Searching for $\nu_\mu \rightarrow \nu_e$ Oscillations with the MINOS Experiment

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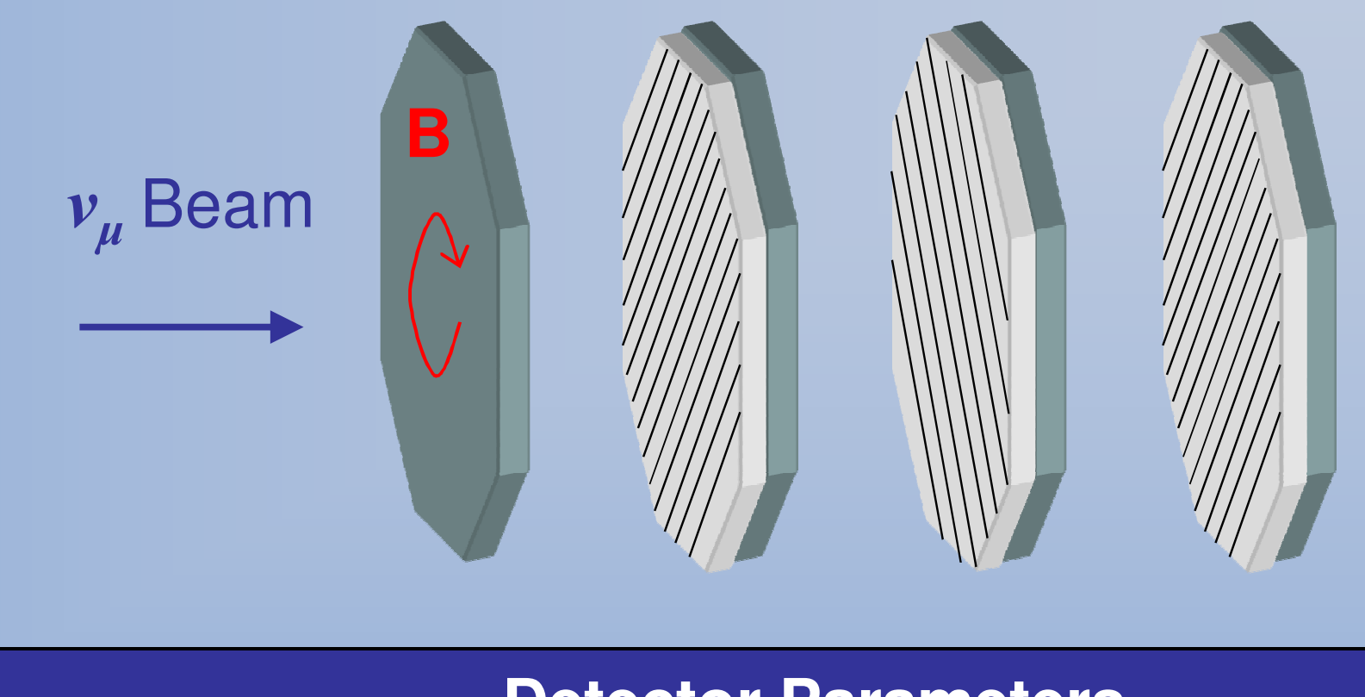
The MINOS Experiment

The MINOS experiment uses the NuMI beam of muon neutrinos produced at Fermilab. A near detector, 1 km from the source, measures the energy spectrum before oscillations have occurred. 735 km away, at the Soudan Laboratory, the far detector measures the oscillated spectrum allowing precision measurements of the oscillation parameters.

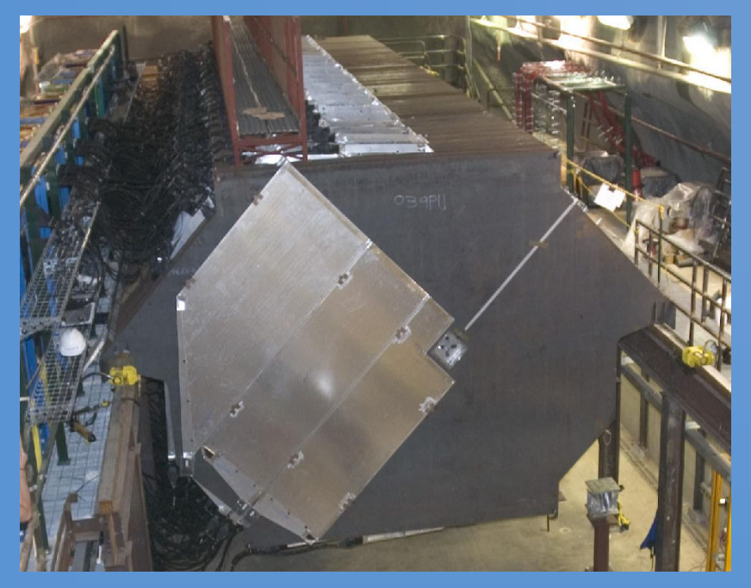
If θ_{13} is non-zero, a small fraction of ν_μ will oscillate to ν_e. If θ_{13} lies at the Chooz limit, MINOS can detect this ν_e appearance to make the first measurement of a non-zero θ_{13}. At $\sin^2(2\theta_{13})=0.15$ we expect 11 signal and 27 background events.

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$ (to leading order)



Detector Parameters		
	Near Detector	Far Detector
Weight	0.98 kilotons	5.4 kilotons
Number of Planes	282	486
Shape and Size	Squashed Octagon 4 m high by 5 m wide	Octagon 8 m wide

Near detector



Far detector

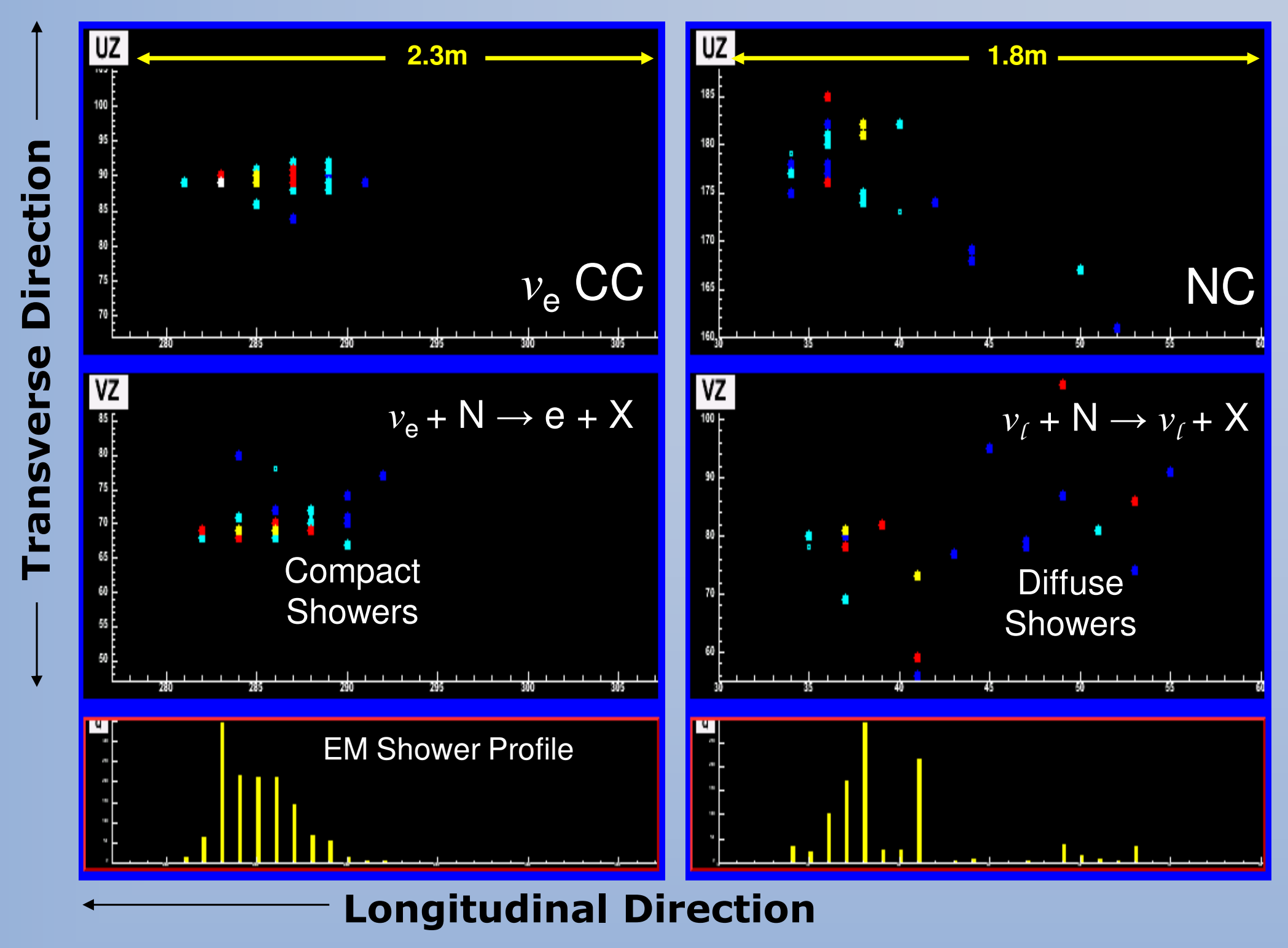
The MINOS detectors are tracking, sampling calorimeters. They consist of alternating planes of 2.5 cm-thick steel, and 1 cm-thick scintillator strips, each strip 4.1 cm wide.

Electron Neutrino Event Selection

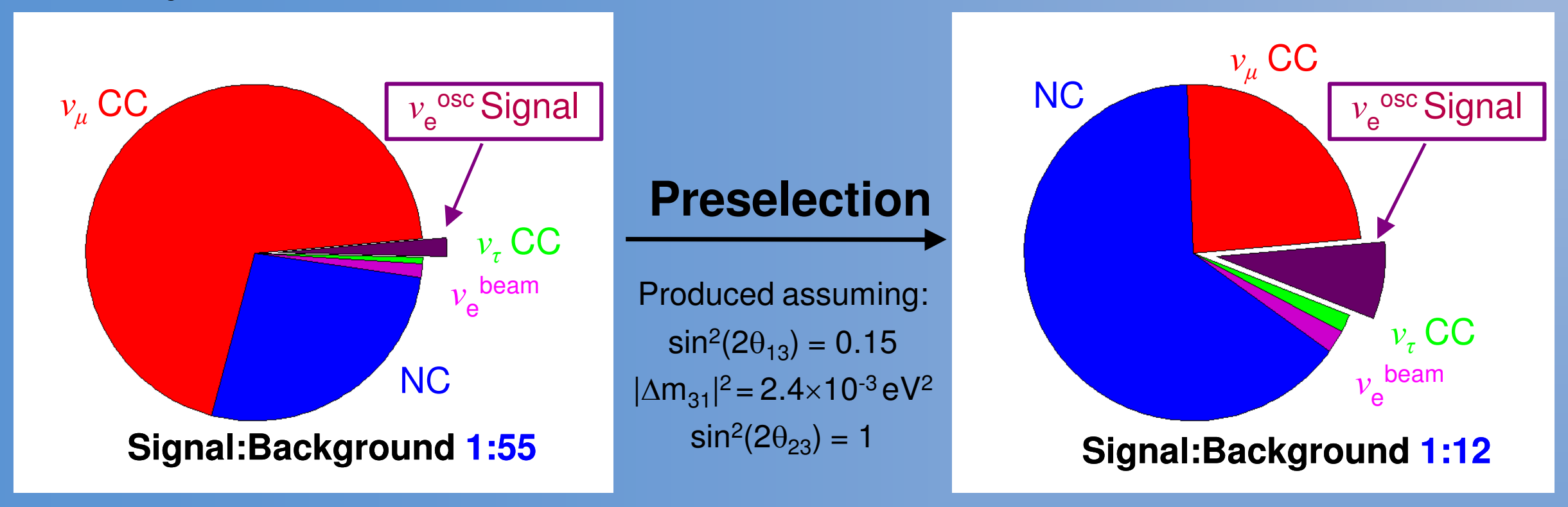
The MINOS detectors are optimized for ν_μ-CC and NC event identification, and are therefore designed for muon tracking and hadronic shower calorimetry. The signal for this analysis is ν_e-CC events, characterized by an electromagnetic shower: a denser energy deposition near the event vertex. The detector granularity is not optimized for distinguishing between hadronic and electromagnetic showers.

EM Showers in MINOS	Detector Parameters
Radiation length in steel: 1.76 cm	Steel thickness: 2.54 cm
Molière radius: 3.7 cm	Strip width: 4.1 cm

A typical 2 GeV ν_e event covers 8 planes x 4 strips



ν_e sample contamination before and after preselection

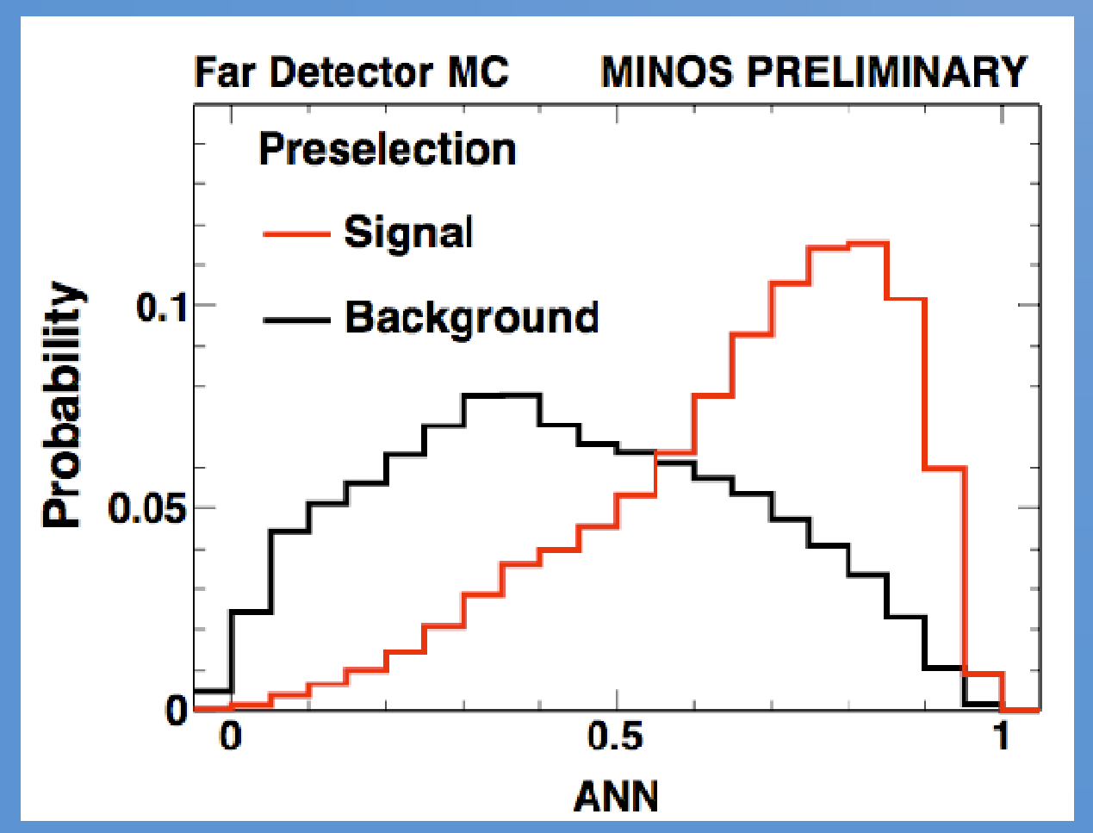


The background is reduced using pre-selection cuts

- Length of any reconstructed track < 25 planes
- Number of track-only planes < 16
- Reconstructed energy 1—8 GeV
- At least one shower with >4 contiguous planes and >0.5 MIP energy deposition

The signal to background ratio is still low: we need a more sophisticated selection algorithm.

Signal-Background Separation of ANN



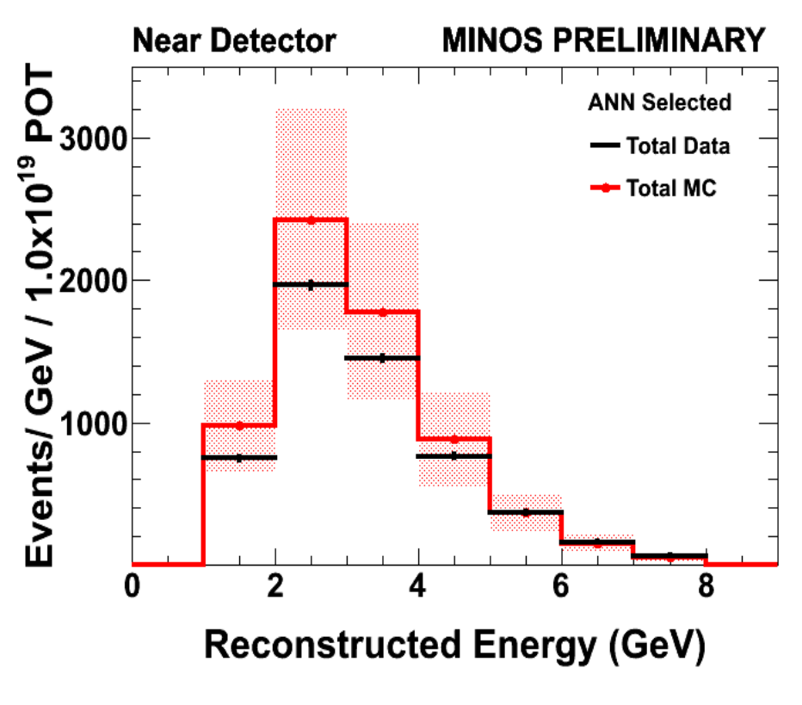
ν_e-CC events are selected by looking at variables which characterise the shower shape, length and width. Eleven variables are combined into an Artificial Neural Network (ANN)

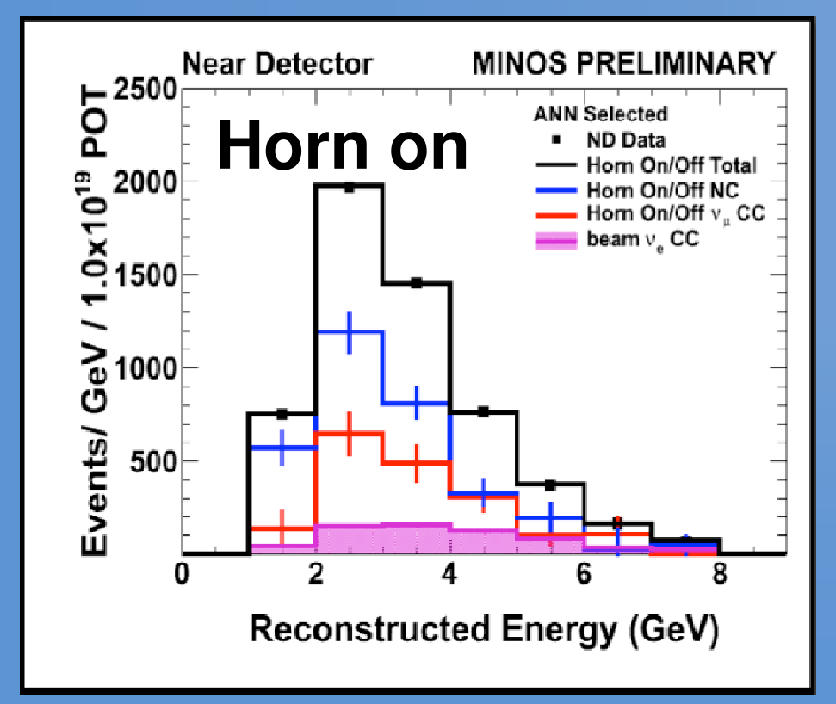
Artificial Neural Network Performance	
Signal efficiency	41%
NC rejection	92.3%
ν_μ-CC rejection	99.4%

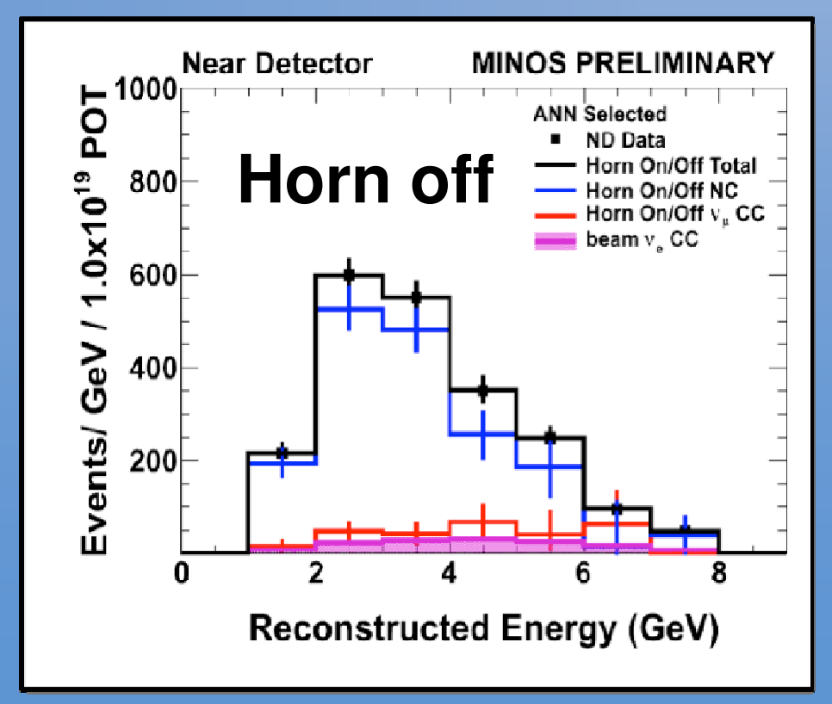
Background Decomposition

The ν_e-selected ND data and MC disagree by up to 20%. This is expected since we are cutting hard to reduce backgrounds, leaving only tails of distributions. This is where the two-detector nature of MINOS comes into its own: we can use the near detector to correct for these discrepancies in the far detector simulation.

The data is made up of a number of background components, primarily NC and ν_μ-CC events, which must be corrected independently. By turning off the current in the NuMI beam focusing horns, the relative background contributions change in a well-modeled way, allowing the individual components to be measured.



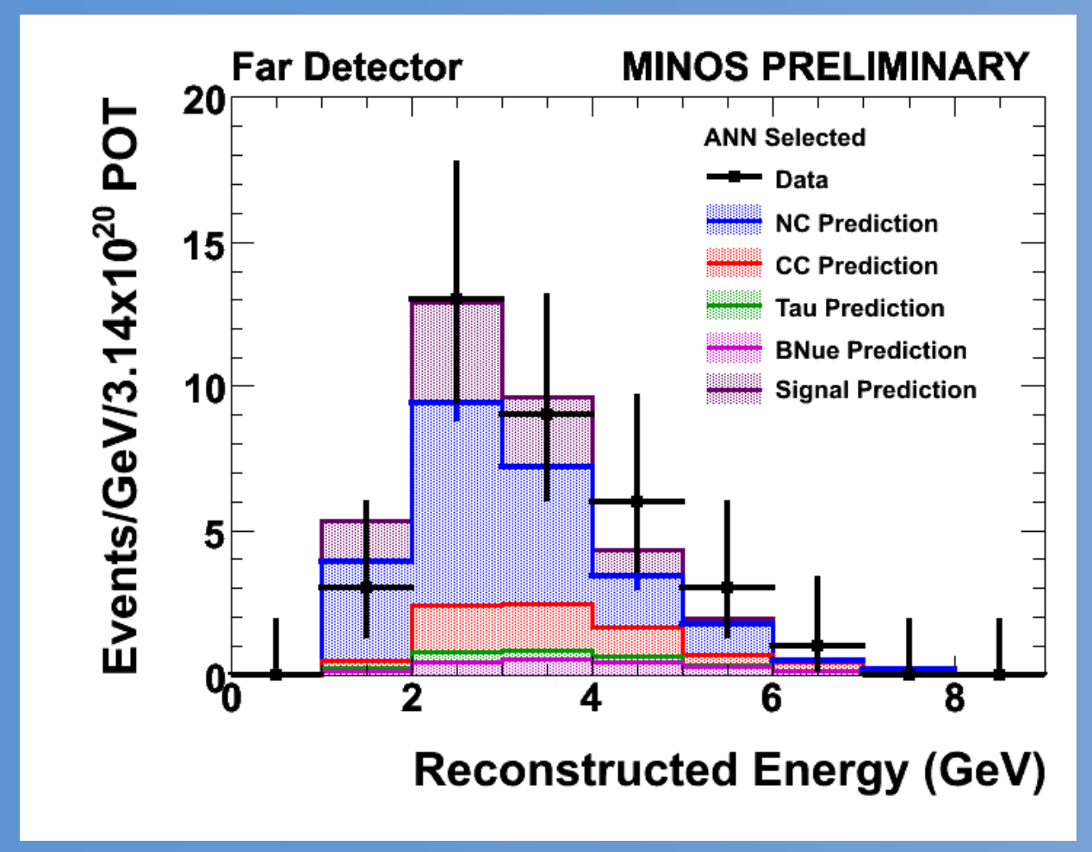


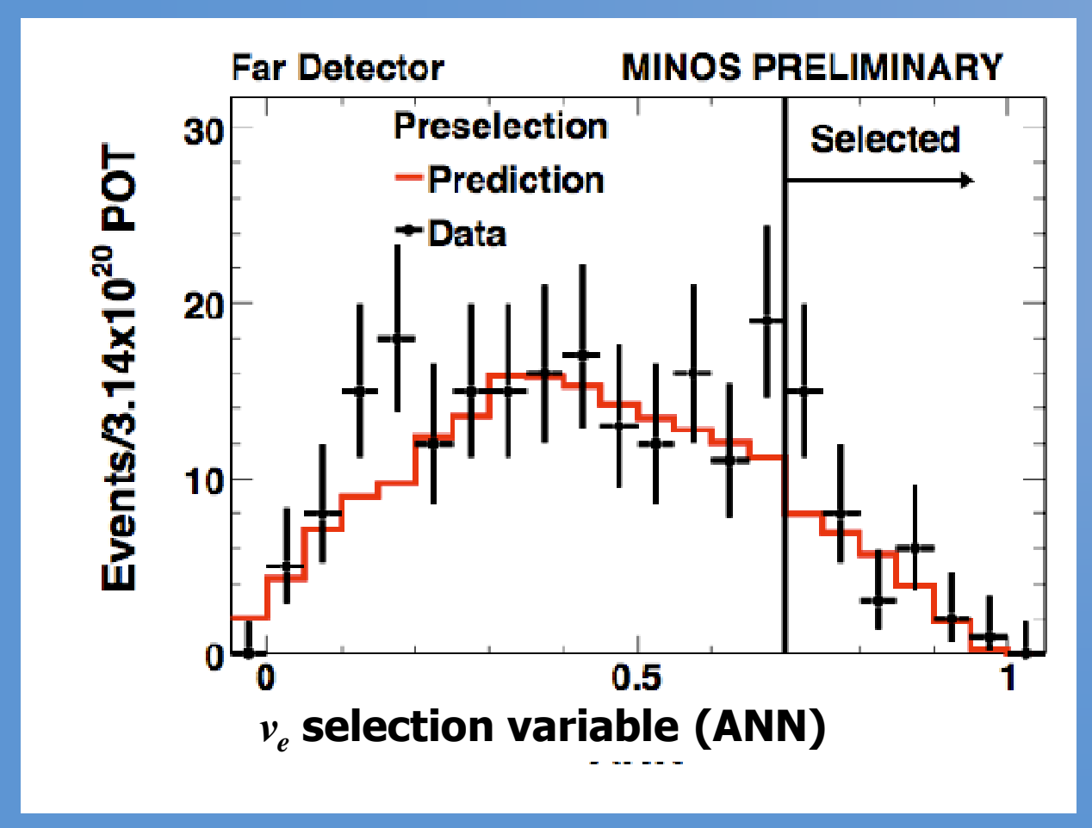


An independent method takes well-understood ν_μ-CC events and removes the muon from the reconstructed event to leave a well-understood sample of hadronic showers. This produces consistent results.

These background corrections are applied to the far detector simulation, to give a systematic uncertainty of 7.3% on the number of selected events, compared to a statistical uncertainty of 19%

Results





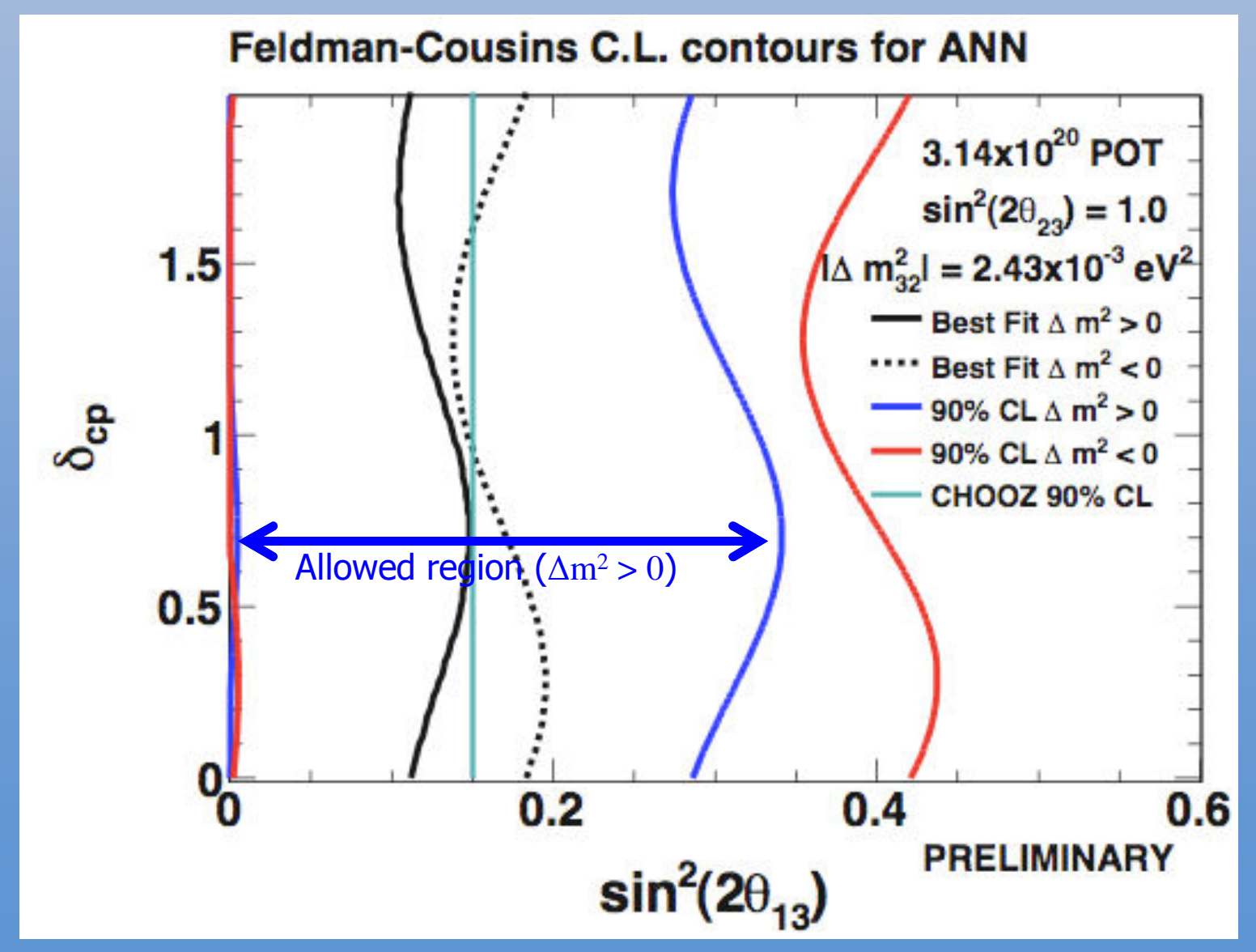
At the far detector 35 ν_e-CC candidate events are seen. The expected background is 27 ± 5 (stat.) ± 2 (syst.) This is an excess of 1.5σ.

The data is fit to an oscillation hypothesis, assuming $\Delta m^2_{atm}=2.43\times10^{-3}$ eV^2 and $\sin^2(2\theta_{23})=1.0$. A Feldman-Cousins method is used to account for systematics.

The best fit θ_{13} is at the Chooz limit:

For the normal mass hierarchy ($\Delta m^2_{atm}<0$):
- $\sin^2(2\theta_{13}) < 0.29$ (90% c.l.), for $\delta_{CP}=0$

For the inverted mass hierarchy ($\Delta m^2_{atm}<0$):
- $\sin^2(2\theta_{13}) < 0.42$ (90% c.l.), for $\delta_{CP}=0$



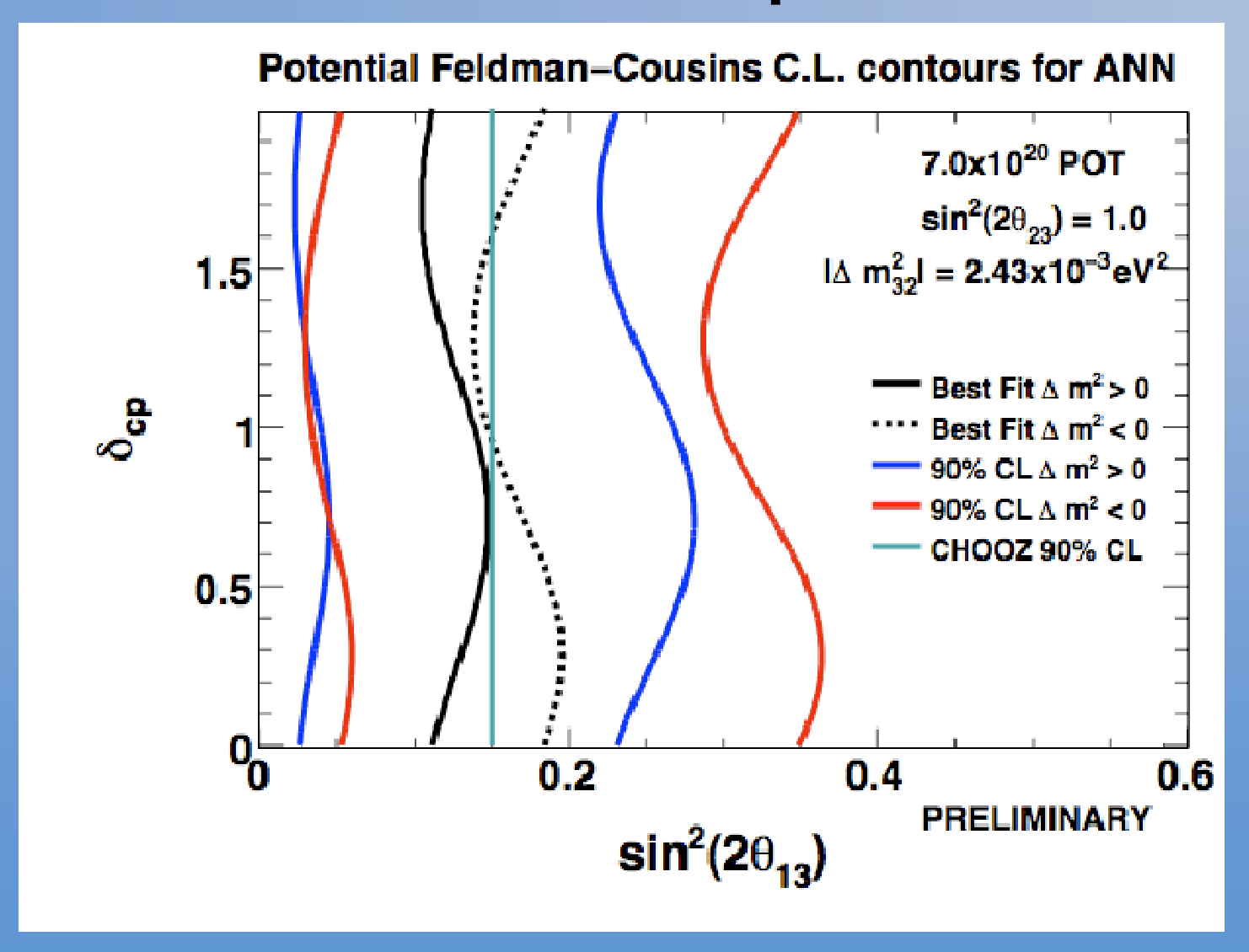
The Future

The results presented here correspond to 3.2×10^{20} protons on target (PoT). As of this June, MINOS has more than doubled this dataset, obtaining 7×10^{20} PoT.

Early next year, this analysis will be updated using the new data.

These graphs show the sensitivity to θ_{13} given our existing data, depending on whether the observed excess persists or goes away in the new data.

If the excess persists



If the excess goes away