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Seasonal Variation of Multiple-Muon Events in MINOS and NOvA

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Seasonal Variations of Multiple Muons at the MINOS Near Detector (ND) and Far Detector (FD) are reported. The features of the data differ from the single-muon seasonal variations seen by both detectors and many other underground experiments. A satisfactory explanation for this result has not been put forward. A preliminary analysis of multiple-muon seasonal variation in the NOvA ND, located near the position of the MINOS ND, supports the MINOS observations.

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1. Introduction

The seasonal variation of the rate of underground muons from cosmic ray showers is a well-measured phenomenon by many current and past underground detectors. It is understood and parametrized as an effect due to changes in the atmosphere together with the competition between pion and kaon interaction and decay [1, 2]. Those parametrizations compare the rates with an effective temperature which is defined over a region of the atmosphere where muons originate. A precise measurement of the seasonal variation can be used to extract the inclusive pion to kaon ratio in hadronic scattering for the first interaction of the primary cosmic ray [2,3]. The calculation of the weights used in the effective temperature assumes that the muons arise from the decay of a pion or kaon produced in the first interaction. This is a useful approximation for single-muon data, but is not appropriate for multiple-muon phenomena. The multiple-muon data from MINOS was described in Ref. [4]. The seasonal variation of MINOS single-muon data had been previously reported from the FD and ND [3,5]. The single-muon data in both the near and far MINOS detectors show a maximum in the summer. In contrast, the multiple-muon data in the MINOS ND showed a maximum in the winter. In the MINOS FD, the effect reverses depending on the separation between muons. Attempts to explain this result in Ref. [4] with geometrical explanations or other explanations quantitatively failed. We are in the process of studying this same issue with data from the NOvA ND, which is located at the same overburden and near the MINOS ND.

The MINOS and NOvA detectors are well described elsewhere [6, 7]. For the purposes of this analysis, it is sufficient to point out that outside the time of the Fermilab beam spill, triggers are dominated by a high flux of cosmic ray muons and muon-induced activity. In most angular directions, those muons are recorded in tens to hundreds of detector elements, and can be reconstructed with high efficiency and negligible background.

2. Results from MINOS

MINOS has reported on the first observation of seasonal modulations in the rates of cosmic ray multiple-muon events at two underground sites, the MINOS ND with an overburden of 225 mwe, and the MINOS FD site at 2100 mwe. Several years worth of data are shown for both detectors in Fig. 1. The data for the much larger FD are broken up by muon separation; i.e. the distance of closest approach of the muon tracks within the detector. When the ND rates are plotted with different separations, no differences are found. At the deeper site, multiple-muon events with muons separated by more than 8 m exhibit a seasonal rate that peaks during the summer, similar to the well-known result from several observations of underground single-muon experiments. In contrast and unexpectedly, the rate of multiple-muon events in the FD separated by less than 5 m, and the rate of multiple-muon events in the shallower ND, exhibit a seasonal rate modulation that peaks in the winter. In Fig. 2, the single and multiple muon rates in the MINOS ND are shown, binned according to calendar month. The differences are striking. Several plausible explanations were investigated by MINOS [4] but could not account for these results. Note that cosine fits are shown solely as a guide to the eye; there is no reason to expect that seasonal effects follow a cosine curve.

3. Preliminary results from NOvA

The NOvA FD is not underground. The NOvA ND is located close to and at the same overburden as the MINOS ND. Two years of preliminary ND data are shown in Fig. 3, between April 2015 and February 2017. The three plots show the effective temperature (an average of the atmospheric temperature weighted by the predicted atmospheric depth of muon production by pion and kaon decay), single-muon rates and multiple-muon rates. As in MINOS, the single-muon rates, which are well correlated with the effective temperature, are maximum in the summer and minimum in the winter. And NOvA also confirms that the ND multiple-muon rates are maximum in the winter.

4. Future Plans

A full simulation of multiple-muon events underground requires detailed knowledge of a myriad of issues, including the chemical composition of cosmic rays, multiplicity distributions in hadronic interactions, correct modeling of strange mesons both with pair production and associated production, and detailed knowledge of several hadronic cross sections, the atmospheric density profile and its time dependence, and full modeling of potentially many generations of the hadronic cascade. The seasonal dependence for multiple muons is potentially much more sensitive to the point of the first interaction of the primary cosmic ray than it is for single muons. Nevertheless, the distribution on the left of Fig. 2 suggests that one single explanation may dominate and account for its seemingly simple shape. The high statistics data from the NOvA ND will be used to further study this phenomenon [8]. The distributions will be studied as a function of zenith angle, multiplicity, muon separation, year-to-year differences and other variables.

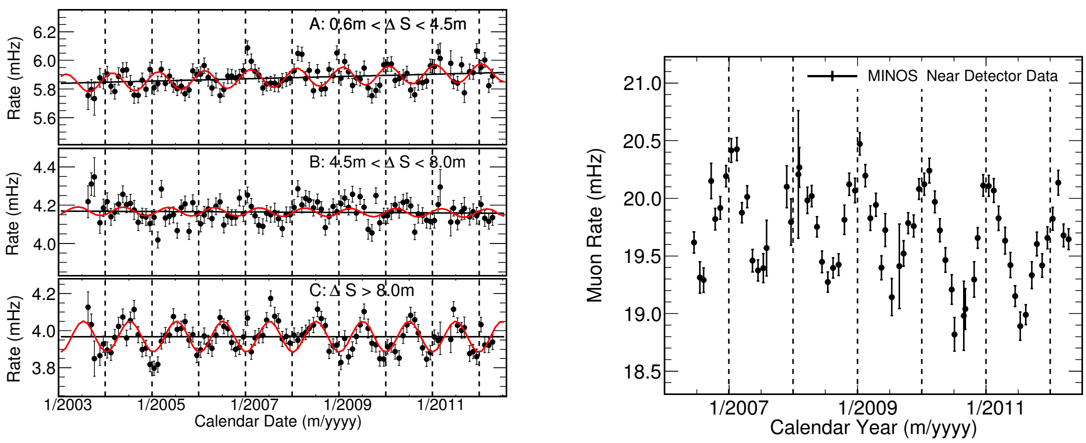

Figure 1: Left: The multiple-muon rate in the MINOS FD as a function of time for different track separations. Each data point corresponds to one calendar month of data. The solid red lines are the best fit to a cosine function. The top graph is for the smallest track separation, the middle graph for mid-range and the bottom graph for the largest. The vertical lines are year boundaries and the solid horizontal line represents the fit without the cosine term. Right: The multiple-muon rate in the MINOS ND as a function of time. Each data point corresponds to one calendar month. A clear modulation in the data is observed with the maximum occurring towards the start of the year. The vertical lines are year boundaries.

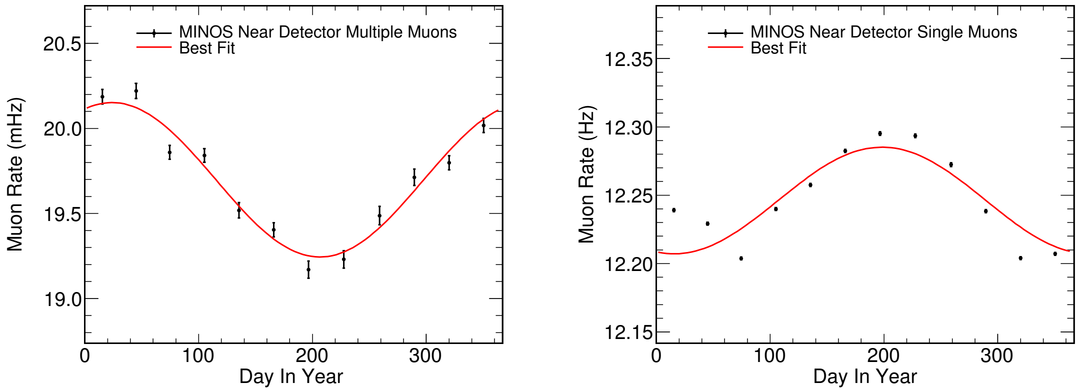

Figure 2: The left figure is the multiple-muon rate in the MINOS ND, binned according to calendar month, with each point showing the average rate for all years of data-taking. The figure also shows a cosine fit to the data. The single-muon rate is shown in the right figure, showing a clearly different seasonal modulation.

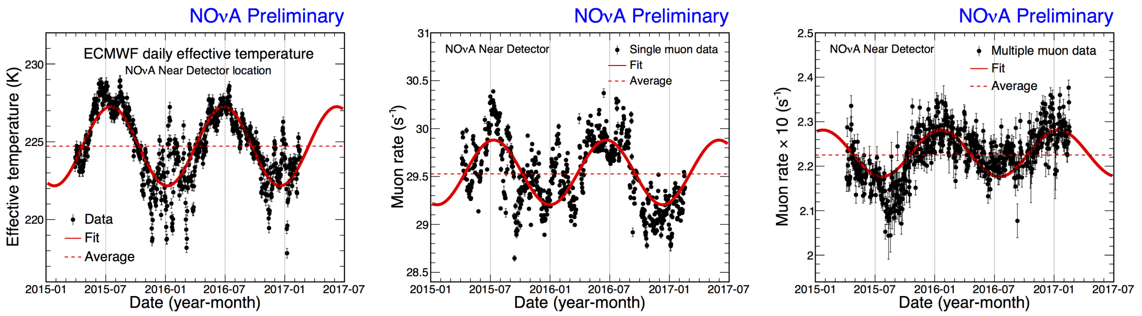

Figure 3: Preliminary data from the NOvA ND. On the left is the effective temperature, in the middle is the single-muon rate and on the right is the multiple-muon rate.

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