Angular Dependence of Cosmic Ray Muon Flux

Michael Sekatchev

Department of Physics and Astronomy
University of British Columbia

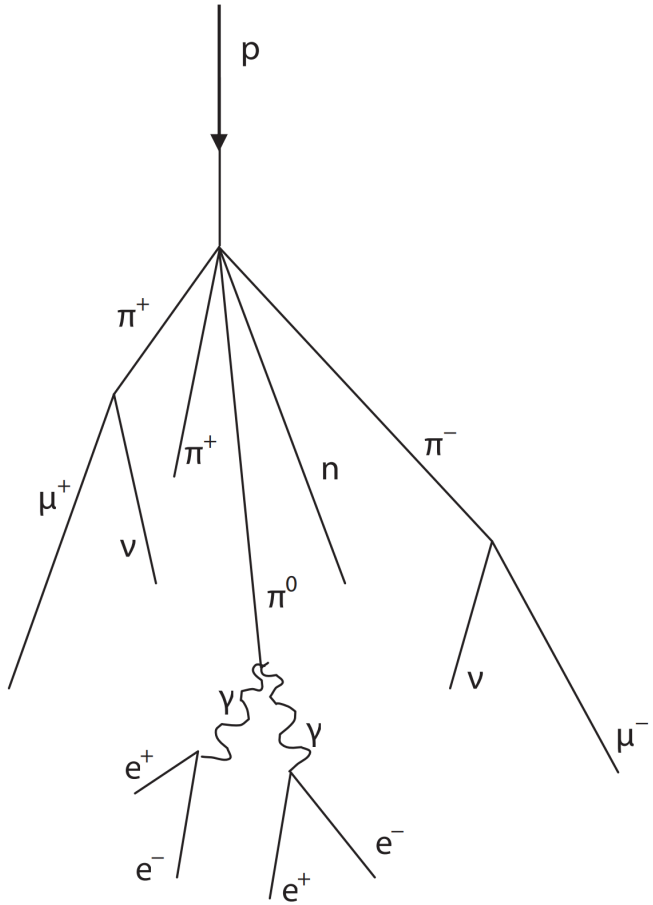
PHYS 409 Experiment 1

December 14, 2022

Table of contents

Introduction – cosmic ray muons

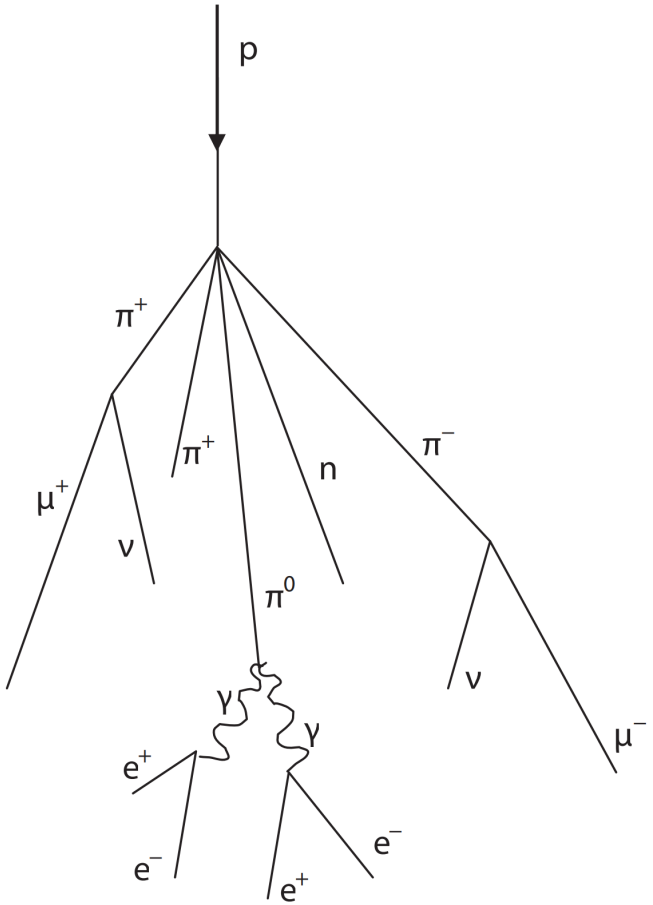
- **Cosmic rays** – mostly (89%) high energy protons (p) bombard our atmosphere from outer space.



Cosmic ray cascade from p striking an air molecule. From SCREAM Project.

Introduction – cosmic ray muons

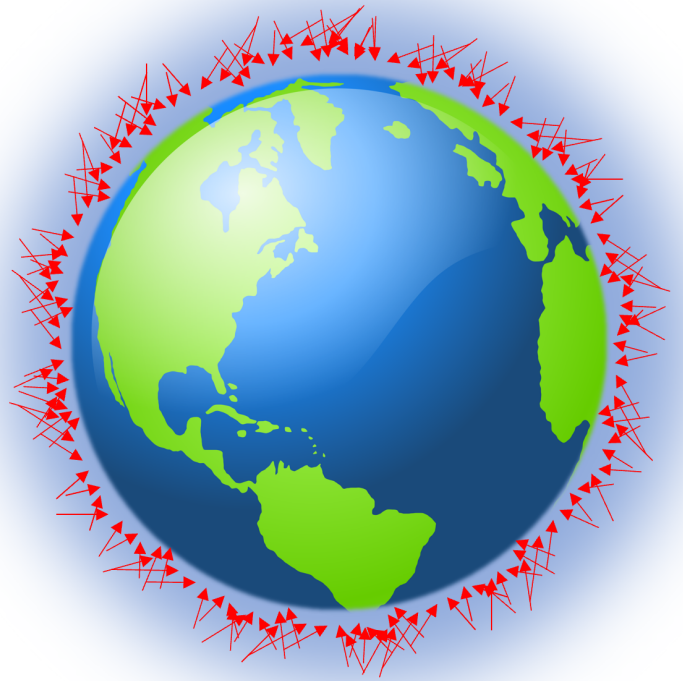
- Protons (p) hit particles in the atmosphere and turn into pions (π).
  $p + p \rightarrow p + p + \pi$
- Pions quickly decay into muons (μ) and neutrinos (ν).
  $\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \pi^- \rightarrow \mu^- + \overline{\nu}_\mu$



Cosmic ray cascade from p striking an air molecule. From SCREAM Project.

Muon flux and lifetime

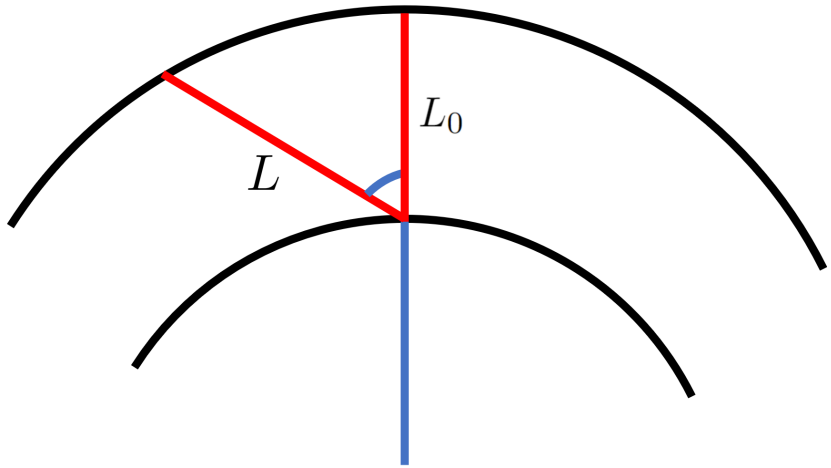
- Muon lifetime:
  $\tau_\mu \approx 2.2\,\mu\text{s} \implies d \approx 660$ m.
- Lifetime **stretched** in our frame:
  $\tau_\mu^{'} \approx \gamma(2.2\,\mu\text{s}) \implies d > 15\,\text{km}.$
  (source)
- On earth's surface, $\sim 1\,\mu/\text{min}/\text{cm}^2$.
  (source)



Earth being bombarded by cosmic ray muons from all directions at all angles.

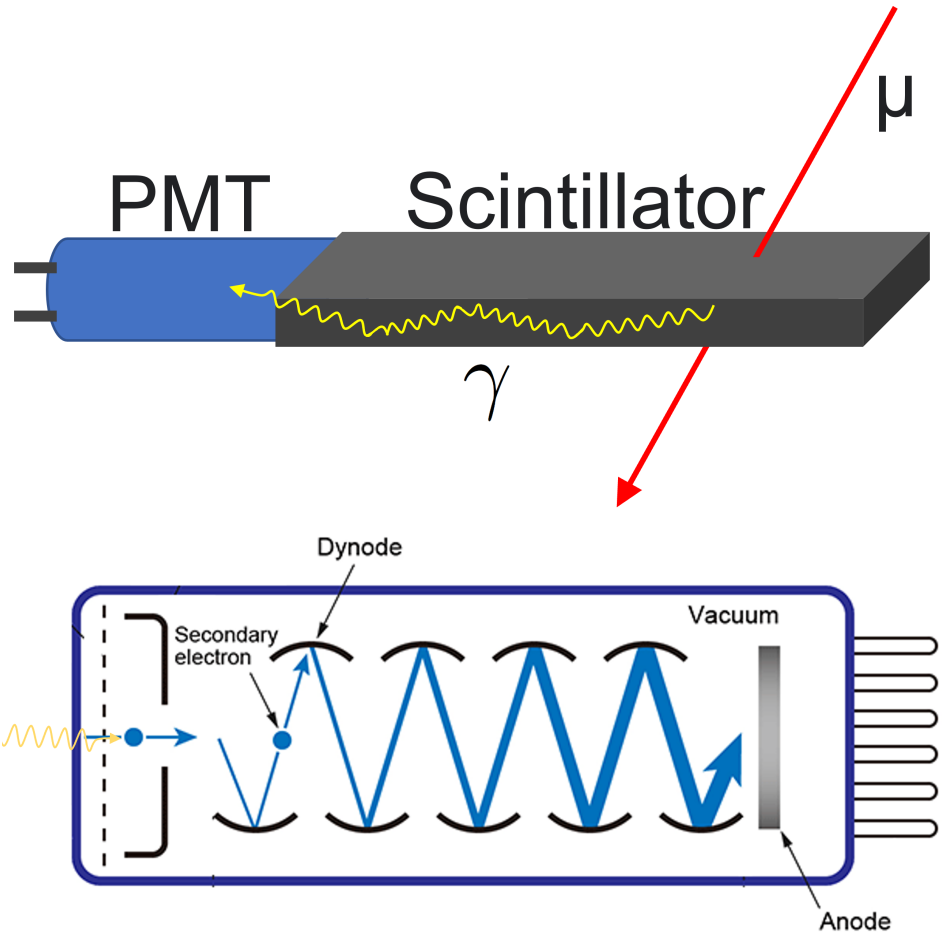
Angular dependence of cosmic ray muon flux

- Muons travelling farther through the atmosphere will have a higher probability of decay.
- Distance through atmosphere increases with angle.
- What is the angular dependence of cosmic ray muons?



$L > L_0$

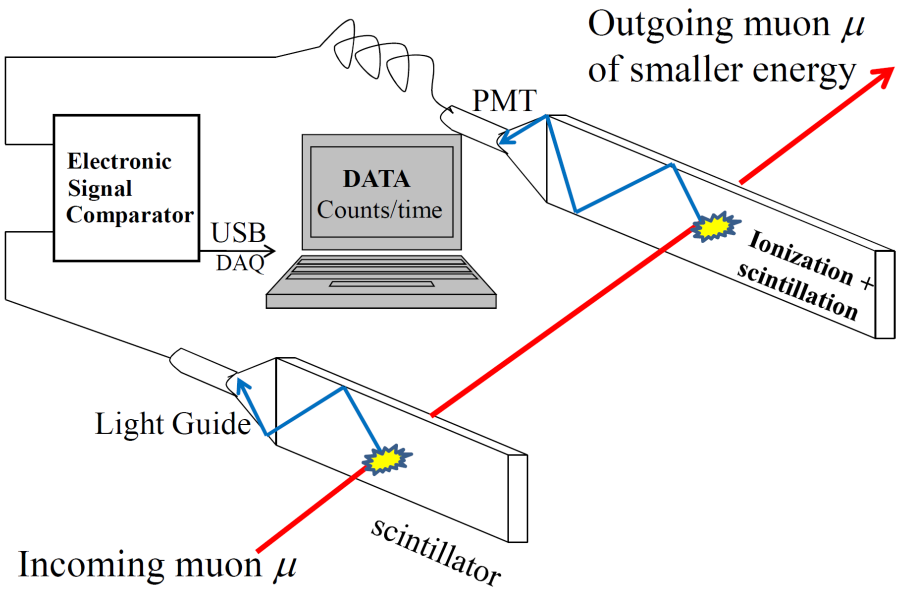
Muon detection



Top: μ excites scintillator, which produces photons (γ). Bottom: inside of a PMT.

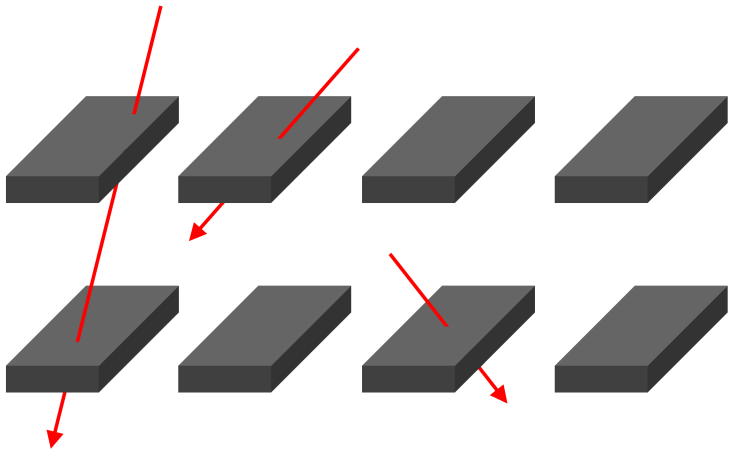
- Incoming muon deposits some energy into scintillator material.
- This causes scintillator to release light (photon).
- Light amplified into a detectable signal by **Photomultiplier tube** (PMT).

Directional muon detection



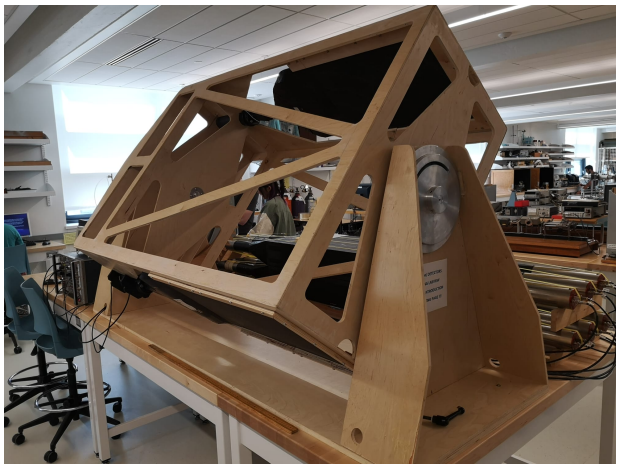
Experimental setup for measuring angular dependence of muon flux. From paper, Flux Variation of Cosmic Muons.

- **Two** scintillator paddles needed for **directionality**, and reduction of electronic noise.



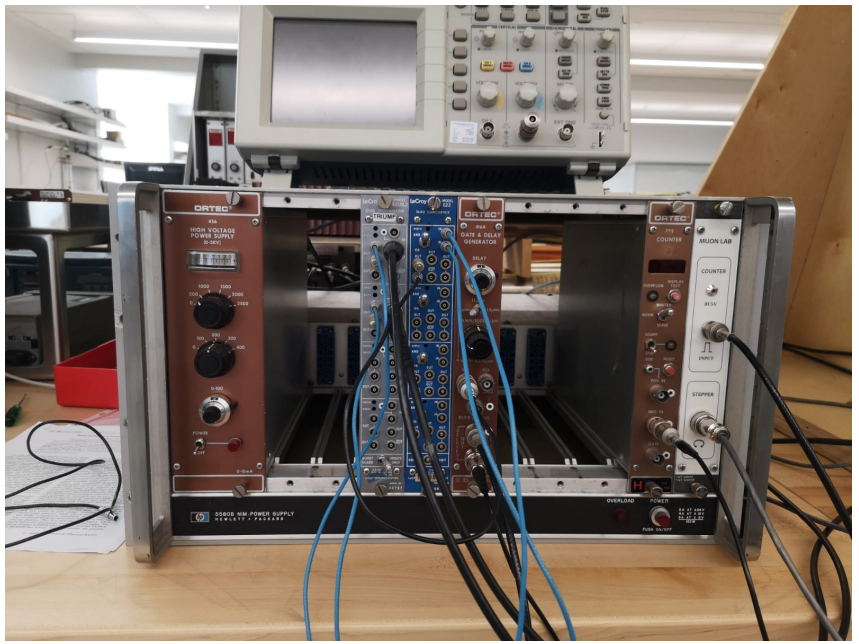
Only the leftmost case should be counted as a muon hit.

Directional muon detection – PHYS 409 setup



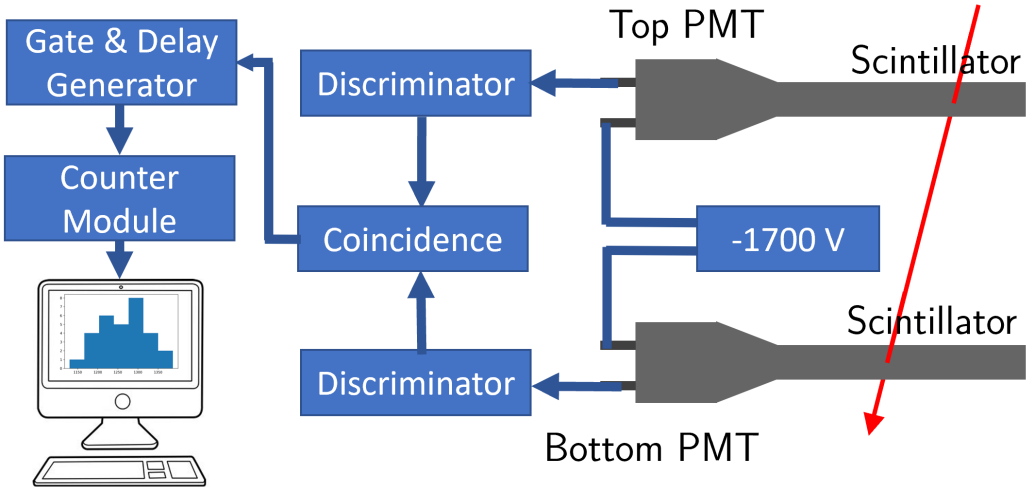
PHYS 409 setup muon flux setup.
Top: $0°$, bottom: $30°$.

- PHYS 409 setup includes a stepper motor for automatically turning through paddle angles.



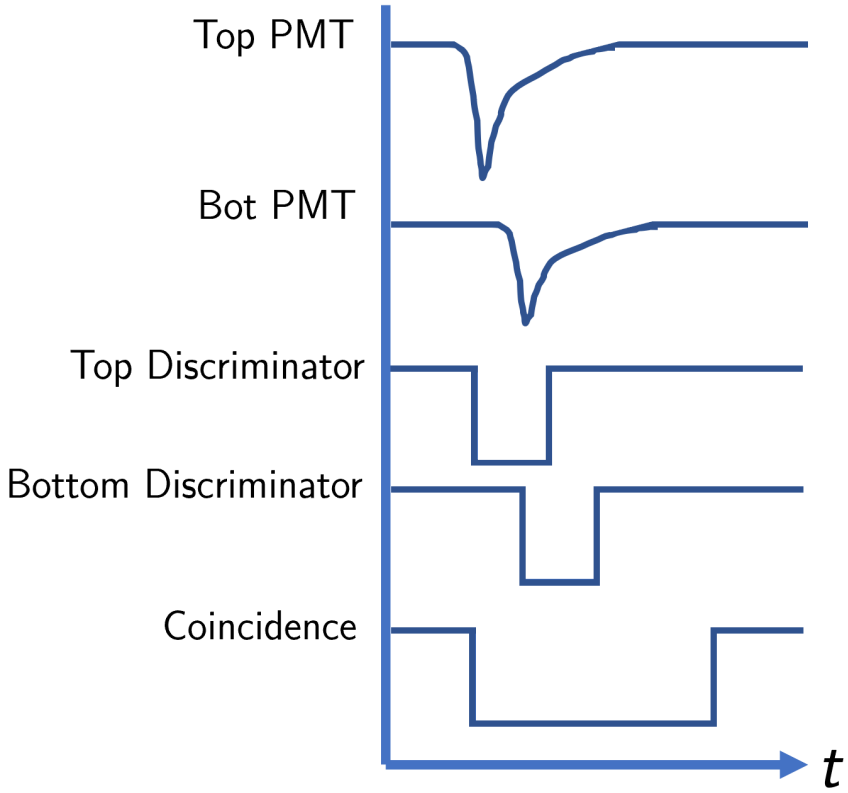
Electronics for discriminating true muon hits.

Electronics for discerning true muon hits



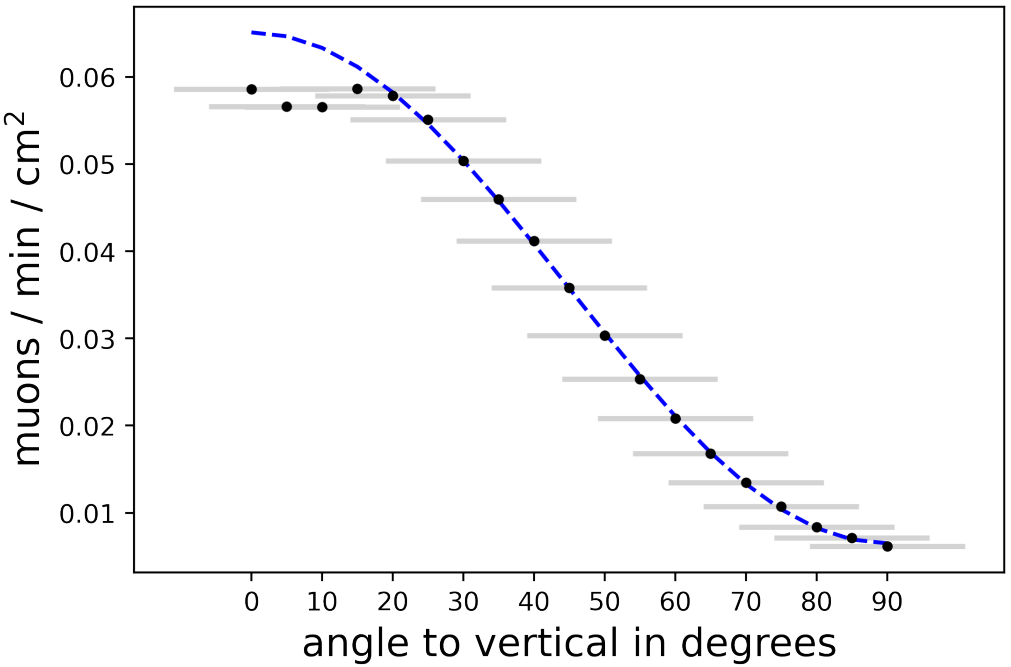
Electronic connections for experiment.

- Discriminators filter out true hits from noise via a **threshold**.
- Coincidence requires signal from both discriminators within an **interval** to confirm a true hit.



Signal (voltage) of each component from a successful muon hit.

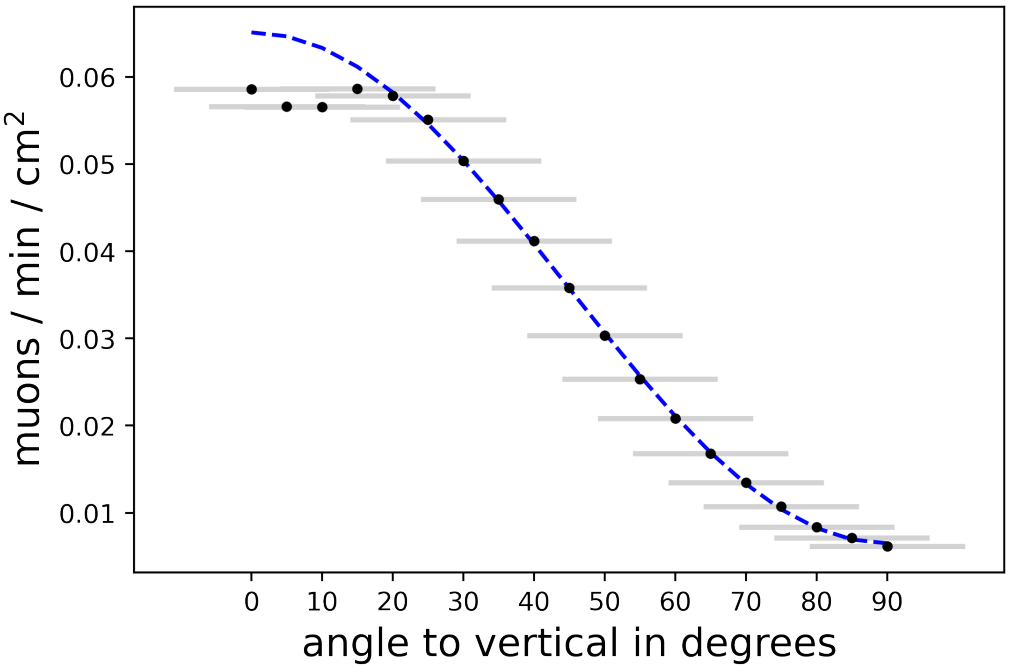
Results – angular dependence of cosmic muon flux



Angular dependence of cosmic muon flux.

- **Horizontal** uncertainty: standard deviation of distribution of incident angles at each angle (**not** uncertainty in peak angle)
- **Vertical** uncertainty: Poisson distribution, $\delta_F = \sqrt{n}$ (it's tiny).

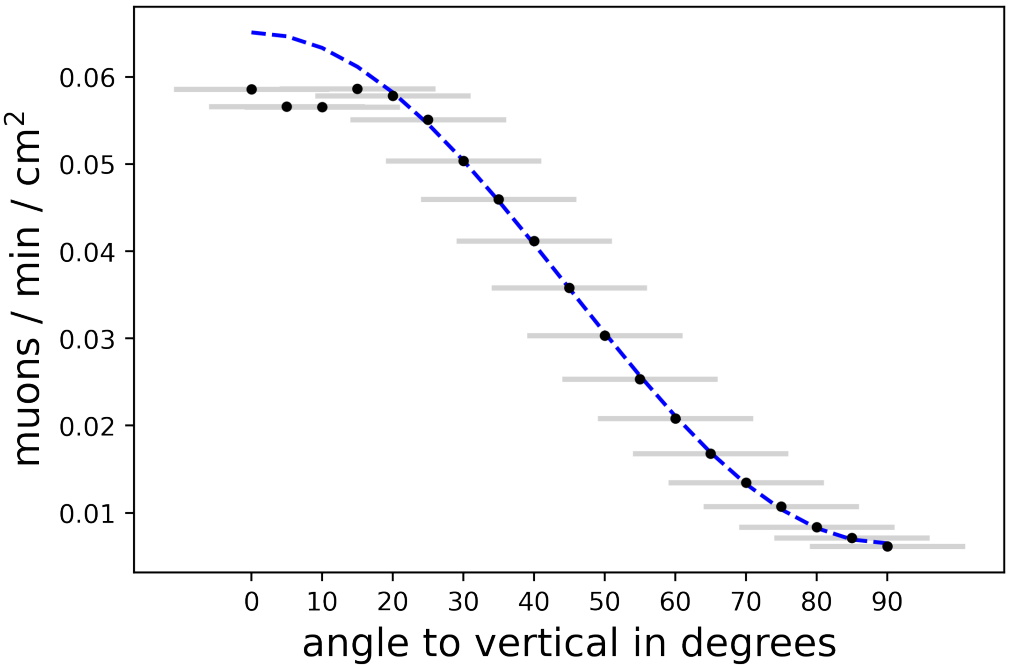
Results – angular dependence of cosmic muon flux



Angular dependence of cosmic muon flux.

- Instrumental/Electronic uncertainty has **not** been accounted for – difficult to estimate.
  (PMT noise, discriminator threshold, coincidence width, wire cross-talk, etc.)

Results – angular dependence of cosmic muon flux



Angular dependence of cosmic muon flux.

- Dip observed in first $\sim 15^\circ$, due to systematic interference?
- The simplest model is

$$F_\mu(\theta) = A\cos^n(\theta) + B.$$

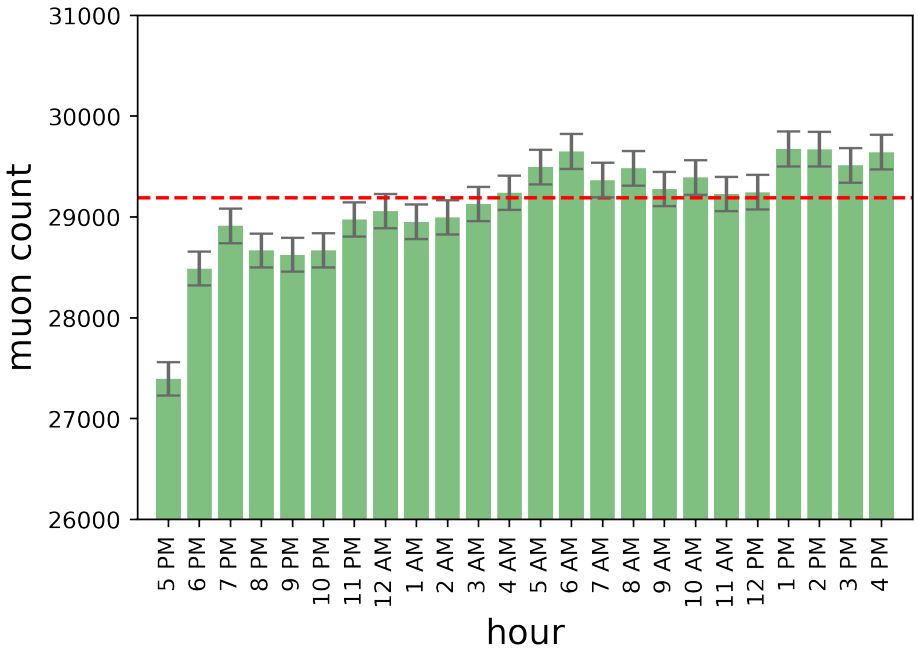
$$A = 5.86\text{e-}2 \pm 4\text{e-}4 \ \frac{\mu}{\text{min}\cdot\text{cm}^2}$$

$$B = 6.5\text{e-}3 \pm 1\text{e-}4 \ \frac{\mu}{\text{min}\cdot\text{cm}^2}$$

$$n = 2.01 \pm 2\text{e-}2$$

$$\chi^2 = 73$$

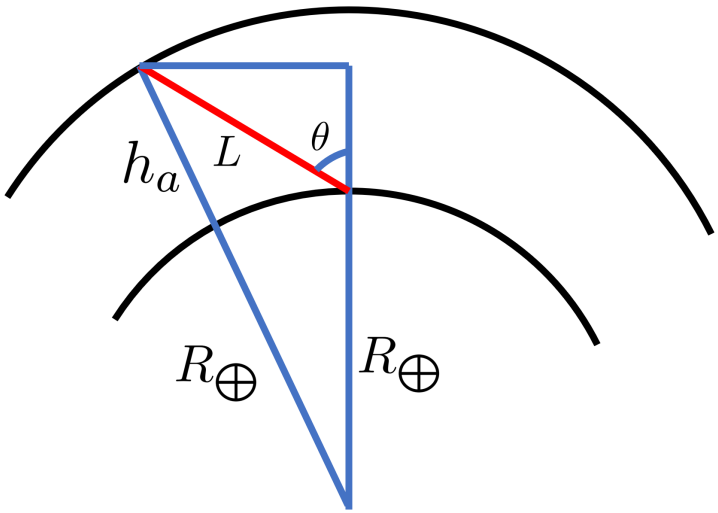
Results – extra details



Hourly flux at $0°$. Error shown is statistical $\sqrt{n}$ only.

- Does the flux vary throughout the day? **No**.
- Warm-up period of $\sim$3 hours observed on first run, not reproduced in subsequent runs.

Muon flux – updated model



Accounting for variation of atmospheric attenuation using L, the distance μ needs to travel through atmosphere.

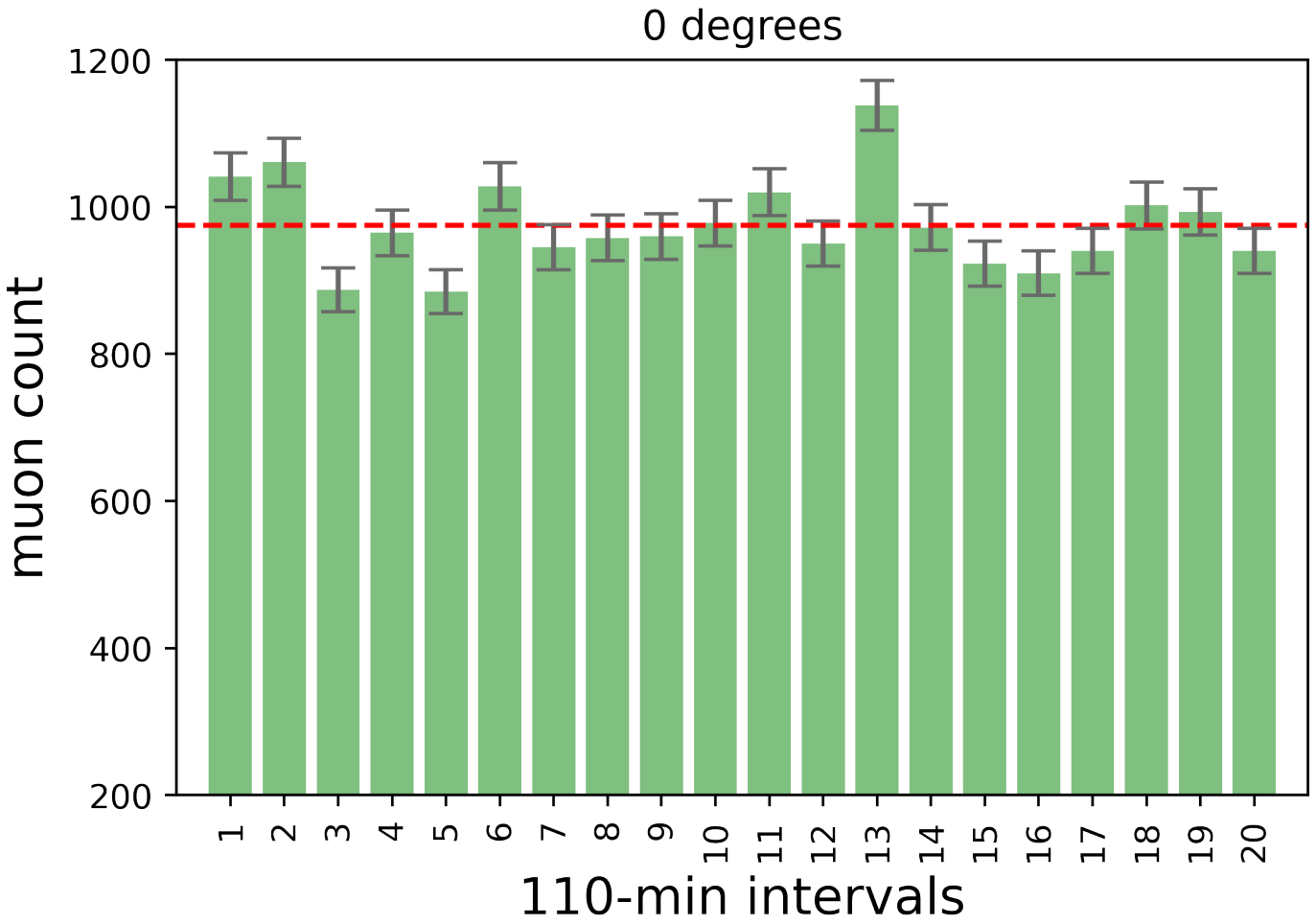
- $\cos^n$ model does not account for many intricacies.
  Example: $n = n(p)$
  (Cosmic Rays at Earth, Grieder)
- Currently testing new model:
  $F(\theta) = F_0 e^{-\alpha L(\theta)}$ where
  $$L(\theta) = -R_\oplus \cos(\theta) + \sqrt{R_\oplus^2 \cos^2(\theta) + 2R_\oplus h_a + h_a^2}$$

Conclusion

- $F_\mu(\theta) = A\cos^n(\theta) + B$ is an approximation of the angular dependence of cosmic muon flux.
- Muon flux is homogeneous – unaffected by time of day.
- Statistical uncertainty $\sqrt{n}$ becomes insignificant for large n.
- Systematic interference observed at angles close to the vertical.

Thank you

Results – extra details



Flux variation at 0° in 110-min intervals (recorded for 5 minutes per bin). Uncertainty is Poissonian $\sqrt{n}$. Shows that there is no warm-up time, compared to the first hourly scan session shown earlier.