New Results for Muon Neutrino to Electron Neutrino Oscillations in the MINOS Experiment

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Neutrino Oscillations

Mixing between flavor states and mass states of neutrinos:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=U\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix},\quad U=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta}\\0&1&0\\-\sin\theta_{13}e^{i\delta}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}$$

$$\theta_{23}\approx 45^o,\ \theta_{12}\approx 34^o$$
$$\theta_{13}<11^o$$
$$\delta=??$$

Probability for muon neutrino to electron neutrino transitions in vacuum

$$P(\nu_\mu\rightarrow\nu_e)\approx\sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

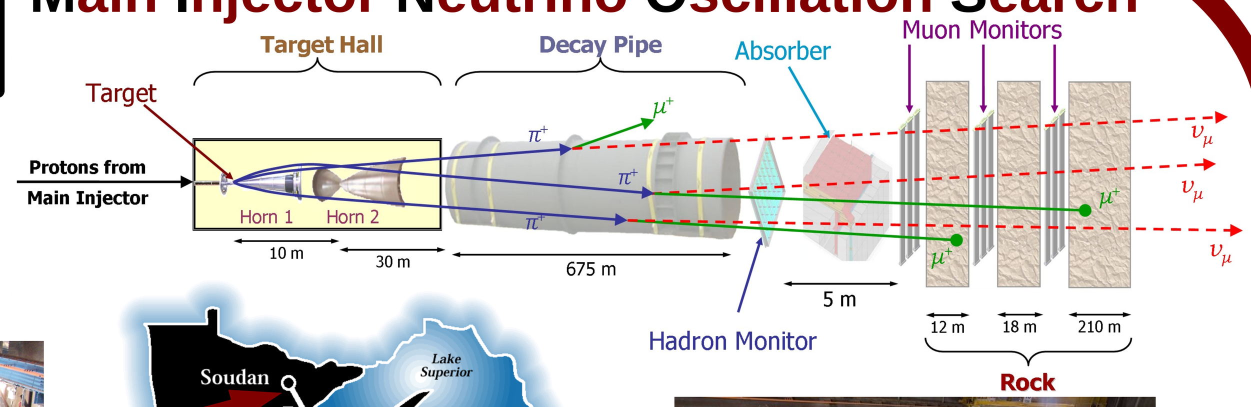
Best limit on θ_{13} from the CHOOZ reactor neutrino experiment

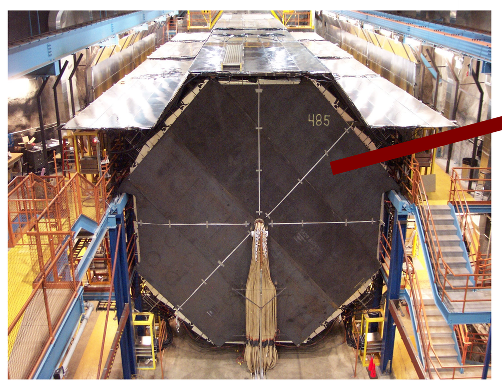
$$\Delta m^2_{ij}=m^2_i-m^2_j$$

MINOS

Main Injector Neutrino Oscillation Search

NuMI ν_μ beam
with 1.3% contamination from ν_e





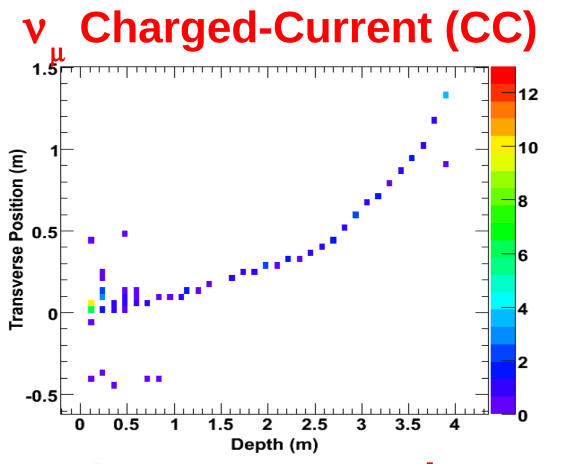
Far Detector (FD)
4 kton fiducial mass
735 km baseline

Near Detector (ND)
0.029 kton fiducial mass
1 km baseline

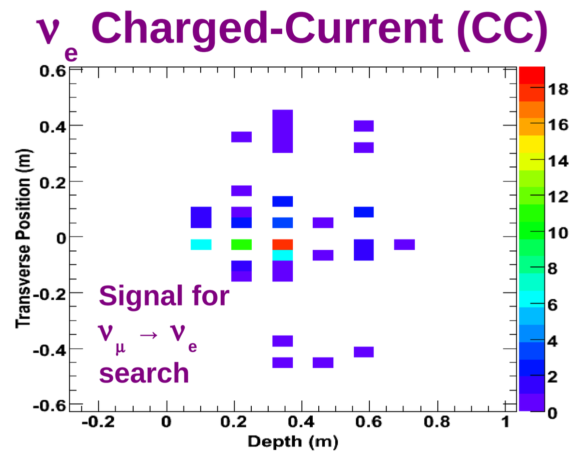
Both detectors are magnetized tracking calorimeters with alternating layers of steel plates (2.54 cm) and scintillator strips (1.0 cm thick, 4.1 cm wide)

Neutrino Interactions in the MINOS detectors

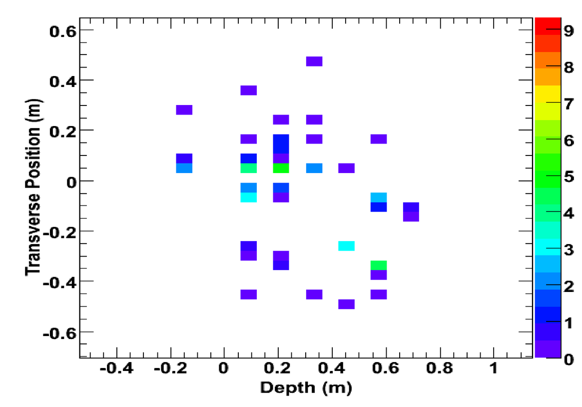
ν_μ Charged-Current (CC) | **ν_e Charged-Current (CC)** | **Neutral Current (NC)**



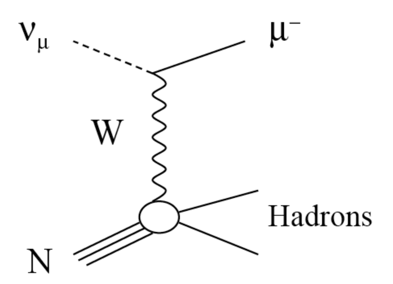
Long muon track

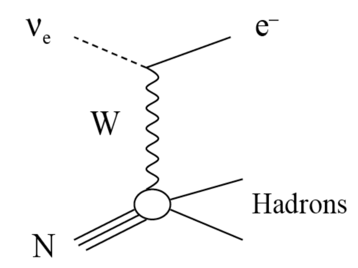


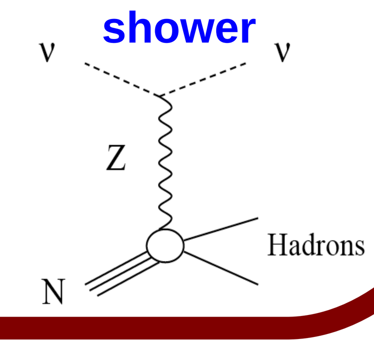
Short with compact shower



Short with more diffuse shower

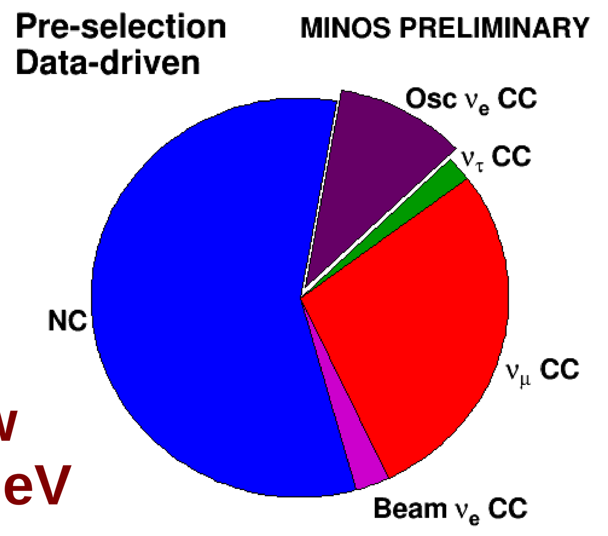






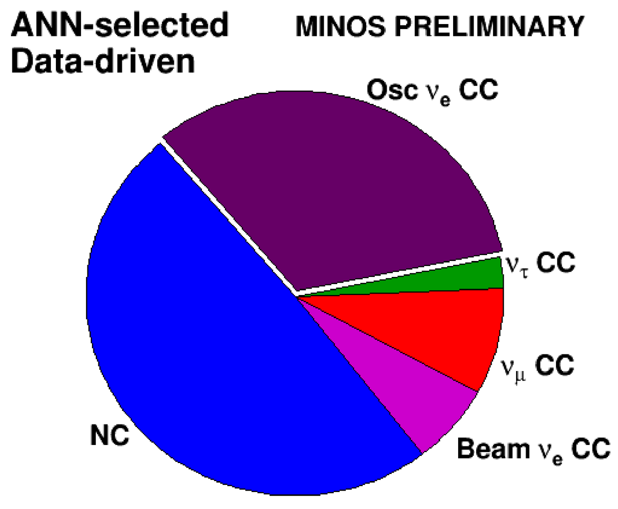
Event Selection

Preselection cuts:
- Detector and beam quality
- Fiducial volume
- Reject cosmic events
- Reject events with long tracks
- Require at least one shower
- Require at least 5 hit planes in a row
- Require reconstructed energy 1-8 GeV

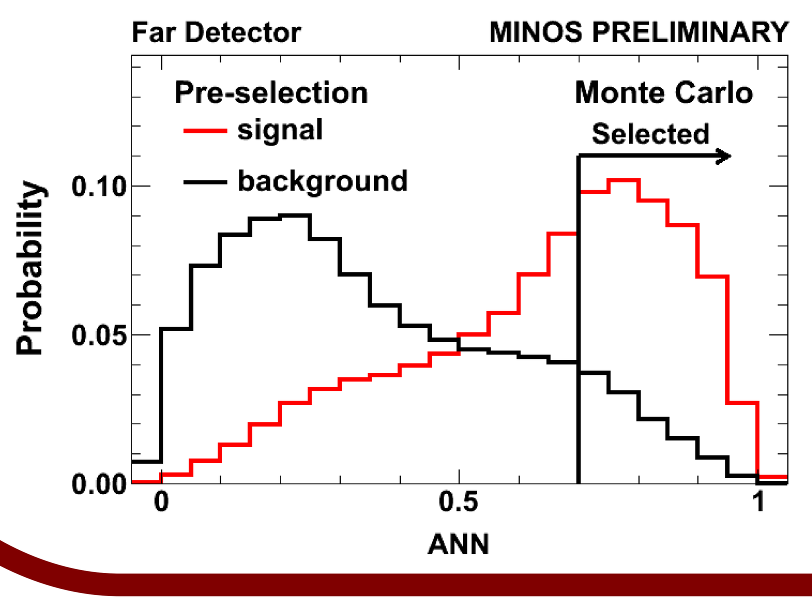


Signal:Background = 1:9

Artificial Neural Network (ANN)
- Uses 11 variables that characterize the shower shape
- Output is used as a final selection variable
- Maximize sensitivity by selecting events with ANN value > 0.7



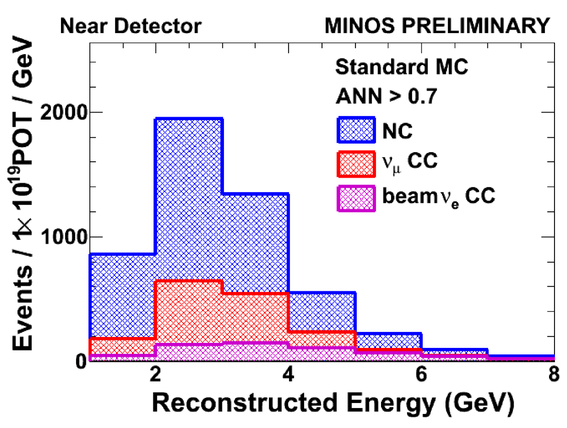
Signal:Background = 1:2

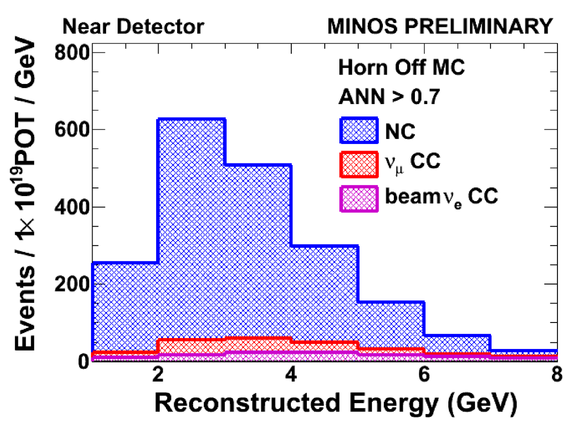


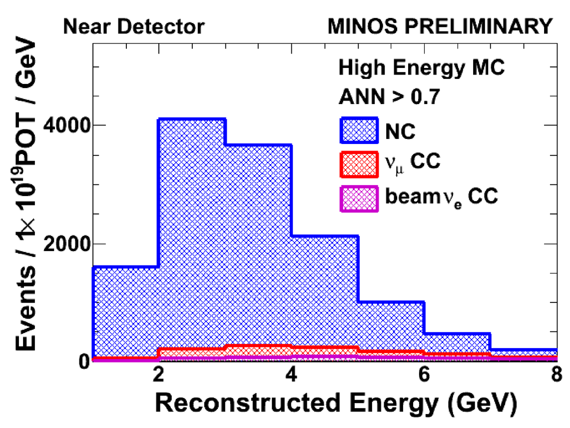
"signal" assumes θ_{13} at the CHOOZ limit

Background Prediction

Step 1: Break the ND data down into the three components (ν_μ CC, NC, and beam ν_e CC) using data from three different beam configurations:







Standard Beam
Pions are focused to create a low energy peak in the neutrino energy spectrum at ~3 GeV.

Horn Off Beam
Without focusing, the low energy peak disappears, reducing the background from short track CC ν_μ events.

High Energy Beam
Target is moved upstream and higher energy pions are focused, again reducing the background from short track CC ν_μ events.

Total measured ND rate in each beam configuration
+
Relative interaction rates for each background component between configurations from the MC simulation

} Fit for the CC ν_μ, NC, and beam ν_e CC components in the standard sample

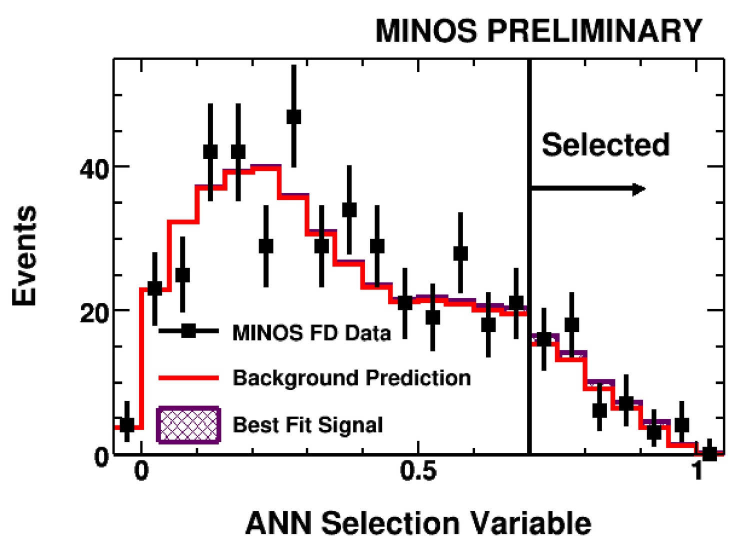
Step 2: Extrapolate each ND component to form a prediction for FD background

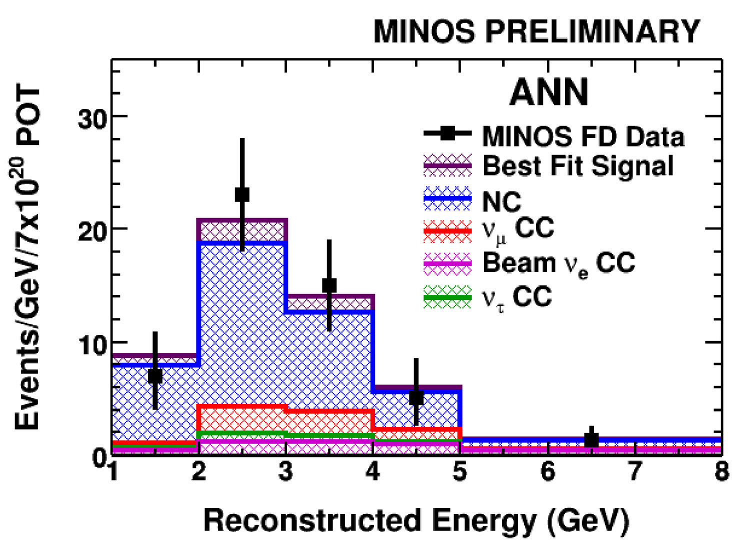
$$F^{Pred}_{\alpha,i}=N^{Data}_{\alpha,i}\times R^{F/N}_{\alpha,i}$$

FD prediction for component α in energy bin i | ND data for component α in energy bin i | Far/Near MC Ratio for component α in energy bin i

Results

Observation: 54 events
Expected Background: 49.1 ± 7.0 (stat) ± 2.7 (syst)

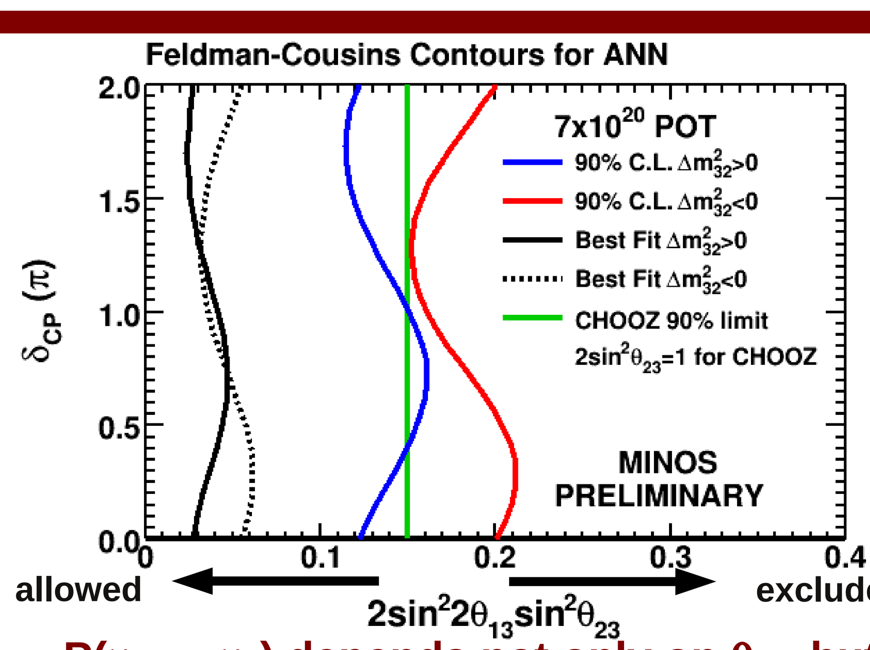




7.0x10^{20} protons-on-target (POT) data set

Assuming:
$2\sin^2(\theta_{23})=1$
$\delta=0$
$\Delta m^2_{32}=2.43\times10^{-3}\text{eV}^2$

90% C.L. limits:
$\sin^2(2\theta_{13})<0.12$ **$\Delta m^2>0$**
$\sin^2(2\theta_{13})<0.20$ **$\Delta m^2<0$**



MINOS is the first experiment to probe θ_{13} with a sensitivity below the CHOOZ limit!

P($\nu_\mu \rightarrow \nu_e$) depends not only on θ_{13}, but also on δ and sign(Δm^2_{32}), so the θ_{13} limit is quoted for all possible values. The MSW matter effect is taken into account.