Test of Quartz Radiators: Mu2e Precision Time Profile Monitor

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Abstract:

Mu2e will look for neutrino-less conversion of a muon to an electron by capturing a muon around an aluminum nucleus. Expected backgrounds occur shortly after proton arrival, and can be eliminated utilizing a pulsed beam with precise timing. The ratio of out of time protons to in time protons is referred to as the "extinction" of the beam, and must be kept below 10^{-5} in the Recycler and 10^{-10} at the Production Target. The Precision Time Profile Monitor (PTPM) will measure the time structure in the Recycler and upstream of the AC dipole. Here we conduct a beam test of Quartz Cherenkov Radiators for this PTPM to examine their response to 120GeV relativistic protons. The Quartz Radiators had about 99% detection efficiency with a time resolution of about 1ns. We estimate after pulsing to produce false signals at a rate less than $2 \cdot 10^{-18}$.

Introduction:

Weak Force Decay (common) | **Direct Conversion (signal)**

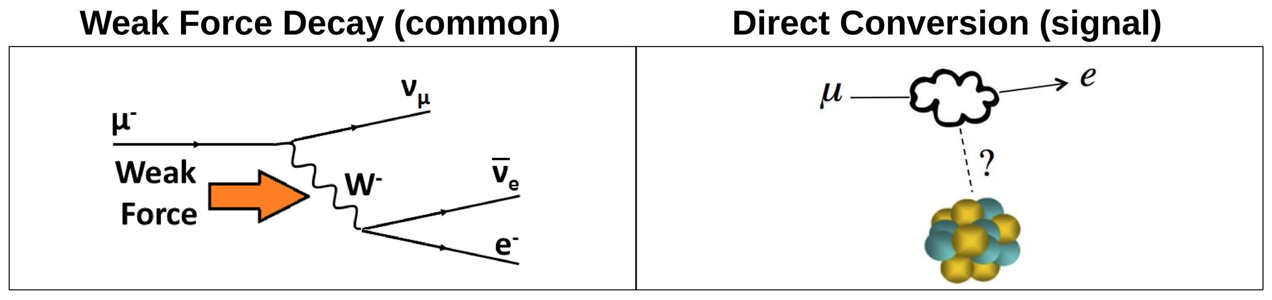


Figure 1: Mu2e will search for Charged Lepton Flavor Violation (CLFV) in the form of a neutrino-less conversion of a muon to an electron plus a photon or other particle ($\mu \rightarrow e + \gamma$).

Mu2e Apparatus

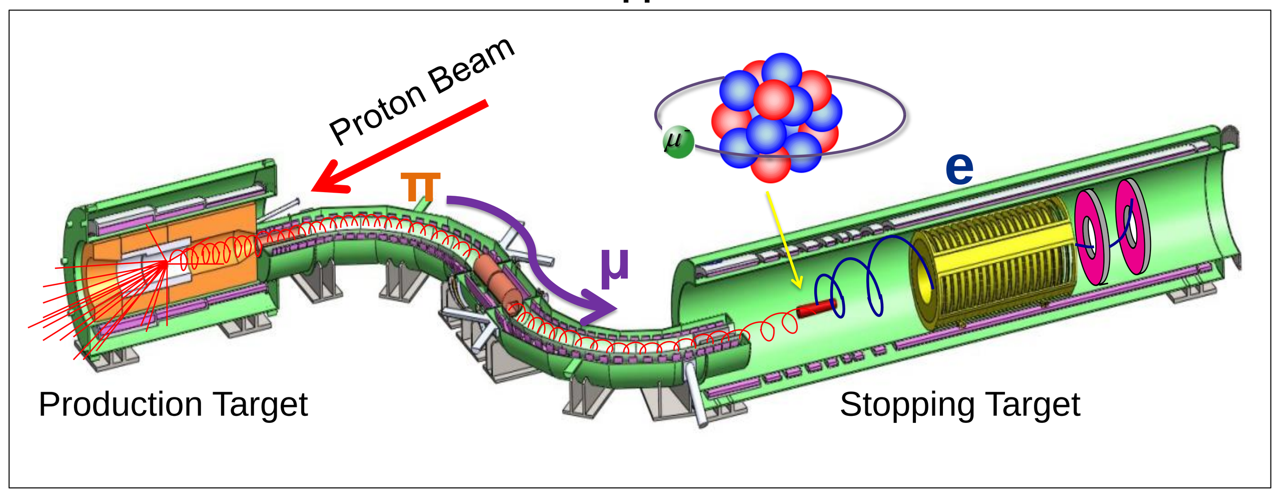


Figure 2: Mu2e will collide protons into a stationary production target that produces pions which decay into muons. The muons can then be captured by aluminum nuclei in the stopping target. If the muon converts into an electron by exchanging a photon with the nucleus, an electron will be released at a distinctive energy of 105MeV. However, pions can also be captured by the aluminum nucleus. The pion can release high energy photons that pair convert to electrons and positrons around the signal energy. This type of background is called "radiative pion capture."

Using Timing to Avoid Backgrounds

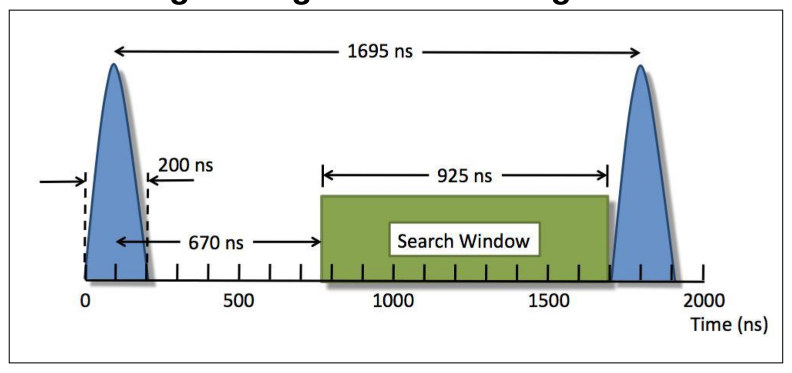


Figure 3: By limiting your search to after all pions have decayed, backgrounds from radiative pion capture are avoided. However, pions produced from out of time protons are not avoided. Thus the extinction of the beam must be very high to eliminate out of time protons.

Mu2e Precision Time Profile Monitor

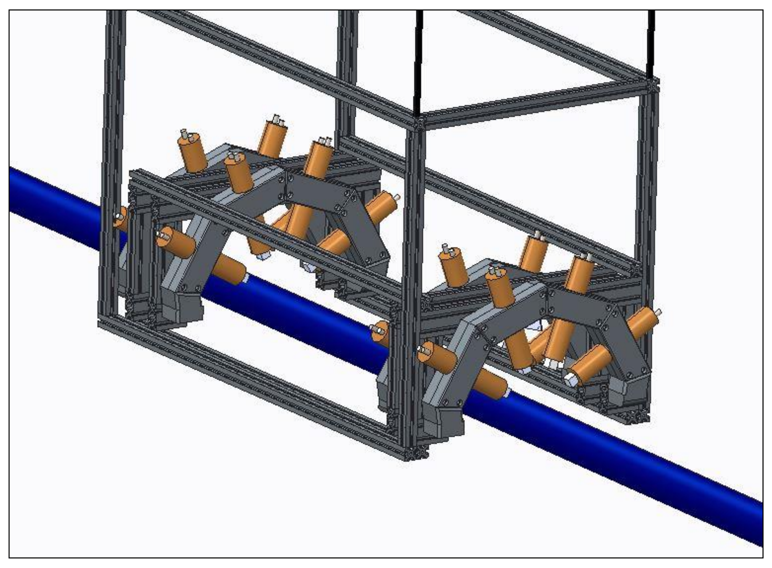


Figure 4: This PTPM will monitor the extinction rate of the proton beam in the Fermilab Recycler to 10^{-5}. The PTPM will consist of four arms of four Quartz Cherenkov radiators to detect protons scattered off a thin target in the beam. From this we can produce a statistical profile of out-of-time protons. Another detector will measure the final extinction of the beam at the production target to 10^{-10}.

Quartz Cherenkov Radiators

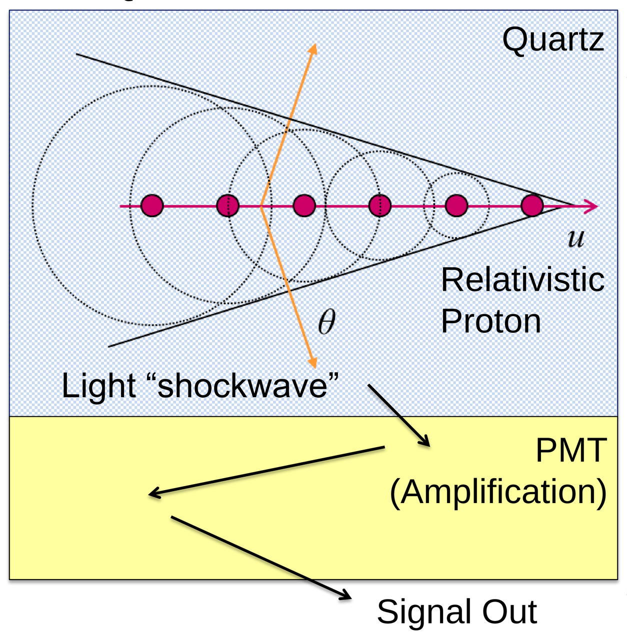


Figure 5: Quartz Cherenkov Radiators produce Cherenkov light. Cherenkov light is produced when a proton travels through a medium faster than light can travel in that medium. This produces a light "shockwave" that can be amplified by the attached photomultiplier tube (PMT). Quartz Cherenkov Radiators were chosen for this application because they are insensitive to soft backgrounds and do not have much afterglow after large signals. However, they do produce smaller signals than traditional scintillators. A major goal of this beam test is to ensure the signal produced is large enough to fit our needs.

Apparatus:

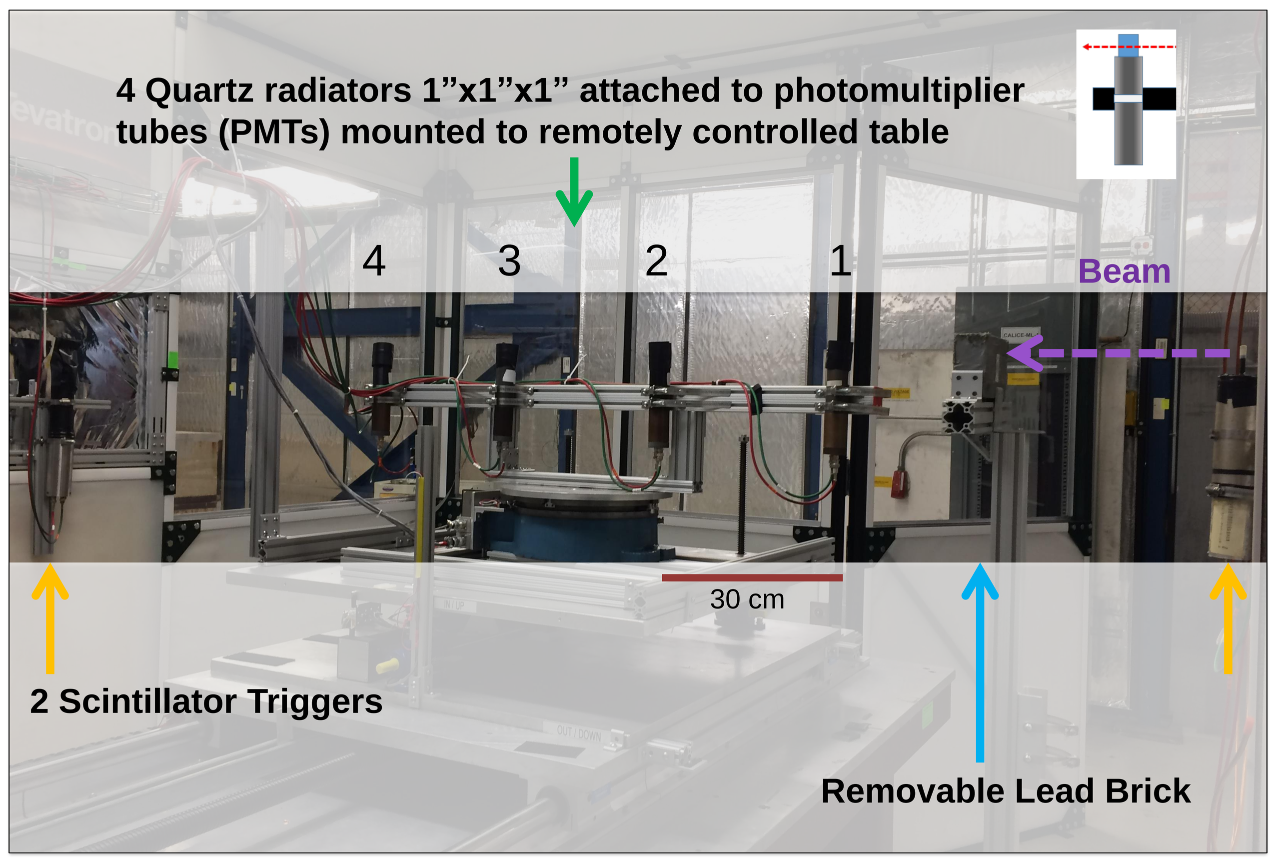


Figure 6: Our beam test was conducted at the Fermilab Test Beam Facility (MTest) using 120 GeV protons. Coincidence of two scintillators shown, as well as three scintillators in the test beam hall were used as a trigger. The data shown was taken at low intensity (~2000 triggers/spill), with the lead brick absent.

Results and Discussion:

Signals versus Background

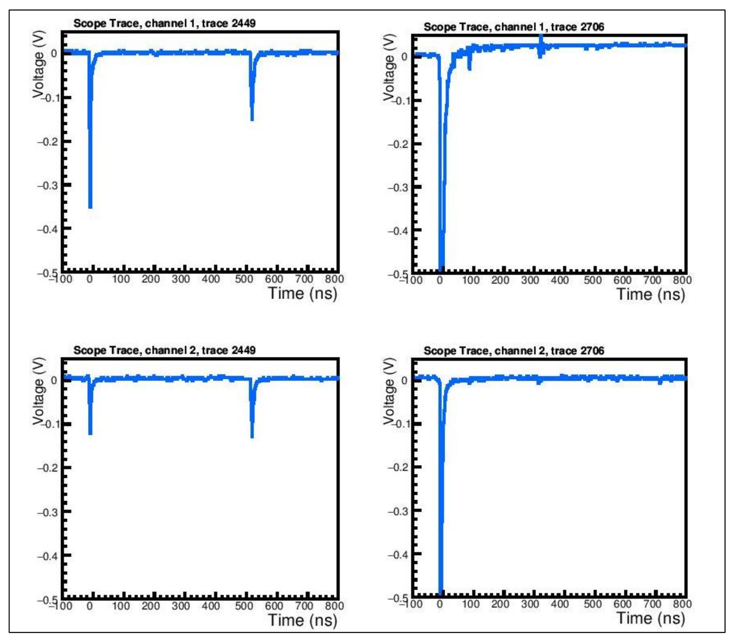


Figure 7: Two events displaying an in time signal (left) and an out of time signal or background (right). In time signals typically produce signals in all four tracks (two shown here) and are from out of time protons. Out of time backgrounds may come from electronic noise, cosmic rays, or after pulsing, and are more likely to appear only in one track.

Signal Arrival Times – In Time Protons

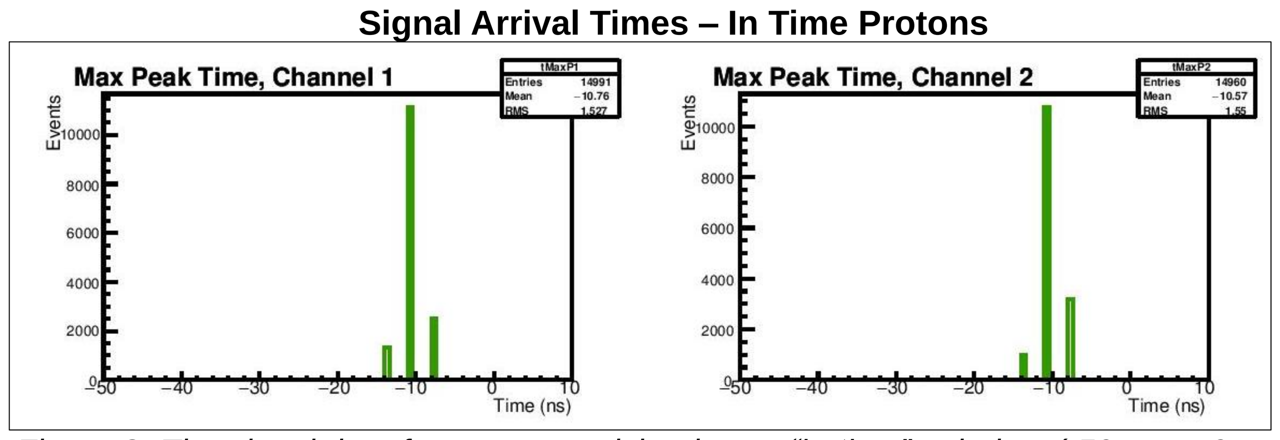
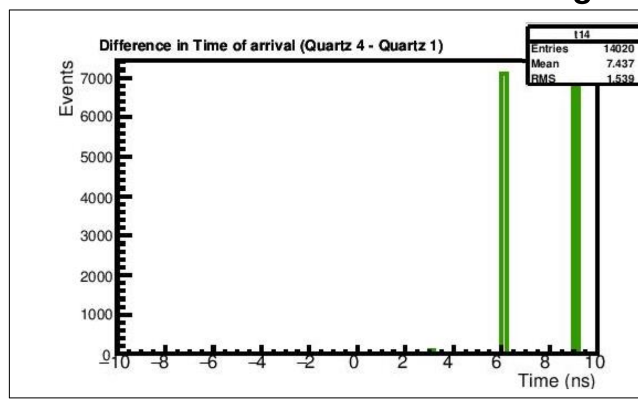


Figure 8: The signal time for protons arriving in our "in time" window (-50 ns to 0ns for Quartz 1,2,3 and -50ns to 10ns for Quartz 4). The signals appear to arrive before the trigger (0ns) because the Quartz signals passed through less wire/electronics to arrive at the oscilloscope.

Timing Resolution



$$\delta^2_{(t_4 - t_1)} = \delta^2_{(t_4)} + \delta^2_{(t_1)}$$

$$\text{If } \delta^2_{(t_4)} \approx \delta^2_{(t_1)} \approx \delta^2_{(t)}$$

$$\delta_{(t_4 - t_1)} = \sqrt{2}\,\delta_{(t)} \leq 1.539\text{ns}$$

Timing Resolution:

$$\delta_{(t)} \leq 1.09\text{ns}$$

Figure 9: The timing resolution was calculated for a single channel using the RMS of the difference in arrival times between two channels. The difference between channels 1 and 4 had the largest RMS (1.539ns).

Signal Heights – In Time Protons

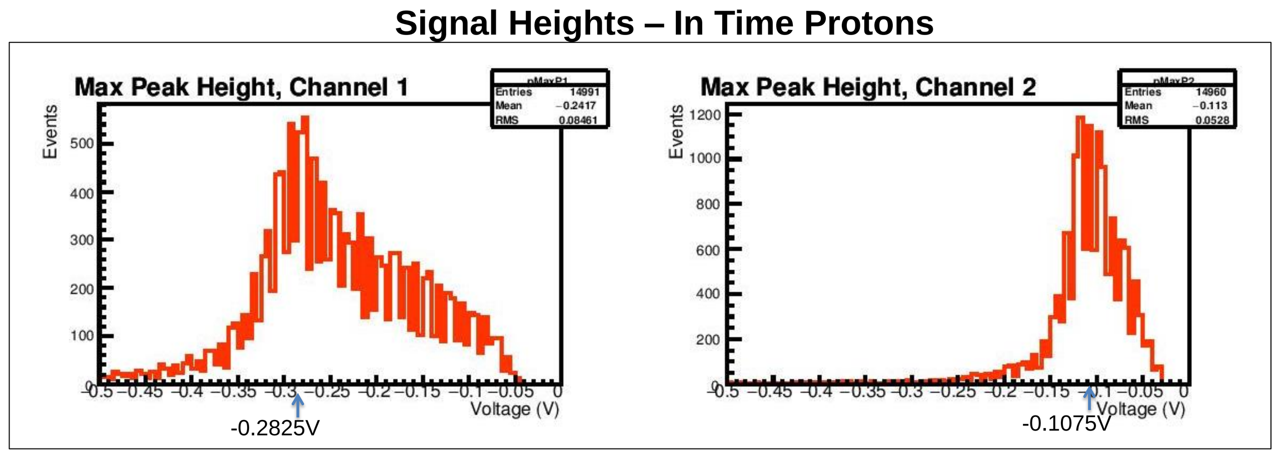


Figure 10: The signal amplitudes follow an approximately Gaussian distribution that is different for each channel. Quartz 3 and 4 (not pictured) had a mean of -2.091V and -1.227V, and maximum at -.2325V and -.1225V respectively.

Determining Thresholds

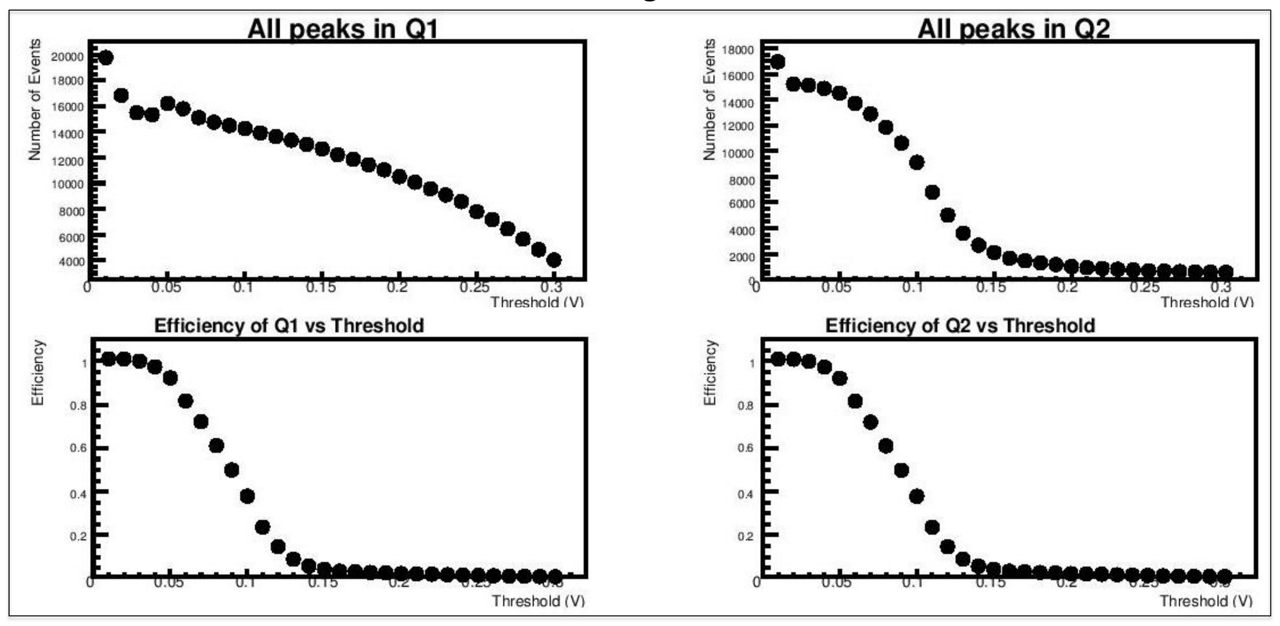


Figure 11: The number of signals ("peaks") above threshold is graphed for thresholds between .01V and .3V in Quartz 1 and 2. There is a slight dip in Quartz 1 between .03V and .04V due to peak structure. The resultant efficiency is also graphed, and falls off steeply after .04V and .03V respectively. From these plots, we decided to set thresholds of .04V, .03V, .04V and .03V for Quartz 1-4 respectively.

Efficiency

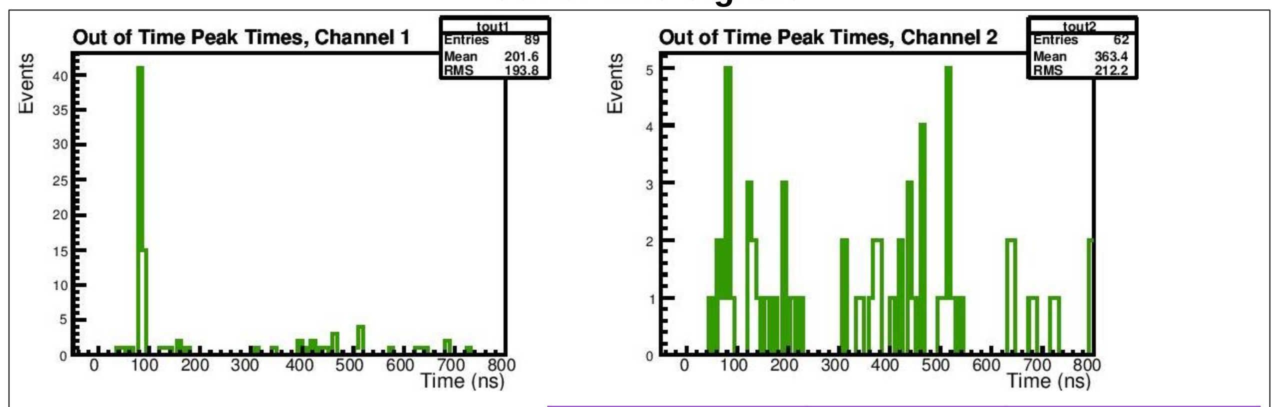
$$\text{Efficiency}_{\text{Quartz (\#)}} = \frac{\text{Number of Quadruple Coincidences}}{\text{Number of Triple Coincidences in other Three Channels}}$$

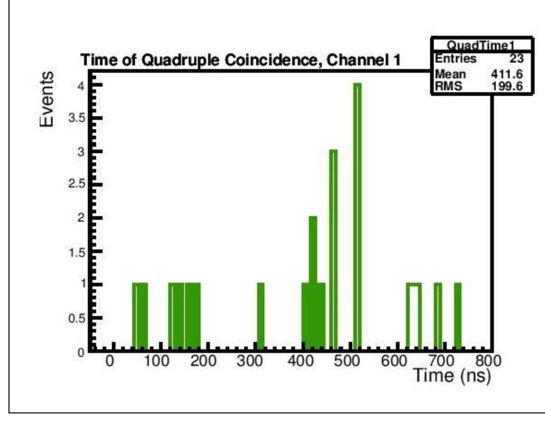
$$\text{FourFold Efficiency} = \text{Efficiency}_{Q1} \bullet \text{Efficiency}_{Q2} \bullet \text{Efficiency}_{Q3} \bullet \text{Efficiency}_{Q4}$$

15000 events	Quadruple Coinc.	Triple Coinc.	Efficiency
Quartz 1	14771	14775	(99.97 ± .02)%
Quartz 2	14771	14804	(99.78 ± .02)%
Quartz 3	14771	14792	(99.86 ± .02)%
Quartz 4	14771	14912	(99.05 ± .02)%
Four-Fold Efficiency			(98.67 ± .05)%

Figure 12: The efficiency of our detector was very close to unity.

Out of time Signals





26000 events	Out of Time Signals	Probability
Quartz 1	89	.00342 ± .00004
Quartz 2	62	.00238 ± .00004
Quartz 3	130	.00500 ± .00004
Quartz 4	30	.00115 ± .00004
Pred. 4-Coinc.	0	$(4.7 \pm .4) \cdot 10^{-11}$
Obs. 4-Coinc.	23	.00088 ± .00004
Obs. Self-Coinc.	0	$<2 \cdot 10^{-18}$ (for 4 channels)

Figure 13: Time distribution and counts for out of time signals (40ns to 800ns). Arrival time is nearly random, especially for 4-coincidences. There may be after pulsing occurring at a low rate around 100ns for Quartz 1 and 3. I tested how often a record with an out of time signal had a out of time signal in the previous record of the same channel. This never occurred in our data set, and thus this effect has at worst a $2 \cdot 10^{-18}$ probability of producing a false 4-coincidence.

References:

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[6] D. Hedin, E. Prebys, "Technical Scope of Work for the 2016 Fermilab Test Beam Facility Program," Beams-doc #5203-v1.

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Mu2e