FAR DETECTOR VOLUME STUDY – MINOS NUE ANALYSIS



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MINOS Experiment



In the MINOS experiment, a beam of mostly muon neutrinos is generated and sent through a Near and a Far detector so as to try to observe and confirm the theory of neutrino oscillations.

The Near detector is located at Fermilab several hundred meters from the target where the beam is generated, and the Far detector is located 735 km away in the Soudan Mine in Minnesota.



NuE Appearance Analysis

The main analysis of MINOS is the detection of muon neutrino disappearance in the Far detector when the energy spectrum is compared to the unoscillated spectrum in the Near detector. This is because the muon neutrinos are expected to oscillate mostly to tau neutrinos, but it is also expected that some of them will oscillate to electron neutrinos.

The probability that a neutrino will oscillate to another is given by:

$$P[\nu_{\alpha} \rightarrow \nu_{\beta}] = \sin^2 2\theta \sin^2 [1.27\Delta m^2 [L/E]]$$

Initial results for the muon neutrino disappearance analysis have been presented at Fermilab on the 30.03.2006, and were shown by Trisha Vahle a few weeks ago.

Another analysis that is expected to be feasible is the detection of electron neutrino appearance in the Far detector (i.e. muon neutrinos oscillating to electron neutrinos on their way to the Far detector) – find $\sin_2 2\theta_{13}$ This analysis is very difficult, as there is significant background not only from neutral current events, but also from beam electron neutrinos.



MINOS Far Detector



The MINOS Far Detector consists of 486 steel / scintillator plates:

- it weighs 5400 tonnes

- it is octagonal with a diameter of 8 m and a length of 30 m in two approximately equal supermodules

- a 1.2 T magnetic field is applied via a magnetic coil passing through the middle of each plate

Each plane is instrumented with 1cm x 4.1 cm scintillator strips, which are read out by using PMTs.

Neutrino events at MINOS

Charged Current event:

Neutral Current Event:





NuE Appearance Analysis

The goal of this study was to investigate whether the MINOS Far Detector fiducial volume for the NuE analysis could be extended or optimized so as to increase the Figure of Merit for the NuE analysis.

FOM = Nue Signal / SQRT(Background)

For this purpose, a total of 400 FD Monte Carlo files was used, including rock muon files (neutrinos that interact in the rock in the Soudan Mine and register in the detector). The sample was oscillated.

This corresponded to 2.906e22 POT, but for the FOM calculation was normalised to 9.25e20.

Analysis Procedure

The analysis procedure for all current PID selections (Ann, FracVars, MDA, and Subshower PID) was as follows:

- 1. Plot all true signal nue vertices, then plot vertices for each PID selection after pre-selection cuts, and finally plot all true signal nue vertices within this PID selection
- 2. Use the resultant histograms to plot efficiencies and purities
- 3. Plot the normalised total figure of merit as the fiducial volume is increased in a given direction (Z or R)
- 4. Compare the total FOM curves to the efficiencies and purities
- 5. From this comparison decide what the optimal volume cuts should be
- 6. Compare the resultant total efficiencies, purities and FOM with the accepted nue fiducial volume. FOM: signal/sqrt(background).
- 7. Conclusions

Applied Pre-selection Cuts

The following pre-selection cuts were applied to the oscillated MC sample when plotting the reconstructed event vertices:

- pulseheight cut <150.00 MeV to exlude everything above the oscillation energy range
- low energy cut >1.0 to eliminate low energy neutral current events
- number of track planes <25 to exclude obvious muons
- number of track like planes <16 to exclude muons

No containment cut was applied here as at this stage this analysis specifically investigates what happens at the edges of the detector, however, this will be investigated further in future analysis.

Volumes for Study

The idea was to apply conservative volume cuts everywhere except one edge and observe how the total FOM changes as the FD fiducial volume is extended until this very edge:



Generation of PID Selection – Z Vertex

First, plots were generated with a conservative cut on fiducial radius R:
0.5m < R < 3.5m
so as to eliminate any potential detector edge and coil effects.

In those plots there was no cut on reconstructed vertex Z so as to include the whole Z range from 0 to 30 m in 505 bins of 5.94 cm each.

Those histograms were generated for all Particle ID selections, i.e. for: Ann PID > 0.8, FracVars PID > 0.6, MDA PID > 0.967, and SubShower PID > 0.6. The results were similar for all PIDs, therefore the following plots mostly show the results for AnnPID, and the other PIDs can be found at the end of this presentation.

> Black – all true signal nue within this volume Blue – PID selection after pre-selection cuts Green – true signal nue within this PID selection

Reconstructed Z Vertex for Ann PID > 0.8

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Reconstructed Vertex Z for AnnPID Cut > 0.8, True Signal Nue and Signal Nue in PID Cut



Reconstructed Z Vertex for Ann PID > 0.8 zoomed in onto in regions of interest





Reconstructed Vertex Z for AnnPID Cut > 0.8, True Signal Nue and Signal Nue in PID Cut



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Comment on PID Selection

It looks like all the PIDs select a spike at the end of the detector, but this could probably be removed by applying the is-Fully-Contained pre-selection cut.

This spike is around 1.5 - 2m wide, and consists almost only of background. In fact, it seems that this spike seems to contain almost no nue – see zoomed in plots. Therefore, even if the is-Fully-Contained cut eliminates most of this spike, it needs to be investigated further.

Also, as can be seen in the next two slides, the PID selection also seems to select rockmuons in the first two planes of the detector.

Background Information in PID selections

The Background was analysed for all PID selections, but is shown here for only the SubShower PID as it is very similar for all PIDs:



Background Information in PID selections 2

The important regions for the background are zoomed in here. Specifically, this shows the rockmuons interacting at the beginning of the detector, and the composition of the selected spike at the end of the detector.

Blue – PID selection Mauve – All NC

Red – All numu CC events Grey Magenta – Nutau CC Pink – NC rock muons Green – Signal nue

Light Blue – Beam nue



Z Vertex – Efficiencies and Purities

The following plots show the efficiencies and purities per plane over the whole Z range for the different PIDs.

The uncertainties are large as the Monte Carlo sample is not enough to smooth out the purities and efficiencies for the Nue Analysis.

Note especially the purity decrease at the end of SM2 due to both the spike in the selection and the decrease in selected signal nue.

Z Vertex - Efficiencies and Purities for Ann PID



Generation of PID Selection – R Vertex

From the previous Z Vertex plots, reasonable conservative cuts were estimated so as to eliminate any potential detector / supermodule edge effects. Those were: SM1: 0.5346m < Z < 13.6633mSM2: 16.4554m < Z < 28.4554m

In those plots there was no cut on reconstructed vertex R so as to include the whole R range from 0 to 4m in 80 bins of 5cm each.

Those histograms were also generated for all PIDs.

Black – all true signal nue within this volume Blue – PID selection after preselection cuts Green – true signal nue within this PID selection

Reconstructed R Vertex for Ann PID > 0.8

Reconstructed Vertex R for AnnPID Cut > 0.8, True Signal Nue and Signal Nue in PID Cut



R Vertex – Efficiencies and Purities for Ann PID

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Efficiency and Purity for AnnPid cut > 0.8



Total Figure of Merit as the Volume is increased

- The Total FOM plots were normalised to 9.25e20 POT and made in 6 stages:
- 1. Keep SM1 volume constant and increase SM2 volume plane by plane. SM1: 0.5346m < Z < 13.6633m, SM2 start at 16.4554m. Do this with conservative R: 0.5m < R < 3.5m.
- 2. Keep SM1 volume constant as before, and increase SM2 volume starting at 28.4554m. R: 0.5m < R < 3.5m.
- 3. Keep SM2 volume constant and increase SM1 volume plane by plane. SM2: 16.4554m < Z < 28.4554m, SM1 start at 0.5346m. R: 0.5m < R < 3.5m.
- 4. Keep SM2 volume constant as before, and increase SM1 volume starting at 13.6633m. R: 0.5m < R < 3.5m.
- 5. Keep Z volume constant. SM1: 0.5346m \rightarrow 13.6633m and 16.4554m \rightarrow 28.4554m. Increase detector volume starting with R = 0.5 m.
- 6. Keep Z volume constant as before, but increase detector volume by increasing R starting at R = 3.5m.



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Step 1 – Increase towards Right Edge of SM2

Total Figure of Merit for 9.25e20 POT as Volume is increased towards Edge







Step 2 – Increase towards Left Edge of SM2



Step 3 – Increase towards Right Edge of SM1

Total Figure of Merit for 9.25e20 POT as Volume is increased towards Edge



Step 4 – Increase towards Left Edge of SM1



Step 5 – Increase outwards in R

Total Figure of Merit for 9.25e20 POT as Volume is increased towards Edge





Step 6 – Increase inwards in R



Comparison of Total FOMs to Purities and Efficiencies for Different PIDs

The next stage was to compare the FOM curves with the purities and efficiencies in the regions of interest for each PID selection in order to determine an optimized volume.

The optimized volume was selected by eye and then crosschecked with the Z and R vertex histograms so as to determine a good cut-off value.

Total FOMs, Purities and Efficiencies for Ann PID





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Total FOMs, Purities and Efficiencies for Ann PID



Optimized Volume

The FOMs, efficiencies and purities were compared to each other for each PID selection and one optimized volume for the reconstructed vertex was determined from these comparisons:

SM1: 0.1188m < Z < 14.4356m SM2: 15.9802m < Z < 29.2277m R: 0.4m < R < 3.87m

This is compared to the currently used fiducial volume: SM1: 0.35m < Z < 14.57mSM2: 16.2m < Z < 29.62mR: 0.4m < R < 3.87m

Total FOMs, Purities and Efficiencies for the 2 Volumes

In this final step, the total FOMs, efficiencies, and purities were calculated for the two volumes:

	Current Fiducial Volume			Optimized Volume		
	FOM	Efficiency	Purity	FOM	Efficiency	Purity
ann PID	1.114	33.90	14.11	1.139	33.95	14.67
fv PID	0.982	34.42	11.17	1.010	34.48	11.76
mda PID	1.111	39.91	12.19	1.137	39.89	12.73
ss PID	0.931	33.81	10.33	0.954	33.89	10.77

Relative increases / decreases when compared to current fiducial volume:

	Percentage Increase					
	FOM	Efficiency	Purity			
ann PID	2.26%	0.15%	3.95%			
fv PID	2.84%	0.19%	5.24%			
mda PID	2.35%	-0.06%	4.42%			
ss PID	2.40%	0.24%	4.28%			

Conclusions

From this analysis, it seems that it would be possible to optimize the FD fiducial volume so as to increase the total FOM, purity, and efficiency.

It is even possible to optimize the volume differently depending on which PID variable is used to select the sample (for Ann PID specifically a somewhat larger volume could have been chosen).

This analysis is primarily a tool as the optimized volume may very well change depending on the pre-selection cuts applied and a possible evolution of the PID variables.

However.....

Future Questions / Work

.....This analysis did not include cosmic muons because this particular MC data sample was not available in the form needed, so this may affect R.

The containment cut will be investigated as the currently used one was not optimized for NuE analysis specifically. It may end up being not the same for the transverse and longitudinal directions.

Maybe an octagonal volume could be used instead of a cylindrical one, as this would increase the total selected volume by 5.5%, but there may be other considerations that may have to be taken into account for this.

An important part of future analysis will also include work on muon removal. Neutral current and charged current events should be very similar to first order, therefore, if the muon track is removed, it should be possible to compare the hadronic showers in both types of events and thus better understand the detector response.



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