New Results from MINOS

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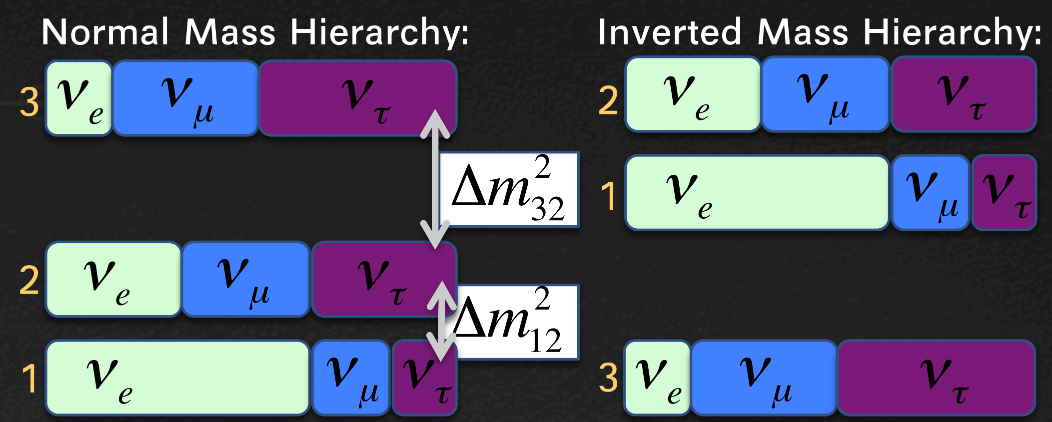
Introduction

- Theory Introduction
- The MINOS Experiment
- Recent MINOS Results
- Electron Neutrino Appearance – NEW Result
- Summary

Neutrinos and Physics Motivation

- There are **3 generations of neutrino**: ν_e, ν_μ, ν_τ
- **neutrinos have mass and they oscillate**
- neutrino oscillations are governed by the PMNS matrix



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

Atmospheric and accelerator experiments (Super-Kamiokande, MINOS):

$\Delta m^2_{atm} = 2.32\times10^{-3} eV^2$

$\sin^2 2\theta_{23} > 0.9$ => $\Theta_{23} \approx 45^\circ$

Θ_{13} is small and CP-violating phase δ is unknown

Solar experiments (SNO, Kamland):

$\Delta m^2_{sol} = 8\times10^{-5} eV^2$

$\Theta_{12} \approx 34^\circ$

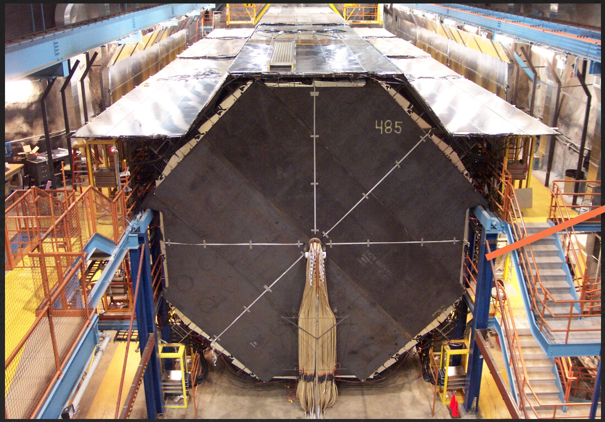
MINOS Experiment

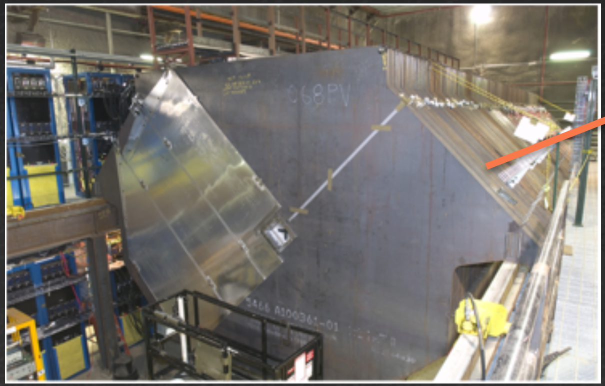
Iron scintillator calorimeters, functionally identical

Far Detector:
- **Spectrum after oscillations**
- 5.4 kT, 8m x 8m x 30m,
- 484 steel/scintillator planes, veto shield

Near Detector:
- **Spectrum before oscillations**
- 1 kT, 3.8m x 4.8 m x 15m,
- 282 steel planes, 153 steel/ scintillator planes

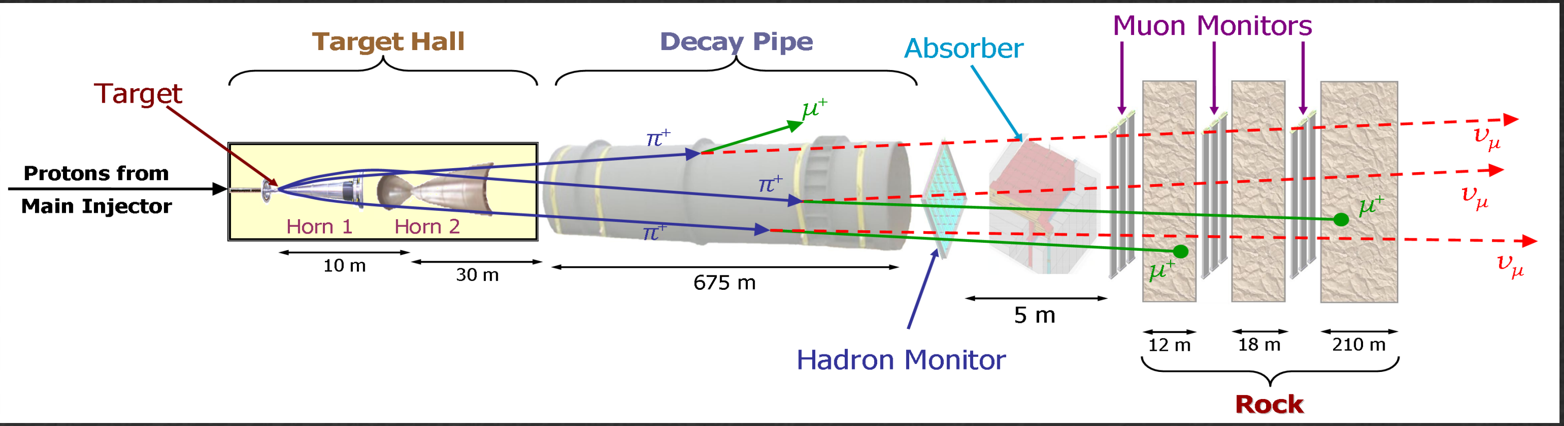
Steel/scintillator planes:
- 1-inch thick steel planes alternating with planes of scintillator strips
- Alternative scint. planes are orthogonal to each other for 3D reconstruction of events



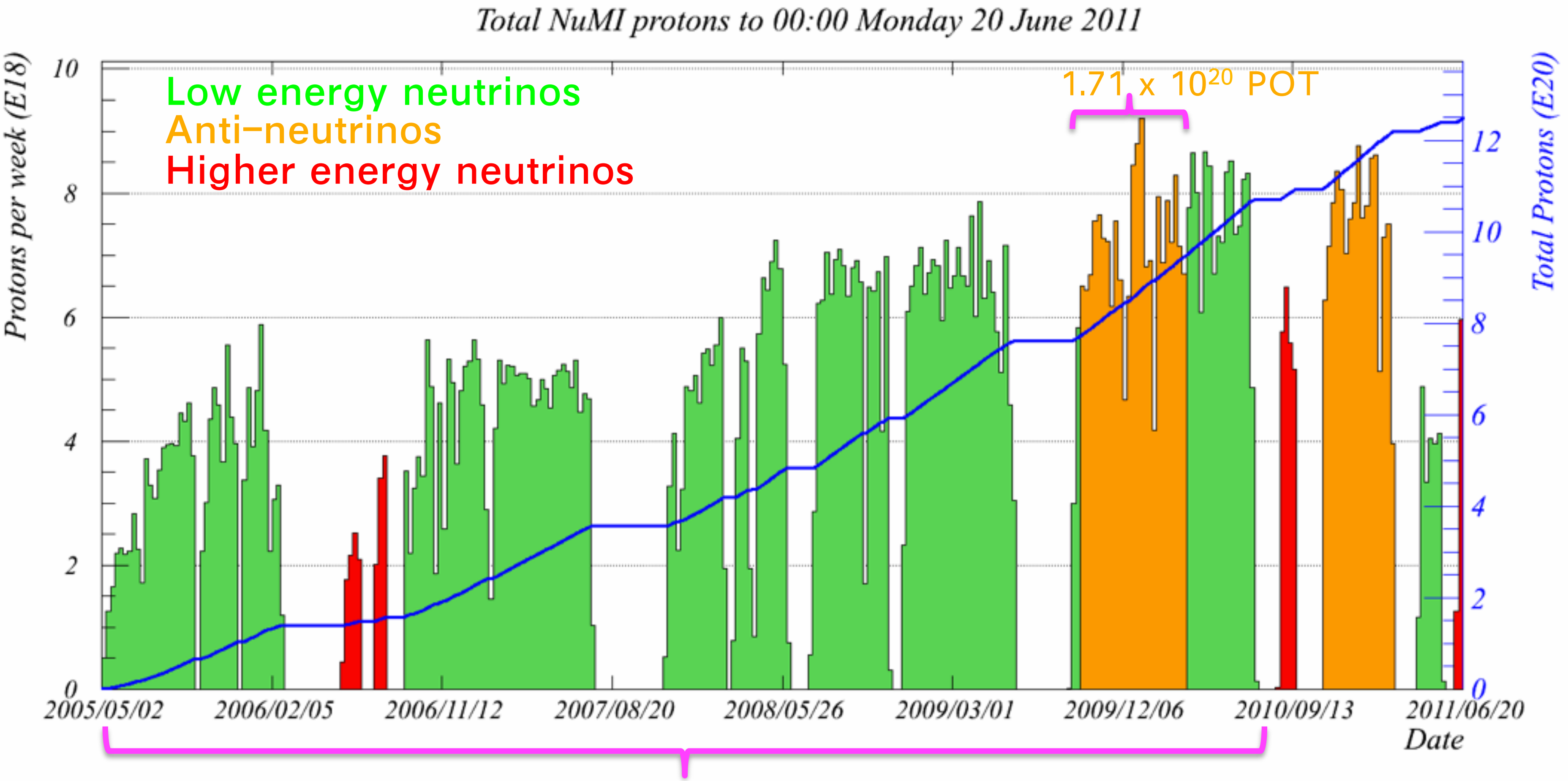


The NuMI Beam

- 120 GeV protons from Main Injector
- impact on graphite target
- ~10μs spill every ~2s, currently ~3.5x10^{13} protons on target/spill
- produced hadrons focused by 2 magnetic horns
- decay into neutrinos and other particles
- absorber/rock remove heavier particles, leave neutrinos
- neutrino energy spectrum can be changed with target position, horn current can be reversed to produce an anti-neutrino beam

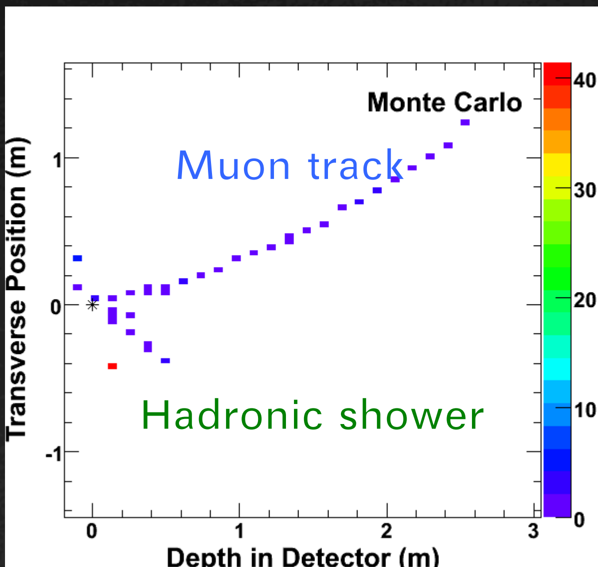


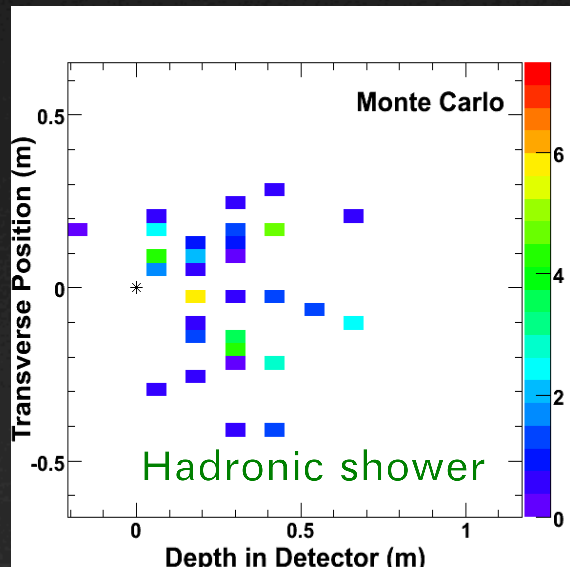
Protons on Target to Date

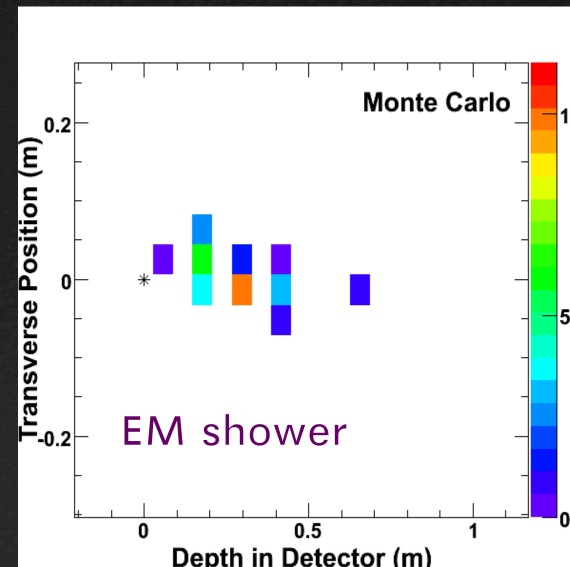


The electron neutrino appearance result presented here uses data from the normal low energy beam configuration – 8.12 x 10^{20} POT (green only)

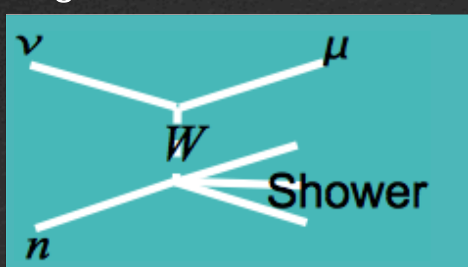
MINOS Event Topology



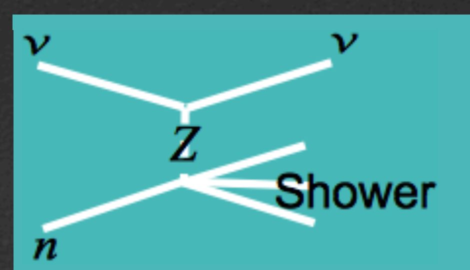




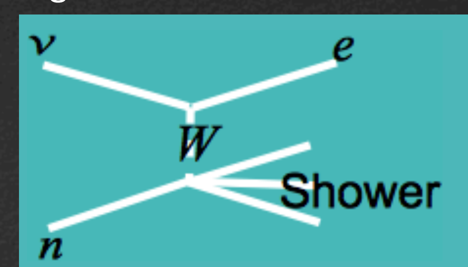
Charged Current – muon ν



Neutral Current



Charged Current – electron ν



UCL

Muon Neutrino Disappearance

Muon neutrinos are observed to disappear as they travel. The most precise result in Δm^2 was obtained by MINOS:

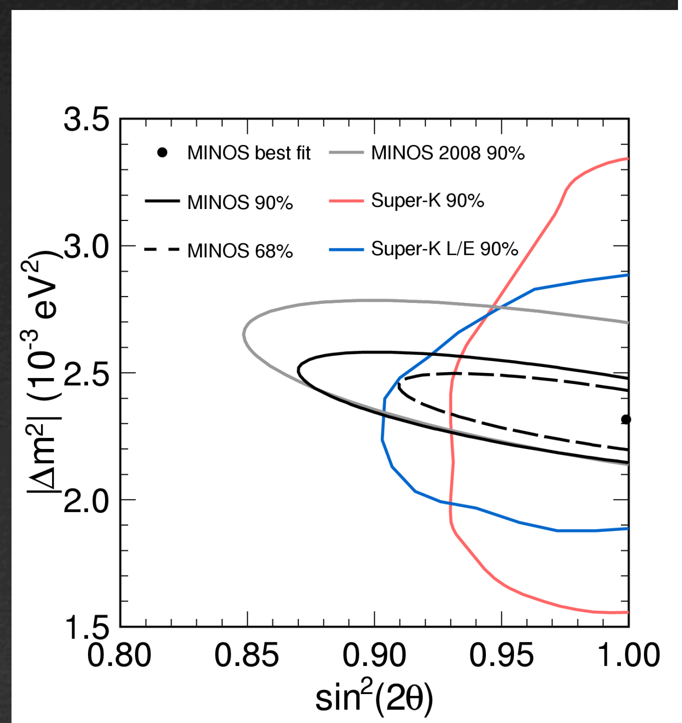
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(1.27\Delta m_{32}^2 L/E)$$

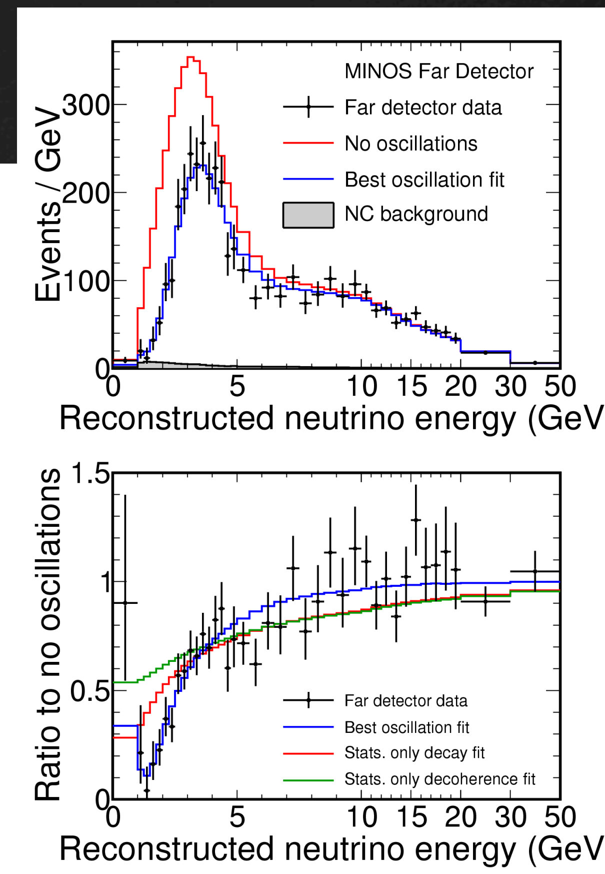
$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) > 0.90 (90\% C.L.)$$

Expected 2451 events
Observed 1986 events

Exclude decay at 7 σ
Exclude decoherence at 9 σ





Phys. Rev. Lett. 106, 181801 (2011)

UCL

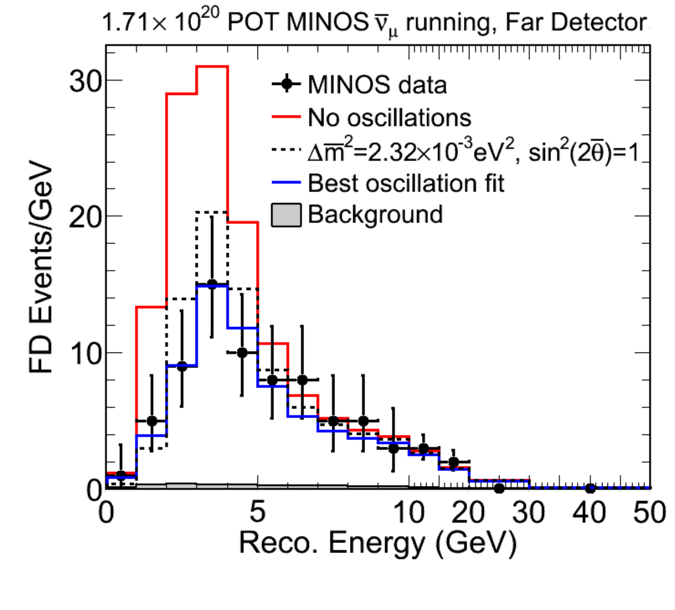
Muon Anti-Neutrino Disappearance

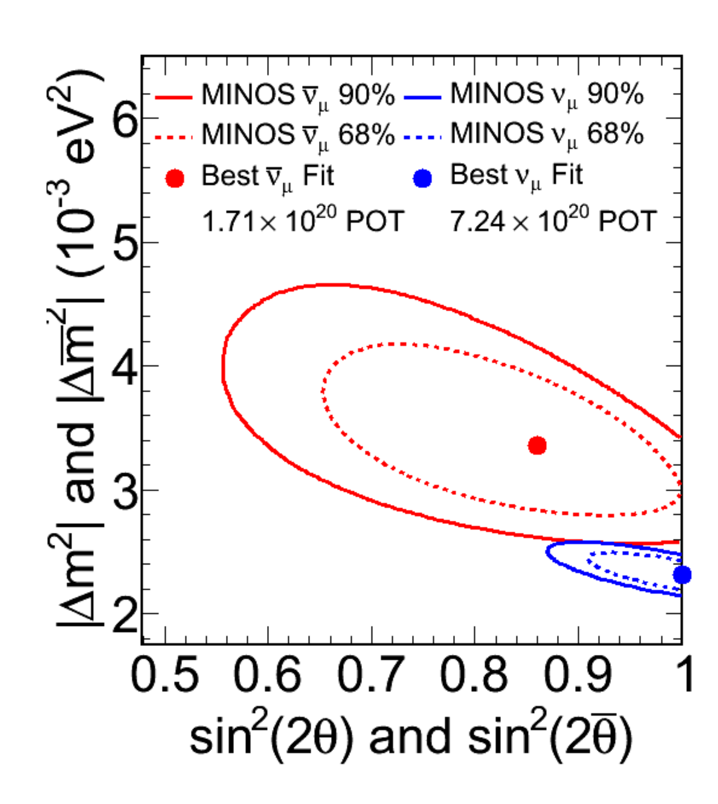
By reversing the horn current, NuMI can create an anti-neutrino beam, can analyze the resulting data in a similar way to the neutrino data

No oscillation Prediction: **156 events**

Observe: **97 events**

No oscillations disfavored at 6.3 σ





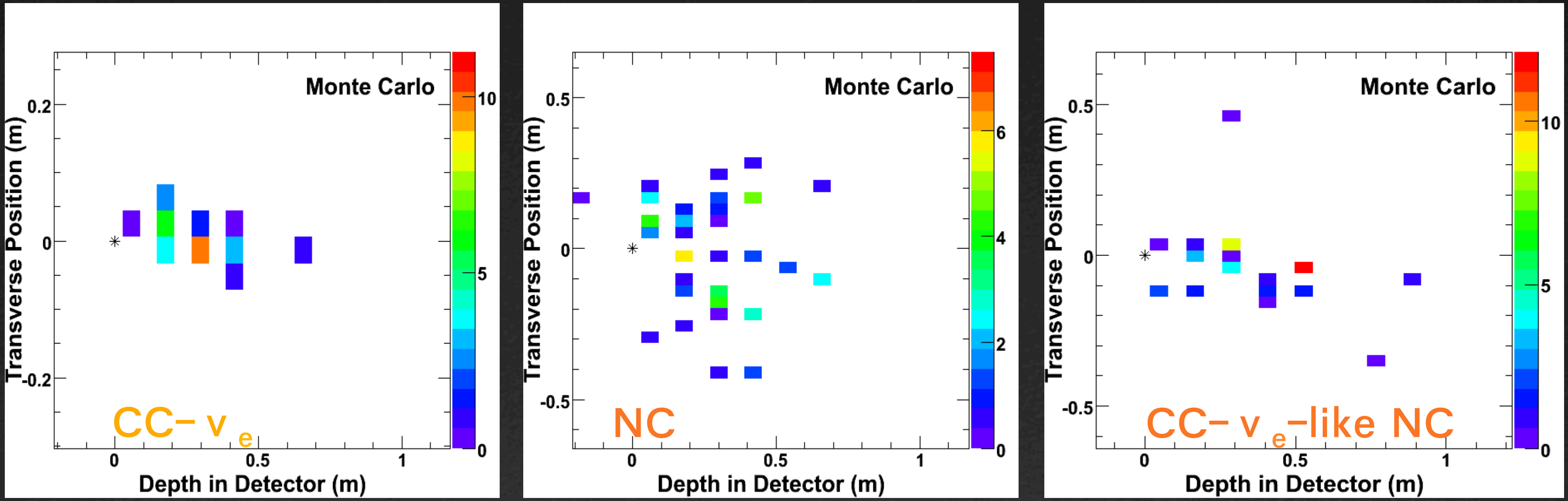
$$\left|\overline{\Delta m^2}\right| = (3.36^{+0.46}_{-0.40}(stat.) \pm 0.06(syst.)) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86^{+0.11}_{-0.12}(stat.) \pm 0.01(syst.)$$

Phys. Rev. Lett. 107, 021801 (2011)

Electron Neutrino Analysis Procedure

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

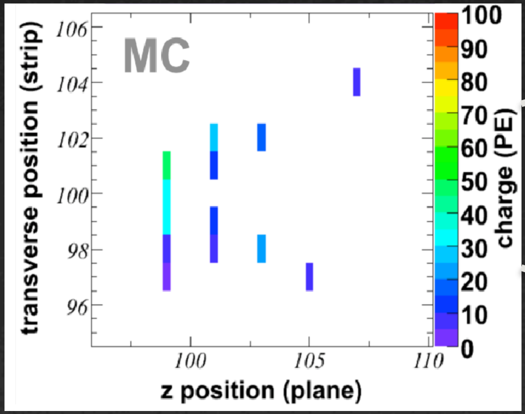


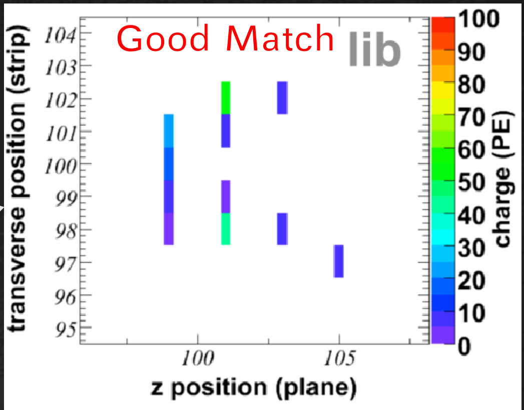
- Determine the criteria for selecting electron neutrino CC events from a background of predominantly NC events
- Translate the observed ND data spectrum into a background prediction for the FD
- Compare the data to the prediction and fit observed spectrum to obtain final exclusion limits
- New for this analysis: shape fitting in 15 bins – 3 bins in PID and 5 in energy

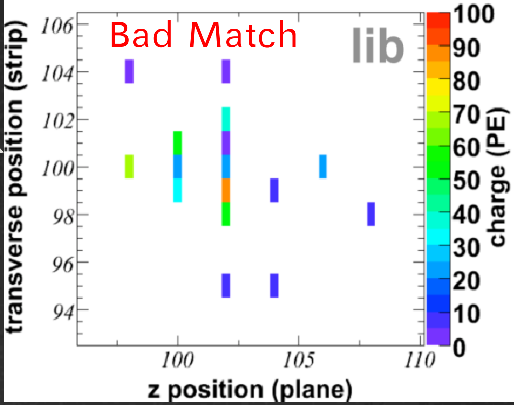
Selection of electron neutrino events

Cuts are applied to remove obvious non-signal events. Those cuts include:

- long track events
- events without a shower and well-defined shower core
- events with energies below 1GeV and above 8GeV







After this pre-selection, a selection PID (also new since last analysis) is used to hone in on the signal events:

- LEM – Library Event Matching Algorithm – it uses a library of 20 million signal and 30 million NC events
- The 50 best matches are found for each event – 3 discriminant variables are constructed and combined in a neural network to obtain the PID

Near Detector Background Decomposition

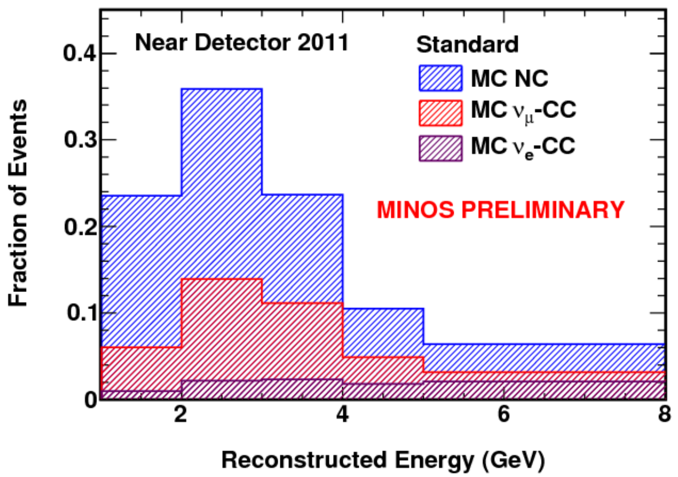
There are three ND components:
- Neutral current background
- High-Y charged current muon neutrino background (muon track is short and is lost in the shower)
- Intrinsic beam electron neutrino CC events

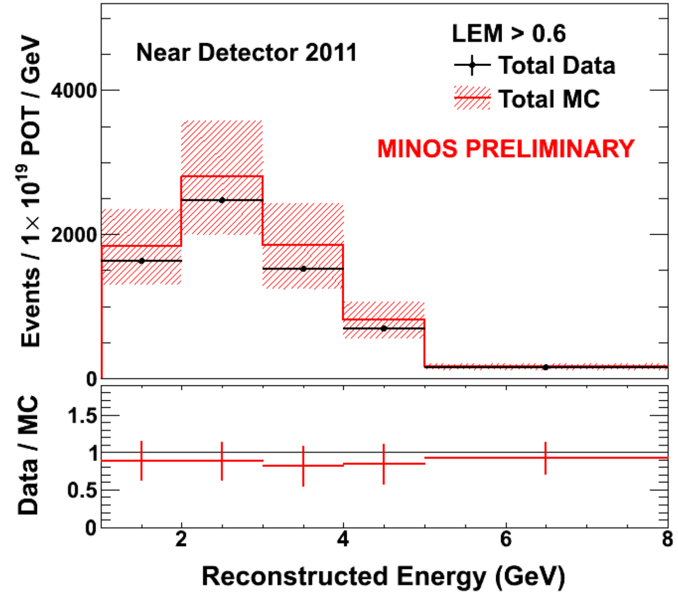
Those individual components need to be extrapolated to the FD separately so as to account for oscillations

The MC and data do not agree perfectly, but we want to use the ND data to make a FD prediction =>

=> Need to decompose the ND data

To calculate each component, can use ND data taken in different beam configurations

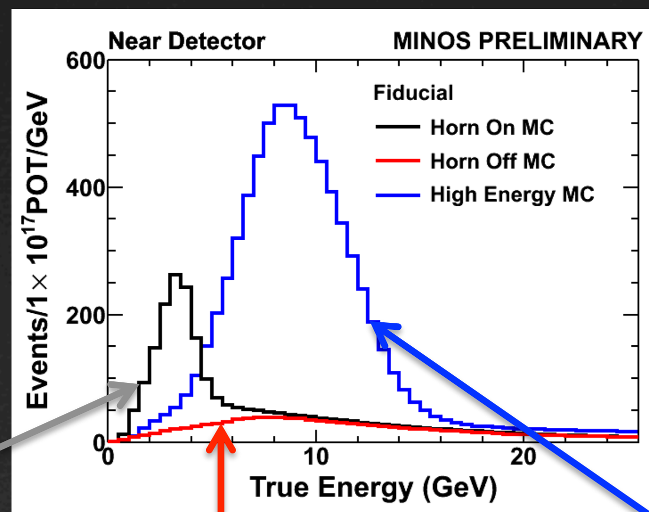




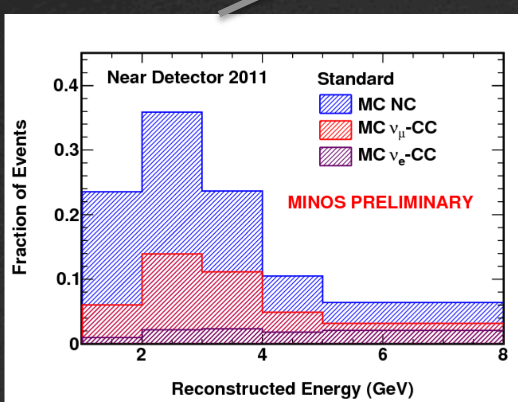
Near Detector Background Decomposition

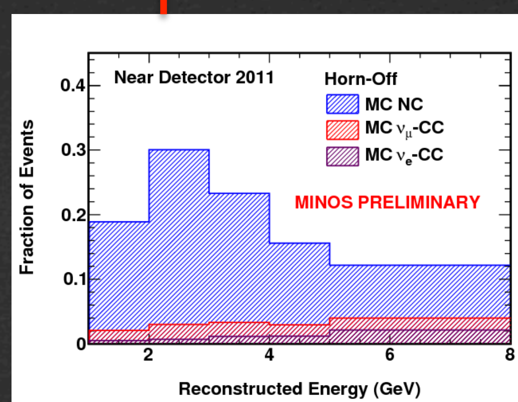
To calculate each background component, ND data taken in different beam configurations can be used:

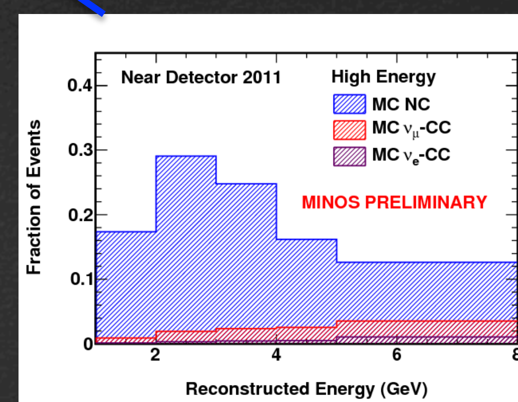
- Can use the total measured data in each beam configuration
- Can use the MC simulations for the relative interaction rates for each background



- Can thus fit for the background components in the standard LE sample

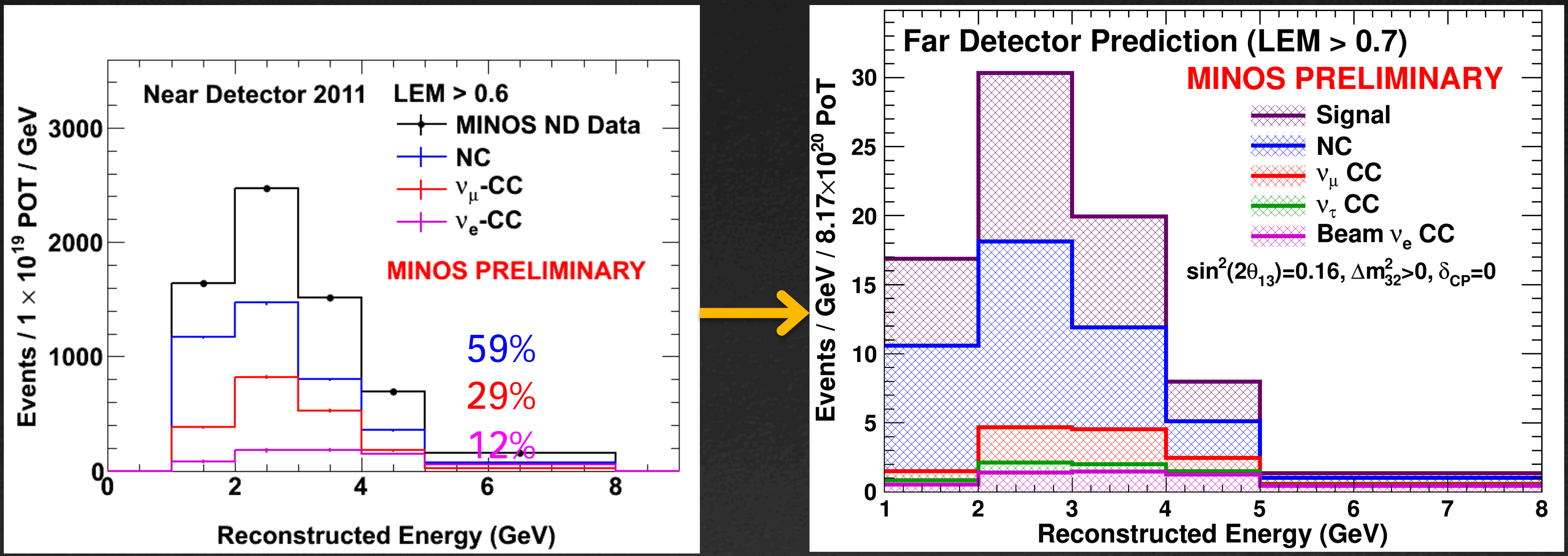






Extrapolation to the Far Detector

Use Far/Near ratios to extrapolate the individual backgrounds to the FD:



Accounts for:
- Flux (e.g. $1/R^2$ fall off)
- Cross-section
- Fiducial volume
- Energy smearing
- Detector effects
- Muon neutrino disappearance

A tau neutrino appearance component is added from oscillated muon neutrinos to the FD prediction

Far Detector Prediction

NC	ν_μ-CC	Beam ν_e-CC	ν_τ-CC	Total	ν_e-CC Signal
34	7	6	2	49	30

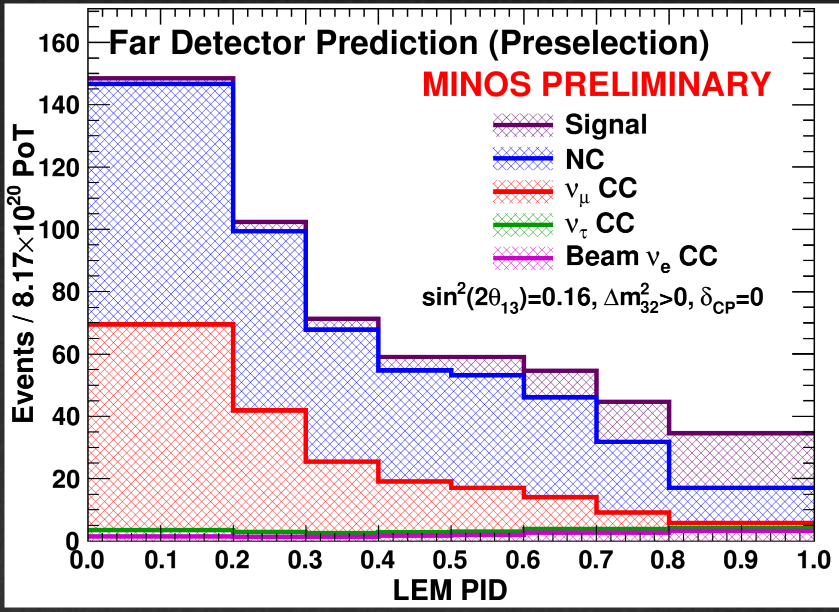
(rounded numbers)

For 8.2×10^{20} POT in the signal enhanced region LEM>0.7, signal at Chooz limit, and $\Delta m^2_{32}=2.32\times10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta_{23}=1$

Systematic uncertainty is 5.7% on the background prediction in region LEM>0.7

Uncertainties include:

- Composition of the ND spectrum
- Far/Near ratio:
  - Calibration – e.g. relative energy calibration, gains, absolute energy calibration
  - Relative Near/Far normalization
  - Hadronisation model
- Other smaller uncertainties



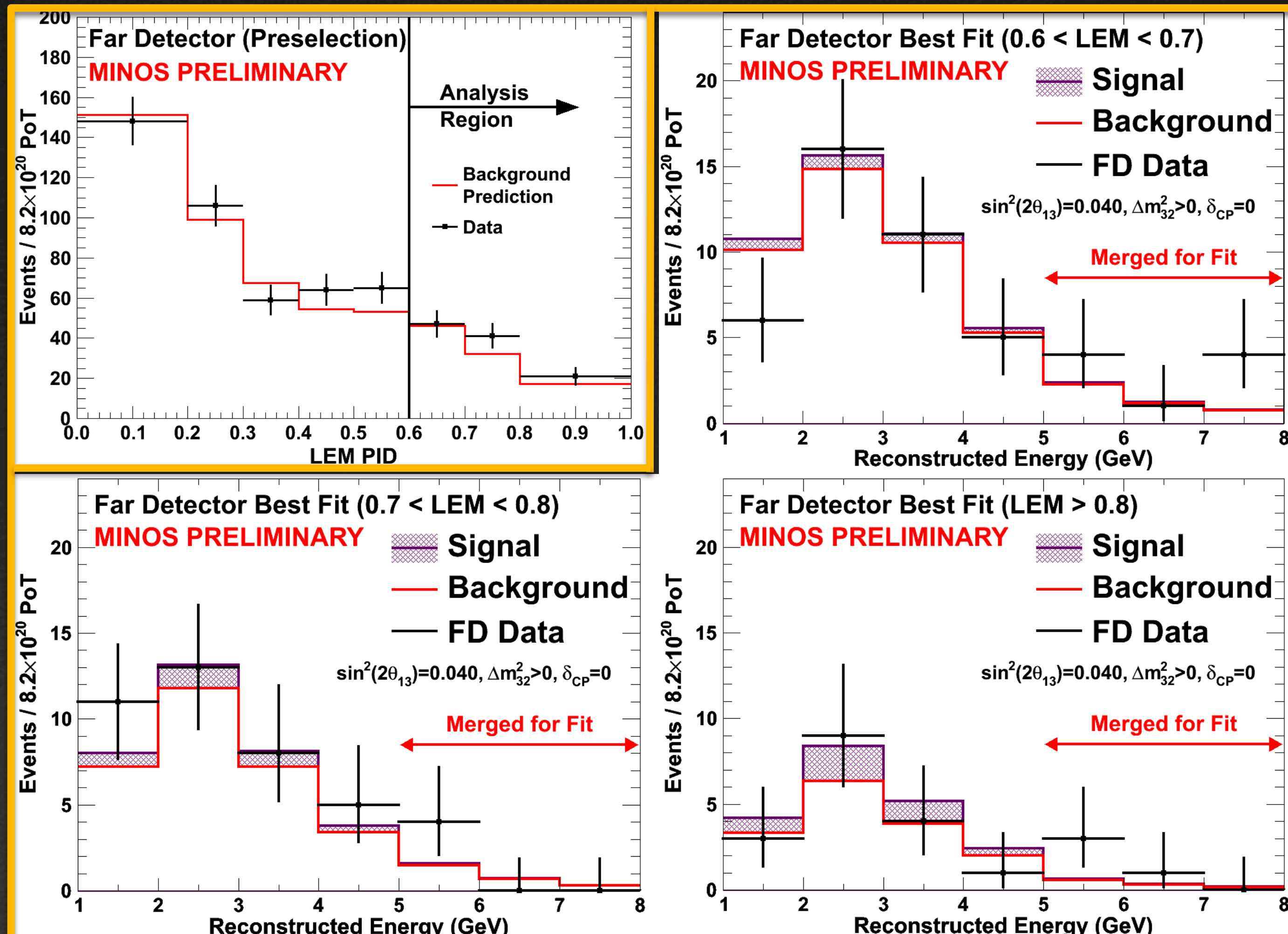
Appearance Result for 15-Bin Fitting

The fit uses 15 bins – three in PID and 5 in reconstructed energy.

Best Fit:

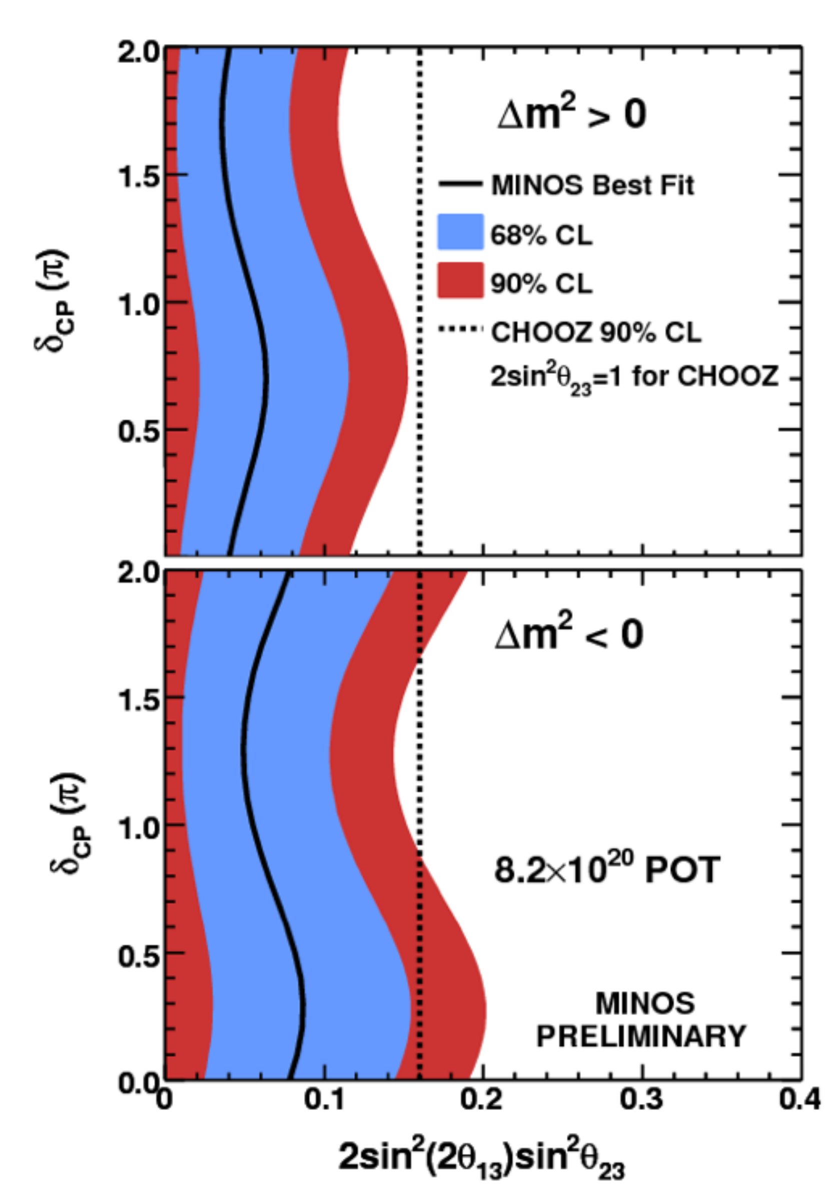
$\sin^2 2\theta_{13} = 0.040$

for $\delta = 0$ and $\sin^2 2\theta_{23} = 1$, normal mass hierarchy



Signal enhanced region LEM>0.7:
expect $49.5 \pm 7.0(\text{stat.}) \pm 2.8(\text{syst.})$, observed 62 events in the FD

Region Allowed by Fit



MINOS has updated its electron neutrino appearance analysis for an exposure of 8.2×10^{20} POT, with shape fitting and a new selection variable

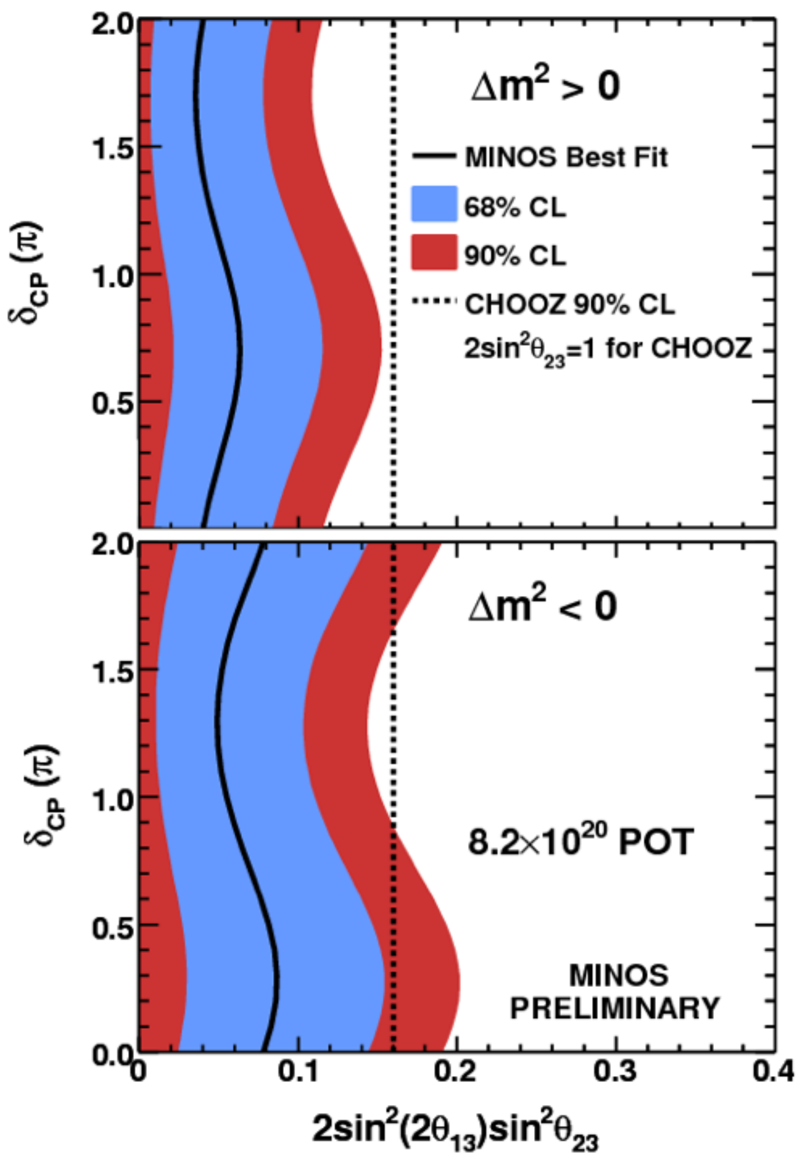
$\sin^2(2\theta_{13})<0.12$ for normal mass hierarchy, <0.19 for inverted hierarchy, at 90% C.L., for $\delta=0$

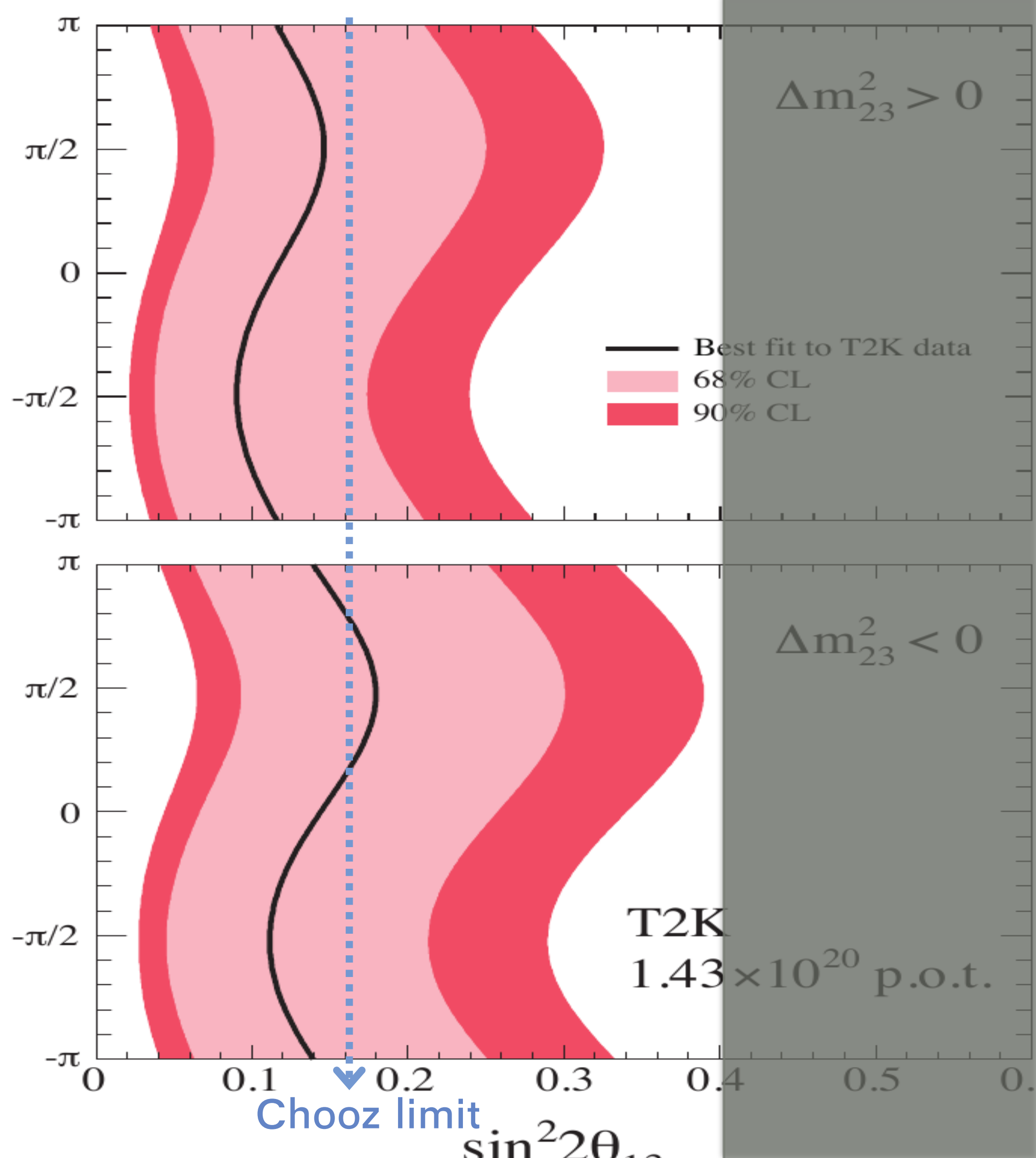
$\sin^2(2\theta_{13})=0.04$ (0.08) are the best fit values

$\sin^2(2\theta_{13})=0$ excluded at 89% C.L.

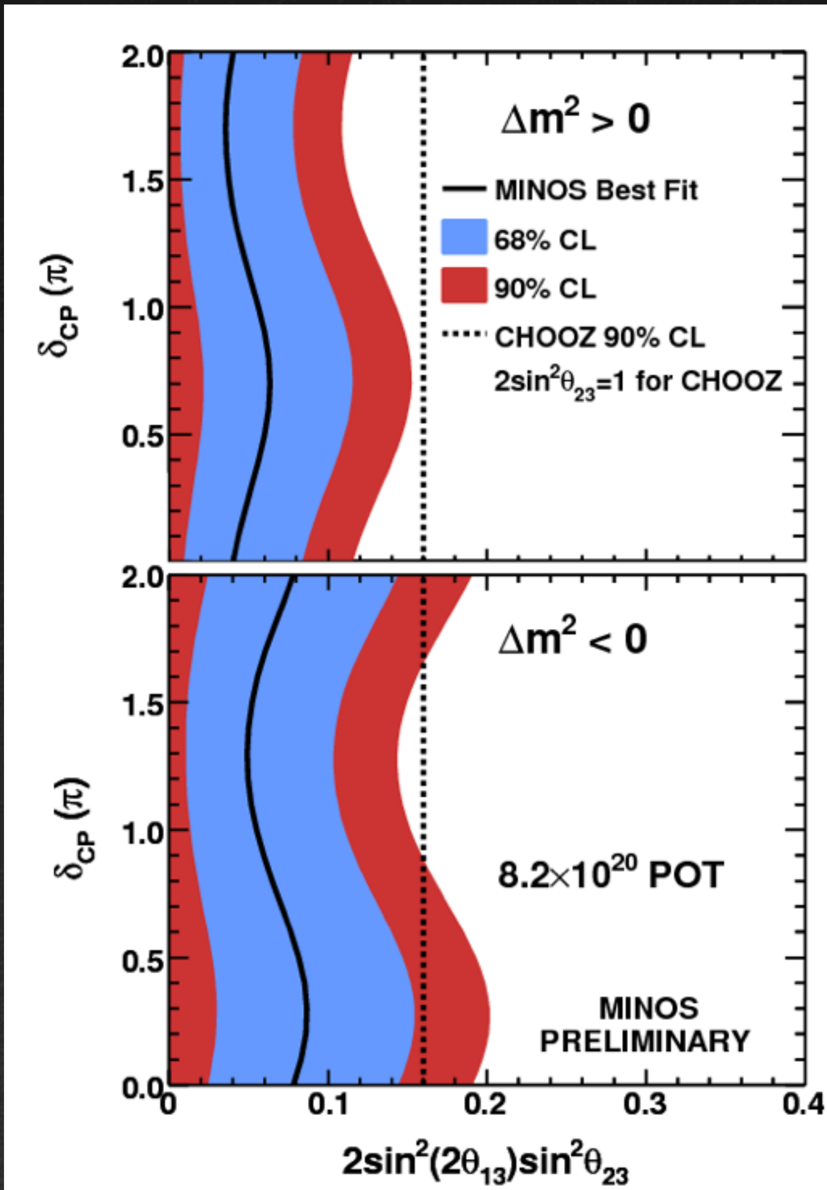
For the first time, an experiment has been able to exclude beyond the Chooz limit in all of the parameter space for the normal mass hierarchy

Region Allowed by Fit – Comparison to T2K Result





Summary



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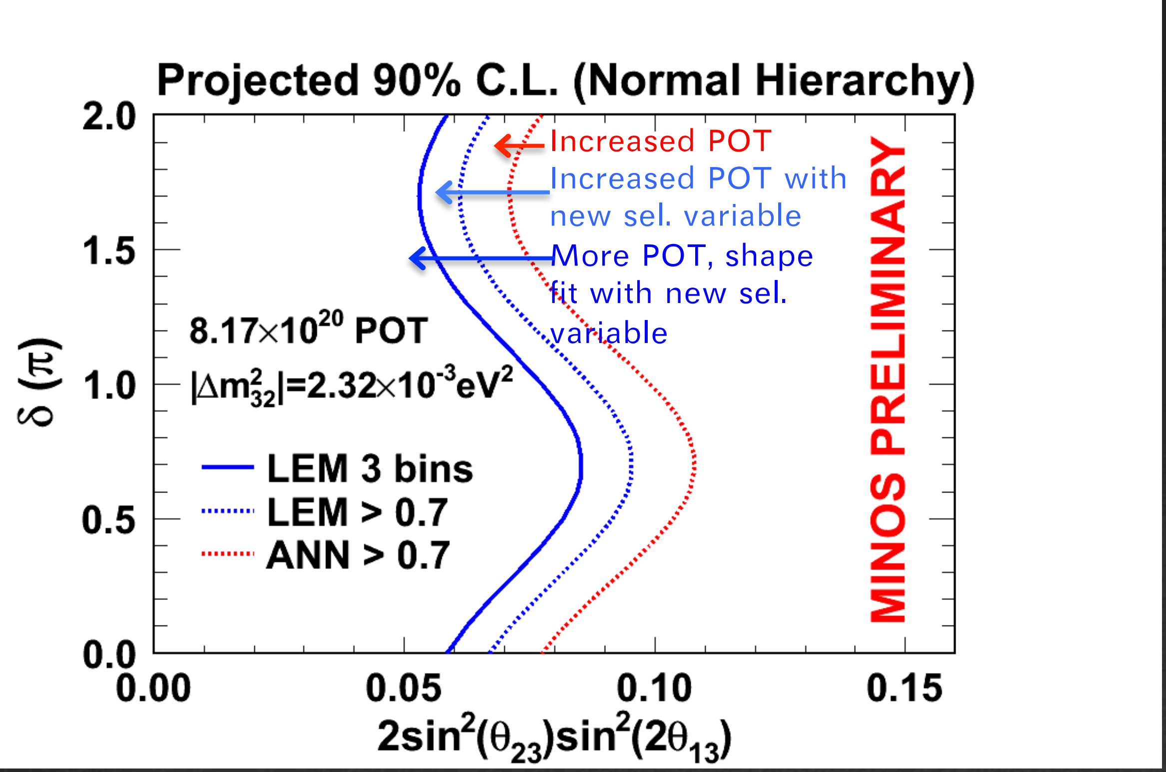
For the first time, an experiment has been able to exclude beyond the Chooz limit in all of the parameter space for the normal mass hierarchy

MINOS is planning to present further new results very soon.

Back-Up

Electron Neutrino Analysis Sensitivity

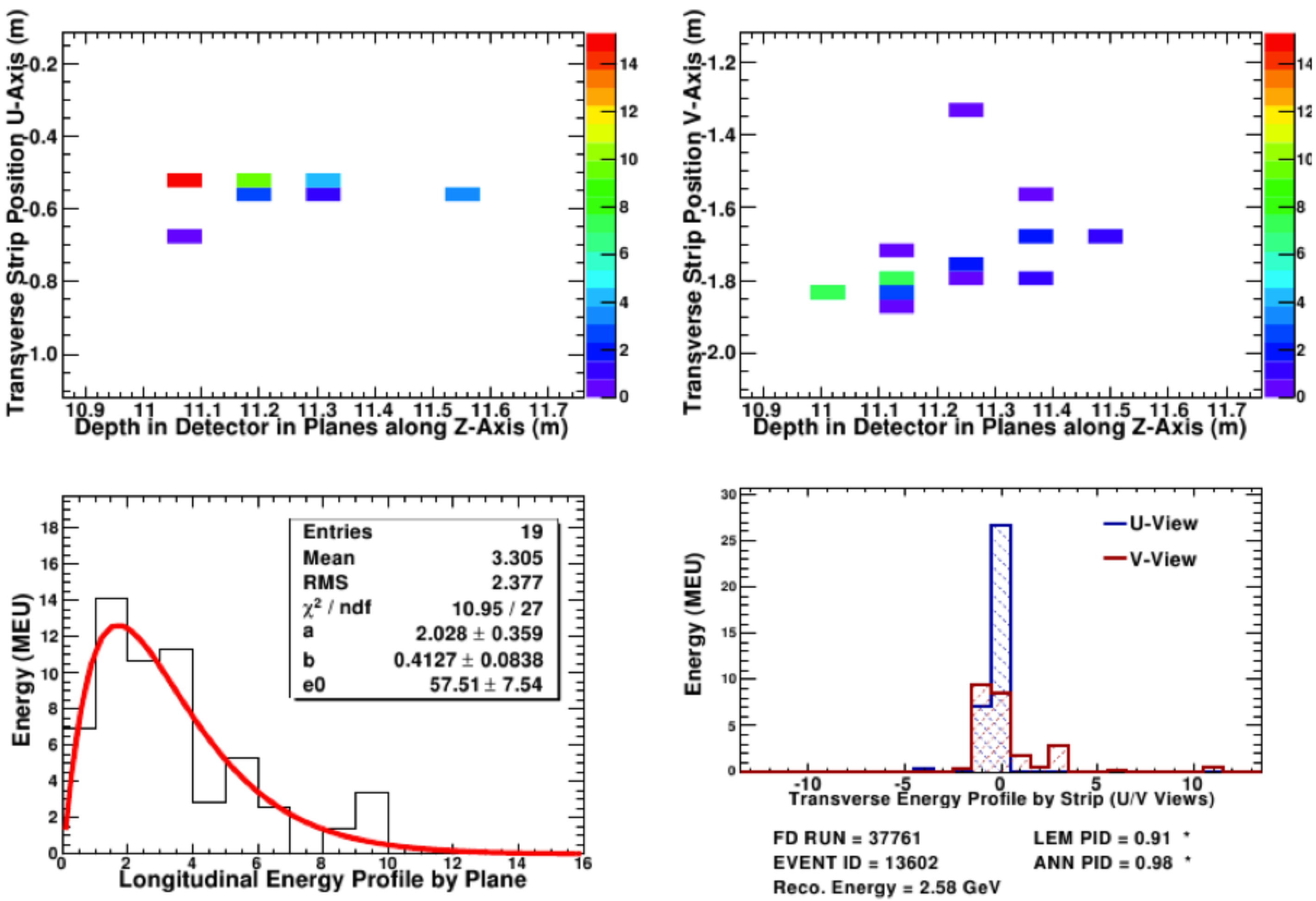


90% upper limit we would set if we observe the background prediction exactly

MINOS sensitivity increased since last analysis in 2010 significantly:

- 17% more data (1.2×10^{20} POT)
- 15% better from improved selection variable
- 12% better from shape fit

Electron Neutrino Appearance Candidate Event

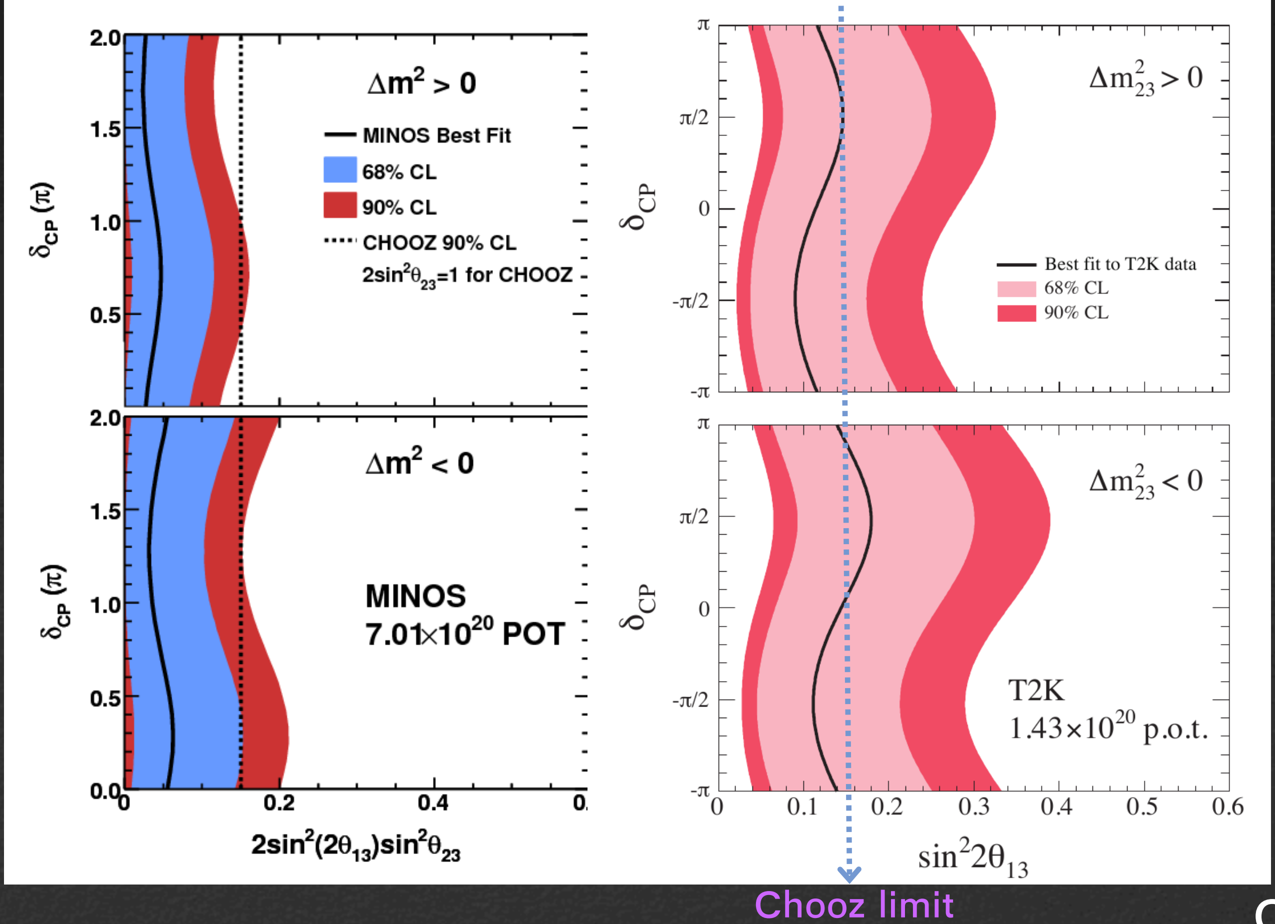


Electron Neutrino Appearance

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

MINOS 2010: predicted => 49 background events observed => 54 events

MINOS sensitivity beyond the Chooz limit for normal mass hierarchy

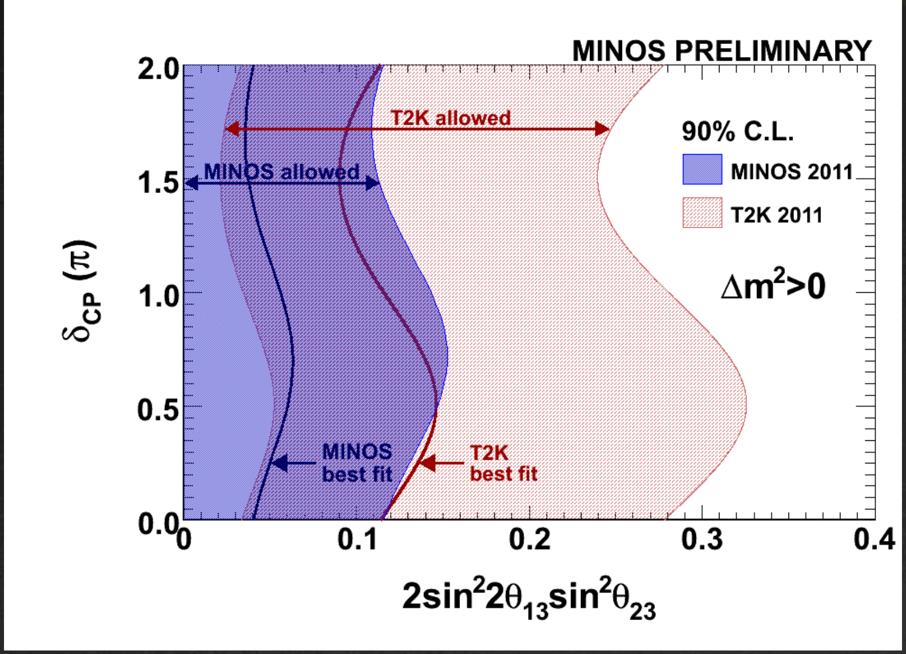


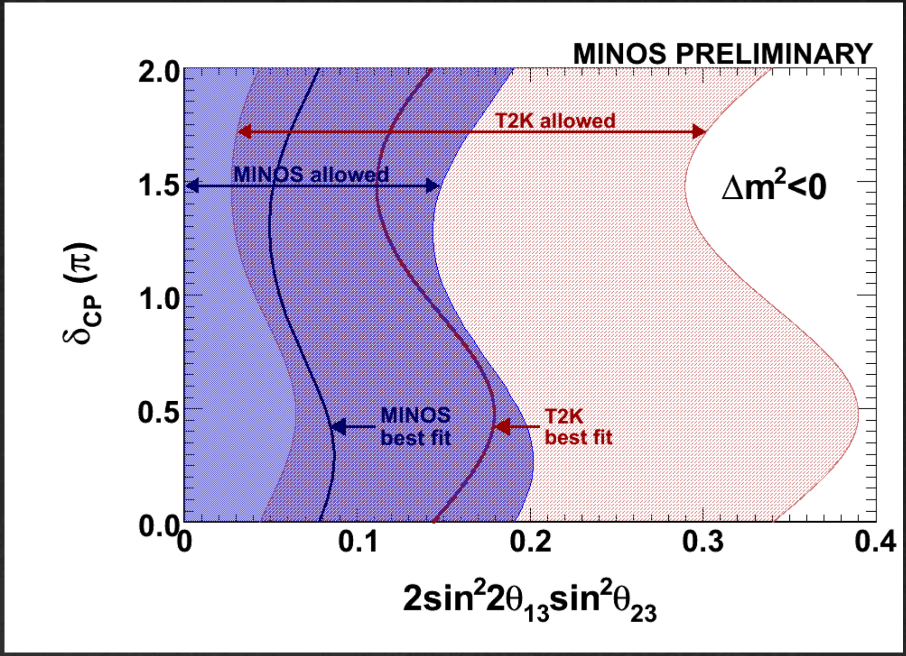
T2K: predicted 1.5 events observed 6 events

Cite paper

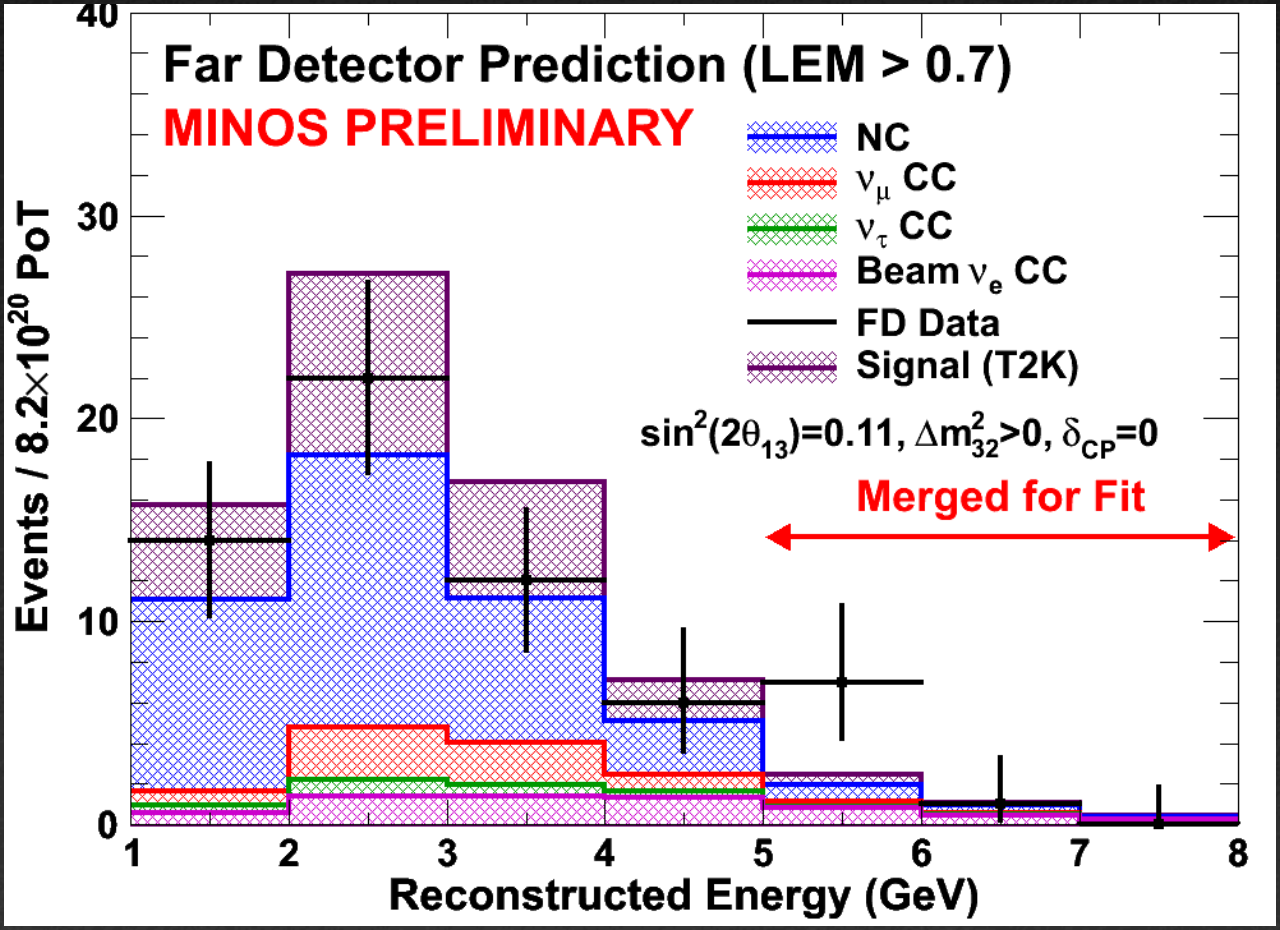
Cite paper

Overlay of MINOS and T2K Results



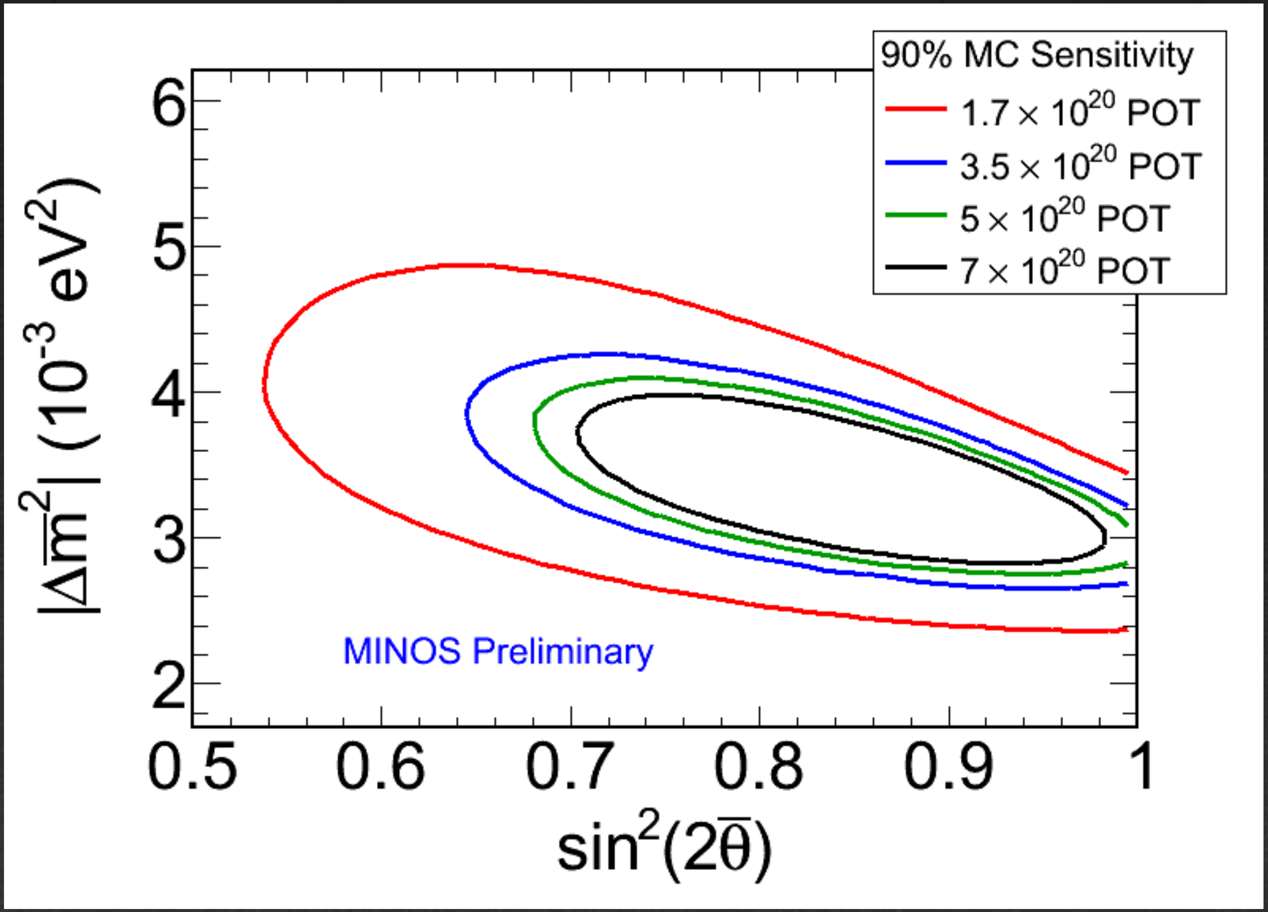


MINOS signal expected at T2K best fit

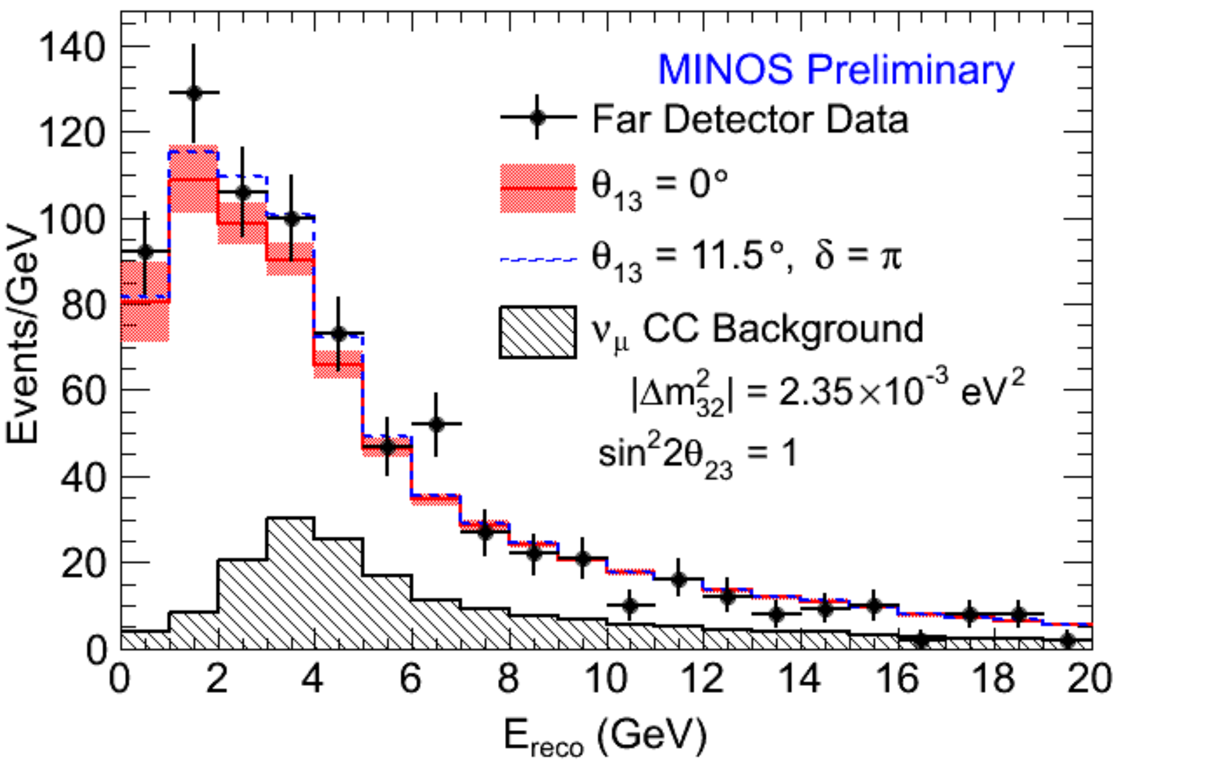


Muon Anti-Neutrino Disappearance

Future sensitivity for anti-neutrino mode:



Neutral Current Events in the Far Detector



Expected 757 events
Observed 802 events

No deficit of NC events

Can set limit on oscillations to sterile neutrinos

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ \ (0.40) \text{ at } 90\% \text{ C.L.}$$