The MINOS experiment 2012 Results

Giles Barr for
The MINOS collaboration

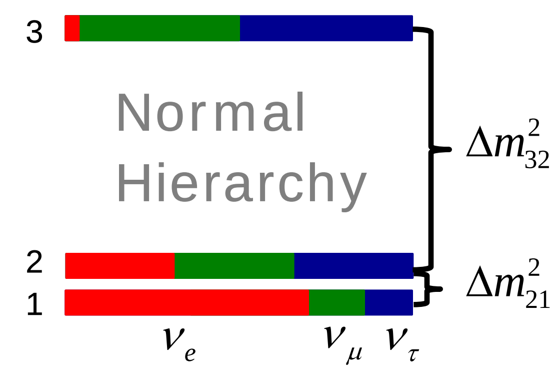
ICHEP 2012 Melbourne

MINOS physics goals

- MINOS optimised for studying atmospheric-scale oscillation effects:
  - intense man-made beam of muon neutrinos
  - identical near and far detectors for optimal cancellation of instrumentation and target nucleus effects

$$\mathbf{U} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{\Delta m^2_{32}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\Delta m^2_{21}}$$

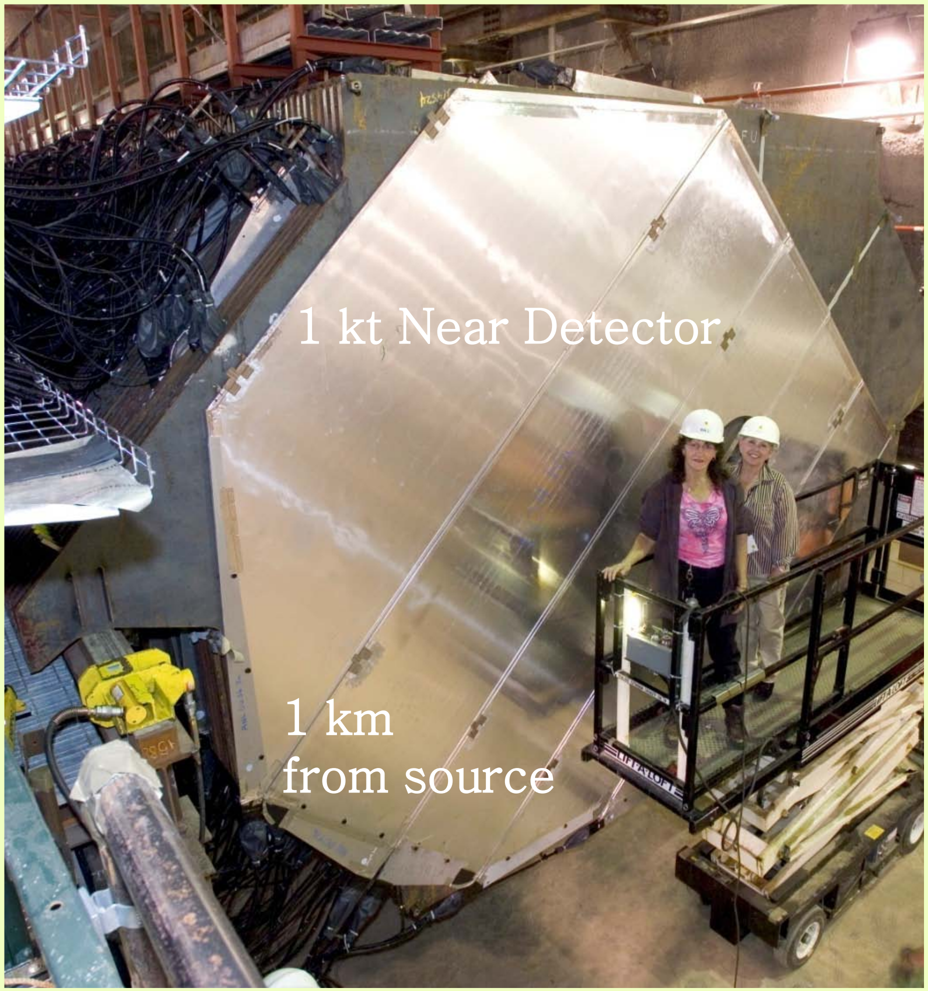
- Muon neutrino disappearance: Δm^2_{32} θ_{23}
- Electron neutrino appearance: θ_{13}
- Sterile neutrino search

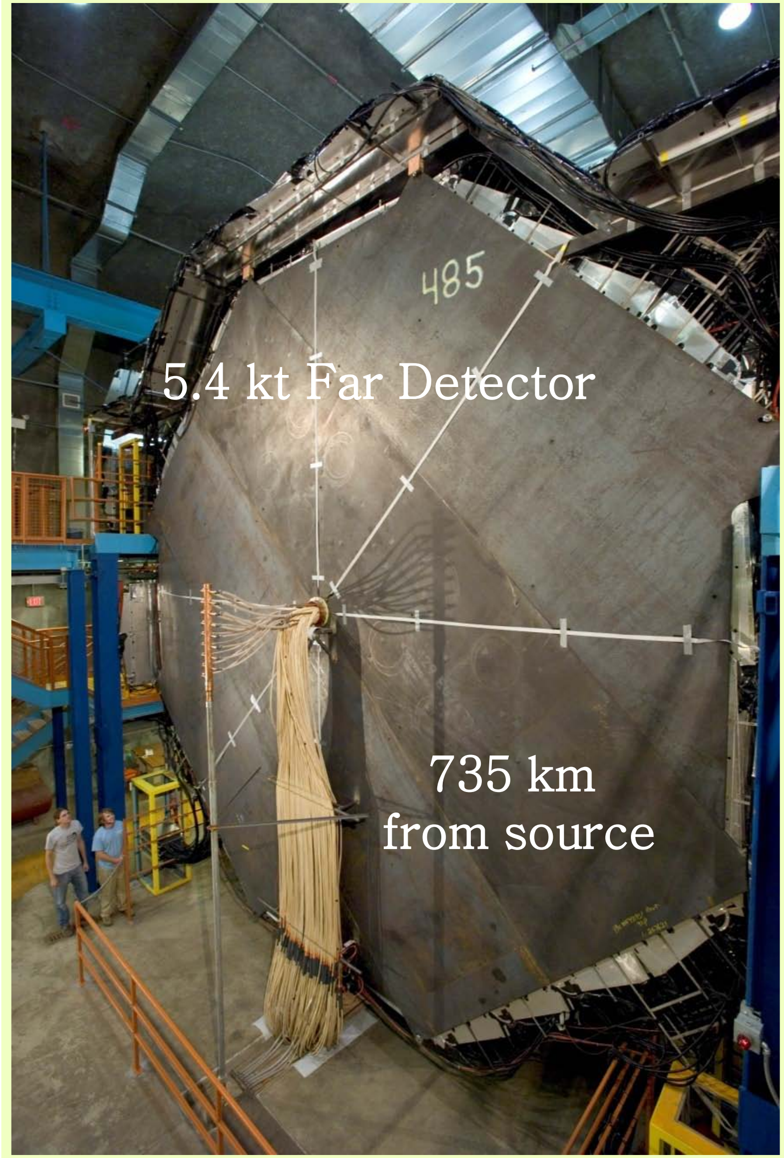


The Detectors

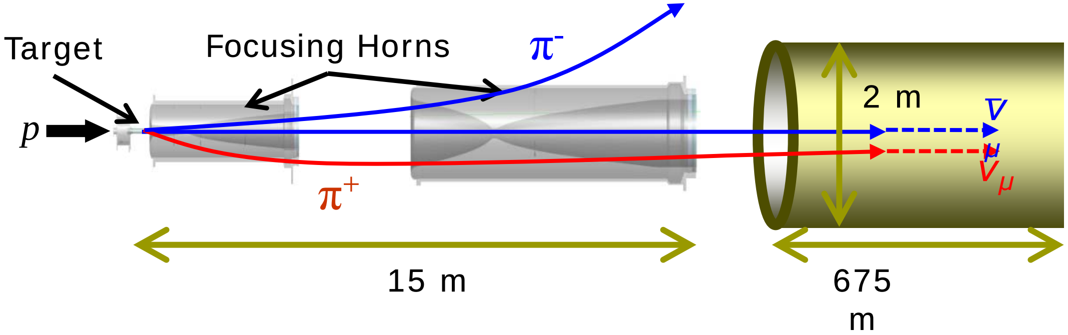
FD running since 2003

ND running since 2005

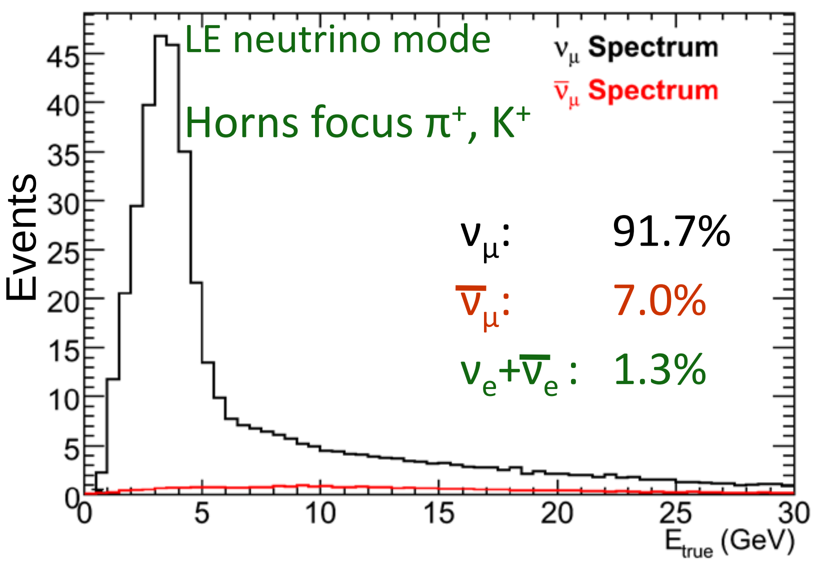


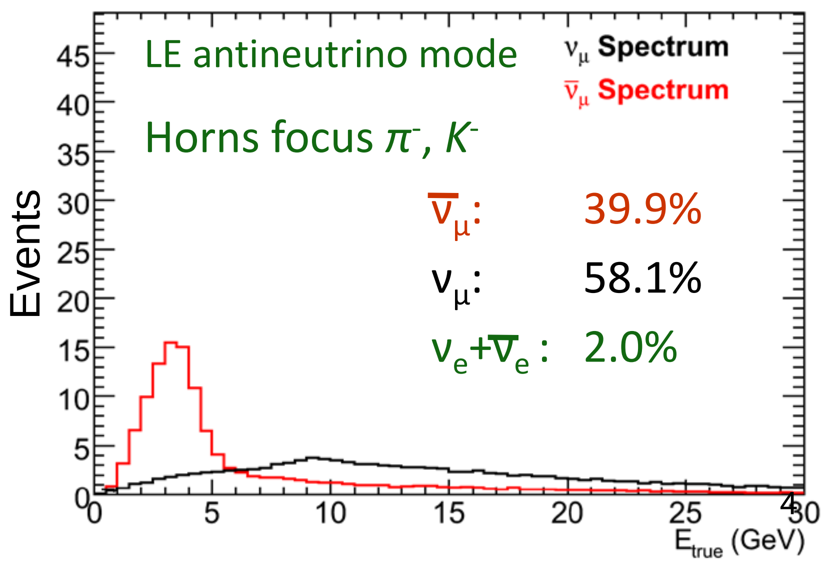


NUMI beam

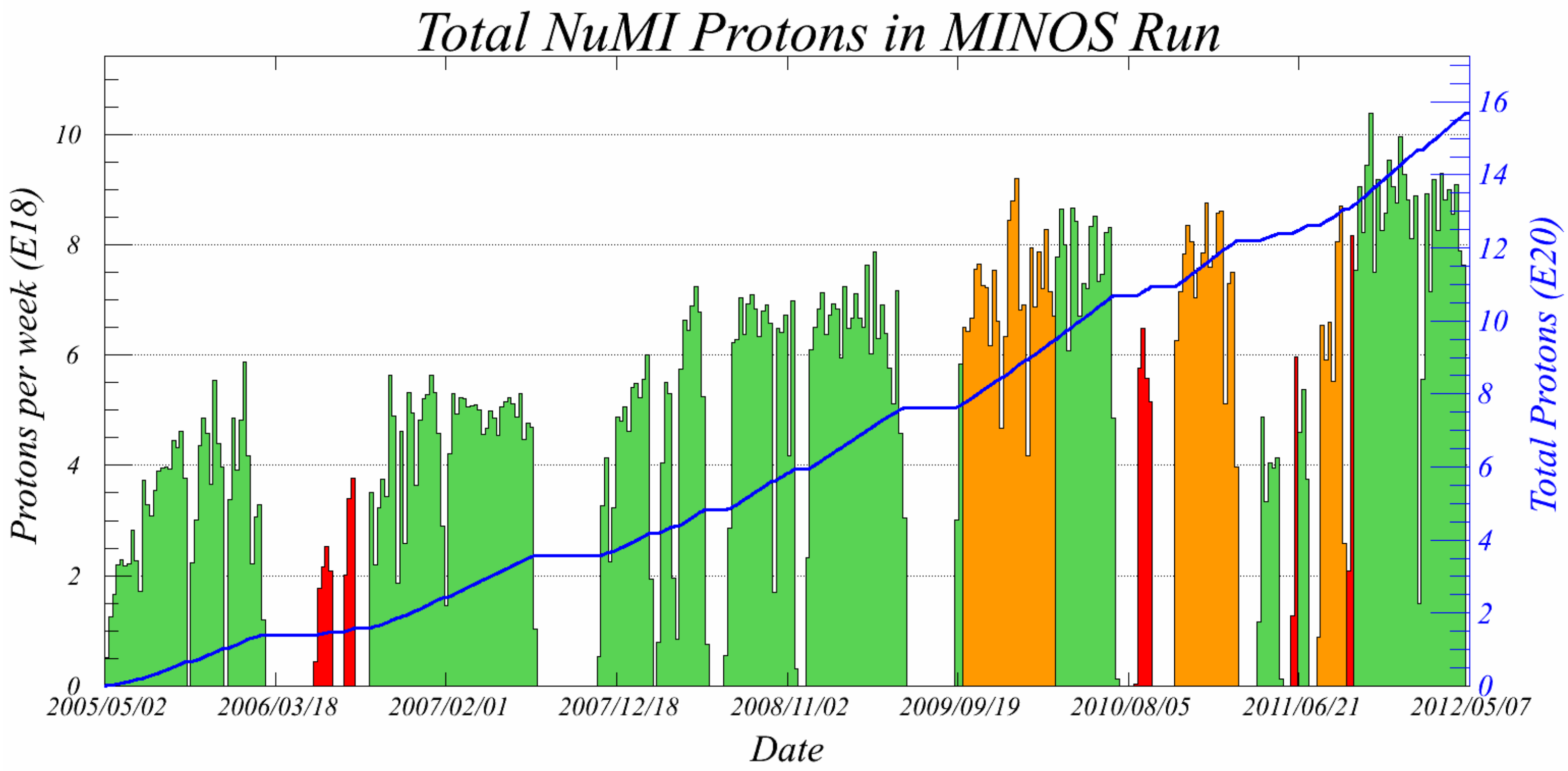


- 120 GeV protons: 10 μs long pulse every 2.2 s
- 2 horns focus secondary π and K
  - Focus either positives (neutrino mode) or negatives (antineutrino mode)
  - Moveable target & horn provides variable beam spectrum
  - Mostly low energy (LE) beam running configuration





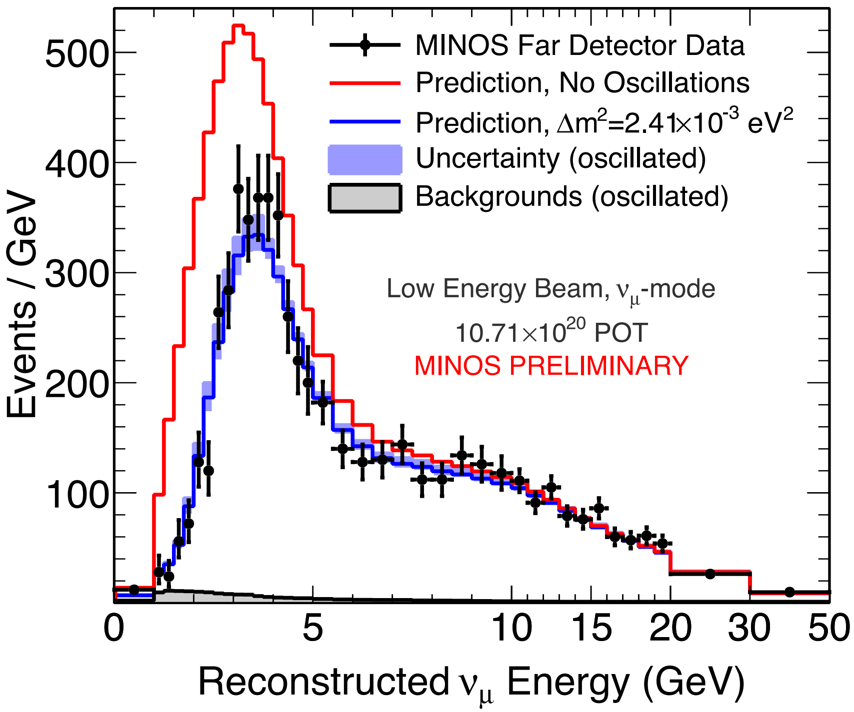
Data collection

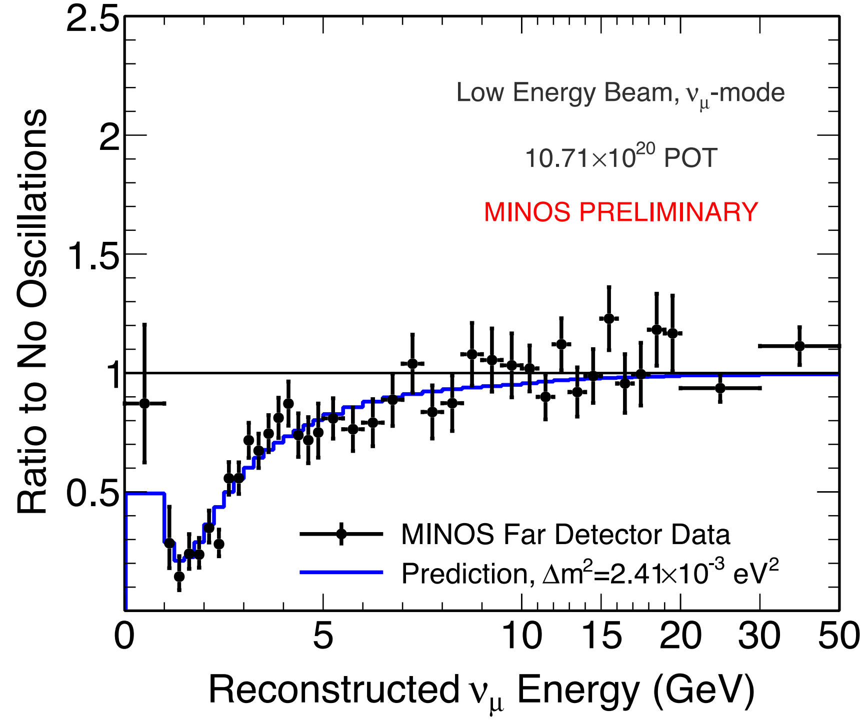


- NuMI beam ended April 30, 2012
- Accumulated more than 15 x 10^{20} POT
  - 10.71 x 10^{20} POT in (LE) neutrino running
  - 3.36 x 10^{20} POT in antineutrino running
  - Other configurations for beam model and background tuning

Neutrino and anti-neutrino disappearance studies

MINOS neutrino results (beam)





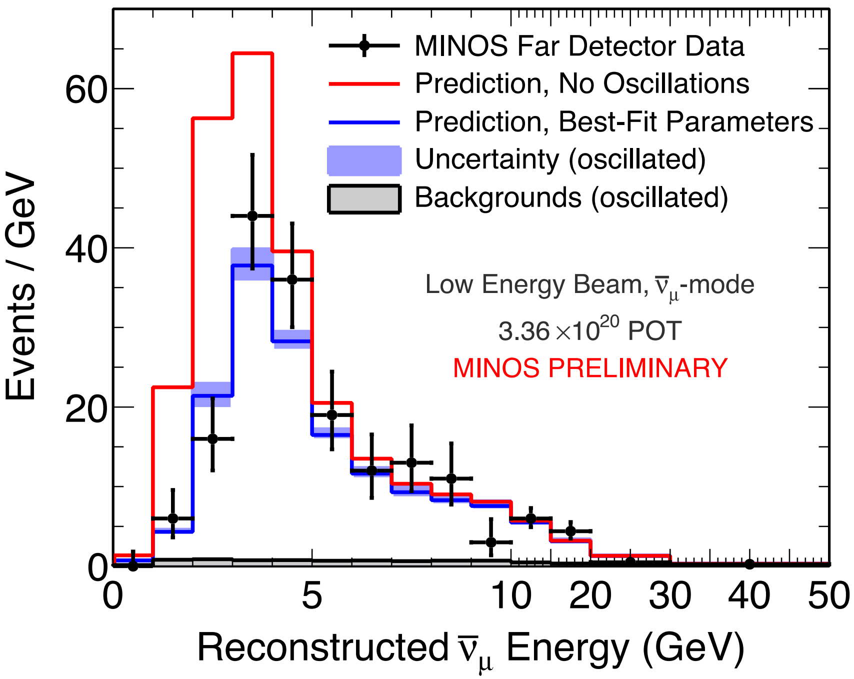
Observed: 2894

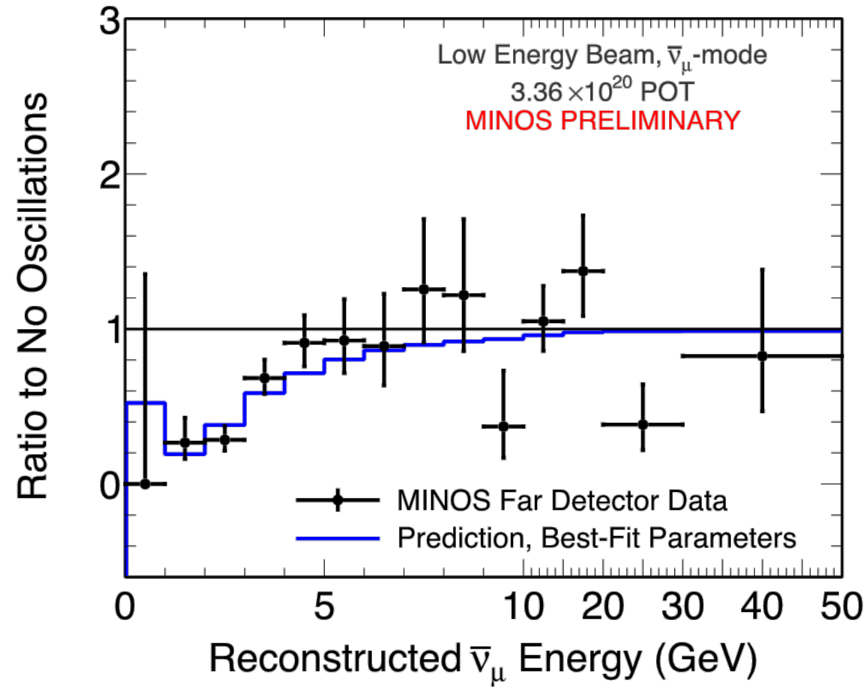
Predicted (no oscillations): 3564

$$\left|\Delta m^2\right| = 2.41^{+0.11}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.94^{+0.04}_{-0.05}$$

MINOS antineutrino results (beam)





Observed: 226

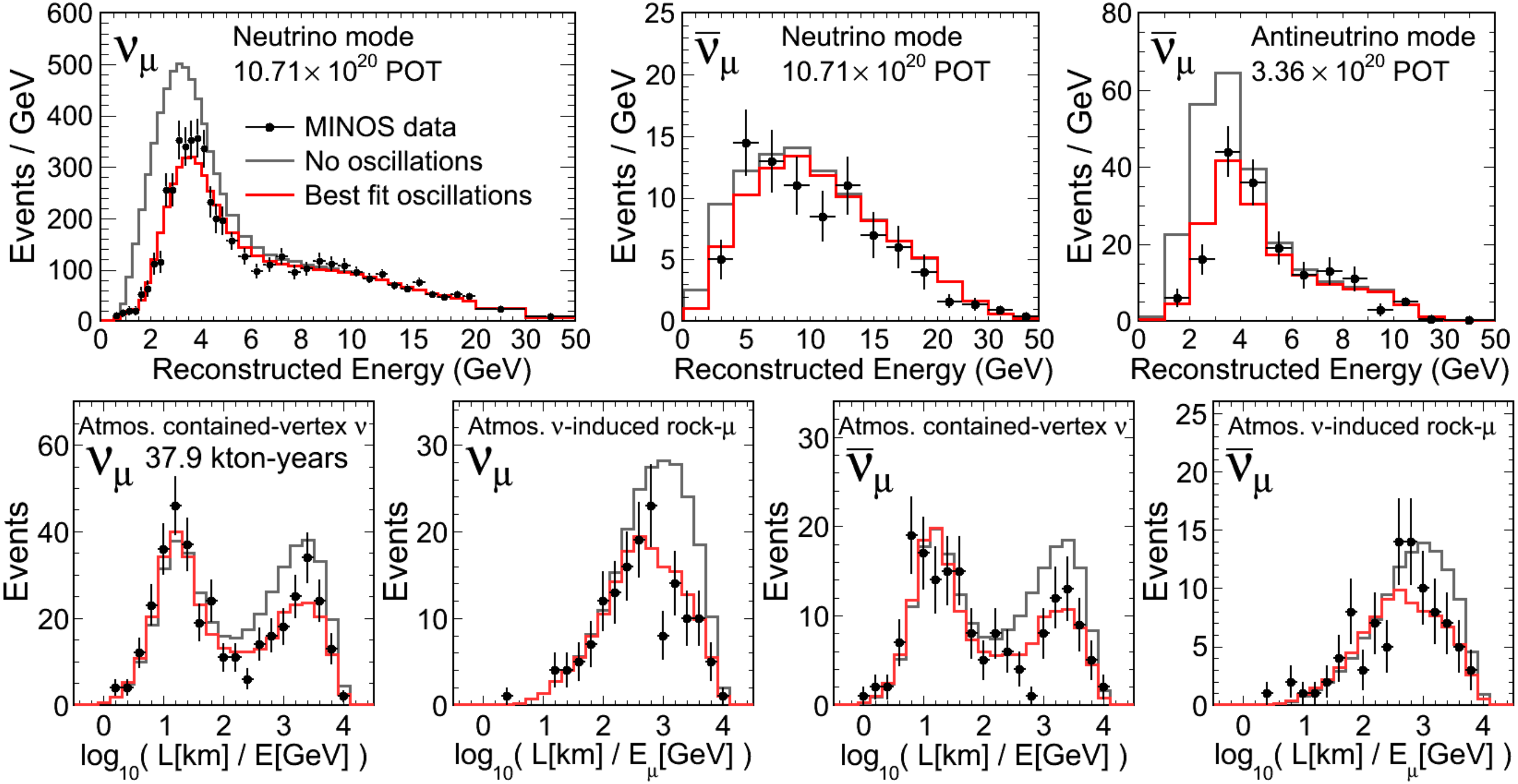
Predicted (no oscillations): 312

$$\left|\Delta \bar{m}^2\right| = 2.64^{+0.28}_{-0.27} \times 10^{-3}\,\text{eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.78 \text{ (90\% C.L.)}$$

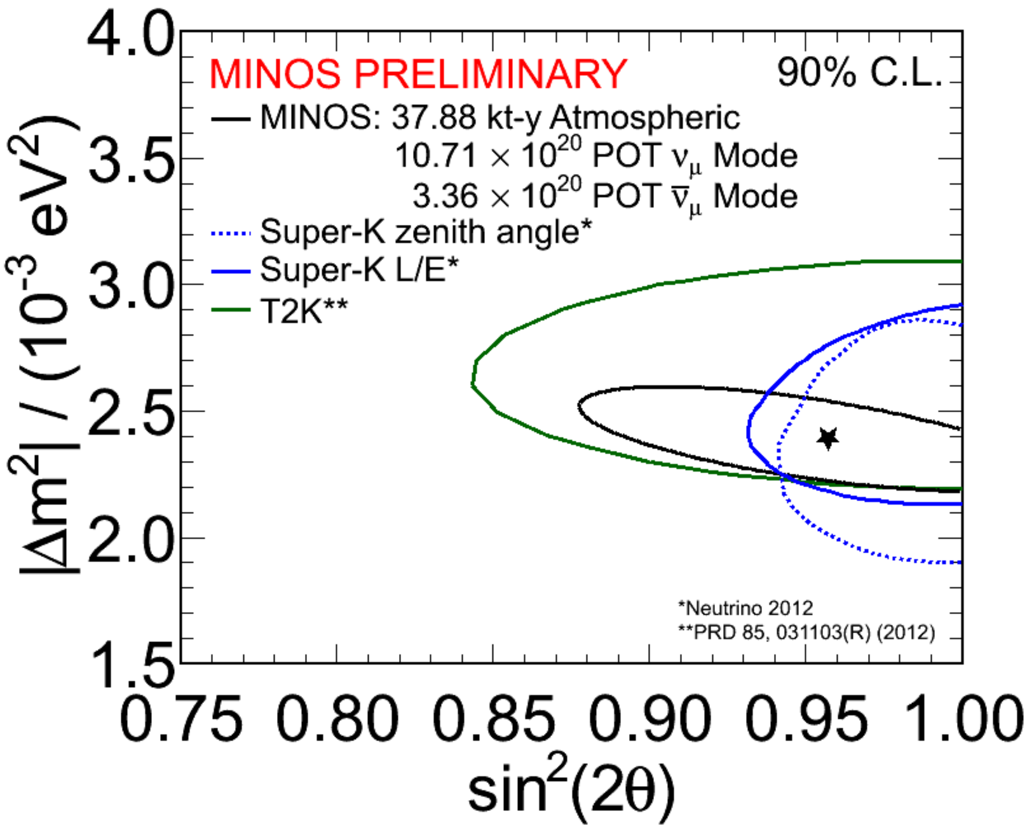
MINOS beam and atmospheric neutrinos and antineutrinos combined

MINOS PRELIMINARY



MINOS all-data compared with world

2-flavour oscillation parameters Δm^2 and $\sin^2 2\vartheta$ are determined by applying a maximum likelihood fit to the MINOS beam and atmospheric neutrino data



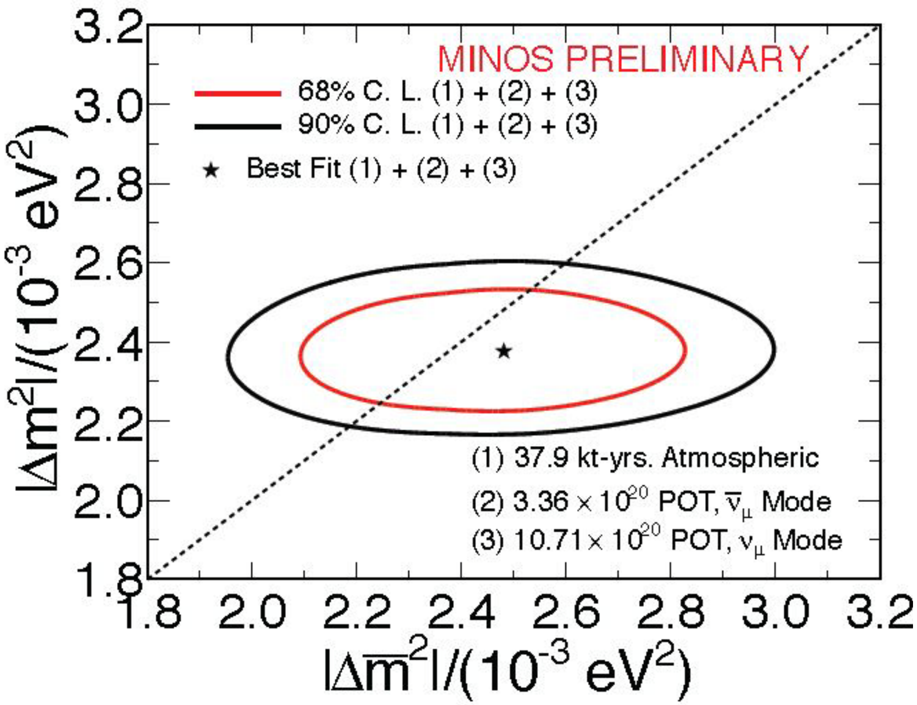
$$\left|\Delta m^2\right| = 2.39^{+0.09}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

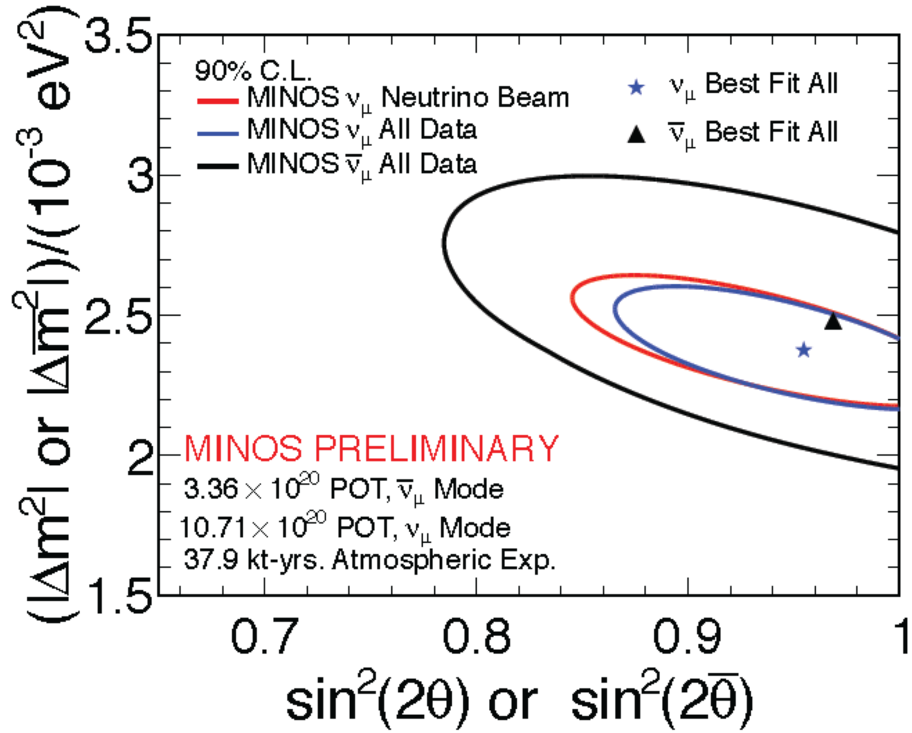
$$\sin^2(2\theta) = 0.957^{+0.035}_{-0.036}$$

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

Neutrinos and antineutrinos compared

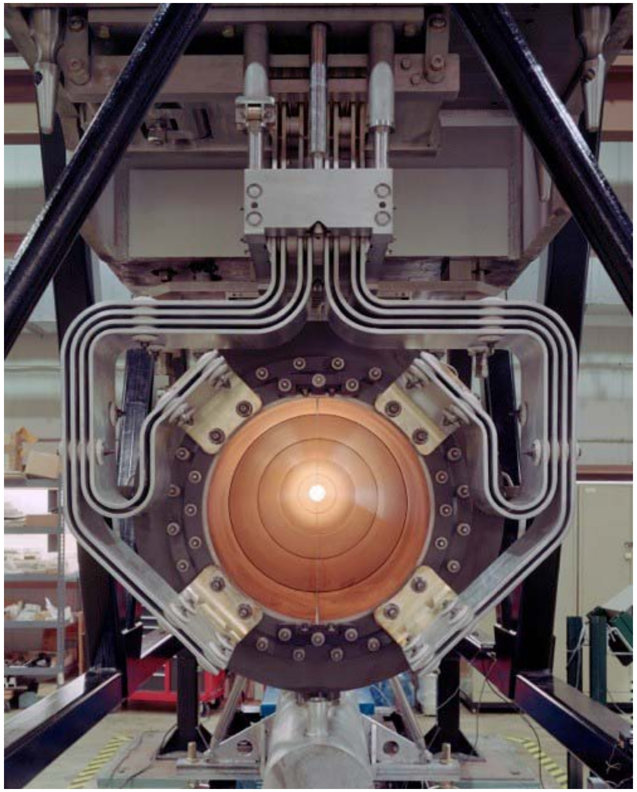
Extended fit allows different oscillation parameters for neutrinos and antineutrinos, and confidence limits are placed on the antineutrino oscillation parameters



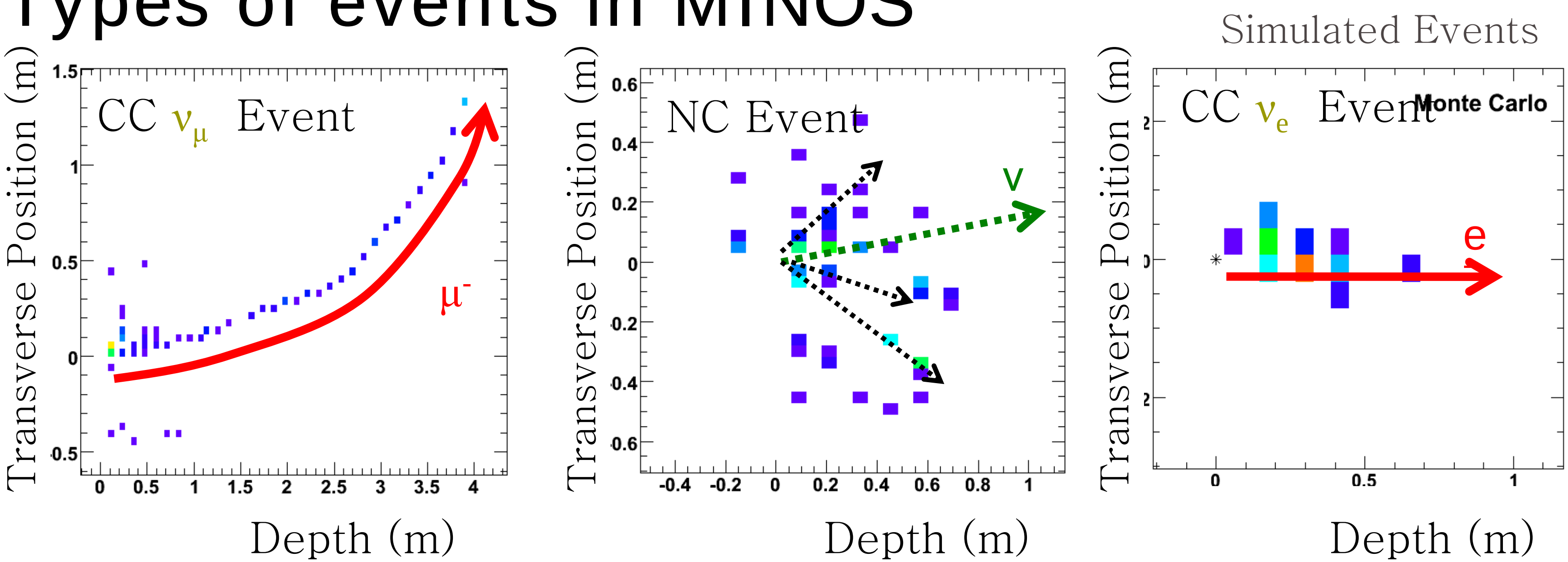


The new data resolves the previous tension between neutrino & antineutrino parameters

Electron neutrino appearance



Types of events in MINOS



- Coarse detector granularity makes ν_e CC id challenging
  - Pattern recognition by finding closest matches with a library of MC events (comparing hit patterns in the two 2D views)
  - Discriminating variables from truth information from best-match library events. Combine into one (LEM) variable.
- Apply selection to ND for background determination
- Vary beam configuration to determine composition (because components extrapolate to FD differently)

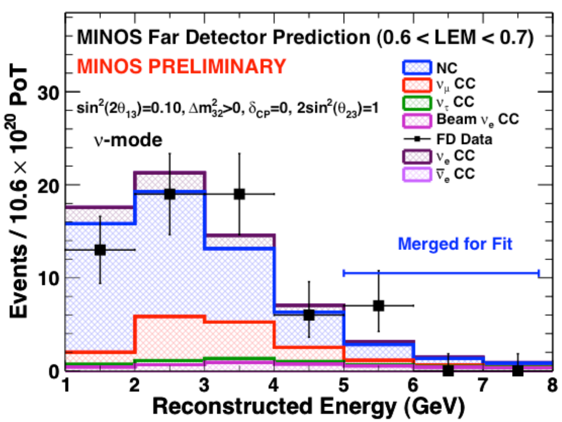
Electron neutrino appearance

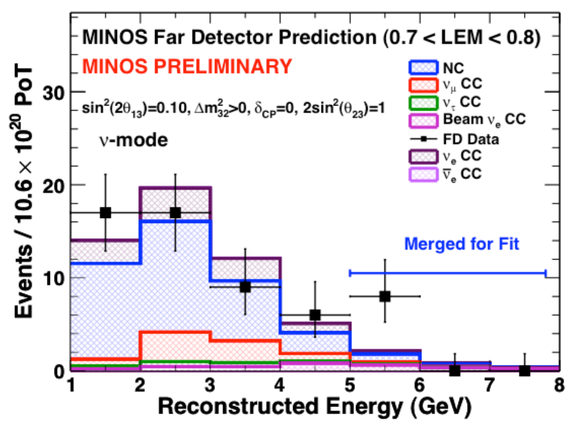
Neutrino running mode:

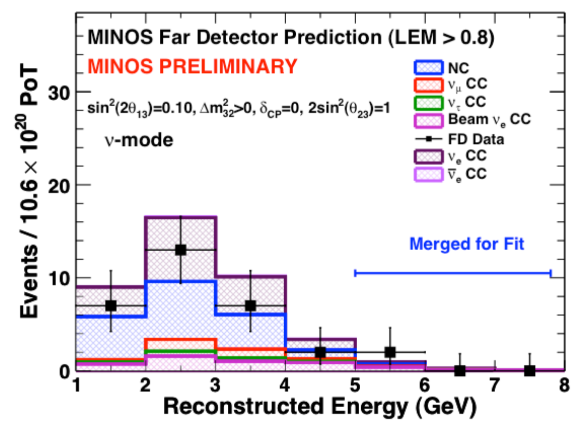
- Observe: 88 Events {
  - If $\theta_{13}=0$: 69.1 bkgnd events
  - If $\sin^2(2\theta_{13})=0.1$: +26.0 events

Antineutrino running mode:

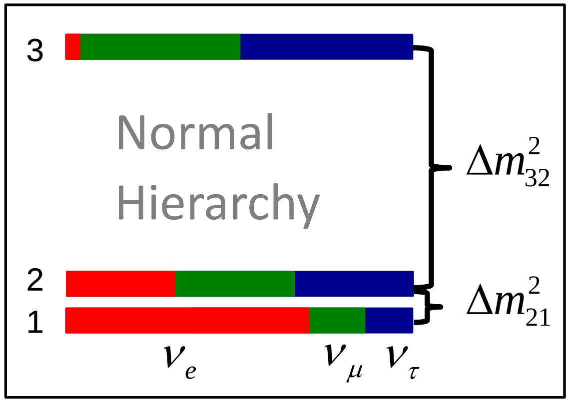
- Observe: 12 Events {
  - If $\theta_{13}=0$: 10.5 bkgnd events
  - If $\sin^2(2\theta_{13})=0.1$: +3.1 events

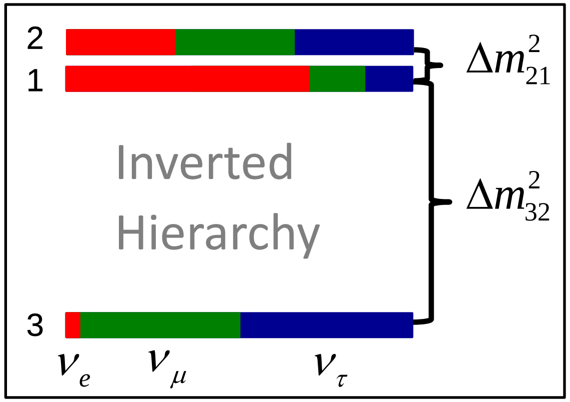


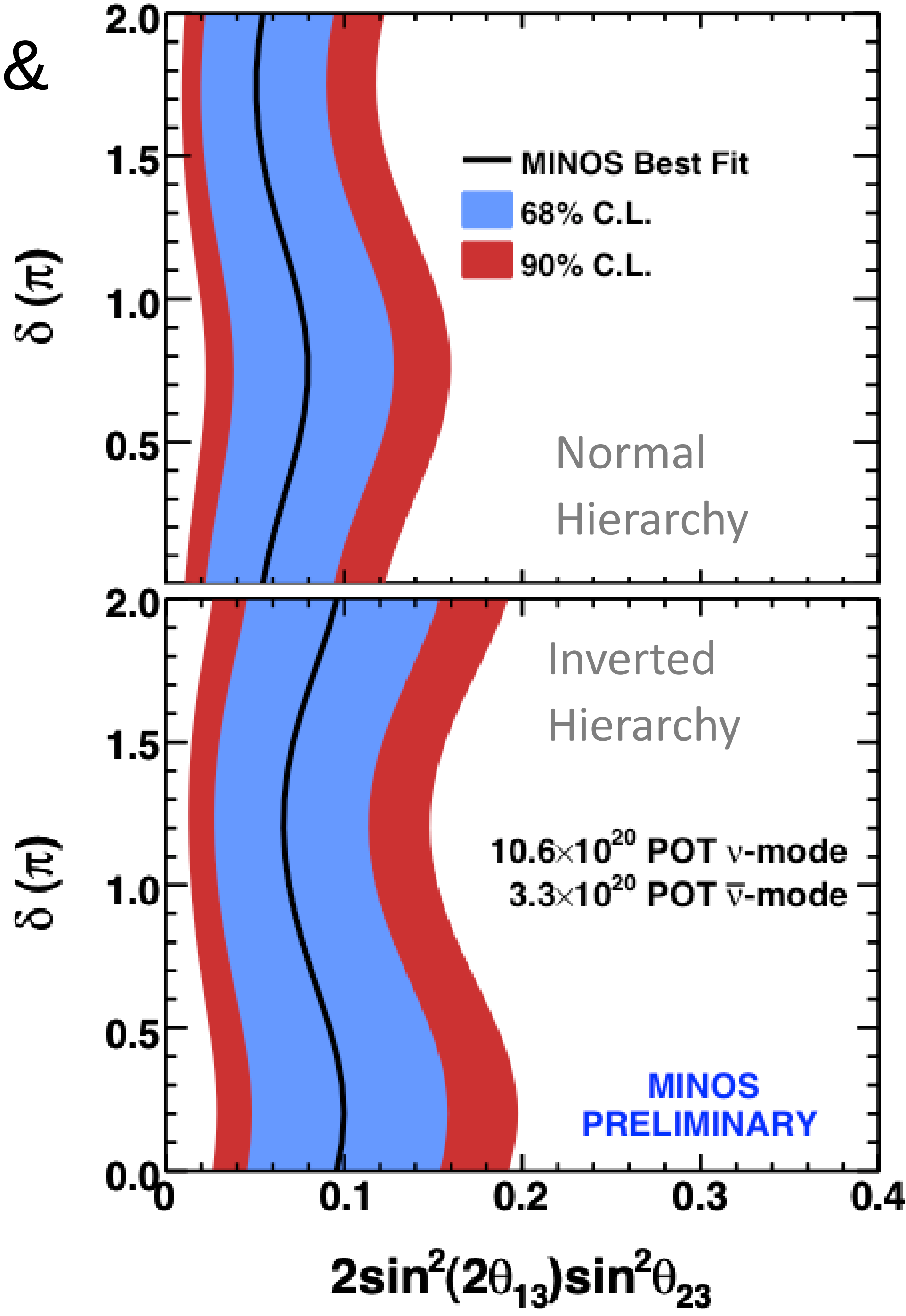


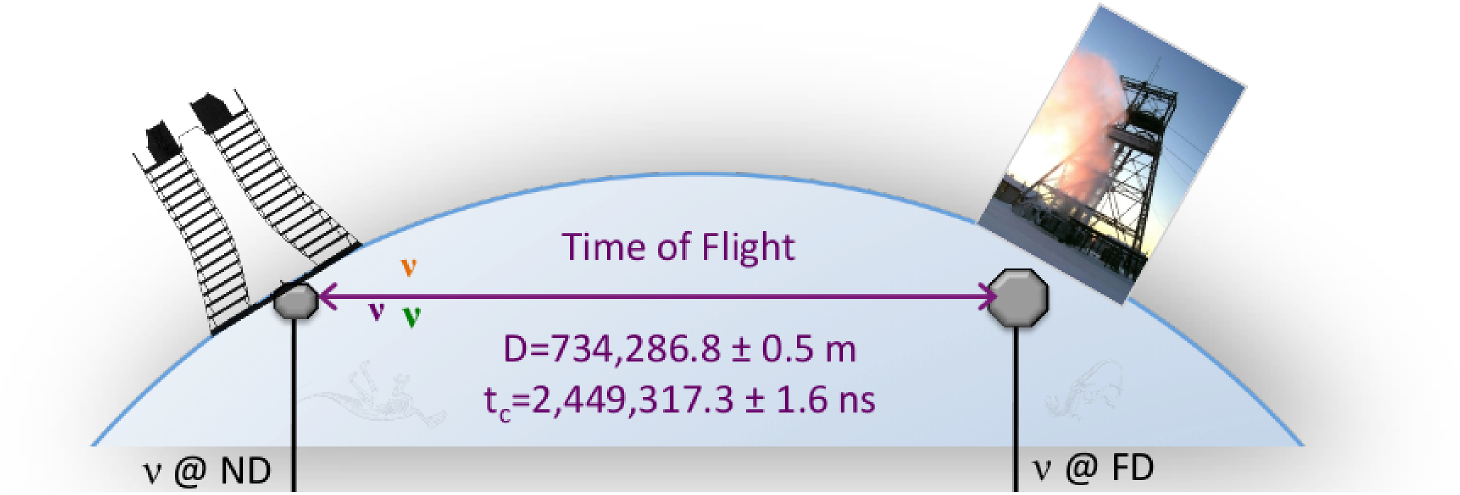


Contour for neutrino & antineutrino data combined



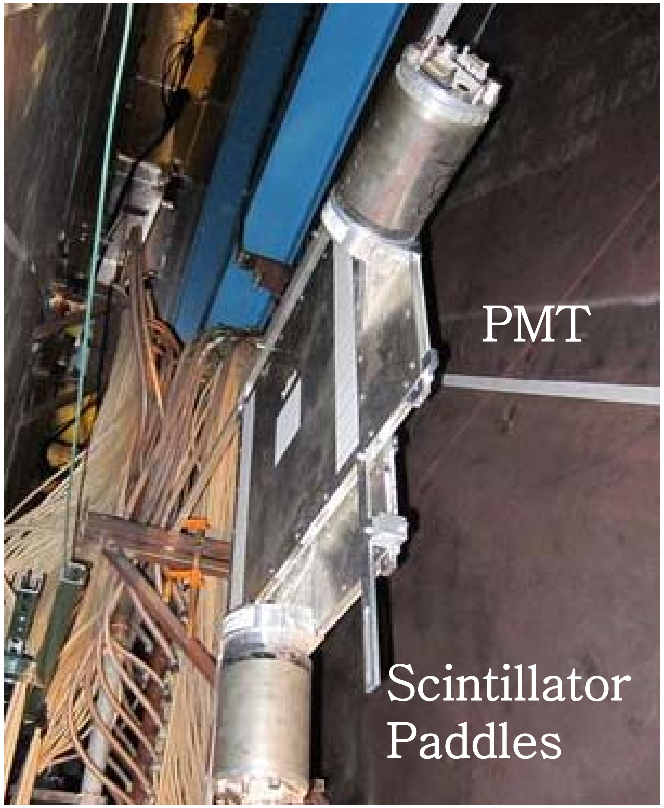






Neutrino time of flight

Upgrade for time of flight



- Added portable detectors for use at both sites: measure muons coincident with MINOS to get relative electronic delays.
- Added multiple good GPS units and careful monitor of time dependence of delays.
- Careful study of existing GPS, ND readout and delays of existing cables

- Measurement with old GPS with data since 2007. Find neutrinos arrive earlier by

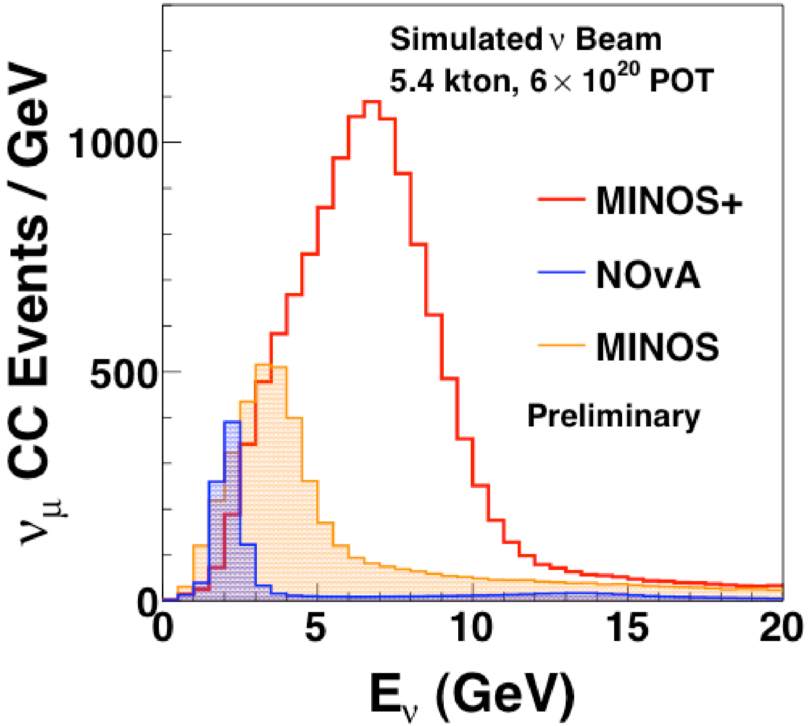
  15 ± 11 (stat.) $\pm$ 29 (syst.) ns

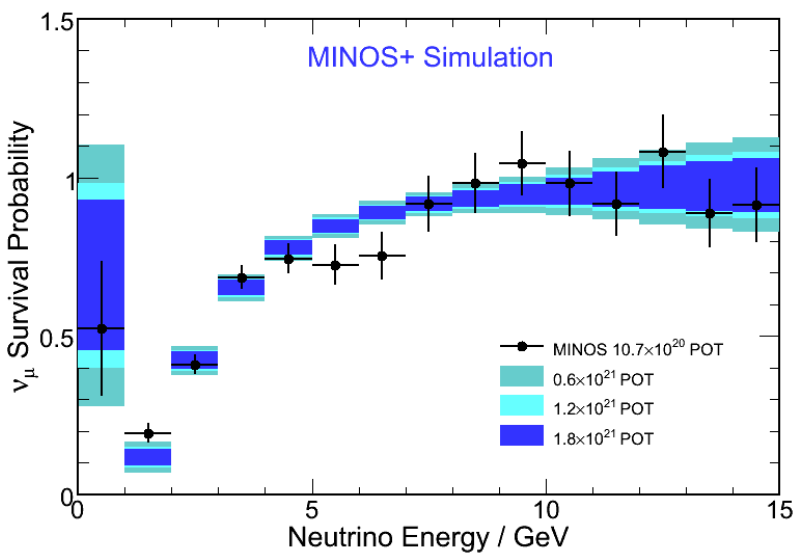
  which is consistent with v=c

- Measurement with new data with new timing equipment in progress

MINOS+

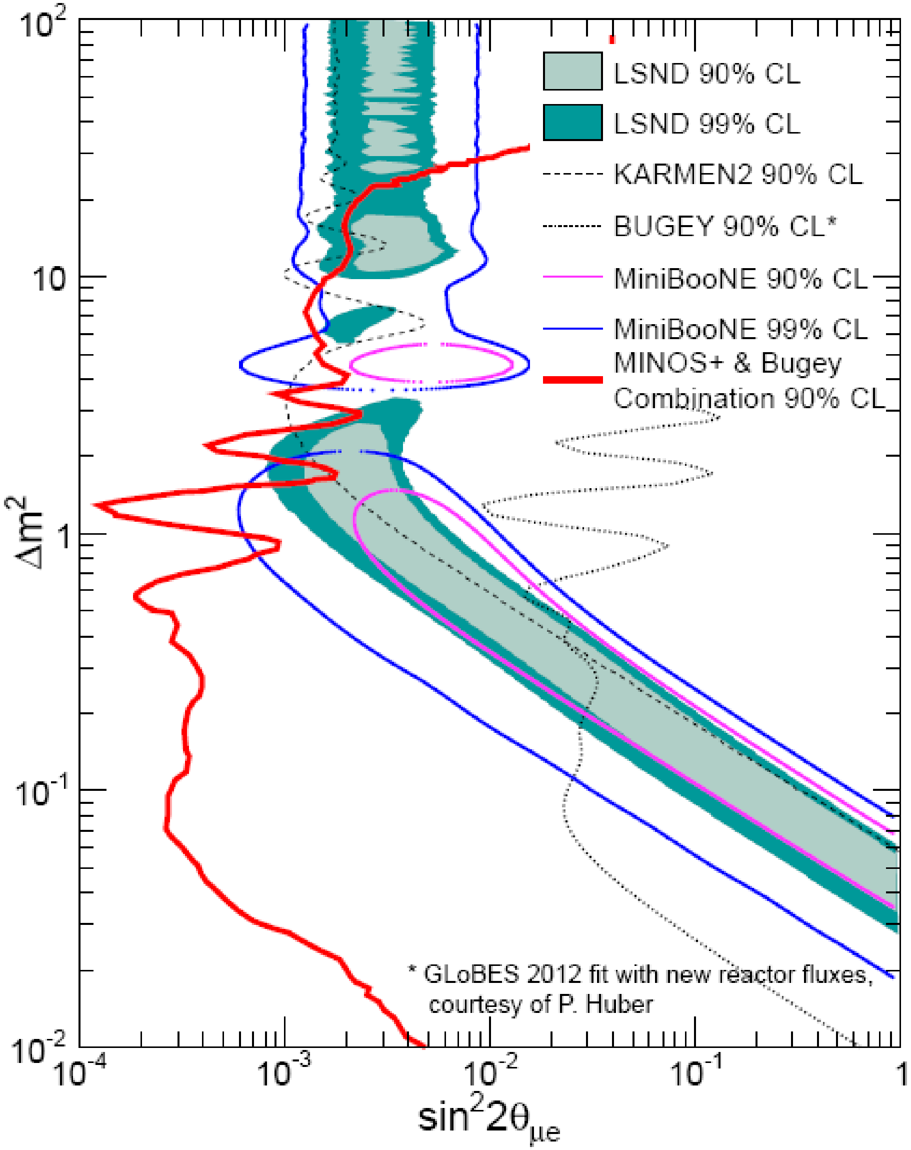
MINOS+



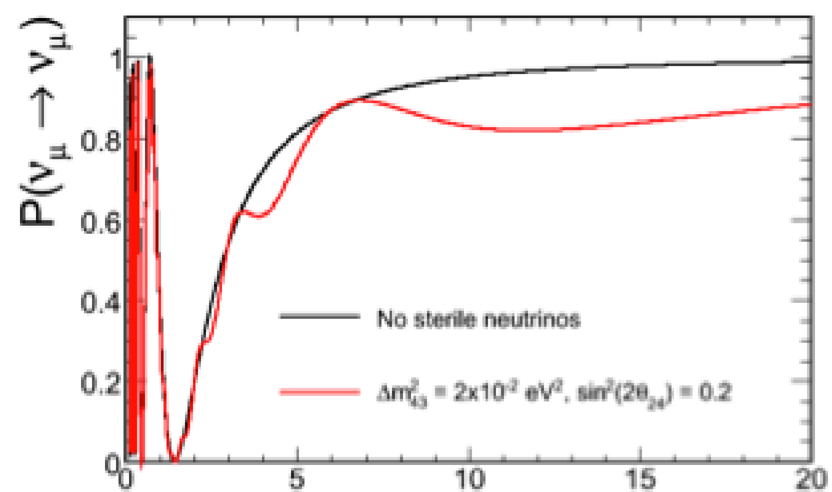


- MINOS will continue to run in the NOvA era
- ME beam peaks above the oscillation dip on axis
- But we get a lot of events!
  - ~4000 muon neutrino CC events per year expected at FD
  - ~80 tau neutrino CC events (with a lot of background)
- Unique test of oscillation paradigm with sensitivity to exotic signals

Estimated sensitivity of MINOS+



- With MINOS+ disappearance & input from Bugey data: We can study almost all of the low mass LSND region



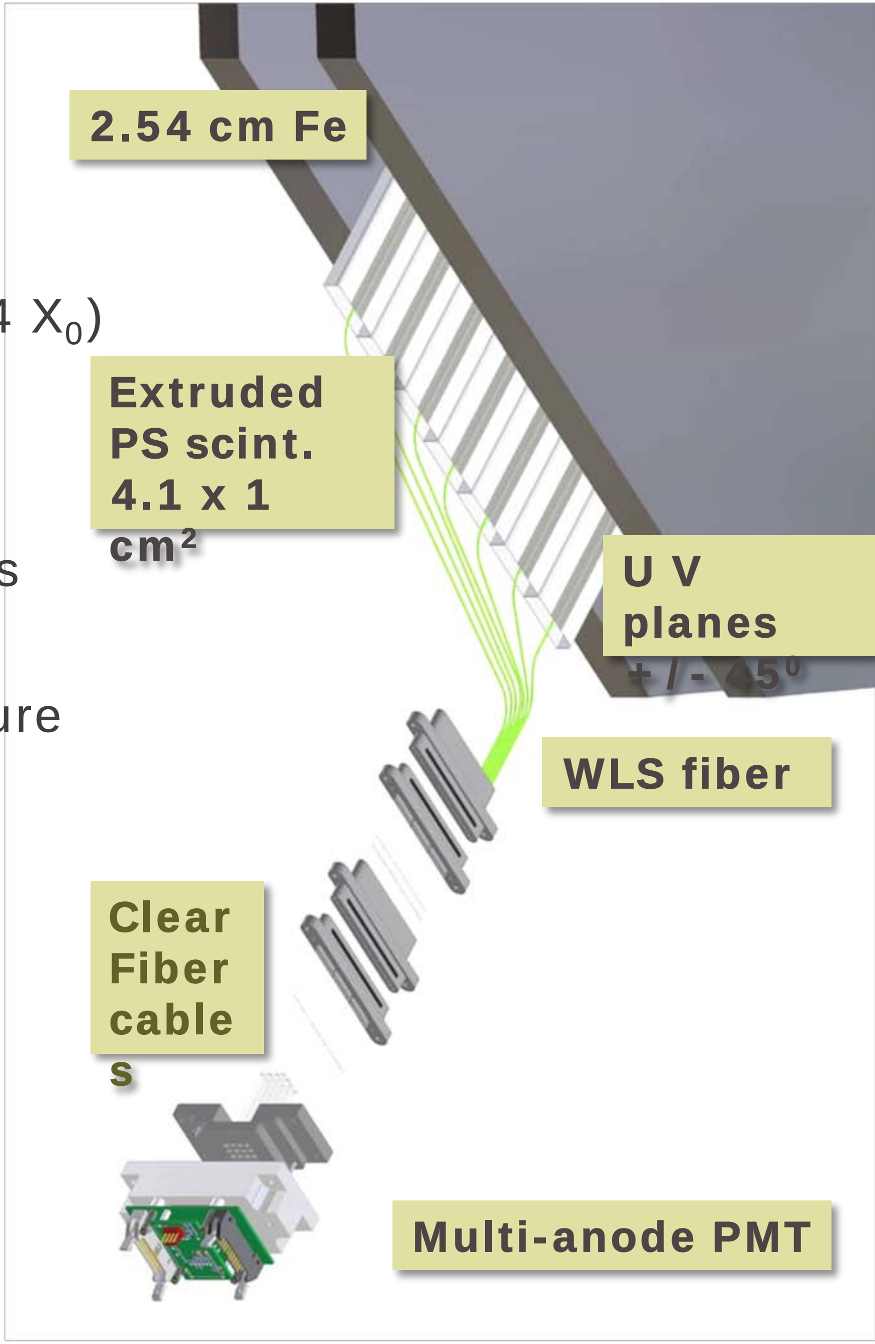
Summary

- Muon neutrino disappearance
  - Mixing may be slightly below maximal
  - MINOS is most accurate for both ν and $\bar{\nu}$ mass splitting
  - Parameters are consistent for neutrinos and antineutrinos
- MINOS rules out $\theta_{13} = 0$ at 2σ
- Neutrino speed consistent with *c*
- MINOS+: Precision studies of oscillation shape and exotica in the NOvA era.

Detector Technology

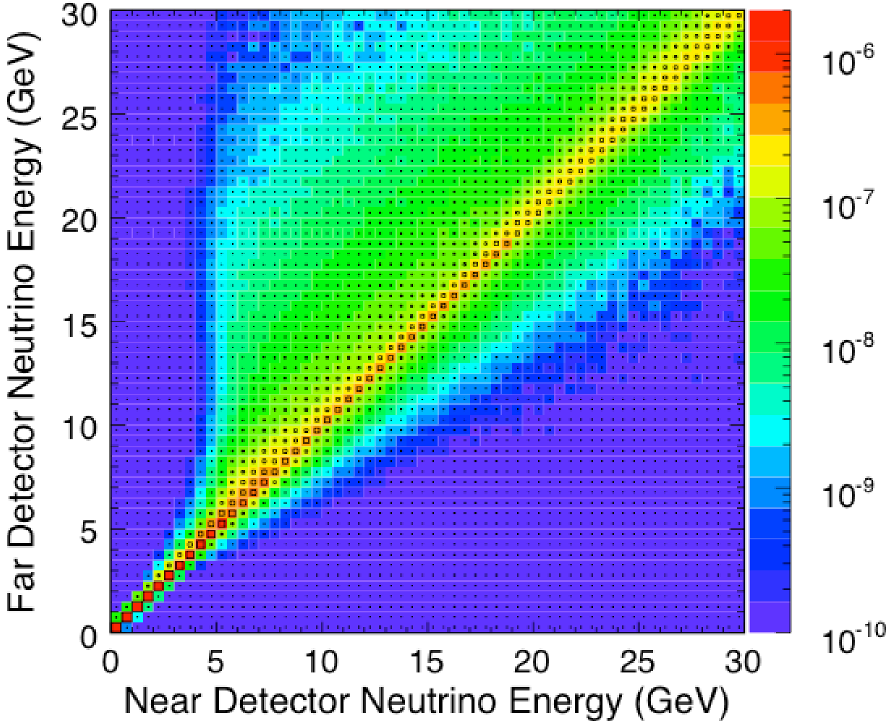
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide

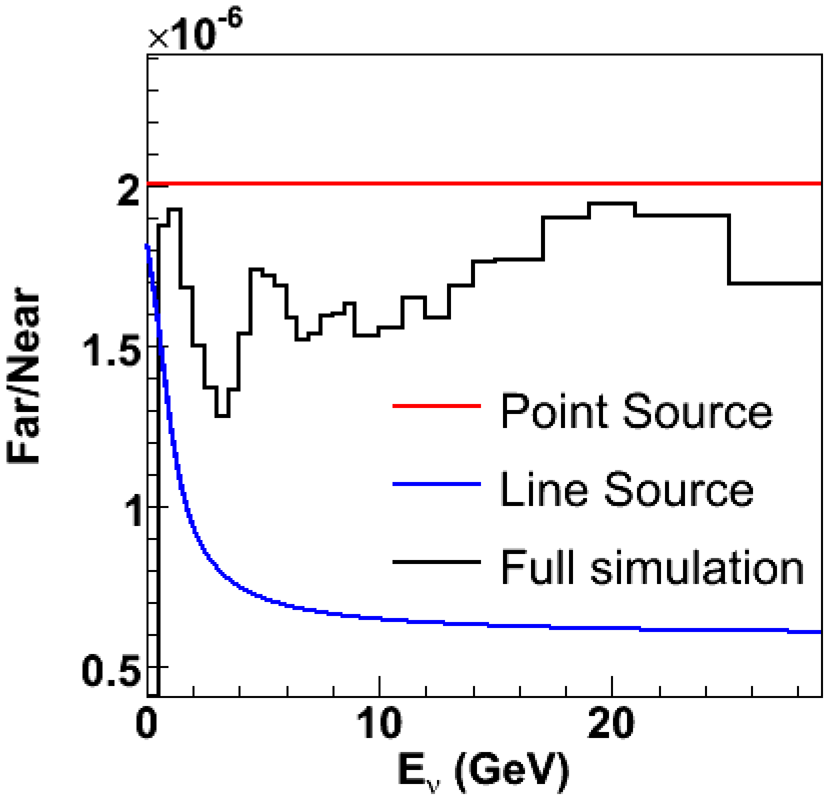
    (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ+ from μ-
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



Spectrum extrapolation

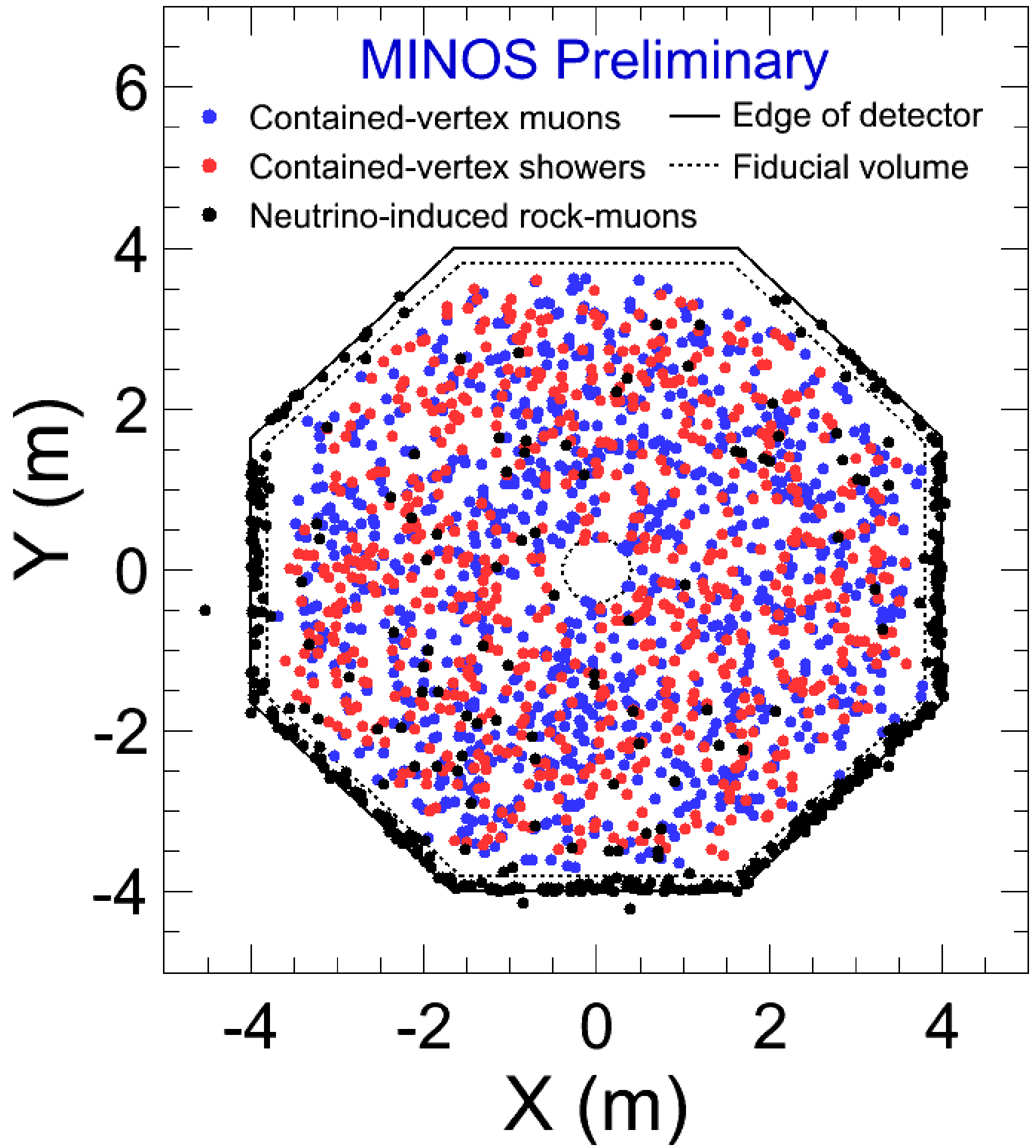
- Muon-neutrino and anti-neutrino analyses: beam matrix for FD prediction of track events
- Electron-neutrino analyses: Far to Near spectrum ratio for FD prediction of shower events





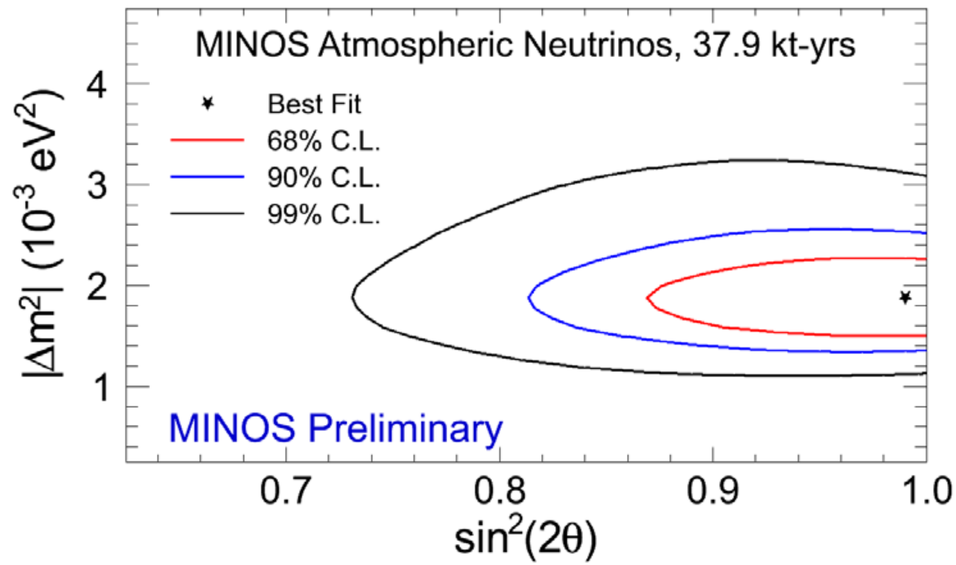
Atmospheric Neutrinos

- 39.7 kton years of atmospheric neutrino data collected since 2003
- 2072 neutrino events
  - 905 contained vertex muon events
  - 466 neutrino induced rock muon events
  - 701 contained vertex showers

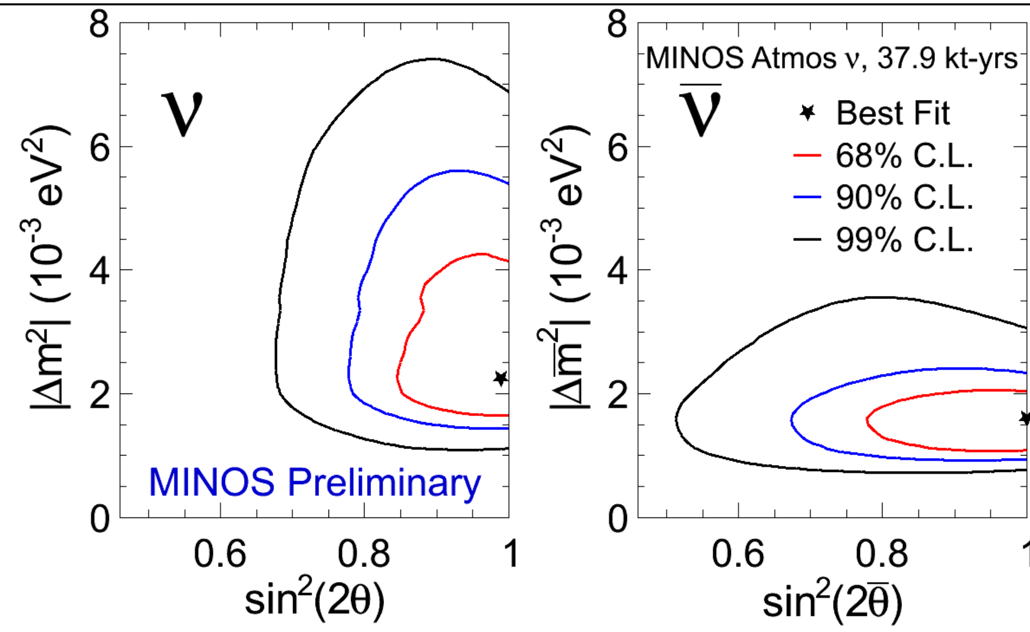


Atmospheric Neutrinos

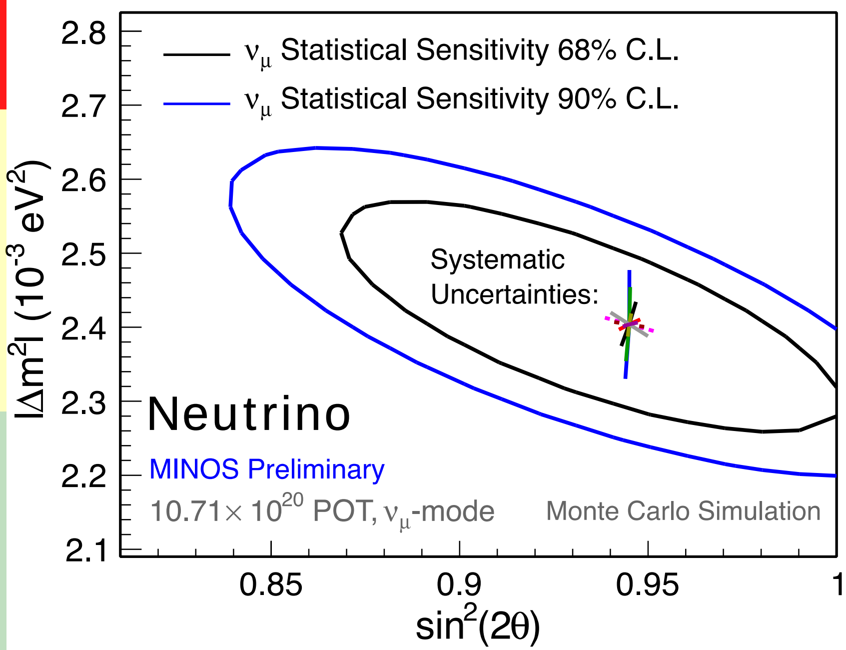
- Without charge sign selection:

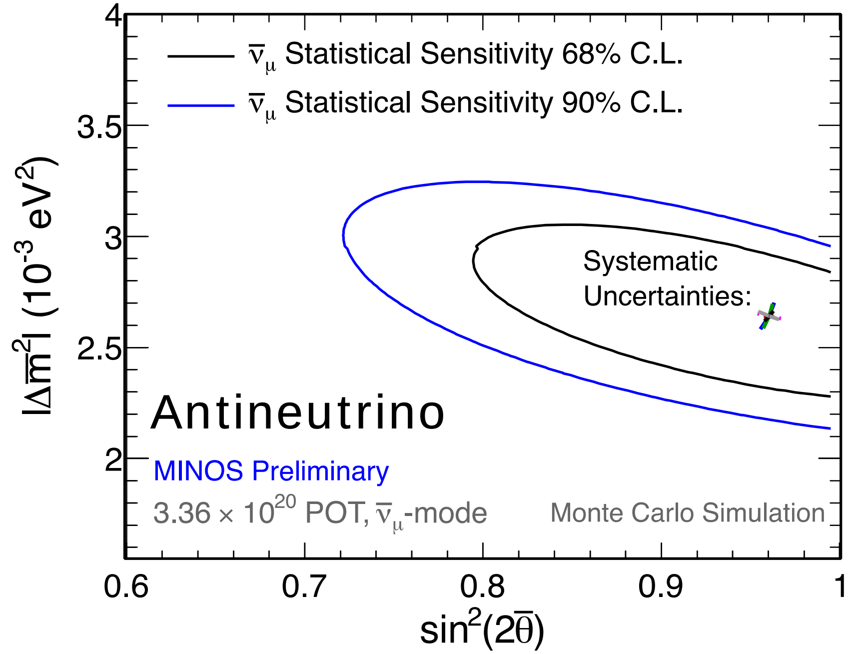


- Separating by charge:



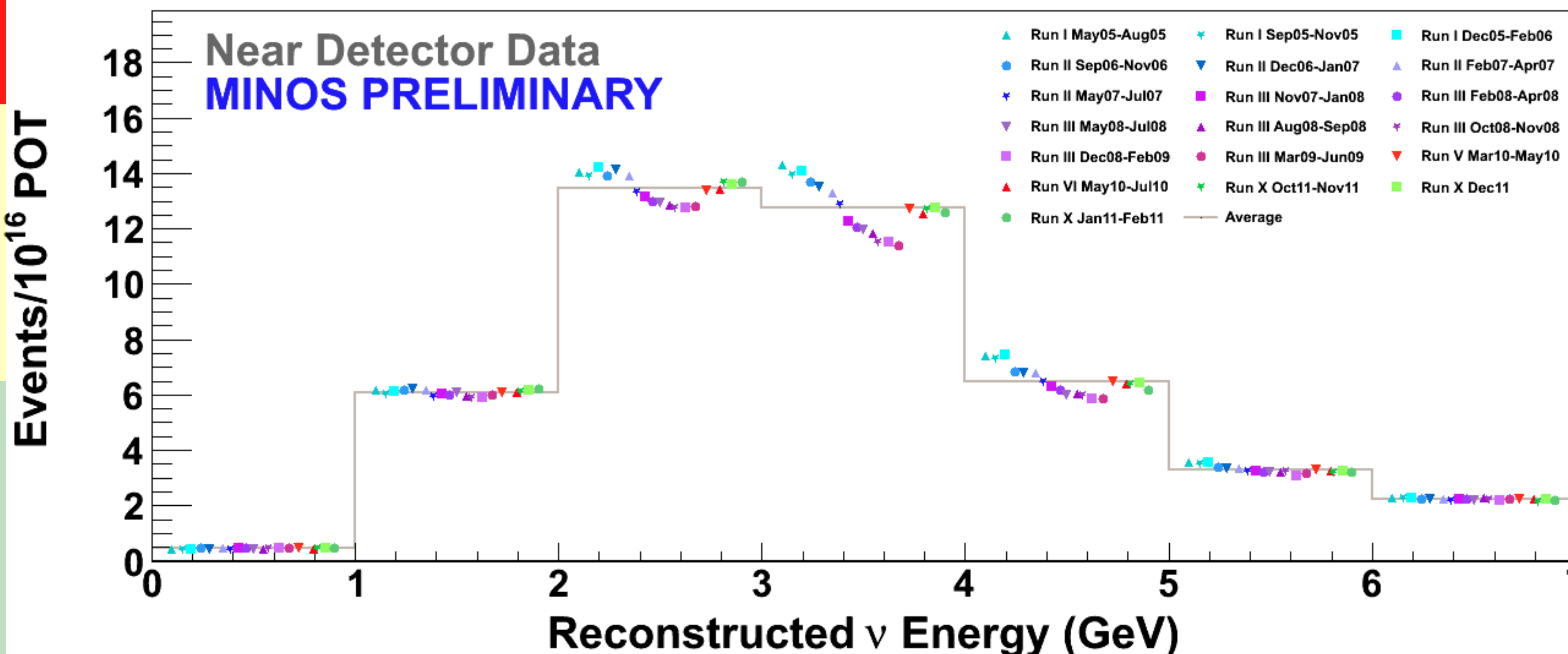
Sensitivity and systematics





- Largest sources of systematic uncertainty
  - Hadronic energy scale
  - Track energy scale
  - Neutral current background
- Still statistics dominated in both modes

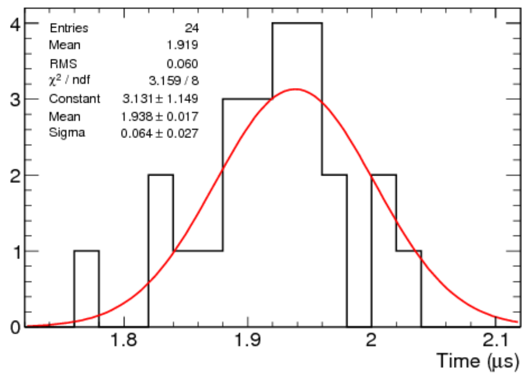
Energy spectrum of muon neutrino events over the MINOS exposure



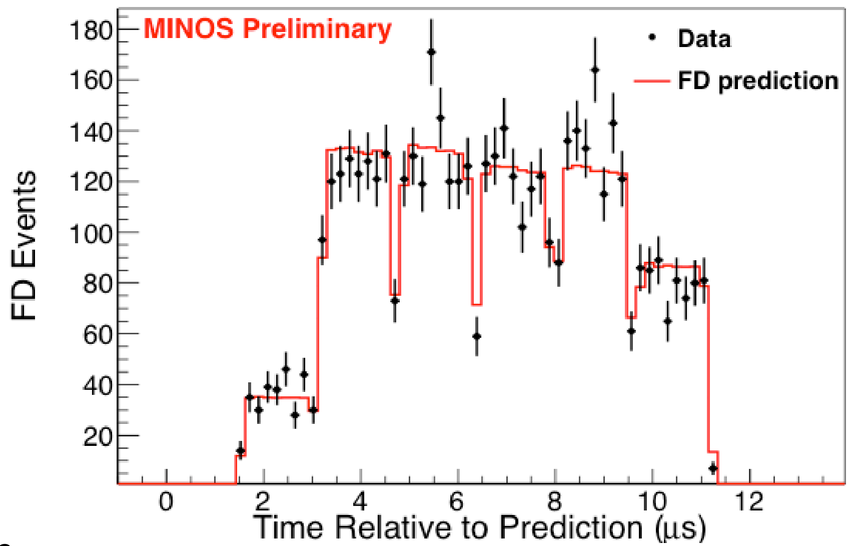
2 significant effects incorporated into the simulations

- Introduction of helium to the decay pipe
- degradation of the target core due to rad damage

Retrospective TOF analysis of 2007-12 data



Cable remeasurement	2007	2012
GPS to ND cable delay	1275 ± 29 ns	1309 ± 1 ns
GPS to FD cable delay	5140 ± 46 ns	5098 ± 2 ns



- 2007 MINOS consistent with v=c. Big uncertainty so it also covered OPERA wrong result.
- From 2007, MINOS stopped TOF studies until OPERA.
- Installed new hardware
  - Used to carefully study old hardware and do retrospective analysis: x8 more data than 2007.
  - Remeasured cable delays
  - 2 fitting methods give arrival time earlier than expected by 15 ± 11 (stat.) ± 29 (syst.) ns
  - 15 ± 11 (stat.) ± 29 (syst.) ns
  - Consistent with speed of light