Intro to the Mu2e tracker

Mu2e summer student lecture series

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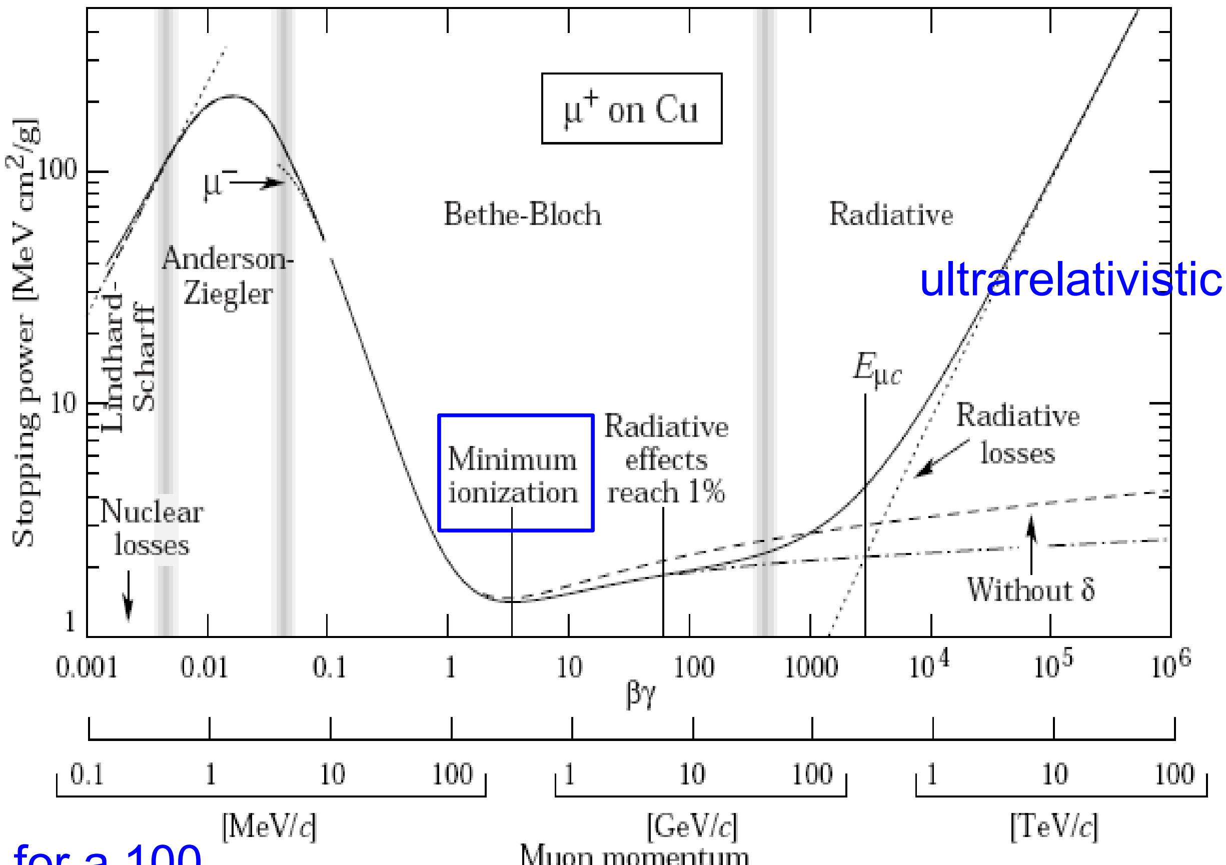
Background material--passage of particles through matter

Mu2e tracker

Passage of particles through matter

All charged particles lose energy through ionization as they pass through matter.
We refer to this process as dE/dx energy loss.

Note units!



ultrarelativistic

Pop quiz: what is γ for a 100 MeV electron? For a 100 MeV muon?

Passage of particles through matter

Special relativity quick review

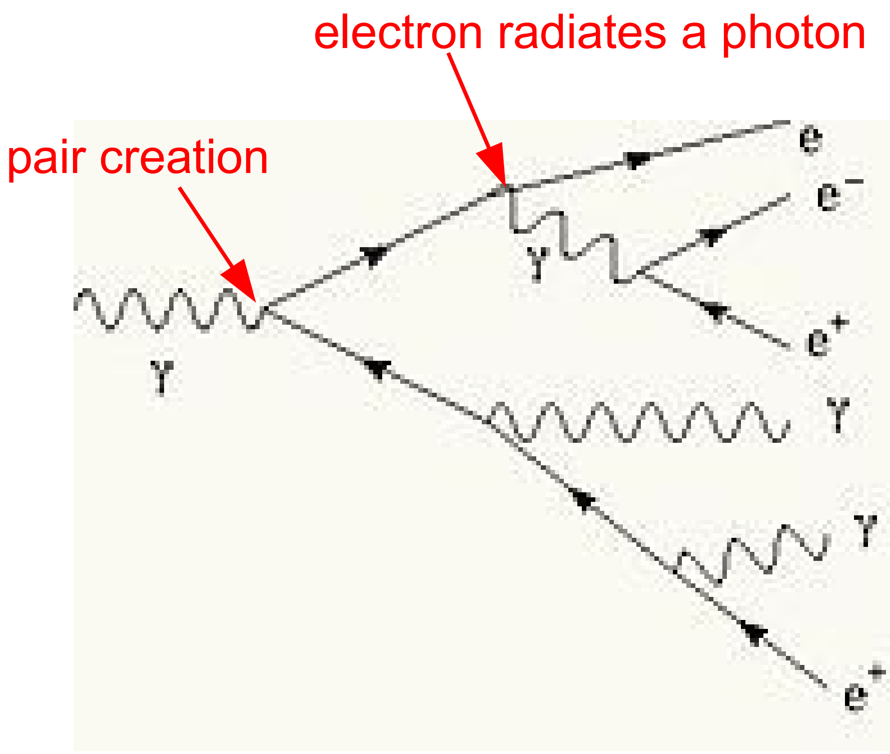
E=γm, so for an electron of momentum 100 MeV, γ=100/.511 = 196. This is pretty far up on the horizontal axis in the previous plot, into the region where the electron will radiate off photons. Notice that I have ignored the mass of the electron compared to the momentum.

For a muon of the same momentum, I can't ignore the muon mass of 105.6 MeV.

$E^2 = p^2+m^2$ so E=145.3 MeV and γ=145.3/105.6 = 1.37, close to minimum ionizing.

So even though electrons and muons are both leptons, they behave quite differently as the move through matter.

Electromagnetic showers

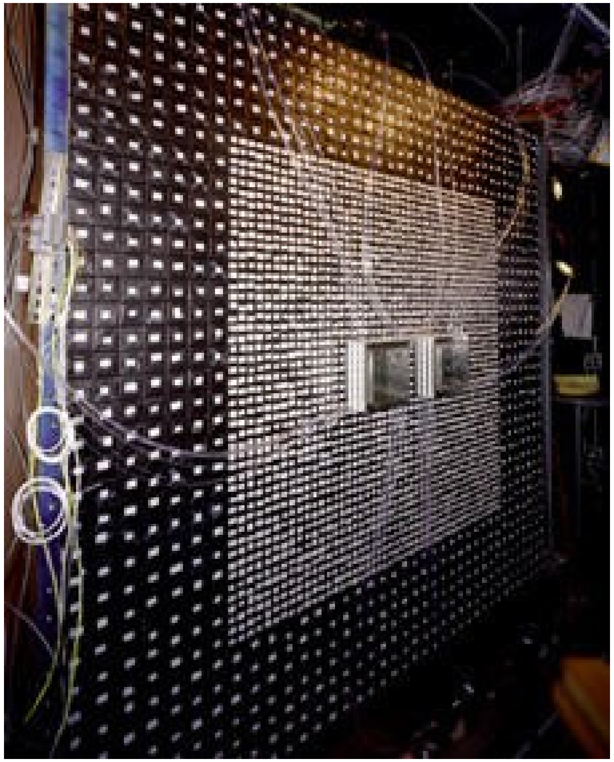


Electrons and photons which are energetic enough make showers of electrons, photons, and positrons, called electromagnetic showers.
Question: what is the minimum energy a photon needs to pair produce?

A calorimeter is a device that measures the energy of a particle by making it shower and measuring the energy in the shower, usually by turning the energy into light.

Electromagnetic calorimeters

For an electron traveling through material,
$E(x)=E_0e^{-x/X0}$ where X_0 is a radiation length, $X_0 \sim 1/Z^2$
So to get an EM shower going, you need material with a short radiation length or large Z, like lead, uranium, or tungsten.
On Mu2e we will use either CsI or BaFl.

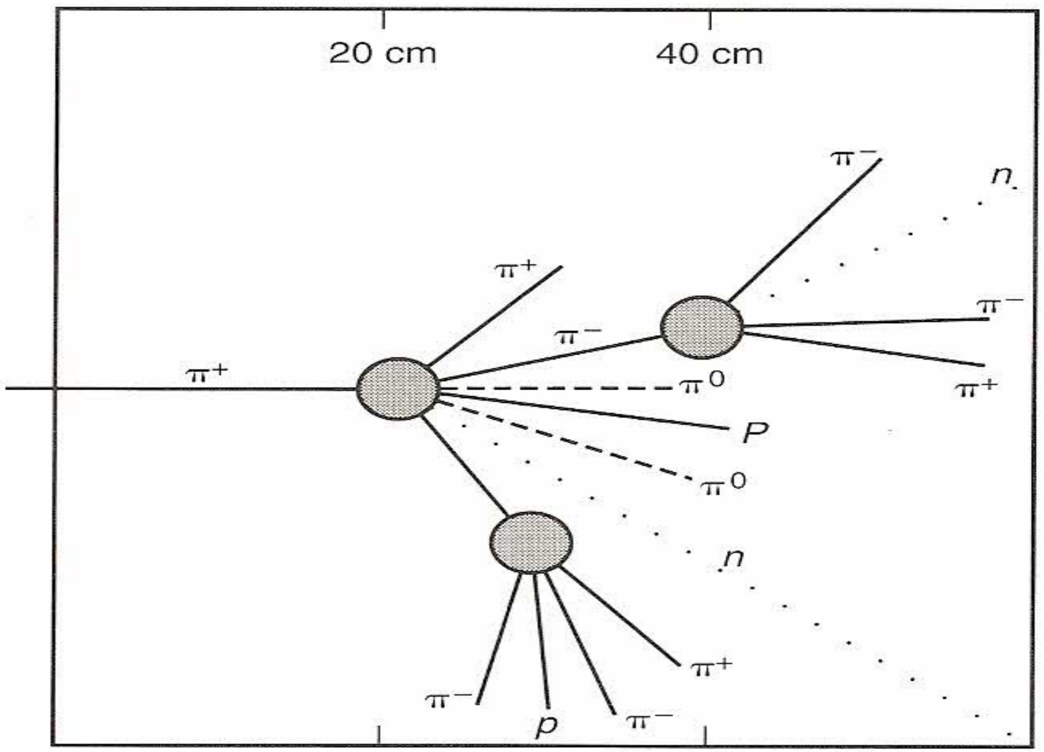


This is the KTeV CsI calorimeter, which has been moved to Japan for an experiment at JPARC.

Hadronic showers

Hadrons are strongly-interacting particles. All particles containing quarks are hadrons.

Hadronic showers are created when a hadron passes through enough material to make many interactions.



Hadronic showers are not as efficient as EM showers at turning the energy into light, so in general

Hadronic showers produce less light than EM showers for a given energy

The energy resolution is worse.

We will not have a hadronic calorimeter in Mu2e.

More on muons

But muons are just like electrons, only heavier. Why don't they make an electromagnetic shower too?

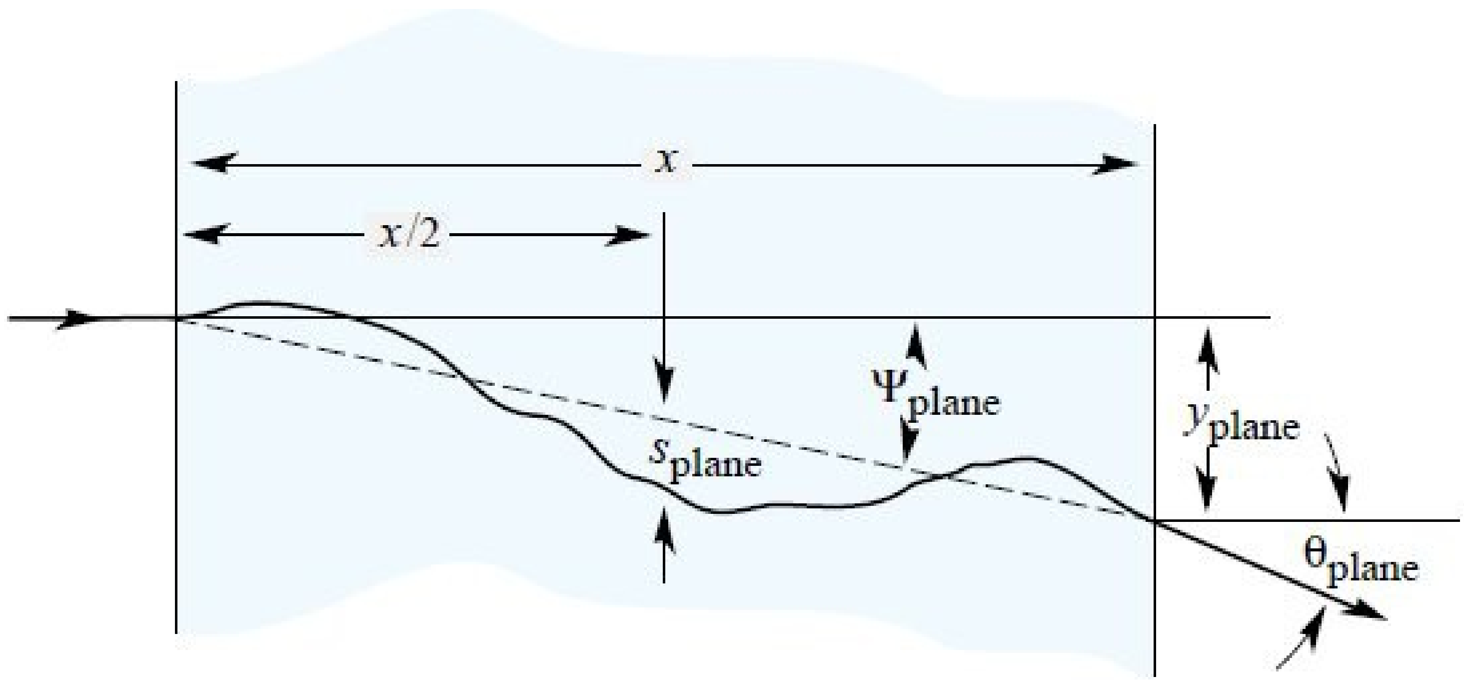
The probability of radiating a photon goes as $1/M^2$ and the muon mass is 200 times the electron mass. If the muon is energetic enough, it will make an EM shower.

Muons at typical Fermilab energies "MIP"* (minimum ionize) through material, losing energy slowly to ionization. They are therefore very penetrating and can pass through even meters of steel without interacting. They do not make hadronic showers at all, and they do not make electromagnetic showers unless they are extremely energetic (over 100 GeV) , because of their large mass.
* There is no noun that can't be verbed.

So the usual way to detect muons is to put up several meters of steel and see what comes through. Only the muons will get through!

Multiple scattering

There is another effect that Mu2e has to worry about. When particles pass through material, in addition to losing energy, their direction gets smeared by many small angle scatters. We call this multiple scattering, and it limits how well you can measure a particle's angle by bending it in a magnetic field.

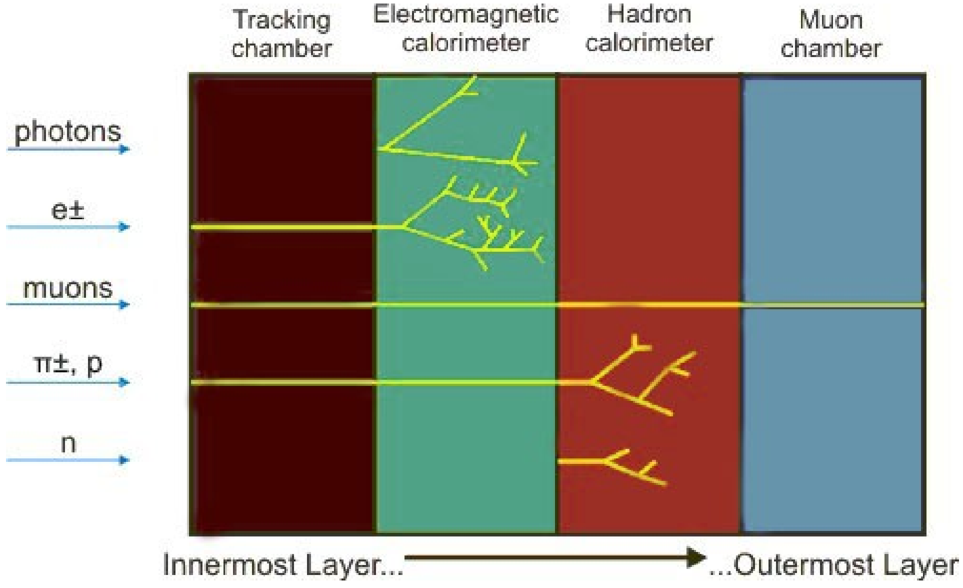


Summary of passage of particles through matter

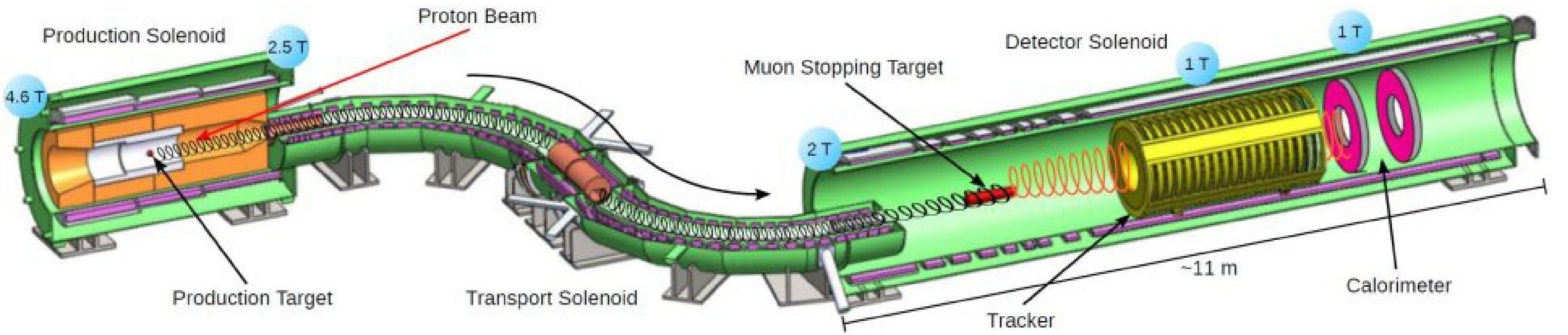
All charged particles will lose energy slowly through dE/dx ionization. Tracking detectors use dE/dx energy loss to detect charged particles. A tracker tries to disturb the trajectory of the particle as little as possible.

Energetic electrons or photons will generate an electromagnetic shower. EM calorimeters are made of materials with high Z which cause a shower to develop in order to measure its total energy. Calorimeters stop the particles completely

Strongly interacting particles (pions, protons, kaons, neutrons...) can form a hadronic shower.

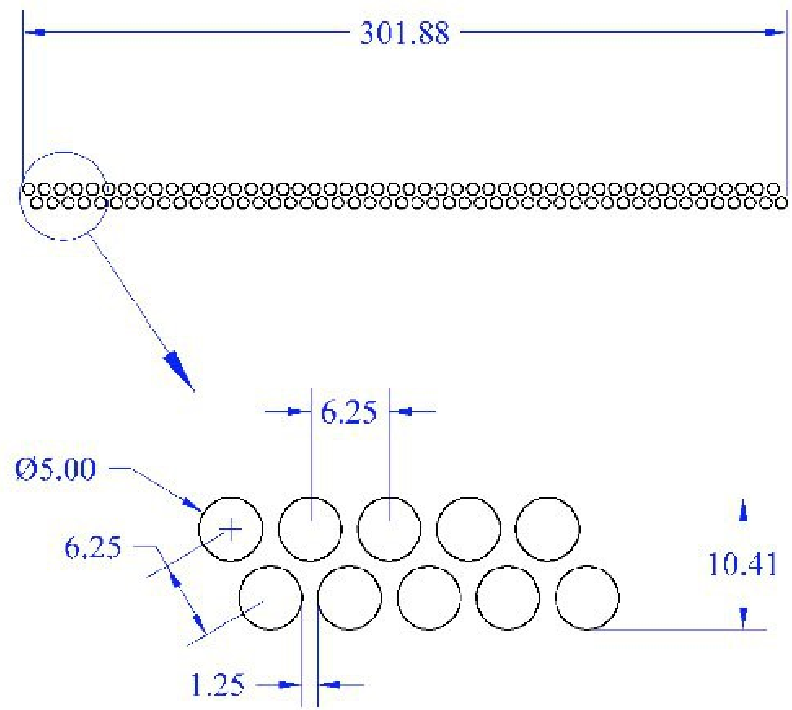


Mu2e detector



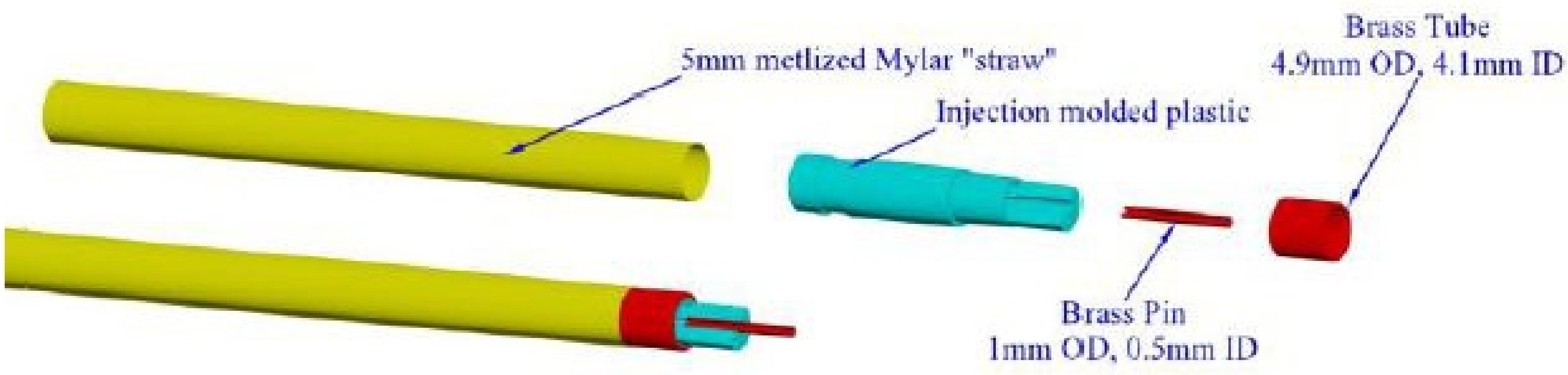
The Mu2e detector. In the detector solenoid we have first the tracker then an EM calorimeter. The muons and electrons spiral in the magnetic field as they travel through the three solenoids.

Mu2e tracker



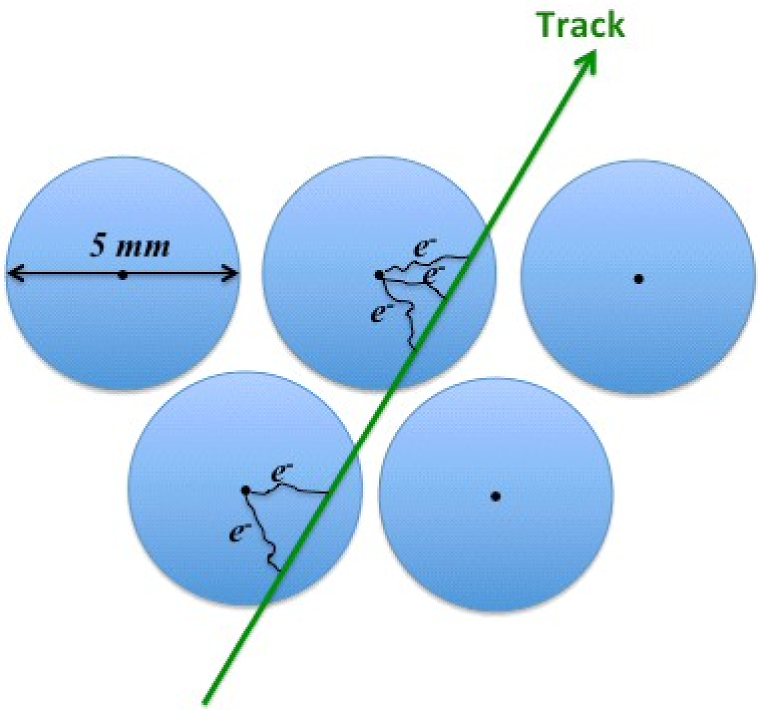
The Mu2e tracker will be made of ~20,000 straw tubes, each of which is 5mm in diameter. The straw is made of 15 micron mylar, and both the inside and outside have an aluminum coating. Inside is also another layer of gold for good conductivity. At the center of each straw is a gold-plated tungsten wire 25microns in diameter.

Mu2e tracker



Close-up view of the straw termination. We need 40,000 of these, one for each end.

Mu2e tracker



The tracker will operate in a vacuum, with 1 atmosphere of $ArCO_2$ gas (80%/20%) inside the straws.

A charged particle passes through the straws, leaving a trail of ions in its wake. The inner surface of the straw is at ground, and the sense wire at the center is a ~1500V positive voltage. The electrons then drift toward the sense wire.

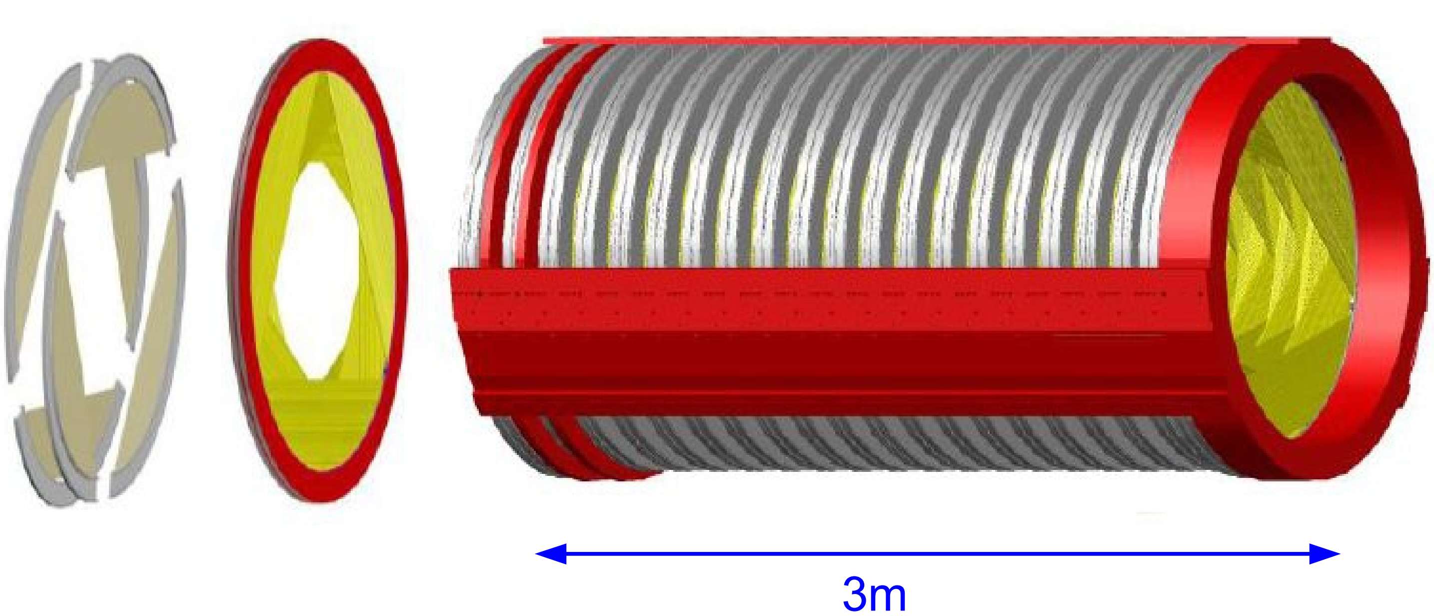
The electric field near the sense wire is strong enough that the electrons gain enough kinetic energy to ionize more atoms of the gas, creating an avalanche, which is then detected by the electronics.

Pop quiz: how does the electric field around the wire depend on r, the distance from the wire? The answer to this question explains why the diameter of the sense wire is so small.

Mu2e tracker

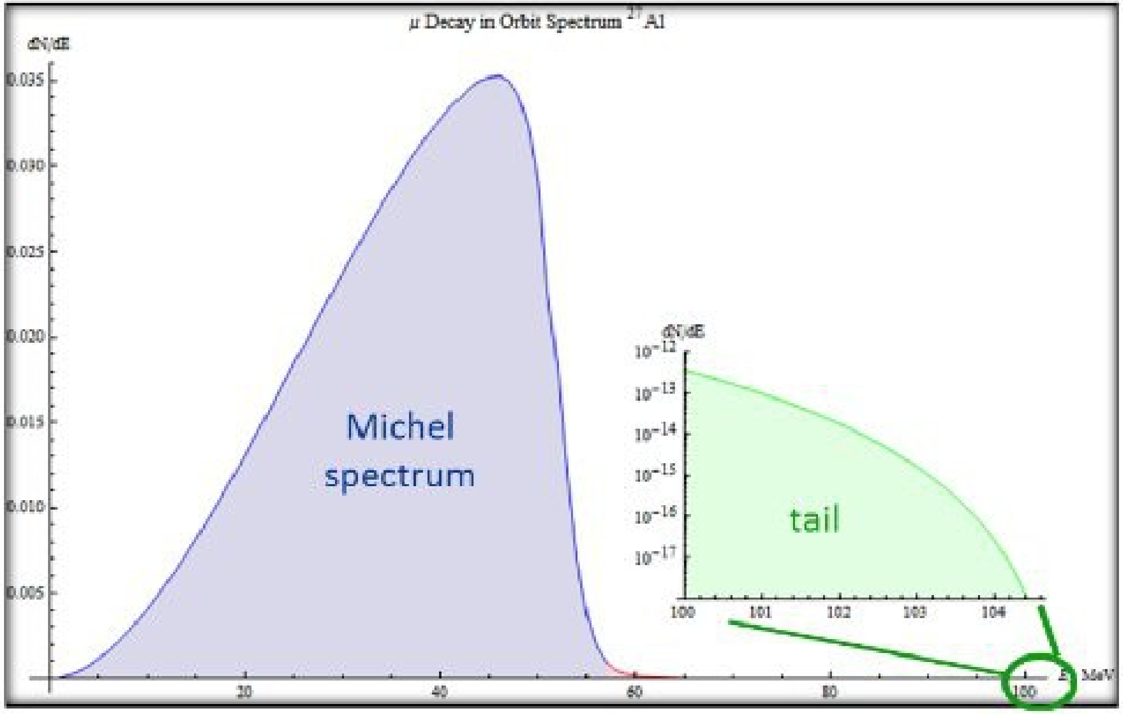
A panel covers an arc of 120 degrees and has 96 straws in two layers. We have made one prototype panel, which is currently in Lab 3 in the Village.

Mu2e tracker



Six panels from a plane, two planes form a station, and there are 18 stations in the full tracker which is 3m long. The entire Mu2e detector, including the tracker, operates in a vacuum, and in a 1Tesla magnetic field.

Decay in orbit background

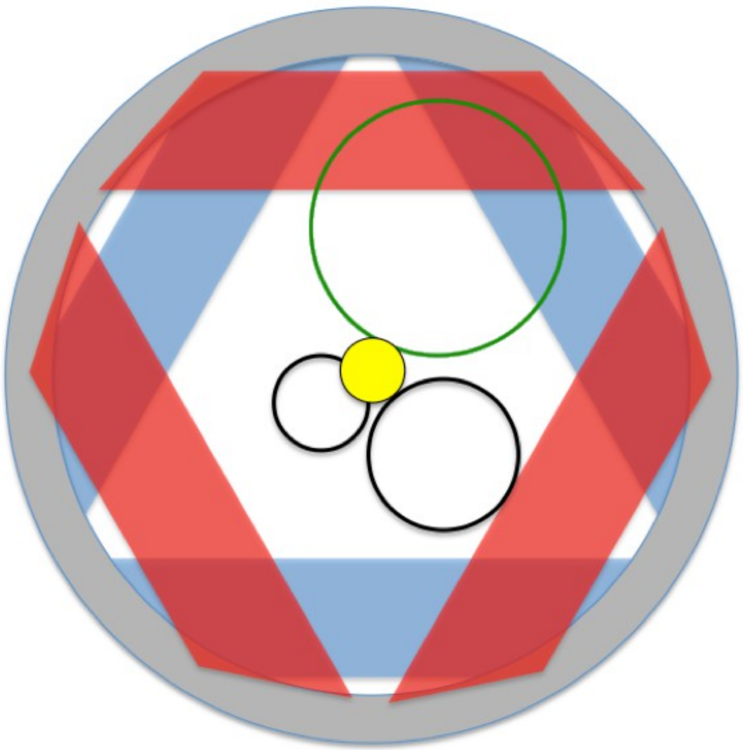


One of the major backgrounds is “decay in orbit”, in which the muon does its ordinary decay

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

This would not be a background except for the presence of the nucleus, which creates a tail.

Tracker geometry



green=signal electron
black=DIO background

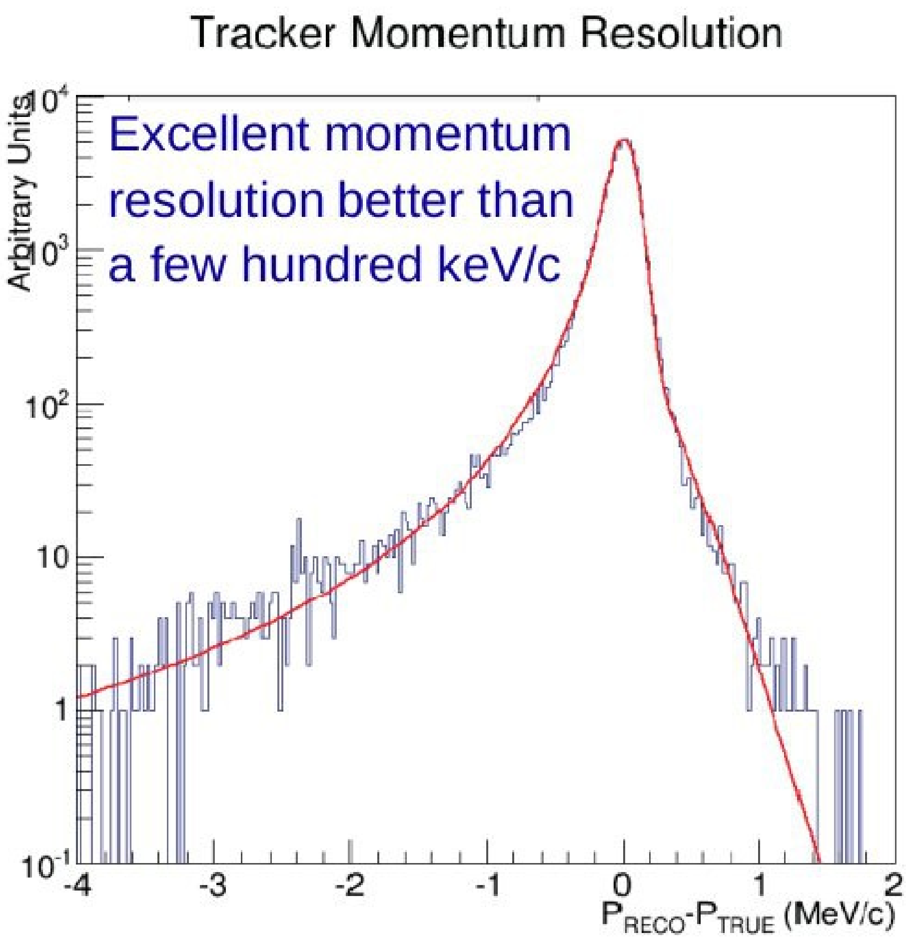
The tracker has a hole in the middle—why?

One of the major backgrounds is “decay in orbit”, in which the muon does its ordinary decay of

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Because the energy is shared between the final electron and two neutrinos, the electrons from DIO have lower momentum and therefore smaller radii of curvature. The geometry of the tracker is designed to be blind to more than 99% of the major background.

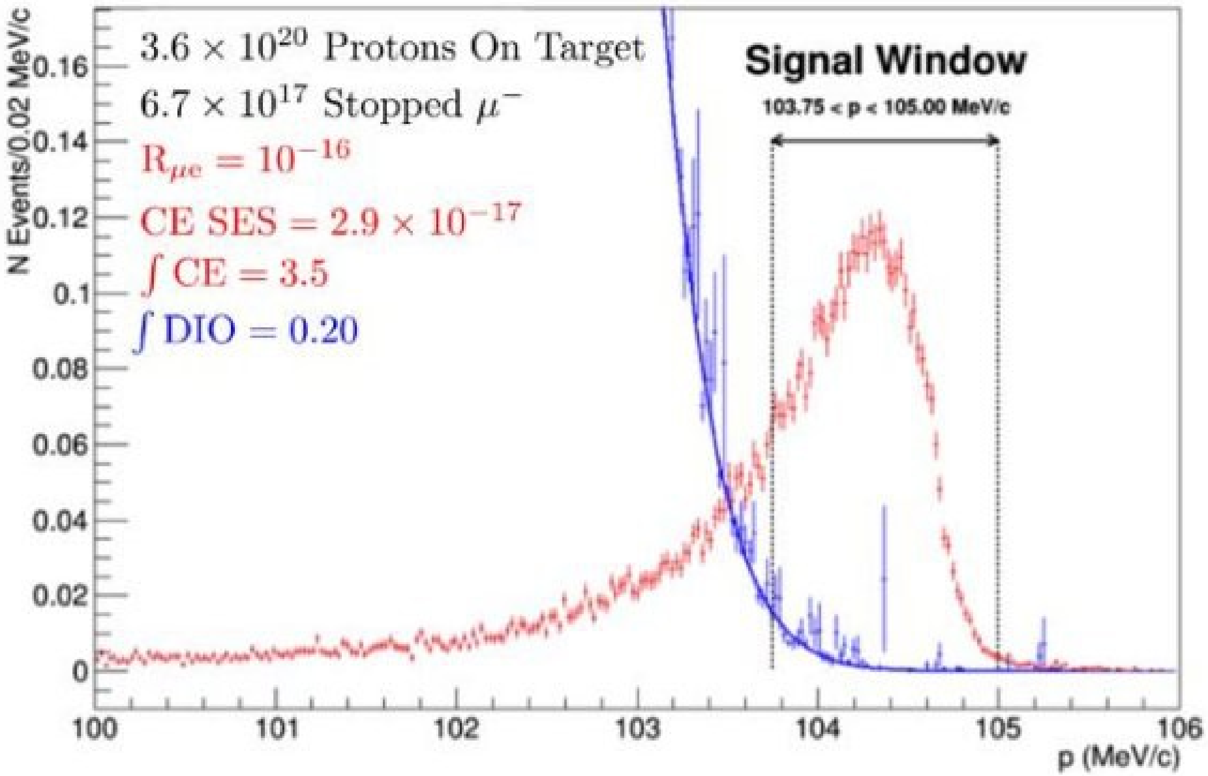
Momentum resolution



To separate the signal from DIO background, we need excellent momentum resolution, which simulations show we can achieve.

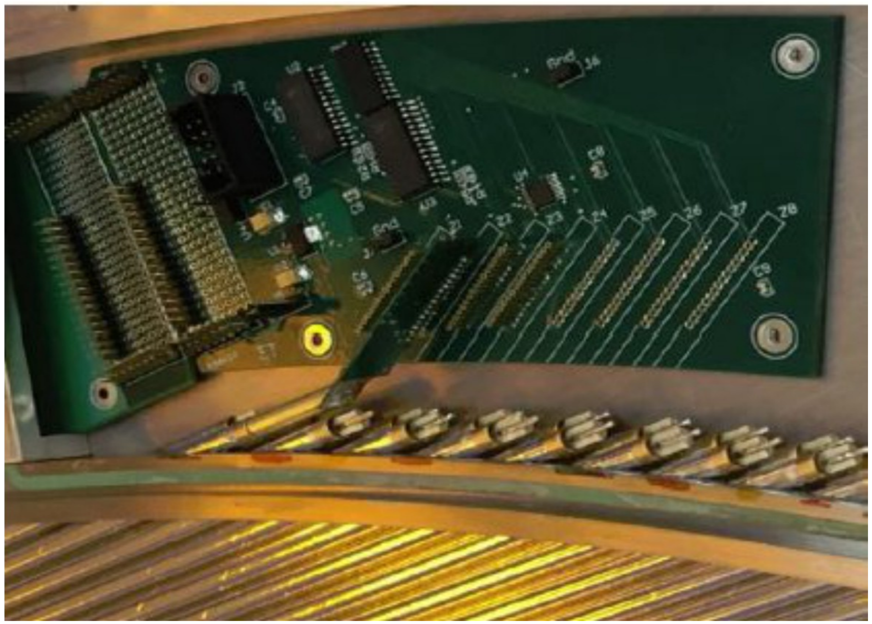
The reason the straws are so thin is to minimize the energy loss and multiple scattering as the electrons pass through the tracker material.

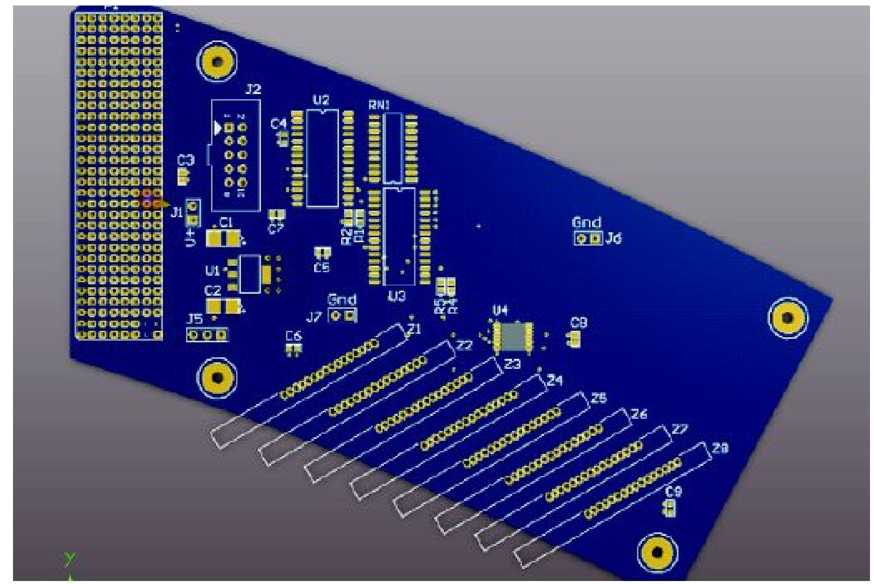
Expected signal and backgound



This is what we might see, if indeed there is a signal.

Tracker electronics

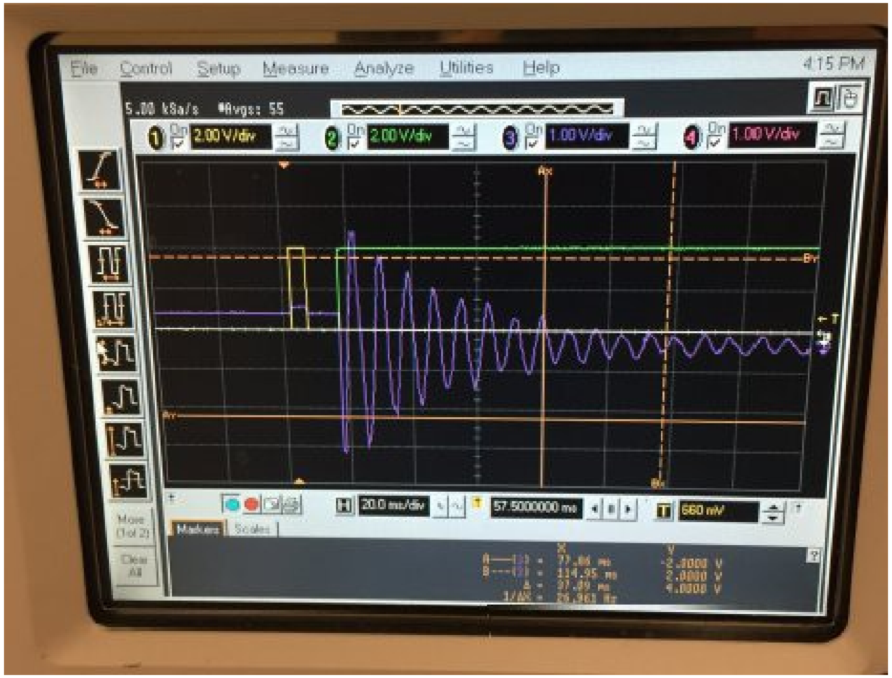


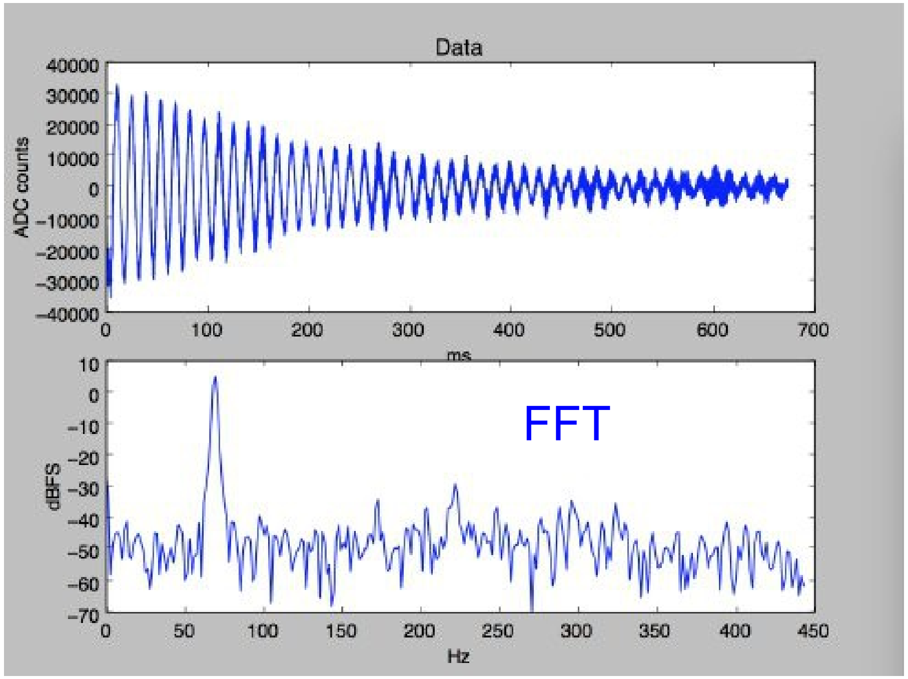


Preamp “mother board”

The straws are read out at both ends, so we need ~40,000 preamplifiers. We have prototypes for a few channels.

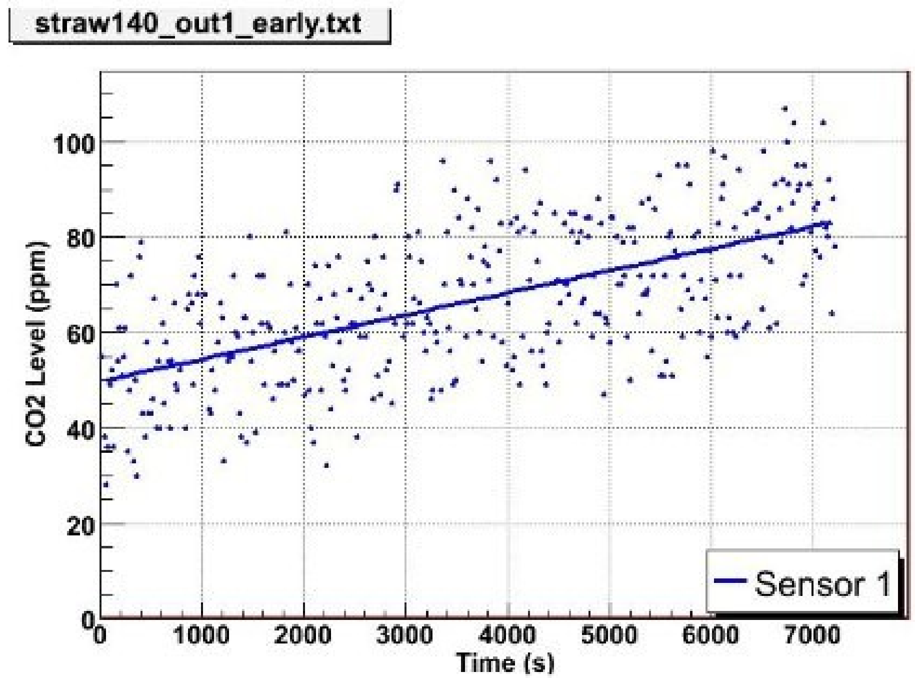
Straw tension measurements





Because the mylar stretches, we have to monitor the tension in the straws over time. We will use a resonance vibration method, extracting the tension from the measured frequency of vibration.

Straw leak tests



The tracker has to operate in vacuum, so the straws can't leak, and the gas manifold can't leak. We will leak-test all 20,000 straws using a method developed at Fermilab with a sensitive CO_2 detector.

Summary

The Mu2e tracker is the central to achieving the goals of the experiment.

It is a very low mass, high precision detector. No one else has built such a low mass detector which operates in a vacuum.

We are working on prototypes and expect to start construction of the first six (real) panels sometime this fall.