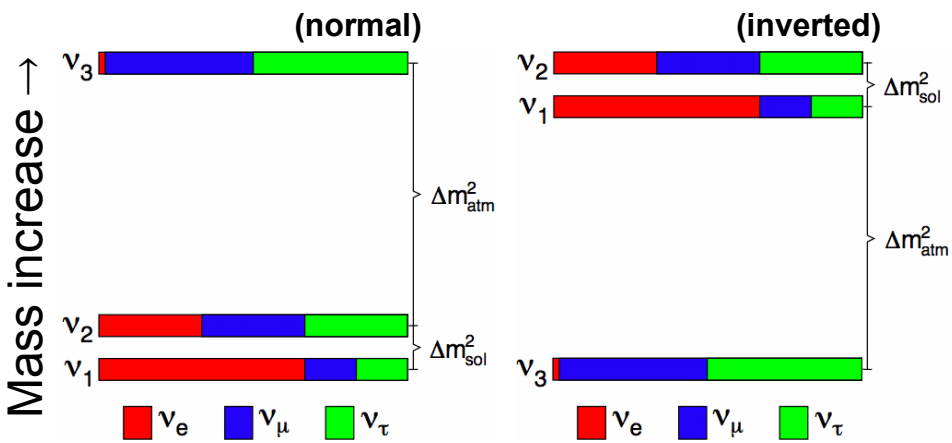
Main Injector Neutrino Oscillation Search (MINOS)

Xiaobo Huang
(for ANL neutrino group)
05/25/2011

HEP Review

Neutrino Mixing and Oscillation



Neutrino oscillation can be explained by the non-coincidence of the mass eigenstates (α) and the flavor eigenstates (i).

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

In 3 neutrino flavor case, the neutrino mixing can be described by 3×3 PMNS matrix,

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha/2} & 0 & 0 \\ 0 & e^{i\beta/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric term
$\theta_{23} \approx 45^\circ \pm 5^\circ$
K2K, MINOS, NOνA

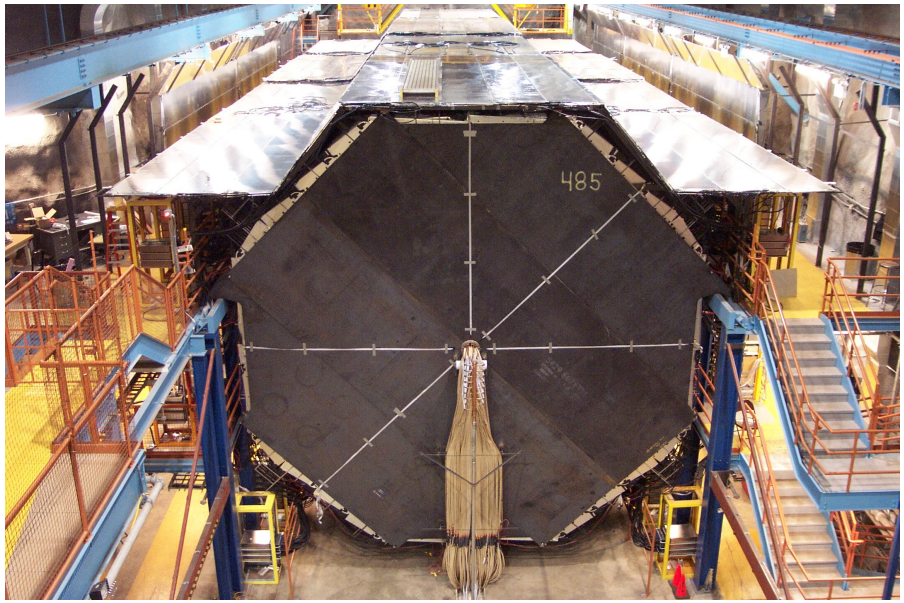
Cross mixing term
$\theta_{13} < 10^\circ$ (90% C.L.),
δ_{CP} unknown
CHOOZ, Double Chooz, Daya Bay
K2K, MINOS, T2K, NOνA

Solar term
$\theta_{12} = 34^\circ \pm 3^\circ$
SNO, KamLand

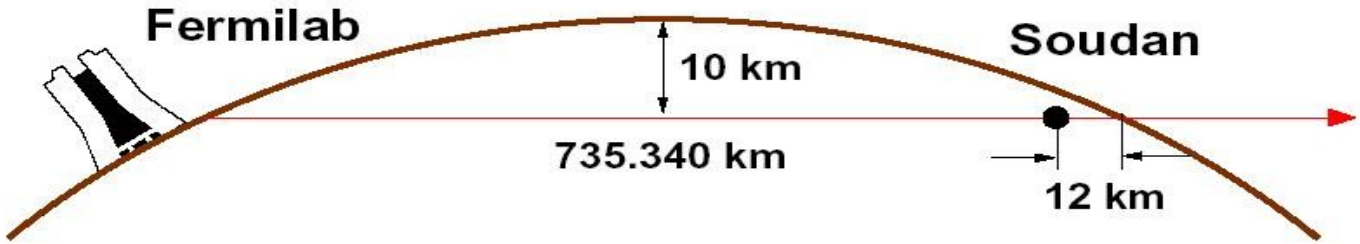
Majorana term
Nuetrinoless double beta decay

MINOS Detectors

Near Detector (ND)
0.98 kT, 1 km downstream
100 m underground at Fermi lab



Far Detector (FD)
5.4 kT, 735 km downstream
714 m underground at Soudan mine



NuMI beam direction ⇒
NuMI is a muon neutrino beam
(contains 7% anti muon neutrino)

Physics Opportunities at MINOS

MINOS provides us with a lot of physics opportunities:

- Measurement of mass splitting $|\Delta m^2_{32}|$ and mixing angle θ_{23}.
- Direct observation of muon anti-neutrino disappearance.
- Attempt to measure θ_{13}.
- Search for sterile neutrinos.
- Cross section measurements.
- Attempt to determine mass hierarchy.

Selection of recent publications (8 in total):

(1) Measurement of the neutrino mass splitting and lepton flavor mixing by MINOS, P. Adamson et al., (accepted at PRL).

(2) Measurement of the underground atmospheric muon charge ratio using the MINOS Near Detector, P. Adamson et al., Phys. Rev. D **83**, 032011 (2011).

(3) Observation in the MINOS far detector of the shadowing of cosmic rays by the sun and moon, P. Adamson et al., Astroparticle Physics, **34** (2011).

(4) New constraints on muon-neutrino to electron-neutrino transitions in MINOS, P. Adamson et al., Phys. Rev. D **82**, 051102 (2010).

(5) Search for Lorentz invariance and CPT violation with the MINOS far detector, P. Adamson et al., Phys. Rev. Lett. **105**, 151601 (2010).

ANL Involvement in MINOS

ANL has deeply involved in the MINOS experiment from the beginning and is still active:

- Scintillator and Electronics.
- Energy Calibration.
- Electron-neutrino appearance analysis.
- Atmospheric neutrino analysis.
- Beam systematics.
- Database maintenance.

MINOS Detectors Calibration

ADC
linearity: LI
Gain: cosmic muon
Drift: cosmic muon

↓

SigLin
Strip-to-strip: cosmic muon

↓

SigCor
Attenuation: cosmic muon

↓

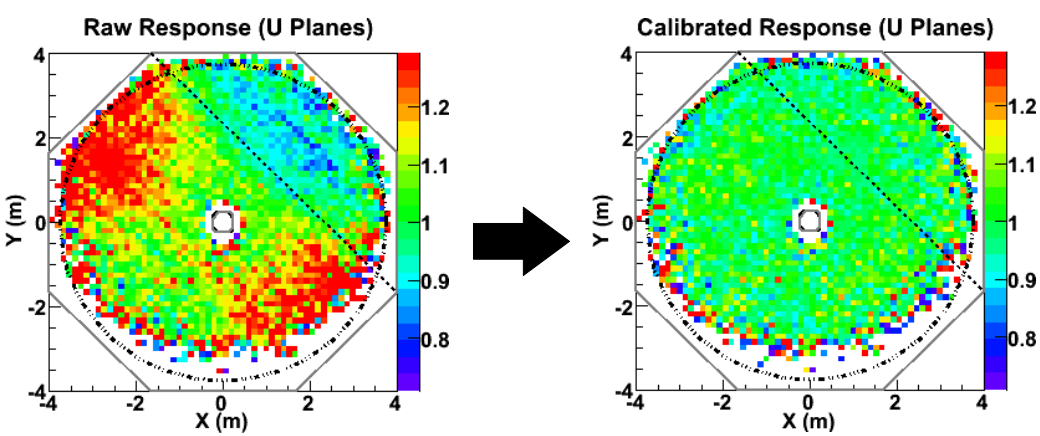
SigMap
Relative calibration: use cosmic stopping muon to get Muon Energy Unit

↓

MEU

MINOS calibration chain

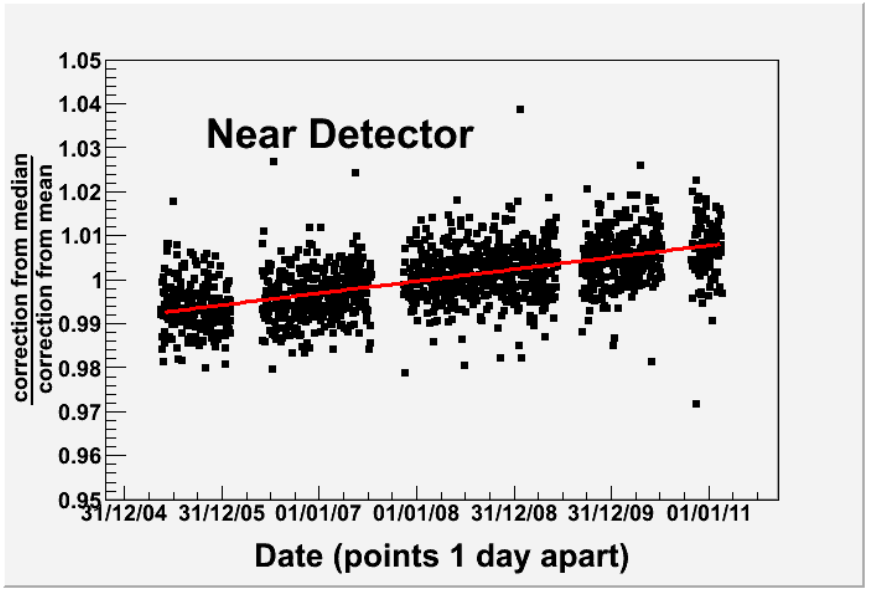
- Calibration group provides calibration used for all physics analysis groups.
- ANL plays an important role in MINOS calibration.
- Sarah Budd is the calibration group convener and doing drift calibration.
- Xiaobo Huang is doing MEU calibration.

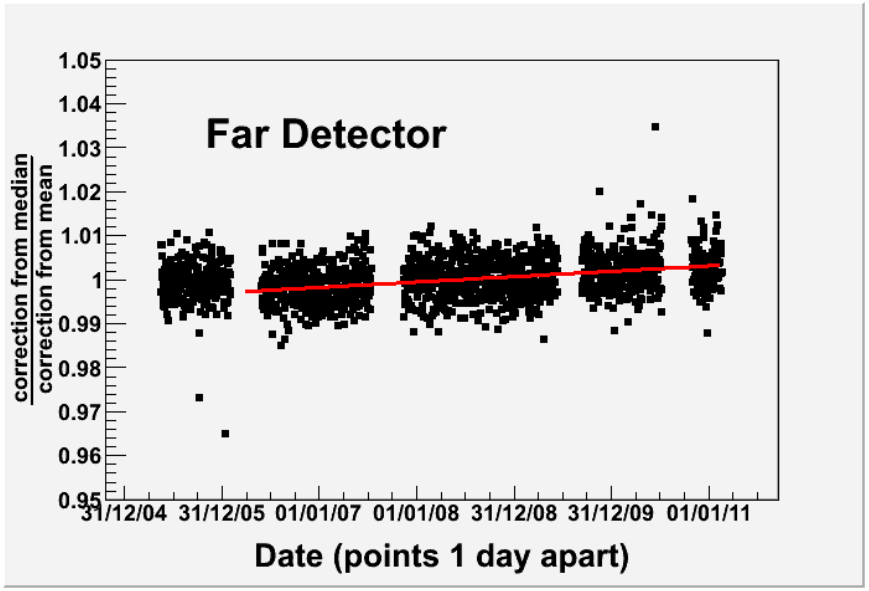


Cosmic muons are used to perform the MINOS calibration. The calibration is good to:

6% (absolute)
2% (relative near/far)

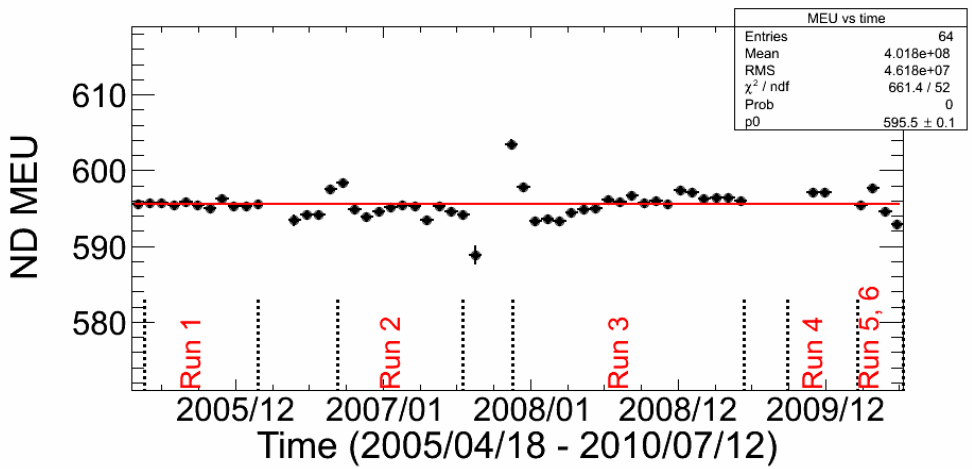
MINOS Detectors Calibration (Drift Calibration)

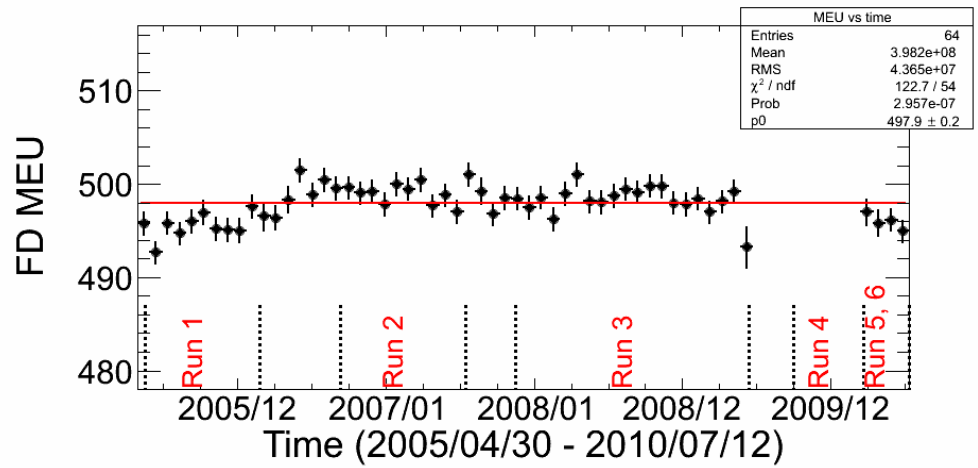




- Cosmic through-going muons are used in the drift calibration.
- Drift systematic error is a max difference in y from 1 of a fitted straight line to the ratio $mean_i$ / $median_i$.
- Near detector drift systematic error is 0.82%, and far detector drift systematic error is 0.33%.

MINOS Detectors Calibration (MEU Calibration)





- MEU calibration is the last step in the MINOS calibration chain.
- Cosmic stopping muons are used in the MEU (Muon Energy Unit) calibration.
- MEU calibration provides relative calibration between MINOS detectors.
- Near detector MEU systematic error is 1.68%, and far detector MEU systematic error is 0.78%.

Electron-neutrino Appearance

Measure θ_{13} via the observation of muon-neutrino to electron-neutrino transition.

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2(1.27\Delta m^2_{31}\frac{L}{E})$$

However, MINOS is not optimized for θ_{13} measurement because of poor EM shower recognition.

Signal Event

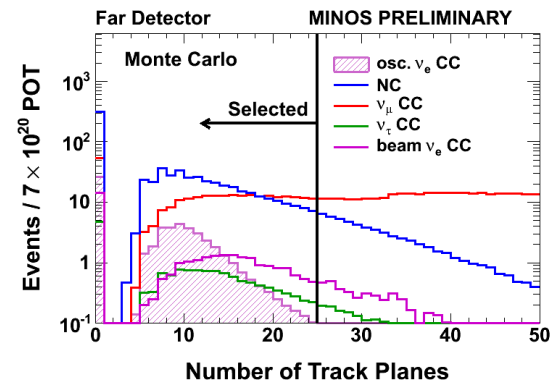
ν_eCC events characterized by compact shower.

Backgrounds

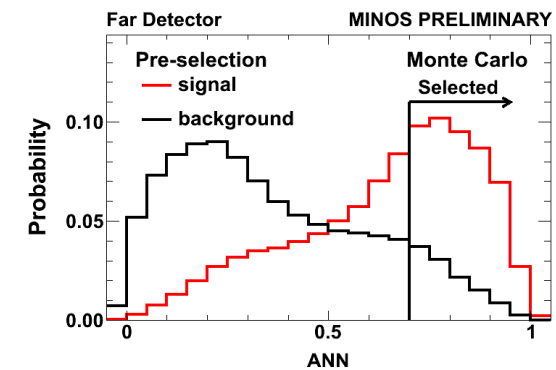
- Neutral current neutrino interaction events
- High p_T ν_μCC events which do not have long track
- Beam ν_eCC events

Analysis strategy

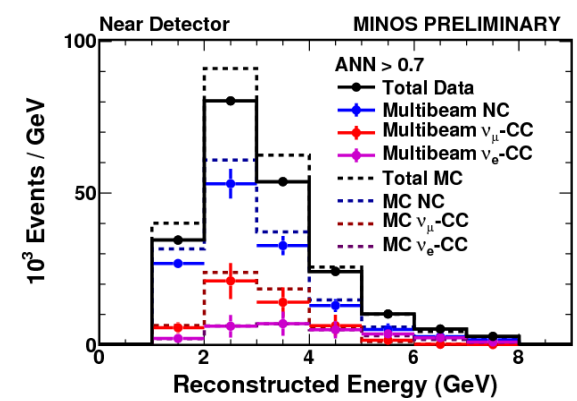
- Preselection cuts most of the ν_μCC events.
- Algorithm to determine EM shower
- Decompose near detector background and extrapolate separately
- Compare to far detector data



preselection



PID

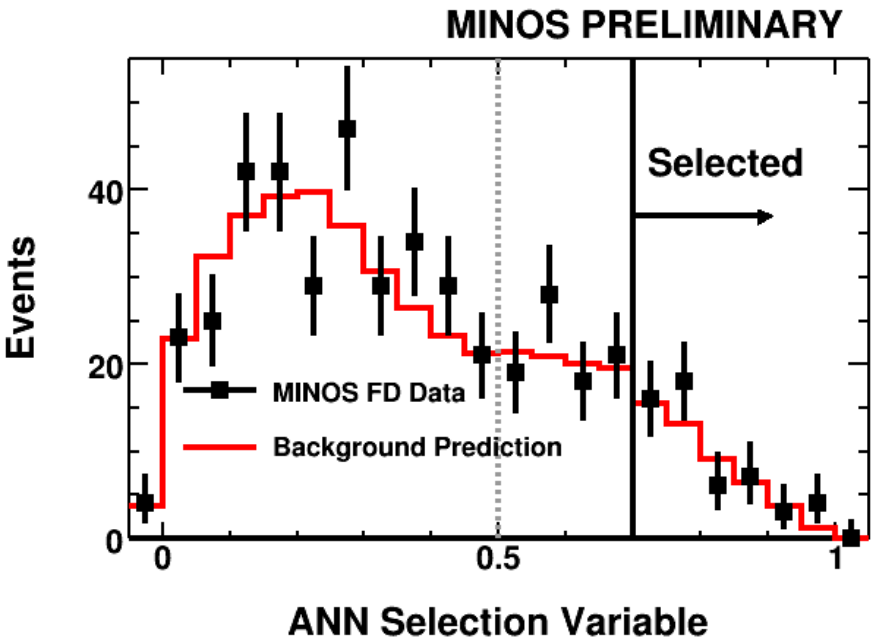


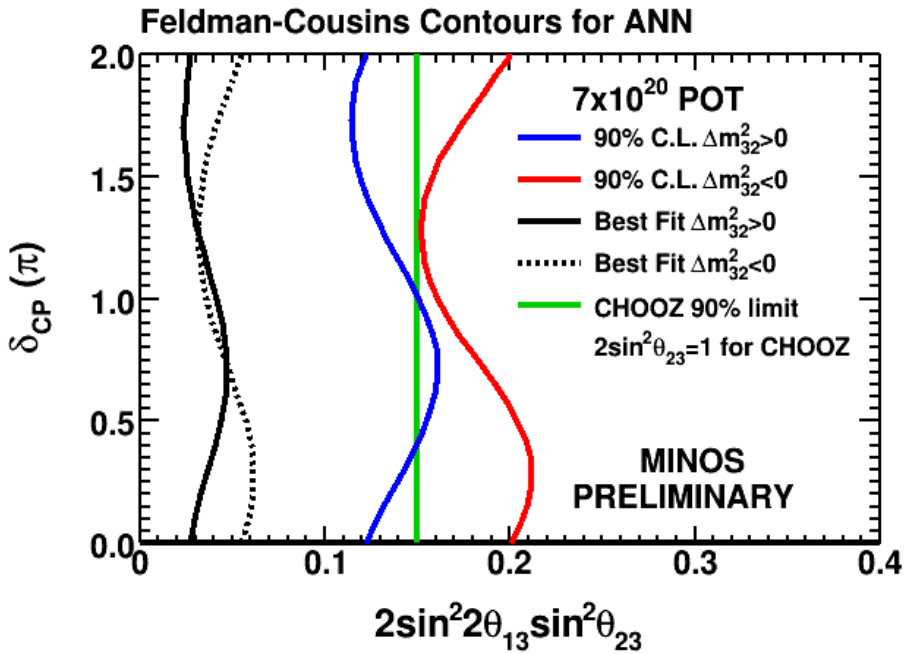
decompose

Electron-neutrino Appearance (ANL Involvement)

- ElectroMagnetic shower energy calibration.
- Near detector background decomposition.
- Beam and flux systematic error.
- Beam Intensity systematic error.
- Calibration related systematic error (absolute energy, relative energy, gain, linearity and strip-to-strip).
- Signal selection efficiency.
- Sideband check of the analysis strategy.

Electron-neutrino Appearance





Expected Background:
49.1 ± 7.0(stat.) ± 2.7(syst.).

Observe 54 events. (0.7σ excess)

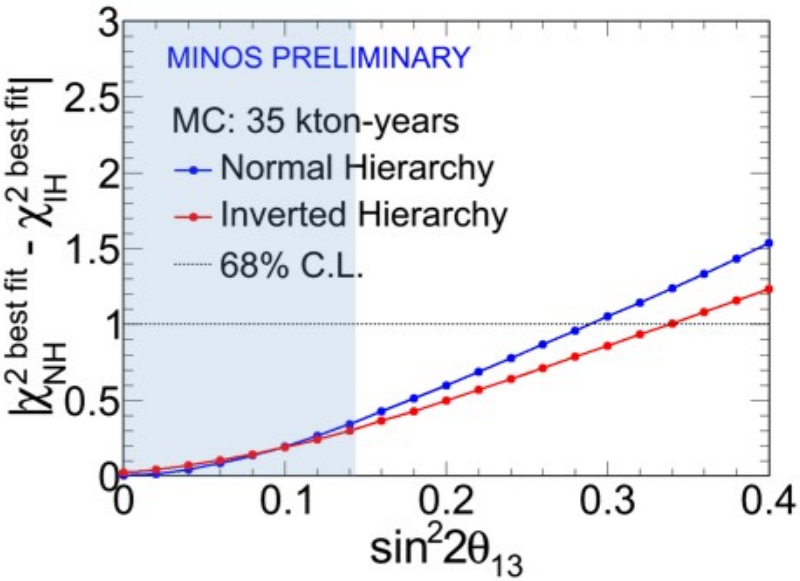
At $\delta = 0$ and $2\sin^2(\theta_{23}) = 1$

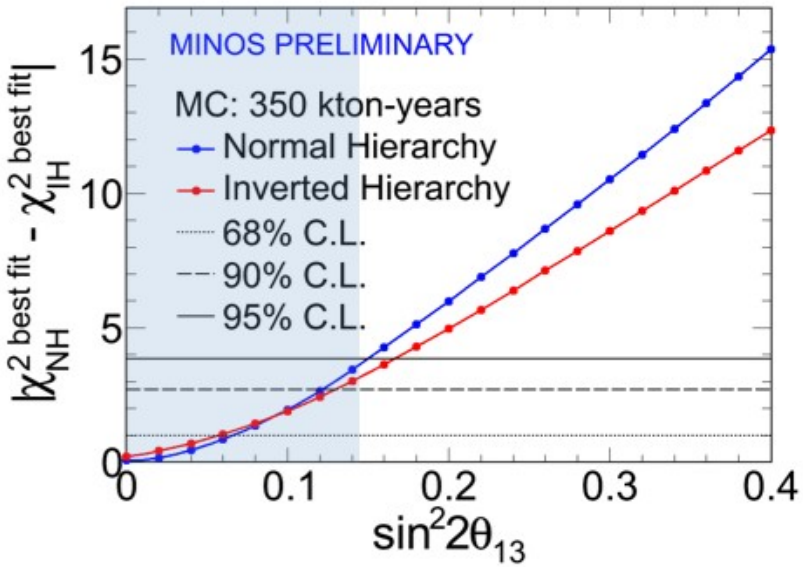
$\sin^2(2\theta_{13}) < 0.12$ (normal hierarchy)

$\sin^2(2\theta_{13}) < 0.20$ (inverted hierarchy)

Atmospheric Neutrinos Analysis

Presence of magnetic field allows discrimination of μ^+ and μ^-.
The muon charge ratio as a function of zenith angle and energy depends on mass hierarchy.
Atmospheric neutrinos contained in the MINOS far detector are used.





MINOS has observed atmospheric neutrinos and is including more data to obtain better sensitivity to the mass hierarchy.

Summary

- The MINOS experiment provides us with great physics opportunities.
- MINOS has made important measurements and set several best limits to neutrino oscillation oscillation parameters.
- MINOS has made interesting attempts to measure mass hierarchy.
- ANL has deeply involved in the MINOS experiment from the beginning.
- ANL is still playing an important role in the MINOS experiment.
- The MINOS experiment is going to end commissioning soon.

Backup Slides

Disappearance Analysis

Measure Δm^2_{32} and $\sin^2 2\theta_{23}$ via the survival probability of neutrinos.

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\,\Delta m^2_{32}\frac{L}{E})$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \approx 1 - \sin^2(2\bar{\theta}_{23})\sin^2(1.27\,\Delta \bar{m}^2_{32}\frac{L}{E})$$

Signal and background

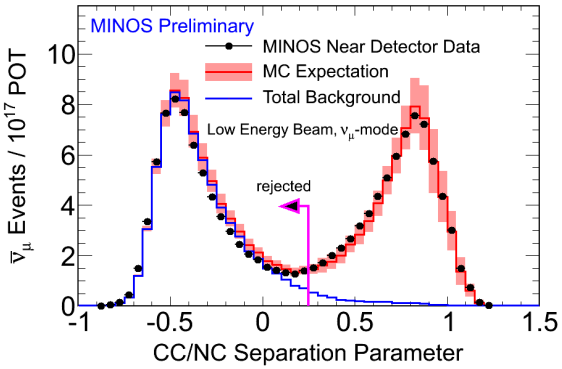
- Signal event has long track. Muon track and anti-muon tracks are distinguished by magnetic field.
- Backgrounds are misidentification of muon charge sign and neutral events with fake muon track.

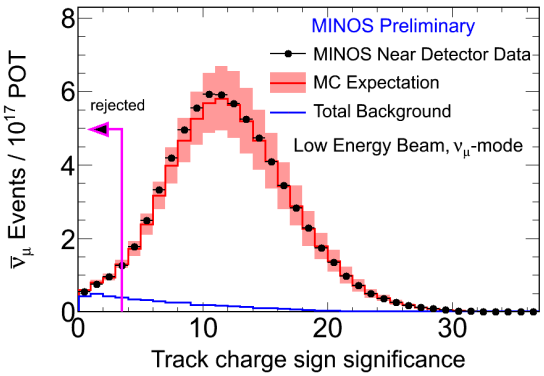
Event selection applied

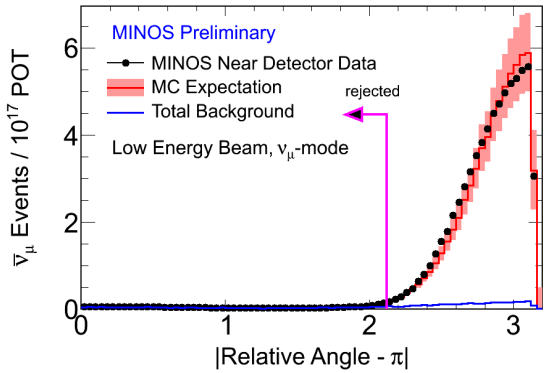
- CC/NC PID (using event topology)

  additional selection for anti-neutrino:
- Track charge sign significance
- Relative angle

ND measurement is extrapolated to the far detector with help from MC.

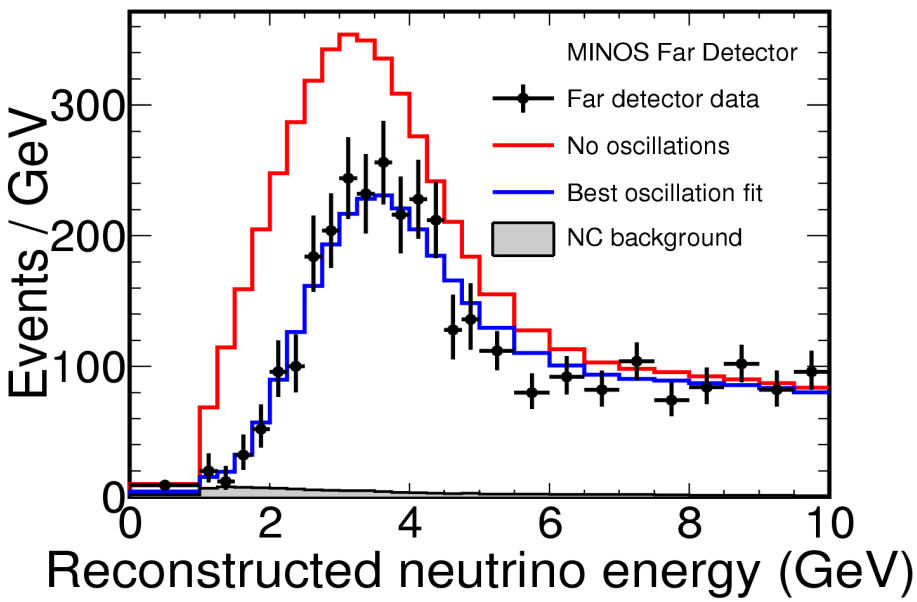


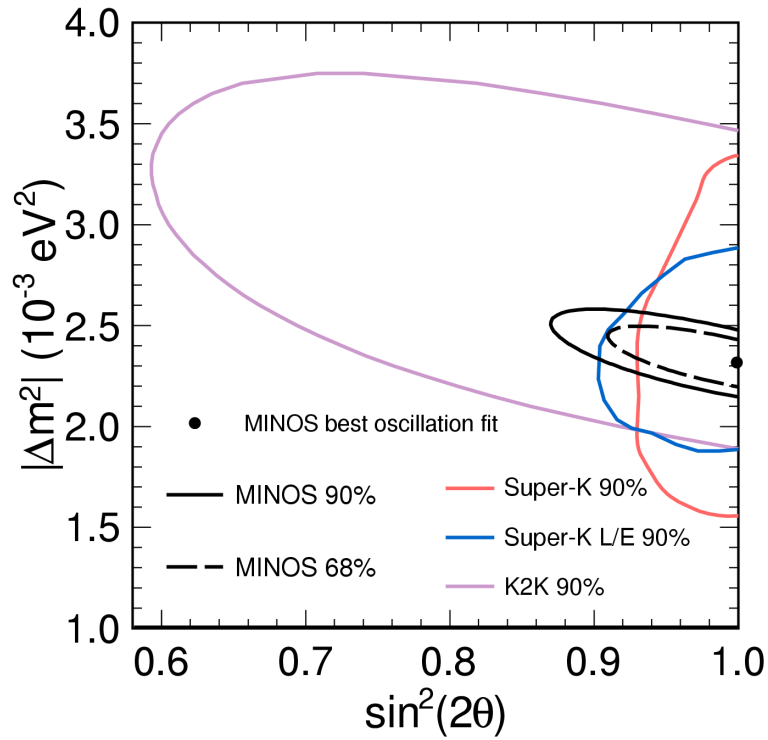




Muon-neutrino Disappearance

Results from 7.25e20 POT data
2451 events expected without oscillation
1986 events observed



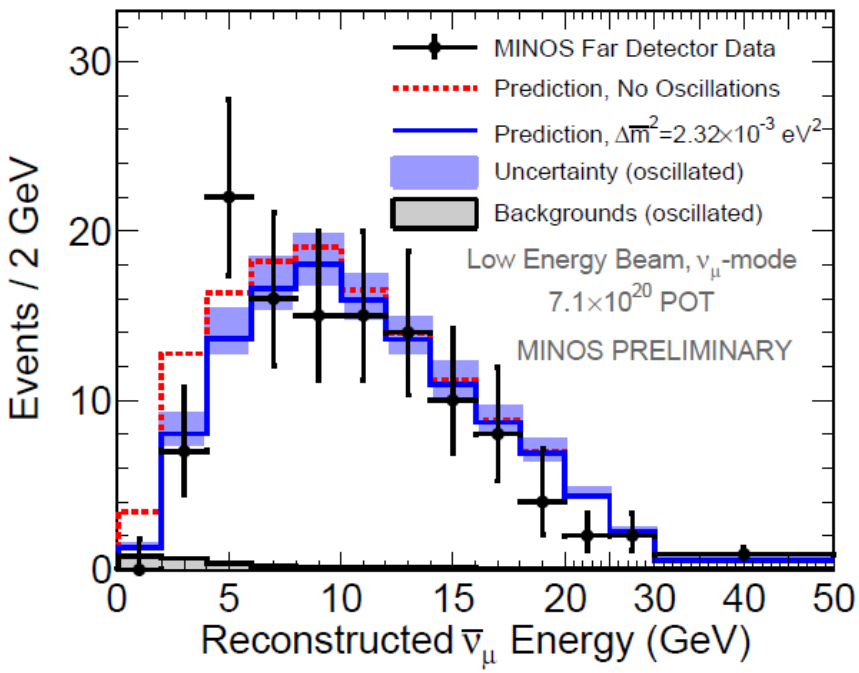


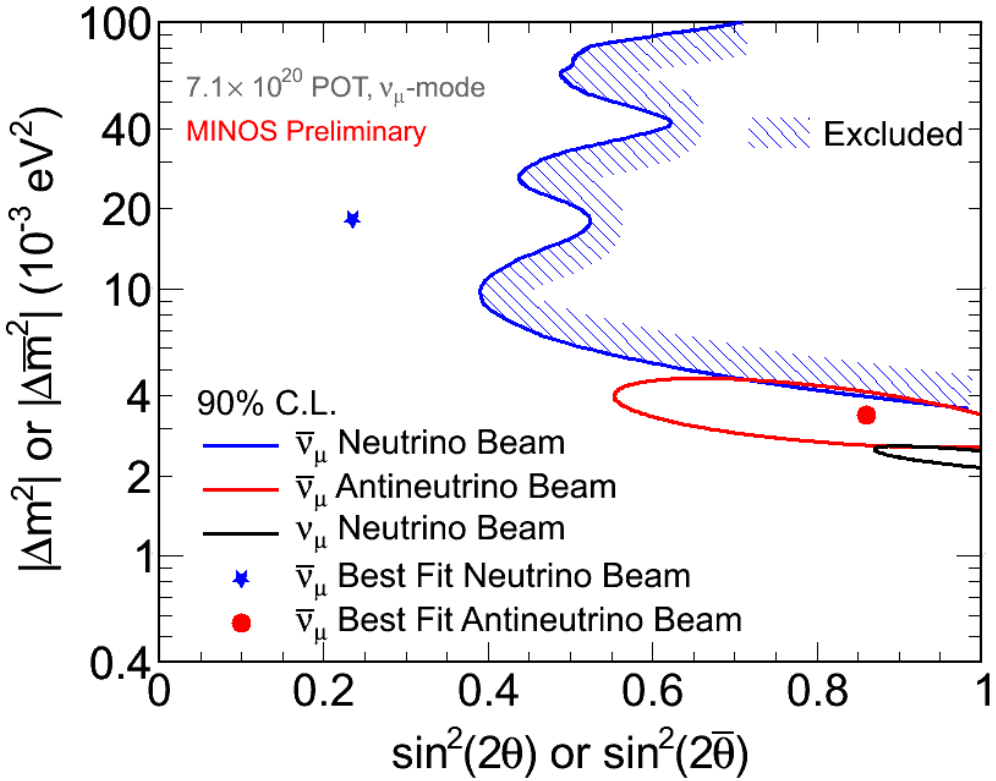
$$|\Delta m^2_{32}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2 2\theta_{23} > 0.90\,(90\,\%\ \mathrm{C.L.})$$

Consistent with maximal mixing.
MINOS makes the best measurement to Δm^2_{32}.

Muon antineutrino Disappearance

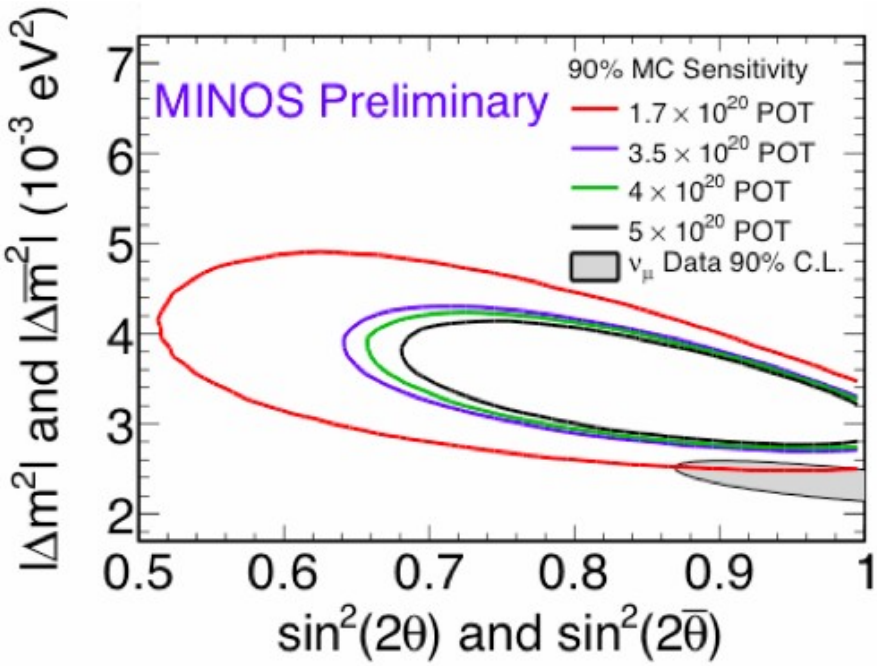
Results from 7.1e20 POT data
150 events expected without oscillation
130 events observed

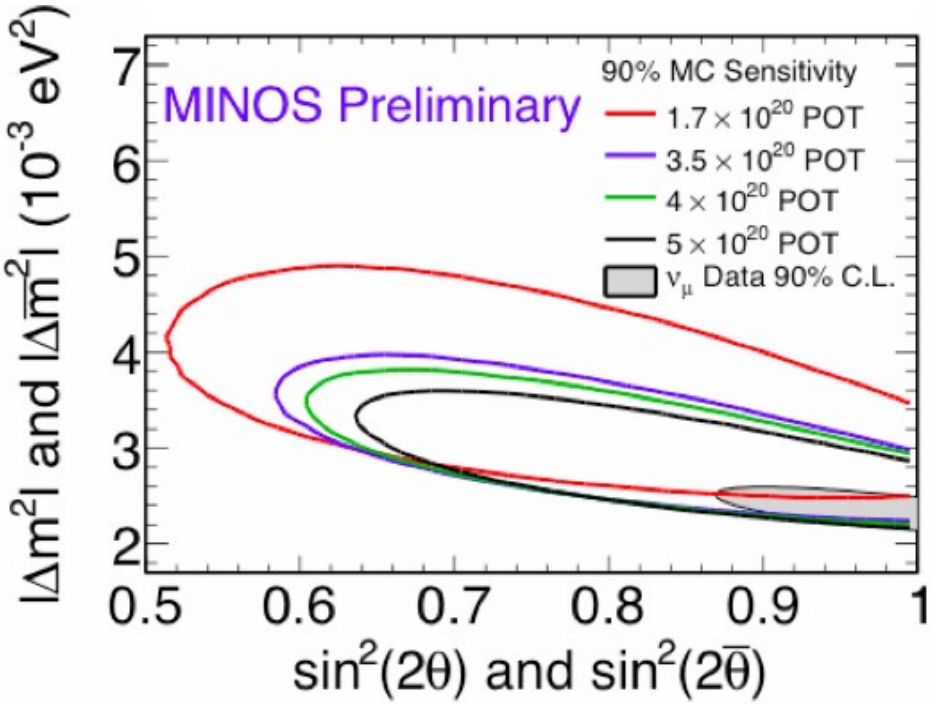




$(3.42 < |\Delta\overline{m}^2| < 1000) \times 10^{-3}$ eV^2 excluded at 90% C.L. at maximal mixing

Future Sensitivity of the MINOS Antineutrino Analysis



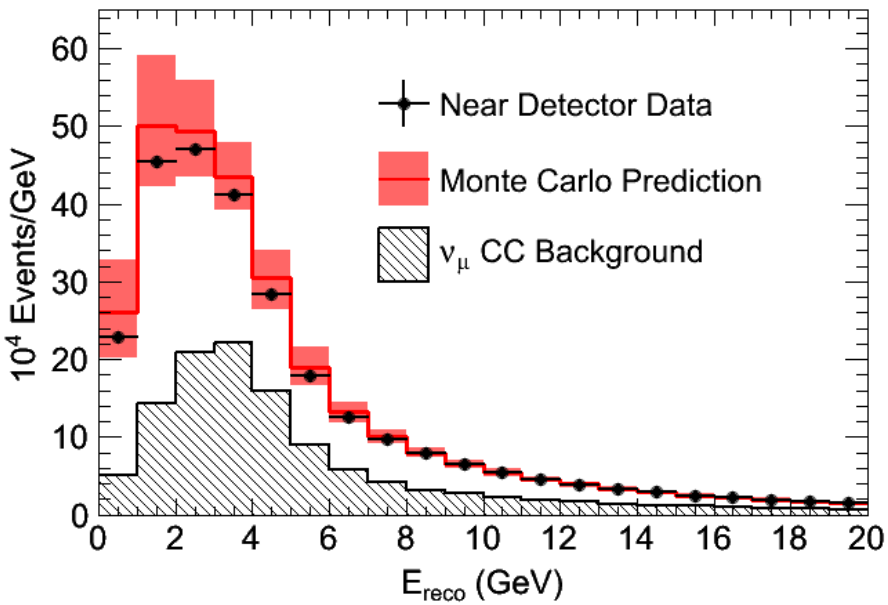


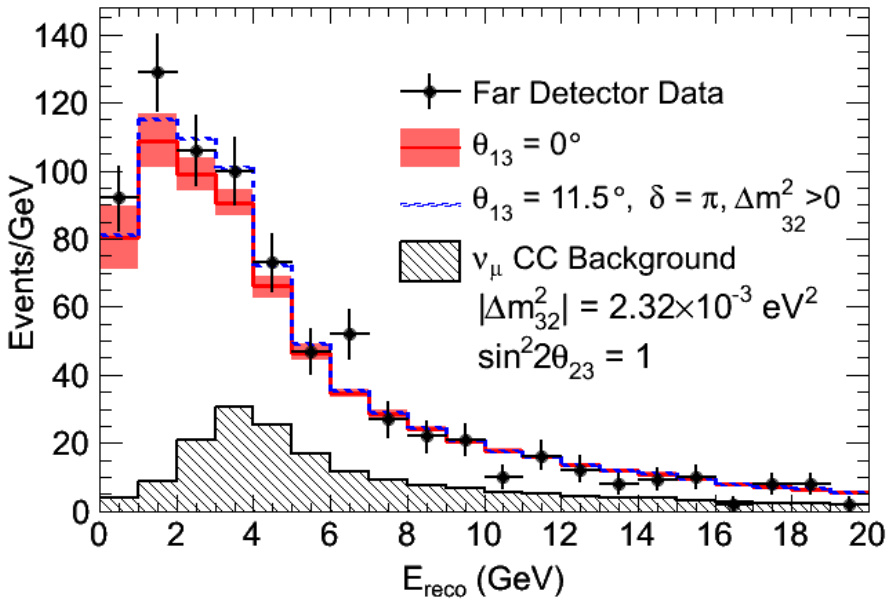
1.7e20 existing anti-ν data + Additional data with same anti-ν parameters

1.7e20 existing anti-ν data + additional data with CC-ν_μ parameters

Sterile Neutrino Analysis

- NC interactions measure the combined neutrino rate and are sensitive to mixing with hypothetical sterile neutrino
- sterile neutrinos, or some other non-SM process needed to explain MiniBooNE/LSND





Based on 7.1 x 10^{20} POT data, we expect 754±28(stat.)±37(sys.) NC events in the far detector and observe 802 events. We obtained the most stringent limit to the fraction of active neutrino transition to sterile neutrinos, for $\theta_{13} = 0^\circ$ (11.5°), is

f_s<0.22(0.40) (at 90% C.L.).