Latest Results from MINOS

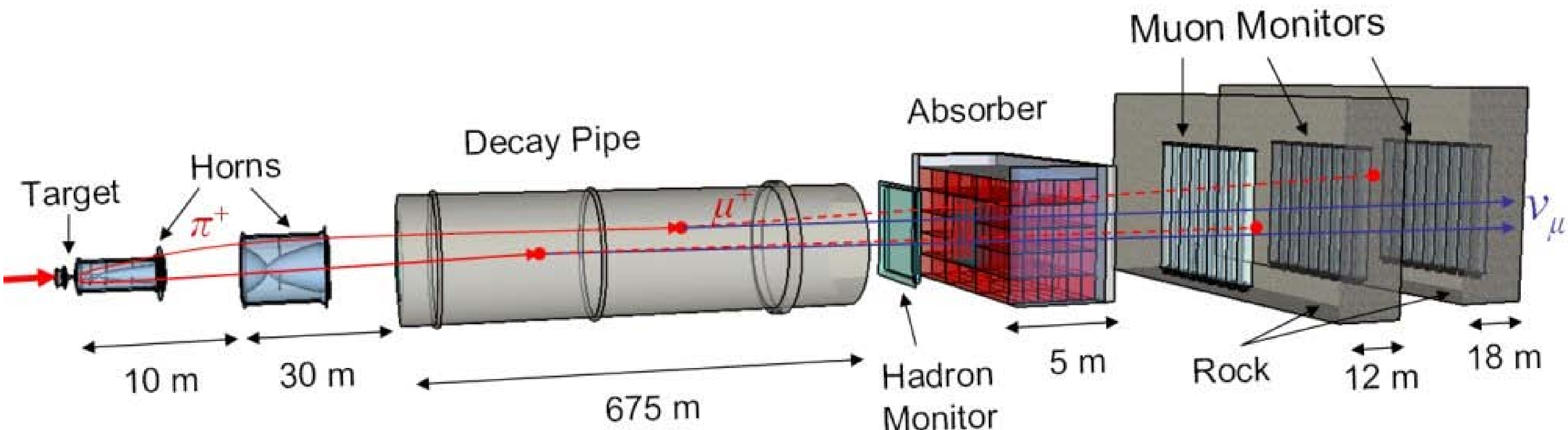
Benton Pahlka
Fermi National Accelerator Lab

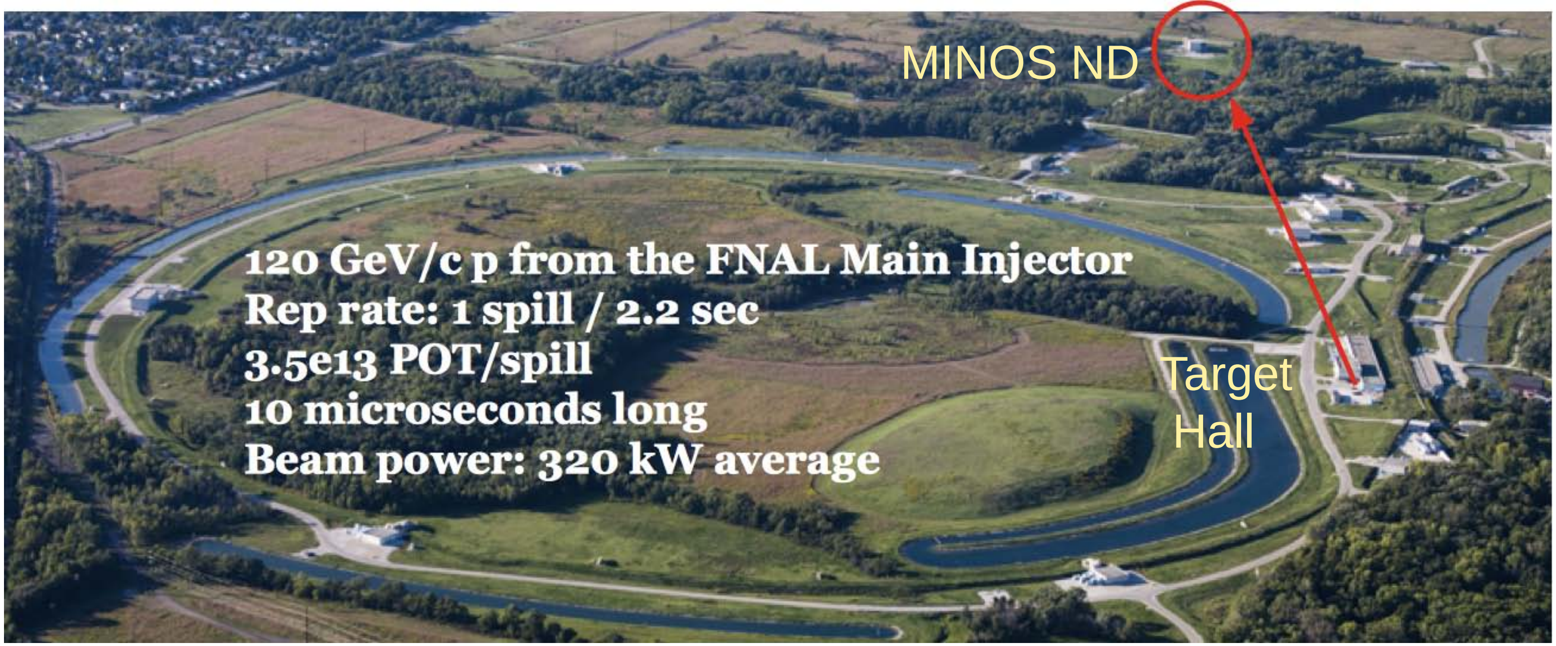
Outline:

- The NuMI beam and MINOS detectors
- Electron neutrino appearance analysis
- Muon neutrino disappearance analysis
- Muon antineutrino disappearance analysis

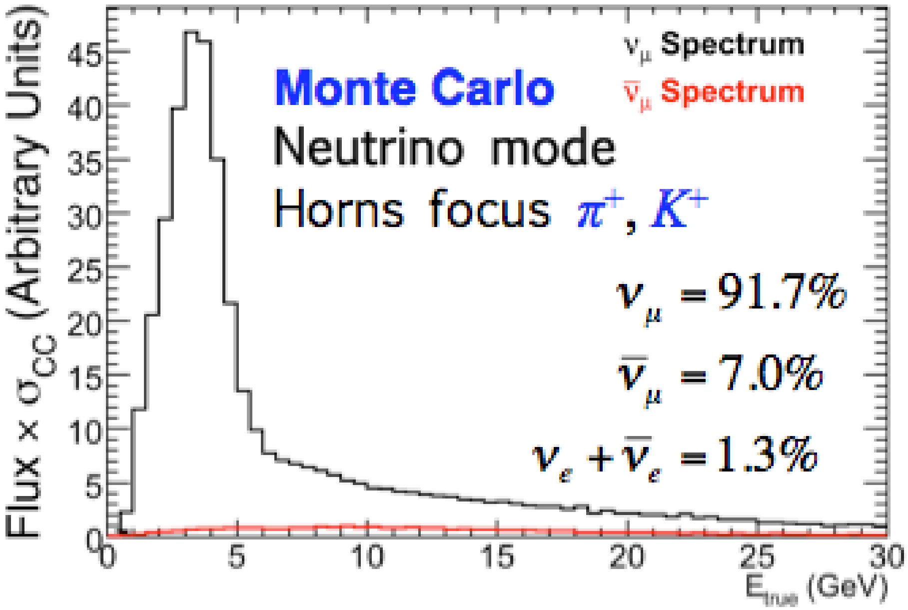
The NuMI Beam and the MINOS Detectors

The NuMI Beam

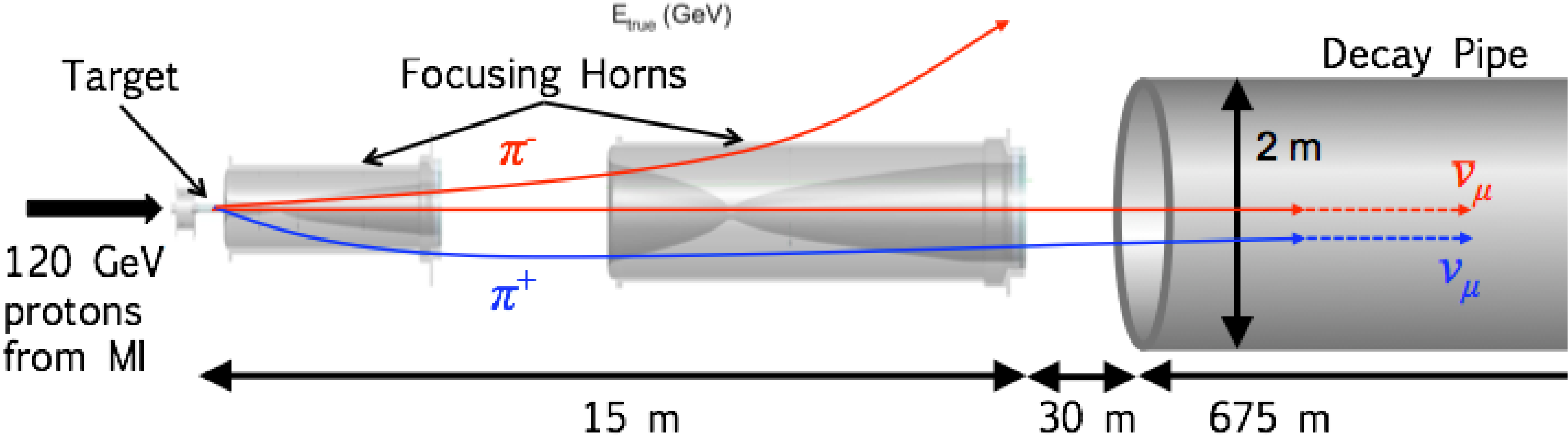




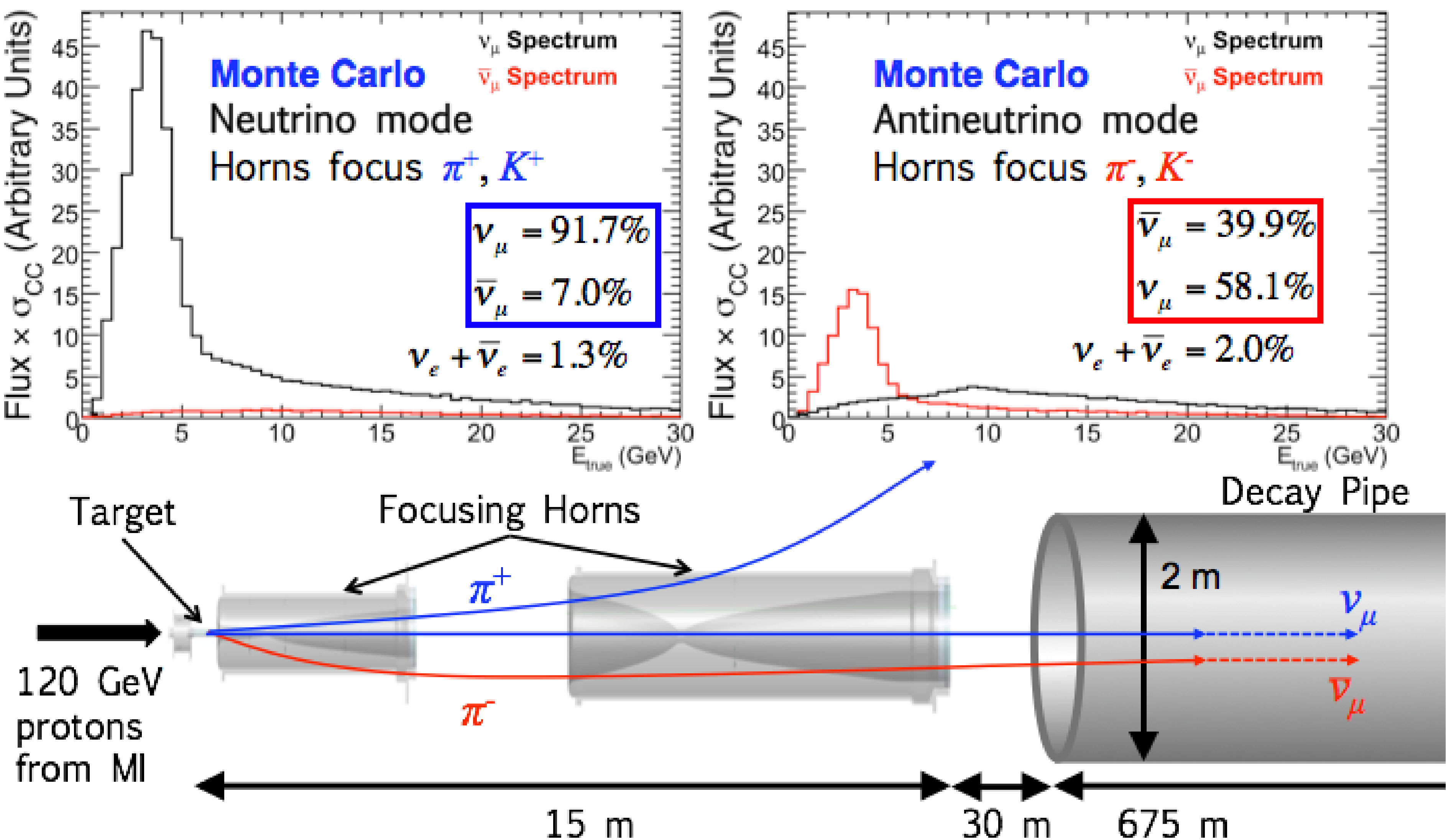
Creating a ν_μ Beam



- 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 ν_μ Beam

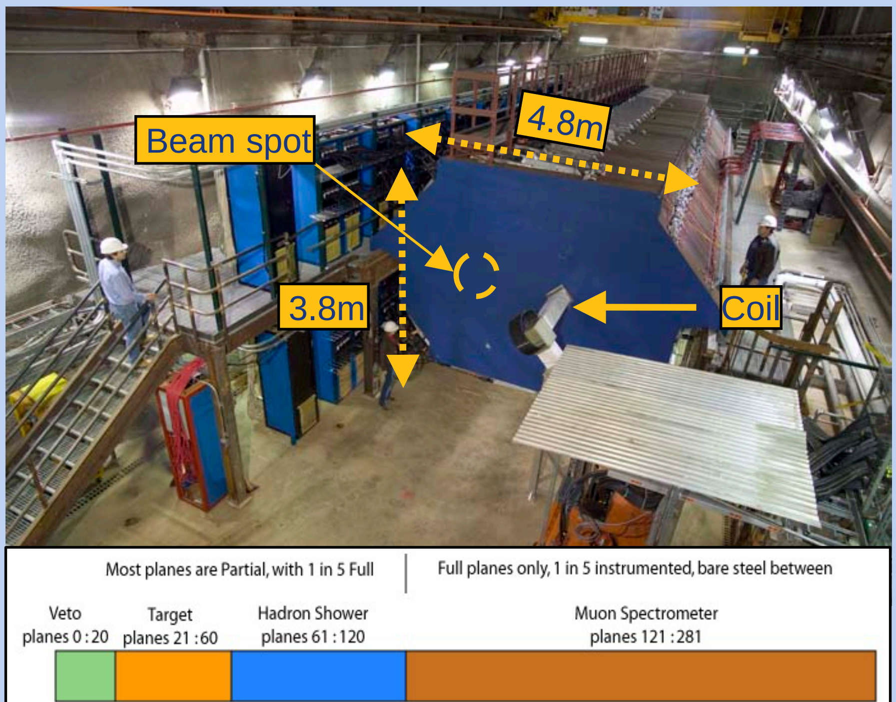


The MINOS Detectors

- Magnetized tracking sampling calorimeters

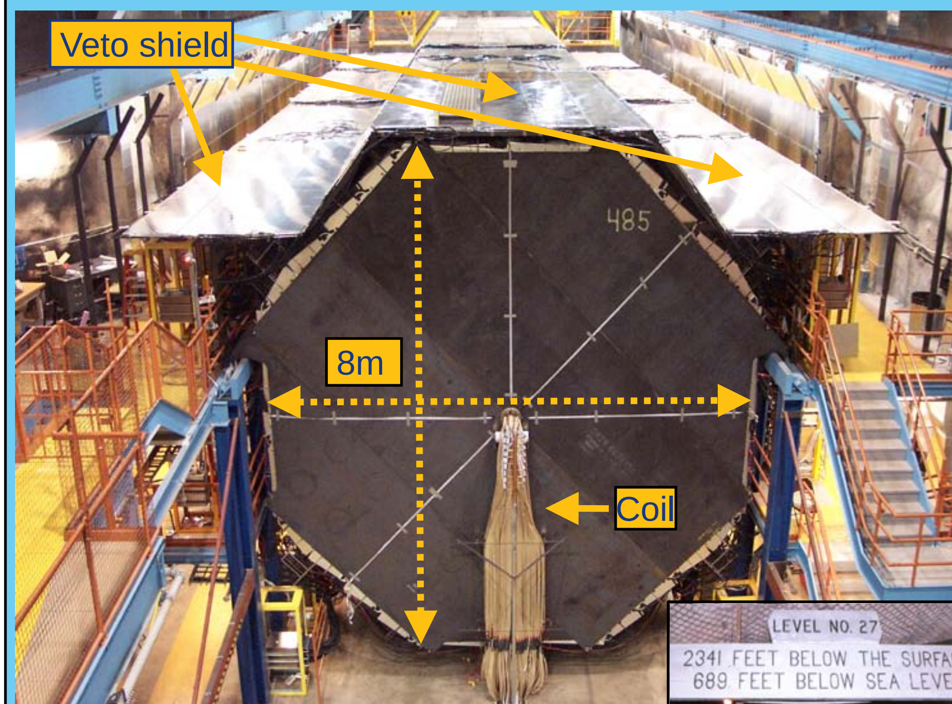
Near Detector

- ~1 kton (980 ton) total mass
- Located 1 km downstream of the target at Fermilab100 m depth



Far Detector

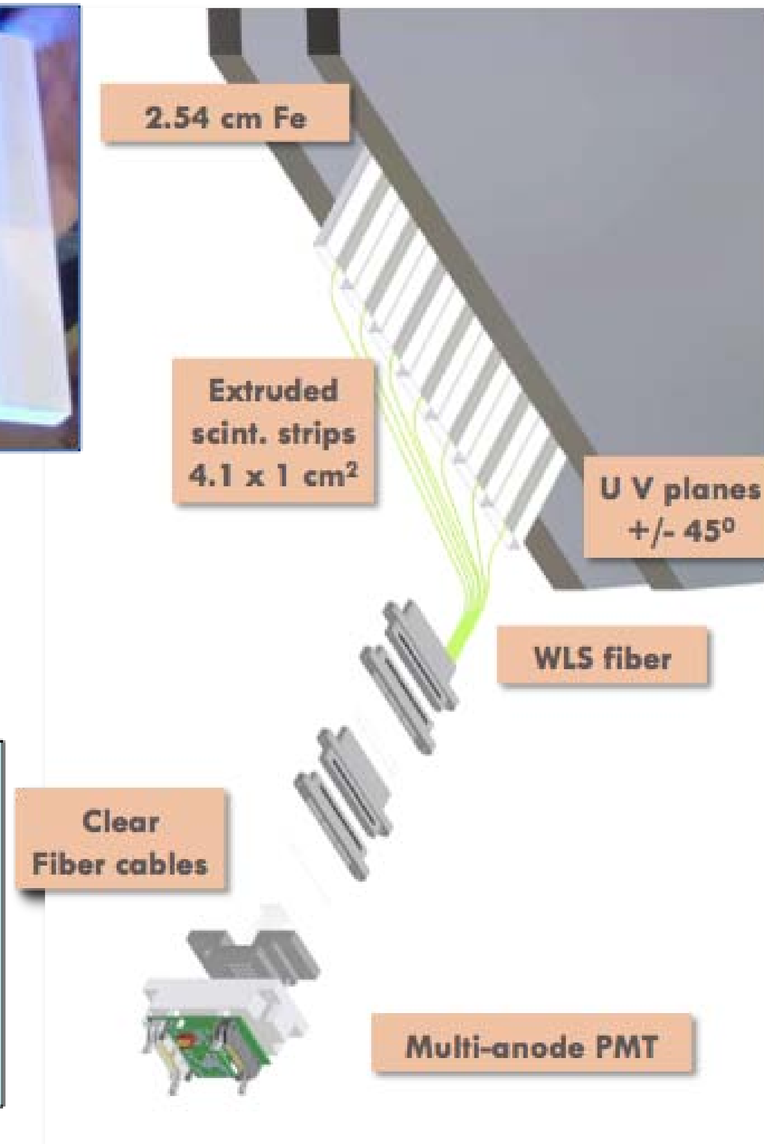
- 5.4 kton, 2 supermodules
- Located 735 km away in Soudan mine, MN 714 m depth

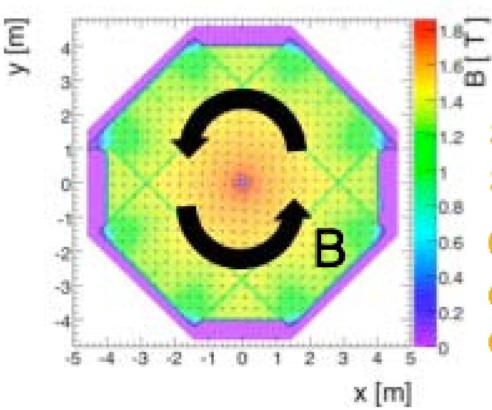


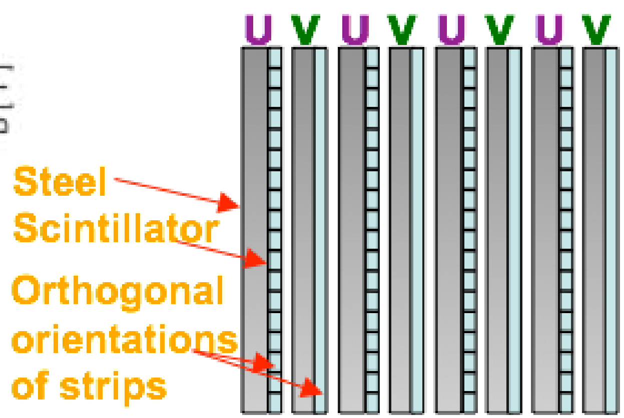
- Functionally equivalent: same segmentation, same materials, same mean B field

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 <Bfield > ~1.3T
- Can measure muon energy from range in detector or from curvature in B field. Able to distinguish μ^+ from μ^-

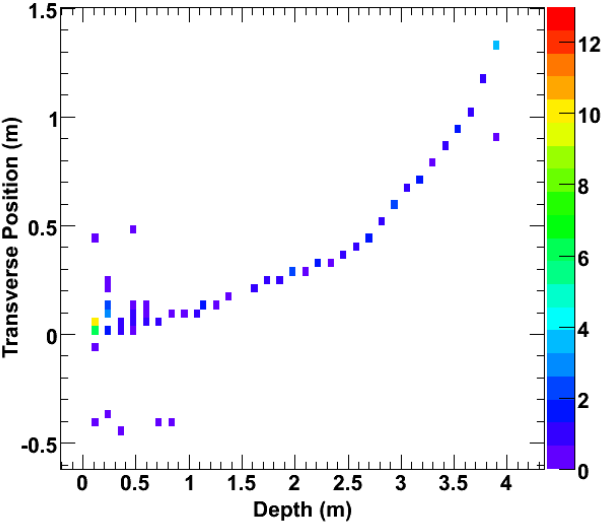


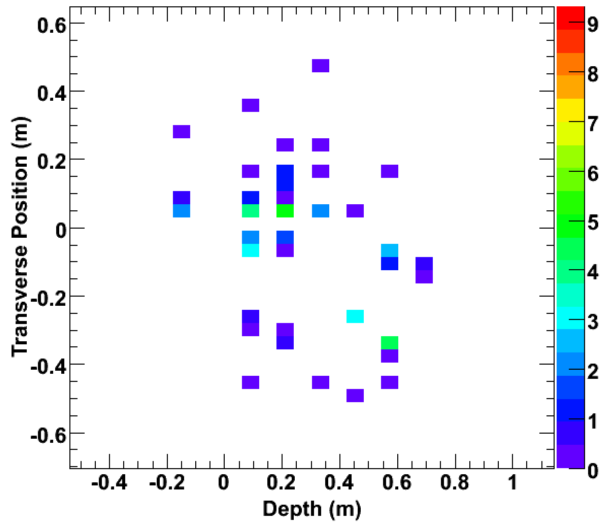


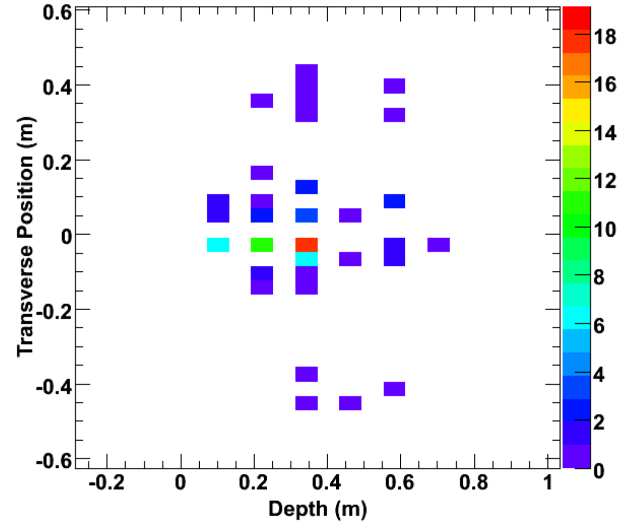


Event Topologies

ν_μ Charged Current (CC) | Neutral Current (NC) | ν_e CC



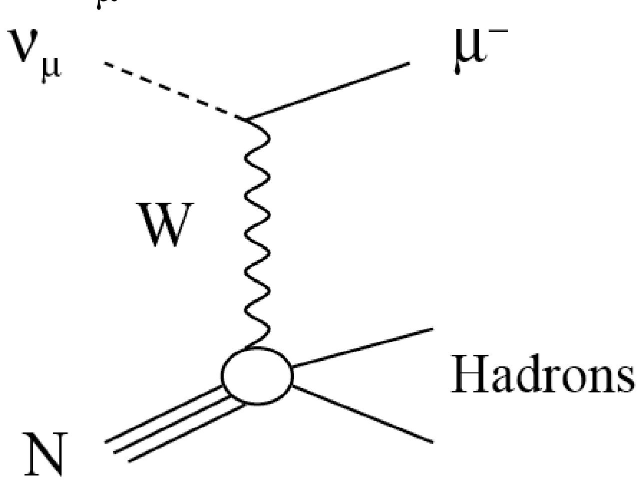


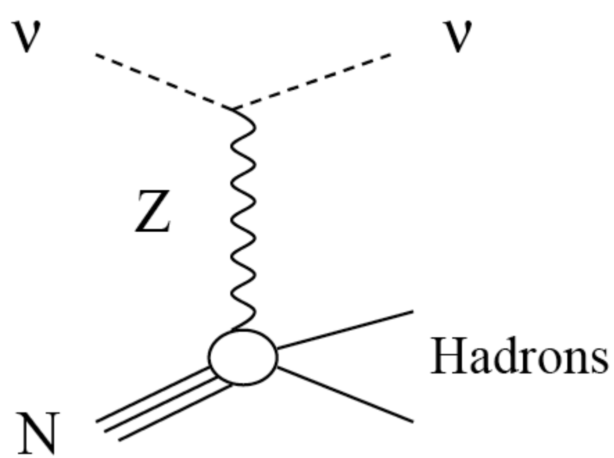


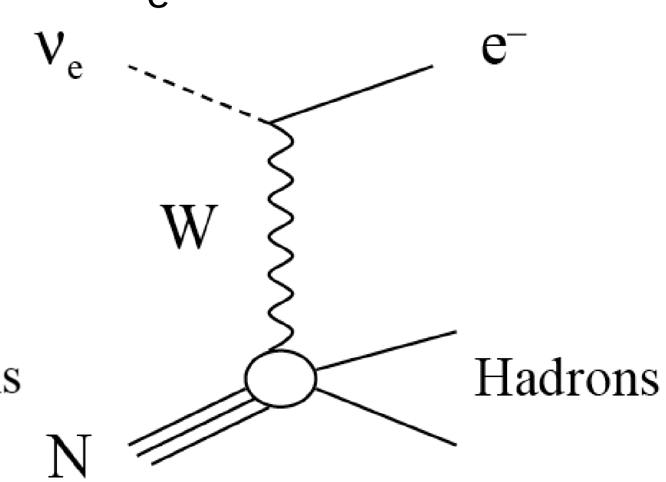
$\nu_\mu + N \rightarrow \mu^- + X$

$\nu + N \rightarrow \nu + X$

$\nu_e + N \rightarrow e^- + X$







Search for Electron Neutrino Appearance

Electron Neutrino Appearance

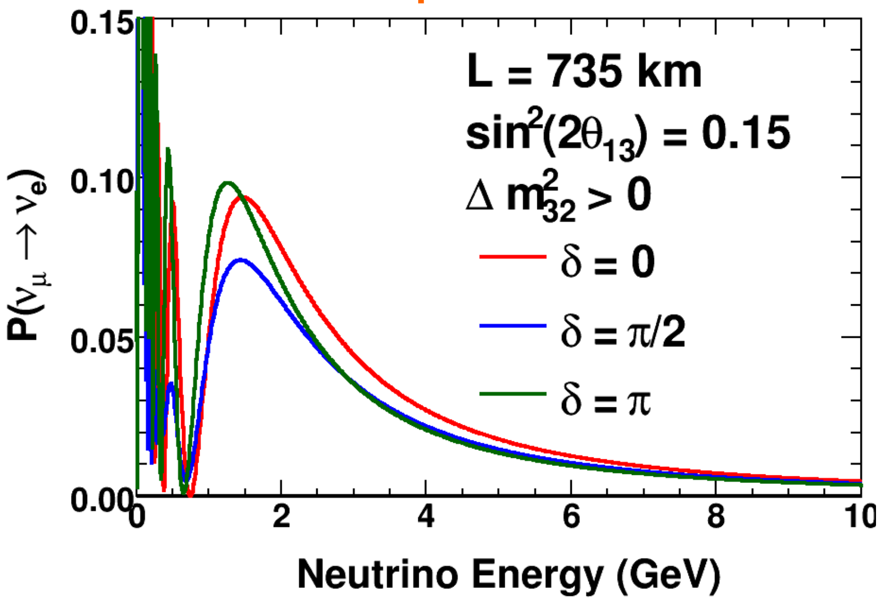
appearance of ν_e in a ν_μ beam

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

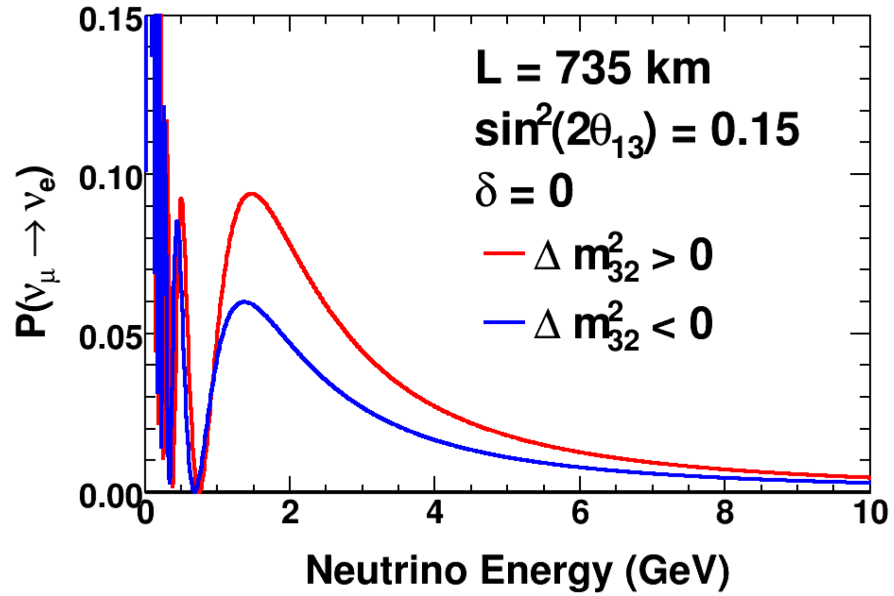
(Dominant term)

Higher order terms that depend on □ and the mass hierarchy

□ dependence



mass hierarchy dependence

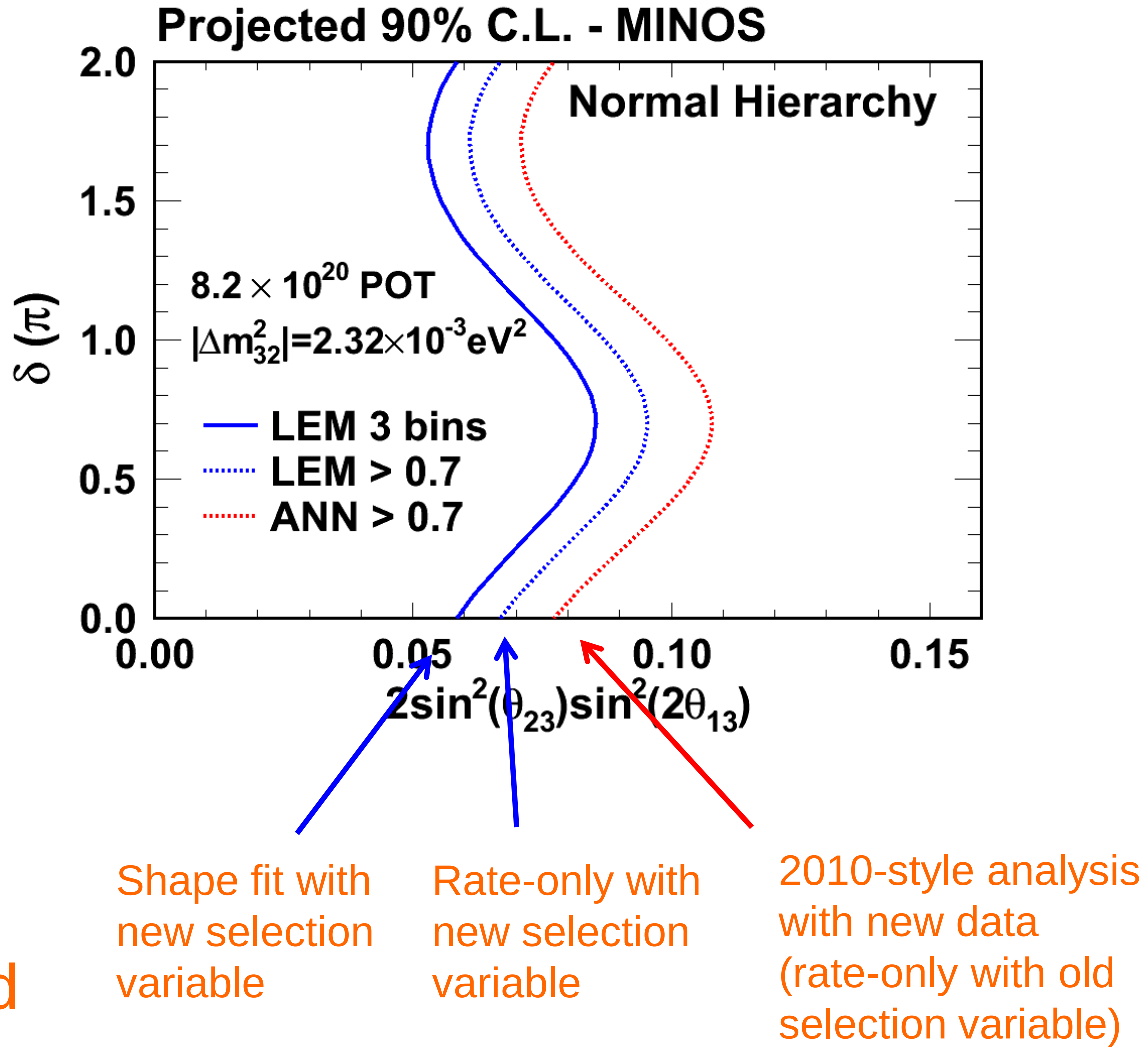


Projected Sensitivity

Since 2010 result:
Phys. Rev. D 82, 051102

- 1.2×10^{20} POT (17% more data)
- Improved event selection variable: 15% sensitivity gain
- Shape fit: 12% sensitivity gain

Sensitivity = 90% CL upper limit we would set if we observed exactly the background prediction.



Library Event Matching (LEM)

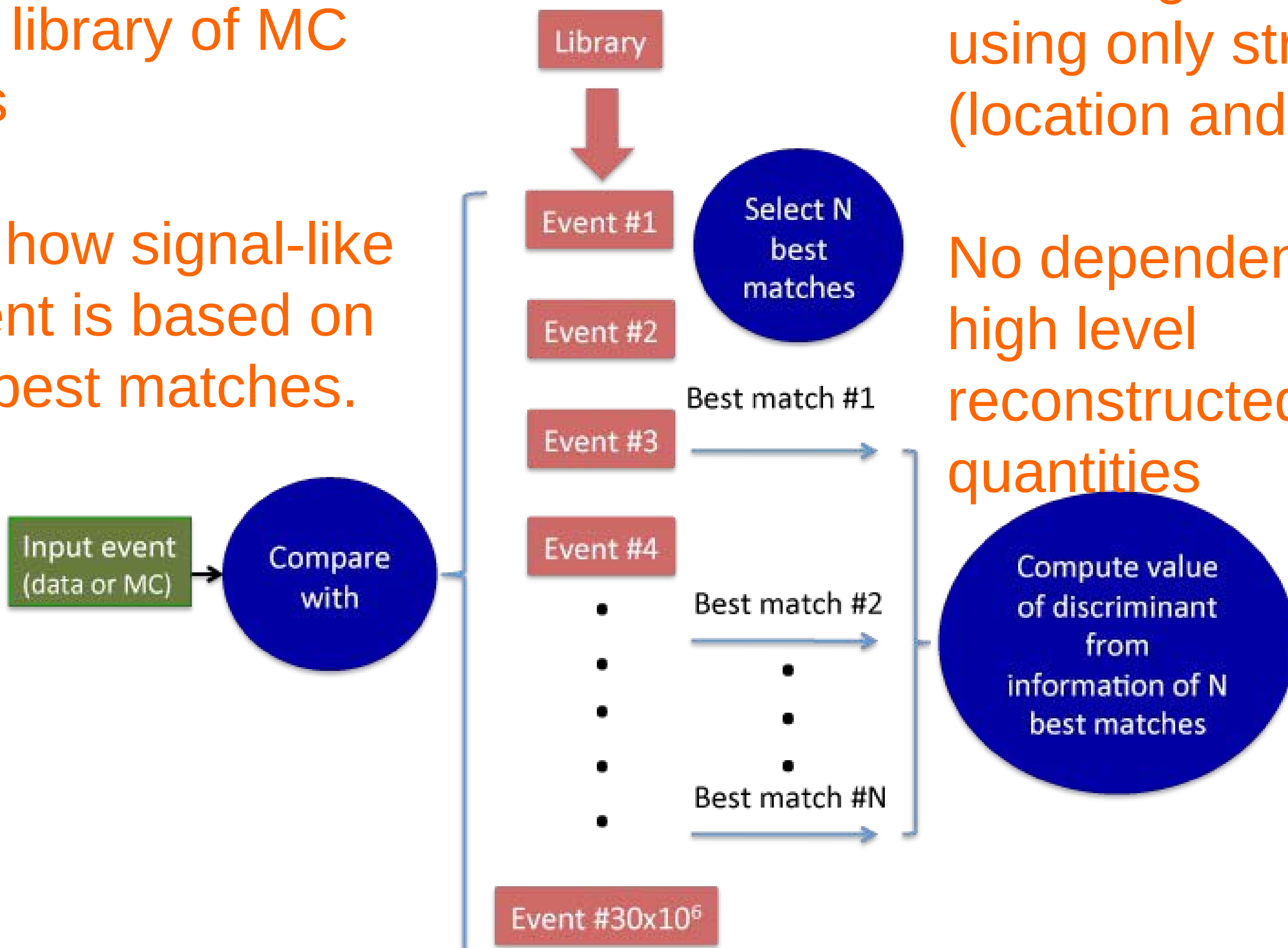
New □$_e$ selection variable!

Find best matches from a library of MC Events

Judge how signal-like an event is based on those best matches.

Matching is done using only strip info (location and charge)

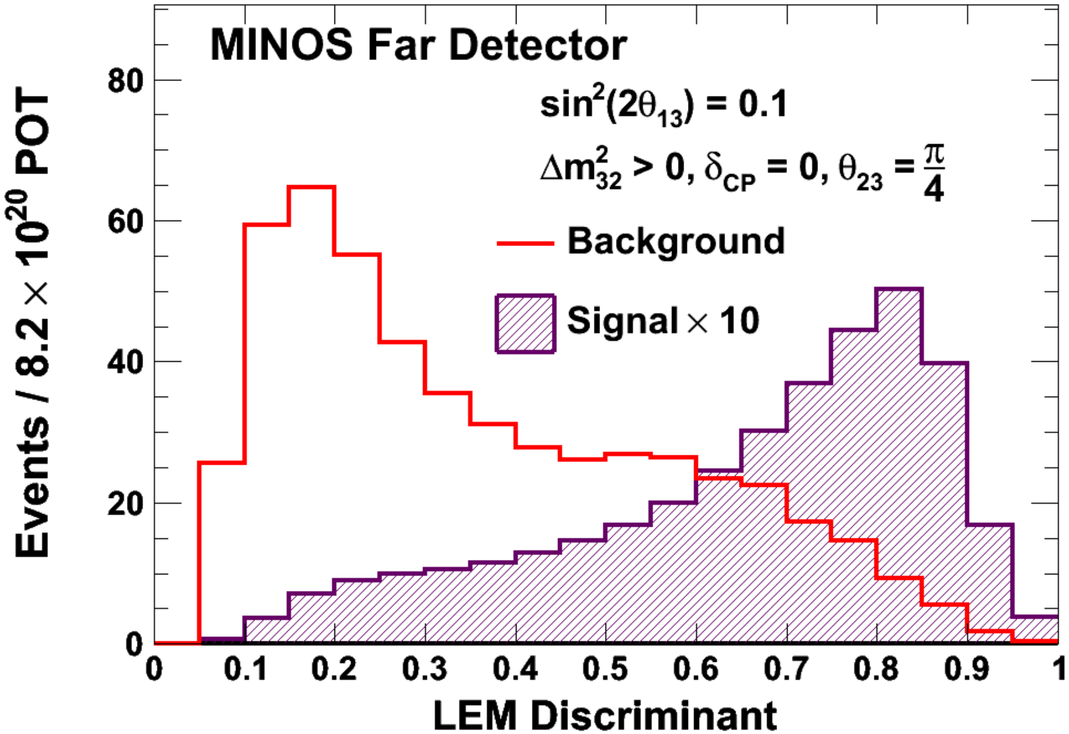
No dependence on high level reconstructed quantities



Library Event Matching (LEM)

Three variables describing best matches + reconstructed energy used as inputs to a neural net

Output of neural net is the LEM selection variable



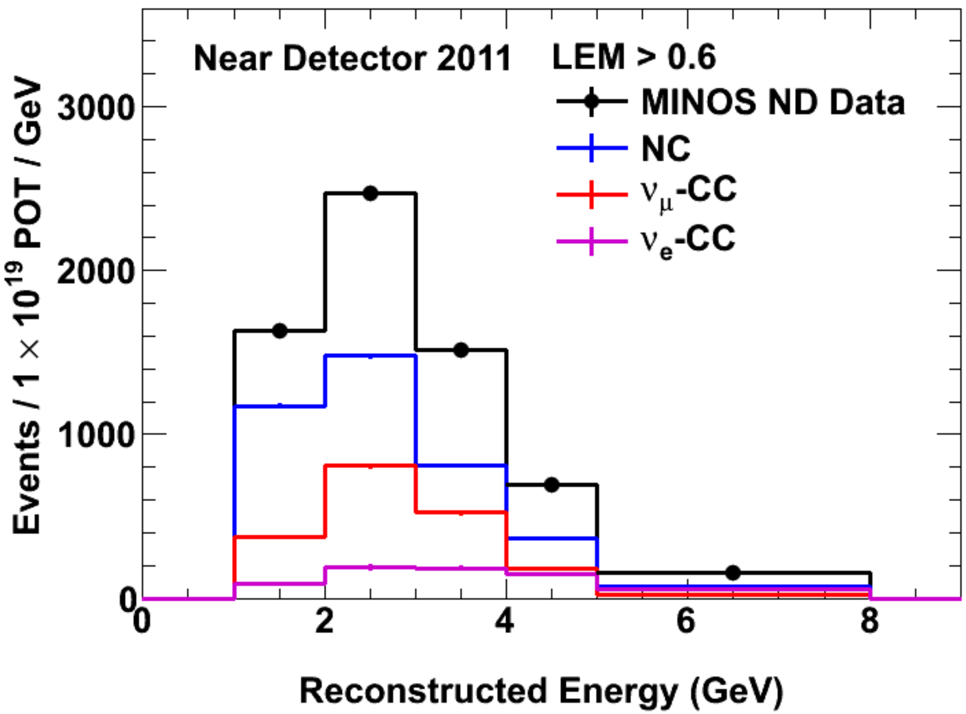
Prior to using LEM, a set of Preselection cuts is applied to remove events that are obviously not signal:

- No long tracks
- At least one well-formed shower
- With visible energy 1-8 GeV

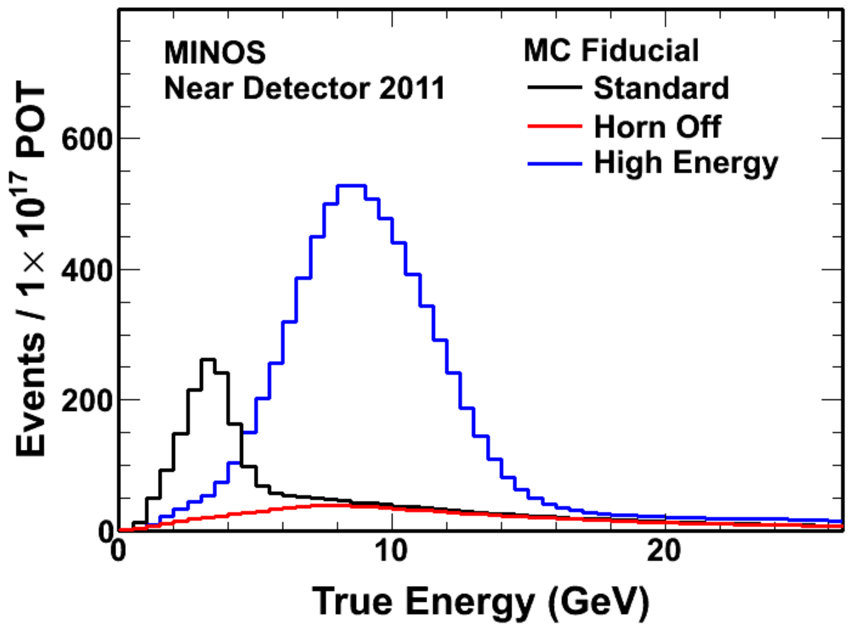
Far Detector Background Prediction

Construct library for each event type:

- neutral current
- charged current ν_μ
- charged current ν_e (beam)



Separate ND data into the 3 event types by fitting data from 3 different beam configurations:



$$F = N \times R^{F/N}$$

ND data

MC Far-to-Near ratio

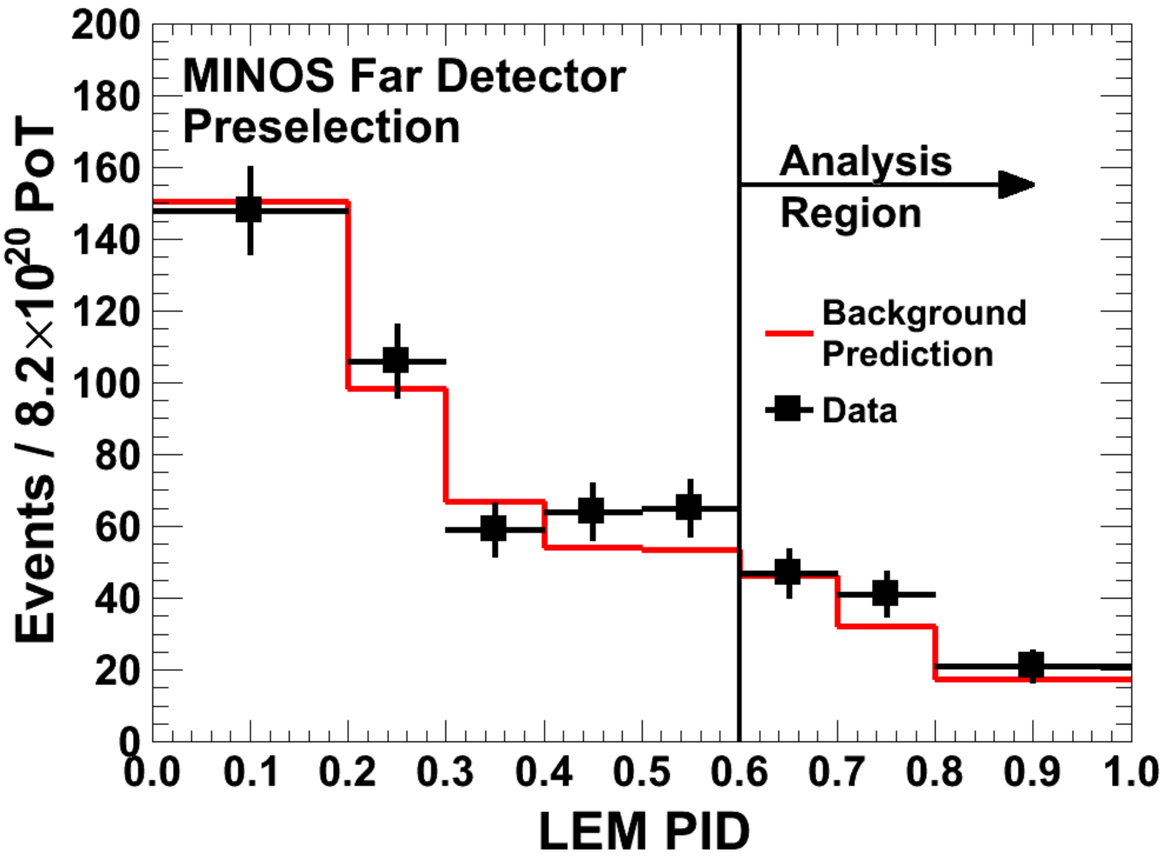
Far Detector Prediction

For 8.2 $\times$ 10^{20} POT
Signal-enhanced region (LEM > 0.7)
Assuming:

- □ = 0
- □m^2 = 2.32 $\times$ 10^{-3} eV^2
- □$_{23}$ = □/4
- $\sin^2 2$□$_{13}$ = 0.1

Component	Number of events
NC	34
ν_μ CC	7
Beam ν_e CC	6
ν_τ	2
Total Background	**49**
ν_e CC signal	**19**

Far Detector Data



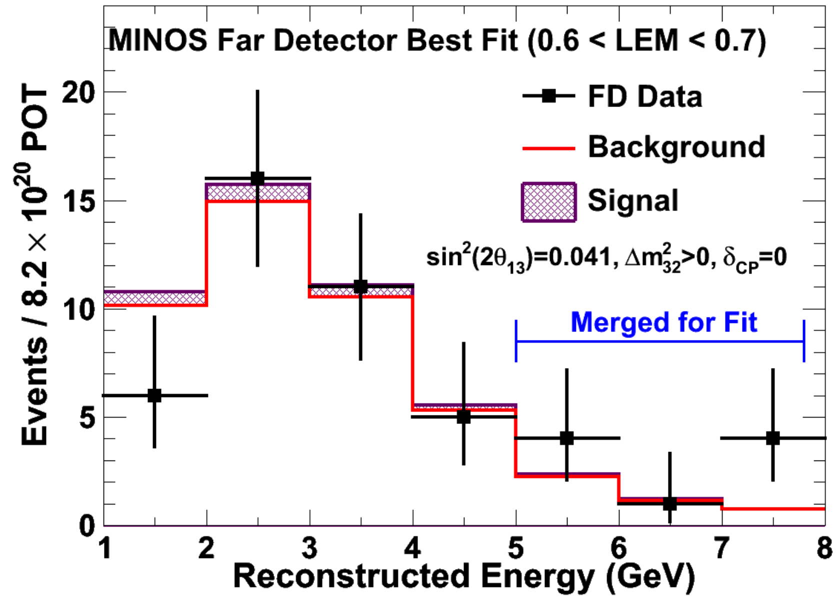
In signal-enhanced region (LEM > 0.7):

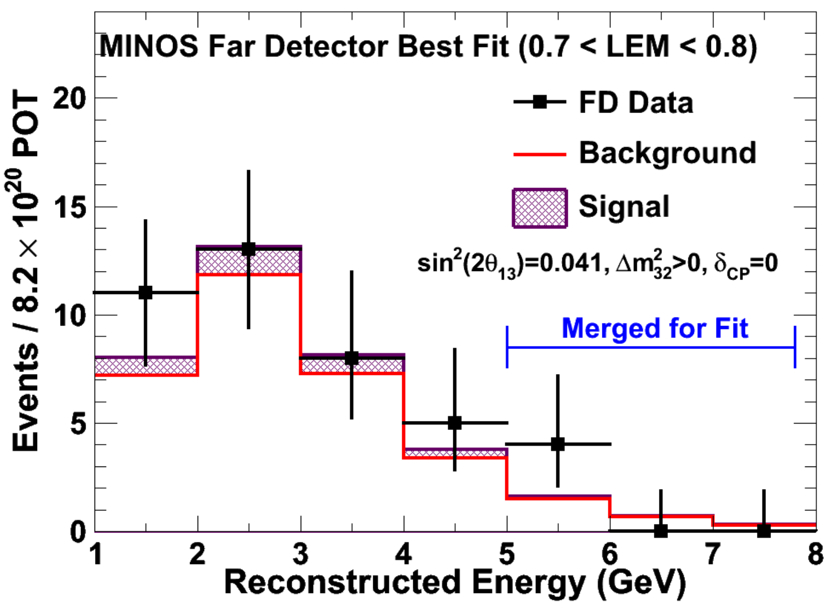
Expected background ($\theta_{13} = 0$):
49.6 ± 2.7 (syst) ± 7.0 (stat)
Observed data: 62

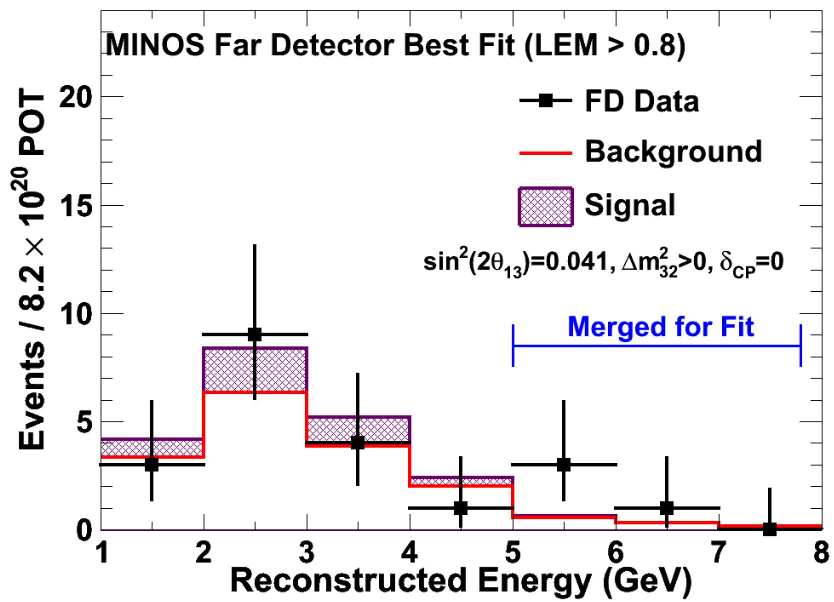
Best Fit

- Assumes □ = 0, $□_{23}$ = □/4, normal hierarchy
- 15 bin shape fit: 3 LEM bins x 5 energy bins

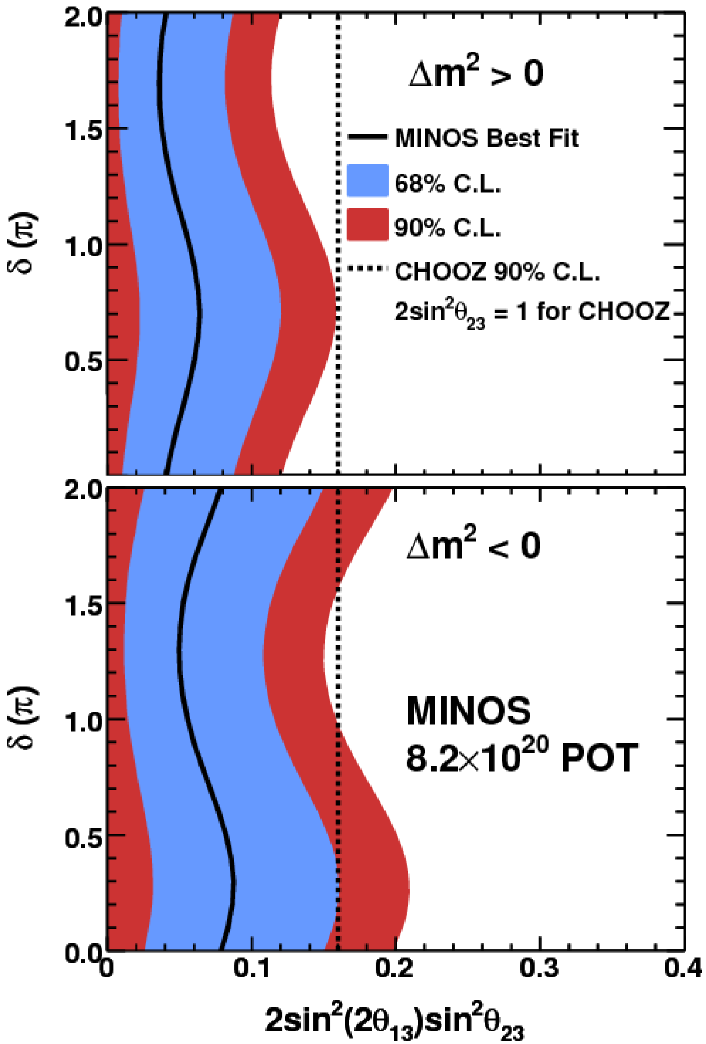
Best fit: $\sin^2 2□_{13} = 0.041$







Allowed Regions



Assuming □ = 0, □$_{23}$ = □/4
for the normal (inverted) hierarchy:

$\sin^2(2\theta_{13}) < 0.12$ (0.20) 90% CL

$\sin^2(2\theta_{13}) = 0.04$ (0.08) Best Fit

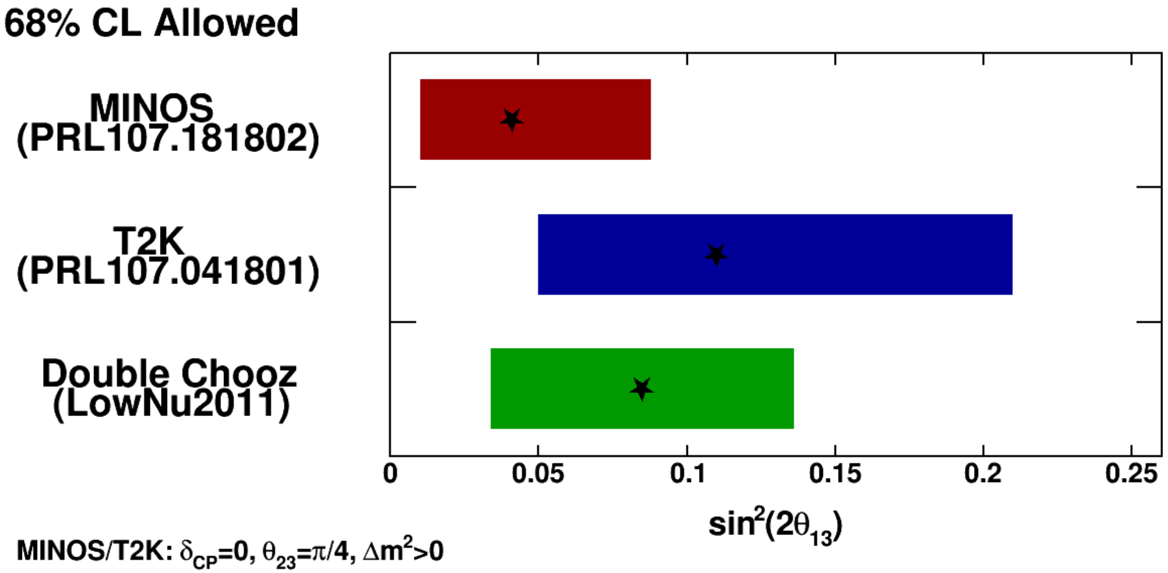
We exclude $\sin^2 2$□$_{13}$= 0 at 89% CL

Feldman-Cousins contours

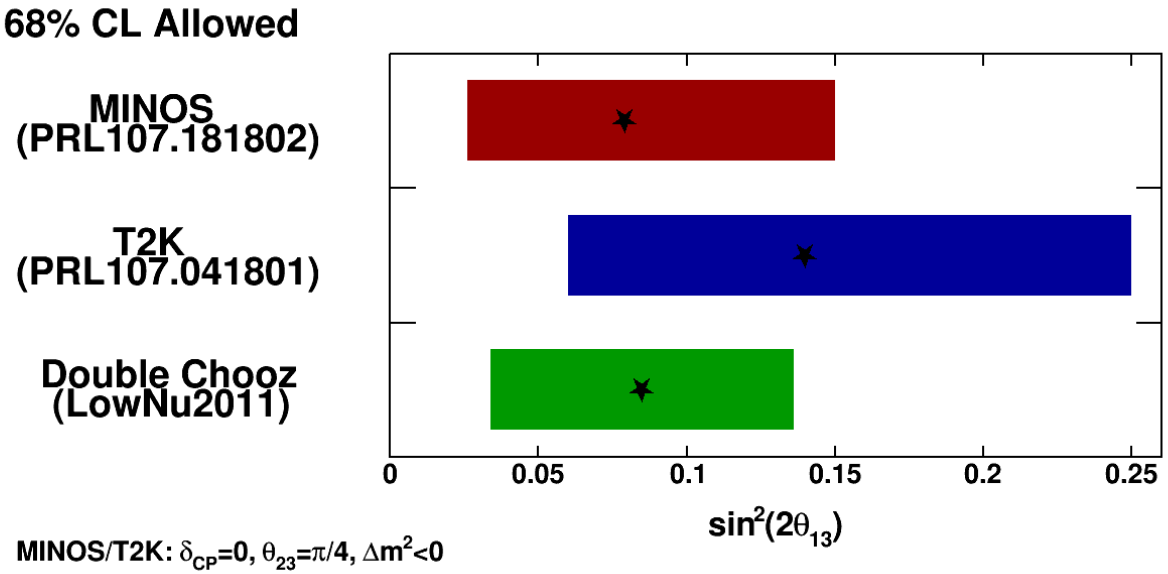
Uncertainties in the other oscillation parameters are included

Phys. Rev. Lett. 107, 181802 (2011)

Allowed Regions



Normal hierarchy

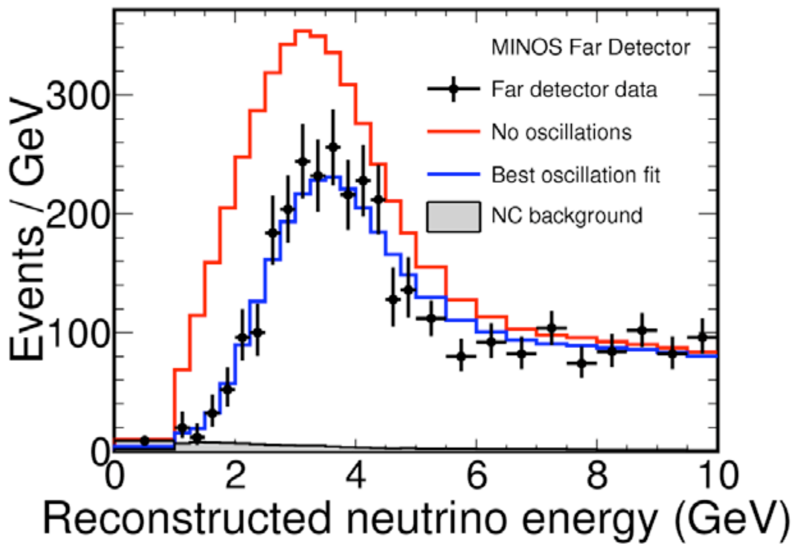


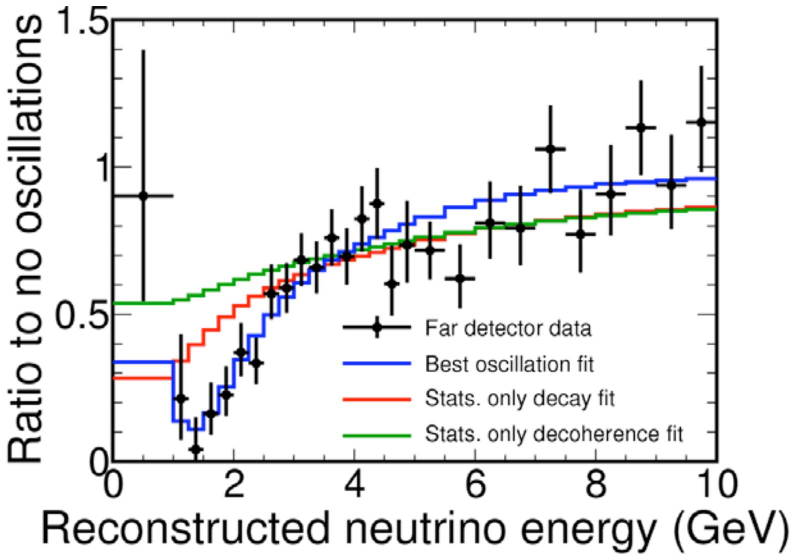
Inverted hierarchy

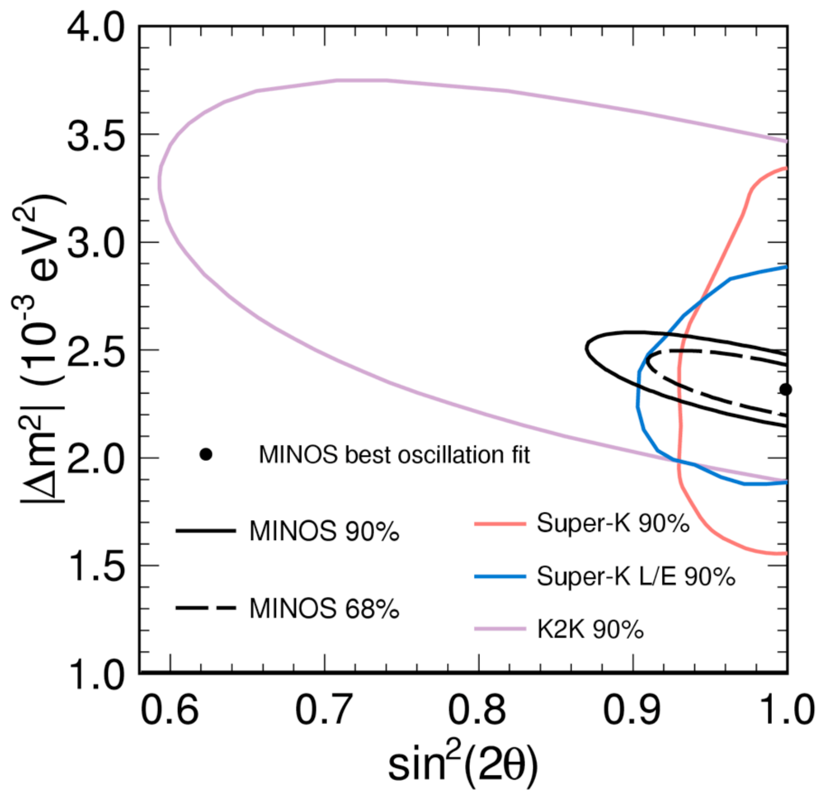
Muon Neutrino Disappearance Analysis

Muon Neutrino Disappearance

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







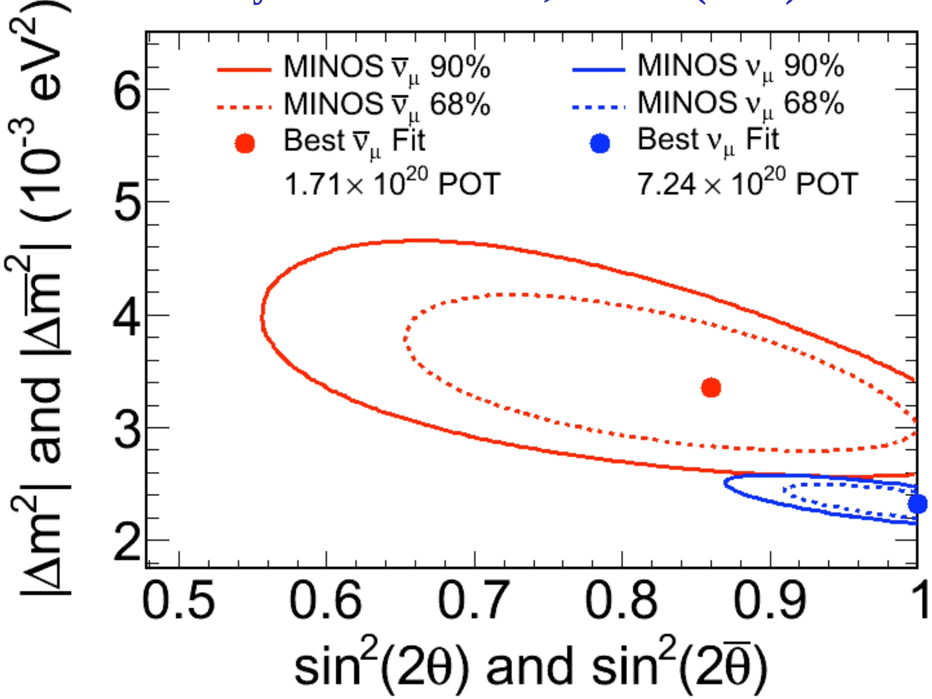
$$|\Delta m^2_{atm}| = 2.32^{+0.12}_{-0.08} \times 10^{-3} eV^2$$
$$\sin^2(2\theta_{23}) > 0.90 \ (90\% \ C.L.)$$

World's most precise $|\Delta m^2_{atm}|$ measurement!

Disfavors alternative hypotheses to oscillations

MINOS 2010 $\bar{\nu}_\mu$ Measurement

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



"The MINOS ν_μ and $\bar{\nu}_\mu$ measurements are consistent at the 2.0% confidence level, assuming identical underlying oscillation parameters."

Antineutrino best fit parameters

$$|\Delta \bar{m}^2_{atm}| = 3.36^{+0.46}_{-0.40} \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.86^{+0.11}_{-0.12}$$

Neutrino best fit parameters

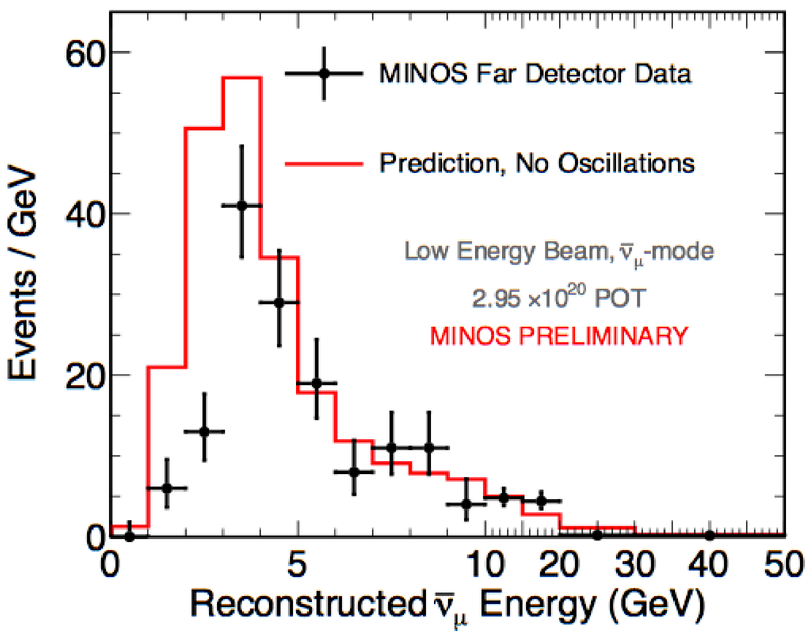
$$|\Delta m^2_{atm}| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.90 \ (90\% \ \mathrm{C.L.})$$

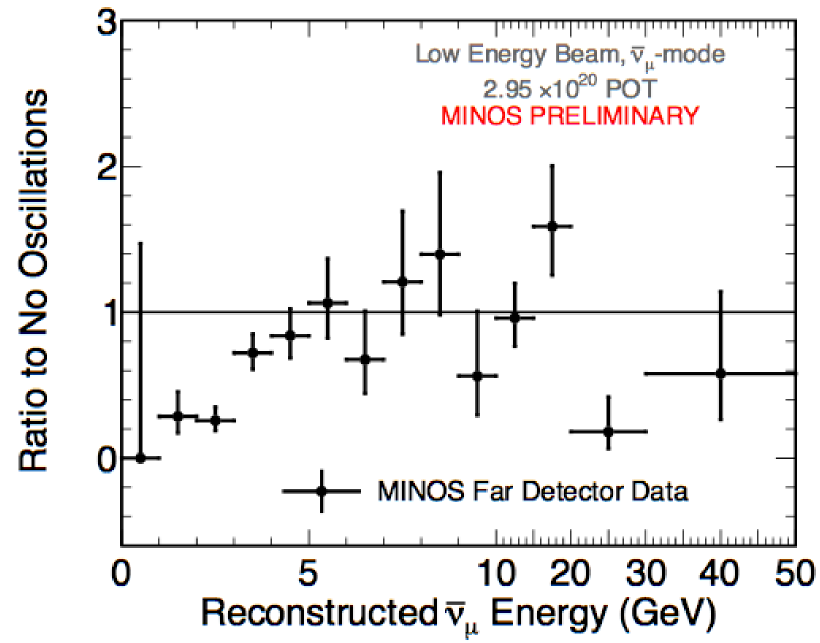
- First MINOS antineutrino analysis, using 1.71×10^{20} POT showed tension between neutrino and antineutrino mixing parameters
- Generated much discussion in conferences and in literature

Analysis of 2.95×10^{20} POT of Antineutrino Data

- ~70% increase in $\bar{\nu}_\mu$ beam exposure
  from 1.71×10^{20} POT to 2.95×10^{20} POT
- Improved analysis
- Aim to clarify 2010 analysis measurement

Far Detector Energy Spectrum



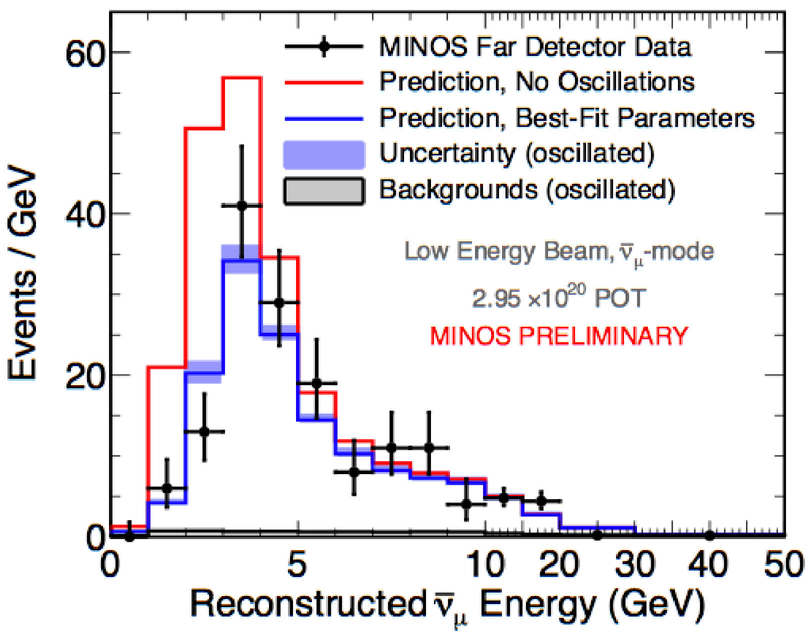


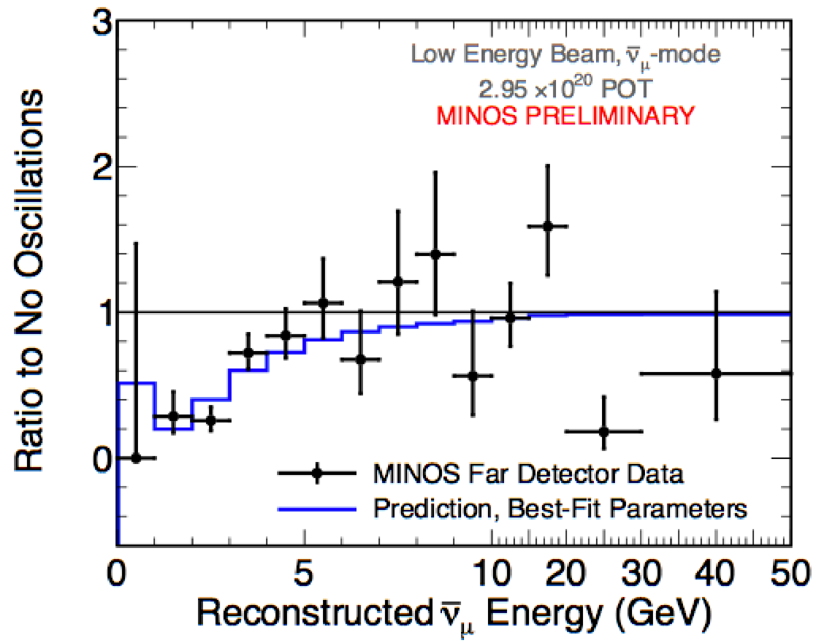
Prediction, No Oscillations: **273 events**

Observed: **193 events**

Null-oscillations excluded at **7.3σ**

Far Detector Energy Spectrum





Prediction, No Oscillations: **273 events**

Observed: **193 events**

Null-oscillations excluded at **7.3σ**

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

$$|\Delta\bar{m}^2_{atm}| = [2.62^{+0.31}_{-0.28}(\text{stat}) \pm 0.09(\text{syst})] \times 10^{-3}\text{eV}^2$$

$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}(\text{stat}) \pm 0.01(\text{syst})$$

Contour Comparisons

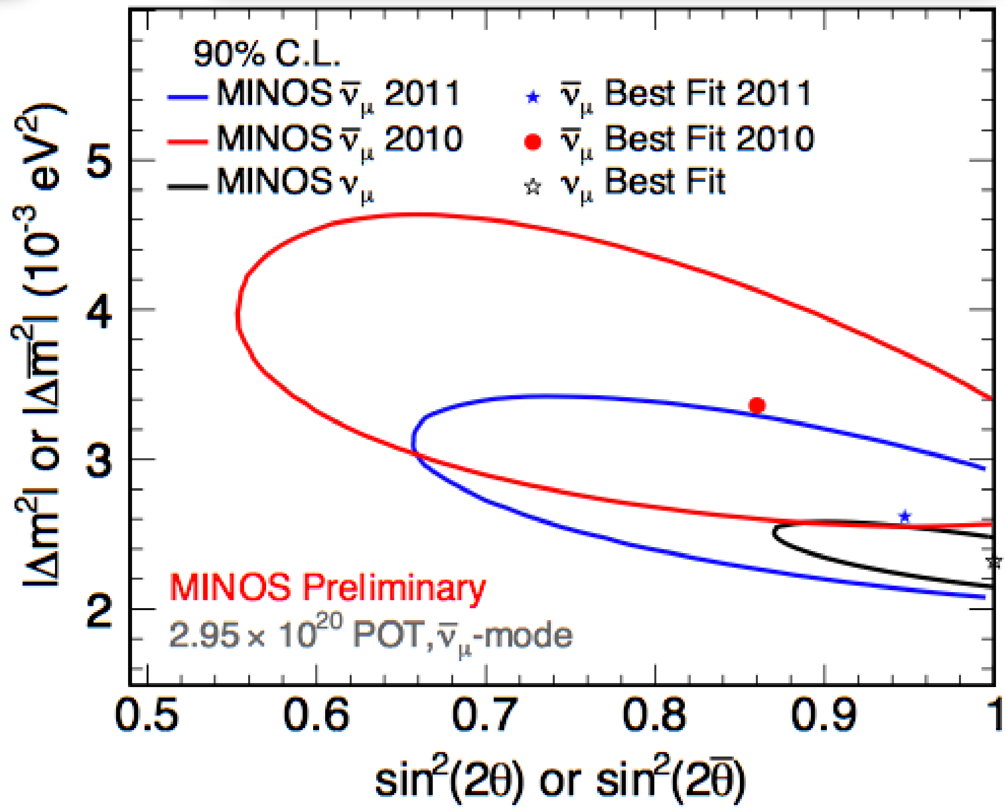
Antineutrinos

$$|\Delta\overline{m}^2_{atm}| = 2.62^{+0.31}_{-0.28} \times 10^{-3}\text{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) > 0.75 \ (90\% \text{ C.L.})$$

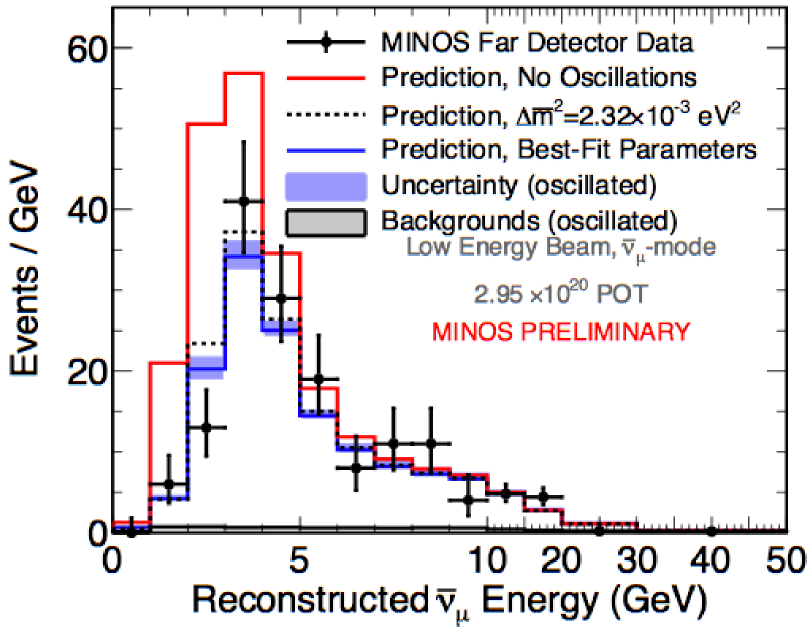
Neutrinos

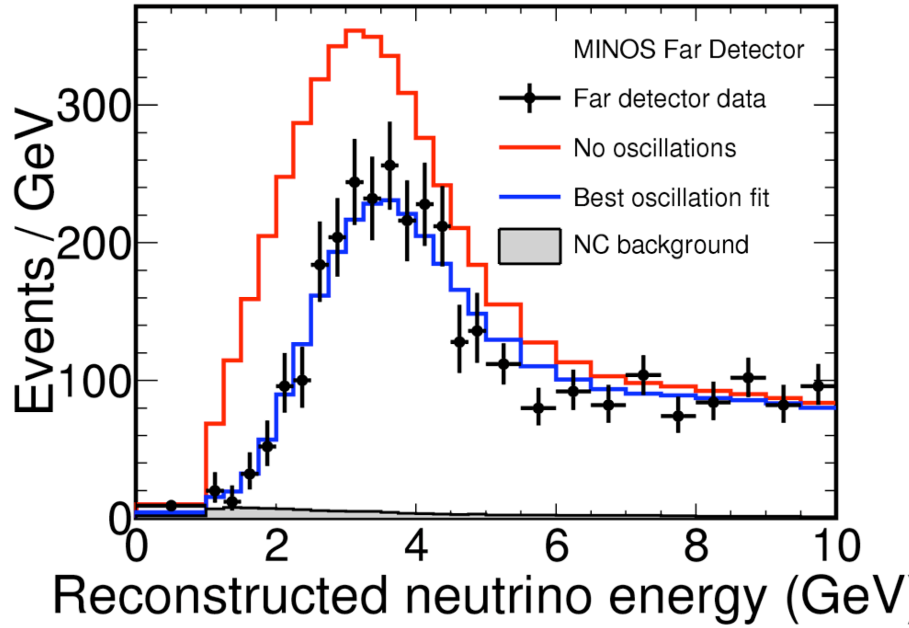
$$|\Delta m^2_{atm}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\text{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.90 \ (90\% \text{ C.L.})$$

- Comparison with MINOS 90% C.L. contour for Run IV antineutrino data
- Comparison with MINOS 90% C.L. contour for neutrino mode



Compatibility with Neutrino Results





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

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$$\sin^2(2\bar{\theta}_{23}) > 0.75\ (90\%\,\mathrm{C.L.})$$

ν_μ Oscillation Best Fit Parameters

$$|\Delta m^2_{atm}| = 2.32^{+0.12}_{-0.08}\times10^{-3}\mathrm{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.90\ (90\%\,\mathrm{C.L.})$$

- Assuming identical underlying oscillation parameters, the $\bar{\nu}_\mu$ and ν_μ oscillation measurements are consistent at the 42% C.L. (was 2.0% C.L. for 2010 analysis)

Conclusions

MINOS has completed an analysis of

- **8.20×10^{20} POT to search for electron neutrino appearance**

$\sin^2(2\theta_{13}) < 0.12$ (0.20) @ 90% CL normal (inverted)

$\sin^2(2\theta_{13}) = 0.04$ (0.08) Best Fit

We exclude $\sin^2 2\square_{13} = 0$ at 89% CL

Conclusions

MINOS has completed an analysis of

- 8.20×10^{20} POT to search for electron neutrino appearance
- **2.95×10^{20} POT to measure muon antineutrino disappearance**

- MINOS makes the world's most precise measurement of the antineutrino atmospheric mass-squared splitting:

$$\left|\Delta \overline{m}^2_{\mathrm{atm}}\right| = \left[2.62^{+0.31}_{-0.28}(\mathrm{stat}) \pm 0.09(\mathrm{syst})\right] \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$

- Result from 2010 analysis was a fluctuation due to low-statistics
  - Antineutrino oscillation parameters consistent with neutrino counterparts with p=42%

Backup

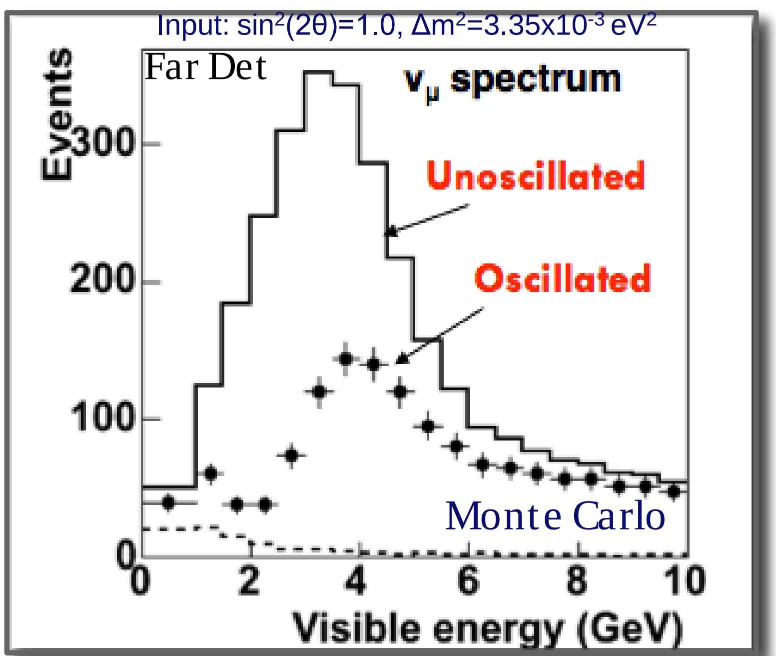
LEM variables:

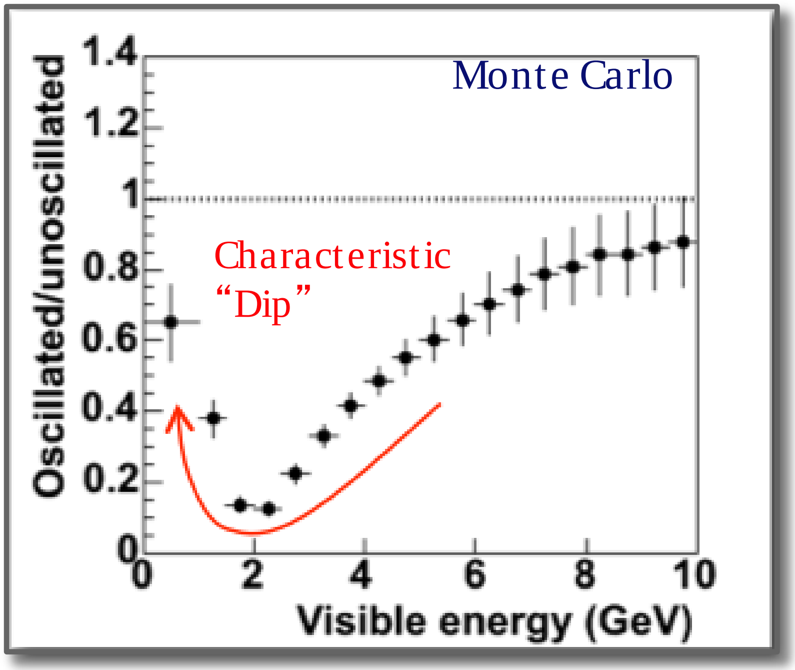
- Fraction of 50 best matched events that are true nue CC
- Average reconstructed inelasticity of those events
- Fraction of charge that overlaps between the input event and each nue CC event

Disappearance Measurements

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

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





Disappearance Measurements

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- Neutrino oscillations deplete rate and distort the energy spectrum

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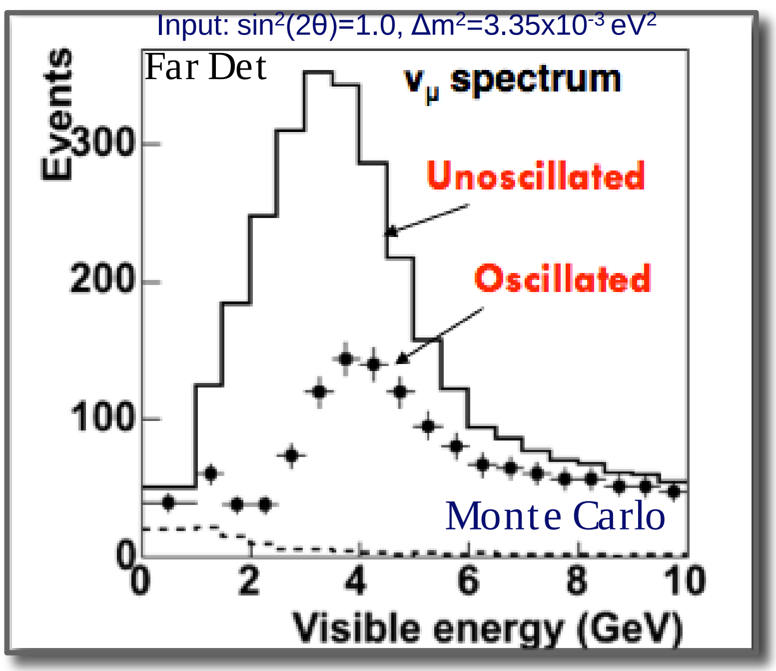
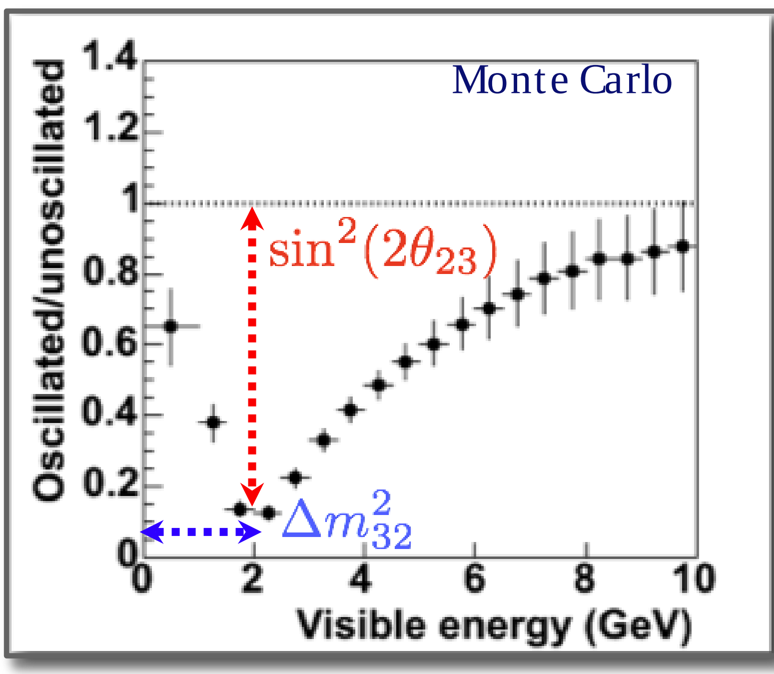
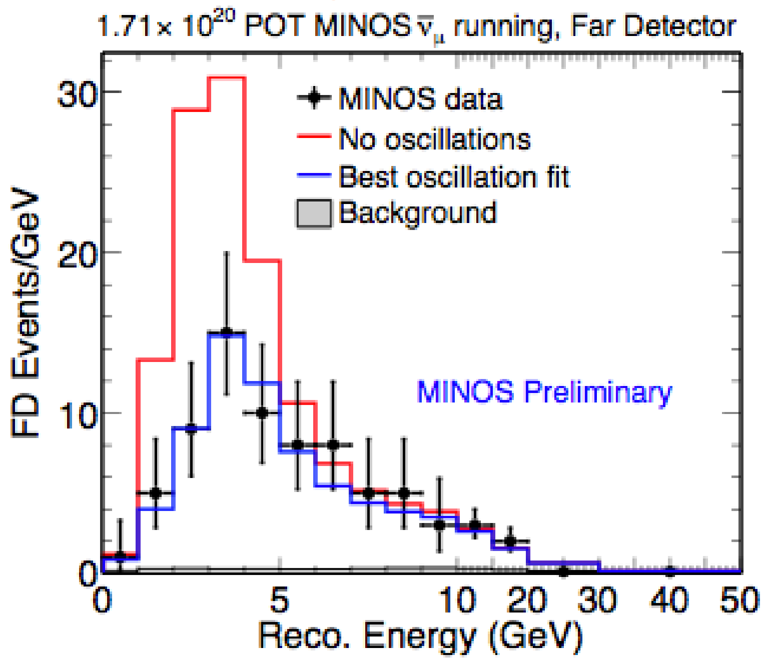


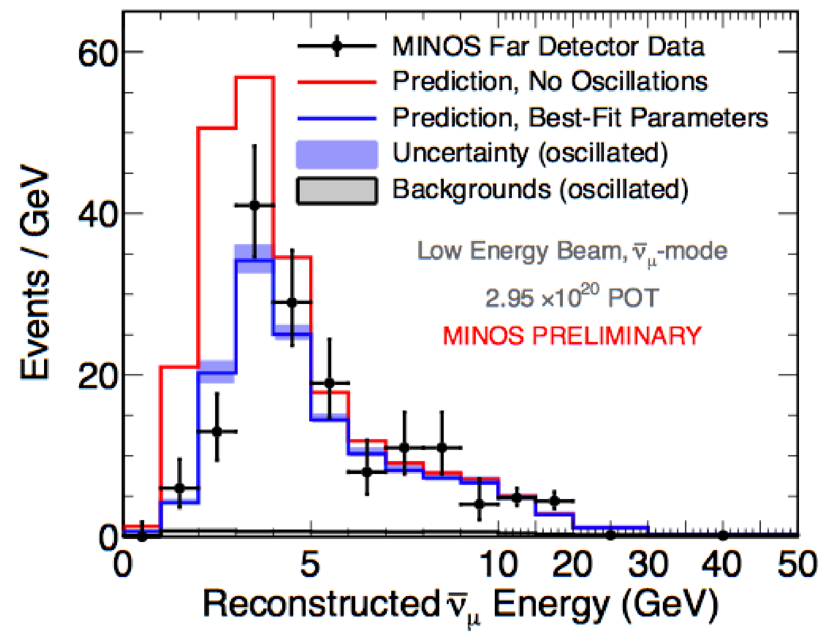


Comparison with Previous Analysis

2010 Analysis, 1.71x10^{20} POT



2011 Analysis, 2.95x10^{20} POT



Prediction, No Oscillations: **155 events**
Observed: **97 events**
Null-oscillations excluded at **6.3σ**

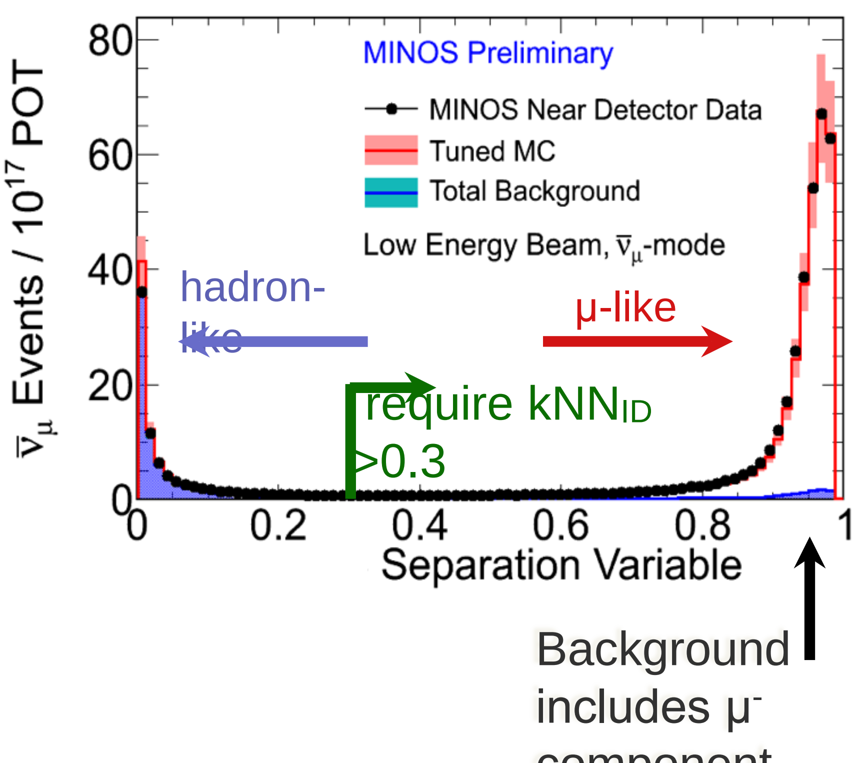
Prediction, No Oscillations: **273 events**
Observed: **193 events**
Null-oscillations excluded at **7.3σ**

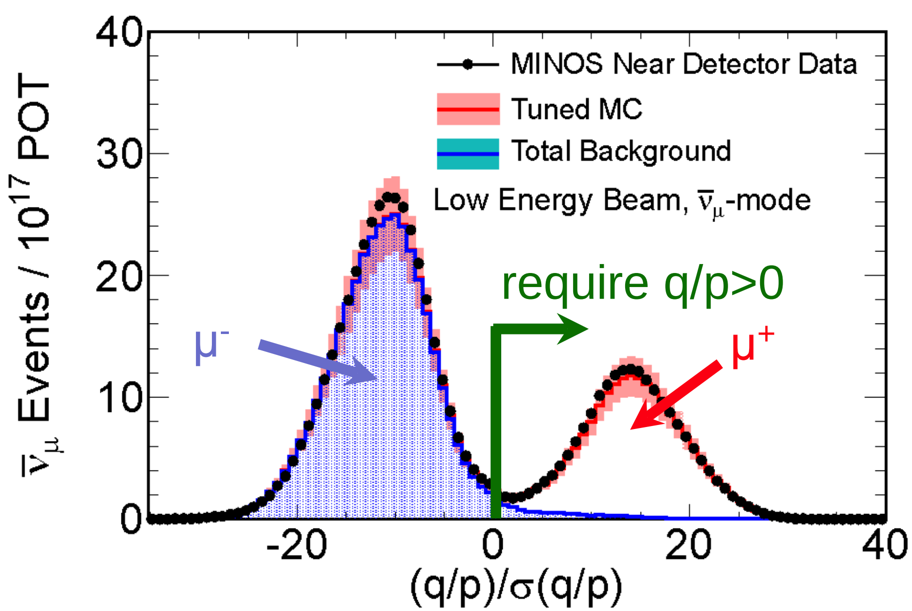
$$|\Delta\bar{m}^2_{atm}| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.86^{+0.11}_{-0.12}$$

$$|\Delta\bar{m}^2_{atm}| = 2.62^{+0.31}_{-0.28} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}$$

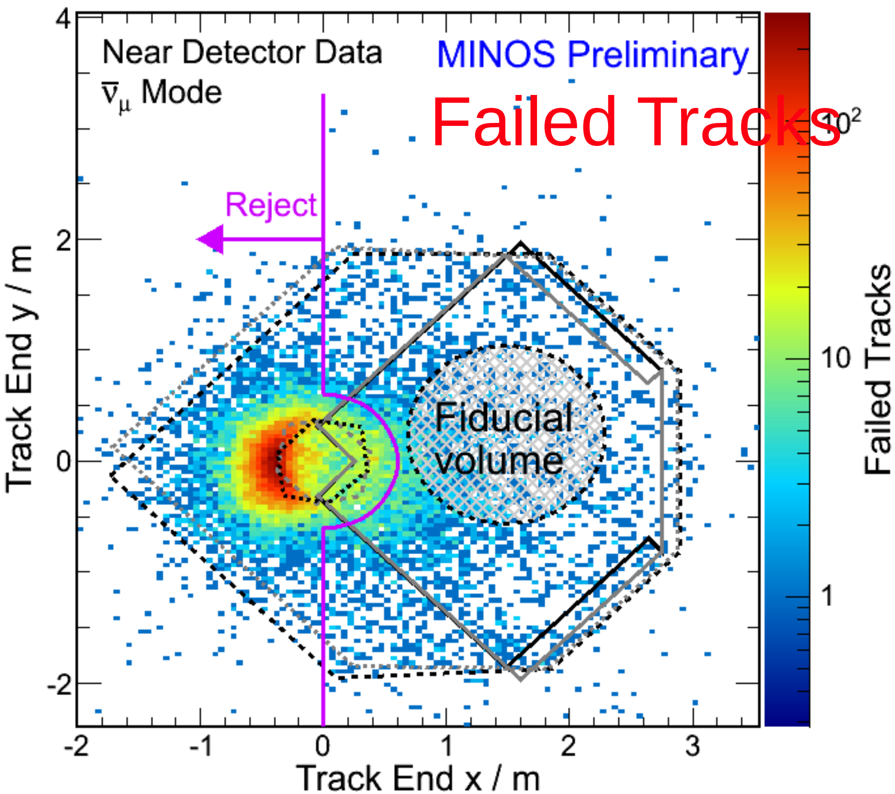
CC/NC and Charge Separation

- Muons from ν_μ, $\bar{\nu}_\mu$ CC interactions are identified as tracks satisfying a multivariate topological ID
- Rejects neutral current backgrounds and high-y CC events
- Muon charge/momentum analyzed by track curvature
- Only accept events with positive reconstructed charge





Coil Hole Selection



End positions of tracks failed by track fitter

- **Track fitter occasionally fails**
  - Most failed tracks end near the coil
  - ND coil difficult to model in MC
  - 4.2% failures in MC, 6.1% in data
- **Coil Hole Selection**
  - Remove all tracks ending near the coil
  - Selection well modeled in MC
  - After selection, failed tracks ~1% in both MC and Data
    - Can safely remove fitter failures

Comparison with Run IV and Run VII

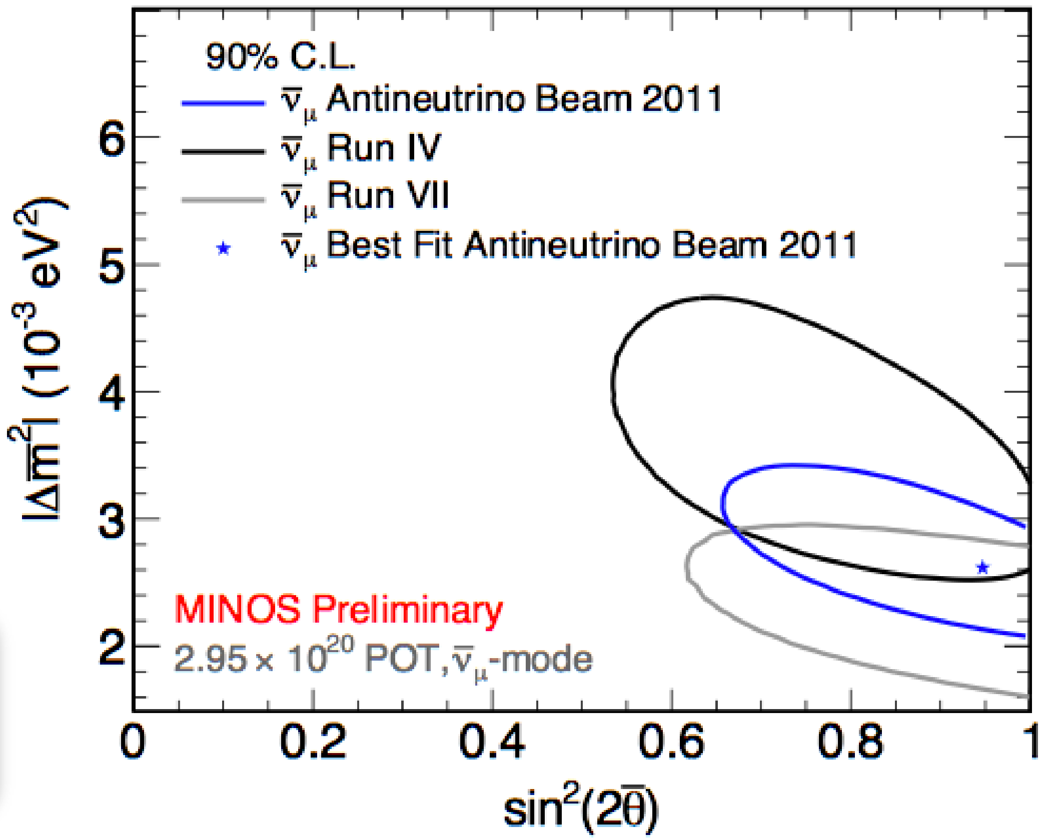
Run IV Only - 2011 Analysis

$$|\Delta\overline{m}^2_{atm}| = 3.46^{+0.47}_{-0.43} \times 10^{-3}\text{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.82^{+0.10}_{-0.11}$$

Run VII Only - 2011 Analysis

$$|\Delta\overline{m}^2_{atm}| = 2.26^{+0.27}_{-0.29} \times 10^{-3}\text{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) > 0.79 \ (90\%\ \text{C.L.})$$

- Comparison with MINOS 90% C.L. contour for Run IV antineutrino data obtained with the new analysis

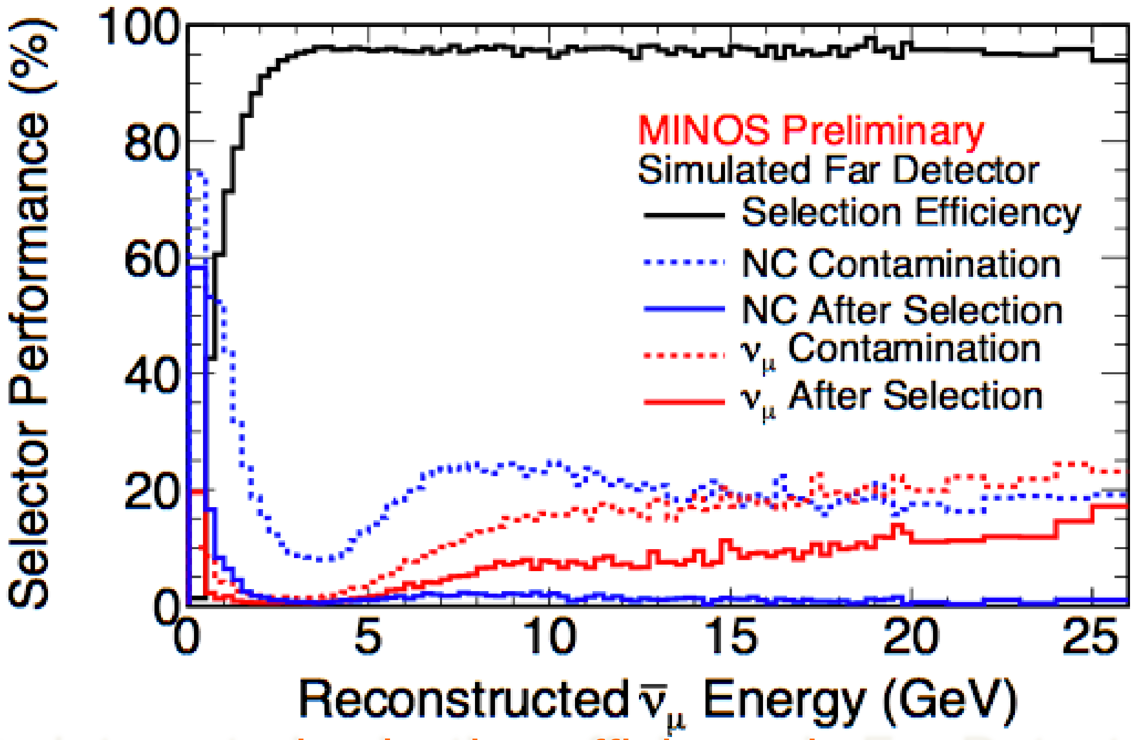


Run IV+Run VII

$$|\Delta\overline{m}^2_{atm}| = 2.62^{+0.31}_{-0.28} \times 10^{-3}\text{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}$$

Far Detector Selection

- Antineutrinos in the Far Detector are selected in the same way as in the Near Detector



	Eff.	Pur.
0 - 6 GeV	96%	98%
6 -20 GeV	98%	91%
20-50 GeV	98%	78%
0-50 GeV	97%	95%

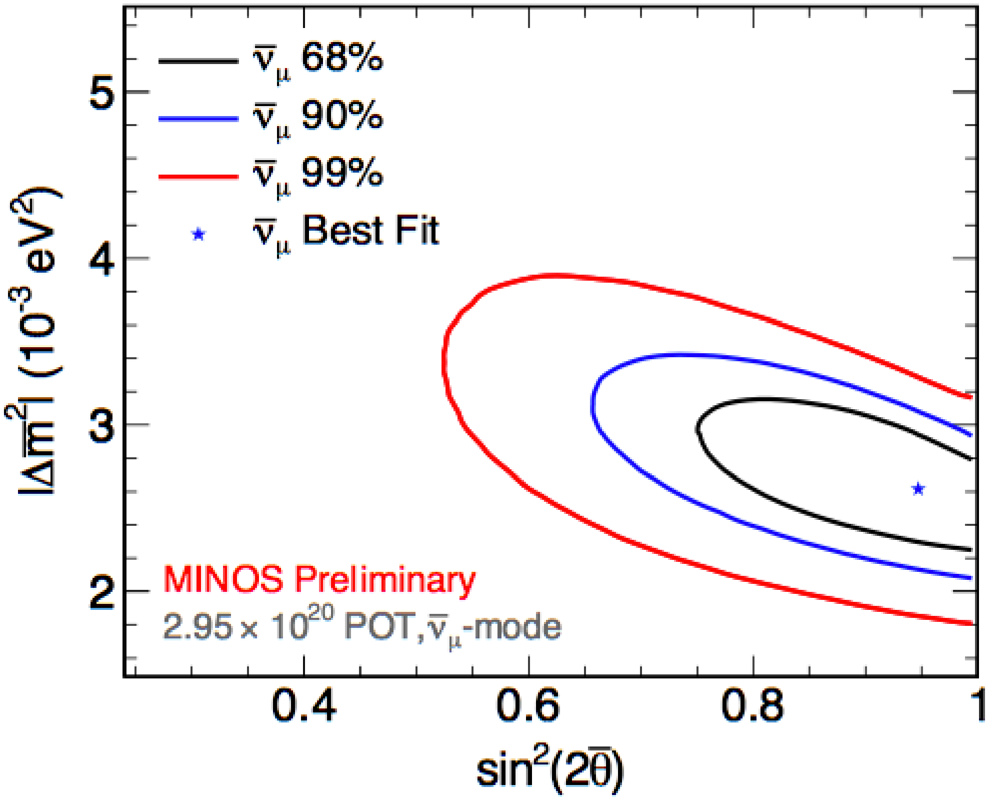
- Integrated selection efficiency in Far Detector is 97%, with 95% sample purity
- Contamination at higher antineutrino energies does not affect oscillation measurement

Run IV + Run VII Allowed Regions

$$|\Delta\bar{m}^2_{atm}| = [2.62^{+0.31}_{-0.28}(\text{stat}) \pm 0.09(\text{syst})] \times 10^{-3}\text{eV}^2$$

$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}(\text{stat}) \pm 0.01(\text{syst})$$

- Contours are Feldman-Cousins corrected
- Systematics included



Contour Comparisons

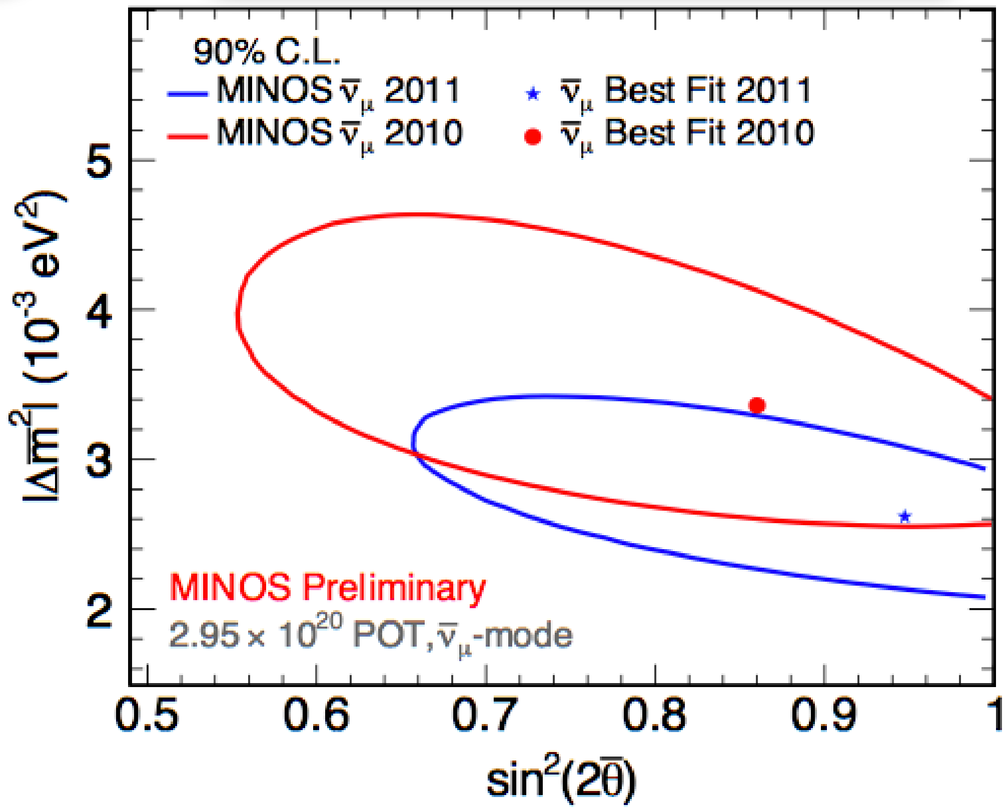
Run IV + Run VII

$$|\Delta\overline{m}^2_{atm}| = 2.62^{+0.31}_{-0.28} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}$$

Run IV Only - 2010 Analysis

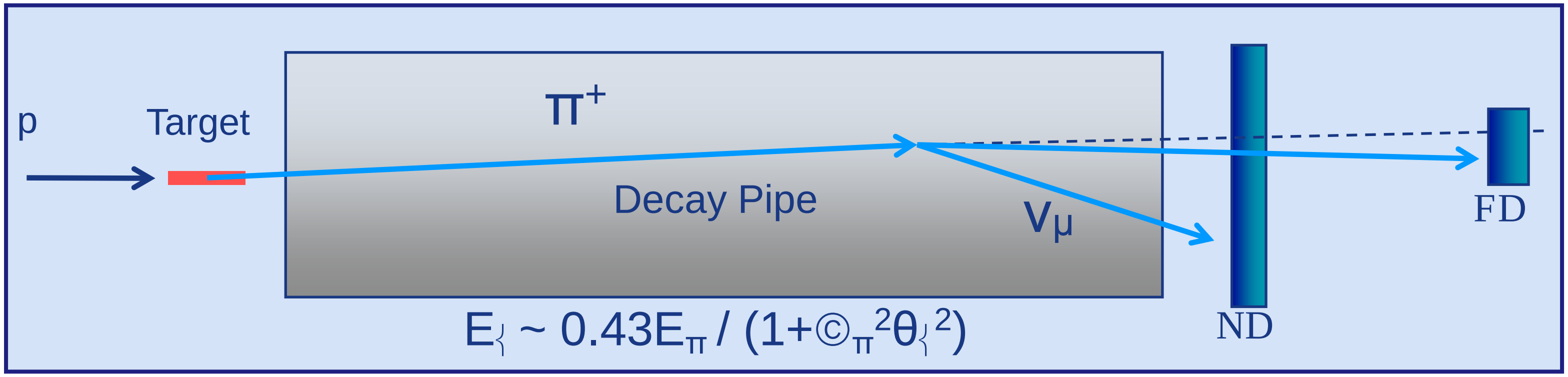
$$|\Delta\overline{m}^2_{atm}| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.86^{+0.11}_{-0.12}$$

- Comparison with MINOS 90% C.L. contour for Run IV antineutrino data



Near to Far Extrapolation

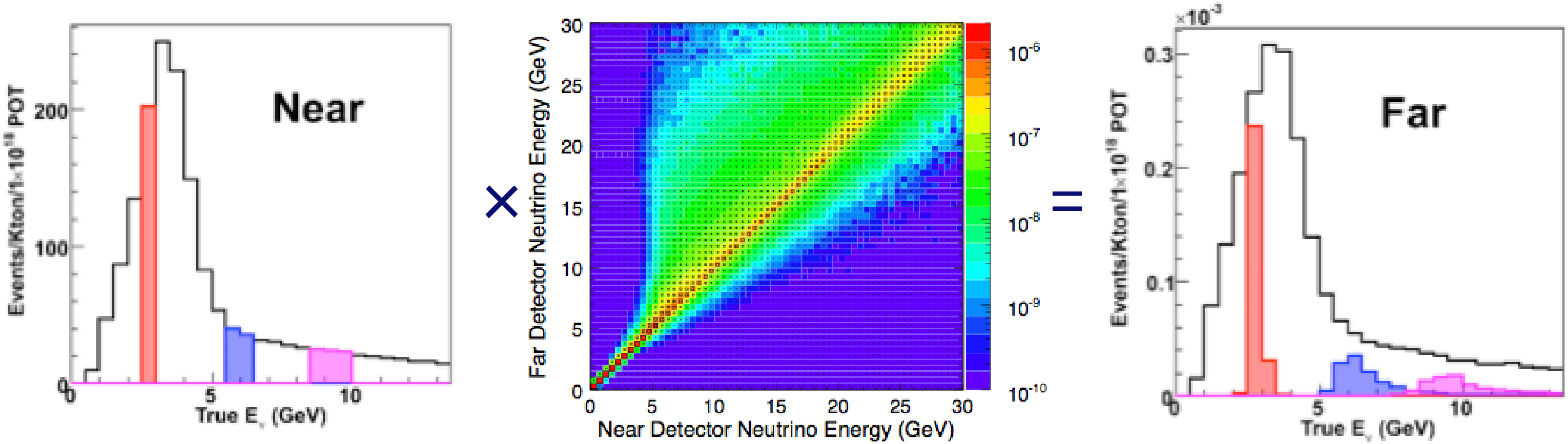
- Far Detector energy spectrum without oscillations is similar, but not the same as the Near Detector spectrum



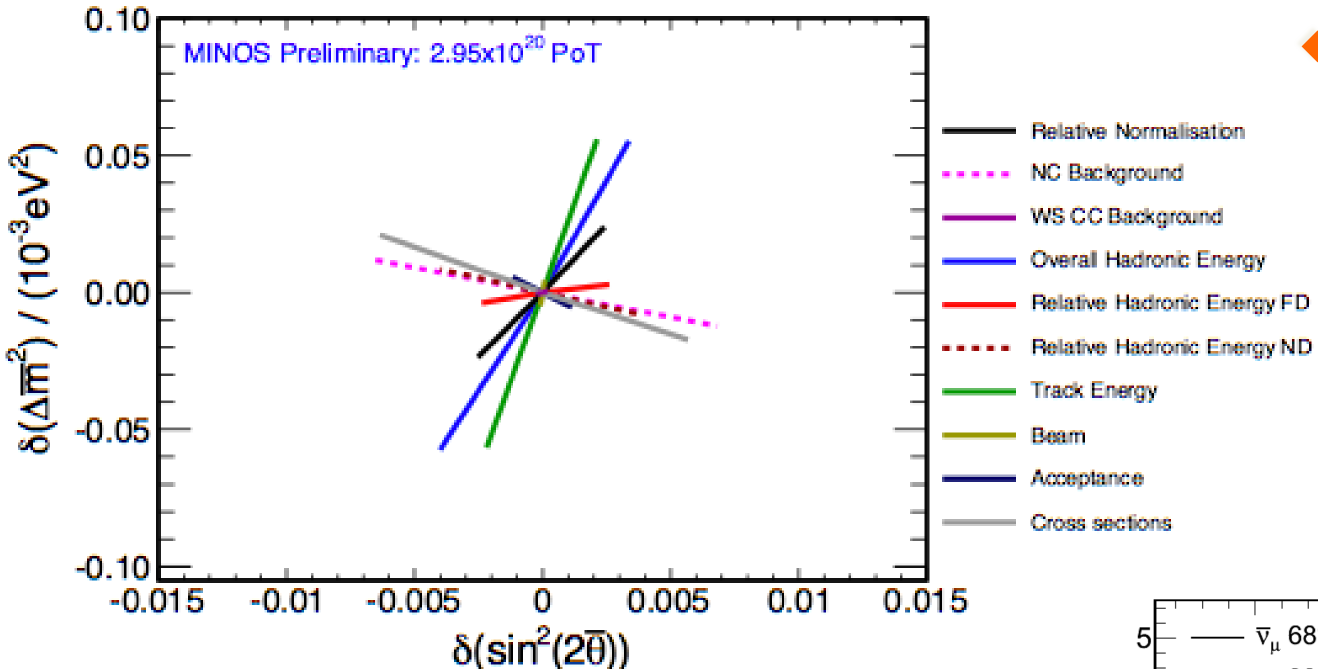
- Neutrino energy depends on angle with original pion direction and the energy of the parent pion
- Near Detector covers a wider solid angle
- Higher energy π travel further downstream the decay pipe and decay closer to the Near Detector

Beam Matrix Extrapolation

- Start with measured Near Detector neutrino energy spectrum
- Use Monte Carlo to provide corrections due to energy smearing and acceptance
- Obtain Far Detector spectrum from Near Detector using a **beam transfer matrix**
  - Matrix encodes knowledge of meson decay kinematics and beamline geometry

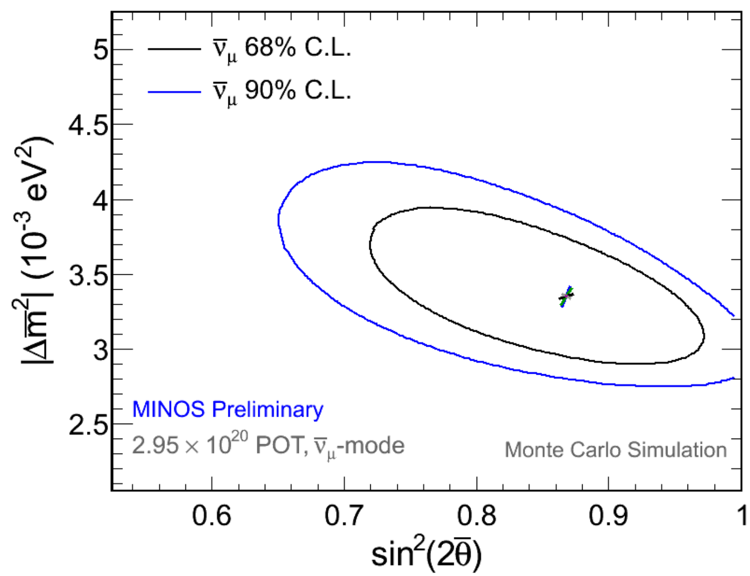


Systematic Uncertainties



- Effect of uncertainties estimated by fitting systematically shifted MC samples

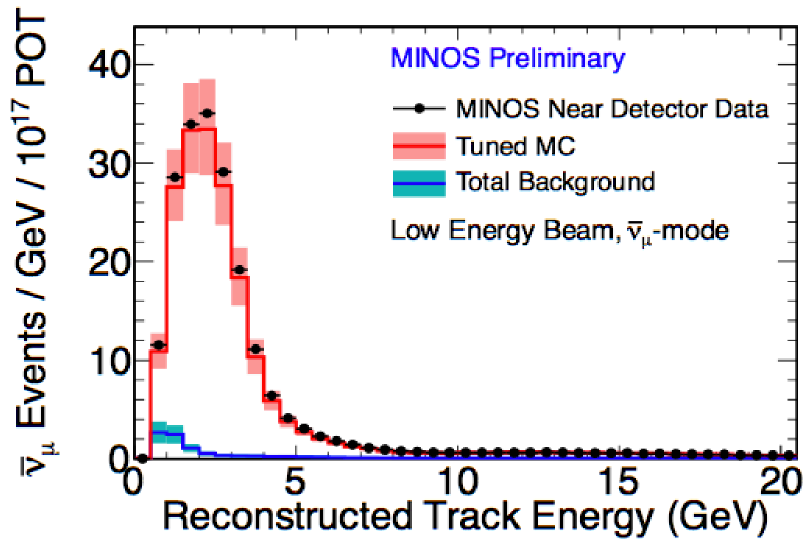
- Plot on the right shows a comparison of statistical sensitivity contours for current antineutrino exposure with size of systematic uncertainties

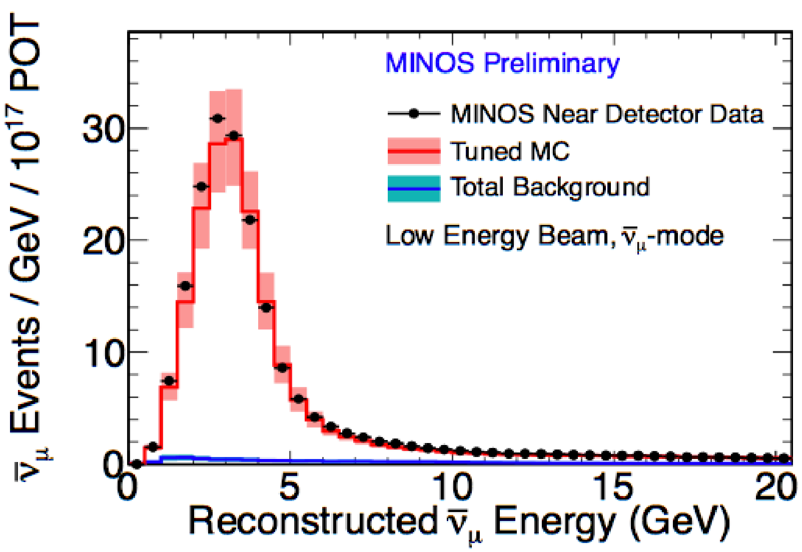


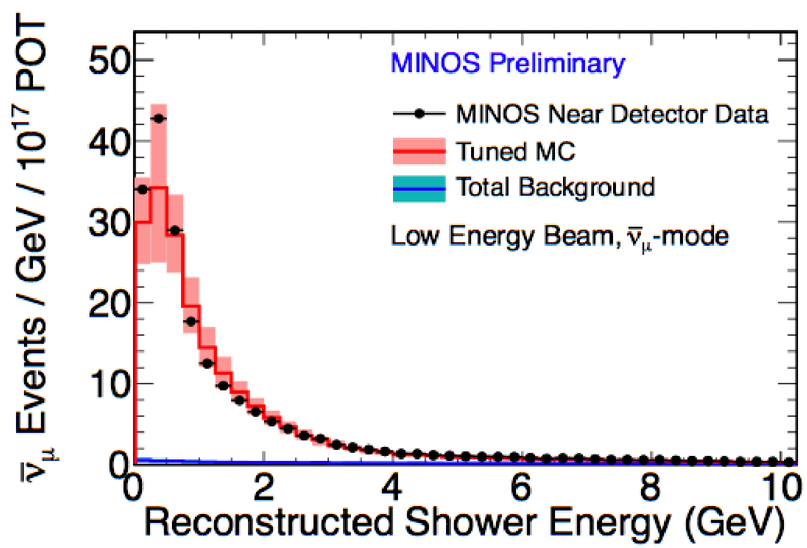
- Current measurement still very statistically-limited

Near Detector Data vs. MC

- Reconstructed track, shower, and antineutrino energy for $\bar{\nu}_\mu$ CC events selected in the Near Detector
- Data and MC differences smaller than size of systematic uncertainties



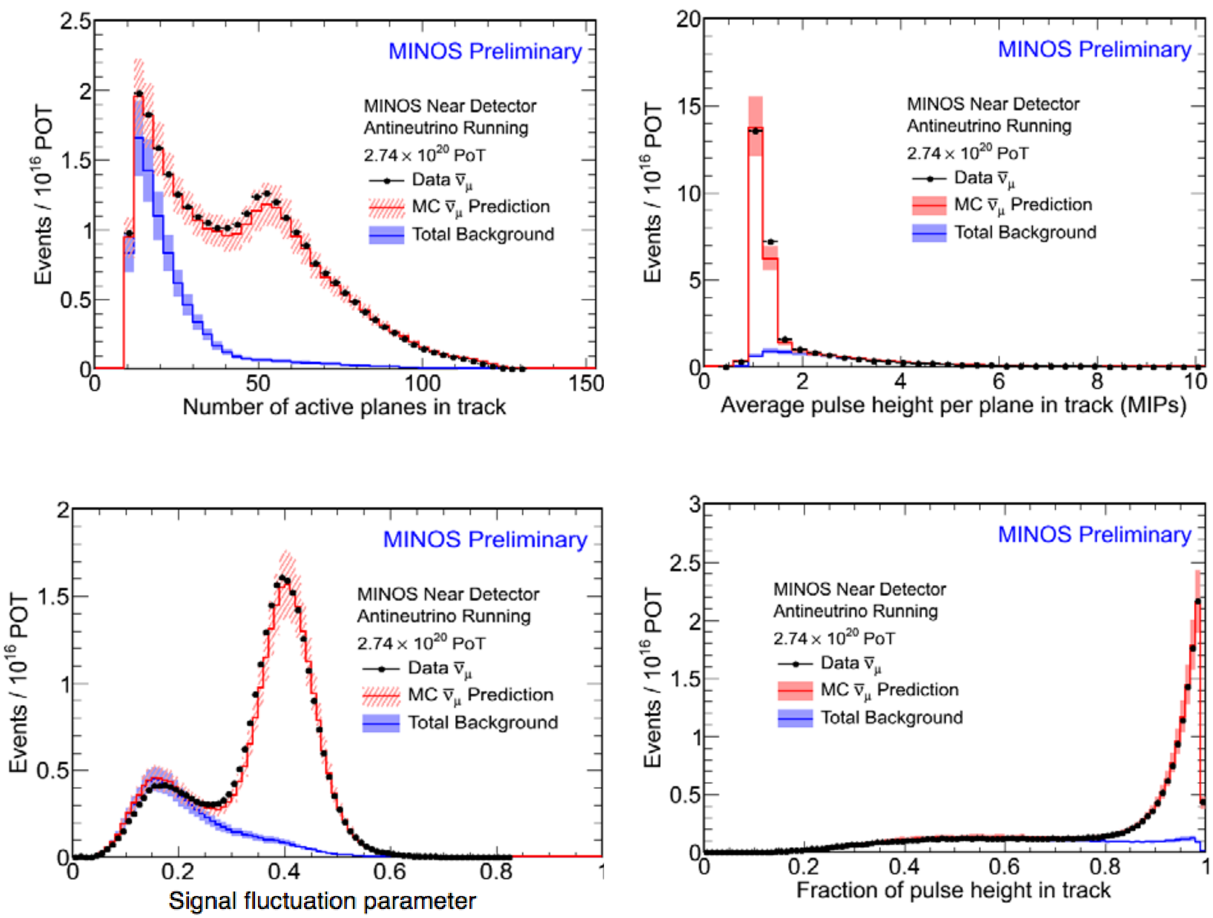




CC and NC Separation

- Muons from ν_μ, $\bar{\nu}_\mu$ CC interactions are identified as tracks satisfying a multivariate, neural net topological ID (kNN)

- **4 kNN Input Variables**
  - Track length
  - Mean dE/dx along track
  - Energy loss fluctuations along track
  - Energy deposition in transverse track profile



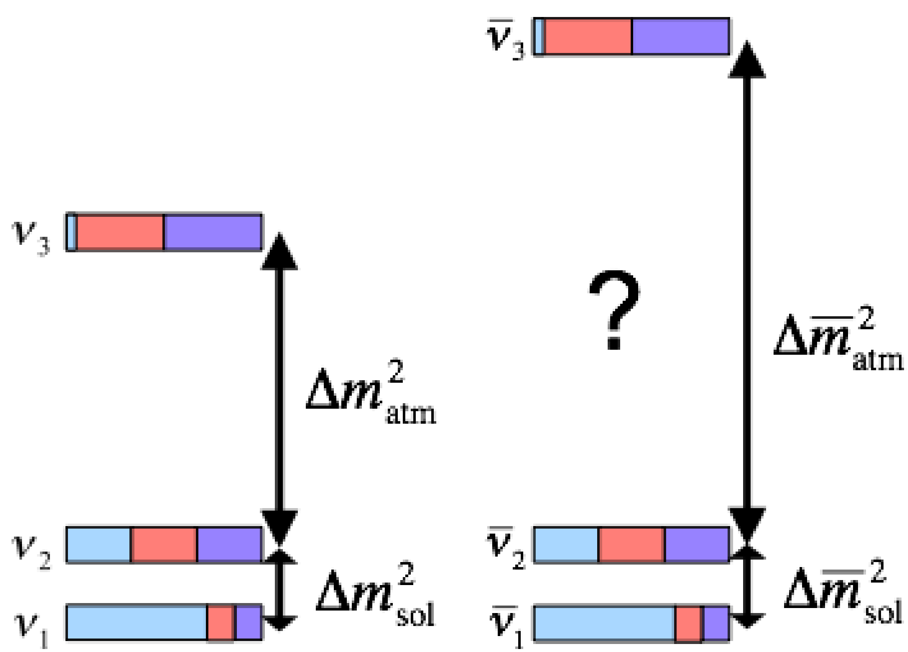
What about antineutrino oscillations?

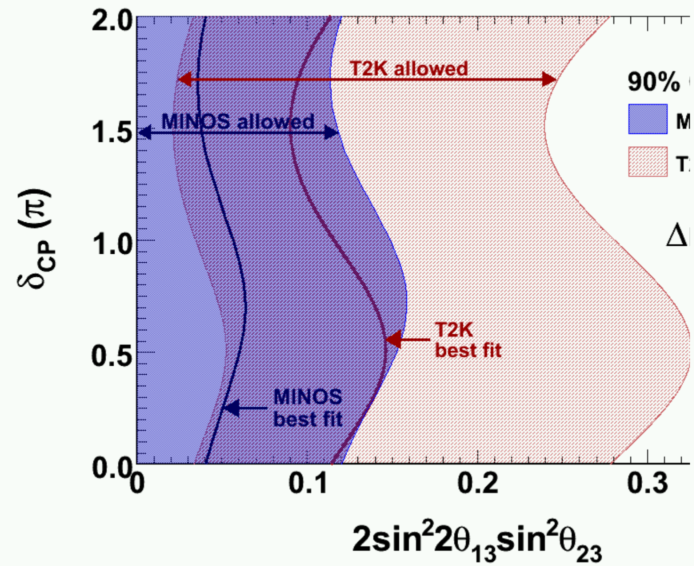
- Antineutrino oscillation parameters known with much less precision
  - MINOS is the only experiment that can perform event-by-event $\bar{\nu}_\mu$ identification
  - Allows for **direct precision measurements of antineutrino oscillations**

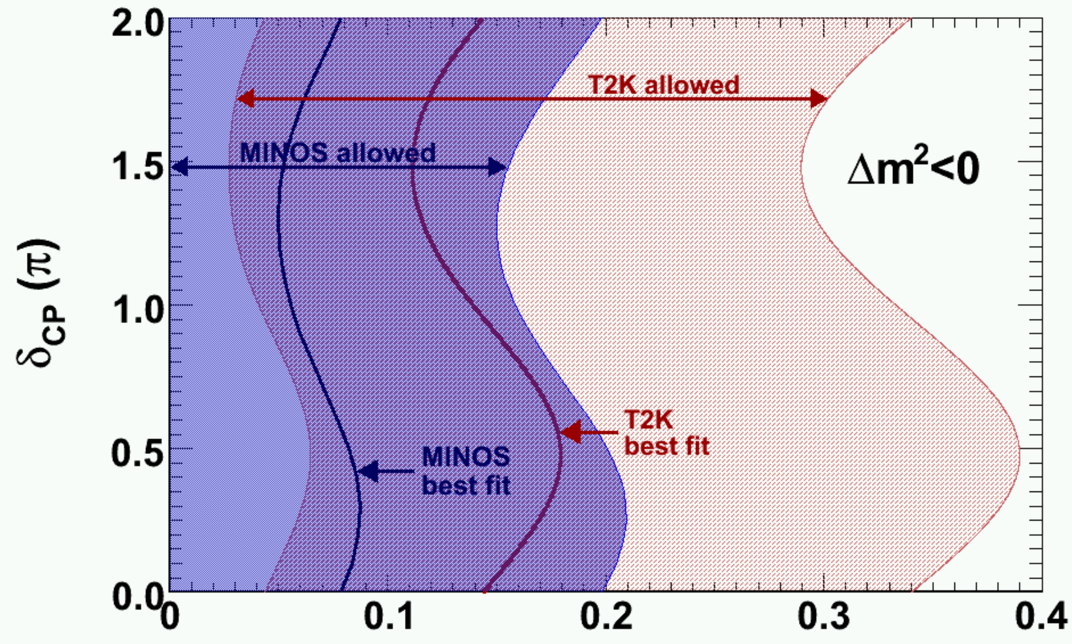
- Differences in neutrino and antineutrino oscillations could be manifest in the respective mass-squared splittings

would be indication of **new physics in the neutrino sector!**

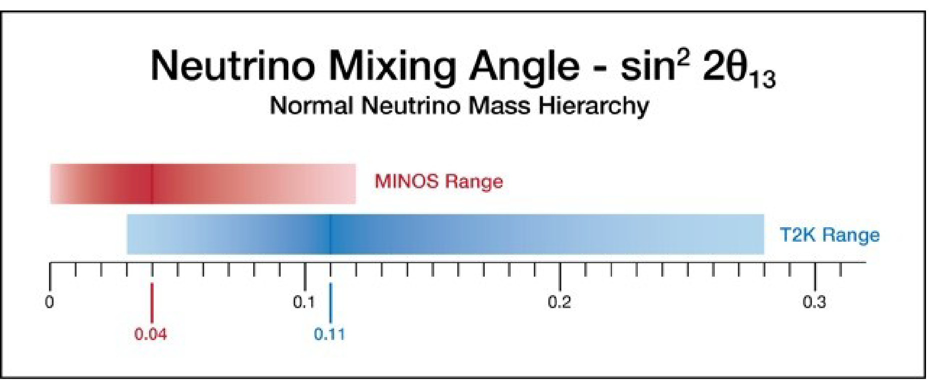
$$P(\nu_\mu \rightarrow \nu_\mu) \stackrel{?}{=} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

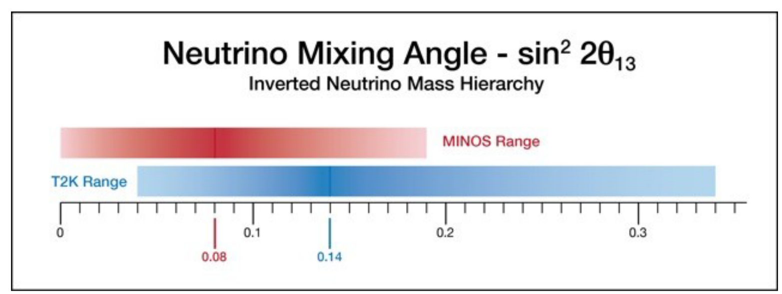




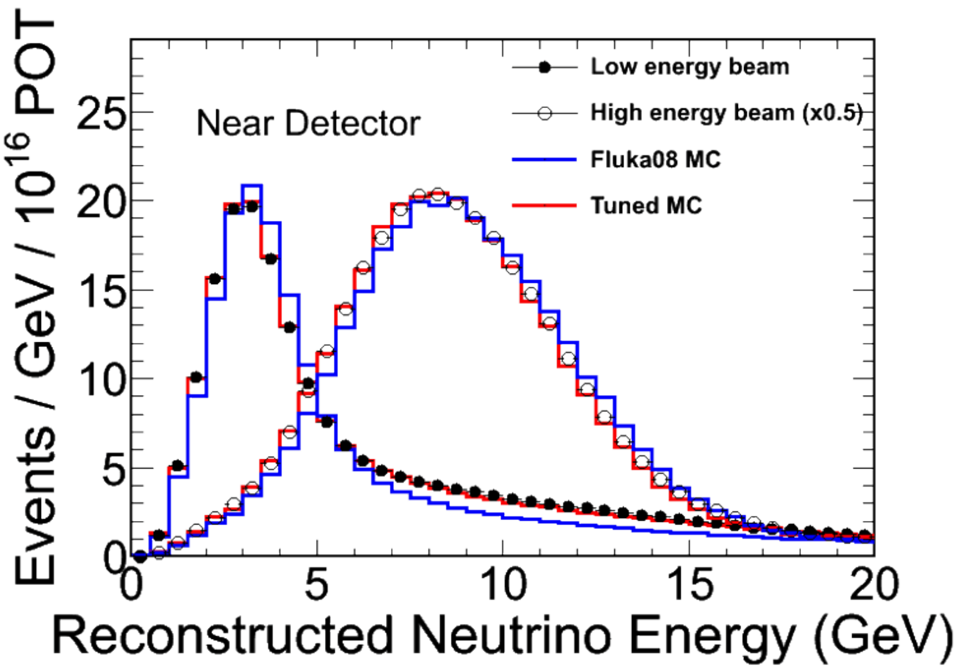


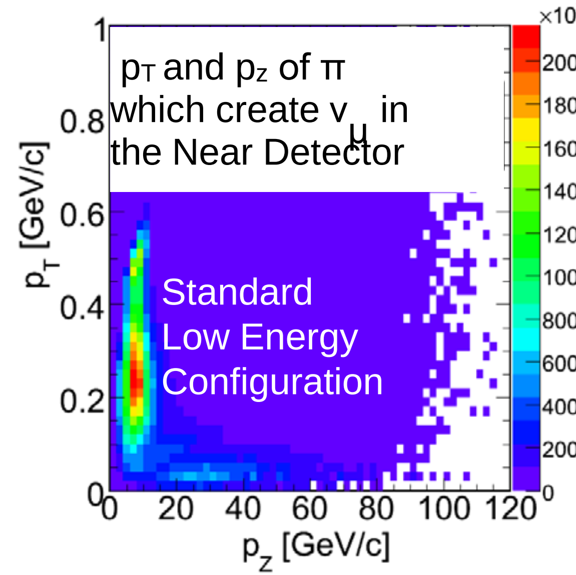
Overlay of our allowed region with T2K's (NOT a combined fit)

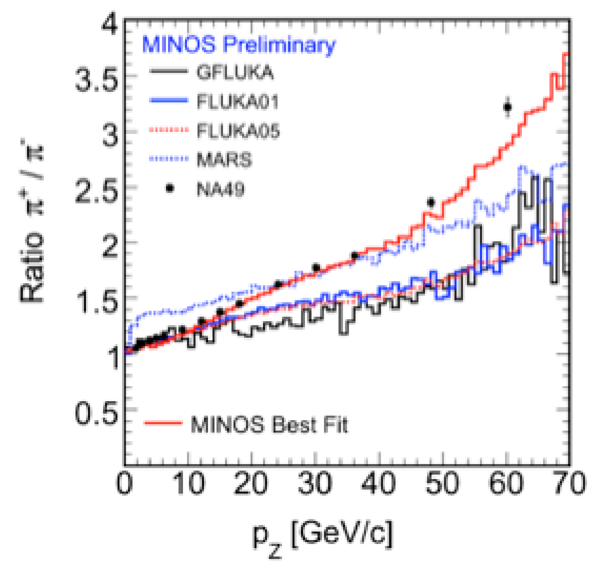




The NuMI Beam







- The beam spectrum can be tuned by varying relative positions of target and magnetic horns
- Hadron production cross-sections reweighted from fits of p_T and p_z to ND ν_μ energy spectrum using 7 beam configurations
- NA49 data used to constrain π^+/π^- and π/K ratios in fits

Neutrino Oscillations

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle \quad (\alpha = e, \mu, \tau)$$

$$U_{PMNS} = \begin{bmatrix} 1 & & \\ & c_{23} & -s_{23} \\ & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & & -s_{13}e^{-i\delta_{CP}} \\ & 1 & \\ s_{13}e^{-i\delta_{CP}} & & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{bmatrix}$$

$c_{lk} = \cos\theta_{lk}$
$s_{lk} = \sin\theta_{lk}$

Atmospheric + Accelerator | Reactor+Accelerator | Solar+Reactor

- **Three active neutrino picture**
- Two mass splittings
  - **Large: $\Delta m^2_{atm} \approx \Delta m^2_{32} \sim 10^{-3}$ eV^2**
  - **Small: $\Delta m^2_{sol} \approx \Delta m^2_{21} \sim 10^{-4}$ eV^2**
- Large atmospheric mixing
  - **$\theta_{23} \sim 45°$**
- Non-maximal solar mixing
  - **$\theta_{12} \sim 34°$**