

# The Latest MINOS Results



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(for the MINOS Collaboration)

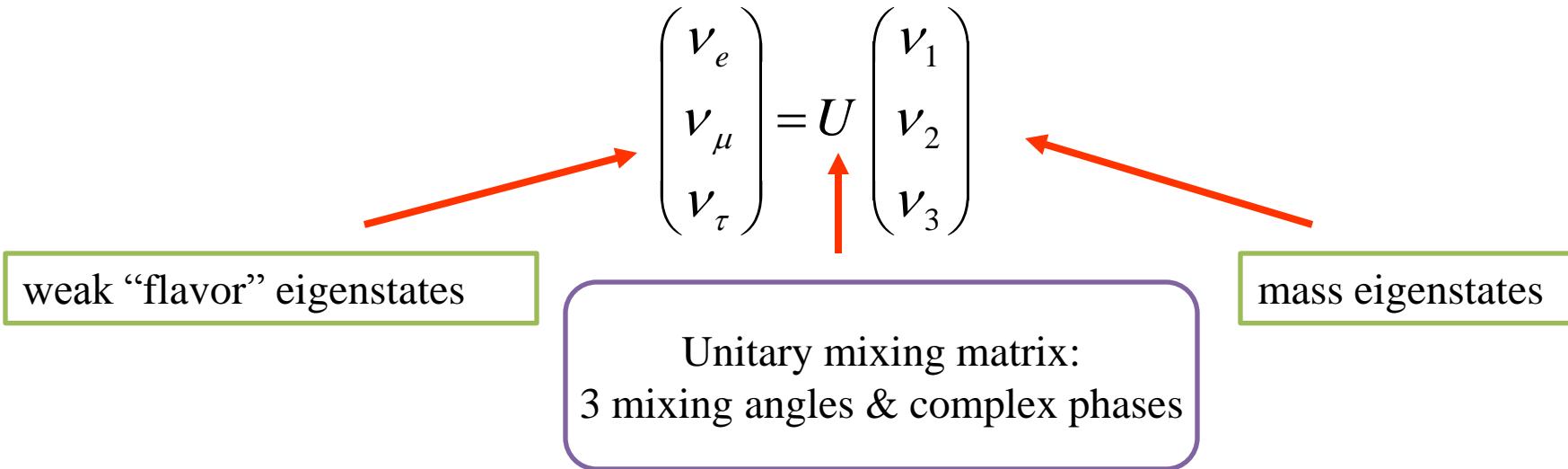


International Symposium on Neutrino Physics and Beyond  
Sept.23-26.2012

# Neutrino Mixing

PMNS Matrix (Pontecorvo-Maki-Nakagawa-Sakata)

analogue to CKM-Matrix in quark sector



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

accessible by MINOS      solar sector      Majorana phases

with  $c_{ij} = \cos(\theta_{ij})$ ,  $s_{ij} = \sin(\theta_{ij})$ ,  $\theta_{ij}$  = mixing angle

# MINOS Physics Goals

- Beam neutrino
  - Test  $\nu_\mu \rightarrow \nu_\tau$  oscillations (Measure precisely  $|\Delta m^2_{32}|$  and  $\sin^2 2\theta_{23}$ )
  - Search for  $\nu_\mu \rightarrow \nu_e$  oscillations (determine  $\theta_{13}$ )
- Atmospheric neutrinos
- Combine results from the beam and atmospheric neutrino
- Compare  $\nu$  to  $\bar{\nu}$  oscillations
- Test exotic models
  - Decay, decoherence, sterile neutrinos, time of flight
- Neutrino interaction physics
- Cosmic rays physics

# The MINOS Experiment

## MINOS - Main Injector Neutrino Oscillation Search

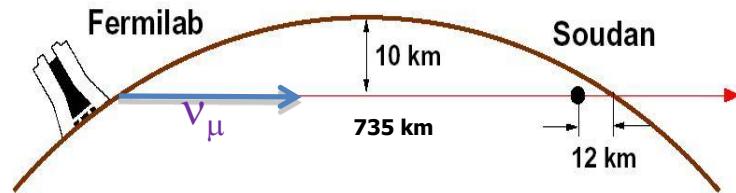
Two functionally identical detectors  
to reduce systematics

### Near Detector

- 1 km from target
- 94 m underground, 225 mwe
- Measures the energy spectrum and beam composition

### Far Detector

- 735 km from target
- 700 m underground, 2070 mwe
- Re-measures the neutrino beam composition



**Near Detector**  
980 tons

**Far Detector**  
5,400 tons

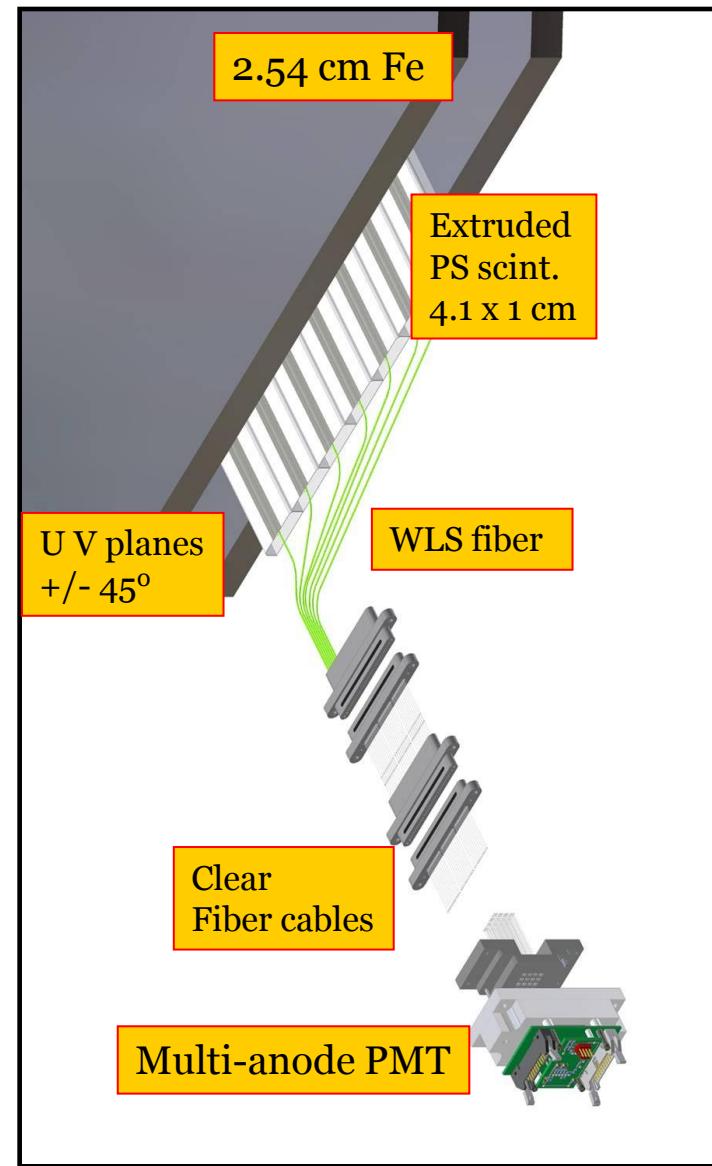
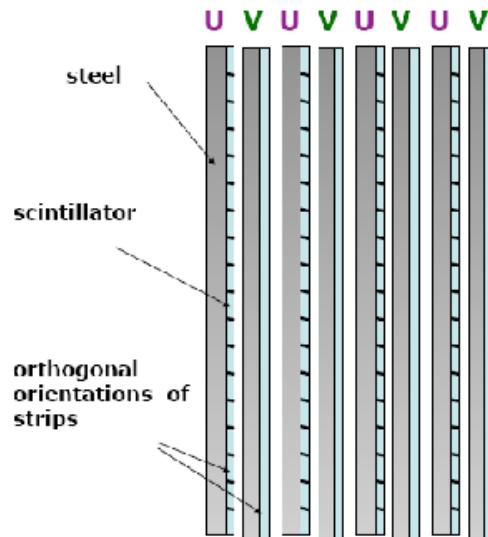
# Detector Technology

## Steel/scintillator tracking calorimeters

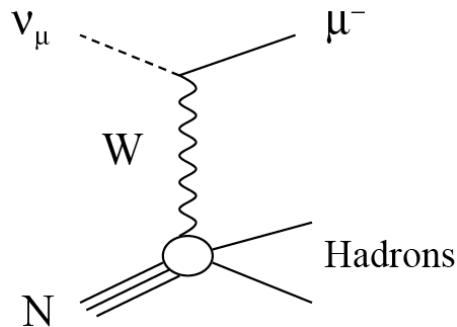
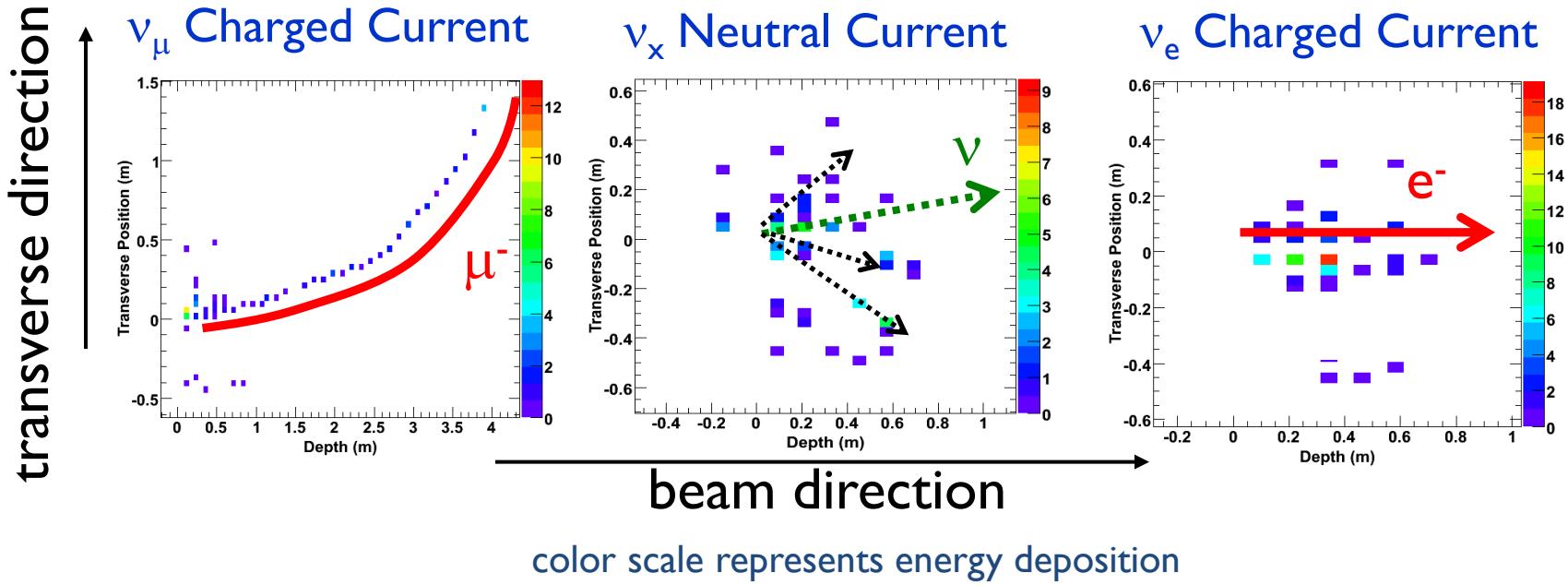
- Alternate orthogonal orientation planes
- Steel absorber 2.54 cm thick
- Scintillator strips 4.1 cm wide, 1.0 cm thick
- 1 GeV muons penetrate 28 layers
- Longitudinal sampling = 1.4 radiation lengths
- Optical WLS fiber readout to multi-anode PMTs

## Magnetized

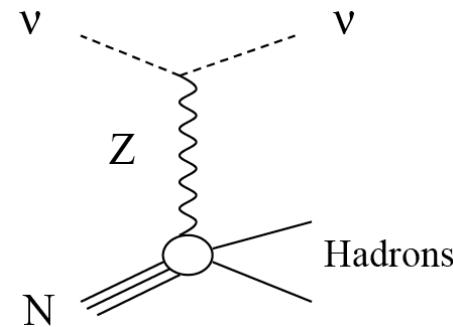
- $\langle B \rangle = 1.3T$
- Muon energy from range/curvature
- Distinguish  $\mu^+$  from  $\mu^-$  tracks



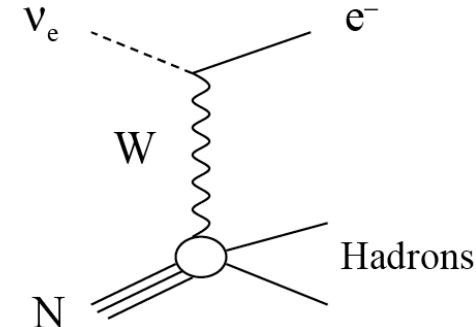
# Neutrino Interactions in Detectors



long  $\mu$  track & possible hadronic activity at vertex

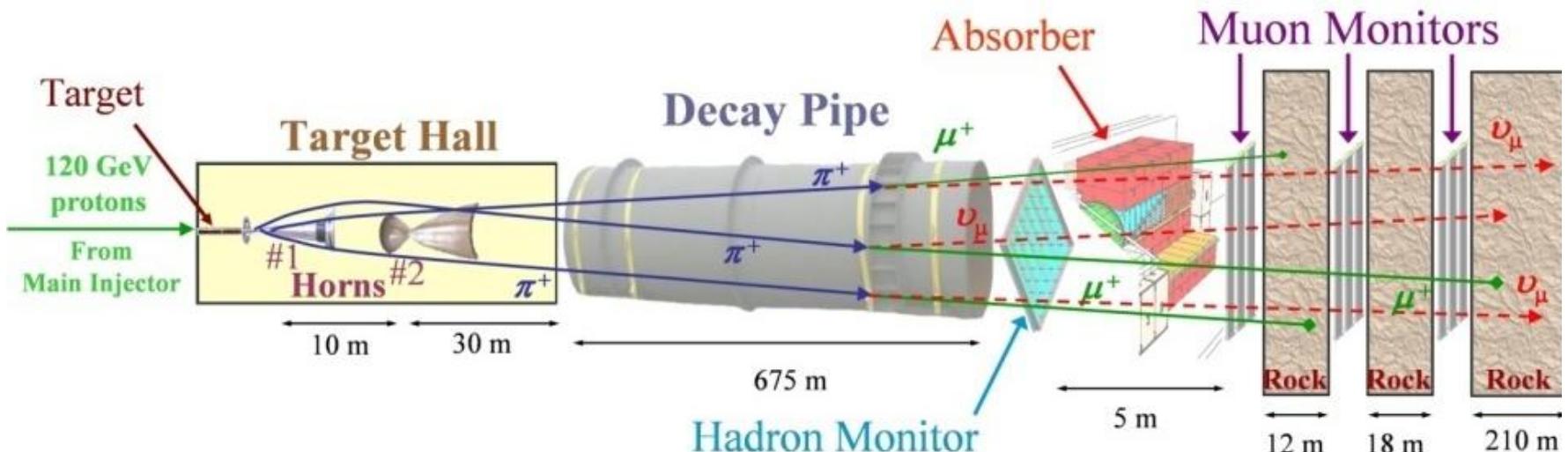


short with diffuse shower

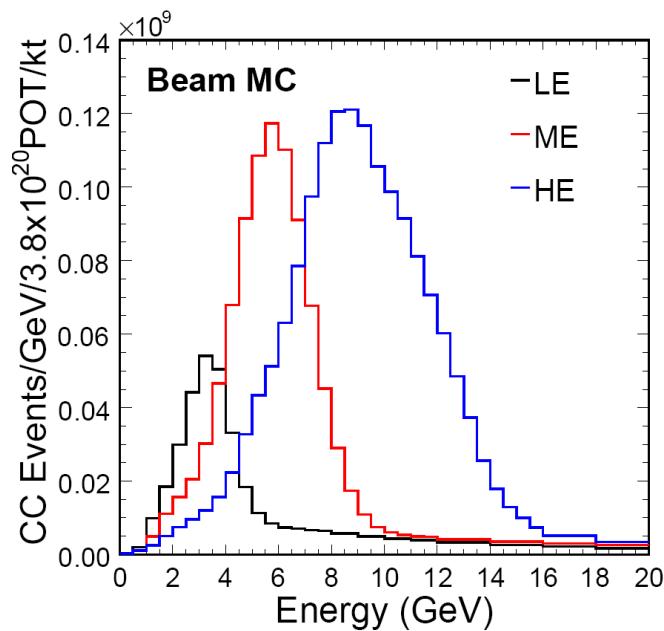


short with compact EM shower profile

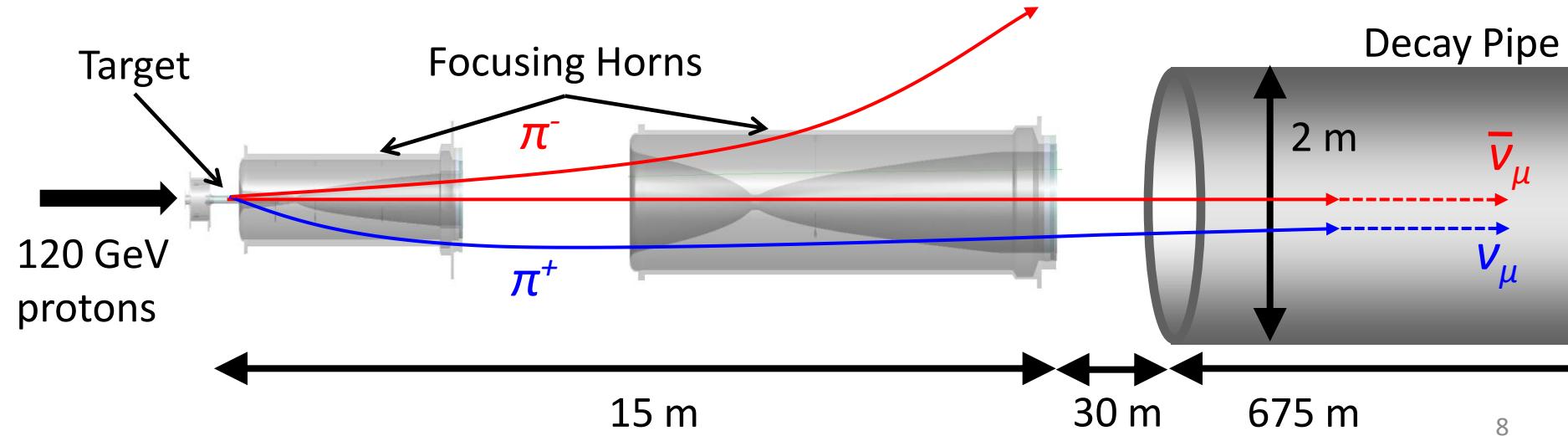
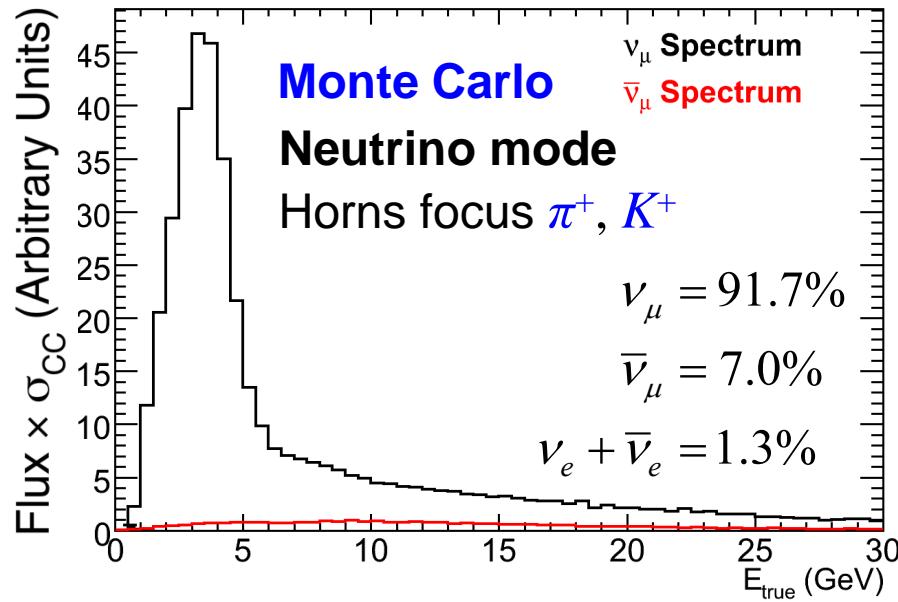
# NuMI Beam



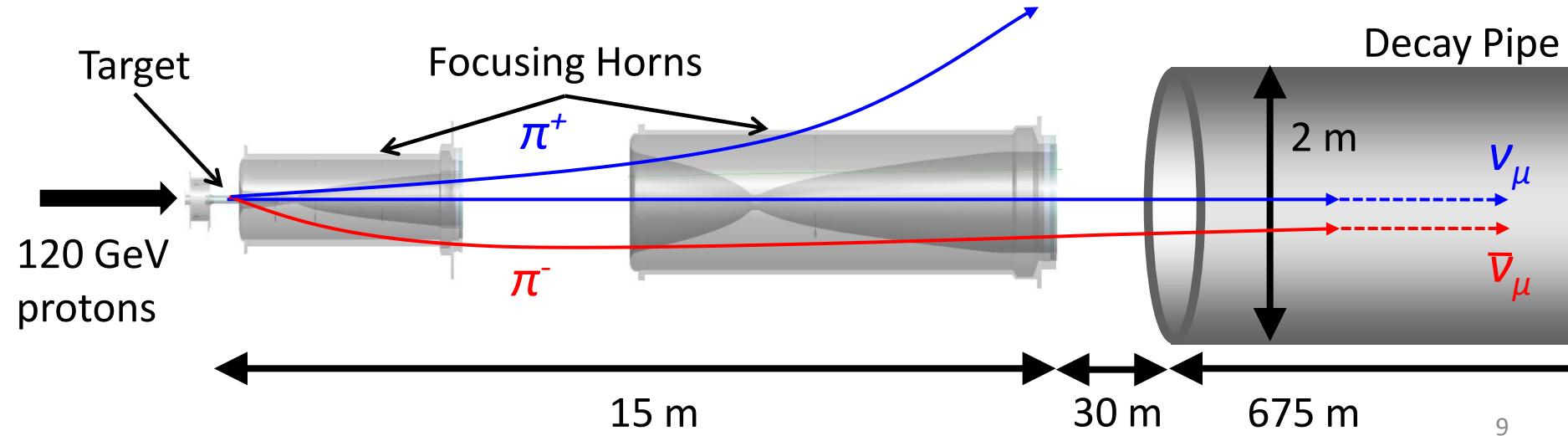
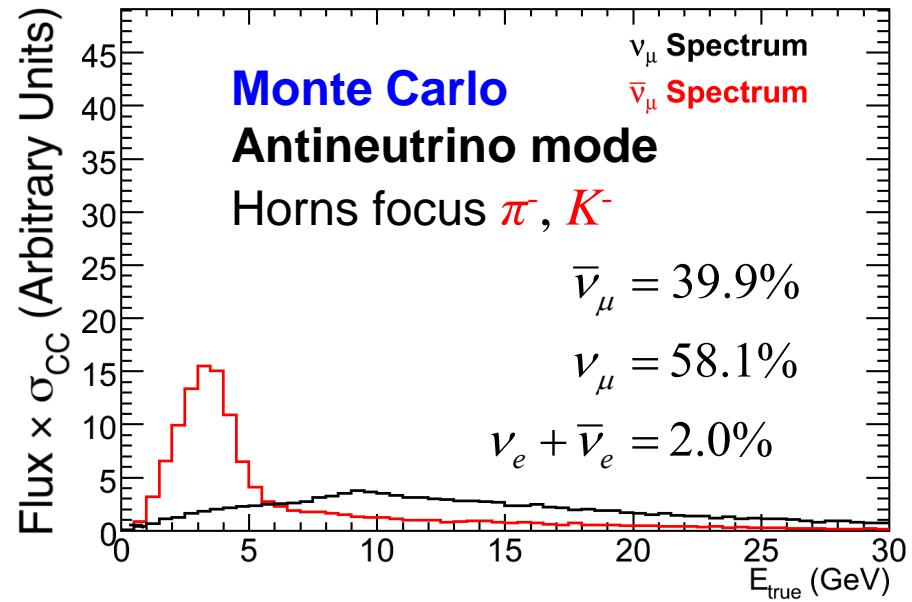
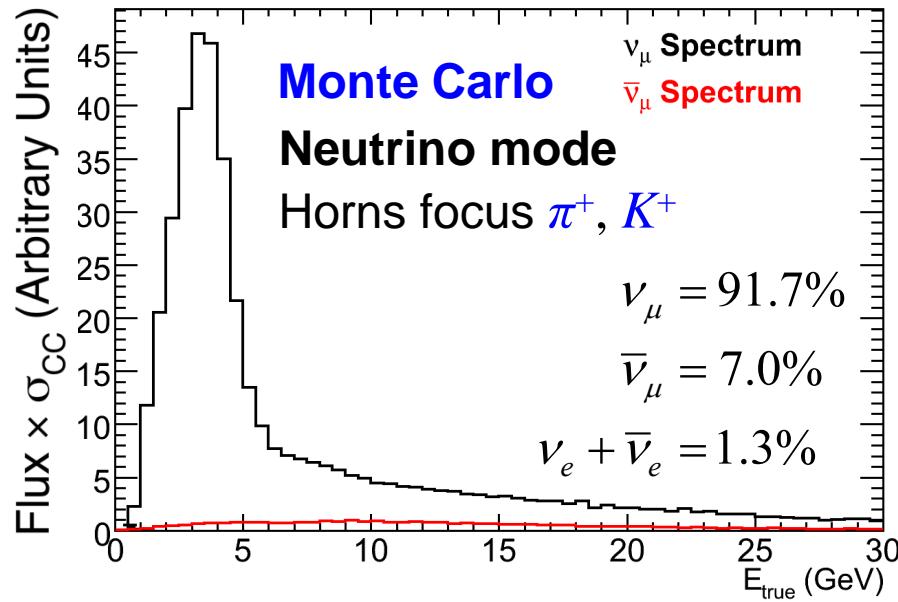
- Accelerate protons in the Main Injector
- 10  $\mu$ s spill of 120 GeV protons every 2.2 s
- Strike with a graphite target to produce mesons ( $\pi$ 's and K's)
- Decay into neutrinos in the 675 m decay pipe
- Neutrino spectrum changes with target position



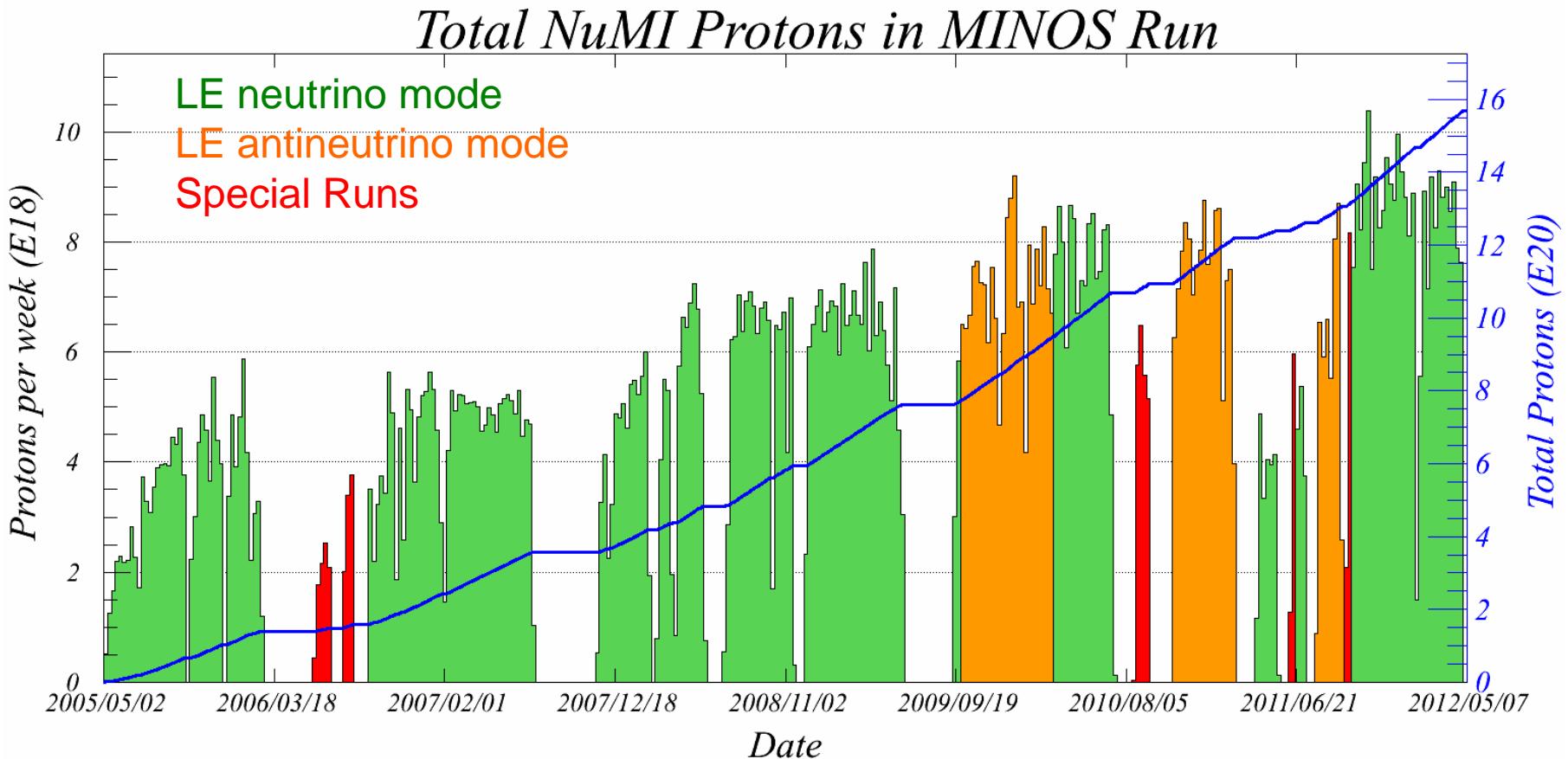
# Neutrino Mode



# Antineutrino Mode



# The MINOS Exposure History (2005-2012)



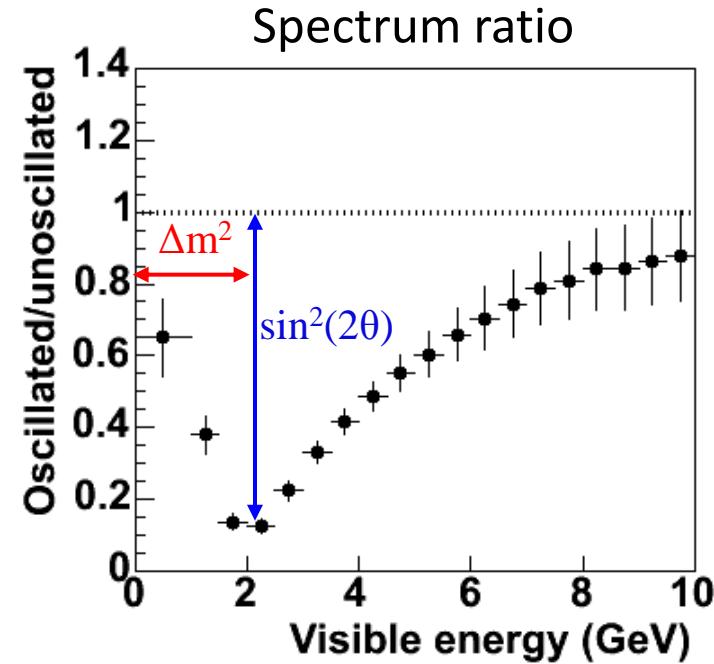
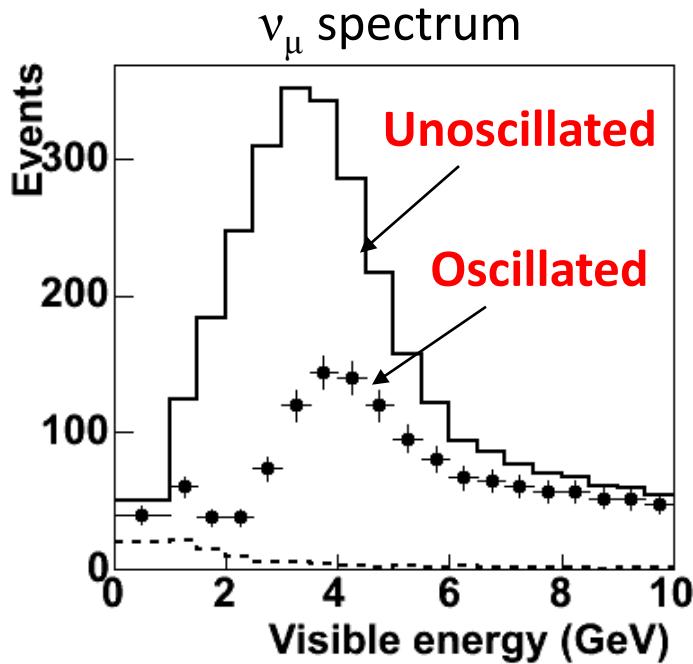
- NuMI beam shut off April 30, 2012
- Accumulated more than  $15 \times 10^{20}$  POT
  - $10.7 \times 10^{20}$  POT in (LE) neutrino running
  - $3.36 \times 10^{20}$  POT in antineutrino running

# $\nu_\mu$ Disappearance Measurement

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{1.267 \Delta m_{32}^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]} \right)$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \sin^2 2\bar{\theta}_{23} \sin^2 \left( \frac{1.267 \Delta \bar{m}_{32}^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]} \right)$$

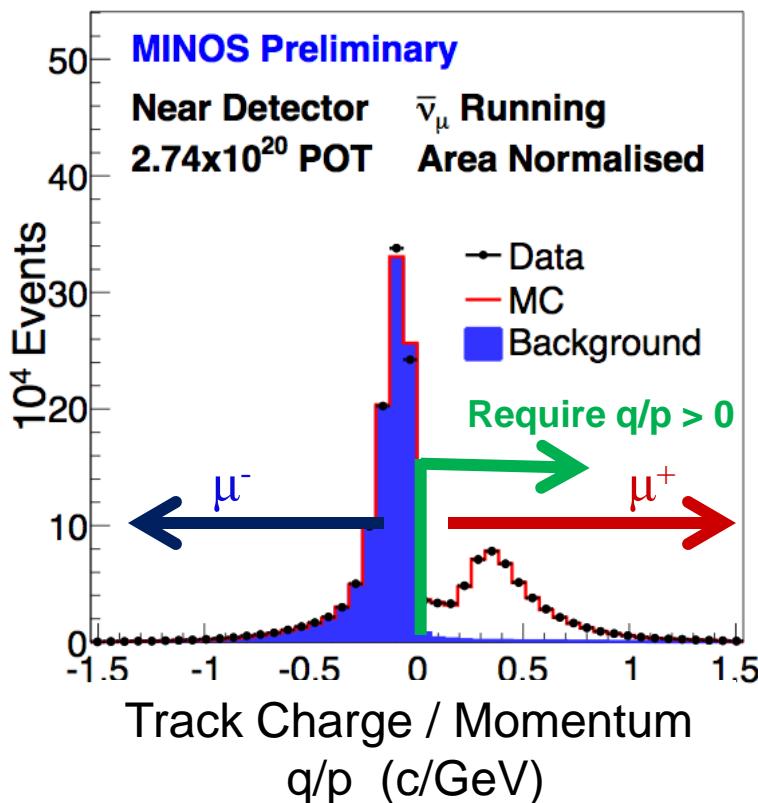
MINOS full 3 flavor analysis in progress



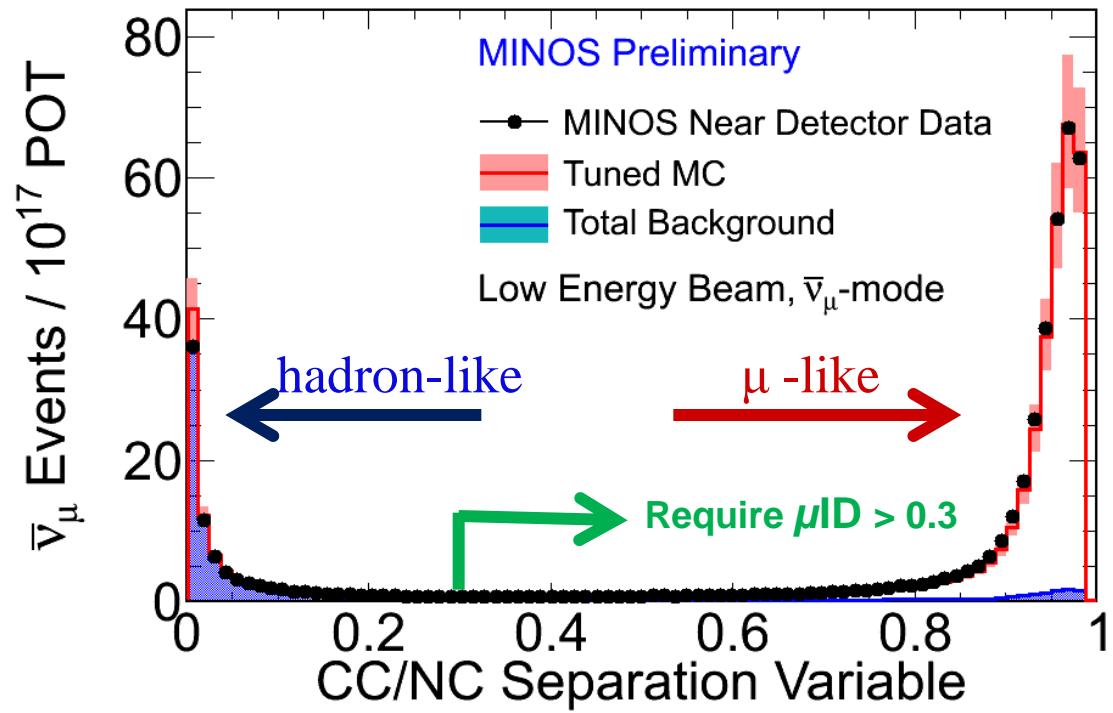
Monte Carlo: Input parameters:  $\sin^2 2\theta = 1.0$ ,  $\Delta m^2 = 3.35 \times 10^{-3}$  eV<sup>2</sup>

# Charge Identification and CC-NC Separation

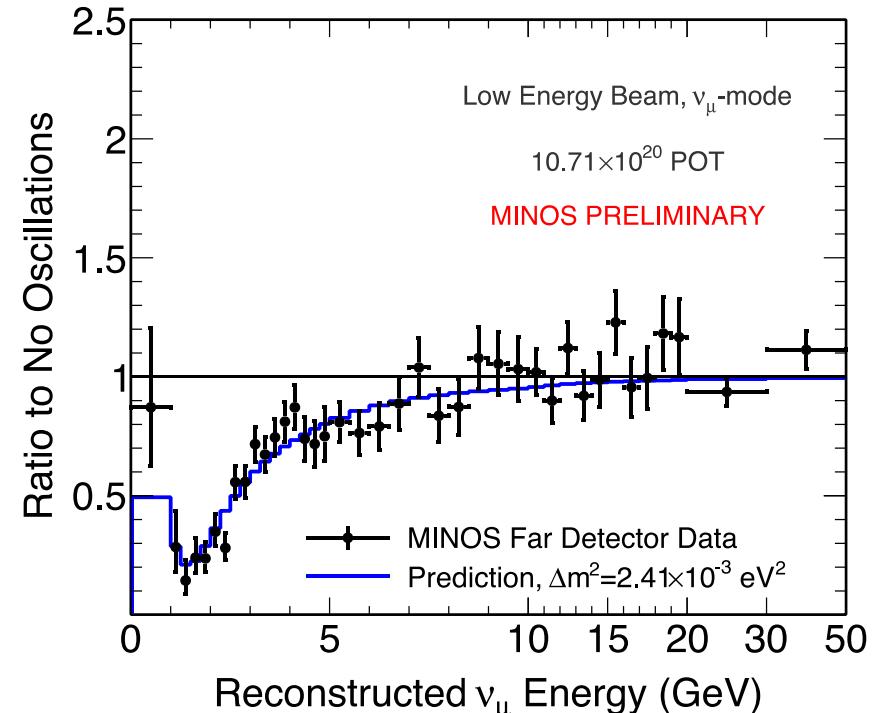
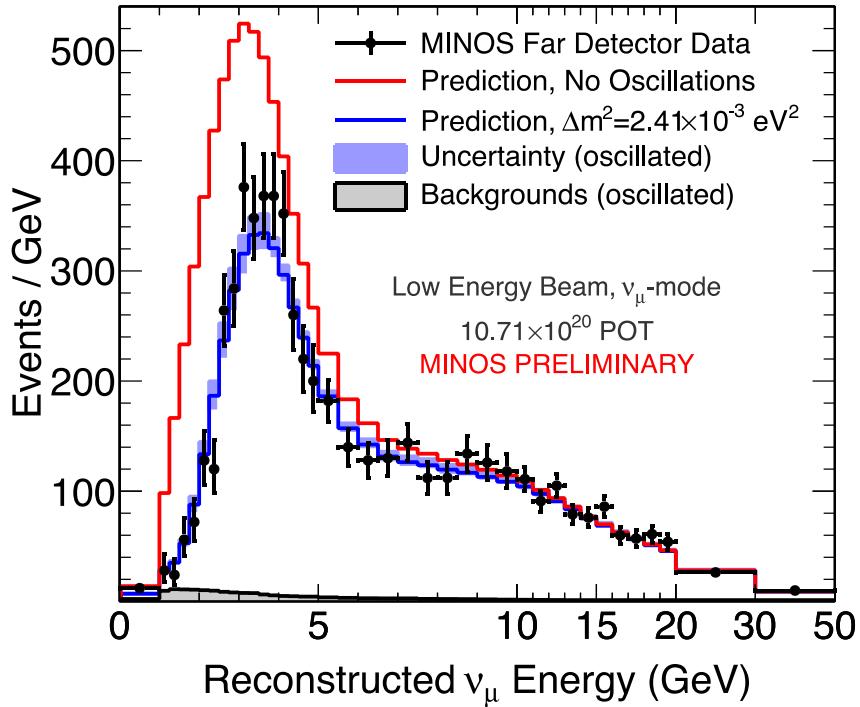
Charge identification via magnetic field bending and track fitting



CC-NC separation via a kNN (k-Nearest-Neighbors) algorithm



# Muon Neutrino Oscillation Results



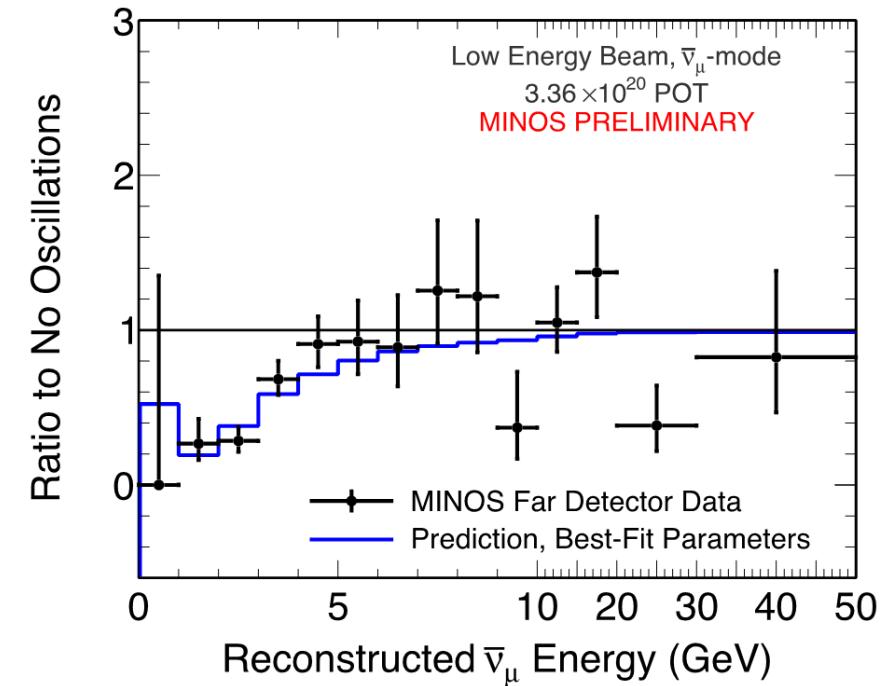
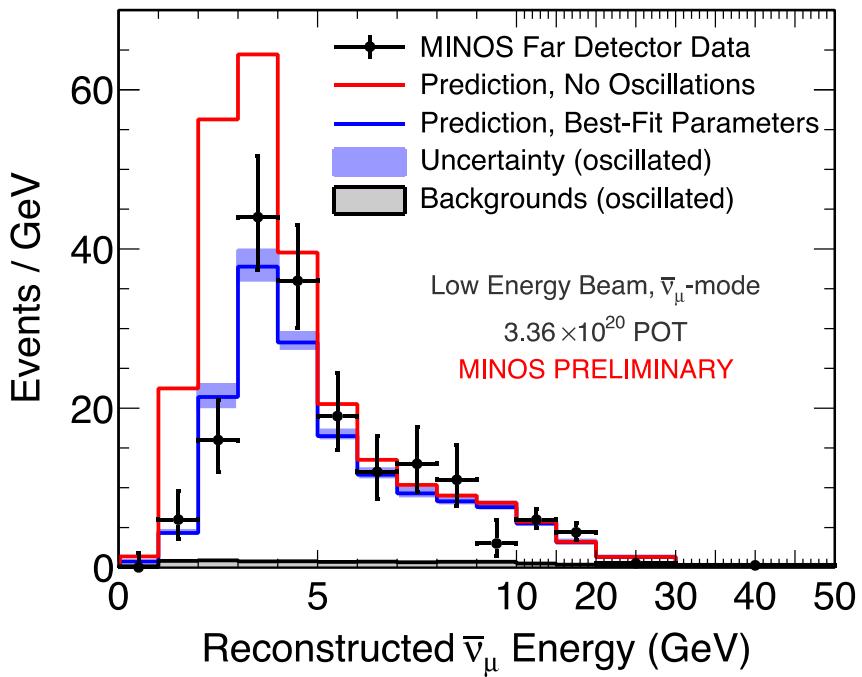
No oscillation Prediction: 3564

Observed: 2894

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

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

# Muon Antineutrino Oscillation Results



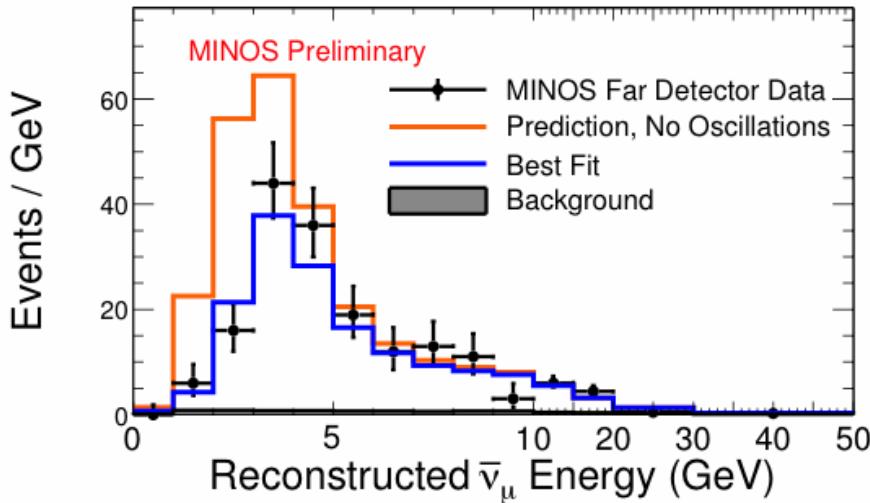
No oscillation Prediction: 312

Observed: 226

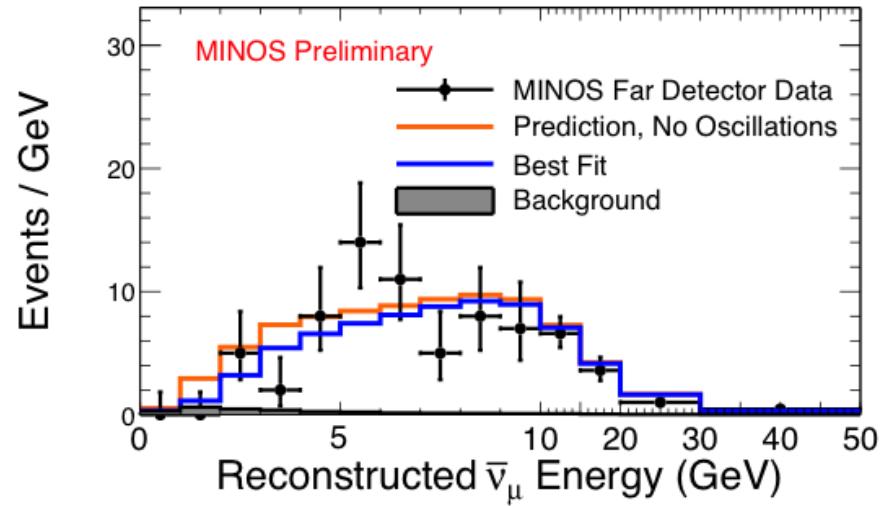
$$|\Delta\bar{m}^2| = 2.64_{-0.27}^{+0.28} \times 10^{-3} \text{ eV}^2$$

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

# More Antineutrinos in Neutrino Mode



in antineutrino mode



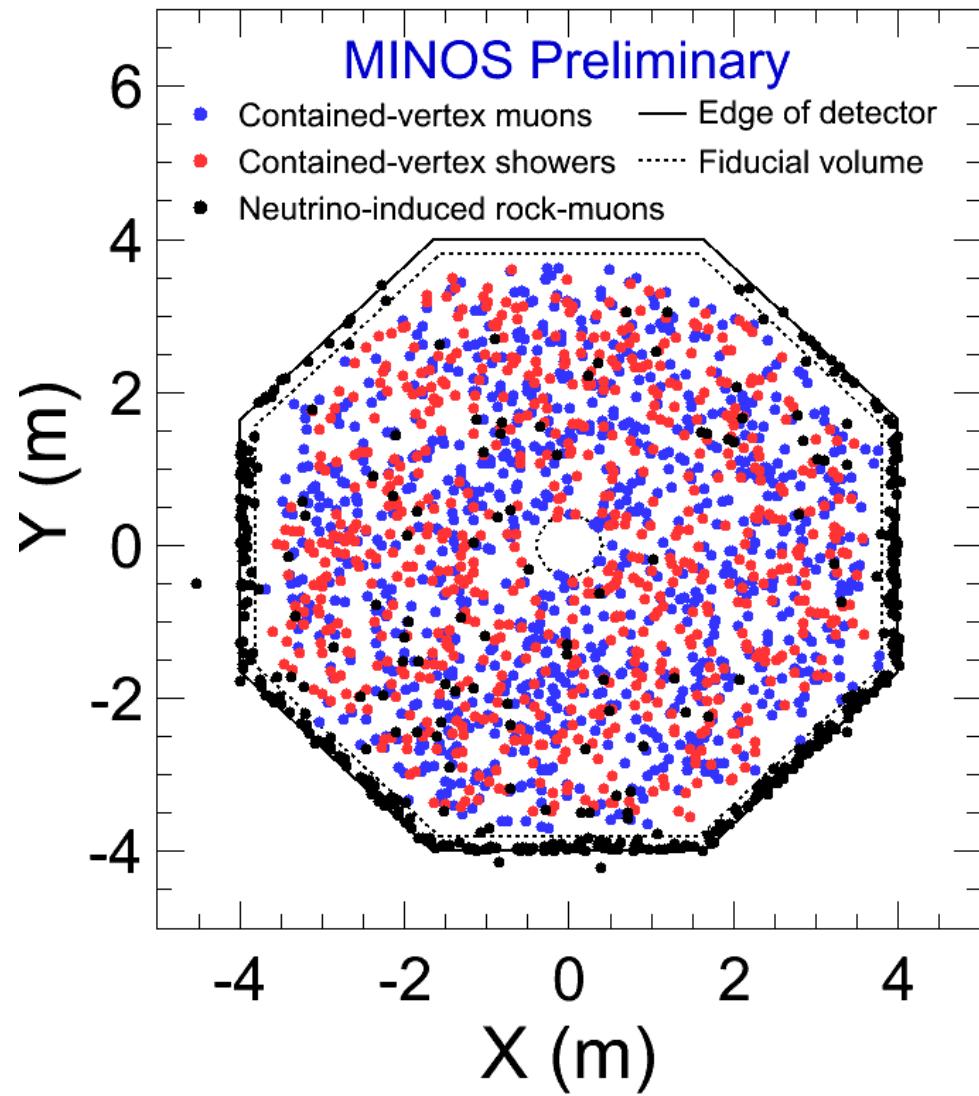
in neutrino mode

No oscillation Prediction: 536  
Observed: 414

$$|\Delta \bar{m}^2| = 2.60_{-0.23}^{+0.28} \times 10^{-3} \text{ eV}^2$$
$$\sin^2(2\bar{\theta}) > 0.80 \text{ (90% C.L.)}$$

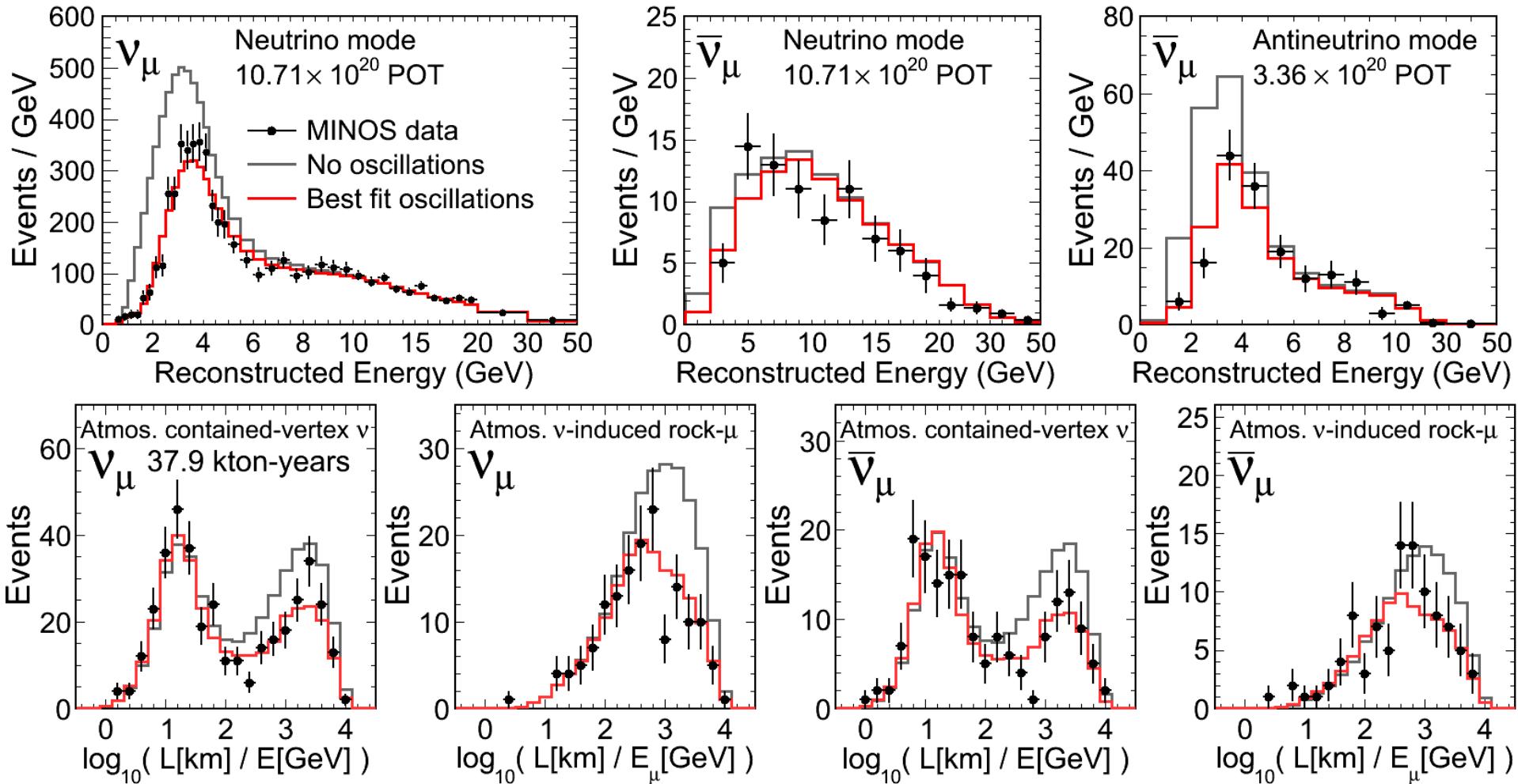
# Atmospheric Neutrinos & Antineutrinos

- 37.9 kton years of atmospheric neutrino data since 2003
- 2072 additional observed events
  - 905 contained-vertex muon events
  - 466 neutrino-induced rock-muon events
  - 701 contained-vertex shower events

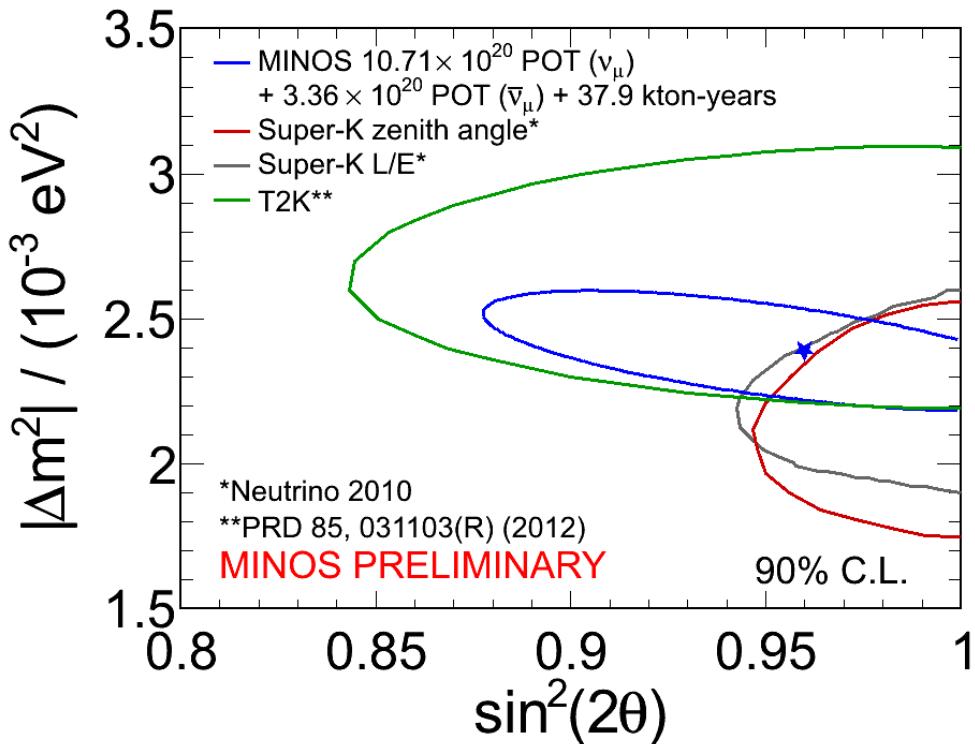


# Atmospheric Neutrinos & Antineutrinos

MINOS PRELIMINARY



# MINOS Combined Full Exposure Contours



Combined neutrino/antineutrino oscillation parameters (joint fit):

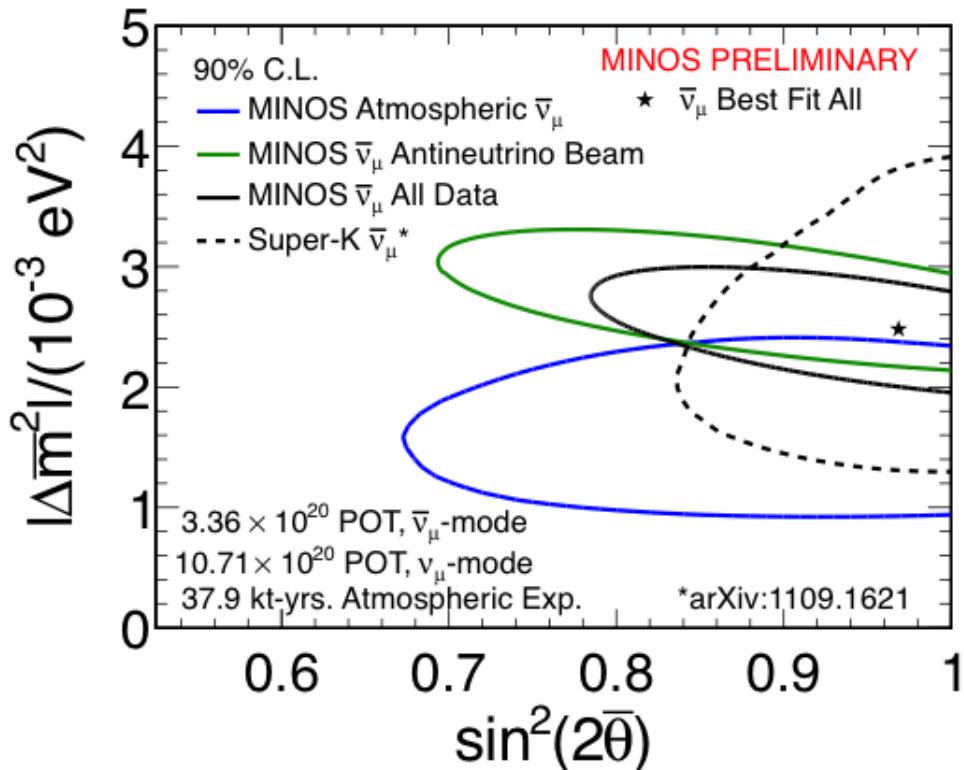
$$|\Delta m^2| = 2.39_{-0.10}^{+0.09} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) = 0.96_{-0.04}^{+0.04}$$

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

All MINOS beam and atmospheric neutrino data in a 2-flavor oscillation parameter maximum likelihood fit (assumes neutrinos and antineutrinos oscillate the same)

# MINOS Combined Antineutrino Contours



$$|\Delta\bar{m}^2| = 2.48_{-0.27}^{+0.22} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.97_{-0.08}^{+0.03}$$

$$\sin^2(2\bar{\theta}) > 0.83 \text{ (90% C.L.)}$$

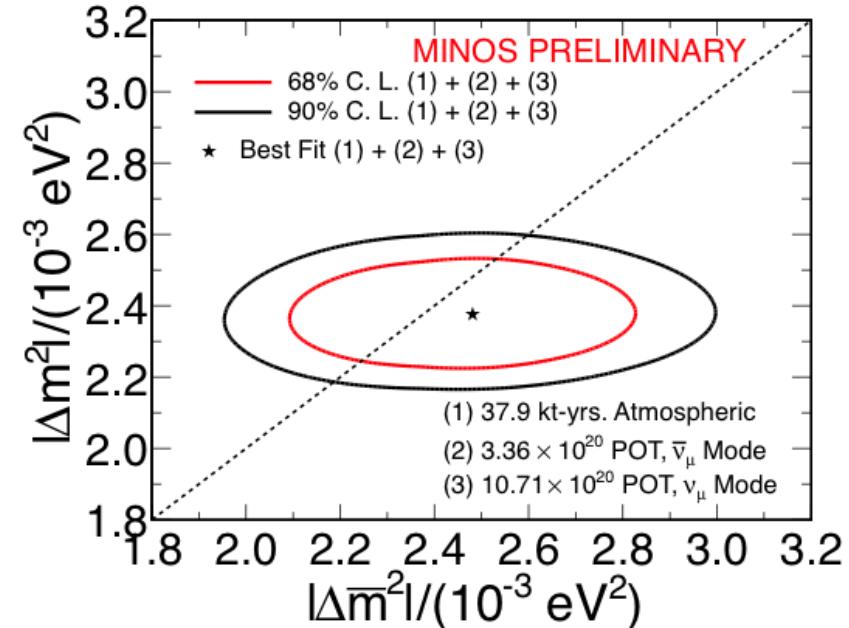
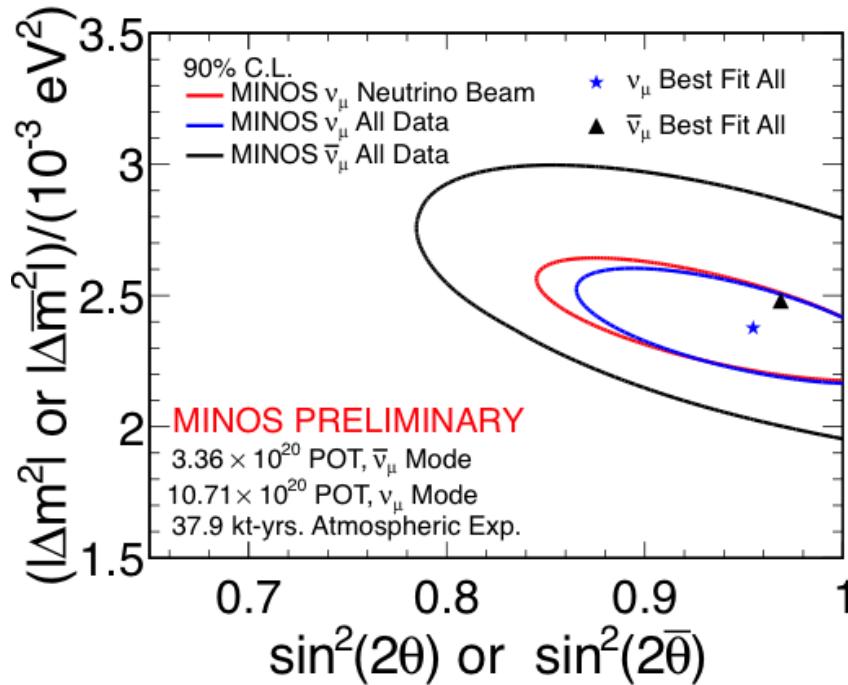
$$|\Delta m^2| = 2.39_{-0.10}^{+0.09} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) = 0.96_{-0.04}^{+0.04}$$

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

All MINOS beam and atmospheric samples in a four parameter fit (neutrinos and antineutrino may oscillate differently)

# Comparing Neutrinos and Antineutrinos



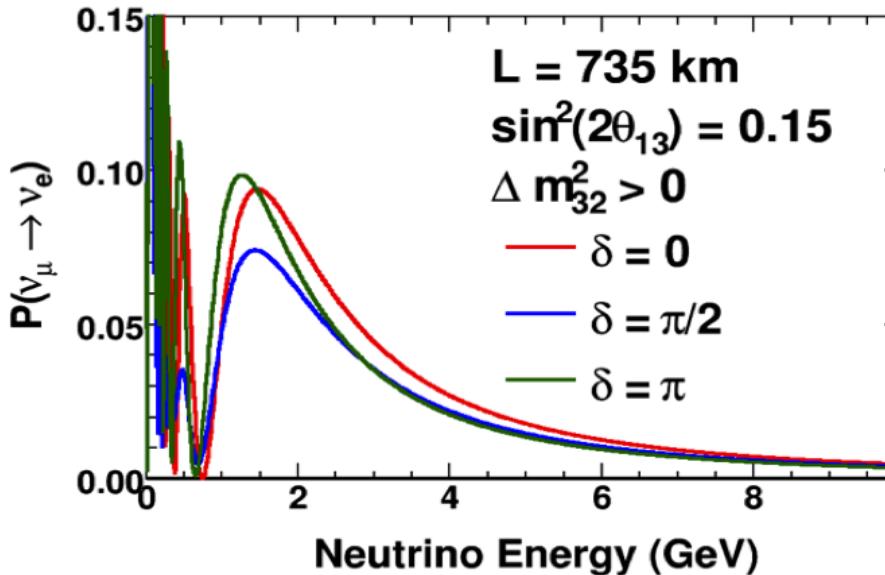
$$|\Delta \bar{m}^2| - |\Delta m^2| = 1.0_{-2.8}^{+2.4} \times 10^{-4} \text{ eV}^2$$

The new data resolves the tension between neutrino & antineutrino parameters in the first batch of data

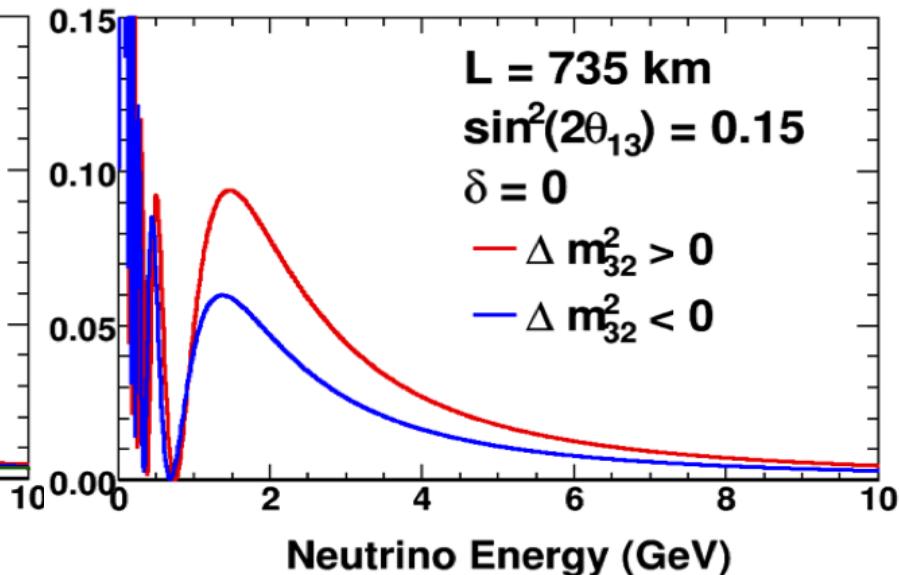
# $\nu_e$ Appearance Measurement

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(\frac{1.267 \Delta m_{31}^2 L}{E}\right) + \dots$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \sin^2(\bar{\theta}_{23}) \sin^2(2\bar{\theta}_{13}) \sin^2\left(\frac{1.267 \Delta \bar{m}_{31}^2 L}{E}\right) + \dots$$



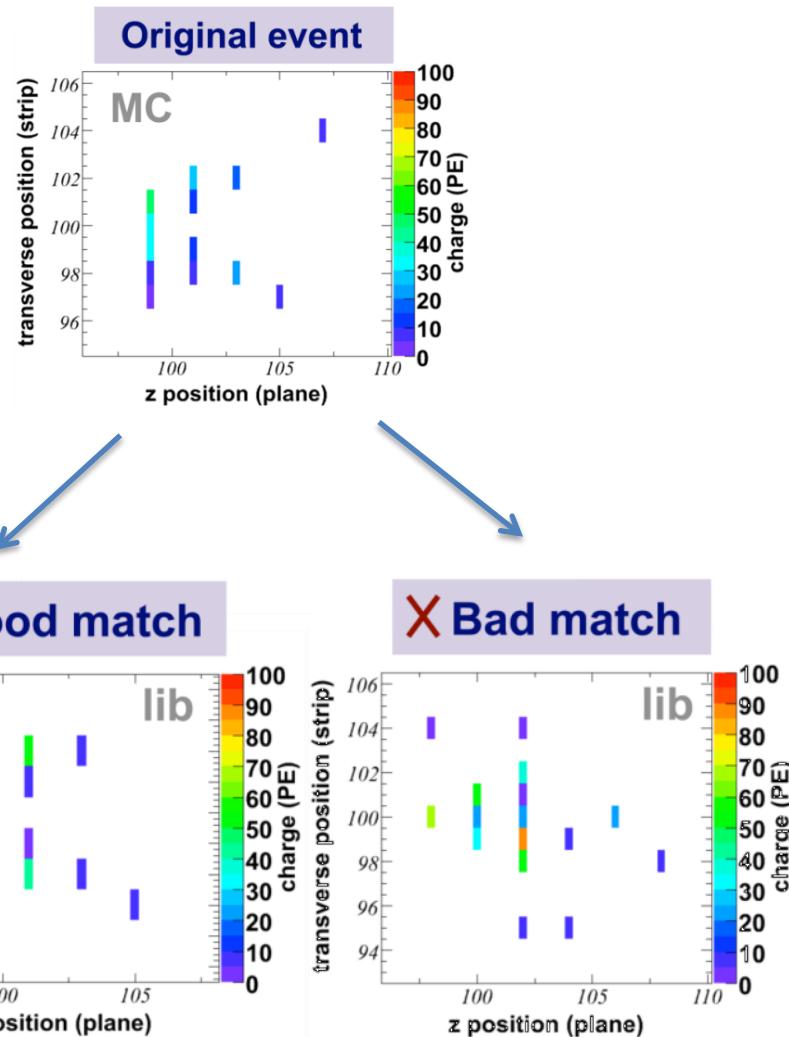
$$\text{if } \delta_{CP} \neq 0, P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



In matter,  $\nu_e$  CC scattering modifies oscillation probability ~30% in MINOS

sensitive to neutrino mixing angle  $\theta_{13}$ ,  $\delta_{CP}$ , mass ordering

# Library Event Matching (LEM) Particle ID



- Cannot identify electrons in an event-by-event basis due to the coarse sampling
- Library Event Matching (LEM)
  - Compare candidate events to a library of MC events strip-by-strip (raw detector hits information)
  - PID based on properties from the best matched library candidate events
- Sensitivity improvement
  - 15% from LEM over neutral network only
  - 12% more from fitting 3 bins of LEM PID times 5 bins of reconstructed energy
  - More than 20% from analysis improvements alone

# Electron Appearance in FHC and RHC Beam

## $\nu$ mode

Expected (LEM>0.7):

69.1 (background, if  $\theta_{13}=0$ )

26.0 (signal, if  $\sin^2(2\theta_{13})=0.1$ )

Observe:

88 events

## $\bar{\nu}$ mode

Expected (LEM>0.7):

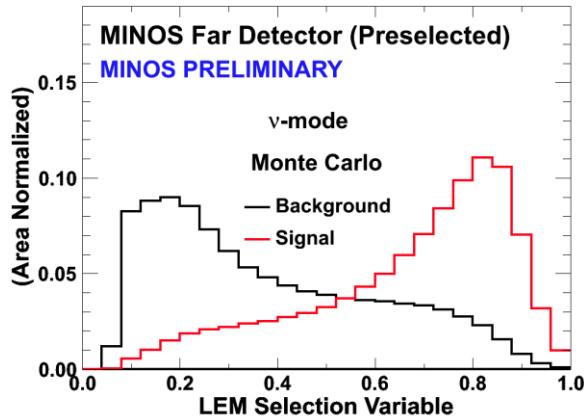
10.5 (background , if  $\theta_{13}=0$ )

3.1 (signal, if  $\sin^2(2\theta_{13})=0.1$ )

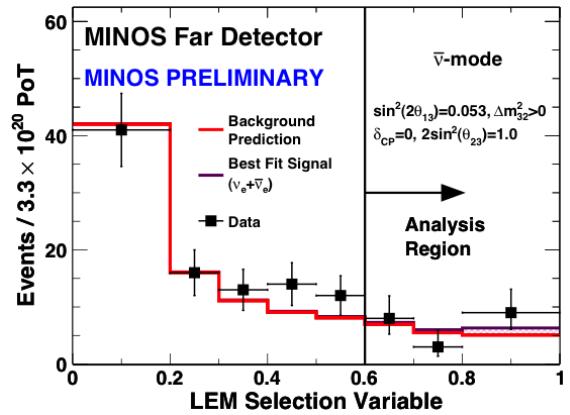
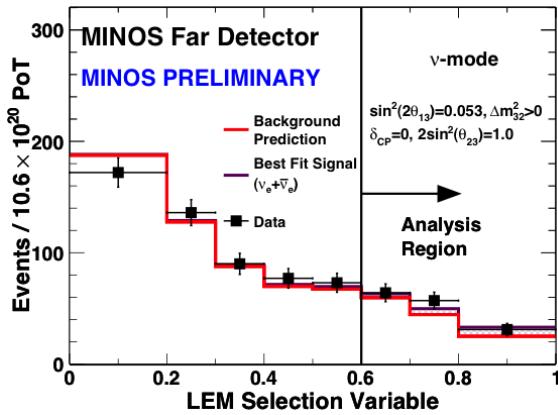
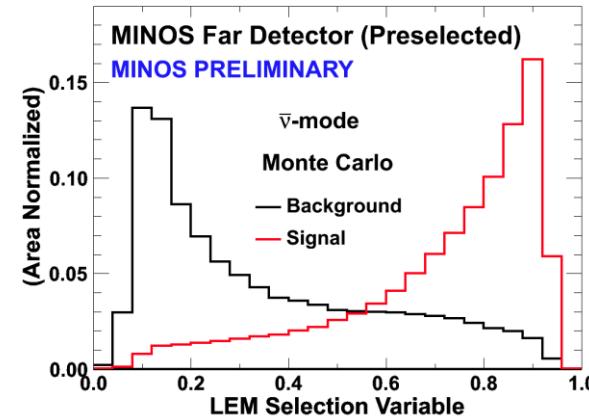
Observe:

12 events

$10.6 \times 10^{20}$  POT ( $\nu$  mode)



$3.3 \times 10^{20}$  ( $\bar{\nu}$  mode)



# $\nu_e$ Appearance: $\nu$ and $\bar{\nu}$ Combined Contour

for  $\delta_{CP}=0$ ,  $\sin^2(2\theta_{23})=1$ ,

normal hierarchy:

$\sin^2(2\theta_{13})=0.053$  at best fit

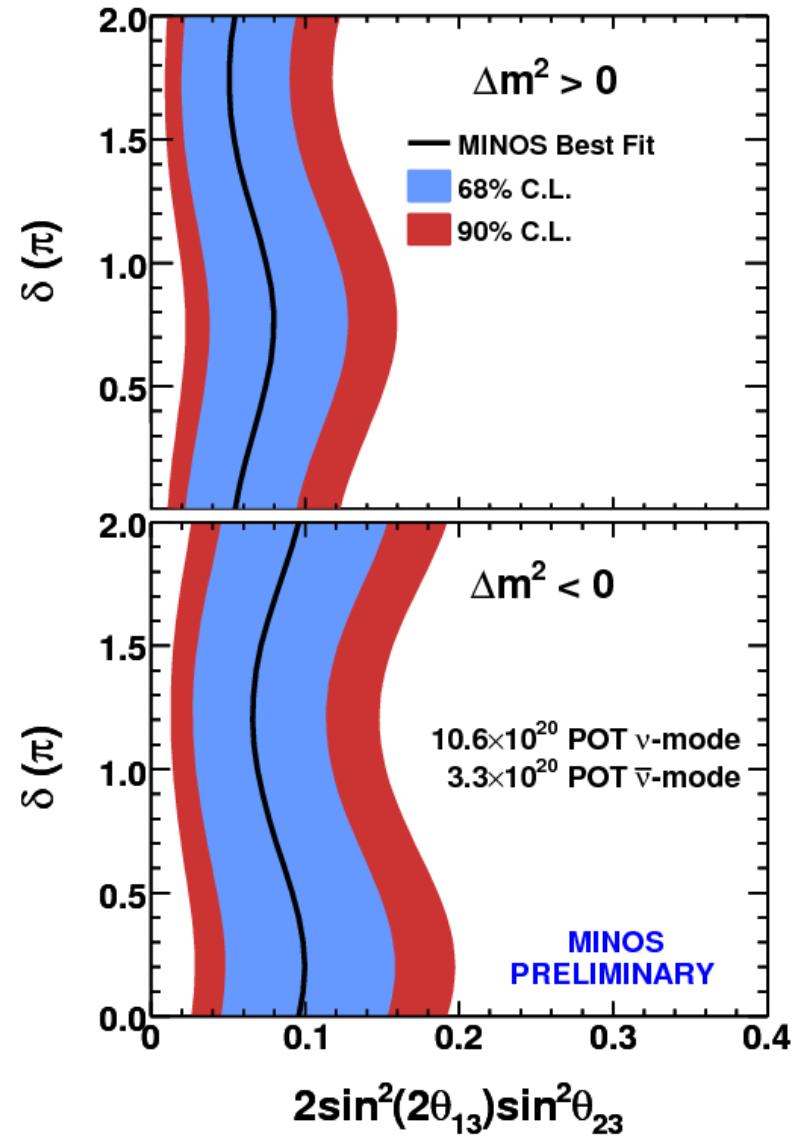
$0.01 < \sin^2(2\theta_{13}) < 0.12$  at 90% C.L.

inverted hierarchy:

$\sin^2(2\theta_{13})=0.094$  at best fit

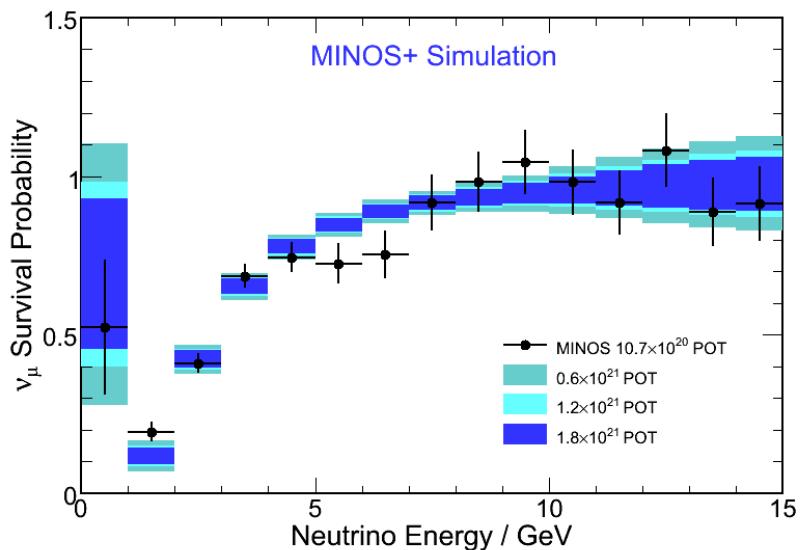
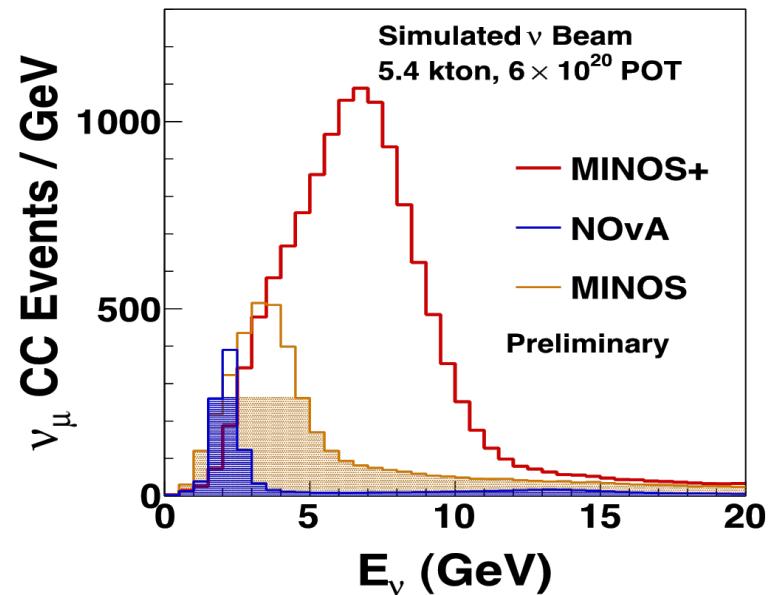
$0.03 < \sin^2(2\theta_{13}) < 0.19$  at 90% C.L.

$\sin^2(2\theta_{13})=0$  excluded at 96% C.L.



# MINOS → MINOS+

- MINOS will continue to run in the NOvA era
- ME beam peaks above the oscillation dip on axis
- Beam power: 320 kW → 700 kW
- Roughly 4000 far detector  $\nu_\mu$  CC events/year
- Precision studies of oscillation shape
- Sensitivity to exotic signals



# Summary of New MINOS Results

- MINOS has completed its low-energy running after  $1.5 \times 10^{21}$  POT
- Analysis with Beam + Atmospheric neutrinos finds:

muon neutrino disappearance	muon antineutrino disappearance
$ \Delta m^2  = 2.39_{-0.10}^{+0.09} \times 10^{-3} \text{ eV}^2$	$ \Delta \bar{m}^2  = 2.48_{-0.27}^{+0.22} \times 10^{-3} \text{ eV}^2$
$\sin^2(2\theta) = 0.96_{-0.04}^{+0.04}$	$\sin^2(2\bar{\theta}) = 0.97_{-0.08}^{+0.03}$
$\sin^2(2\theta) > 0.90$ (90% C.L.)	$\sin^2(2\bar{\theta}) > 0.83$ (90% C.L.)
- Electron neutrino appearance:

$0.01(0.03) < \sin^2(2\theta_{13}) < 0.12(0.19)$  at 90% C.L.  
for  $\delta_{CP} = 0$ ,  $\sin^2(2\theta_{23}) = 1$ , normal (inverted) hierarchy  
 $\sin^2(2\theta_{13}) = 0$  excluded at 96%
- MINOS+ has an exciting program with medium energy running

# Acknowledgments

- The MINOS Collaboration would like to thank the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the MINOS experiment.
- We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and the Minnesota DNR for hosting us.

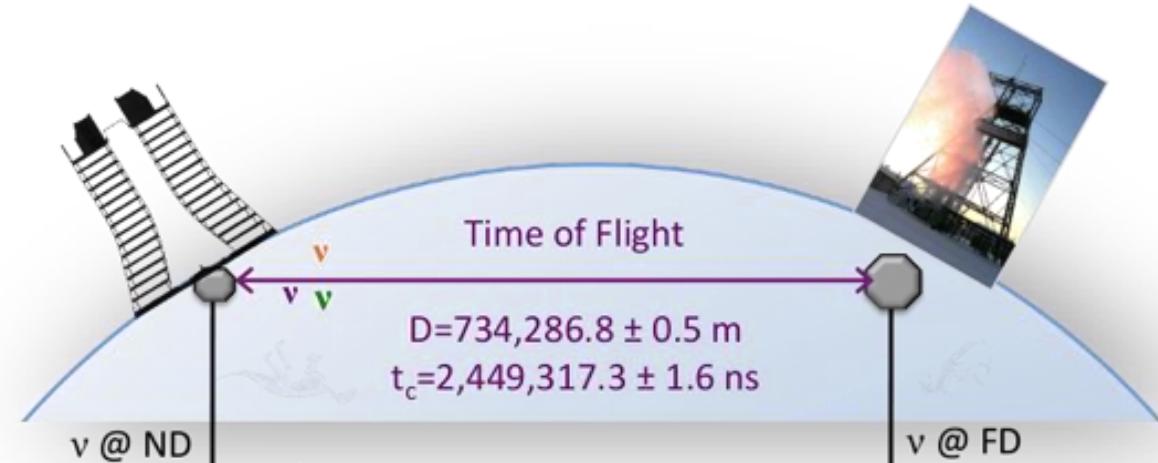


Minnesota  
Department of Natural Resources



# Back Up

# Measure Neutrino Time of Flight



- Initial result after first year of data indicated neutrinos arrived at FD earlier than expected:  
 $126 \pm 32 \text{ (stat.)} \pm 64 \text{ (syst.)} \text{ ns}^{\dagger}$
- We revisit this analysis with a factor of 8 more events and a refined systematic error analysis

<sup>†</sup>Phys. Rev. D76 (2007) 072005

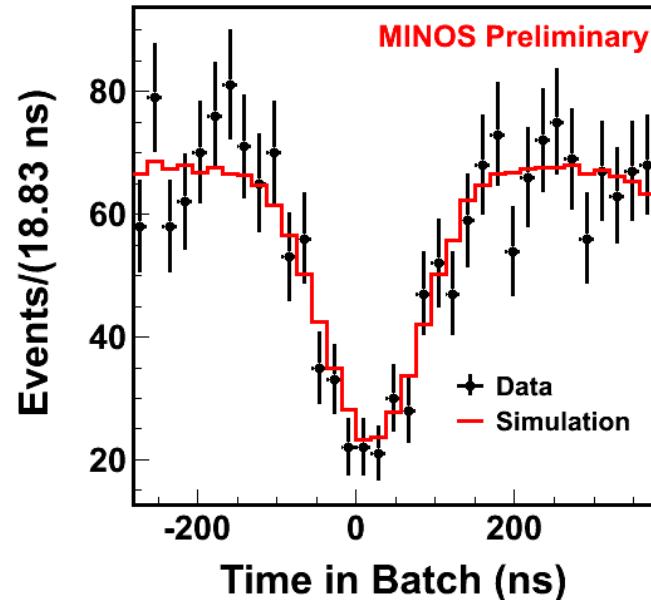
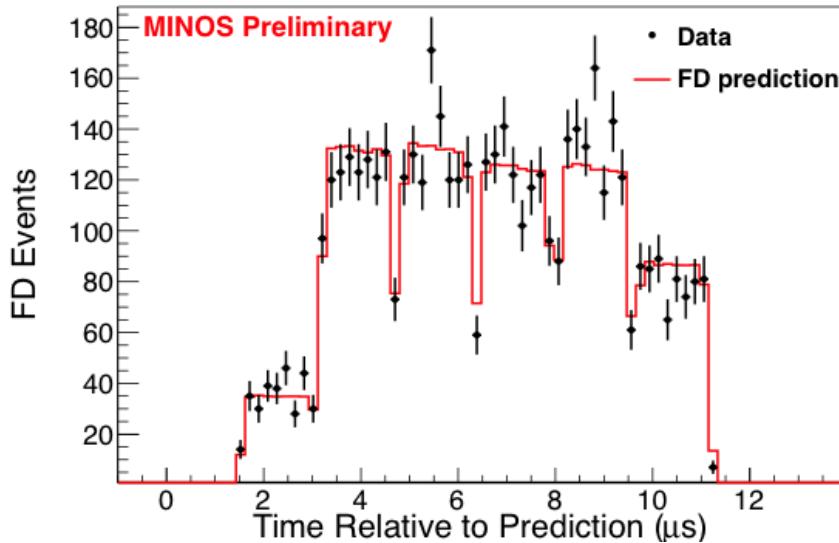
# Major Systematic Uncertainties

- Arrival times as recorded at each detector must be corrected for (sizeable) cable delays and electronics latencies
- Dominant systematics in first analysis improved:

	2007	2012
GPS antenna to ND cable delay	$1275 \pm 29$ ns	$1309 \pm 1$ ns
GPS antenna to FD cable delay	$5140 \pm 46$ ns	$5098 \pm 2$ ns

- Relative ND/FD electronics latencies determined by special purpose Auxiliary Detector with independent readout:  **$\pm 1$  ns**
- Total systematic from cable/electronic latency:  **$\pm 4$  ns**

# TOF Analyses and Results



- Full spill approach
    - event time within spill in ND predicts FD distribution
    - Vary time of flight to match data
  - Wrapped Spill approach
    - Measure event time within batch
    - Find batch gap time in each detector
    - Subtract for time of flight
- neutrinos arrive earlier than expected by:
- $18 \pm 11 \text{ (stat.)} \pm 29 \text{ (syst.)} \text{ ns}$
- $11 \pm 11 \text{ (stat.)} \pm 29 \text{ (syst.)} \text{ ns}$
- The two approaches give consistent results
  - The two results are consistent with neutrinos traveling at the speed of light
  - Analysis with improved timing system pending