



Measurement of the Atmospheric Muon Charge Ratio at TeV Energies with MINOS

S.L. MUFSON¹ AND B.J. REBEL² FOR THE MINOS COLLABORATION

¹ *Indiana University, Bloomington, IN 47405 USA*

² *Fermi National Accelerator Laboratory, Batavia, IL 60510 USA*

mufson@astro.indiana.edu

Abstract: The MINOS far detector in the Soudan mine, Minnesota, USA has been taking charge-separated cosmic ray muon data since the beginning of August, 2003 at a depth of 2070 meters-water-equivalent. The data with both forward and reversed magnetic field running configurations were combined to minimize systematic errors in the determination of the underground muon charge ratio. When averaged, two independent analyses find the charge ratio underground to be $N_{\mu^+}/N_{\mu^-} = 1.374 \pm 0.004$ (stat.) $^{+0.012}_{-0.010}$ (sys.). Using the map of the Soudan rock overburden, the muon momenta as measured underground were projected to the corresponding values at the surface in the energy range 1-7 TeV. Within this range of energies at the surface, the MINOS data are consistent with the charge ratio being energy independent at the two standard deviation level. When the MINOS results are compared with measurements at lower energies, a clear rise in the charge ratio in the energy range 0.3 – 1.0 TeV is apparent. A qualitative model shows that the rise is consistent with an increasing contribution of kaon decays to the muon charge ratio.

Introduction

The MINOS far detector is a 5.4 kton steel-scintillator sampling calorimeter outfitted with magnetized steel planes. It is located at the Soudan Underground Laboratory, Minnesota, USA at a depth of 710 meters below the surface. MINOS is the deepest experiment to measure cosmic ray muons with a magnetized detector, thus providing a capability to distinguish μ^+ from μ^- with large statistics. Measurements of the cosmic ray muon charge ratio from a few GeV to a few TeV are important in understanding the physics of cosmic ray interactions in the atmosphere and in constraining calculations of the atmospheric neutrino fluxes. A detailed description of the analysis presented here can be found in [1].

Muon Charge Ratio Underground

The results presented here are based on data recorded between August 1, 2003 and February 28, 2006. The data were taken with two different magnetic field orientations to minimize systematic er-

rors in the calculation of the charge ratio. These two configurations are: Forward Field (DF) running, which is the default configuration for MINOS data-taking with the NuMI beam from Fermilab and Reverse Field (DR) running, in which the coil current is reversed. The data analyzed here were obtained in 609.8 live days of DF running and 201.8 live days of DR running. There were 29.0M events in the DF sample and 8.9M events in the DR sample. This analysis requires the clear separation of μ^+ from μ^- with minimal systematic uncertainty. After cuts, there were 1.44M events remaining in the DF sample and 444.5k events remaining in the DR sample.

The muon charge ratio N_{μ^+}/N_{μ^-} underground was determined by combining the DF and DR data sets with methods that cancel geometrical acceptance effects, alignment errors, and systematics linear in time. Define

$$r_a = (N_{\mu^+}/t)_{DF}/(N_{\mu^-}/t)_{DR}, \quad (1)$$

and

$$r_b = (N_{\mu^+}/t)_{DR}/(N_{\mu^-}/t)_{DF}, \quad (2)$$

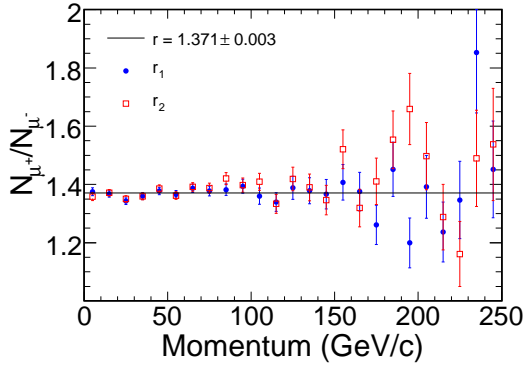


Figure 1: The charge ratio N_{μ^+}/N_{μ^-} underground as a function of fit momentum. The errors shown are statistical. Superposed is the fit to a constant charge ratio N_{μ^+}/N_{μ^-} .

where N_{μ^+} and N_{μ^-} are the number of observed positive and negative muons, respectively, and t is the live time for the two data sets. Eliminating the Forward and Reverse live times between the two equations gives a measurement of the mean charge ratio, r , in which both geometrical acceptance and live time biases cancel,

$$r = [r_a \times r_b]^{1/2} \quad (3)$$

$$= [(N_{\mu^+}/N_{\mu^-})_{DF} \times (N_{\mu^+}/N_{\mu^-})_{DR}]^{1/2}.$$

Fig. 1 shows the charge ratio N_{μ^+}/N_{μ^-} as a function of the fit momentum as determined by eq.(3) for one of the two independent analyses used to compute the charge ratio. Averaging the results of the two independent analyses (*MIC*, *BdL*) and carefully considering the systematic errors gives the charge ratio underground as measured by MINOS:

$$r = 1.374 \pm 0.004 \text{ (stat.)}_{-0.010}^{+0.012} \text{ (sys.)}. \quad (4)$$

Muon Charge Ratio at the Surface

A slant depth map is required to infer the muon momentum at the surface from the momentum measured underground. This slant depth map in terms of standard rock was determined by fitting the measured MINOS vertical muon intensity underground to the “world survey” vertical muon intensity [2] with the slant depth, X (m.w.e.), as

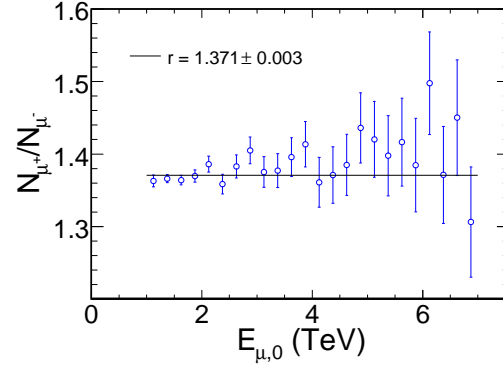


Figure 2: The muon charge ratio N_{μ^+}/N_{μ^-} at the Earth’s surface. The errors shown are statistical. Superposed is the fit to a constant charge ratio N_{μ^+}/N_{μ^-} .

the fit parameter. The slant depth map was then converted from standard rock to Soudan rock using Soudan rock parameters. Using the MINOS slant depth map, the muon energies E_{μ} underground for the *MIC* data sample were projected to their surface values $E_{\mu,0}$ using

$$E_{\mu,0} = (E_{\mu} + a/b)e^{bX} - a/b, \quad (5)$$

where the parameters a and b describe the energy lost by collisional and radiative processes in Soudan rock, respectively, and X is the slant depth [3]. The muons with their associated energies at the surface were sorted into histograms according to their charge sign and from these histograms the charge ratio N_{μ^+}/N_{μ^-} at the surface as a function of $E_{\mu,0}$ was computed. The results are shown in Fig. 2. A fit to a constant charge ratio between 1.0 – 7.0 TeV gives

$$N_{\mu^+}/N_{\mu^-} = 1.371 \pm 0.003 \text{ (stat.)}_{-0.010}^{+0.012} \text{ (sys.)}, \quad (6)$$

with $\chi^2/ndf = 63.2/67$. Systematic errors were determined by Monte Carlo simulation. The data are consistent with the charge ratio being energy independent at the two standard deviation level.

Discussion

The projection of the MINOS charge ratio data back to the surface, plotted in Fig. 2, yields a

charge ratio significantly higher at a few TeV than the charge ratio measured by other experiments at surface energies below 300 GeV [4]. This rise in the charge ratio at TeV energies is, however, expected as the result of the increasing contribution of kaons to the cosmic ray muon flux at these energies and the greater likelihood for kaons to decay to μ^+ than for pions to decay to μ^+ [3].

A qualitative model of the charge ratio as a function of surface energy [5], the ‘ πK ’ model, shows that the rise in the charge ratio at TeV energies is consistent with this expectation. Let f_{π^+} be the fraction of all pion decays with a detected muon that is positive. Then $(1 - f_{\pi^+})$ is the fraction of all pion decays with a detected muon that is negative. Similarly, let f_{K^+} be the fraction of all kaon decays with a detected muon that is positive and $(1 - f_{K^+})$ be the fraction of all kaon decays with a detected muon that is negative. The simplest assumption to make in this model is that f_{π^+} and f_{K^+} are independent of energy. Although this assumption neglects many physical processes that may play a role at these energies, it is an assumption that is a reasonable choice to qualitatively describe our results: a rise in the charge ratio from a plateau at a few hundred MeV to a second higher plateau at a few TeV. This rise has already been seen in the results from the CORT cosmic ray Monte Carlo [6] and the models of Lipari [7].

We tested this simple model with the MINOS data and the L3+C data [4] to find the values of f_{π^+} and f_{K^+} that best describe the data. These data were used because they are the only ones that have angular information needed for the fit. We found the best fit values for f_{π^+} and f_{K^+} with a grid search over (f_{π^+}, f_{K^+}) parameter space. At each point in the space a χ^2 statistic was used to compare the charge ratio as a function of surface energy, $E_{\mu,0}$, and zenith angle, $\cos\theta$ with the model predictions. The uncertainties in each solid angle bin were computed as the quadratic sum of the statistical and systematic errors. The χ^2 minimum is found at $f_{\pi^+} = 0.55$ and $f_{K^+} = 0.67$, with $\chi^2/ndf \simeq 1$. In Fig. 3, we have superposed the πK model onto the MINOS and L3+C data sets [4]. The qualitative results of the model are that the observed rise in the muon charge ratio can be explained by the increasing importance of kaon decays to the muon charge ratio as the energy increases from 0.3 – 1

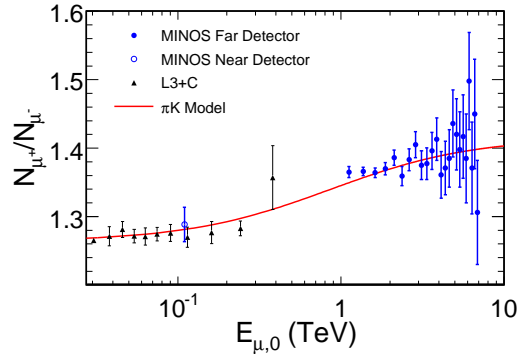


Figure 3: The πK model superposed onto the MINOS and L3+C data sets. The L3+C data are taken from [4].

TeV and that values of f_{π^+} and f_{K^+} that are independent of energy are sufficient to describe the MINOS and L3+C data.

Fig. 3 also demonstrates that these results are not the consequence of a systematic offset between MINOS and L3+C. In this figure, the charge ratio determined by the MINOS near detector [8] has been superposed. This additional data point is clearly consistent with the L3+C data and the πK model.

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