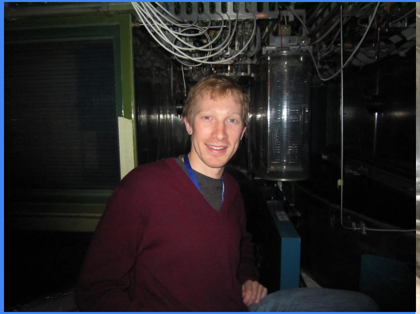


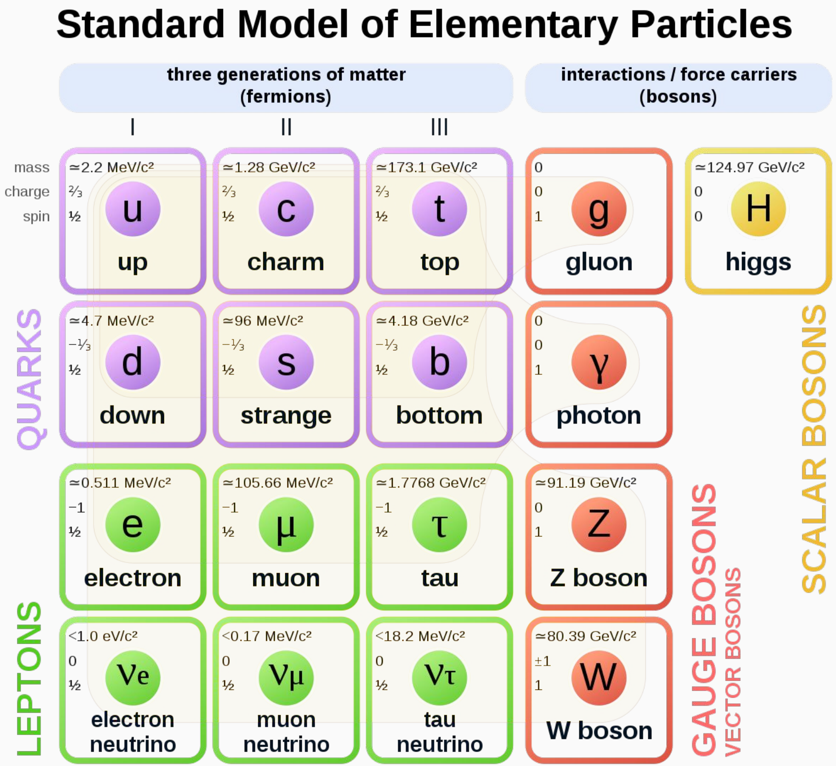
Inside NA61 detector at CERN

MINOS hall at Fermilab

The Mu2e Experiment

U of M Quarknet Workshop
Ben Messerly
2021-08-13

A Business Proposal

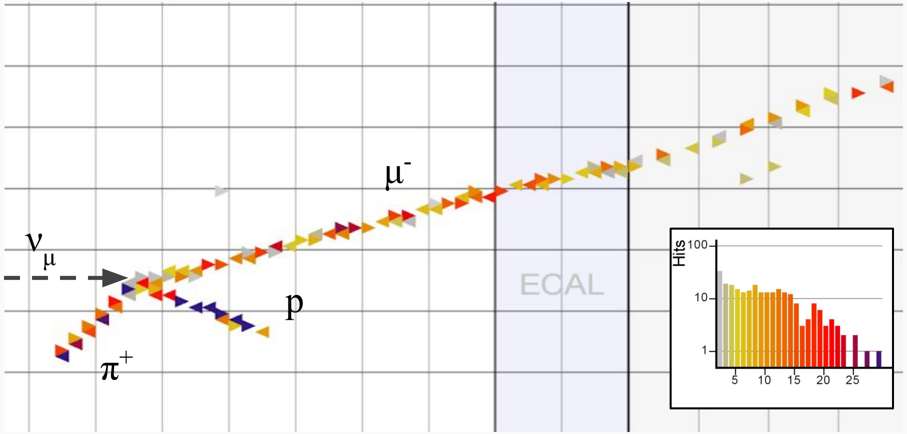


Previous Research: neutrinos

<u>Measured a neutrino cross section (interaction probability)</u>

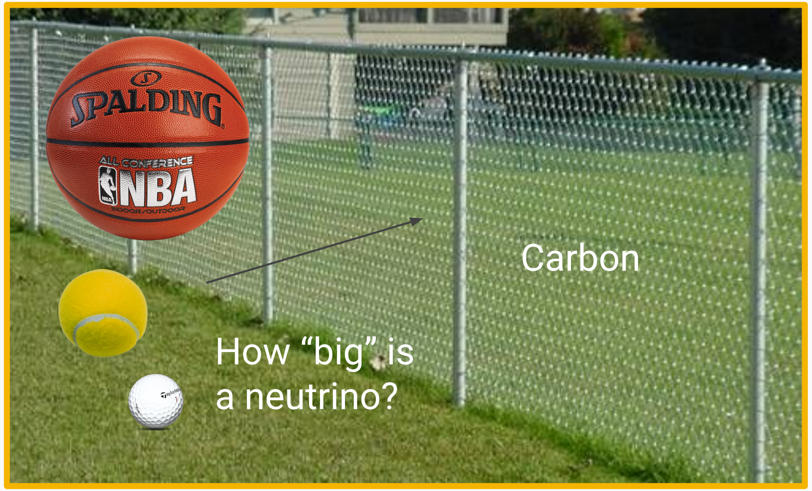
→ inform neutrino oscillation research

→ probe the (very complicated) nucleus



$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^+ + X$$

[MINERvA Experiment]



Today’s Topic: Mu2e

Cocktail Party Explanation:

We’re looking for ways that the standard model is incomplete/wrong!

Many standard model extensions predict the *changing* of one particle into its sister particles (muons $\rightarrow$ electrons).

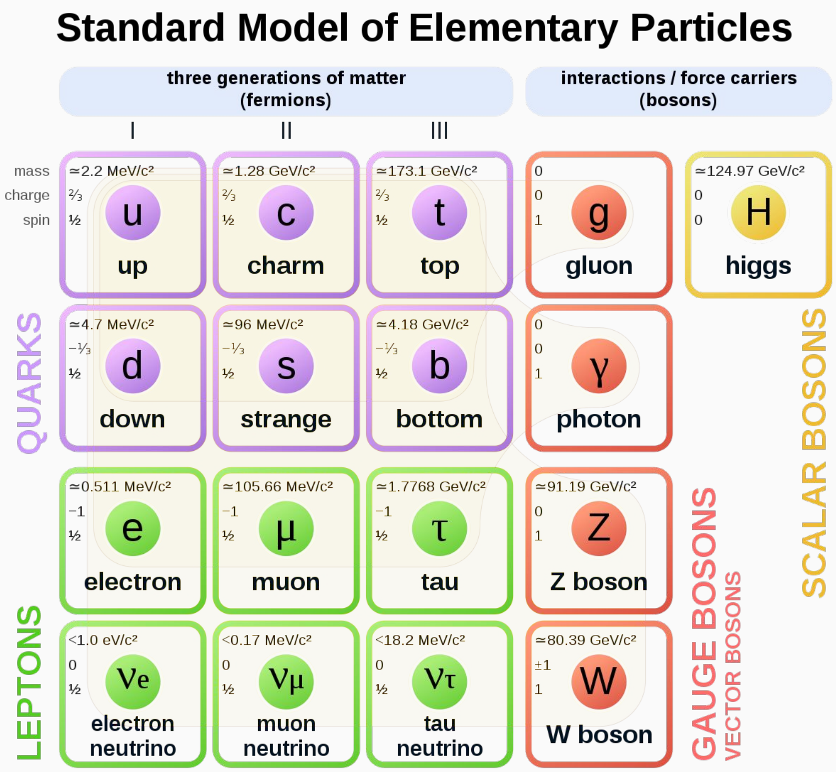
There’s a lot of standard model precedence for this.

Let’s look for it!

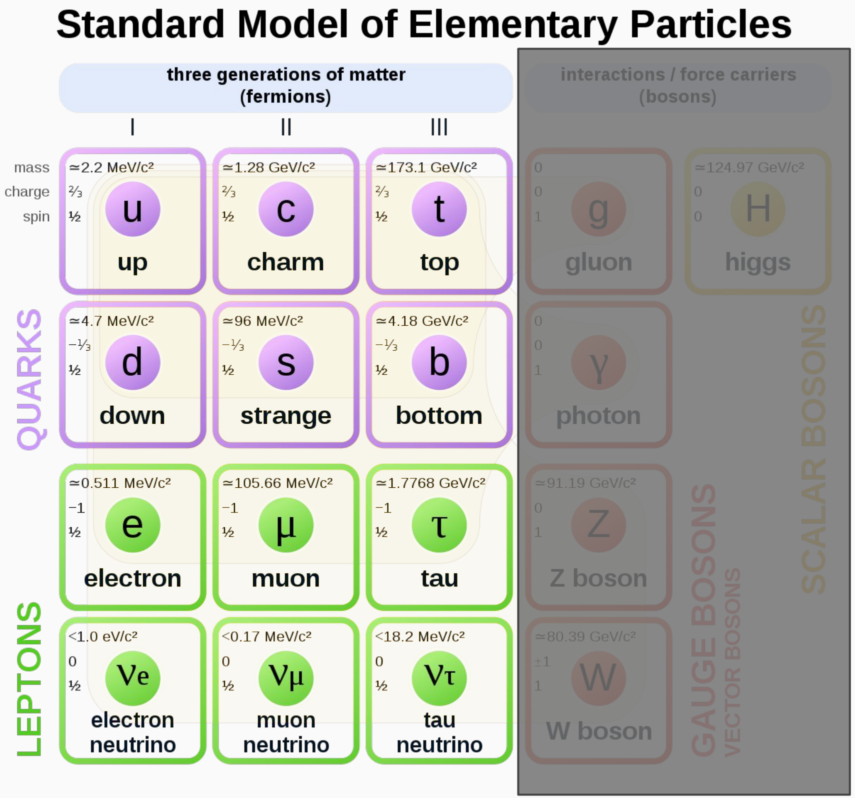
How?

Make a bunch of muons and wait for them to *change* into an electron!

Intergenerational Mixing in the Standard model



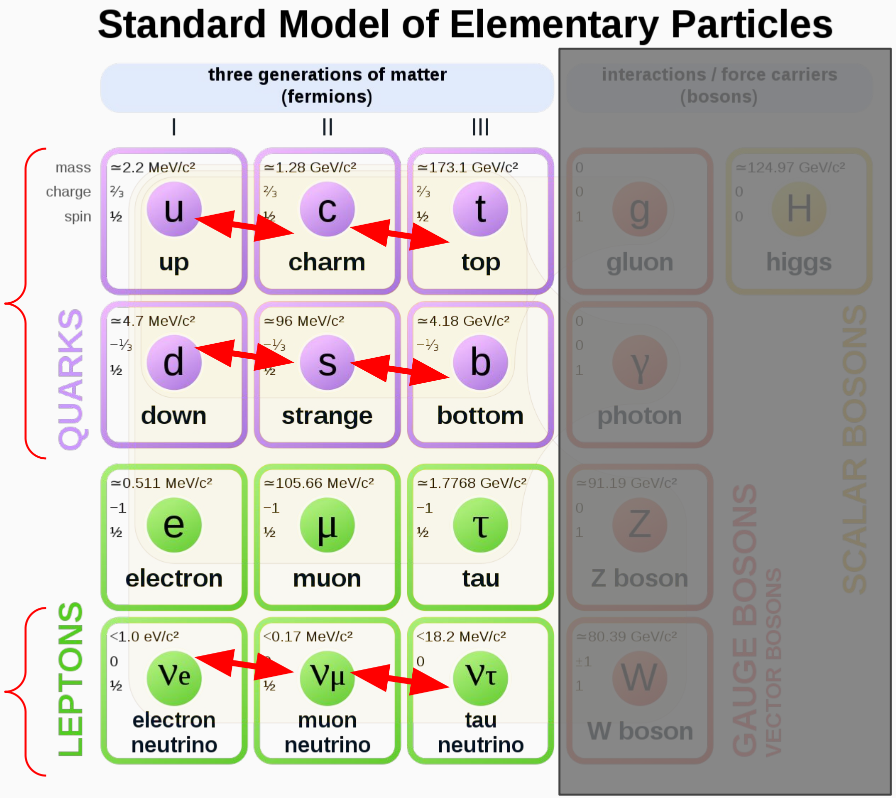
Intergenerational Mixing in the Standard model



Intergenerational Mixing in the Standard model

Quark mixing: observed

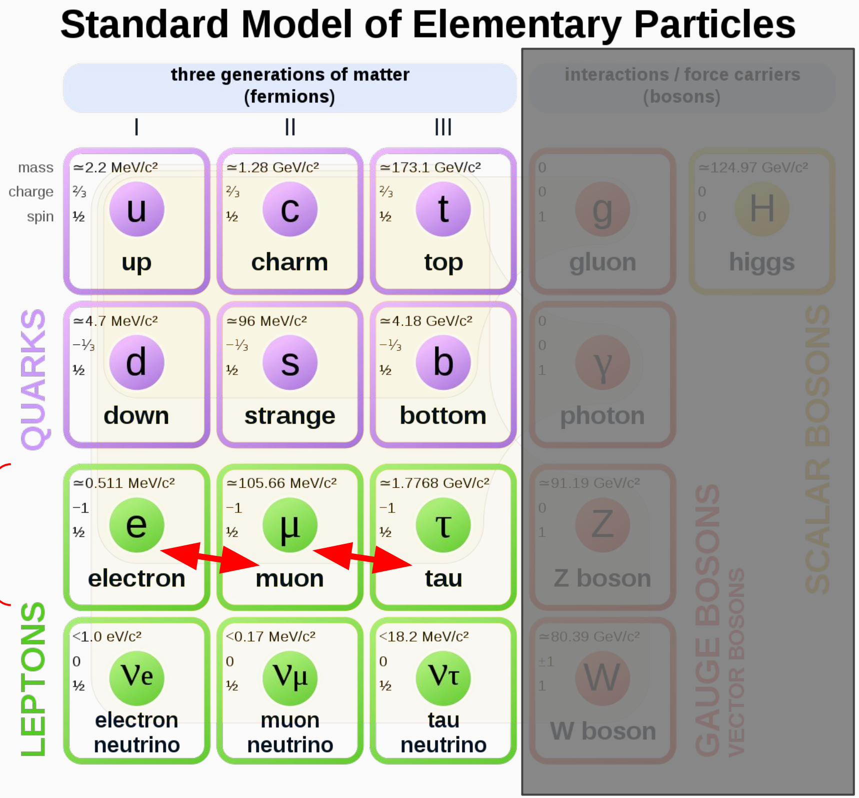
Neutral lepton (neutrino) mixing (oscillation): observed



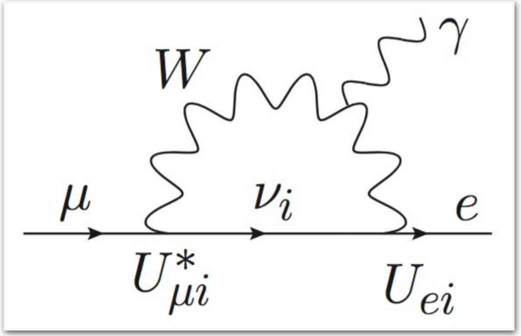
Intergenerational Mixing in the Standard model

Charged lepton mixing:
not observed

AKA “charged lepton flavor violation”, CLFV



CLFV in the Standard Model



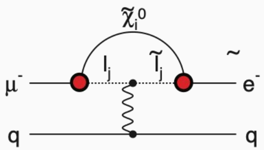
So unlikely that it's "impossible".

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

CLFV Beyond the Standard Model

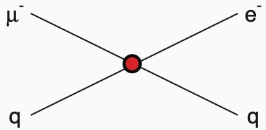
Supersymmetry

rate ~ 10^{-15}



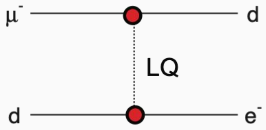
Compositeness

$\Lambda_c \sim 3000$ TeV



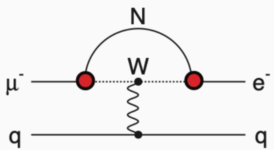
Leptoquark

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



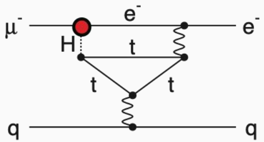
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\mathrm{x}10^{-13}$



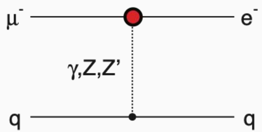
Second Higgs Doublet

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

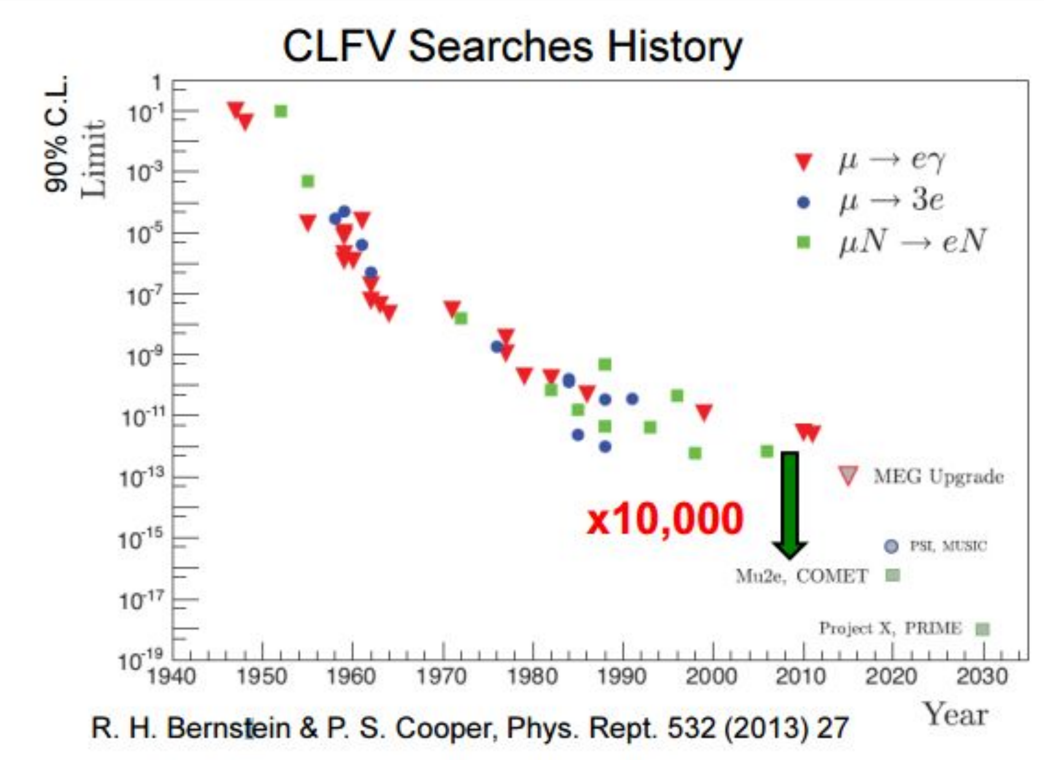


Heavy Z' Anomal. Z Coupling

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



We’ve Looked

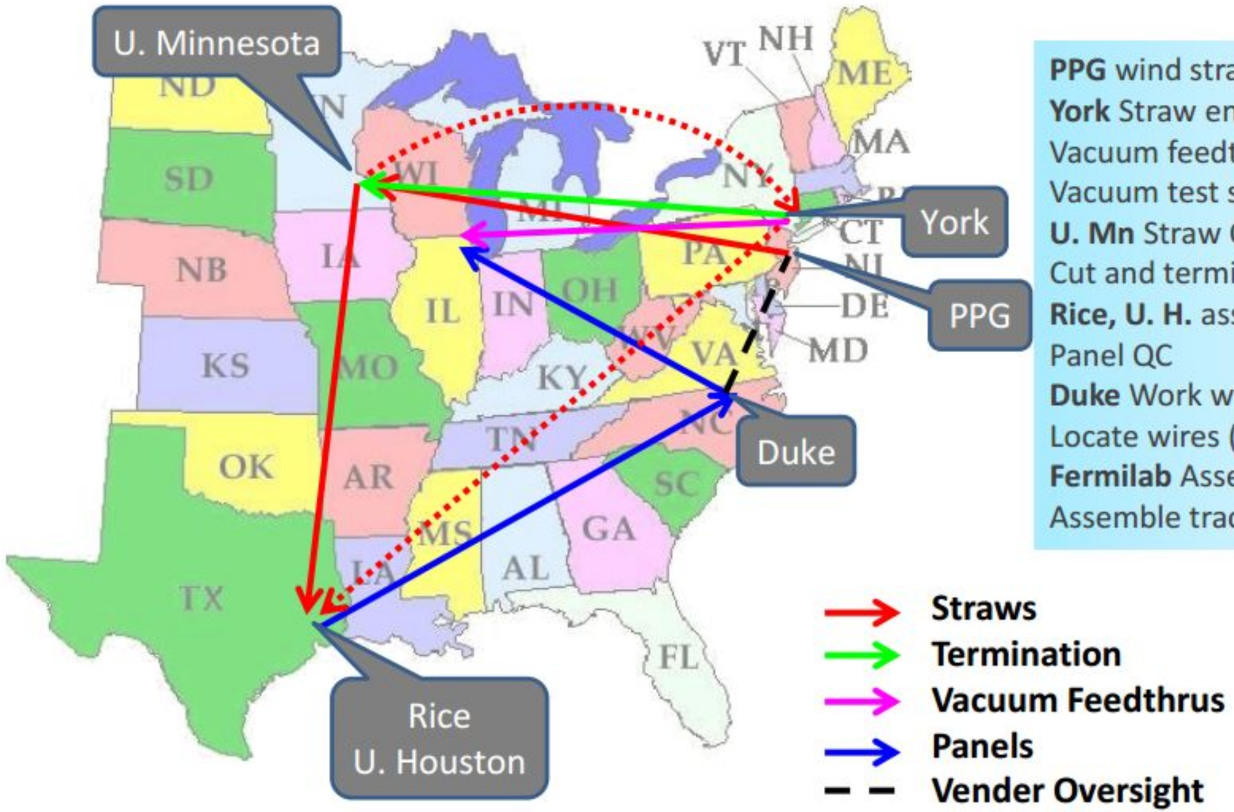


CLFV Searches History
90% C.L. Limit
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
1940 1950 1960 1970 1980 1990 2000 2010 2020 2030
Year
$\mu \to e\gamma$
$\mu \to 3e$
$\mu N \to eN$
MEG Upgrade
x10,000
PSI, MUSIC
Mu2e, COMET
Project X, PRIME
R. H. Bernstein & P. S. Cooper, Phys. Rept. 532 (2013) 27

Enter: Mu2e

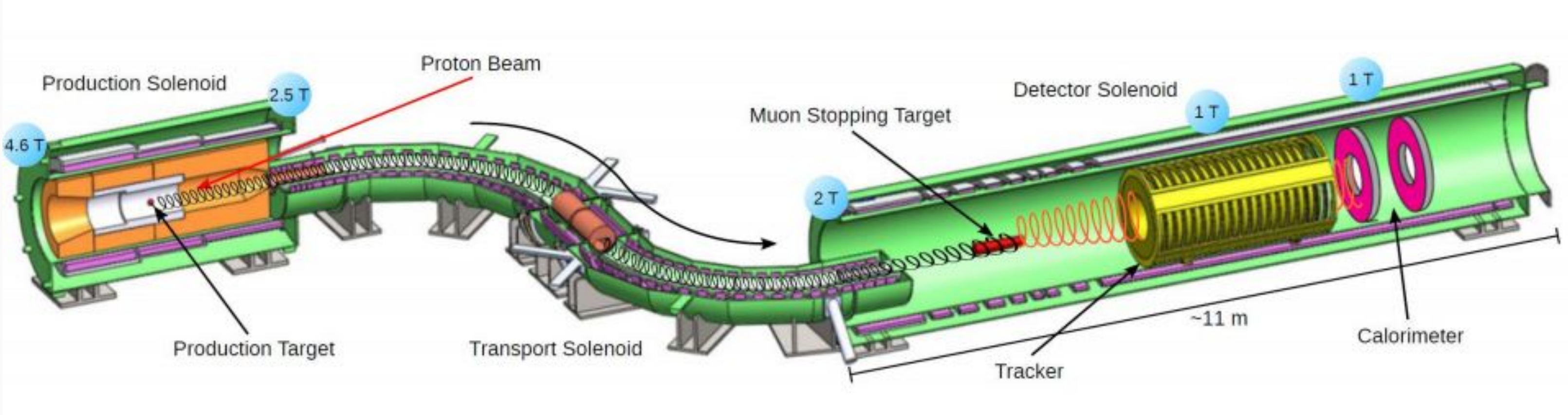
Mu2e Hall

Tracker construction



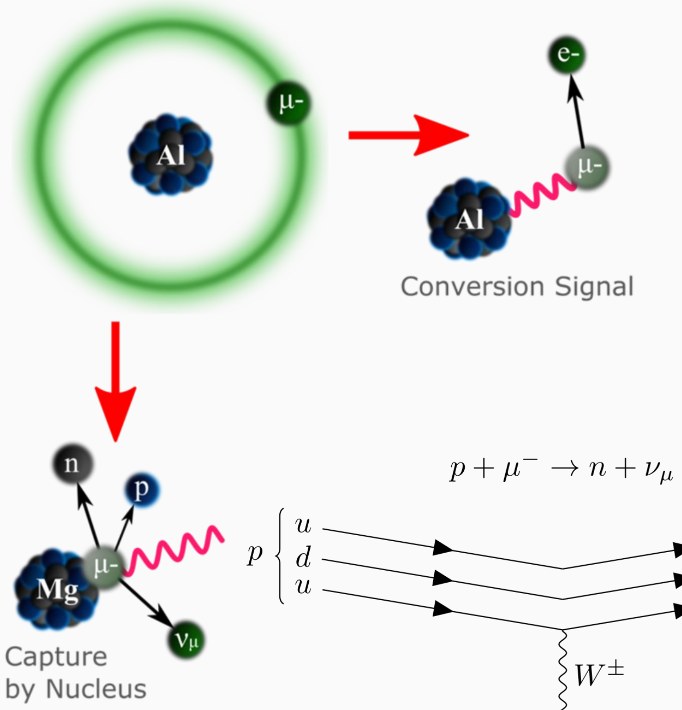
PPG wind straws
York Straw ends
Vacuum feedthroughs
Vacuum test straws
U. Mn Straw QC
Cut and terminate straws
Rice, U. H. assemble panels
Panel QC
Duke Work with PPG
Locate wires (x-ray)
Fermilab Assemble planes
Assemble tracker

Mu2e Experimental Design

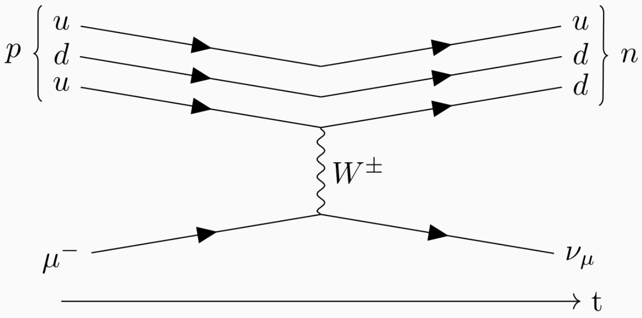


- Create a beam of muons
- Stop the muons in aluminum
- Let aluminum to facilitate the muon → electron conversion
- Observe electrons

What happens in Aluminum



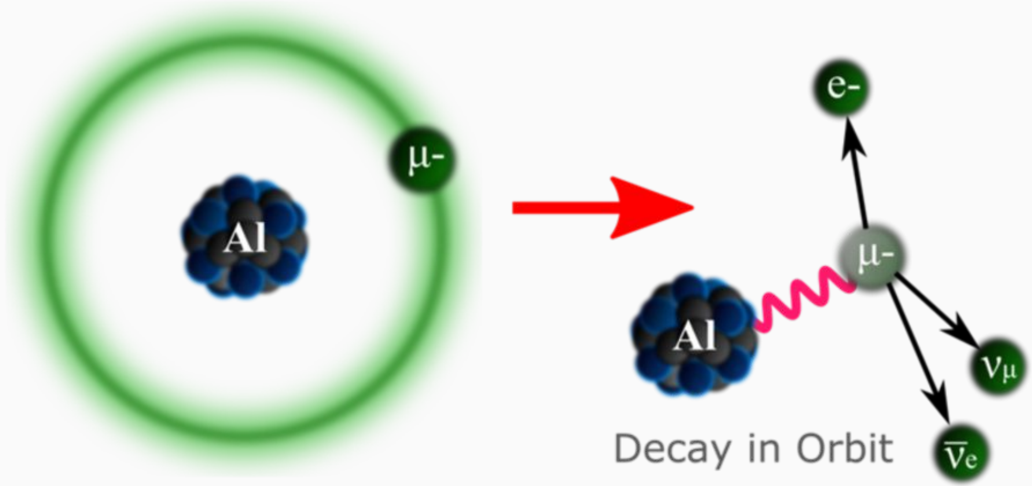
$$p + \mu^- \rightarrow n + \nu_\mu$$

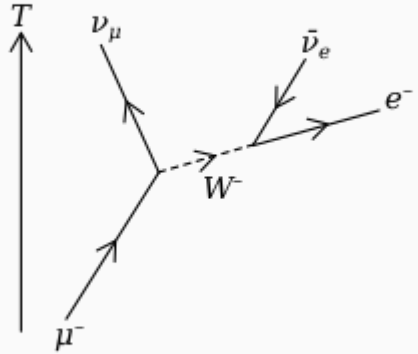


$$R_{\mu e} = \frac{\Gamma(\mu N \rightarrow e N)}{\Gamma(\mu \rightarrow \text{capture})}$$

$$R_{\mu e} < 7 \times 10^{-13}$$

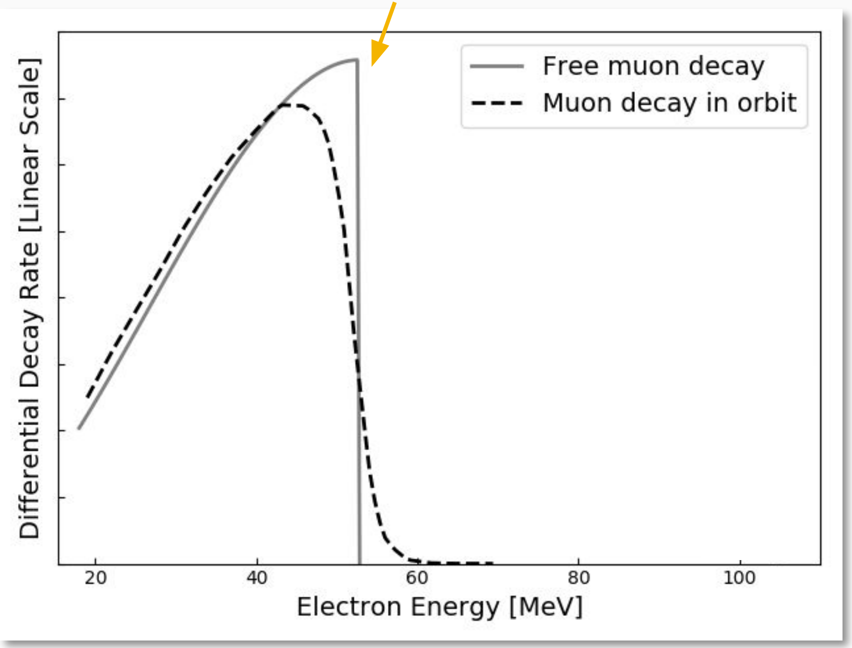
Background: free muon decay

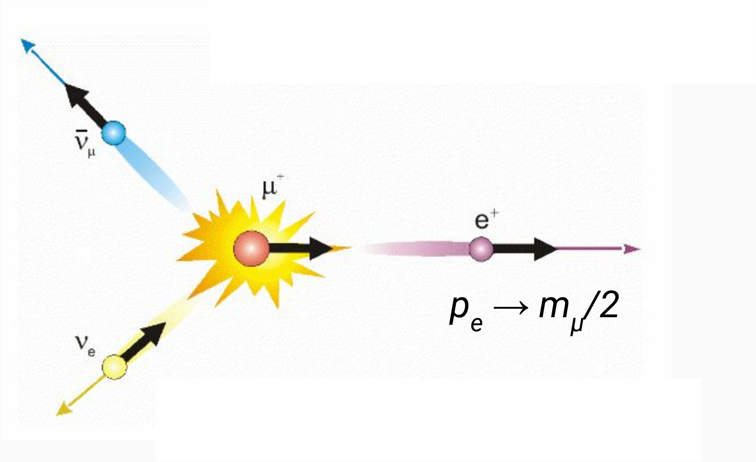




What Mu2e will see

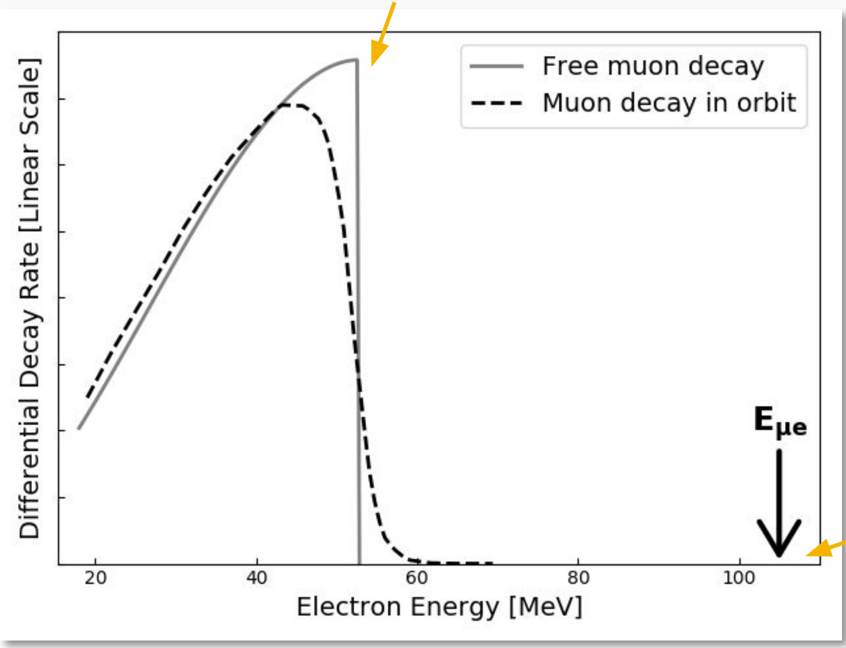
$m_\mu/2$

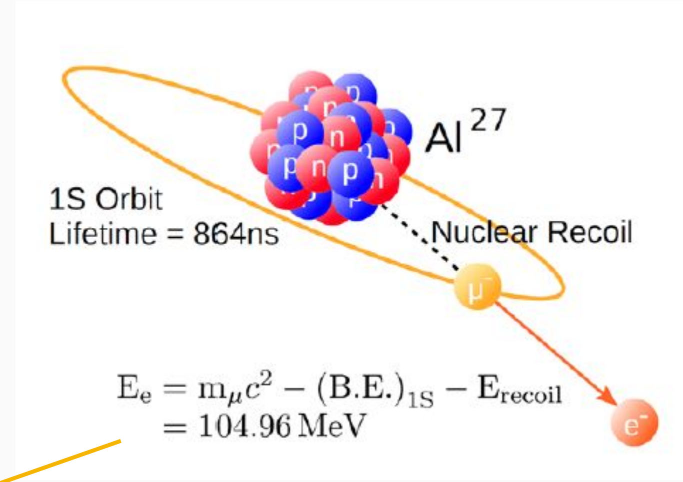




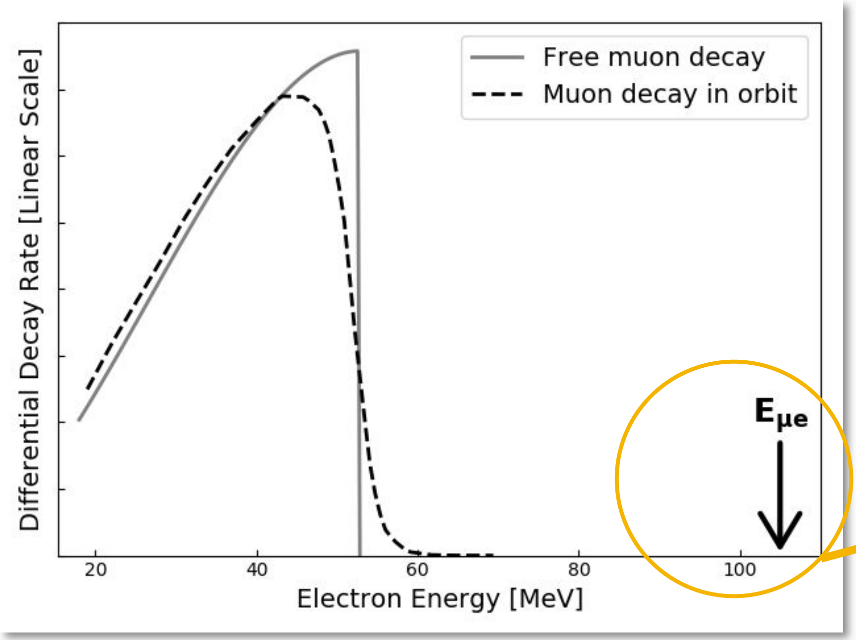
What Mu2e will see

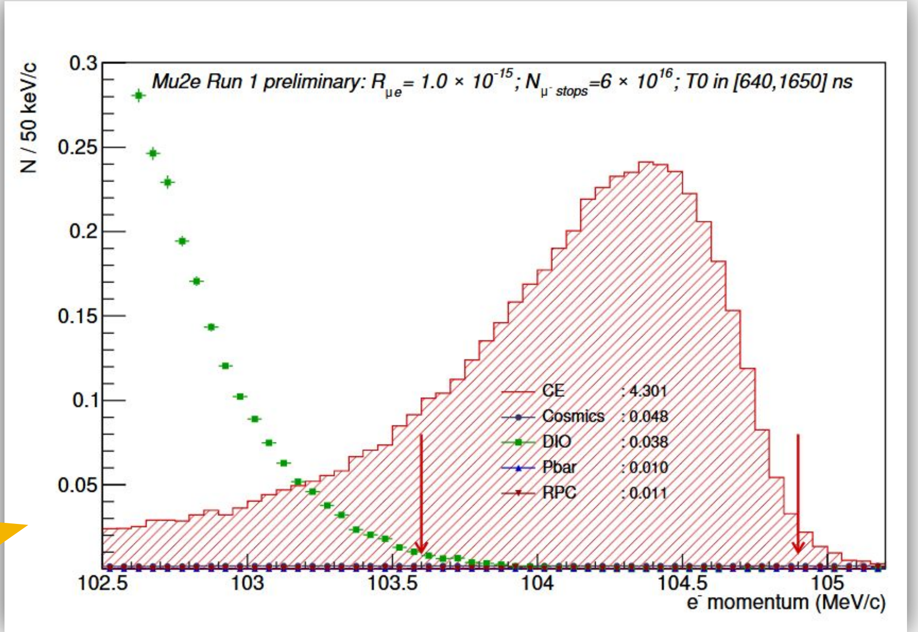
$m_\mu/2$





What Mu2e is looking for





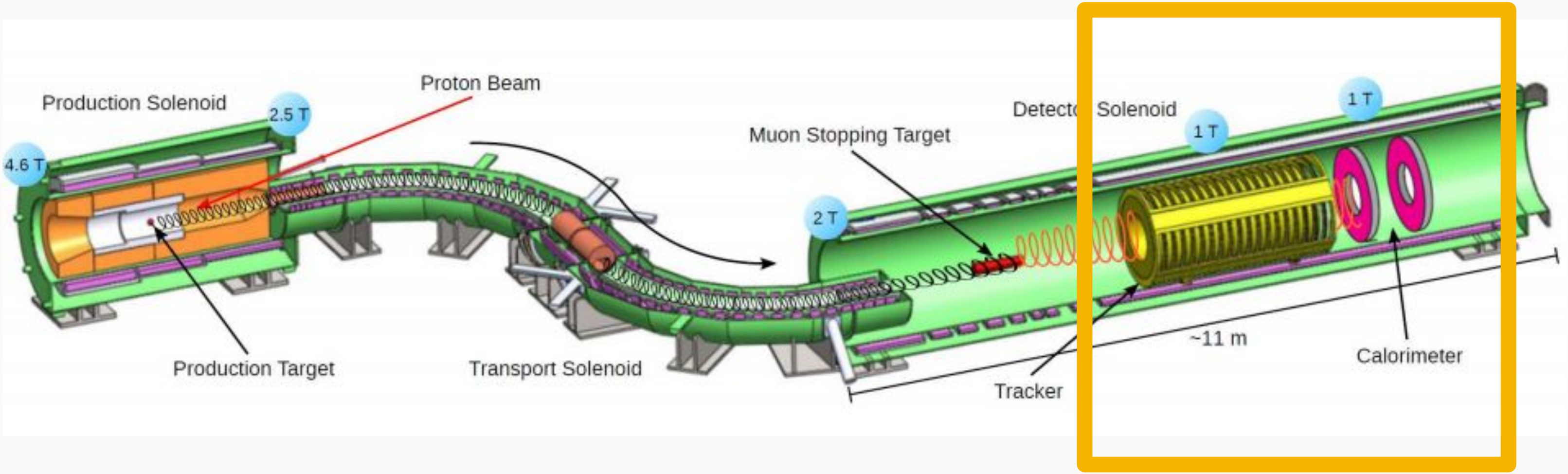
Mu2e’s Charge

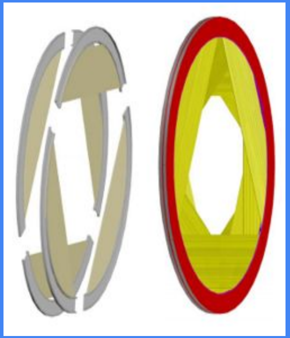
- **Observe electrons with 105 MeV/c momentum**
  - Current *Standard* model of particle physics predicts we won’t see any
  - But this is where our the current model might be wrong!
  - → nobel prize
- **Or don’t**
  - wipe out whole categories of possible new theories

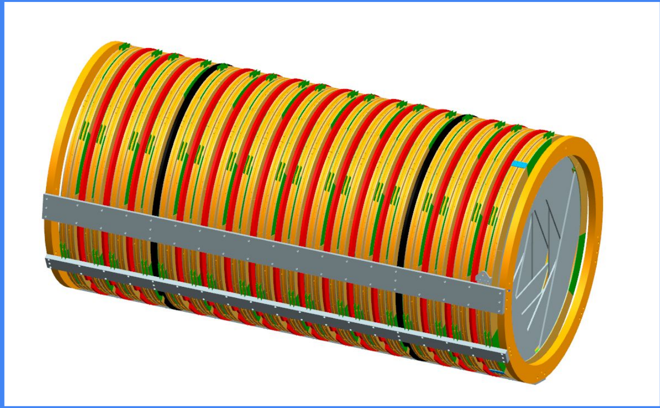
Mu2e's Strategy

1. Send *lots* of muons through our detector
2. Take pictures of their electrons
3. Look among the pictures for electrons of 105 MeV/c momentum
4. Find such electrons. Or don't.
5. Profit

Mu2e Tracker



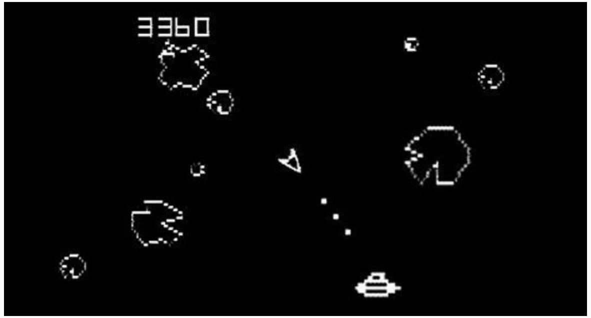




The Mu2e Tracker

Which is being built, as we speak, upstairs in PAN 450

Take “digital pictures” of particles

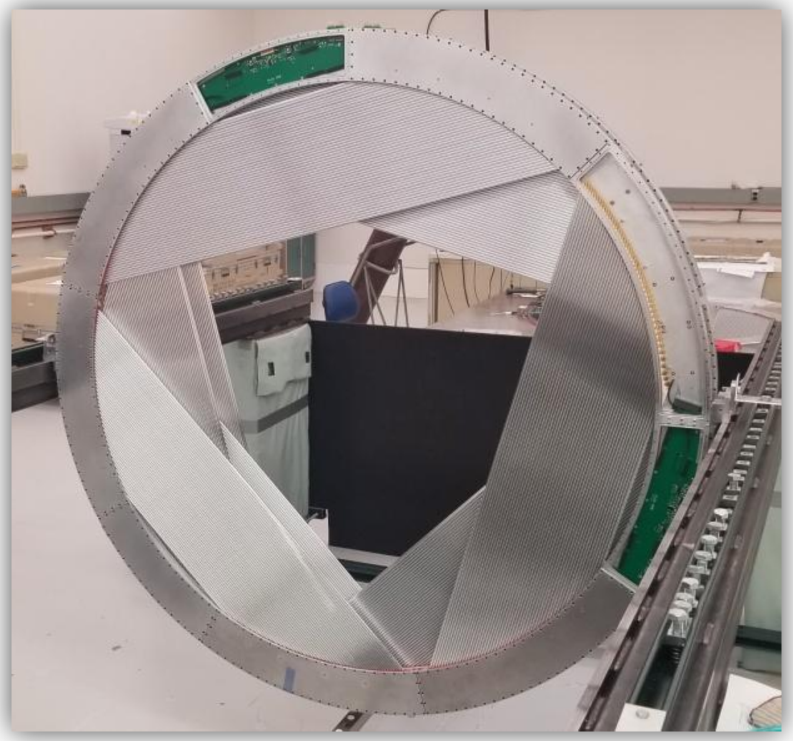


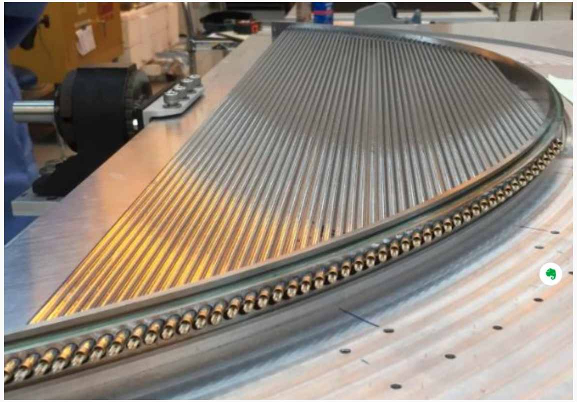
Our pictures will be pixelated ^

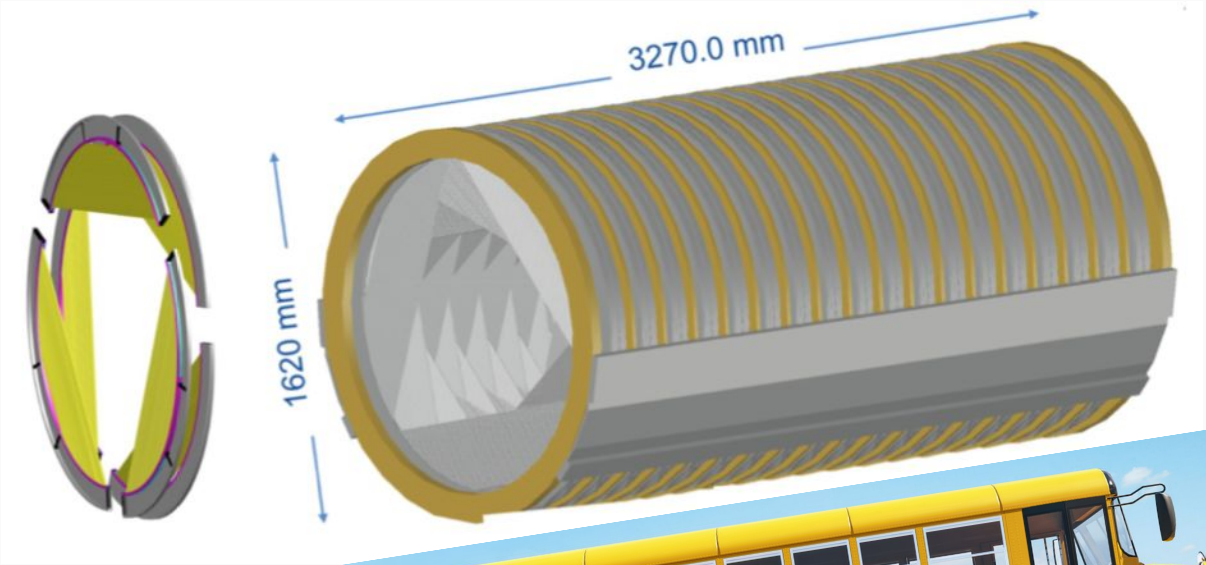
iPhone: 12 MEGApixel = 12 million pixels
Mu2e: 20 KILOpixel = 21,000 pixels (straws)

- But mu2e is 3D!

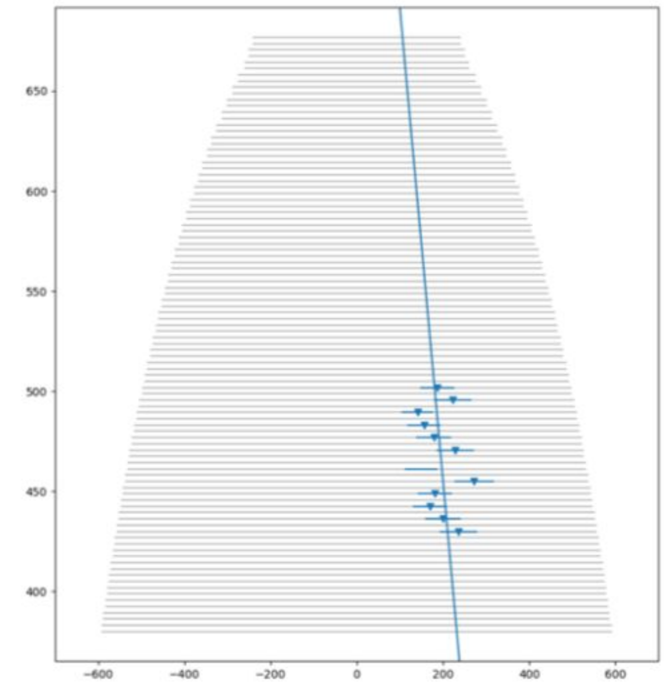
Annular (Ringlike) Tracker Geometry

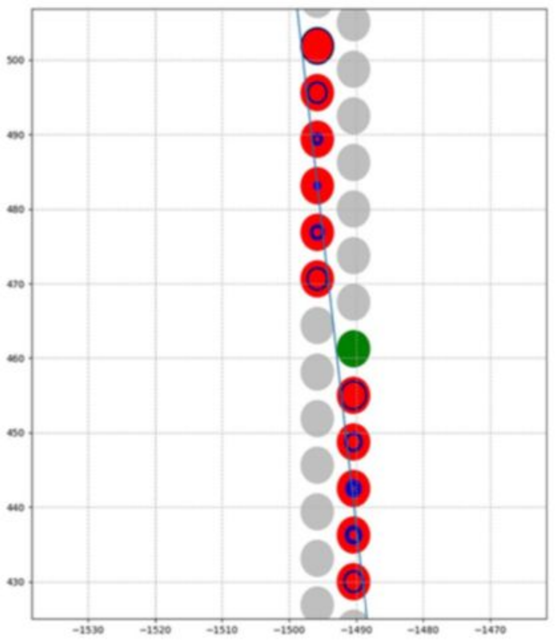





3270.0 mm
1620 mm

Particles won’t typically collide and stop in our detector



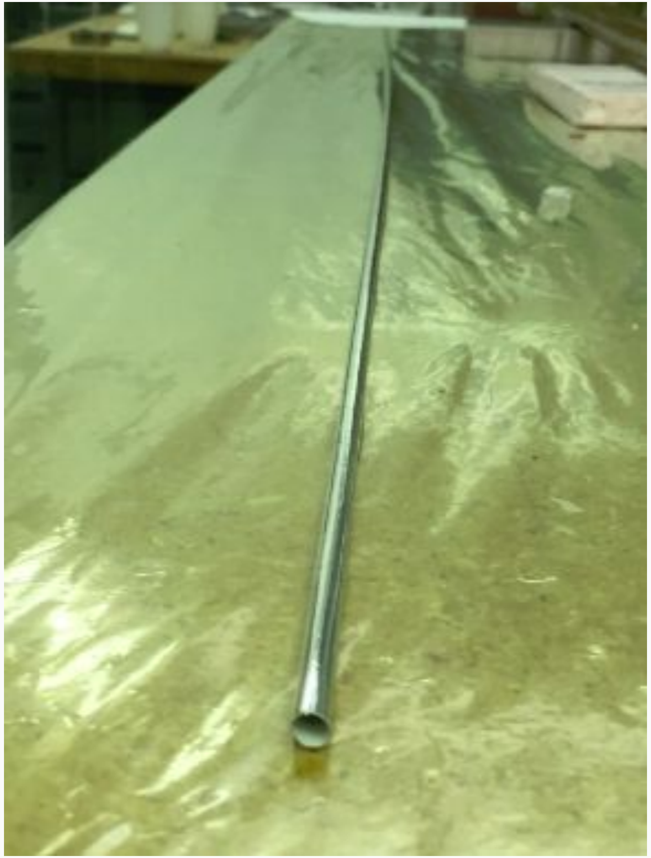


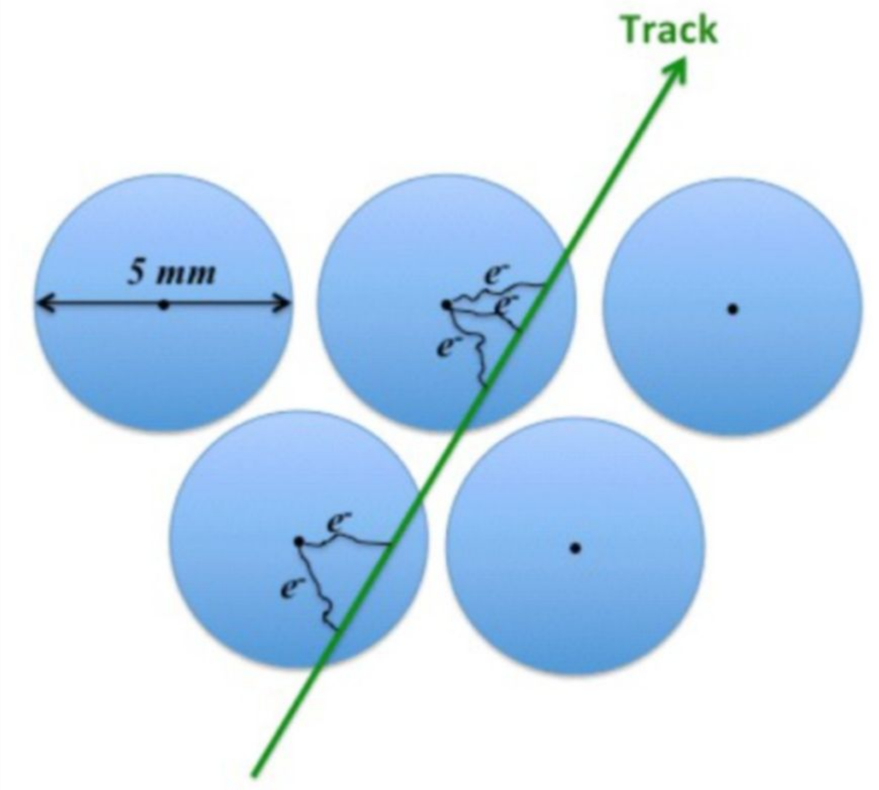
Particles leave energy behind in each straw.
Convert that energy into a digital “hit”

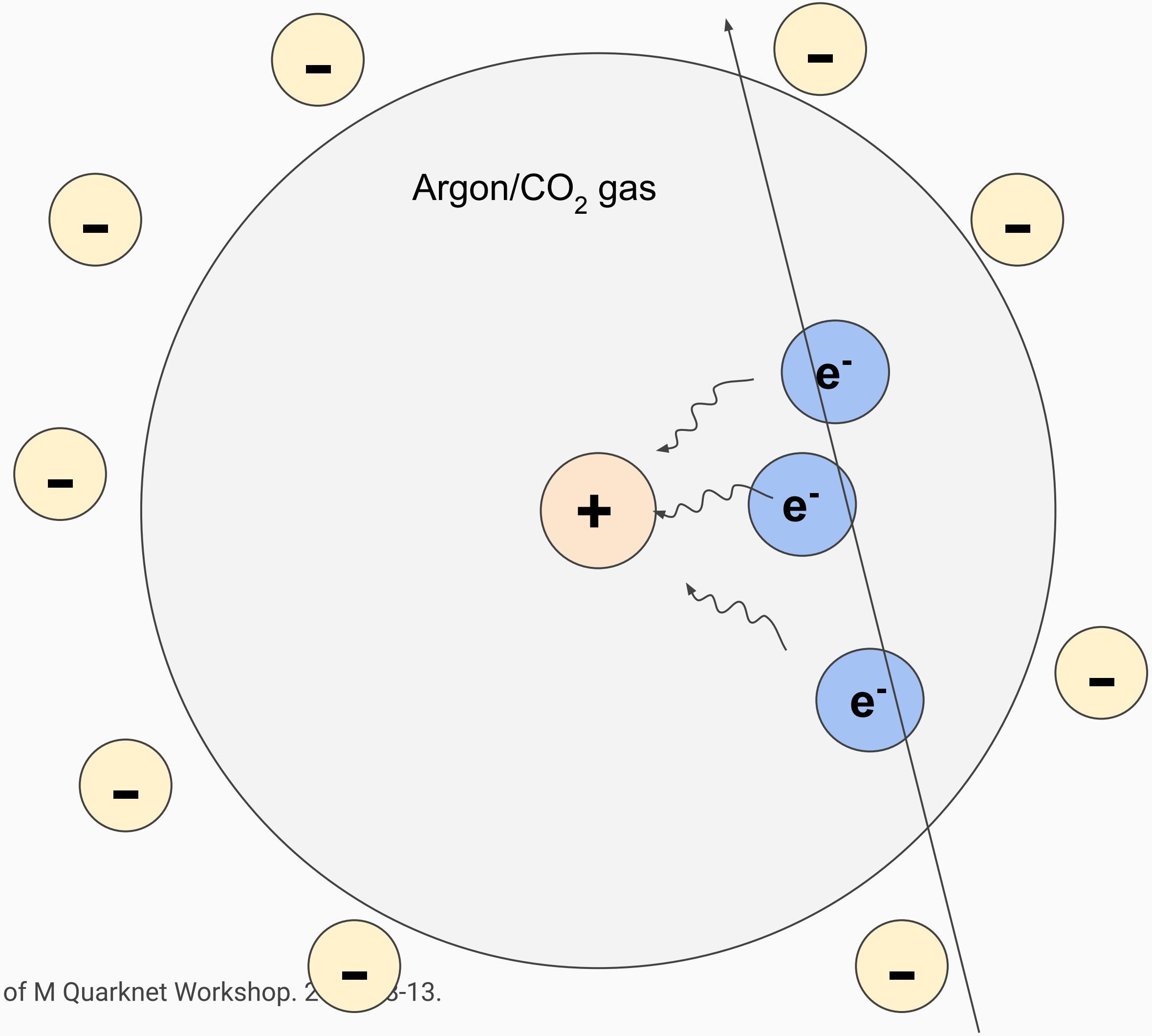
Straws

Physical description:

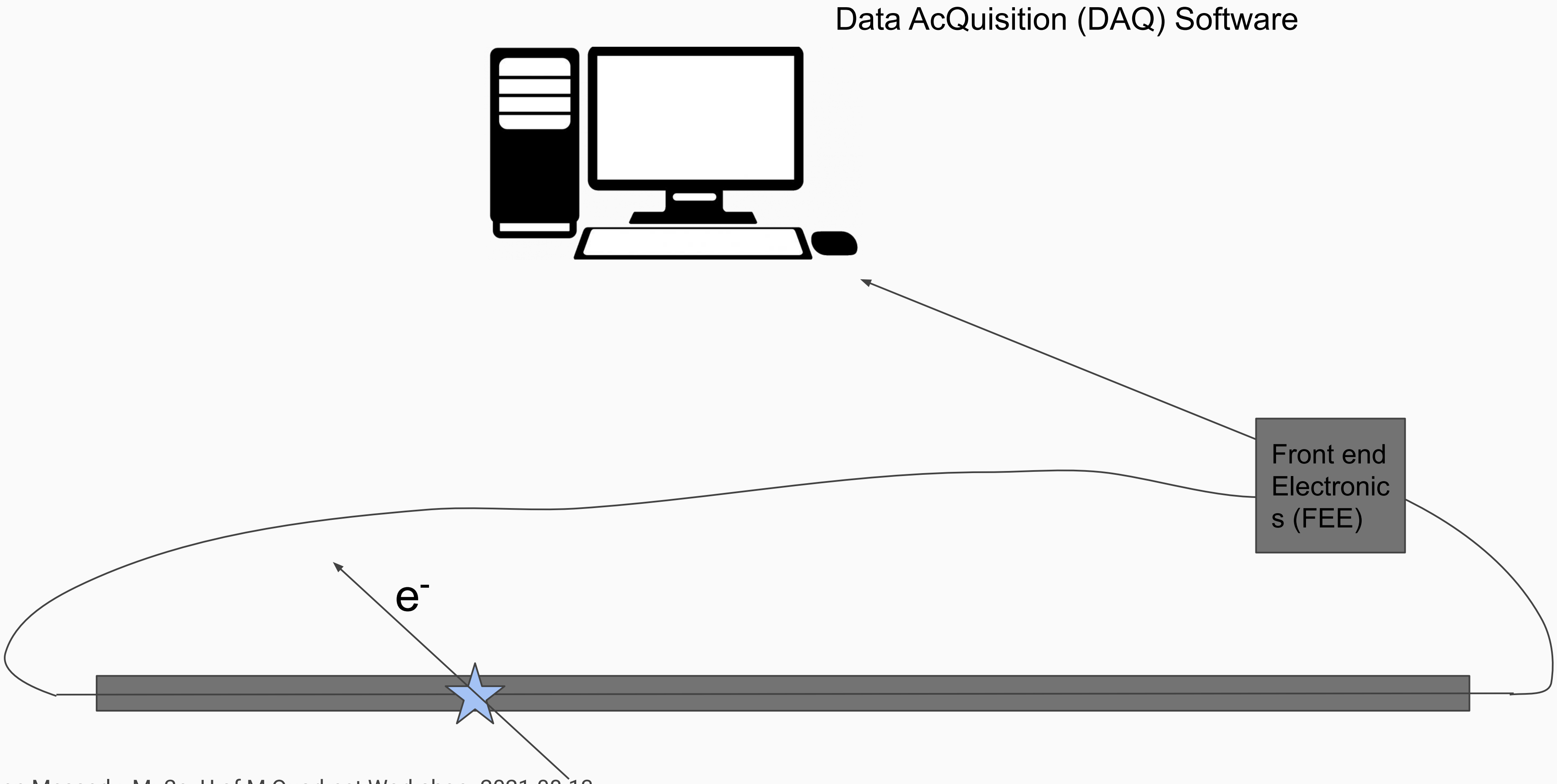
- 15 µm thick Mylar straws
- 5 mm diameter
- Length from 45 to 120 cm
- 500 Å of aluminum on both inside and outside
- An additional 200 Å of gold on the inside




Track
5 mm
e
e
e
e
e

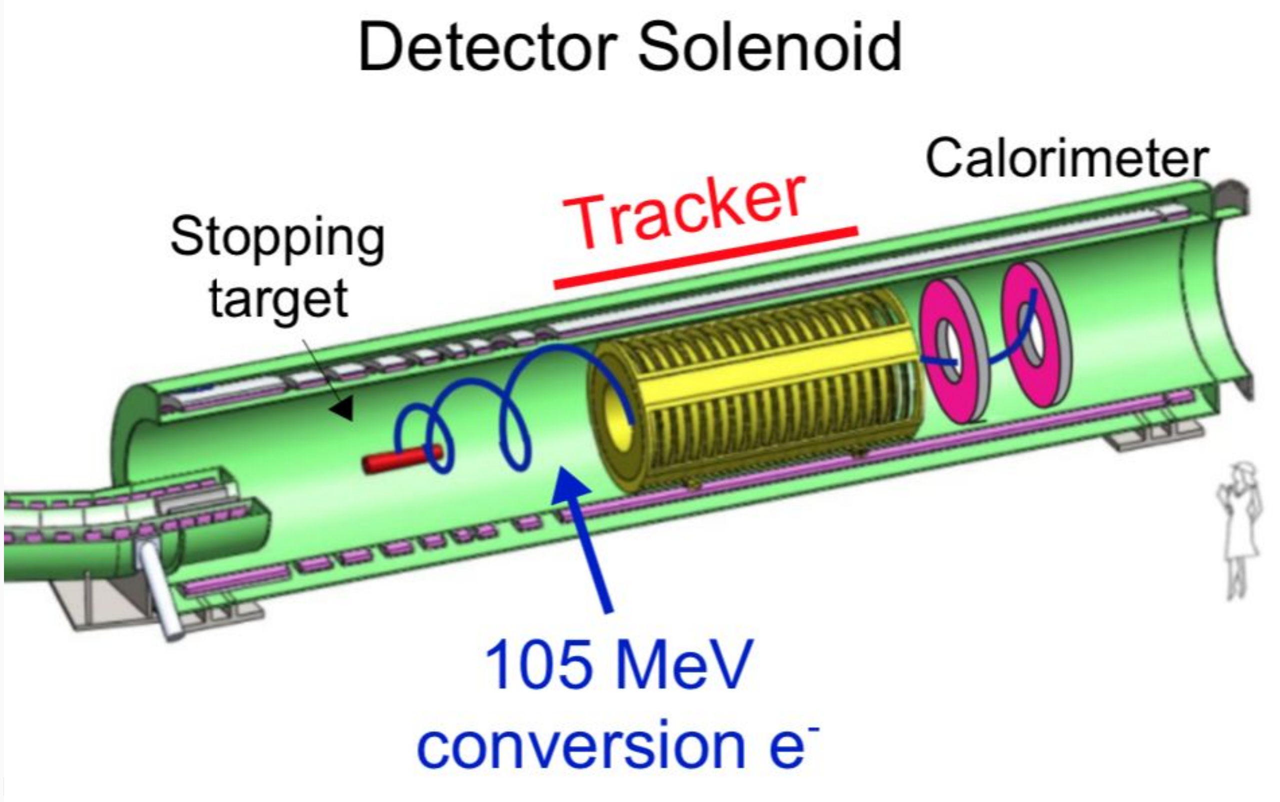


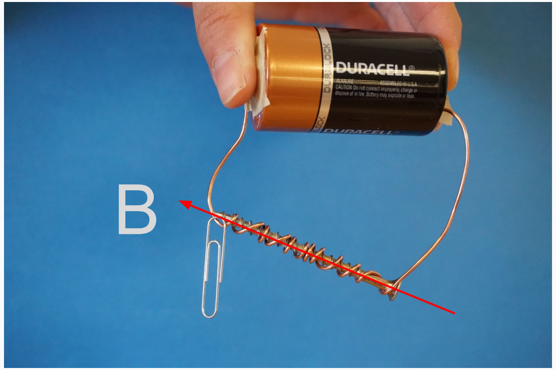
Ben Messerly. Mu2e. U of M Quarknet Workshop. 2[illegible]3-13.


Data AcQuisition (DAQ) Software
Front end Electronic s (FEE)
e-

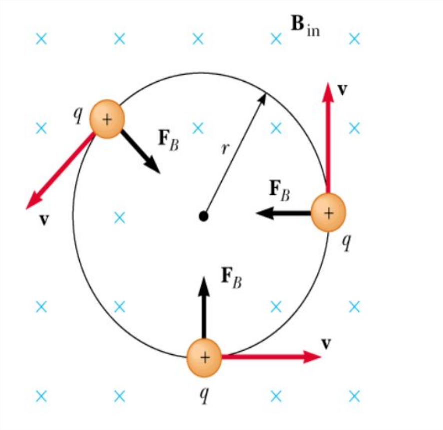
Magnetic Field

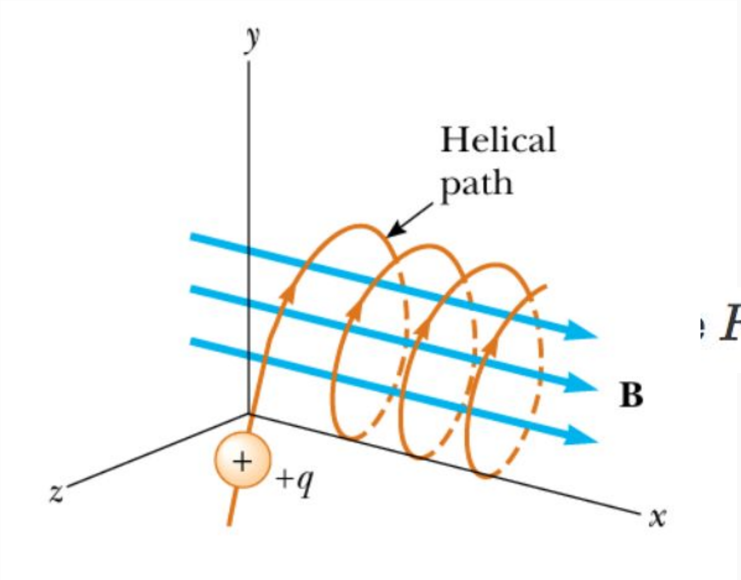
Solenoid = coil of wire, carrying current, creating magnetic B field





Electrons moving in a uniform magnetic field





$$\vec{F} = q\vec{v} \; x \; \vec{B}$$

$$F_B = qvB \sin\theta$$

$$F_\perp = q\,v_\perp\,B \sin 90° = q\,v_\perp\,B$$

$$qvB = \frac{mv^2}{r}.$$

Centripetal Force

Radius of helix

$$r = \frac{mv}{qB}.$$

How fast is a 105 MeV electron?

E_e = rest mass of electron + kinetic energy of electron

105 MeV = $m_e c^2 + \gamma m_e c^2$,

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

m_e = 0.511 MeV/c^2

Solve for velocity, *v*

Input:

$$\sqrt{1 - \frac{0.511^2}{(105 - 0.511)^2}}$$

Result:

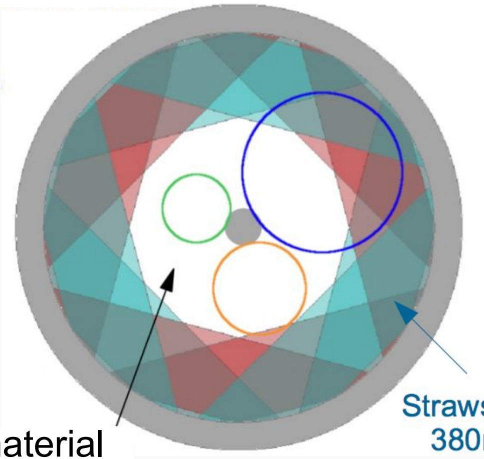
0.99998804160…

105 MeV Electron is travelling 99.9988% of the speed of light

Radius of helix (Relativistic!)

$$r = \frac{mv}{qB}.$$

$$\frac{(m_e \text{ (electron mass)})\,(c \text{ (speed of light)}) \times 0.9999}{e^- \text{ (electron)} \;\; \text{electric charge } (q) \times 1\ \text{T (tesla)}} \longrightarrow 1.70434\ \text{mm (millimeters)}$$



If ALL electron velocity is in the x-y direction…

Still too-small of a helix radius!

Radius of helix (Relativistic!)

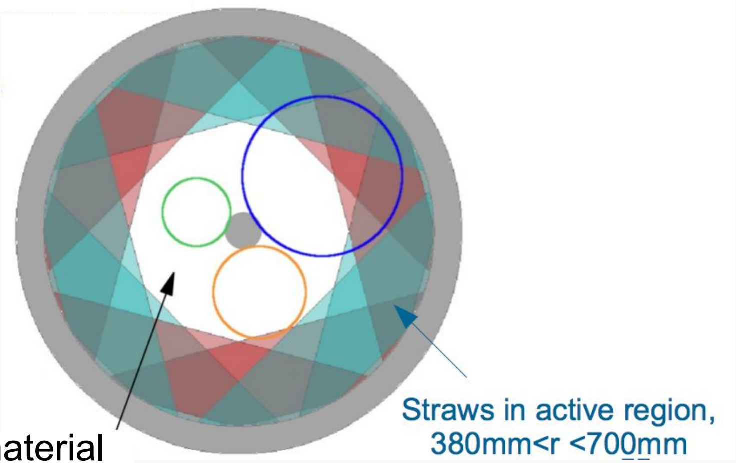
$$r = \frac{mv\gamma}{qB}.$$

$$\frac{(m_e \text{ (electron mass)})(c \text{ (speed of light)}) \times 0.9999}{e^- \text{ (electron) electric charge } (q) \times 1\ \text{T (tesla)}} \longrightarrow 1.70434\ \text{mm (millimeters)}$$

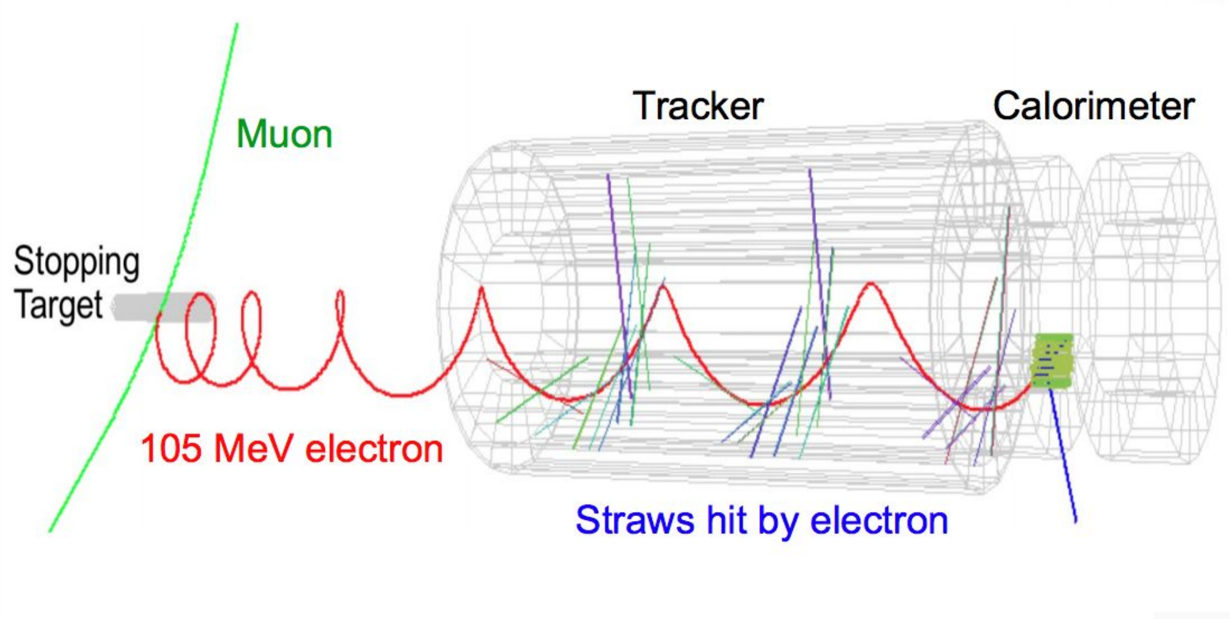
I need a relativistic gamma γ factor in the numerator. A 105 MeV electron has γ = 207.

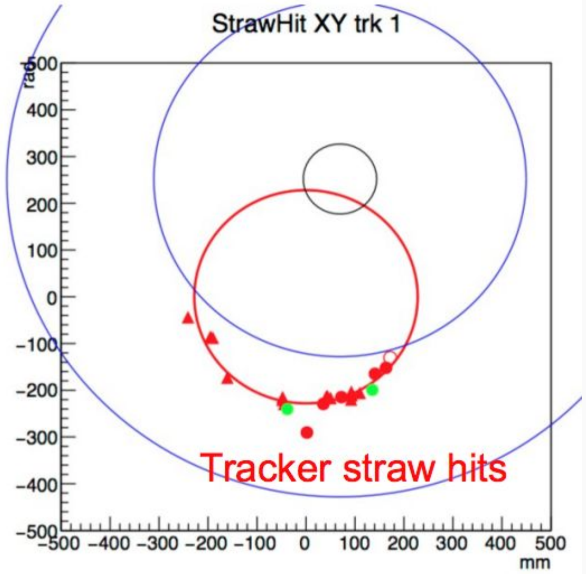
1.7mm * 207 = 350 mm

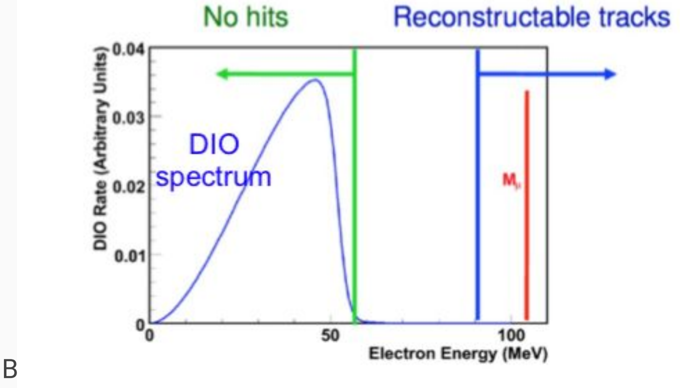
And to get from 350-700, the magnetic field is in fact NOT uniform.



Vacuum, no detector material

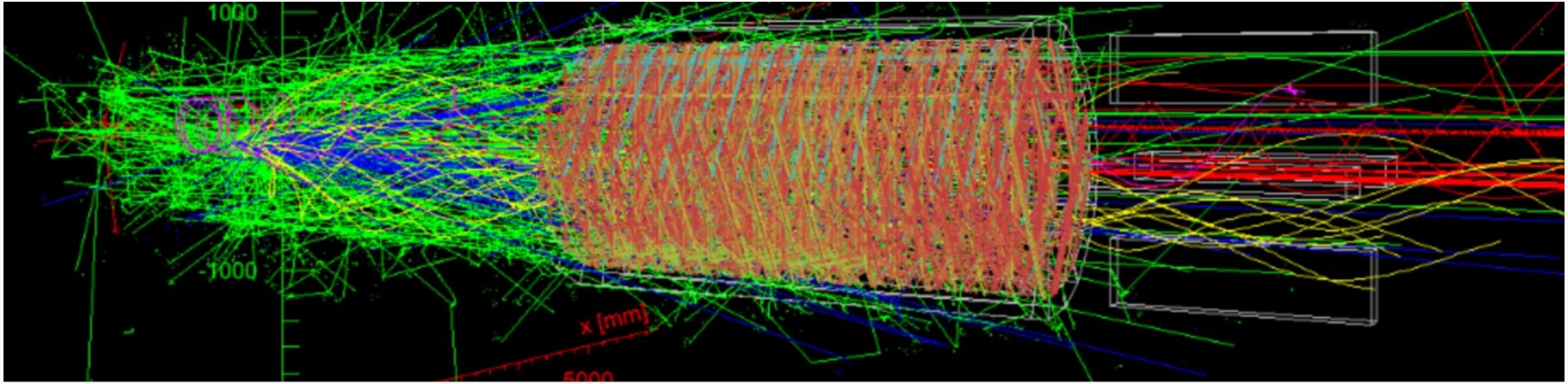






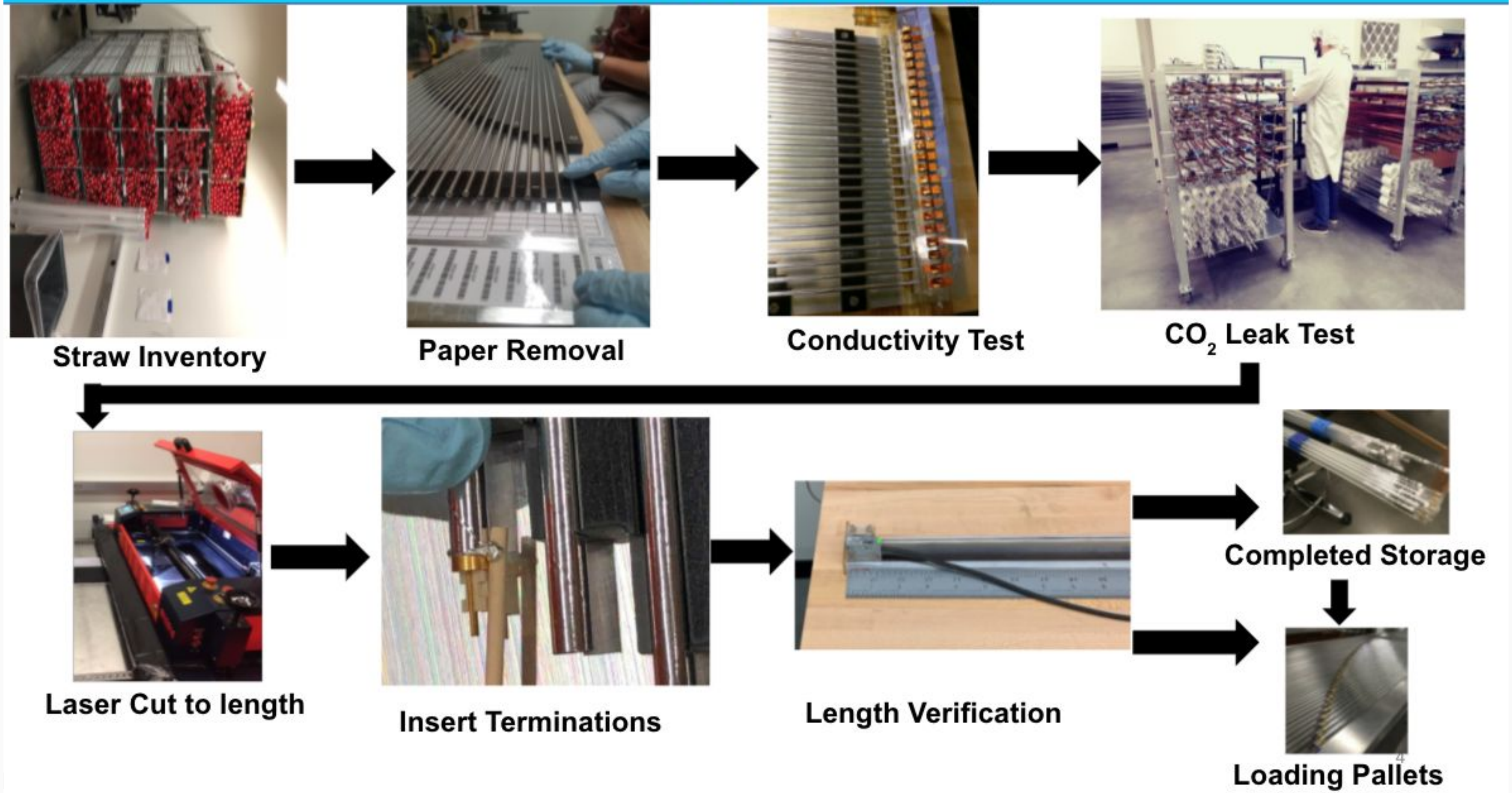
Still: use helix radius to determine, and the track more generally, to measure electron velocity.

B -13.

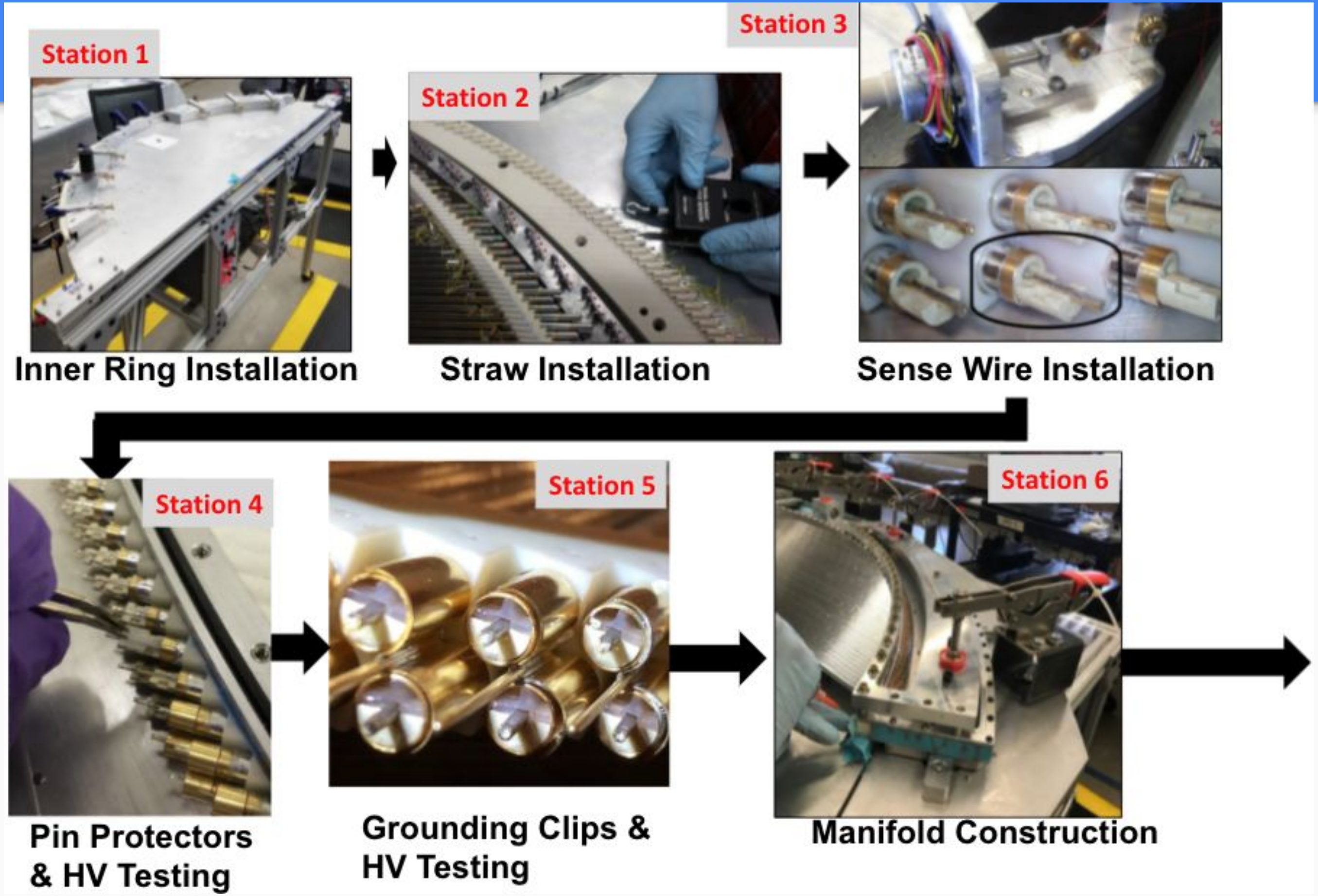


Signal electron + all hits over 500-1695 ns window

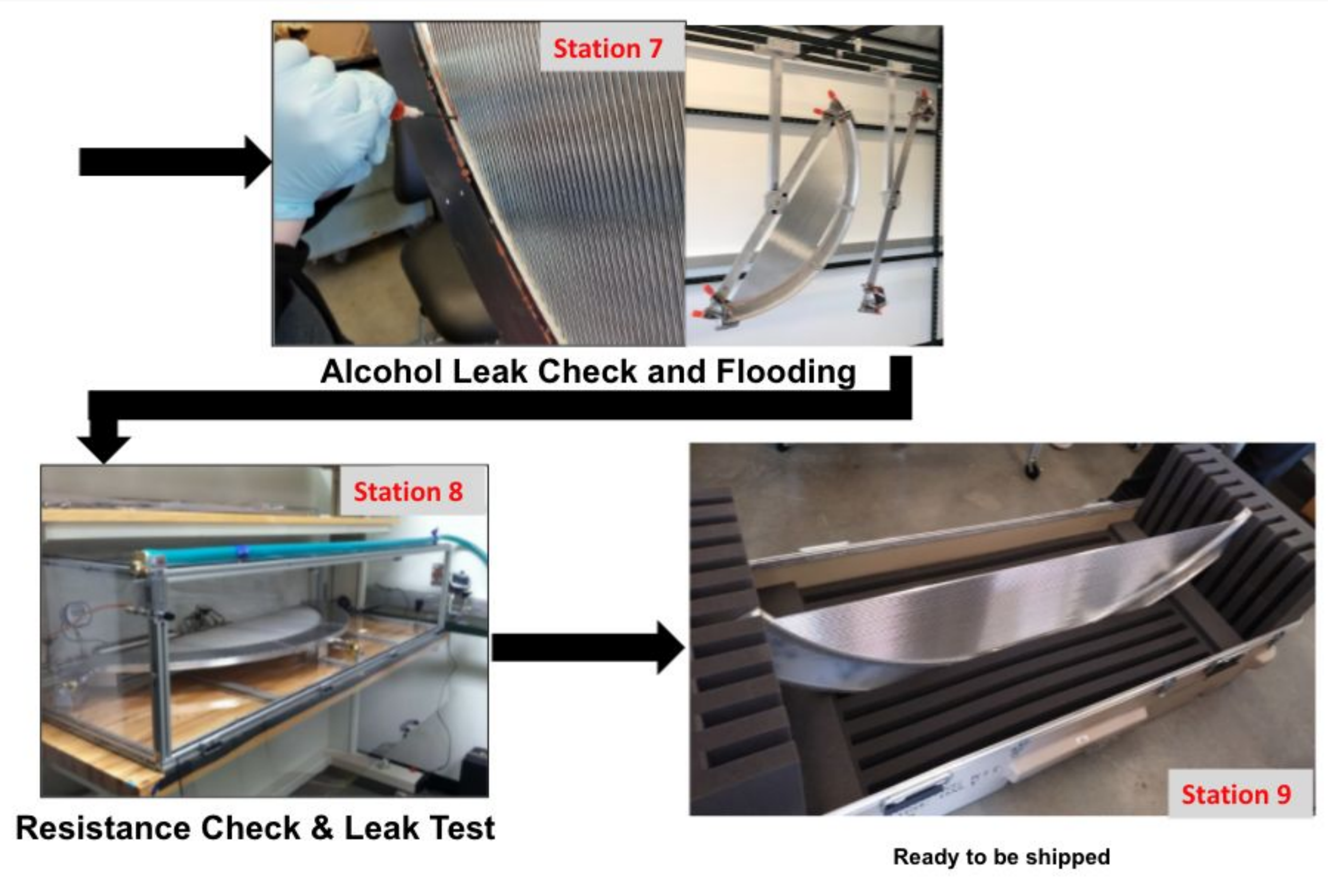
Straw Processing



Panel Production



Panel Production Continued

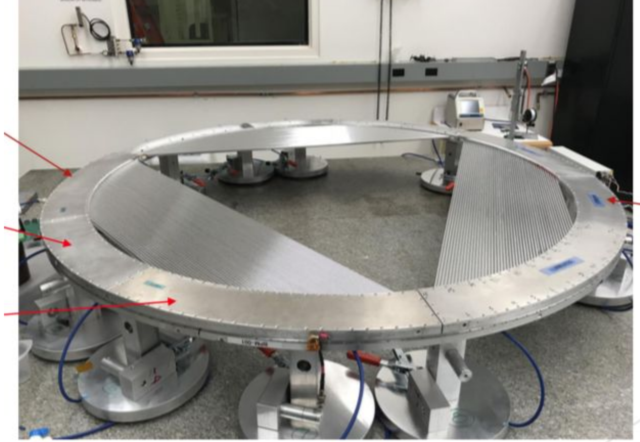


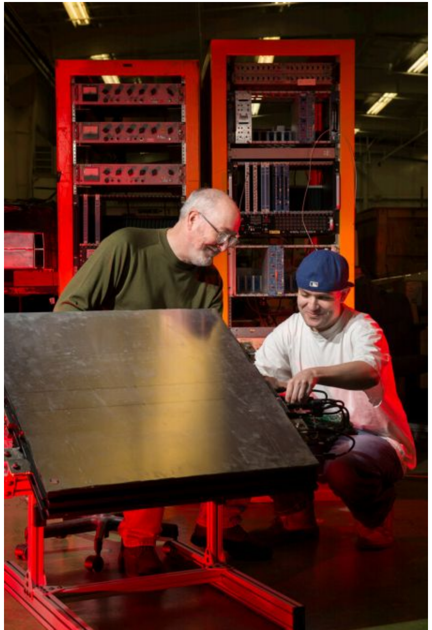
Ask Me About

- Coding
- College research opportunities
- Problem solving
- Group work
- Exams/Courses vs research
- Data Science
- My job plans
- College Prep

- Neutrinos
- Particle beams
- Data flow in particle physics
- High school physics in the lab
- My role as IT/software engineer/database admin for mu2e

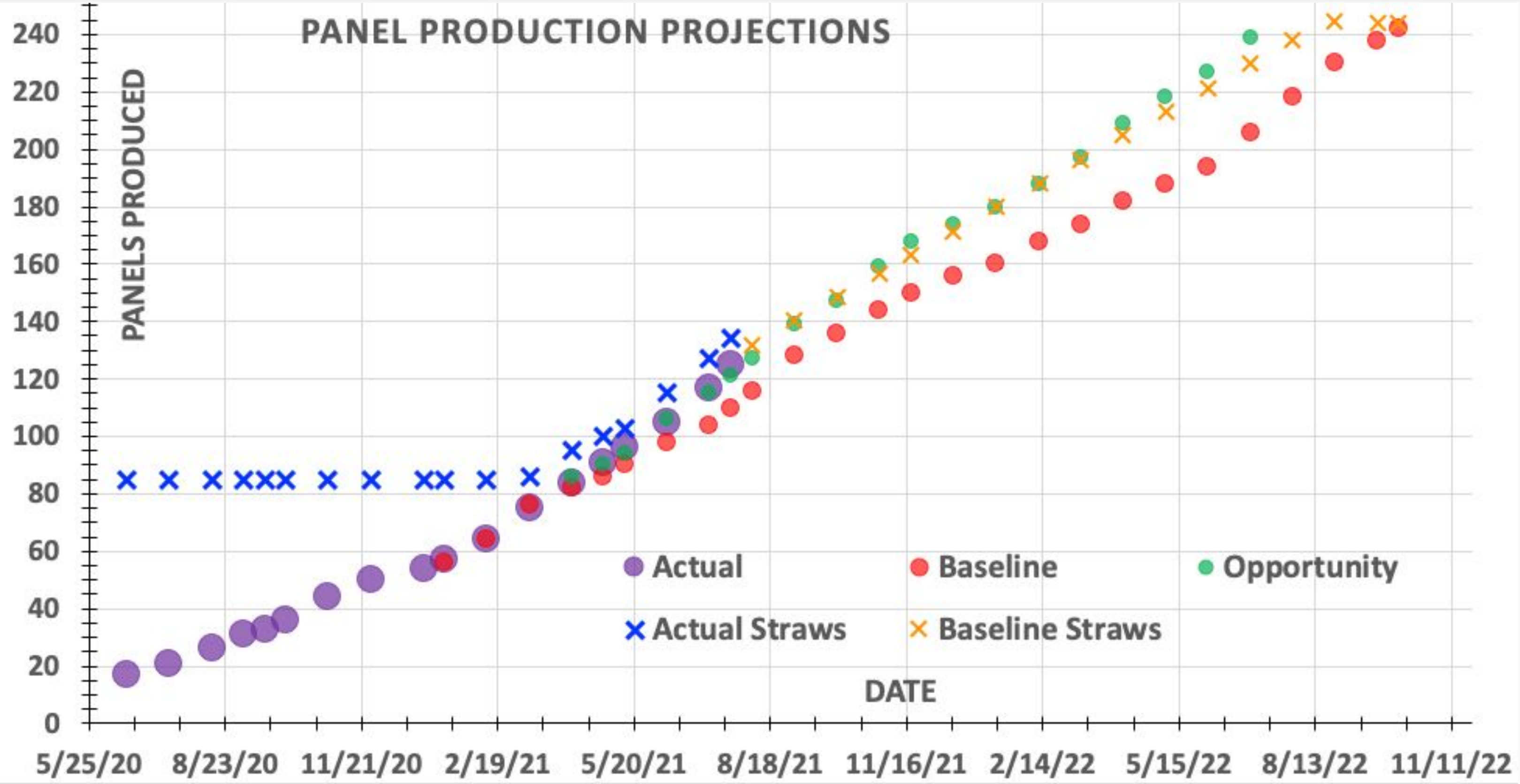
TS Coil Module prototype at Fermilab





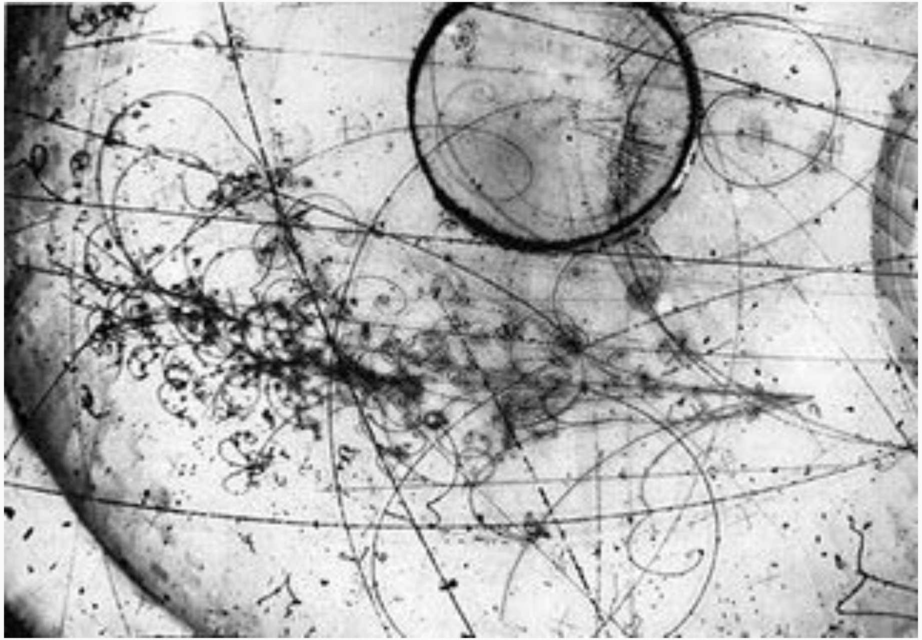
backup

Mu2e Tracker Panel Production Schedule at UMN



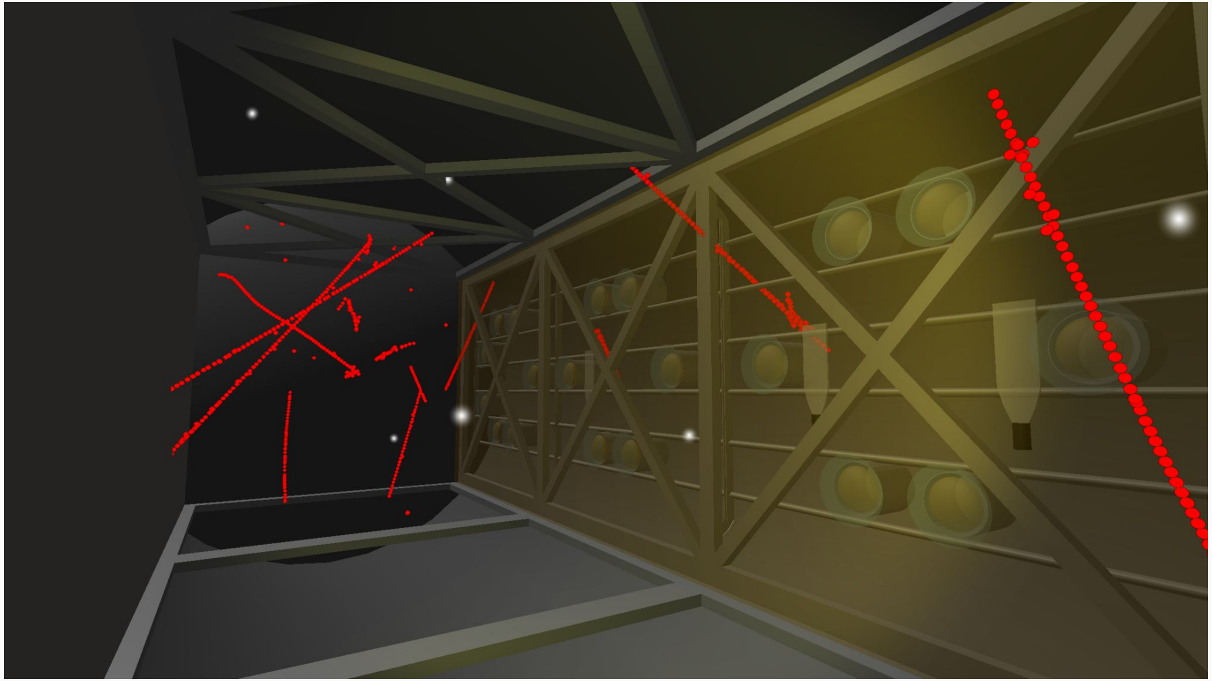
Bubble chamber is another type of detector

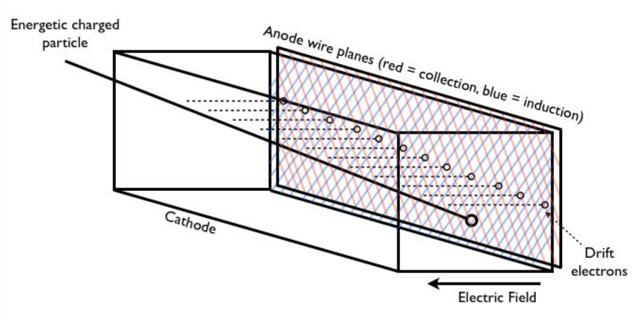
021-08-13.



Not pixelated! analog! Real camera film took this picture!

Time Projection Chamber is another type of detector





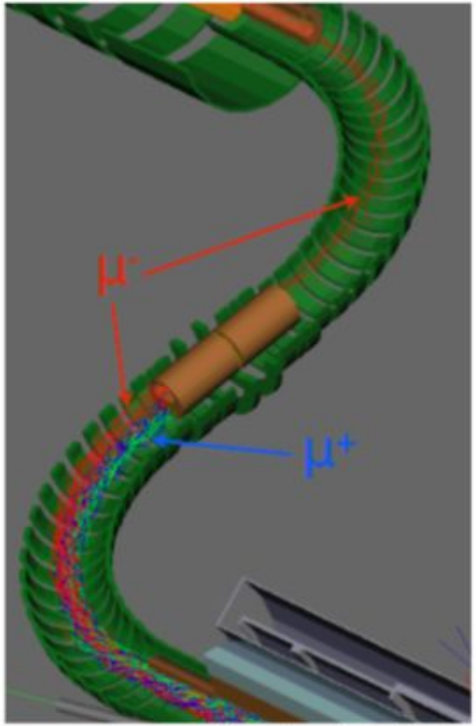
http://venu.physics.ox.ac.uk/

← pixelated

Transport Solenoid

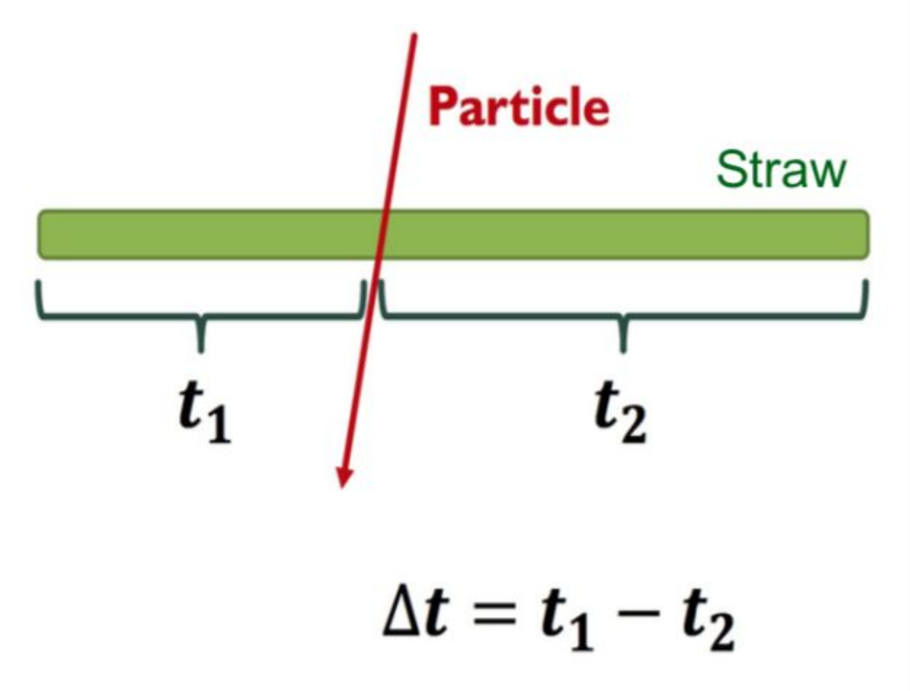
- 'S' Shape blocks line-of-sight particles
- Bend creates a charge and momentum dependent vertical shift
- Asymmetric collimator rejects positive and high momentum particles.
    - Collimator can be rotated for opposite selection to test background.

Detector Solenoid



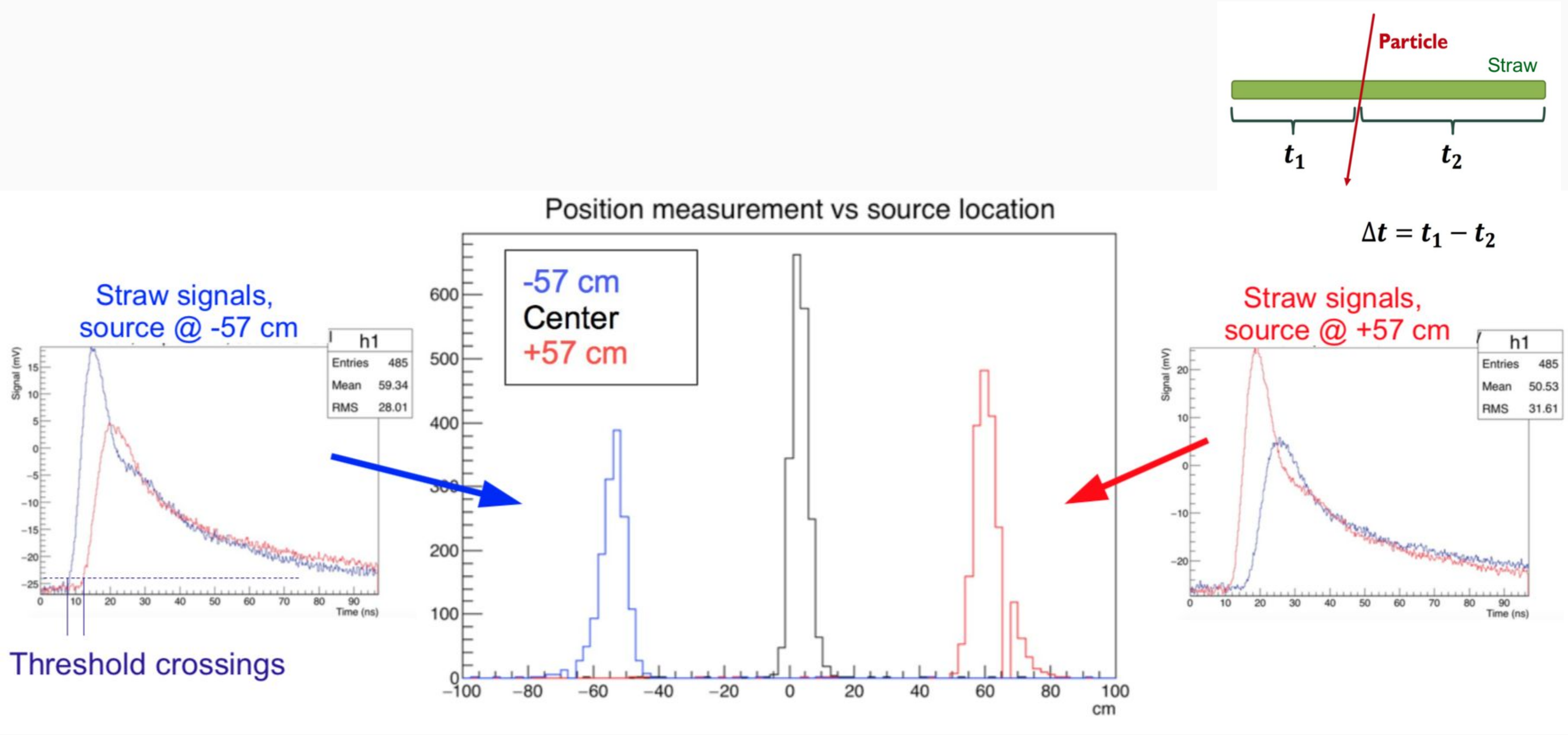
Production Solenoid

Where along the straw did the electron actually pass through?



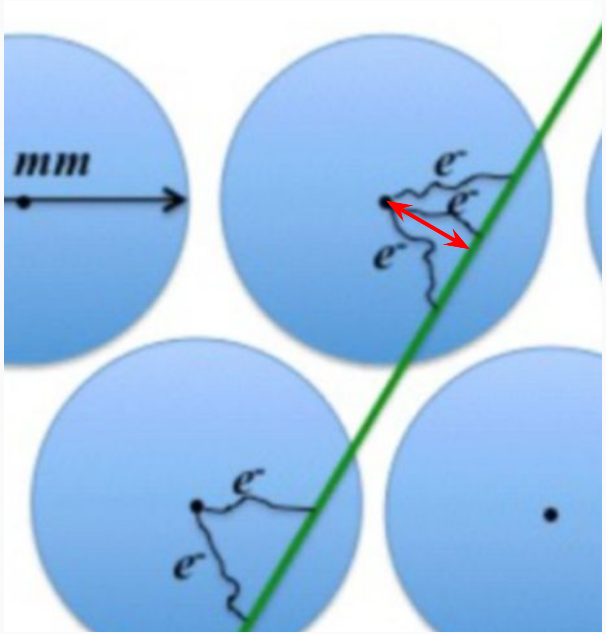
Ben Messerly. Mu2e. U of M Quarknet Workshop. 2021-08-13.

Where along the straw did the electron actually pass through?



B

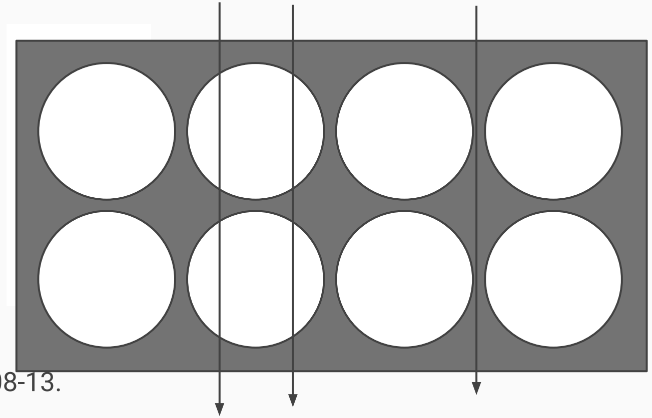
Where *in* the straw did the electron pass



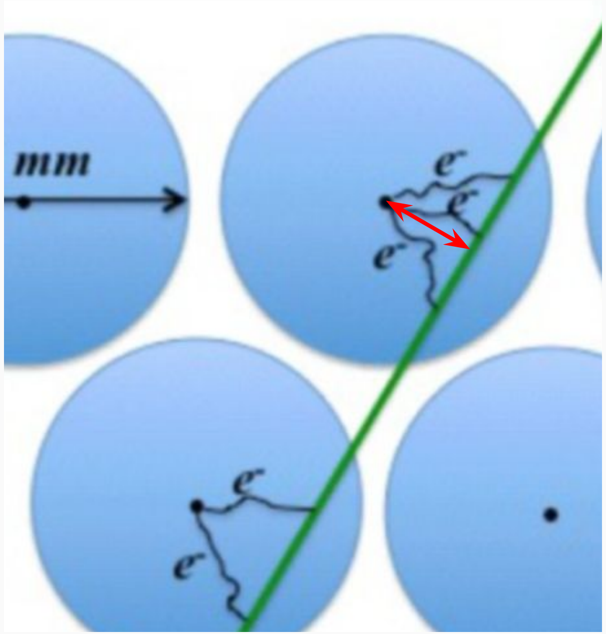
Drift radius = “distance of closest approach”

“Staggered” / overlapping top and bottom layer design: Track always* passes through at least two straws!

Gives us a finer position “resolution”, better efficiency, left vs right side of the wire



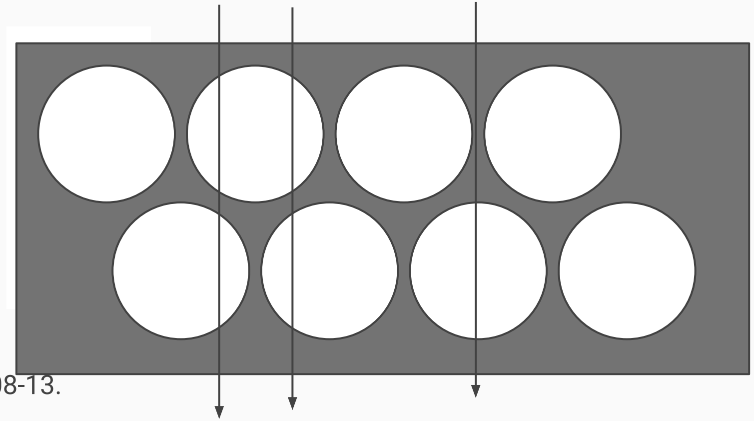
Where *in* the straw did the electron pass



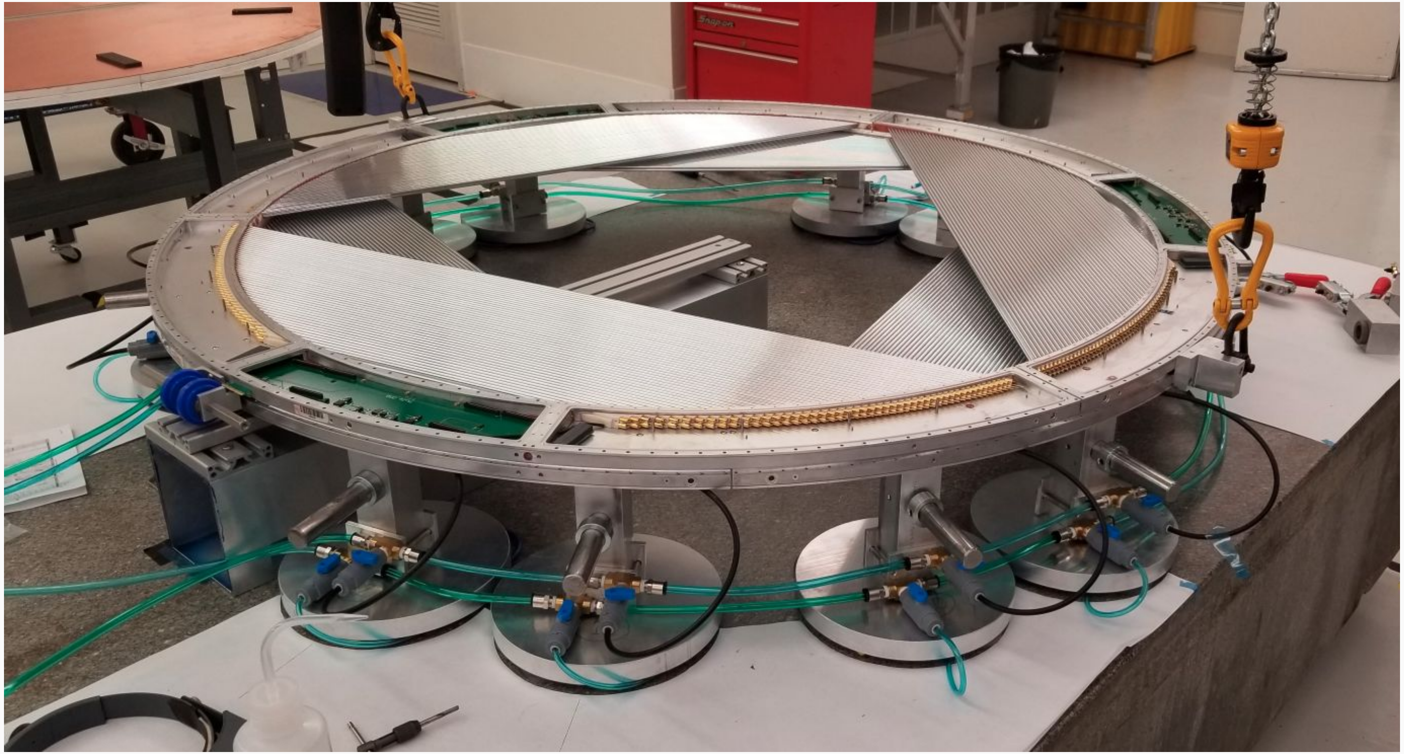
Drift radius = “distance of closest approach”

“Staggered” / overlapping top and bottom layer design: Track always* passes through at least two straws!

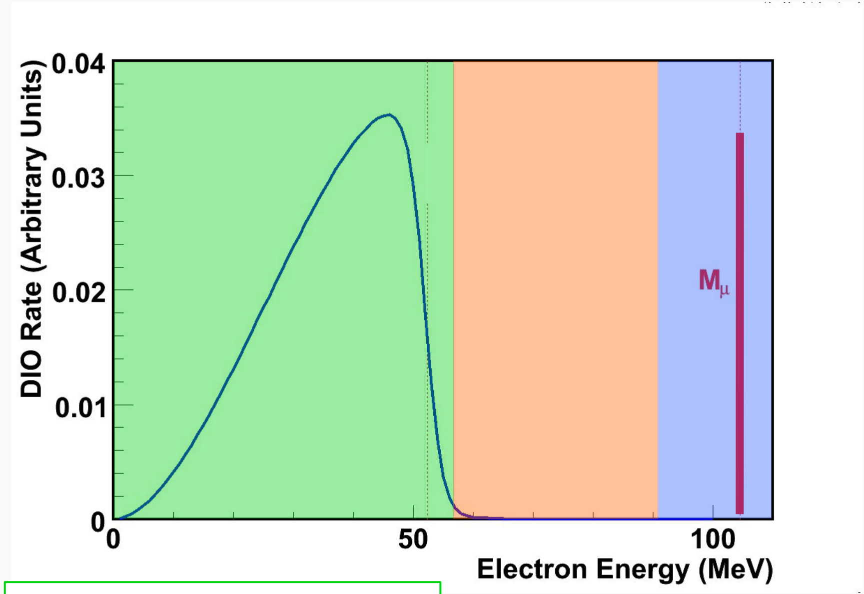
Gives us a finer position “resolution”, better efficiency, left vs right side of the wire



Why do we rotate the panels relative to each other



Mu2e signal hits selected by annular geometry

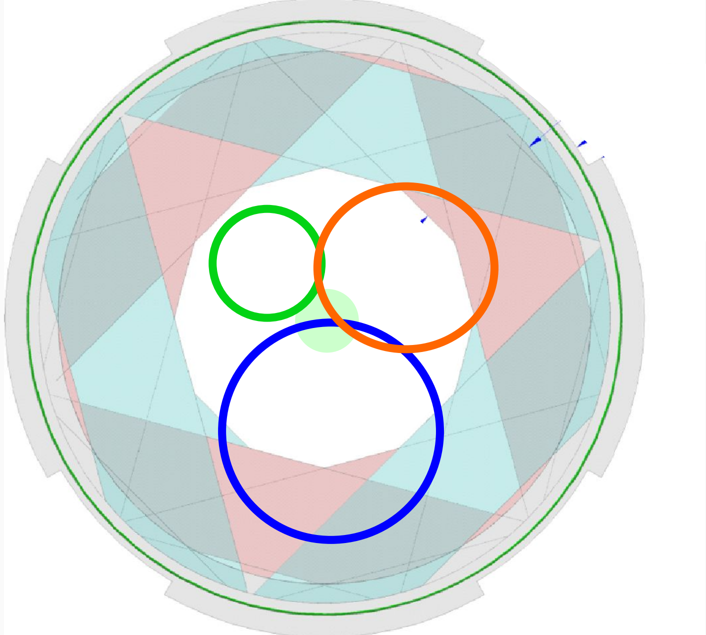


No hits in detector

Some hits in detector.
Tracks not reconstructable.

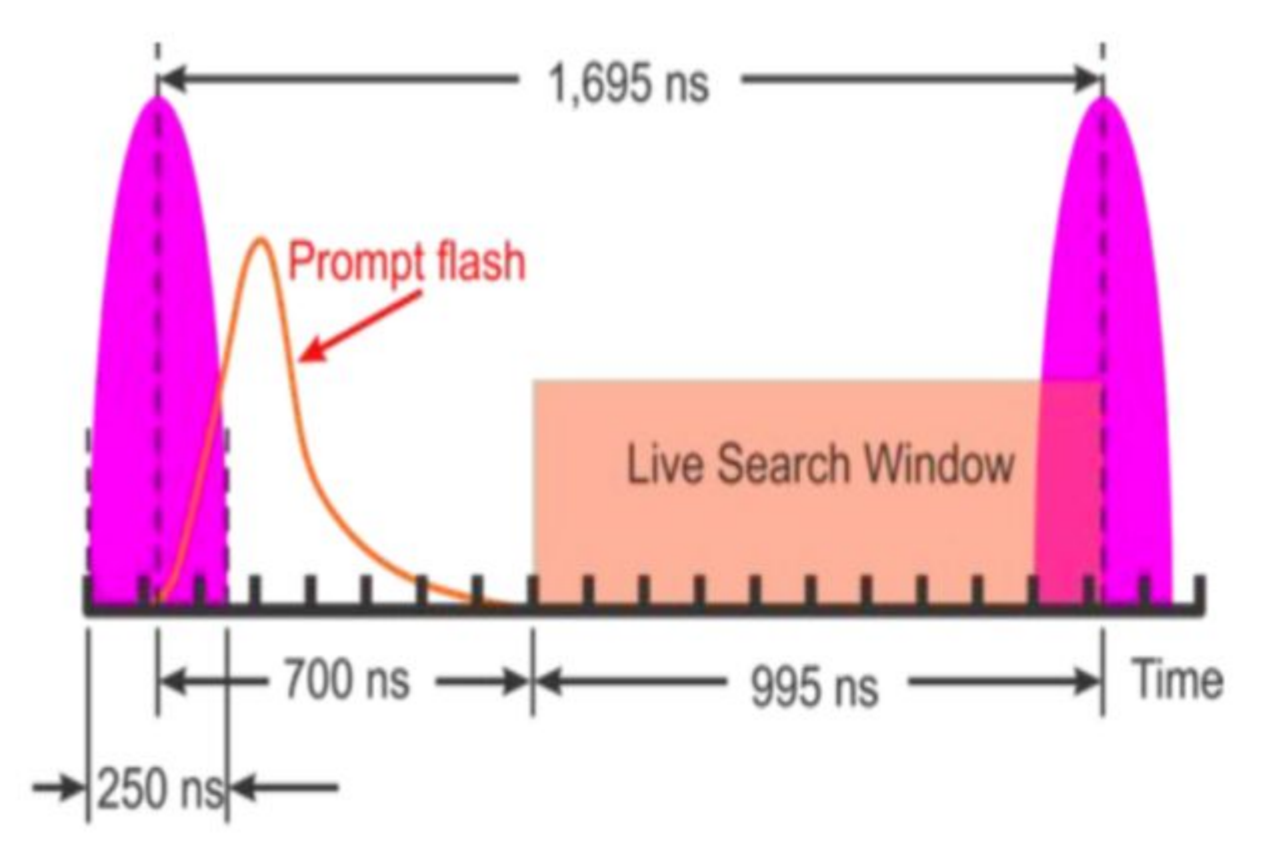
Reconstructable tracks
Momentum resolution σ < 180 keV/c

$$p = qBr$$



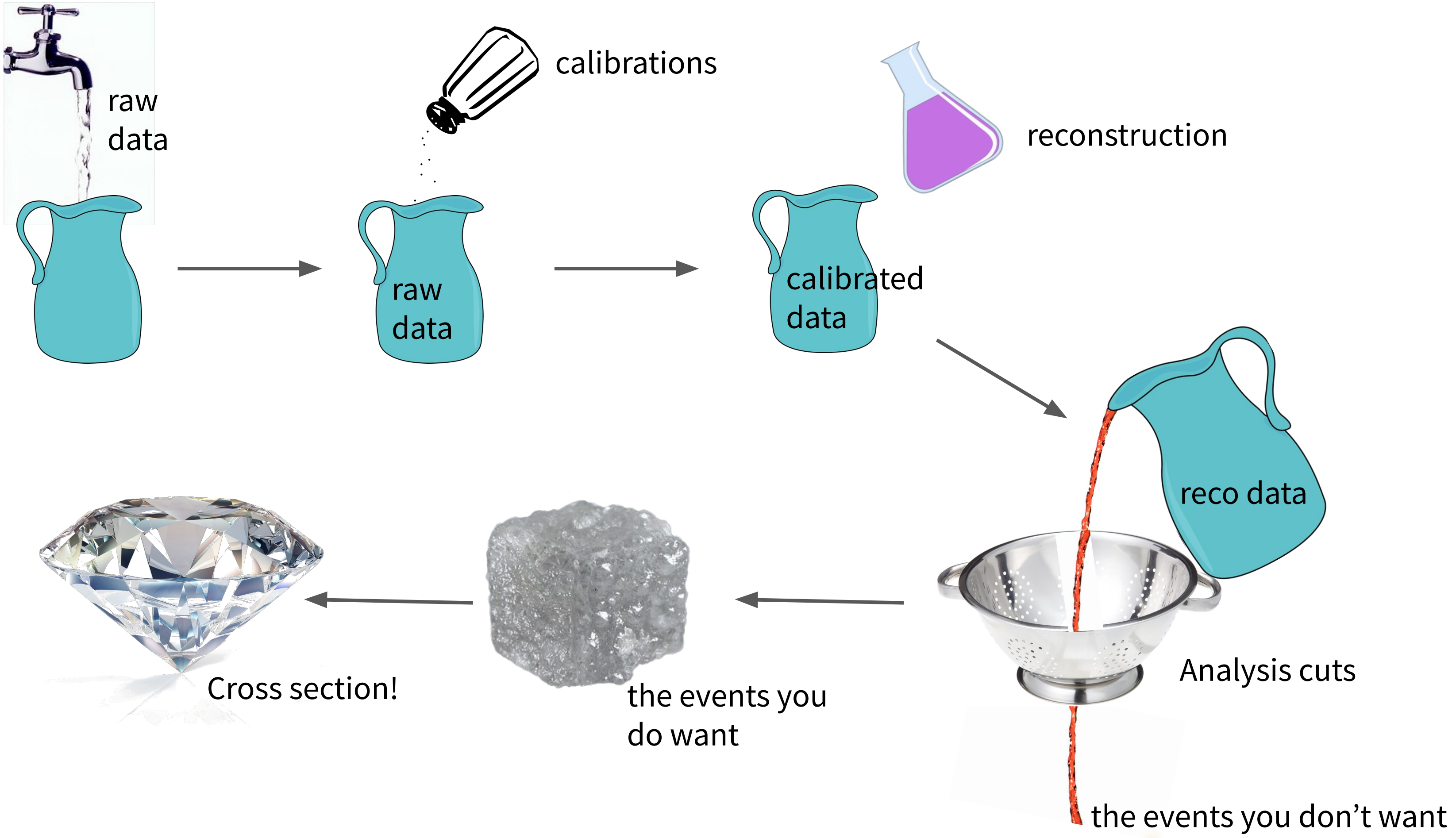
Beam's-eye view of Tracker

Mu2e Collaboration, No



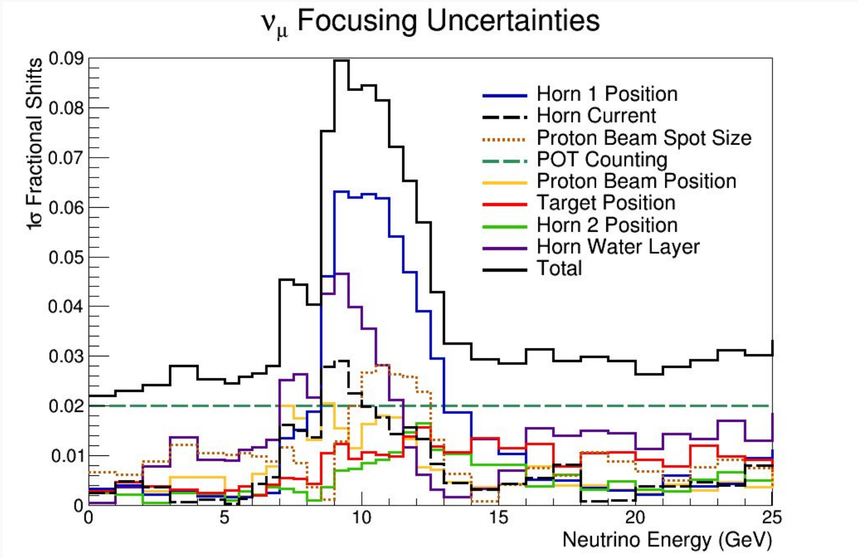
Mu2e beam pulse timeline

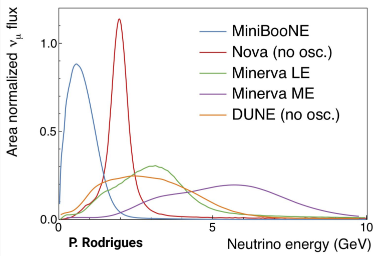
Data flow in particle physics



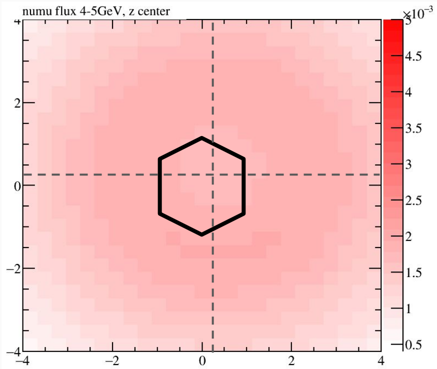
Mu2e lab data collection software
https://github.com/bamesserly/mu2e-tracker-factory

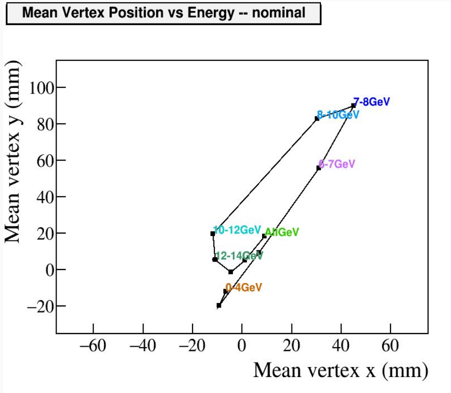
NuMI Flux Simulation – Focusing System

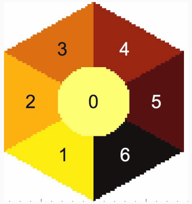


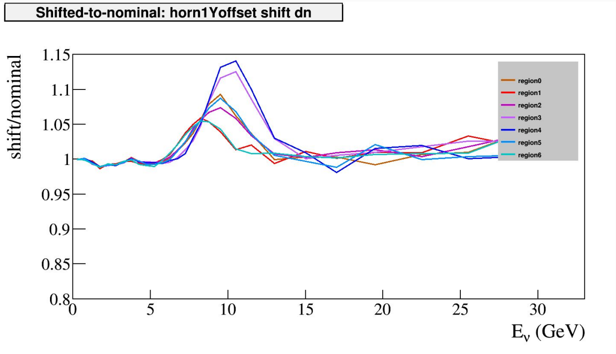


Systematic Uncertainties





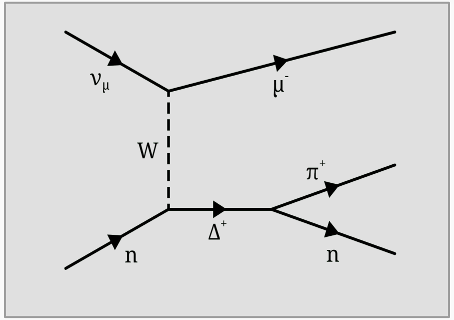


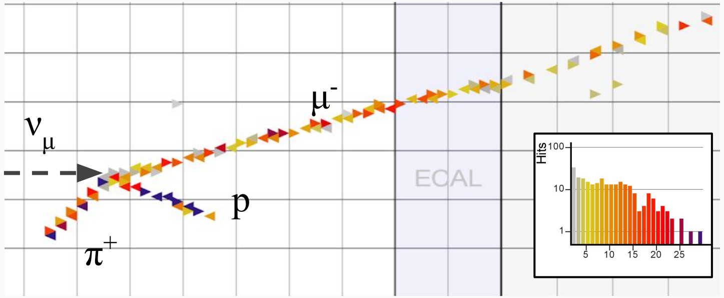


Beam Visualization

0.5 mm sensitivity to magnet position

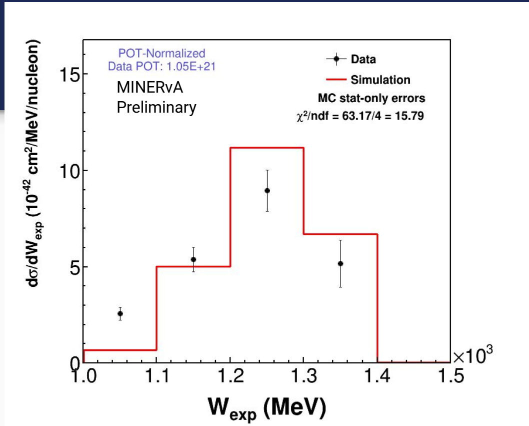
Pion Production Cross Section

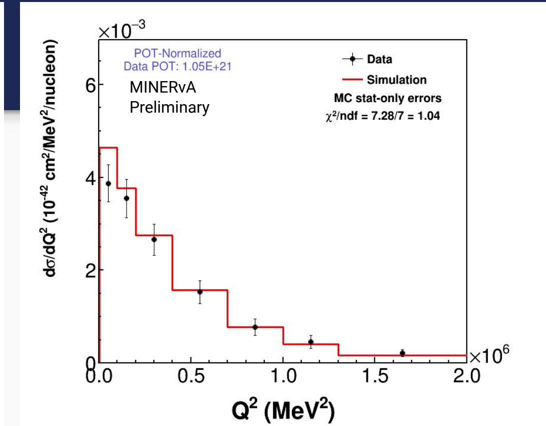


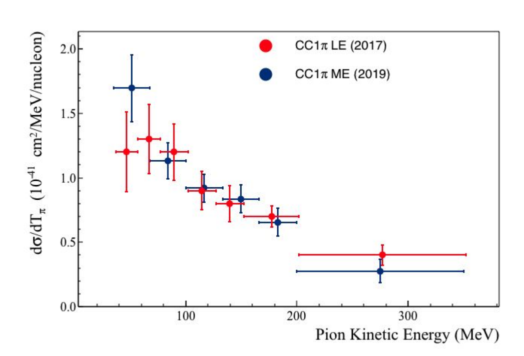


ν_μ + CH → μ^- + 1π^+ + X

Includes: resonance, coherent, DIS, non-resonant

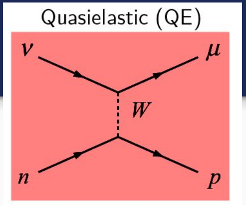




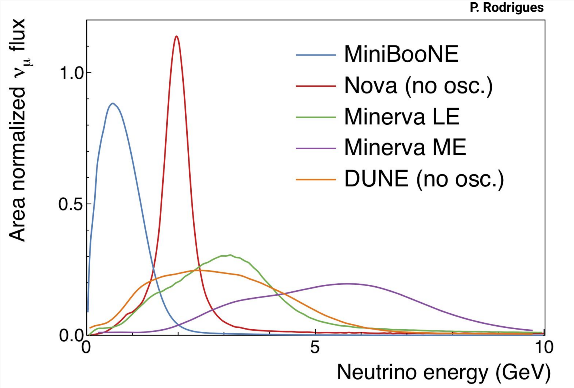


- Differential cross sections in 9 variables
- 1e21 POT, 20k+ signal events
- Minimally model dependent
- <E_ν> ~ 7 GeV
- Generally good agreement with GENIE, consistent with <E_ν> ~ 3.5 GeV results
- Publication in preparation

Neutrino Flux and Cross Section Challenges



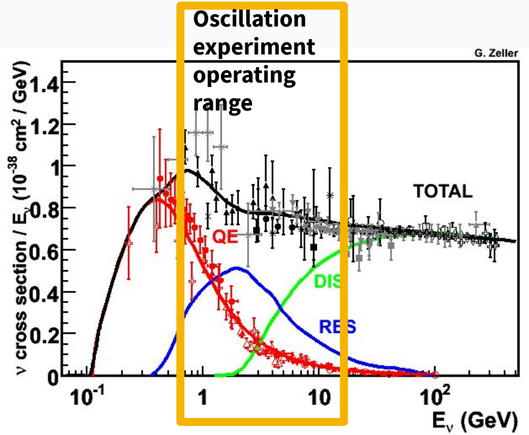
Flux Φ

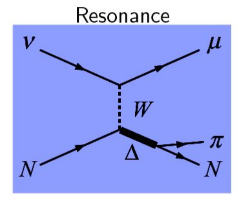


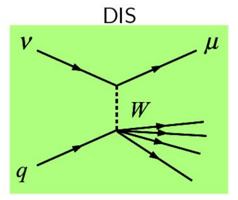
- Neutrino beams not monoenergetic
- Standard candle interactions limited
- *In situ* monitoring overlaps with physics measurements

→ **Sophisticated simulations needed**

Cross Sections σ





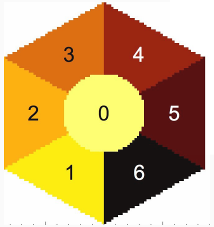


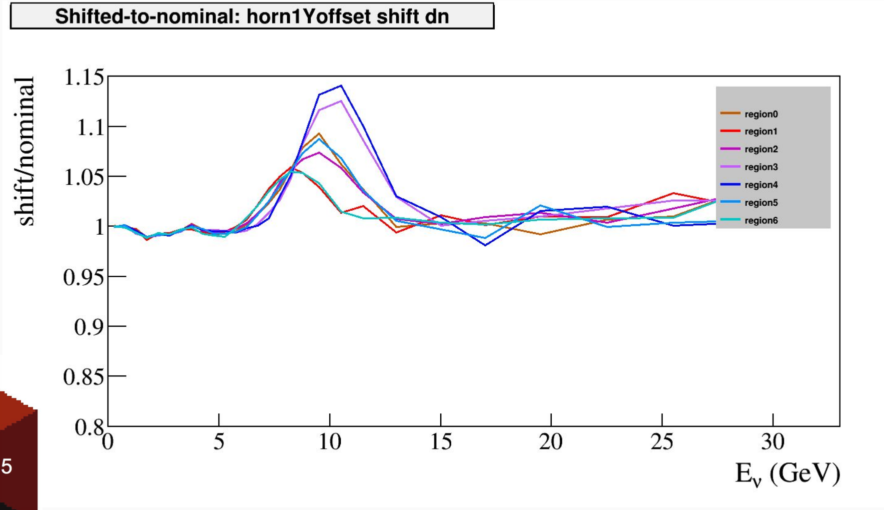
- Must reconstruct neutrino energy from event
- Several overlapping ν interaction channels
- Detectors of complex nuclei
  - E_ν is obscured by nuclear physics

→ $\mathbf{E_{reconstructed} \neq E_\nu}$

Flux Simulation: Focusing System Geometry

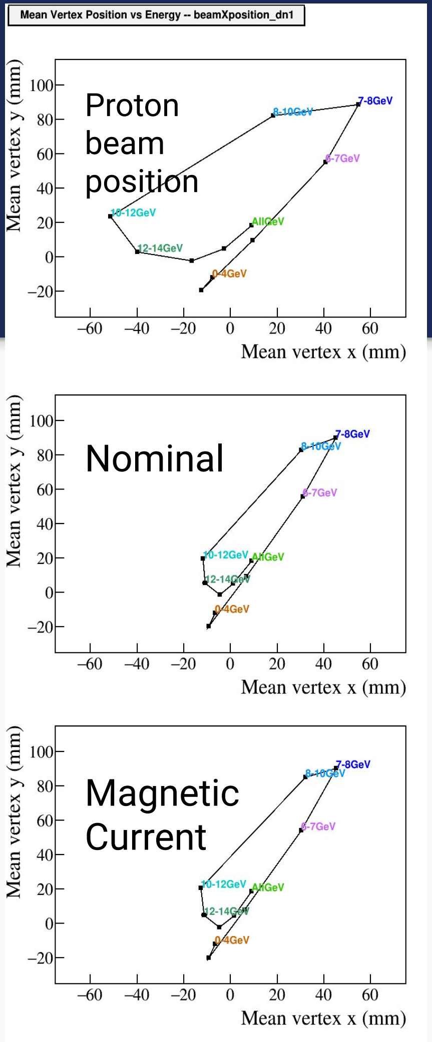
- Sophisticated model of each beamline component
- Resulting flux simulation very sensitive to small deviations in beamline parameters





0.5 mm sensitivity to magnet position

Focusing System

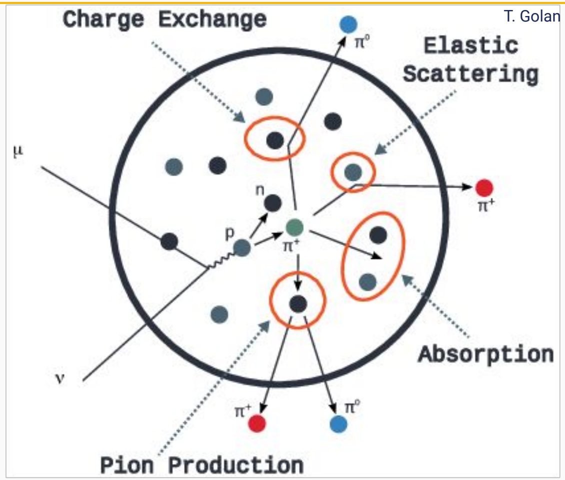


Conclusions

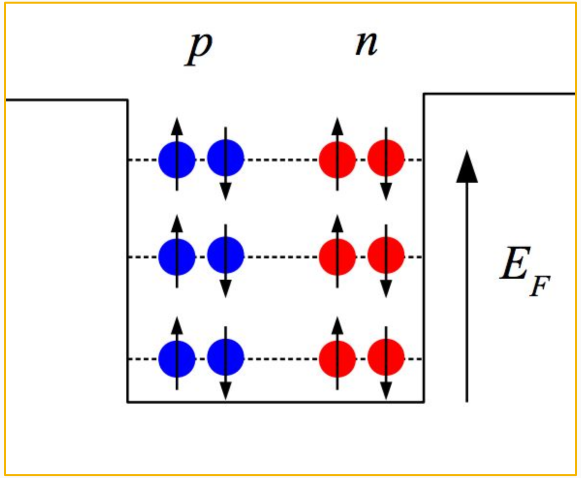
- Energy dependence is not axially symmetric
- Useful distinction between axially symmetric and asymmetric parameters.
- New metrics useful lens through which to approach beam model design.

Pion Production Modeling and Challenges

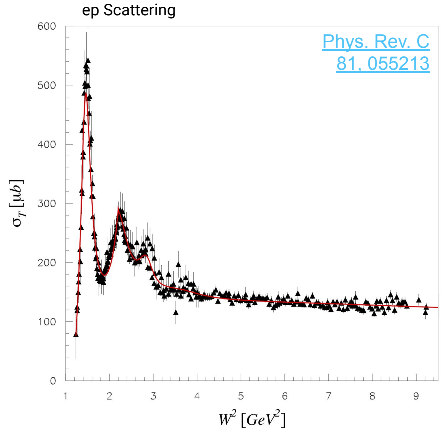
Pions produced by more than just simple νN resonance pion production



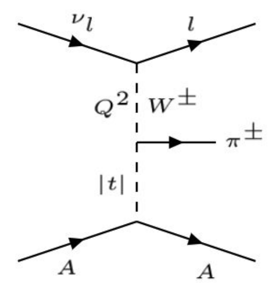
Final State Interactions ^



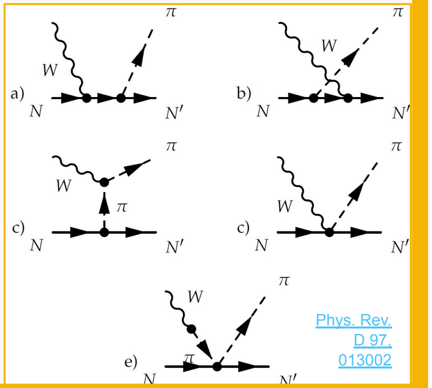
Initial State Nuclear Mod-ifications ←



Higher resonances →



Coherent Pion Production ←



Non-Resonant Pion production ←

Basic physics of the lab

Tension Measurement (What is it?)

The Problem : We need to determine what tension of parts of the detector.

- **Straws**
  - **Thin-walled**
  - **Hallow**
  - **Conductive**
- **Wires**
  - **Very small**
  - **String-like**
  - **Not visible**
  - **Conductive**

Solution :

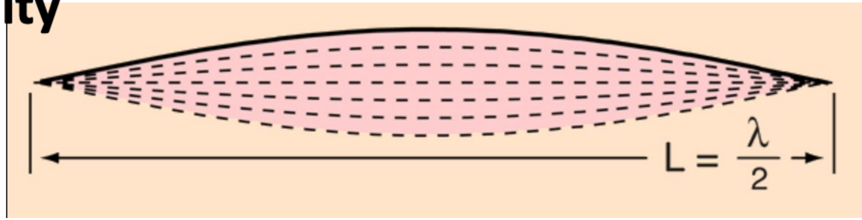
There is a resonant frequency at which strings vibrate.

Measure frequency → Tension

For a string this equation is

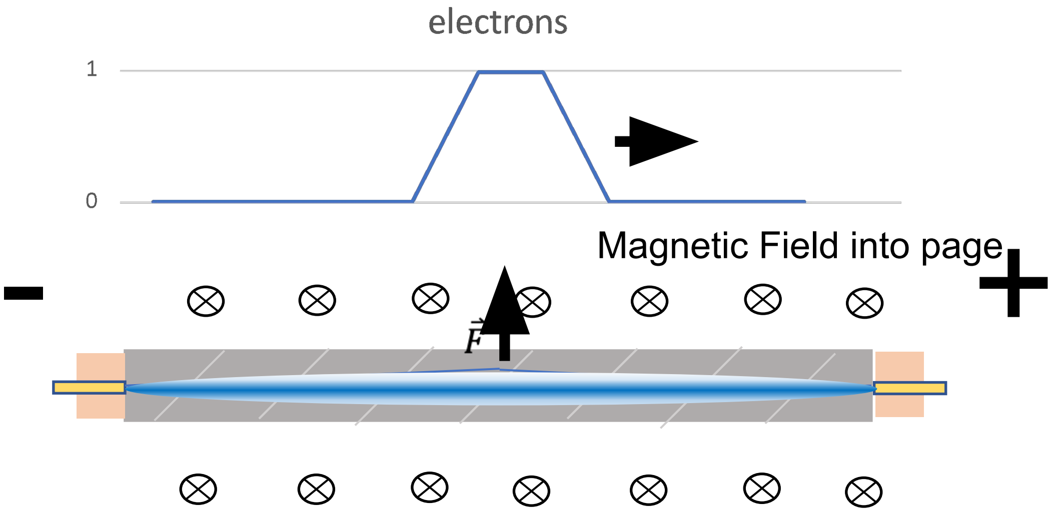
$$T = f^2 \lambda^2 \rho$$

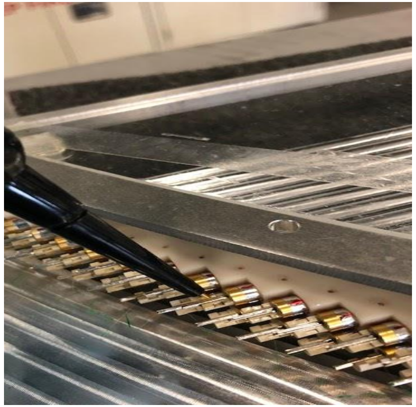
f is frequency
λ is wavelength
ρ **is linear density**



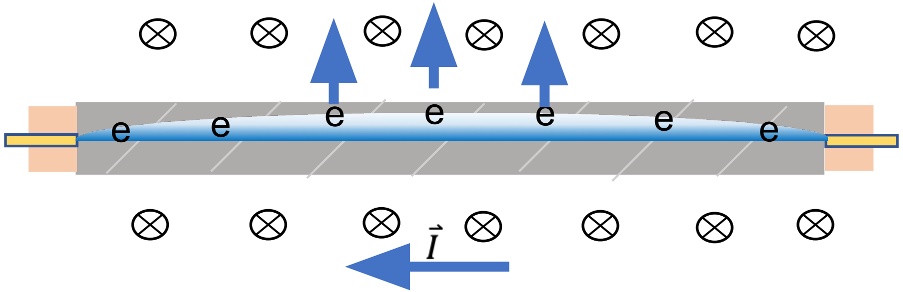
What The Pluck?

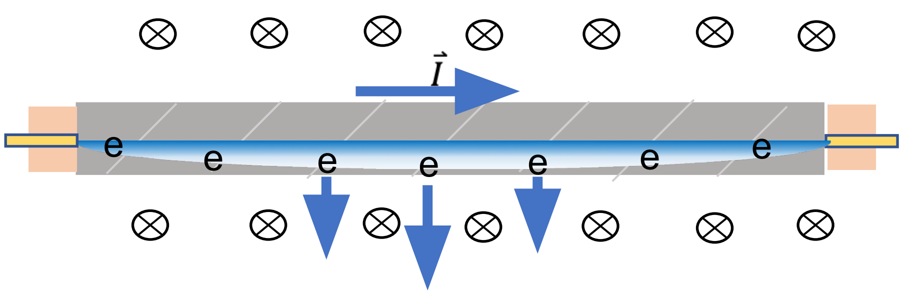
- Attach Power source to pins
- Apply a magnetic field
- Send a large pulse of electrons
    - 5 ms
    - 10 V amplitude
- 10 msec delay
- Non-resonate waves die
- Resonate waves propagate





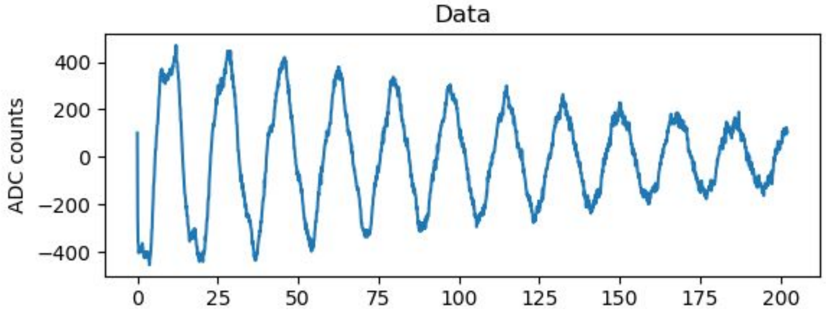
Inducing Current





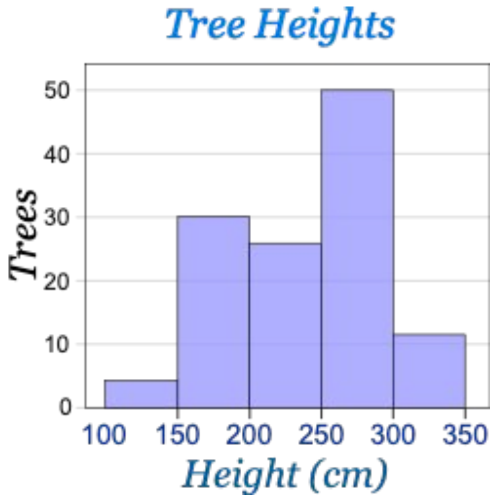
Once “plucked” by the electric pulse the wire will then oscillate.

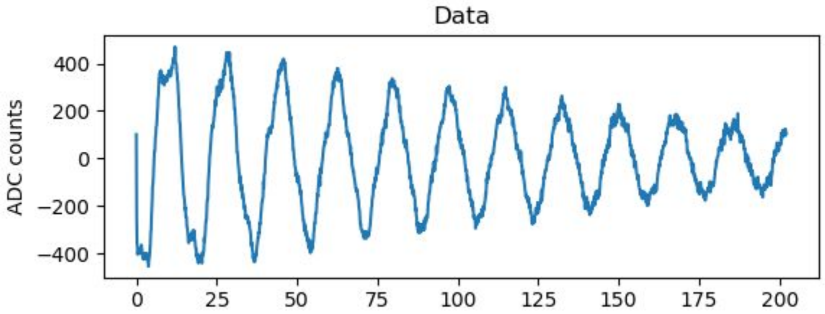
The conductive wire is full of free flowing electrons.
As it oscillates in the magnetic field, an electrical current is induced back and forth.
Sampling the current quickly (8900 Hz), we get a data source which looks clear.



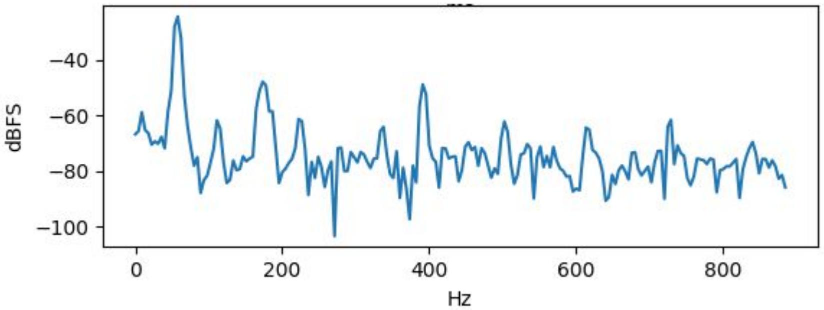
t
(millisecs)

Transforms





t
(millisecs)



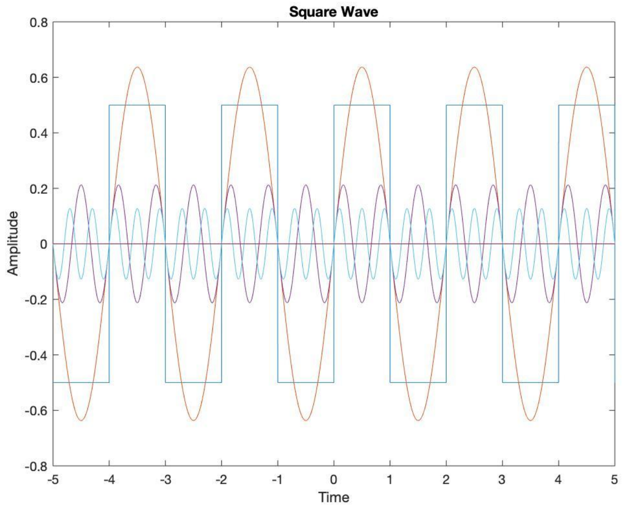
Fourier Transform

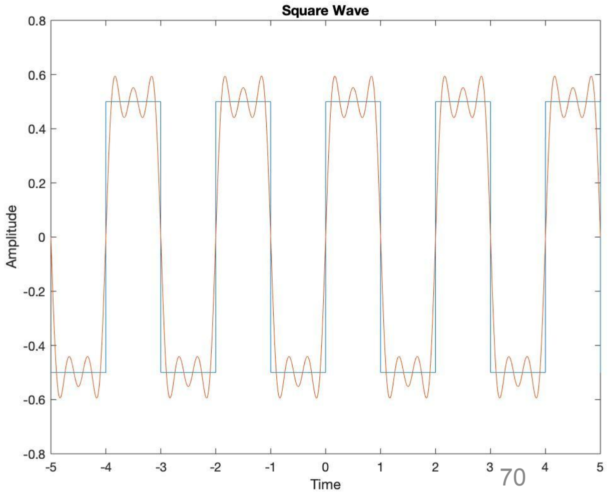
Fourier Theory says any signal can be mimicked by an infinite number of sin and cos waves

Fast Fourier Transform is an algorithm for quickly computing the strength of these waves.

This is used all over the place in modern technology :

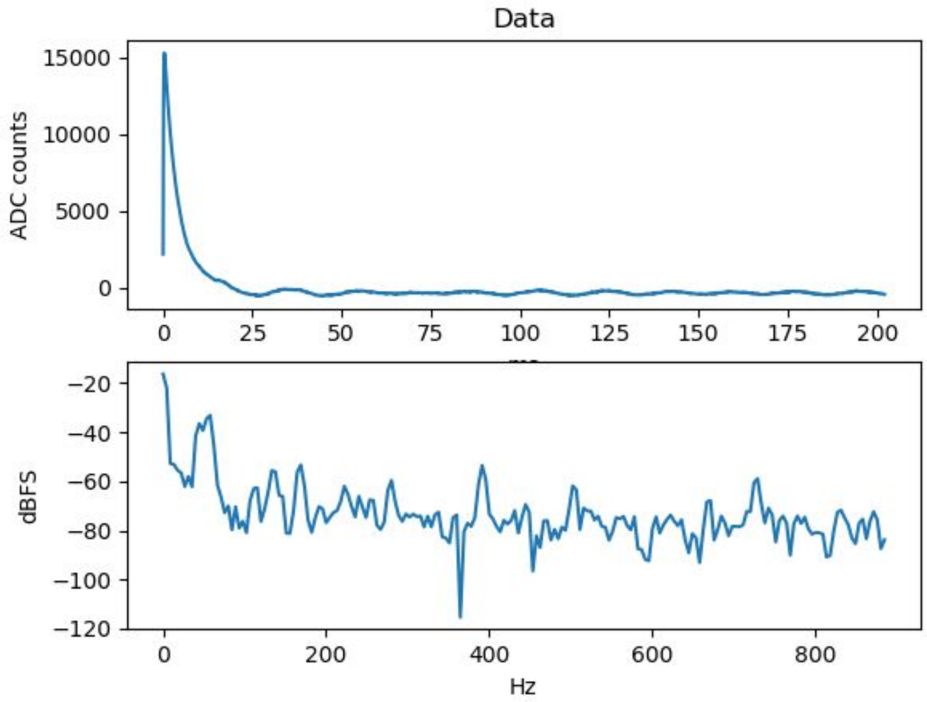
- **Data/Image compression**
- **Noise filtering**
- **MRI/CT Scans**





Background Noise and other things

- **frequency near 0 Hz ⇒ Catching Initial pulse**
- **Frequency near 60 Hz ⇒ US electrical mains**
- **Always another frequency ? Check room air flow**



Straws vs Wire Vibrations

$$f_1 = \frac{\sqrt{\frac{T}{m/L}}}{2L}$$

T = string tension

m = string mass

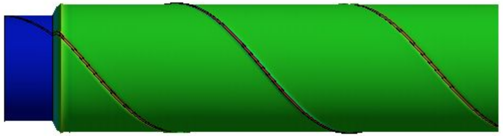
L = string length

Straws :

Tensions ~400-600 g

frequency ~10Hz - 60 Hz

$$\nu = \frac{K}{2L}\sqrt{m} + \frac{c}{L^2}$$

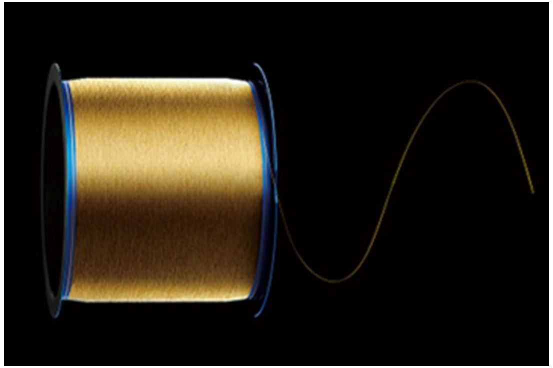


Wires :

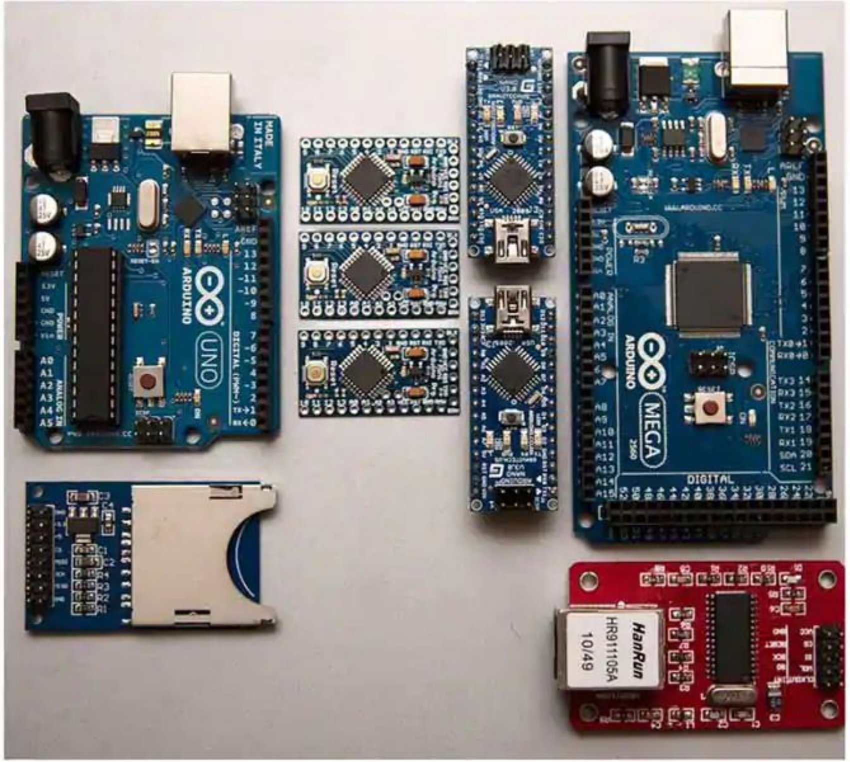
Tensions ~80 g

frequency ~40Hz - 120 Hz

$$\nu = \frac{K}{2L}\sqrt{m}$$



Arduinos

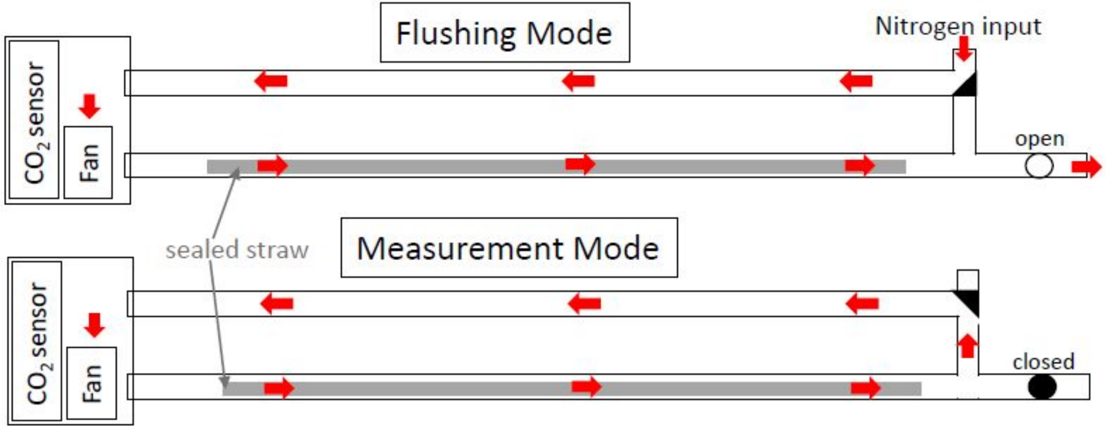


- Miniature computers (microcontrollers) which run most of our electronics in the lab.
- Can measure voltage quickly and accurately
  - ADC input (0 to +3.3V)
  - ADC resolution is about 0.81 mV
  - ADC sampling rate 1 MHz

Leak Tests (Overview)

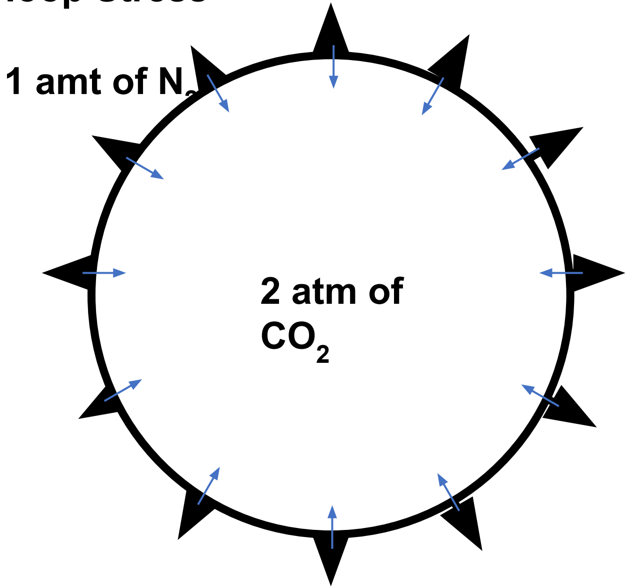
Procedure:

- Fill a straw with pure CO_2 at 15 psi over ambient pressure
- Pressurized straw is put in a chamber filled with N_2
- CO_2 detectors measure CO_2 in chamber
- Arduino reads CO_2 detectors, plots leak rate of straws



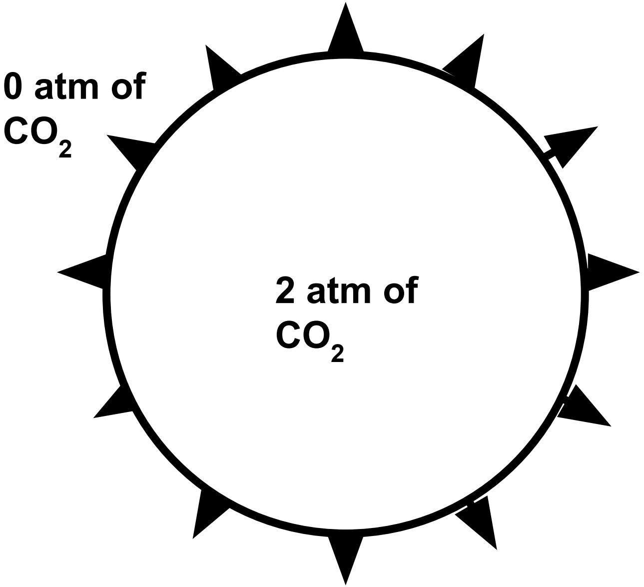
Straws Leaking

Pressure on the Straw
Hoop Stress



Leak rate adjustment :
Partial pressure 2x
Gas Mixture ~5x

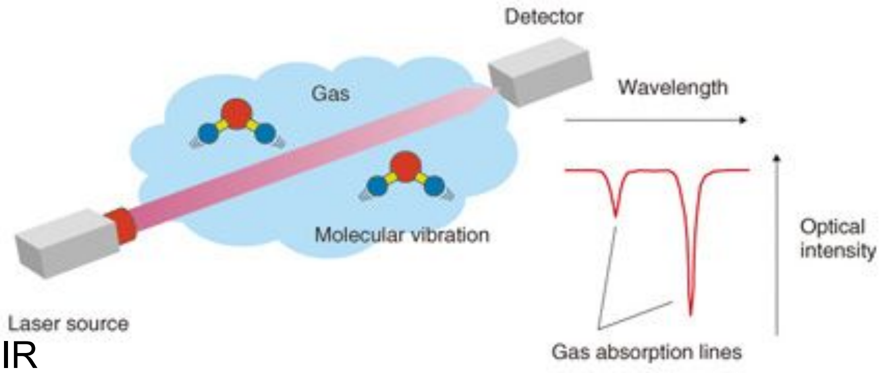
Partial Pressure
Gas



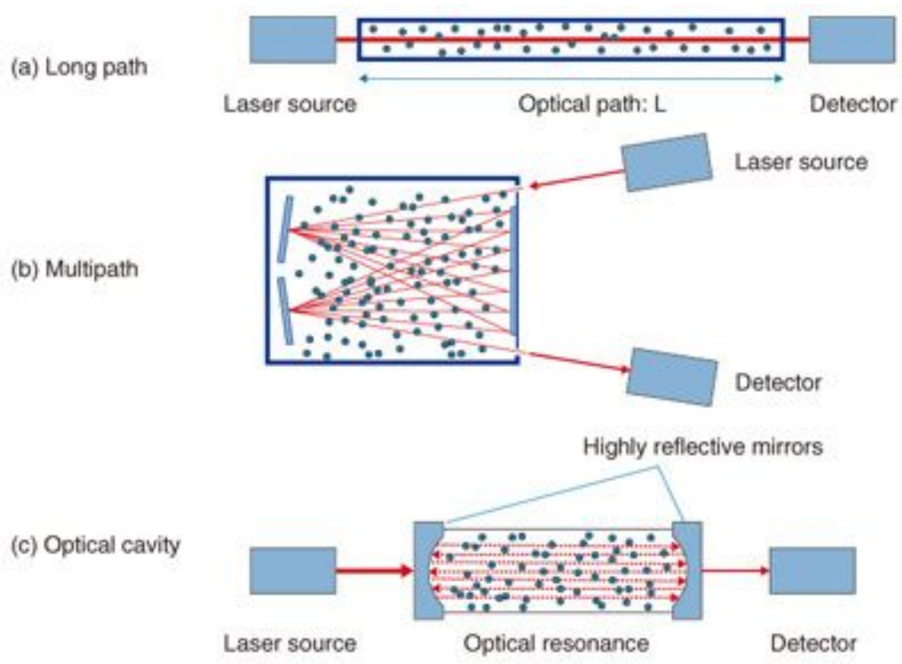
Not adjusted for :
Straw Tensioning
~1/3x

Collapsed straw

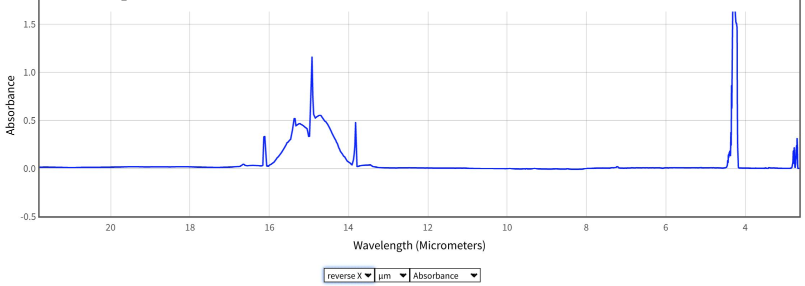
Measuring the CO_2 Level in the Chamber



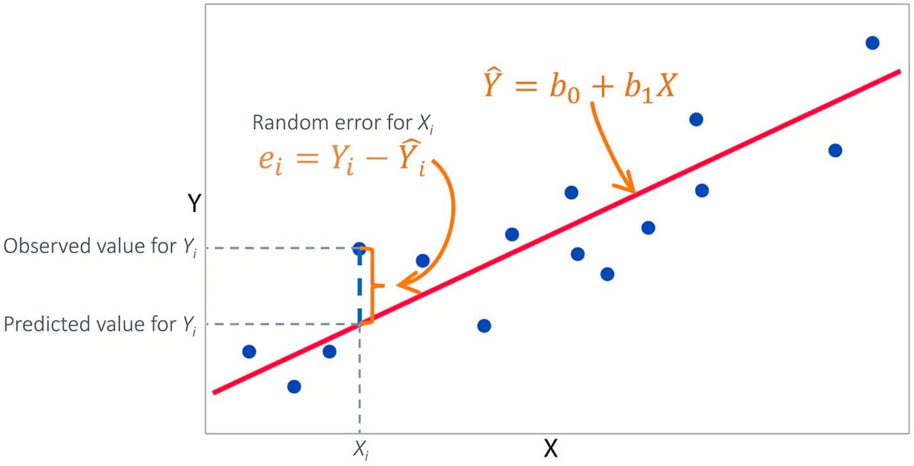
IR
Source

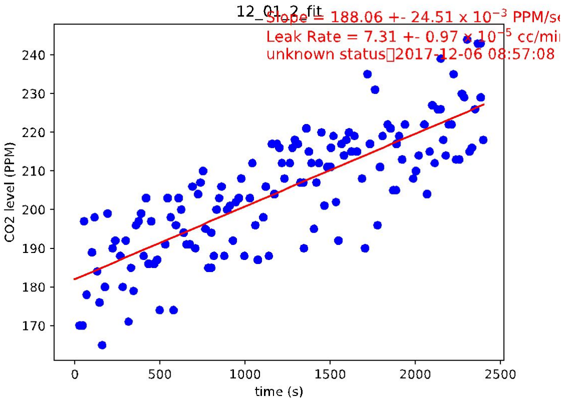


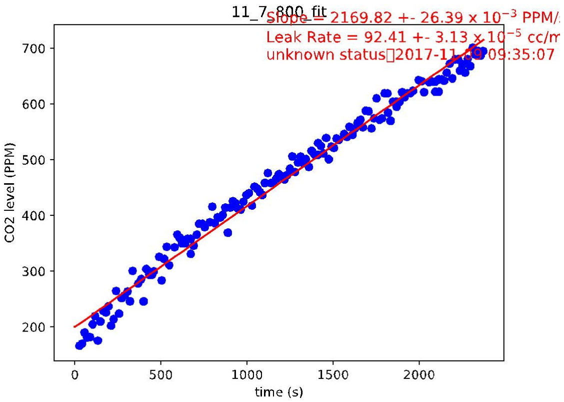
Carbon Dioxide Absorbance in IR Spectrum



Fitting the leak rate







Uncertainty in the leak rate is a function of :

- **The number of data points**
- **The uncertainty of each datapoint**
- **Time elapsed**

Takes ~40 minutes and 100 datapoints to reach 10^{-6} sccm uncertainty

Epoxy, on both your houses



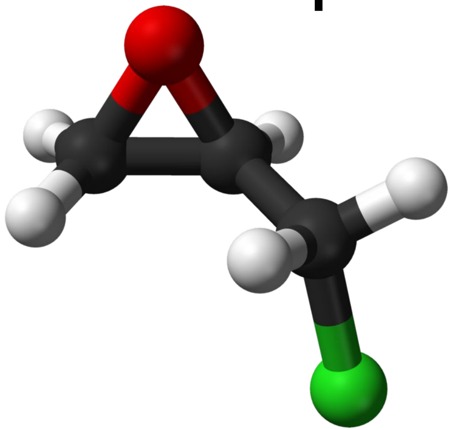
Epoxy is used everyday in many industrial processes.

It is also being used for art and home decorating.

Why is Epoxy good:

- **Rigid but tough bond**
  - **often used as alternatives to welding or rivets**
- **Excellent adhesion to metals**
- **Chemical and environmental resistance**
  - **Many are rad-hard with minimal outgassing**
- **Easy application**
- **Can fill gaps and create seals**

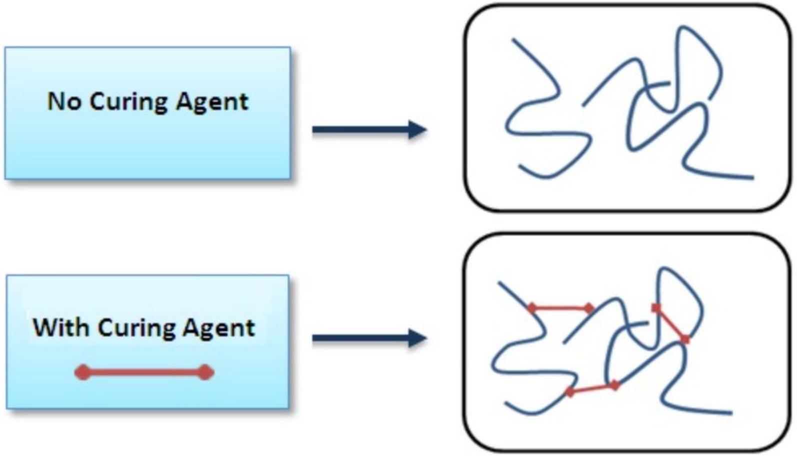
What is Epoxy



EPOXY
What we call epoxy is cured epoxy resin.
Epoxy Adhesive
Two parts : the resin and the curing agent. When the resin and the curing agent react together, the hardening process ensues.

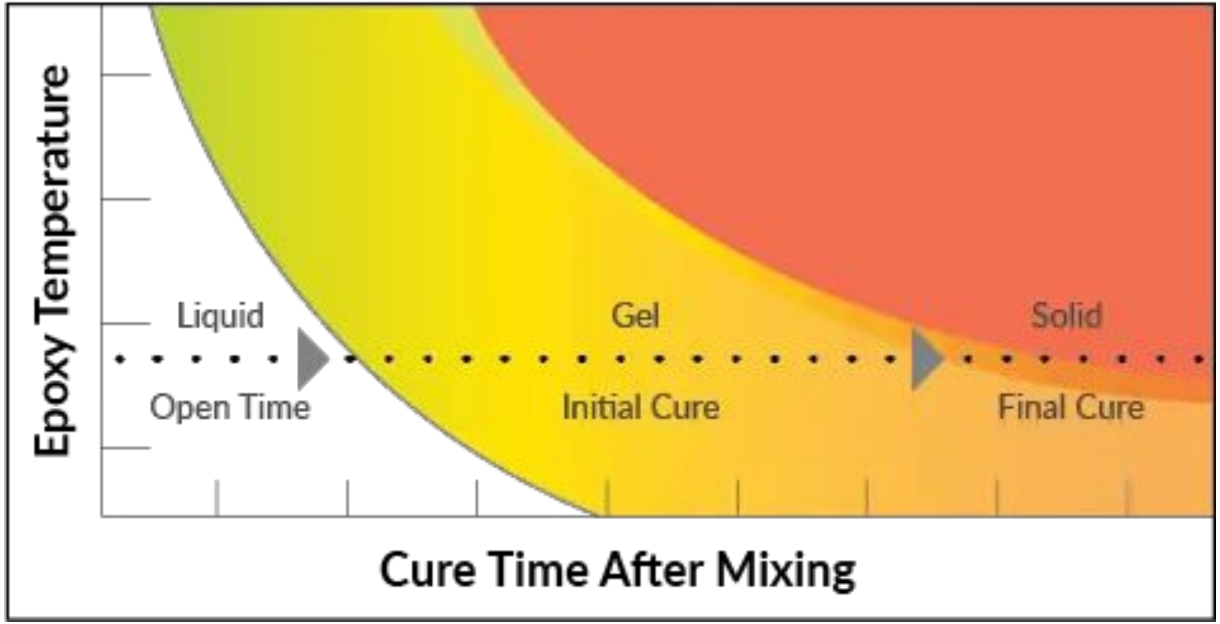
Resin is usually made of a complex hydrocarbon like bisphenol ($C_{15}H_{16}O_2$). This is a combination of acetone and phenol.

- When discovered this originally came from Coal Tar.
- Now we get this from petroleum.

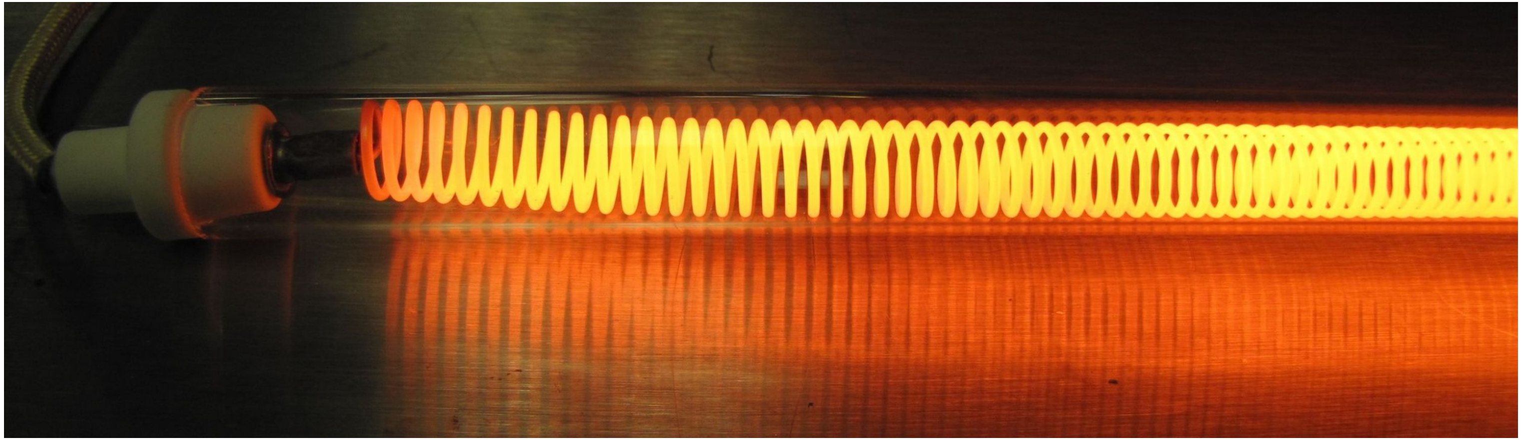


The Cure

As it cures, mixed epoxy changes from a liquid state, to a gel, to a solid



Electrical Heating



Power Formula : $P=I^2R$

As electrons travel in a wire, they run into other particles. Each kentic interaction deposits energy into the material. Material heats up.

- **Thin lines of metal that go underneath each of the PAASs.**
- **Well insolated**
- **Heating box has an adjustable resistance which controls the current.**