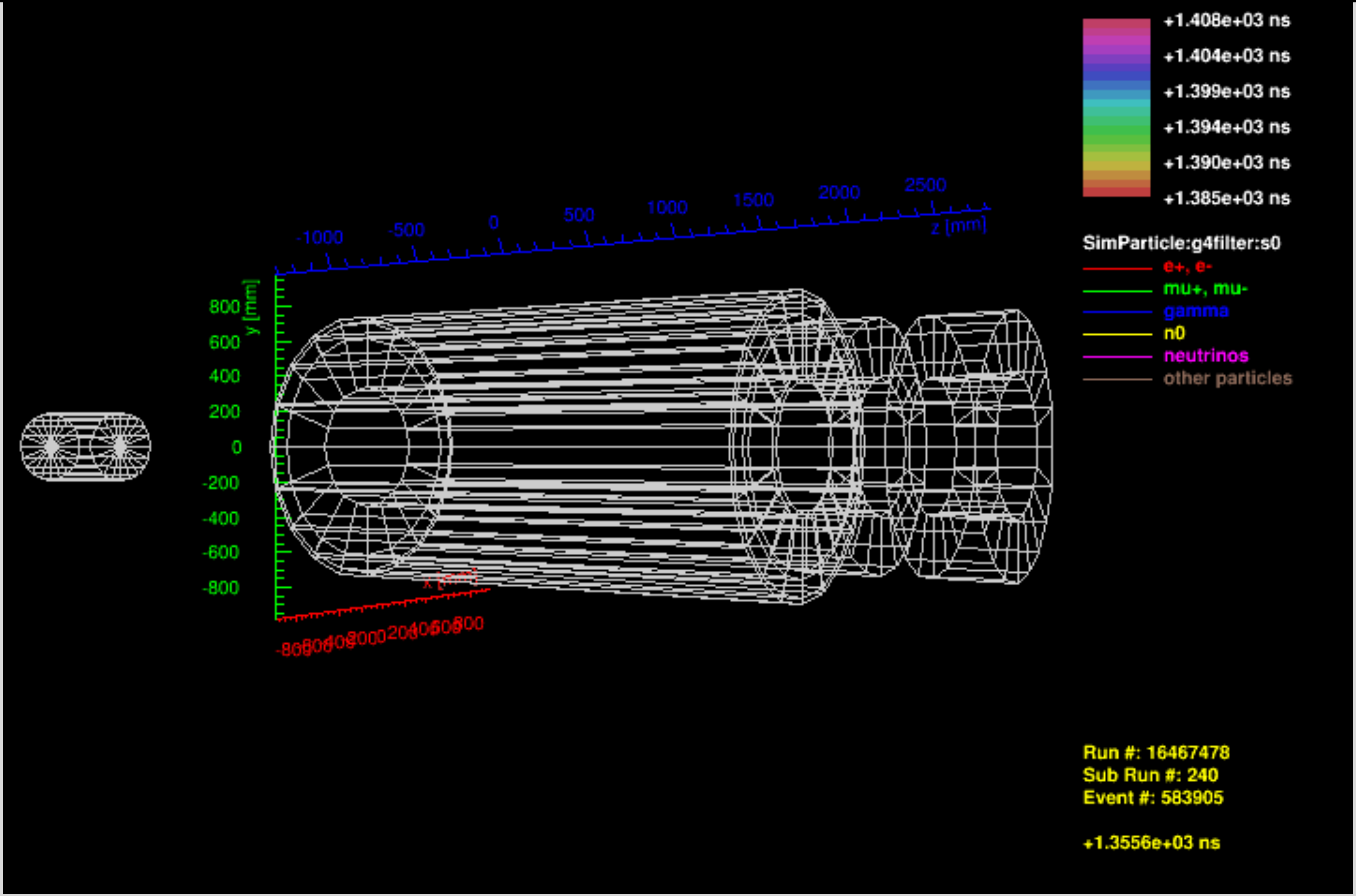
  (radius = 36-70 cm)



~2000 BaF_2 crystals with hexagonal cross-section ~3 cm diameter, ~20 cm long ($10X_0$)

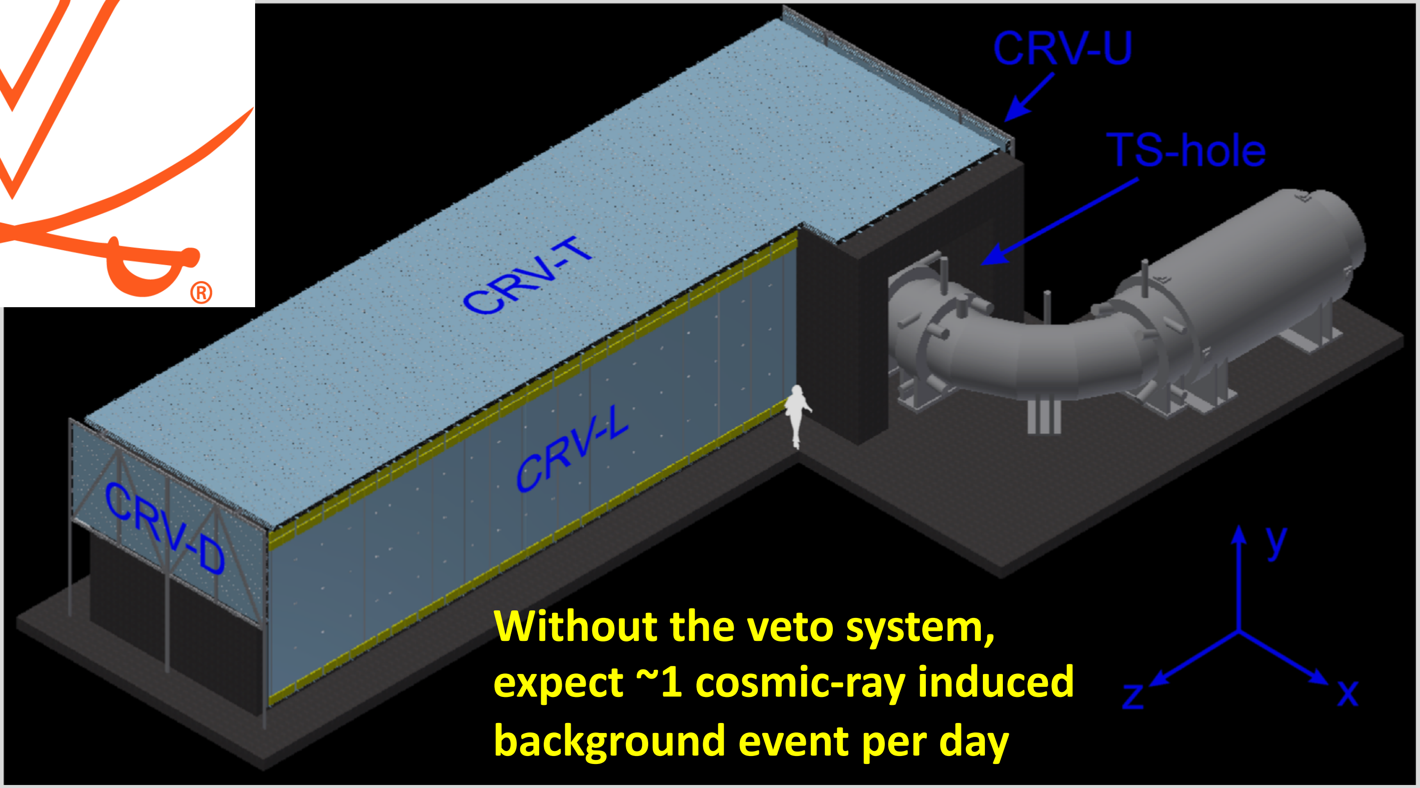
Two photo-sensors/crystal on back (APDs or SiPMs)

A cosmic background…



Cosmic aside…

The Mu2e Cosmic-Ray Veto

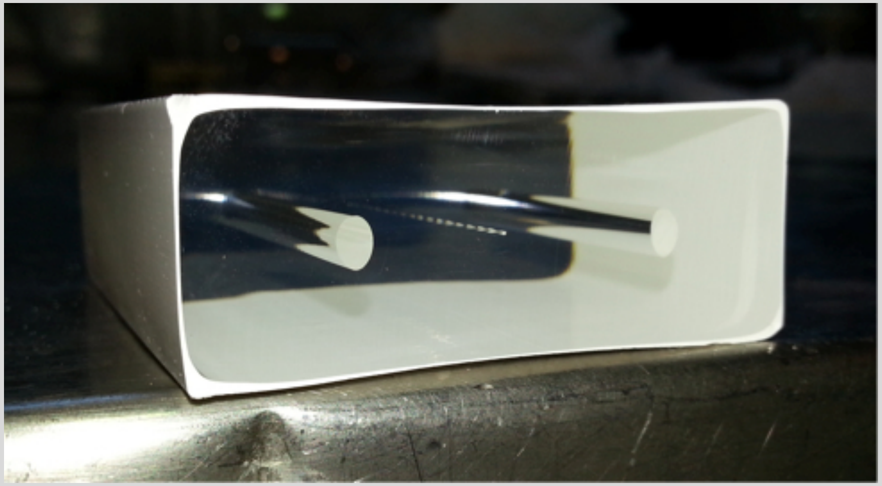


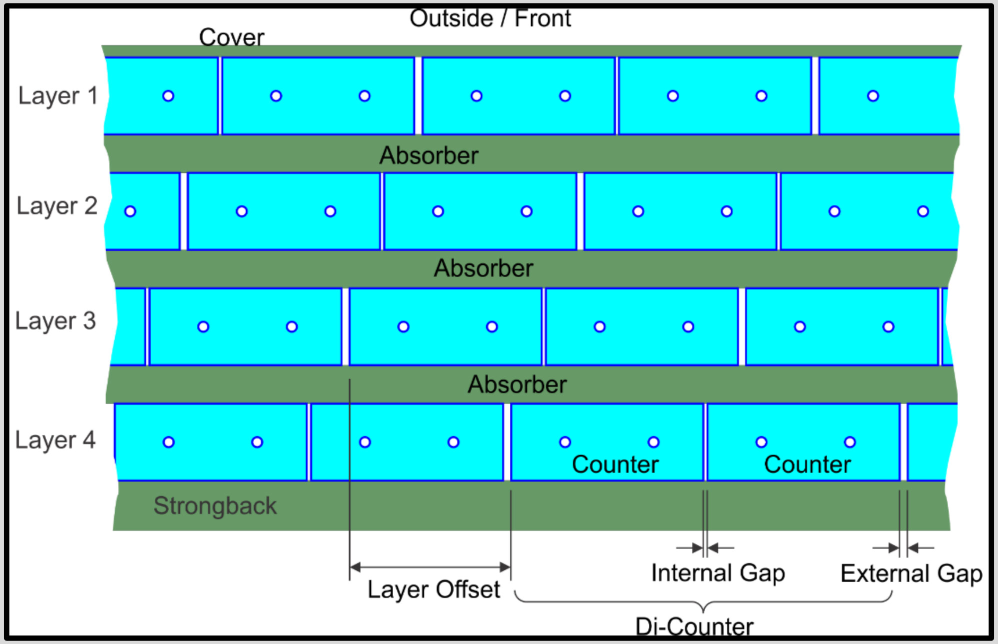
Without the veto system, expect ~1 cosmic-ray induced background event per day

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

Veto system covers entire Detector Solenoid and half of the Transfer Solenoid.

The Mu2e Cosmic-Ray Veto



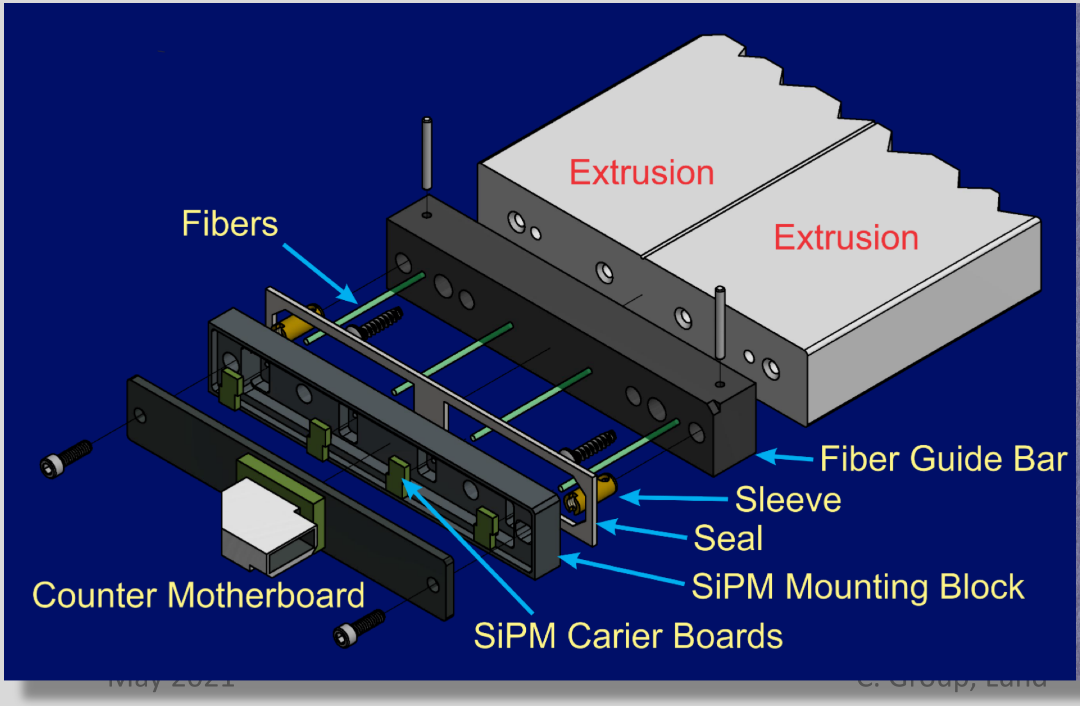


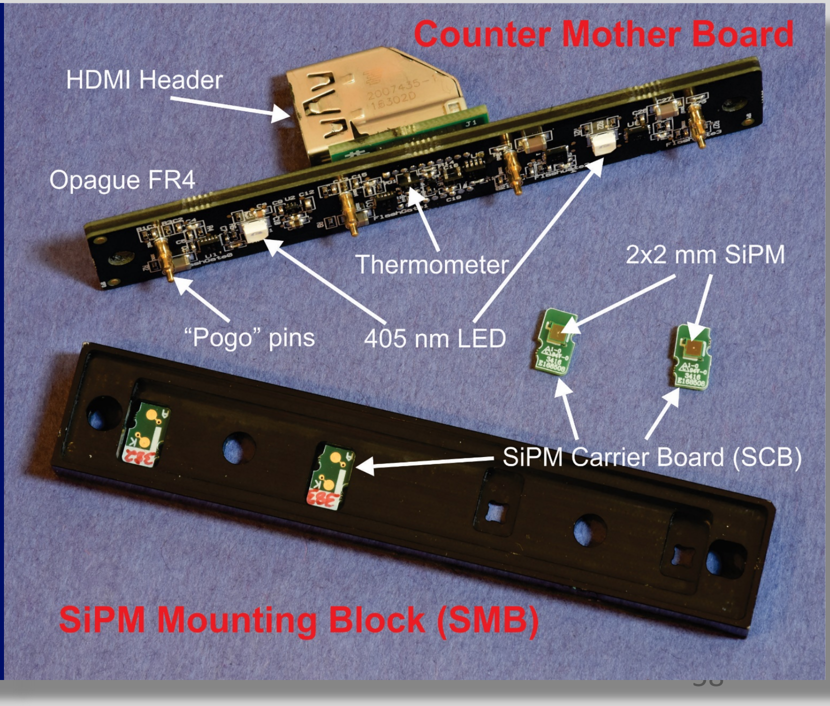
Will use 4 overlapping layers of scintillator bars separated by ~ 10 mm absorber

- 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
- Requirement: ~99.99 % veto efficiency

CRV building block: di-counter

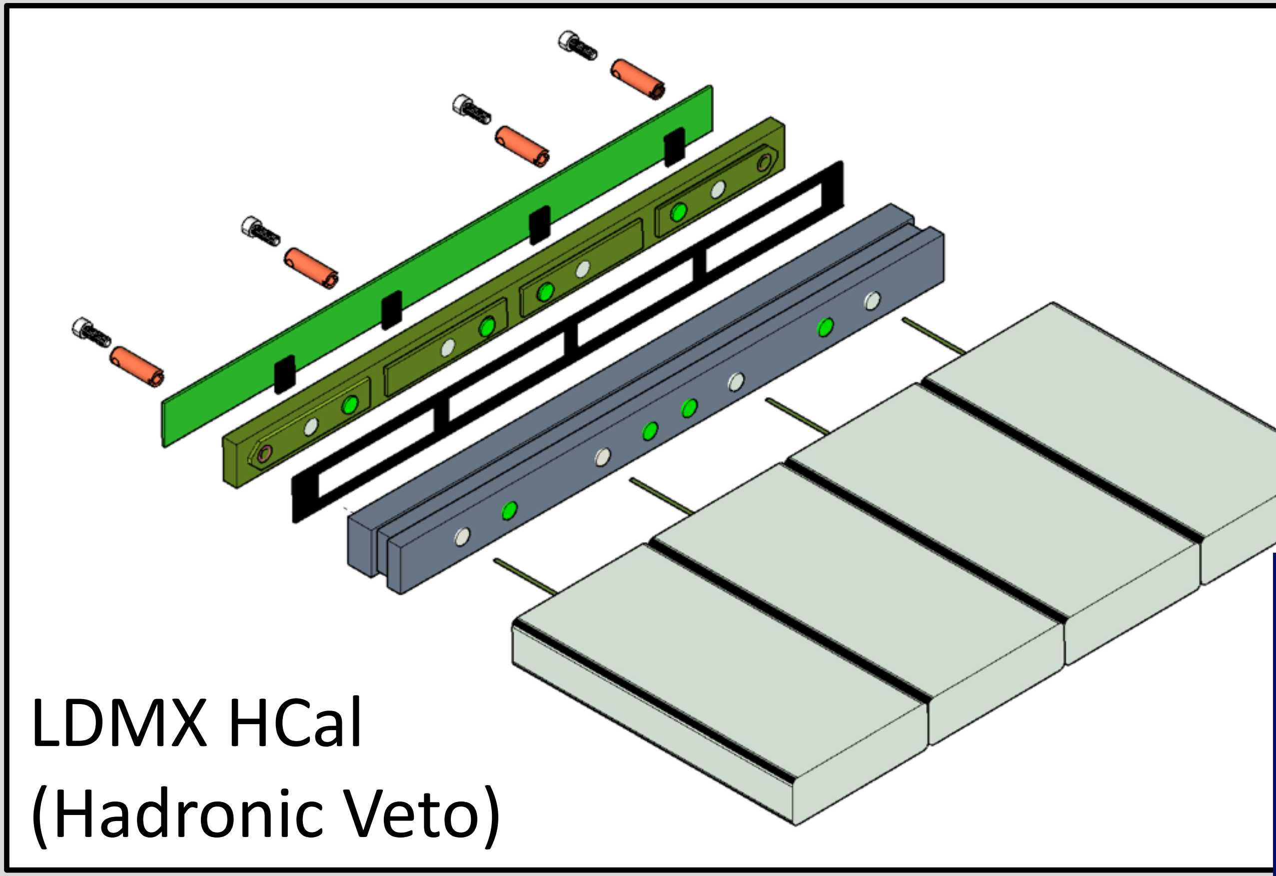
- Counters: extruded polystyrene doped with 1% PPO + 0.05% POPOP, coated with TiO2
    - Glued in pairs to make a di-counter
- Each counter has two 1.4 mm wavelength-shifting fibers placed in channels
- Fiber Guide Bar is glued and polished on both sides
- Fibers are read out by 2x2 mm SiPMs, pushed by pogo pins





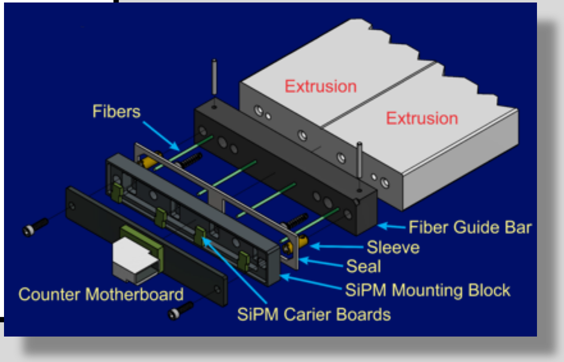
LDMX HCAL and the Mu2e CRV

LDMX “Quad-bar” design - modified from the CRV design



LDMX HCal
(Hadronic Veto)

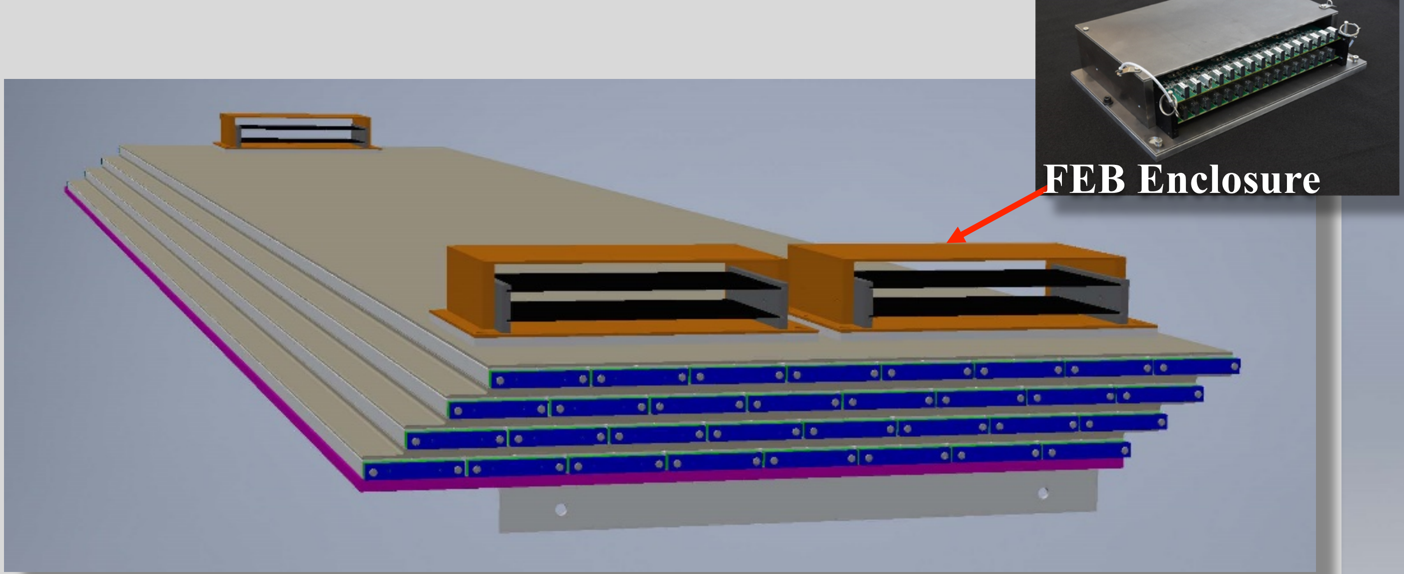
Mu2e CRV



Current studies show that the HCal can achieve the required veto efficiency.

CRV module

- Di-counters are used to build a module
  - 4 layers of 8 di-counters separated by aluminum absorbers
- Entire assembly epoxied together
- Offsets between each layer mitigate an impact from projective cracks
- Weight: up to 1091 kg
- Number of modules: 84



Prototypes

The Fabrication Team

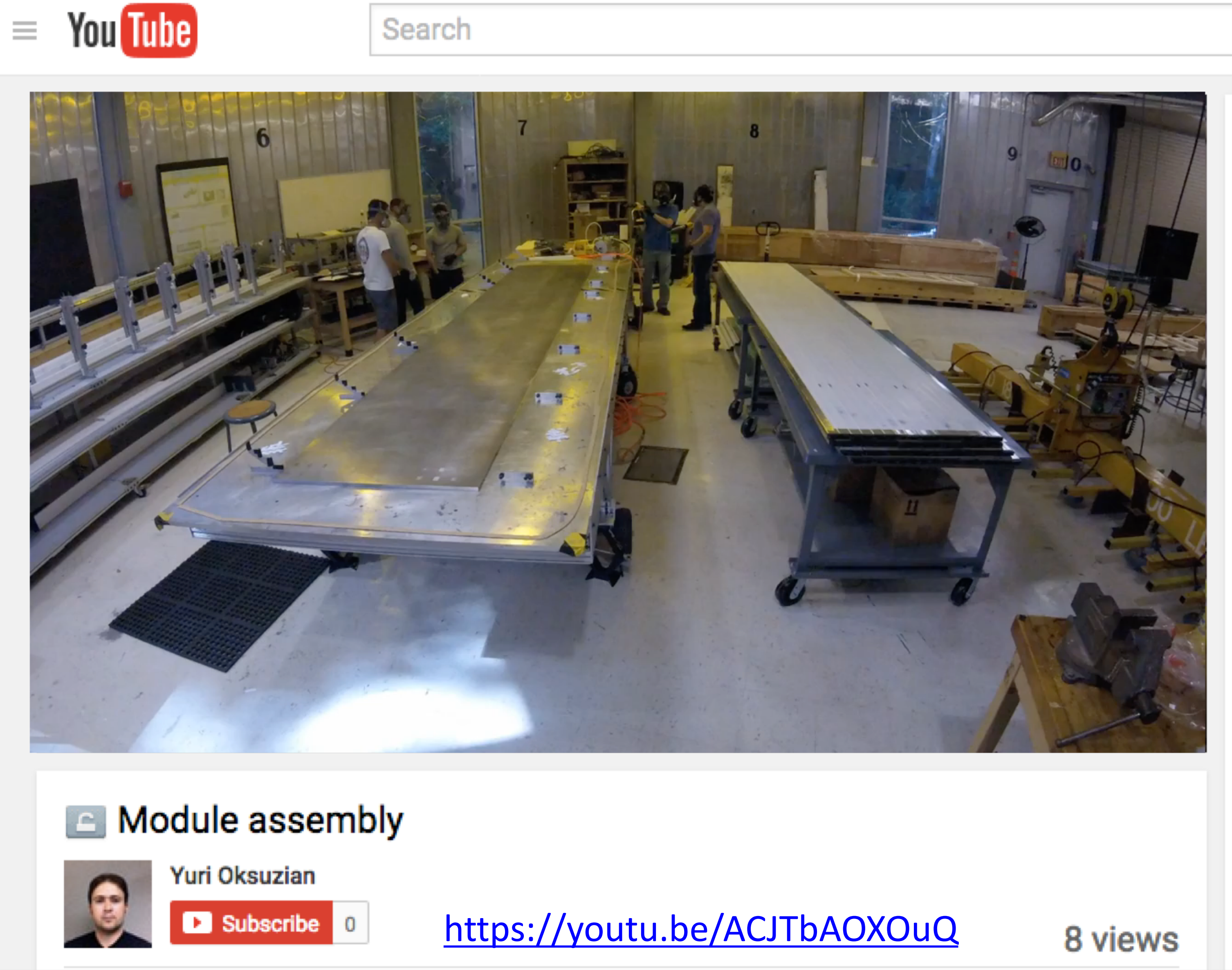
UVA Fabrication Team
(Summer 2019)

A few minutes in the module factory

New!

https://www.youtube.com/watch?v=KwEU-RRCaH8&feature=youtu.be

CRV Module Assembly (the movie)



Module assembly

Yuri Oksuzian

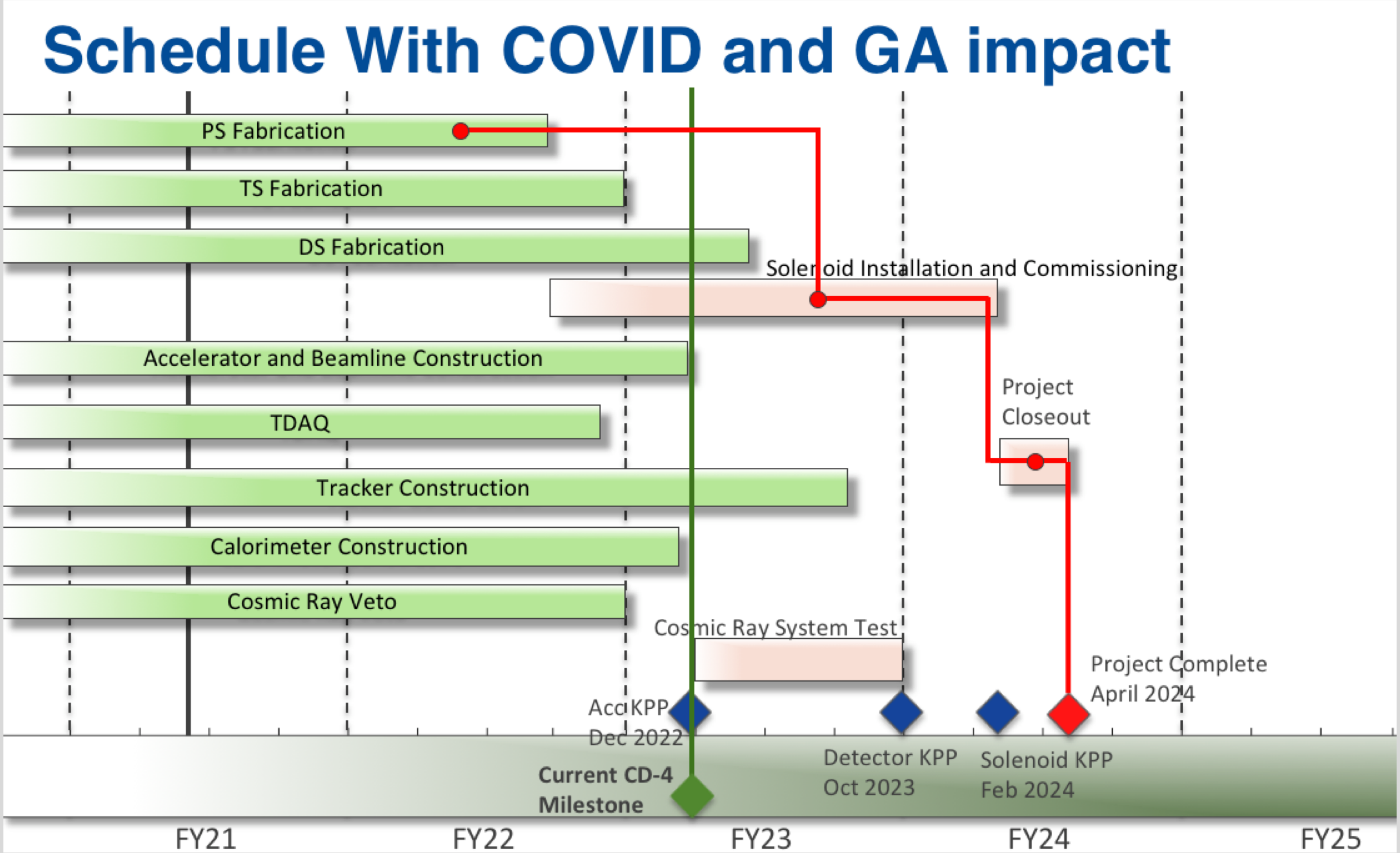
https://youtu.be/ACJTbAOXOuQ

CRV Challenges

- The CRV must provide extremely high efficiency while operating in a challenging radiation environment.
  - The production target is bombarded with ~10^{20} protons and the stopping target with ~10^{18} muons in a three-year period. Both regions cause a large background of neutrons and gamma rays.
  - Deadtime caused by the CRV and radiation damage to detector components are a concern.
- 99.99% veto efficiency is required. The detector is large, and modules must meet strict tolerance requirements to avoid gaps in coverage.

Back to Mu2e…

Mu2e Schedule

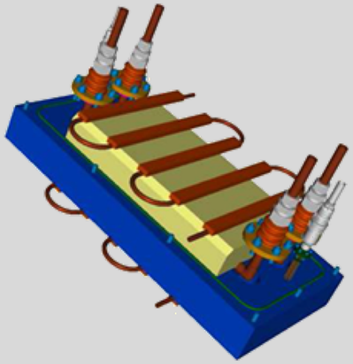


Where we are: Civil Construction

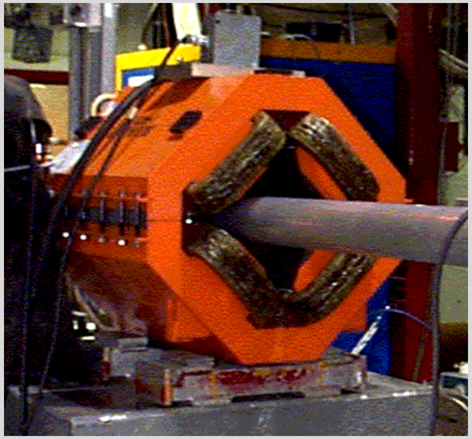
Building is complete!

Where we are: Beamline, Solenoids

Extinction Dipole



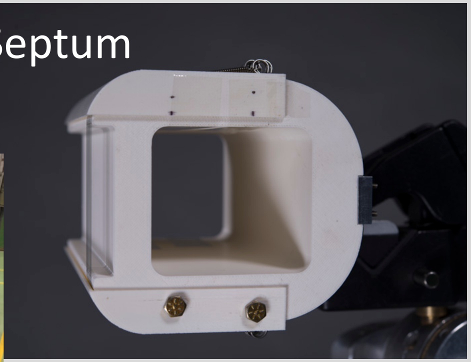
Quadrupole



- PS, DS built by General Atomics
- TS built by ASG + Fermilab
- Cable production complete

75 km of superconducting cable

Septum



Transport Solenoid coils

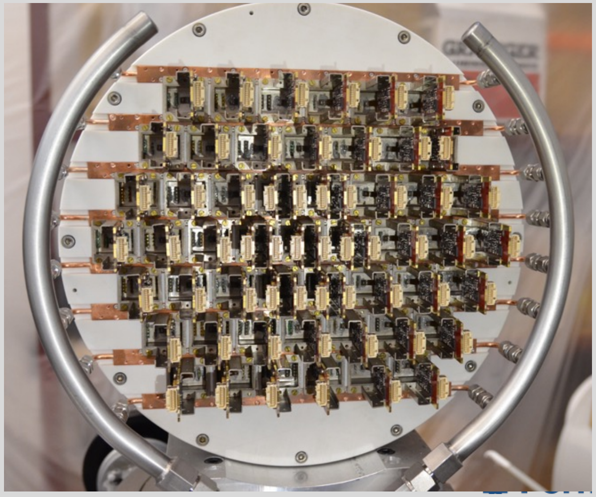
Accelerator work ~50% complete; solenoid work ~60% complete

Where we are: Detectors

Straw Tube Tracker

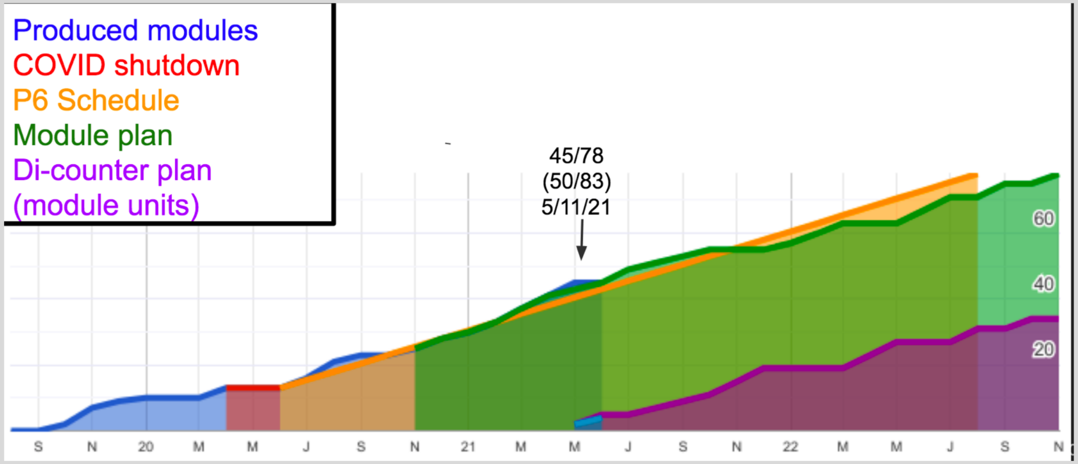
Cosmic Ray Veto module

Calorimeter Crystal Test



Full production efforts are underway for all systems.

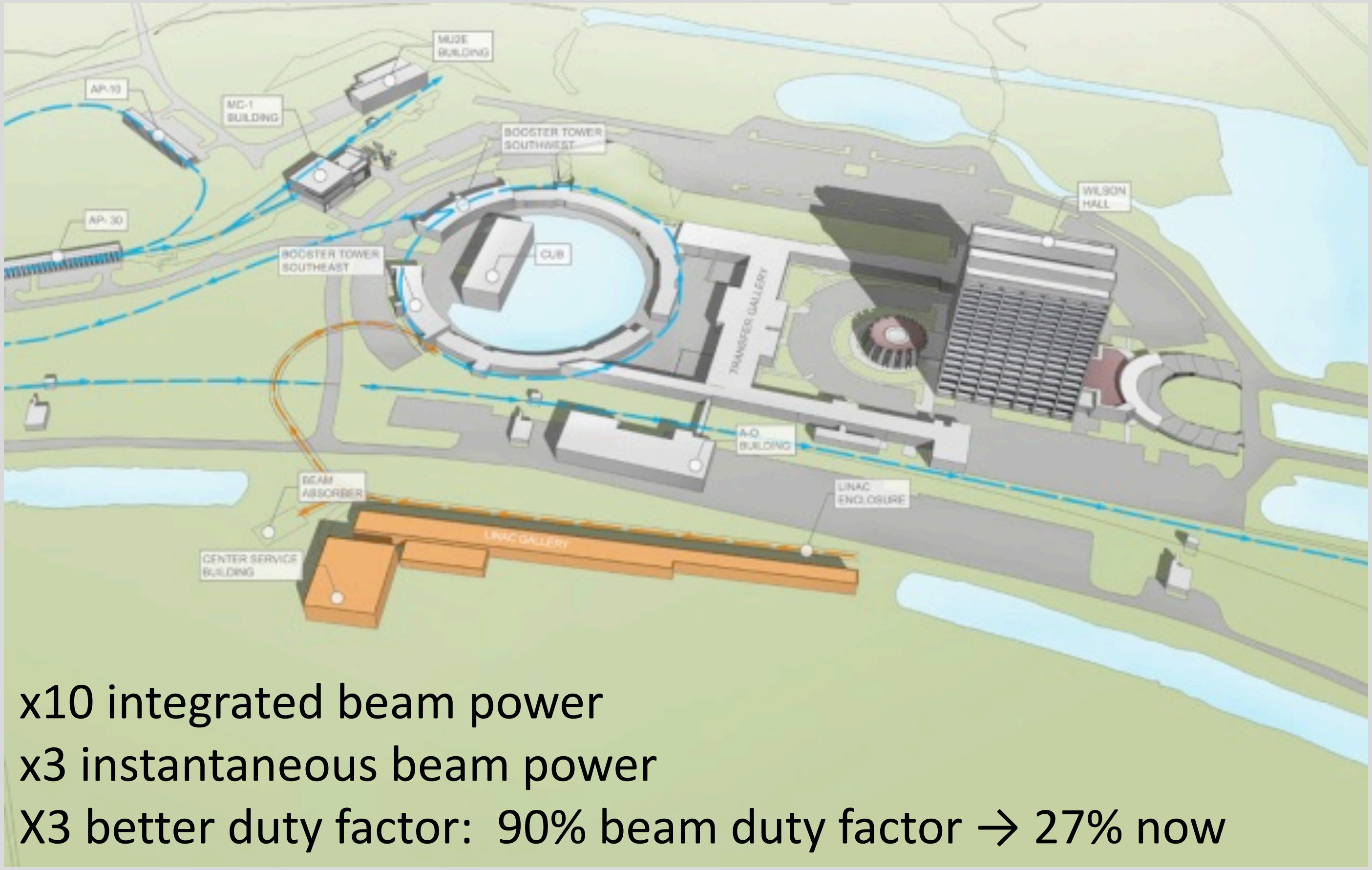
Where we are: Mu2e CRV



60% Complete

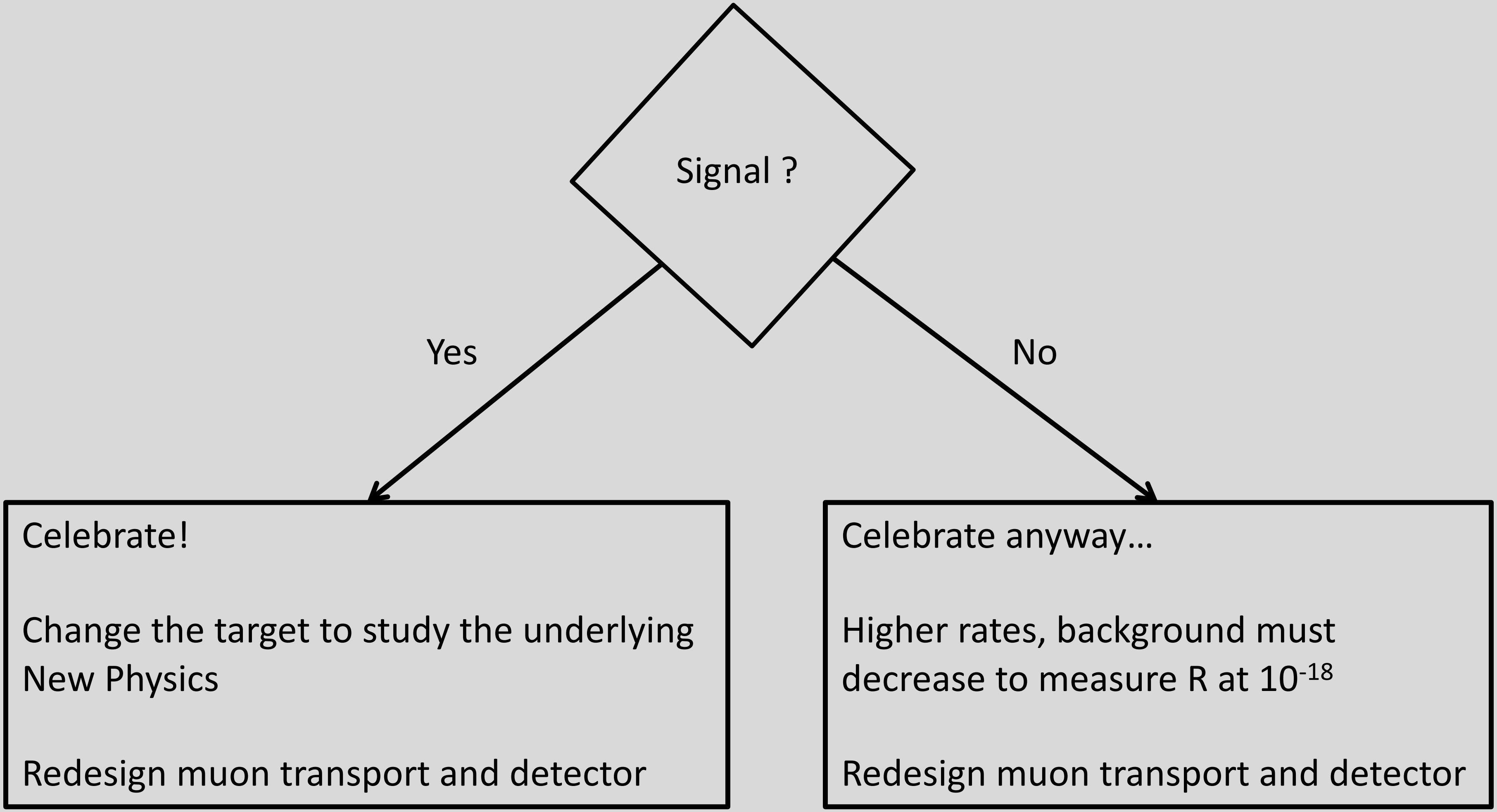
Farther in the Future: Mu2e-II

- Goal: increase sensitivity by order of magnitude: 2.5×10^{-18}!
- PIP-II: 0.8 GeV LINAC proton beam; tunable bunch spacing
- Snowmass 2014 study very promising: R&D needed (arXiv:1307.1168)
- Expression of Interest (EOI): arXiv: 1802.02599



x10 integrated beam power
x3 instantaneous beam power
X3 better duty factor: 90% beam duty factor → 27% now

Mu2e upgrade?



Signal ?

Yes

No

Celebrate!

Change the target to study the underlying New Physics

Redesign muon transport and detector

Celebrate anyway…

Higher rates, background must decrease to measure R at 10^{-18}

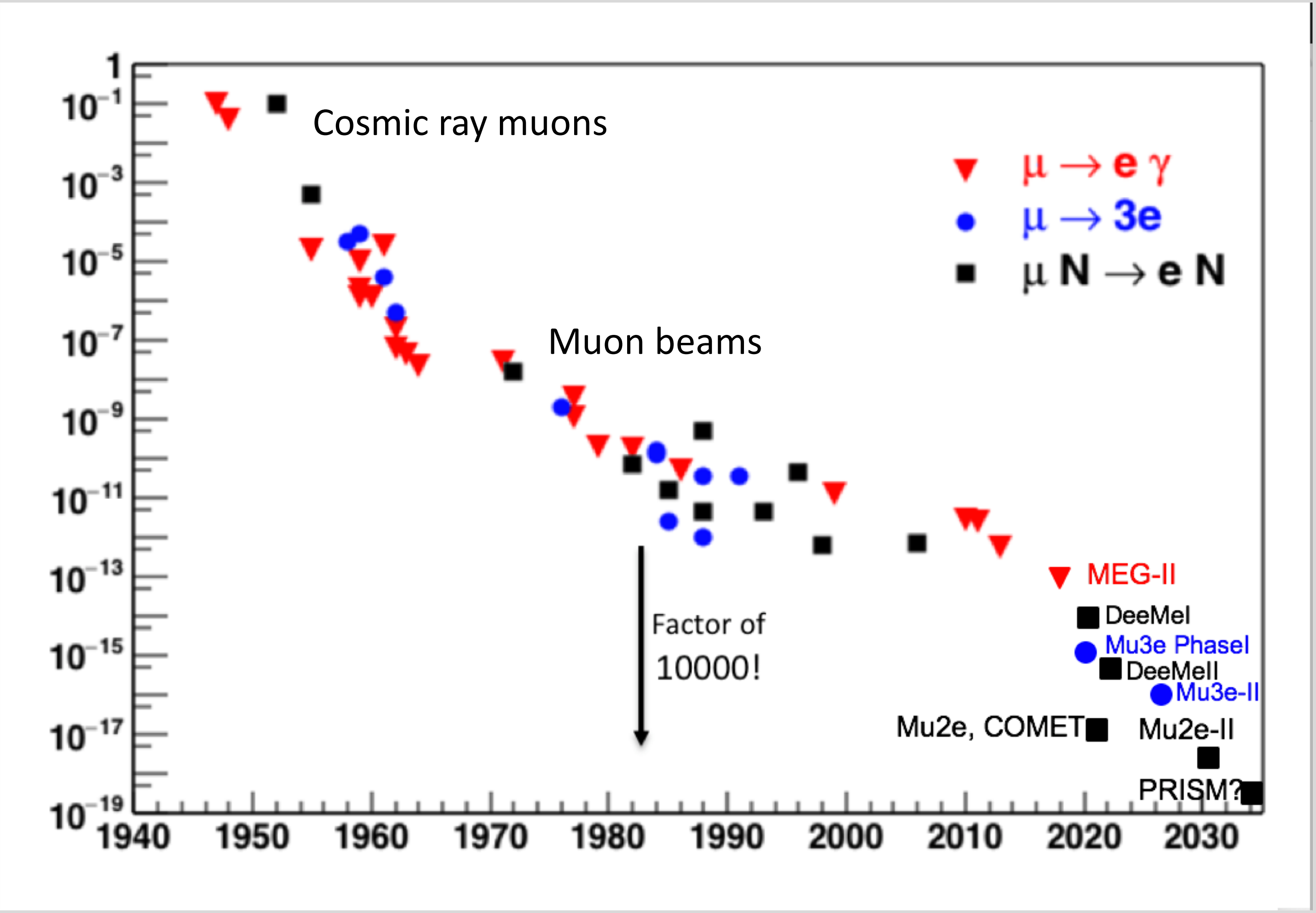
Redesign muon transport and detector

Keys to Mu2e Success

- Excellent momentum resolution (<200 keV/c core)
- ~10^{18} muons: High rate stopped muon per proton on target due to magnetic mirrors.
- Pulsed proton beam with ideal pulse frequency
  - Narrow proton pulses (< +/- 125 ns)
  - Very few out-of-time protons (< 10^{-10})
- "Hollow" detectors blind to bulk of low-momentum decay-in-orbit spectrum.
- High cosmic-ray-veto efficiency (>99.99%)

A Renaissance for Muon Physics!

Many other CLFV efforts that I did not describe!



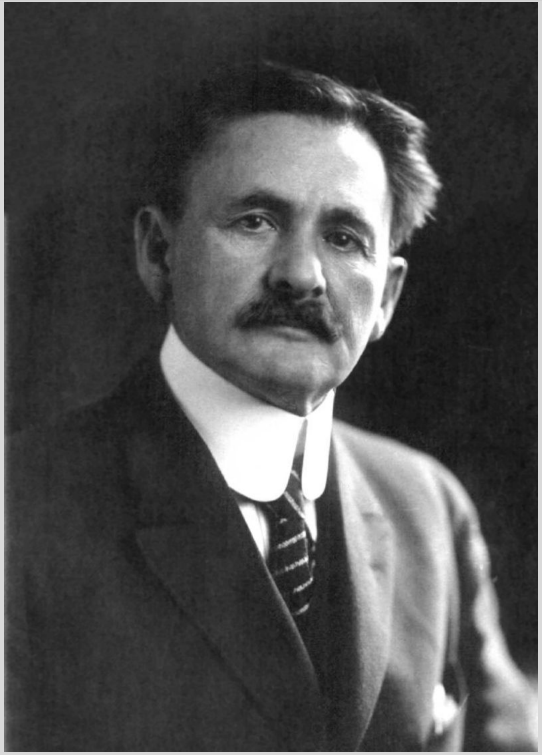
Anything left to learn?

“”””

While it is never safe to affirm that the future of Physical Science has no marvels in store even more astonishing than those of the past, it seems probable that **most of the grand underlying principles have been firmly established** and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice... An eminent physicist remarked that **the future truths of physical science are to be looked for in the sixth place of decimals.**

“”””

Nobel prize for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid"



Albert A. Michelson
~1900

wikiquote.org

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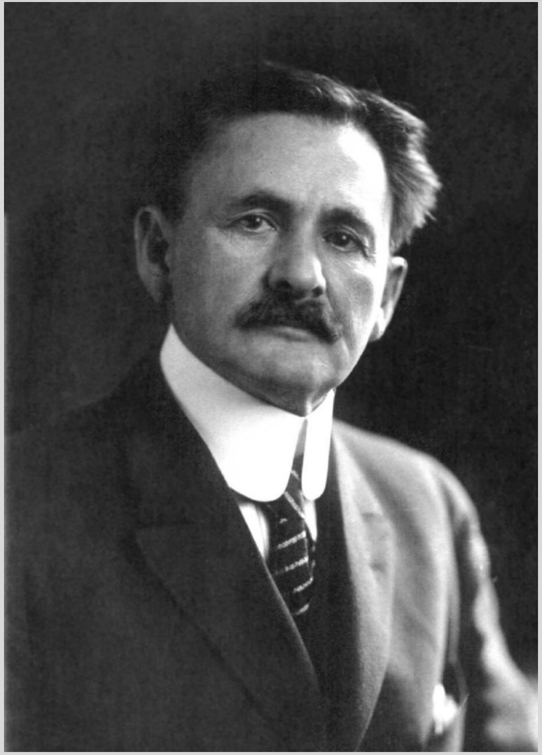
“”””

Or, maybe the 16th decimal place!

Nobel prize for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid"



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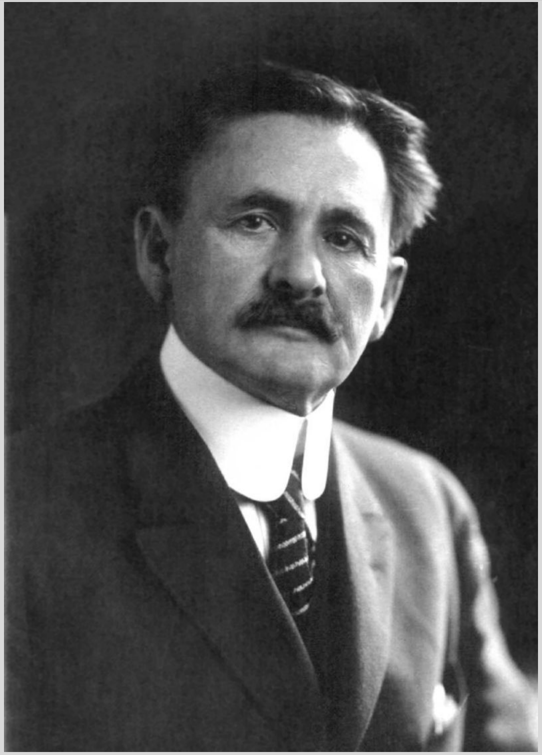


Albert A. Michelson
~1900

wikiquote.org

Summary

- There is a rich history of muon physics that is currently undergoing a **major renaissance**…
- Mu2e's goal is to improve sensitivity by 4 orders-of-magnitude relative to past CLFV searches.
- Results will be complementary to the LHC and sensitive to mass scales many orders of magnitude higher than can be directly probed.
- At UVA we have lead the effort to design and prototype a high-efficiency cosmic ray veto system for Mu2e.
- Hoping for a major discovery in the mid 2020's!

Backup

The students take their epoxy work very seriously…

Abstract

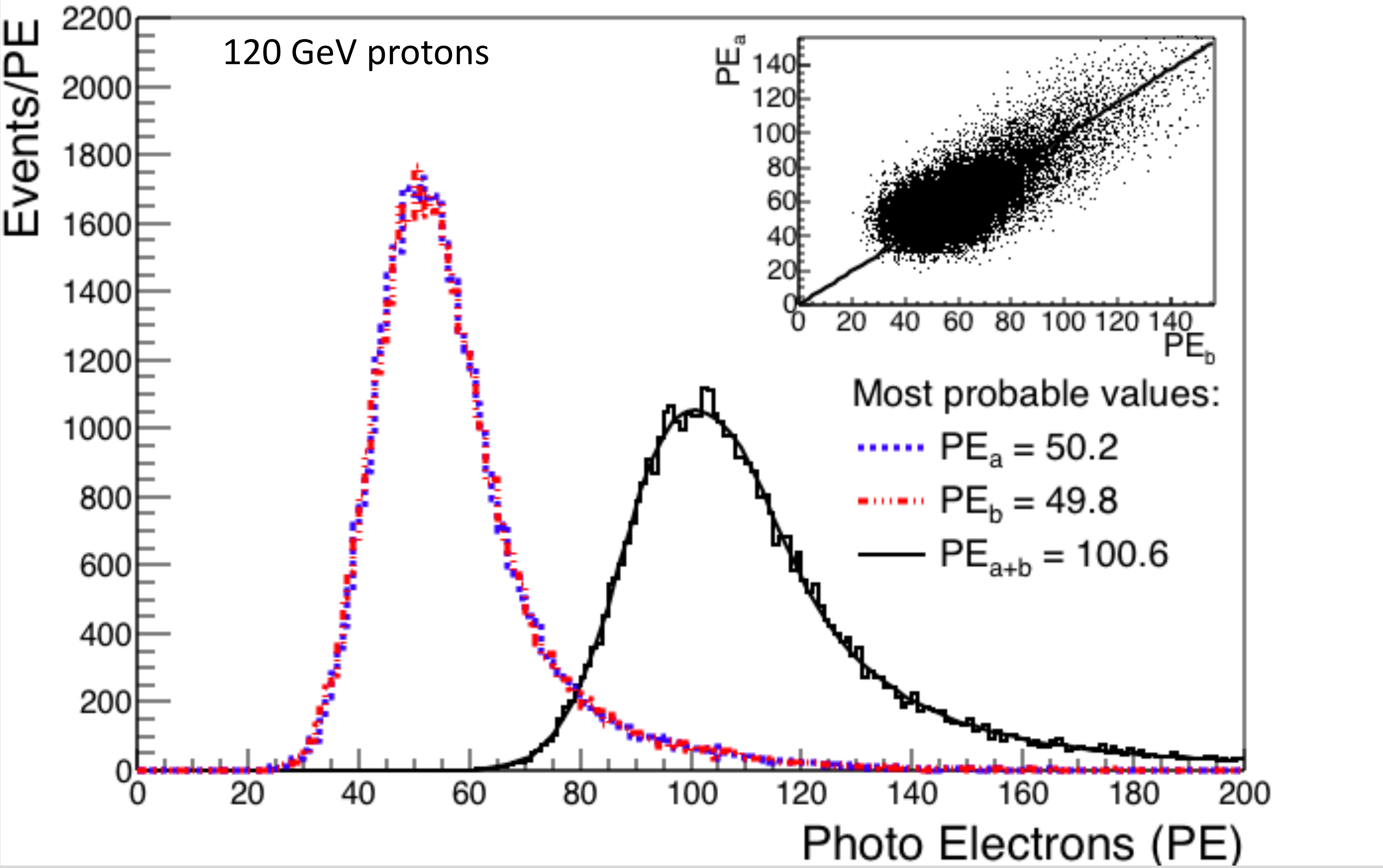
A Renaissance for Muon Physics

Who ordered that?

In a sense, the muon has been a thorn in the side of particle physicists since its discovery in 1936. Still, we seek answers related to questions of flavor. Why three families? Why are the lepton masses so different? Who ordered that? Experiments searching for charged lepton flavor violation seemed to run out of sensitivity gains in the 1990s. However, a rebirth is ongoing! A new series of experiments, led by new technologies, are poised to push sensitivities down several orders of magnitude. Soon, the muon sector may lead to discoveries that will help answer the most fundamental questions of particle physics.

CRV Counter Test Beam Performance

NIM, Volume 890, 11 May 2018, Pages 84-95, arXiv:1709.06587



Why Muon-to-Electron Conversion?

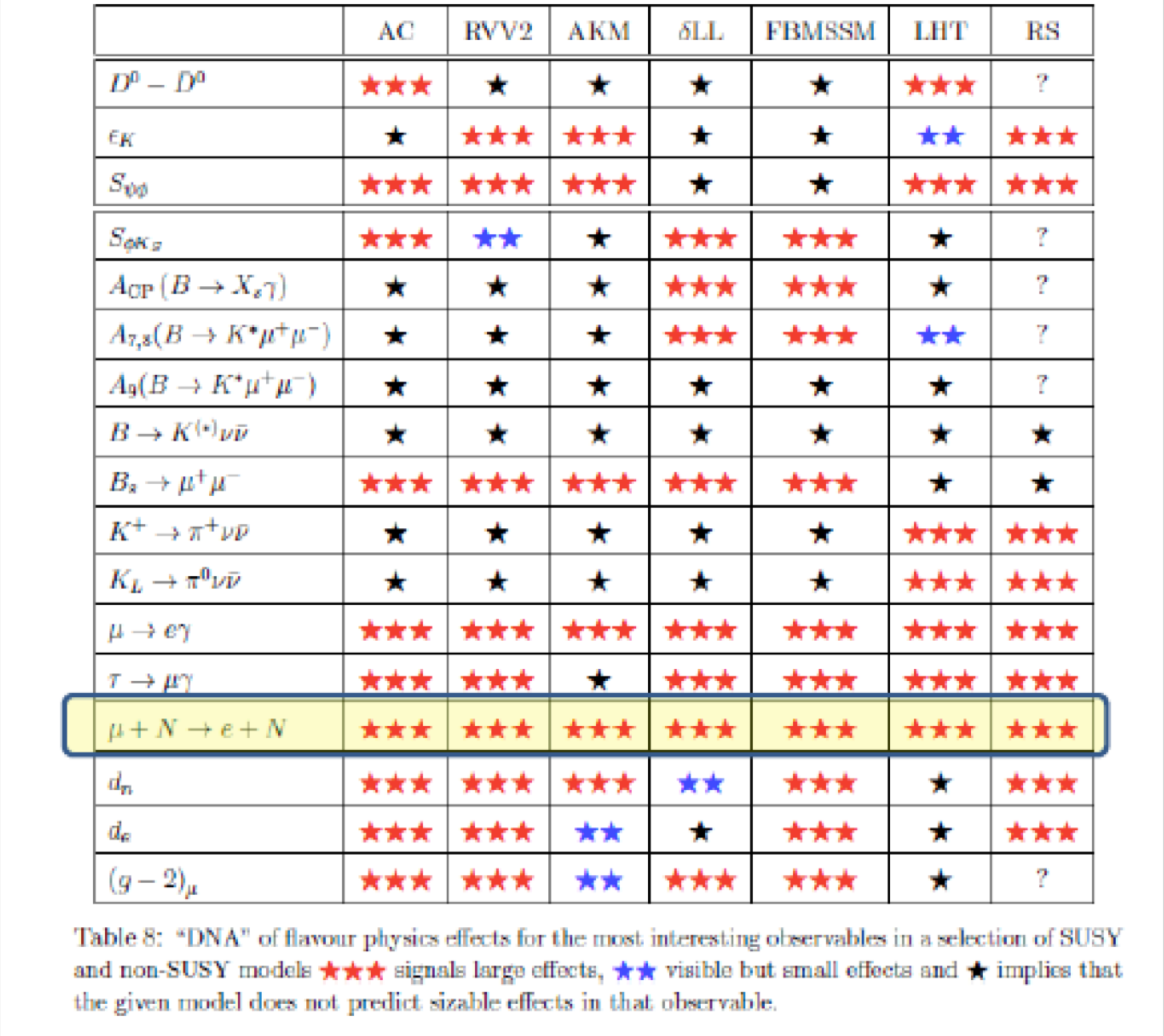
Different SUSY and and otherBSM modules


★★★ Large effects

★★ Visible, but small

★ No sizable effect

Altmannshofer et al., NPB 830, 17 (2010)



	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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

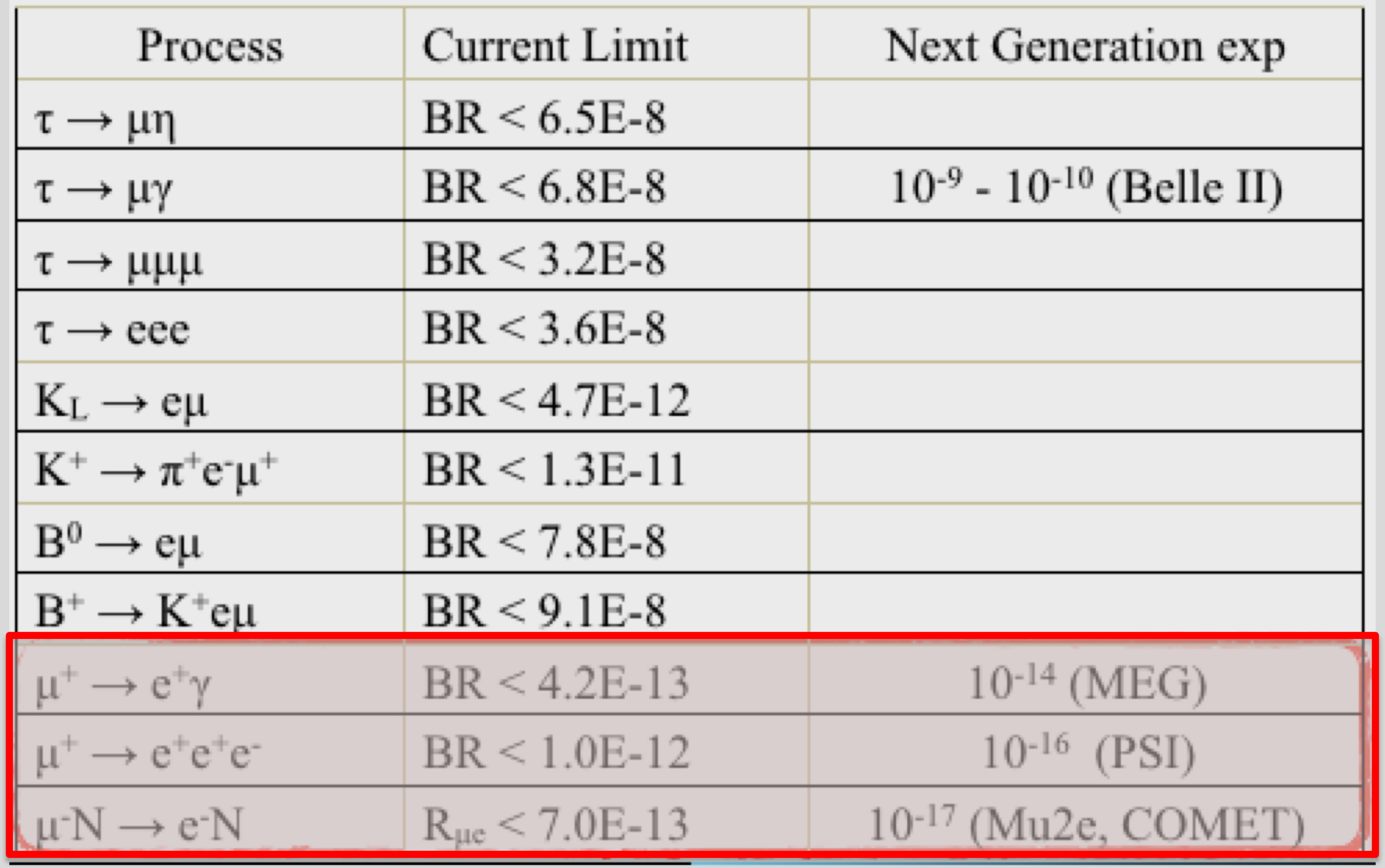
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

A quote from a Rutherford Lecture

- In 1909, an undergraduate, Ernest Marsden, was being trained by Geiger.
- "I had observed the scattering of alpha-particles, and Dr. Geiger in my laboratory had examined it in detail. He found, in thin pieces of heavy metal, that the scattering was usually small, of the order of one degree. One day Geiger came to me and said, "Don't you think that young Marsden, whom I am training in radioactive methods, ought to begin a small research?" Now I had thought that, too, so I said, " **Why not let him see if any alpha-particles can be scattered through a large angle?" I may tell you in confidence that I did not believe that they would be,** since we knew the alpha-particle was a very fast, massive particle with a great deal of energy, and you could show that if the scattering was due to the accumulated effect of a number of small scatterings, the chance of an alpha-particle's being scattered backward was very small. Then I remember **two or three days later Geiger coming to me in great excitement and saying "We have been able to get some of the alpha-particles coming backward …" It was quite the most incredible event that ever happened to me in my life.** It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

Limits on CLFV processes

Muon Sector: Global interest and most stringent limits
(a Renaissance?)

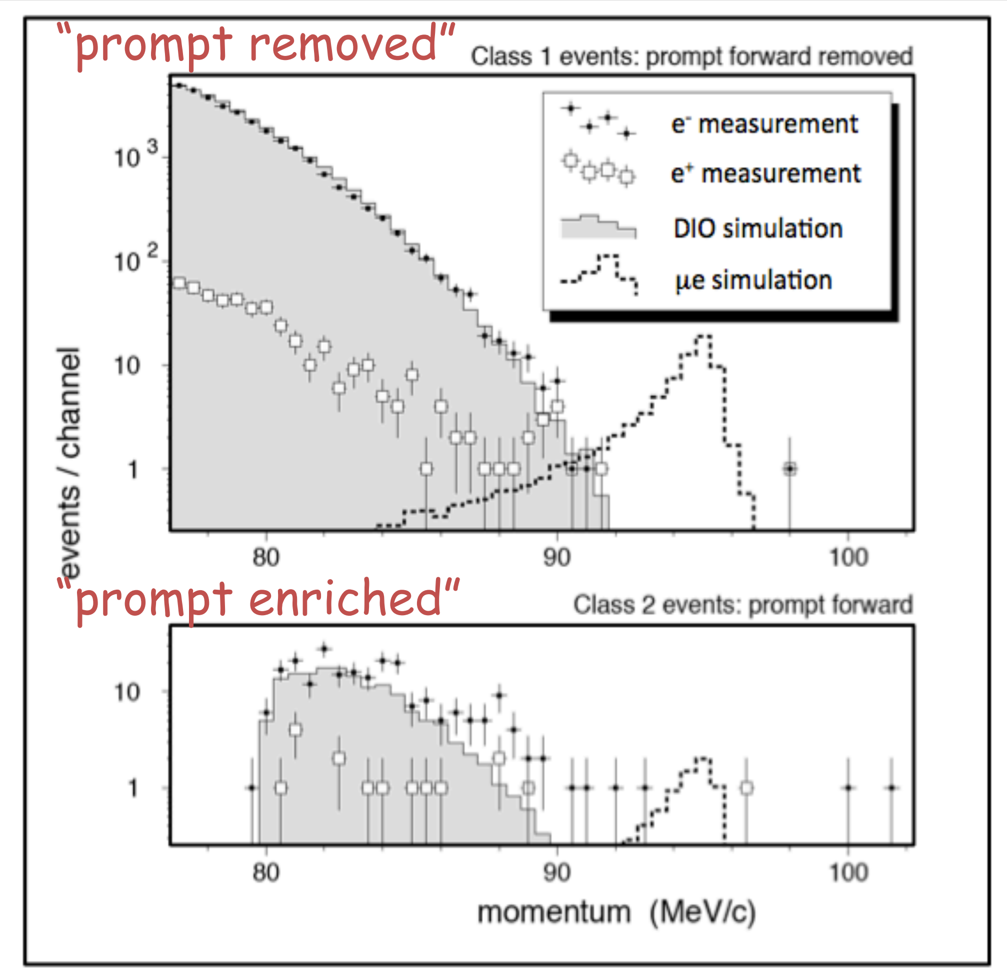


Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2E-8	
$\tau \rightarrow eee$	BR < 3.6E-8	
$K_L \rightarrow e\mu$	BR < 4.7E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3E-11	
$B^0 \rightarrow e\mu$	BR < 7.8E-8	
$B^+ \rightarrow K^+ e\mu$	BR < 9.1E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+ e^+ e^-$	BR < 1.0E-12	10^{-16} (PSI)
$\mu^- N \rightarrow e^- N$	$R_{\mu e}$ < 7.0E-13	10^{-17} (Mu2e, COMET)

Current best result: Sindrum II

SINDRUM II at PSI

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



"prompt removed"

"prompt enriched"

Final results on Au:

$R_{\mu e} < 7\times10^{-13}$ @ 90% CL

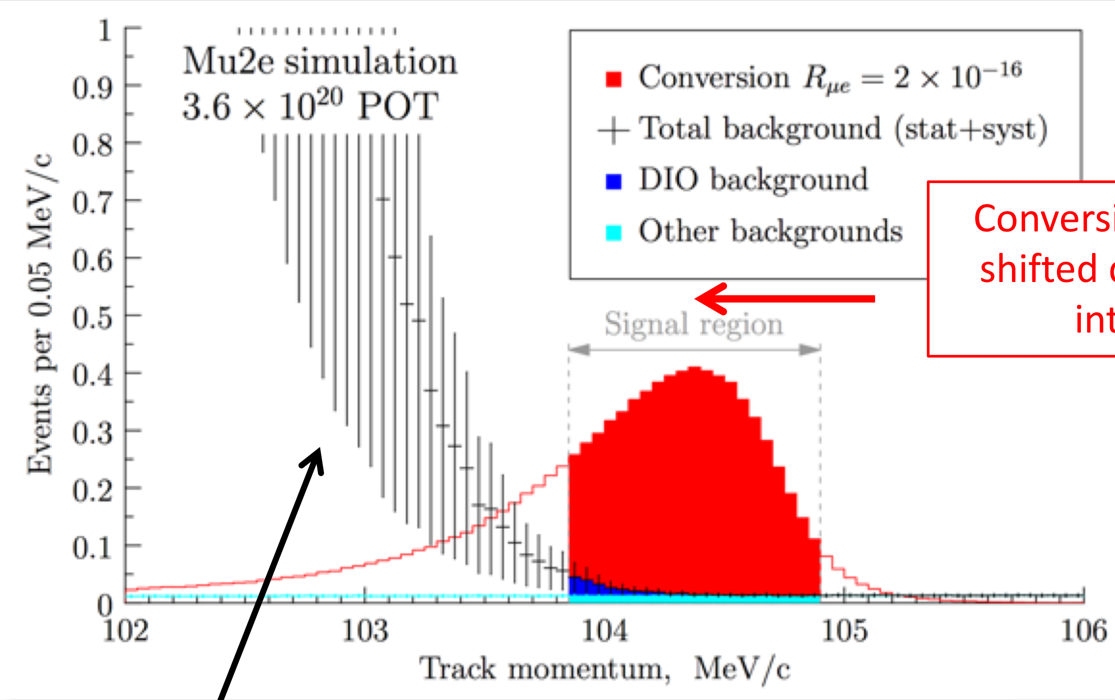
One candidate event past the end of the spectrum. Pion capture, cosmic ray?

Timing cut shows the contribution of prompt background (0.3 ns muon pulse separated by 20 ns)

Little time separation between signal and prompt background, this becomes problematic at higher rate.

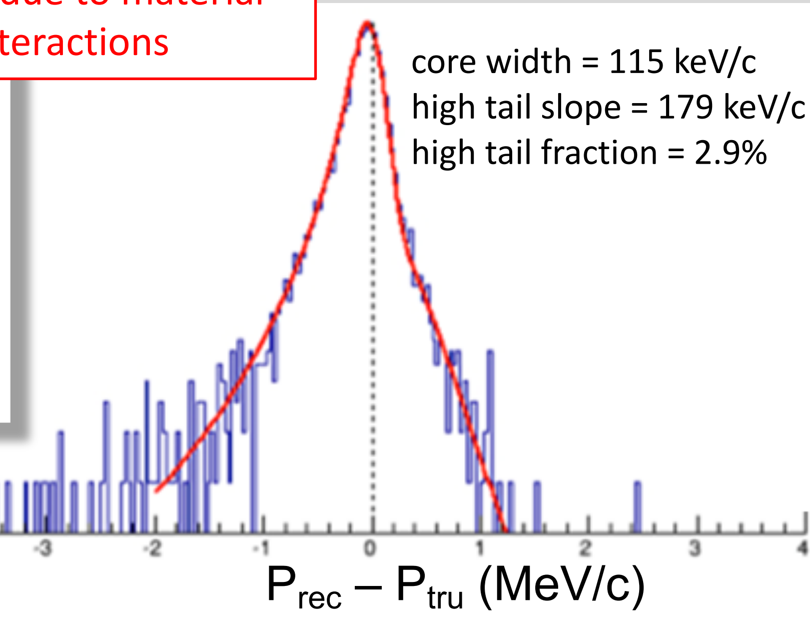
Tracker performance

- DIO spectrum spreads to the signal region.
- In addition, signal is smeared due to energy losses
- Need good momentum resolution- **<u>< 200 KeV/c</u>** is achievable



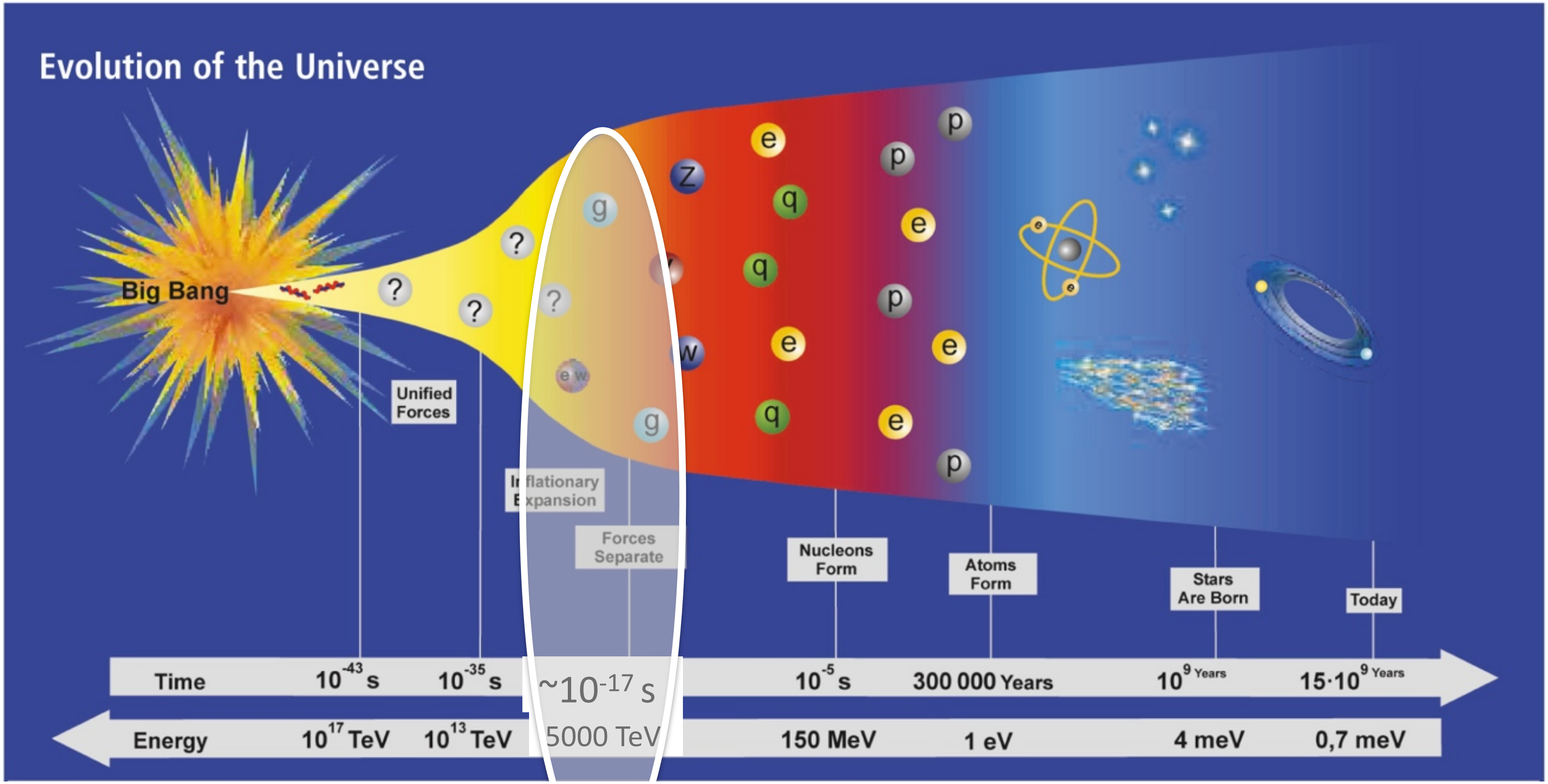
Conversion momentum shifted due to material interactions

Long DIO tail due to nuclear recoil



core width = 115 keV/c
high tail slope = 179 keV/c
high tail fraction = 2.9%

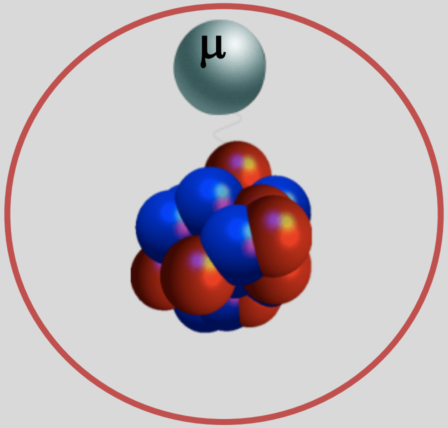
Probing the history of the Universe



Mu2e is sensitive to physics that was crucially important when the Universe was only 10^{-17} s old!

Experimental Signature

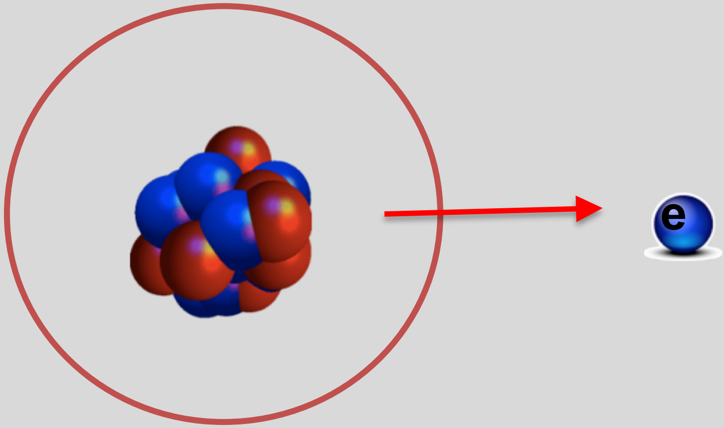
$$\mu^- N \rightarrow e^- N$$



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

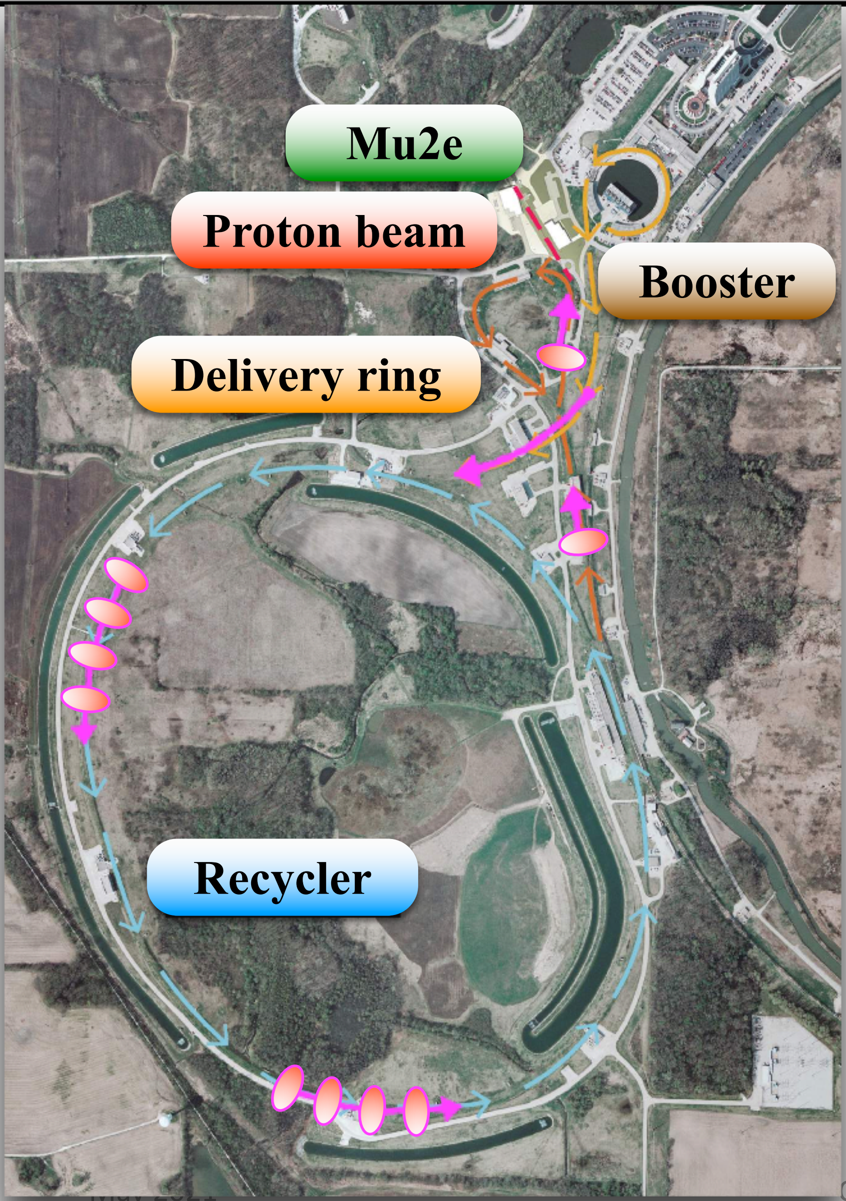
(Electron E depends on Z)

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



- Nucleus coherently recoils off outgoing electron, no breakup

Mu2e proton beam



Fermilab ideally suited for Mu2e!

- Mu2e will recycle the existing accelerator infrastructure
- **Booster** provides batches of 8 GeV protons to recycler -- 4×10^{12} protons every 1/15th second
- **Recycler** divides proton batches into 8 smaller bunches
- **Delivery ring** gets 1 out of 8 bunches from recycler
- **Mu2e** gets the **proton beam** pulses from delivery ring every 1695 ns