Neutral Current Interactions in MINOS

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Abstract: The **M**ain **I**njector **N**eutrino **O**scillation **S**earch (MINOS) long-baseline experiment has been actively collecting beam data since 2005, having already accumulated 3×10^{20} protons-on-target (POT). The several million neutrinos per year observed at the Near detector may improve the existing body of knowledge of neutrino cross-sections and the Near-Far comparison of the observed energy spectrum neutral current events constrains oscillations into sterile neutrinos. MINOS capabilities of observing neutral current neutrino events are described and the employed methodology for event selection is discussed, along with preliminary results obtained. An outlook on the expected neutral current related contributions from MINOS is also presented.

Neutrino Interactions in the MINOS Detectors

The design and response of the MINOS Near and Far Detectors (ND and FD) are detailed elsewhere in these proceedings [1]. There are two main types of neutrino interactions observed in the detectors: Charged Current (CC) interactions, proceeding through the exchange of a $W^{\pm}$ boson with creation of the associated charged lepton, typically defined by a long muon track accompanied by a small hadronic shower at the event vertex caused by nuclear fragmentation; Neutral Current (NC) interactions, proceeding through exchange of a Z^0 with the neutrino leaving the detector, which appear as diffuse showers with typical length much shorter than the length of a muon track in a CC event. Correct identification of NC events in the MINOS detectors is difficult due to to short CC events with high hadronic inelasticity, featuring a short muon track often concealed by the hadronic shower or easily confused with the short charged pion tracks also found in NC events.

Events reconstructed in the fiducial volume of the Near and Far detectors are very similar. However, the high statistics environment of the Near detector, where multiple interactions occur for each beam spill, requires the application of a *slicer* al-

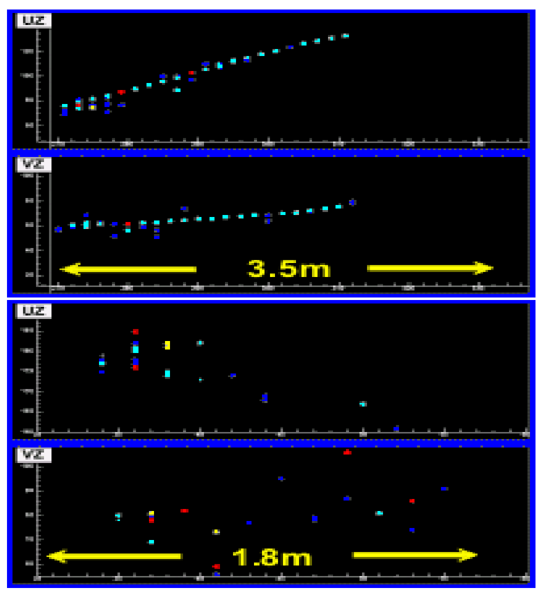

Figure 1: Example of CC (top) and NC (bottom) interactions in the MINOS detectors. Longitudinal views UZ and VZ are shown in both cases. CC events are characterized by a long muon track and hadronic activity at the vertex, whereas NC events are shorter, displaying a diffuse hadronic shower.

gorithm, making use of timing and spatial cuts to identify individual events within the 1.8 μs spill duration.

Late activity caused by neutrons or photomultiplier tube afterpulsing can introduce large time gaps in the event, causing it to be split by the *slicer*. In other instances, gaps in the hit strip pattern can cause a single shower to be reconstructed as multiple showers. For showers along the track direction, the reconstruction may fail to associate the shower with the track, with a separate event being formed. Many of these split events will display only a small fraction of the total pulse height deposited by the neutrino interaction. Therefore, split events are highly undesirable as they result in double-counting of neutrino interactions and bad energy resolution.

One other class of problematic events consists of interactions occurring outside the fiducial volume but reconstructed with the vertex inside the fiducial volume. This is due to bad vertexing or poor reconstruction of very steep showers and also non-fiducial events entering the Near Detector through its partially instrumented regions. These events, informally referred to as *leakage* events, will very often have only a small fraction of their energy reconstructed and be easily misclassified. A possible example is a CC interaction outside the detector where the muon track misses the detector entirely, but some hadronic activity is reconstructed as a shower inside the detector volume. Such observed event would present obvious characteristics of a NC interaction.

Different methodologies have been devised to deal with these pathologic events and are described below.

Data Cleaning and NC Event Selection

The first step in selecting an NC event sample consists of applying fiducial volume cuts, which, in the case of the Near Detector, require the longitudinal coordinate of the event vertex to be between 1.73 m and 4.74 m upstream of the first ND plane and also that the vertex is contained inside the partially instrumented region and at least 50 cm away from the edges of that region. If two reconstructed events result from the same neutrino interaction, they should appear close in time and/or in space. The former should occur for slicing or shower reconstruction failures, whereas the latter would indicate late activity. To remove these spurious events, cuts on the time separation of events as well as on the longitudinal distance between the vertices of the two events are applied. The event time used in the former cut is defined using the median of strip times in a 5 plane window around the event vertex.

For the case of *leakage* events, two distinct types of cuts are applied. Firstly, a *steepness* variable, defined as the ratio of strips per plane divided by the total number of planes in the event, is used to characterize very steep showers. A high *steepness* value means the shower spans few planes but has many strip hits, making it more likely that the event results from activity entering the detector from the sides.

The second type of cuts uses activity in the sparsely instrumented regions on either side of the detector as a *leakage* veto. Cuts are applied to the summed pulse height and the number of strip hits in each of the two veto regions (*vetoLeft* and *vetoRight*). Finally, from MonteCarlo studies, it is known that most events with large discrepancy between the expected energy deposition and total effectively reconstructed pulse height usually display a very low reconstructed strip count. Cutting of these low number of strip events improves rejection of both split and *leakage* events.

These pre-selection cuts are applied to beam spills containing any number of events, are collectively referred to as *high multiplicity spill cleaning* cuts and are described in detail in [2]. Applying these cuts, an event will remain in the sample if:

- time separation between events $|\Delta t| > 40$ ns
- spatial separation $|\Delta z| > 1\,\mathrm{m}$, if ($40\,\mathrm{ns} < |\Delta t| < 120\,\mathrm{ns}$)
- steepness < 1.0
- number of event strips > 4

  For events with energy below 5 GeV and with shower planes > track planes:

- $(veto[Left, Right]Strips < 4)$ OR $(veto[Left, Right]PH < 1000)$

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An alternative *data cleaning* approach [3], whereby only beam spills with no more than two events reconstructed in the ND are considered, was also employed. This approach, known as *low multiplicity spill cleaning*, attempts to minimize any effects due to slicing or beam intensity fluctuations during data taking. Its application results in substantial cuts in usable event statistics, a compromise that can be contemplated for ND data, given the large number of neutrino interactions in each beam spill ($\sim$ 10 neutrinos per spill for 1.3×10^{13} protons per spill). Results with both types of cleaning are shown in Fig. 3.

After pre-selection cuts are applied, the event selection proceeds via cuts on variables that attempt to maximize discrimination between NC events and potential CC background events. These variables are the length of the event in planes, the number of reconstructed tracks and the difference in planes between the lengths of the primary track and primary shower in the event. The cut locations were determined to be the ones maximizing efficiency and purity in the selected sample. An event is thus classified as NC-like if:

- Event Length is less than 40 planes
- Event has no reconstructed track
- Event has a track and the track is no more than 10 planes longer than the shower.

Distributions of the selection variables with *high multiplicity spill cleaning* cuts applied, comparing ND Data with MonteCarlo and the selected CC background, are shown in Fig. 2.

The selected NC sample has 75.6% efficiency, 52.3% purity when *high multiplicity spill cleaning* is applied and 0.26% efficiency, 53.4% purity if the *low multiplicity spill cleaning* cut is used instead. The obtained energy spectra for Data and MC using both cleaning methods is depicted in Fig. 3. A systematic error envelope is calculated by producing energy spectra for which systematic parameters, such as cross-section uncertainties, CC background or normalization, are varied by $\pm 1\,\sigma$ from their nominal value. The individual effects of each systematic parameter over each energy bin are then added in quadrature to obtain the displayed error envelope.

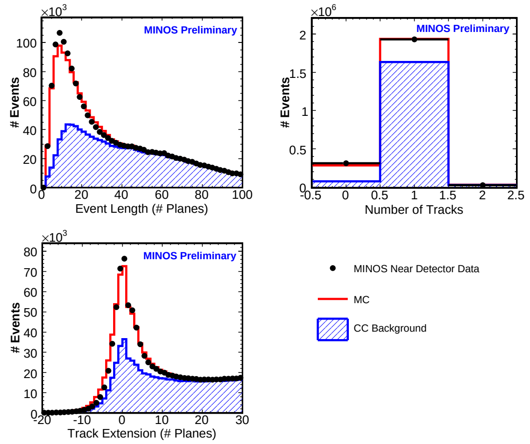

Figure 2: The three Variables used in selecting Neutral Current like events in the MINOS Near Detector. Poorly reconstructed events are removed using a combination of timing and topology cuts. The black dots are data, the red line is the Monte Carlo, and the shaded blue is the Charged Current background. These data correspond to 12.23×10^{19} Protons on Target (POT).

Sterile Neutrino Search and Outlook

Recent results from the MiniBooNE experiment [5], which looked for $\nu_\mu \rightarrow \nu_e$ appearance on a short baseline of 540 m using a neutrino beam with a mean energy of $\sim 700\,\mathrm{MeV}$, mostly rule out the possibility of oscillations at the mass-squared $1\,\mathrm{eV}^2$ scale, a possibility reported by the LSND experiment [6]. However, LSND claimed a signal for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance, therefore completion of MiniBooNE's anti-neutrino run will be required before a more definitive answer is available. Very recent review papers incorporating these results claim a 3+1 (3 weak interacting and 1 sterile neutrino) scenario is strongly disfavored, whereas a 3+2 scheme with two sterile neutrinos can fit the available data [7]. MINOS can make a contribution in the search for sterile neutrinos by studying disappearance of NC events measured at the FD relative to the flux observed at the ND. NC events are not affected by $\nu_\mu \rightarrow \nu_\tau$ oscillations, but would suffer depletion if $\nu_\mu \rightarrow \nu_s$ oscillations were to occur. In such scenario, the number of NC events

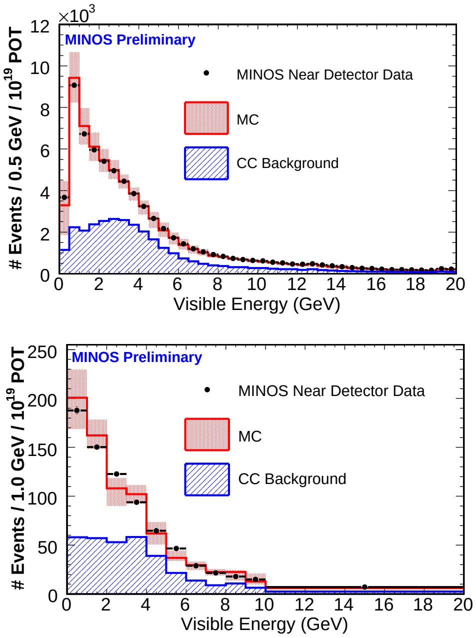

Figure 3: The Neutral Current selected energy spectrum in the Near Detector. Poorly reconstructed events are removed using a combination of timing and topology cuts (top) or by selecting spills in which only one or two events are reconstructed (bottom). The black dots are the data, the red bars are the statistical and systematic error bars around the Monte Carlo, and the shaded blue is the Charged Current background. The Neutral Current selection has purities of 52.3% (top) and 53.4% (bottom). The data correspond to 12.23×10^{19} POT.

observed at the FD would be reduced according to:

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_s) &= \mathrm{f_s} \sin^2(2\theta_{23}) \sin^2\left(1.27\Delta m^2_{32}\frac{L}{E}\right) \\ &= \mathrm{f_s}\left[1 - \mathrm{P}(\nu_\mu \rightarrow \nu_\mu)\right] \end{aligned} \quad (1)$$

where $\mathrm{f_s}$ is the fraction of events converted to sterile neutrinos, L[km] is the distance from the target, E[GeV] is the neutrino energy, and $|\Delta m^2_{32}|$ is measured in eV^2/c^4. In Fig. 4, the potential sensitivity of MINOS to $\nu_\mu \rightarrow \nu_s$ is exemplified. The first results of this analysis are expected later this year, using a sample of 3.5×10^{20} POT.

Work is also being developed on measuring NC cross-sections, largely unconstrained by current

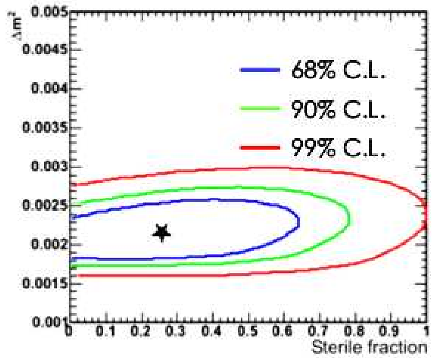

Figure 4: MINOS expected sensitivity to a sterile neutrino fraction measurement for different confidence levels. Used input values were $|\Delta m^2_{32}| = 2.1 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2(2\theta_{23}) = 0.9$ and $\mathrm{f_s} = 0.2$. The data correspond to an exposure of 7.4×10^{20} POT.

knowledge for neutrino energies of $\sim$1 GeV, using the copious statistics available at the MINOS Near Detector. Results from this study should be available soon and may improve sensitivity to the sterile fraction measurement.

Acknowledgments

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