Measuring ν and $\bar{\nu}$ with MINOS and MINOS+

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Project X Physics Study Workshop
Fermilab

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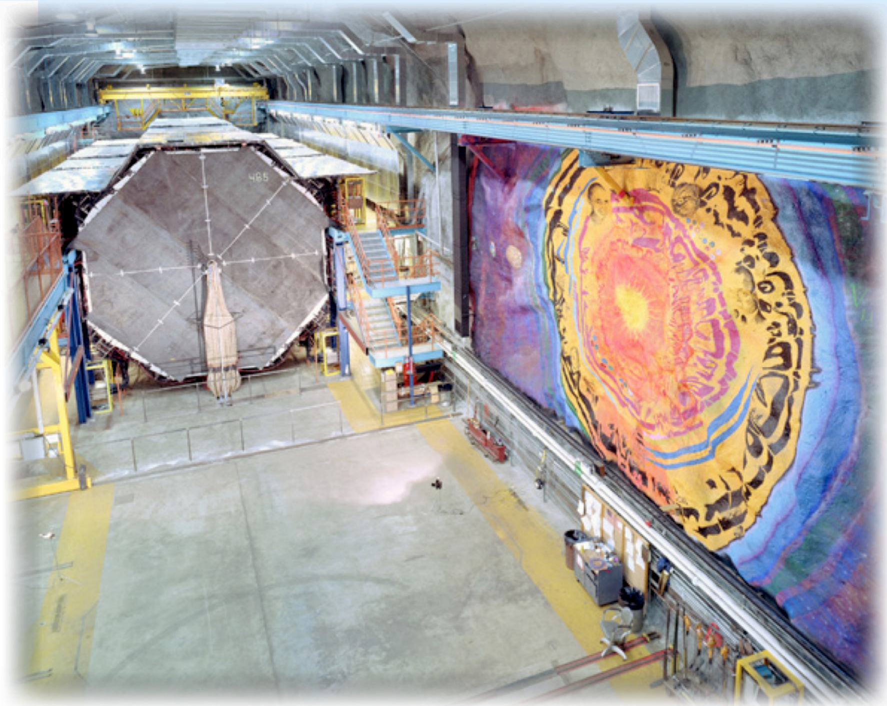


Outline

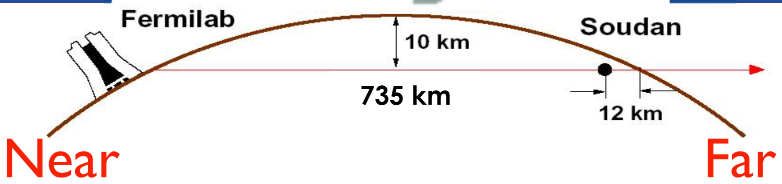
- The MINOS Concept
- NuMI Neutrino and Antineutrino Running
- Disappearance Results
- Appearance Results
- MINOS+ Prospects

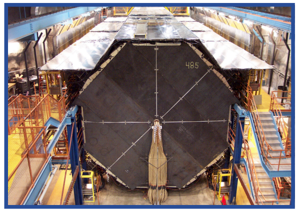
Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab Goias • Harvard • Holy Cross • IIT • Indiana • Iowa State • Minnesota-Twin Cities Minnesota-Duluth • Otterbein • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary

MINOS Overview

- **MINOS (Main Injector Neutrino Oscillation Search)**
  - High intensity **NuMI ν_μ beam** produced at Fermilab
  - **Near Detector** at Fermilab
  - **Far Detector**, 735 km away, in the Soudan mine, MN

- **Basic Concept:**
  - Compare Far Detector observations with extrapolation of Near Detector measurement to study neutrino oscillations

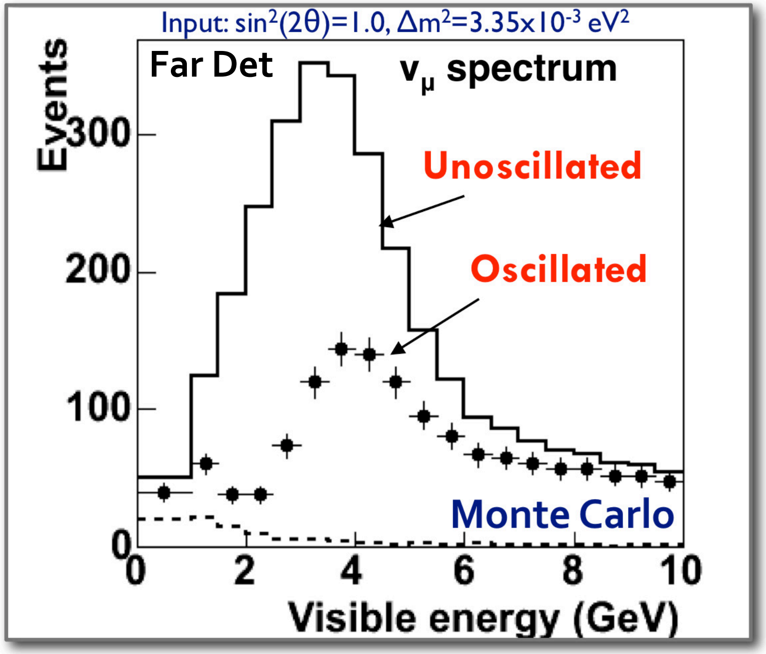


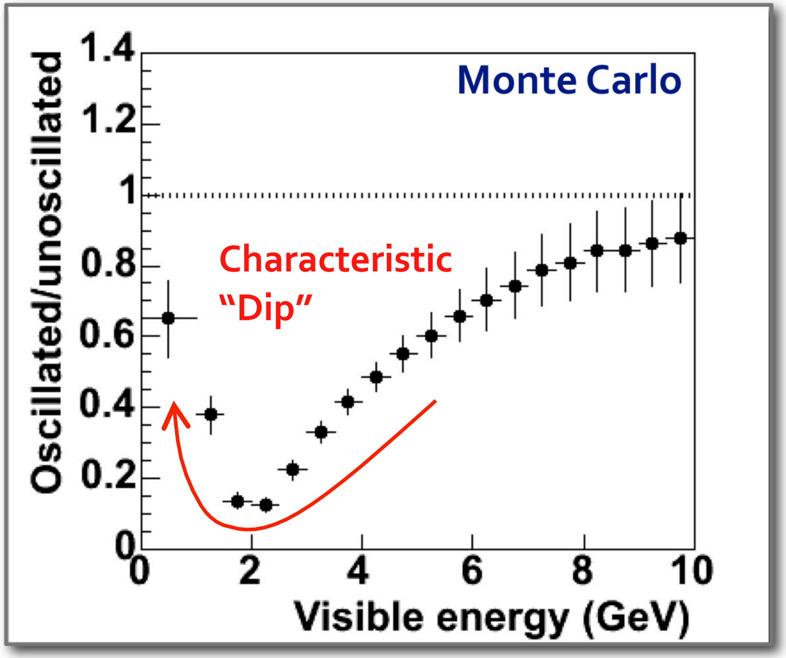


MINOS Oscillation Measurement

- Compare unoscillated Far Detector prediction from Near Detector with Far Detector measurement
  - Neutrino oscillations deplete rate and distort the energy spectrum

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23})\sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$





MINOS Oscillation Measurement

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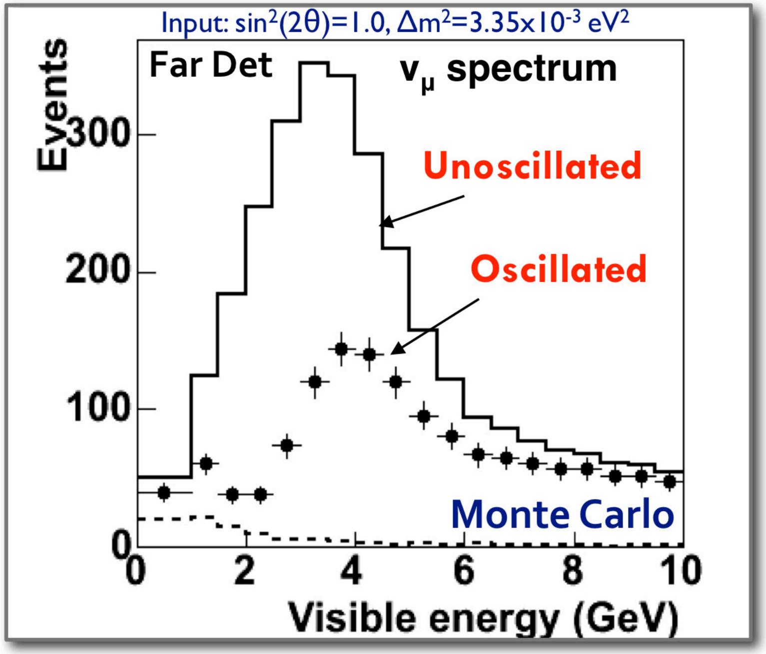
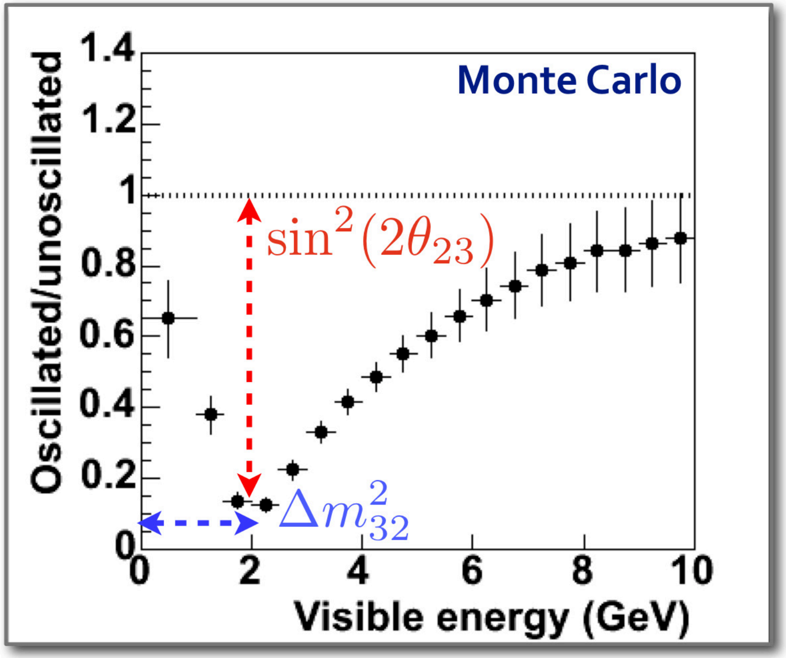
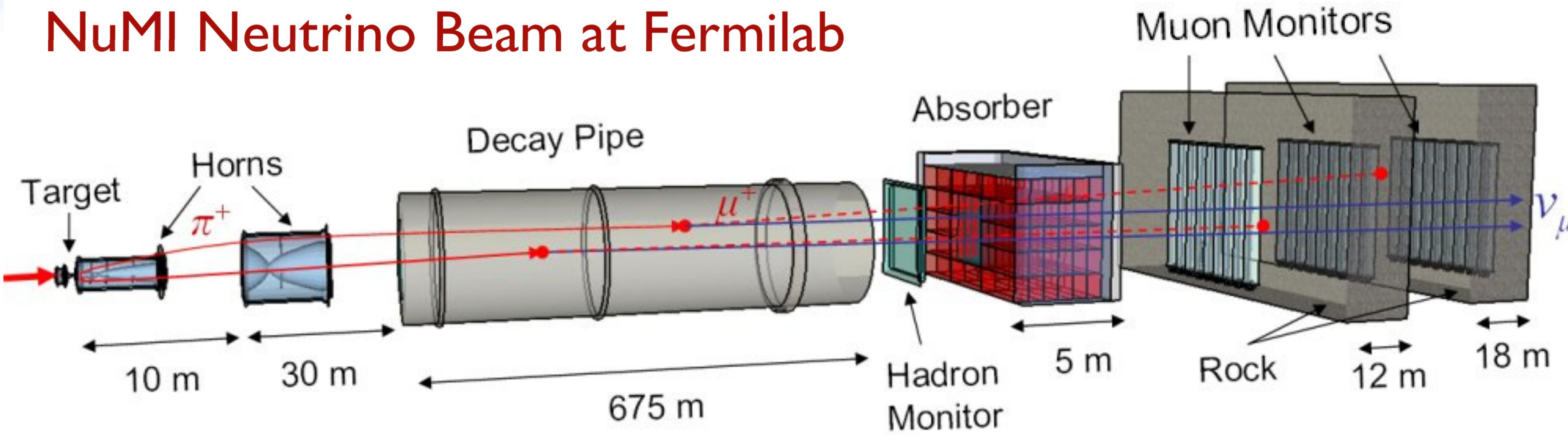
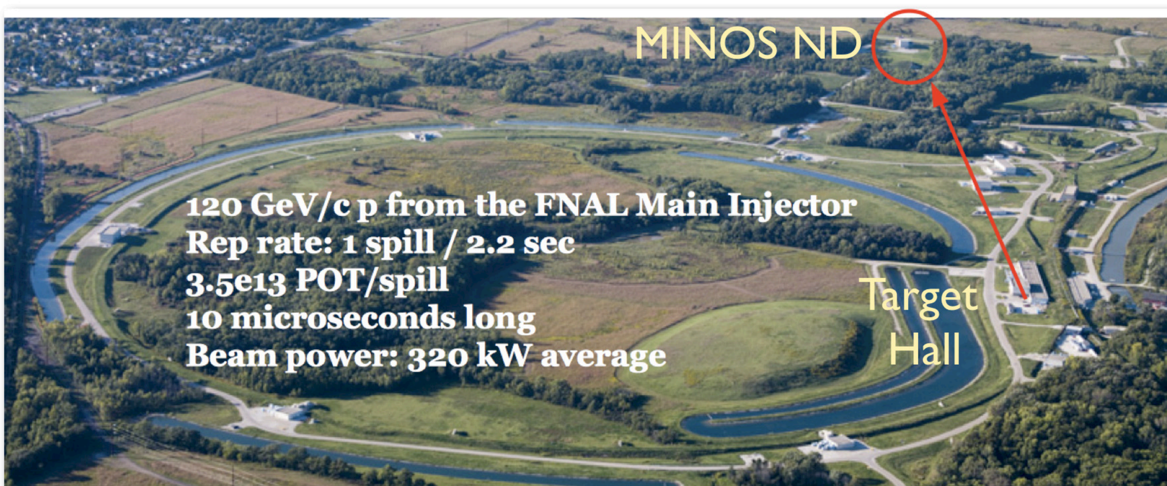
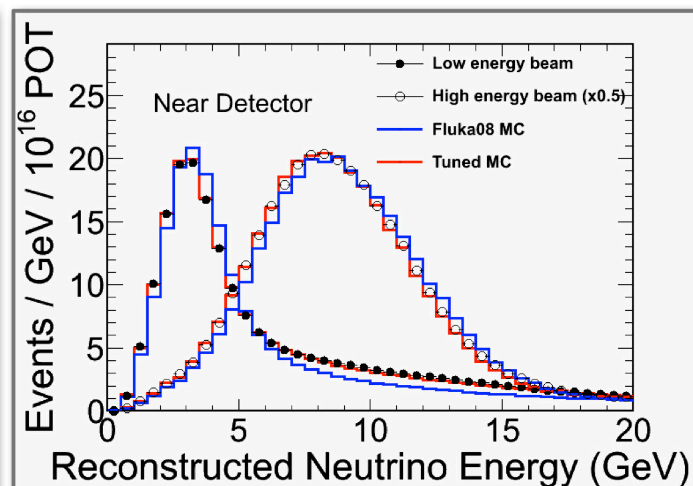




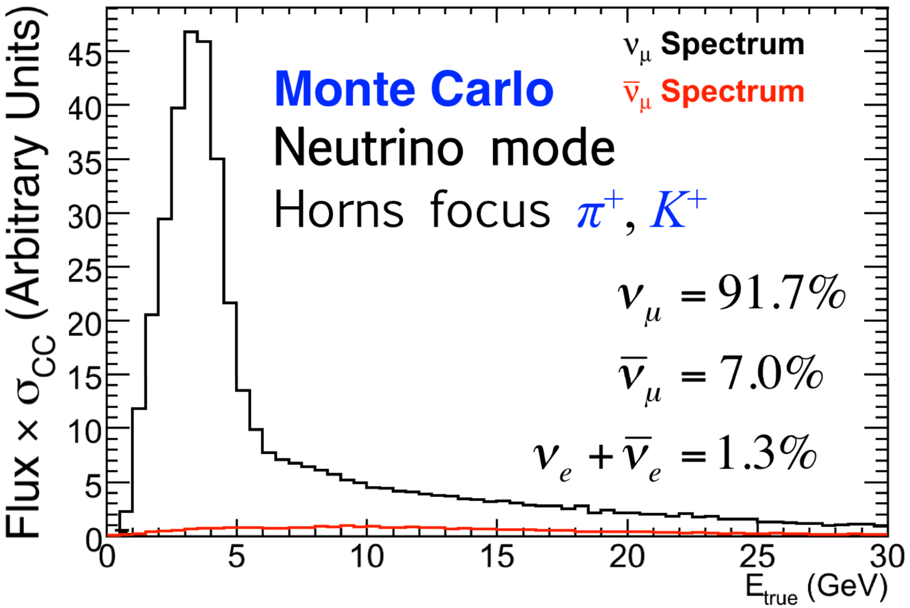
The NuMI Beam



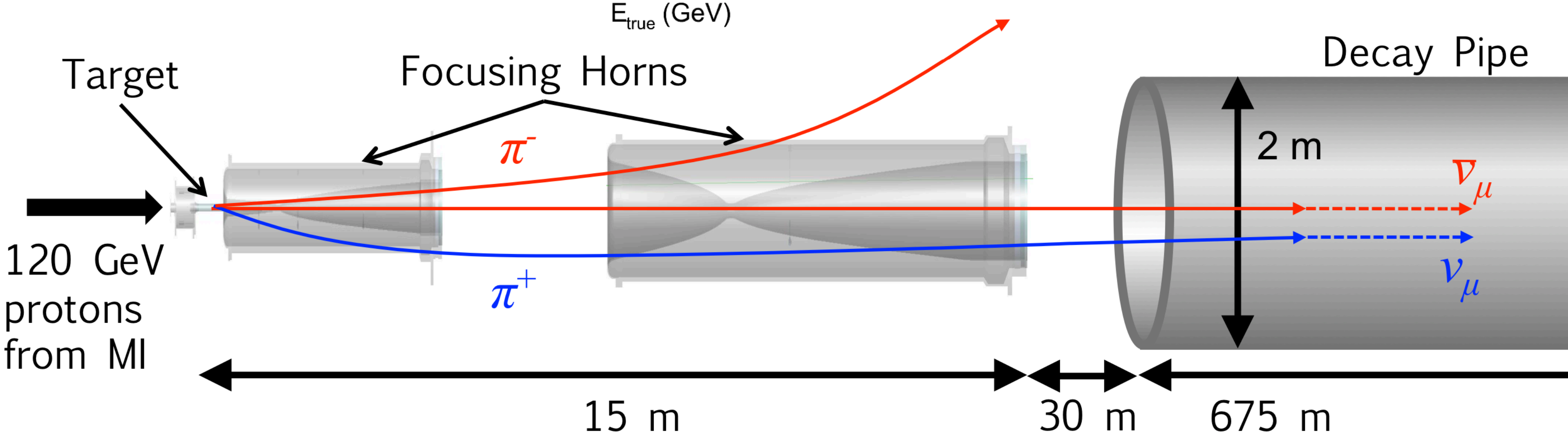




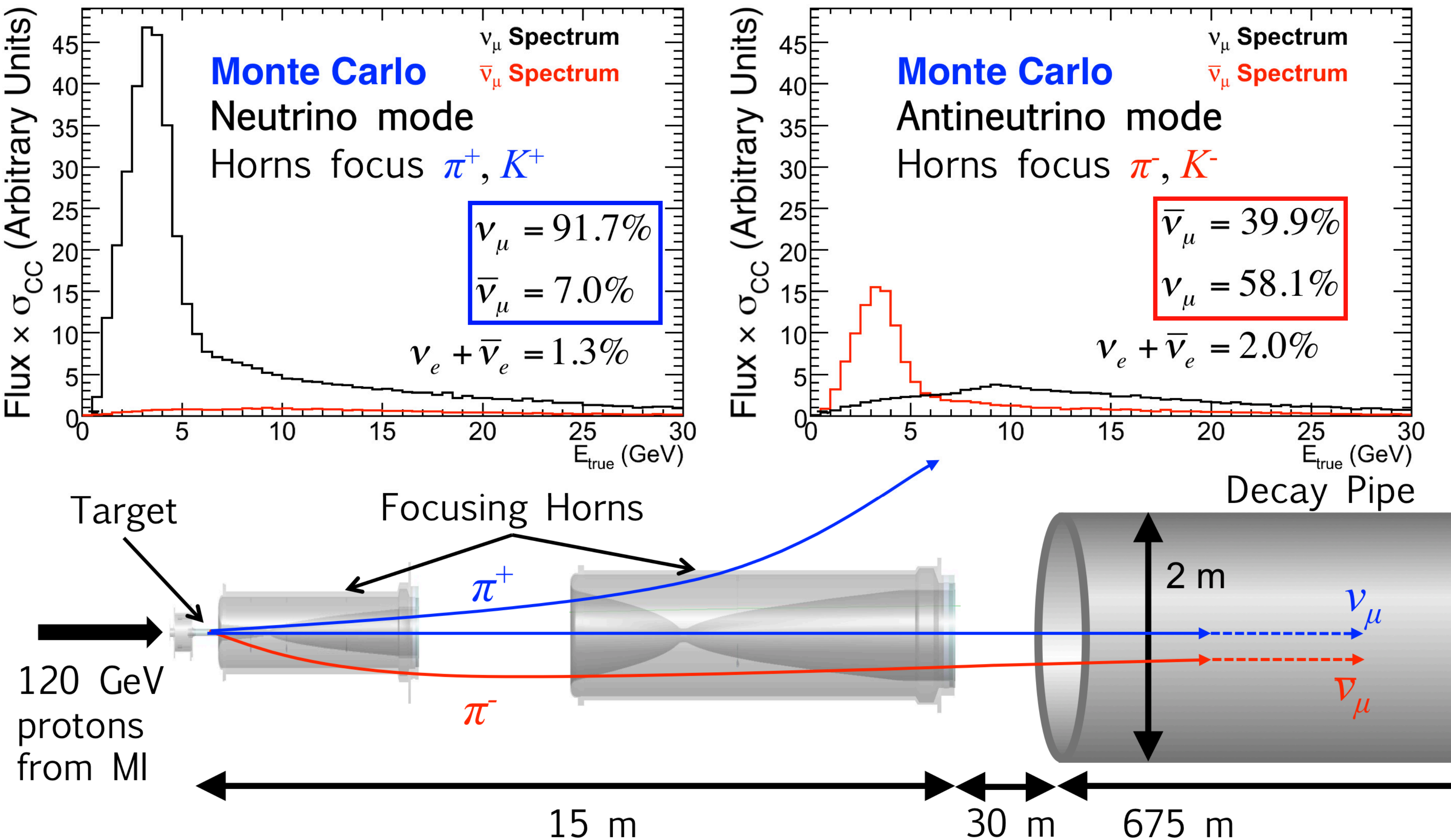
Neutrino Running



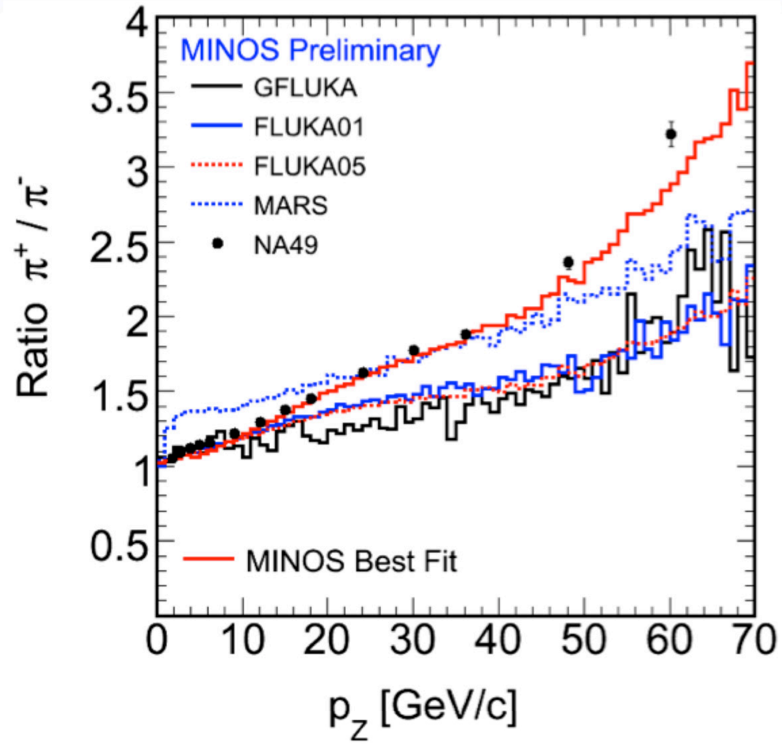
- Horns focus π^+, K^+, which decay into ν_μ
- Higher energy $\bar{\nu}_\mu$ from very forward π^-
- Most of MINOS beam data taken in this configuration



Creating a $\bar{\nu}_\mu$ Beam



Why is the $\bar{\nu}_\mu$ peak lower?



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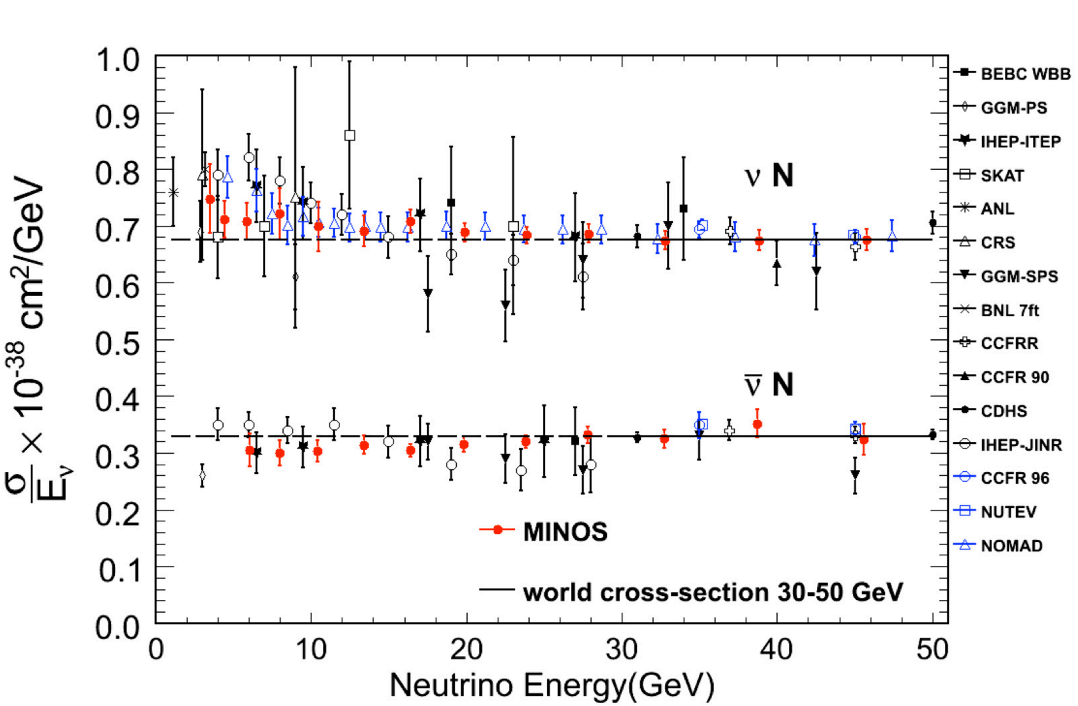
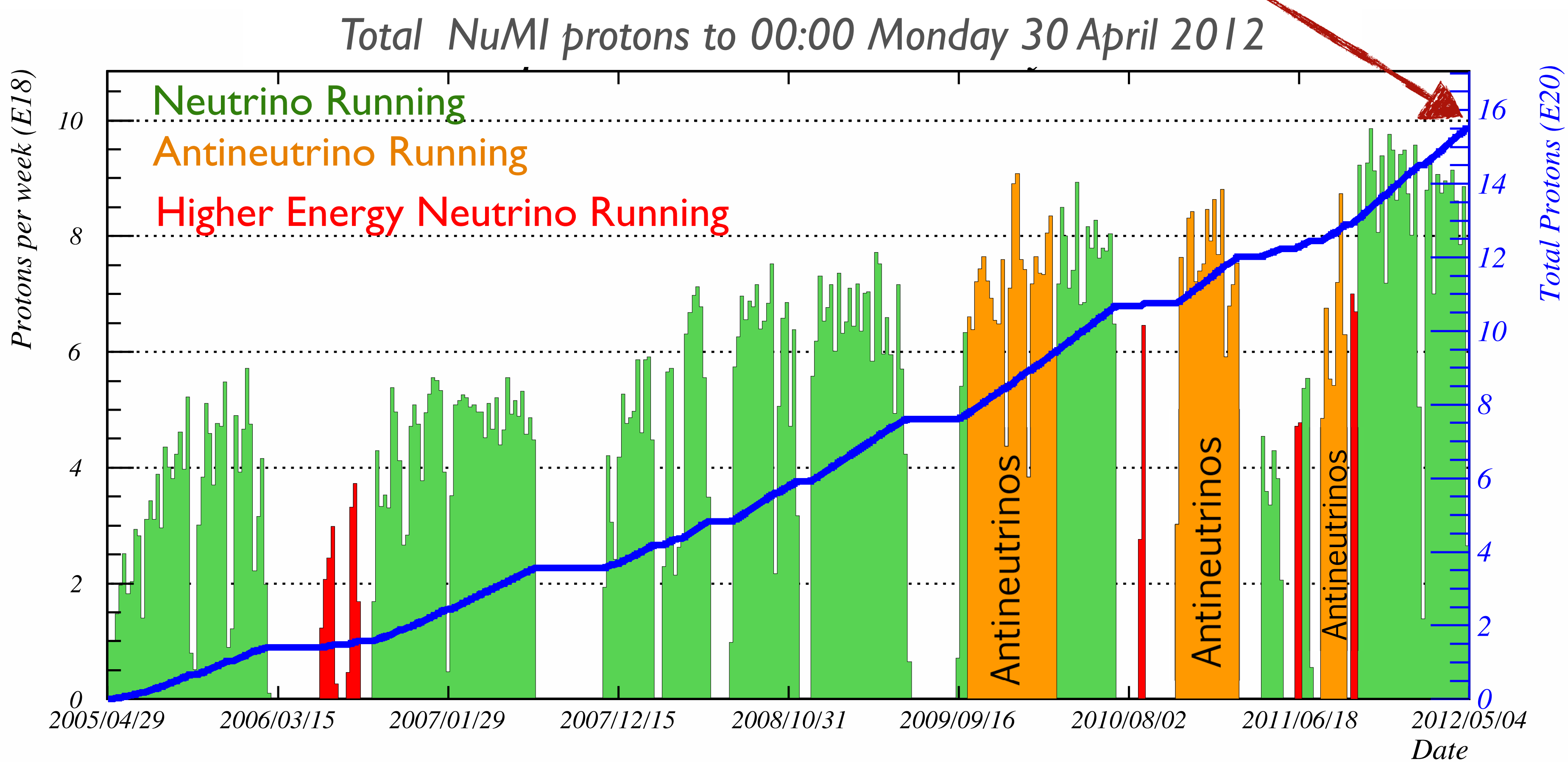


Phys. Rev. D 81 072002 (2010)

- Why is the $\bar{\nu}_\mu$ peak lower by a factor of 3?
  - ×1.3 from lower π^- production
  - ×2.3 from lower $\bar{\nu}_\mu$ cross section

Accumulated Beam Data

>15×10[20] protons-on-target delivered since 2005!



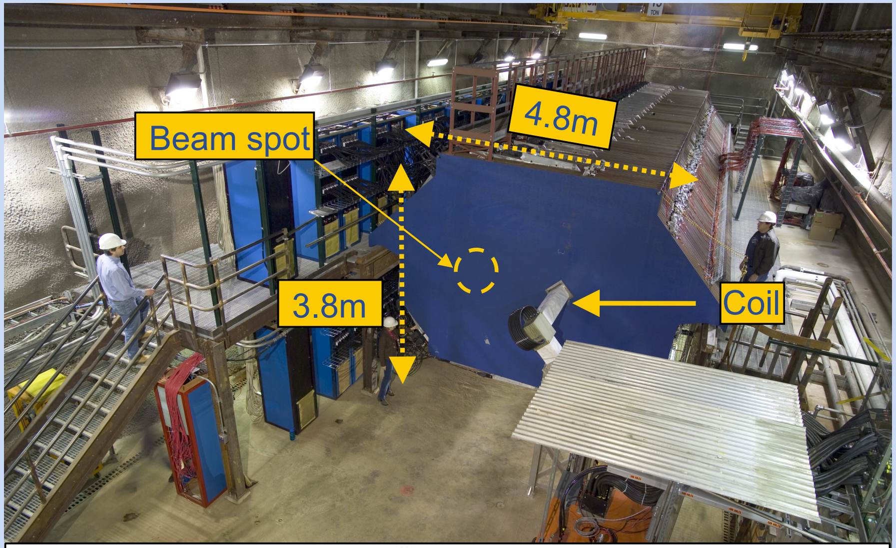
- 10.7×10^{20} POT in LE neutrino running
- 3.36×10^{20} POT in Antineutrino running

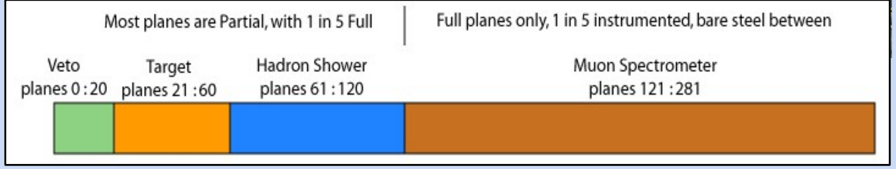
MINOS Detectors

- Magnetized tracking sampling calorimeters

Near Detector

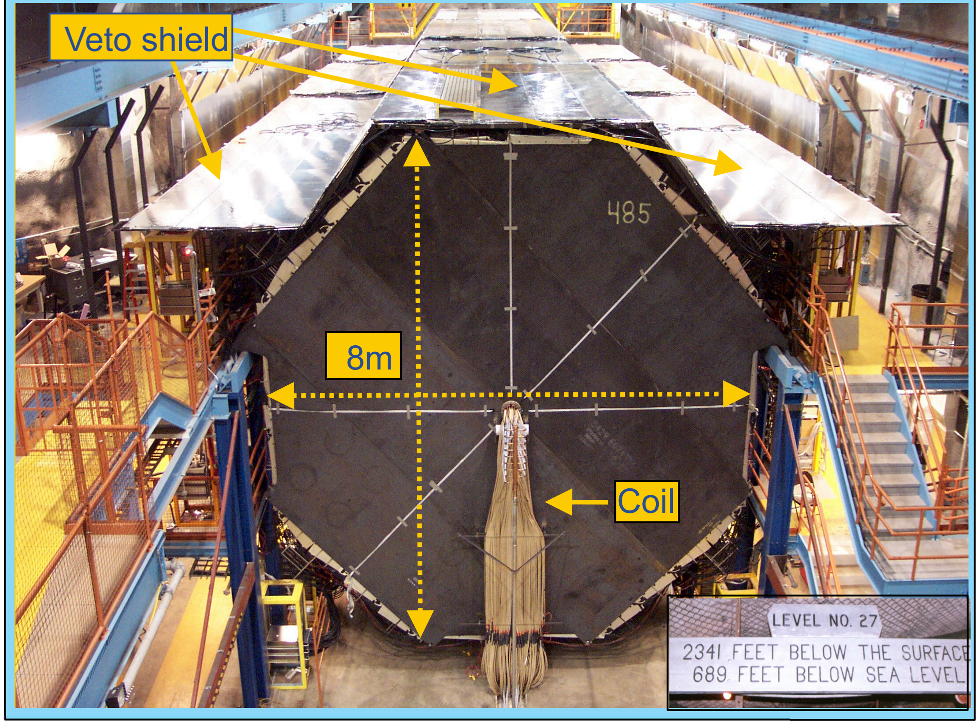
- ~1 kton (980 ton) total mass
- Located 1 km downstream of the target at Fermilab
- 100 m depth





Far Detector

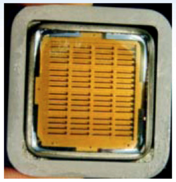
- 5.4 kton, 2 supermodules
- Located 735 km away in Soudan mine, MN
- 714 m depth



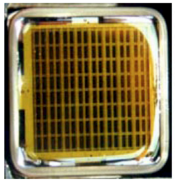
- Functionally equivalent: same segmentation, same materials, same mean B field

Detector Technology

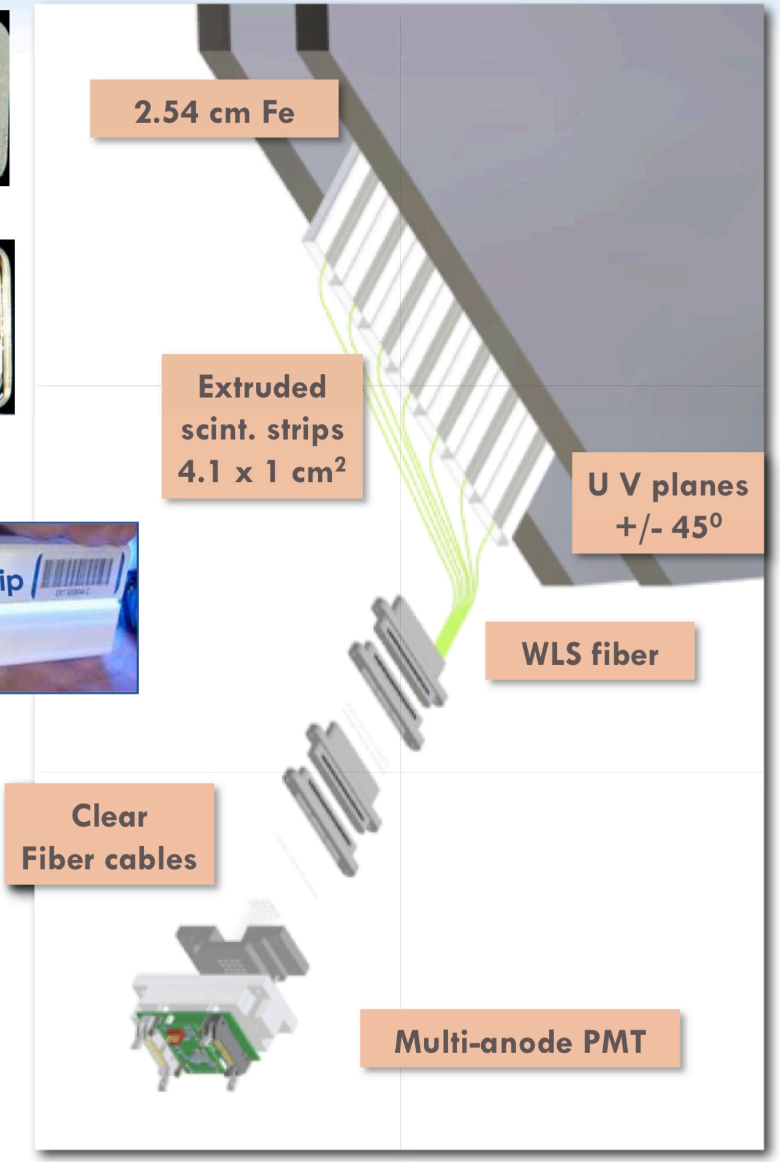
- Steel/Scintillator Tracking Calorimeters
  - 2.54 cm-thick steel plates (5.96 cm between plates)
  - 1 cm-thick, 4.1 cm-wide extruded polystyrene scintillator strips
- Both magnetized with <B field>~1.3T
  - Can measure muon energy from range in detector or from curvature in B field
  - Able to distinguish μ^+ from μ^-

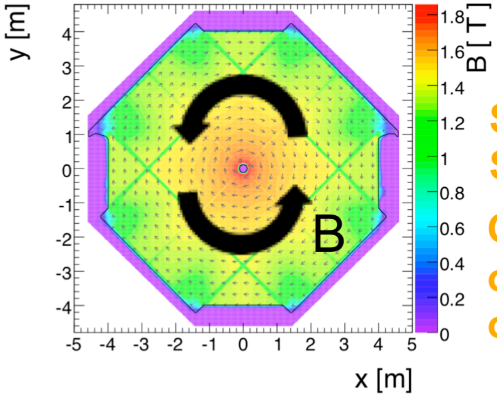


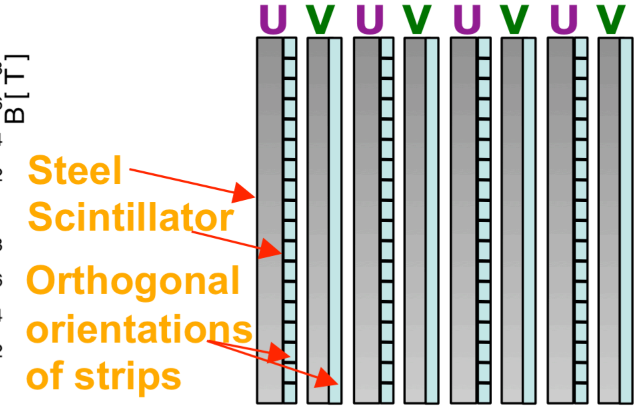
M16



M64

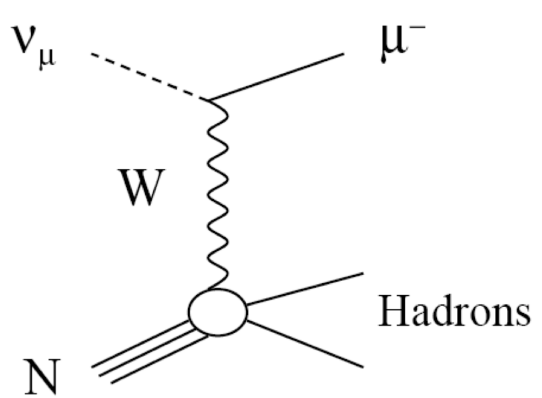


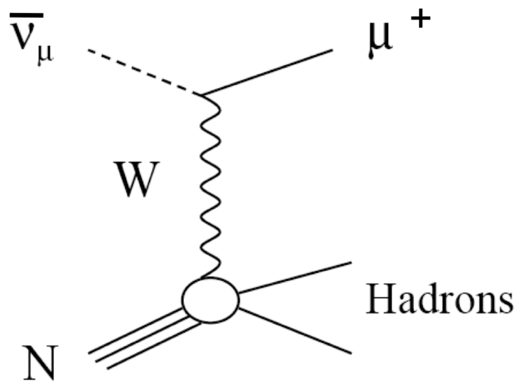


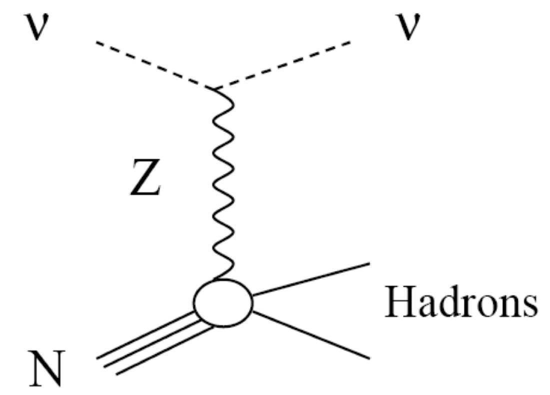


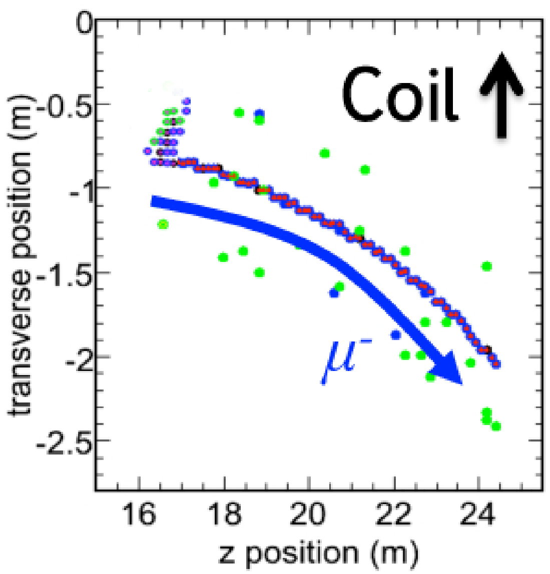
Event Topologies

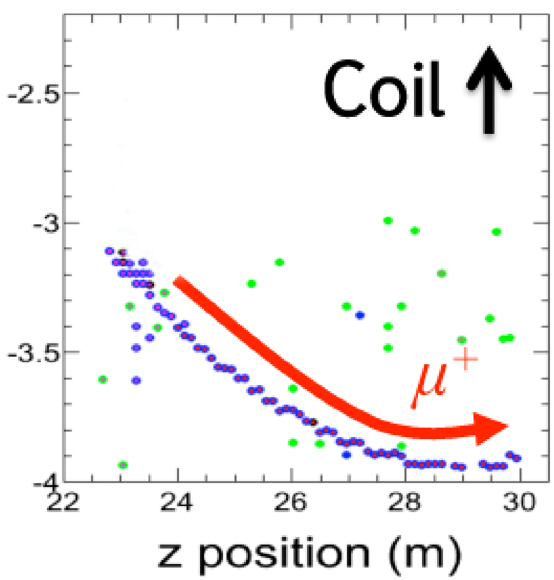
ν_μ CC Event	$\bar{\nu}_\mu$ CC Event	NC Event

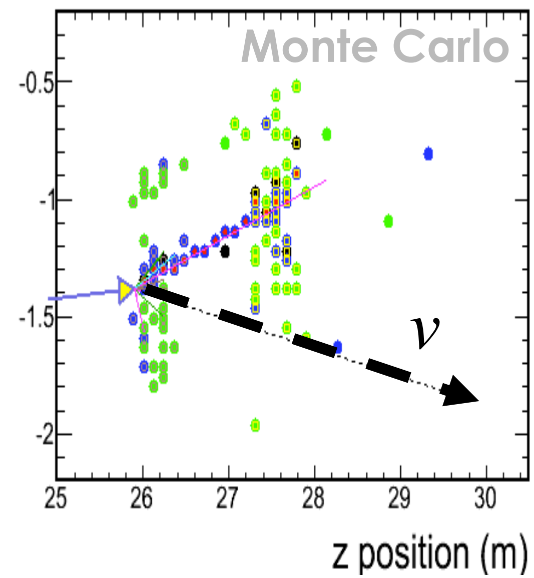






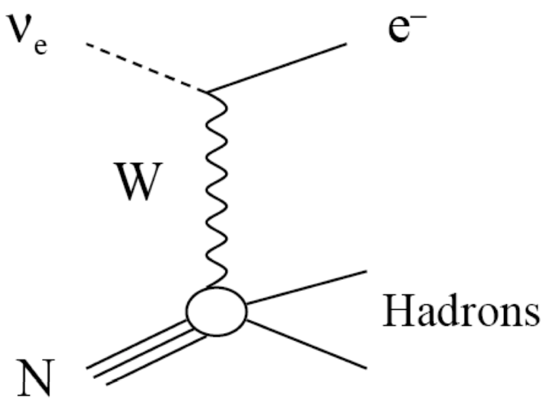


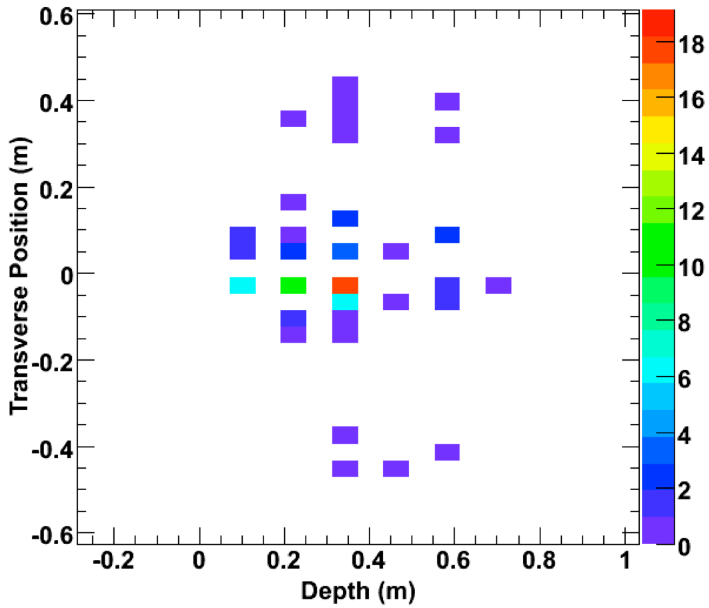




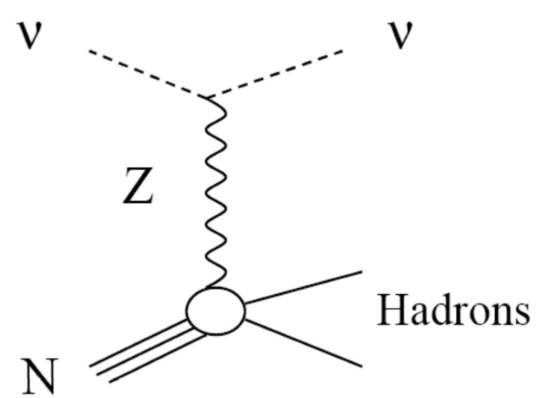
Event Topologies

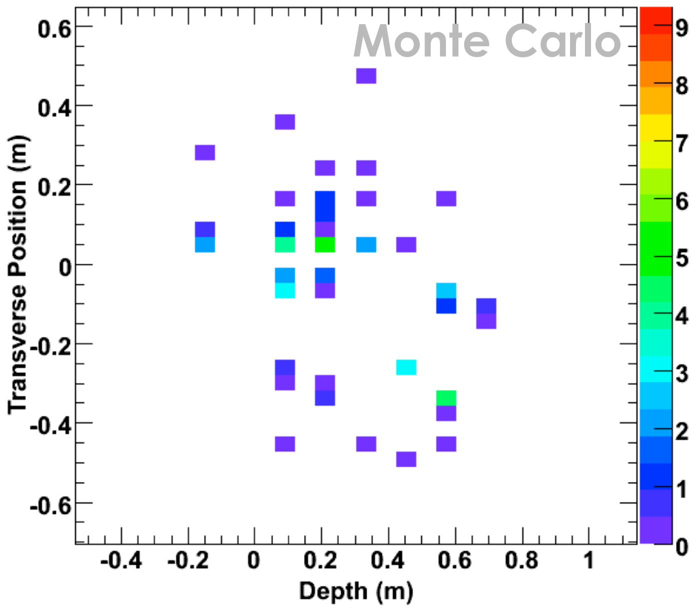
ν_e CC Event





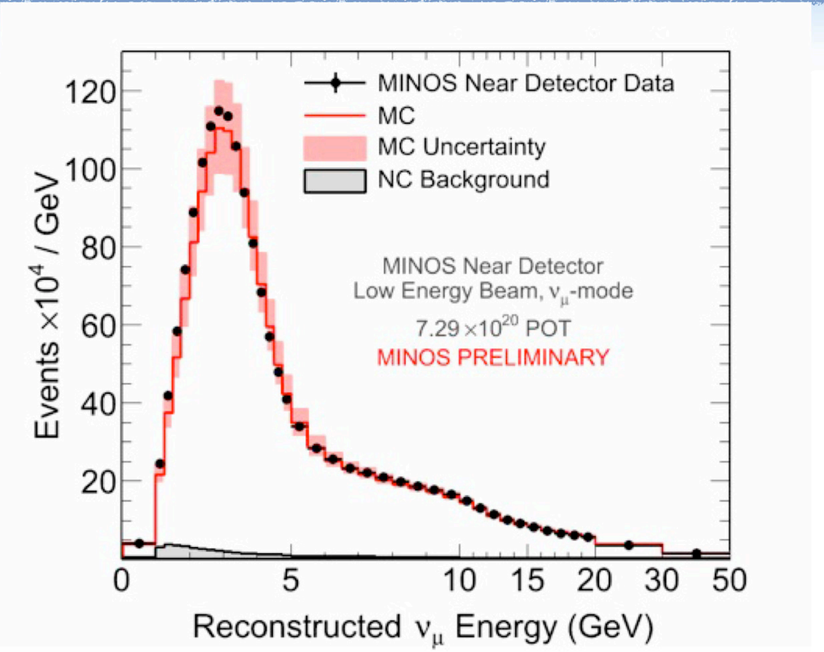
NC Event

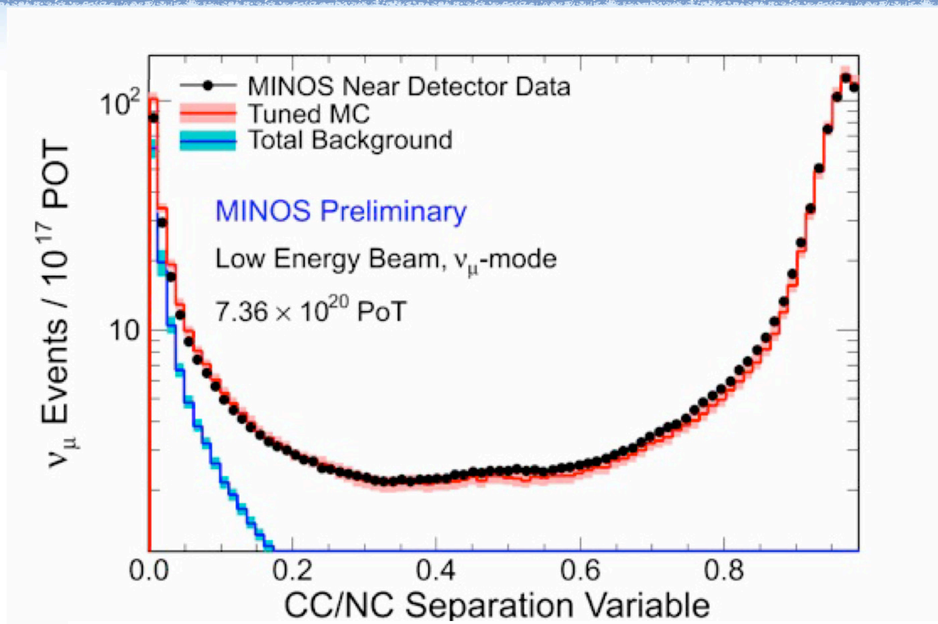




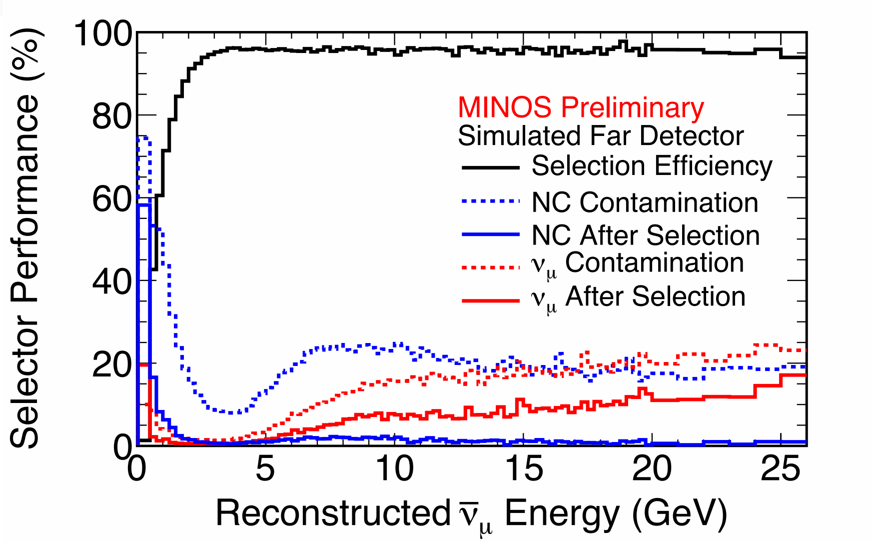
Disappearance Measurements

Event Selection



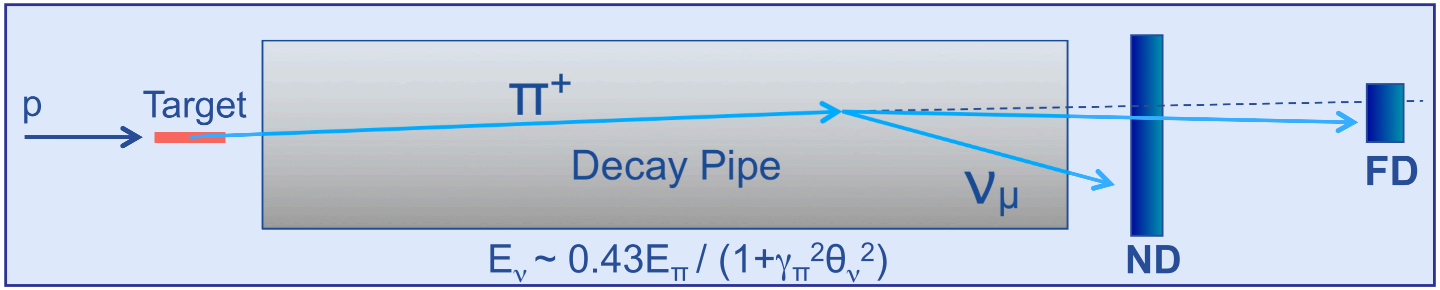


- Muons from ν_μ, $\bar{\nu}_\mu$ CC interactions selected by multivariate algorithm based on a k-Nearest-Neighbor technique
  - Rejects neutral current backgrounds and high-y CC events
- $\bar{\nu}_\mu$ CC candidates identified by positive reconstructed muon charge
- ν contamination at higher antineutrino energies does not affect $\bar{\nu}_\mu$ CC oscillation measurement

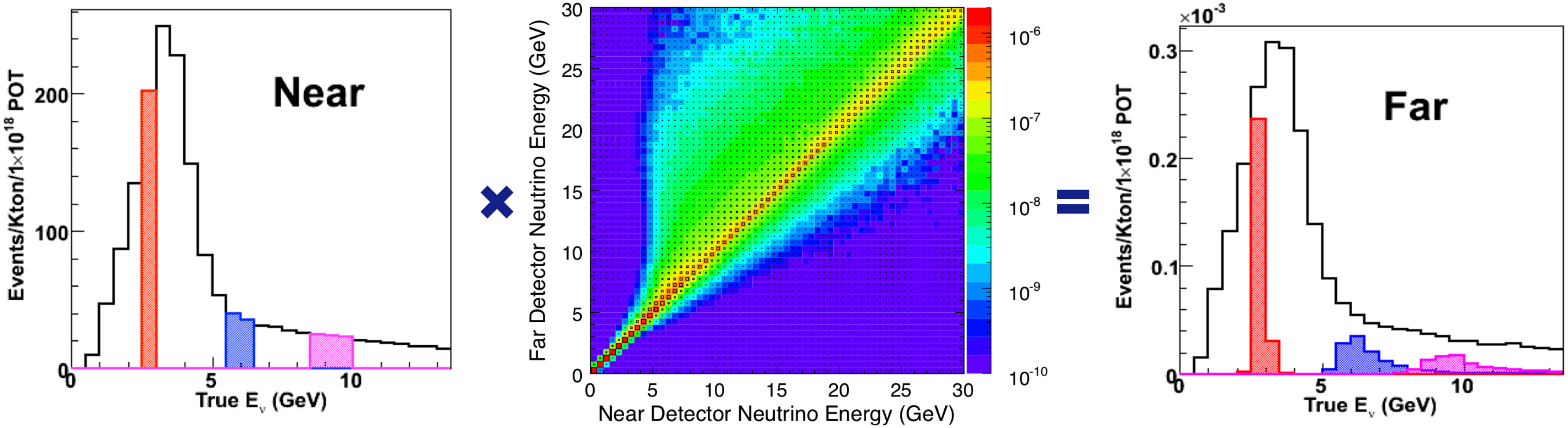


Predicting the FD Spectrum

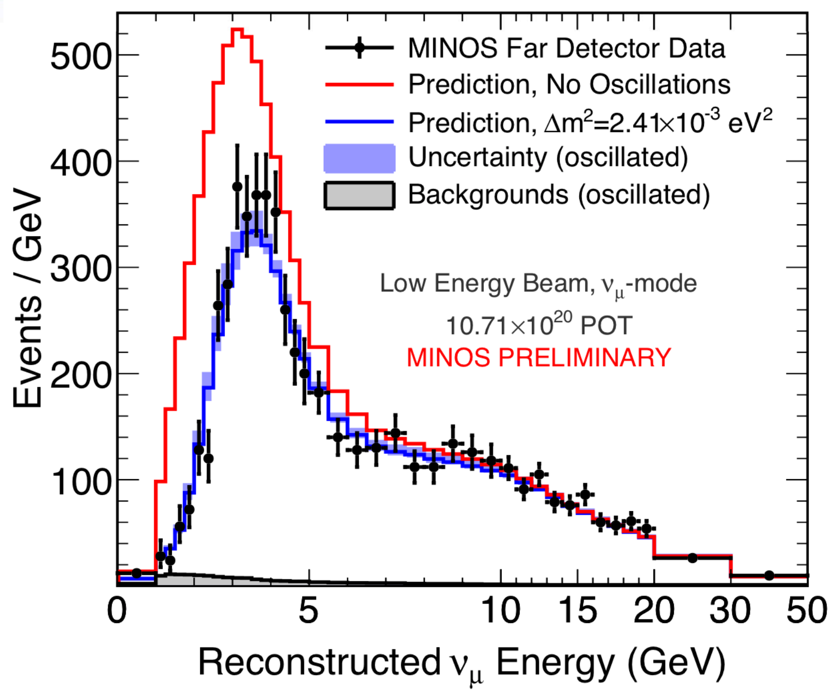
- Use the Near detector data to predict Far detector without oscillations
- FD energy spectrum without oscillations is similar to $1/R^2$ -scaled ND but not the same

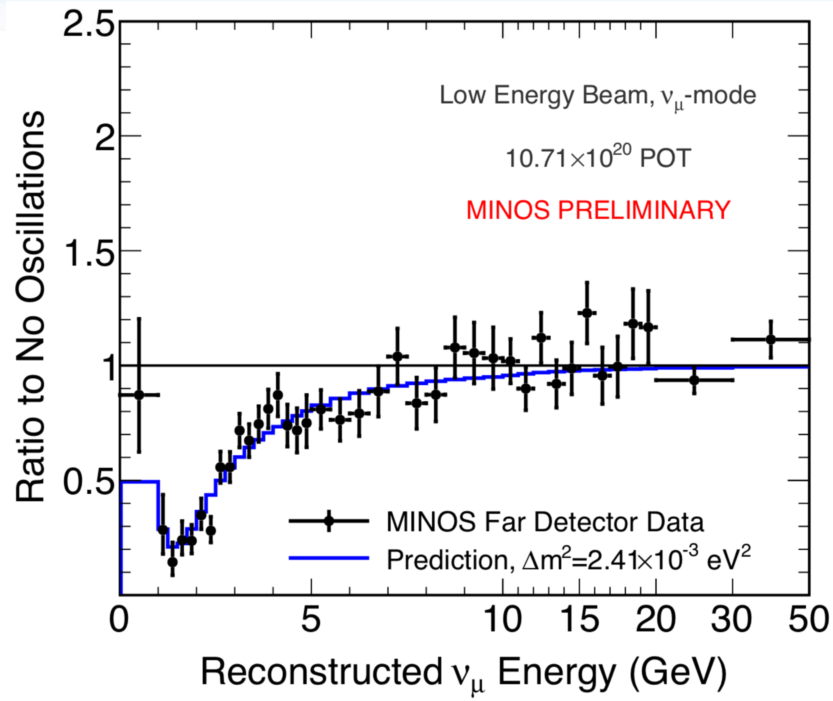


- Neutrino energy depends on angle with original pion direction and parent pion energy
- Obtain Far Detector spectrum from Near Detector using a beam transfer matrix
  - Matrix encodes knowledge of meson decay kinematics and beamline geometry



Muon Neutrino Results





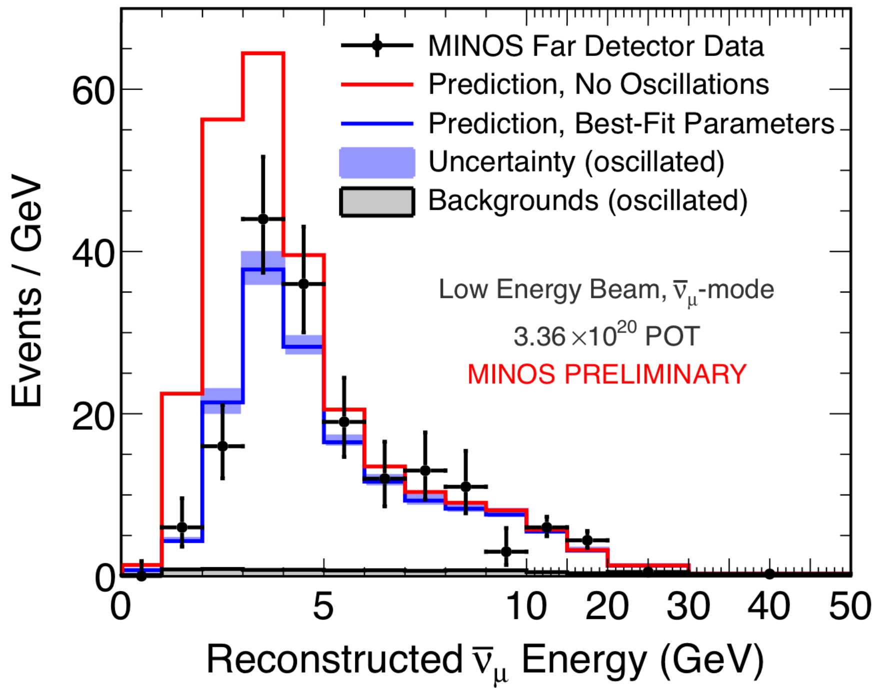
Prediction, No Oscillations: **3564 events**

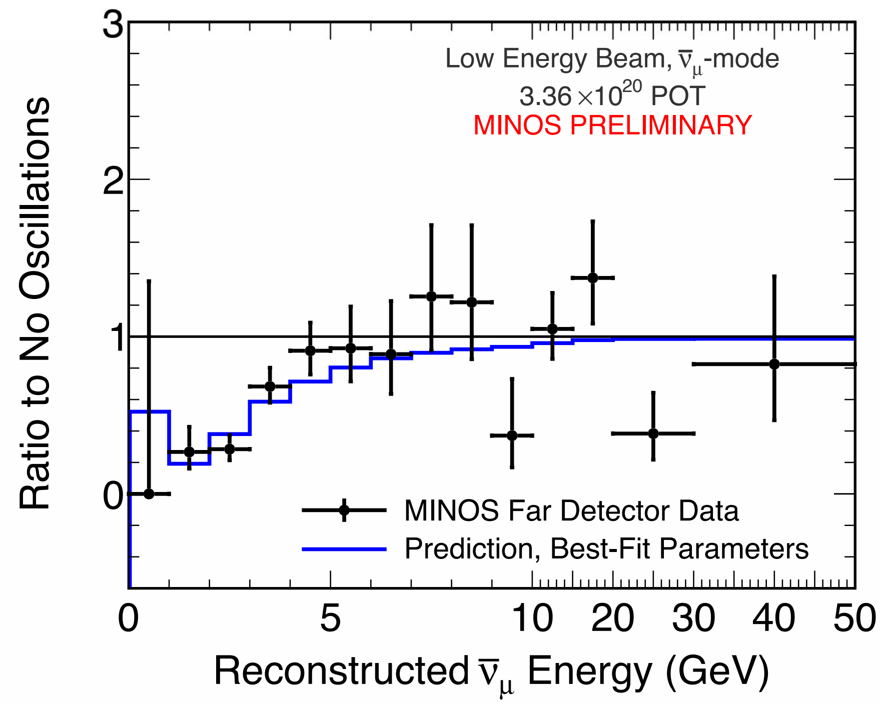
Observed: **2894 events**

ν_μ Oscillations Best Fit Parameters

$$|\Delta m^2_{atm}| = 2.41^{+0.11}_{-0.10} \times 10^{-3} eV^2$$
$$\sin^2(2\theta) = 0.94^{+0.04}_{-0.05}$$

Muon Antineutrino Results





Prediction, No Oscillations: **312 events**

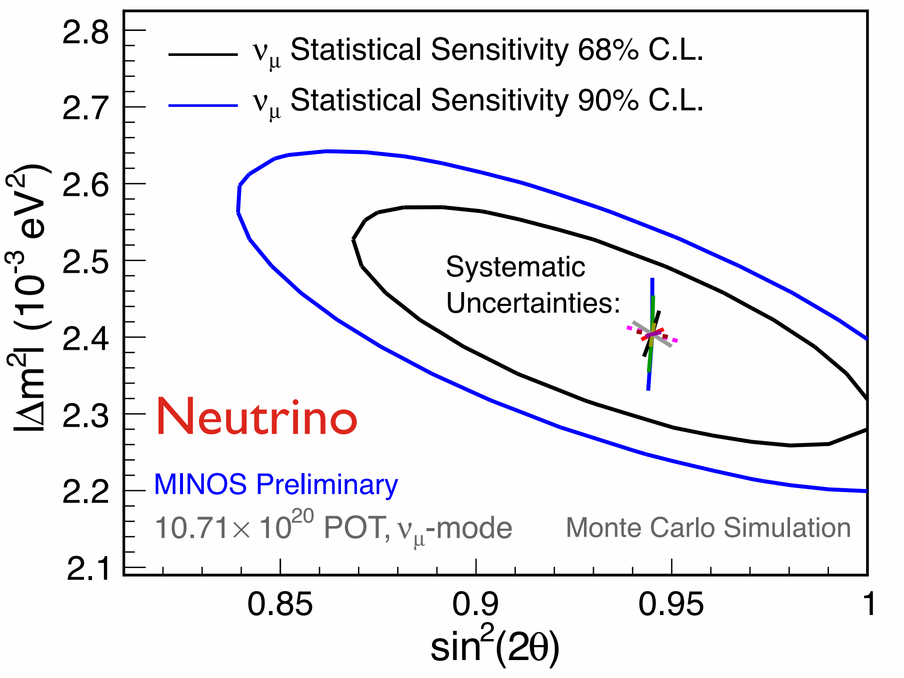
Observed: **226 events**

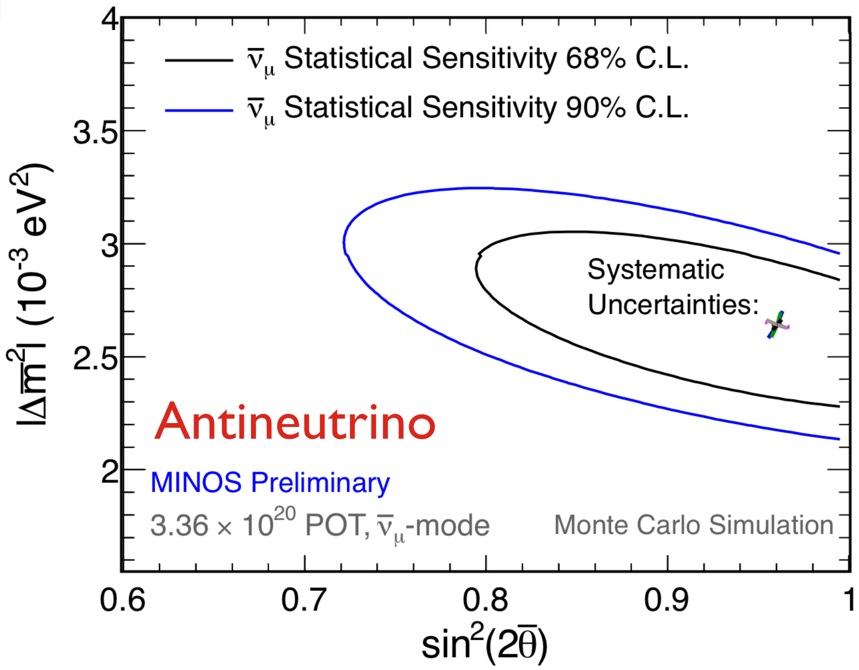
$\bar{\nu}_\mu$ Oscillations Best Fit Parameters

$$|\Delta\bar{m}^2_{atm}| = 2.64^{+0.28}_{-0.27}\times10^{-3}\mathrm{eV}^2$$

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

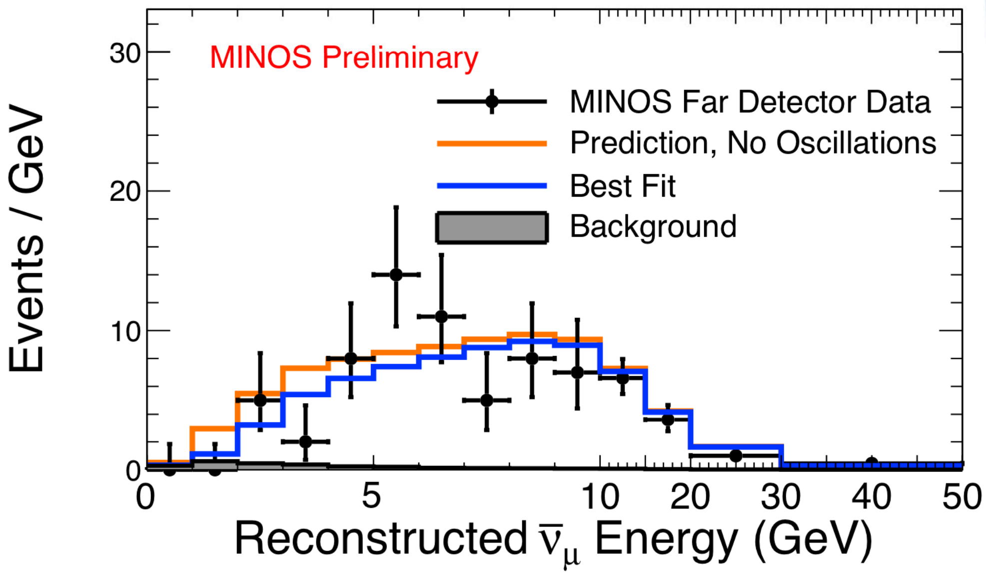
Effect of Systematics

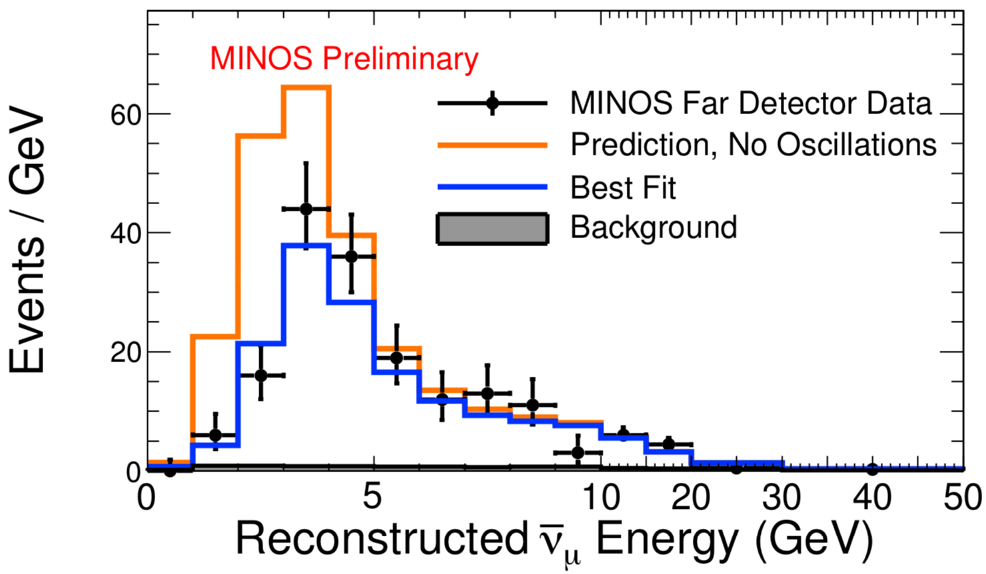




- Largest systematic uncertainties from:
  - Hadronic Energy Scale
  - Track Energy Scale
  - Neutral Current Background
- Both measurements still statistically-limited

$\bar{\nu}_\mu$ in Neutrino Running





- Analyze 7% antineutrino component of neutrino beam
- Complementary information from higher energy events
- Combine with results from dedicated antineutrino running

Prediction, No Oscillations: **536 events**

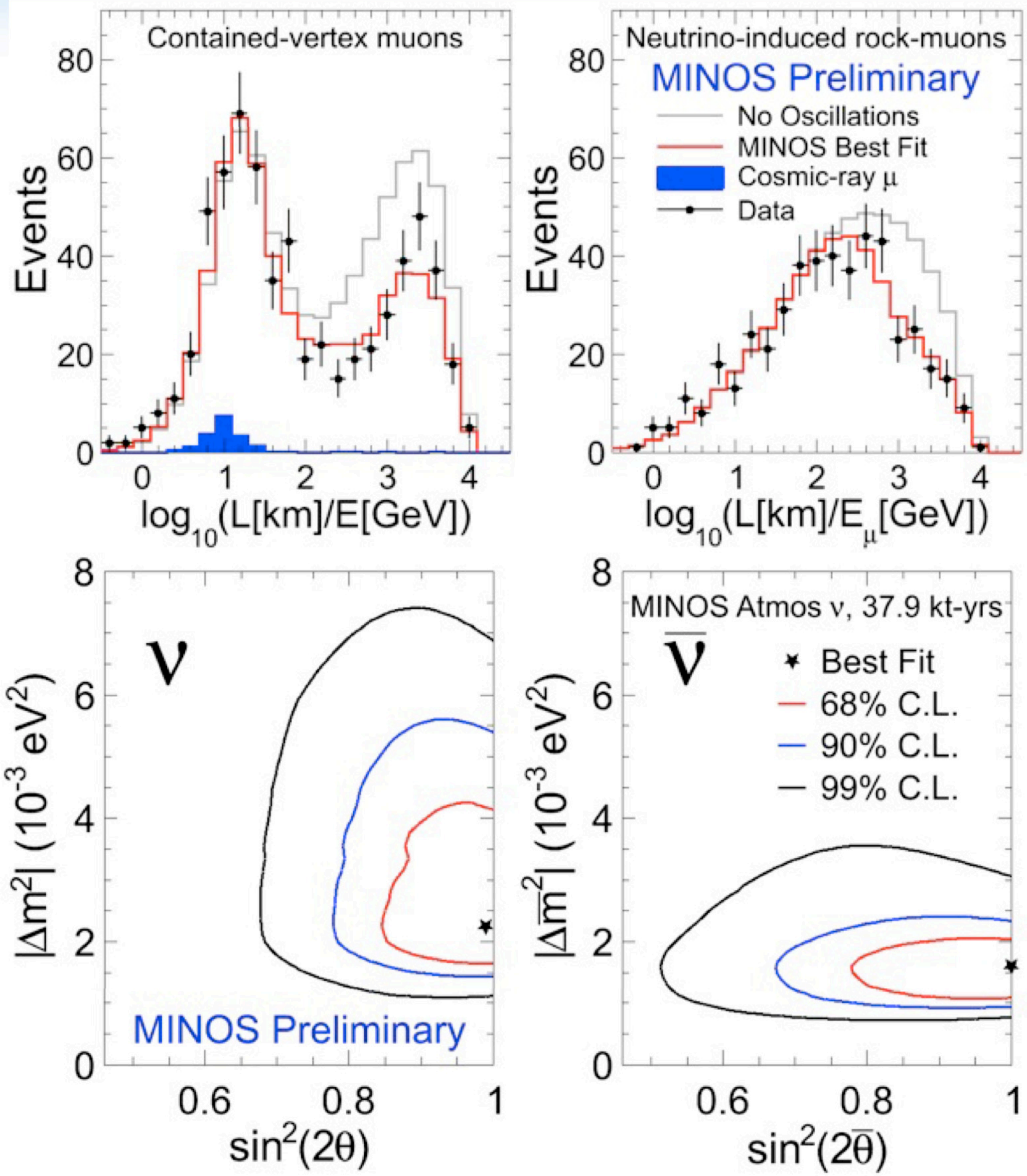
Observed: **414 events**

$$\left|\Delta \overline{m}^2_{atm}\right| = 2.60^{+0.28}_{-0.23} \times 10^{-3} eV^2$$

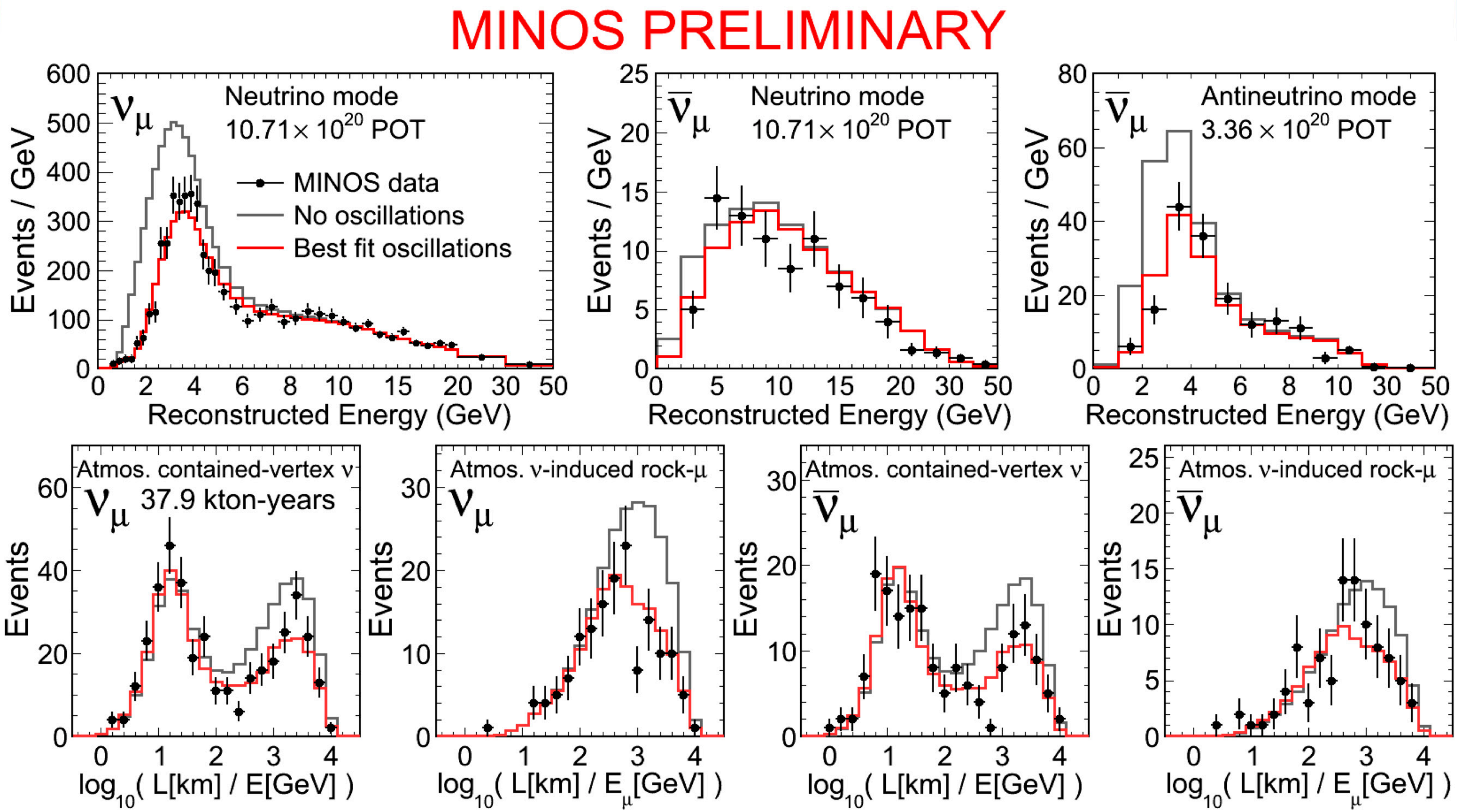
$$\sin^2(2\bar{\theta}) > 0.80 \ (90\% \text{ C.L.})$$

Atmospheric Neutrinos

- MINOS has accumulated 2553 live days or 37.9 kton-years of atmospheric neutrino data since 2003
  - 2072 atmospheric neutrino candidates observed
- Oscillations clearly seen
- Magnetic field allows for event-by-event charge separation
  - Competitive antineutrino oscillation measurement!



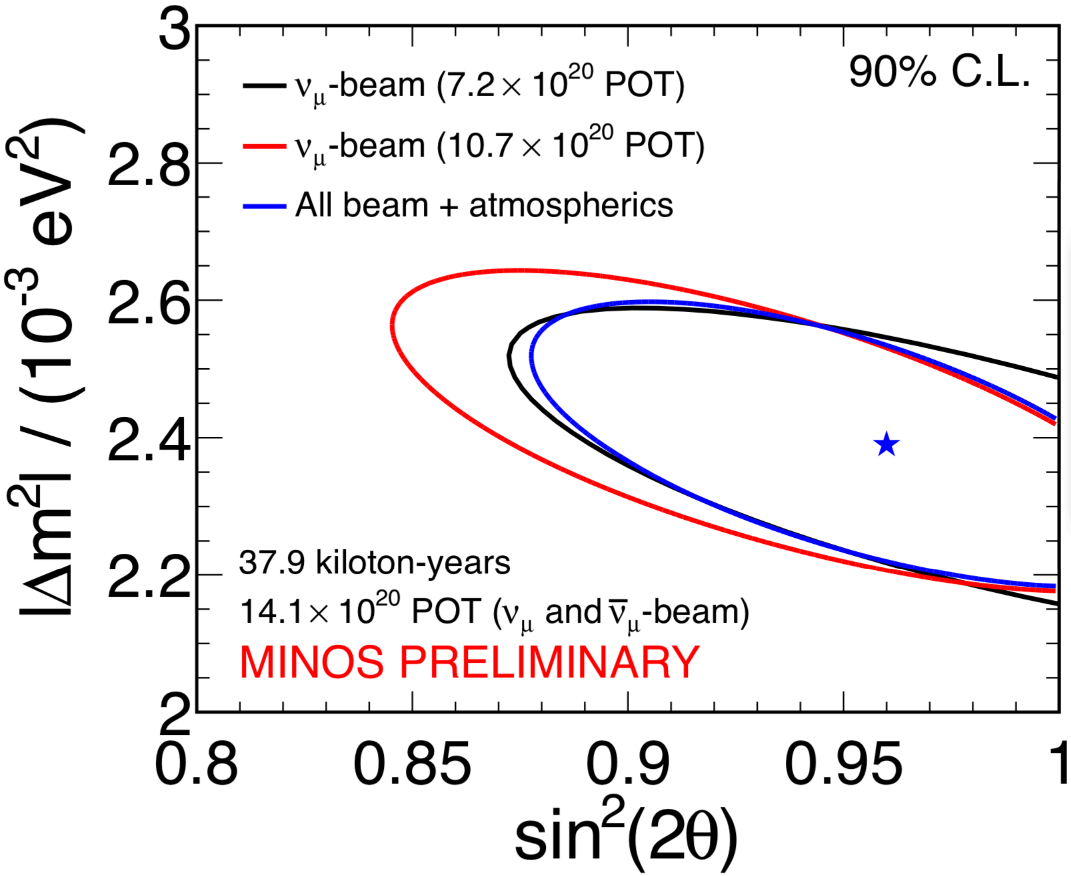
Beam + Atmospherics



- Include 15 sources of systematics uncertainty as nuisance parameters in fit when including atmospherics
- Oscillations are a good fit: 64% of pseudo-experiments have worse χ^2

Beam + Atmospherics Results

- Allowed 90% C.L. regions for combined fit
- Two parameter fit: assumes identical neutrino/antineutrino oscillations



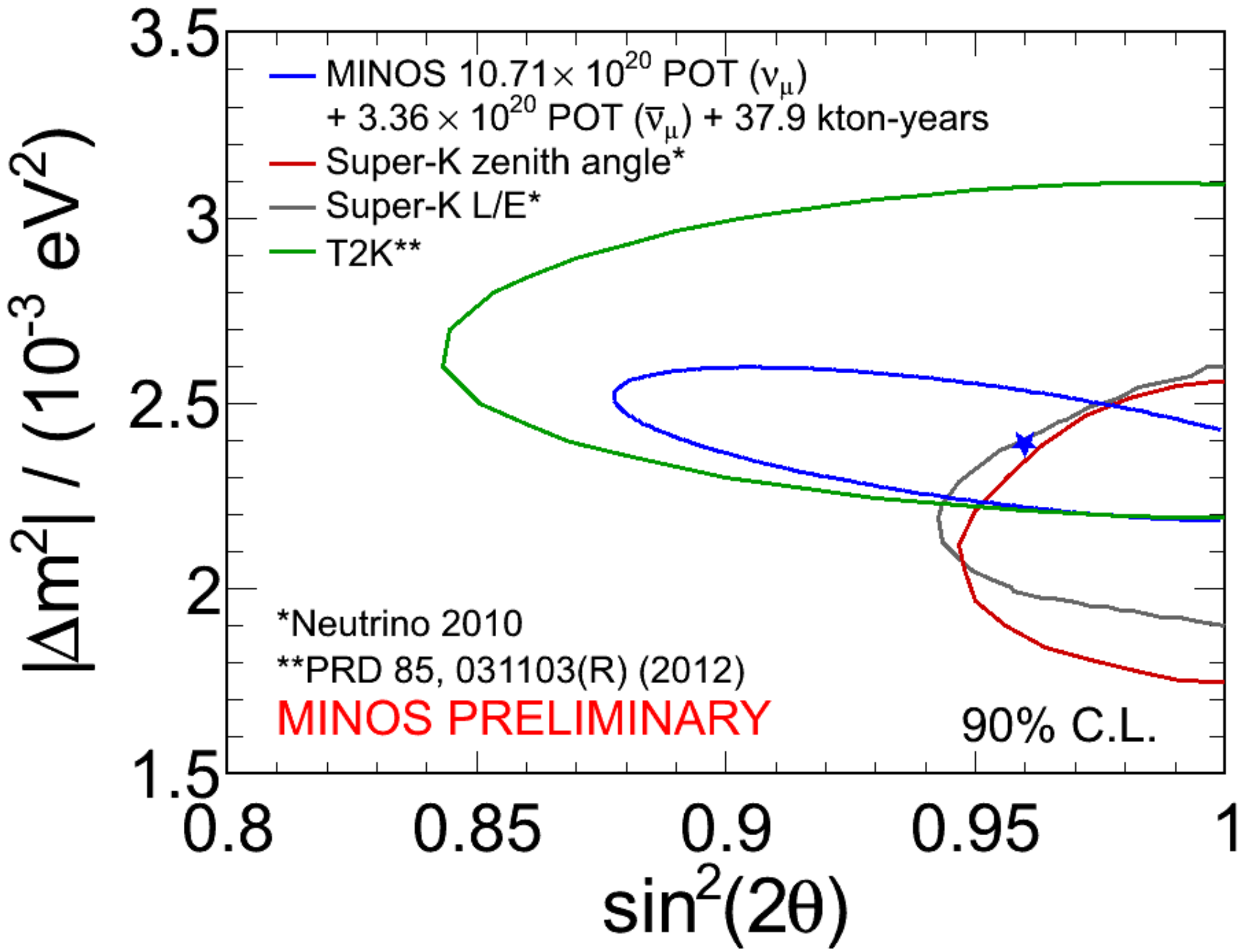
Combined Best Fit Parameters

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

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

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

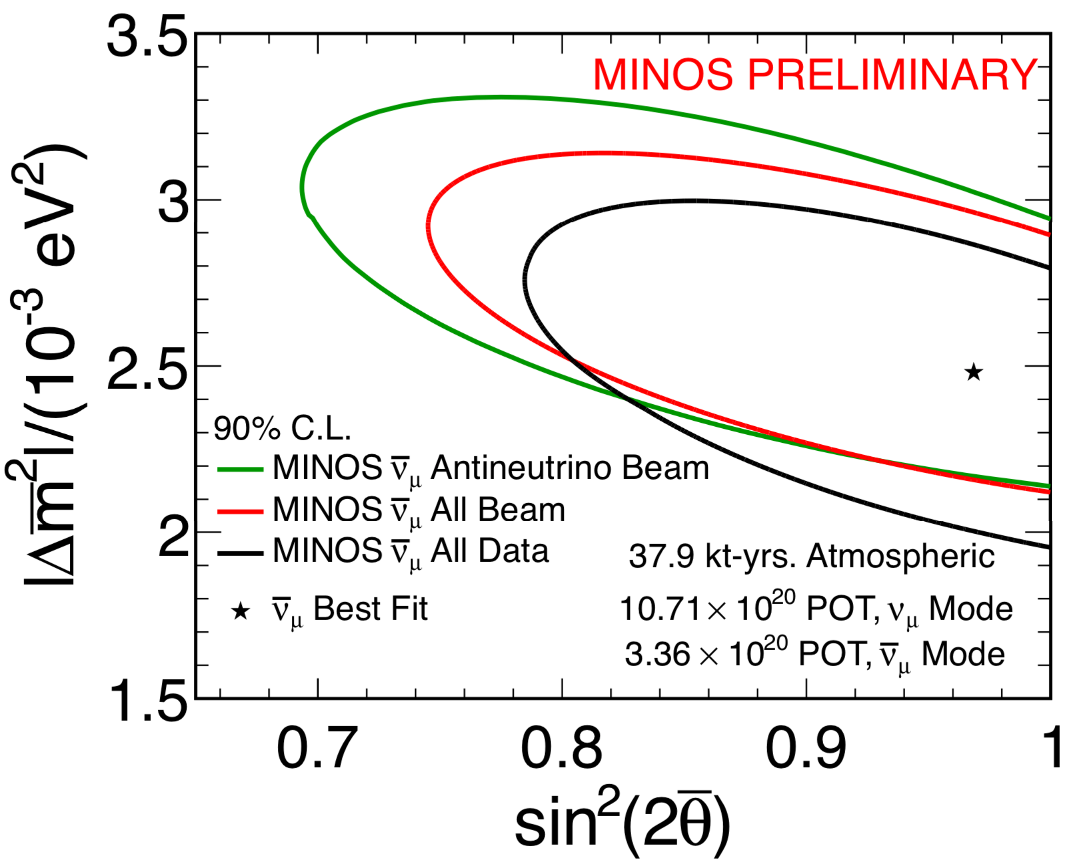
World Picture (MINOS, SuperK, T2K)



MINOS makes a ~4% measurement of $|\Delta m^2_{atm}|$!

Beam + Atmospherics $\bar{\nu}_\mu$

- Results for combination of beam and atmospheric antineutrinos
- Four parameter fit: neutrino and antineutrinos may oscillate differently



Combined $\bar{\nu}_\mu$ Best Fit Parameters

$$\left|\Delta \overline{m}^2_{atm}\right| = 2.48^{+0.22}_{-0.27} \times 10^{-3} eV^2$$

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

Beam + Atmospherics $\bar{\nu}_\mu$

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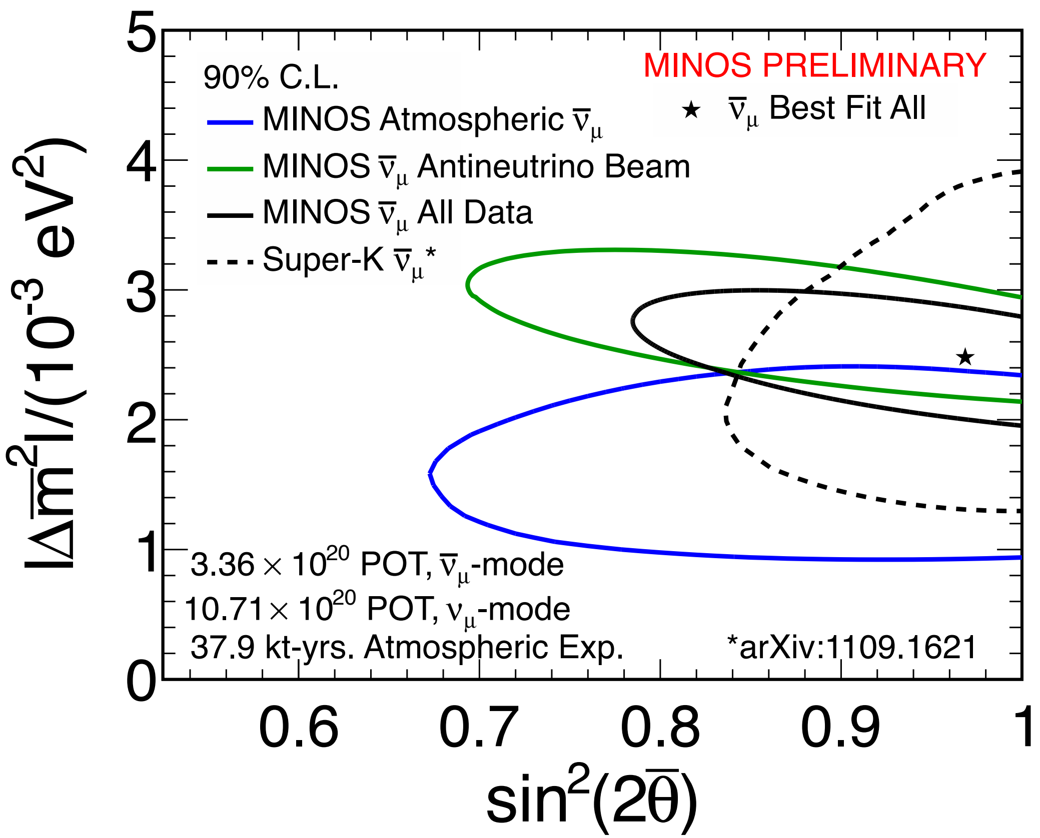

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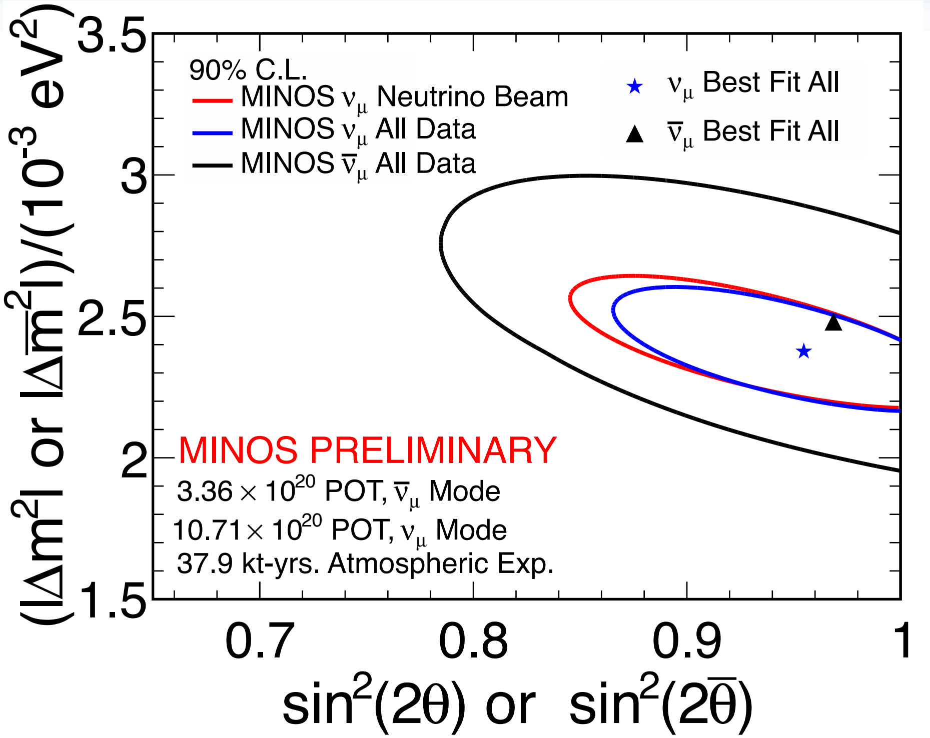
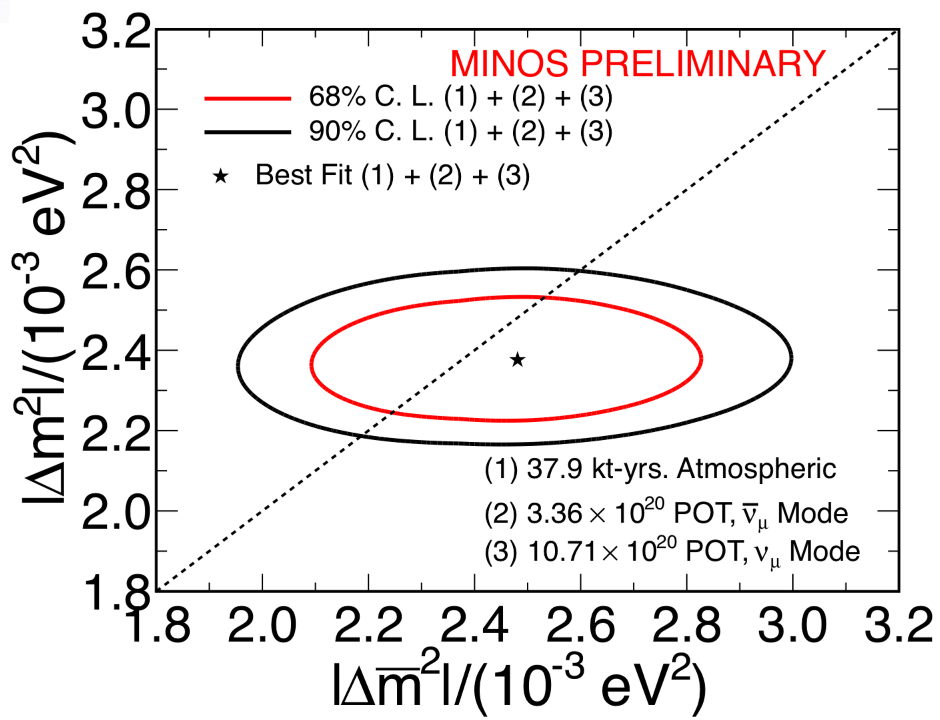
Neutrinos vs. Antineutrinos





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

- Neutrino and antineutrino results very consistent with each other

Appearance Measurements

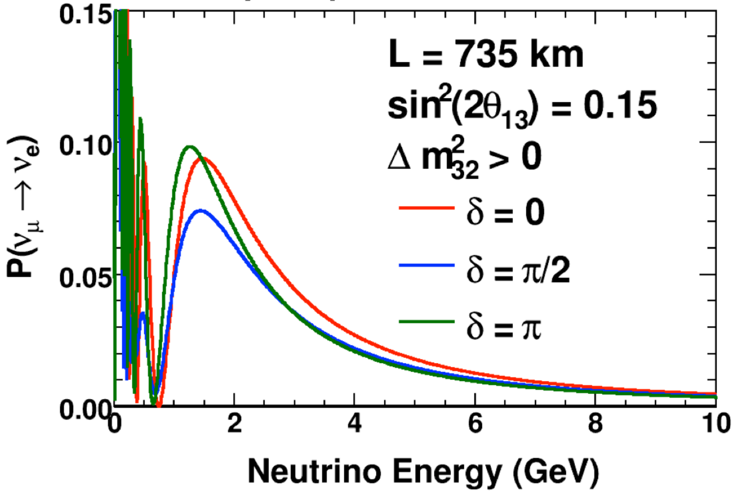
MINOS Search for θ_{13}

Probability for ν_e appearance in a ν_μ beam is given by:

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30}$$

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A^2}$$
$$+2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

Probability depends on θ_{13} and δ_{CP}



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

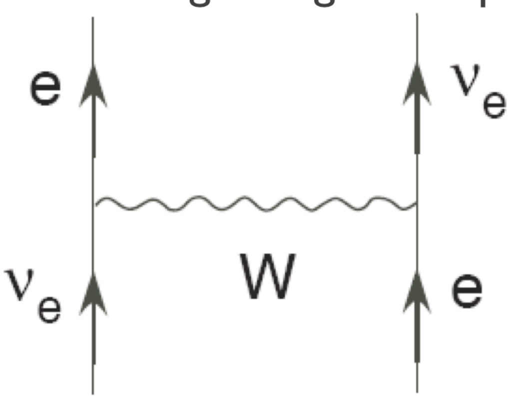
MINOS Search for θ_{13}

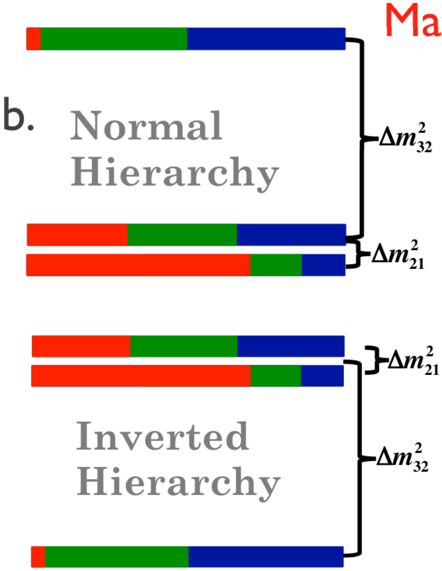
Probability for ν_e appearance in a ν_μ beam is given by:

$$A \overset{(-)}{\equiv +} \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\ \text{GeV}} \qquad \Delta \equiv \frac{\Delta m_{31}^2 L}{4E} \qquad \alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sim \frac{1}{30}$$

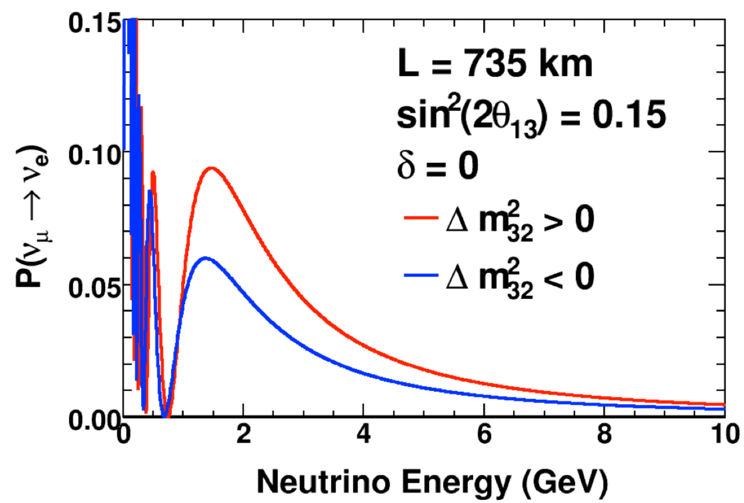
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A^2}$$
$$+2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

Coherent forward ν_e-e scattering changes osc. prob.





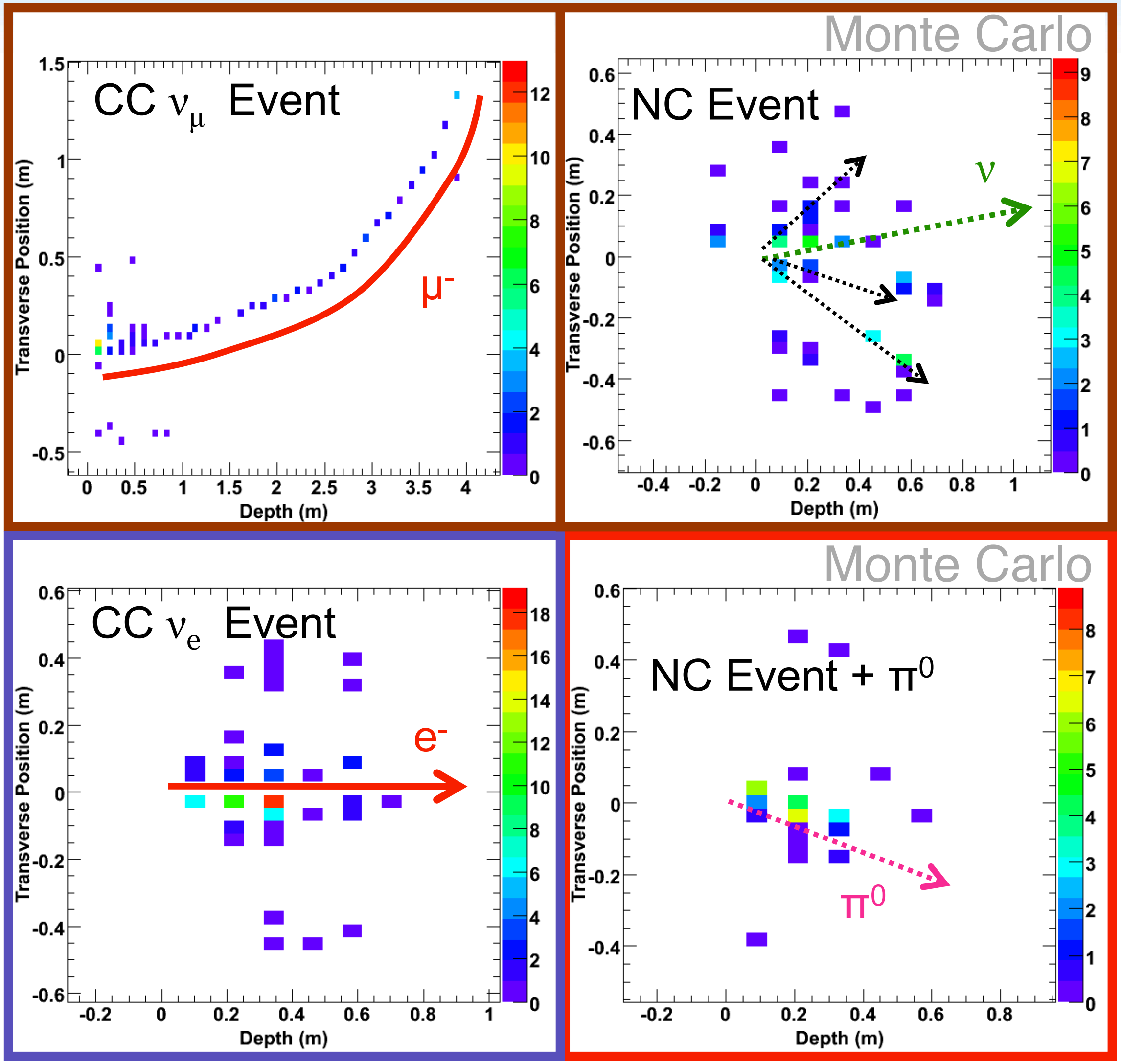
Matter effects => dependence on mass hierarchy



Signal and Backgrounds

Reducible Background

Signal

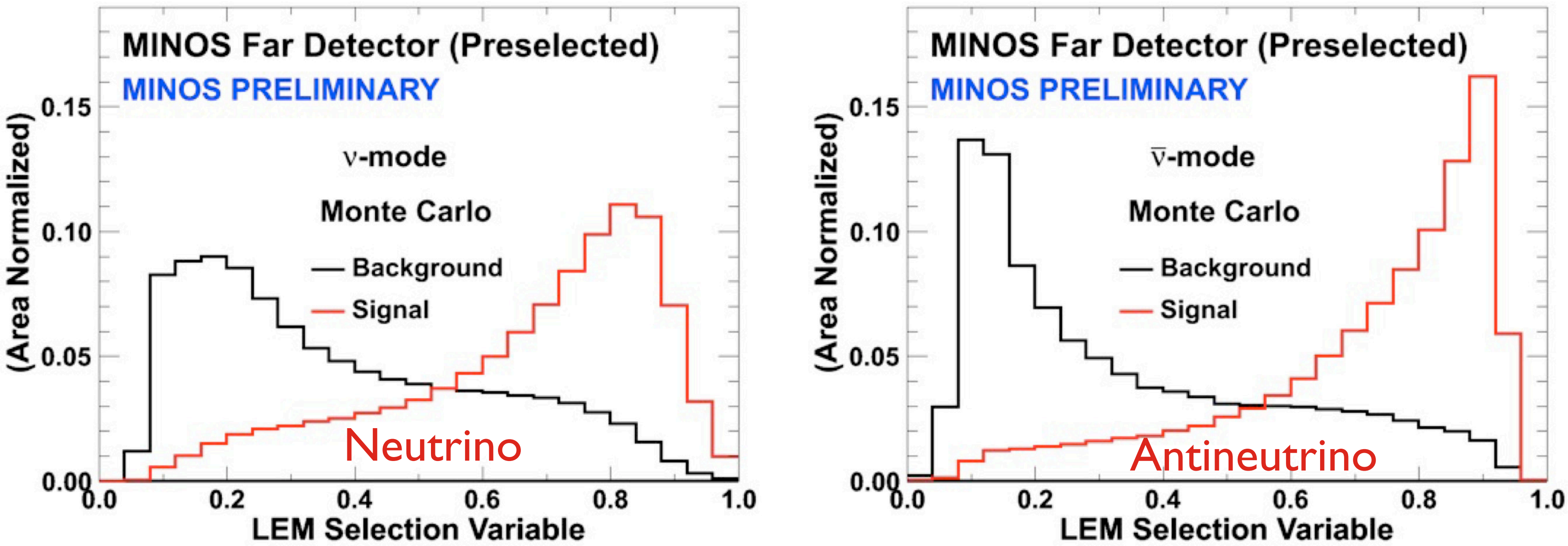


Irreducible Background

- Steel thickness ~ 1.4 radiation lengths, strip width > Molière radius

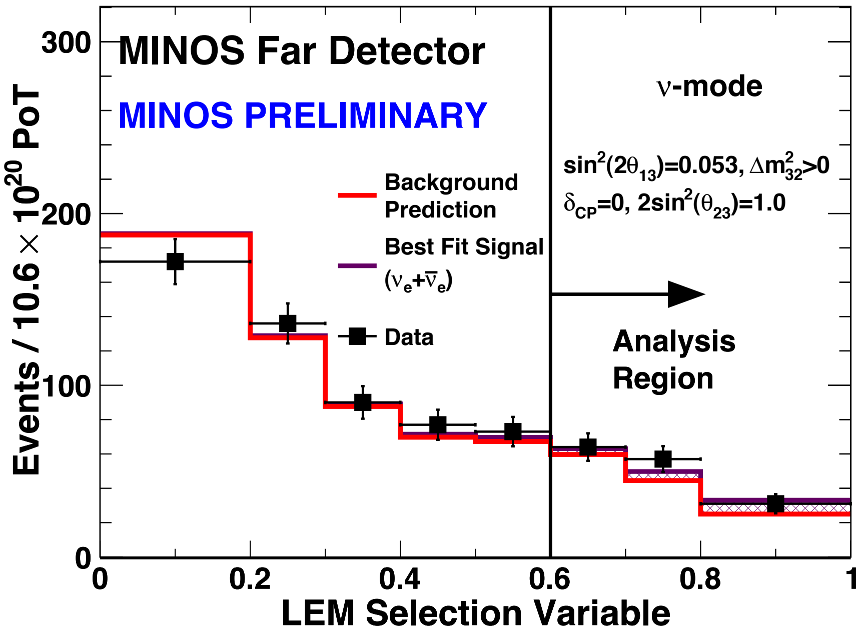
Electron Neutrino Selection

- Identifying CC ν_e candidates in MINOS is challenging
  - Use a computer-intensive technique that matches data events to a library of MC events (LEM: Library Event Matching)
  - Discriminant variable is based on truth information from the library events that best match the candidate

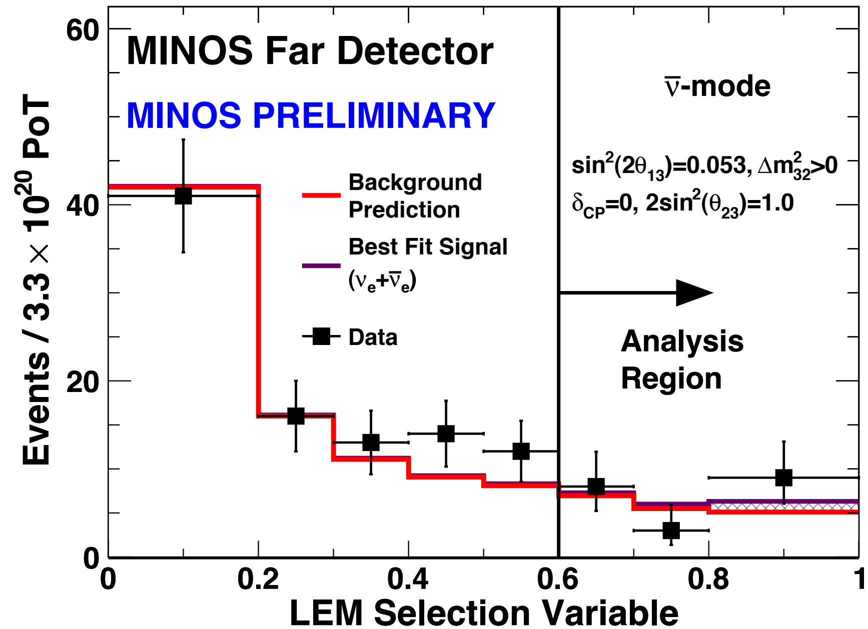


ν_e Appearance Results

Neutrino Running



Antineutrino Running



Observed: 88 events

θ_{13}=0 Prediction: 69.1 background events

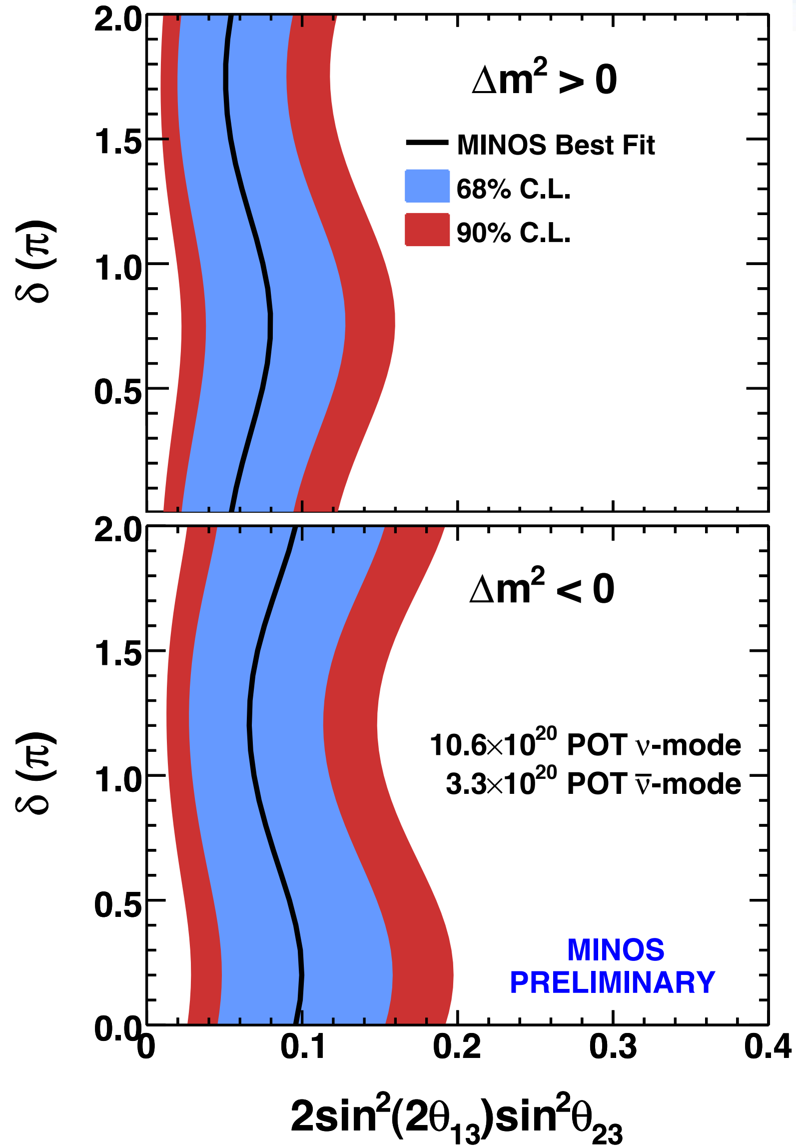
$\sin^2(2\theta_{13})$=0.1: +26.0 events

Observed: 12 events

θ_{13}=0 Prediction: 10.5 background events

$\sin^2(2\theta_{13})$=0.1: +3.1 events

ν_e Appearance Contours



- Assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$
- Best fit for normal (inverted) hierarchy:

$$\sin^2 2\theta_{13} = 0.053\ (0.094)$$

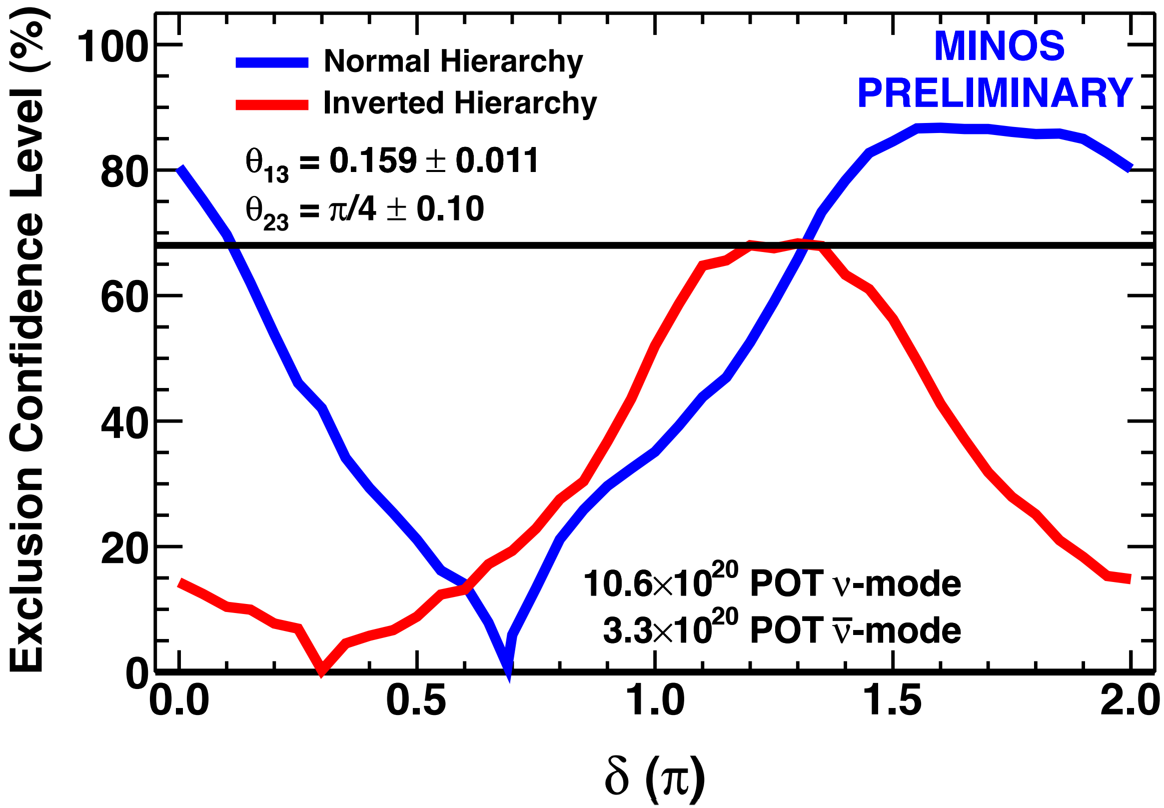
- Exclusion limits

$$0.01 < \sin^2 2\theta_{13} < 0.12 \text{ at } 90\% \text{ C.L.}$$
$$(0.03) \qquad\qquad (0.19)$$

- MINOS excludes $\sin^2 2\theta_{13}=0$ at 96% C.L.

Mass Hierarchy and δ_{CP}

- Using the recent measurements of θ_{13} by reactor experiments, some combinations of mass hierarchy and δ_{CP} are disfavored by the MINOS data

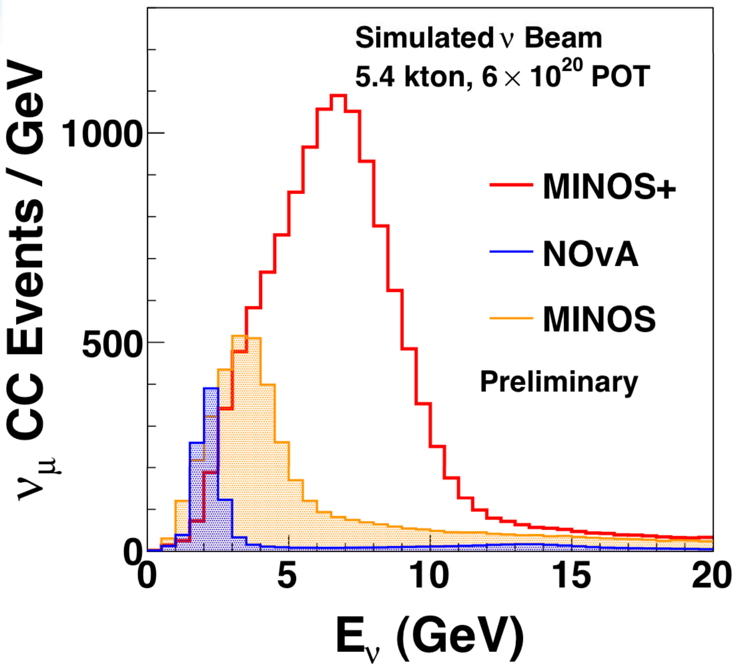


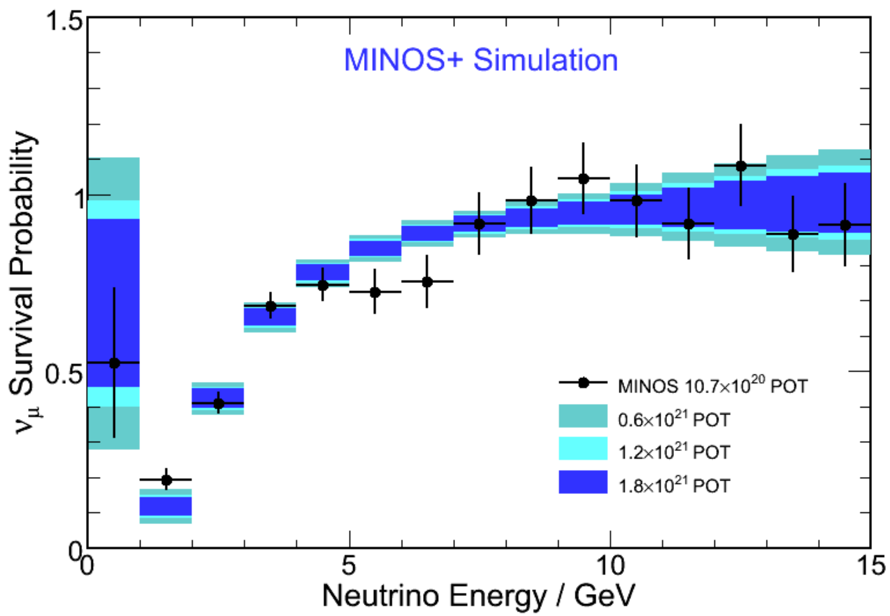
- Pseudo-experiment studies show that we favor the correct hierarchy in 60% of the experiments (compared to 50% by chance)
- Slight preference for inverted mass hierarchy with $-2\Delta \ln L=0.20$


MINOS
+

MINOS+

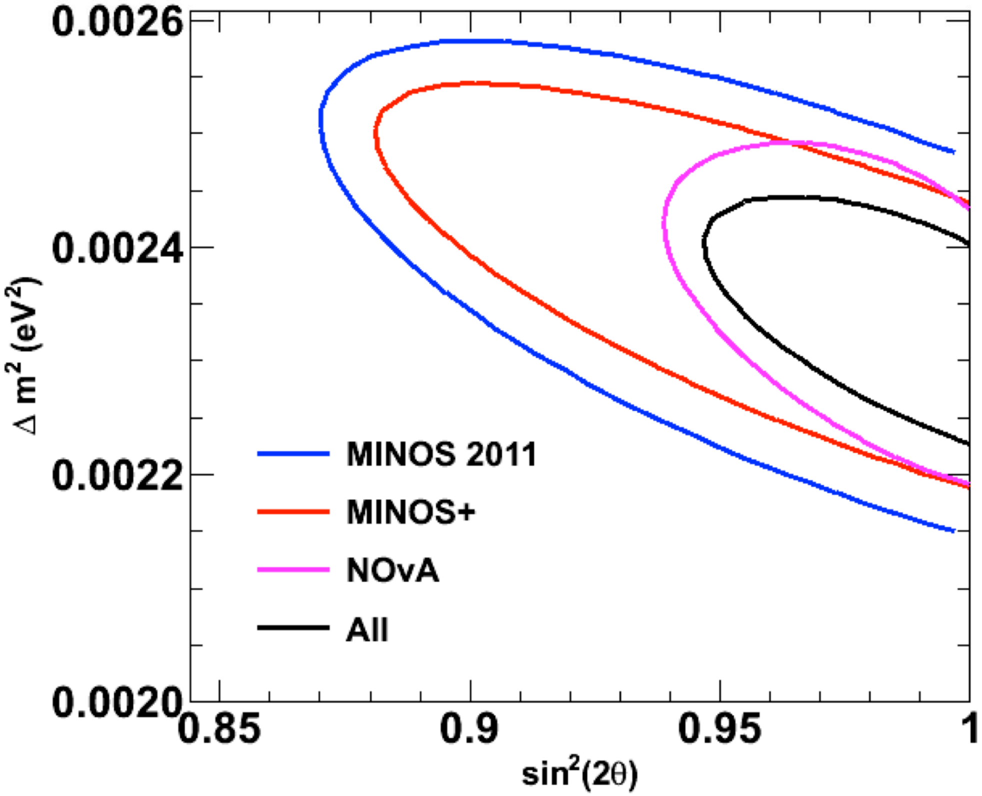
- The MINOS detectors will continue operating during the NOνA run, using the NuMI beam upgraded to 700 kW beam power
  - Run for 3 years with at least 1 in antineutrino mode
  - Medium Energy beam peaked at ~7 GeV (4000 ν_μ CC events/year expected at the FD)
  - 80 tau neutrino CC events/year expected





- Improve precision of current MINOS measurements
- Probe oscillations in higher energy regions
- Sensitivity to exotic signals

$\sin^2 2\theta$ and Δm^2

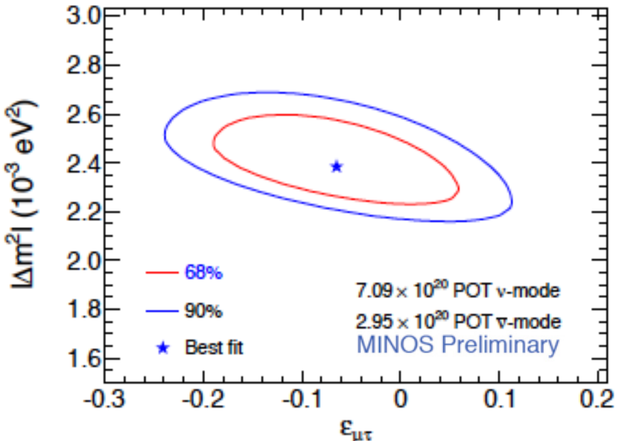


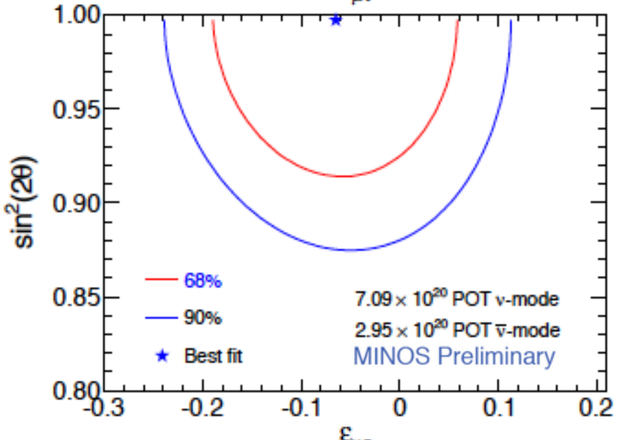
- Sensitivity after 3 year of MINOS+
- MINOS+ measurement of Δm^2 will still dominate during first year (2013-2014), as NOνA Far Detector only ~50% complete

MINOS and MINOS+ NSI

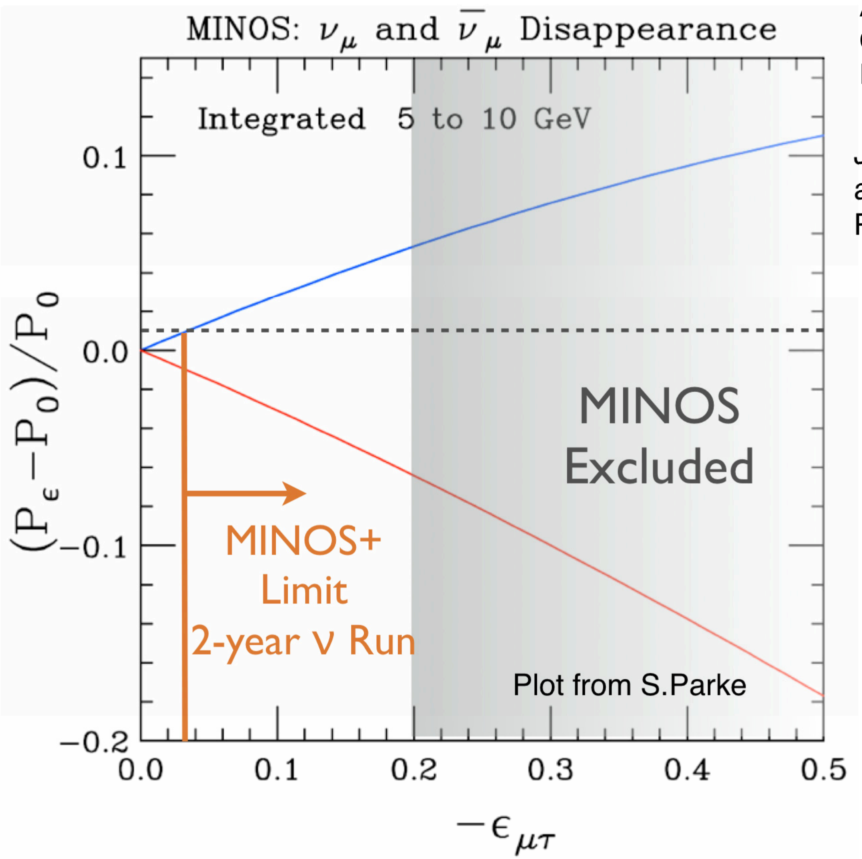
- Non-Standard Interactions affect neutrino propagation in the same way as MSW matter effects

$$i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{31}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23}\end{pmatrix} \pm \sqrt{2}G_F N_e(r)\begin{pmatrix} \varepsilon^e_{\mu\mu} & \varepsilon^e_{\mu\tau} \\ \varepsilon^{e\star}_{\mu\tau} & \varepsilon^e_{\tau\tau}\end{pmatrix}\right]\vec{\nu}; \quad \vec{\nu} = (\nu_\mu, \nu_\tau)^T$$





$$\Delta m^2 = 2.39^{+0.135}_{-0.105} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2(2\theta) > 0.91 \text{ (90\% C.L.)}$$
$$-0.200 < \varepsilon_{\mu\tau} < 0.070 \text{ (90\% C.L.)}$$

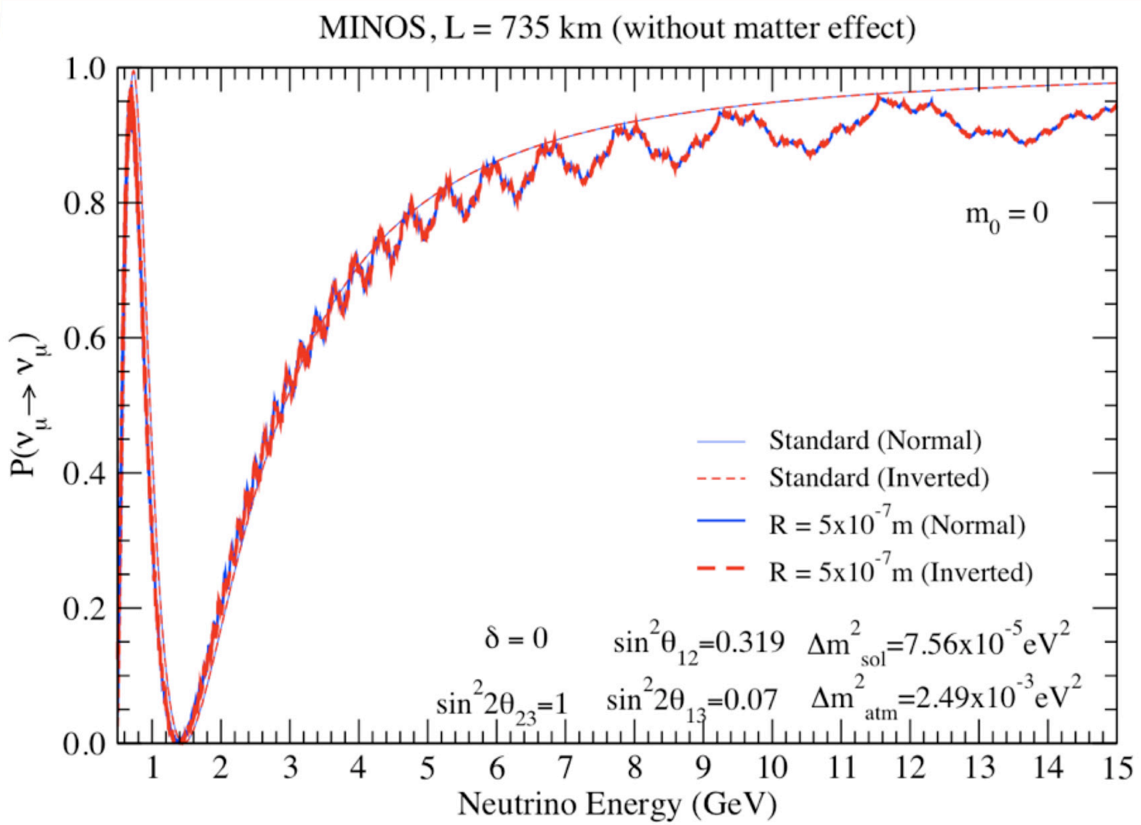


Alexander Friedland, Cecilia Lunardini, Phys.Rev.D74:033012, 2006

J.Kopp, P.A.N. Machado and S.Parke, Phys.Rev.D82:113002 (2010)

- NSI parameter $\varepsilon_{\mu\tau}$ can be significantly constrained thanks to MINOS+ large statistics

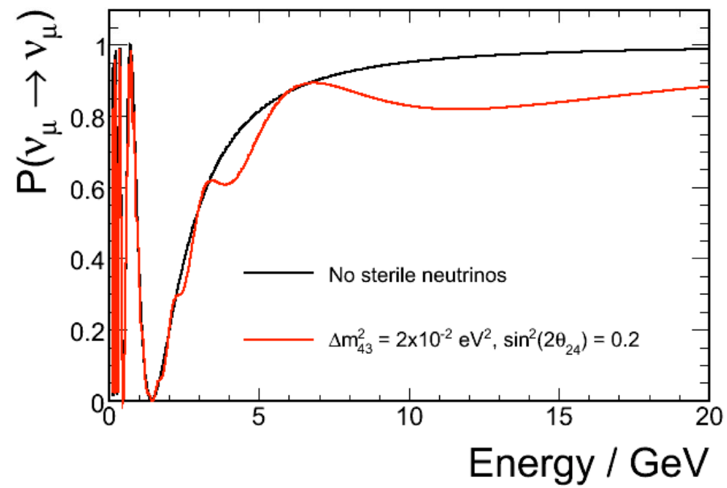
Search for Extra-Dimensions

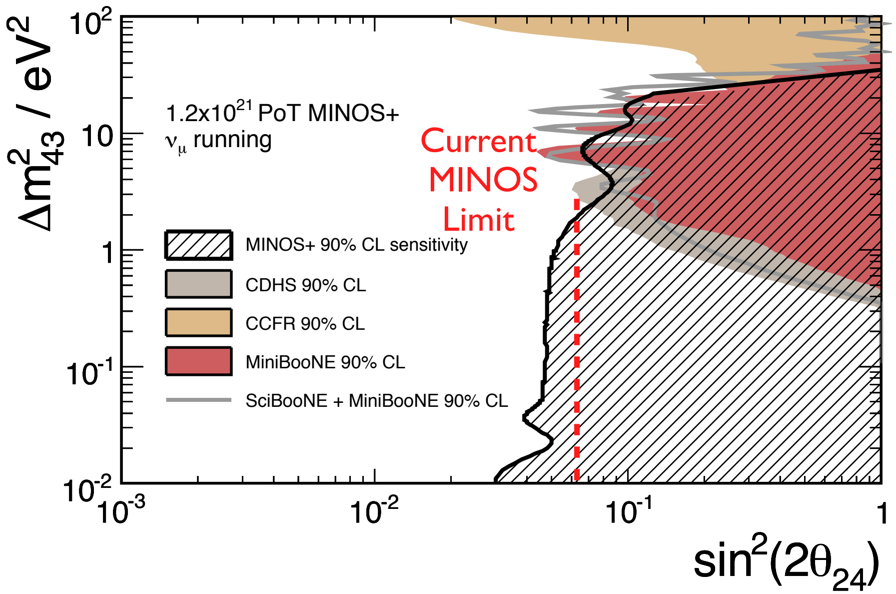


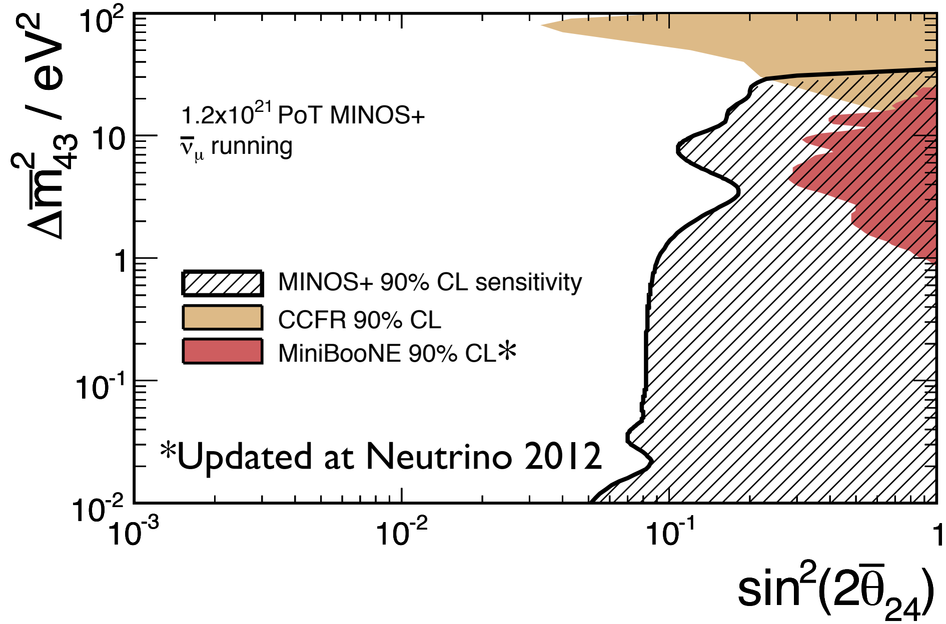
- Machado, Nunokawa, Zukanovich Funchal **Phys. Rev. D 84, 013003 (2011)**
- Right-handed neutrinos propagate in extra-dimension of size *R*. Kaluza-Klein modes mix with regular oscillations
- MINOS+ can exclude extra dimensions with R > 0.1 micron
- Better than NOvA and T2K due to KK effect mostly at higher energies

Sterile Neutrino Mixing

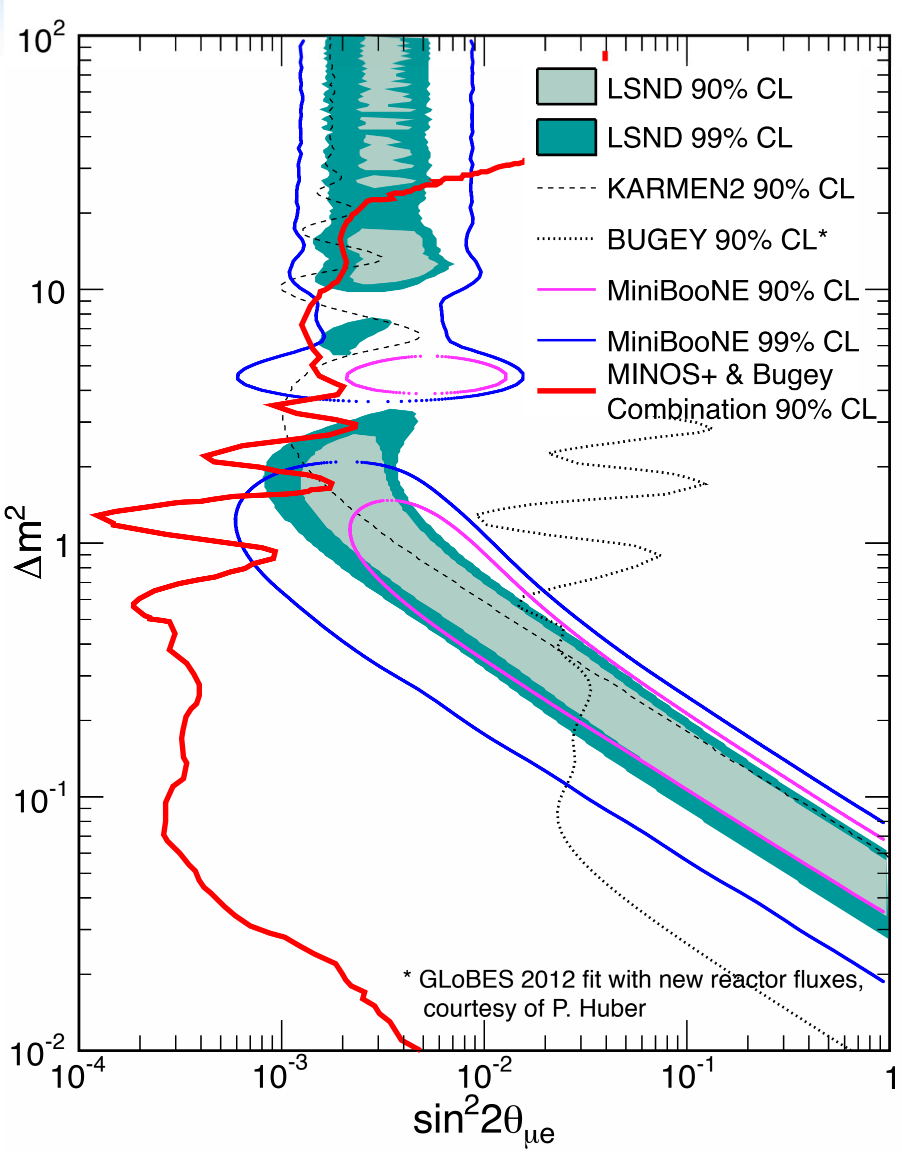
- MINOS+ large statistics can improve significantly disappearance constraints on sterile mixing models
- Plots below show MINOS+ θ_{24} 90% C.L. sensitivity compared with other disappearance experiments
- Will also make measurements in dedicated antineutrino running (~1-2 years)





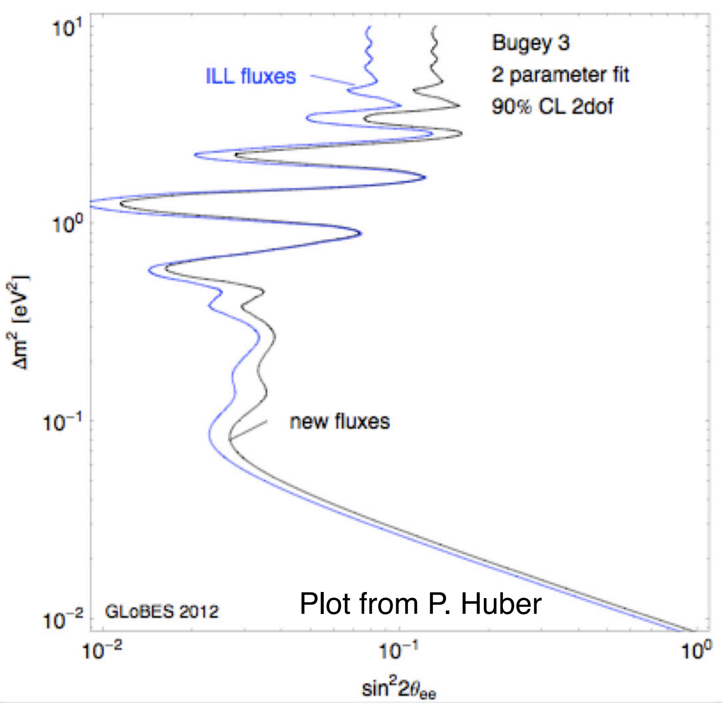


Sterile Neutrino Constraints



- Combining the disappearance constraints from MINOS+ with complementary disappearance constraints from reactor experiments, the low-mass LSND appearance signal can be almost ruled out

- Note: $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 \times |U_{\mu 4}|^2$



Summary

- Analysis of the MINOS complete beam+atmospheric data sample provides most precise measurement of atmospheric mass-squared splitting for both neutrinos and antineutrinos:

$$|\Delta m^2_{\rm atm}| = 2.39^{+0.09}_{-0.10} \times 10^{-3} {\rm eV}^2$$
$$\sin^2(2\theta) = 0.96^{+0.04}_{-0.04}$$

$$|\Delta \overline{m}^2_{\rm atm}| = 2.48^{+0.22}_{-0.27} \times 10^{-3} {\rm eV}^2$$
$$\sin^2(2\bar{\theta}) = 0.97^{+0.03}_{-0.08}$$

- Searches for ν_e appearance find:

$$0.01 < \sin^2 2\theta_{13} < 0.12 \quad \text{at } 90\% \text{ C.L.}$$
$$(0.03) \qquad\qquad (0.19)$$

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

MINOS excludes $\sin^2 2\theta_{13}=0$ at 96% C.L.

- Starting in 2013, MINOS+ will be a discovery instrument for the next decade and will contribute higher precision measurements, as well as test exotic neutrino models
- New neutrino surprises could be just around the corner!