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Measurement of the Atmospheric Muon Charge Ratio using the MINOS Near Detector

J. K. DE JONG[1] FOR THE MINOS COLLABORATION
[1]*Illinois Institute of Technology. Chicago Illinois 60616 USA*
dejong@iit.edu

Abstract: The magnetized MINOS near detector has been collecting charge-separated atmospheric muon events since January 2005. To reduce the systematics due to muon acceptance equal periods of forward and reverse magnetic field data were combined. This has allowed an accurate measurement of the muon charge ratio to be performed with 8.52 days of data. We report a charge ratio of 1.288±0.004(stat.)±0.025(syst.) at a mean surface energy of 110 GeV.

Introduction

The MINOS experiment consists of two steel-scintillating sampling calorimeter detectors. The 980 ton near detector is used to characterize the spectrum of the neutrino beam and is located at Fermilab in a cavern 100 m underground at the end of the NuMI beam facility (approximately 1 km from the primary proton target). The 5.4 kton far detector is located 732 km further downstream and is 710 meters below the surface. MINOS looks for neutrino oscillations by identifying changes to the neutrino spectrum.

Atmospheric muons are produced by cosmic ray primaries striking the top of the atmosphere. Since the majority of cosmic rays are positively charged there will be an excess of positive over negative pions and kaons produced in the subsequent hadronic shower. The fraction of pions and kaons that decay, versus those that interact, will dictate the scale of the atmospheric muon charge ratio (R=N_{μ^+}/N_{μ^-})[1].

Both MINOS detectors utilize toroidally magnetized steel planes as the passive absorber material. This magnetic field, which varies between 1 and 2 Tesla, allows them to distinguish between positive and negative muons. The MINOS far detector has measured the atmospheric muon charge ratio at surface energies between 1 and 7 TeV and is discussed in [2]. This note will discuss the measurement of the atmospheric muon charge ratio performed with the MINOS near detector.

Discussion

The MINOS Near Detector

The MINOS near detector is a steel scintillating sampling calorimeter with tracking, energy and topology measurement capabilities. It measures roughly 3.8 m tall, 4.8 m wide and 16.6 m long. The detector contains 282 vertical layers. Each layer contains a 2.54 cm thick steel plane, a 1.0 cm thick scintillating plane and a 2.4 cm air gap. Each scintillator plane is comprised of either 64("partial plane") or 96("full plane") scintillating strips which are each 4.1 cm wide. The strips in each scintillating layer are rotated by 45° with respect to the previous layer to allow for 3 dimensional track reconstruction.

The magnetic focusing horns produce a narrow neutrino beam, with a radius of approximately 1 m at the near detector. It was therefore not necessary to fully instrument all regions of the detector. The first 120 planes located on the upstream portion of the detector comprise the calorimeter. In the calorimeter every 5th plane is fully instrumented covering the cross-sectional area defined by the steel planes. The following 4 planes are partially instrumented. The last 162 planes located on the downstream side of the detector make up the spectrometer. In this region only every 5th plane is instrumented, but instrumented with full scintillator coverage. This region aids in the momentum determination of long tracks.

The Analysis

The MINOS near detector has been collecting charge separated muons with a rate of 10 Hz since January 2005. To ensure a good atmospheric muon sample, data cleaning cuts have been applied. It is required that the event contain a single well reconstructed ($\chi^2_{fit}/ndof$ <1.5, as assigned by the Kalman fitter) downward going muon track, with a track vertex that lies within 50 cm of the detector edge. It is also required that the magnetic field be in a well defined state during that event.

When measuring the charge ratio the track charge needs to be identified with a certain degree of confidence. The track fitter assigns for each track a quantity of $(q/p) \pm \sigma(q/p)$. A track with a large value of $(q/p)/\sigma(q/p)$ is a track with a high confidence in the assigned charge. Furthermore, one would expect that a long track occurring in a region of high magnetic field would have a high degree of curvature. The more hits that occurred along this track the greater the confidence in said degree of curvature and consequently in the charge. It was found that placing a cut on the number of track hits that occurred in the fiducial area defined by the partial planes within a radius of 2.2 m from the magnetic coil hole was a good variable to increase charge identification confidence. This will be referred to as the minimum plane cut (MPC).

In this analysis there are two distinct systematic errors: acceptance and randomization. The "forward" toroidal magnetic field will defocus downstream going μ^+ and upstream going μ^-. The field direction is therefore responsible for charged signed geometrical acceptances. Combining equal periods of forward ($N^F_{\mu^+}$,$N^F_{\mu^-}$) and reverse ($N^R_{\mu^+}$,$N^R_{\mu^-}$) field data should reduce the effects of this systematic error. For this analysis we use 368392 seconds(4.26 days) of forward field running, and 368450 seconds of reverse field running. The charge ratio, R, is then calculated as

$$R = (N^F_{\mu^+} + N^R_{\mu^+})/(N^F_{\mu^-} + N^R_{\mu^-}) \qquad (1)$$

Randomization refers to any process which results in the track charge being assigned randomly. Muon "scatter" is an example of this systematic. These track topologies are smooth but have a discontinuity, or kink, at some point along the track. The track fitter assigns these tracks a low momentum and a random charge (depending on field and muon scatter direction) with a high degree of confidence. The discontinuity scale is determined by measuring the maximum change in the directional cosine at any point along the track. To simplify notation "curvature" will be used synonymously with "change in directional cosine" for the remainder of this note. Low momentum muons which have large curvature at all points along the track will appear kinked under this definition. Comparing the average to the maximum curvature of the track will indicate wither the local curvature is physical. Figure 1 plots the charge ratio as defined by equation 1, as a function of both maximum curvature and average curvature. The weaker the cut on the average curvature the more dominant the randomization systematic becomes and the charge ratio tends towards 1.

Figure 2 plots the charge ratio as a function of both $(q/p)/\sigma(q/p)$ (after the curvature cuts and including MPC>20) and the minimum plane cut (curvature+$(q/p)/\sigma(q/p)$ >2.8). In both cases we see that the charge ratio flattens off indicating that the systematics due to randomization have been reduced. After these cuts we obtain a charge ratio of 1.278 with 246392 muons.

Discussion of Errors

A brief summary of the errors considered is given below:

- Apart from the standard statistical error, slightly increasing the magnitude of the MPC and the charge confidence cut yield a total statistical error of ±0.004.
- Several other cuts, similar in vein to the MPC, were investigated. The standard de-

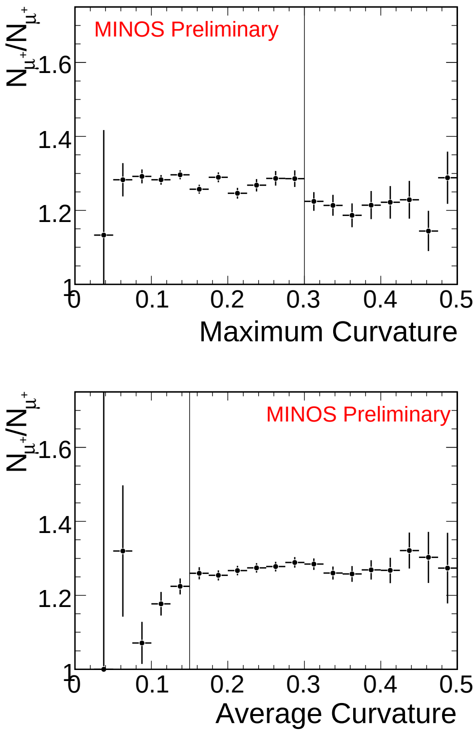

Figure 1: Charge Ratio versus curvature after requiring a minimum plane cut of greater than 20 planes and $(q/p)/\sigma(q/p)$ >2.8. The effects of randomization are reduced when we require the average curvature be greater than 0.15 and that the maximum change in direction cosine be <0.3.

viation of the charge ratio when these cuts were utilized is 0.0062.

- If the muons were classified as either stopping (the track end was located > 50 cm away from the detector edge) or throughgoing, the charge ratio was either 1.299 or 1.2730 respectively. The maximum deviation (0.021) from the average value of 1.278 is taken as the systematic error.

- The charge ratio can also be calculated as:

$$R = (N^F_{\mu^+})/(N^R_{\mu^-}) = 1.287$$
$$R = (N^R_{\mu^+})/(N^F_{\mu^-}) = 1.270$$

  The systematic is taken as half the difference between these two values, ±0.0085.

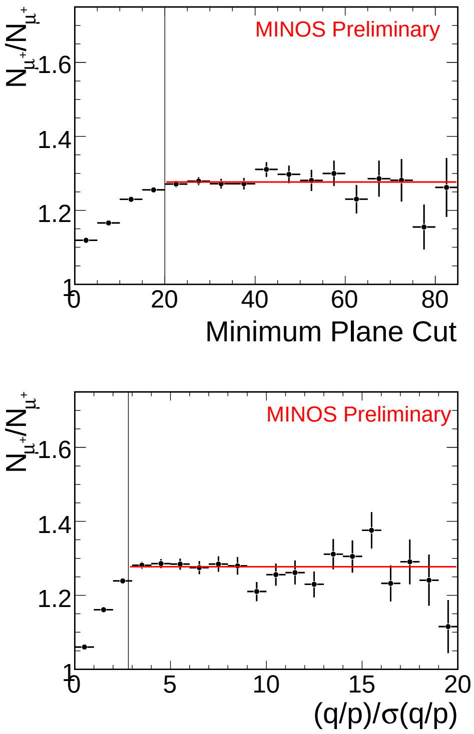

Figure 2: The charge ratio as a function of (t) the minimum plane cut and the (b) charge confidence cut. The vertical lines indicate the values used for the analysis cuts.

- A monte-carlo study was performed to determine how accurately muons were assigned charge. It was found that, on average, the incorrect charge was assigned to 1.5% of the muon events. This miss-identification has the effect of reducing the charge ratio from 1.288 to 1.278. The charge ratio is taken to be 1.288 with a systematic error of ±0.01.

Combining, in quadrature, these errors we obtain a charge ratio of 1.288±0.004(stat.)±0.025(syst.).

Projection to the surface

The overburden at the MINOS near detector is comprised of two layers. The first, nearest the surface, is a glacial till layer approximately 22.2 m thick with an average density of 2.29 g/cm^3. The second layer, dolomite/shale bedrock, is roughly 72.1 m thick with a slightly higher density of 2.41 g/cm^3. The slant depth, measured in meters water equivalent (mwe), is calculated then as 224.6 mwe/cos(θ_Z). The minimum surface energy, accounting for ionization and radiation energy losses, that a muon must have to reach the detector can be parameterized[3] as:

$$E_{min}(GeV) = \frac{\exp(\frac{\text{Slant Depth}}{2298\text{ mwe}}) - 0.998}{0.00192\text{ GeV}^{-1}} \quad (2)$$

The mean reconstructed energy of the muons at the MINOS near detector is approximately 8 GeV. Projecting these muons back to the surface the mean energy is 110 GeV. As a function of surface energy (in 50 GeV bins) the muon charge ratio as measured by the MINOS near detector is given in figure 3. Also plotted on this figure is the muon charge ratio as measured by the L3+C collaboration.[4].

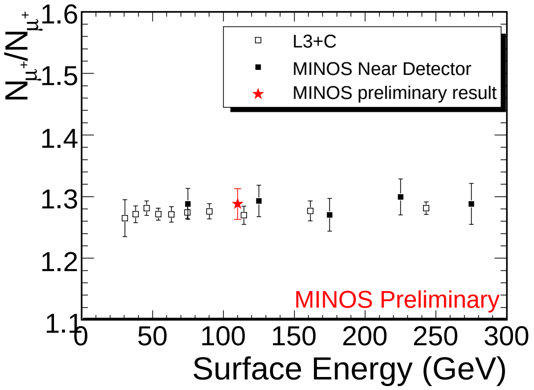

Figure 3: Charge ratio as a function of surface energy. The closed squares represent MINOS data(statistical + average systematic), the open squares L3+C and the star is the MINOS near detector average result.

Conclusions

The muon charge ratio, for muons with a mean surface energy of 110 GeV, has been measured using only 8.5 days of data at the MINOS near detector to be 1.288±0.004(stat)±0.025(syst) which agrees very well with the measurement performed by L3+C of (1.285±0.003(stat)±0.019(syst.))[4] from 20 to 500 GeV. The MINOS collaboration is expecting to increase the size of the reverse field data set and will publish the results for the larger data set at a later date.

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References

[1] Goodman, M. and Schreiner, P. for the MINOS collaboration, Interpretation of the Atmospheric Muon Charge Ratio in MINOS, these proceedings.
[2] Mufson, S. L. and Rebel, B. J. for the MINOS collaboration, Measurement of the Atmospheric Muon Charge Ratio at TeV Energies with MINOS, these proceedings.
[3] Reichenbacher, J. , Calculation of the Underground Muon Intensity Crouch Curve from a Parameterization, these proceedings.
[4] P. Achard et al. (L3 Collaboration), *Phys. Let. B* **598**, 15-32 (2004), hep-ex/0408114.