The search for CLFV with the Mu2e Experiment

Kevin Lynch, AD/TSD and Mu2e

FNAL Summer 2023 Lecture Series: STEM at Work

27 July 2023

What we'll cover…

- Let's start at the beginning
- What is CLFV?
- What is Mu2e and how does it work?
- Summary

What exactly to physicists think we already now?

- Example: Gravity, or Why Things Fall

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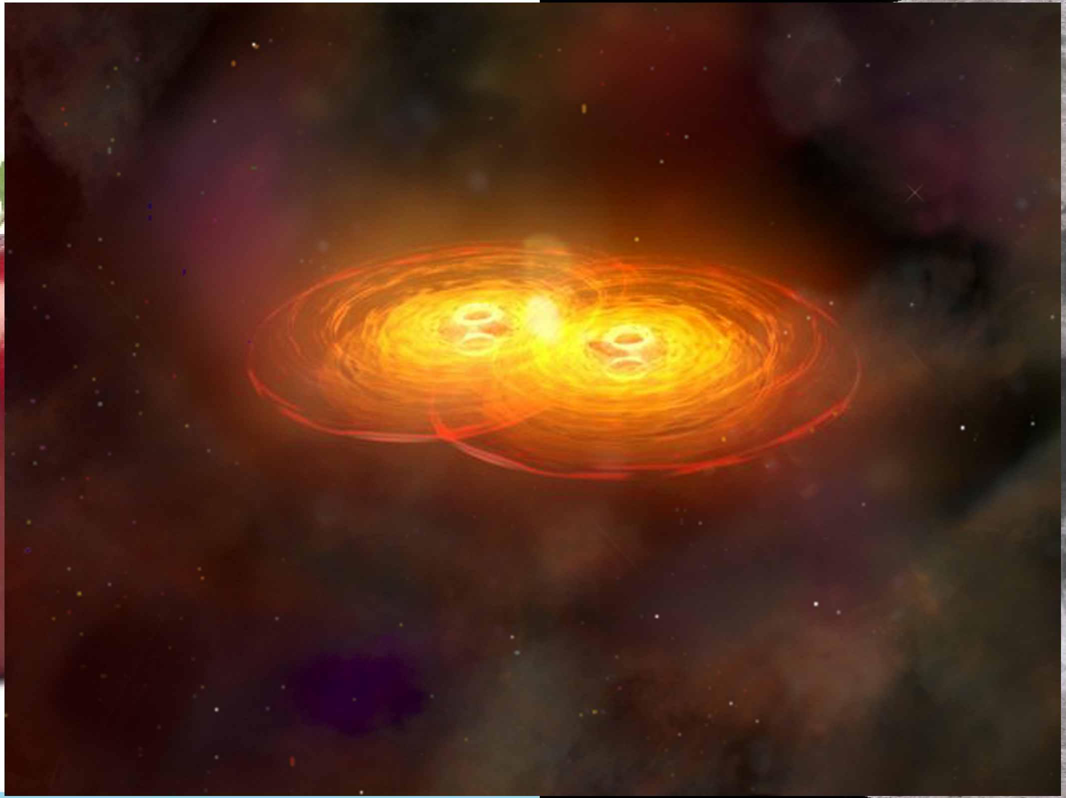

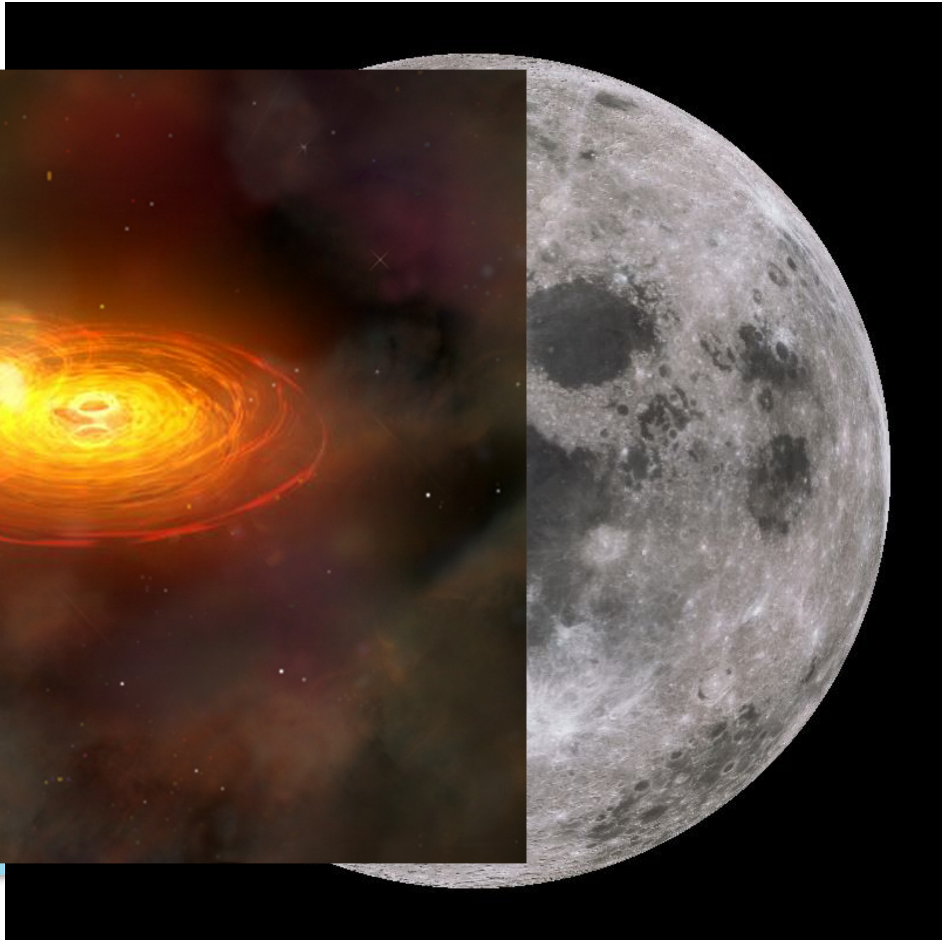

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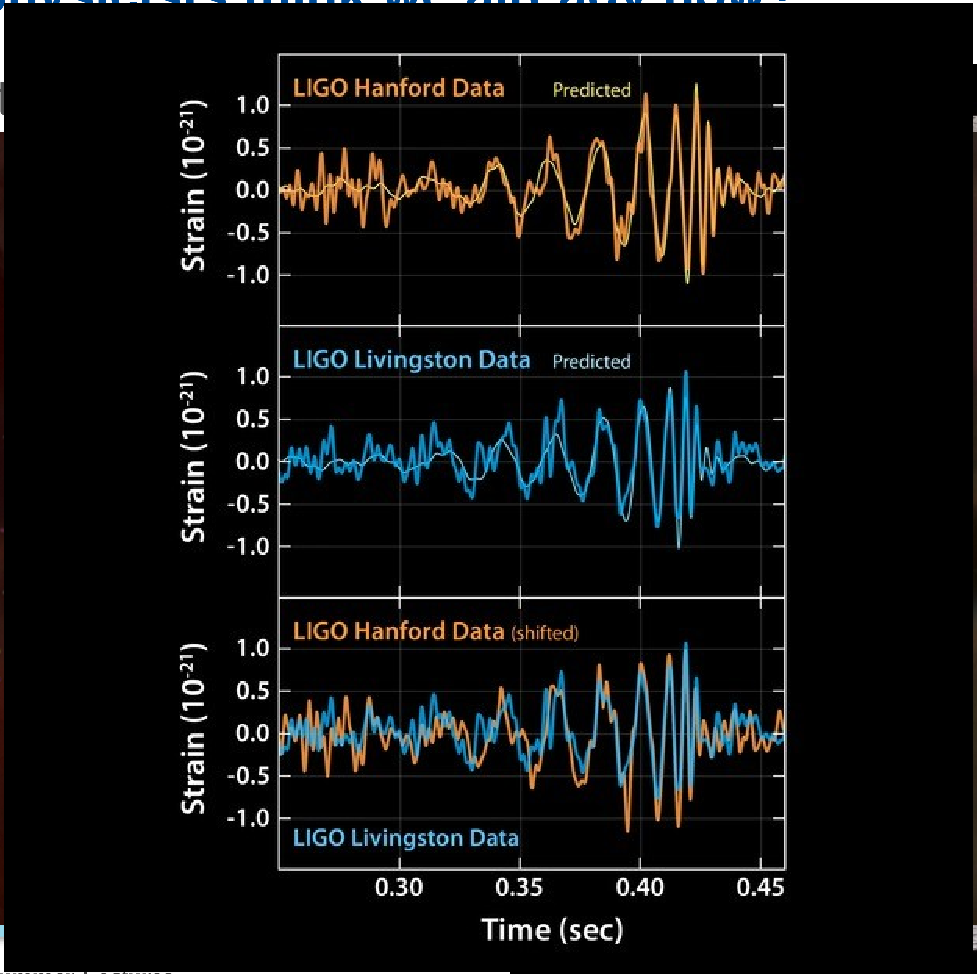

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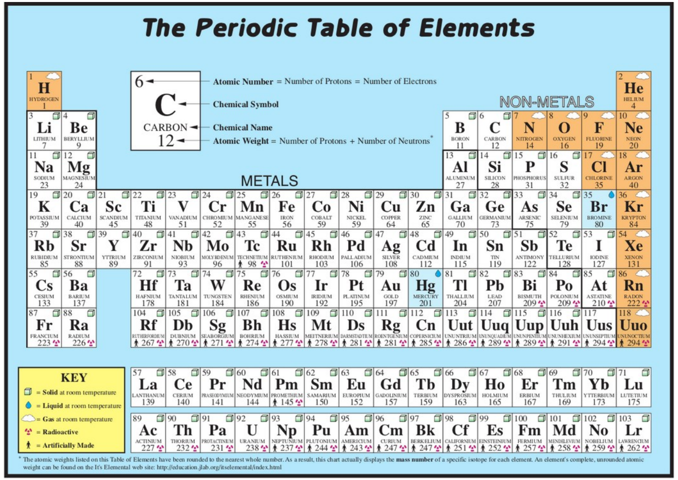
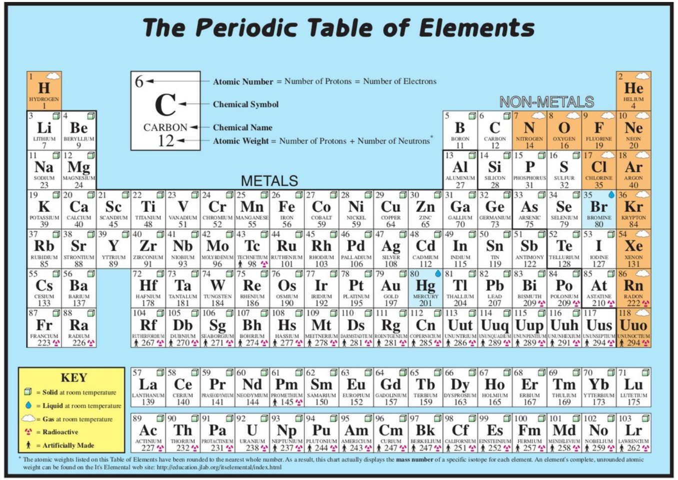

The Periodic Table of Elements
Atomic Number = Number of Protons = Number of Electrons
Chemical Symbol
Chemical Name
Atomic Weight = Number of Protons + Number of Neutrons*
6
C
CARBON
12
NON-METALS
METALS
KEY
= Solid at room temperature
= Liquid at room temperature
= Gas at room temperature
= Radioactive
= Artificially Made

What else?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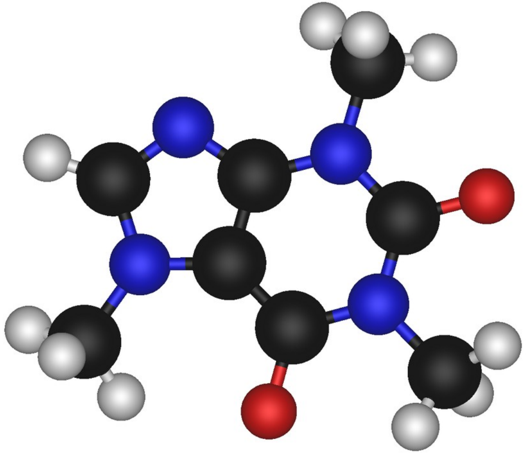

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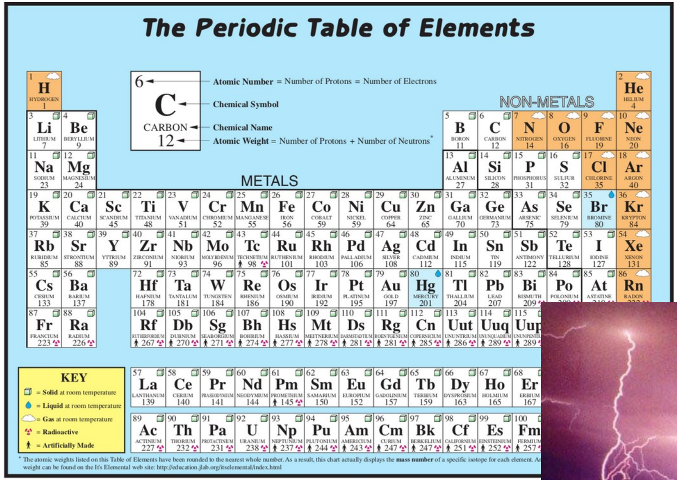
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Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Uuq Uup
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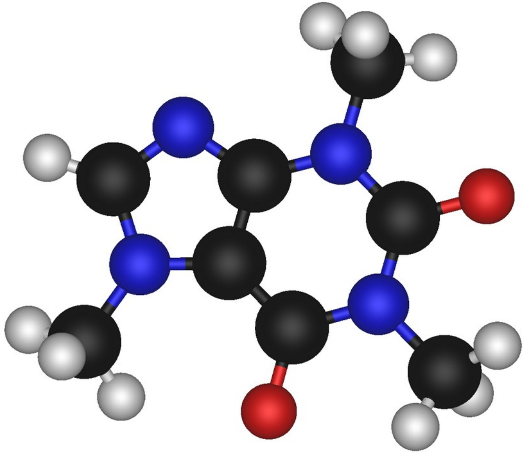

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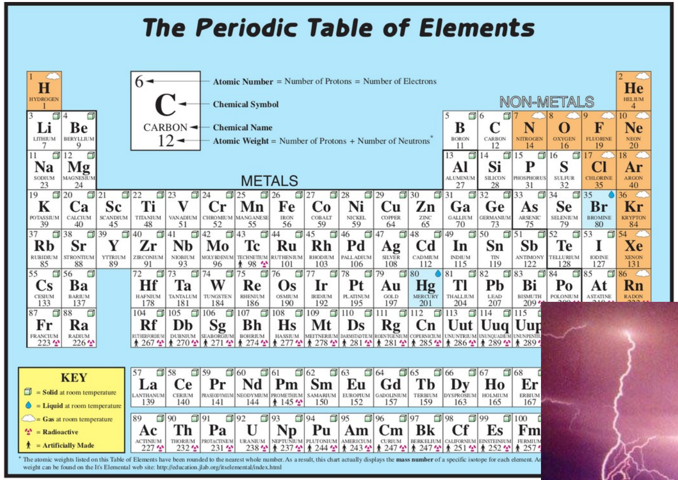

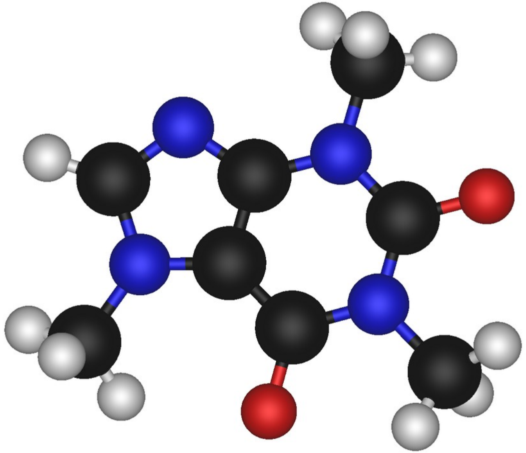

Fermilab

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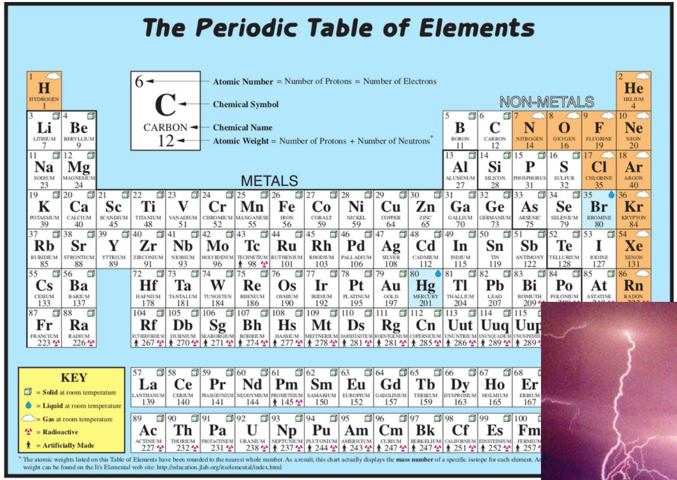

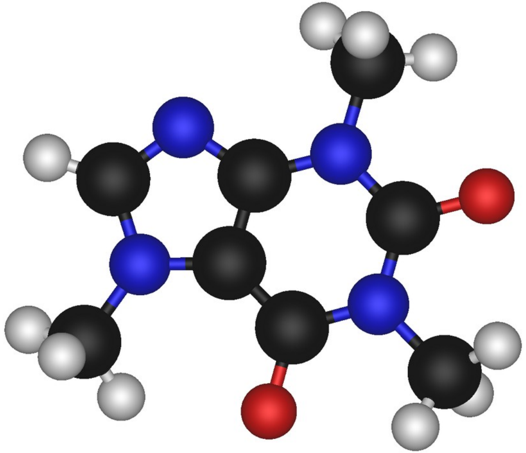

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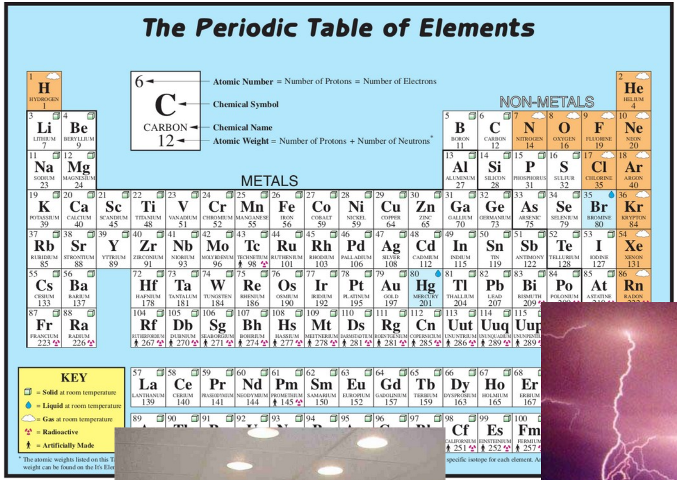

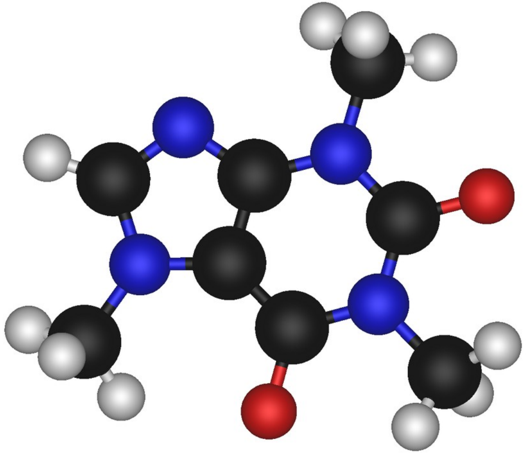

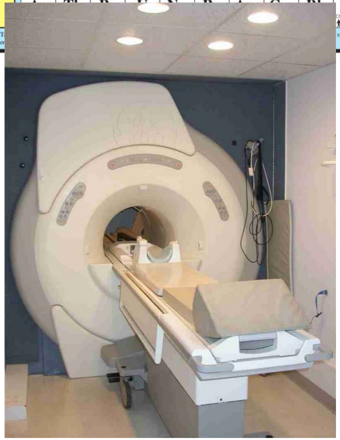

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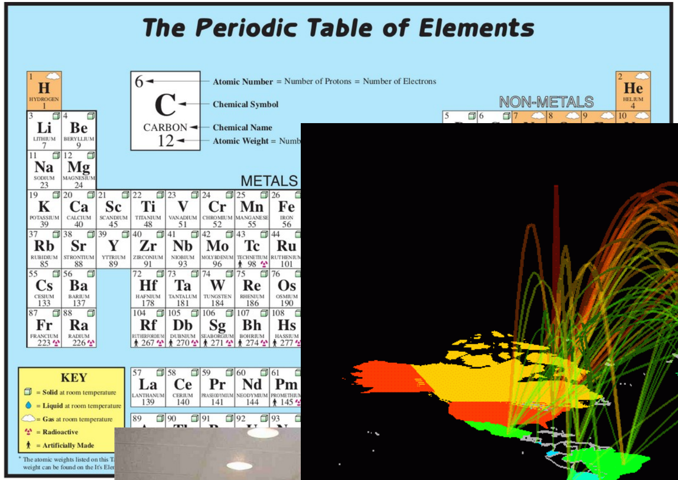
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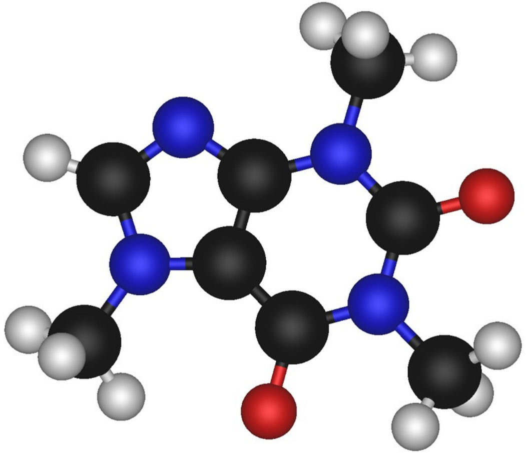

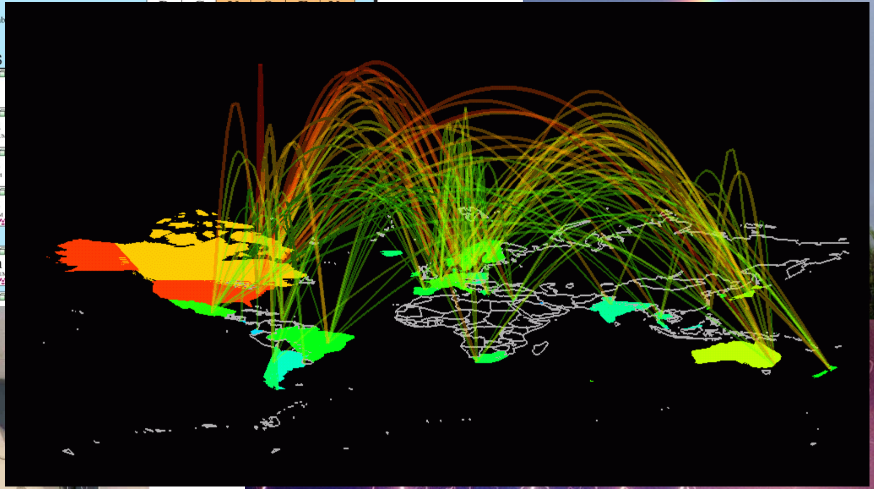

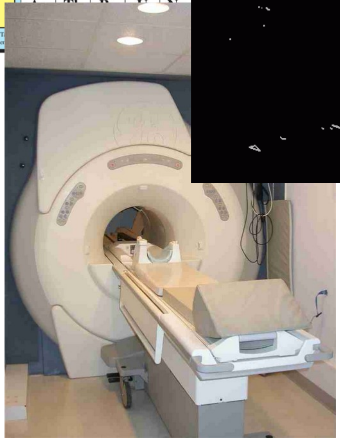

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Fermilab

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We have theories and models that we think can describe most of these - but we don’t really understand all the “whys” and “whats” and “hows” – and there are things we know we don’t know!

Quantum Field Theory and the *Standard Model* quantify what we know

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Matter

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Forces

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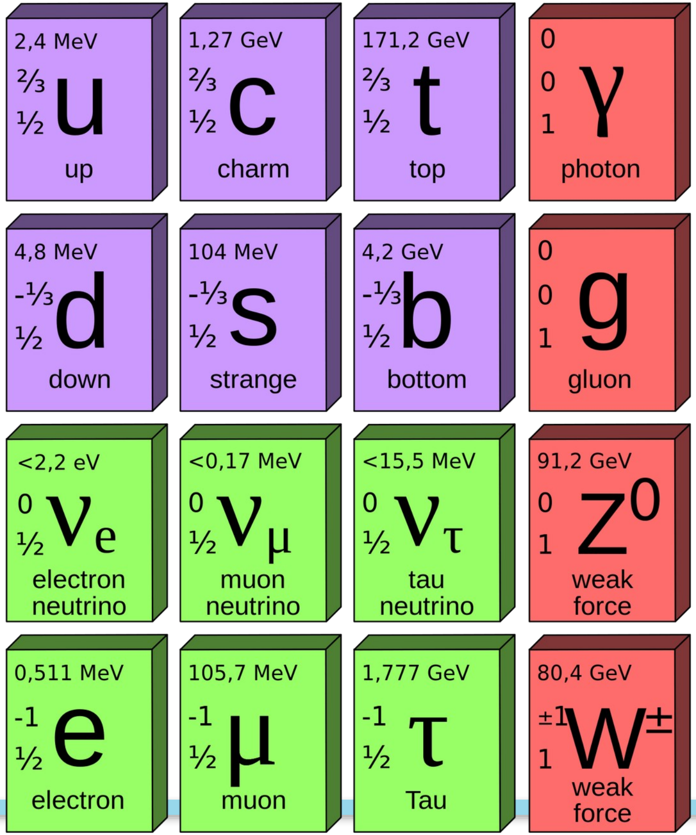

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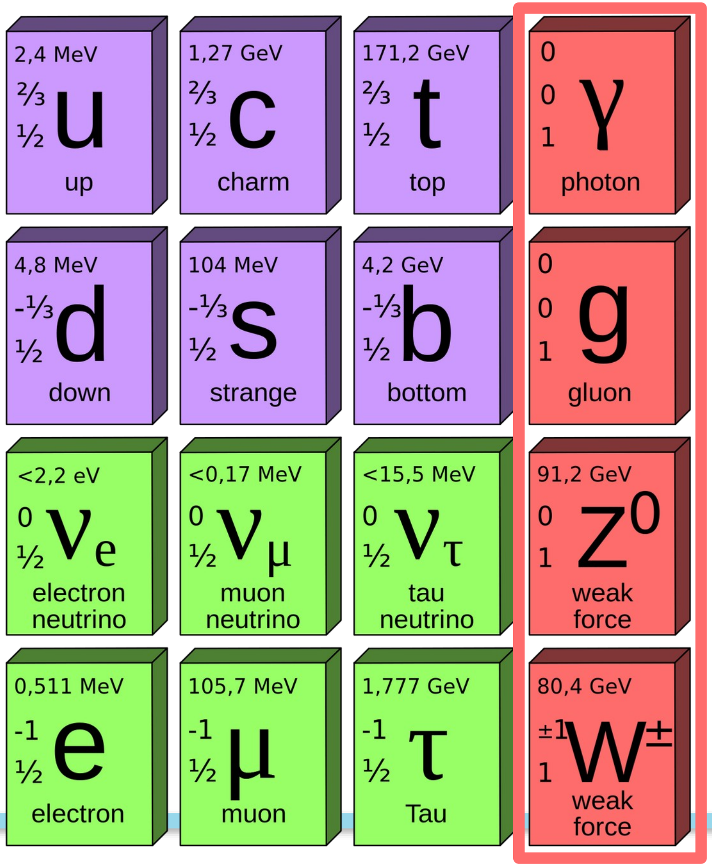

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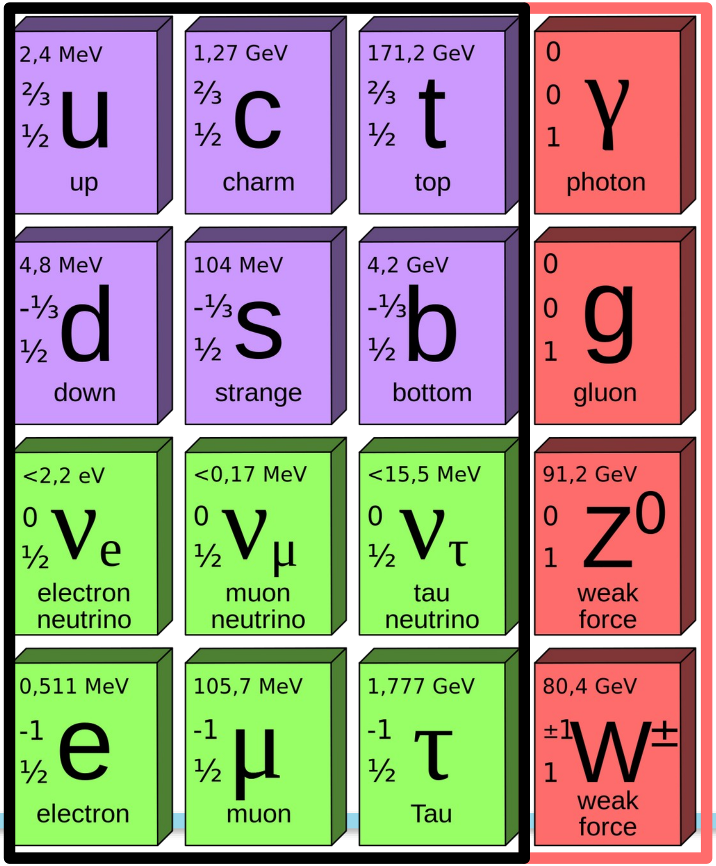

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***Quantum Field Theory* and the *Standard Model* quantify what we know**

Quarks

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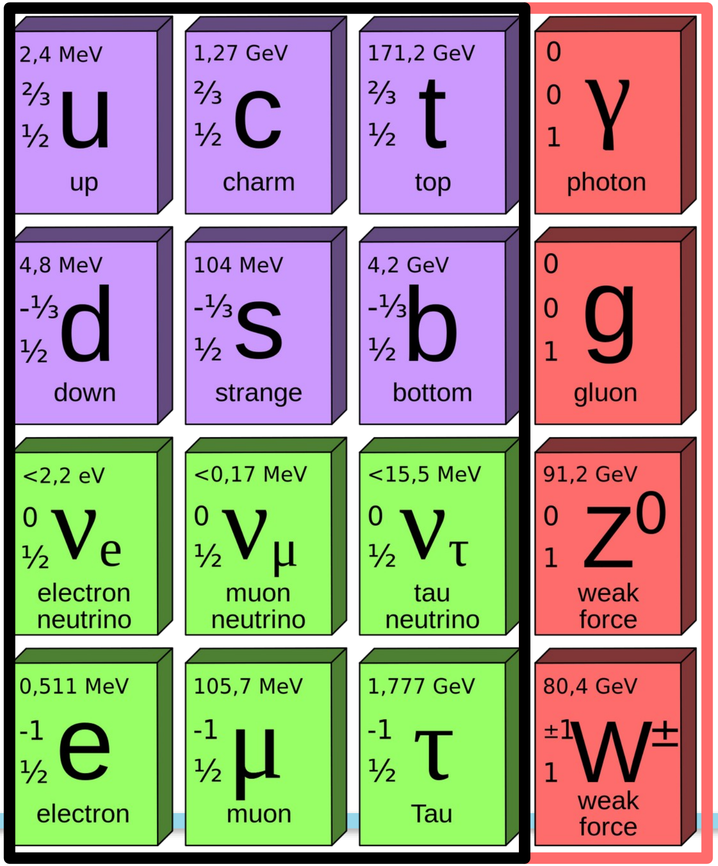

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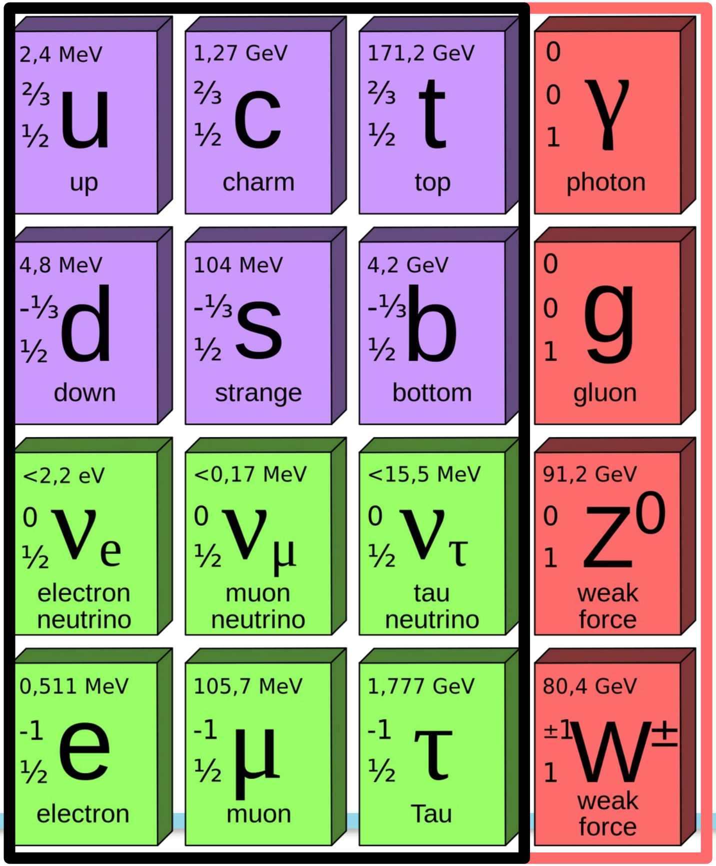

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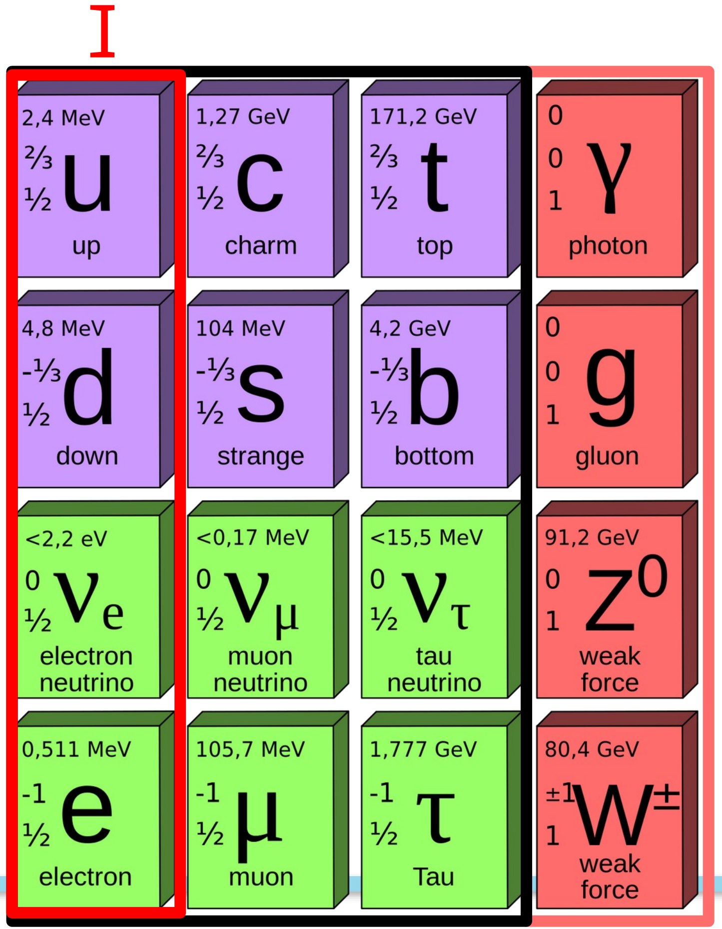

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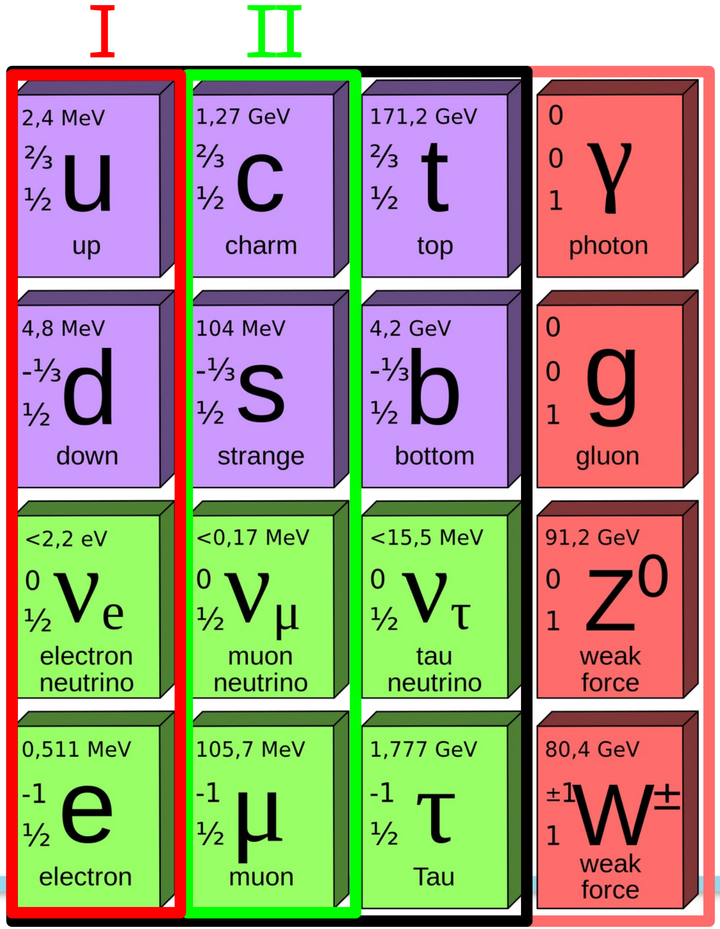

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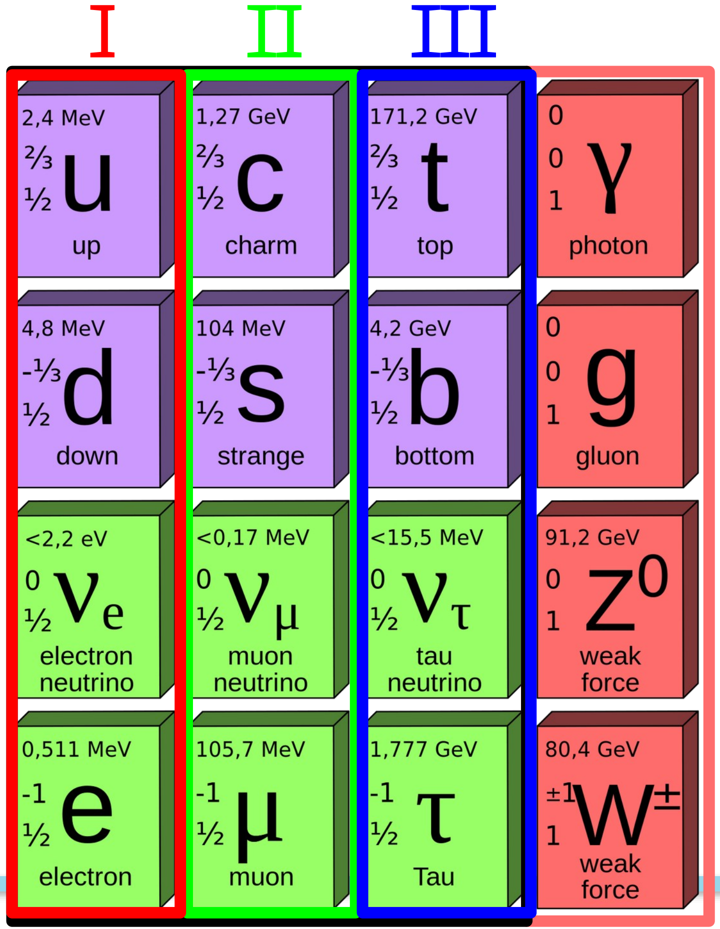

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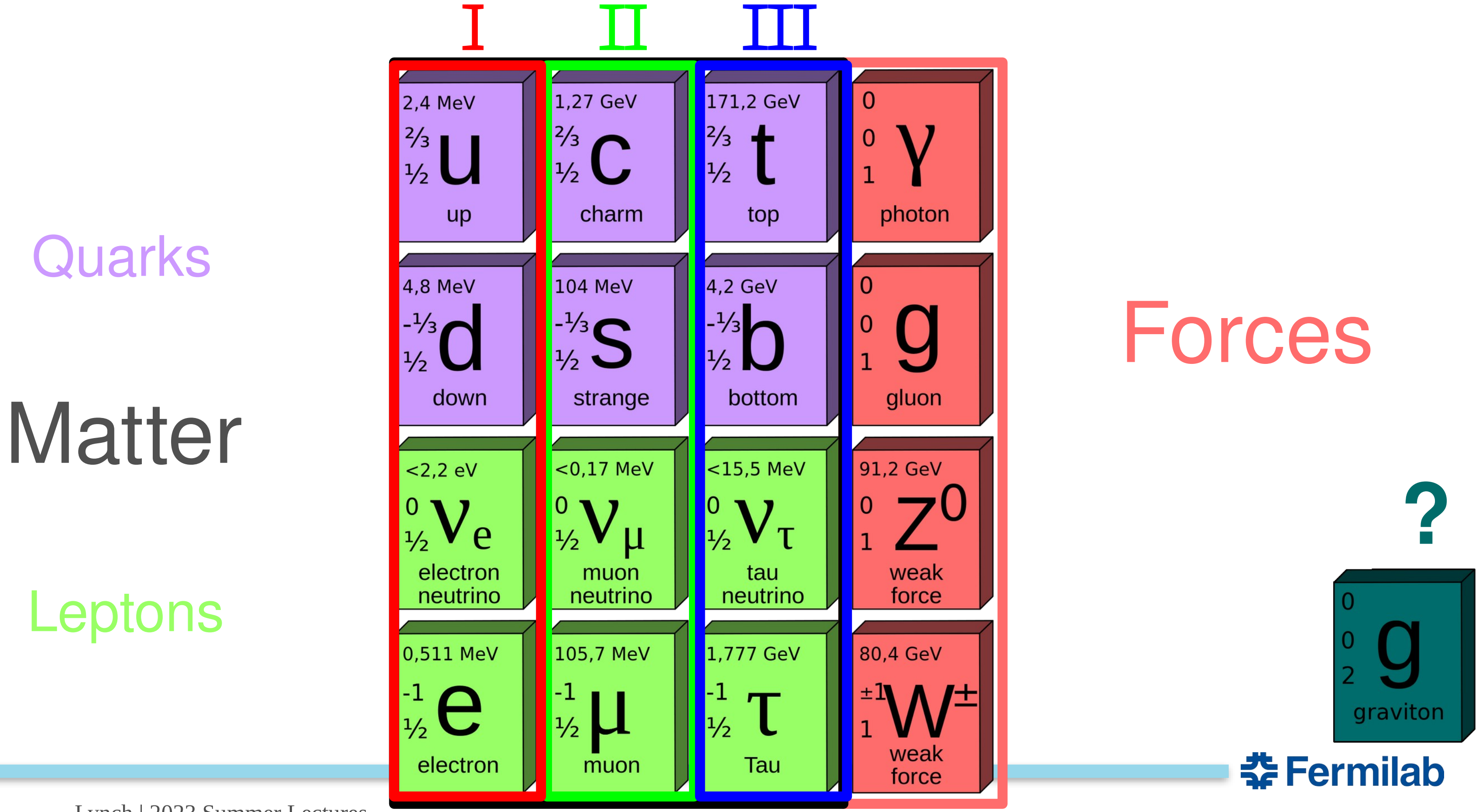

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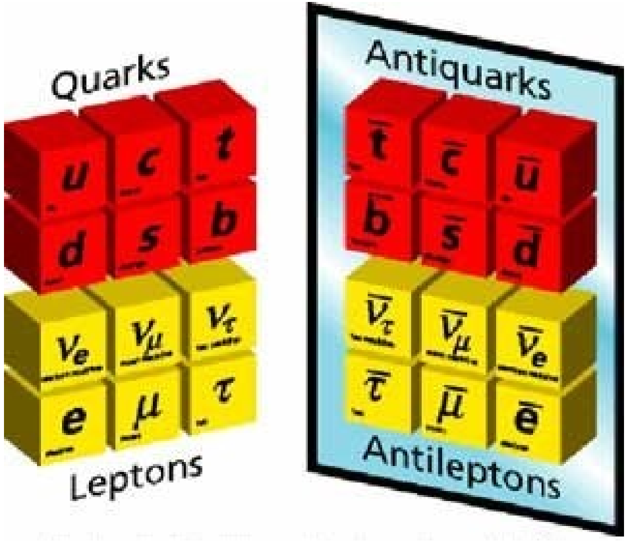
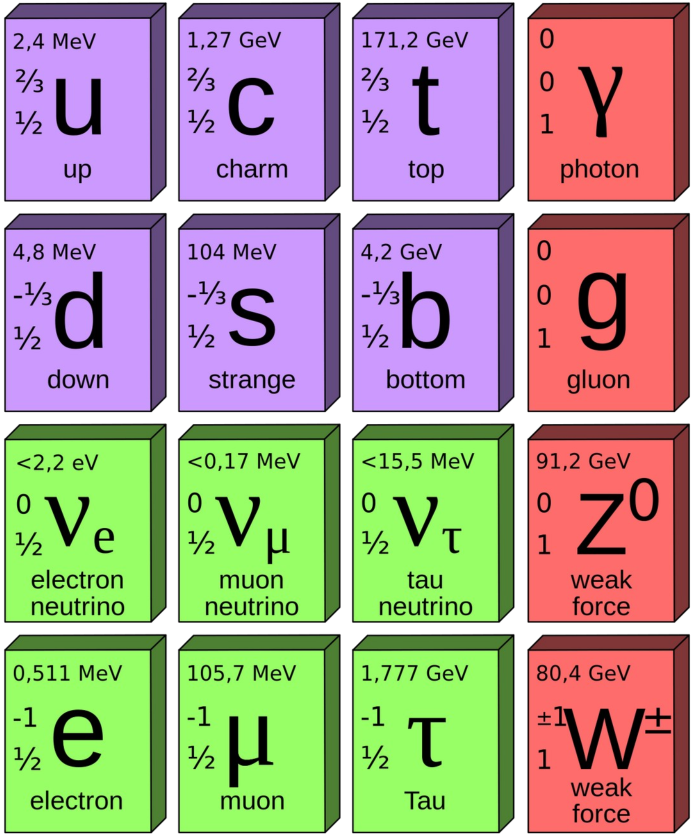


And there's a mirror world of "antimatter"



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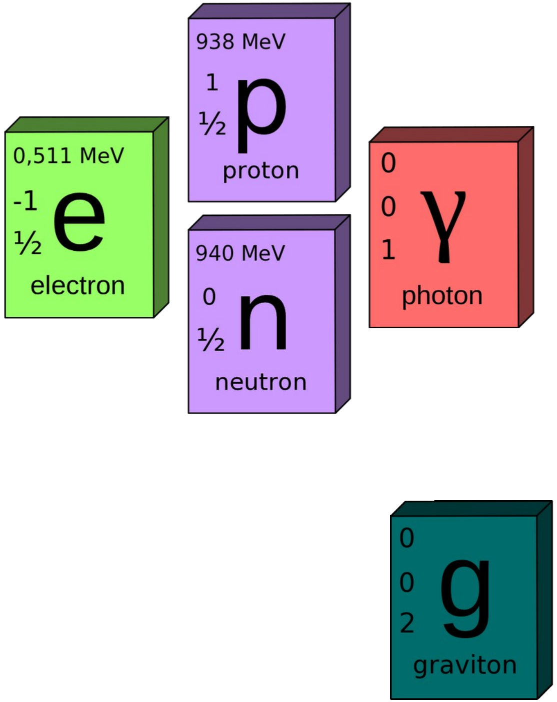
It is the *Standard Model* that quantifies what we know

But we don’t see all this complexity in our everyday existence!



There are no experiments in conflict* with the Standard Model …

*for certain values of the word "conflict"

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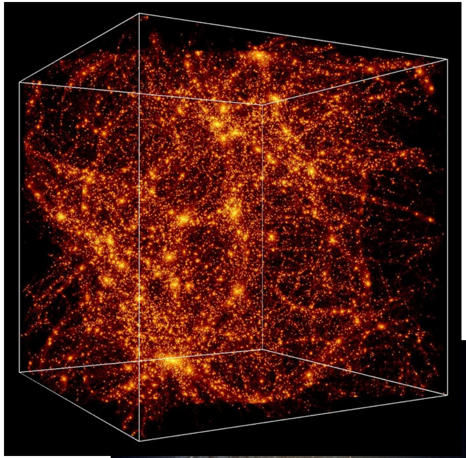

From the very largest known structures…

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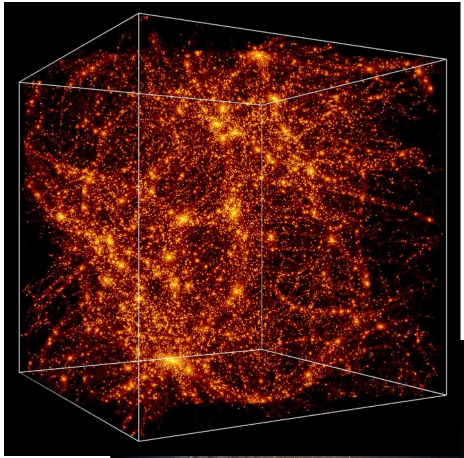
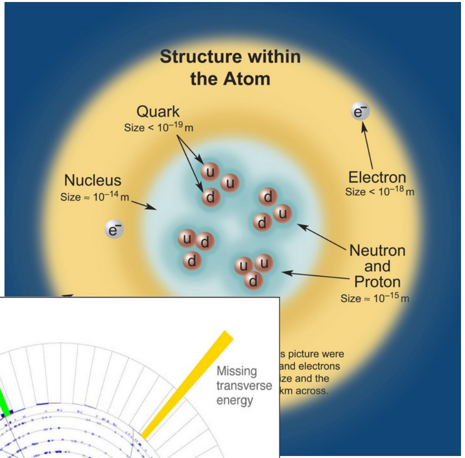
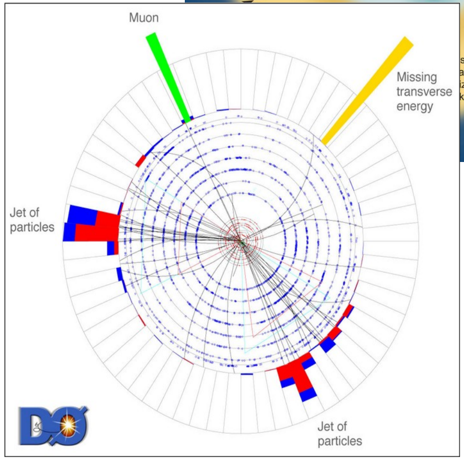


From the very largest known structures…

… to the very smallest!





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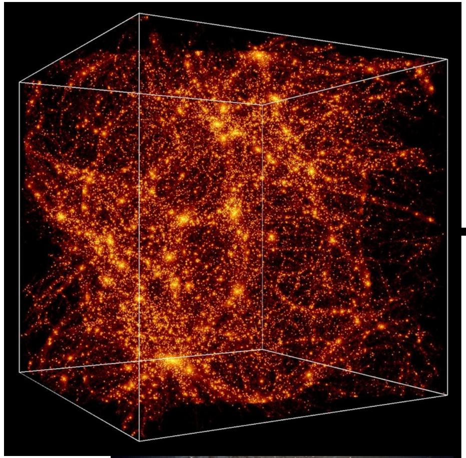
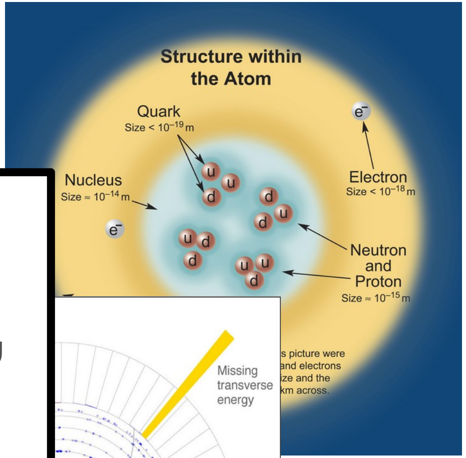
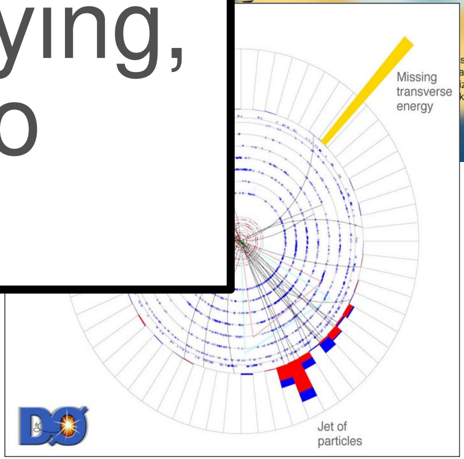


From the very
largest known

This is extremely
frustrating, annoying,
and difficult to
understand!

very
smallest!





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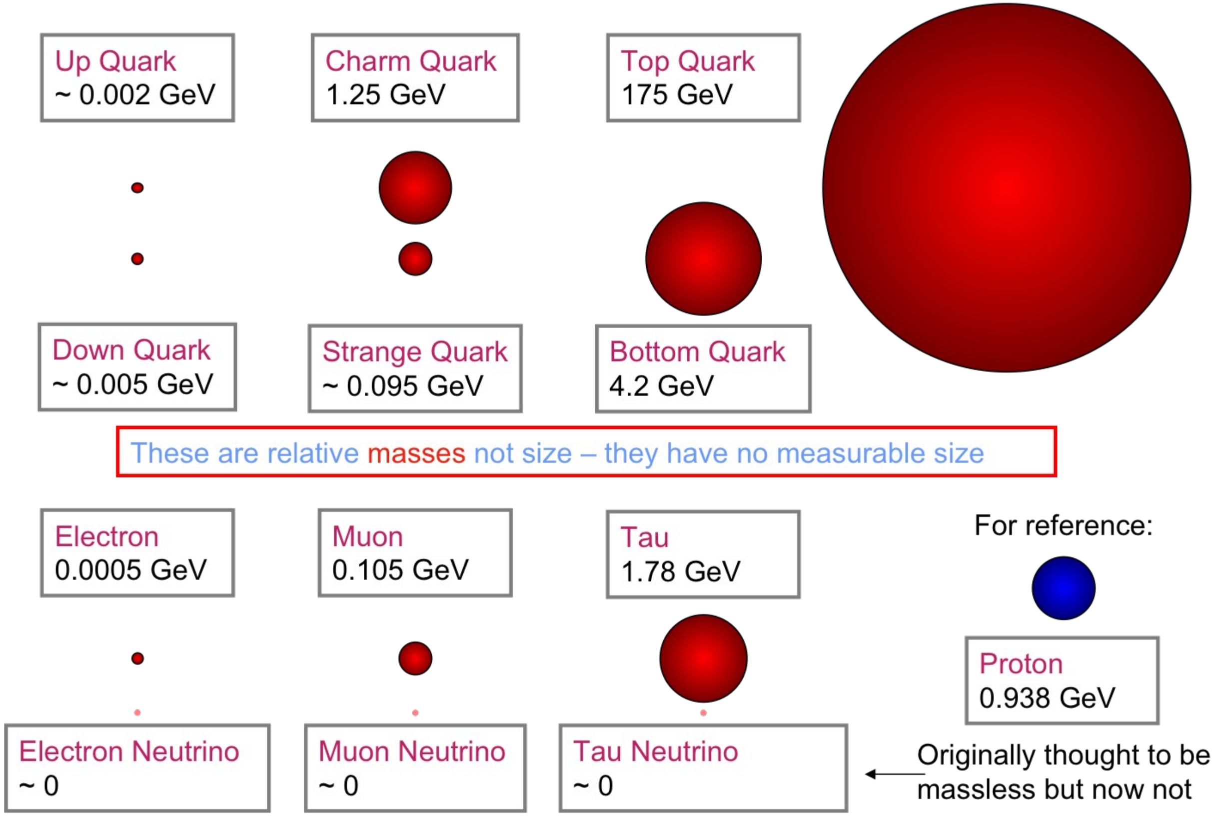

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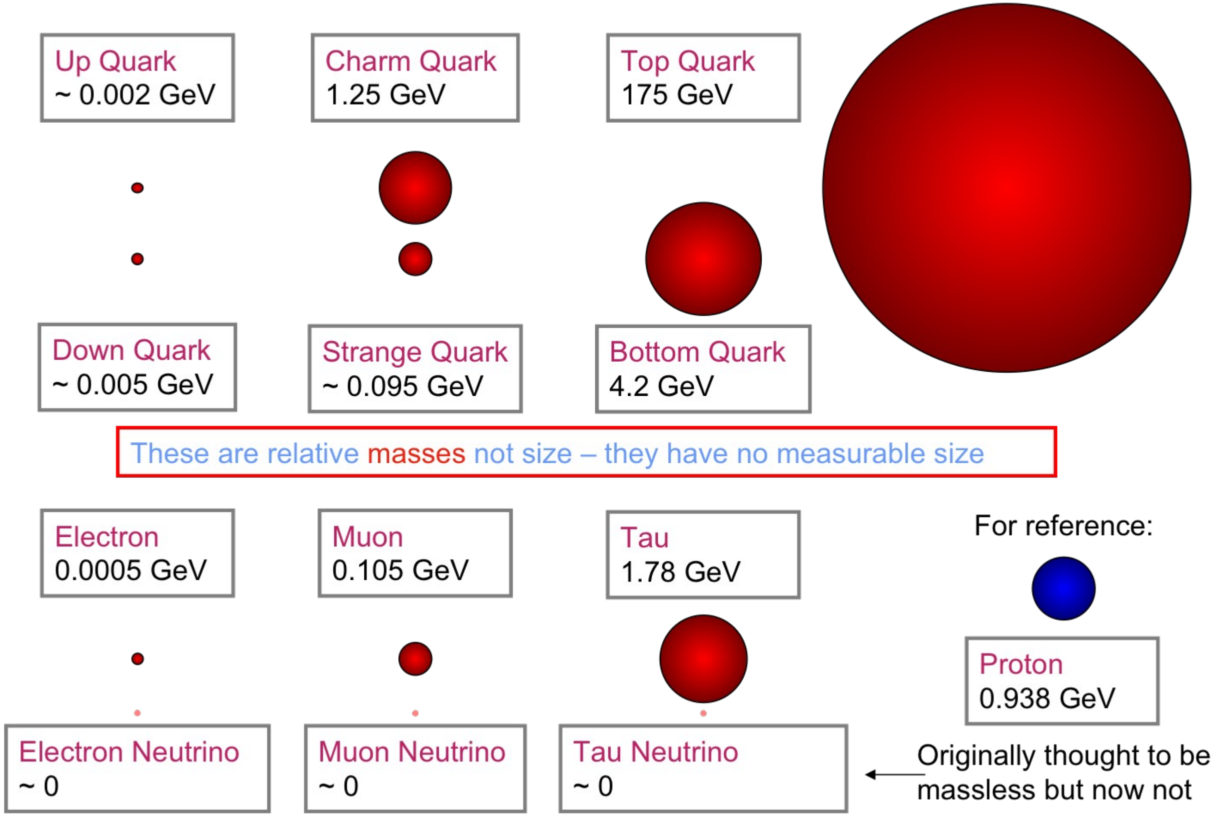

We have a descriptive – but not explanatory! - solution: the Higgs Boson

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96% of the universe is ***not*** the stuff I've told you about! And we have no idea what that other stuff is!

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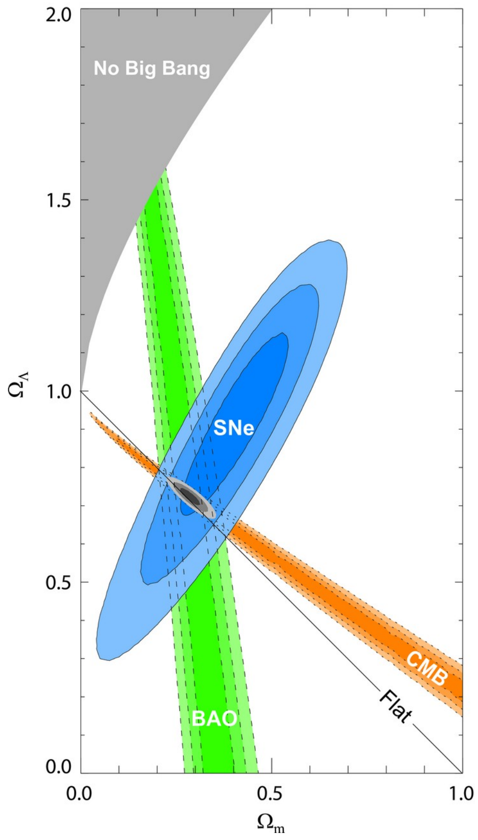

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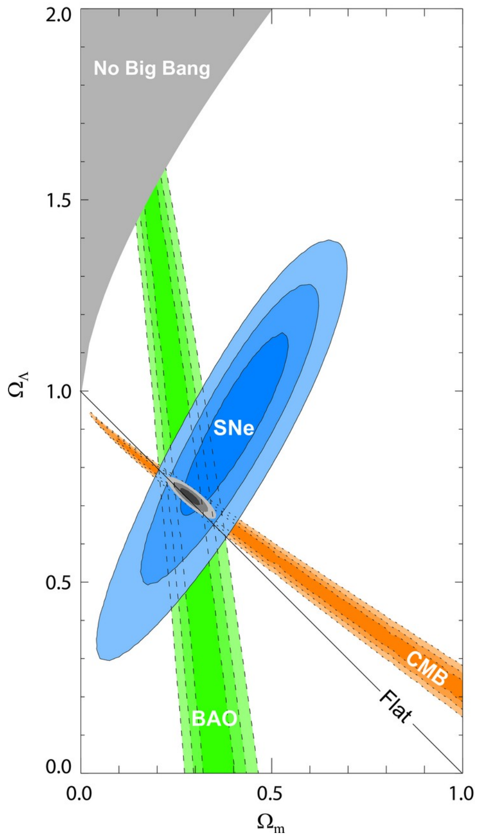

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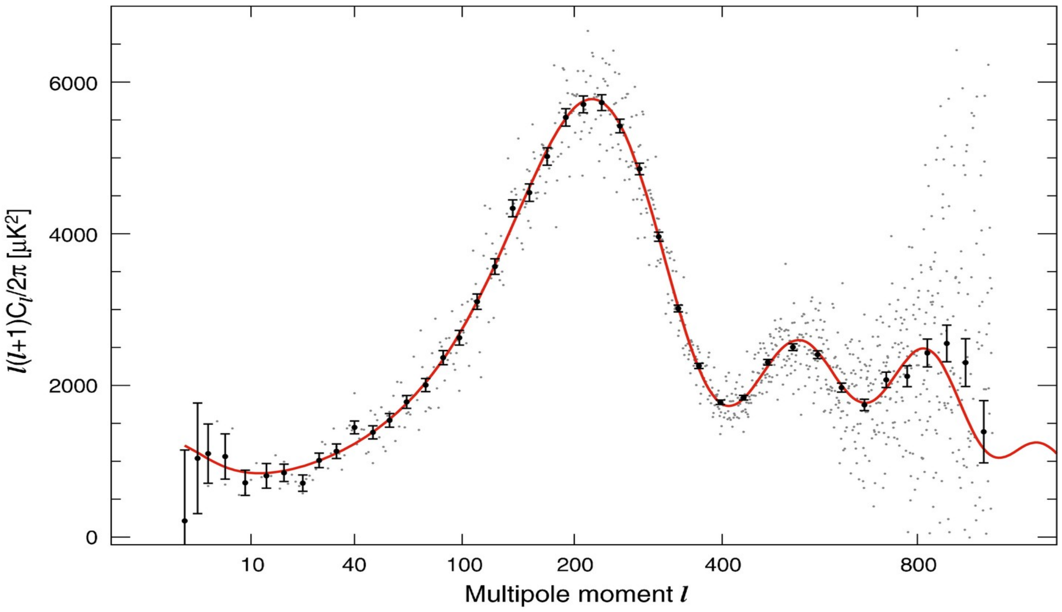

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- Modified gravity
- Extra dimensions to the universe
  - Both small and large varieties
- Add new particles
  - Supersymmetry
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  - Strongly and weakly interacting
- And lots of others!

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None of these scenarios (yet) provide a complete, consistent solution ... and they never will, in the absence of guidance from *experiments*.

How do we think about potential *high energy physics** experiments?

* There are also lots of non-HEP experiments you could do!

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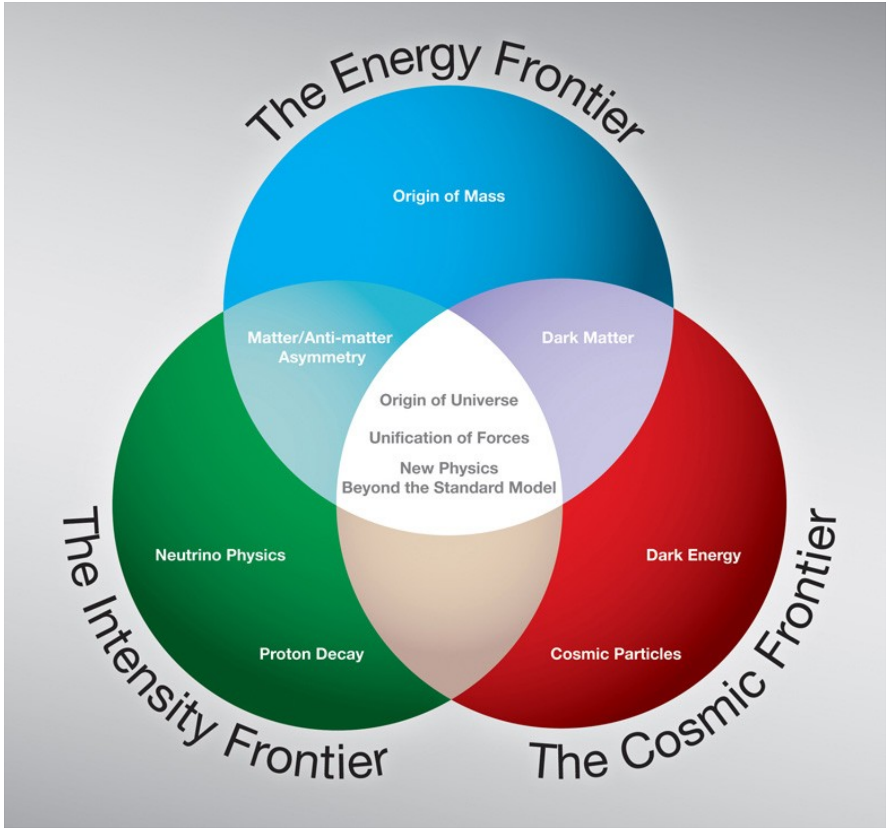

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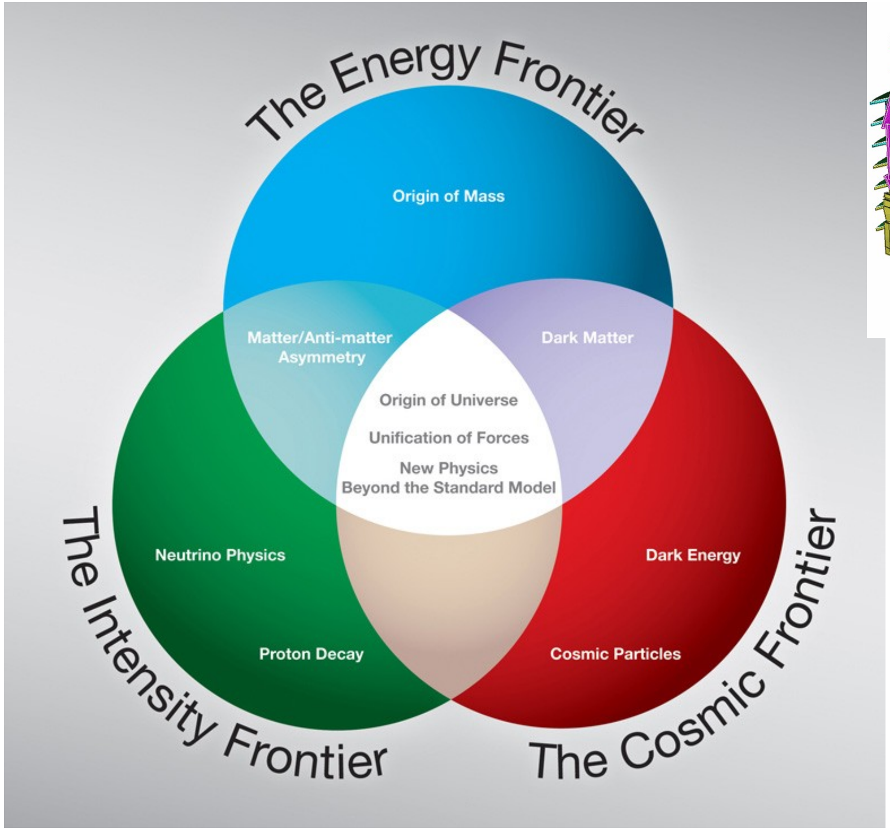

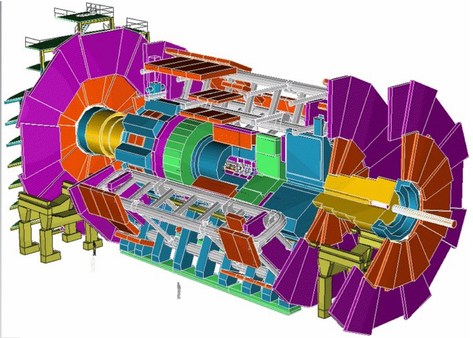

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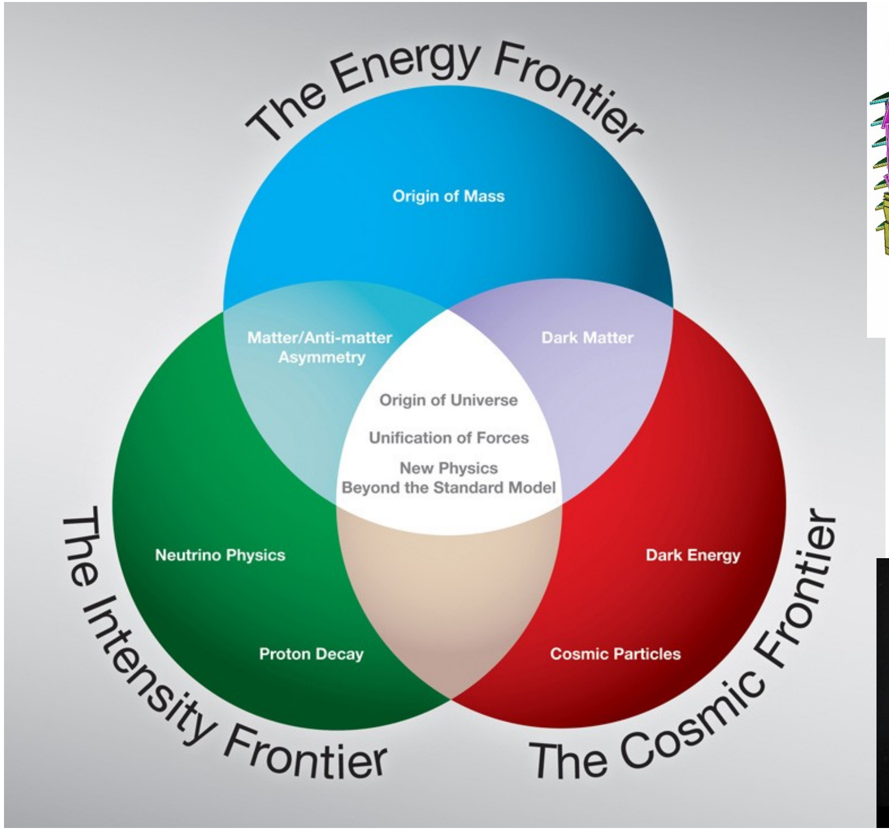

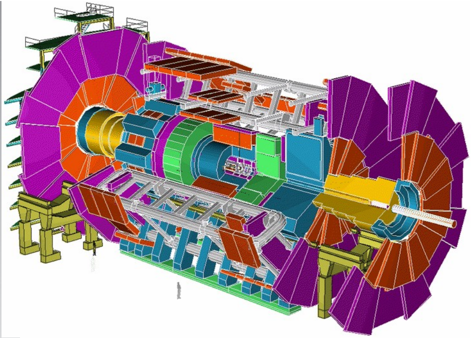

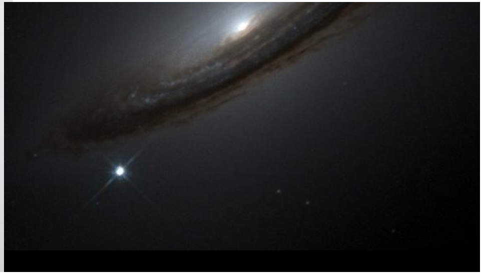

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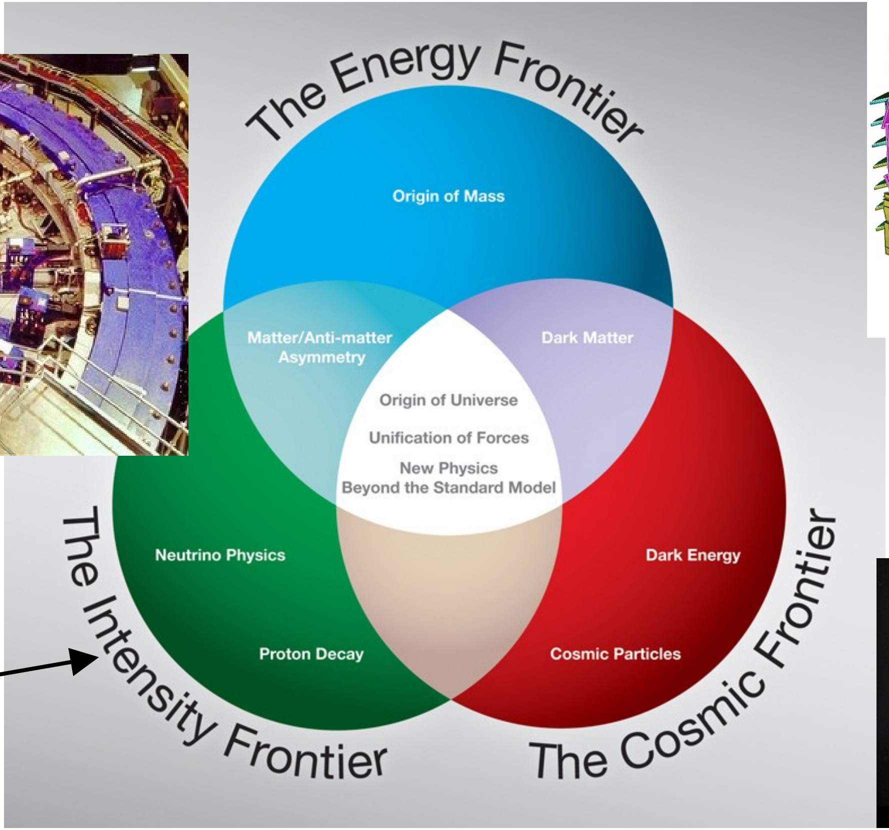

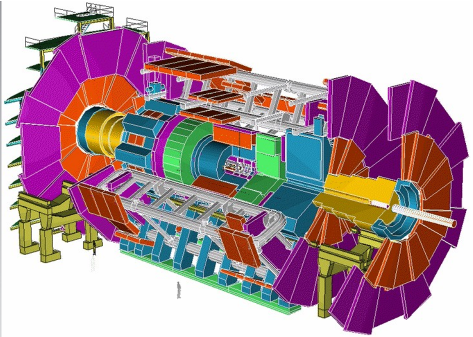

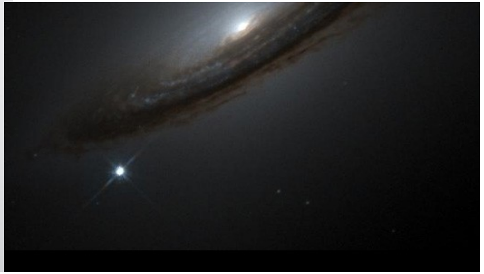

Mu2e lives here!

* There are also lots of non-HEP experiments you could do!

Intensity Frontier experiments are further split into two classes

- Precision Measurements
  - Try to measure specific parameters with ridiculously high precision
    - Eg: Muon g-2
- Rare and Forbidden Process Searches
  - We look in huge piles of data for
    - Events the Standard Model predicts are extremely rare, in the hopes they occur more/less often, or
    - Events the Standard Model predicts don’t happen at all, in the hopes that they occur more often than that
    - Eg: Mu2e

Precision Measurements: How far to Two Brothers?

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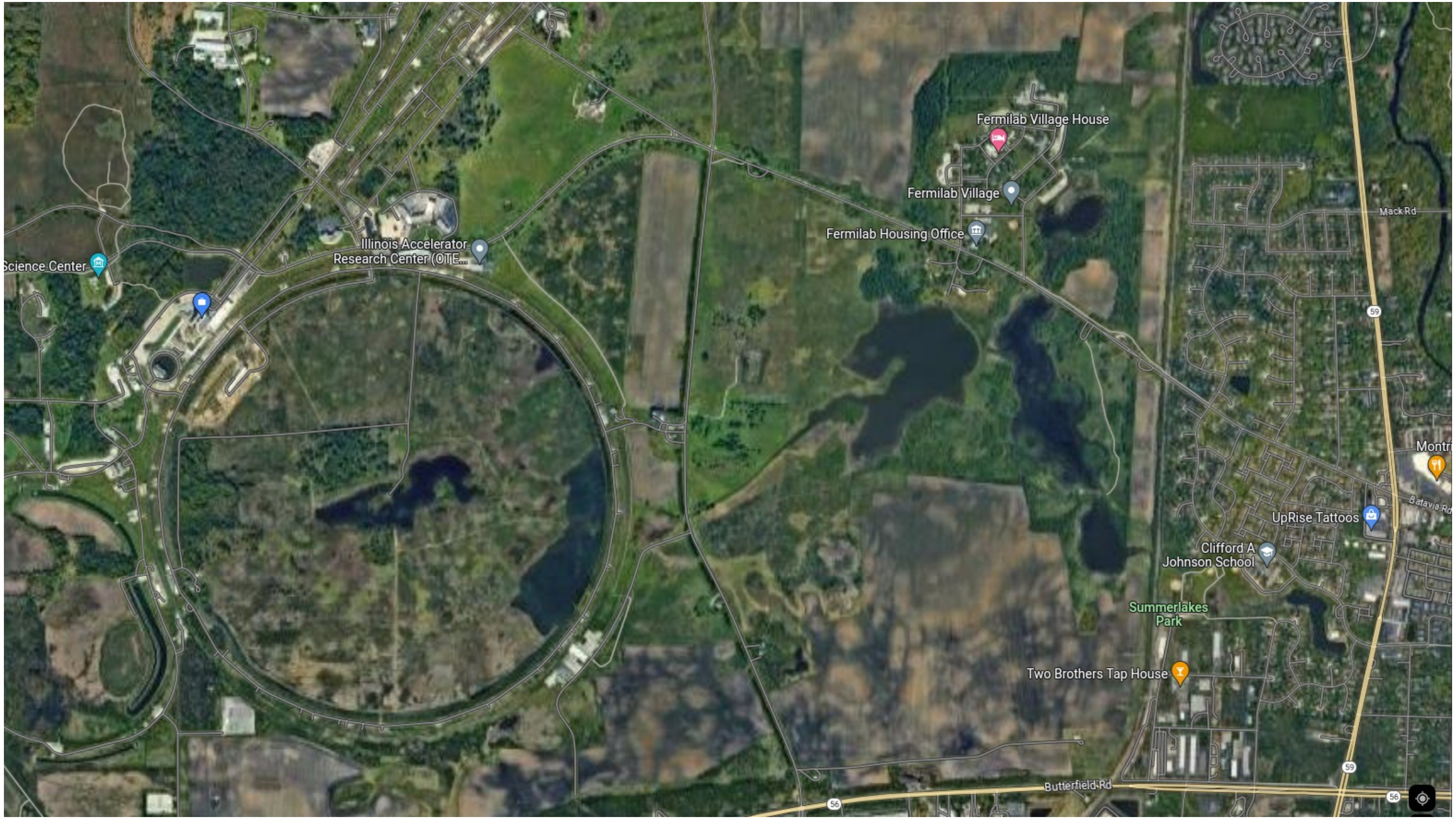

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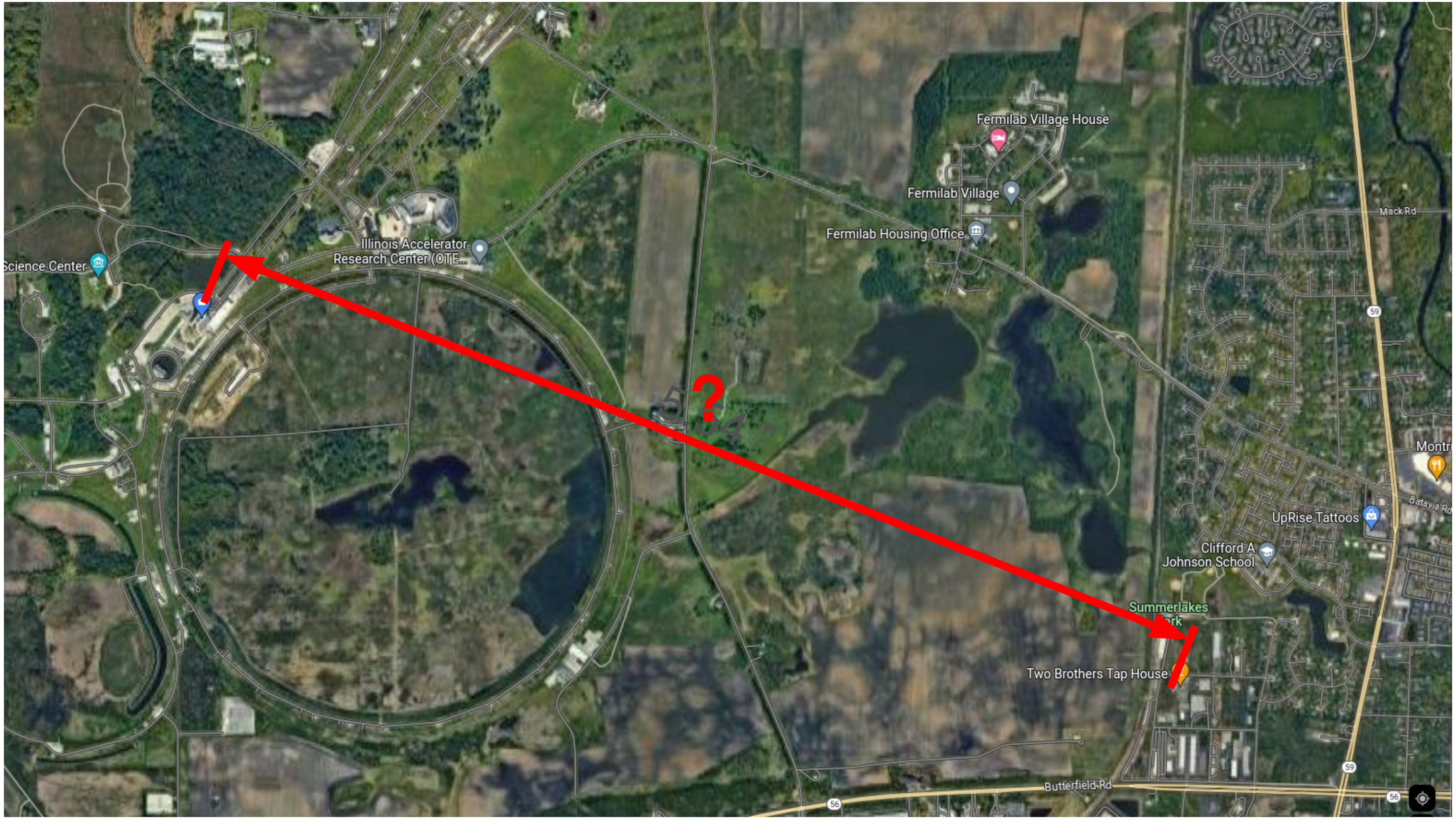

Fermilab

Rare Searches: what is the natural frequency of people with blue hair?

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Oh, and, make sure you aren't fooled by people who *dye* their hair blue … and then lie about it!

As I’ve hinted, these measurements have two problems to overcome

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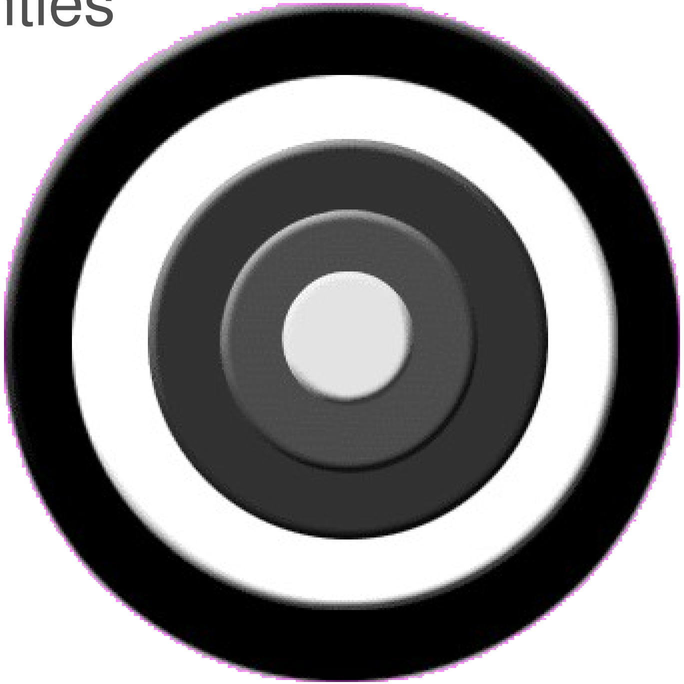
Systematic Uncertainties



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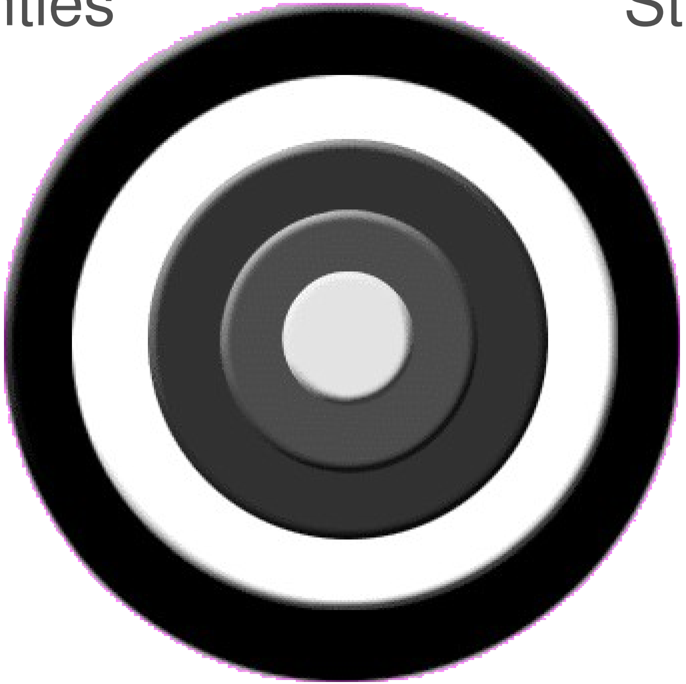
Statistical Uncertainties



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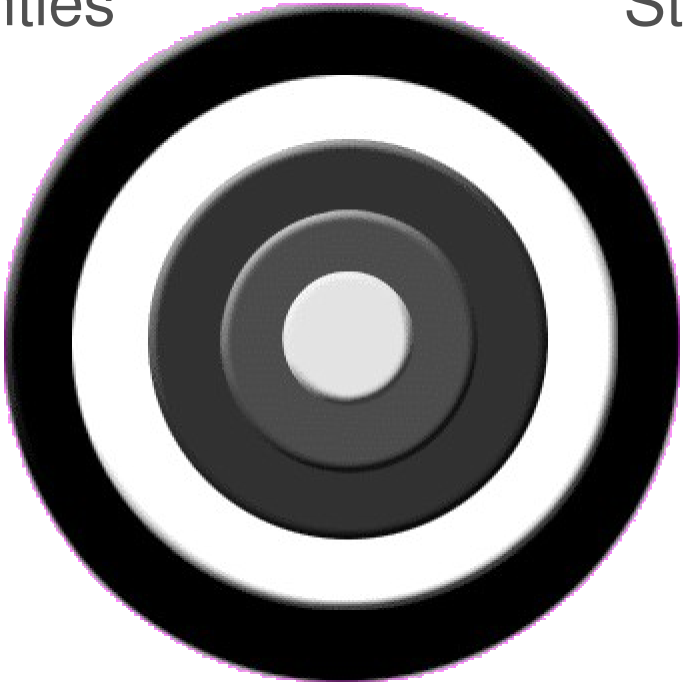

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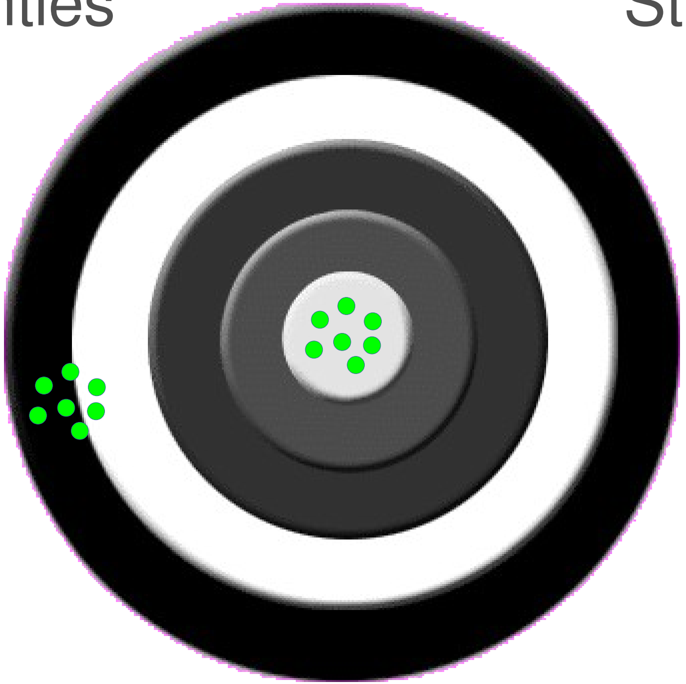

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Fermilab

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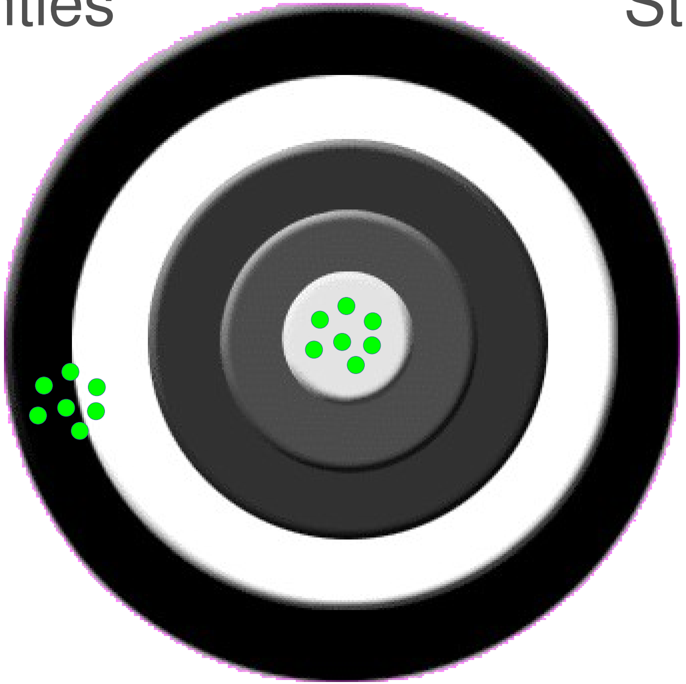

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$$\frac{\delta\tau}{\tau} \propto \frac{1}{\sqrt{N}}$$

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Systematic Uncertainties

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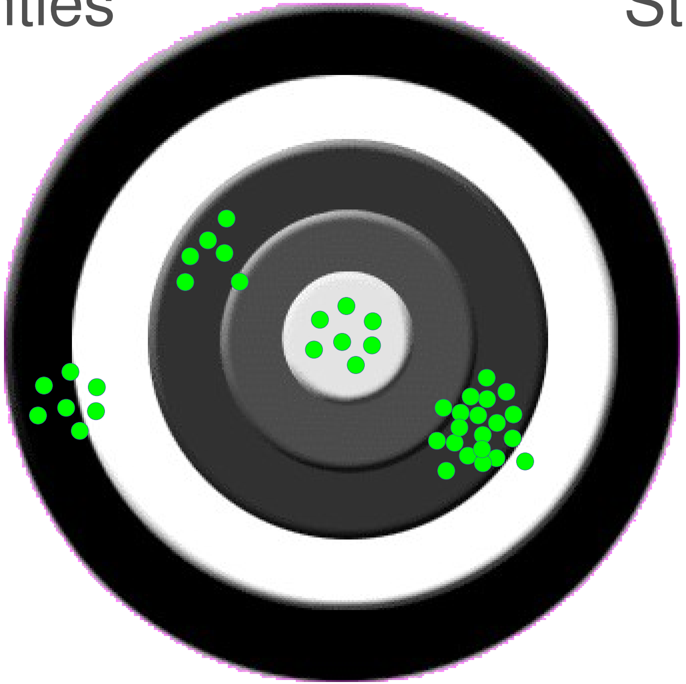

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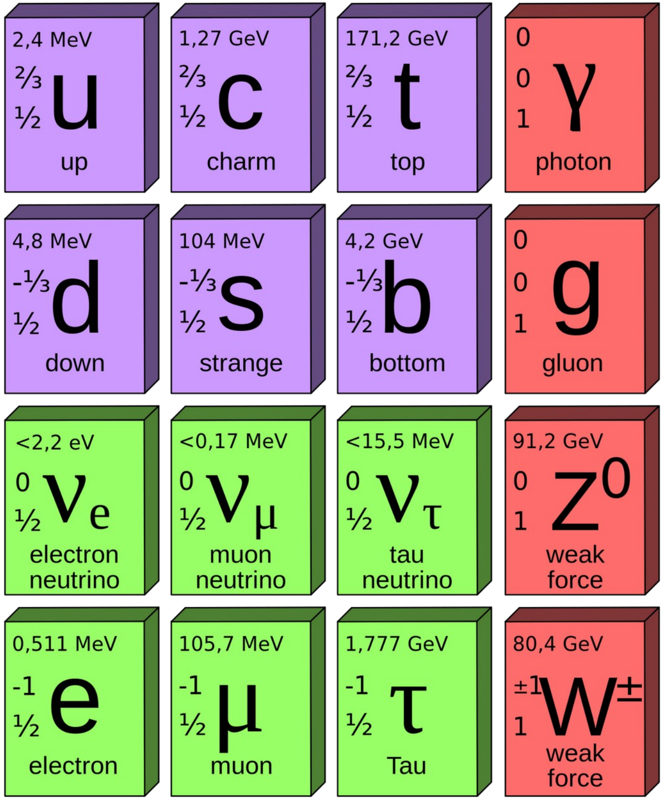

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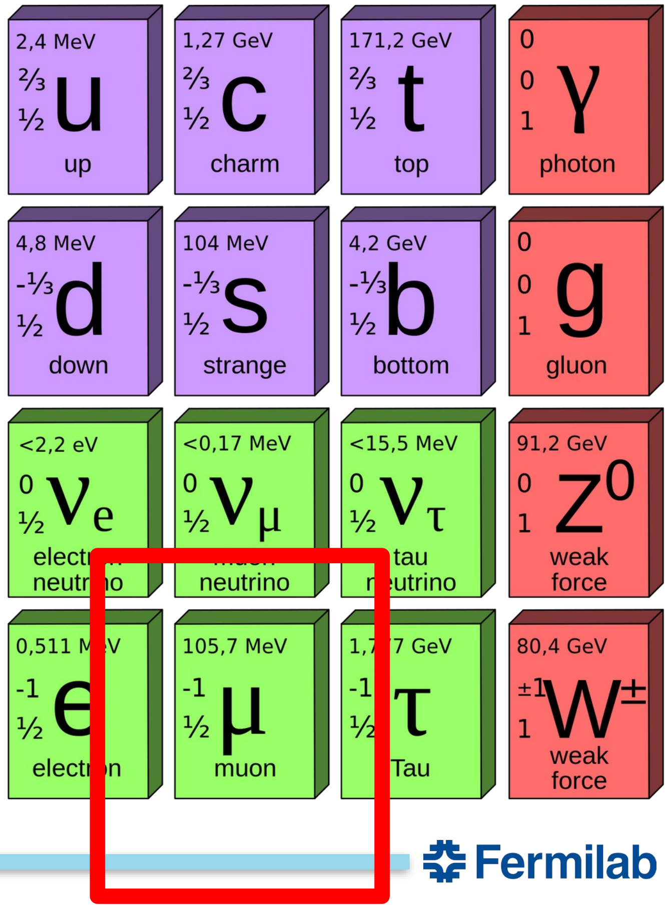

Fermilab

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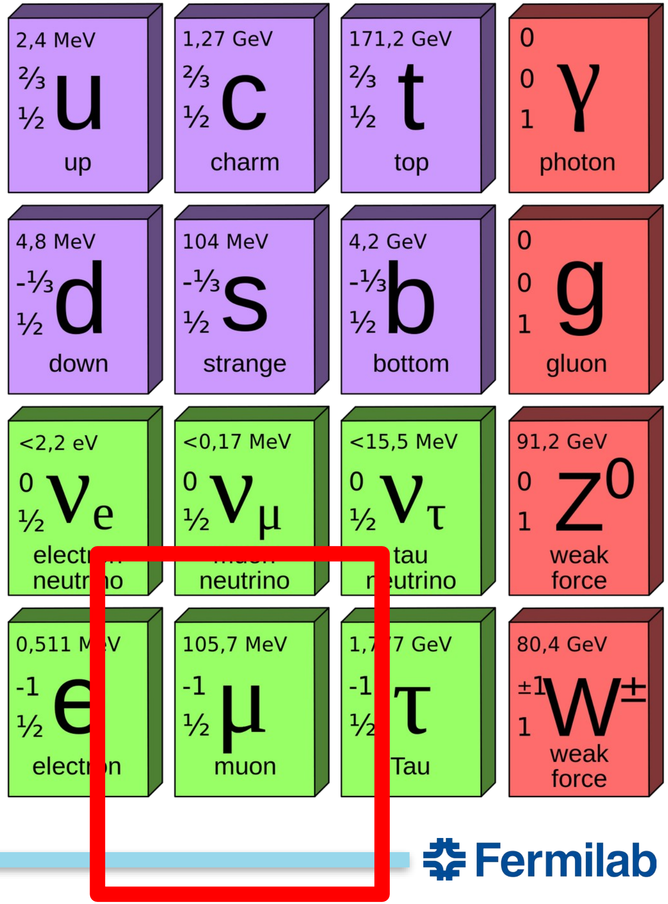
I.I.Rabi: “Who ordered that?”



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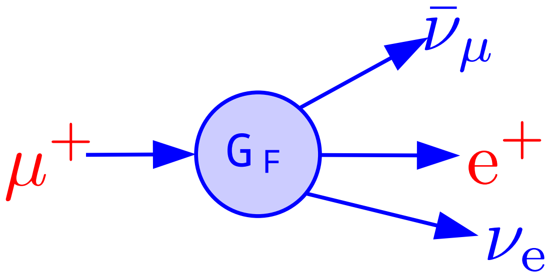

Ordinary
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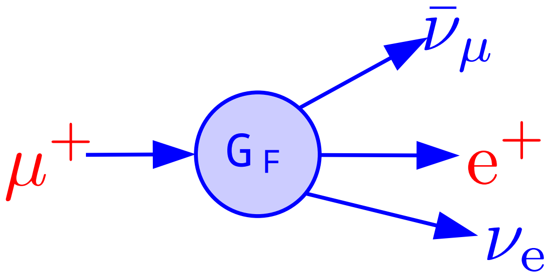

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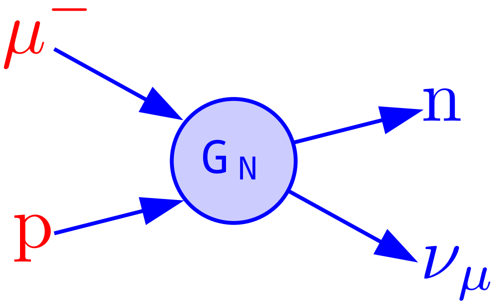

Muon Nuclear Capture

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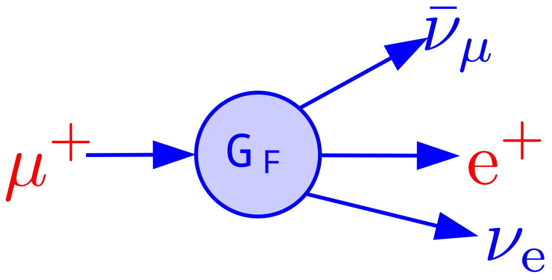

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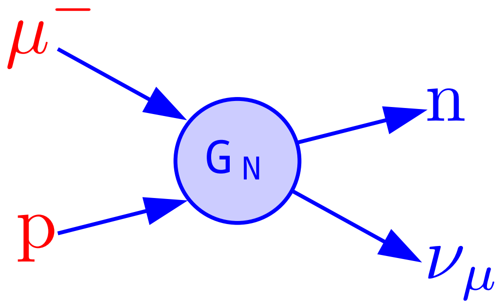

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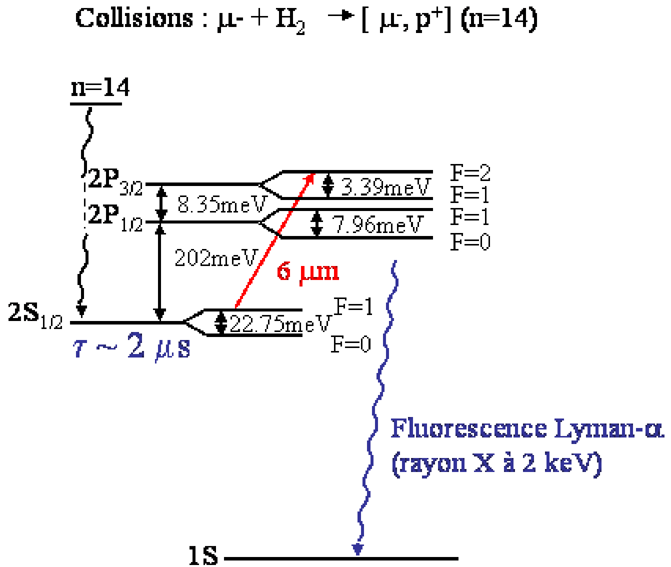


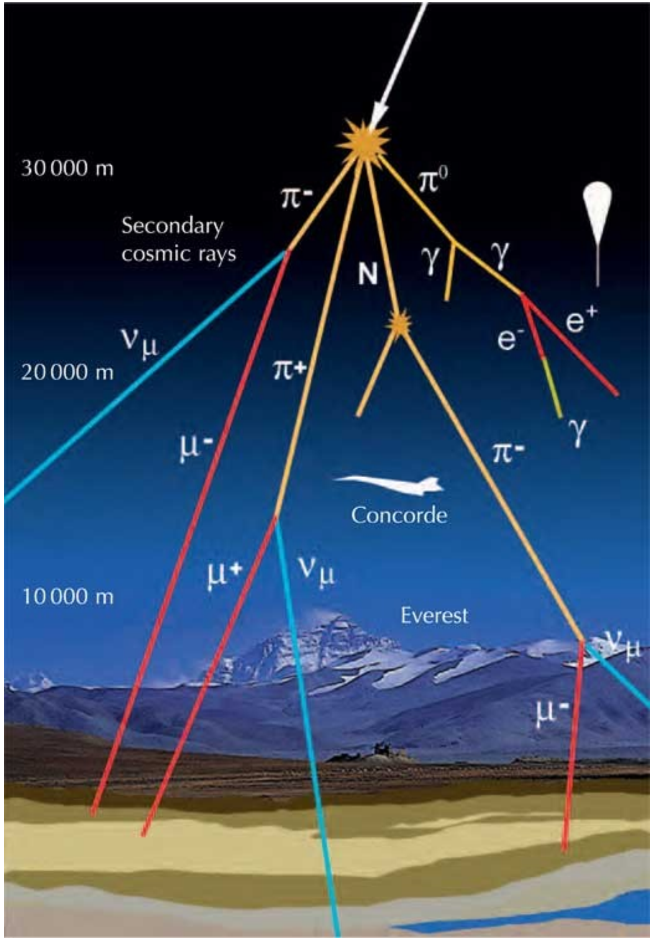
Chemistry!

Fermilab

Making muons is easy!

You bathe in cosmic ray muons every second of your life!

- ~1 per square centimeter per minute at sea level
- 10,000 will pass through you during this talk!



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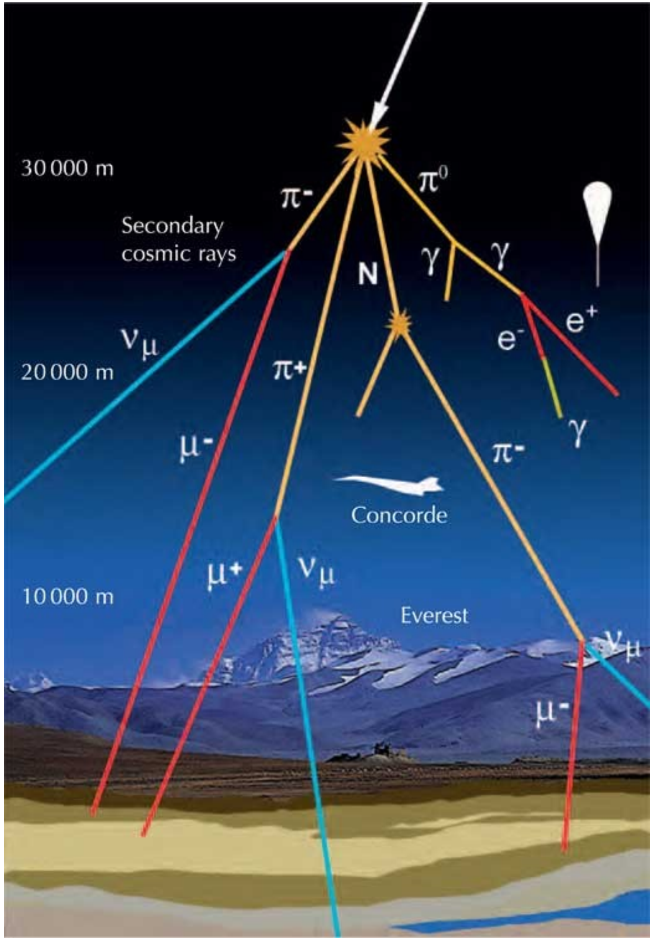
$$\text{Protons} + \text{nucleii} \rightarrow \text{``junk''} + \text{pions}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

99.99%

$$\pi^0 \rightarrow \gamma + \gamma$$



Fermilab

In the Standard Model*, once a muon always a muon

- That is, lepton flavor (and number!) are *conserved*

*with strictly massless neutrinos

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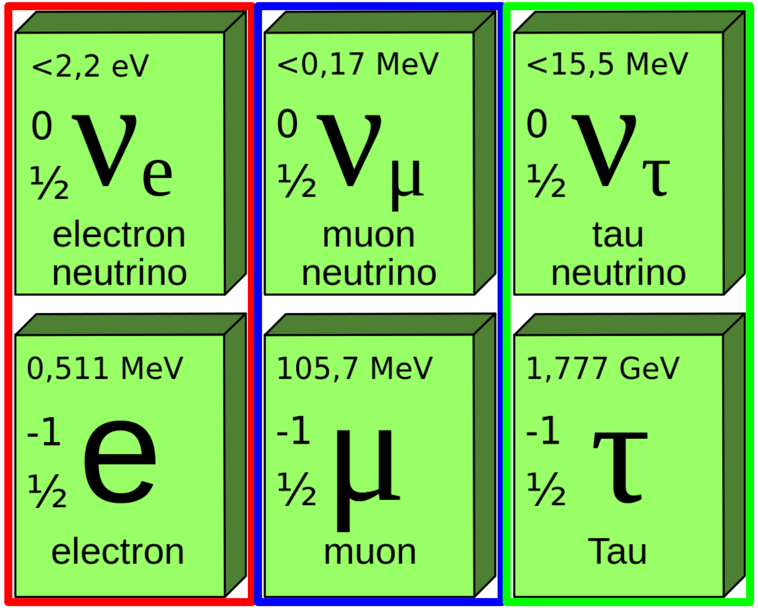

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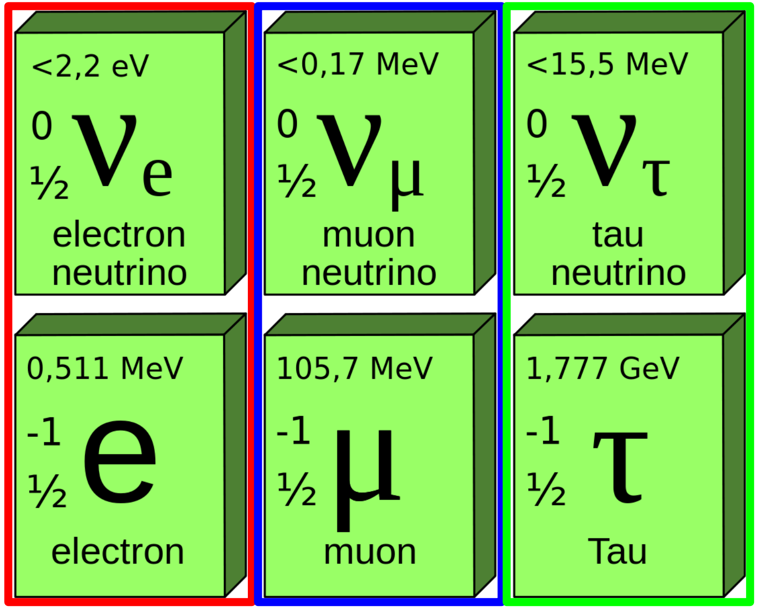

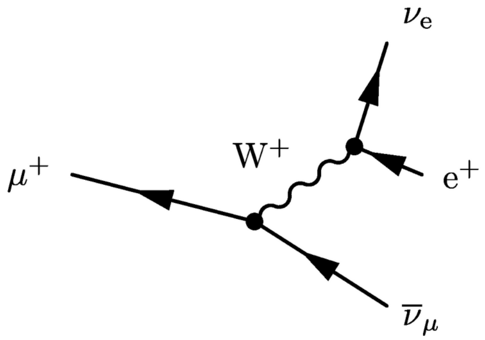

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Fermilab

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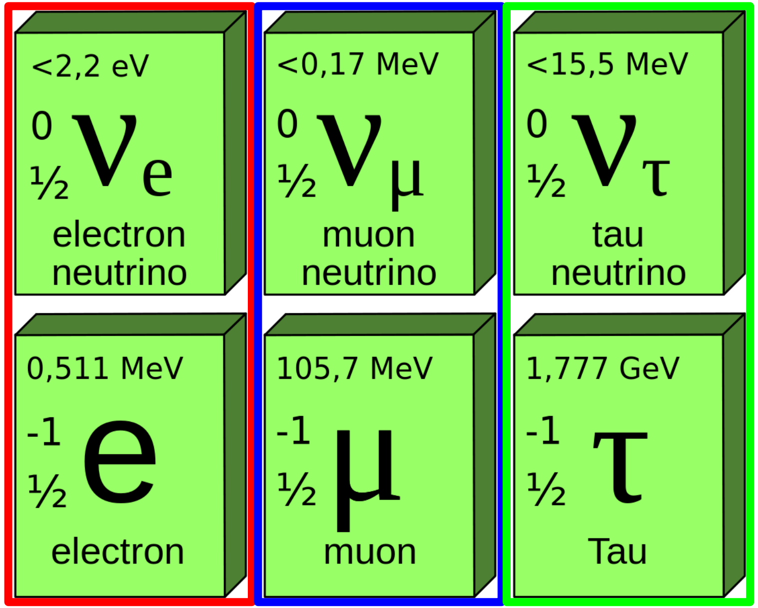

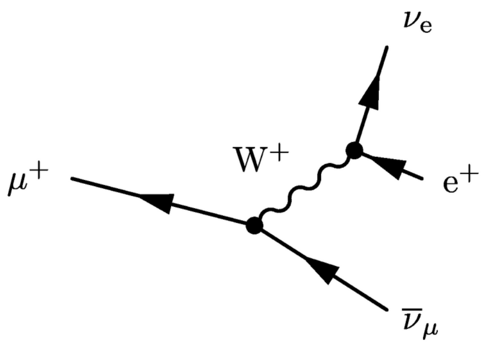

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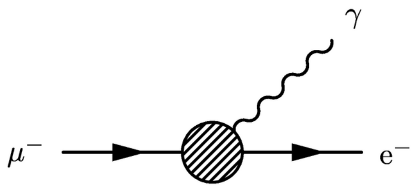

This is *forbidden*

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Mu2e (and our competitor COMET) are searches for charged lepton flavor violation with discovery potential

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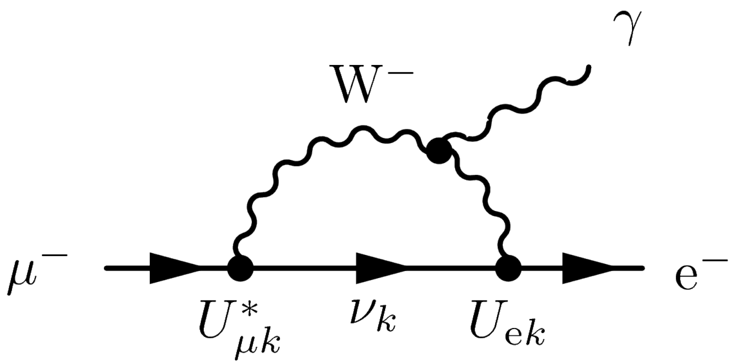
Although it has never been observed, we know that CLFV **must** occur, *even in the Standard Model*, through neutrino loop effects.



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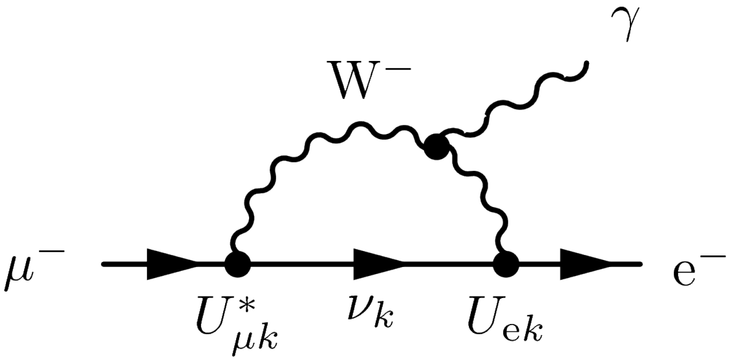
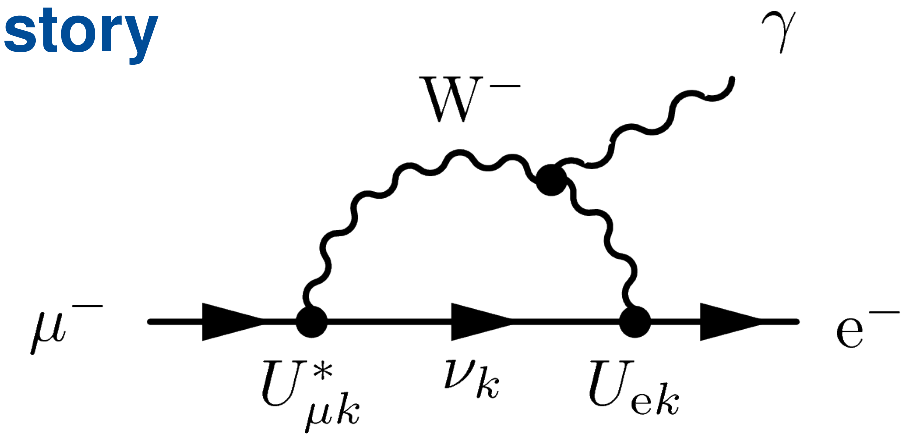


However, the predicted SM rates are unobservably small:

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

Fermilab

This is a good news/bad news story



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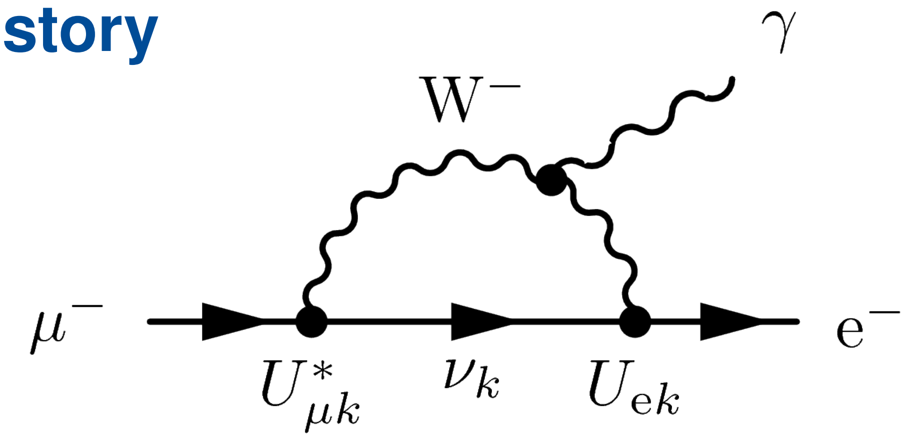

Fermilab

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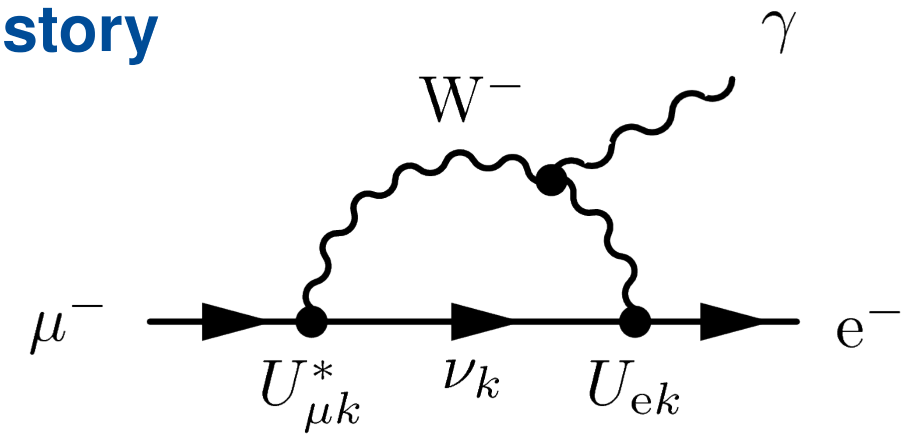
First, the bad news: we'll never observe this!



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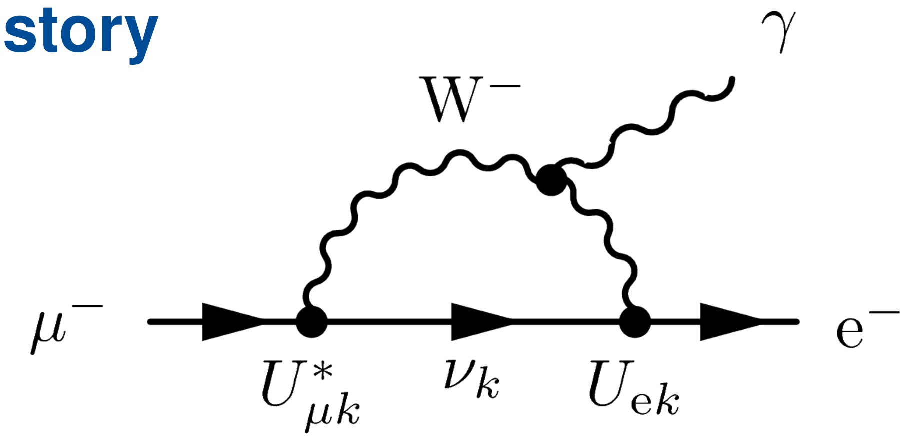

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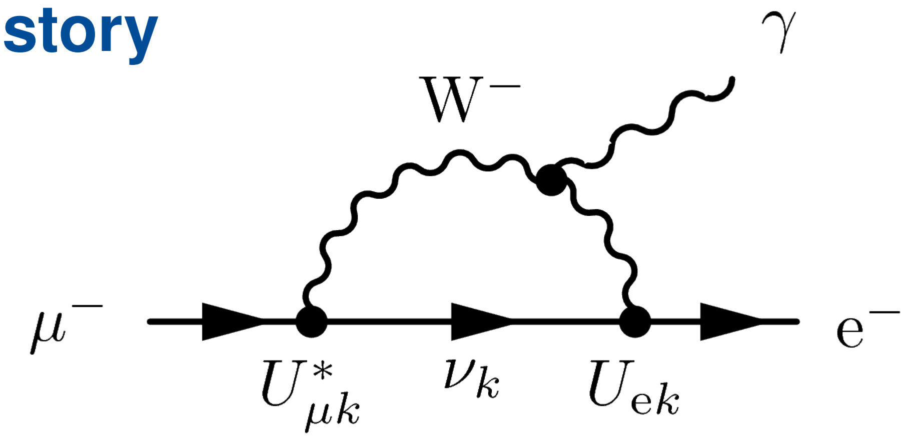

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Any signal of CLFV is unambiguous evidence for physics beyond the Standard Model!

There are many potential signatures of CLFV physics in the muon sector

Surface muon beams

$$\mu^+ \to \mathrm{e}^+\gamma$$

$$\mu^+ \to \mathrm{e}^+\mathrm{e}^+\mathrm{e}^-$$

$$\mu^+e^- \leftrightarrow \mu^-e^+$$

Double CLFV!

"High" energy beams

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

$$\mu^- A(Z,N) \to \mathrm{e}^+ A(Z-2,N)$$

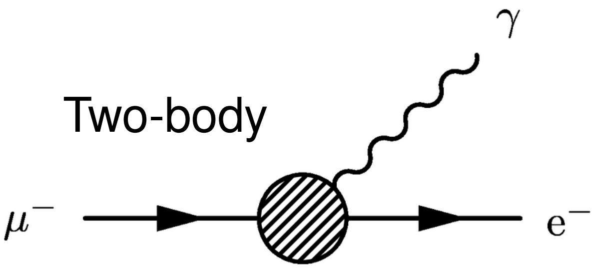
CLFV and LNV!

There are a large number of experiments proposed to further address these channels; I apologize for only mentioning those I'm involved with.

Fermilab

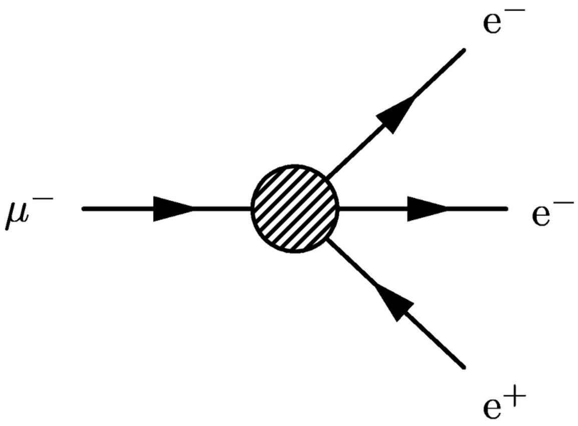
The most powerful signatures are being actively pursued

$$\mu^+ \rightarrow e^+\gamma$$



MEG/MEG-II at PSI

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



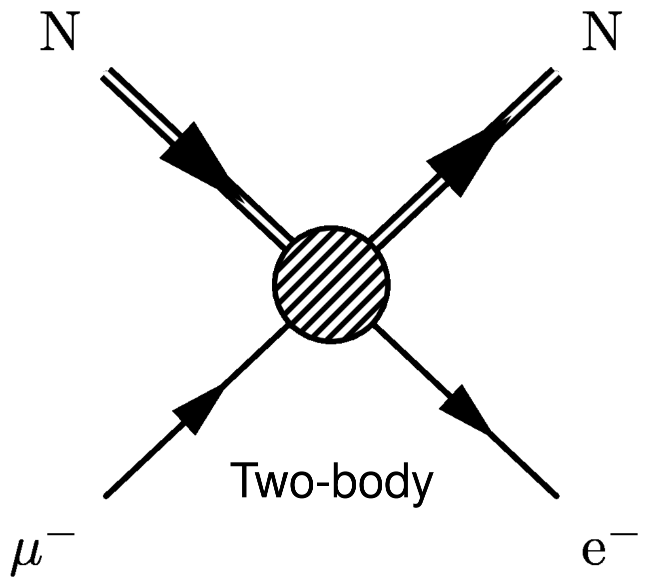
Mu3e at PSI

Coherent neutrinoless conversion is the Mu2e program

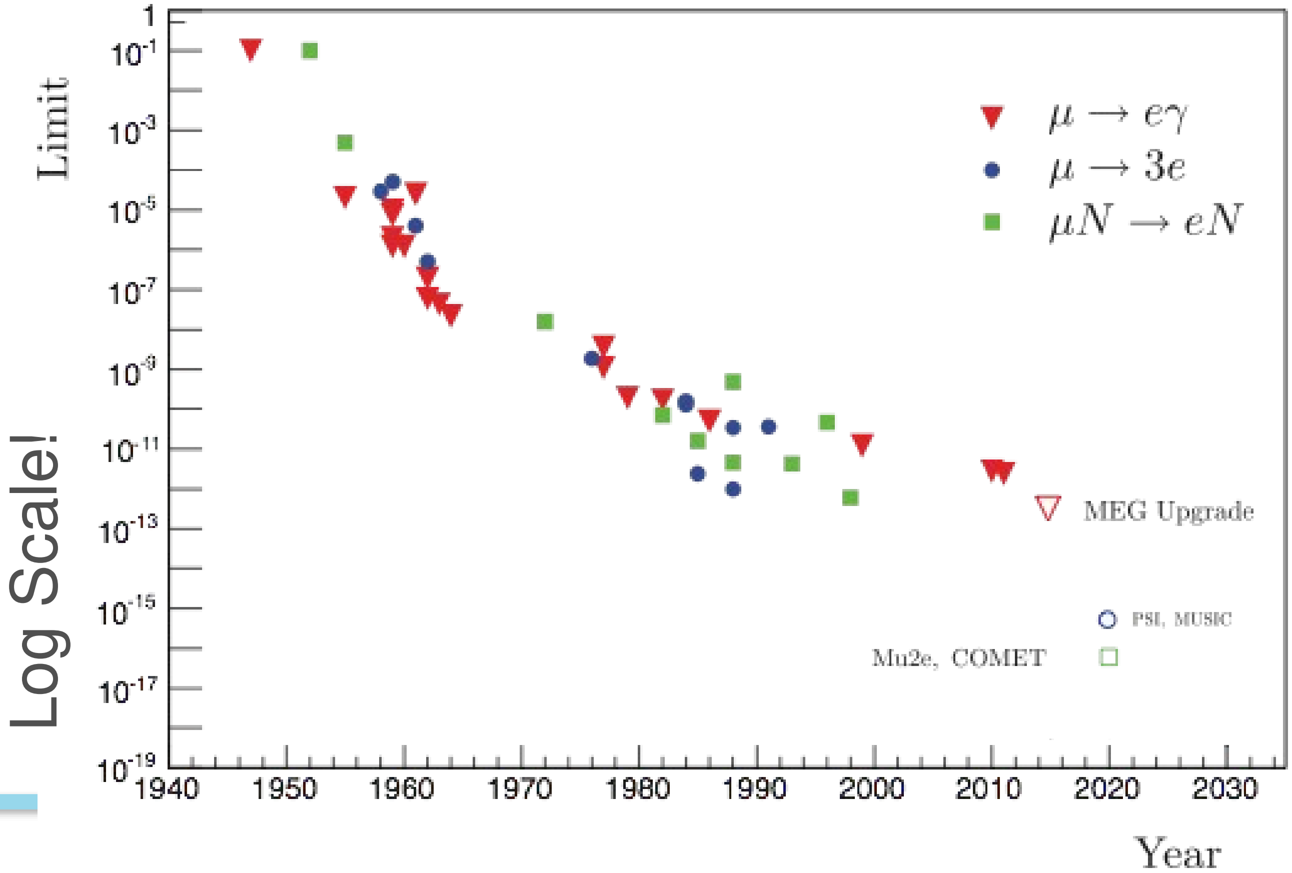
Mu2e and COMET will search for Coherent Conversion

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

$$R_{\mu \mathrm{e}} = \frac{\Gamma\left(\mu^- A \rightarrow e^- A\right)}{\Gamma\left(\mu^- A \rightarrow \nu_\mu A'\right)}$$



We're extending a long line of experiments designed to understand the mystery of muon flavor



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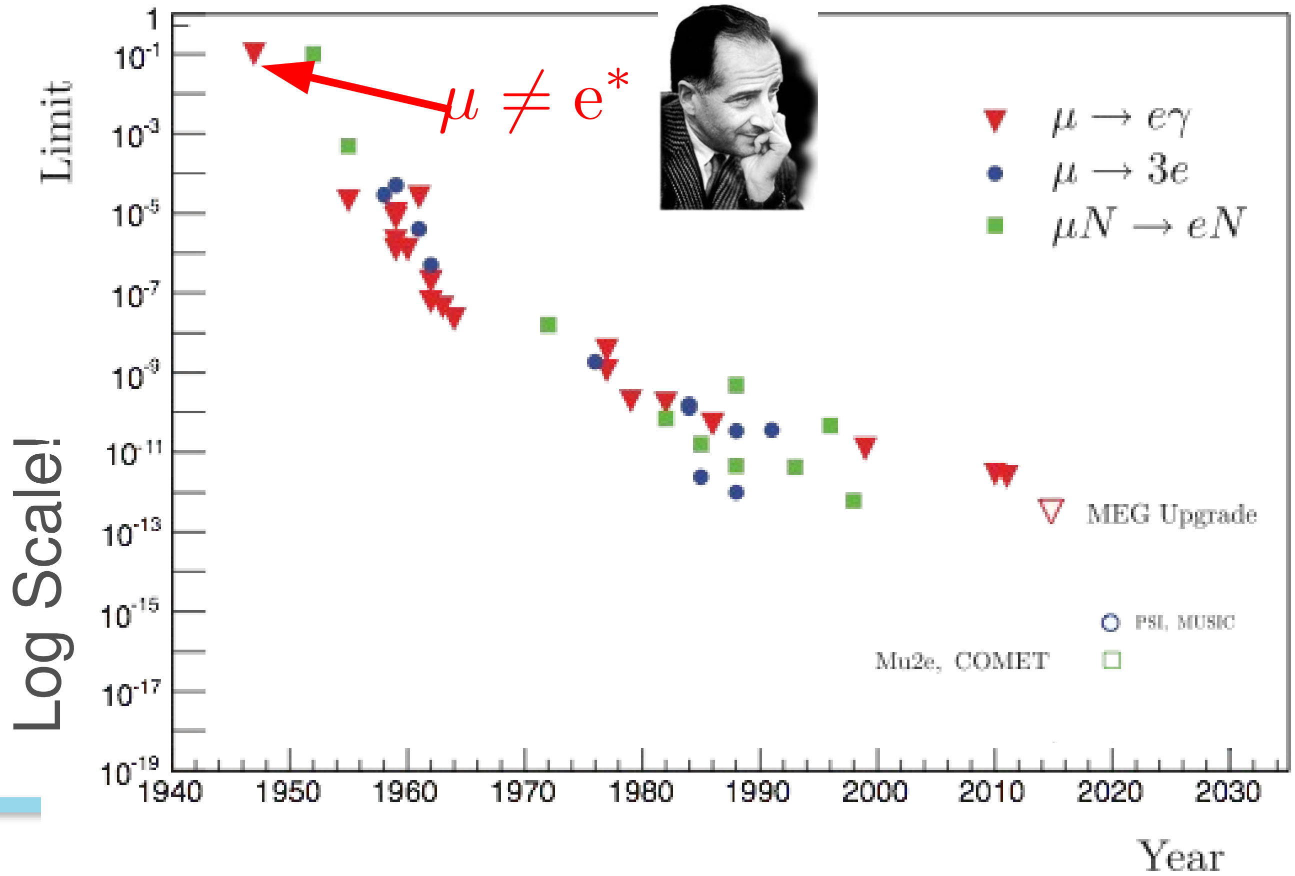

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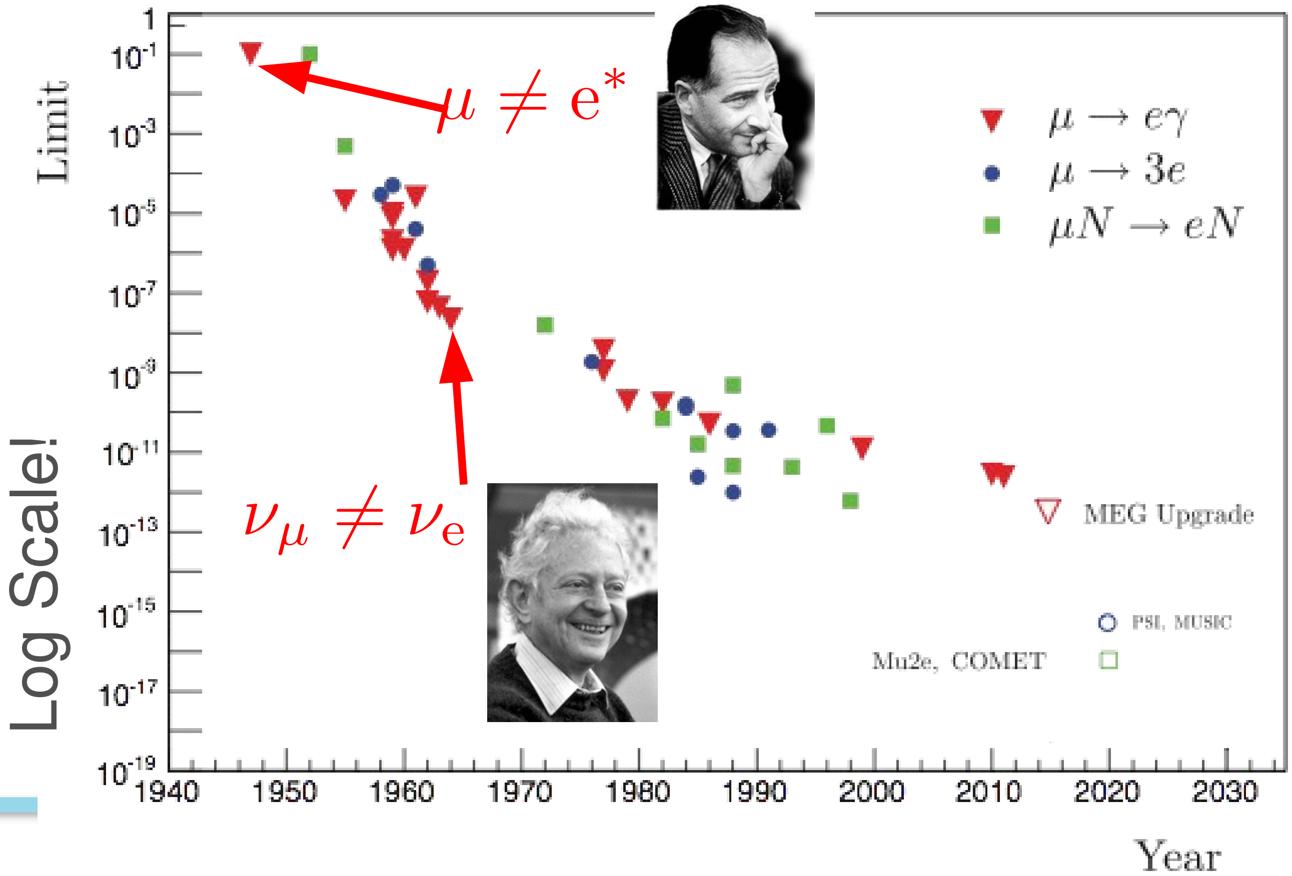

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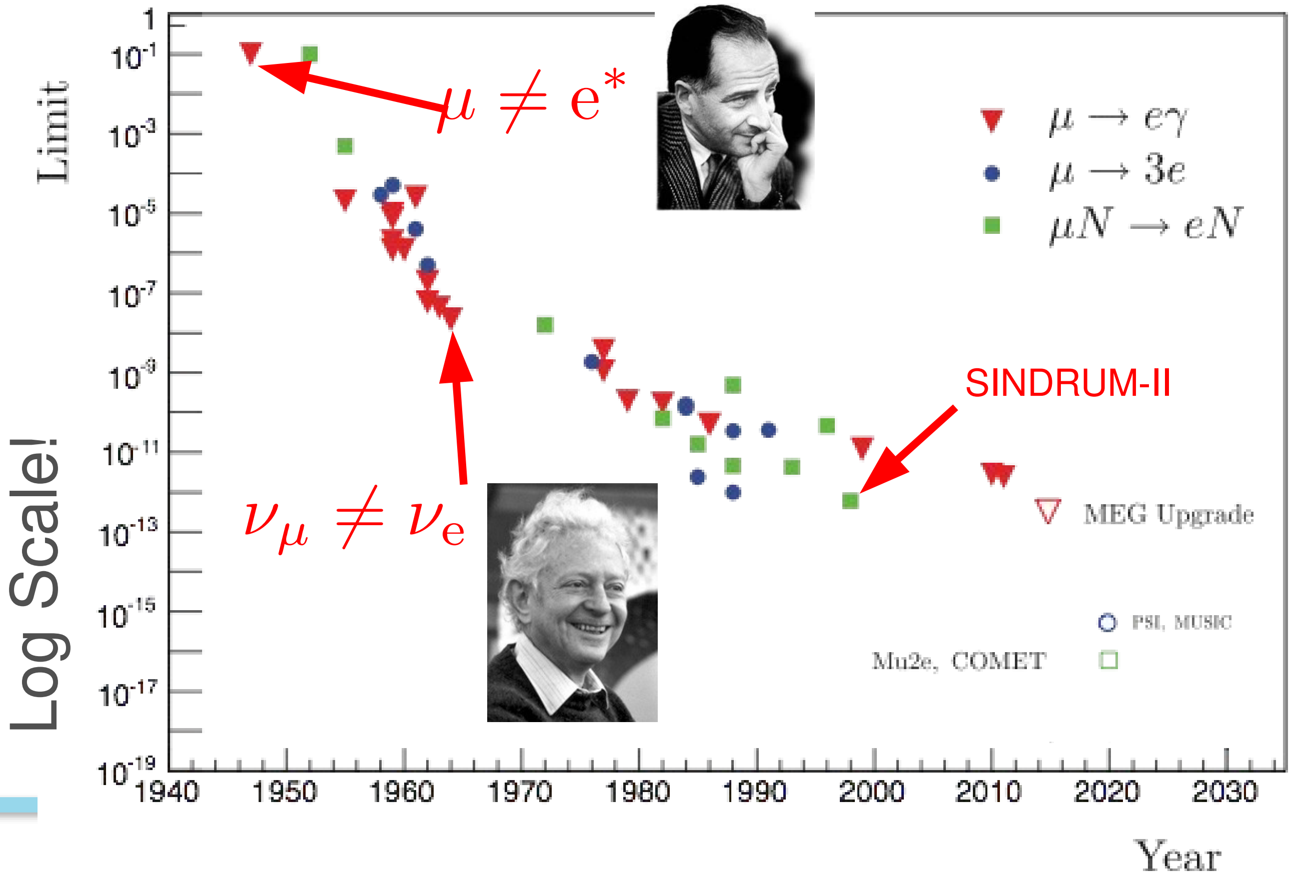

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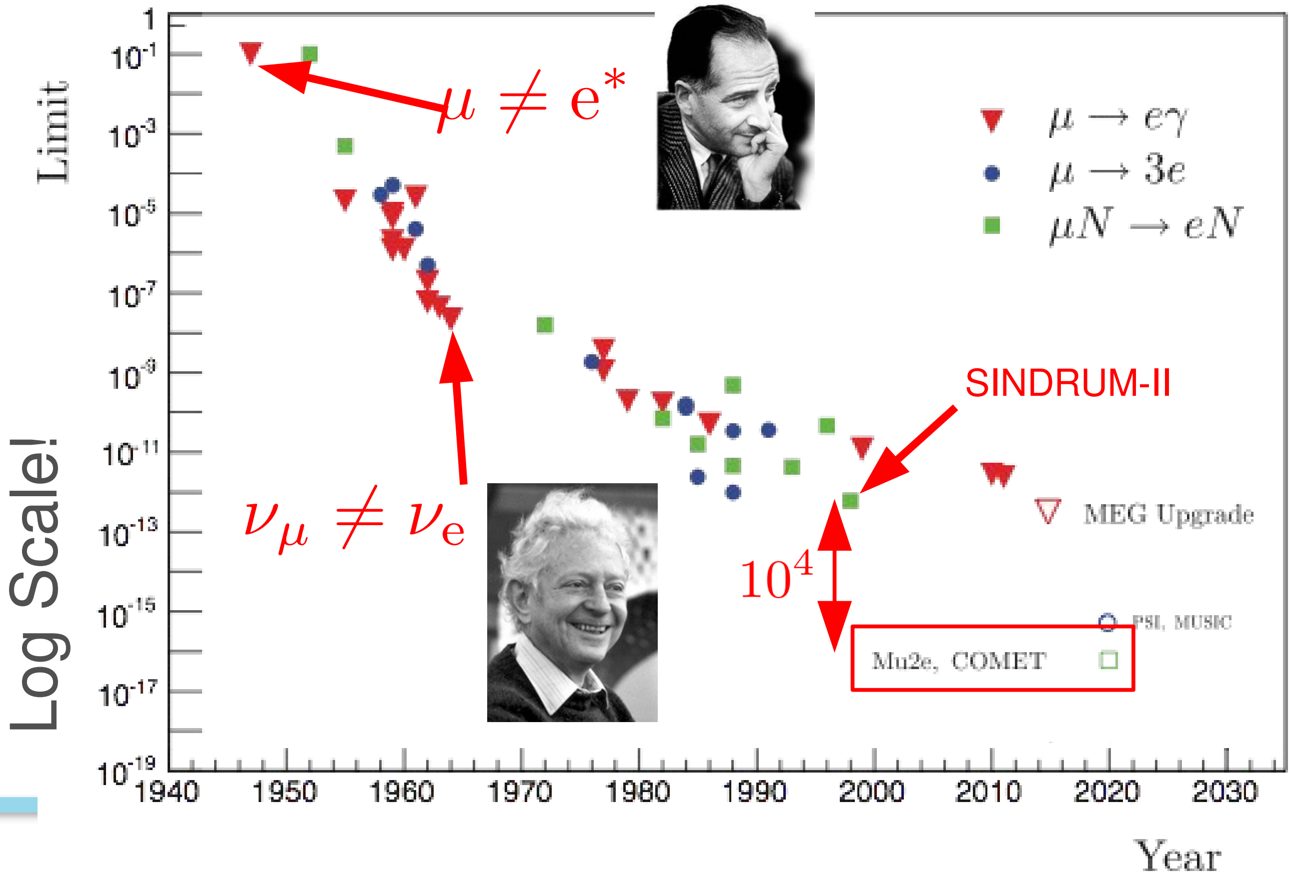

Fermilab

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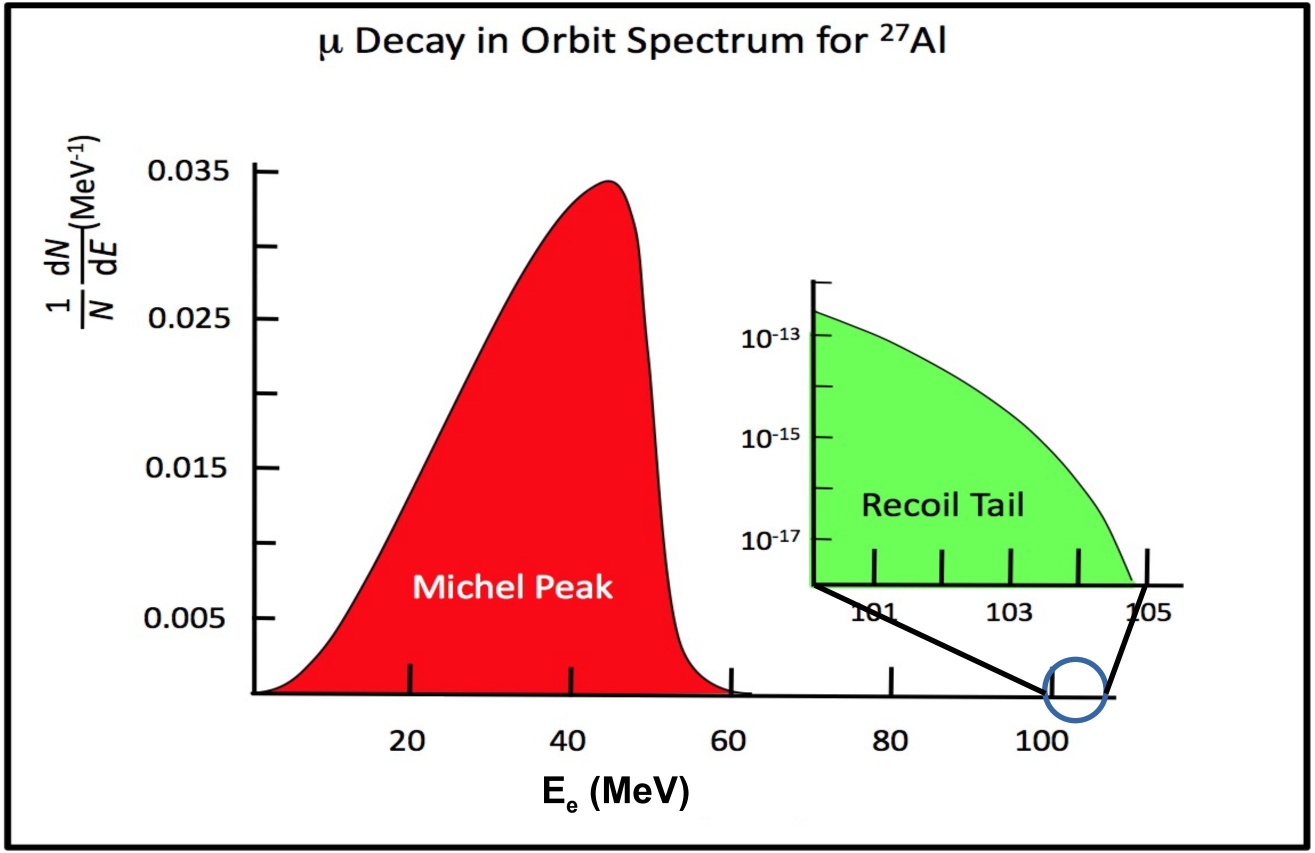

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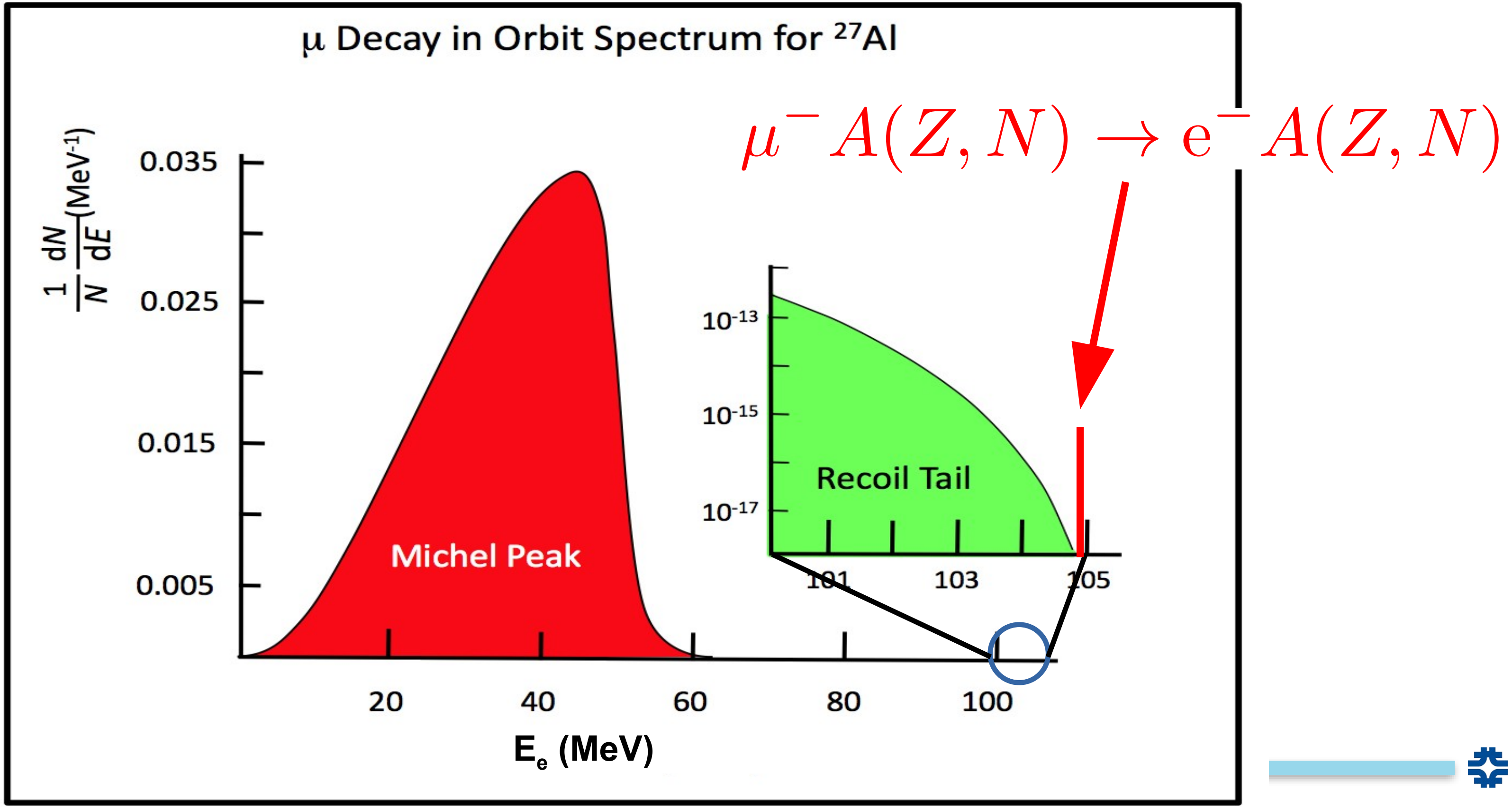

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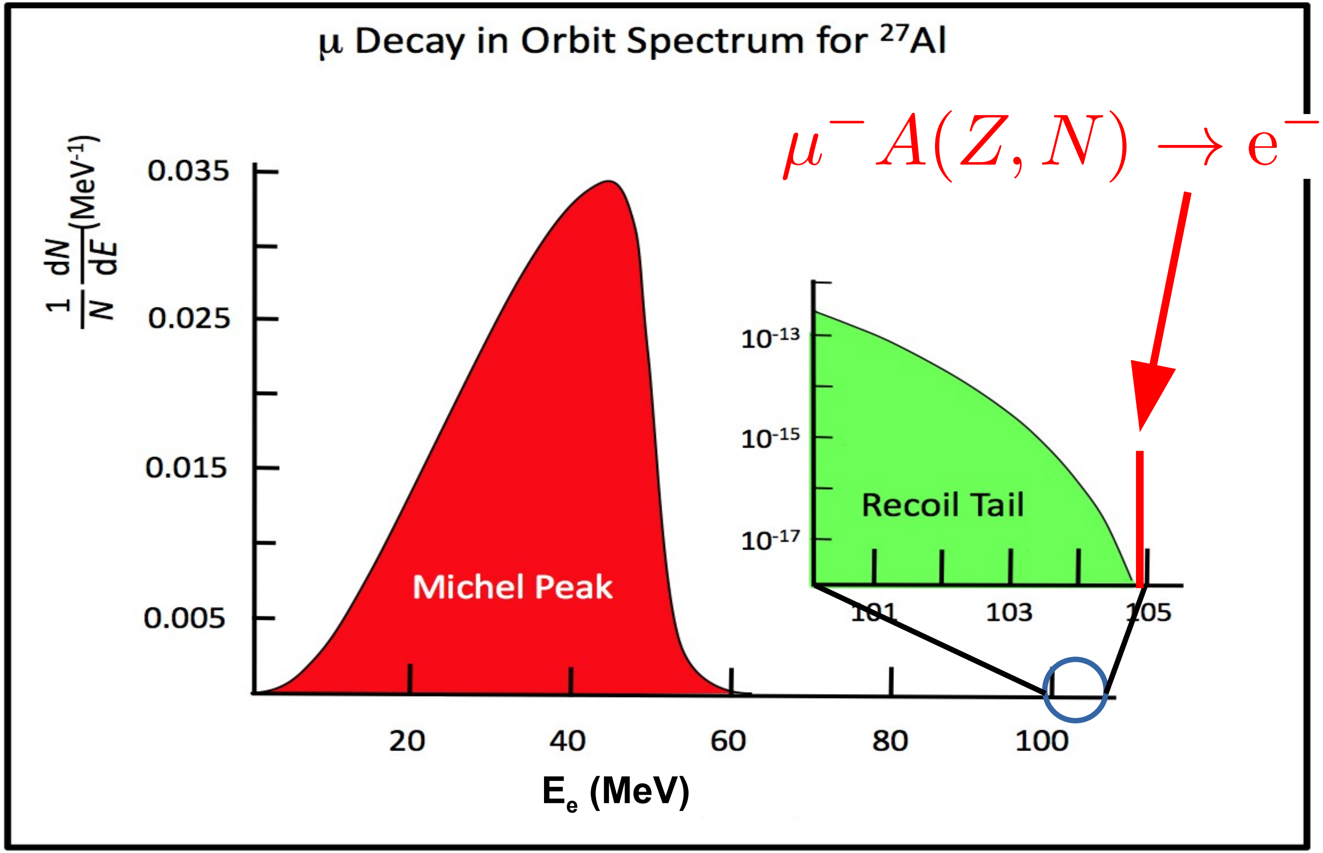
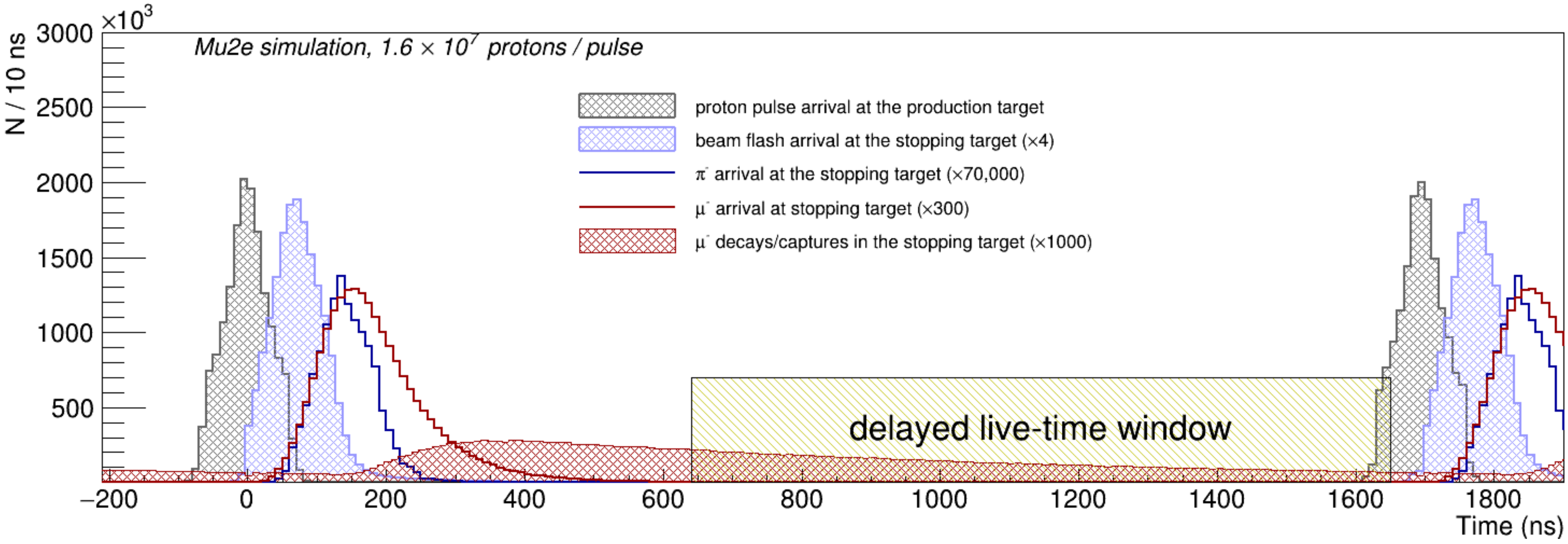


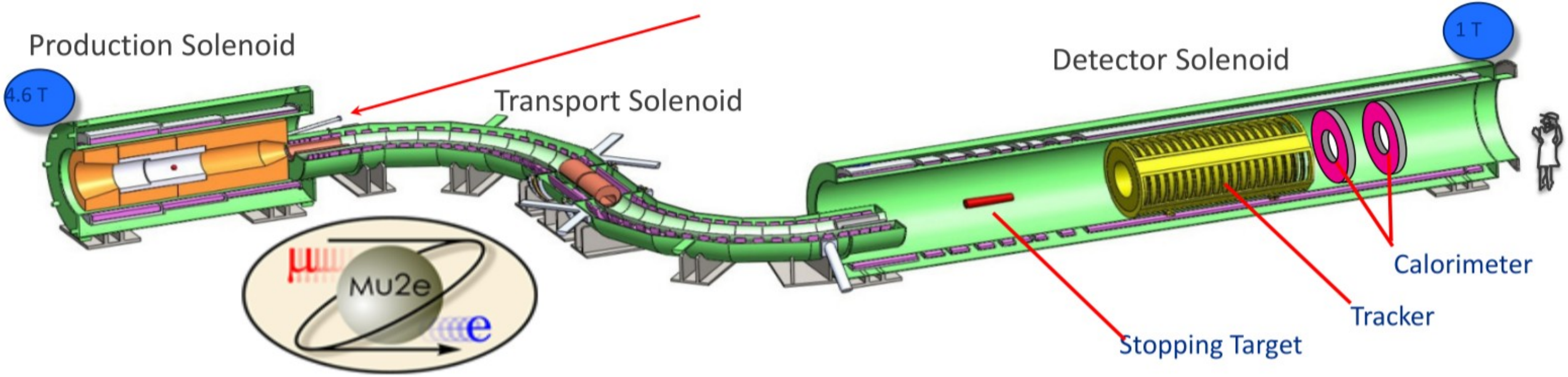
$$\mu^- A(Z,N) \rightarrow e^- A(Z,N)$$

Our signal is a mono-energetic electron at 105 MeV, above the background tail!

Beam induced backgrounds can be reduced by using a pulsed beam source … which we can generate at Fermilab



Let's first explore how Mu2e will tackle this challenge



Where do our protons come from? Keep this constraint in mind:

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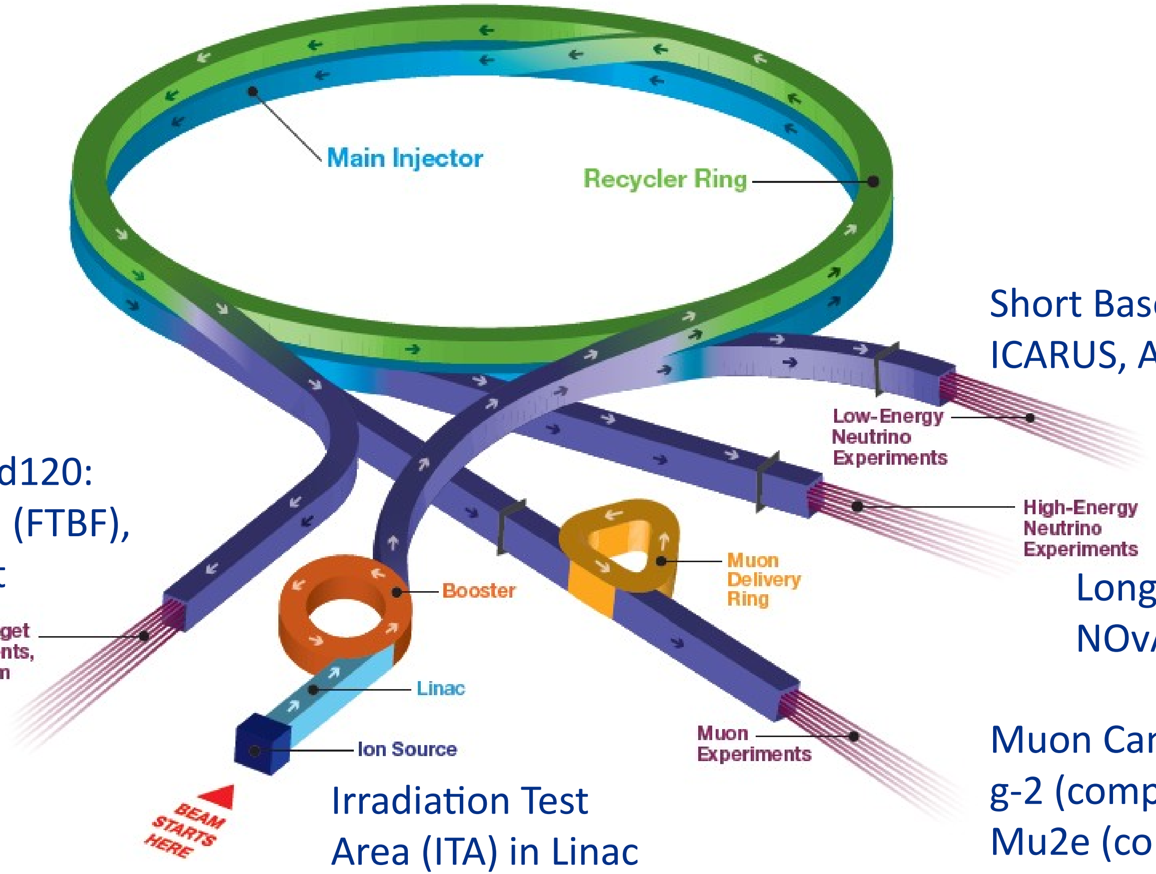
Since the end of Tevatron running, *neutrino physics* has driven the proton economics at Fermilab, and that *will* remain the key driver for the next 30+ years!

Cartoon of the current accelerator complex



SwitchYard120: test beam (FTBF), SpinQuest

Short Baseline Neutrino: ICARUS, ANNIE, SBND

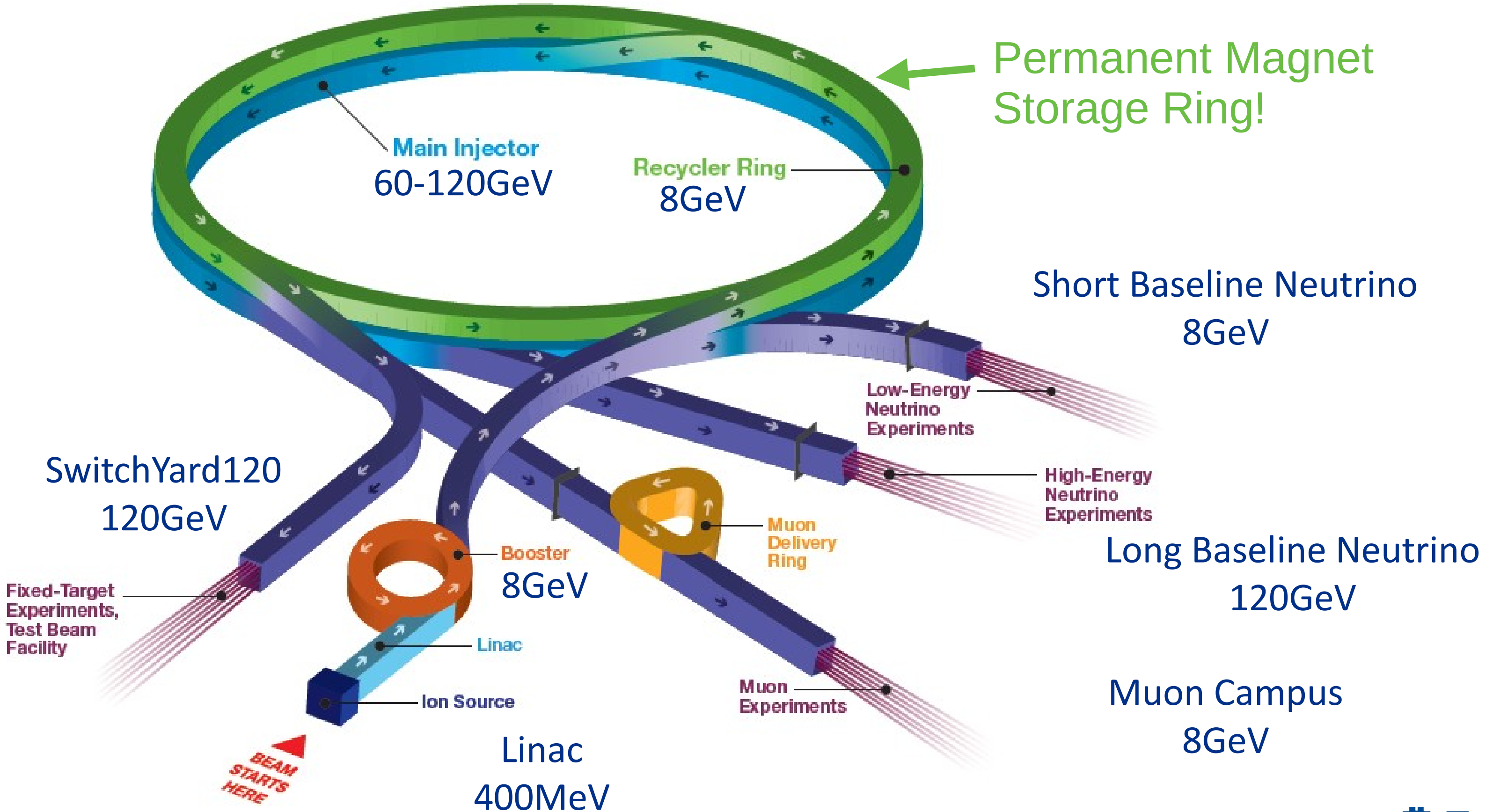
Long Baseline Neutrino: NOvA

Irradiation Test Area (ITA) in Linac

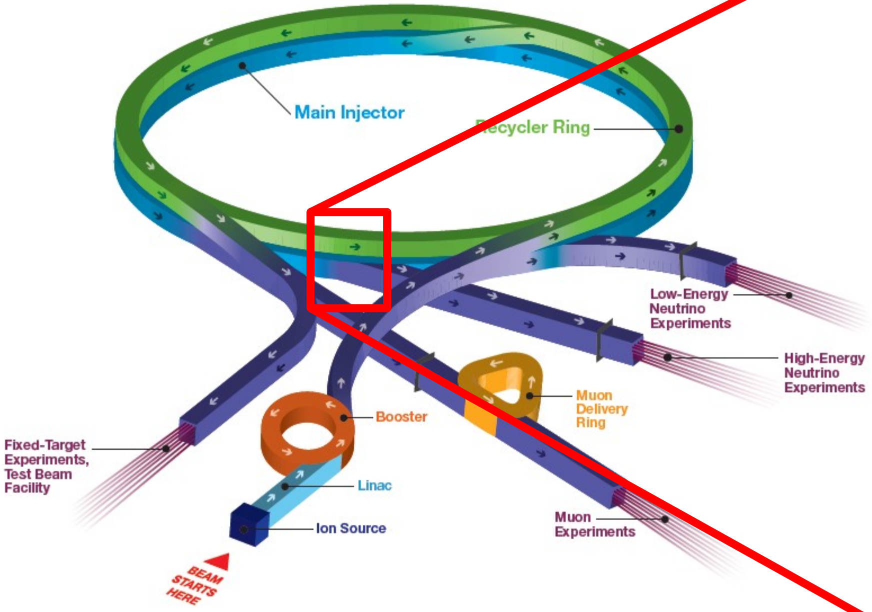
Muon Campus: g-2 (completes this year), Mu2e (commissioning)

From M. Convery

Cartoon of the current accelerator complex



Reminder that these cartoons hide a wealth of complex and interesting science and engineering



Reminder that these cartoons hide a wealth of complex and interesting science and engineering

Recycler Ring

NuMI Extraction Line

Main Injector

They also hide a vast hierarchy of scales!

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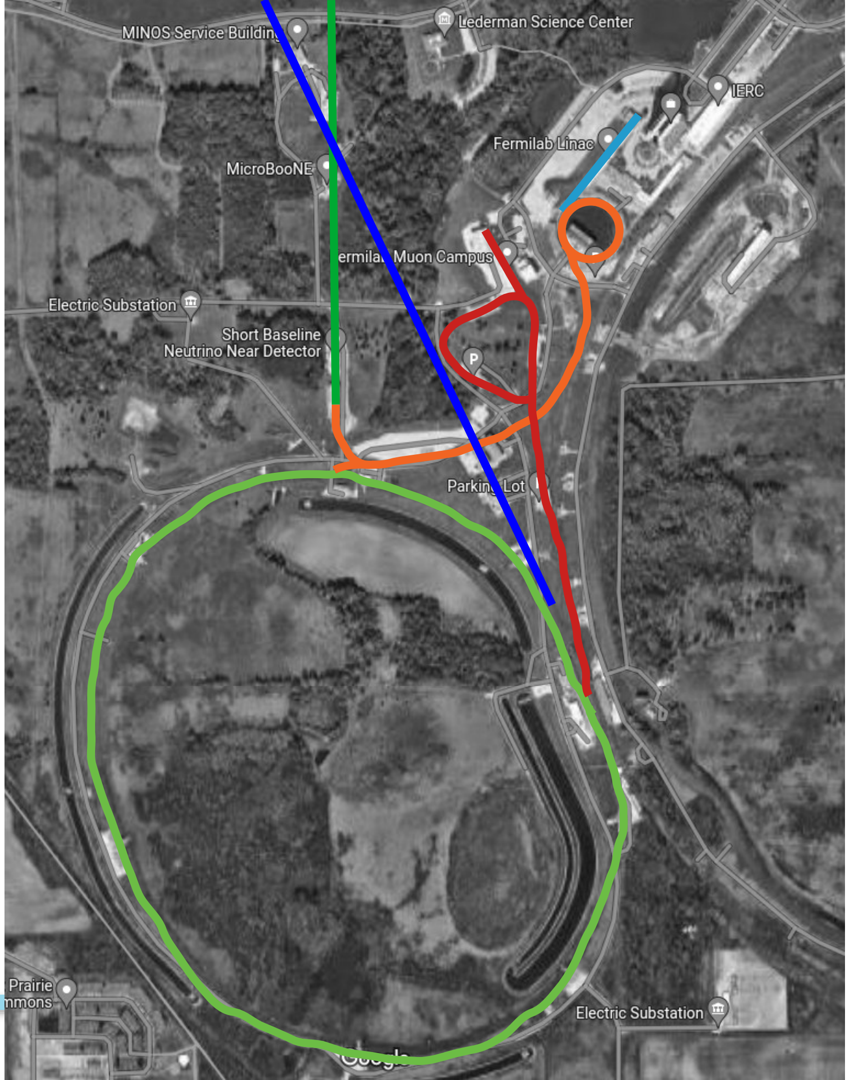
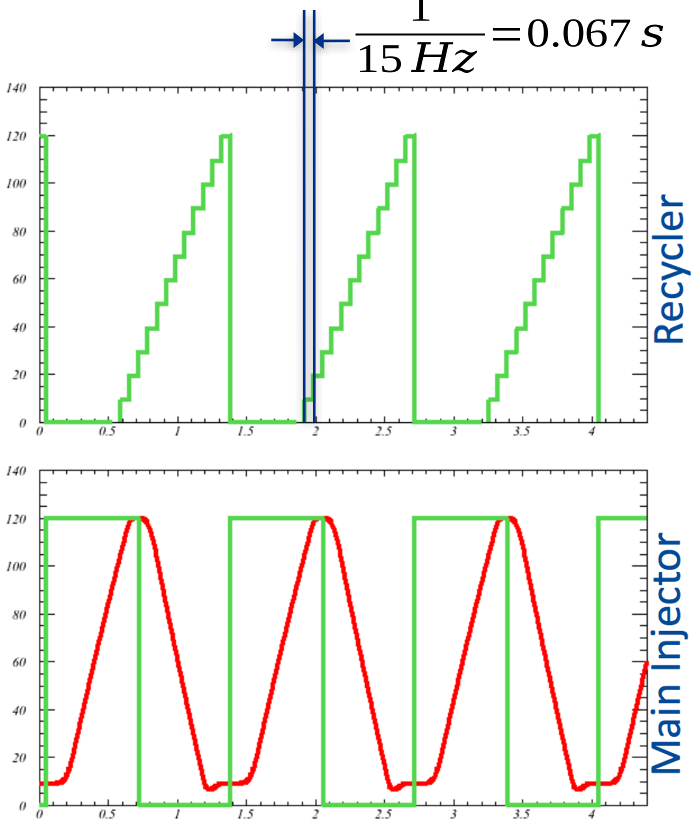
- Linac (400MeV)
- Booster (8GeV)
- RR/MI (8GeV/120GeV)
- Muon Campus (3.094GeV/8GeV)
- BNB (8GeV)
- NuMI (120GeV)



The accelerator timeline is organized around the NuMI program

- H^- linac (1970, 1993, 2012)
  – 400 MeV linac ~20mA
- Booster synchrotron (1970)
  – H^- stripping injection (1978)
    - 16 turns to ~4.7×10^{12} p per pulse
  – Resonant Ramp from 0.4 to 8 GeV at 15 Hz
- Recycler (1998)
  – 3.3 km permanent magnet 8 GeV ring
  – Slip-stacking 12 Booster batches, ~56×10^{12} p
  – Also re-bunches beam for Muon Campus
- Main Injector (1998, but!)
  – 8 to 120 GeV ramp, cycle time 1.133*-1.4 s



1.33s cycle shown

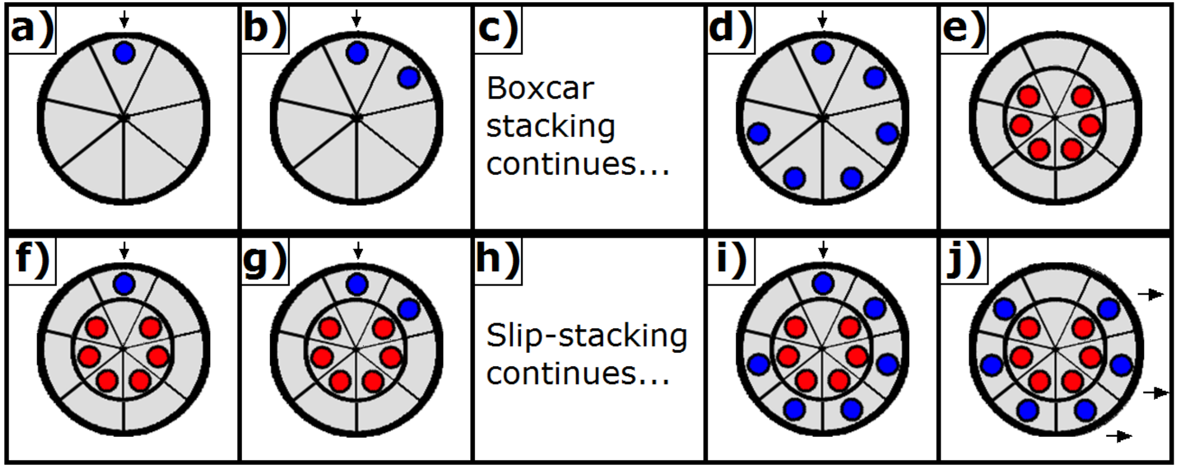
* 1.067s has been demonstrated recently!

Fermilab
From M. Convery

Stacking beam in the Recycler is the key timeline constraint

- Slip stacking is a method of injecting multiple beams at different momenta into the same circular machine.
  - We combine slip stacking with boxcar stacking to stuff beam into the Recycler

7x as many 53MHz RF buckets in RR/MI as in Booster (588/84) … 81 filled buckets per transfer

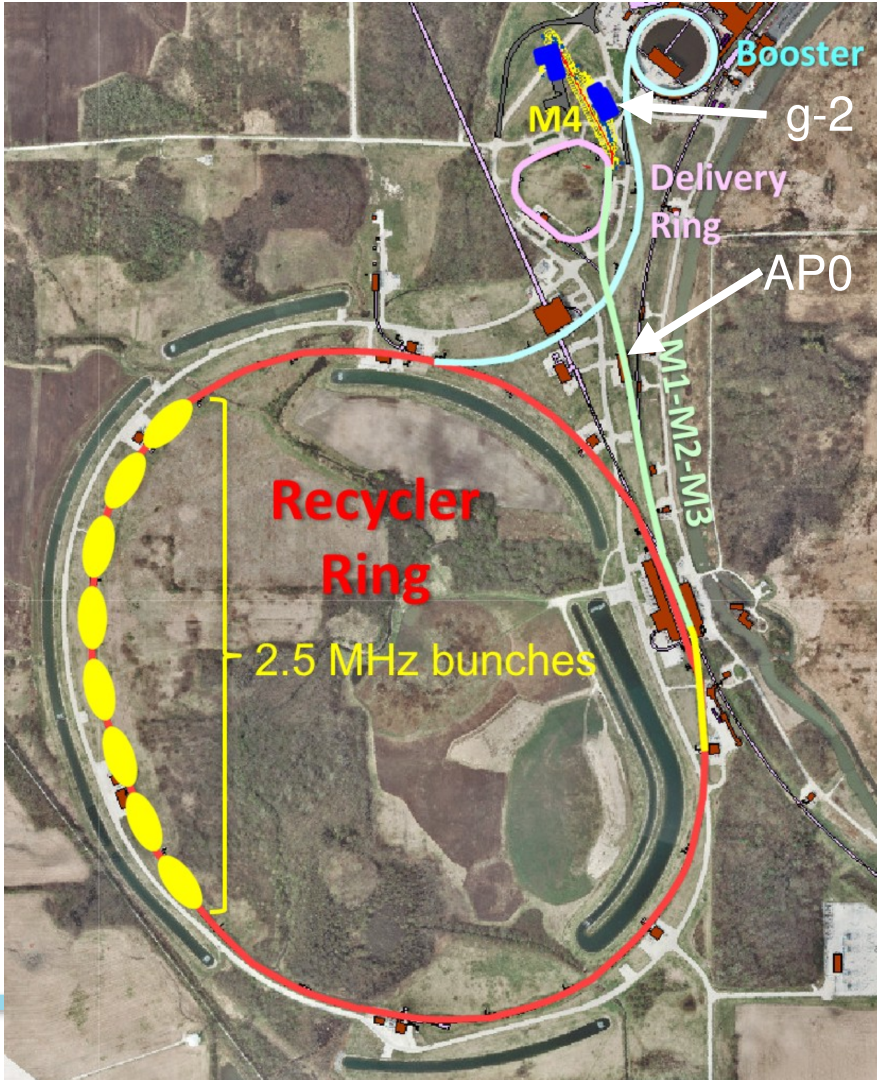


- These manipulations require 13 ticks of the Booster clock
  - 12 for injection, one for extraction

Fermilab

We want to take those spare protons and move them to Mu2e

- Each Booster batch is rebunched from 81 x 53MHz to 4 x 2.5MHz
- The rebunched beam pulses are extracted one at a time from the RR
- These pulses are injected into the 2.36MHz DR
- Those protons are then slow extracted to the experiment



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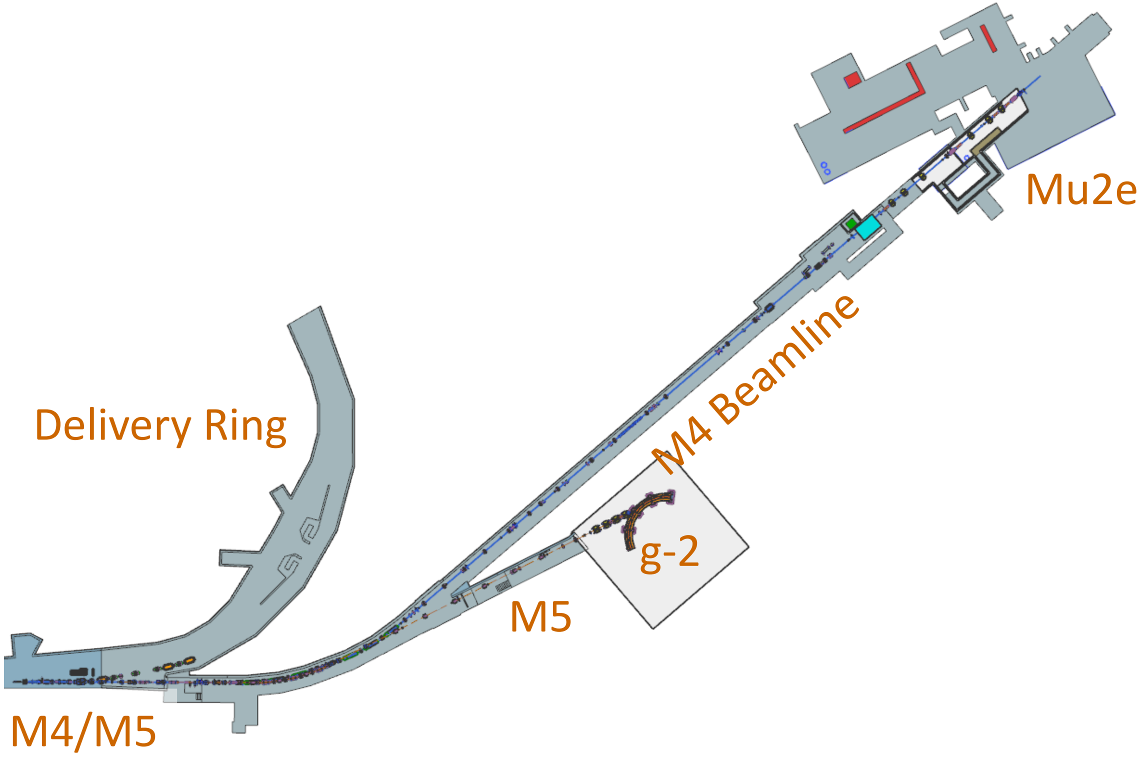

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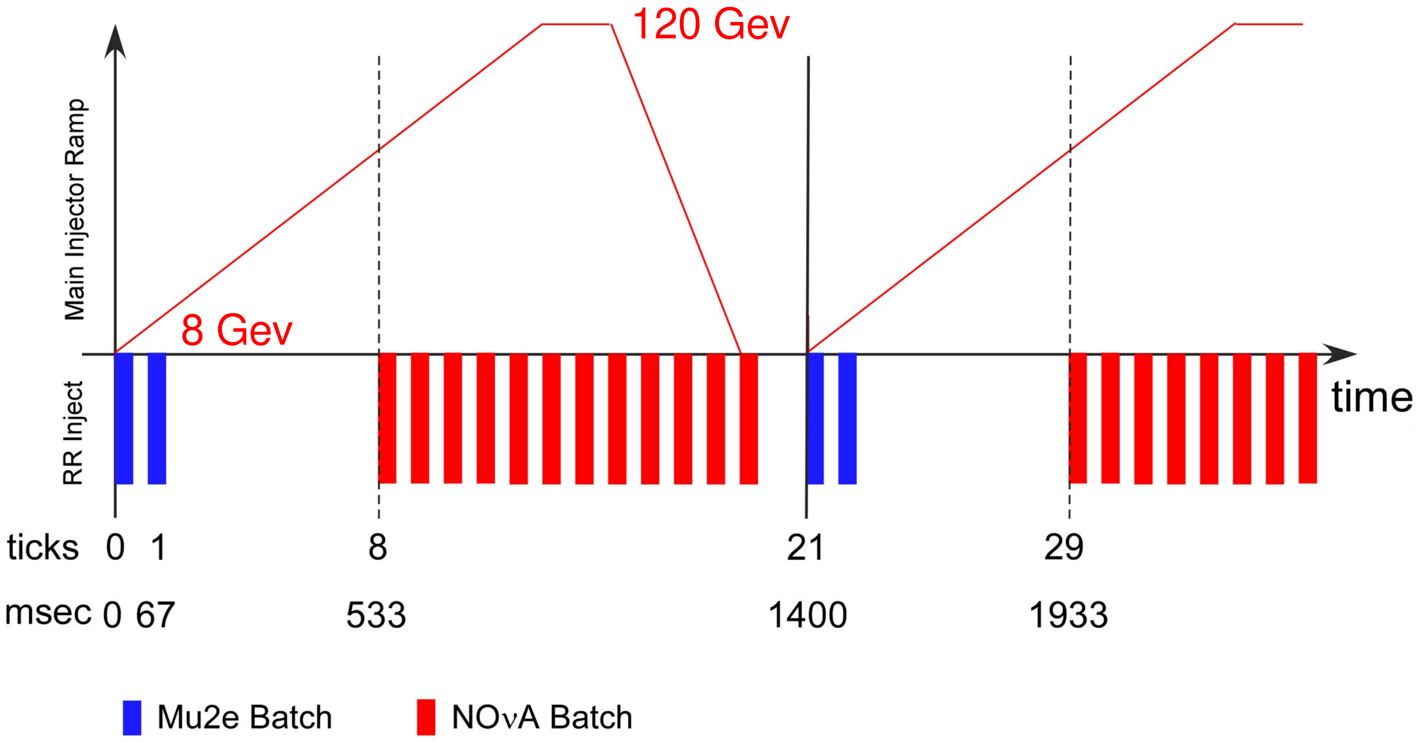
Fermilab

All our machine timelines are built around moving 12 successive Booster batches to the MI – how does this impact muons?



1 tick = 1/15 sec

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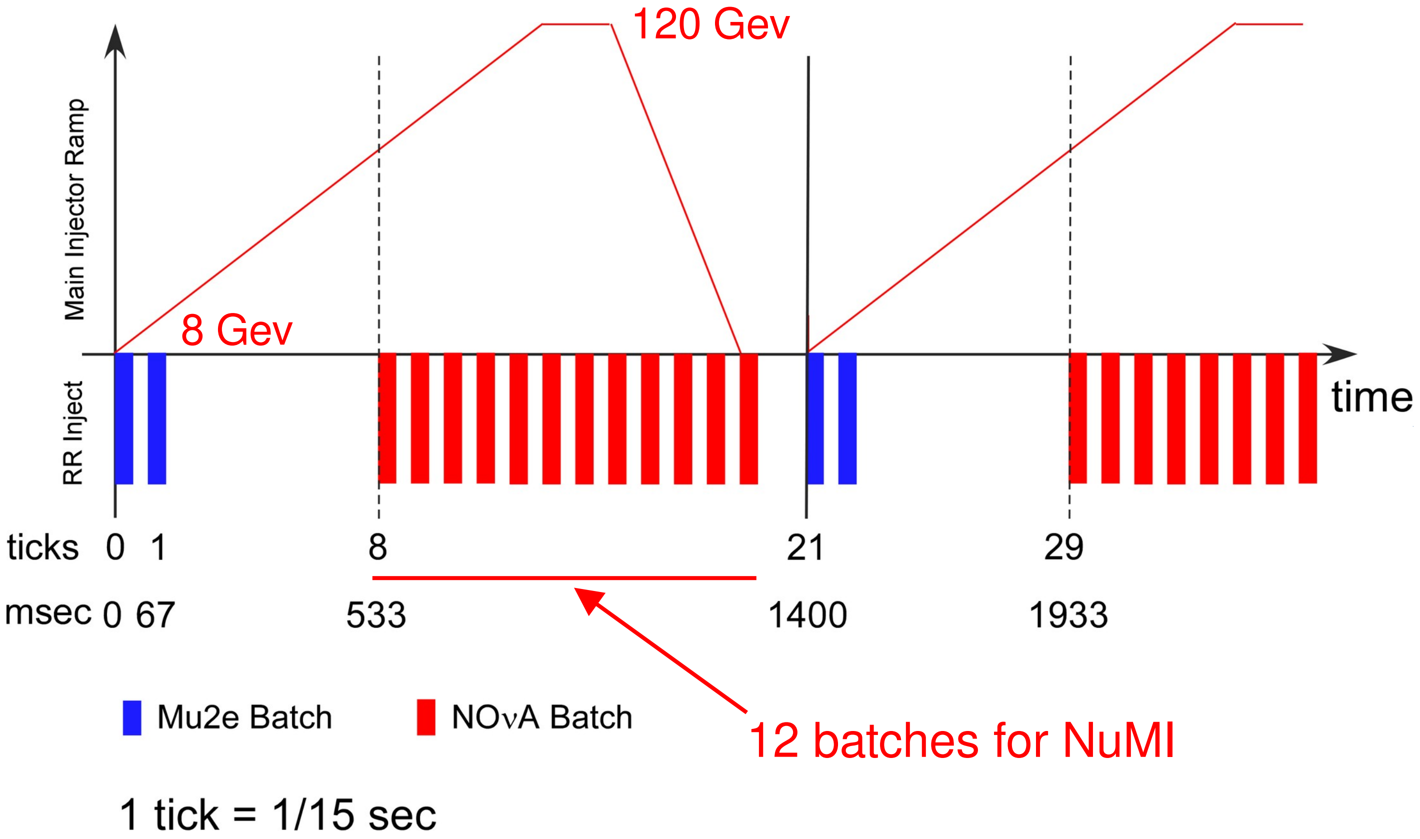

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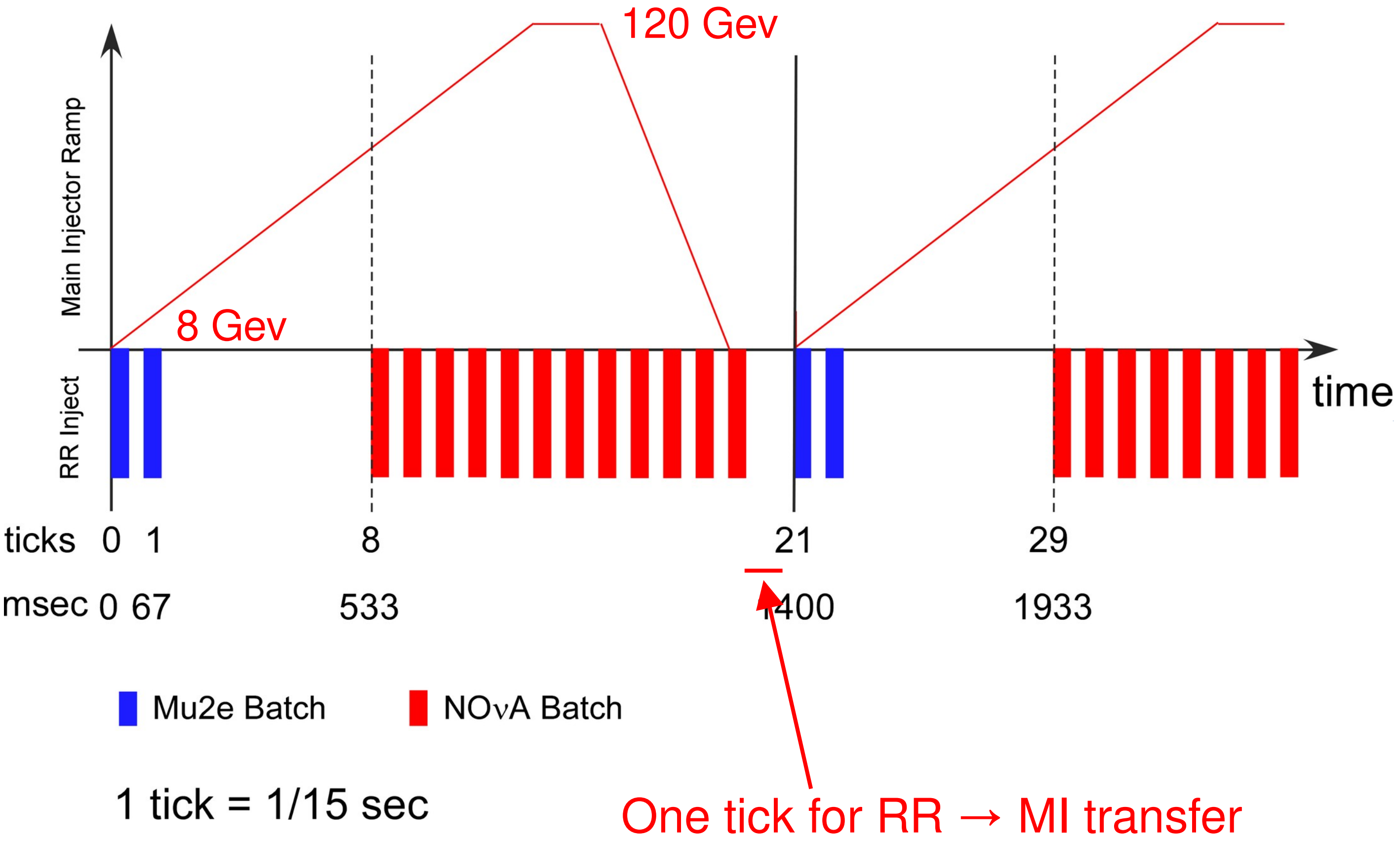

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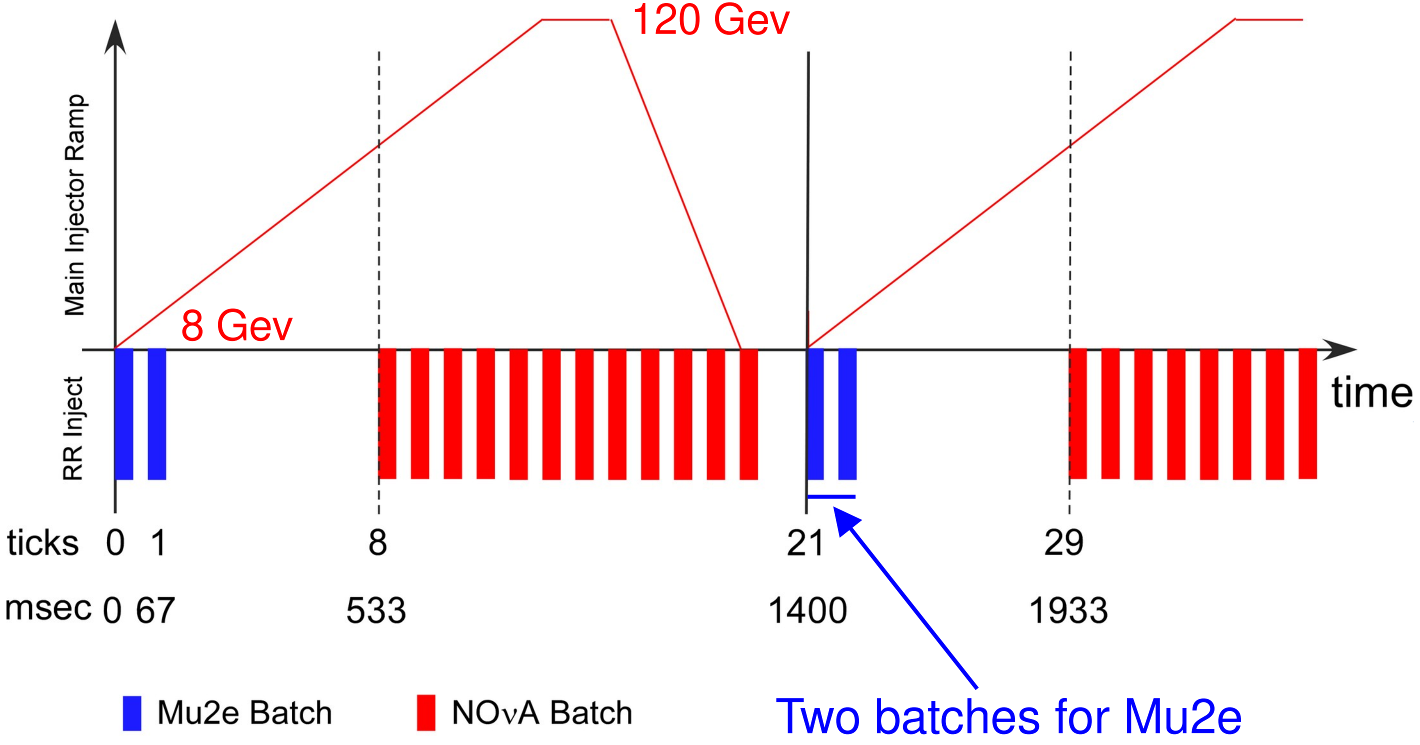

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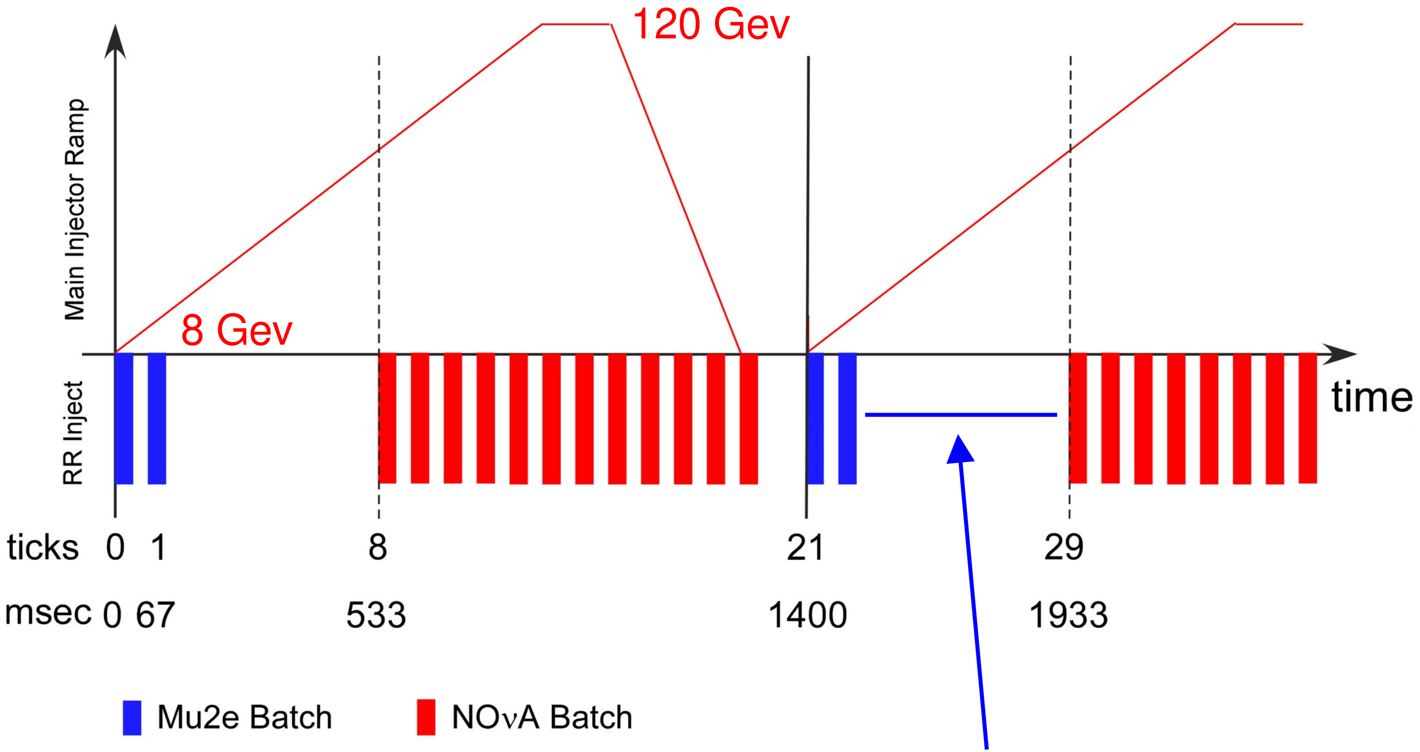
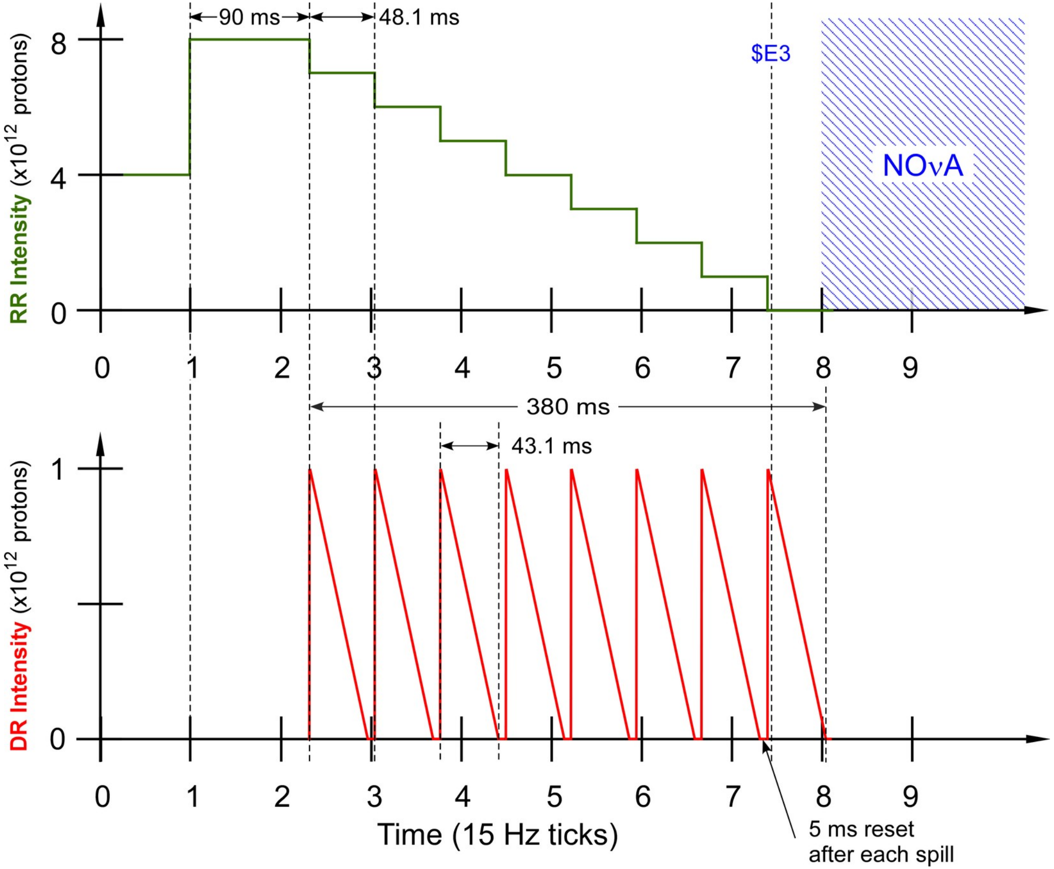


1 tick = 1/15 sec

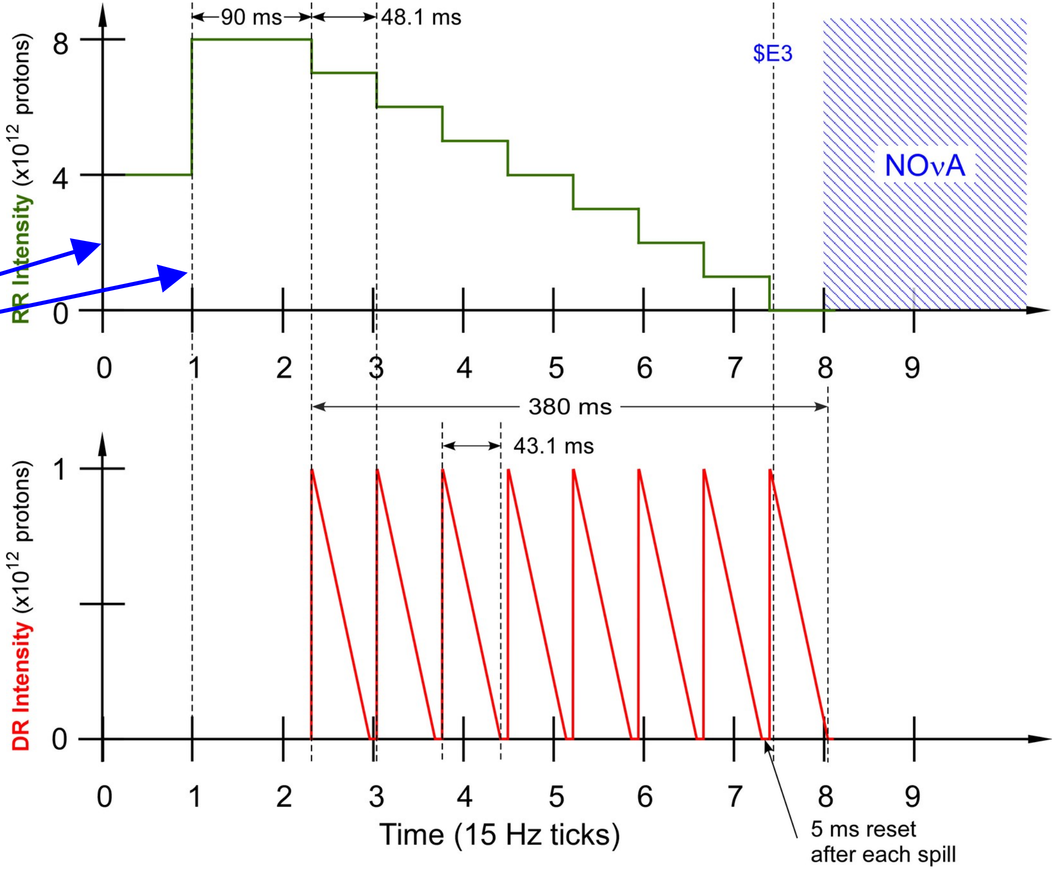
Rebunching and transfer to DR
81x2 53MHz → 1x8 2.5MHz

Beam to Mu2e is resonantly extracted from the DR over 8 ticks

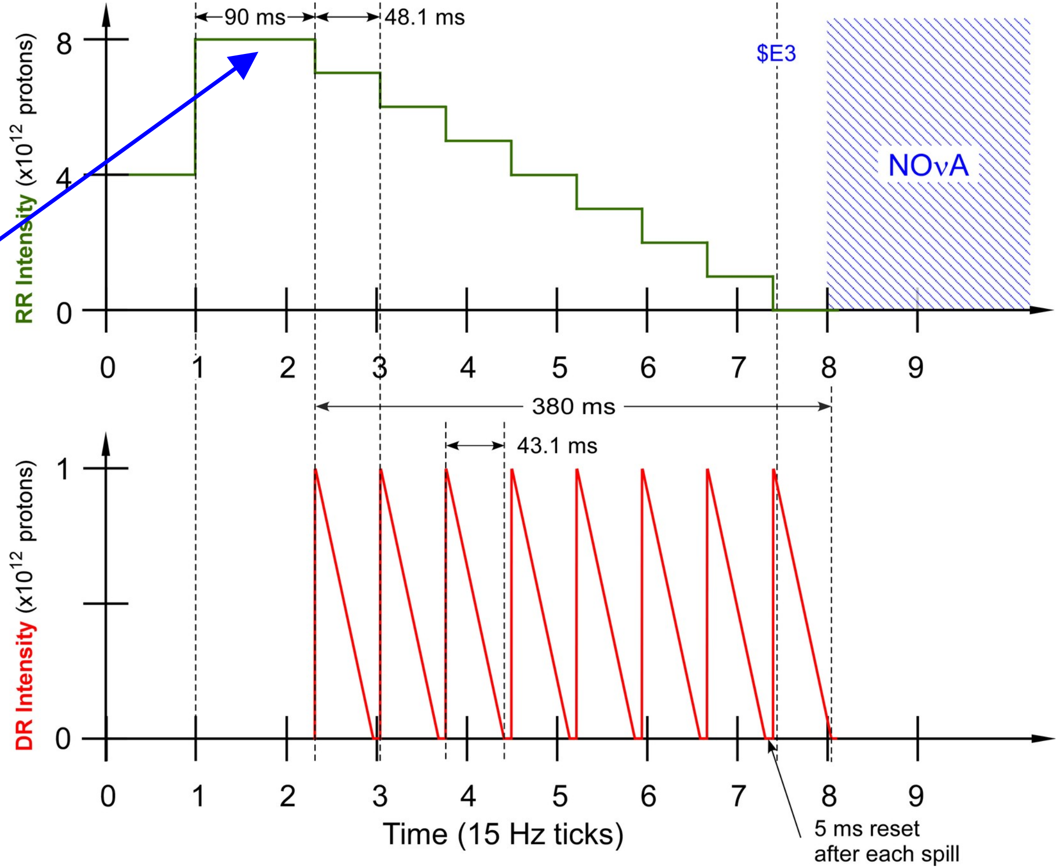


Beam to Mu2e is resonantly extracted from the DR over 8 ticks

Two batches from Booster

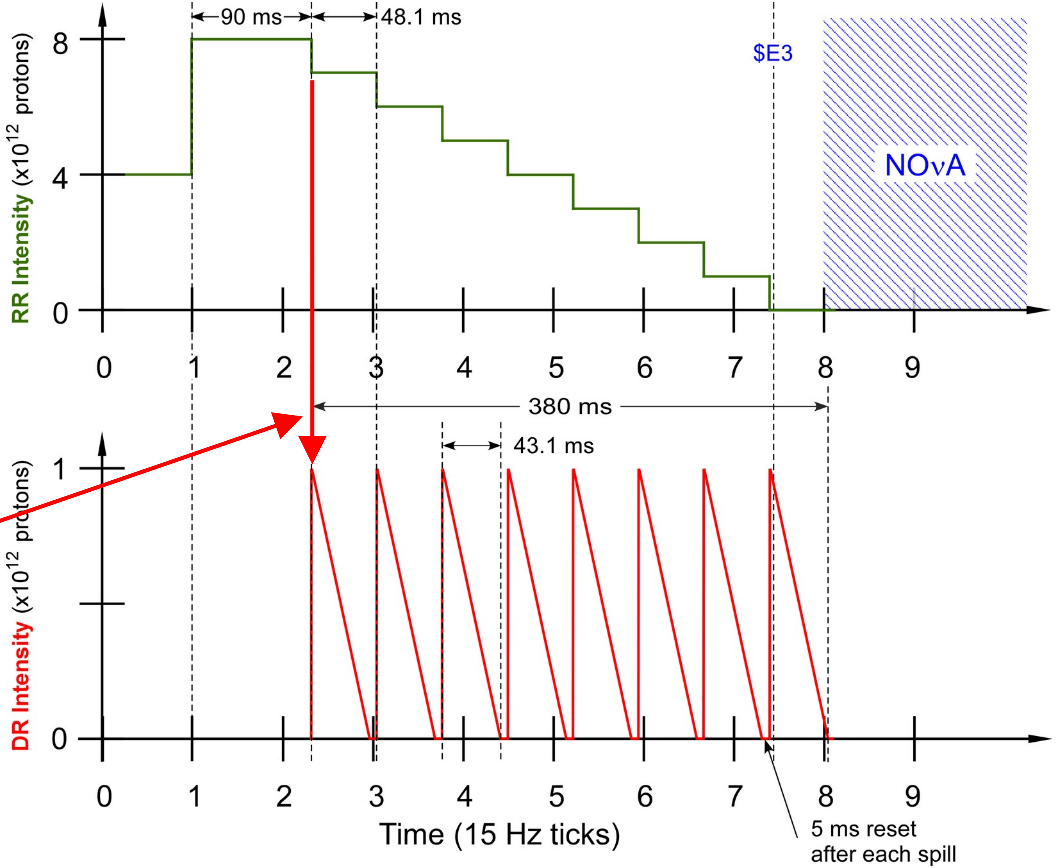


Beam to Mu2e is resonantly extracted from the DR over 8 ticks



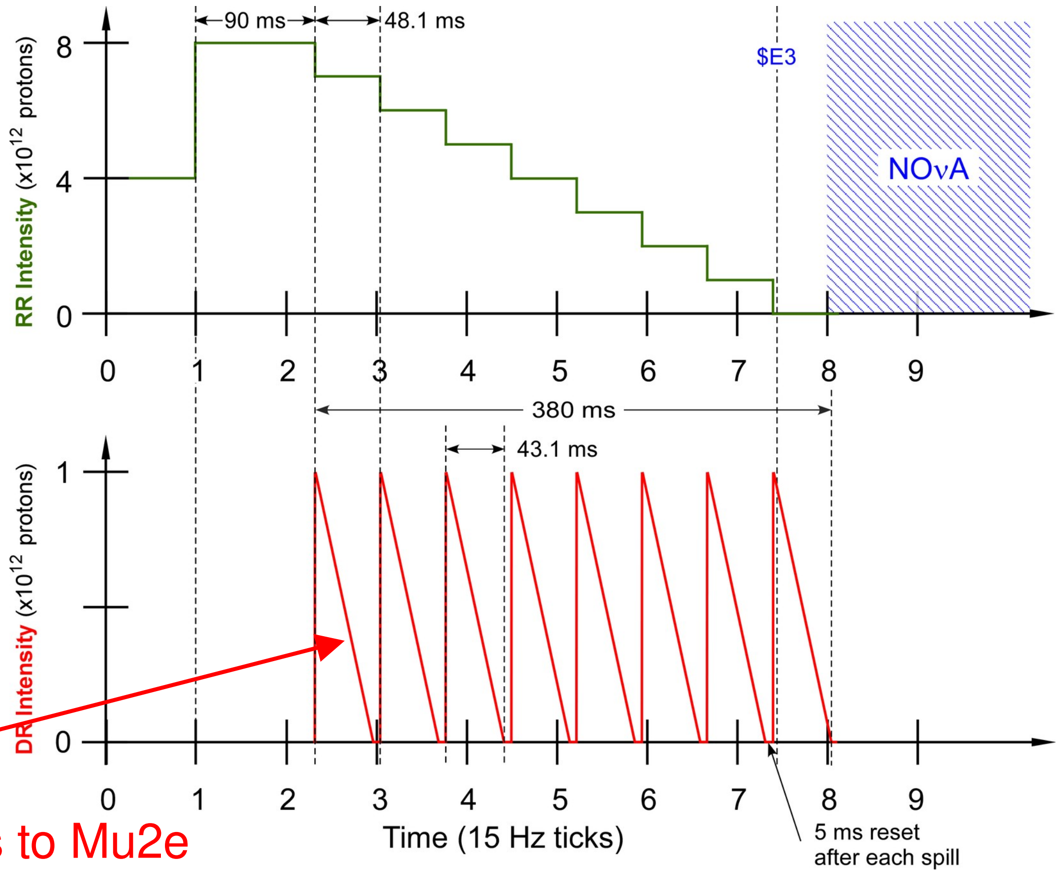
Rebatching takes >1 15Hz tick!!!

Beam to Mu2e is resonantly extracted from the DR over 8 ticks



Move one of the new batches to DR
2.5MHz → 2.36MHz!

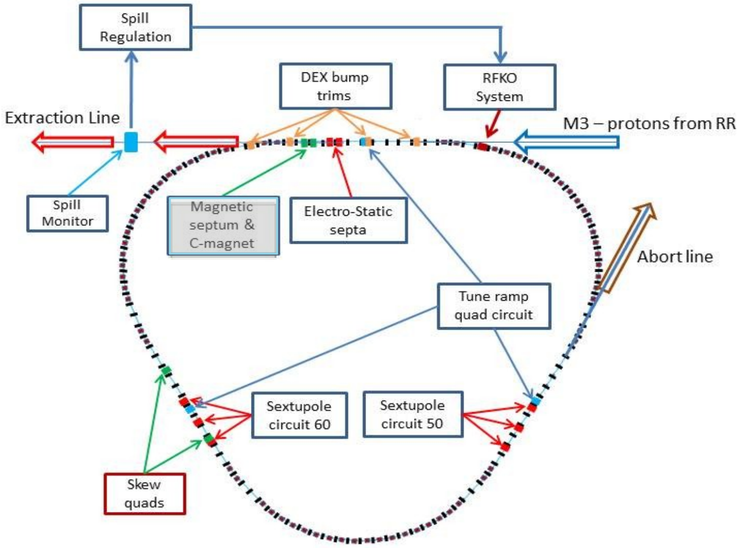
Beam to Mu2e is resonantly extracted from the DR over 8 ticks

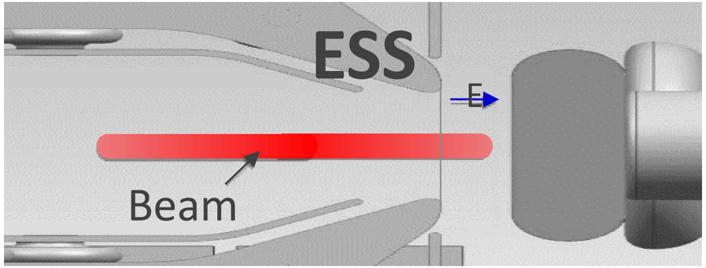


Resonant extraction ~25-30k pulses to Mu2e

Mu2e resonantly extracts from the delivery ring

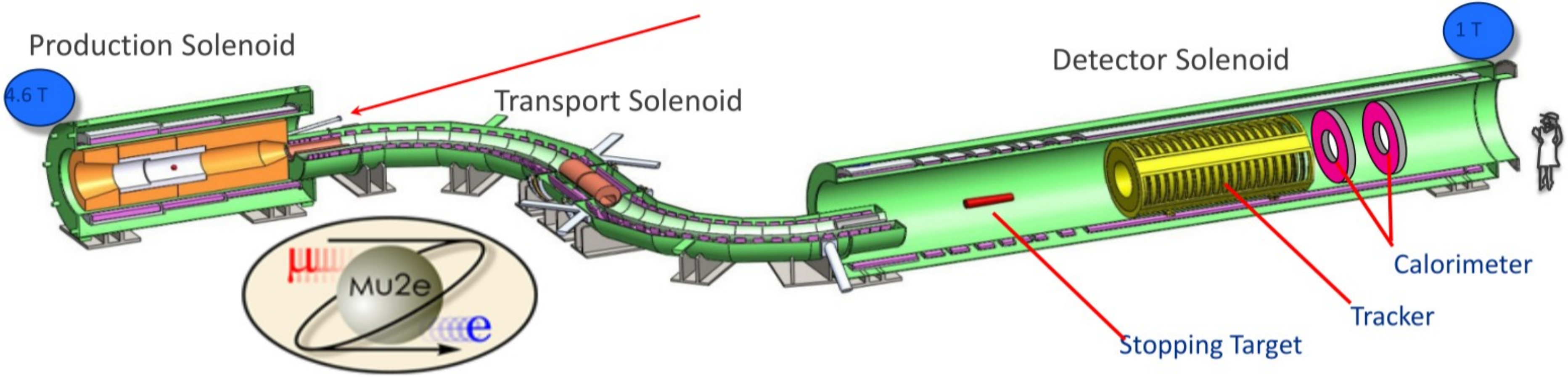
- Quadrupoles intentionally drive a 1/3 integer resonance in the horizontal tune.
- Sextupoles induce a controlled beam instability.
- Septum foils peel off a bunch each turn.
- Dynamic spill regulation control is accomplished by tune corrections and RFKO.
- Full extraction occurs over ~25-30k turns.
- Remaining beam is dumped, and the cycle starts again.



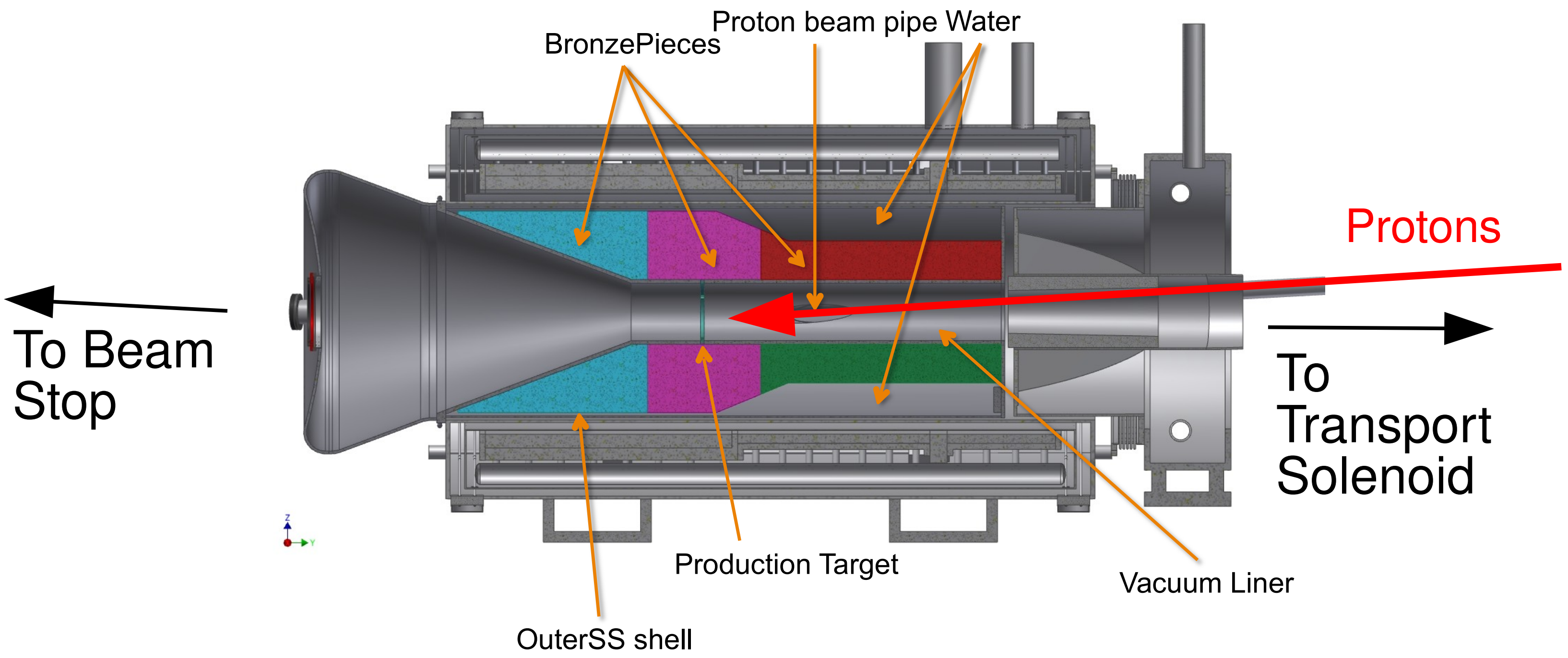


The delivery ring orbital period – 1695ns – drives the interpulse spacing in Mu2e, and is a nearly ideal match to the muonic aluminum lifetime of 864ns.

Twenty slides ago, I showed you this picture

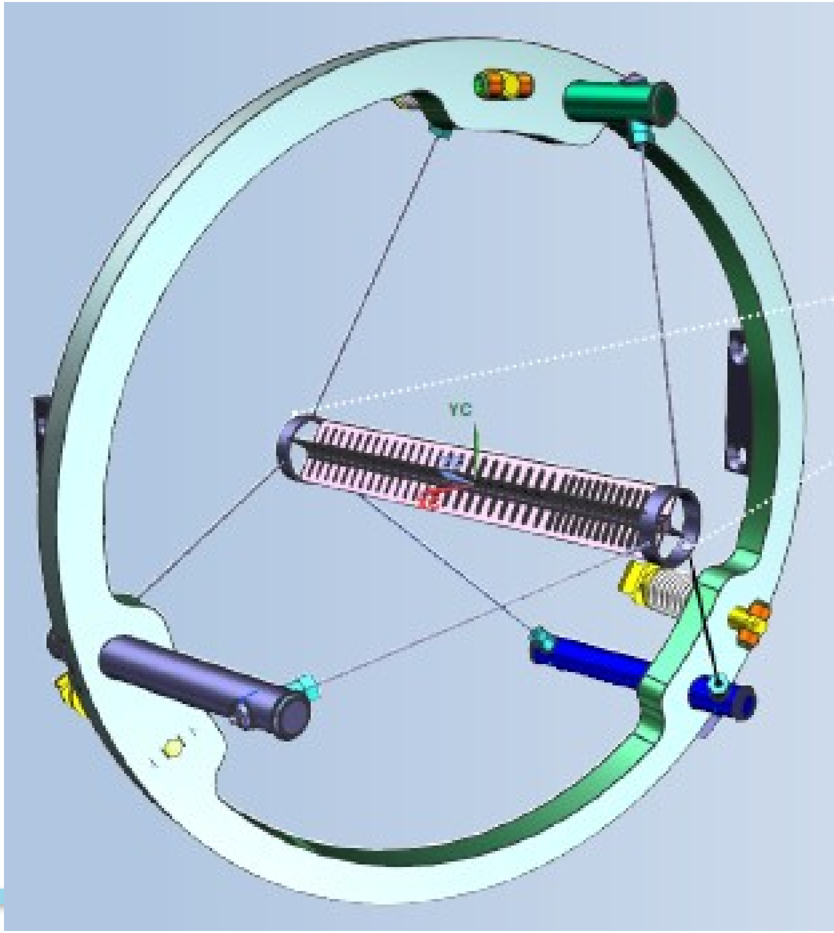


The production target is mounted inside a high field Production Solenoid, and we capture and transport backward muons

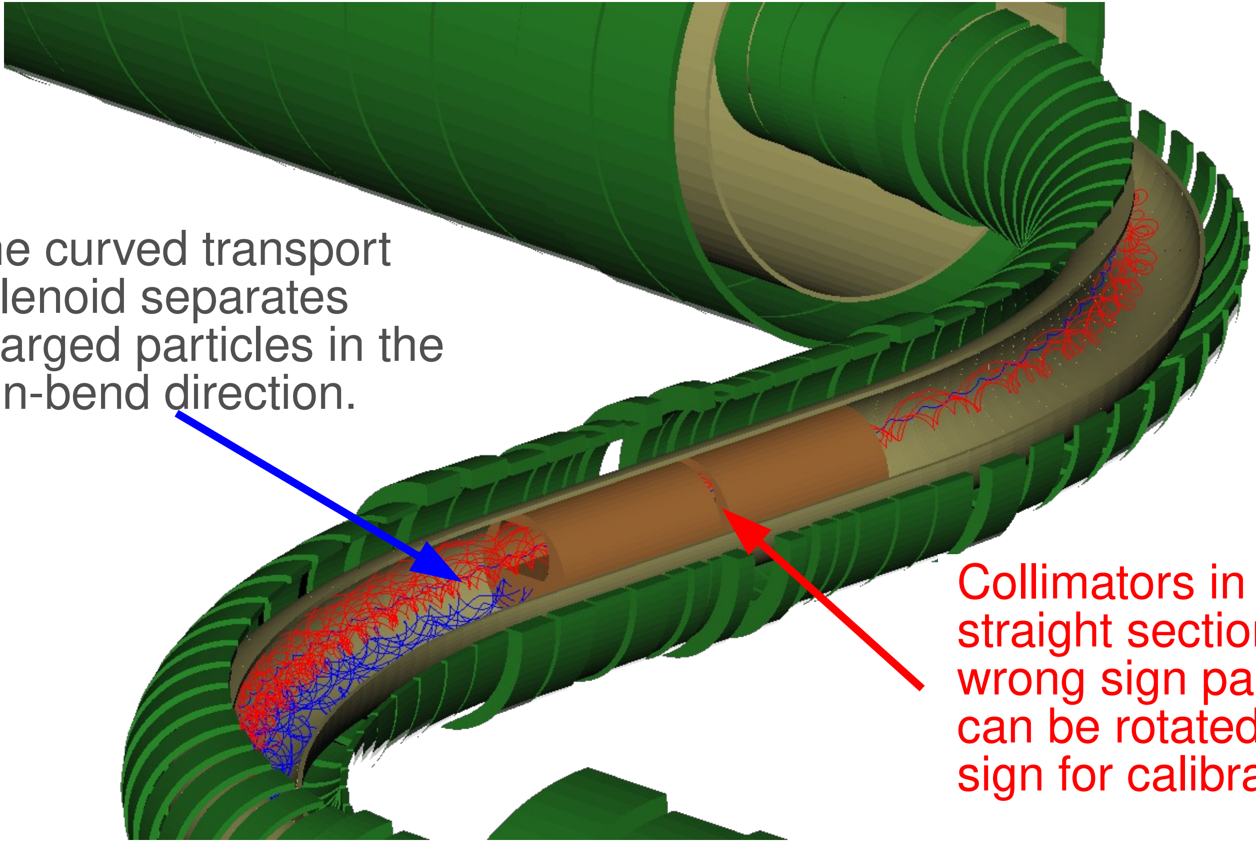


The production target is a radiatively cooled tungsten structure

- Bicycle wheel support
- LaO_2-doped Tungsten, core is EDMed from single rod
- Longitudinally segmented cylinder (stress management):
  - 3.15 mm radius, 160+60 mm length
- Longitudinal fins (structure and thermal management)
- 1mm tungsten spokes
- ~ 700 W power absorption
- ~ 1500 K temperature



The Transport Solenoid sign-selects with a collimator



The curved transport solenoid separates charged particles in the non-bend direction.

Collimators in the central straight section reject most wrong sign particles, and can be rotated to change sign for calibration runs.

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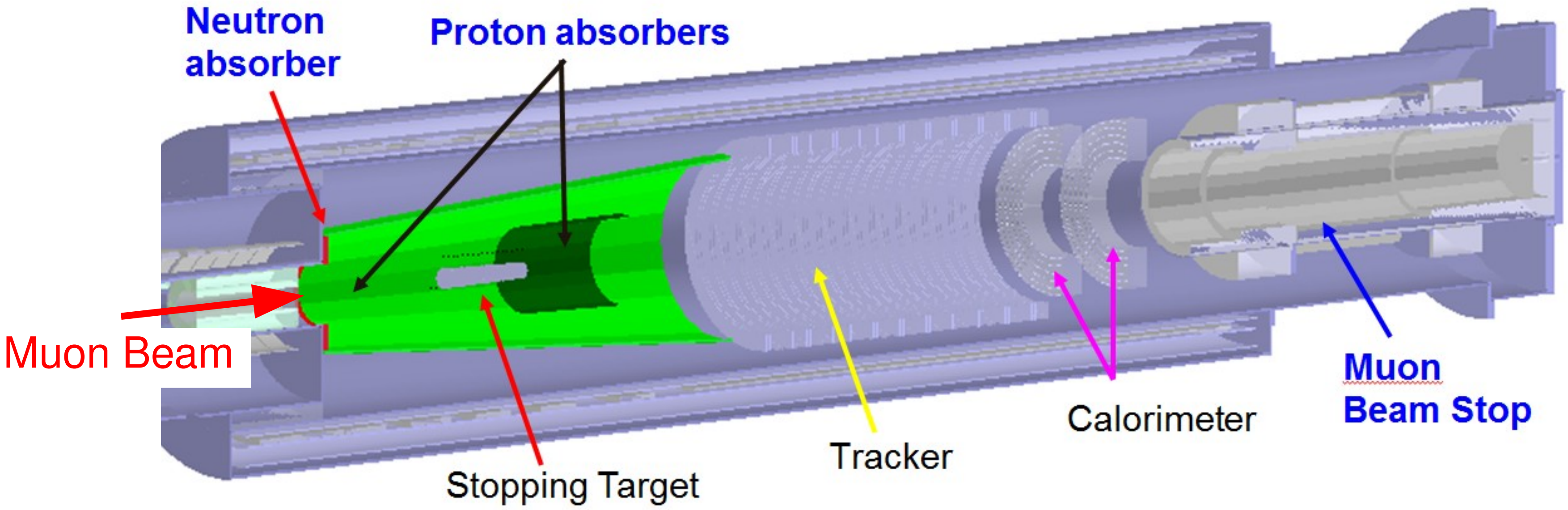
The Detector Solenoid is the heart of the experiment



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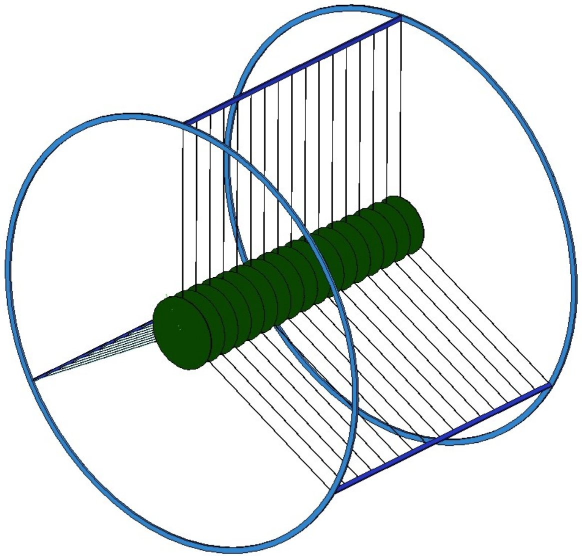
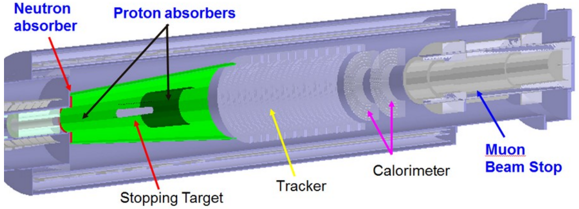
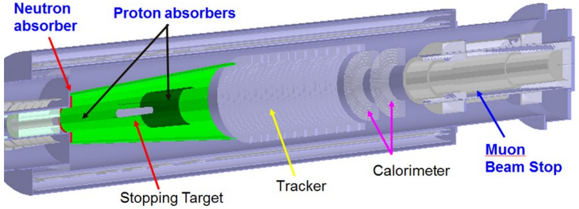
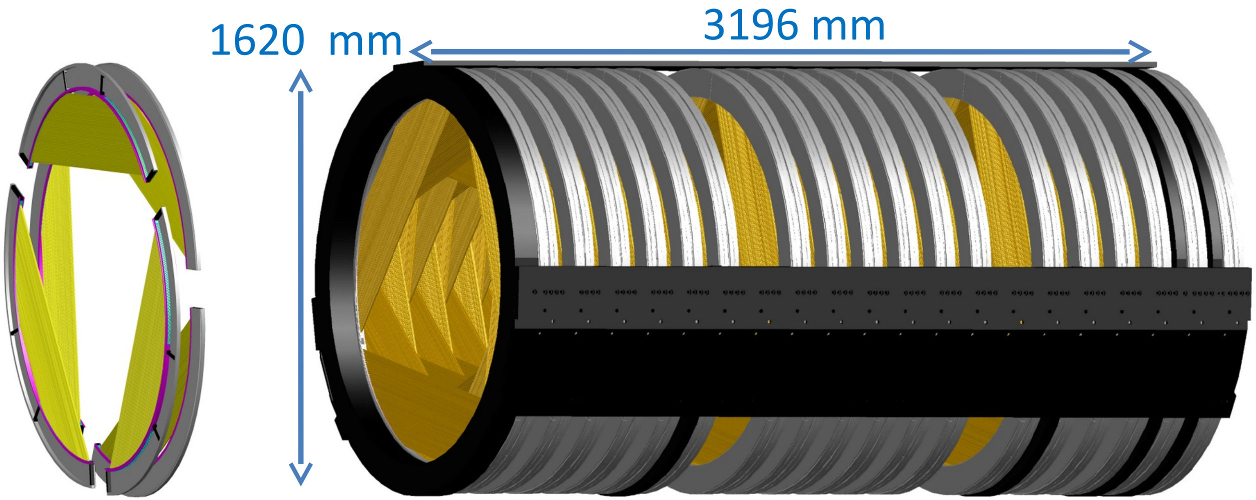




The stopping target is 17 Al foils to intercept and stop the secondary beam

The Detector Solenoid is the heart of the experiment

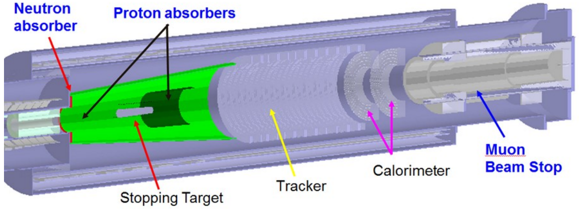


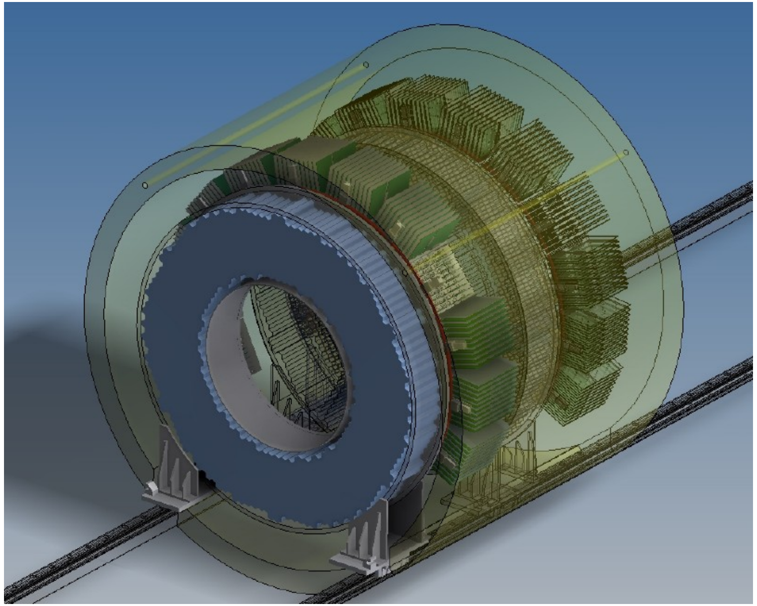


The electron tracker is a low mass straw tube design with 18 stations of tubes transverse to the secondary beam, with 21,000 straws in total.

It provides precision momentum measurement.

The Detector Solenoid is the heart of the experiment



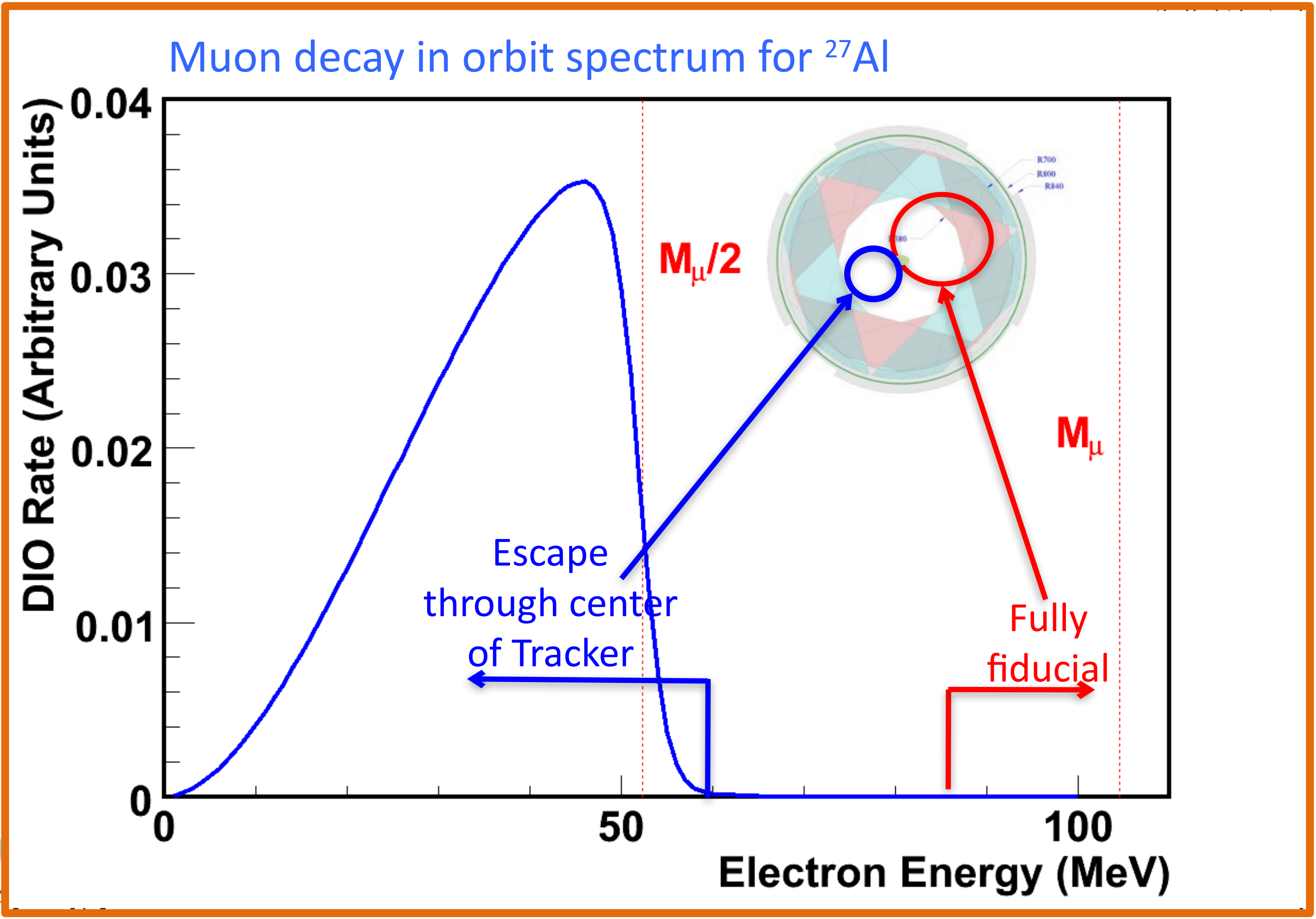


The calorimeter is a two layer, annular, undoped CsI crystal calorimeter.

It provides precision timing and particle ID

Detectors are uninstrumented along the axis of the solenoid

The vast majority of remnant beam, brehmstrahlung, and muon decay products escape down this central hole and are captured in a muon beam stop designed to prevent "back splash"



Mu2e running will be split by the LBNF shutdown

Construction should complete in 2025, with commissioning and Run 1 physics data in 2026-2027.

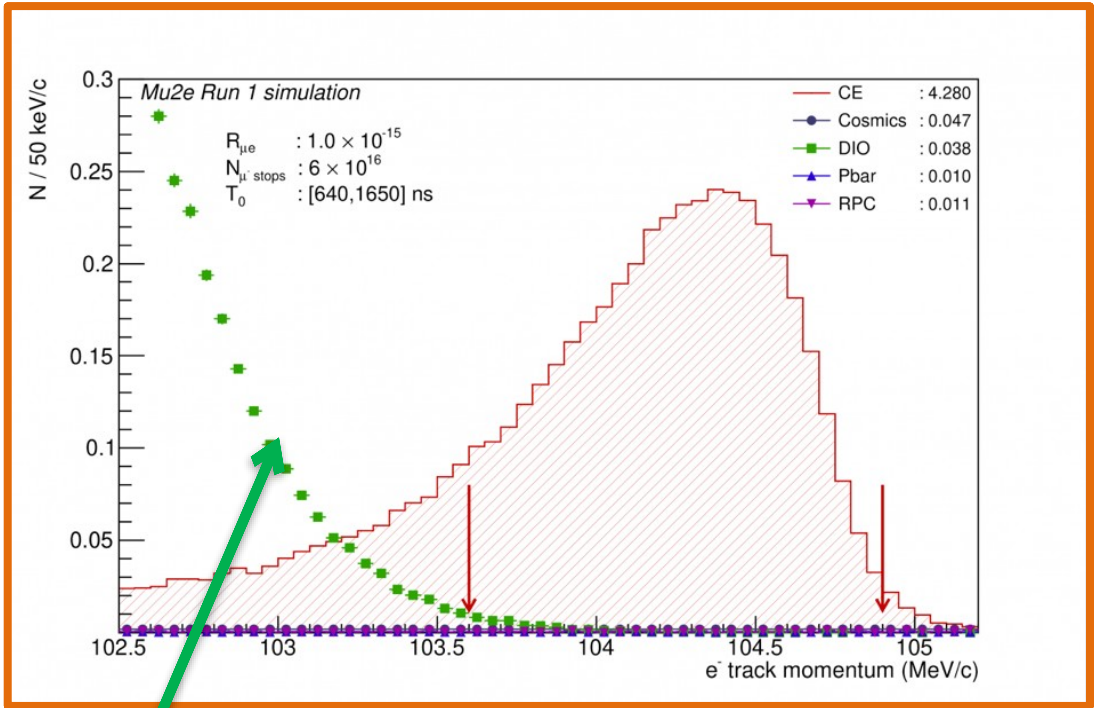
Recently completed a sensitivity estimate for Run 1:

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

Run 2 will commence in 2029 with a goal to improve the measurement to 10000x better than SINDRUM-II.

For the full dataset, our expected sensitivity

- 90% CL R < few x 10^{-17}



Long DIO tail due to nuclear recoil

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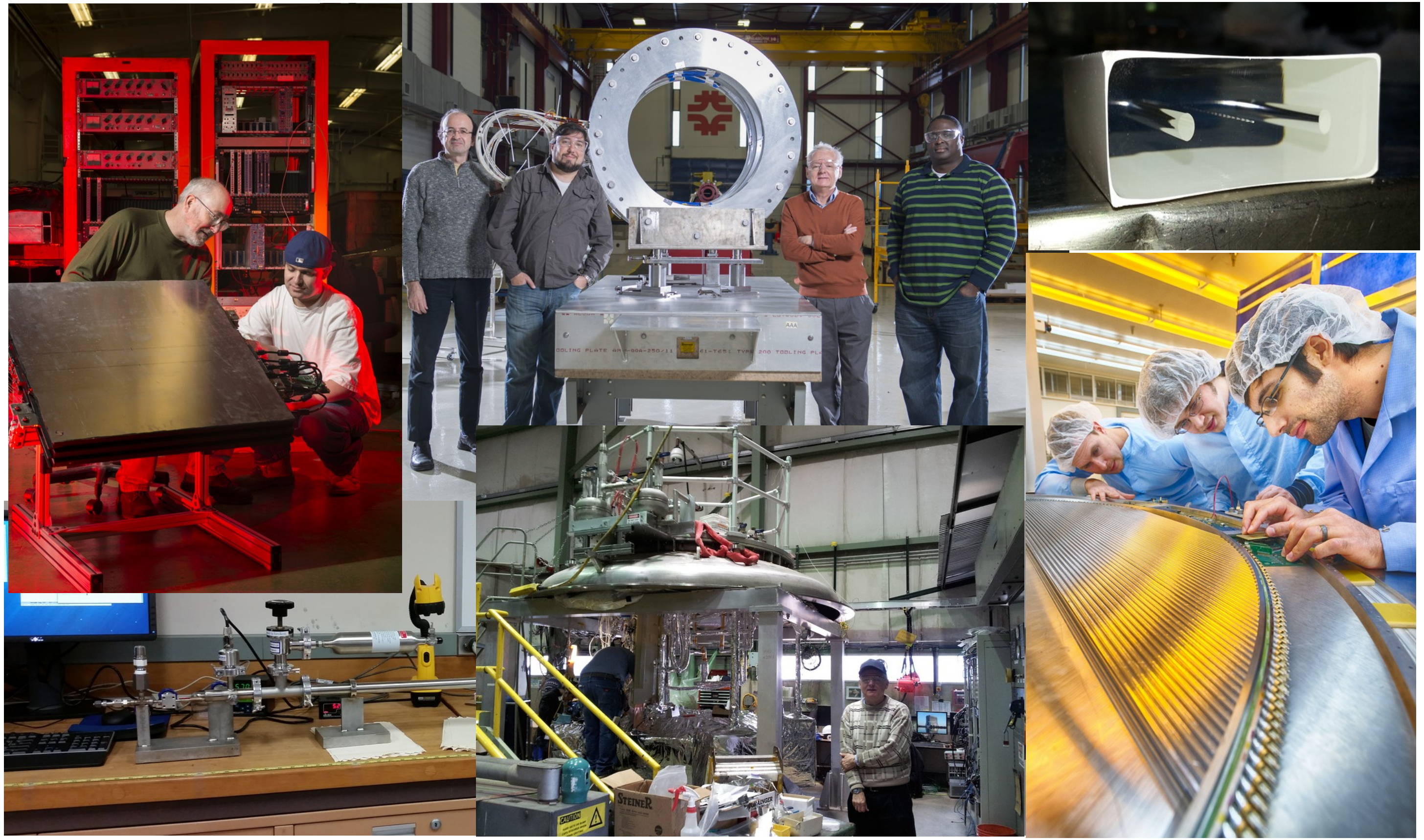
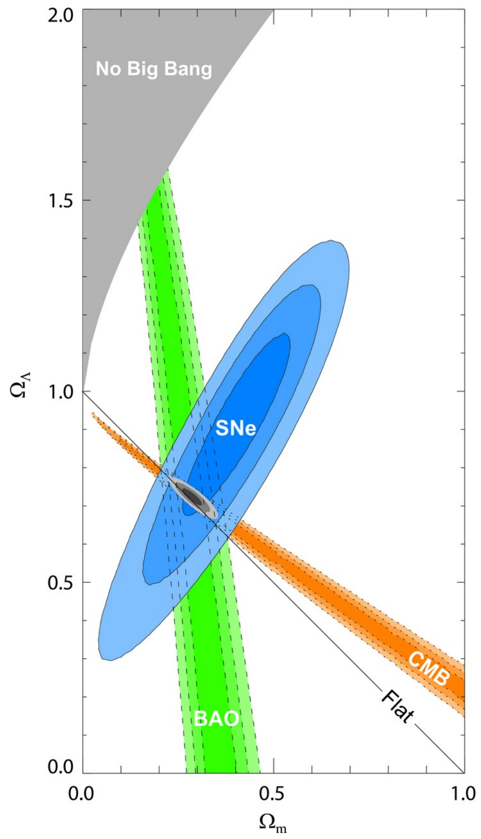
To summarize…

- Fundamental muon physics today is focused on CLFV searches
  - $\mu \rightarrow e\,\gamma$
  - $\mu \rightarrow eee$
  - $\mu^- N \rightarrow e^- N$
- Mu2e and COMET are friendly competition in the conversion search with much shared DNA
  - Both aim for a 10,000x improvement over SINDRUM-II
- We're either going to discover new physics in the next few years, or we'll provide a nearly unprecedented improvement in sensitivity, either of which beg for a next generation experiment
  - Although I couldn't talk about them today, there are ideas to gain an additional 2-3 orders of magnitude with future searches in these and other channels

Thanks for your interest and attention!



But it gets even worse: the vacuum energy problem



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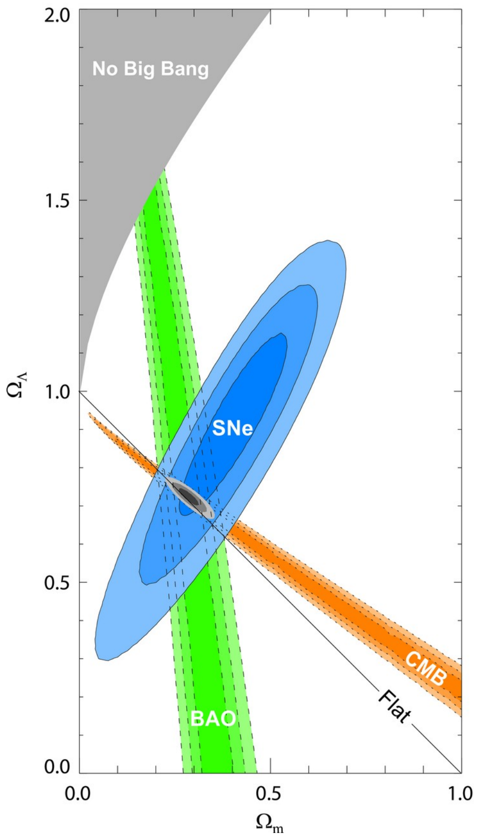
Some of that stuff - aka the *dark energy* - controls the ultimate fate of the universe!



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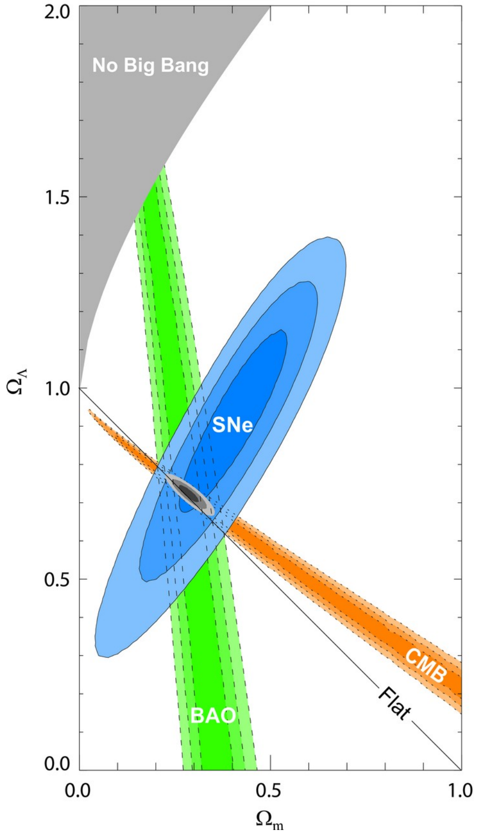
Measured Cosmological Constant

$$\Lambda_{\mathrm{CDM}} = 10^{-47}\,\mathrm{GeV}^4$$



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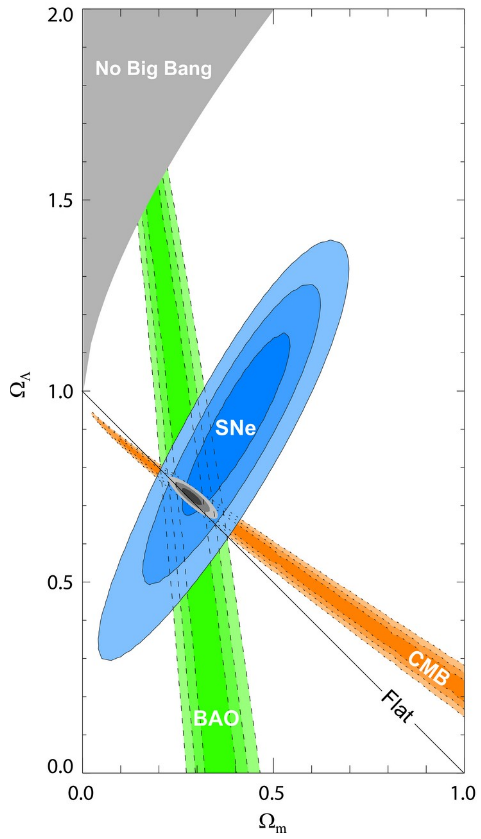

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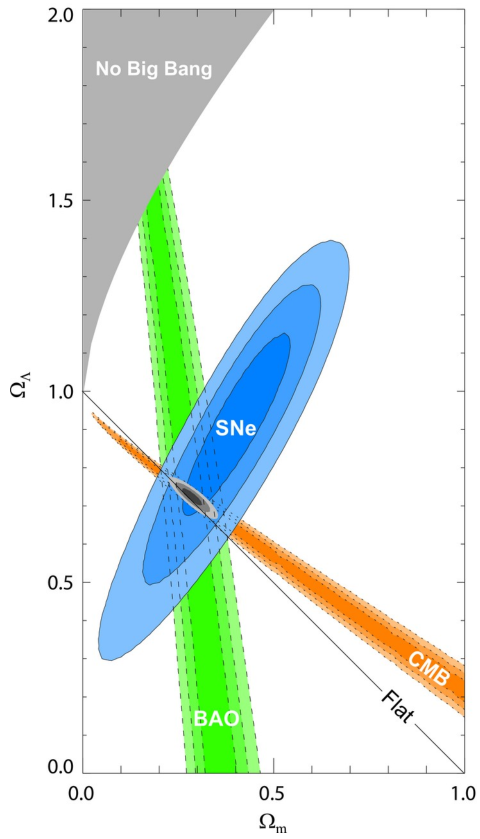

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