Reconstructing Cosmic Ray Events With Muon Data

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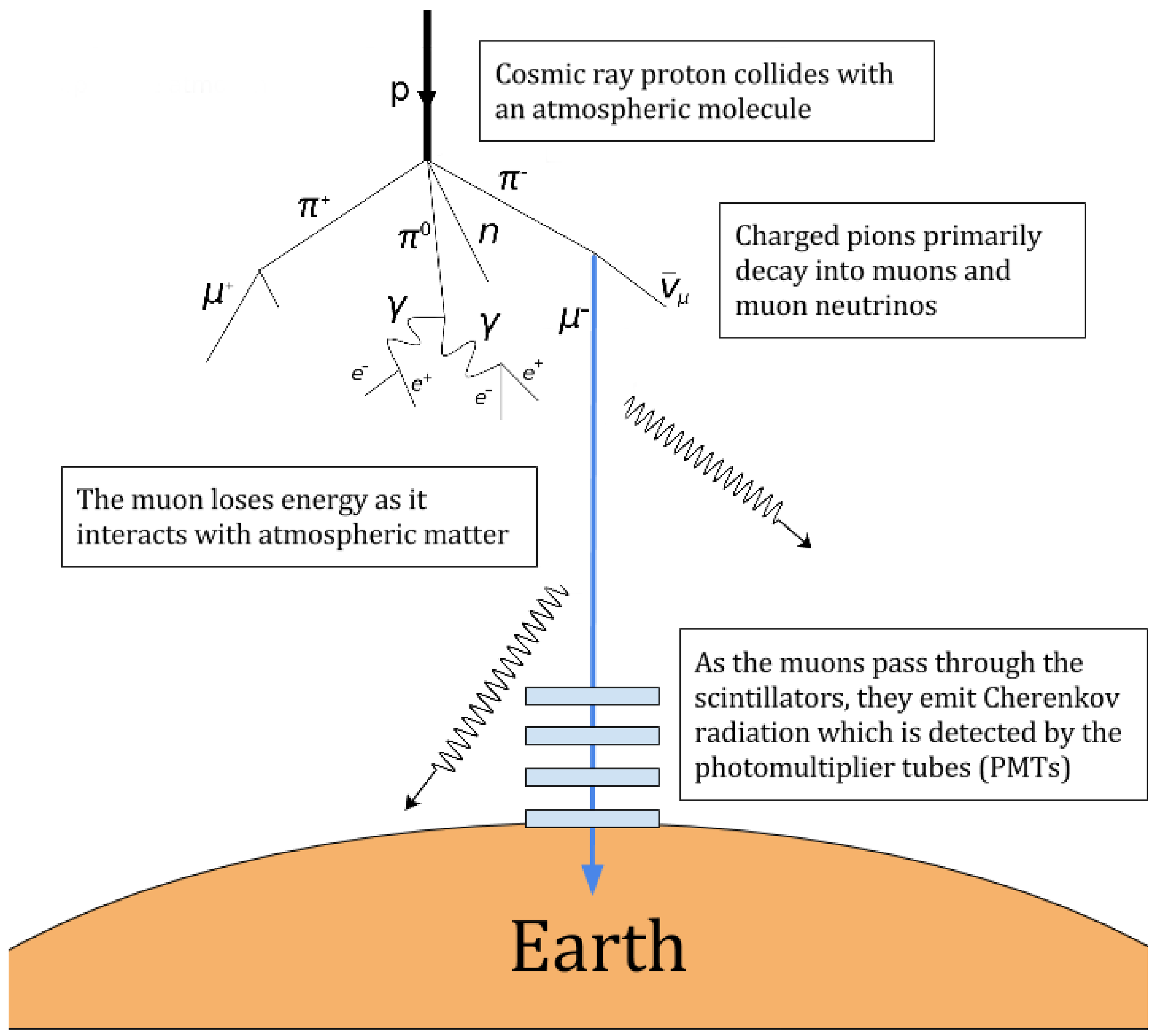
Abstract

The purpose of this investigation was to use the data collected from a cosmic ray muon detector (CRMD) and information about how muons interact with atmospheric matter to create a model for reconstruction of part of a cosmic ray shower. Using this model, we can use a muon's velocity to find the energy and momentum of the charged pions created by the cosmic rays.



Calculating ΔE_μ

As muons travel through the atmosphere, they can lose energy through two types of processes:

- ionization of atoms
- radiation (bremsstrahlung, e^-e^+ pair production)

For high-momentum charged particles, the average energy loss rate is $\approx 0.2\ \mathrm{MeV}/(\mathrm{kg\,m^2})$[1]. With this, we can model total energy loss as a function of geometric altitude of muon formation:

$$\Delta E_\mu = 0.2\mathrm{MeV}/(\mathrm{kg\,m^2}) \int_0^z \rho dz$$

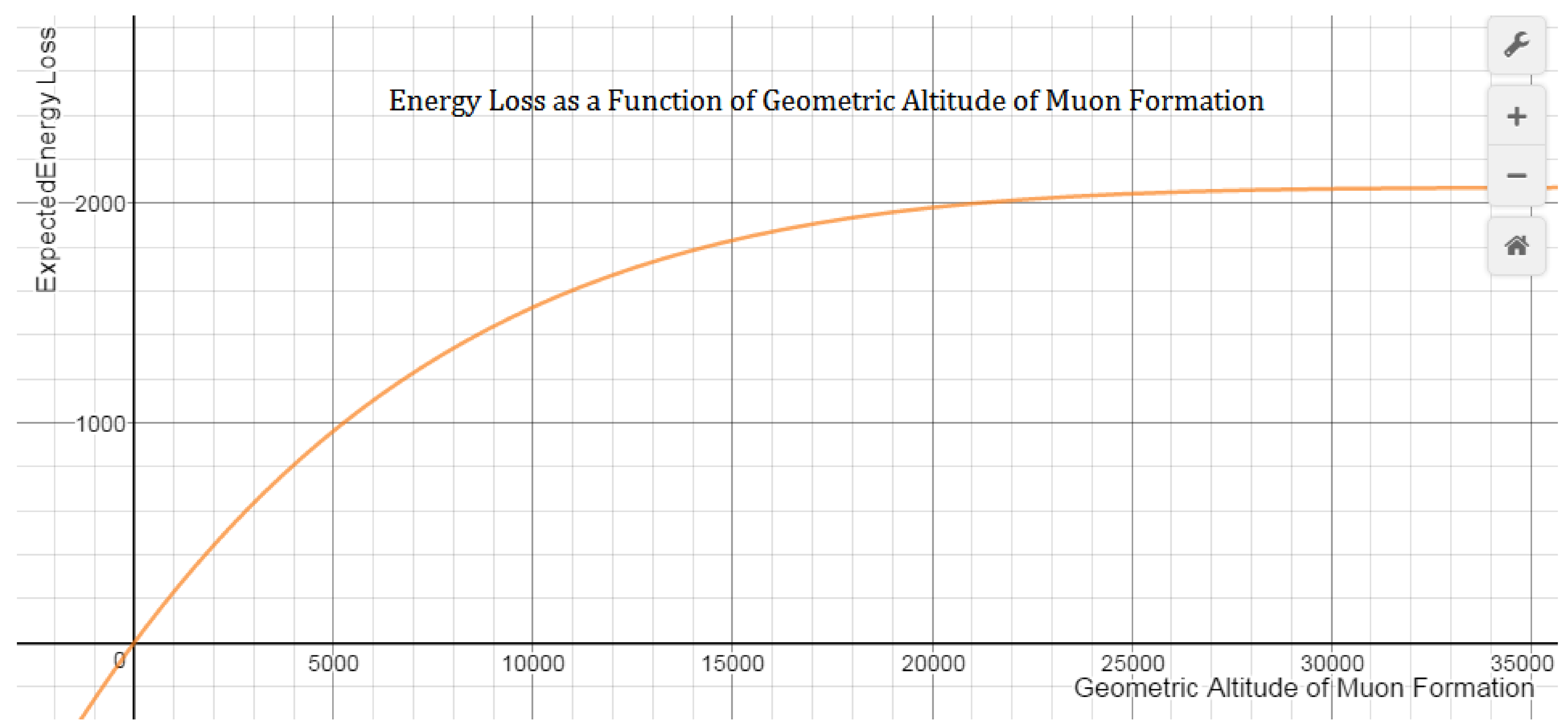
where z is altitude of muon formation and ρ is the air density.

Modeling Atmospheric Density

The International Standard Atmosphere (ISA) models temperature and pressure as varying with geopotential altitude, calculated as: $h = \frac{zr_e}{z+r_e}$ [2]. The equations listed below are accurate up to the tropopause.

$$T(h) = T_0 - (0.0065\mathrm{K\,m^{-1}})h,\ p(h) = p_0\left(1 - \frac{Lh}{T_0}\right)^{\frac{gM}{RL}}$$

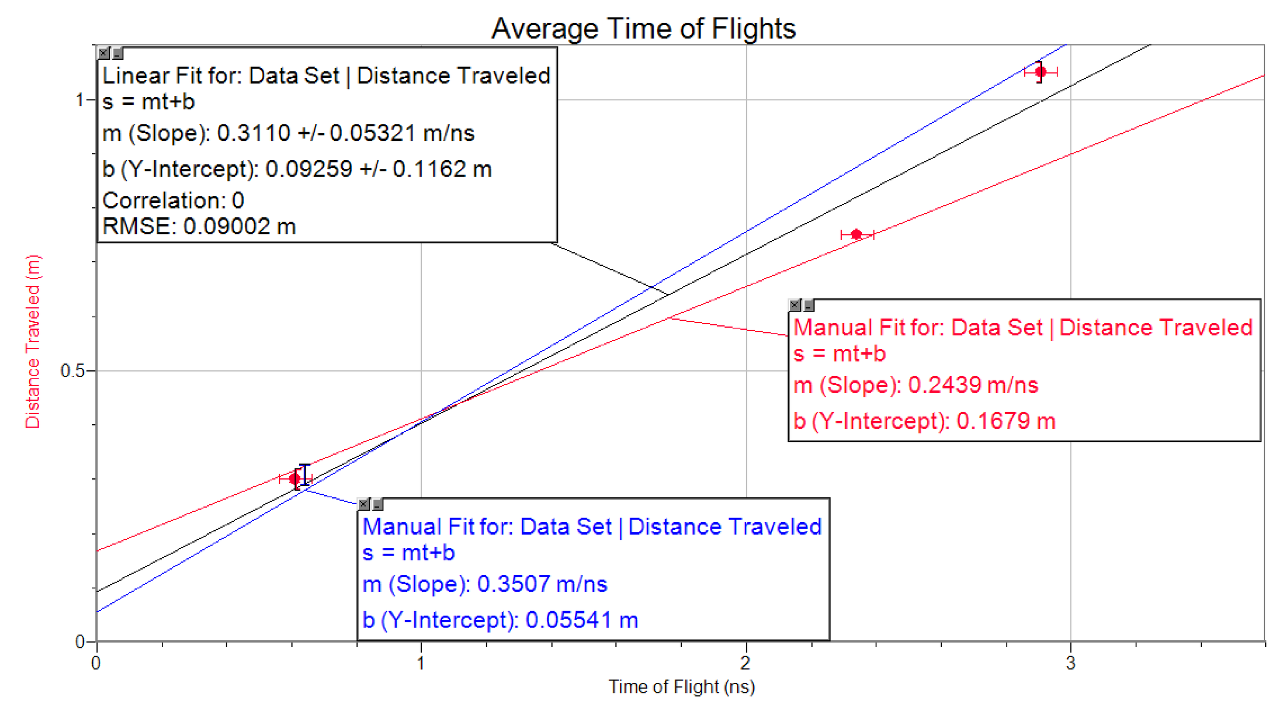
Applying these equations to the Ideal Gas Law, $\rho = \frac{pM}{RT}$, we can model air density for the troposphere, which varies in height from 7km − 20km, depending on latitude. This model also relies on the assumptions of standard pressure and temperature, along with lack of humidity.

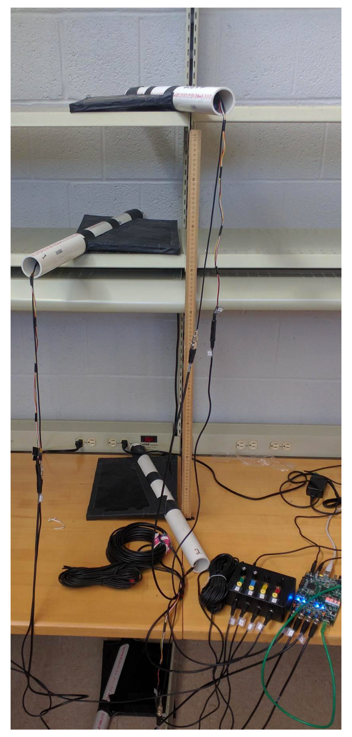


If created at 15km, the average muon will lose ≈ 1.8GeV upon reaching the surface

Calculating Muon Speed

By putting three scintillator paddles in a stacked configuration and using the Cosmic Ray e-Lab, I was able to use the data collected to create a linear regression of time of flight versus distance traveled by muons. This regression equation produces the average speed of the muons in the form of its slope.





LEFT: $|v_{average}| = 0.3110\mathrm{m\,ns^{-1}} > c$, violating special relativity.
RIGHT: An image of the scintillators. The bottom paddle was malfunctioning, so its data was not included.

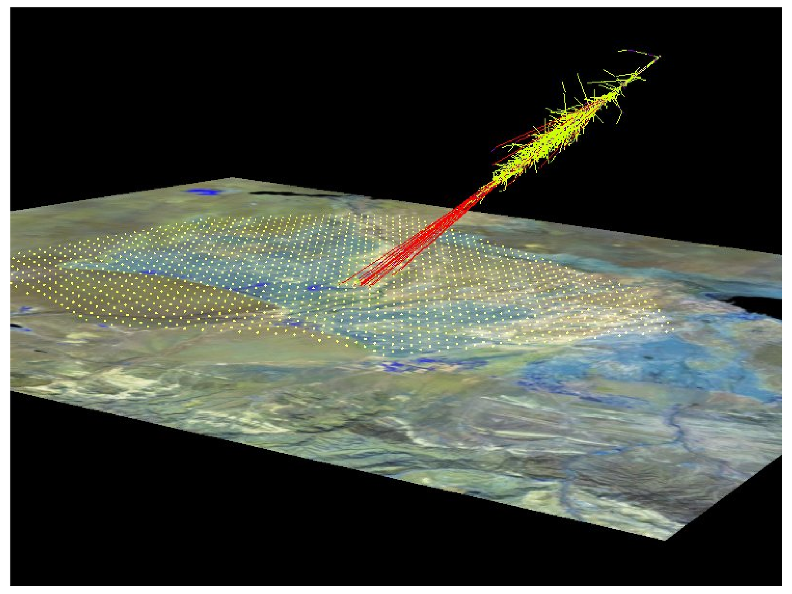
There are two main reasons why our data was inaccurate and imprecise:

- Differences in how quickly a pulse emitted by a PMT travels
- The CRMD measures time of flight to only 0.1ns

Small changes in relativistic speeds can lead to drastic changes in the Lorentz factor, which is essential in calculating muon momentum and energy. Thus, we can see that using muon speed is not an effective method for reconstructing cosmic ray events.

So How Can We Reconstruct Cosmic Ray Events?

The Pierre Auger Observatory is capable of detecting muon showers several kilometers wide [3]. It can use data on the spread of the shower to estimate the energy of the cosmic ray along with the distribution of particles produced by the event.



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References

[1] J.J. Beatty, J. Matthews, S.P. Wakely. *Cosmic Rays*. http://pdg.lbl.gov/2015/reviews/rpp2015-rev-cosmic-rays.pdf

[2] Mustafa Cavcar. *The International Standard Atmosphere (ISA)* http://home.anadolu.edu.tr/~mcavcar/common/ISAweb.pdf

[3] Pierre Auger Observatory. *Cosmic Ray Mystery* https://www.auger.org/index.php/cosmic-rays/cosmic-ray-mystery

[4] Cosmus, From the University of Chicago http://astro.uchicago.edu/cosmus/projects/auger/

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