Beam Test of Quartz Radiators for Mu2e Precision Timing Profile Monitor

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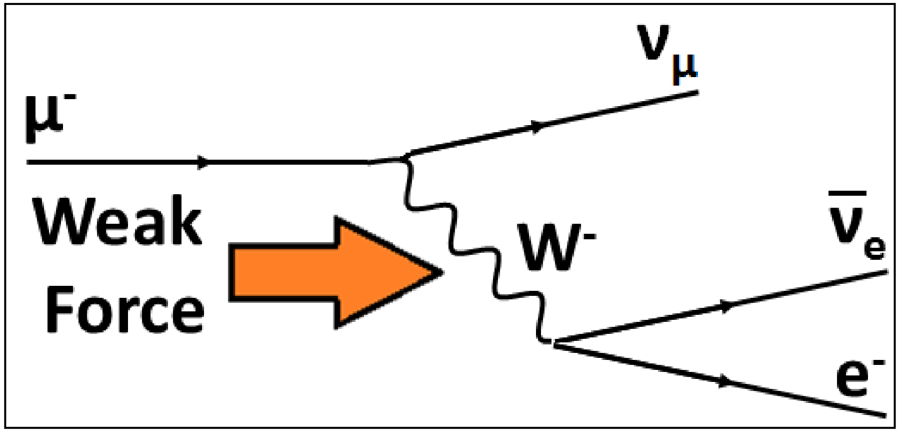
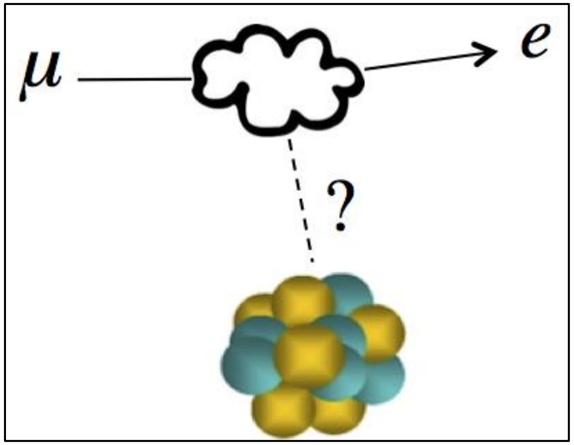
Mu2e

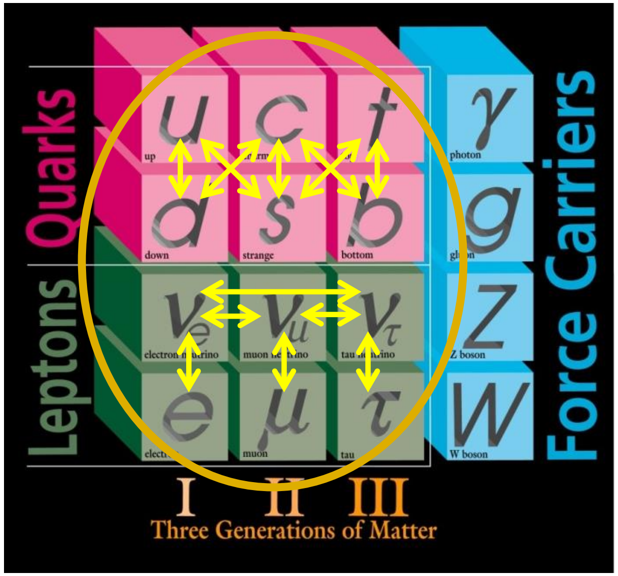


Weak Force Decay (common)

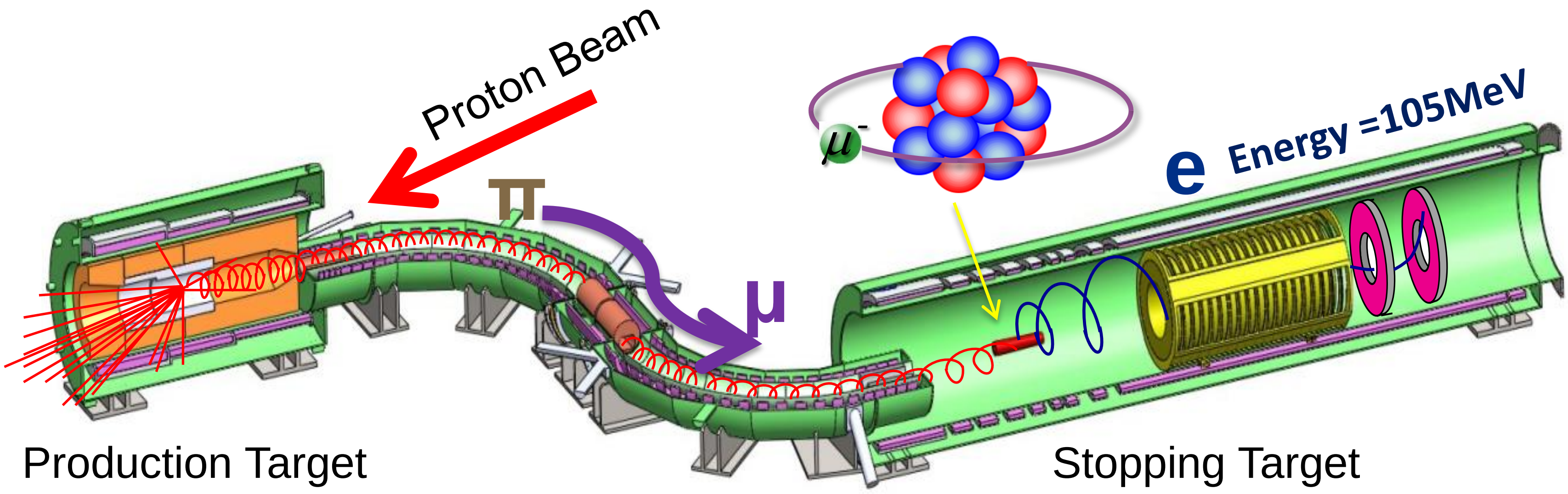


Direct Conversion (signal)

- Search for Charged Lepton Flavor Violation (CLFV) in the form of neutrino-less muon to electron conversion (μ → e + γ).
- Neutrinos mix, quarks interconvert, why not leptons?

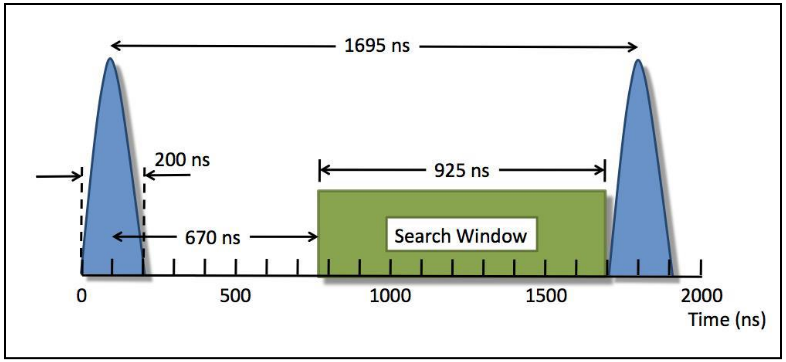


Mu2e



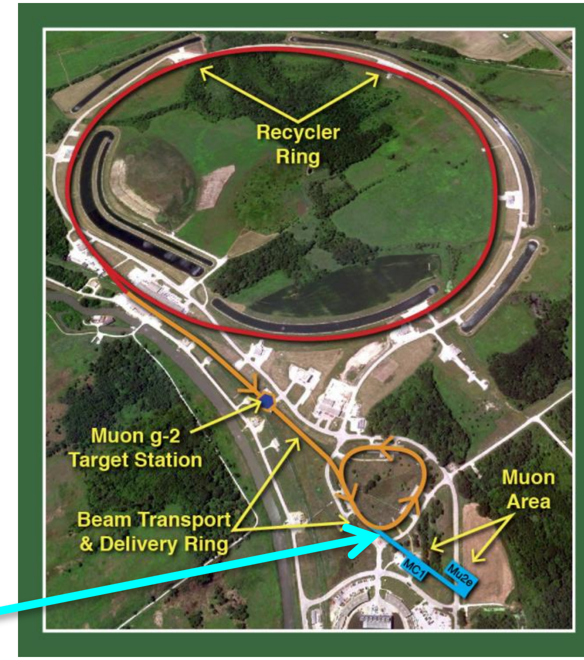
- Collide protons into production target, produce pions that decay into muons
- Capture muons around aluminum nuclei
- If a muon converts to an electron by exchanging a photon (or other particle) with the nucleus, the electron will be given off at 105MeV

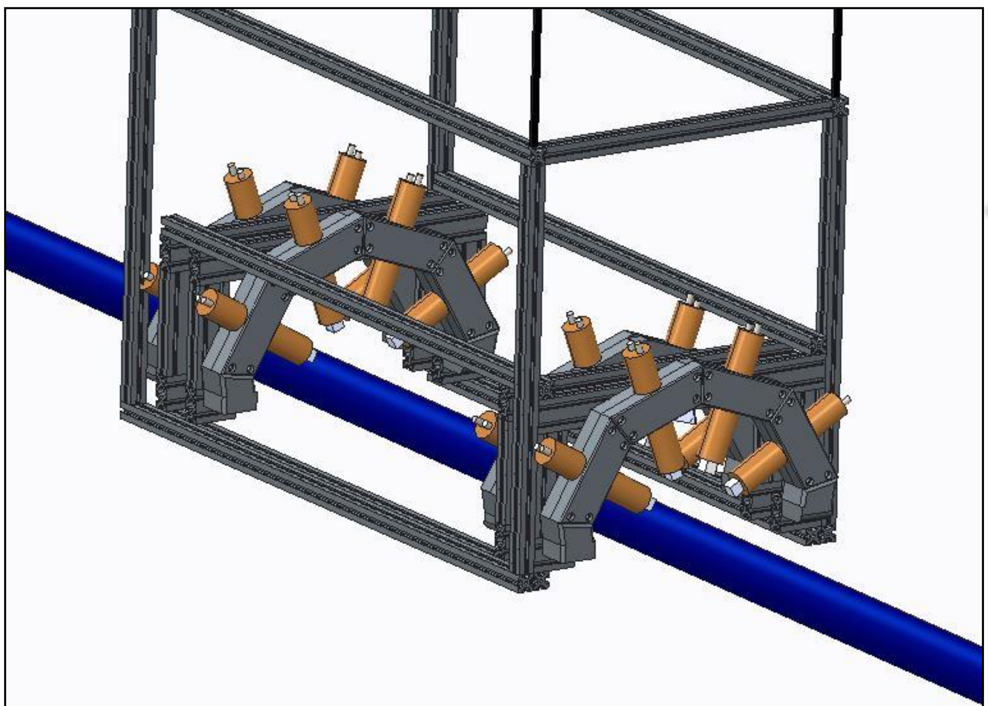
- Limit search to after background products have decayed
- Out of time particles may still appear in this window -> Precision Timing required!



Precision Beam Timing Monitor

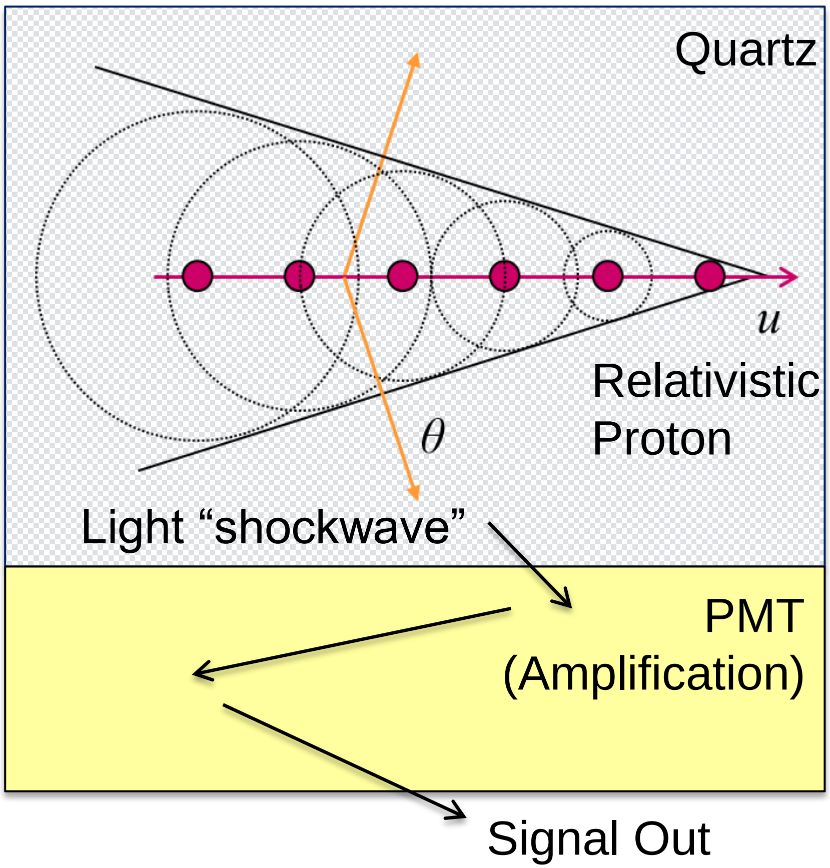
- Ratio of out of time protons to in time protons ("extinction") must be 10^{-5} in the recycler and delivery ring, and 10^{-10} at production target





- Upstream monitor (left)
    - 4 arms with 4 Quartz Cherenkov Radiators each
    - Detect protons scattered off a thin foil in the beam
    - Build statistical profile of out of time protons

Quartz Cherenkov Radiators



Cherenkov light produced when a charged particle travels faster than light can travel in a medium

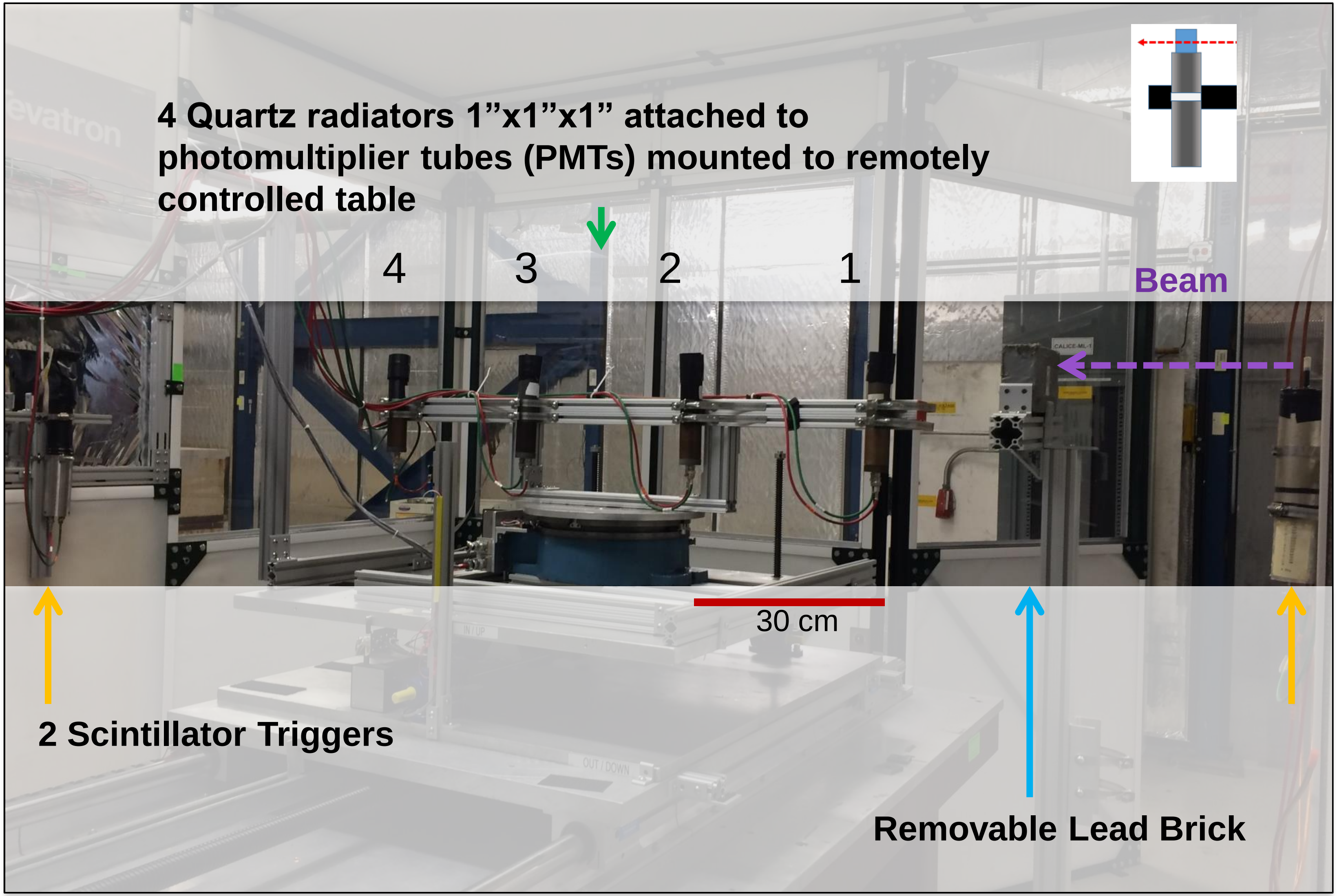
Advantages over Scintillators:

- Insensitive to low energy backgrounds
- Low afterglow after large signals

Disadvantage:

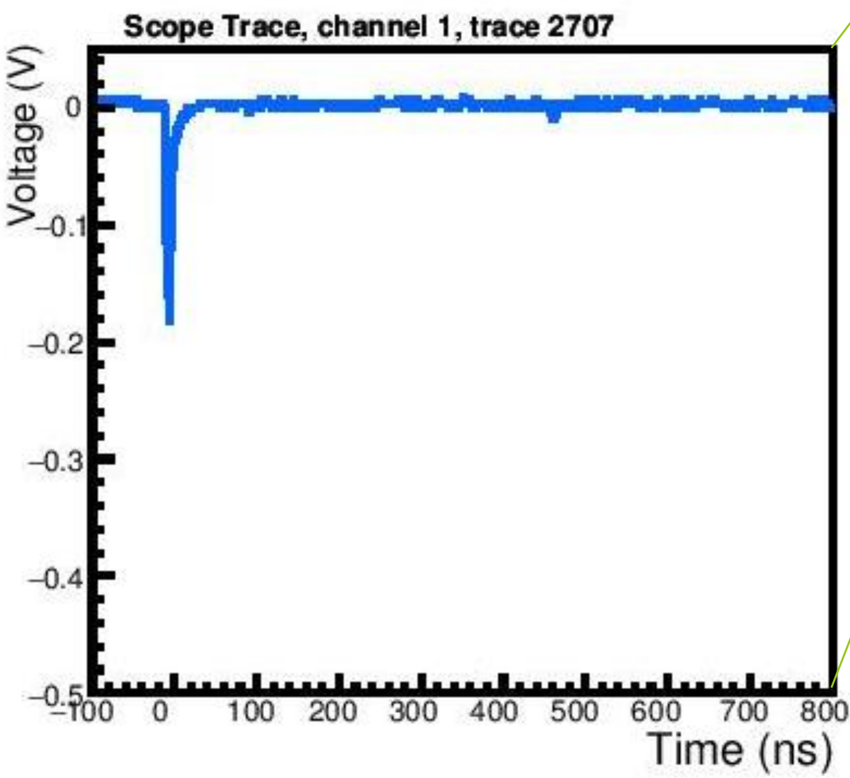
- Smaller signal

Beam Test Setup:

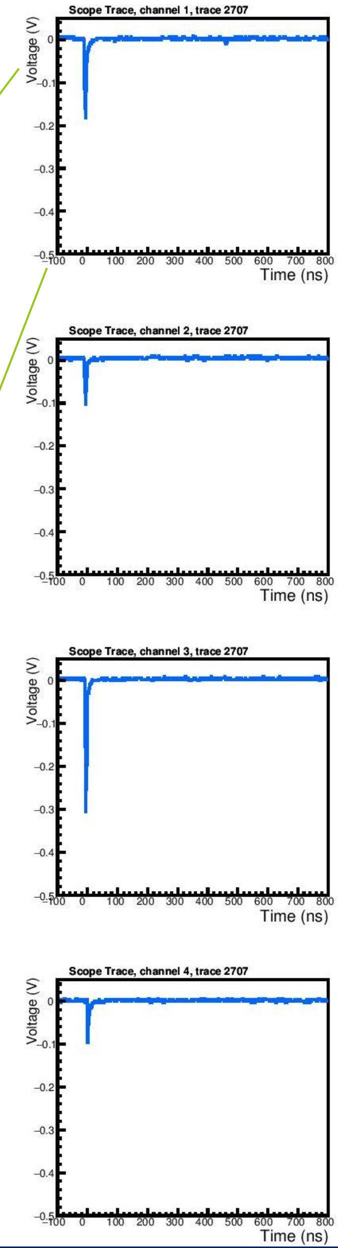


Signals

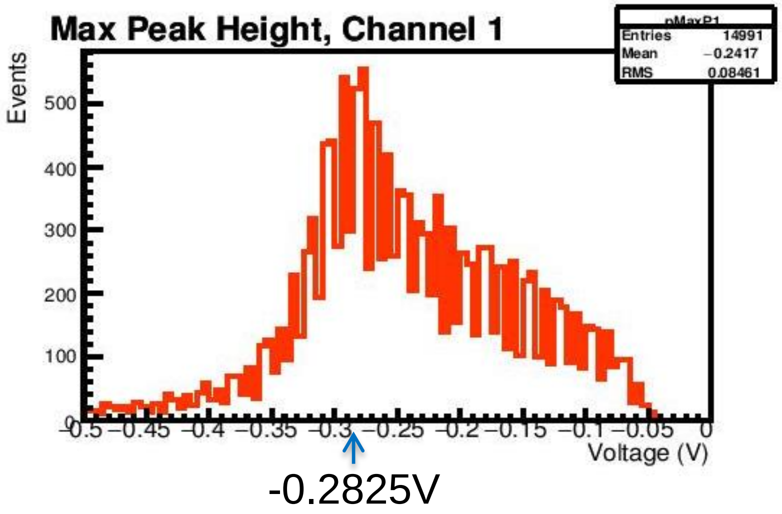
- Interested in:
  - Amplitude of Signal
  - Arrival Time of Signal
  - Out of Time Signals

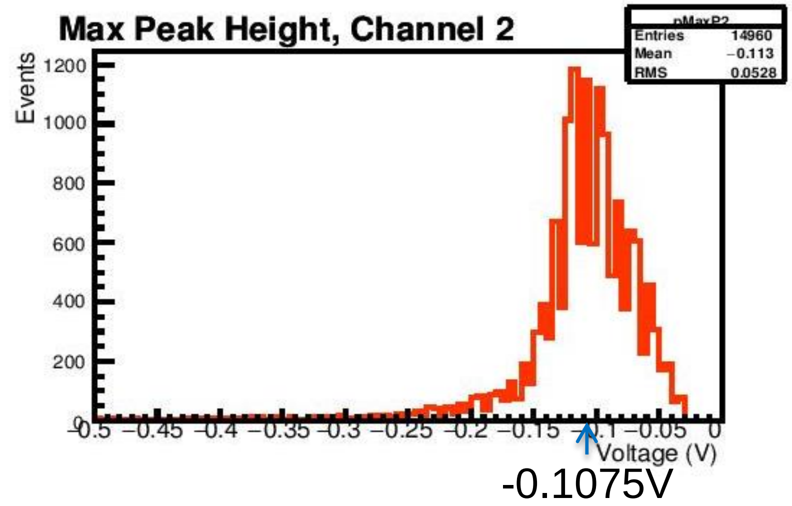


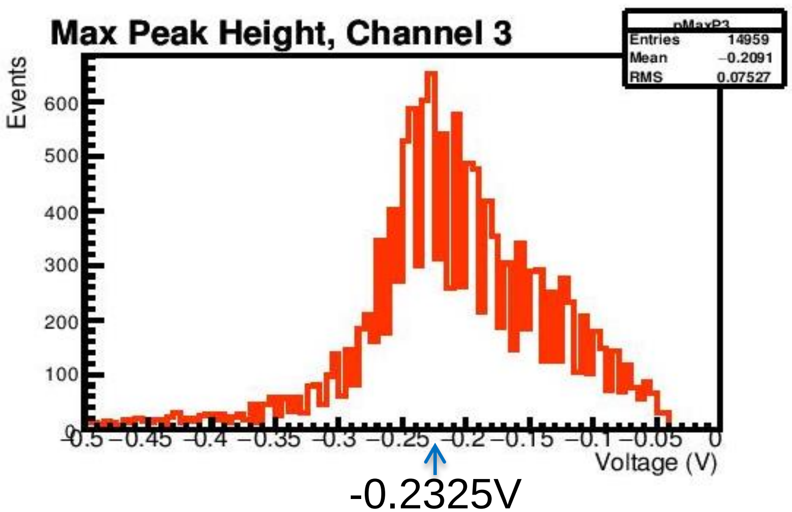
One Proton Event

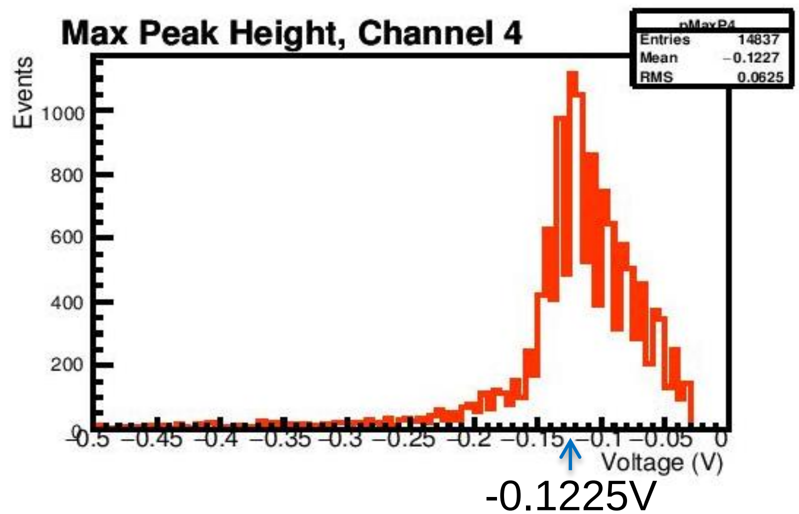


Amplitude of Signals (maximum in-time peak)









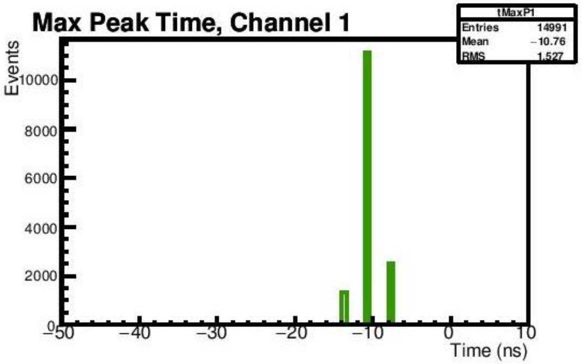
Resultant Efficiency

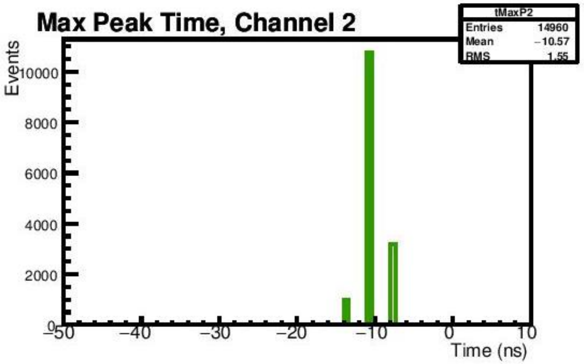
15000 events	Quadruple Coinc.	Triple Coinc.	Efficiency
Quartz 1	14771	14775	(99.97 ± .02)%
Quartz 2	14771	14804	(99.78 ± .02)%
Quartz 3	14771	14792	(99.86 ± .02)%
Quartz 4	14771	14912	(99.05 ± .02)%
Four-Fold Efficiency			(98.67 ± .05)%

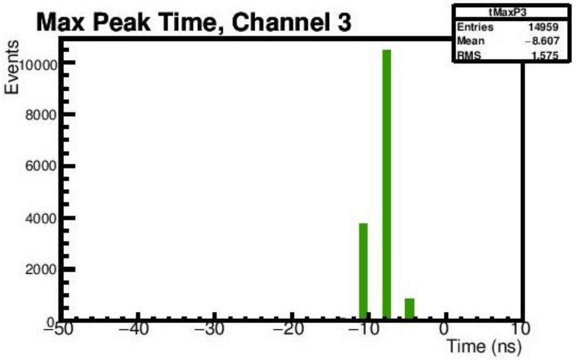
$$\text{Efficiency}_{\text{Quartz (\#)}} = \frac{\text{Number of Quadruple Coincidences}}{\text{Number of Triple Coincidences in other Three Channels}}$$

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

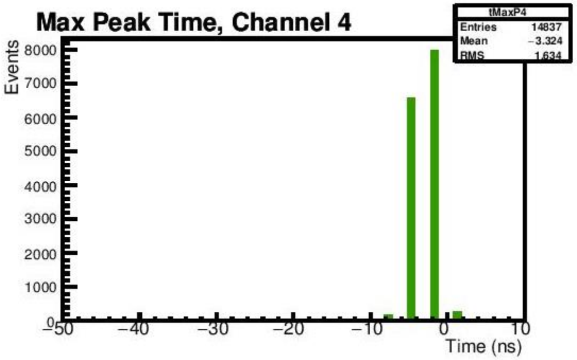
Signal Arrival Time – In Time Signals



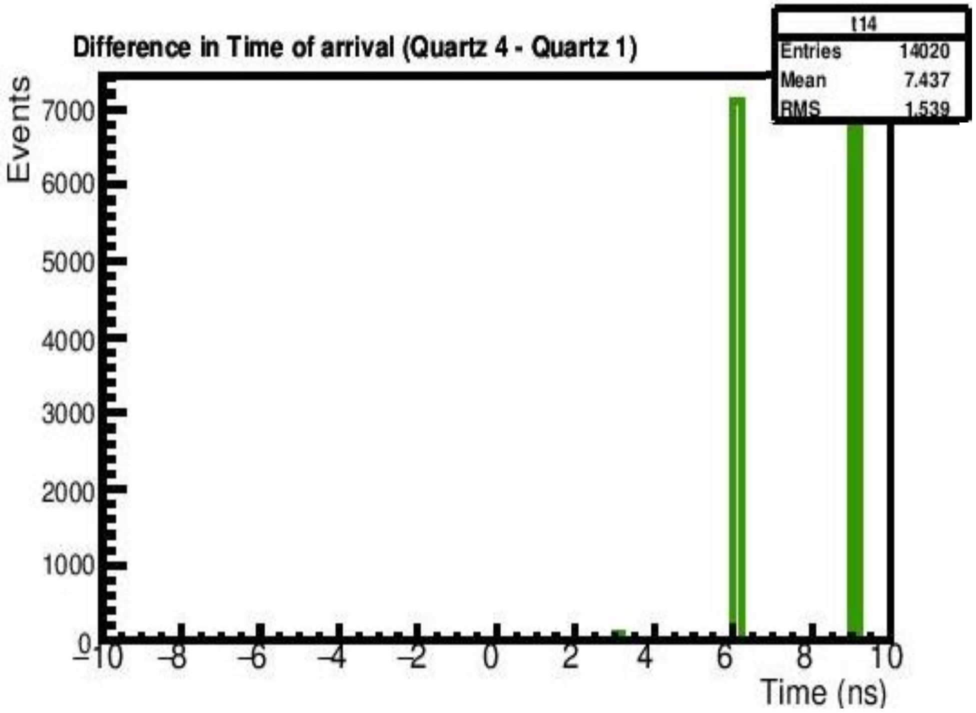




- 0ns is the trigger time
- Defined "In Time Signals" as between -50ns to 0ns for Quartz 1-3, and -50ns to 10ns for Quartz 4
- Signals occur before 0ns because trigger signal passed through more electronics/wires on route to oscilloscope



Time Resolution



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

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:

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

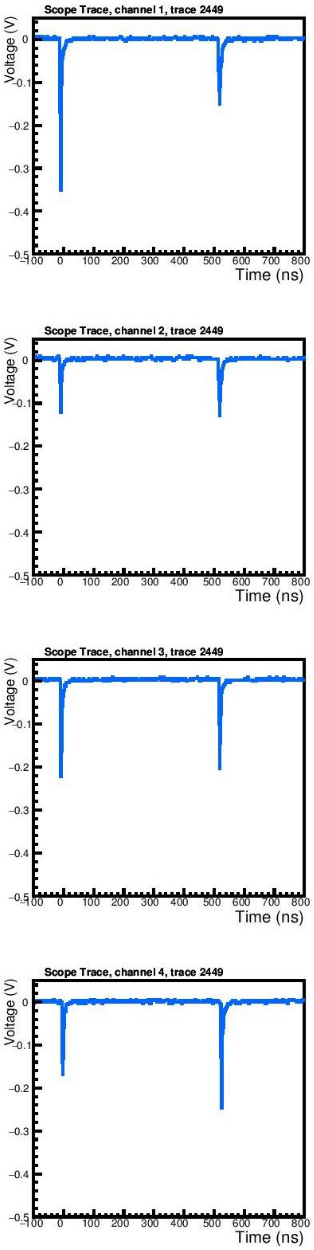
- By taking the difference between two channels, smaller time resolution
- Difference between channels 1 and 4 had the largest RMS
- Time resolution is 1.09ns or better

Out of Time Signals

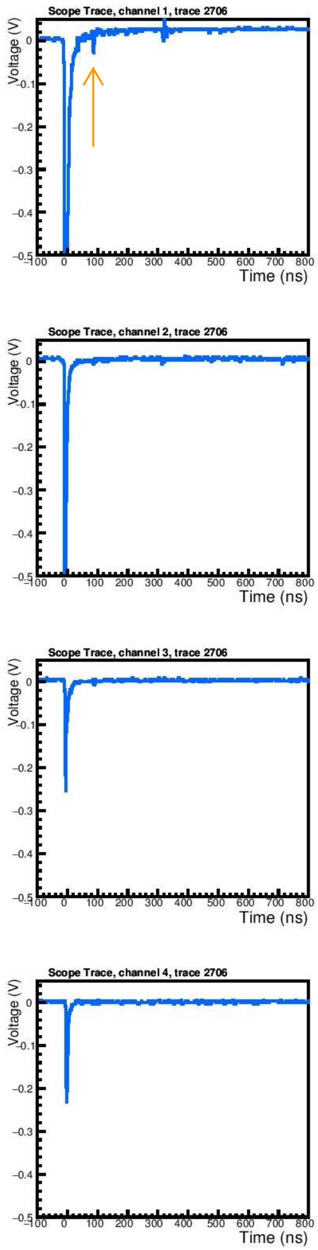
- If caused by out of time protons, usually leave track in all four quartz
- After pulsing occurs randomly, usually just in one channel
- If there is time structure in after pulsing, however, higher possibility of false coincidence

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

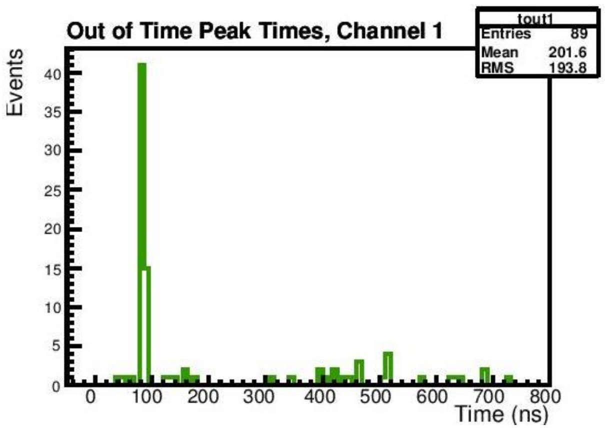
Multiple Proton Event

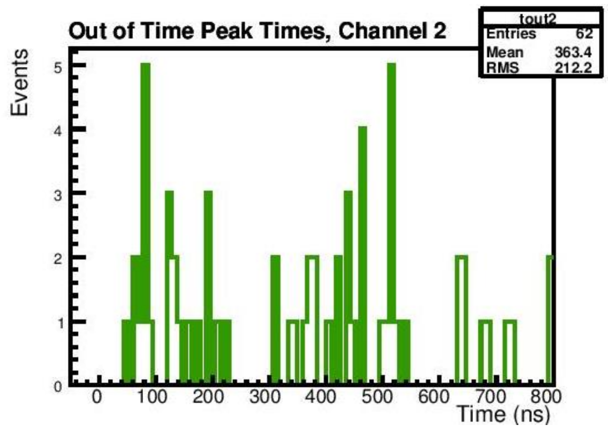


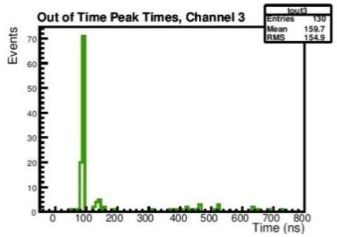
After Pulsing

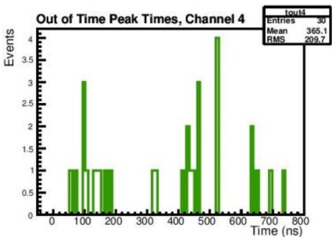


Signal Arrival Time - Out of Time Signals

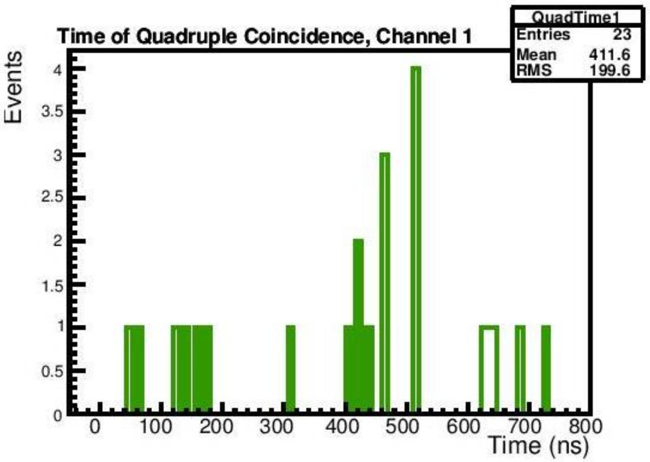








Quadruple Coincidences

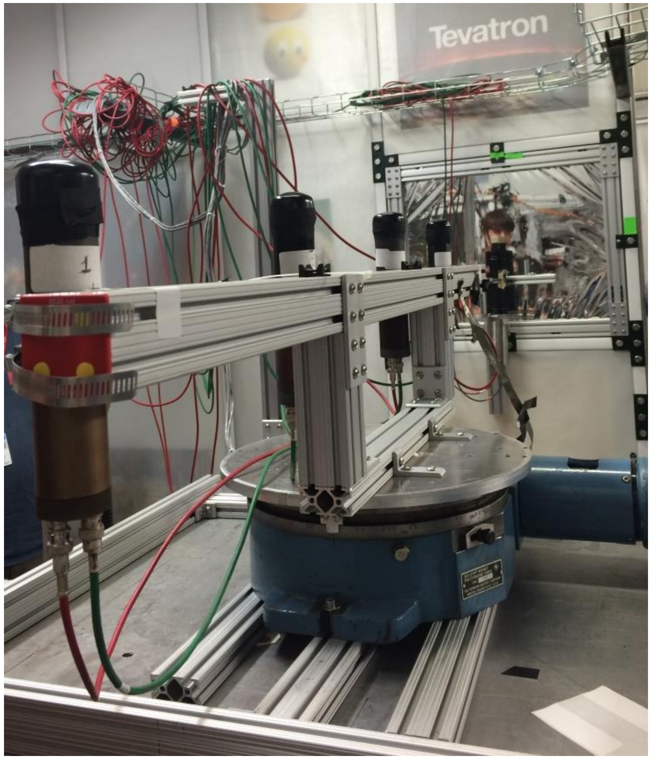


- Random arrival times, esp. for quadruple coincidence
- May be small amount of after pulsing around ~100ns for Quartz 1 & 3
- To calculate probability of this producing false quadruple coincidence, tested how often a record with an out of time signal had an out of time signal in previous record of same channel:

26000 events	Events	Probability
Obs. Self-Coinc.	0	$<2\cdot10^{-18}$ (for 4 channels)

Summary:

- Signal generated by Quartz Radiators is sufficient to detect protons with high efficiency (98.7%)
- Signal time resolution is 1.09ns or better
- After pulsing will at worst produce quadruple coincidences at a rate of $2 \bullet 10^{-18}$



Questions?

References:

[1] C. B. Mott, “Research and Development for the Mu2e Extinction Monitor,” M.S. Thesis, Physics Dept., Northern Illinois Univ., De Kalb, IL, 2016.

[2] E. Prebys, M. Jamison-Koenig, L. Rudd, “Tests of Quartz Radiators for Beam Precision Timing Monitor.” Beams-doc #5018-v3, 2015.

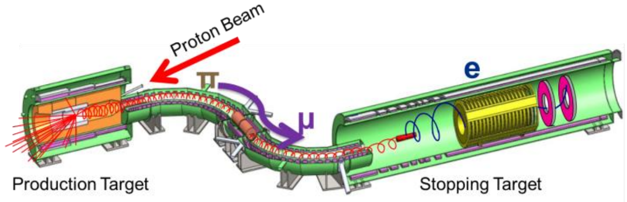
[3] L. Rudd, “Characterization of Quartz Radiators for Mu2e Upstream Extinction Monitor,” Beams-doc #5016-v1, 2015.

[4] S. Werkema, “The Fermilab Muon Campus – The Experiments, Projects, and Status,” Beams-doc #4716-v1.

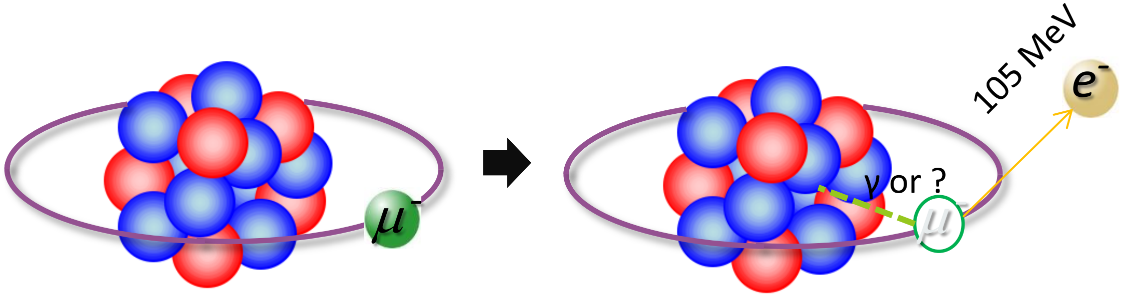
[5] H. Alaeian, “An Introduction to Cherenkov Radiation,” (15 March 2014), [Online], Available: http://large.stanford.edu/courses/2014/ph241/alaeian2/.

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

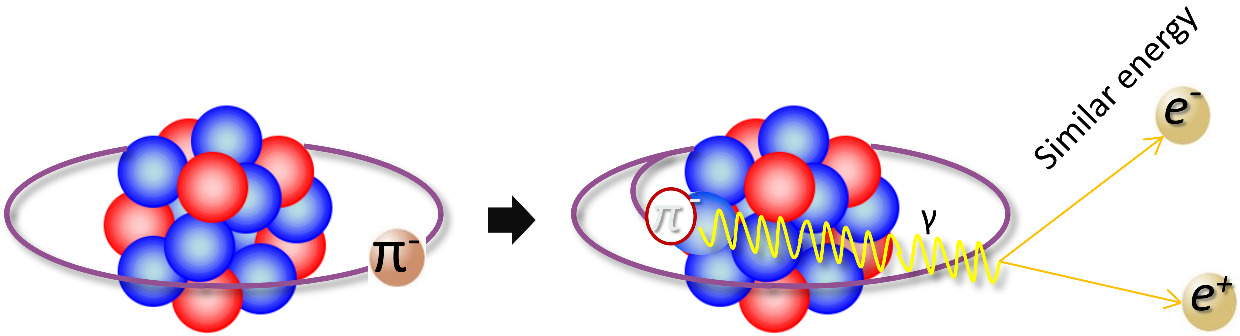
Radiative Pion Capture



Muon to Electron Conversion (Signal)



Radiative Pion Capture (Background)



- Pions can also be captured by Al nuclei and produce e⁻ around the signal energy
- Limit search window to after pions have decayed
- Cannot exclude out of time pions
  -> precision timing of beam required!