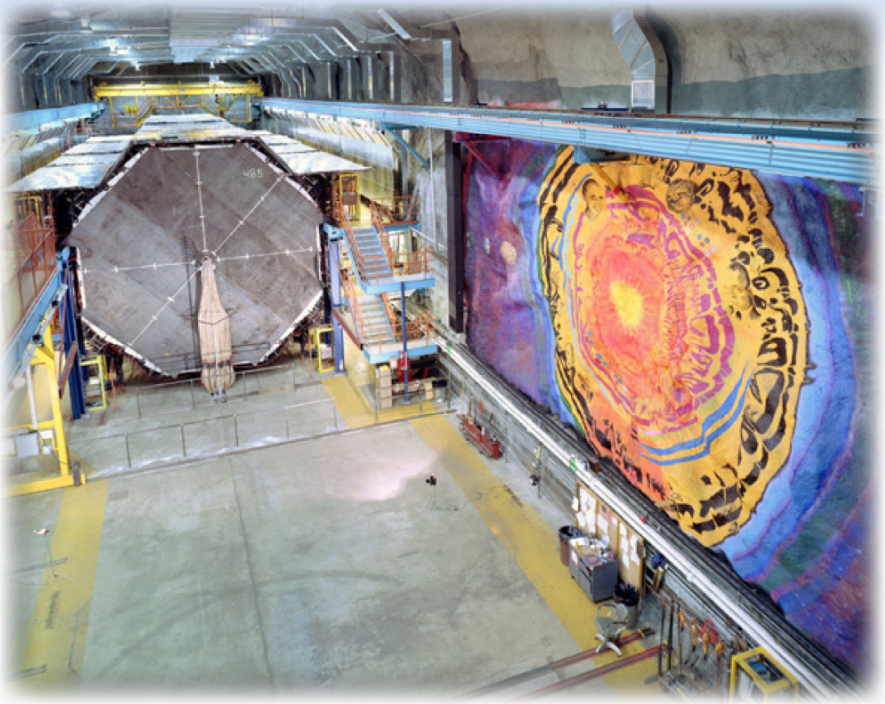
New Antineutrino Oscillation Results from MINOS

Alexandre Sousa
Harvard University
for the MINOS Collaboration

Joint Experimental - Theoretical Seminar

Fermilab
August 25, 2011



Outline

- MINOS Overview
- Neutrino Oscillations
- The NuMI Beam and the MINOS Detectors
- Analysis of 2.95×10^{20} POT of Antineutrino Data
- New Results!



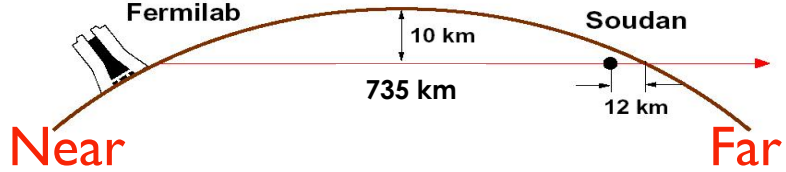
Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
Goias • Harvard • Holy Cross • IIT • Indiana • Iowa State • Minnesota-Twin Cities
Minnesota-Duluth • Otterbein • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina •
Stanford • Sussex • Texas A&M • Texas-Austin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

MINOS Overview

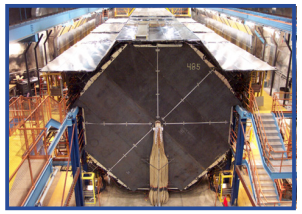
- **MINOS (Main Injector Neutrino Oscillation Search)**
  - High intensity **NuMI ν_μ beam** produced at Fermilab
  - **Near Detector** at Fermilab
  - **Far Detector**, 735 km away, in the Soudan mine, MN
- Magnetized detectors allow unique ability to distinguish between ν_μ and $\overline{\nu}_\mu$ charged-current interactions on an event-by-event basis
- Compare Far Detector observations with extrapolation of Near Detector measurement to study neutrino oscillations











Neutrino Oscillations

Neutrino Oscillations

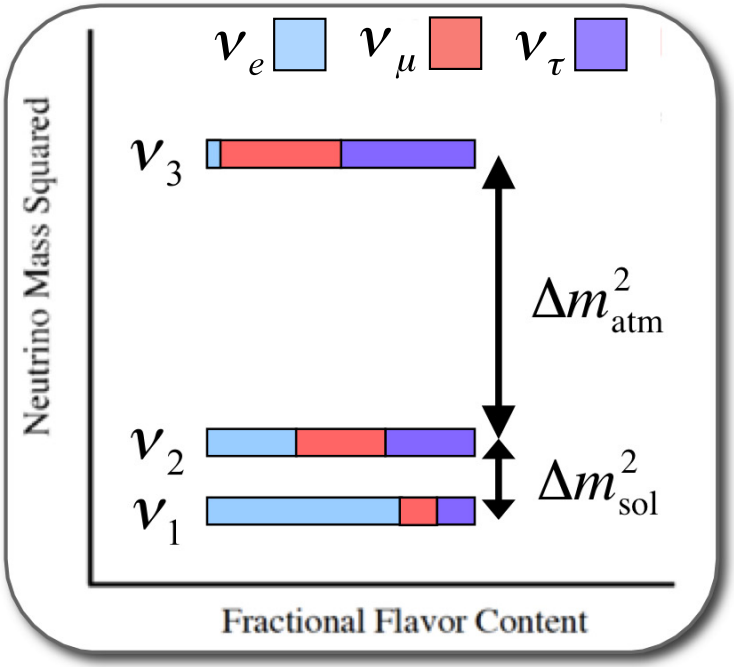
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle \quad (\alpha = e, \mu, \tau)$$

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

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

Atmospheric + Accelerator | Reactor+Accelerator | Solar+Reactor

- **Three active neutrino picture**
  - Two mass splittings
    - **Large: $\Delta m^2_{atm} \approx \Delta m^2_{32} \sim 10^{-3}$ eV²**
    - **Small: $\Delta m^2_{sol} \approx \Delta m^2_{21} \sim 10^{-4}$ eV²**
  - Large atmospheric mixing
    - **$\theta_{23} \sim 45°$**
  - Non-maximal solar mixing
    - **$\theta_{12} \sim 34°$**



- MINOS is sensitive to the larger mass splitting and the θ_{23} mixing angle

Neutrino Oscillations

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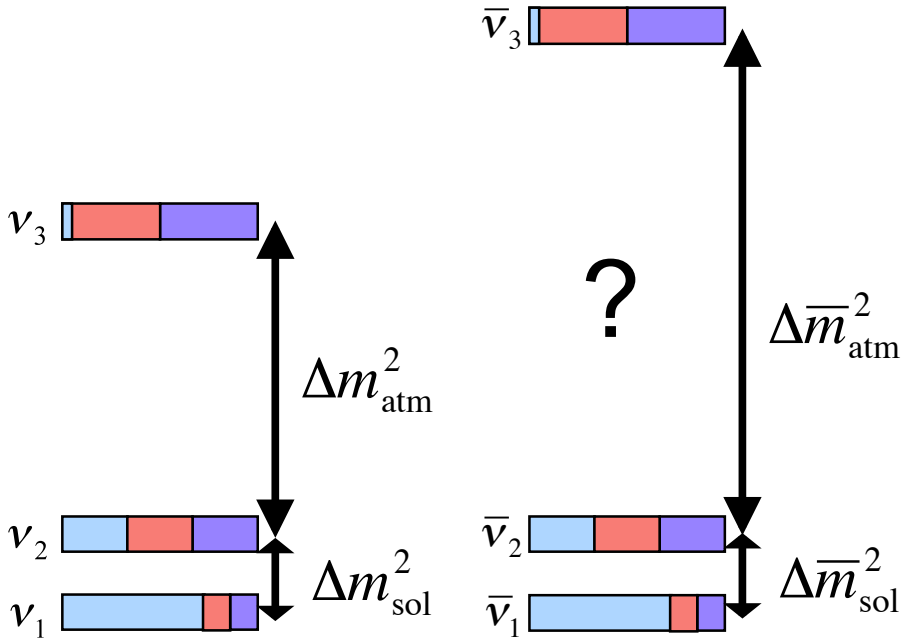
- **What about antineutrinos?**

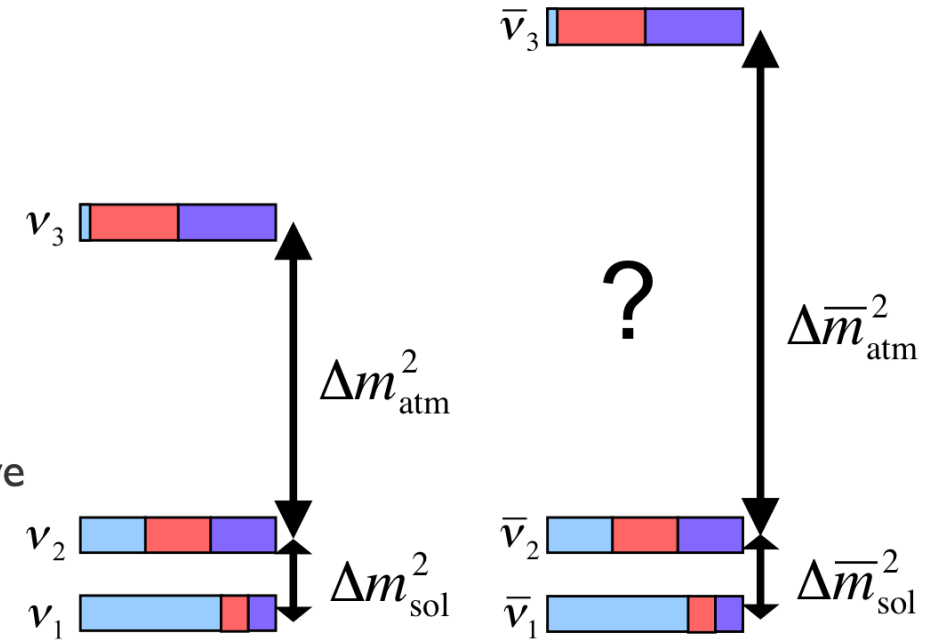


What about $\bar{\nu}$?

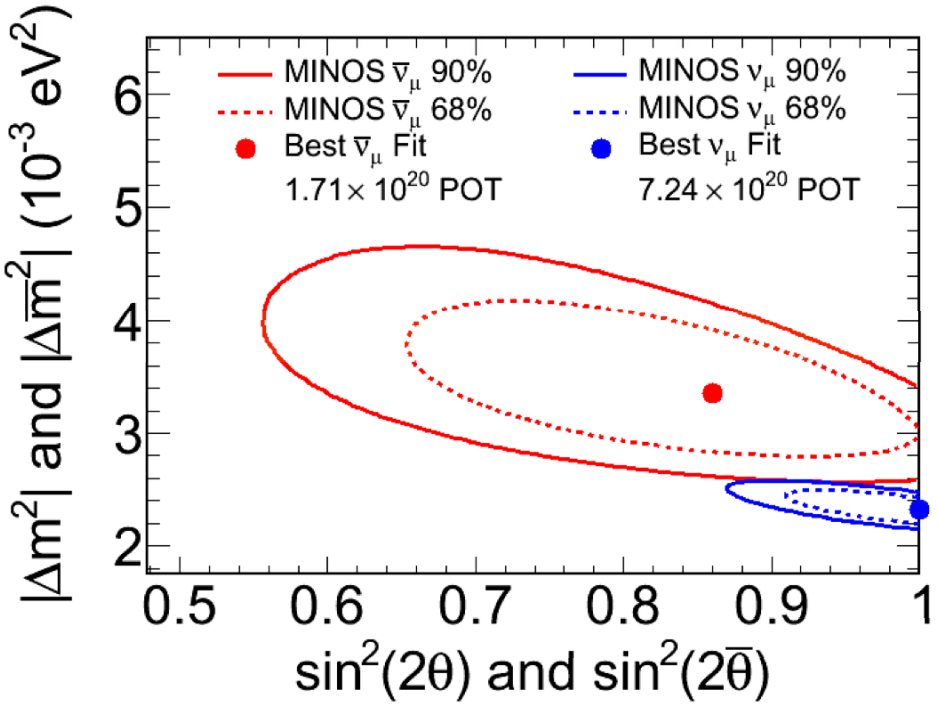
$$P\left(\nu_\mu \rightarrow \nu_\mu\right) \stackrel{?}{=} P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu\right)$$

- 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!**



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

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

Neutrino best fit parameters

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

- 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

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

- Example: results shown in 8 different talks at Neutrino Telescopes 2011 in Venice

I. CPT violation in three-neutrino models — M. Maltoni 2

Minos disappearance: ν_μ vs $\bar{\nu}_\mu$

- in June 2010 Minos presented new data on ν_μ vs $\bar{\nu}_\mu$ disappearance [1];
- some tension appears between neutrino and anti-neutrino results;
- Tension (our fit): $\chi^2_{CPT} - \chi^2_{\overline{CPT}} = 5.6\ (2.4\sigma) \Rightarrow$ small but not totally negligible;
- **more data needed before speculations!**
- Still, let's speculate: **IF** confirmed, it could be
  - evidence of CPT violation;
  - or just "conventional" New Physics…
- in either case, how does this relates to other neutrino experiments?

$|\Delta\bar{m}^2_{atm}| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ eV^2$, $\sin^2(2\bar{\theta}_{23}) = 0.86 \pm 0.11$ [1]

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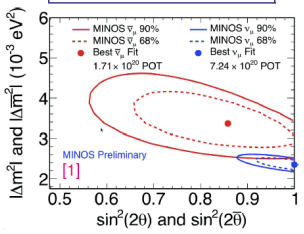

[1] A. Himmel, talk at Fermilab Joint Experimental-Theoretical Seminar, 14/06/2010.
[2] P. Adamson *et al.* [MINOS collaboration], arXiv:1103.0340.

Michele Maltoni <michele.maltoni@csic.es> — NeuTel 2011, 16/03/2011

- Possible explanations in literature:

- CPT and Lorentz Violation

L. Liu, J. Tian and Z. Zhao, Phys.Lett. B702 154 (2011)
J.S. Diaz and V.A. Kostelecký, arXiv:hep-ph/1108.1799

- Non-Standard Interactions

J. Kopp, P.A.N. Machado and S.J. Parke, Phys.Rev. D82 113002 (2010)
W.A. Mann, D. Cherdack, W. Musial and T. Kafka, Phys.Rev. D82 113010 (2010)

G. Altarelli

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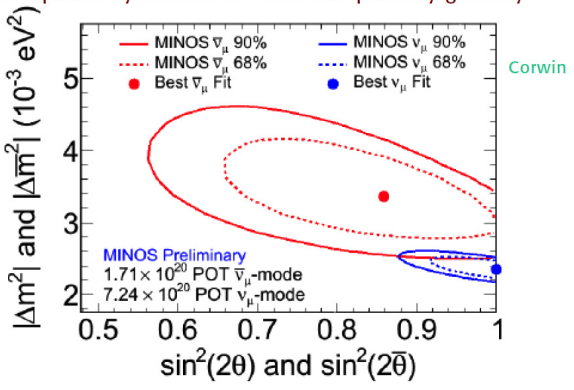

Corwin

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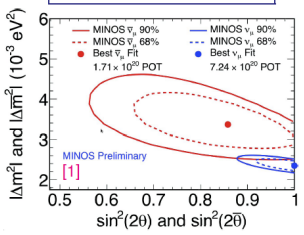

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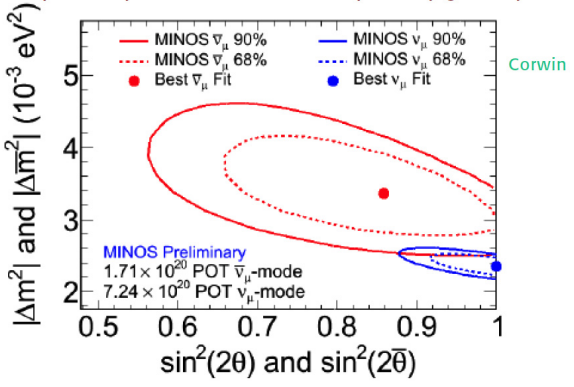

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physicsworld.com

Neutrino surprise emerges from MINOS

Jun 18, 2010 15 comments

The MINOS experiment was set up to study neutrino oscillation by making the first high precision measurements of a controlled beam of neutrinos produced within a particle accelerator environment. Each experimental run begins at Fermilab near Chicago where a target is bombarded with energetic protons to produce a beam of neutrinos, called the NuMI beam. This is fired through the Earth towards the Soudan mine in

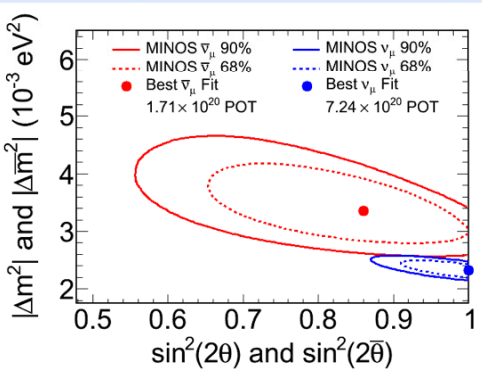
It would not just demolish any particular model, it would require revision of the whole way we do particle physics.

David Wark, Imperial College

Strong case to take more $\bar{\nu}_\mu$ data!

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

- **For today's results:**
  - ~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



PRL 107, 021801 (2011) | Selected for a Viewpoint in *Physics* | PHYSICAL REVIEW LETTERS | week ending 8 JULY 2011

First Direct Observation of Muon Antineutrino Disappearance

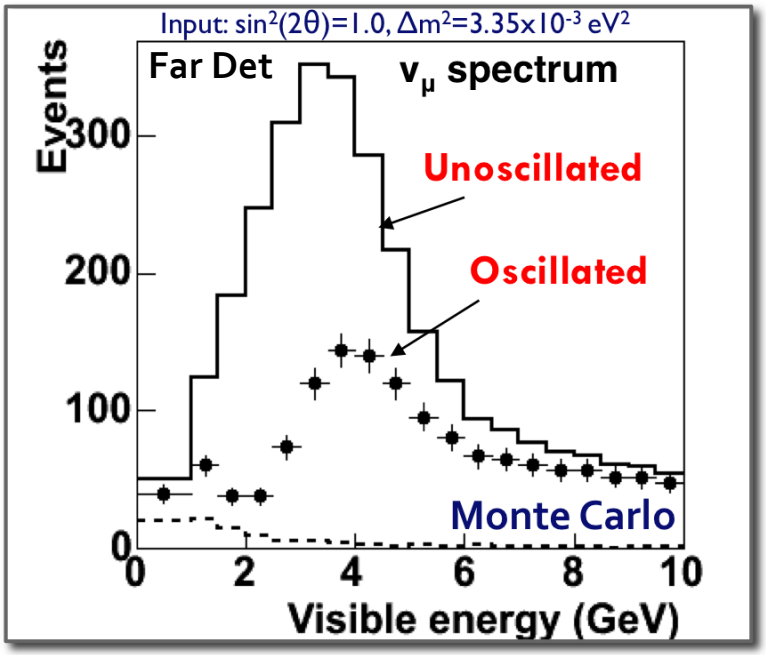
P. Adamson,[7] C. Andreopoulos,[20] D. J. Auty,[24] D. S. Ayres,[1] C. Backhouse,[18] G. Barr,[18] M. Bishai,[3] A. Blake,[5] G. J. Bock,[7] D. J. Boehnlein,[7] D. Bogert,[7] S. Cavanaugh,[9] D. Cherdack,[27] S. Childress,[7] B. C. Choudhary,[7] J. A. B. Coelho,[6] S. J. Coleman,[29] L. Corwin,[12] D. Cronin-Hennessy,[15] I. Z. Danko,[19] J. K. de Jong,[18] N. E. Devenish,[24] M. V. Diwan,[3] M. Dorman,[14] C. O. Escobar,[6] J. J. Evans,[14] E. Falk,[24] G. J. Feldman,[9] M. V. Frohne,[10] H. R. Gallagher,[27] R. A. Gomes,[8] M. C. Goodman,[1] P. Gouffon,[21] N. Graf,[11] R. Gran,[16] N. Grant,[20] K. Grzelak,[28] A. Habig,[16] D. Harris,[7] J. Hartnell,[24,20] R. Hatcher,[7] A. Himmel,[4] A. Holin,[14] C. Howcroft,[4] X. Huang,[1] J. Hylen,[7] J. Ilic,[20] G. M. Irwin,[23] Z. Isvan,[19] D. E. Jaffe,[3] C. James,[7] D. Jensen,[7] T. Kafka,[27] S. M. S. Kasahara,[15] G. Koizumi,[7] S. Kopp,[26] M. Kordosky,[29] A. Kreymer,[7] K. Lang,[26] G. Lefeuvre,[24] J. Ling,[3,22] P. J. Litchfield,[15,20] L. Loiacono,[26] P. Lucas,[7] W. A. Mann,[27] M. L. Marshak,[15] N. Mayer,[12] A. M. McGowan,[1] R. Mehdiyev,[26] J. R. Meier,[15] M. D. Messier,[12] W. H. Miller,[15] S. R. Mishra,[22] J. Mitchell,[5] C. D. Moore,[7] J. Morfín,[7] L. Mualem,[4] S. Mufson,[12] J. Musser,[12] D. Naples,[19] J. K. Nelson,[29] H. B. Newman,[4] R. J. Nichol,[14] T. C. Nicholls,[20] J. A. Nowak,[15] J. P. Ochoa-Ricoux,[4] W. P. Oliver,[27] M. Orchanian,[4] R. Ospanov,[26] J. Paley,[1,12] R. B. Patterson,[4] G. Pawloski,[23] G. F. Pearce,[20] D. A. Petyt,[15] S. Phan-Budd,[1] R. K. Plunkett,[7] X. Qiu,[23] J. Ratchford,[26] T. M. Raufer,[20] B. Rebel,[7] P. A. Rodrigues,[18] C. Rosenfeld,[22] H. A. Rubin,[11] M. C. Sanchez,[13,1,9] J. Schneps,[27] P. Schreiner,[1] P. Shanahan,[7] A. Sousa,[9] P. Stamoulis,[2] M. Strait,[15] N. Tagg,[17] R. L. Talaga,[1] E. Tetteh-Lartey,[25] J. Thomas,[14] M. A. Thomson,[5] G. Tinti,[18] R. Toner,[5] G. Tzanakos,[2] J. Urheim,[12] P. Vahle,[29] B. Viren,[3] A. Weber,[18] R. C. Webb,[25] C. White,[11] L. Whitehead,[3] S. G. Wojcicki,[23] T. Yang,[23] and R. Zwaska[7]

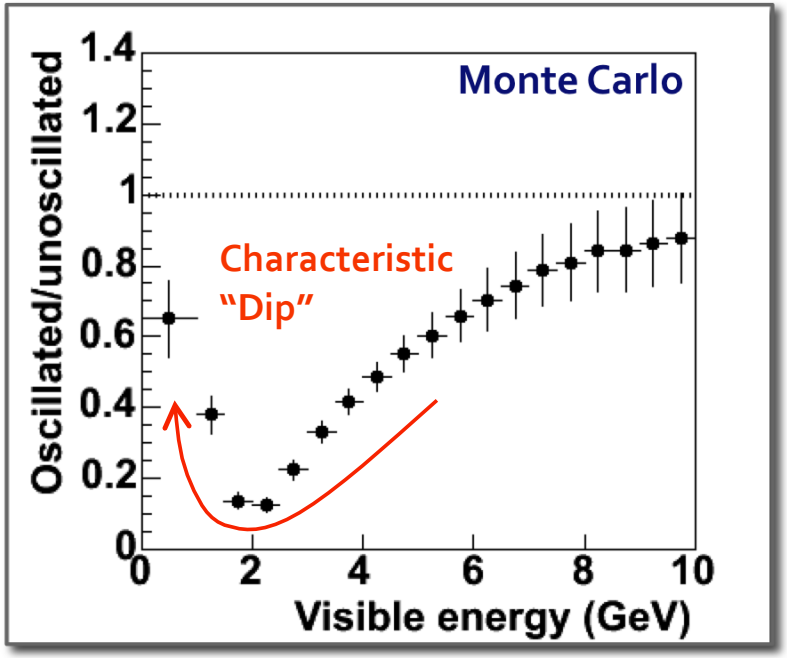
(MINOS Collaboration)

MINOS Oscillation Measurement

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

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





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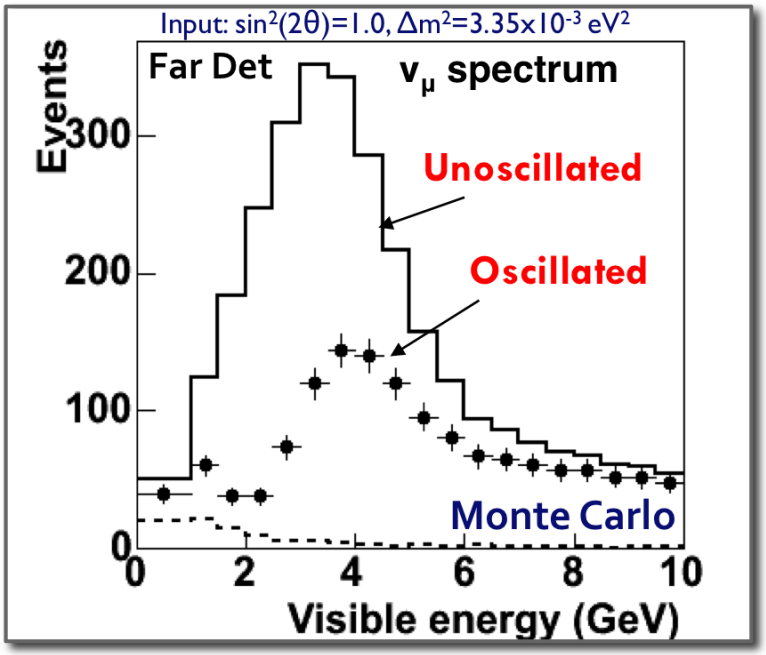
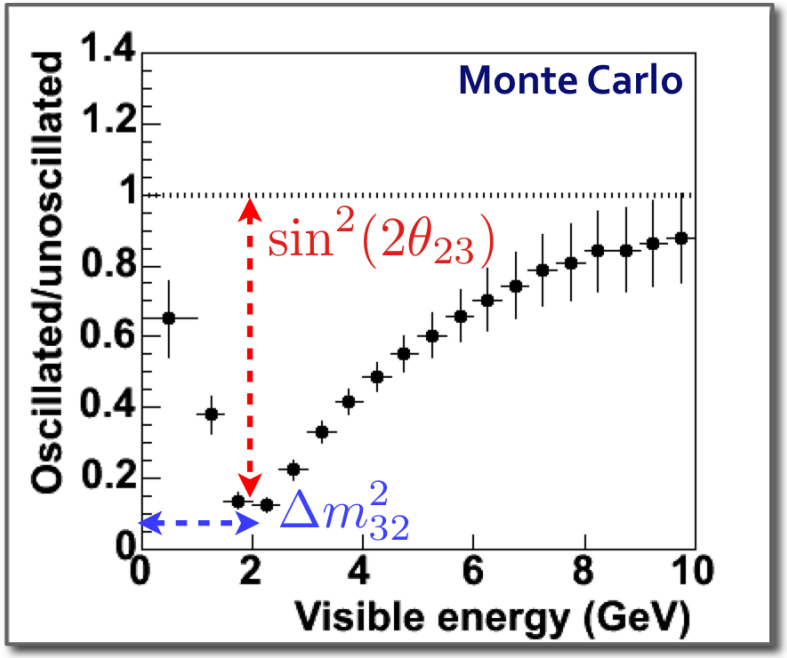
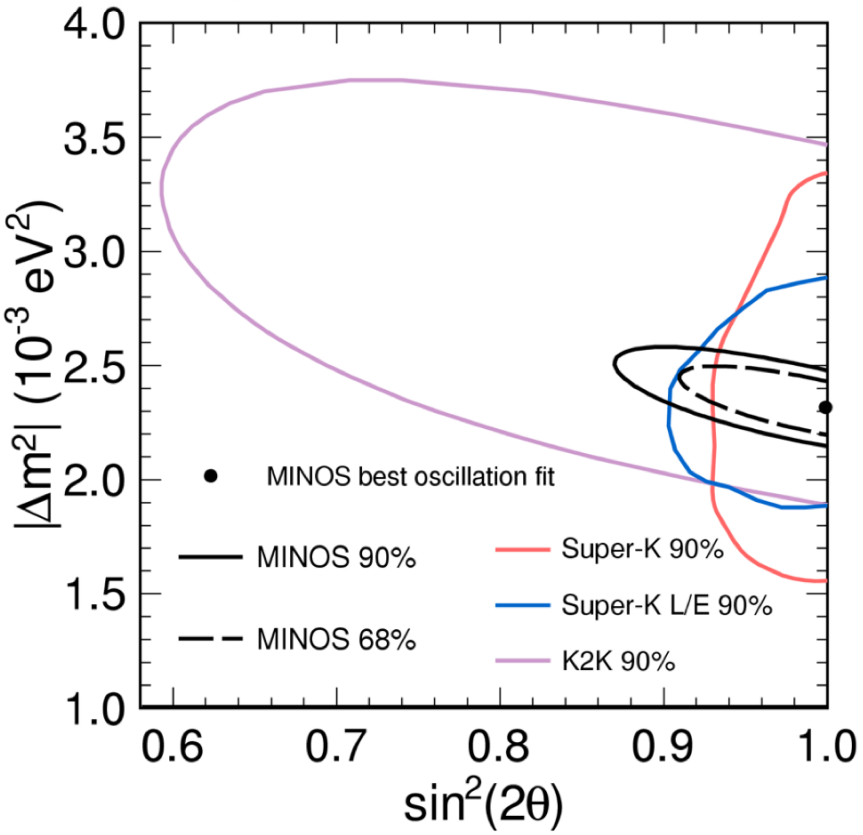




MINOS Physics

- Measure $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance

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



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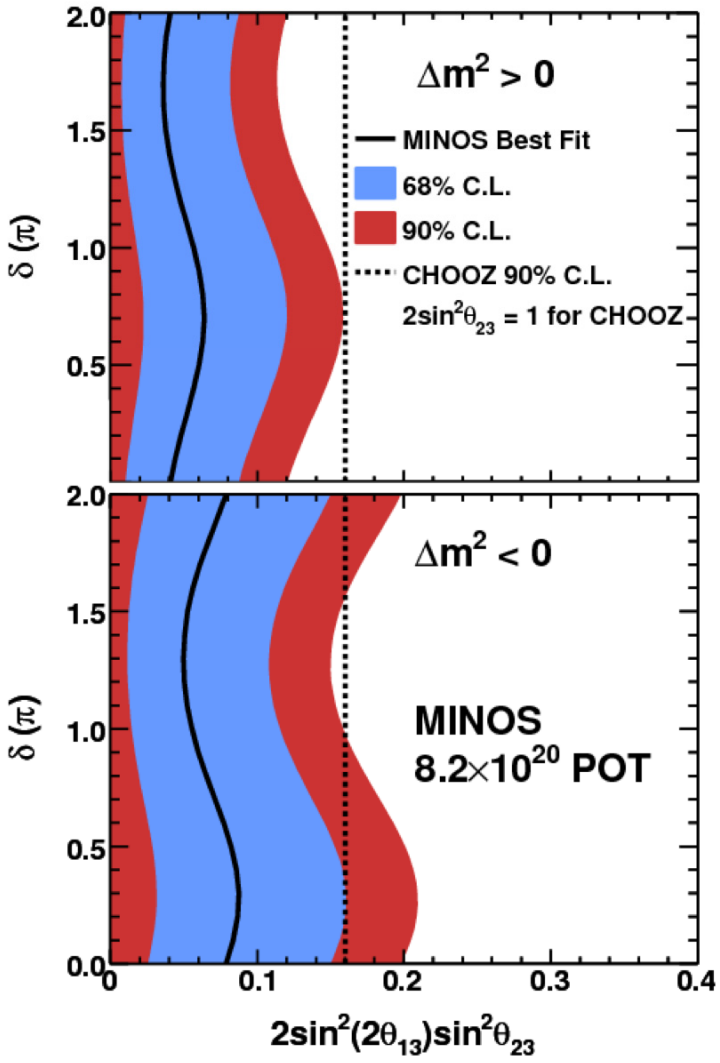
- Look for ν_e appearance to search for $\nu_\mu \rightarrow \nu_e$ oscillations

arXiv:hep-ex/1108.0015, accepted by PRL



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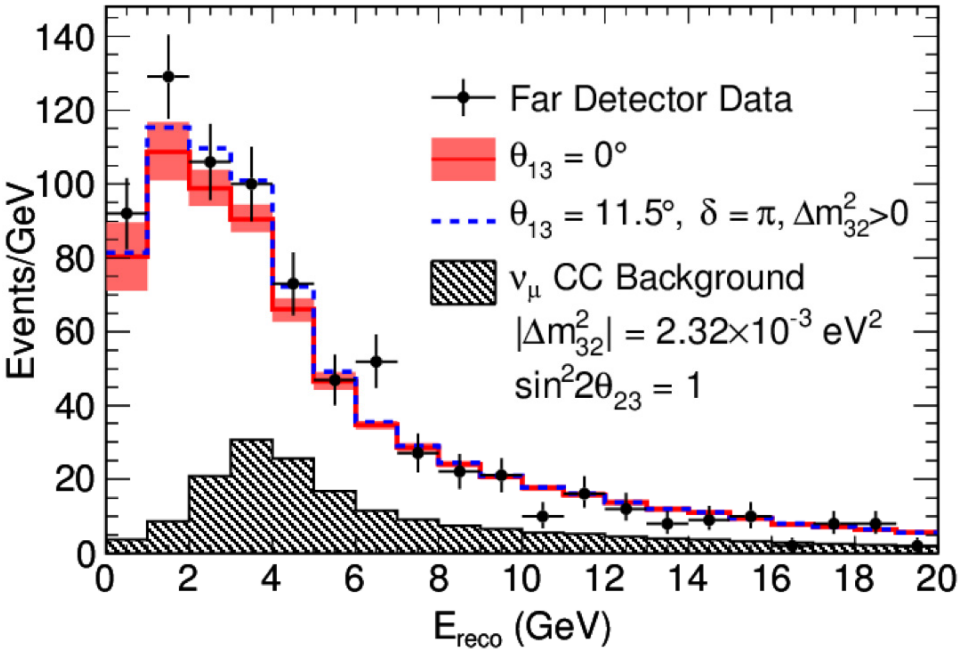
Phys. Rev. Lett. 107, 011802 (2011)



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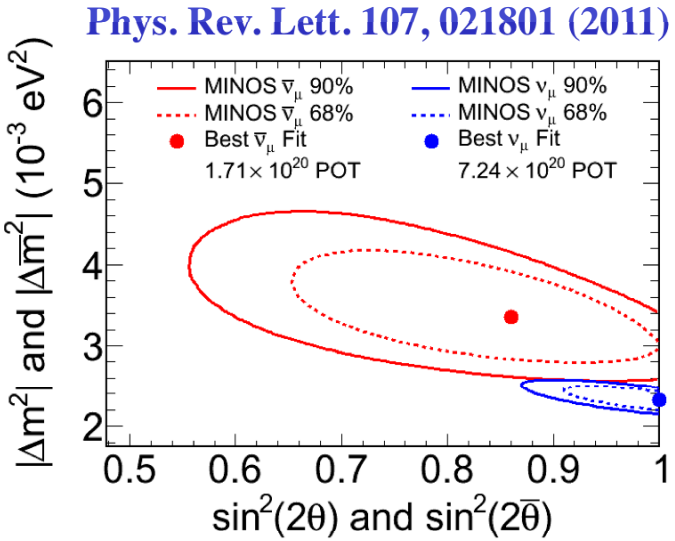
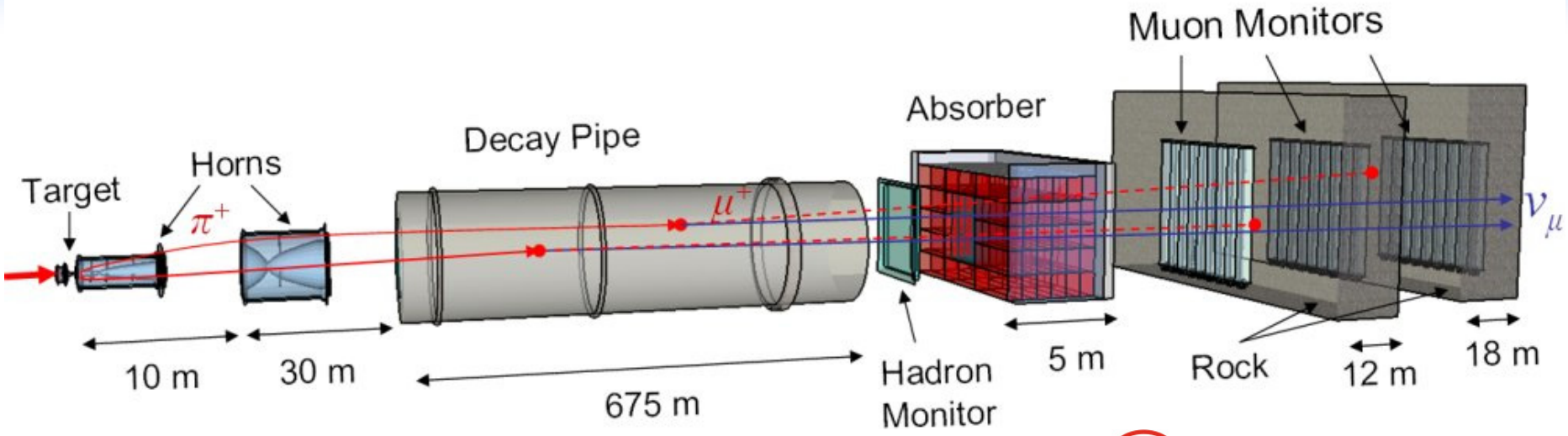
- Search for sterile neutrinos via neutral current disappearance
- Measure $|\Delta \bar{m}^2_{atm}|$ and $\sin^2(2\bar{\theta}_{23})$ via $\bar{\nu}_\mu$ disappearance

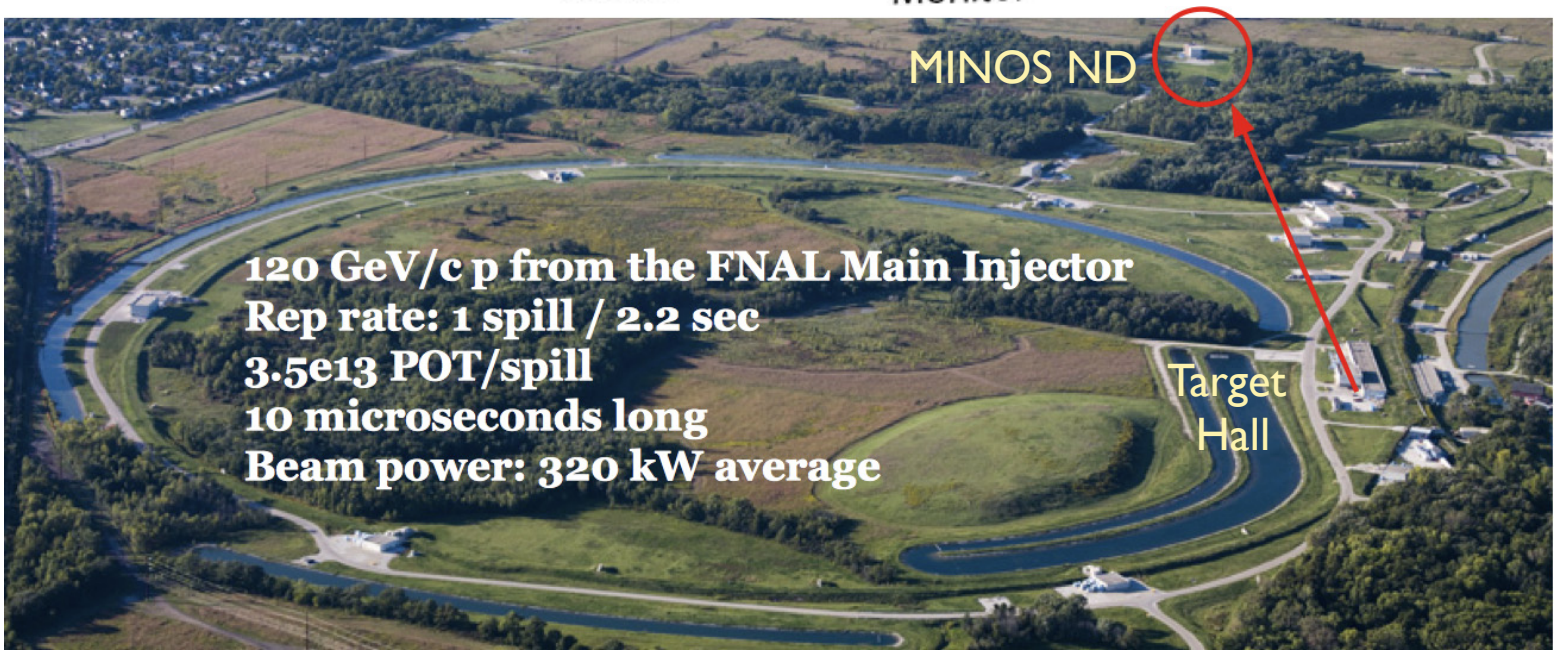
Today's Results!



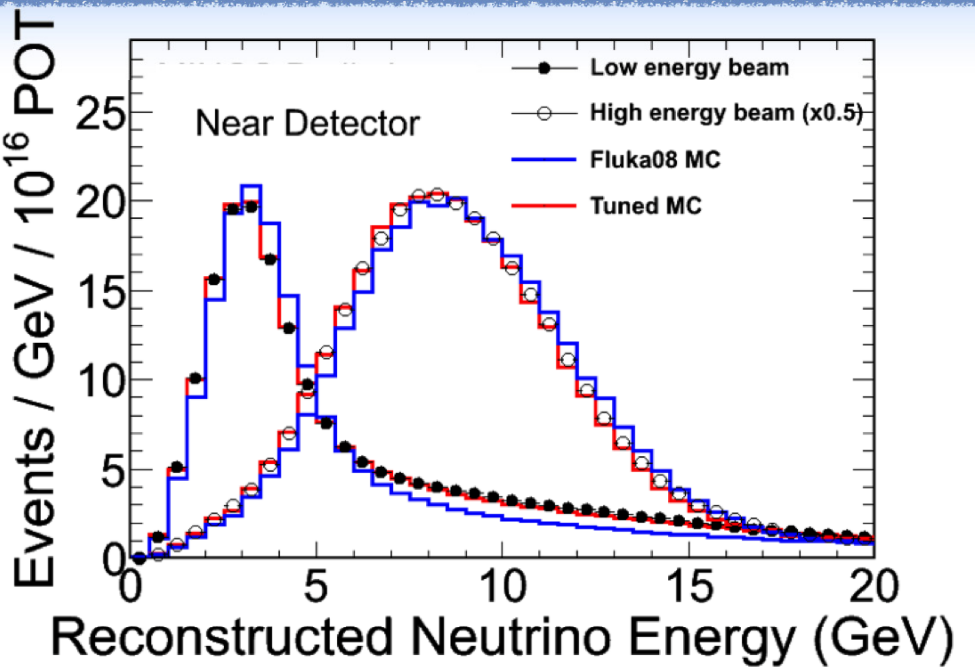
The NuMI Beam and the MINOS Detectors

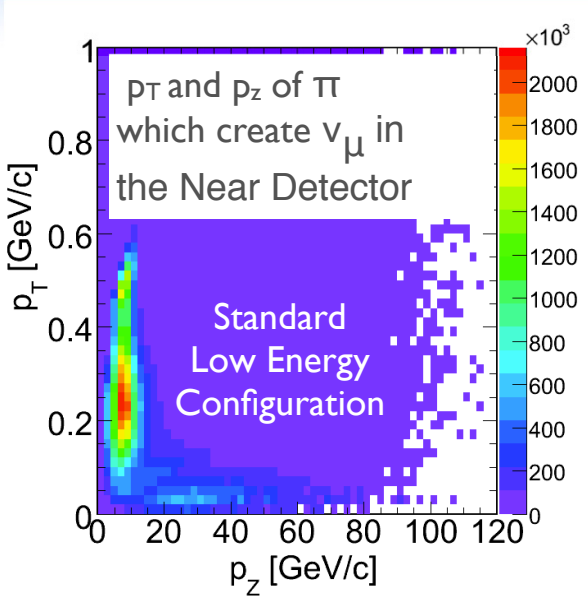
The NuMI Beam



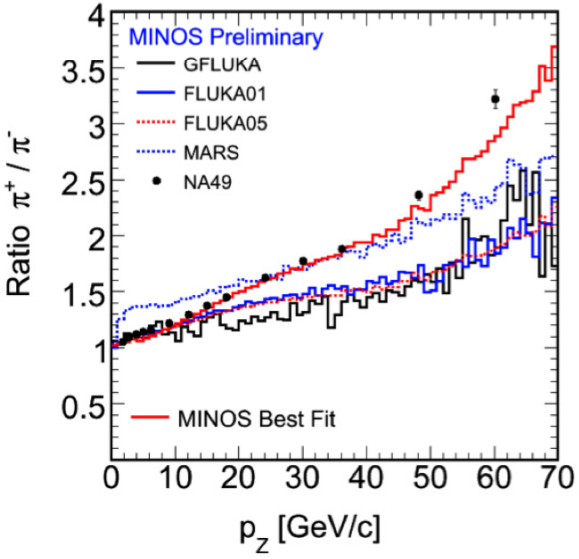


The NuMI Beam

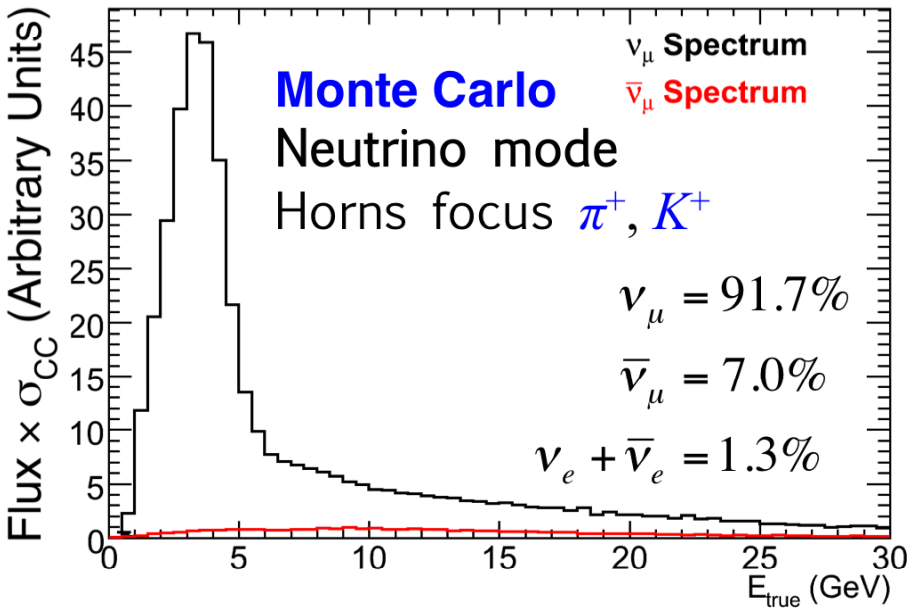




- The Beam spectrum can be tuned by varying relative positions of target and magnetic horns
- Hadron production cross-sections reweighted from fits of p_T and p_z to ND ν_μ energy spectrum using 7 beam configurations
- NA49 data used to constrain π^+/π^- and π/K ratios in fits



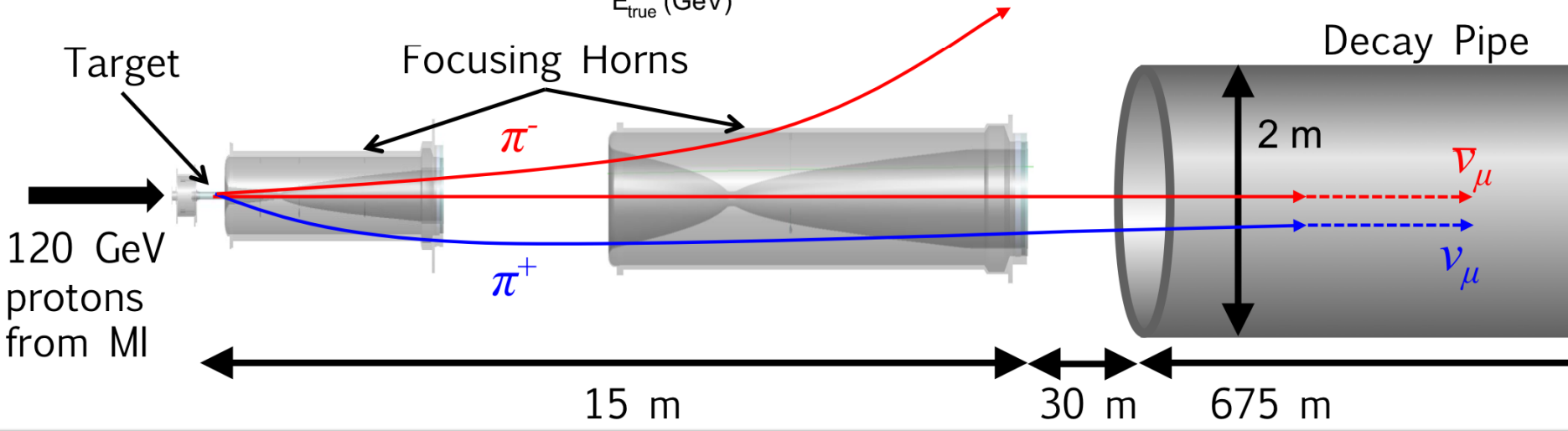
Neutrino Running



Horns focus π^+, K^+, which decay into ν_μ

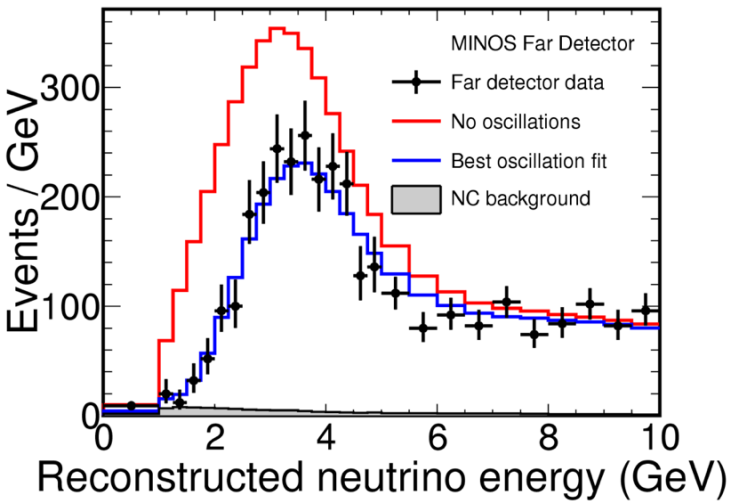
Higher energy $\bar{\nu}_\mu$ from very forward π^-

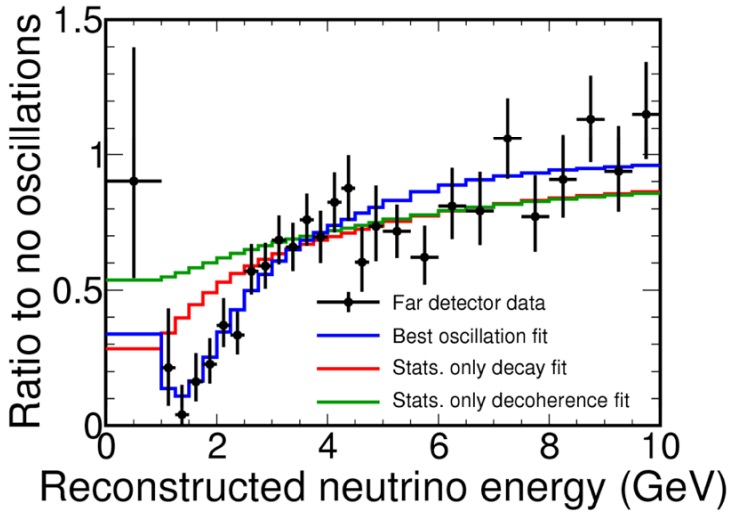
Most of MINOS beam data taken in this configuration

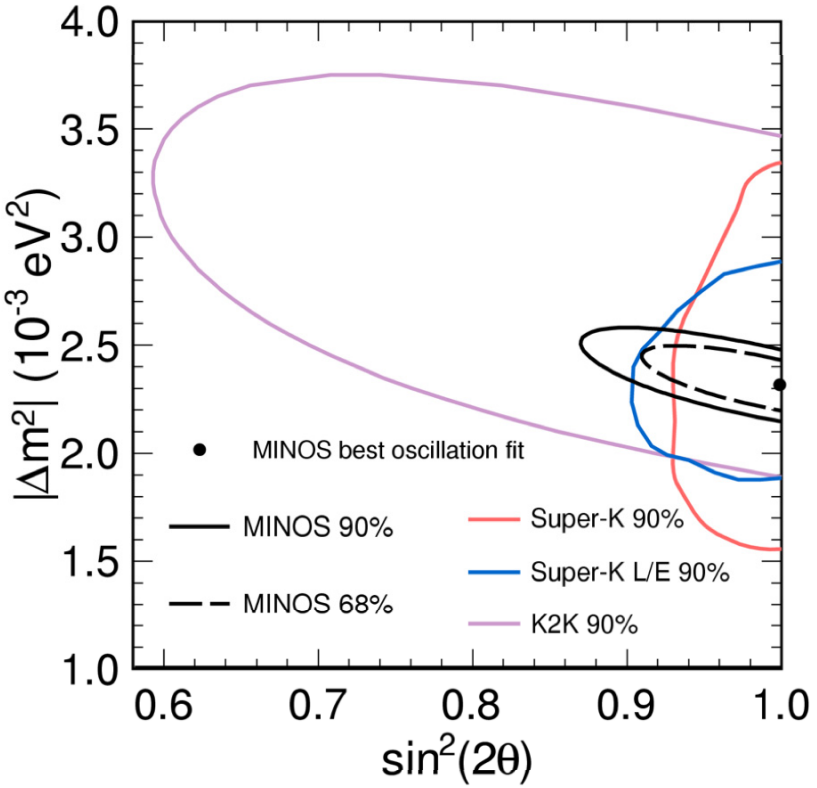


Neutrino Disappearance

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





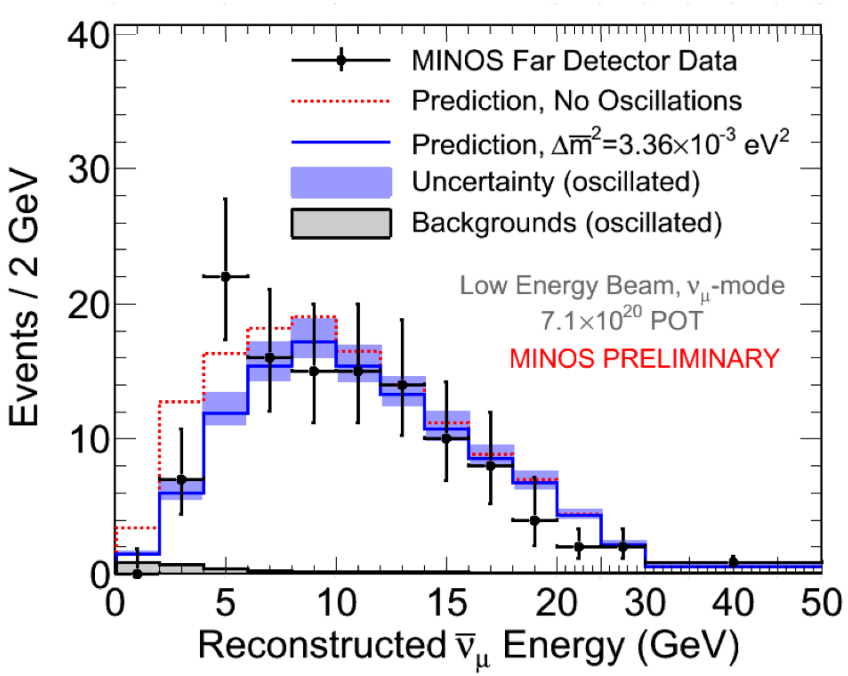


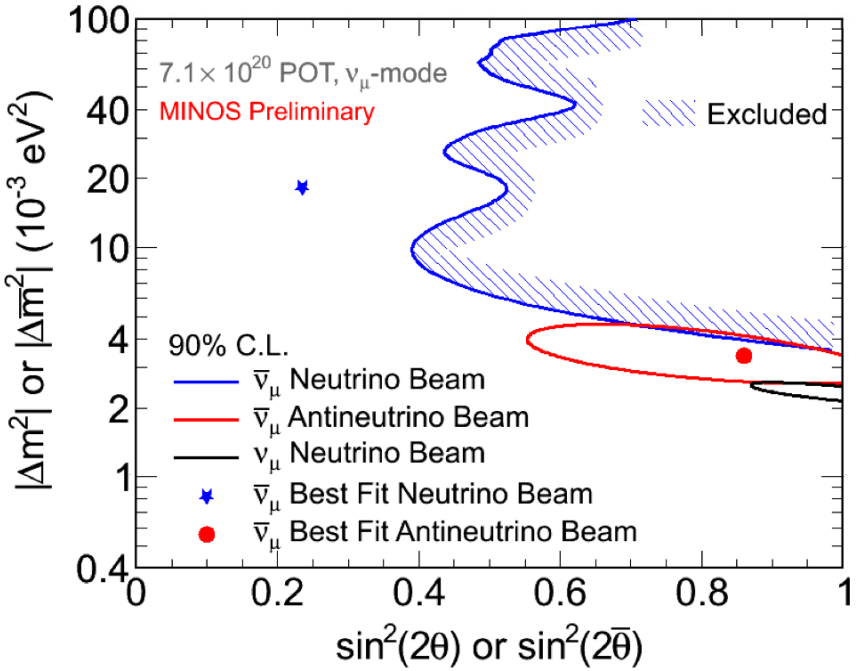
$$|\Delta m^2_{\rm atm}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}{\rm eV}^2$$
$$\sin^2(2\theta_{23}) > 0.90\ (90\%\,{\rm C.L.})$$

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

Disfavors alternative hypotheses to oscillations

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



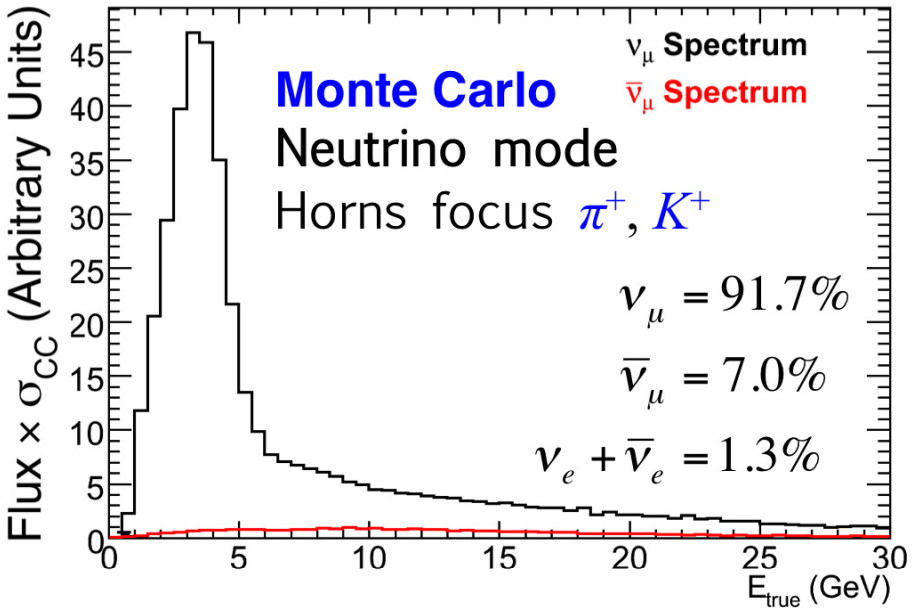


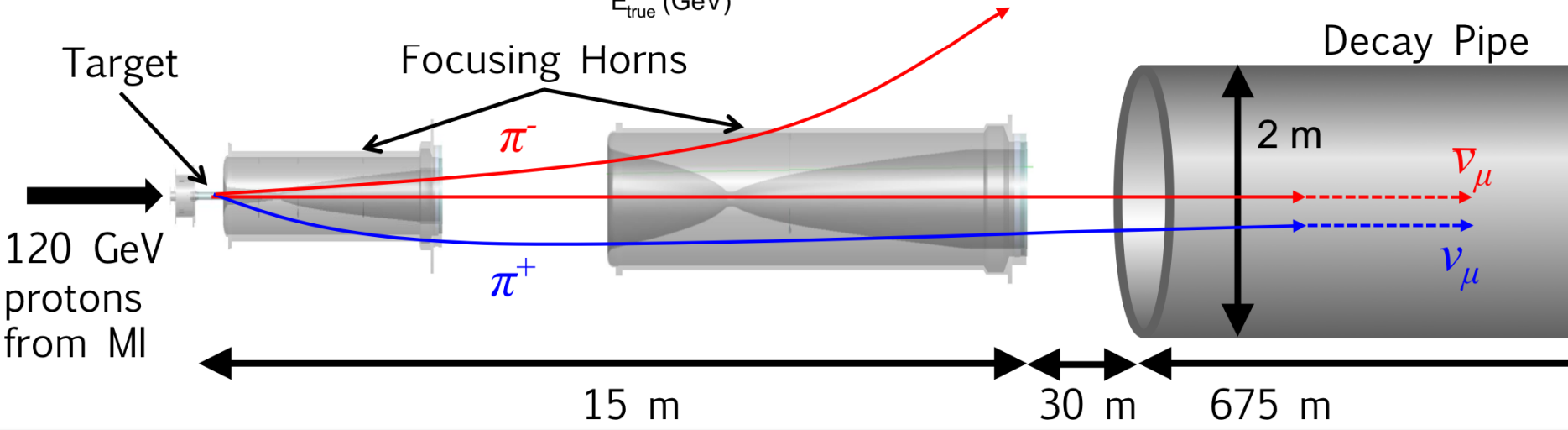
- Analyze 7% antineutrino component of neutrino beam
- Complementary information from higher energy events
- Results consistent with the other MINOS disappearance analysis

$$|\Delta\overline{m}^2_{\rm atm}| < 3.37\times10^{-3}{\rm eV}^2 \ \ (90\%\ {\rm C.L.})$$
$$\text{if} \ \ \sin^2(2\bar{\theta}_{23}) = 1.0$$

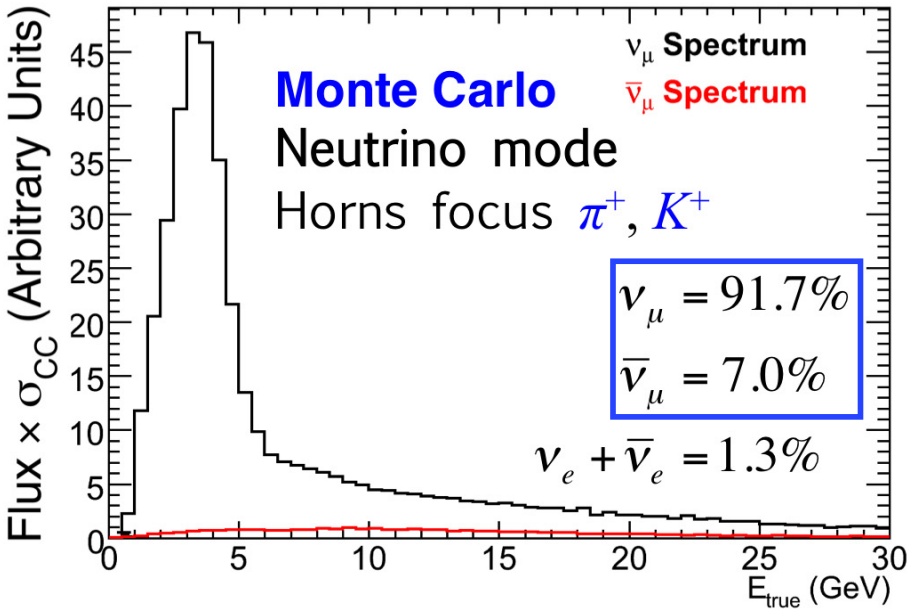
arXiv:hep-ex/1108.1509, submitted to Phys. Rev. D (RC)

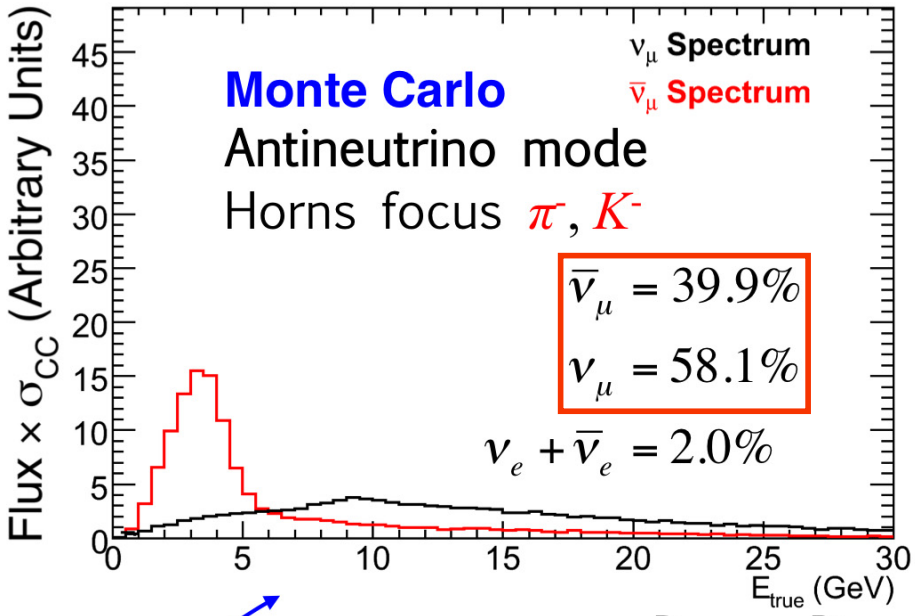
Creating a $\bar{\nu}_\mu$ Beam

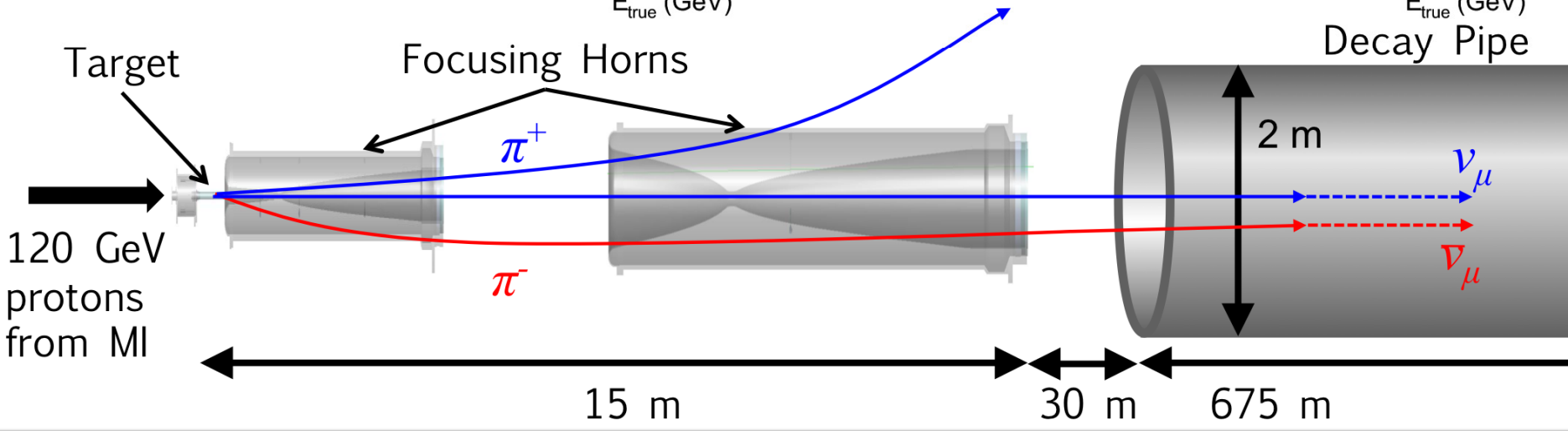




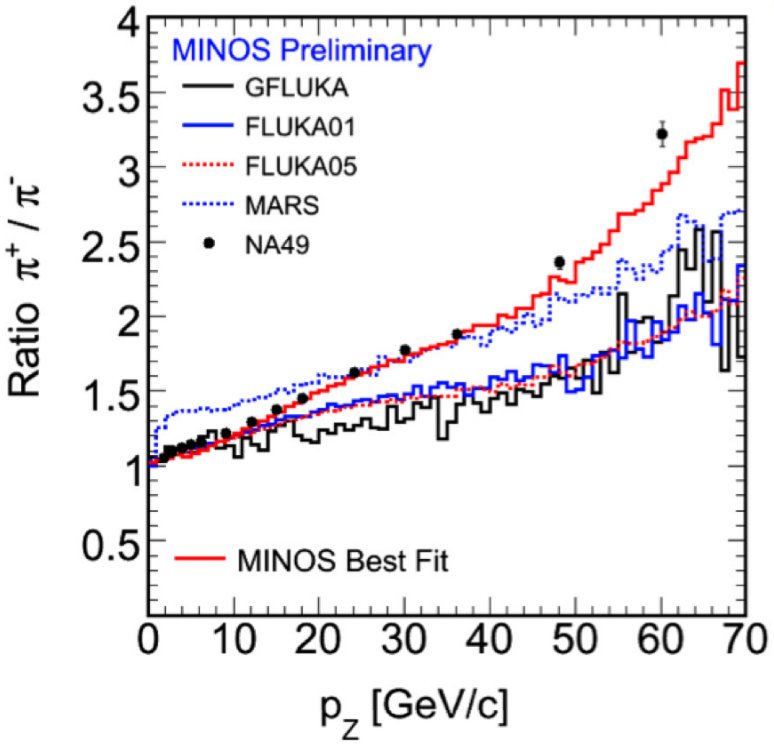
Creating a $\bar{\nu}_\mu$ Beam



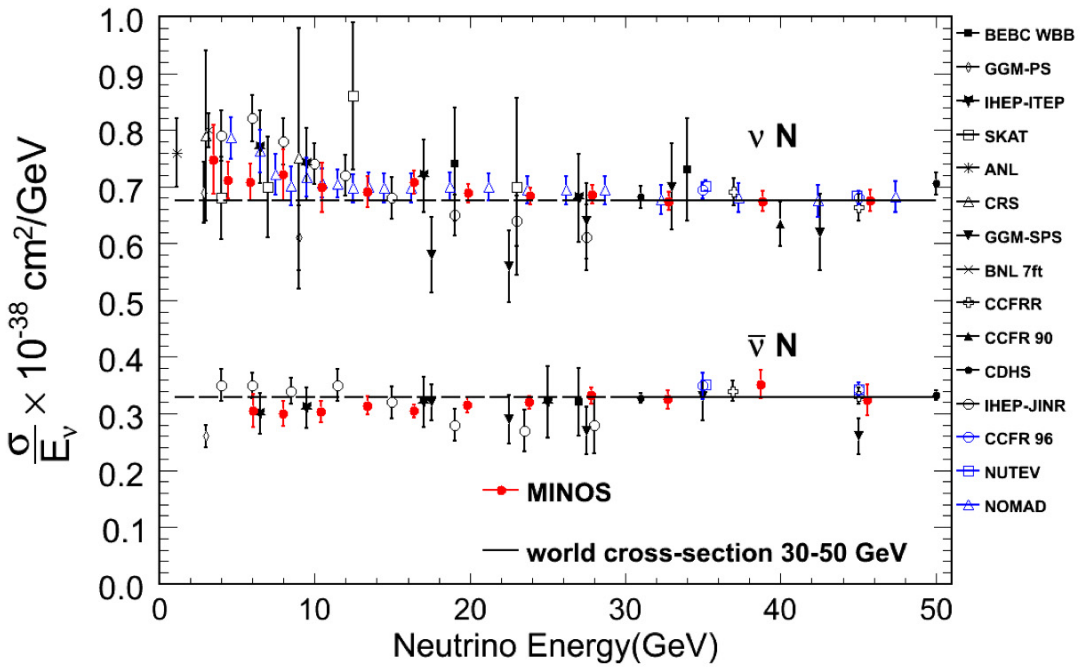




Antineutrino Cross Sections



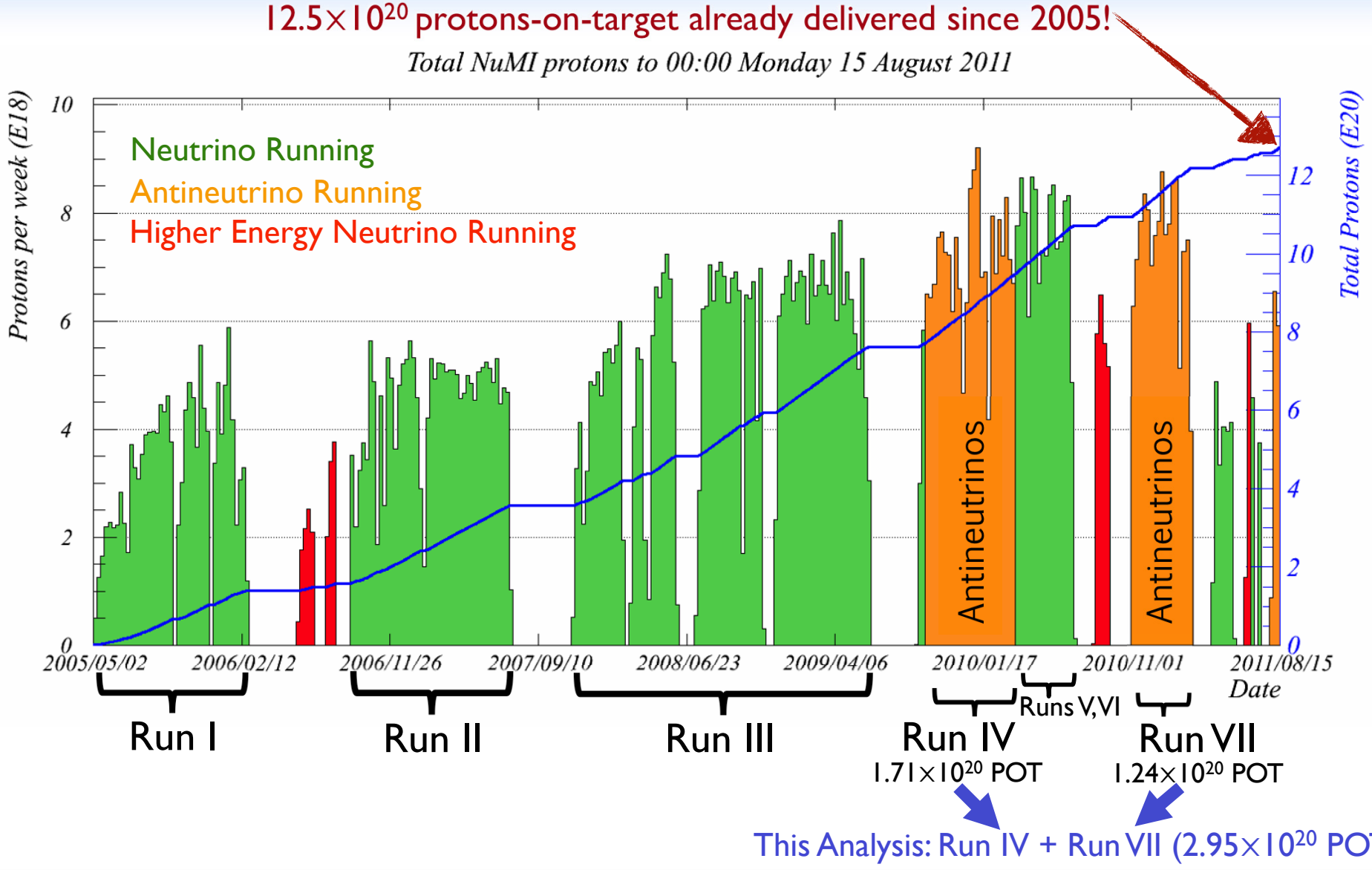
Eur. Phys. J. C 49 897 (2007)



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

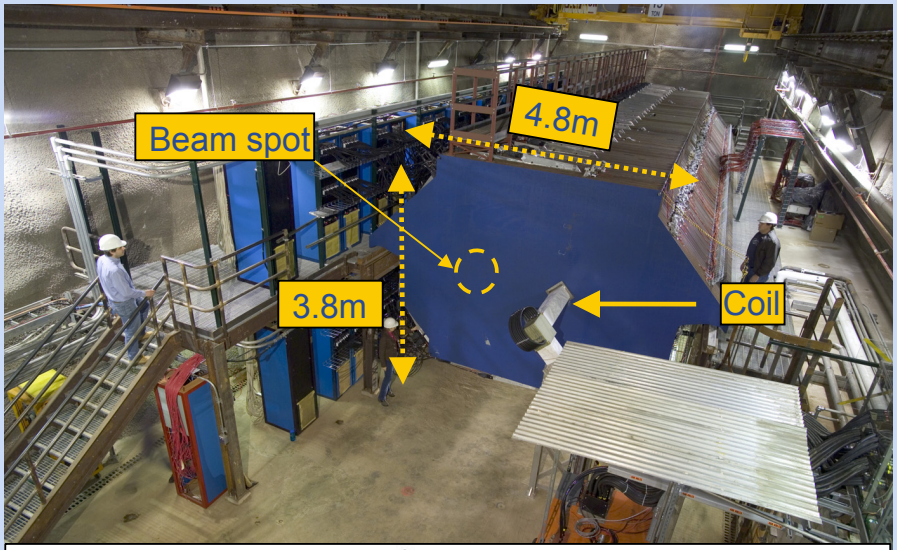


MINOS Detectors

- Magnetized tracking sampling calorimeters

Near Detector

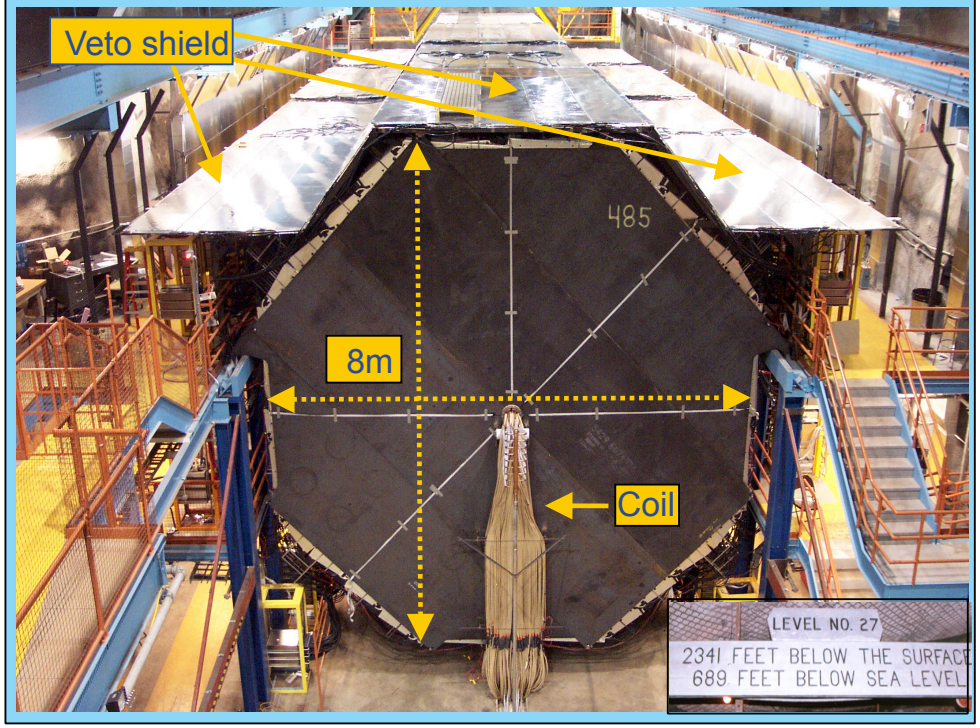
- ~1 kton (980 ton) total mass
- Located 1 km downstream of the target at Fermilab
- 100 m depth





Far Detector

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

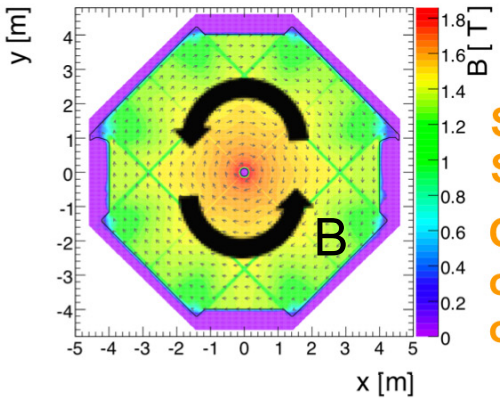


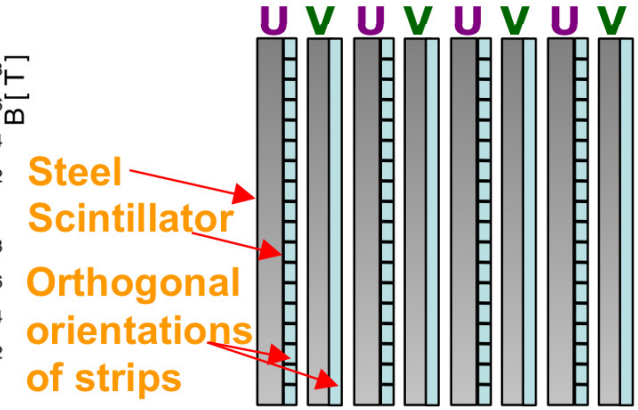
- Functionally equivalent: same segmentation, same materials, same mean B field

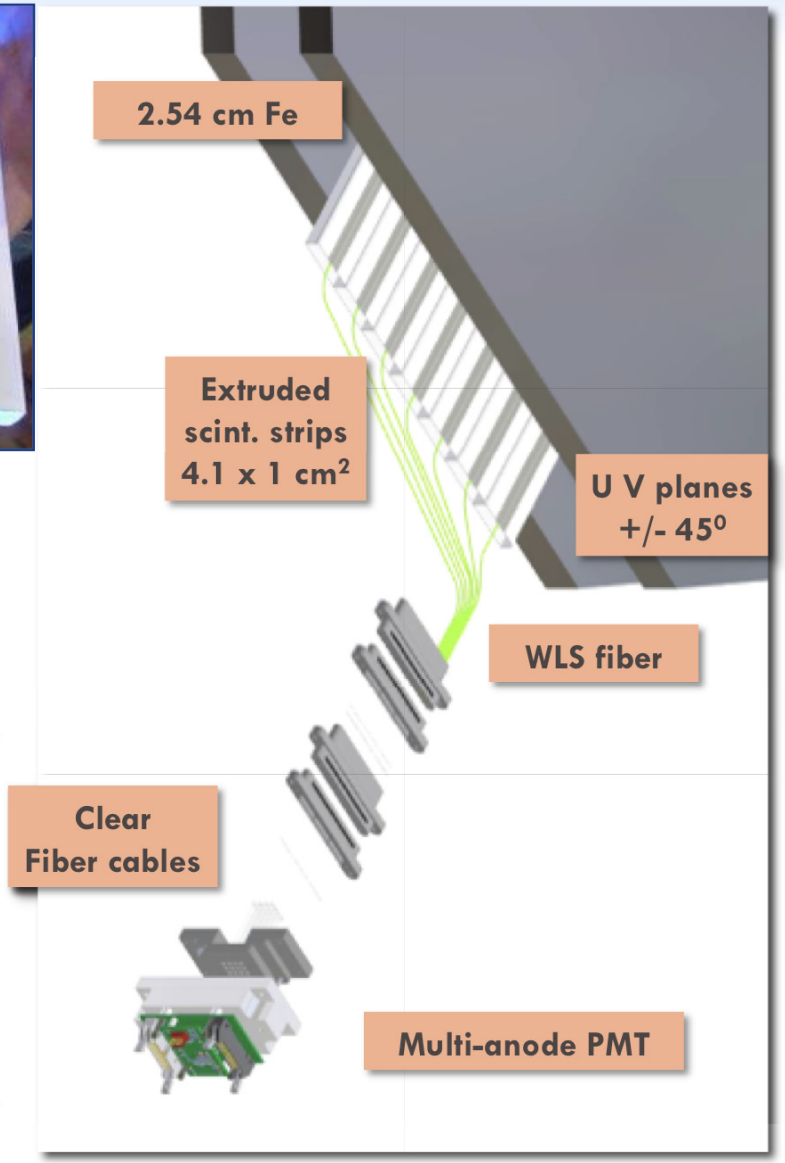
Detector Technology

- 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^-





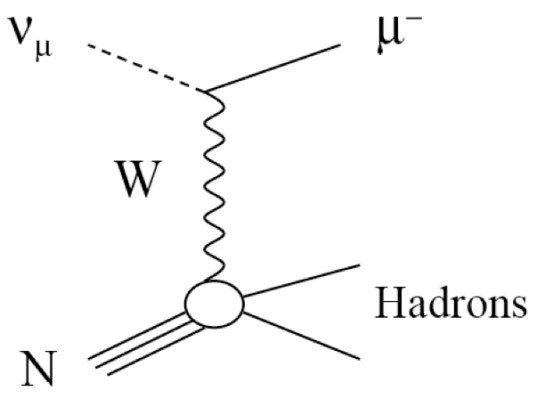




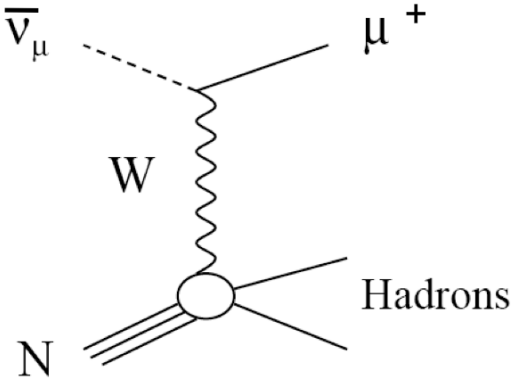
Event Topologies



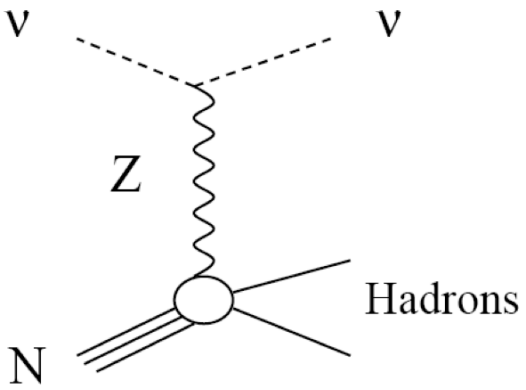
ν_μ CC Event

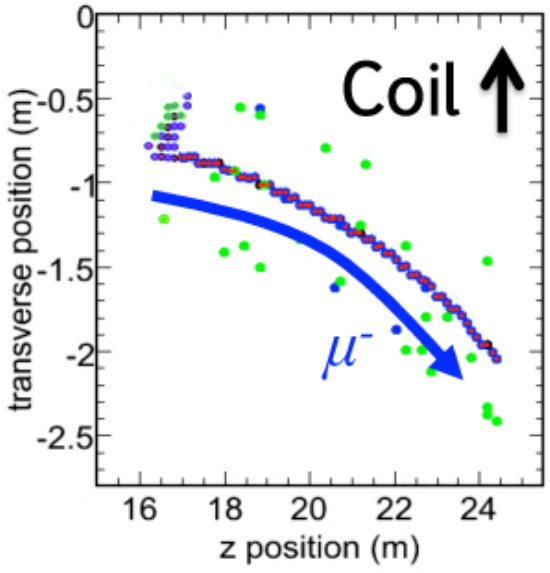


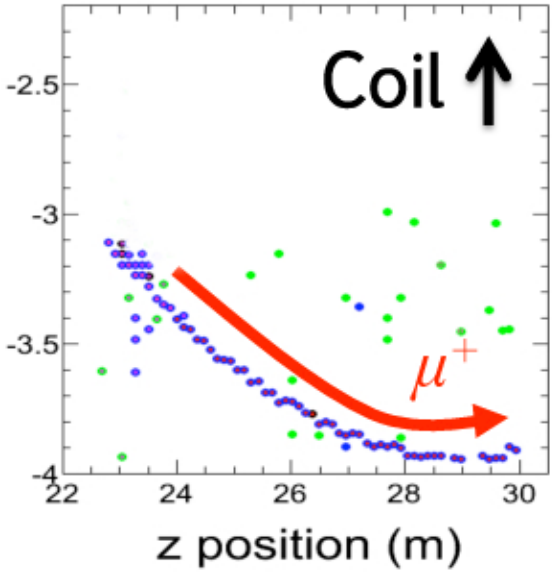
$\bar{\nu}_\mu$ CC Event

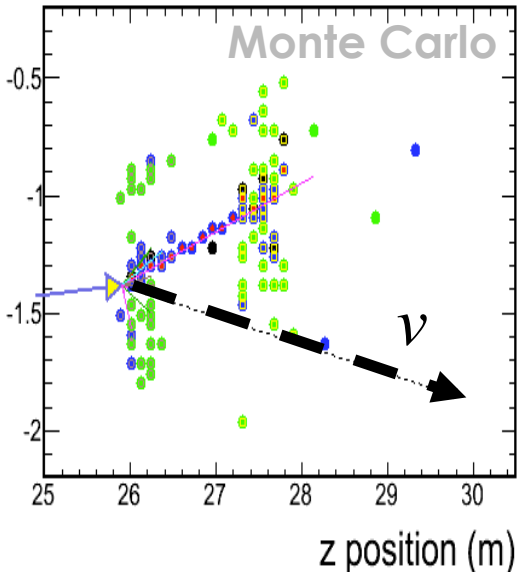


NC Event









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

Analysis Overview



NuMI $\bar{\nu}_\mu$ beam data

ND Measurement
Analyze beam flavor content, neutrino flux, rates
Obtain ND $\bar{\nu}_\mu$-like energy spectrum

Blind to full FD sample until freezing of analysis procedures

Predict the Far Detector
Transfer ND to FD, function of flux, cross sections, efficiency, energy resolution

FD Measurement
Analyze beam flavor, rates
Obtain FD $\bar{\nu}_\mu$-like energy spectrum

Fit osc. prediction to data
Derive oscillation parameter values and uncertainties

- **What changed since the 2010 analysis?**
  - Increased antineutrino data exposure from 1.71×10^{20} POT to 2.95×10^{20} POT
  - New Near Detector coil hole selection
  - New shower energy estimator

CC, NC Separation

- Muons from ν_μ, $\overline{\nu}_\mu$ CC interactions are identified as tracks satisfying a multivariate topological ID that uses a kNN algorithm

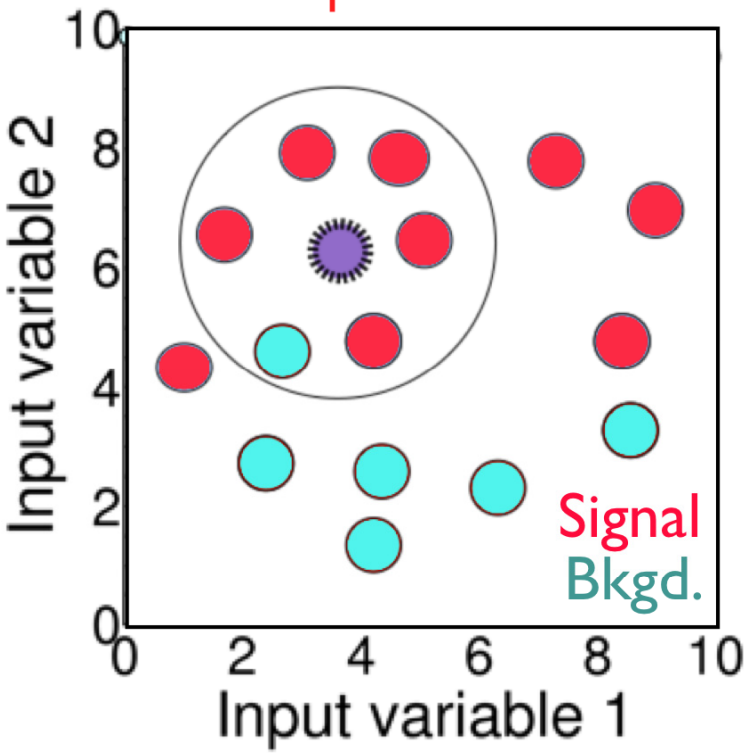
- **kNearest-Neighbors Algorithm**
  - Determine distance of "query" event to each of MC signal and bkgd. events in multivariate space
    - e.g. Euclidean distance

$$D = \left(\sum_{i=1}^{N_{\text{Var}}} |X_i^{MC} - X_i^{Q}|^2 \right)^{\frac{1}{2}}$$

  - Use the "k" MC events with smaller distances to classify "query" event:

$$\text{kNN}_{\text{ID}} = \frac{k_S}{k_S + k_B}$$

kNN example with 2 variables



k=6, k_S=5, k_B=1 ⇒ kNN_{ID}=5/6

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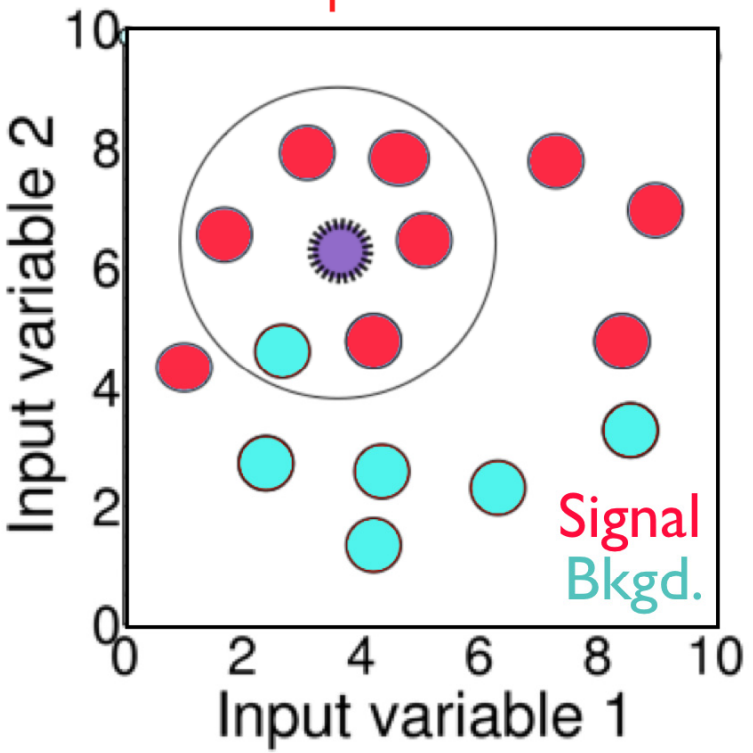


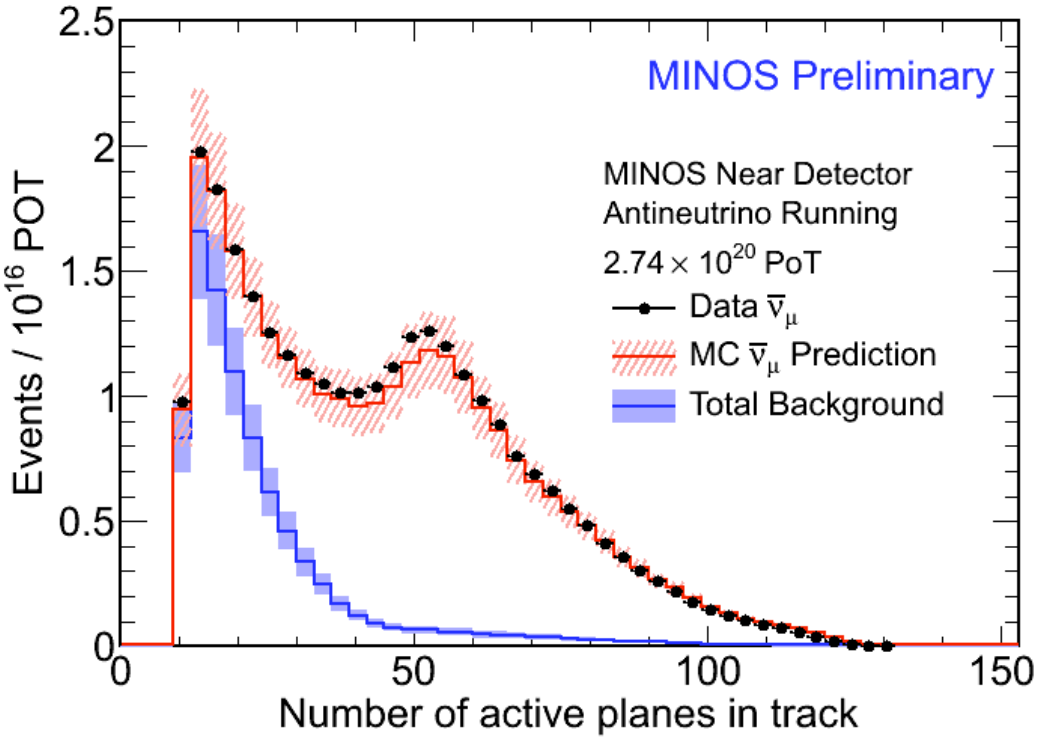
k=6, k_S=5, k_B=1 ⇒ kNN_{ID}=5/6

- MINOS kNN algorithm uses 4 input variables and k=80

CC, NC Separation

- Muons from ν_μ, $\bar{\nu}_\mu$ CC interactions are identified as tracks satisfying a multivariate topological ID that uses a kNN algorithm

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



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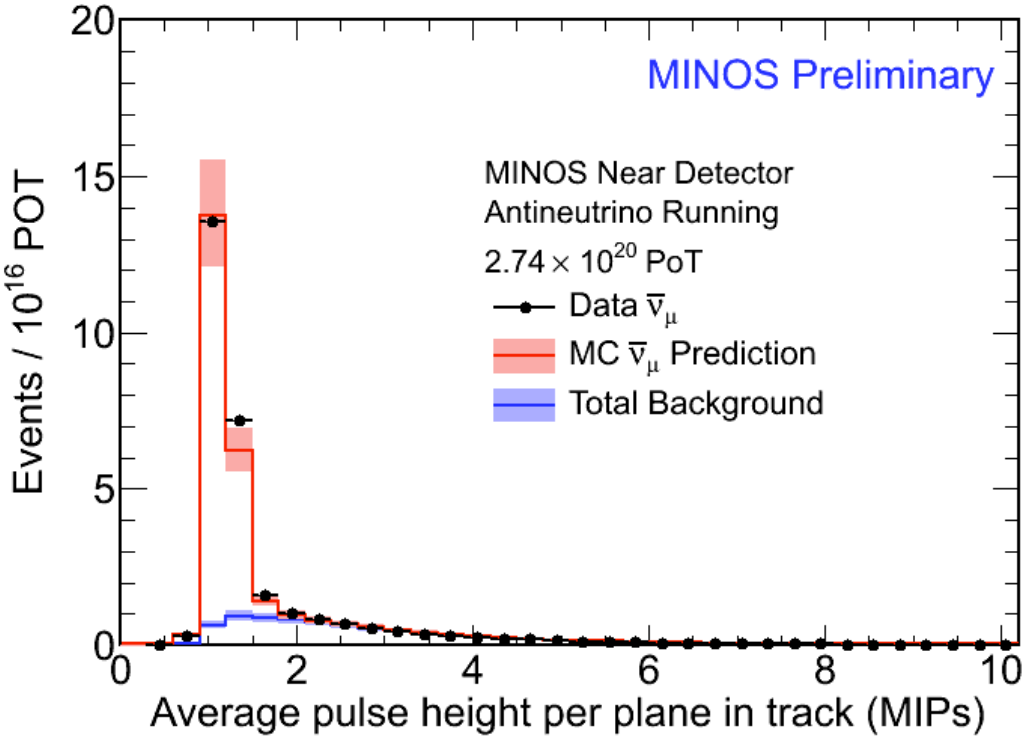

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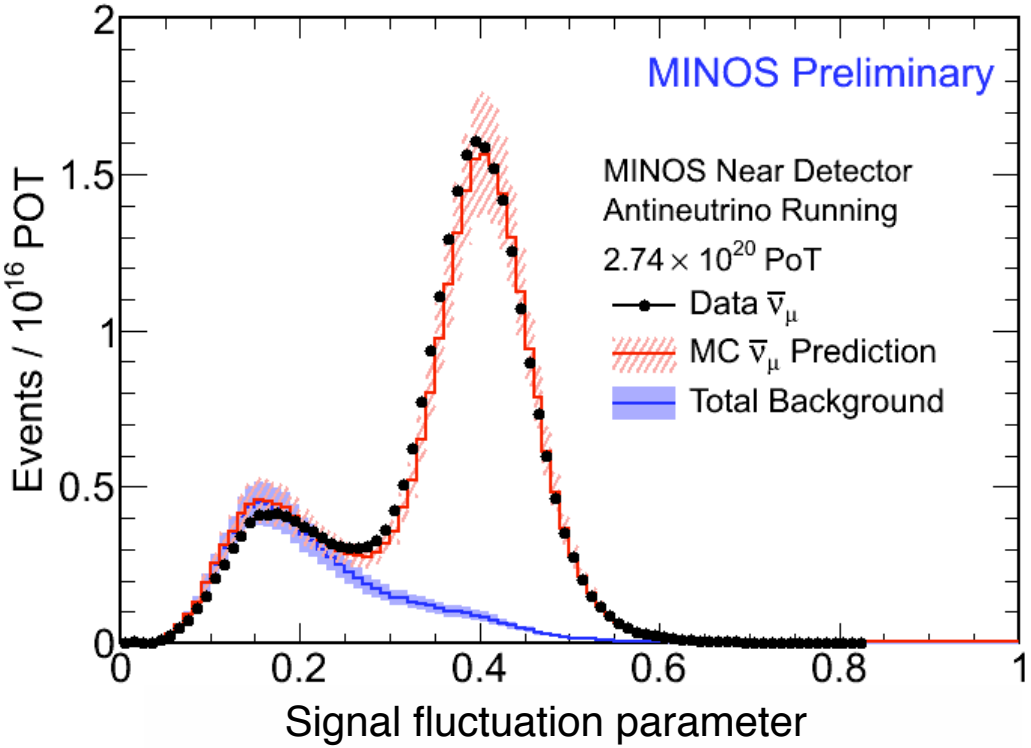

CC, NC Separation

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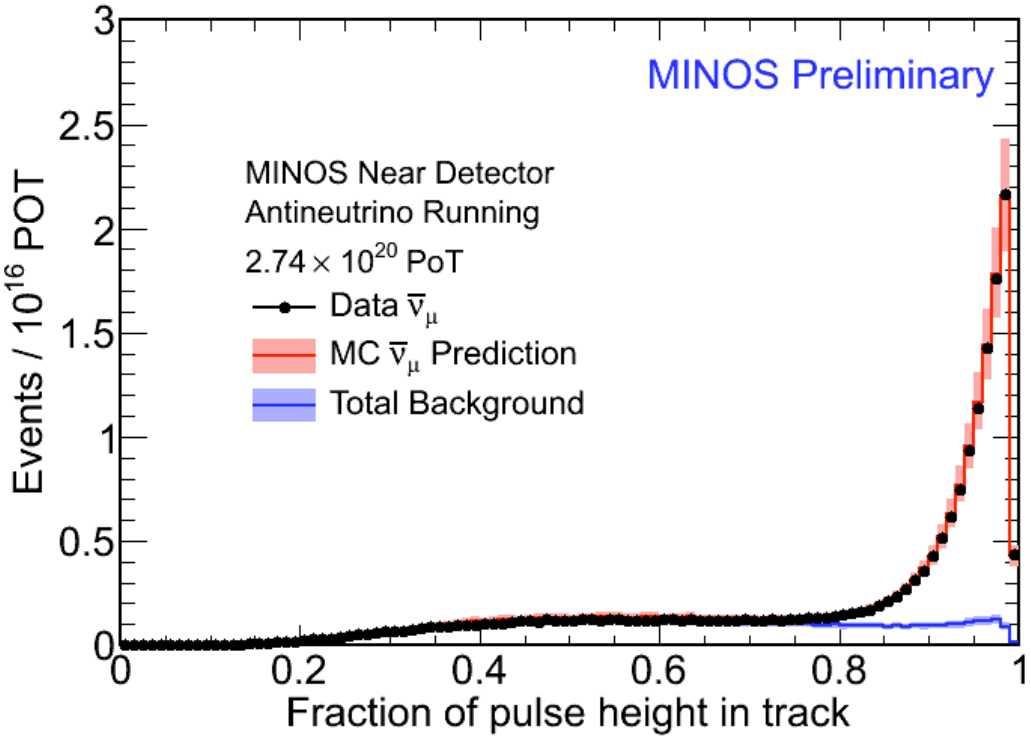
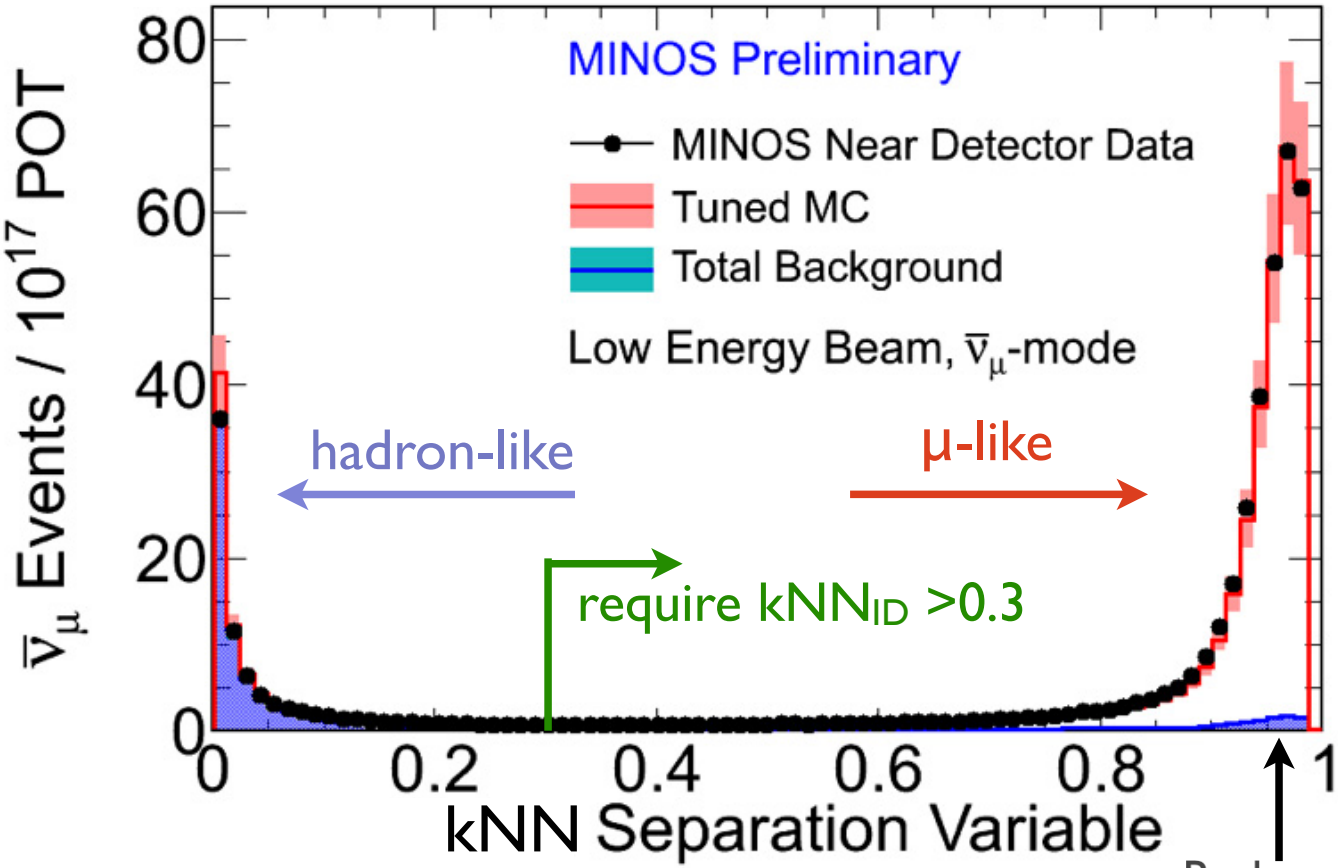


CC,NC Separation

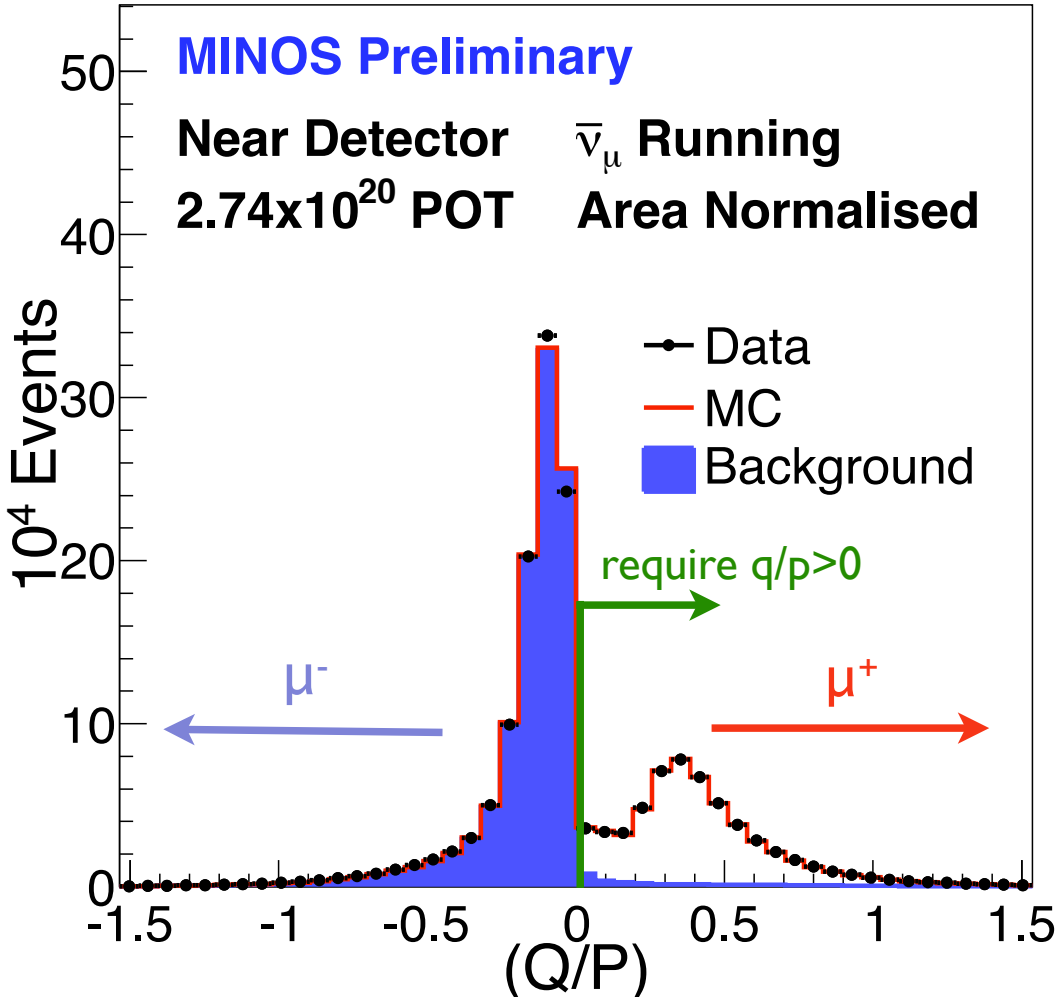
- Muons from ν_μ, $\bar{\nu}_\mu$ CC interactions are identified as tracks satisfying a multivariate topological ID
  - Rejects neutral current backgrounds and high-y CC events



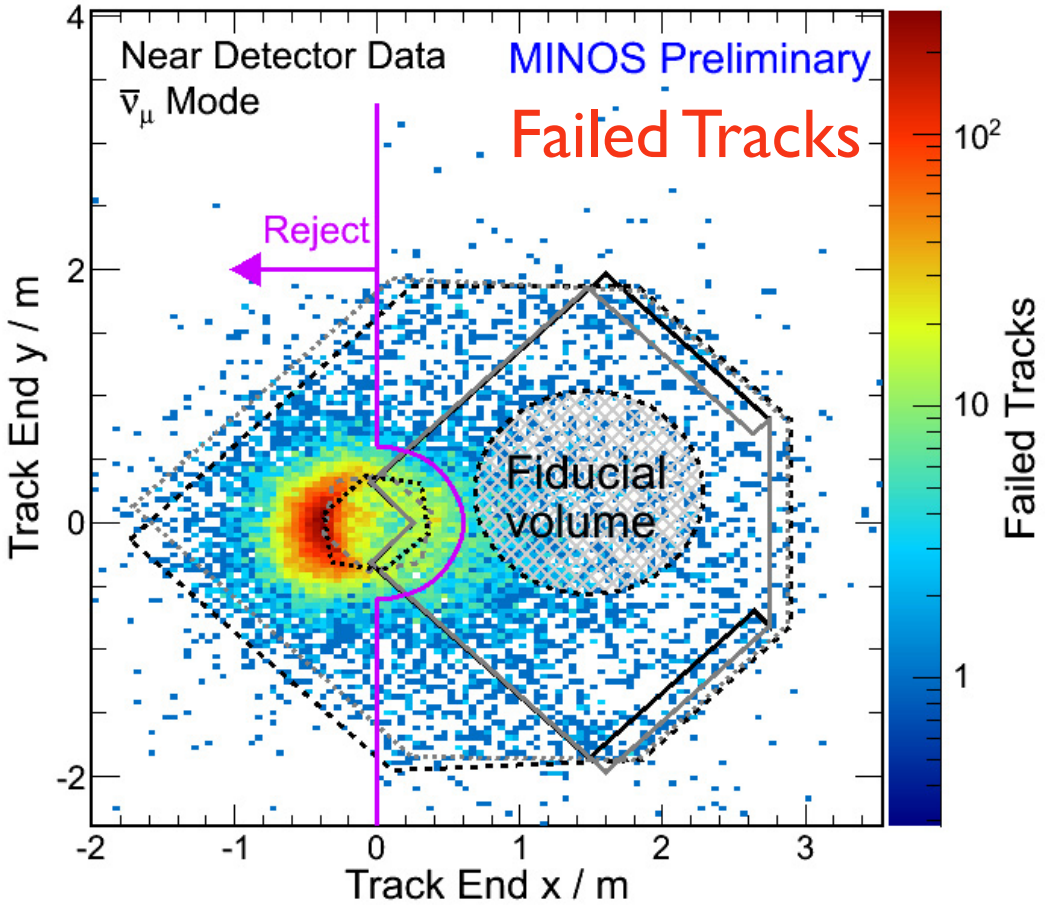
$$\mathrm{kNN_{ID}} = \frac{k_{CC}}{k_{CC} + k_{NC}}$$

μ Charge Identification

- Muon charge/momentum analyzed by track curvature
- Only accept events with positive reconstructed charge



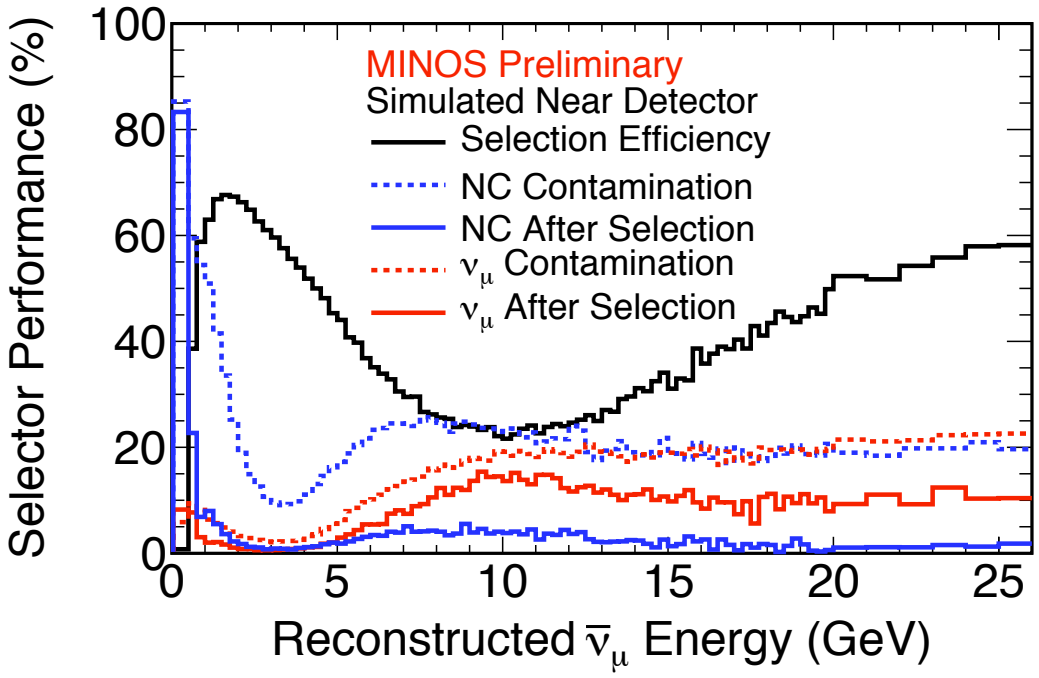
New! - Coil Hole Selection

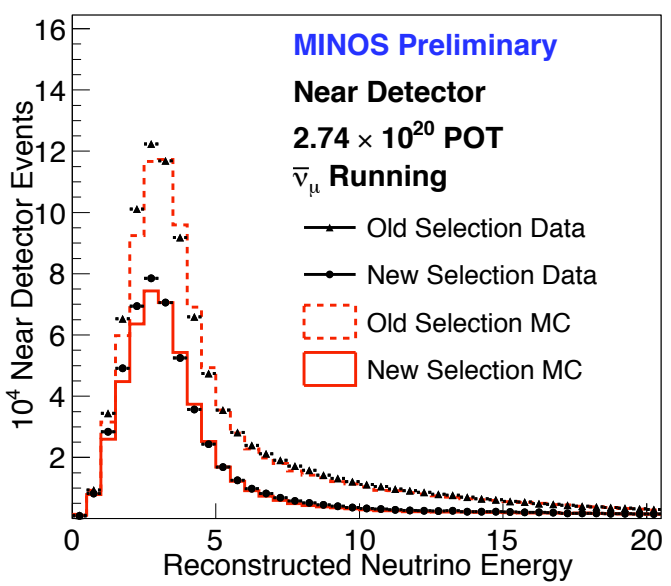


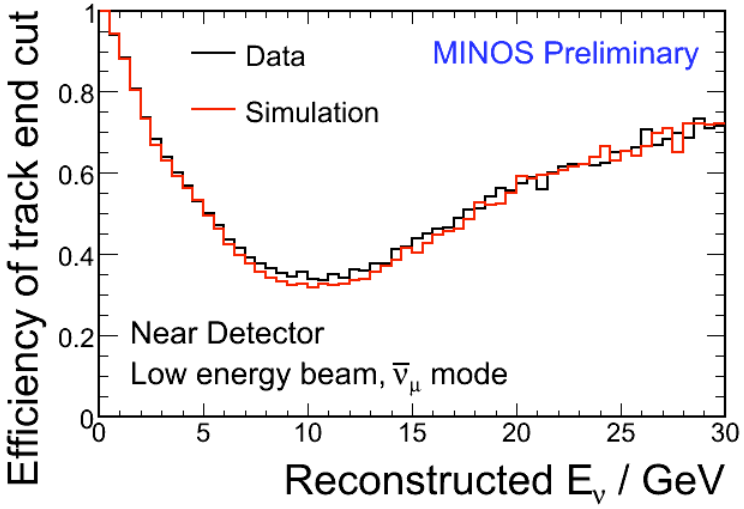
End positions of tracks failed by track fitter

- **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

ND Selection Efficiency



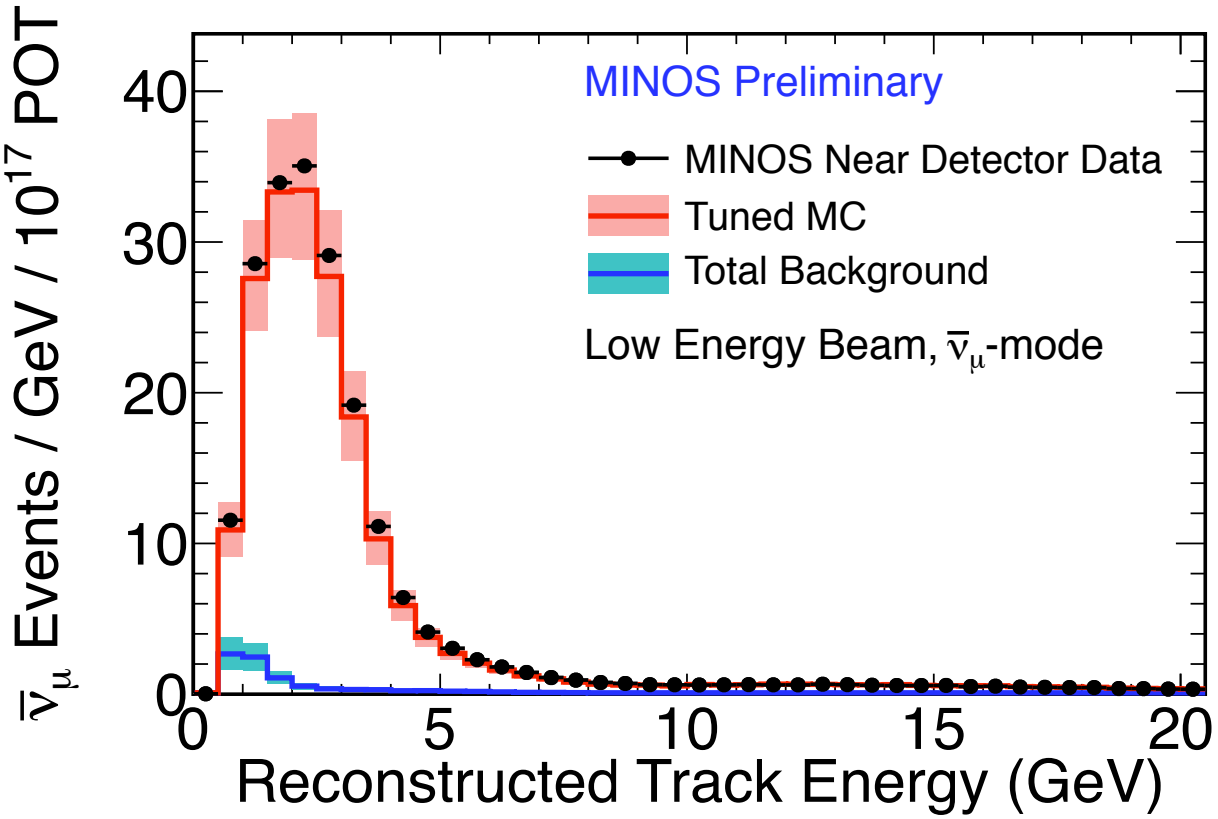




- Broad dip in efficiency due to coil hole selection
  - 53% integrated efficiency, 94% purity
- Shape and magnitude of dip are well modeled by Monte Carlo

Near Detector Data vs. MC

- Reconstructed track energy for $\bar{\nu}_\mu$ CC events selected in the Near Detector



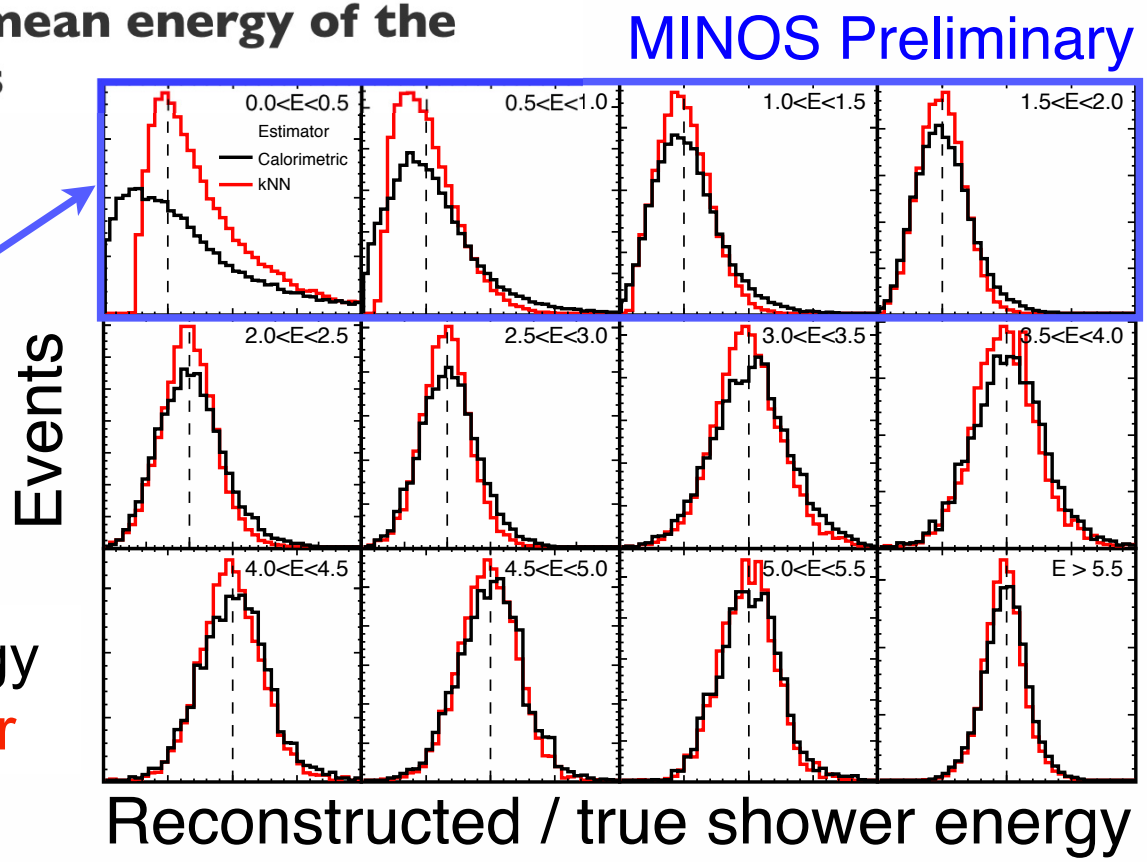
- Data and MC differences smaller than size of systematic uncertainties

New! - kNN Shower Energy

- **Use kNN with three parameters:**
  - the shower energy within 1 m of the track vertex
  - the number of planes in the shower
  - the energy in the second reconstructed shower
- **Estimator is the mean energy of the nearest neighbors**

- Same shower energy estimator used in the 2010 ν_μ CC disappearance analysis

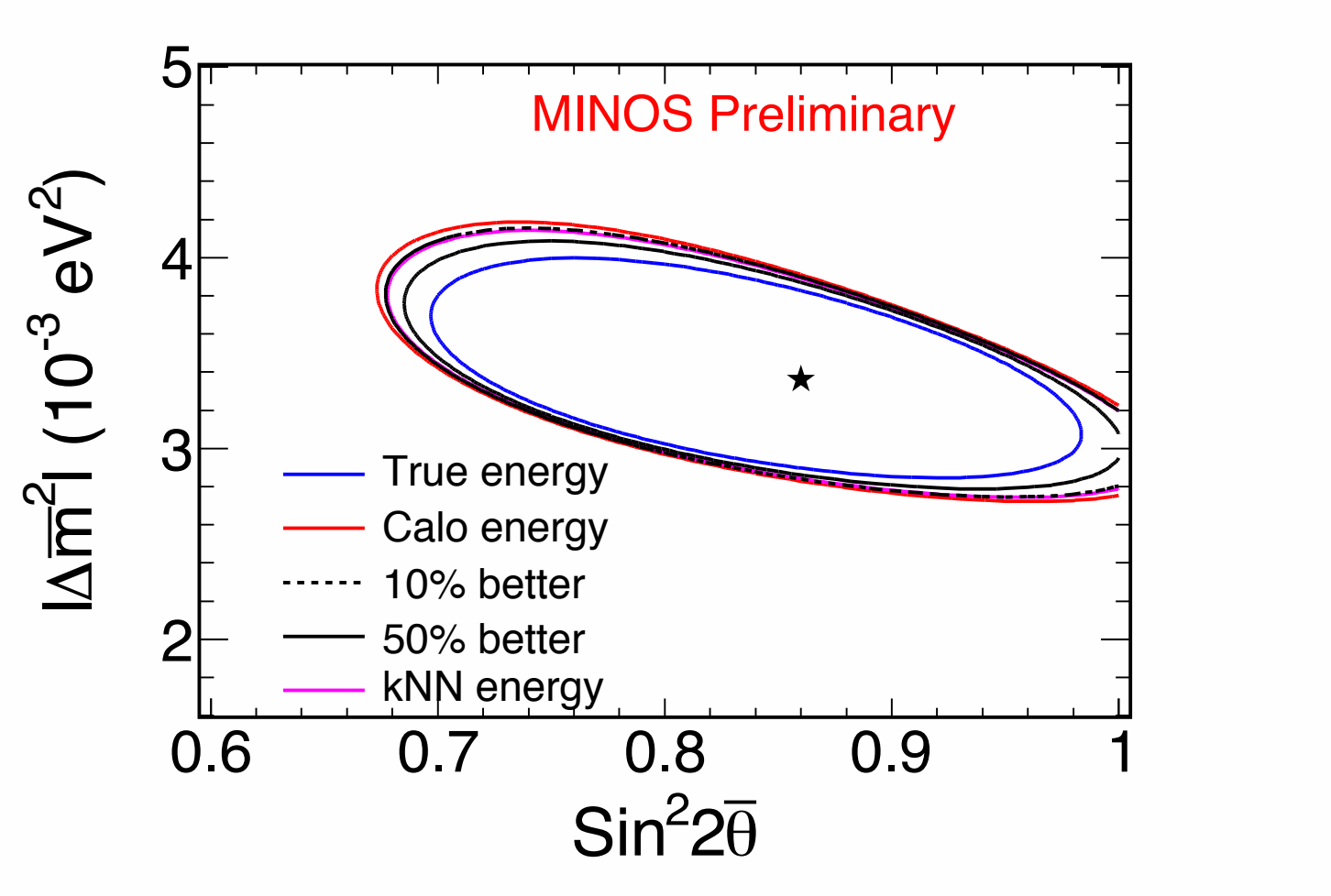
Shower energy resolution improved below 2 GeV



Original Energy
New Estimator

kNN Shower Energy

- Sensitivity of 2010 antineutrino analysis improved by ~10% with adoption of the new shower energy estimator



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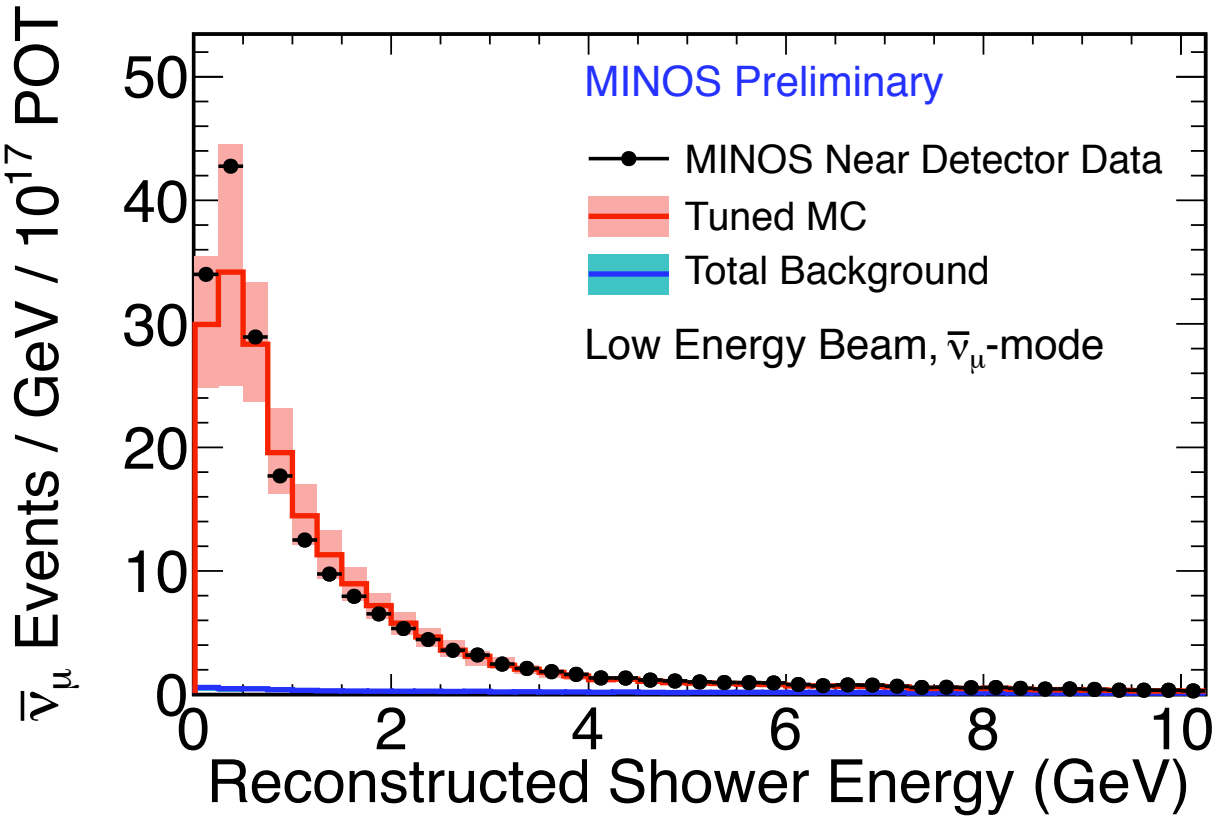
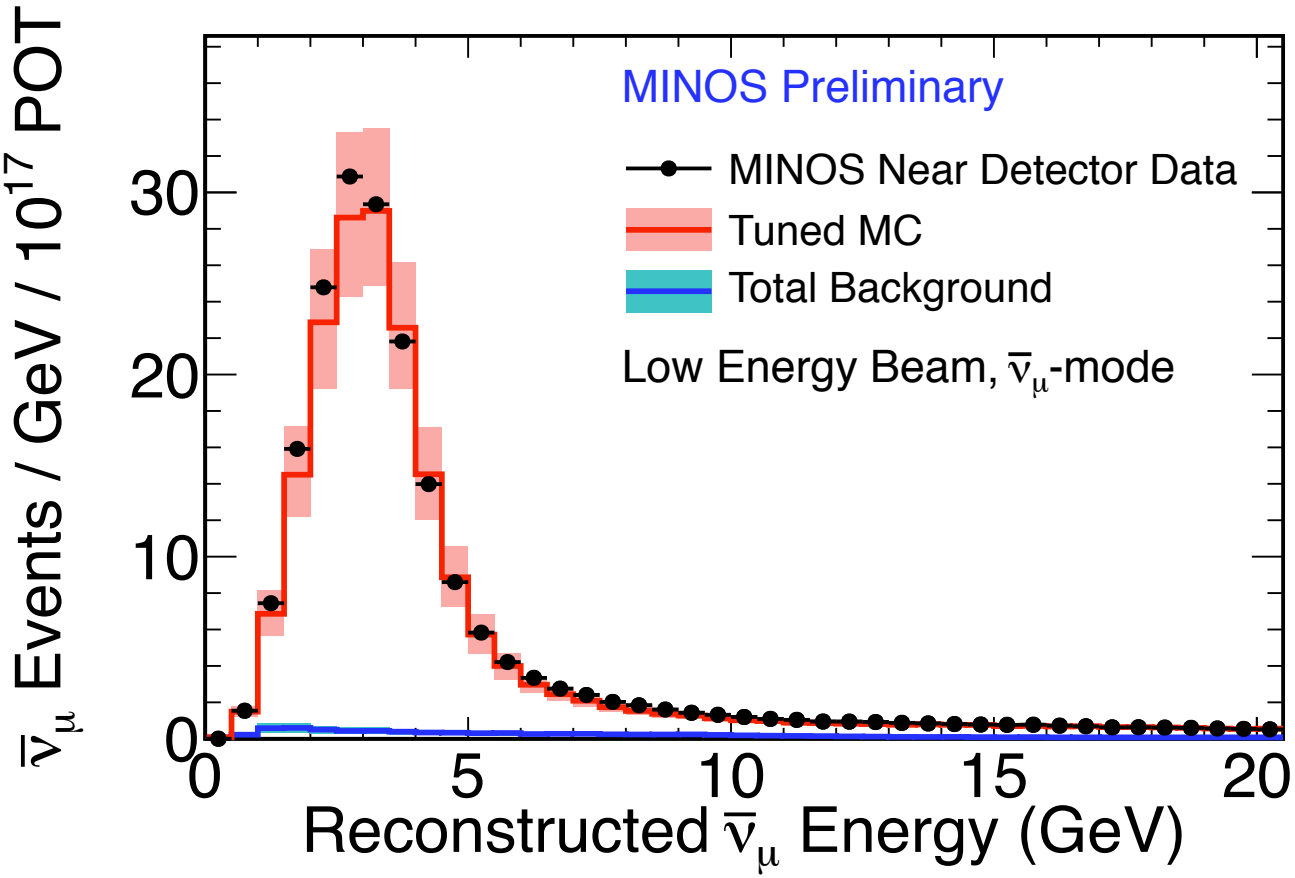


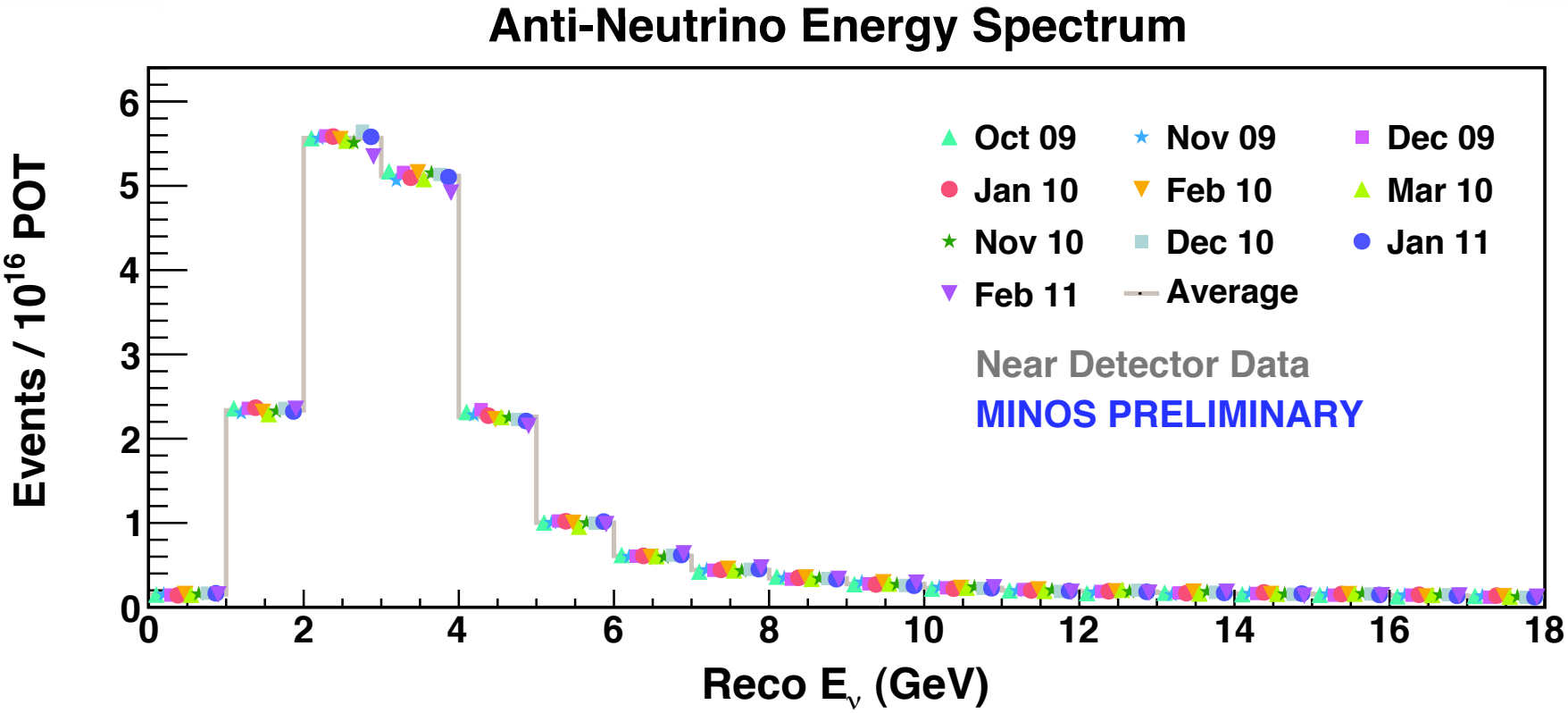
- Data and MC differences smaller than size of systematic uncertainties

Near Detector Energy Spectrum

- Reconstructed antineutrino energy for $\bar{\nu}_\mu$ CC events selected in the Near Detector



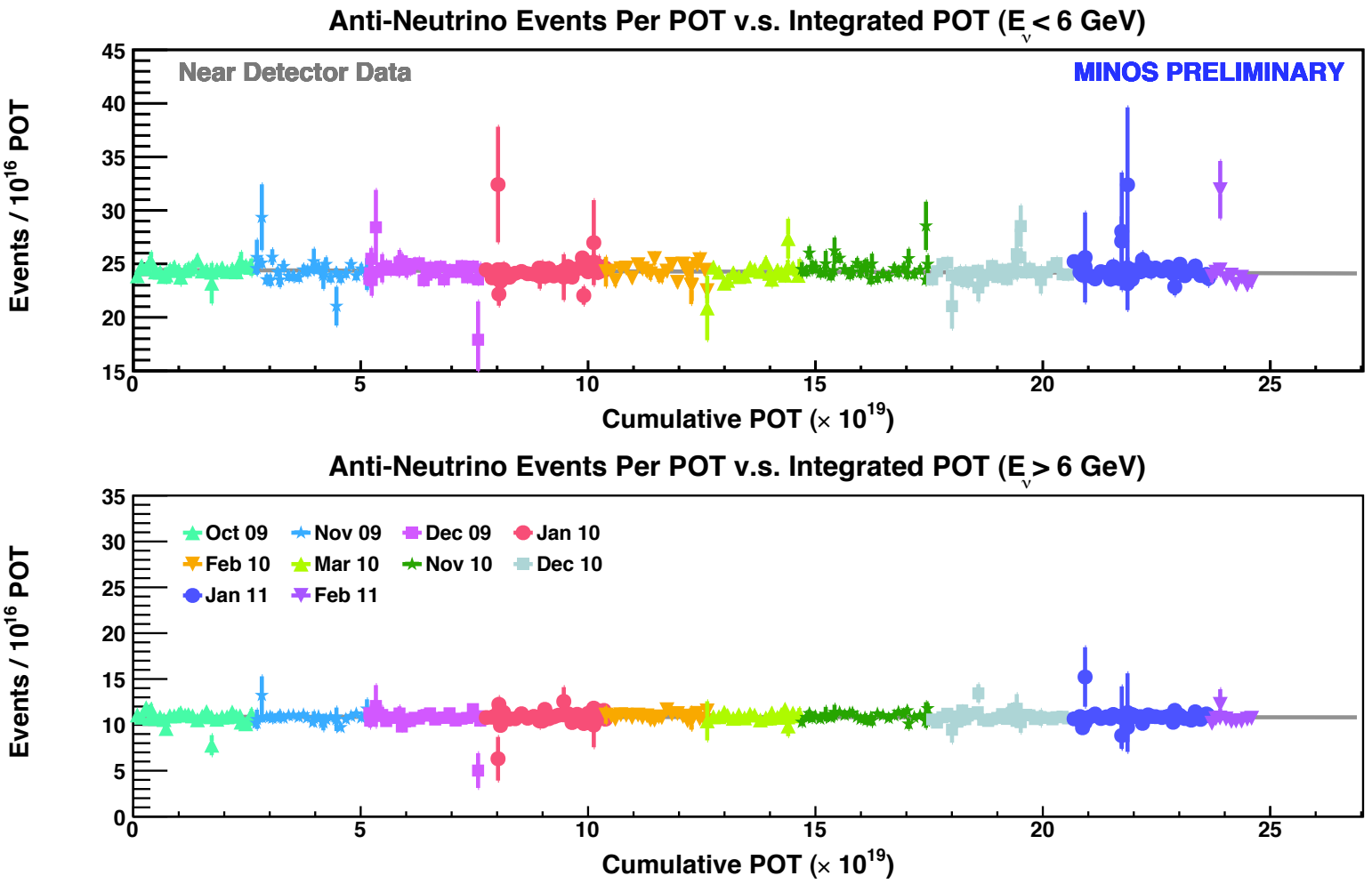
ND Data Stability



- Shape of the $\bar{\nu}_\mu$-selected ND energy spectrum very stable throughout the antineutrino running period
- Feb '11 drop in the falling edge of the focusing peak tracked down to water leak into target can, a few days before target failure occurred
  - Cancels out between detectors

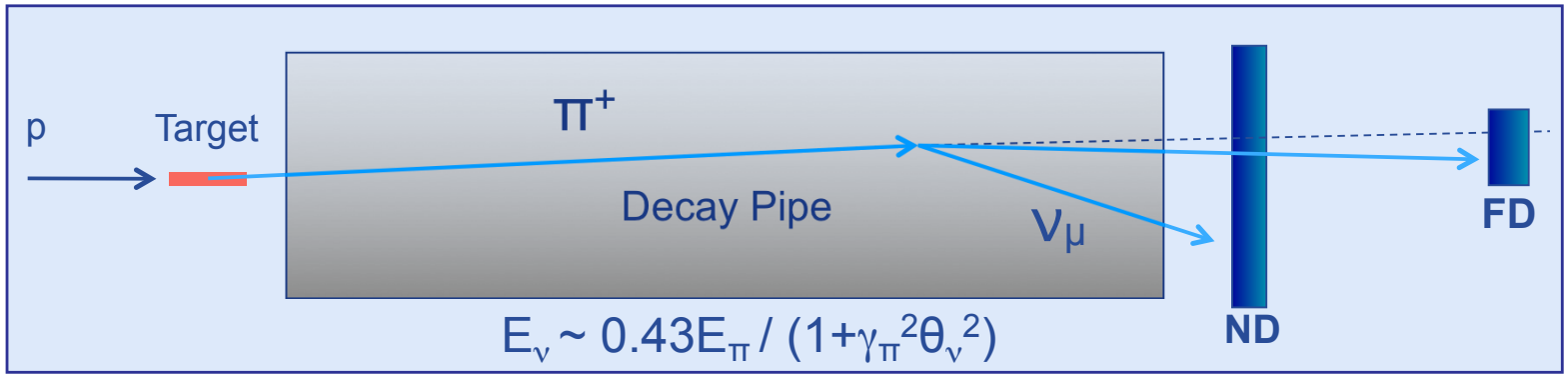
Data Stability

- Number of selected antineutrino events as a function of accumulated POT very stable throughout the antineutrino running period



Near to Far Extrapolation

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



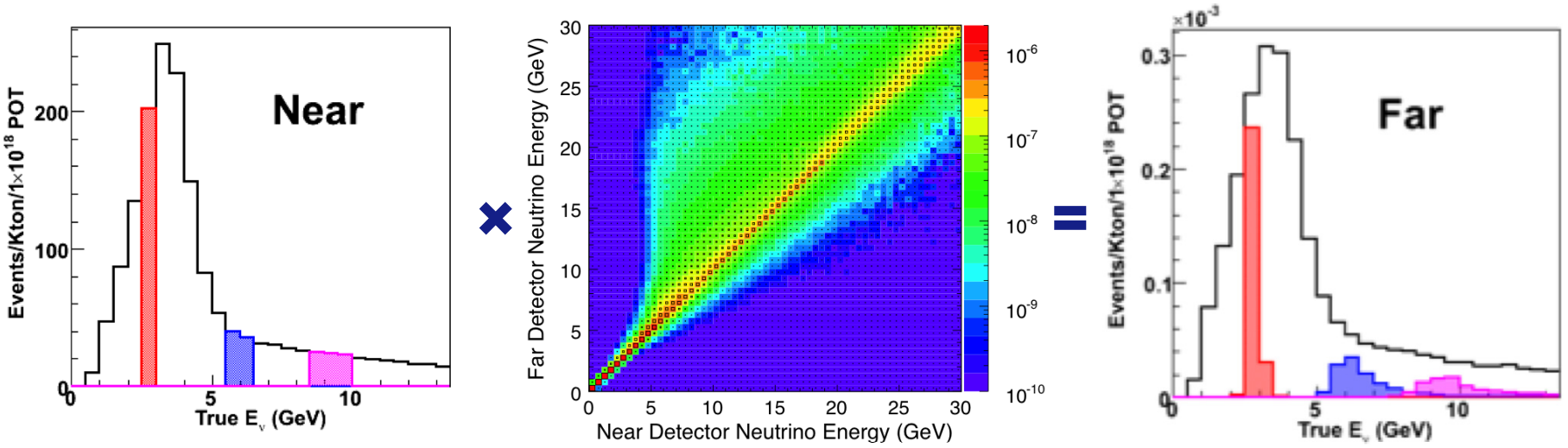
- Neutrino energy depends on angle with original pion direction and the energy of the parent pion

- Near Detector covers a wider solid angle

- Higher energy π travel further downstream the decay pipe and decay closer to the Near Detector

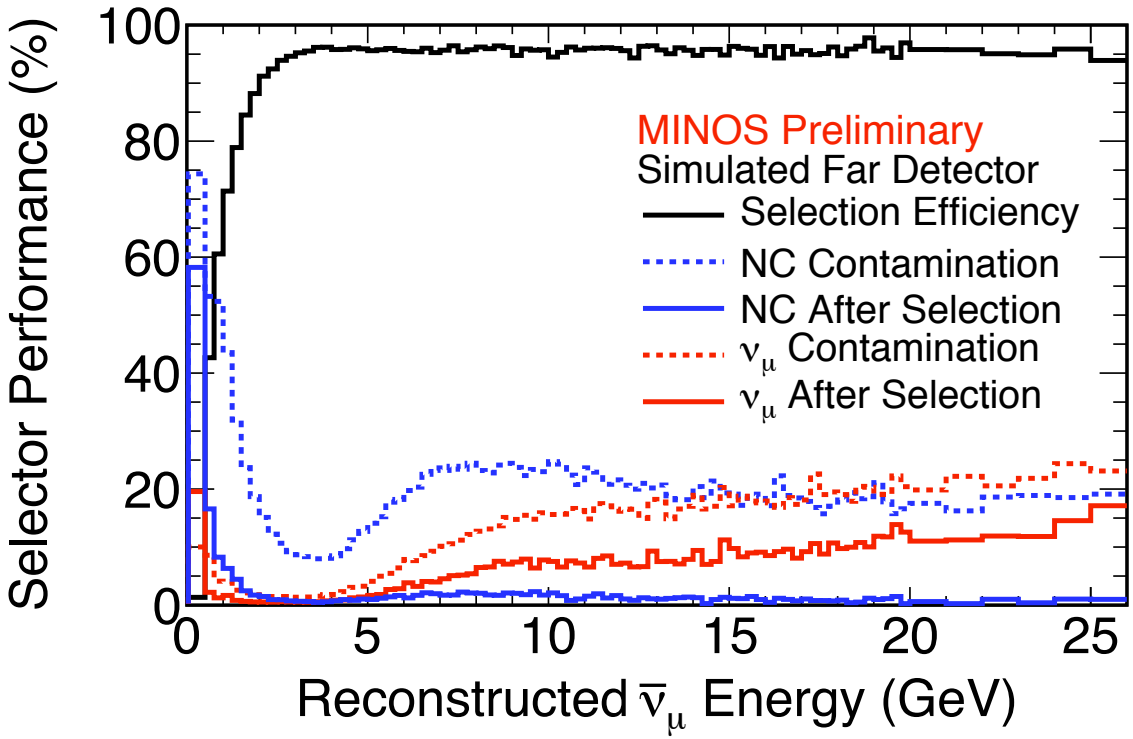
Beam Matrix Extrapolation

- 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



Far Detector Selection

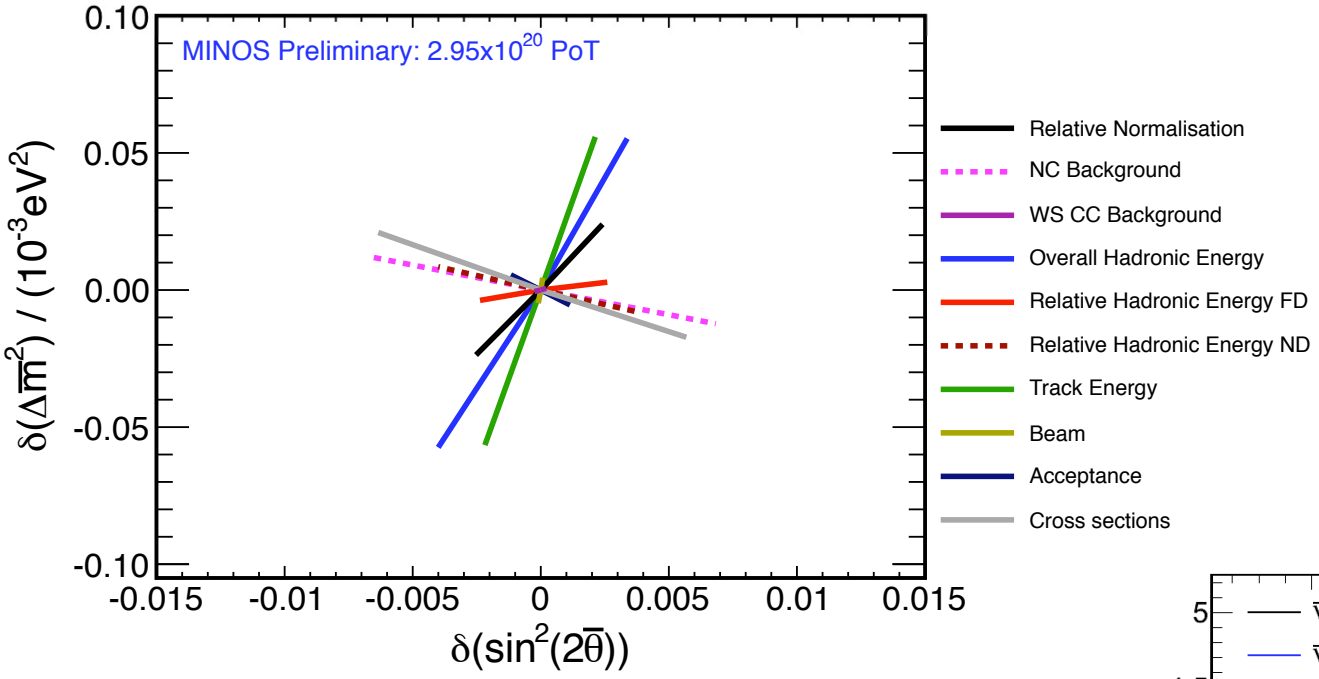
- Antineutrinos in the Far Detector are selected in the same way as in the Near Detector, but no coil cut is applied



	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 94% sample purity
- Contamination at higher antineutrino energies does not affect oscillation measurement

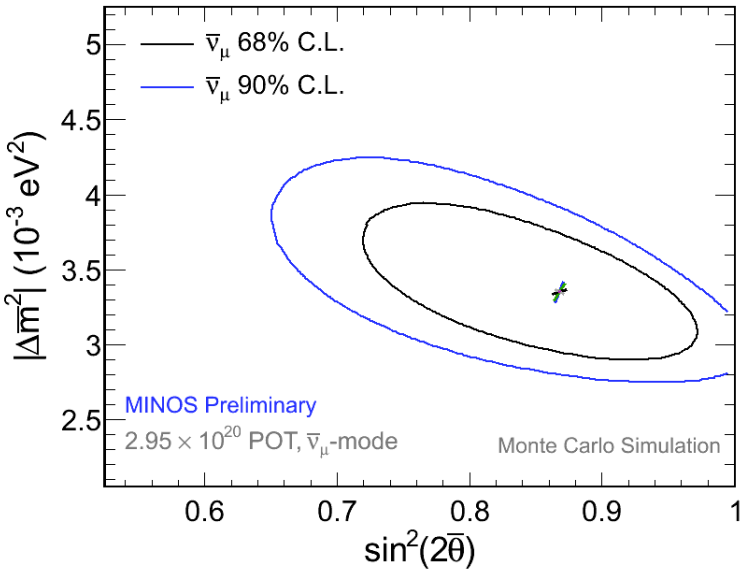
Systematic Uncertainties



- 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

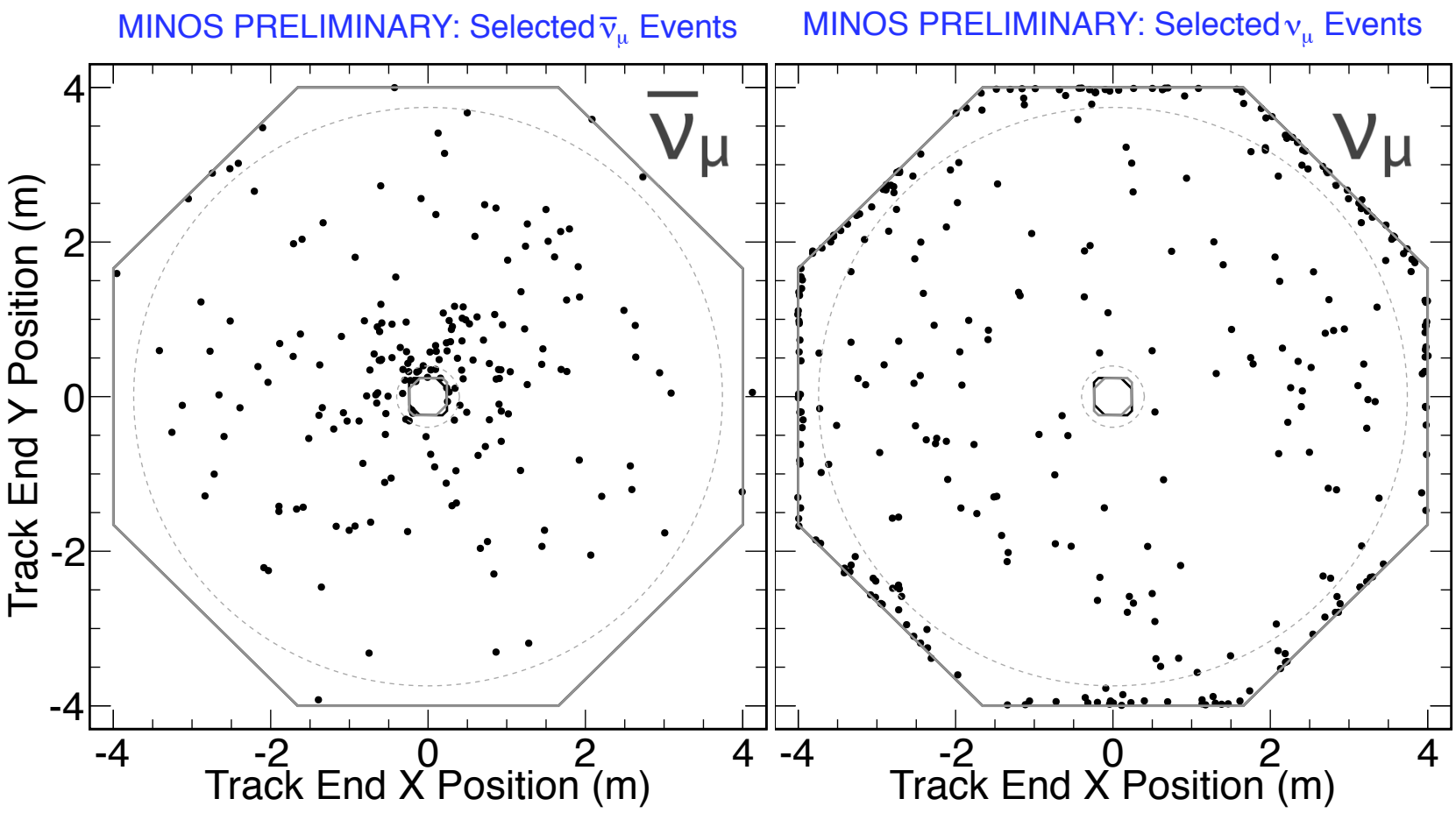




Analysis Results

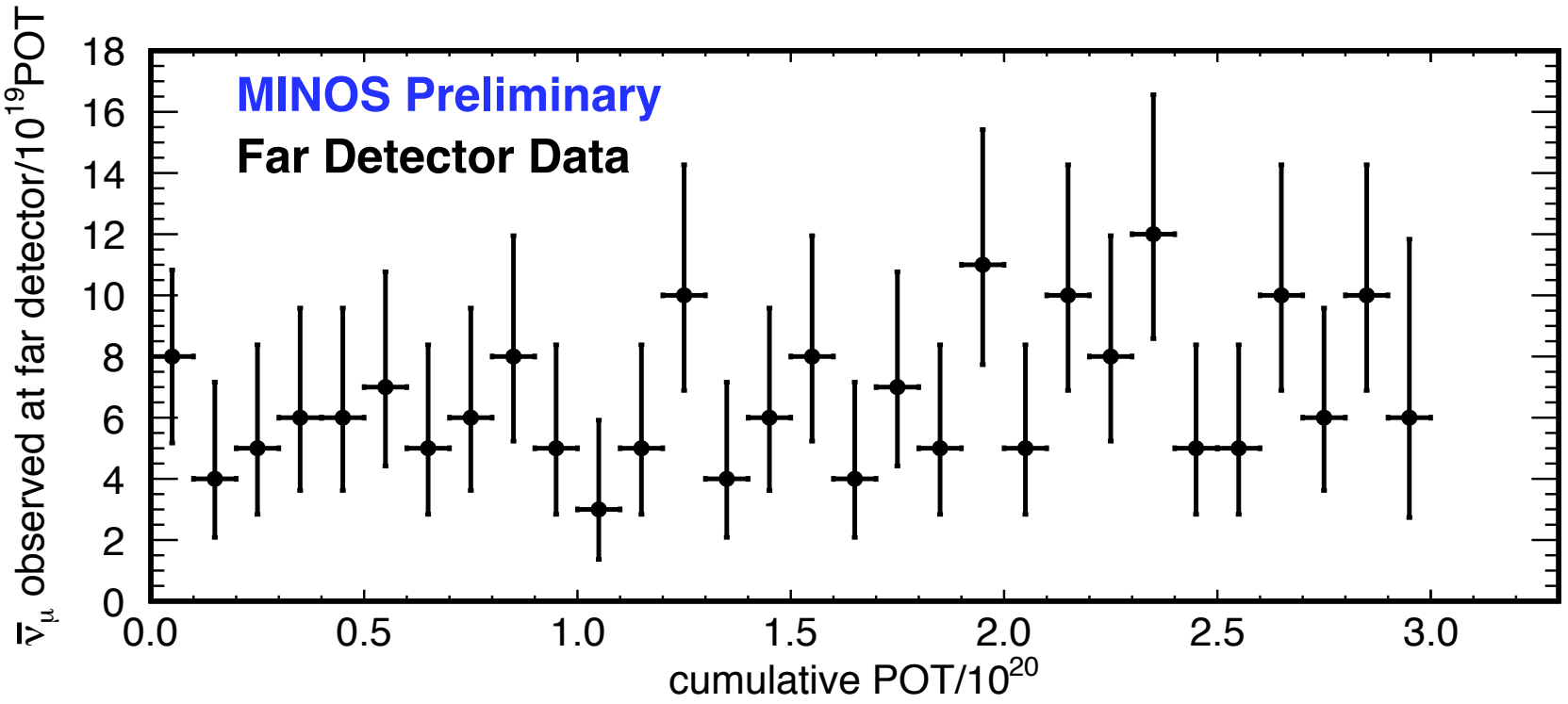
Far Detector Data Checks

- Track end positions in Far Detector show antineutrinos are focused towards the magnetic coil, while neutrinos are defocused outwards



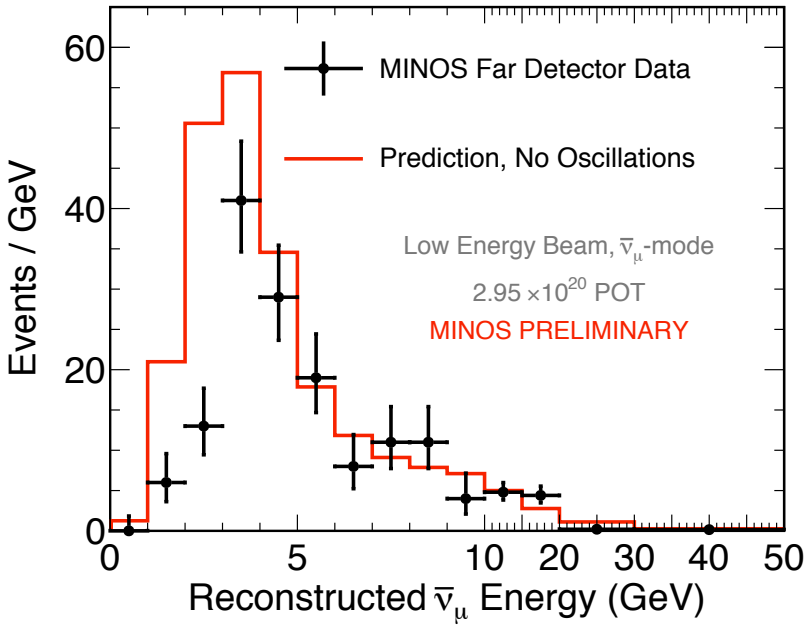
Far Detector Data Rates

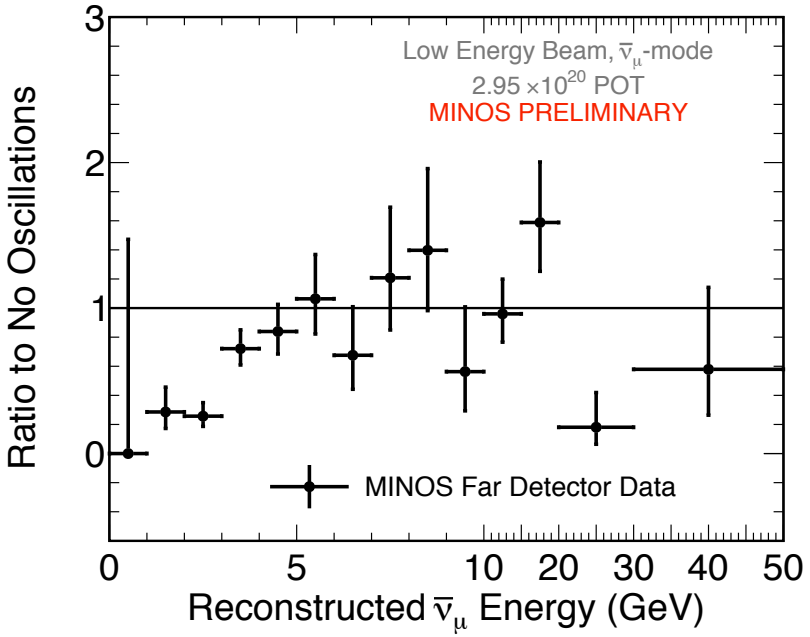
- $\bar{\nu}_\mu$ event selection rate in the Far Detector as a function of accumulated POT



- Accounting for statistical uncertainties, event rates in Run IV and Run VII are consistent

Far Detector Energy Spectrum



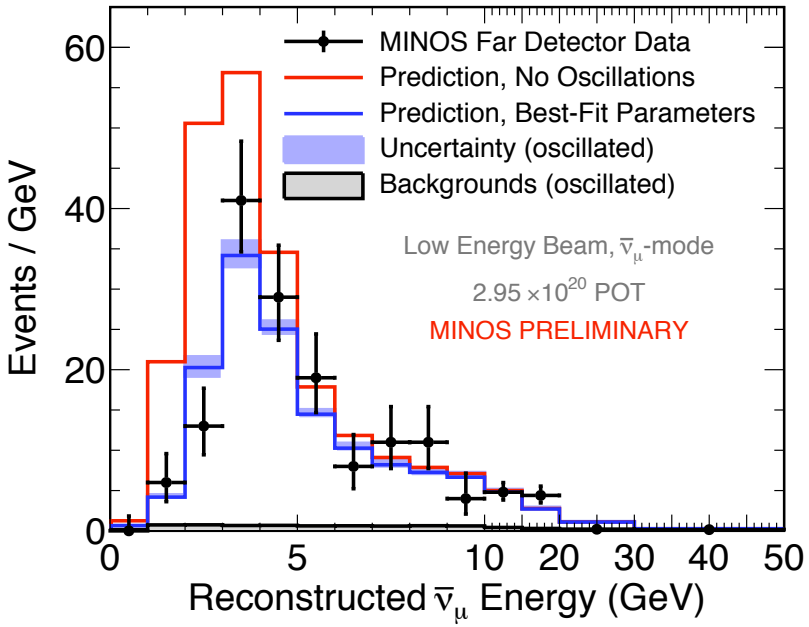


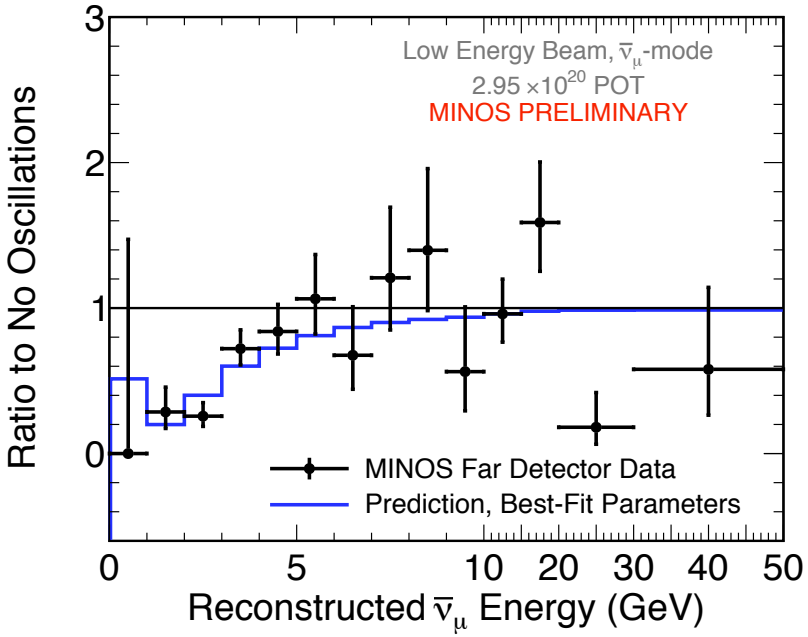
Prediction, No Oscillations: **273 events**

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**

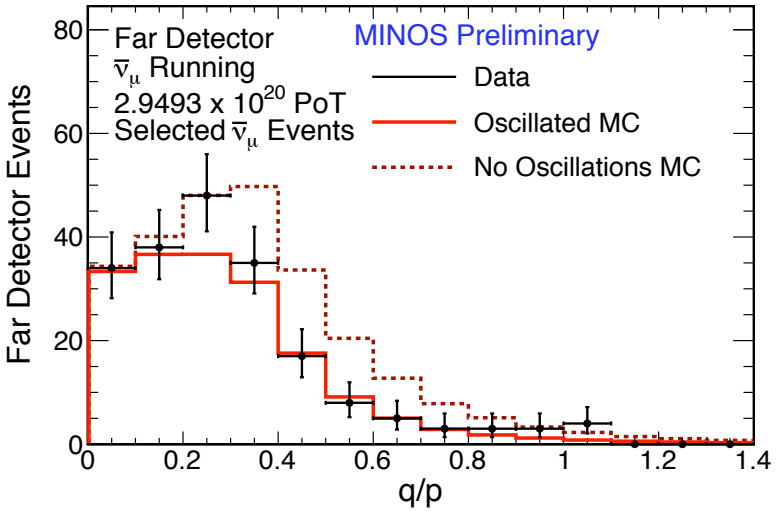
$\bar{\nu}_\mu$ Oscillations Best Fit Parameters

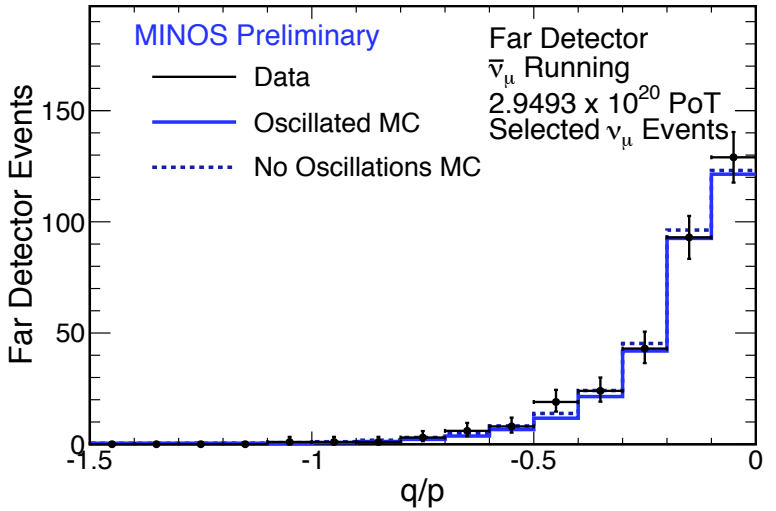
$$|\Delta\bar{m}^2_{\rm atm}| = \left[2.62^{+0.31}_{-0.28}({\rm stat}) \pm 0.09({\rm syst})\right] \times 10^{-3}{\rm eV}^2$$

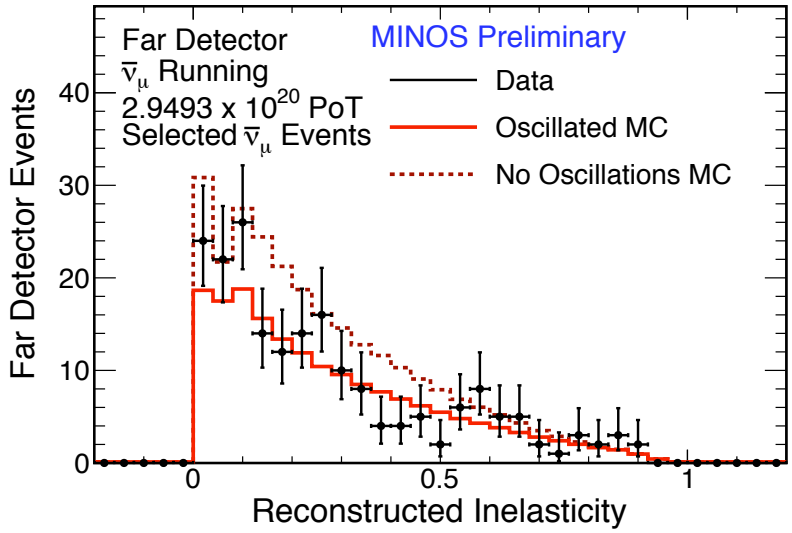
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}({\rm stat}) \pm 0.01({\rm syst})$$

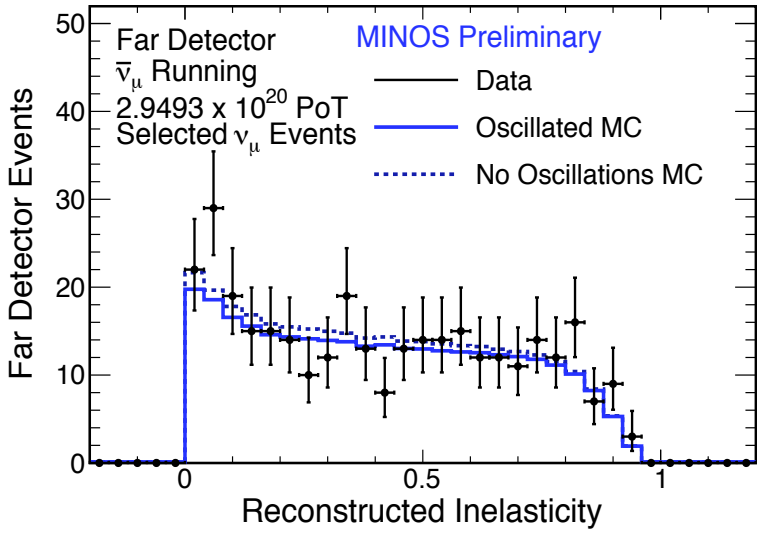
Far Detector Data Checks

- Good data/MC agreement in charge/momentum and inelasticity distributions



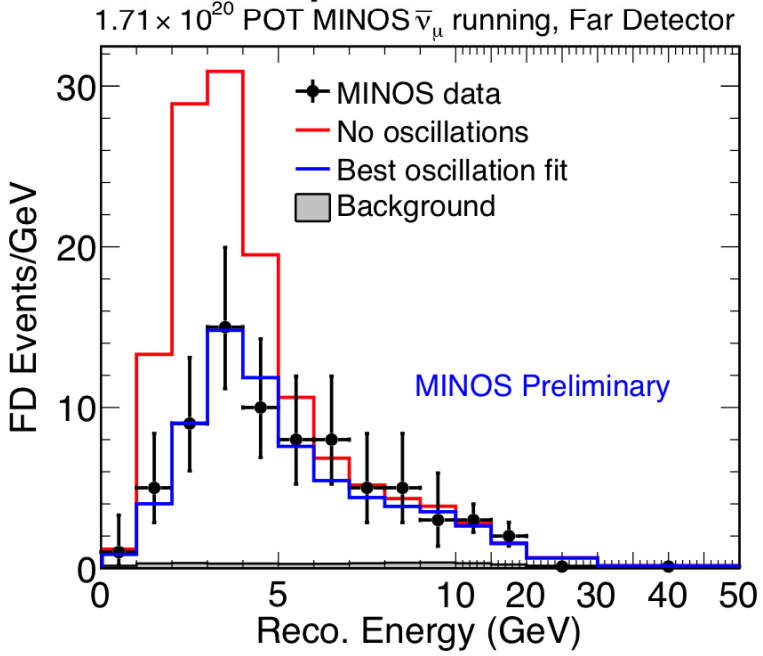






Comparison with Run IV

2010 Analysis, 1.71x10^{20} POT



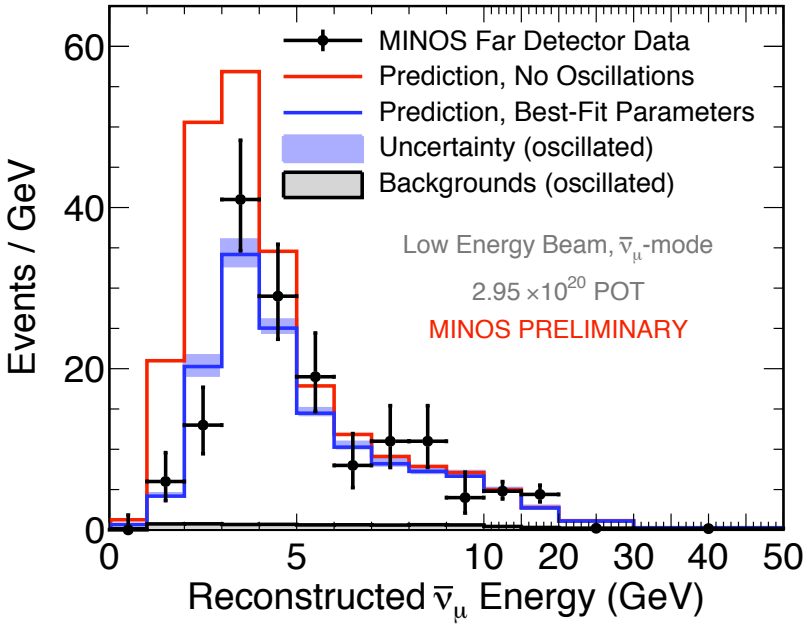
Prediction, No Oscillations: **155 events**

Observed: **97 events**

Null-oscillations excluded at **6.3σ**

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

2011 Analysis, 2.95x10^{20} POT



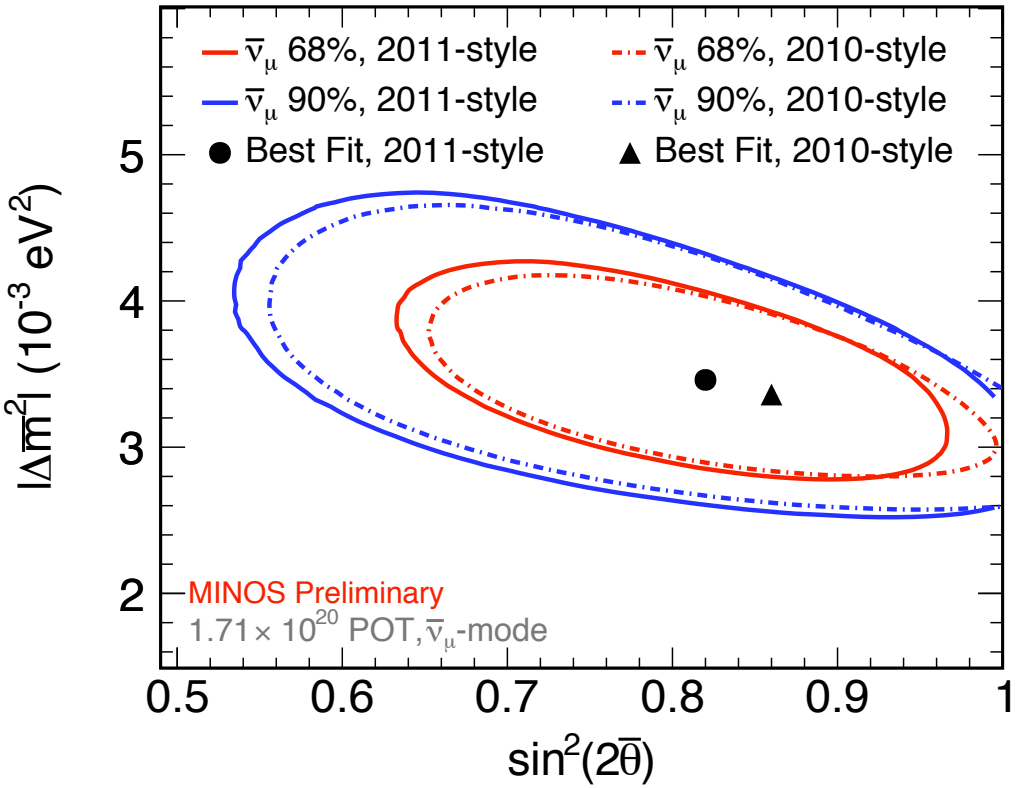
Prediction, No Oscillations: **273 events**

Observed: **193 events**

Null-oscillations excluded at **7.3σ**

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

Run IV-Only Contours 2011 vs. 2010



2010 Analysis, 1.71x10^{20} POT

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

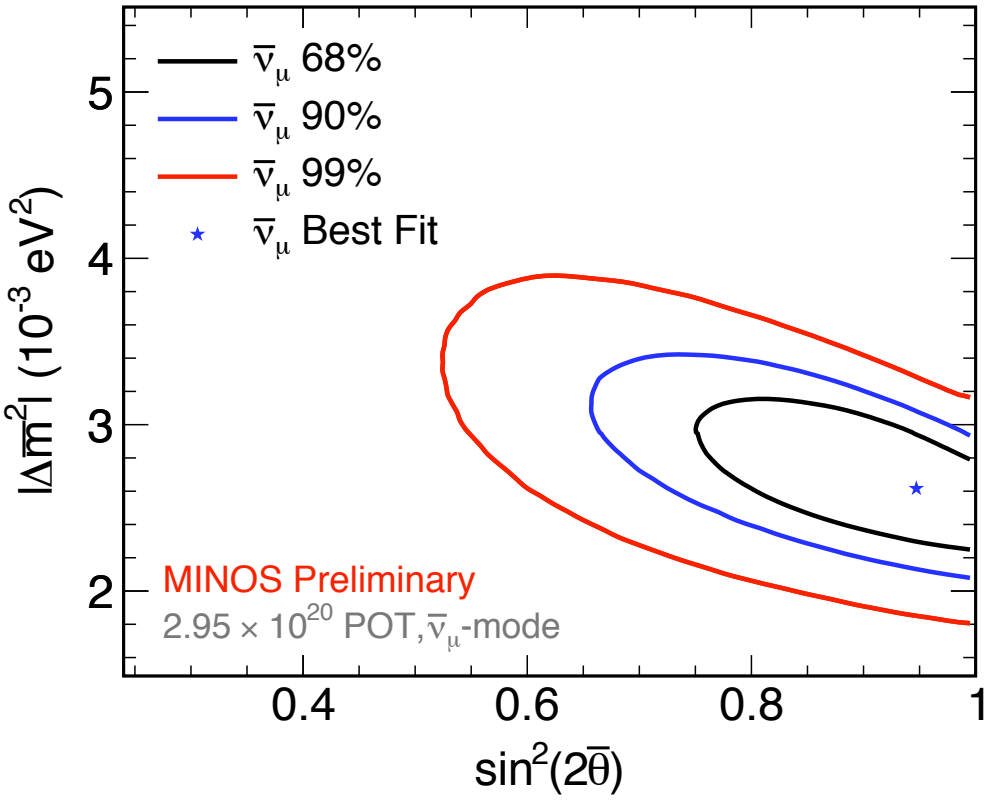
2011 Analysis, 1.71x10^{20} POT

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

Run IV+Run VII Allowed Regions

$$|\Delta\bar{m}^2_{\rm atm}| = \left[2.62^{+0.31}_{-0.28}({\rm stat}) \pm 0.09({\rm syst})\right] \times 10^{-3}{\rm eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}({\rm stat}) \pm 0.01({\rm syst})$$

- Contours are Feldman-Cousins corrected
  - Systematics included



Contour Comparisons



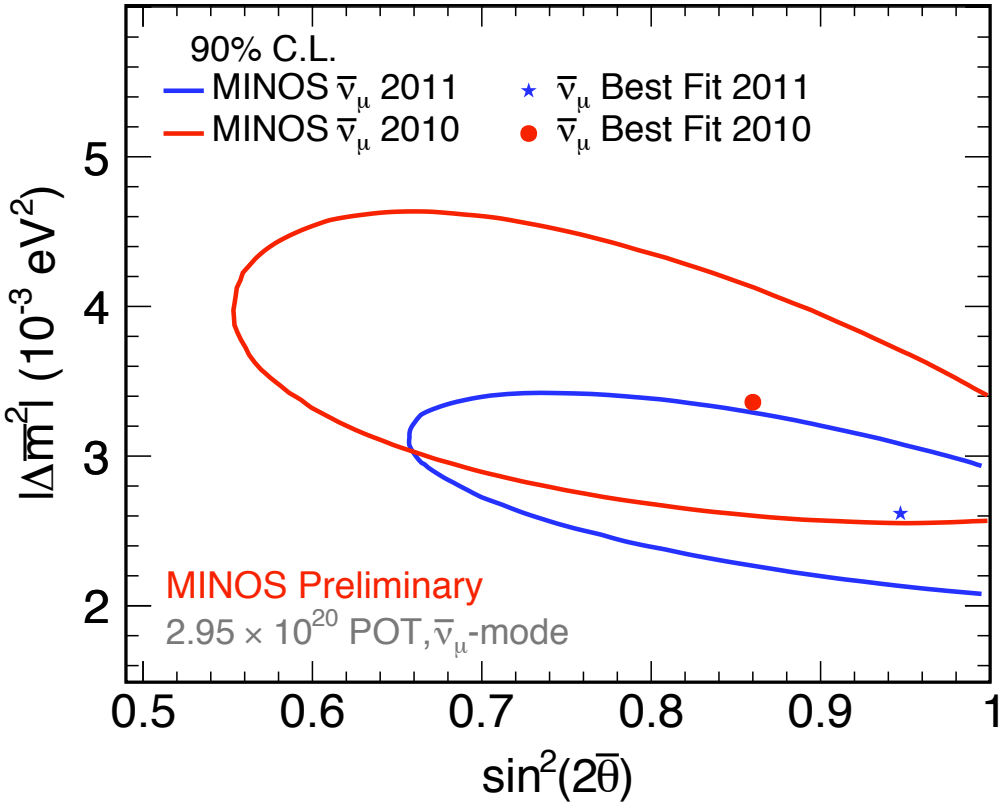
Run IV + Run VII

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

Run IV Only - 2010 Analysis

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

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



Contour Comparisons



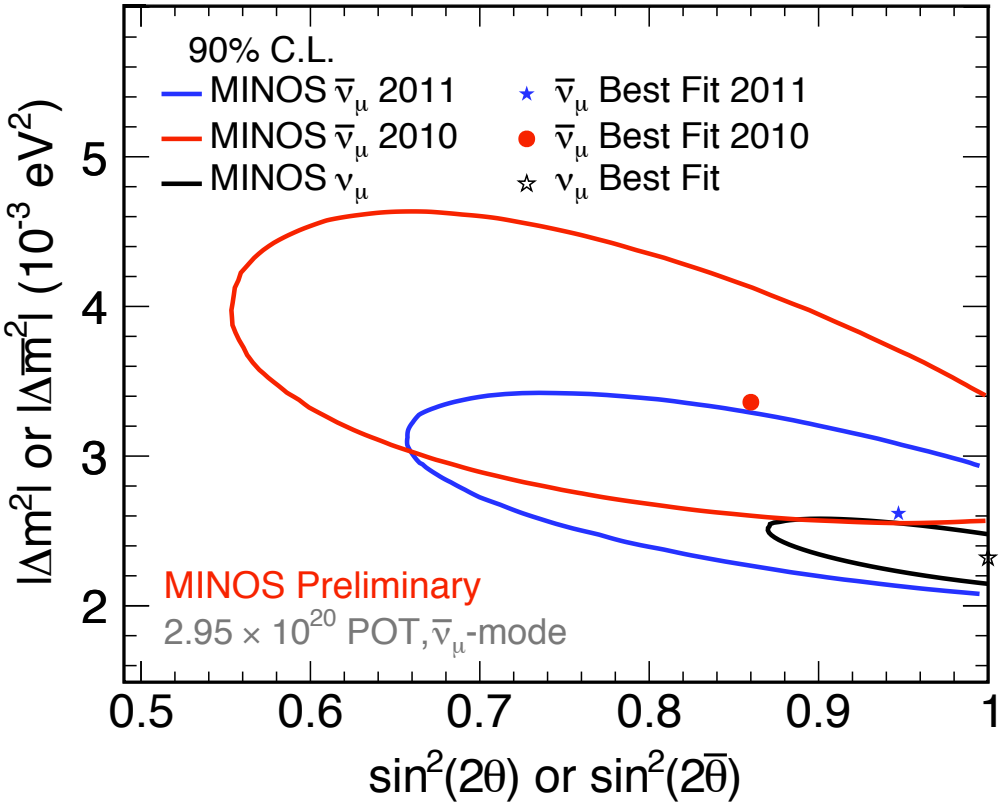
Antineutrinos

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

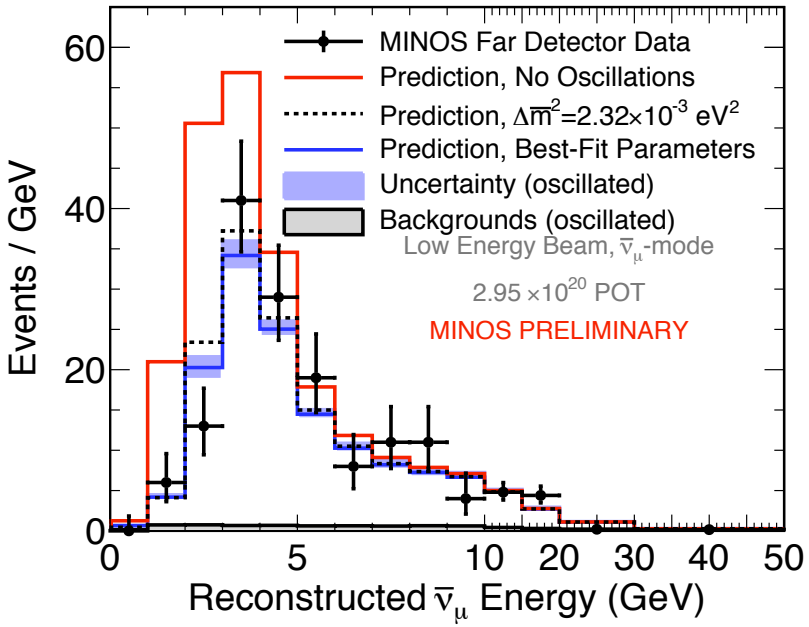
Neutrinos

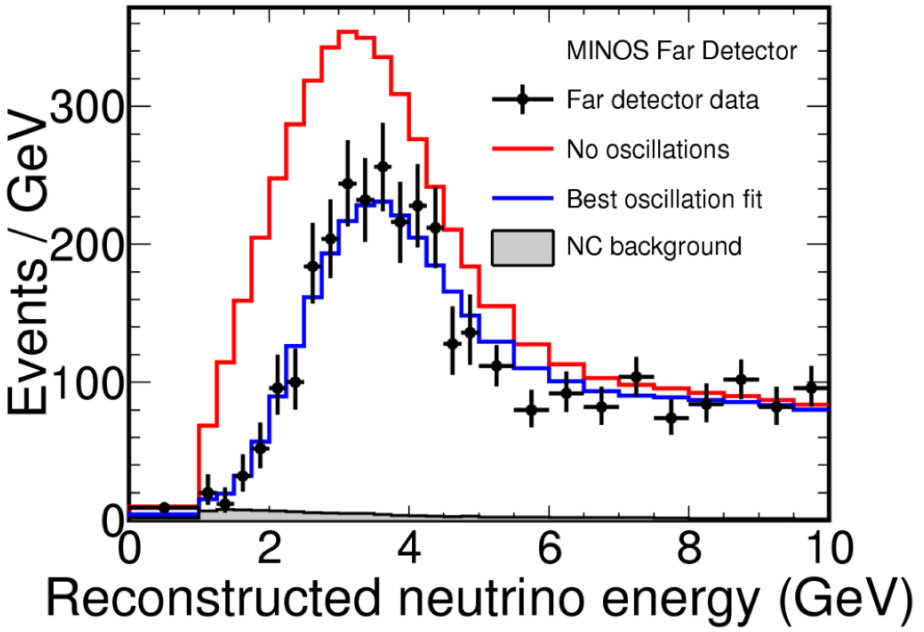
$$|\Delta m^2_{\rm atm}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}{\rm eV}^2$$
$$\sin^2(2\theta_{23}) > 0.90 \ (90\%\ {\rm C.L.})$$

- 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

$$|\Delta\overline{m}^2_{\rm atm}| = 2.62^{+0.31}_{-0.28}\times10^{-3}{\rm eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) > 0.75\ (90\%\ {\rm C.L.})$$

ν_μ Oscillation Best Fit Parameters

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

- 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)

Comparison with Run IV, VII



Run IV Only - 2011 Analysis

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

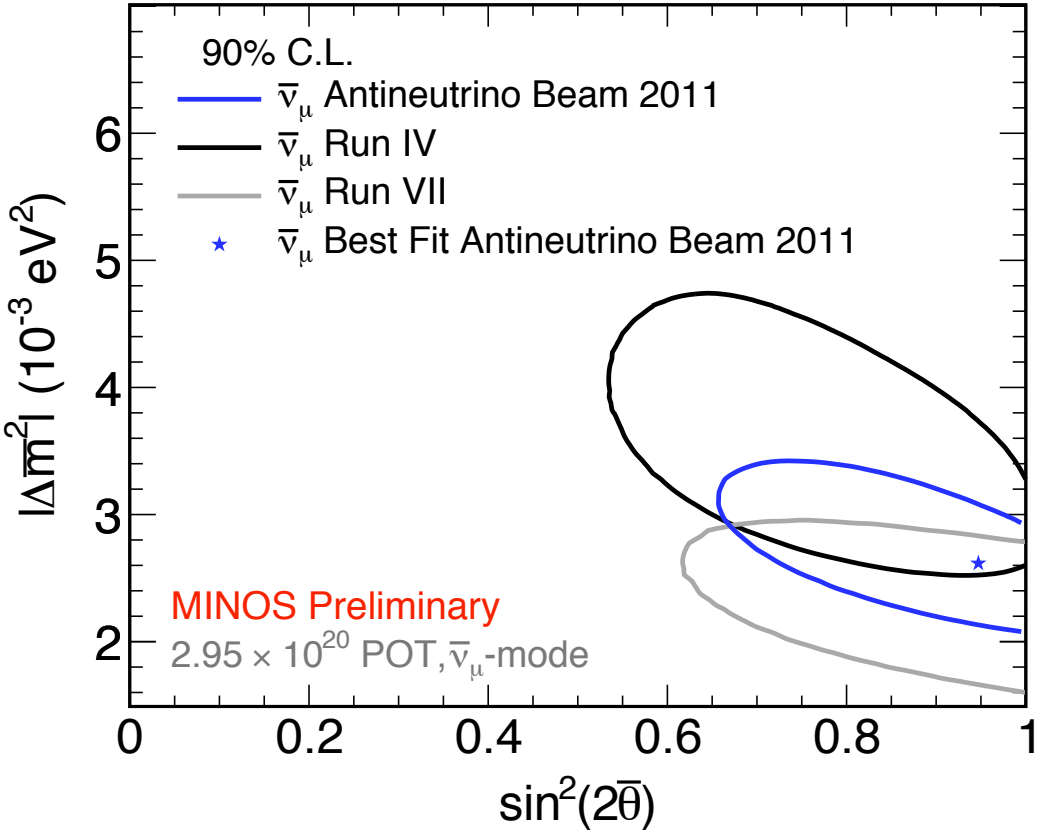
Run VII Only - 2011 Analysis

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

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

Run IV+Run VII

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



Contour Comparisons

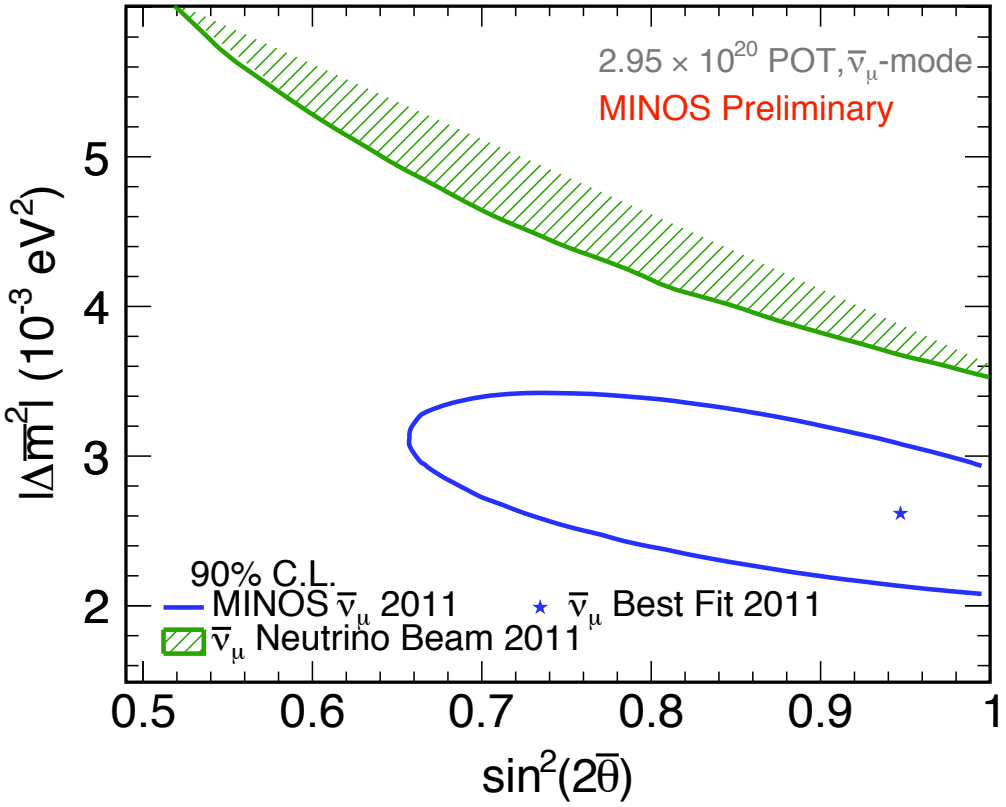
Antineutrinos

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

Antineutrinos in Neutrino Running

$$|\Delta\overline{m}^2_{\rm atm}| < 3.37 \times 10^{-3}{\rm eV}^2 \ (90\%\ {\rm C.L.})$$
$$\text{if } \sin^2(2\bar{\theta}_{23}) = 1.0$$

- Comparison with MINOS 90% C.L. exclusion from selecting antineutrinos in neutrino running

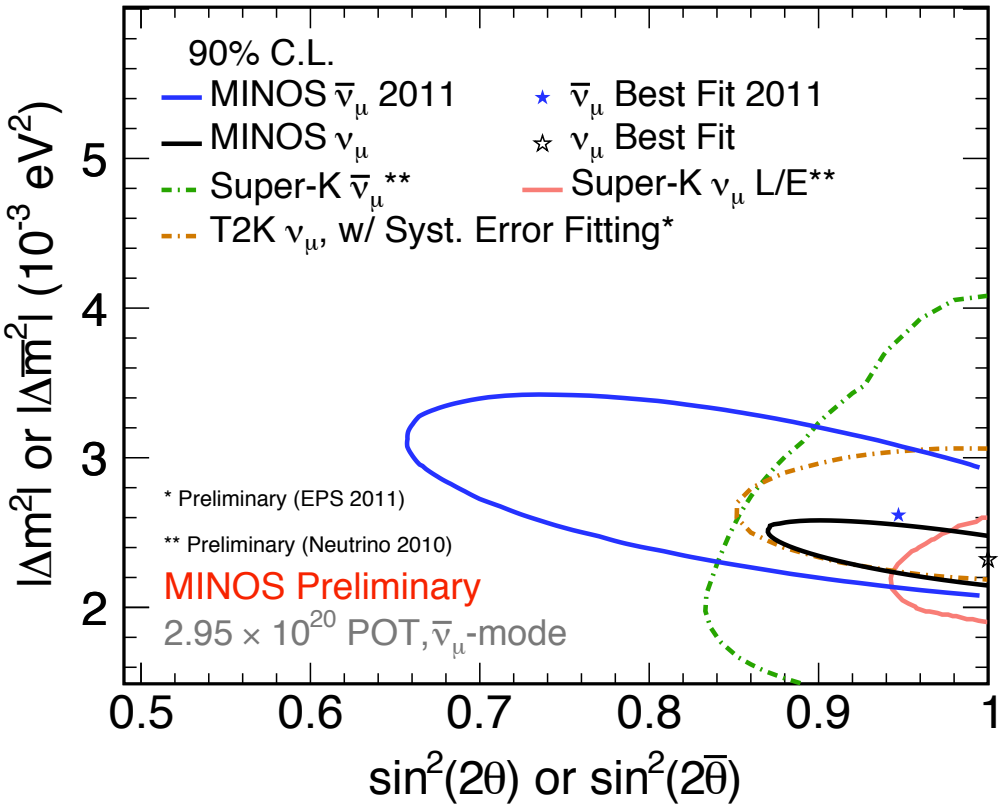


Contour Comparisons

$$|\Delta\bar{m}^2_{\rm atm}| = \left[2.62^{+0.31}_{-0.28}({\rm stat}) \pm 0.09({\rm syst})\right] \times 10^{-3}{\rm eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}({\rm stat}) \pm 0.01({\rm syst})$$

- Comparison with MINOS 90% C.L. contour for neutrino mode
- Comparison with T2K ν_μ and Super-K ν_μ, $\bar{\nu}_\mu$ results

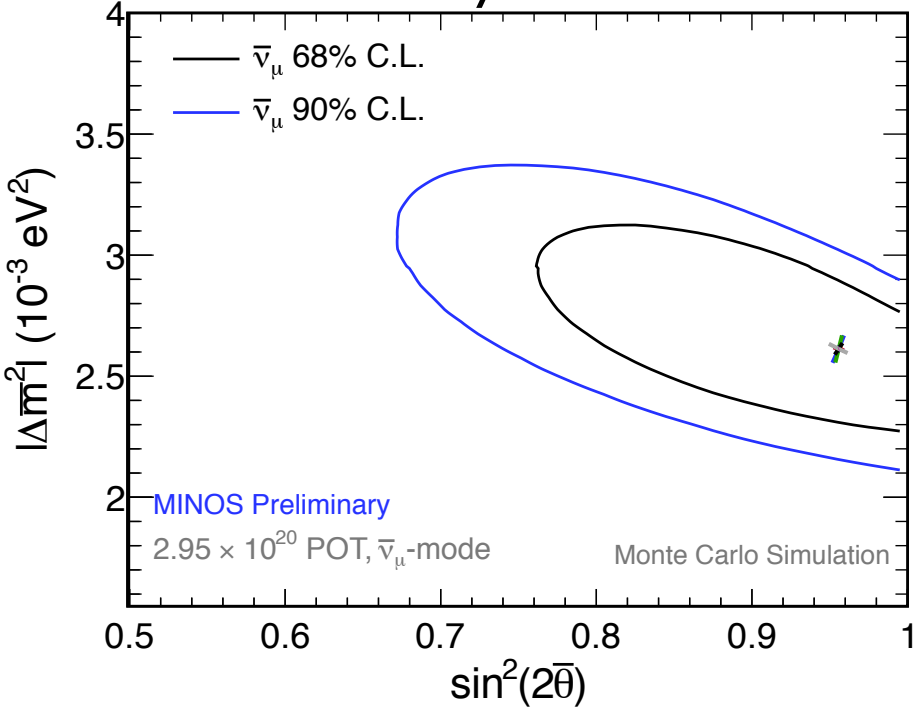
World's most precise measurement of $|\Delta\bar{m}^2_{\rm atm}|$!



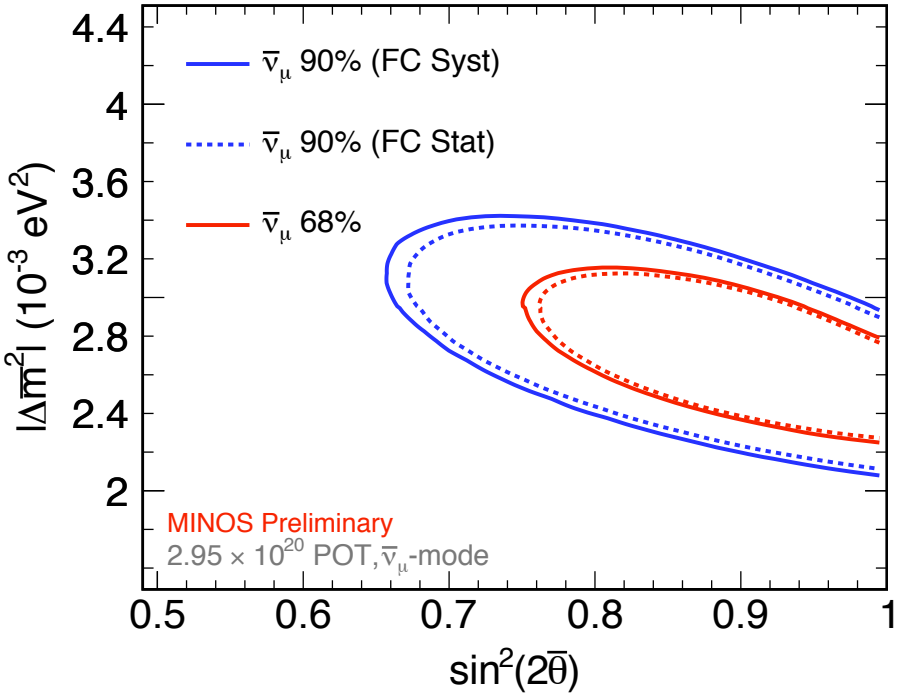
Effect of Systematics

$$|\Delta\bar{m}^2_{\rm atm}| = \left[2.62^{+0.31}_{-0.28}({\rm stat}) \pm 0.09({\rm syst})\right] \times 10^{-3}{\rm eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}({\rm stat}) \pm 0.01({\rm syst})$$

Stat. sensitivity at new best fit



Contours from fit to data



- Measurement is statistically-limited

Future Sensitivities

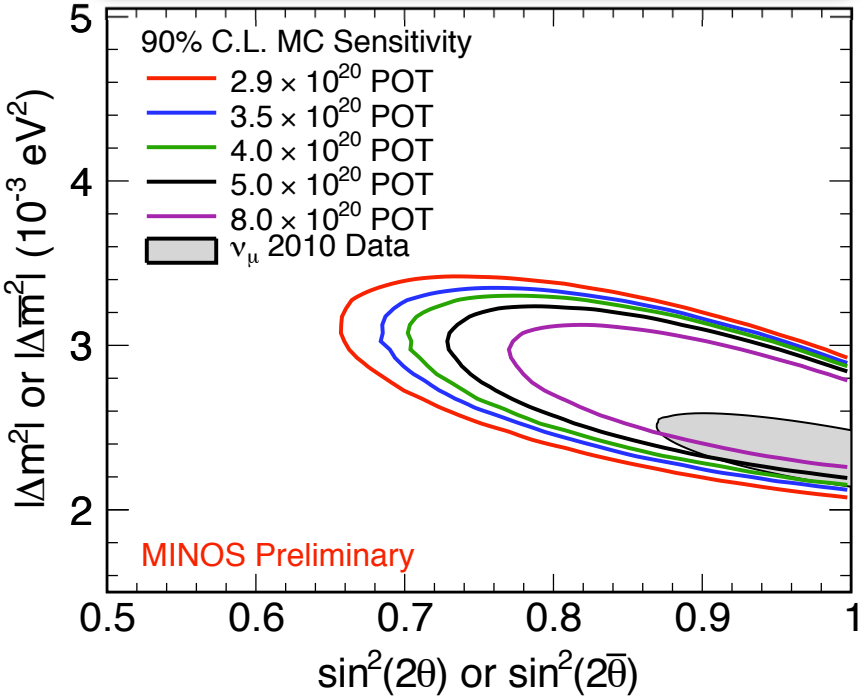
- Sensitivities for current and further antineutrino running assuming:

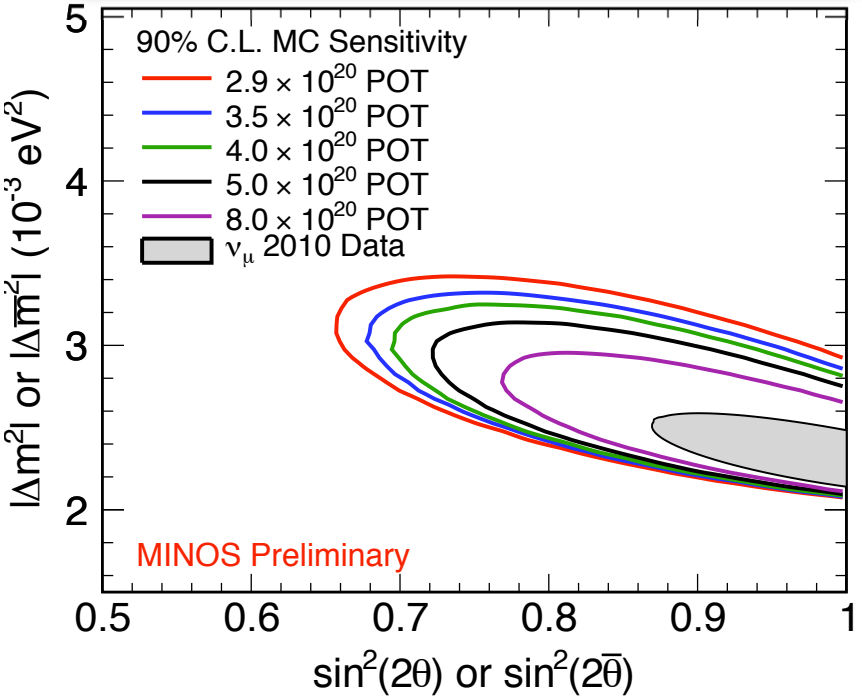
Antineutrino best fit parameters

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

Neutrino best fit parameters

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





More antineutrino data being collected right now!

Conclusions



- MINOS has completed an analysis of 2.95×10^{20} POT of dedicated antineutrino beam running

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

$$|\Delta\overline{m}^2_{\rm atm}| = \left[2.62^{+0.31}_{-0.28}({\rm stat}) \pm 0.09({\rm syst})\right] \times 10^{-3}{\rm eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}({\rm stat}) \pm 0.01({\rm syst})$$

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

- Further antineutrino running underway. Should provide significant improvements in measurement precision

Thank You!



On behalf of the MINOS Collaboration, I would like to express our gratitude to the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the experiment

We thank the crew at the Soudan Underground Laboratory for their tireless work in keeping the Far Detector running

We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and the Minnesota DNR for hosting us











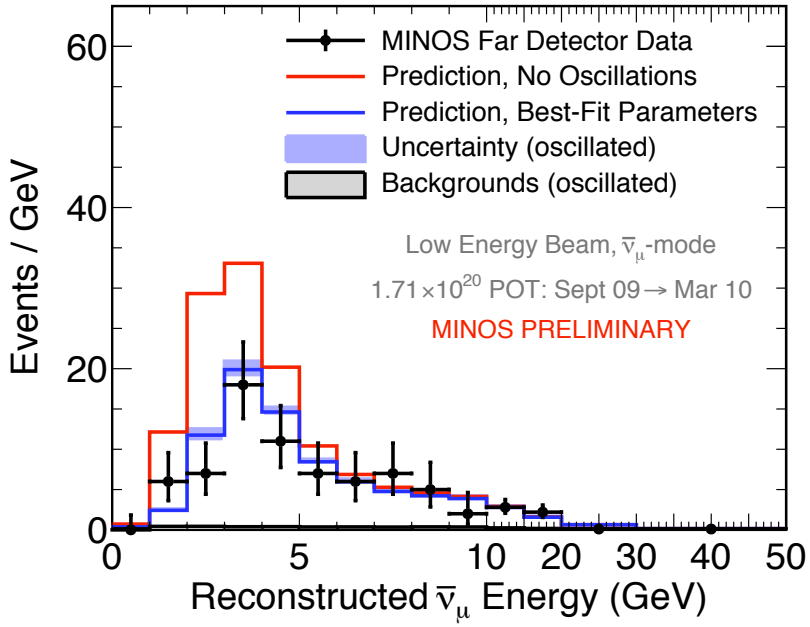




Backup

Comparison with Run IV-2011

2011 Analysis, 1.71×10^{20} POT

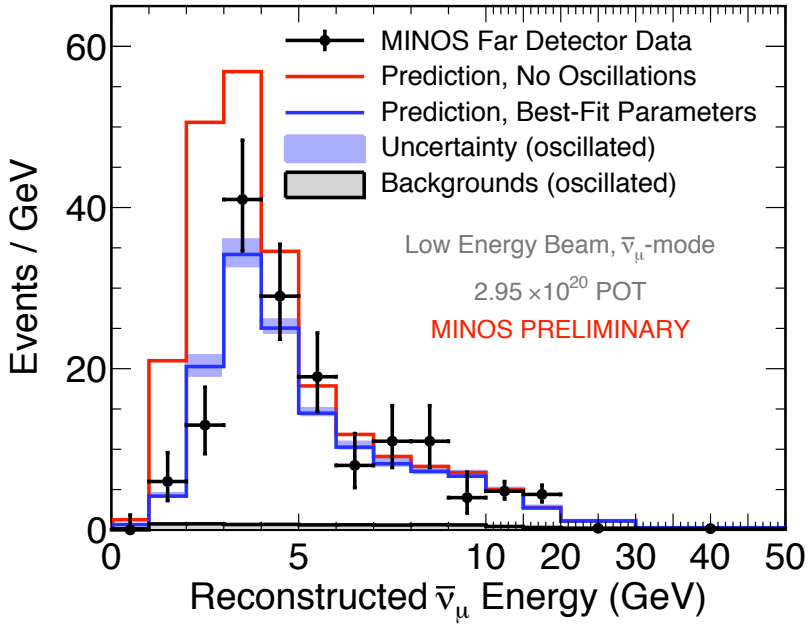


Prediction, No Oscillations: **157 events**

Observed: **97 events**

$$|\Delta\bar{m}^2_{\rm atm}| = 3.46^{+0.47}_{-0.43}\times10^{-3}{\rm eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.82^{+0.10}_{-0.11}$$

2011 Analysis, 2.95×10^{20} POT



Prediction, No Oscillations: **273 events**

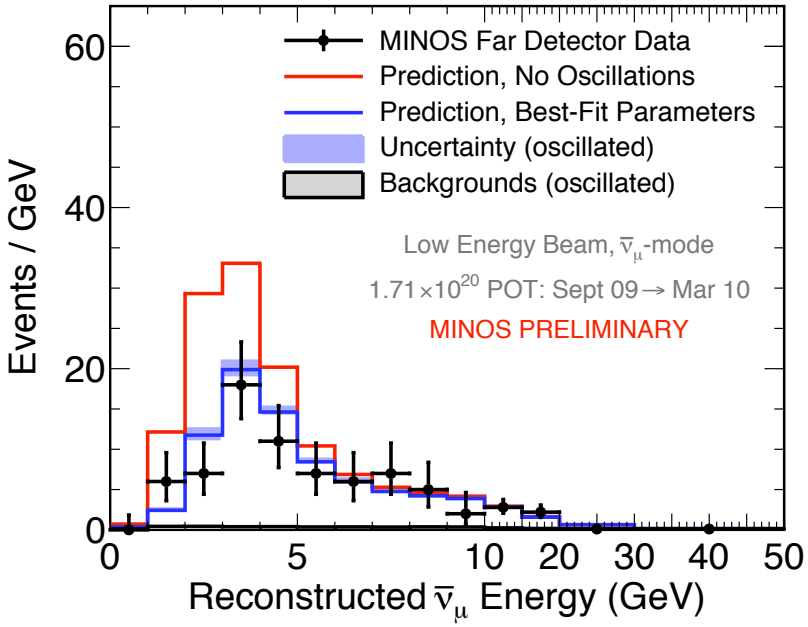
Observed: **193 events**

$$|\Delta\bar{m}^2_{\rm atm}| = 2.62^{+0.31}_{-0.28}\times10^{-3}{\rm eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}$$

Run IV and Run VII



2011 Analysis, 1.71×10^{20} POT

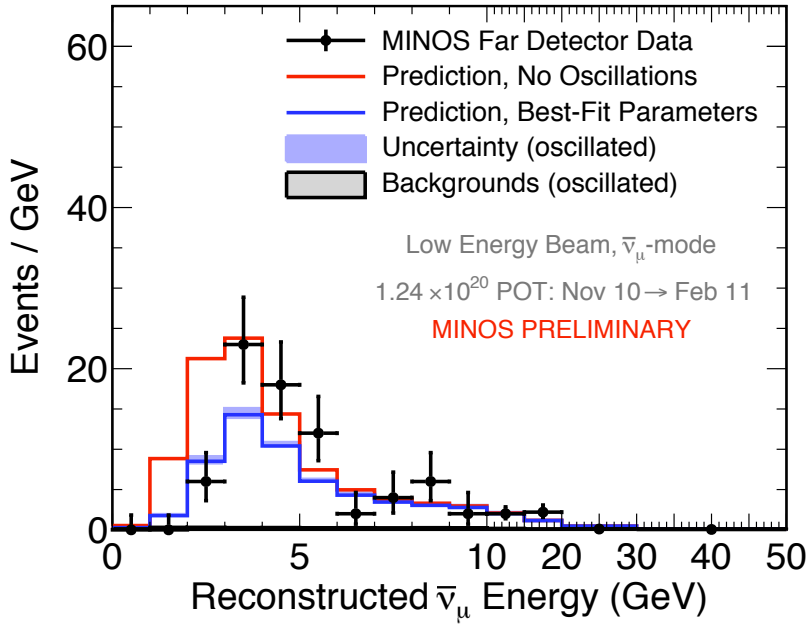


Prediction, No Oscillations: **157 events**

Observed: **97 events**

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

2011 Analysis, 1.24×10^{20} POT

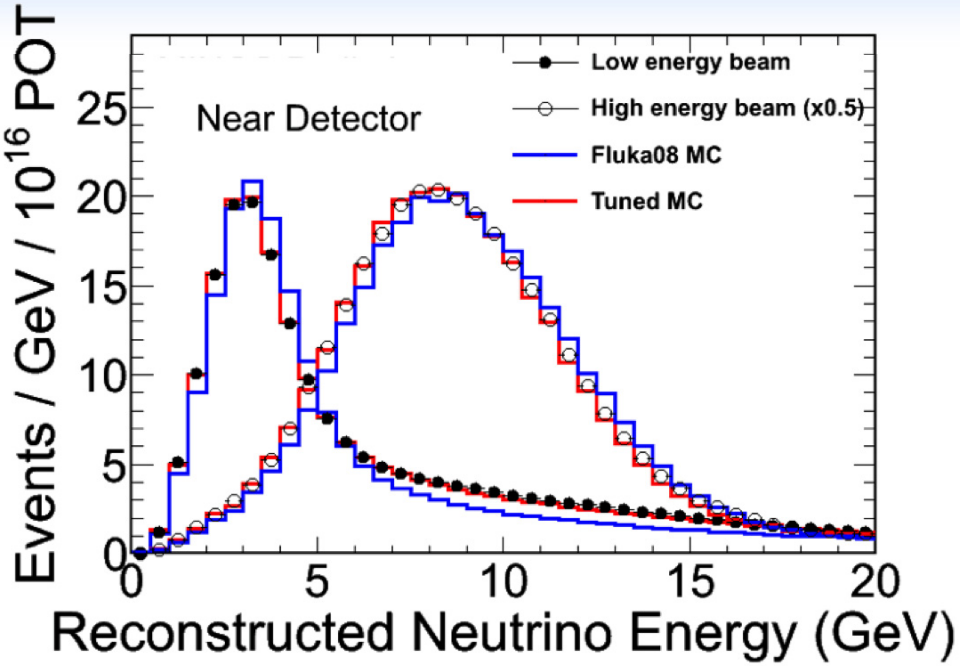


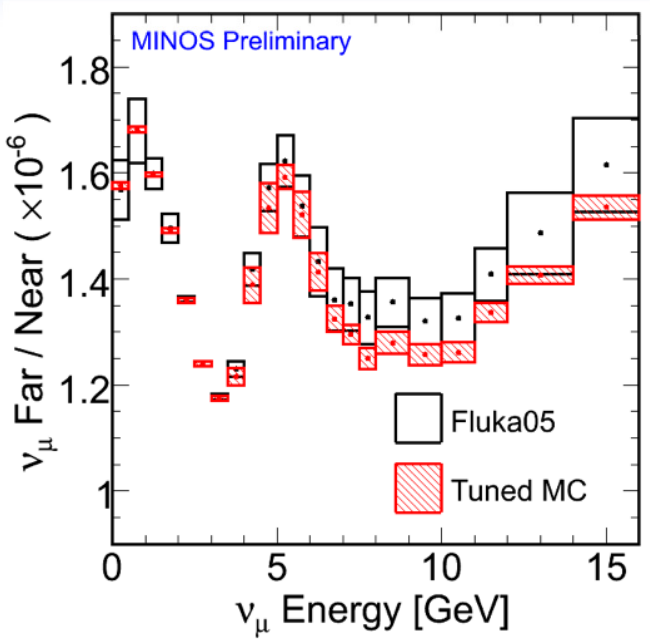
Prediction, No Oscillations: **116 events**

Observed: **96 events**

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

Hadron Production Tuning

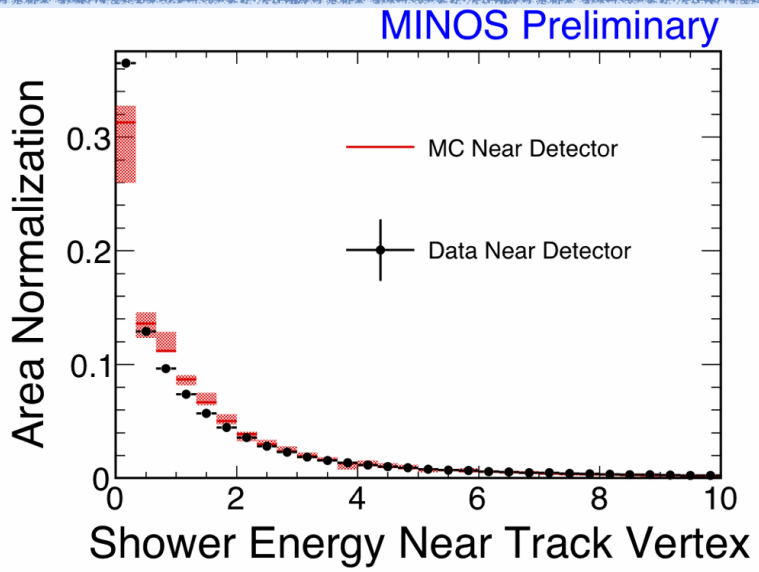


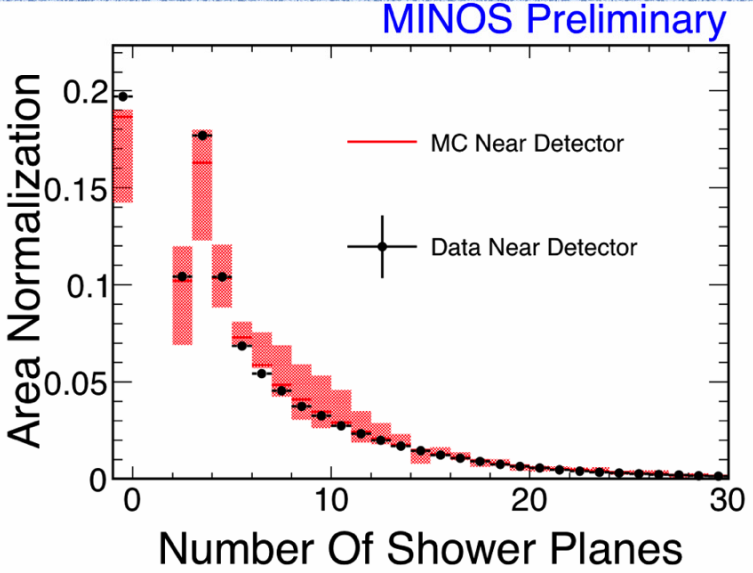


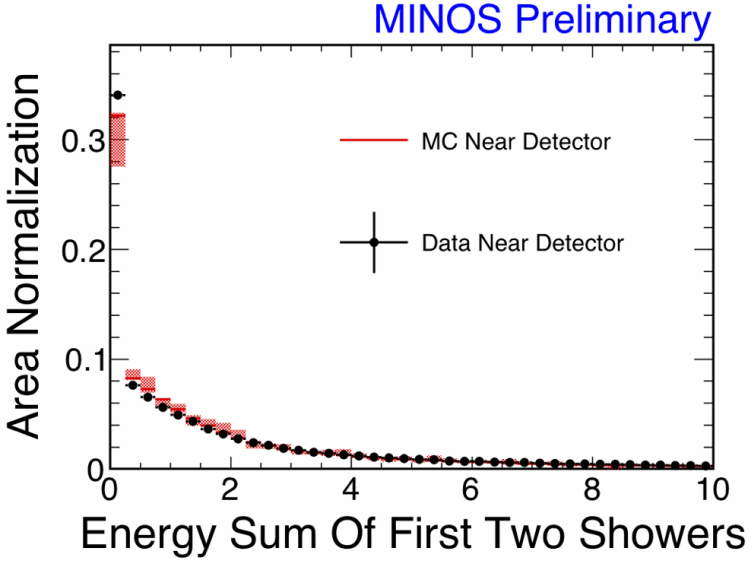
- Hadron production cross-sections reweighted in fit to ND ν_μ energy spectrum from 7 beam configurations
- NA49 data used to constrain π^+/π^- and π/K ratios in fit

Fit improves Far/Near ratio and verifies robustness of Near → Far extrapolation

kNN Shower Energy Input Variables





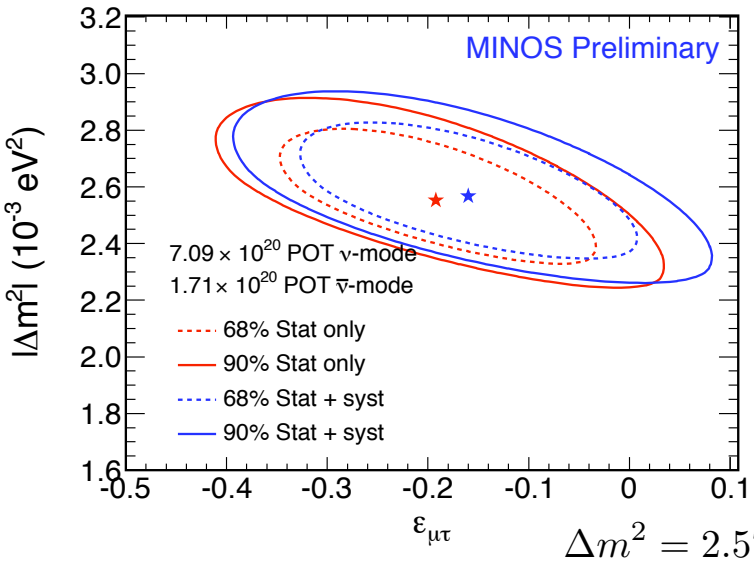


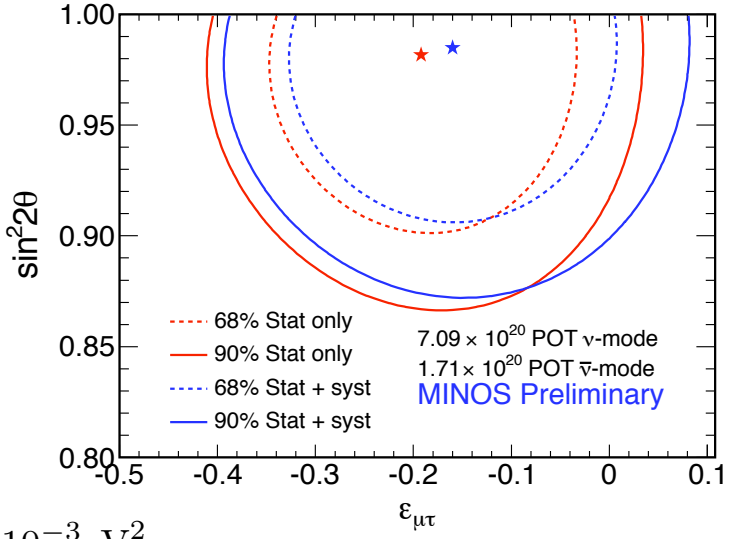
Run IV NSI Results

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

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

- Using neutrino and antineutrino data, MINOS can measure $\varepsilon_{\mu\tau}$
  - $\varepsilon_{\mu\tau}$ switches sign between neutrinos and antineutrinos





$$\Delta m^2 = 2.57 \pm 0.15 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.98 \pm 0.08$$

$$\epsilon_{\mu\tau} = -0.163 \pm 0.16$$