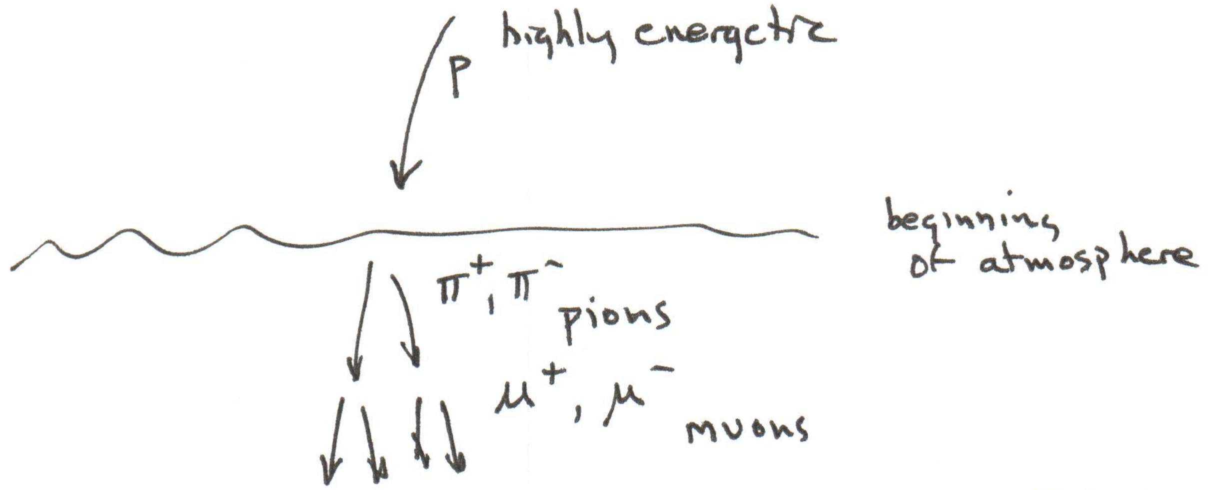
Muon Lifetime Measurement

Muons are elementary particles that are formed about 10 km above the Earth as cosmic rays, mostly protons, collide with the nuclei in the air



The muons travel mostly downwards toward Earth with very high energy in the 0.1 – 30 GeV range.

$M_\mu \simeq 200\ M_e$

$m_e \sim 0.5$ MeV

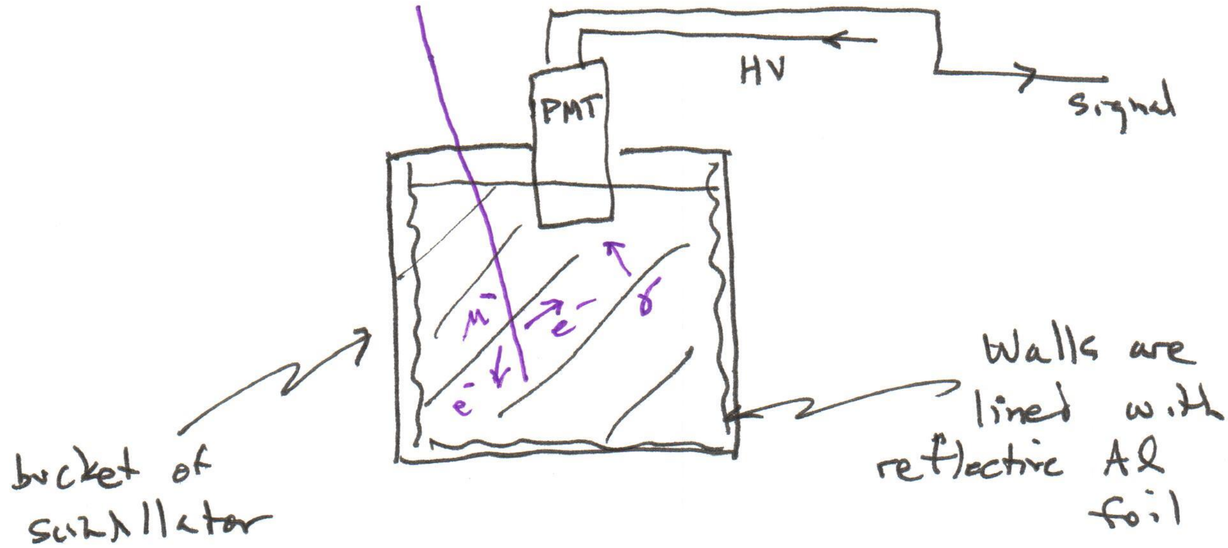
$M_\mu \sim 100$ MeV

Despite the increasingly dense atmosphere the are largely undeflected, and they don't suffer much Brehmstrahlung (braking) radiation as e^- would.

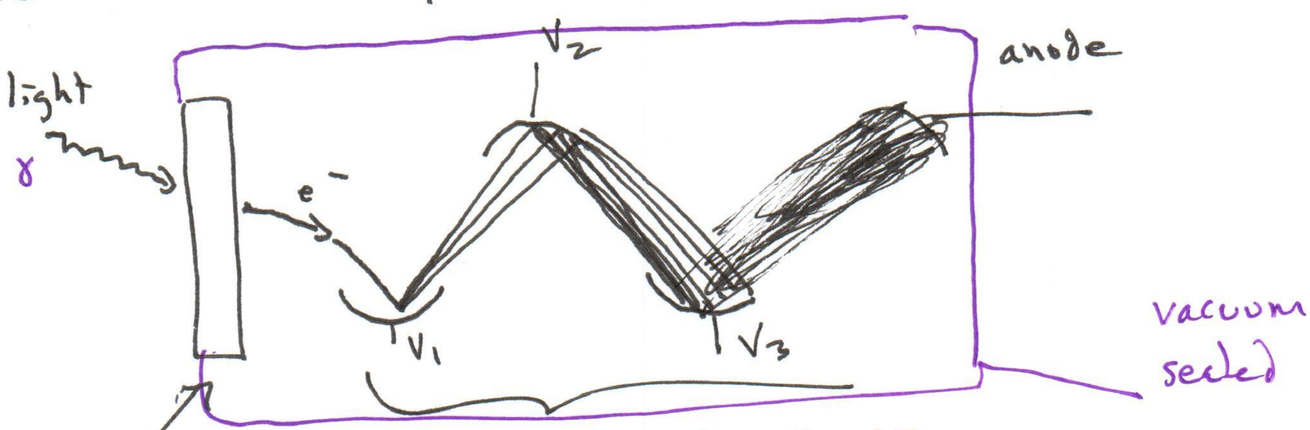
Flux is around $10{,}000/m^2$ at sea level, and somewhat higher as you climb up mountains (sorry, unavailable in Iowa).

We can capture a small fraction of these as they streak through Chemistry → Biology → Physics, Noyce basement

There we have a 5-gallon bucket filled with scintillator oil, a substance (typically anthracene ) that emits flashes of light, bursts of photons when ionizing radiation passes through.



We collect the light with a photomultiplier tube, here shown sideways:

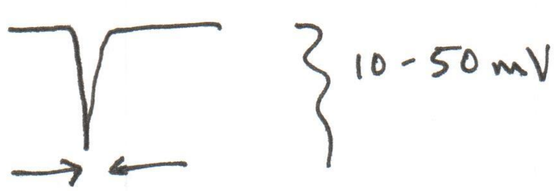


photocathode emits electrons

typically 8 – 12 dynode stages to give 3–5 x gain in number of electrons

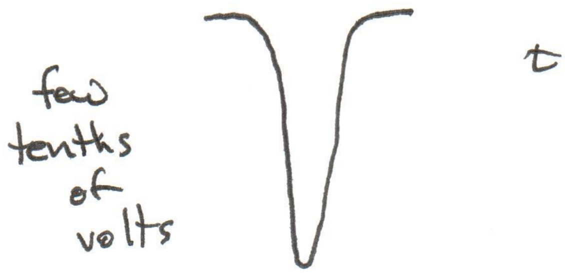
Held around ~ 100 V apart (i.e. $V_{n+1} - V_n \approx +100V$) to accelerate e^- between stages

Signals are small ; and fast



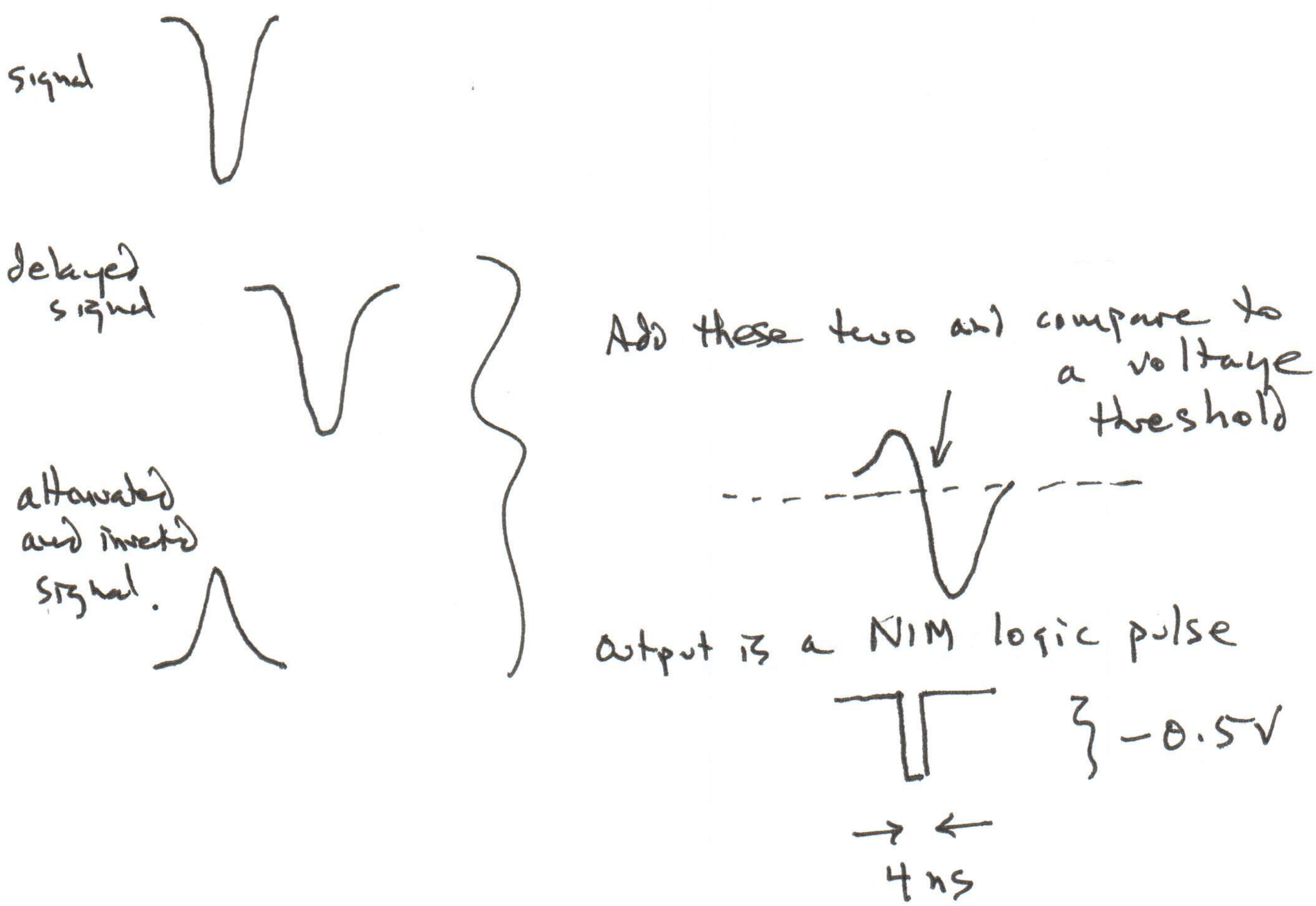
Cabling : use 50Ω cables to avoid reflections (recall Waves Lab)

These signals are still too small so we amplify them electronically, keeping them around 20 ns wide



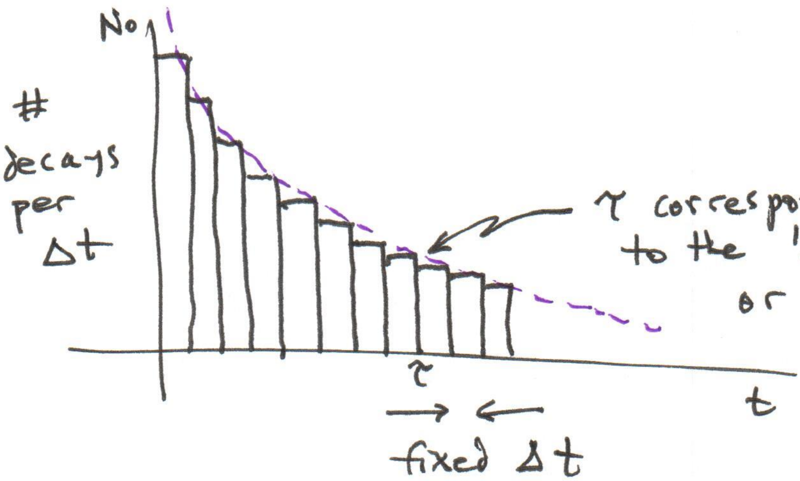
And then we send them through a constant fraction discriminator (there's a nice Wikipedia page showing how this works) in order to get arrival times that do not depend much on pulse height.

Cartoon sketch of a CFD operation:



An aside: how do you usually measure nuclear decay?

Start with a chunk of radioactive material and measure the number of decay events for fixed time intervals



$$N = N_0 e^{-t/\tau}$$

τ corresponds to the $1/e$ point, or about 37% of N_0.

In practice you find the mean lifetime τ by plotting on semi-log scale:

$$\ln\left(\frac{N}{N_0}\right) = \ln\left(e^{-t/\tau}\right)$$

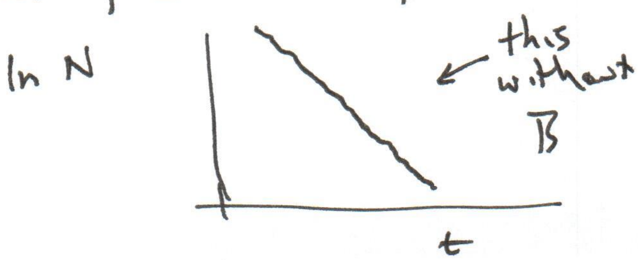
$$\ln N - \ln N_0 = -t/\tau$$

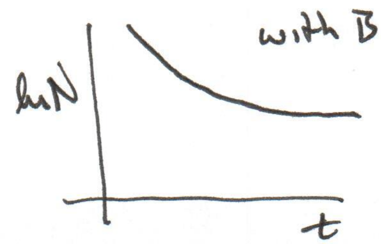
so plotting $\ln N$ vs t yields a slope of $-\frac{1}{\tau}$.

Also in practice, you might need to subtract off some background counts, because taking the log of

$$N = \left(N_0 e^{-t/\tau} + B\right)$$

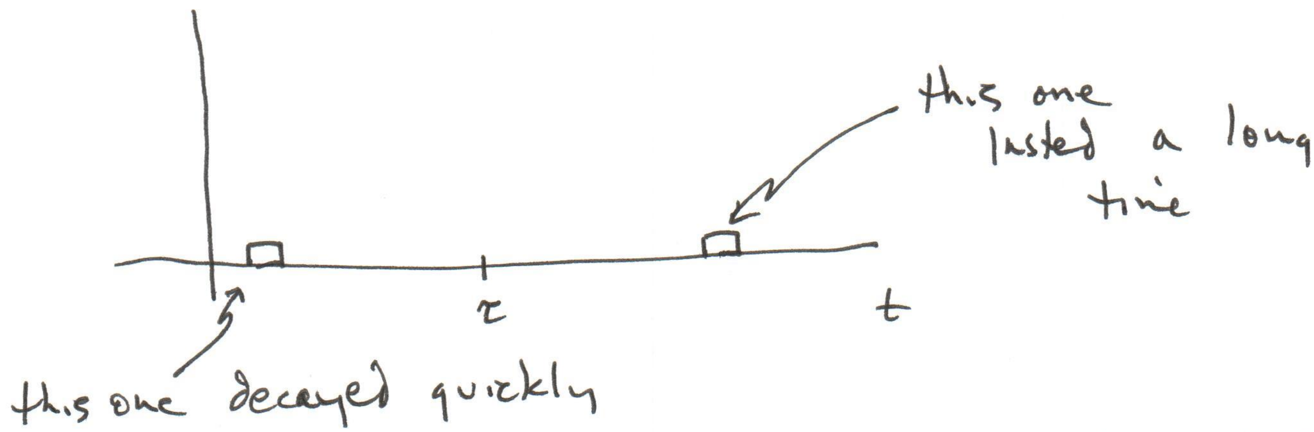
doesn't give a straight line unless you subtract B.





Alternative viewpoint of this radioactive decay plot:

What if you observed each nucleus and plotted its actual life on a histogram?



You would end up with the same plot as shown before. Most of them decay within about one mean lifetime τ.

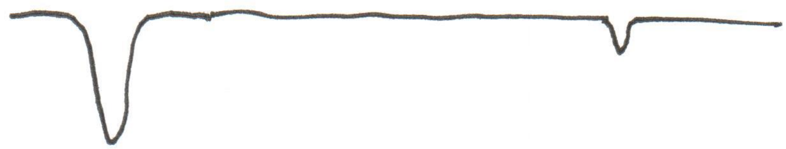
This is what we do here. A single muon enters the bucket and happens to get stopped. It is now at rest in the lab frame (famously, we get so many muons hitting the Earth because in their frame the 10 km distance to the ground is length-contracted, a striking illustration of Special Relativity), and so we can measure its proper lifetime by starting a clock.

And then we wait until the muon decays, typically

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

which gives off a second burst of photons that stops our clock.

Here's why we need a CFD: 1^{st} pulse is big (because the muon loses 100s of MeV in stopping) but second is smaller because only energy available is difference between muon mass and electron mass, and we don't see the neutrinos.



arrives and stop   decays, electron released

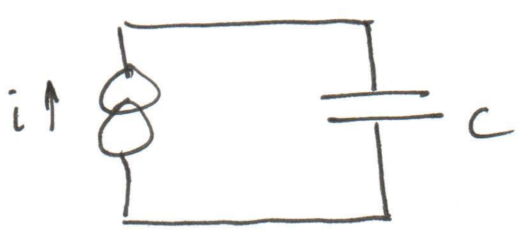
CFD

START   STOP

} NIM logic signals "nuclear instrumentation module"

I've labeled the pulses as time-ordered pairs.

Next we send the pulse pairs to a Time-To-Amplitude Converter (TAC). Upon receipt of a START signal it starts to charge a capacitor in a linear ramp. This is done by applying a constant current to the timing capacitor:



Recall $C = \frac{Q}{V}$

thus $V = \frac{Q}{C}$

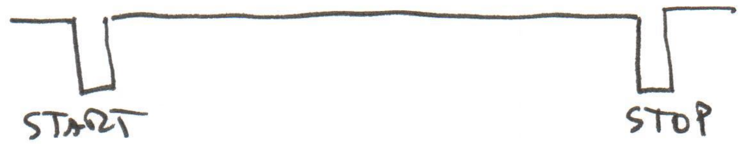
and hence $\frac{dV}{dt} = \frac{1}{C}\frac{dQ}{dt}$

$$\frac{dV}{dt} = \frac{i}{C}$$

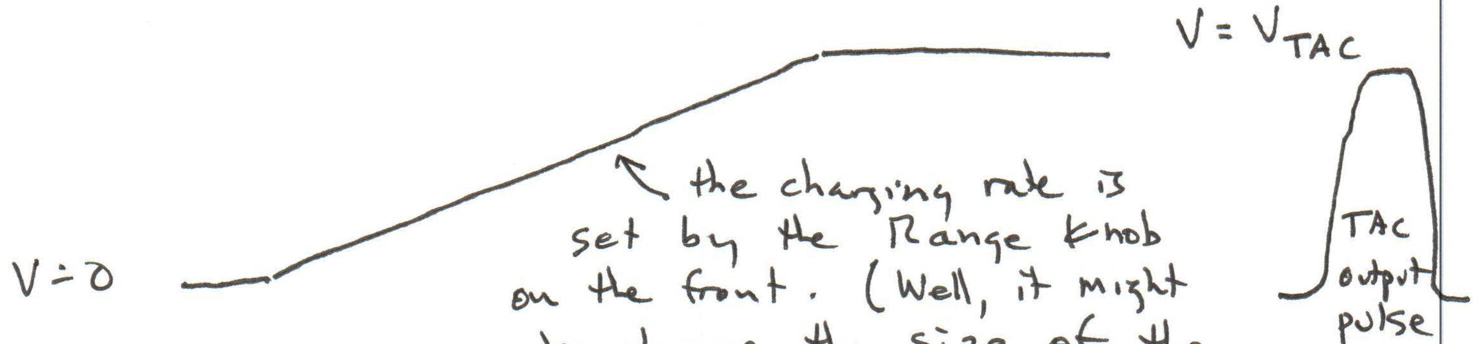
and so $V = \int \frac{i}{C}\,dt + V_0$

we set to 0.

Internally it does this :



[If no STOP appears, the TAC resets and begins to accept the next pulse as a START]



the charging rate is set by the Range knob on the front. (Well, it might also change the size of the timing capacitor, but not to worry)

TAC settings : typically we select a Range of 50 μs full scale. It's a linear device, so $\Delta t = (t_{STOP} - t_{START})$ in the 0 – 50 μs time range will give a V_{TAC} of 0 – 10 Volts.

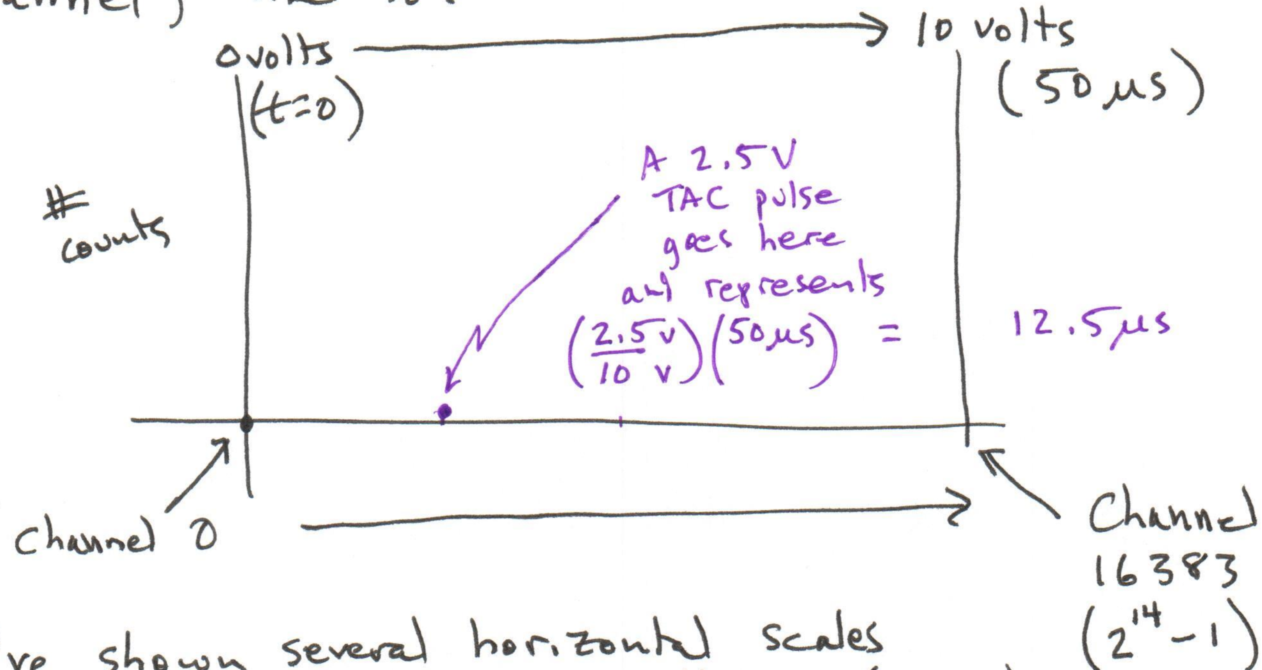
e.g. A 5 μs Δt yields $V_{TAC} = 1.0$ V.

Why do we set such a long Range when we are looking ~~for~~ at particles with $\tau \approx 2\ \mu s$?

We care a lot about capturing the events at the beginning, but we have to account for any baseline.

By looking over a range of > 20 lifetimes we make sure that no real muon decays occur at long stopping times (Try this : what is $Ne^{-\frac{20\tau}{\tau}}$? What fraction of a count would you see ?)

Now we have all the pieces except for storing the data. You'll see that the TAC puts out a pulse of height V_{TAC} that is between 0 and 10 V tall. We send that to the multichannel analyzer (MCA), which is just a high-speed digitizer. It measures the pulse height, and then sorts it into a bin (called a channel) like so:



I've shown several horizontal scales corresponding to the actual voltage (0-10V), the range set on the TAC (0-50µs), and the channel into which that TAC pulse gets put.

That's it for the data acquisition. We now just collect for a long time and watch the decay curve appear.

I will download the MCA raw data on Sunday night.