The Multiple Muon Charge Ratio in MINOS Far Detector*

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(Dated: December 20, 2015)

Abstract

The charge ratio, $R_\mu = N_{\mu^+}/N_{\mu^-}$, for cosmogenic multiple-muon events observed at an underground depth of 2070 mwe has been measured using the MINOS Far Detector. The multiple-muon charge ratio is determined to be $R_{\mu.} = 1.104 \pm 0.006(stat.)^{+0.009}_{-0.010}(syst.)$. This measurement serves to constrain models of cosmic ray interactions at TeV energies.

INTRODUCTION

Atmospheric muons are produced when primary cosmic ray nuclei interact near the top of the atmosphere to produce hadronic showers which contain pions and kaons. These secondary mesons can either interact in further collisions in the atmosphere or decay to produce atmospheric muons. Since the majority of primary cosmic rays are protons, there is an excess of positively charged mesons (K^+, π^+) in the showers, and consequently, the atmospheric muon charge ratio for single muons is larger than unity. Due to the steeply falling primary cosmic ray energy spectrum, which follows an $E^{-2.7}$ power law, a single-muon event in a deep underground detector is more likely from the decay of a leading hadron than from a secondary hadron or later generation hadrons. Conversely, observation of a multiple muon event, one where two or more nearly parallel, time-coincident muon tracks are observed in the detector underground, must involve more than the decay of a single leading hadron. These muons are decay products of mesons which are generated in the hadronic core of the atmospheric cascade.

Precision measurements of R_μ in cosmic rays can be used to improve models of the interactions of cosmic rays in the atmosphere. In addition, measurements of the cosmic ray muon charge ratio from a few GeV to a few TeV are important for constraining calculations of atmospheric neutrino fluxes. These are of interest both for detailed measurements of neutrino oscillations in atmospheric neutrino experiments and also for calculations of backgrounds for neutrino telescopes.

THE MINOS FAR DETECTOR

The MINOS Far detector is a steel-scintillator sampling and tracking calorimeter located at a depth of 2070 m.w.e. in the Soudan Underground Laboratory, in Minnesota. The detector consists of two supermodules separated by a gap of 1.15 m and has a total dimension of $8 \times 8 \times 31$ m^3. The two supermodules contain a total of 486 octagonal steel planes, interleaved with 484 planes of extruded polystyrene scintillator strips. Each scintillator plane has 192 strips of width 4.1cm. The scintillator strips in alternating detector planes are oriented at $\pm 45^o$ to the vertical. Light from charged particles traversing the plastic scintillator is collected with wavelength shifting (WLS) plastic fibers embedded within the scintillator strips. The WLS fibers are coupled to clear optical fibers at both ends of a strip and are read out using 16-pixel multianode phototmultiplier tubes (PMT's).

To measure the momentum of muons traversing the detector, the steel has been magnetized into a toroidal field configuration. In one magnetic field setting, negative muons resulting from interactions of neutrinos from the Fermilab NuMI beam are focused toward the center of the detector. This magnetic field orientation will be referred to as the forward field (FF) configuration. In the reverse field (RF) configuration, the coil current is reversed and positive muons are focused into the detector.

DATA ANALYSIS

The multiple muon sample used in this analysis was recorded between August 2003 and April 2012. During the data taking period, the detector run with both the FF and RF magnetic field configurations. Table I summarizes the number of muon tracks that pass each of the selection cuts. A sample of 312514 muons in multiple-muon events was obtained after all the cuts shown in Table I were applied. To eliminate biases from acceptance effects due to magnetic field, detector asymmetry and detector alignment, data taken in both magnetic field configurations is combined with a geometric mean (GM). Figure 1 shows the measured muon charge ratio as a function of the charge significance $(q/p)/\sigma(q/p)$ and BdL, for data collected in both magnetic field orientations respectively. Table II shows the measured muon charge ratio as a function of muon multiplicity for forward data (FF), reverse data (RF) and combined (GM) data sets. The obtained uncorrected charge ratio measurement is $R_{uncorr.} = 1.091 \pm 0.005(stat.)$

To obtain the true charge ratio of the multiple-muon events reaching the MINOS FD, $R_{uncorr.}$ must be corrected to account for the charge-separation efficiency, ε (which is obtained from Monte Carlo simulation). The corrected charge ratio, $R_{corr.}$, is related to the

TABLE I: Summary of the applied cuts. Each row shows the total number of muons in both field configurations remaining after all the applied cuts to data. The numbers in parenthesis show the percentage of muons remaining.

Cuts	Number of muons remaining	
Preselected tracks	8.35×10^6	(100%)
Analysis cuts		
parallel tracks ($< 5°$)	7.31×10^6	(87.5%)
20 planes	5.88×10^6	(70.5%)
2 m track length	5.87×10^6	(70.3%)
downward-going track	5.86×10^6	(70.2%)
fiducial volume	5.75×10^6	(68.9%)
fit quality: $\chi^2/ndf < 2$	5.17×10^6	(61.9%)
Charge-sign quality cuts		
$(q/p)/\sigma(q/p) > 3$	1.08×10^6	(13.0%)
$BdL > 5$ T·m	3.12×10^5	(3.7%)

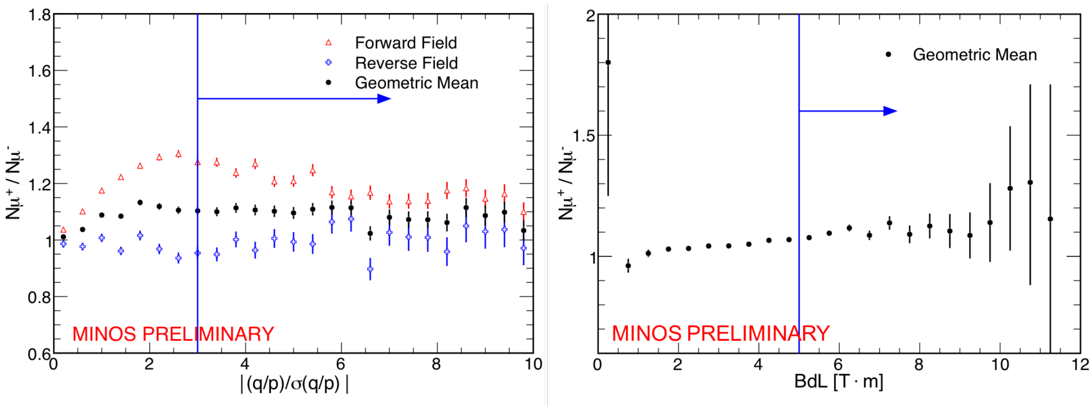

FIG. 1: Charge ratio for reconstructed multiple-muon tracks as a function of the charge significance (left), and BdL (right), after applying all the selection cuts. The vertical line denotes the minimum value for tracks used in the charge ratio measurement.

uncorrected GM, $R_{uncorr.}$, and the charge-separation efficiency, ε, by $R_{corr.} = \frac{R_{uncorr.} - (\frac{1-\varepsilon}{\varepsilon})}{1 - R_{uncorr.} \times (\frac{1-\varepsilon}{\varepsilon})}$. The systematic error in the charge ratio measurement comes from the contribution of possible failure to cancel effects of magnetic field and alignment errors by reversing the magnetic field (bias) and dealing with reconstruction failures that tend to give a random charge determination (randomization). The multiple-muon charge ratio after charge efficiency correction is $R_{corr.} = 1.104 \pm 0.006(stat.)^{+0.009}_{-0.010}(syst.)$.

TABLE II: Measured muon charge ratio, $R_{uncorr.}$, as a function of muon multiplicity, M, for forward and reverse data, and the GM combination. Only statistical errors are shown.

M	Forward Field (FF)	Reverse Field (RF)	Geometric Mean (GM)
2	1.195 ± 0.005	1.025 ± 0.010	1.107 ± 0.006
3	1.157 ± 0.012	0.943 ± 0.020	1.044 ± 0.012
4	1.165 ± 0.021	0.929 ± 0.035	1.040 ± 0.022
5	1.210 ± 0.037	0.856 ± 0.055	1.018 ± 0.036
6	1.153 ± 0.057	0.882 ± 0.088	1.009 ± 0.056
7	1.192 ± 0.098	0.761 ± 0.121	0.952 ± 0.085
8	1.061 ± 0.149	0.692 ± 0.212	0.857 ± 0.145
9	1.000 ± 0.218	0.556 ± 0.310	0.745 ± 0.223
10	1.400 ± 0.580	0.500 ± 0.612	0.837 ± 0.541
All	1.187 ± 0.005	1.002 ± 0.008	1.091 ± 0.005

CONCLUSIONS

The calculated underground multiple-muon charge ratio ($R_{corr.}$) is lower than the single muon charge ratio measurements obtained by several experiments in the past [1]. This result gives support to the hypotheses about the decrease of the charge ratio for multiple-muon events mentioned in the Introduction, providing a better understanding of the mechanism of multiple-muon production in the atmosphere. The result is also consistent with the last OPERA multiple-muon charge ratio measurement [2].

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* *Presented at NuFact15, 10-15 Aug 2015, Rio de Janeiro, Brazil [C15-08-10.2]*

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