30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07
Mérida, México

Observation of Seasonal Variations with the MINOS Far Detector

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Abstract: An observation of seasonal variations in underground muon rate, R_μ, has been performed at Soudan, MN, by the MINOS Far Detector. The four percent fluctuation seen over three years was highly correlated to the temperature variations of the upper atmosphere. The coefficient relating variations in temperature to variations in muon rate was found to be: $\alpha_T = (T/R_\mu)(\partial R_\mu/\partial T) = 0.87 \pm 0.03$, which is near the expectation of 0.91.

Introduction & Motivation

When cosmic rays interact with molecules in the Troposphere, mesons are produced which either interact again and produce low energy cascades or decay into muons. While the temperature of the Stratosphere varies considerably within the day in areas far from the equator, the temperature of the Troposphere remains nearly constant, slowly changing over longer timescales such as seasons. Increases in temperature of the Troposphere cause increases in volume and atmospheric scale height, thus the height of the primary cosmic ray interaction. The higher in the atmosphere mesons are produced, the more time they have to decay to muons, thus the rate of muons underground will increase as temperature increases [1–3]. Though this effect has been measured by underground experiments, there has been little agreement with the expectation.

MINOS is a long baseline neutrino oscillation experiment, with a ν_μ beam and Near Detector at Fermi National Accelerator Laboratory in Batavia, IL. The Far Detector is a 5.4 kt magnetized scintillator and steel tracking calorimeter located 720 m underground (2100 mwe) at the Soudan Underground Mine State Park in Northern Minnesota. Its depth, large acceptance and flat overburden make it possible to observe cosmic-ray induced muons of minimum surface energy 0.7 TeV without preference to direction, and thus detect the small sea-sonal fluctuations in arrival rate. The seasonal effect is enhanced as muon energy increases, and the large size of the Far Detector allows a significant accumulation of statistics with which to perform this analysis. Additionally, the Far Detector has a magnetic field, which allows the separation of particles by charge, so MINOS will be the first experiment to measure seasonal variations for μ^+ separate from μ^-. The consistency and availability of radiosonde temperature measurements from the NOAA IGRA (Integrated Global Radiosonde Archive [4]) over the duration of the data set ensures a high statistics temperature sample as well, increasing the probability of a positive correlation. The data used in this analysis were collected over three years, from 1 August 2003 - 1 August 2006 for three complete cycles, numbering 24 million muons. The relationship between the temperature and intensity can be expressed as [1]:

$$\frac{\Delta I_\mu}{I_\mu^0} = \int_0^\infty dX\, \alpha(X) \frac{\Delta T(X)}{T(X)} \qquad (1)$$

where ΔI_μ are the fluctuations about I_μ^0. The short lived mesons produced in the upper atmosphere interact or decay as they descend toward the earth. The meson decay channels result in muons with nearly the same energy as the parent meson, while interactions produce lower energy cascades that are filtered by the rock overburden above the Far Detector. These outcomes are energy dependent, separated by the "critical energy" [2]. The "Effec-

tive Temperature" (T_{eff}) approximates the upper atmosphere as an isothermal body, weighting the temperature of the pressure levels to have a uniform amount of matter. In the π scaling limit, T_{eff} is [2]:

$$T_{eff} = \frac{\int \frac{dX}{X} T(X) \left(e^{\frac{-X}{\Lambda_\pi}} - e^{\frac{-X}{\Lambda_N}} \right)}{\int \frac{dX}{X} \left(e^{\frac{-X}{\Lambda_\pi}} - e^{\frac{-X}{\Lambda_N}} \right)}, \quad (2)$$

where X is the scale height of the atmosphere, $\Lambda_N = 120\,\mathrm{gm/cm^2}$ and $\Lambda_\pi = 160\,\mathrm{gm/cm^2}$ are the nucleon and pion atmospheric attenuation lengths, respectively. For a detector counting discrete particles, the intensity is written $I_\mu = R_i/\epsilon A_{eff}\Omega$, where $R_i = N_i/t_i$, the number of muons observed over time t_i, A_{eff} is the effective area, ϵ is the efficiency, and Ω is the solid angle observed. Every term but the rate is constant over time, so: $\frac{\Delta I_\mu}{I_\mu^0} = \frac{\Delta R_\mu}{\langle R_\mu \rangle}$. With these definitions and eq. 1, we can write the experimental determination of α_T:

$$\int_0^\infty dX \alpha(X) \frac{\Delta T(X)}{T(X)} = \alpha_T \frac{\Delta T_{eff}}{<T_{eff}>} = \frac{\Delta R_\mu}{<R_\mu>}. \quad (3)$$

The Data

The data for this analysis were accumulated over a three year span, beginning on 1 August, 2003, at a time when the detector was fully operational. Beginning with 40.3 million cosmic ray tracks, a series of cuts were performed [5]. Pre-analysis cuts include: failure of demultiplexing figure of merit, multiple muon (multiple muons aren't included in the Monte Carlo), "bad run" and bad magnet coil status. Analysis cuts include: track length less than 2 m number of planes less than 20, $\chi^2_{reco} > 1.0$ and either track vertex or end point outside of the fiducial volume of the detector. A total of 24.7 million events survived these cuts for the combined sample. T_{eff} was found using weather data from International Falls, MN weather station. Balloon flights were usually done twice a day, with the maximum height reached at noon and midnight, and sampled temperatures from at least six different heights. Days in which there were not exactly two temperature readings or that both measurements did not
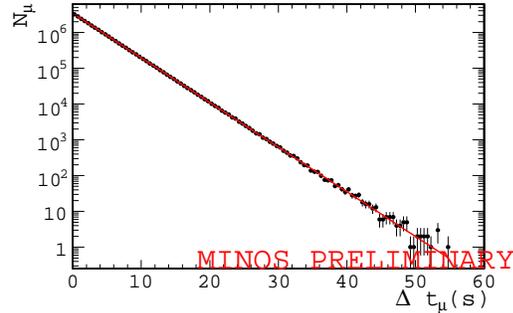

Figure 1: Time between consecutive μ arrivals in log y. A Poisson fit gives $\chi^2/ndof = 90.87/105$; $\langle R_\mu \rangle$ (from slope) $= 0.2872 \pm 0.0001$

reach a column depth of at least $60\,\mathrm{gm/cm^2}$ were excluded from the data set.

Analysis

Upon examination of the data, it was found that on four days there were fluctuations that deviated in an erratic manner. The great stability of the detector over the 1096 days of data and the fact that they were documented by the Control Room Logbook made these days stand out and diagnose as hardware issues. To find the rate for each day, the number of muons counted was divided by that day's livetime. T_{eff} was calculated for two times each day using the IGRA temperature data and 2, and the error was found by $\sigma^2 = \left\langle T_{eff}^2 \right\rangle - \langle T_{eff} \rangle^2$ added in quadrature with $0.05°$. The fit results from Fig. 1 was used to find $\langle R_\mu \rangle$ over three years, 0.287 Hz. Histograms of the deviations from the mean for both R_μ and T_{eff} are shown in Fig. 2, binned by day. The expected periodic fluctuation in T_{eff}, with maxima in July, minima in January, is very clearly shown, as is a very similar (nearly indistinguishable) fluctuation in R_μ. An independent analysis used a smoothed time series, and their results were highly consistent with what is shown here. To quantify the correlation between rate and temperature, a plot of $R_\mu(T_{eff})$ was produced (Fig. 3) and a linear regression was fit using ROOT's MINUIT fitting package. This package accounts for error bars on both the x and y axis using a numerical minimization method. This fit gives $\alpha_T = 0.87 \pm 0.03$ from the slope. In order
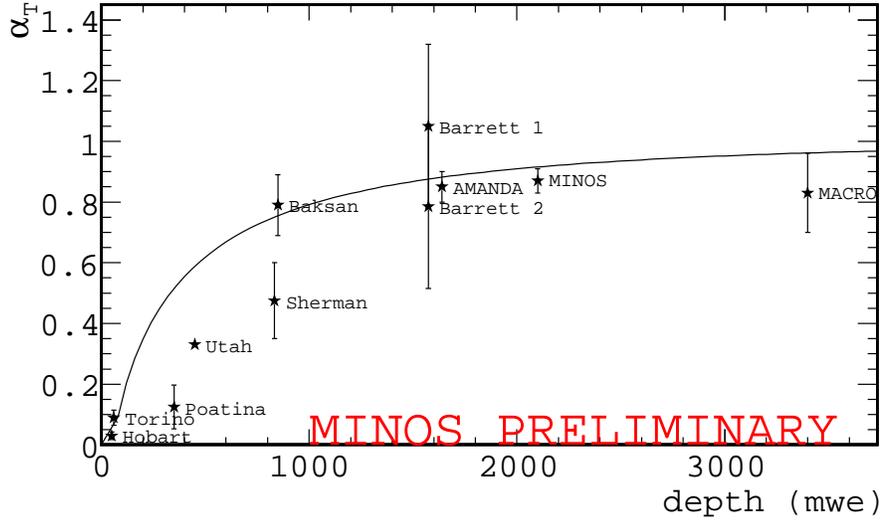
Figure 4: The theoretical $\alpha_T(X)$ (solid curve) for slant depths up to 4000 mwe. The MINOS point is from this analysis, Barrett 1,2 [1], AMANDA [3]; all other points from [2]
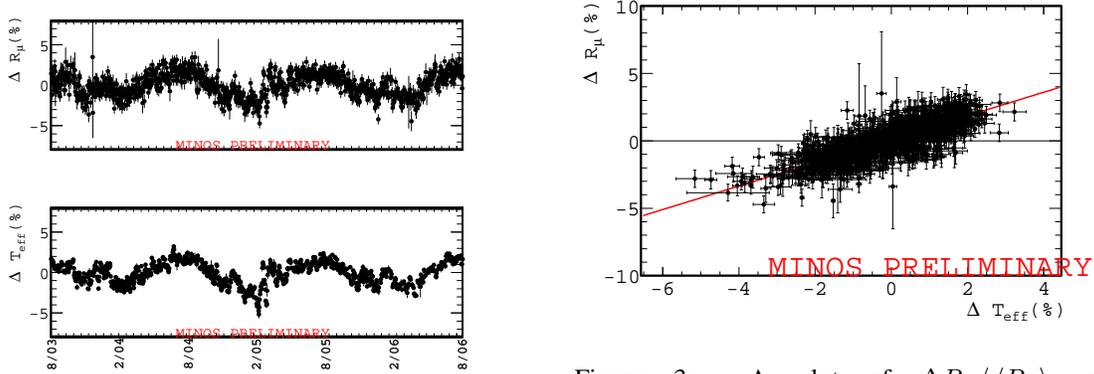

Figure 2: ΔR_μ, (top), and ΔT_{eff} (bottom) from 8/03-8/06, binned by day.

Figure 3: A plot of $\Delta R_\mu / \langle R_\mu \rangle$ vs. $\Delta T_{eff} / \langle T_{eff} \rangle$ for single muons. The fit $\chi^2/ndof = 1420/953$, and correlation coefficient R = 0.79.

to compare our experimental α_T to the theoretical expectation, a simple numerical program was written to find the expected value given by [1]:

$$\langle \alpha_T \rangle_\pi = \left\langle 1 + \frac{\gamma}{(\gamma+1)} \times \frac{\epsilon_\pi}{1.1 E_{th} cos\theta} \right\rangle \quad (4)$$

Note that this expression is only valid for pions. Future work will involve this kaon contribution, which should lower the expected α_T since kaons are short lived and always decay. A muon energy and $\cos\theta$ were chosen out of the differential muon intensity [6],

$$\frac{dI_\mu}{dE_\mu} = 0.14 E_\mu^{-(\gamma+1)} \left[\frac{1}{1 + 1.1 E_\mu \cos\theta/\epsilon_\pi} \right] \quad (5)$$

where $\gamma = 1.7$ is the muons spectral index [5]. a random azimuthal angle, ϕ was chosen and combined with $\cos\theta$ and Soudan rock overburden map [7] to find the slant depth. The threshold surface energy required for a muon to survive this column depth is found from $E_{th}(\theta,\phi) = a(e^{bX}-1)$, where $a = 0.45$ TeV and $b = 0.44 \, [\text{mwe}]^{-1}$ for Soudan rock [5], column depth $X = X(\theta,\phi)$, and if the chosen $E_\mu > E_{th}$, it was used in the calculation of the theoretical $\langle \alpha_T \rangle_\pi$. This was repeated for 10,000 successful E_μ to find $\langle \alpha_T \rangle_\pi = 0.91$ for MINOS, which is very near to the experimental value, 0.87 ± 0.03. To compare the MINOS re-

sult with other underground experiments, this process was repeated for standard rock ($a = 0.50\,\text{TeV}$ and $b = 0.4\,[\text{mwe}]^{-1}$), flat overburden, and $X = H\cos\theta$, where H is the detector depth in mwe, using 10,000 successful muons at depths from 0 to 4,000 mwe. The result of this calculation, along with data from other experiments, can be seen in Fig. 4. The MINOS result matches the expectation and has tighter error bars than both recent results, AMANDA (± 0.05 [3]) and MACRO (± 0.13 [2]).

The curvature of the track is used to determine the momentum and charge of the particle, so a charge sign confidence cut was required. This cut was charge over momentum divided by the error in the determination of charge over momentum ($\frac{q/p}{\sigma_{q/p}} > 2.2$), determined from previous investigations of the muon charge ratio. That left 8.8 million
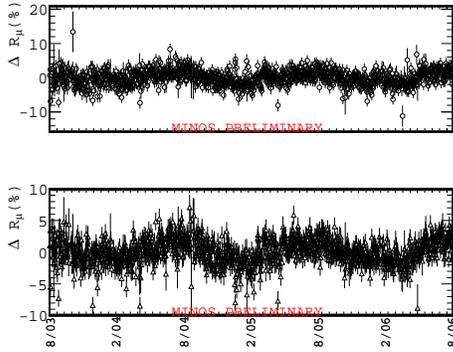

Figure 5: $\Delta R_\mu / \langle R_\mu \rangle$ for μ^+ (open triangles, top) and μ^- (open circles, bottom), binned by day.

events; 5.1 million positive, 3.7 million negative, which is consistent with the published MINOS charge ratio. Fig. 5(t) shows ΔR_{μ^+} (open triangles) and Fig. 5(b) shows ΔR_{μ^+} (open circles) over the same time period, binned by day. The sample of muons is smaller than for the μ_{tot} sample, thus the error bars on R_μ are larger, but the trade off is that the error bars on the temperature are much smaller since the small fluctuations over several days are not washed out. Performing the same fit of $R_\mu(T_{eff})$ as for the μ_{tot} sample on μ^+ separate from μ^- resulted in a slope of 0.845 ± 0.036 and 0.843 ± 0.042 respectively. These correspond highly to each other, and are within one sigma of α_T found from the μ_{tot} sample.

Conclusions

A three year sample of 42 million cosmic ray induced muons has been collected by the MINOS Far Detector and daily rate fluctuations have been compared to daily fluctuations in atmospheric temperature, and these distributions were shown to be highly correlated, with a correlation coefficient of 0.79. The constant of proportionality relating the two distributions, α_T, was found to be 0.87 ± 0.03, which, within the error band, is in good agreement with the theoretical expectation in the pion-only approximation of $\langle \alpha_T \rangle_\pi = 0.91$. This suggests that the majority of muons seen in the Far Detector were generated by pion parents.

Acknowledgments

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