The (Speed and) Decay of Cosmic-Ray Muons

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Goals

- test relativity (time dilation)
- determine the mean lifetime of muons

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- determine the mean lifetime of muons

Muons

- elementary particle
- unit negative charge
- spin $1/2$
- unstable

Why Muons?

- unstable
- long mean lifetime ($\approx 2.2\,\mu s$)
- naturally abundant
- penetrating

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Why Muons?

- contact point between theory and reality (we can predict mean lifetime from Fermi β-decay, if we know the mass)

Experimental Outline

- muons generated by cosmic-rays above 15 km
- capture muons in a block of plastic scintillator
- record arrival & decay events

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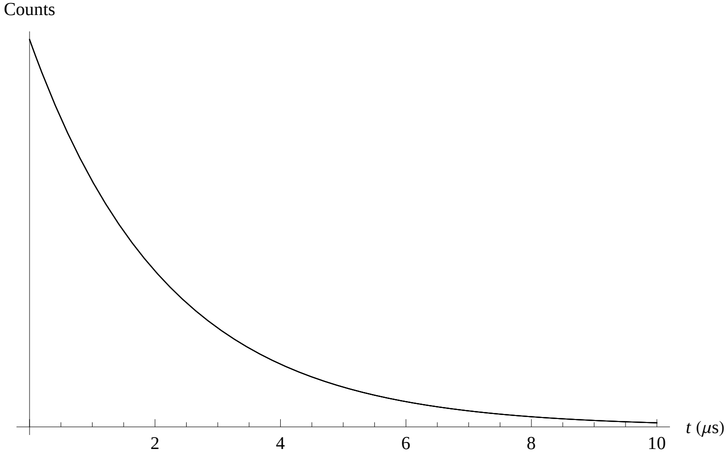
Expected Results

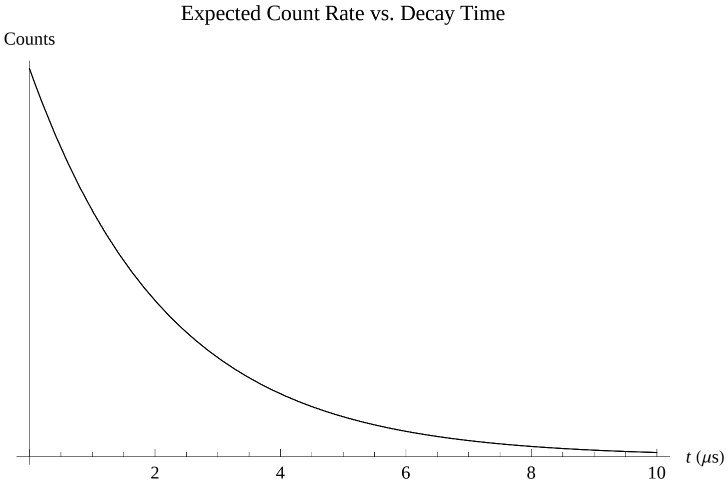
$$N(t) = N_0 e^{-t/\tau}$$

Expected Count Rate vs. Decay Time

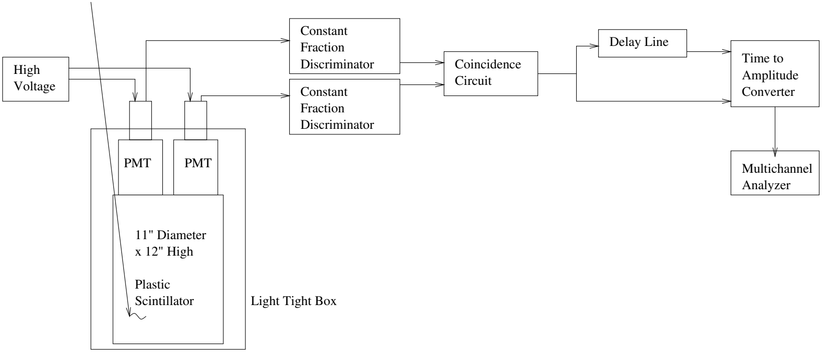


Expected Results

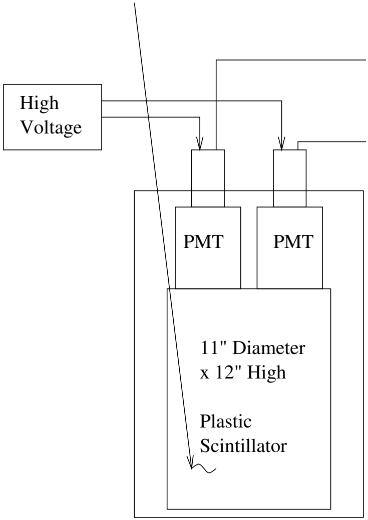
But only if there's no noise!



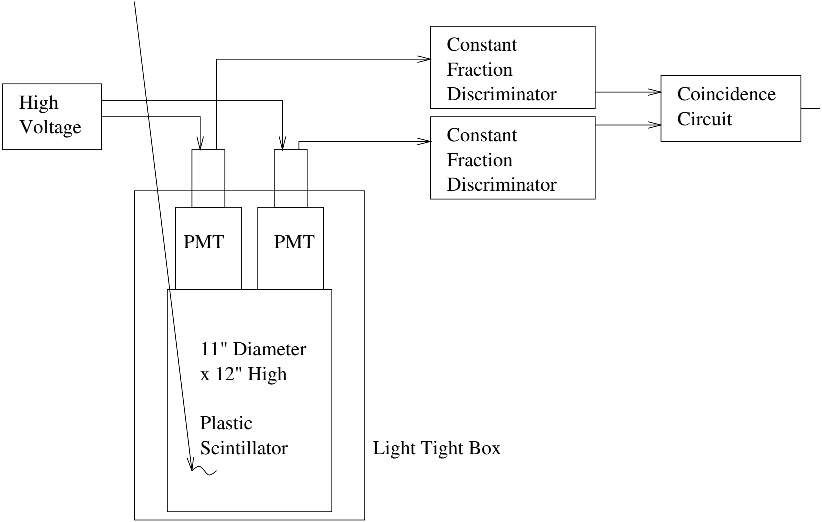
Experimental Setup



Muon Detection



Noise Removal

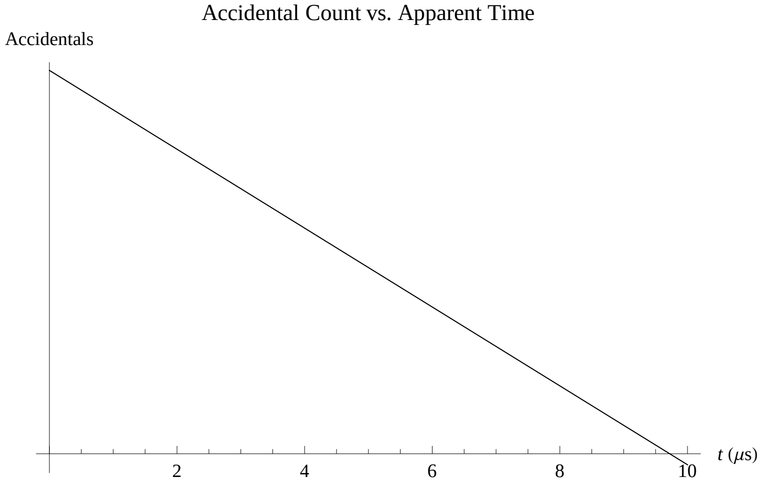


Noise Removal

$$\#\ \text{Accidentals} = T n_1 n_2 \Delta t$$

Noise Removal

If $n_1 = 10^4\ \text{s}^{-1}$, $n_2 = 2 \cdot 10^4\ \text{s}^{-1}$, $T = 1$ hour, $\Delta t = 100$ ns,



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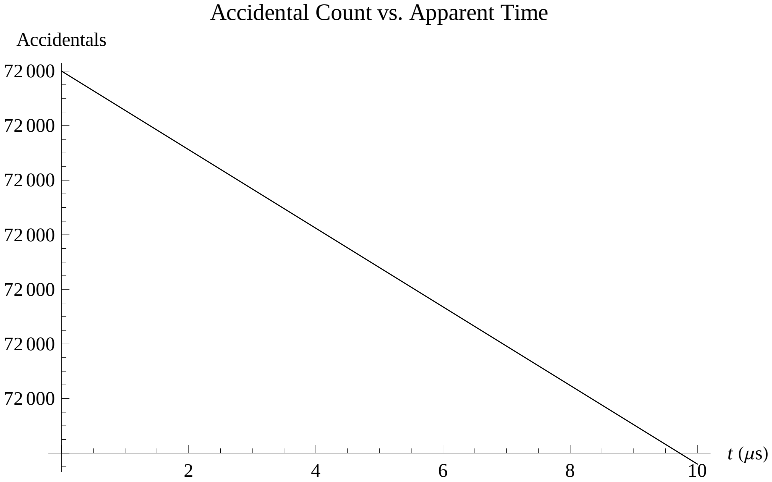

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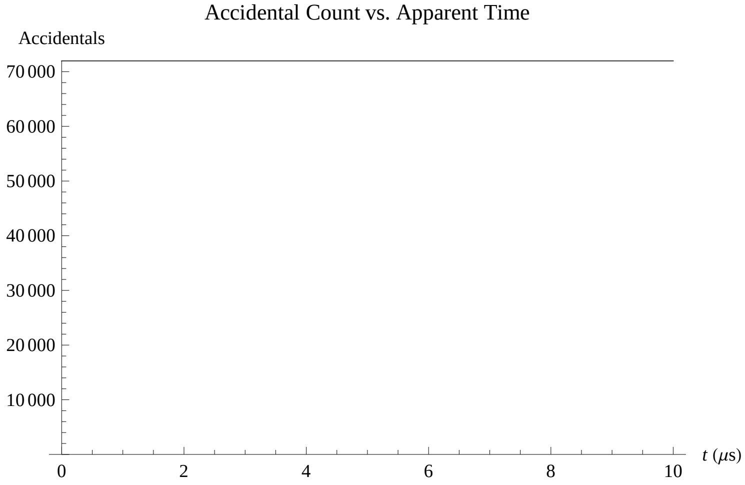

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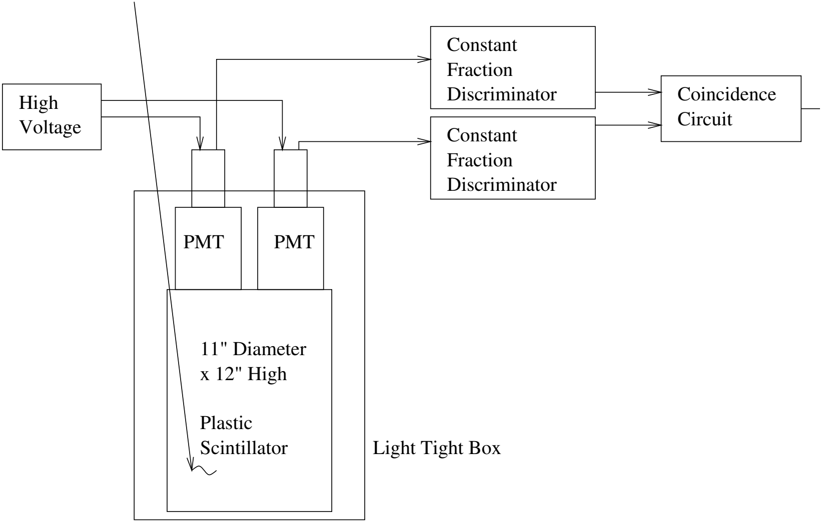

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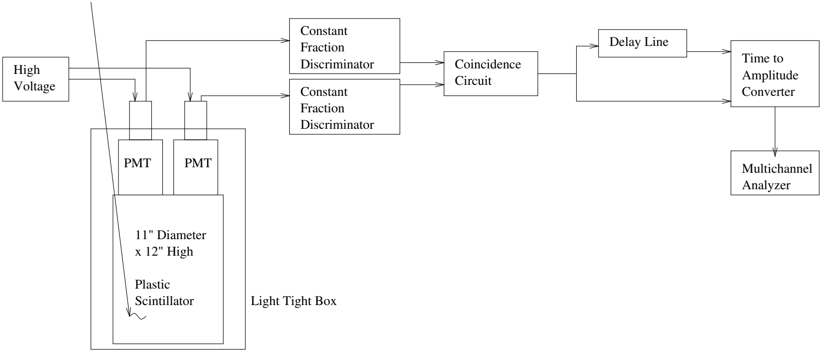

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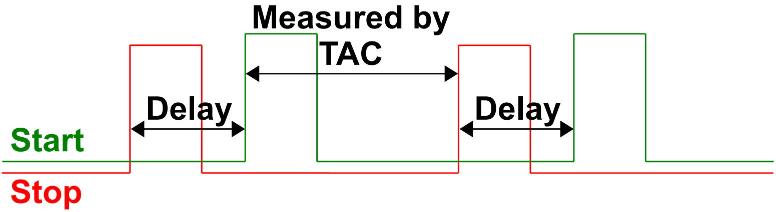
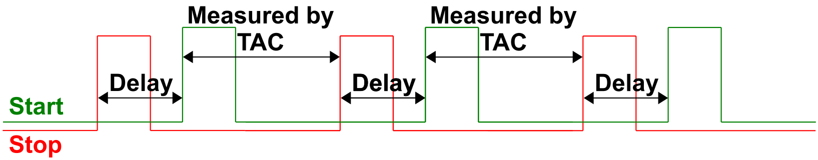


Arrival times of pulses along the STOP input (red) and the START input (green) of the TAC.

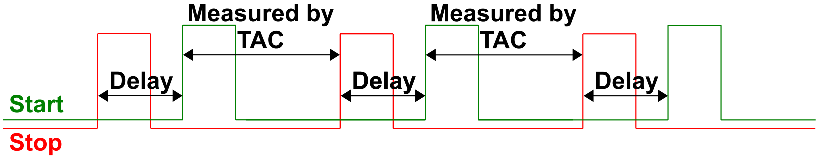
Experimental Setup

arrival interval $\approx$ decay time



Experimental Setup

arrival interval $\approx \frac{1}{2}$ decay time



Experimental Setup

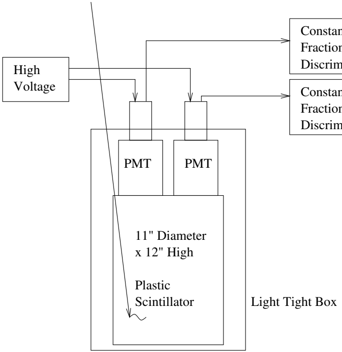
arrival interval $\gg$ decay time

Experimental Setup

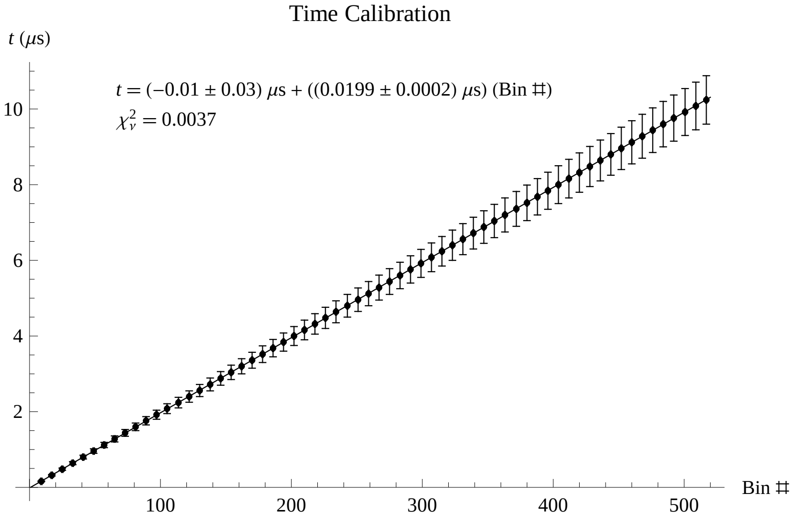
Lifetime: $\approx 2.2\,\mu\text{s}$

Arrival Rate: $\approx (0.2 \pm 0.1)\,\text{s}^{-1}$

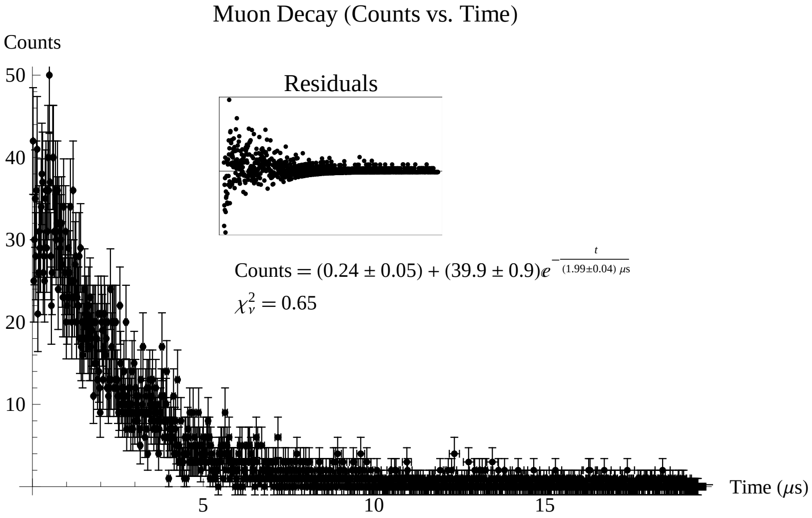
Experimental Setup



Time Calibration



Results



Muon Decay (Counts vs. Time)
Counts
50
40
30
20
10
5
10
15
Time (μs)
Residuals
$\text{Counts} = (0.24 \pm 0.05) + (39.9 \pm 0.9)e^{-\frac{t}{(1.99\pm0.04)\ \mu\text{s}}}$
$\chi_\nu^2 = 0.65$

Results

My Value: $\tau = (1.986 \pm 0.042)\,\mu\mathrm{s}$

Book Value: $\tau = 2.197\,034(21)\,\mu\mathrm{s}$

My Value: $m_\mu = (107.96 \pm 0.46)\,\mathrm{MeV}/c^2$

Book Value: $m_\mu = 105.658\,366\,68(38)\,\mathrm{MeV}/c^2$

Sources of Error

- systematic: didn't account for the delay in the cable, so all my times are shorter than they should be
- poor estimation of errors (least squares gives $(2.30 \pm 0.04)\,\mu s$)
- not enough data to get an estimate of the accidentals (if I fit to $ae^{-t/\tau}$, I get $(2.06 \pm 0.04)\,\mu s$)

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Testing Relativity: Muon Travel Time

- generated 10-15 km above sea level
- others' experiments suggest most likely momentum is 1 GeV / c
- to go 10-15 km at this momentum (which corresponds to 0.994c) takes 30-50 µs
- (but if we throw away all of special relativity, then this momentum corresponds to 9.5c, and it only takes 5 µs)

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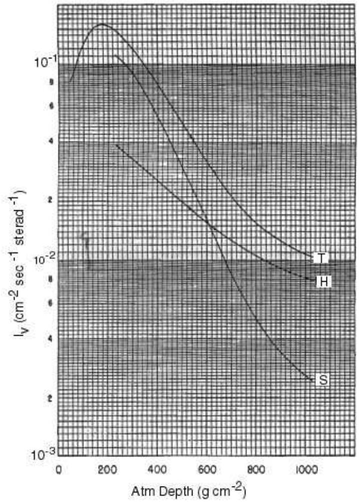

Testing Relativity: Muon Intensity

- about $10^{-2}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ (muons intensity at sea level)
- without time dilation, it takes at least 30 µs to get down to sea level
- if we take $\tau \approx 2\,\mu\mathrm{s}$, if there is no time dilation, we see $3 \cdot 10^{-5}\%$ of muons
- corresponds to about $10^{5}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ at 10 km up

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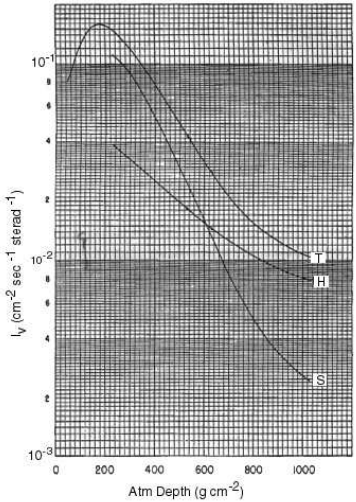

Testing Relativity

Relativity Wins!

Thank You!

Any questions?