New Results from MINOS

120 scientists
30 institutions

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Goias • Harvard • Holy Cross • IIT • Indiana • Iowa State • Minnesota-Twin Cities
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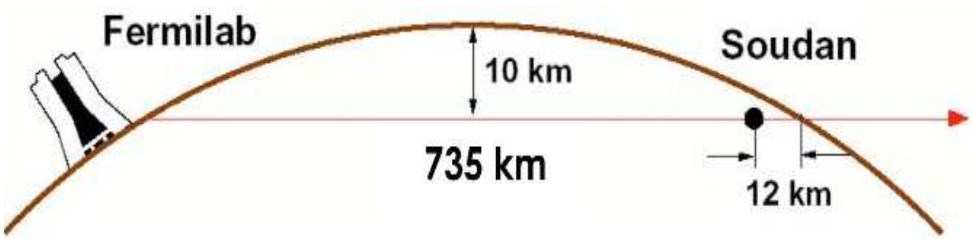
Donna Naples
University of Pittsburgh
for the MINOS Collaboration

12th International Conference on Topics in Astroparticle and Underground Physics
September 7, 2011

MINOS Overview



MINOS (Main Injector Neutrino Oscillation Search)

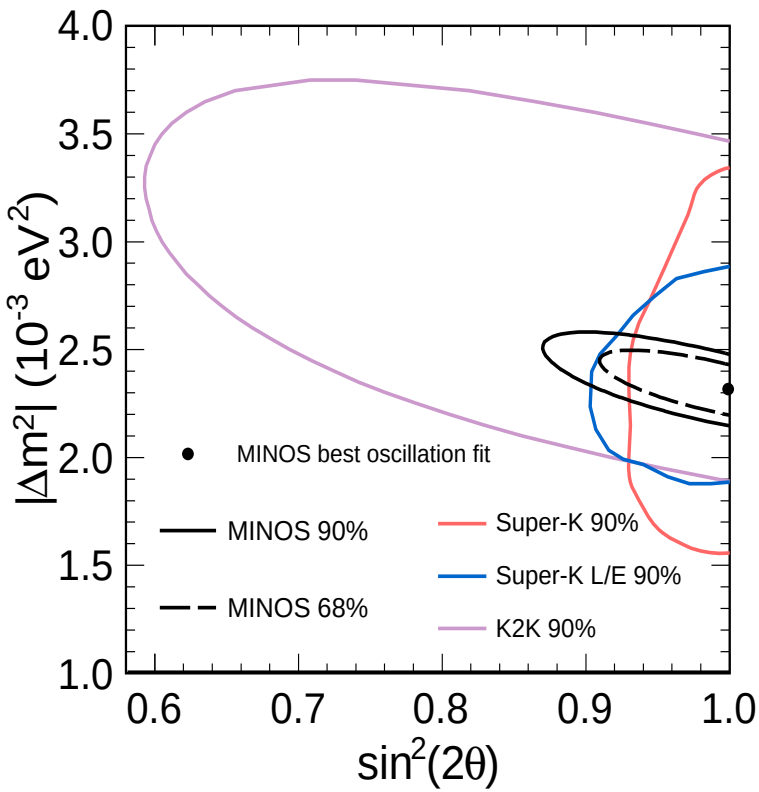
- High intensity NuMI beam produced at Fermilab
- 1kT Near Detector (ND) at Fermilab.
  - *measures unoscillated spectrum.*
- 5.4kT Far detector (FD) at Soudan, MN
  - *measures spectrum at L=735 km*

- Compare Far and Near rates and spectra to measure neutrino oscillations.

MINOS Physics

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

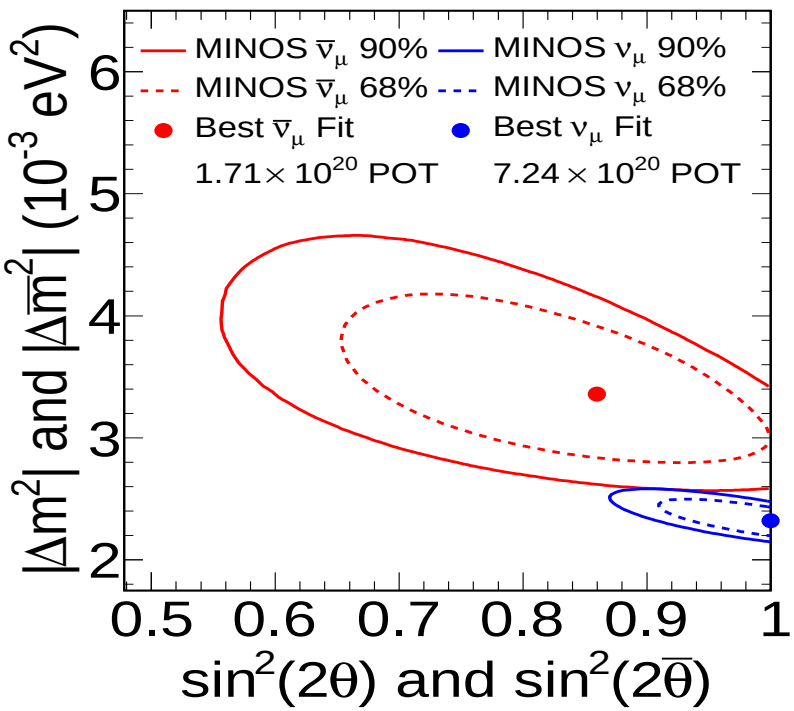
- Measure $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance.



MINOS Physics

- Measure $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance.
- Direct measurement $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance.
  - New result based on ∼70% more data.

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

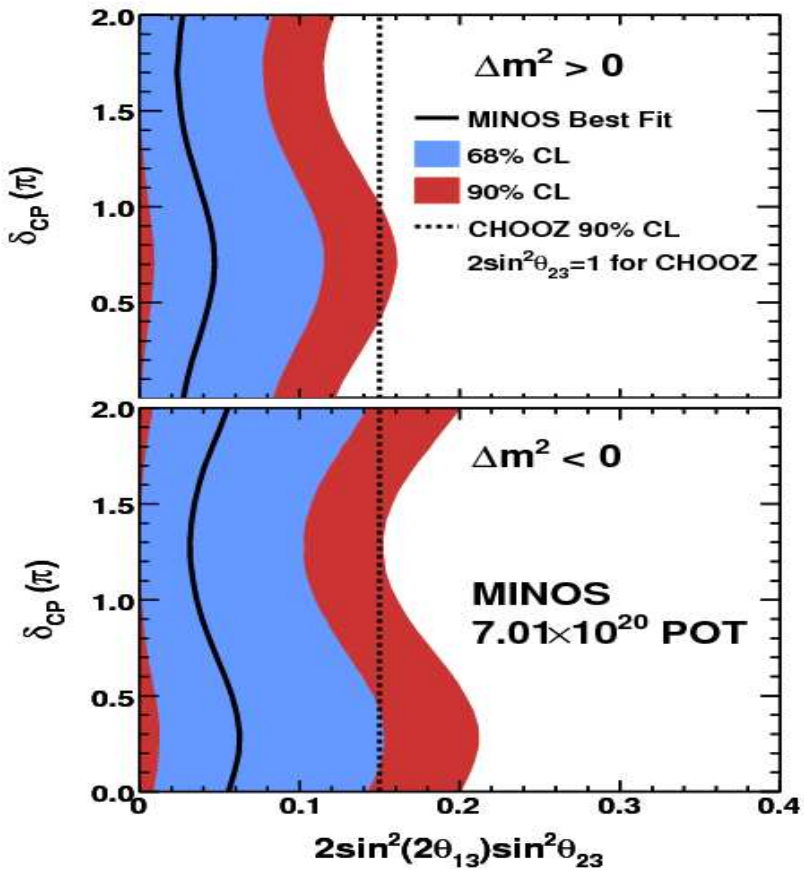


- First result based on 1.71×10^{20} PoT.
- ν_μ and $\overline{\nu}_\mu$ parameters consistent at the 2% level.
  - New Physics ? (NSI, CPT symmetry violation, etc.)

MINOS Physics

- Measure $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance.
- Direct measurement of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance.
  - ▷ New result based on ∼70% more data.
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillation via ν_e appearance.
  - ▷ New result with improved analysis technique and more statistics.

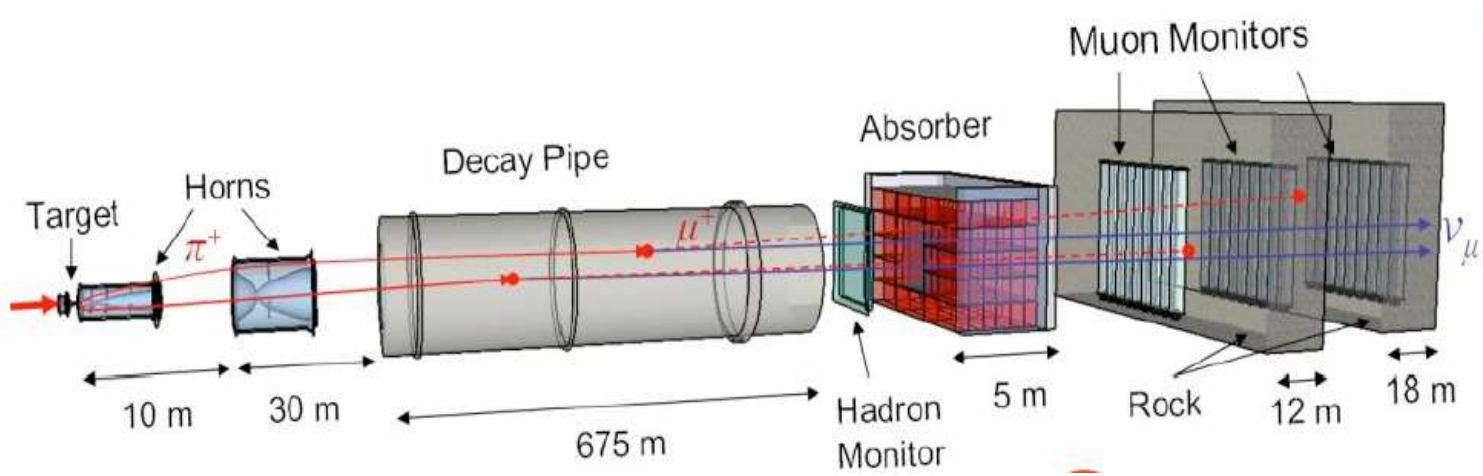
Phys. Rev. D 82, 051102 (2010).

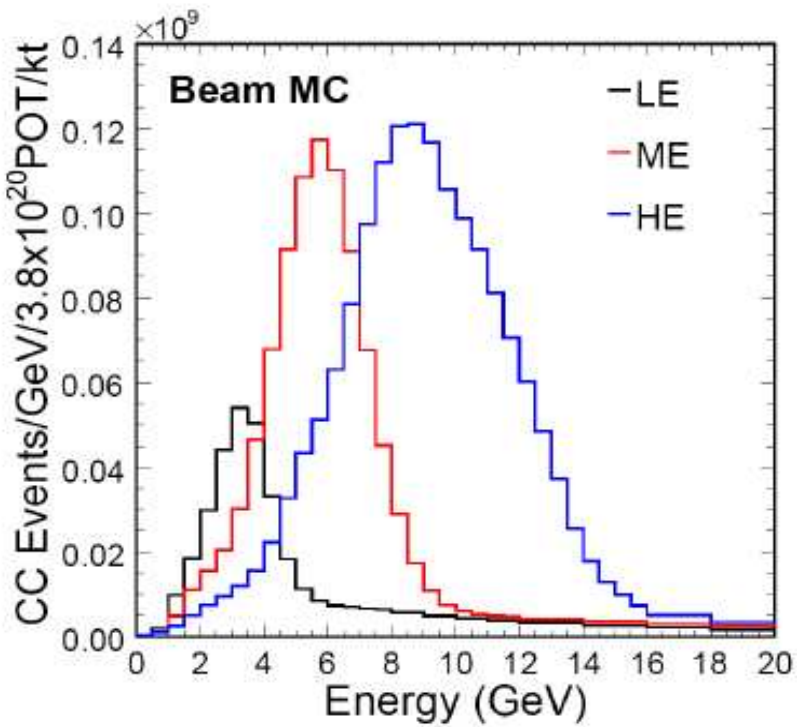


MINOS Physics

- Measure $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance.
- Direct measurement of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance.
  - New result based on $\sim$70% more data.
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillation via ν_e appearance.
  - New result with improved analysis technique and more statistics.
- Searches for sterile neutrinos.
- Atmospheric ν and cosmic ray physics
- ν and $\overline{\nu}$ interaction cross sections.

NuMI Beam at Fermilab



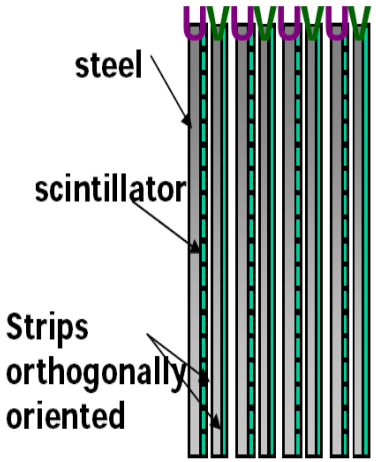


- Movable target allows tunable beam energy (peak energies 3-10 GeV)
  - Most of MINOS data taken in Low Energy (LE) mode.
  - Other modes used to tune particle production model.
- Run in Reverse Horn Current (RHC) mode to produce a beam with a large fraction of muon antineutrinos.

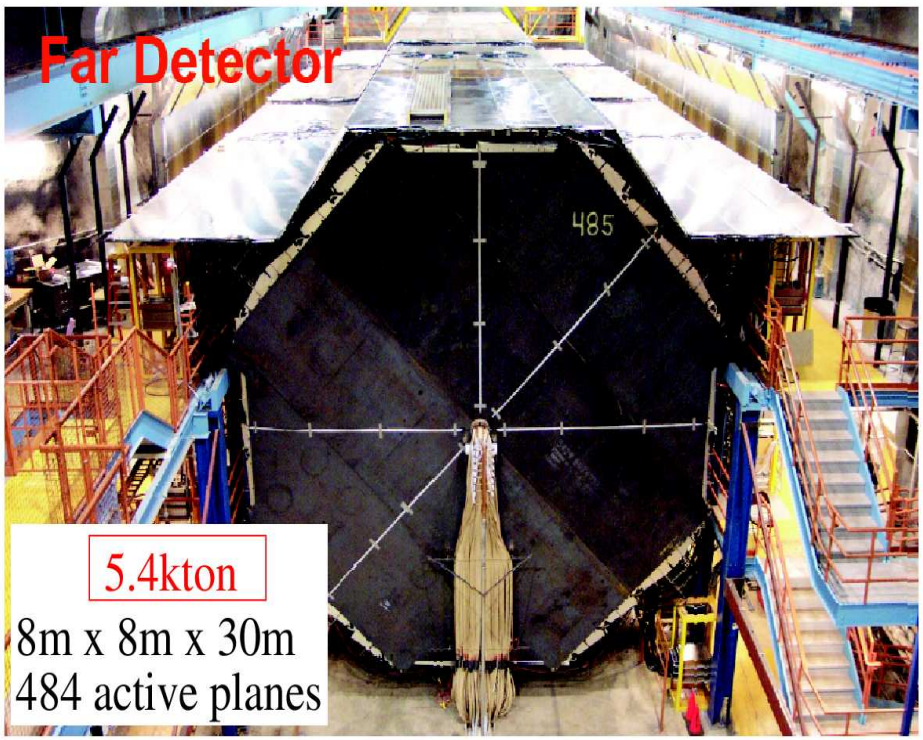
MINOS Detectors

Functionally equivalent detectors:
Magnetized tracking calorimeters

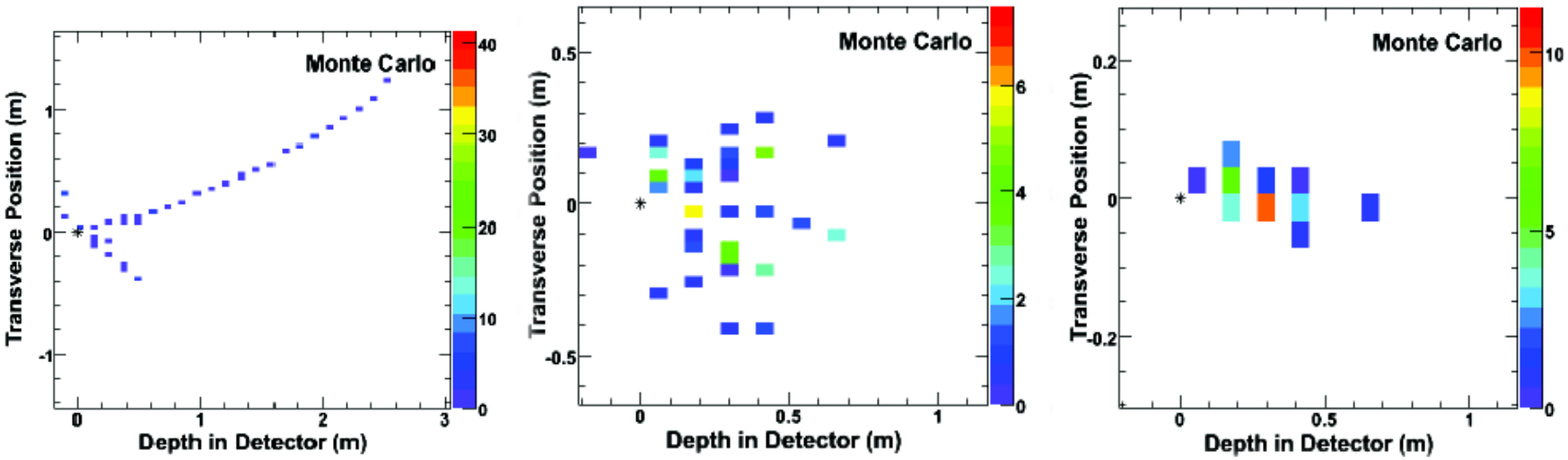
- Share same detector technology and granularity.
- Azimuthal $\mathbf{B}$ field allows track momentum measurement and charged-sign tagging.

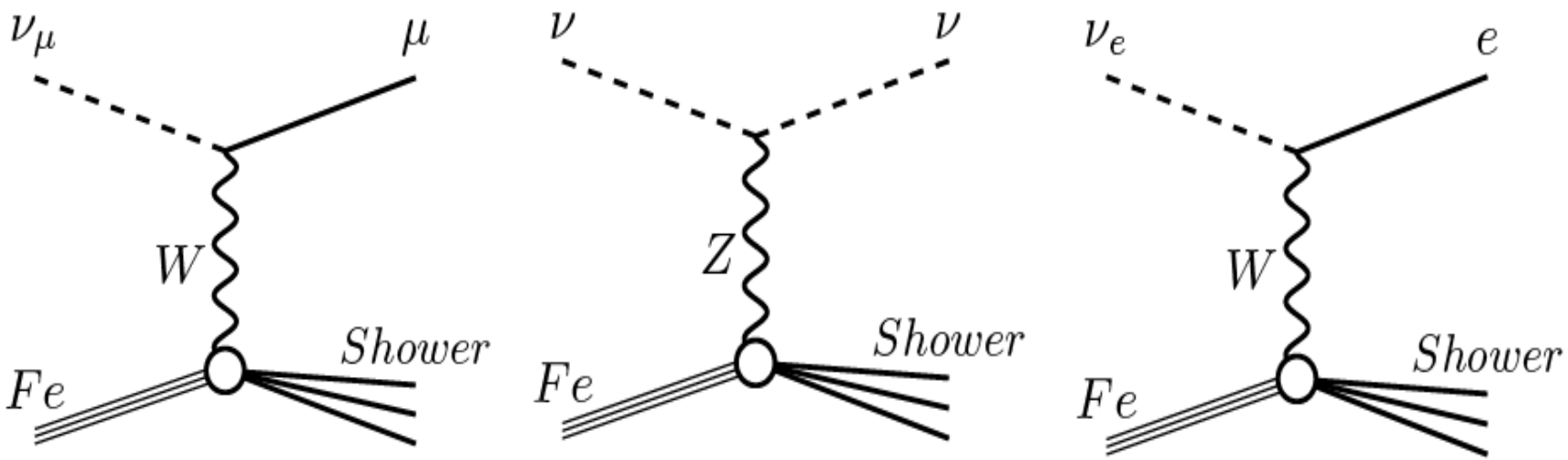


- 1cm thick planes of scintillator (4.1cm wide strips).
- Sampling every 2.54cm of steel.
- Magnetized steel plates $\langle B \rangle = 1.3\mathrm{T}$



MINOS Event Topologies



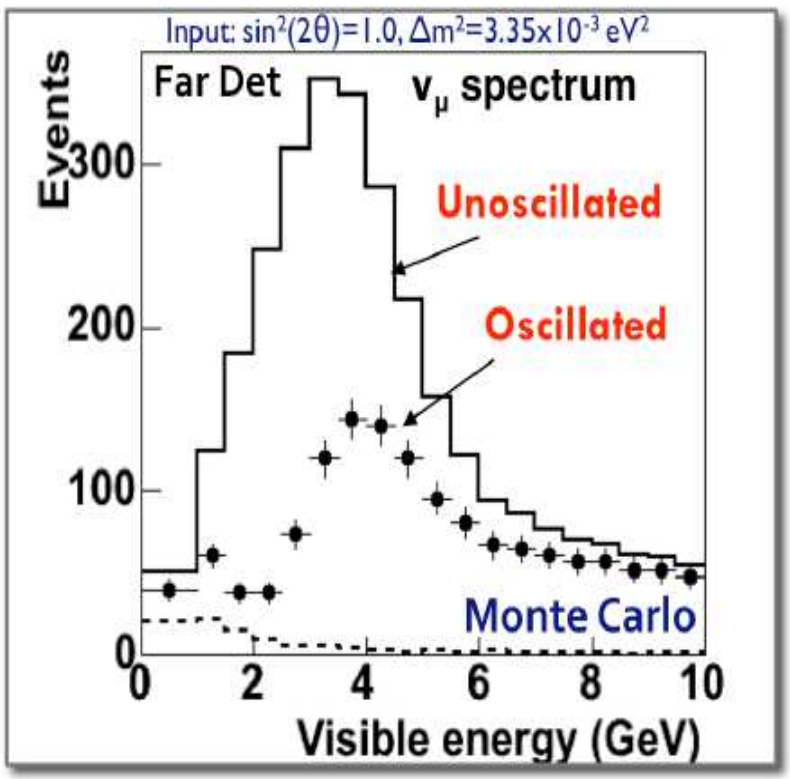


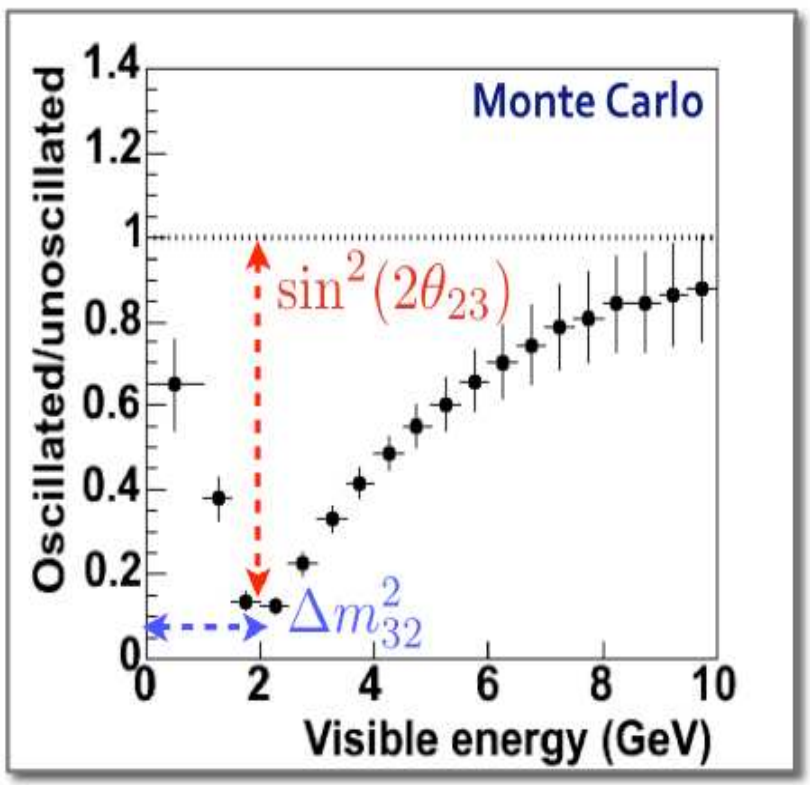
Antineutrino Disappearance

Survival Probability

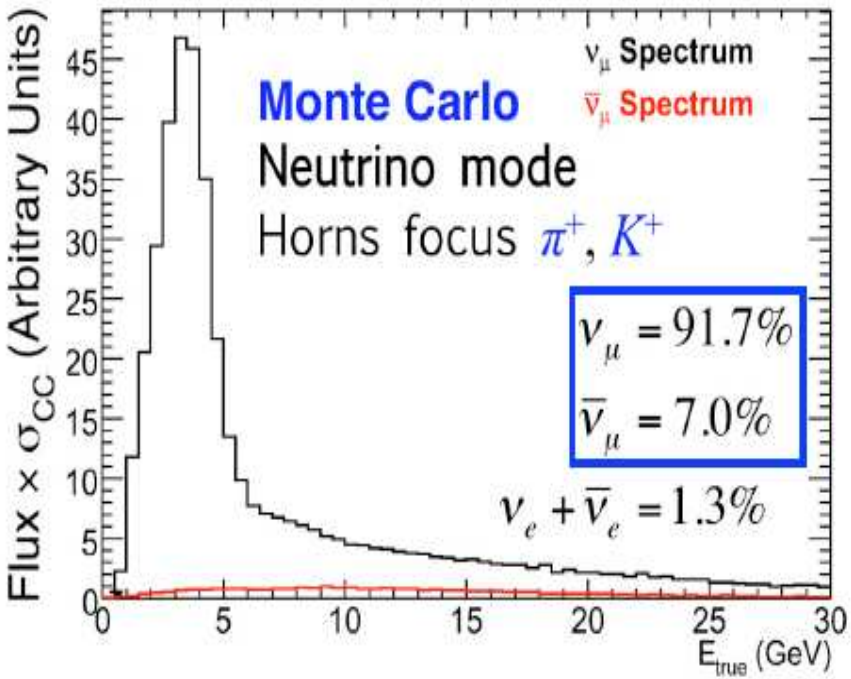
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(1.27 \Delta m^2_{32} \frac{L}{E}\right)$$

- Neutrino oscillations deplete the rate and distort the energy spectrum.

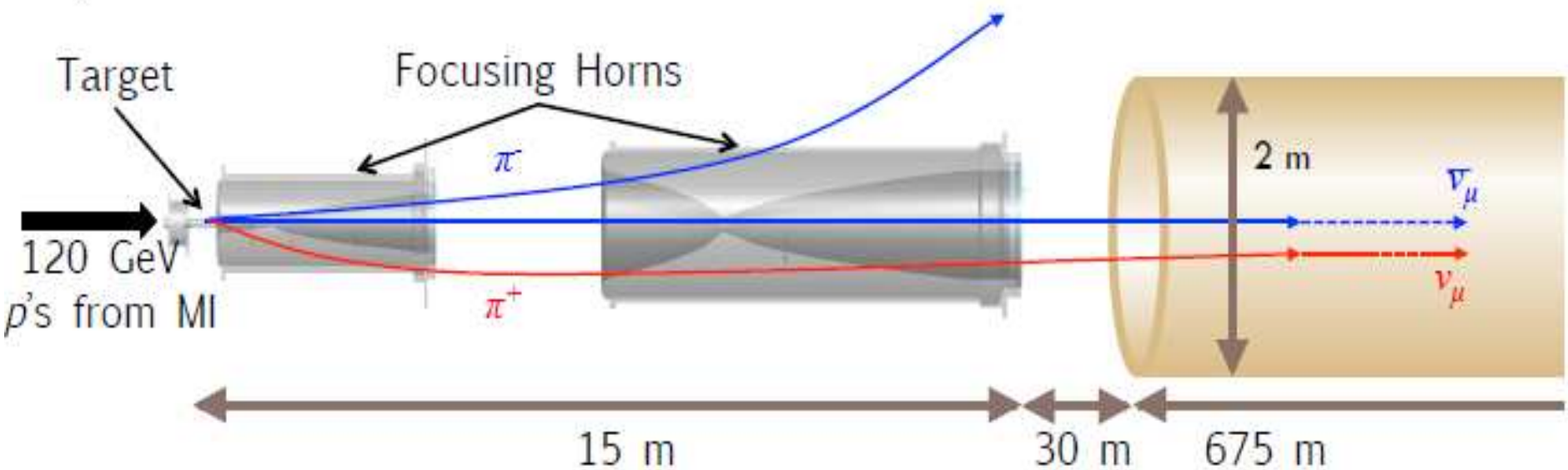




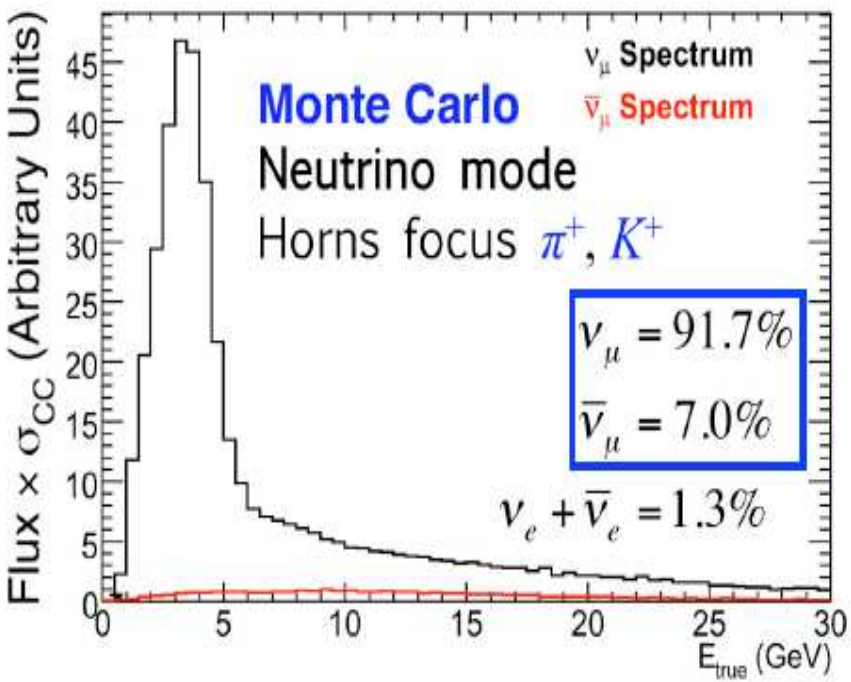
NuMI Beam ν_μ and $\overline{\nu}_\mu$ Running

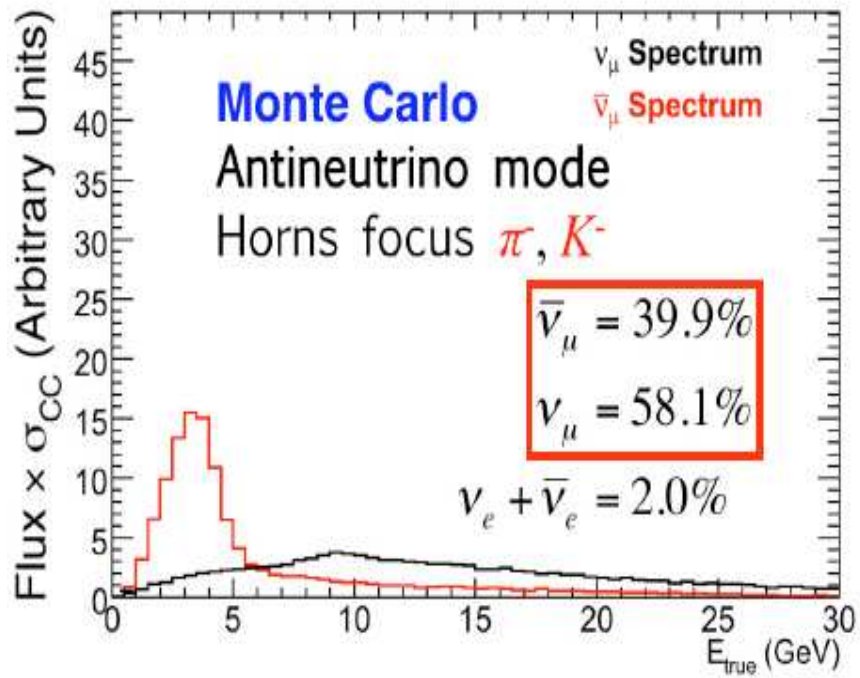


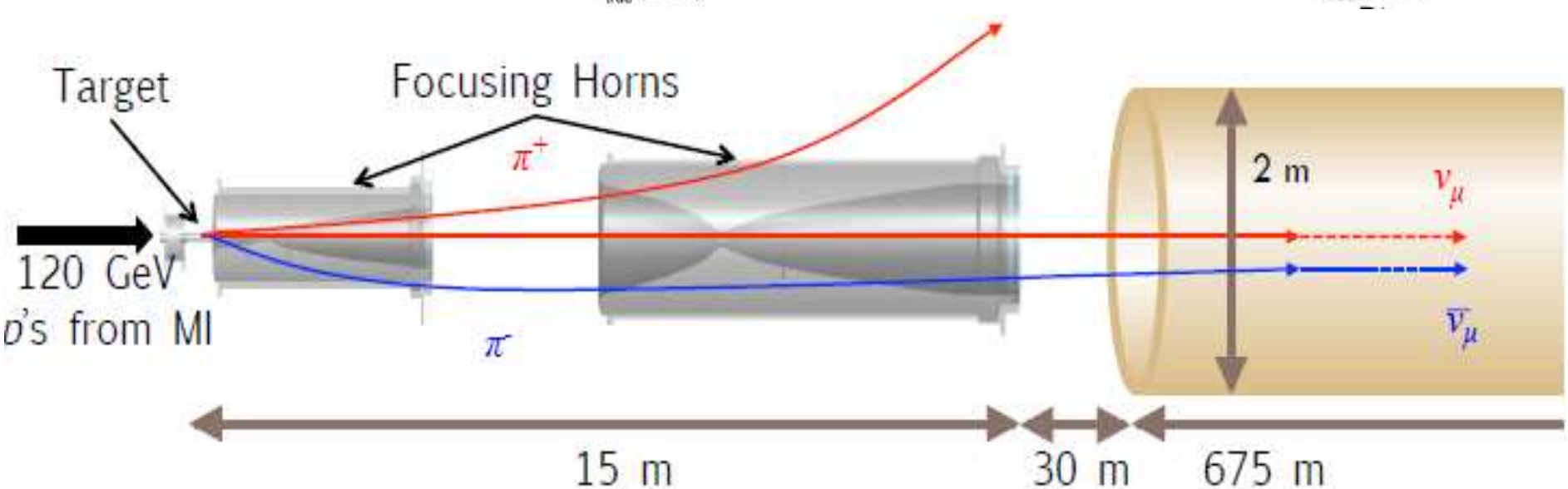
- Most of MINOS data is taken in this mode.
- Horns focus π^+,K^+ which decay into ν_μ
- Small fraction of $\overline{\nu}_\mu$ at higher energy from very forward π^-.



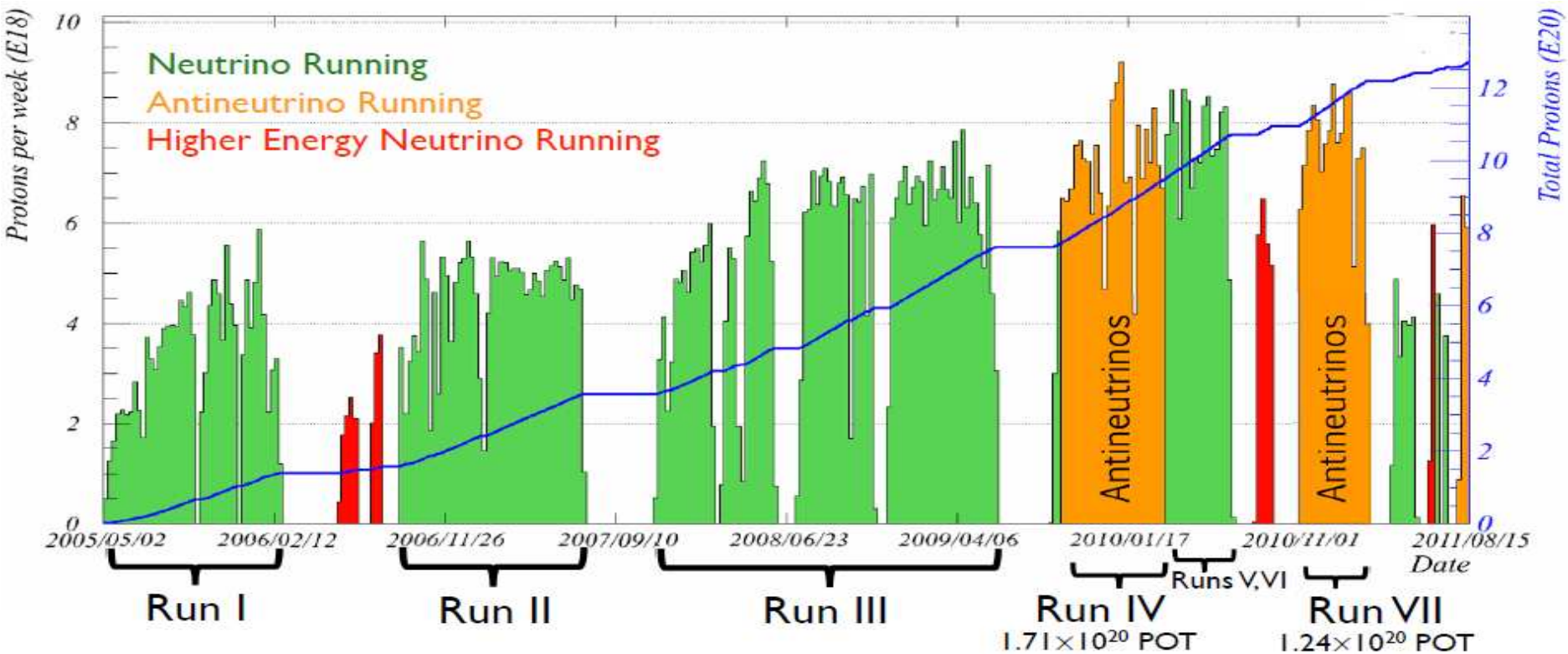
NuMI Beam ν_μ and $\bar{\nu}_\mu$ Running







Minos Data Samples



Two antineutrino beam exposures

- **Run IV** 1.71×10^{20} PoT
- **Run VII** 1.24×10^{20} PoT
- 2011 $\overline{\nu}_\mu$ Result: Combined Runs IV+VII (2.95×10^{20} PoT) .

ν_e Appearance result

- Neutrino beam running only
  - New result 8.2×10^{20} PoT (previous 7.0×10^{20} PoT).

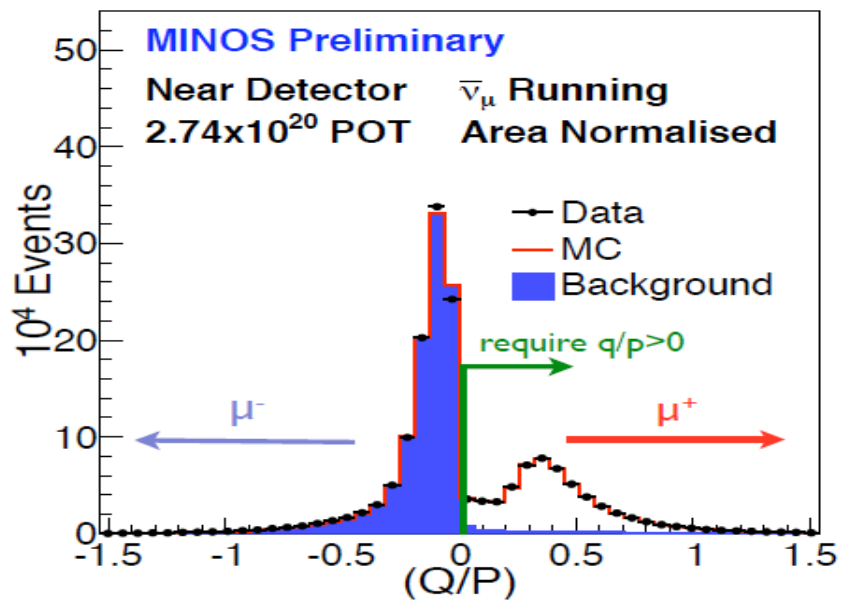
Antineutrino Disappearance Analysis

- Select $\overline{\nu}_\mu$-CC sample in ND and FD (FD sample is blinded until analysis is finalized).

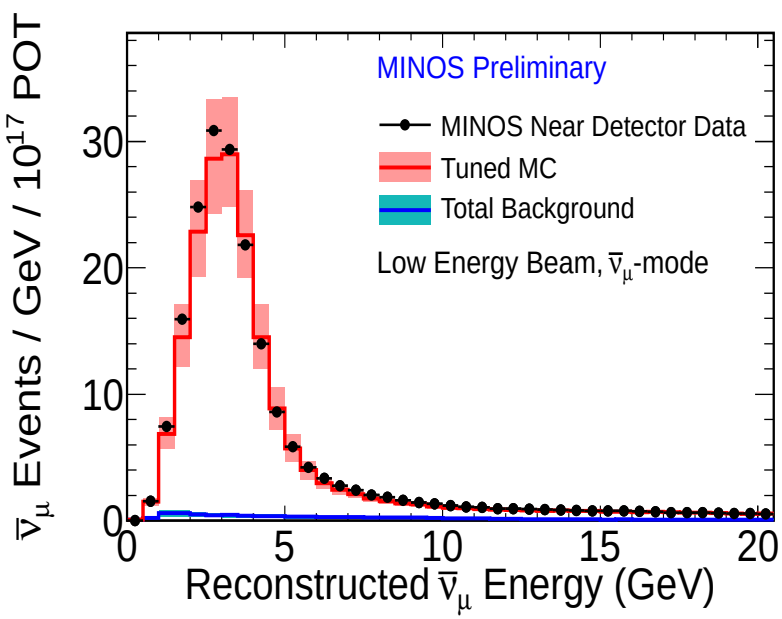
- Select CC events with μ track
  - KNN Algorithm with 4-input variables.
- Select μ^+ from track curvature.

(In signal region E_ν <6 GeV)

Efficiency	**ND: 53%**	**FD: 96%**
Purity	**ND: 94%**	**FD: 98%**

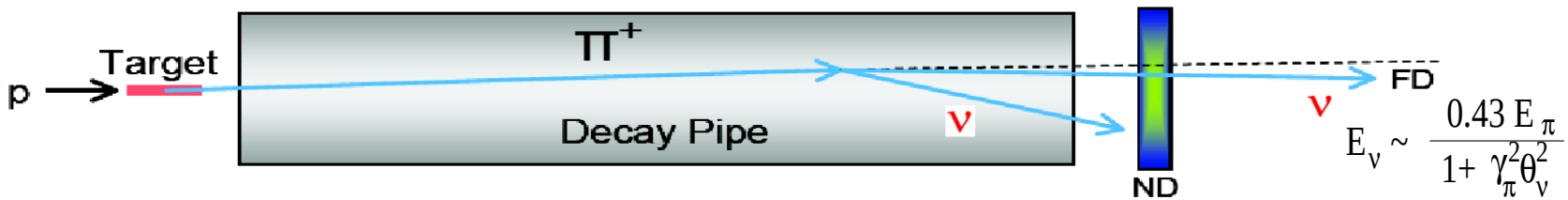


- Measured ND spectrum is used to predict FD event rate and spectrum.
  - Beam flux is tuned by fitting production x_f and p_t distributions using several beam configurations.
  - External input from NA49 π^+/π^- and K/π ratios.



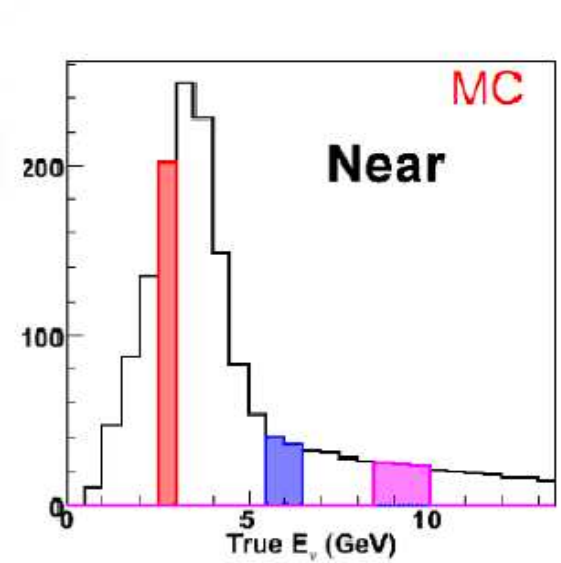
Near to Far Extrapolation

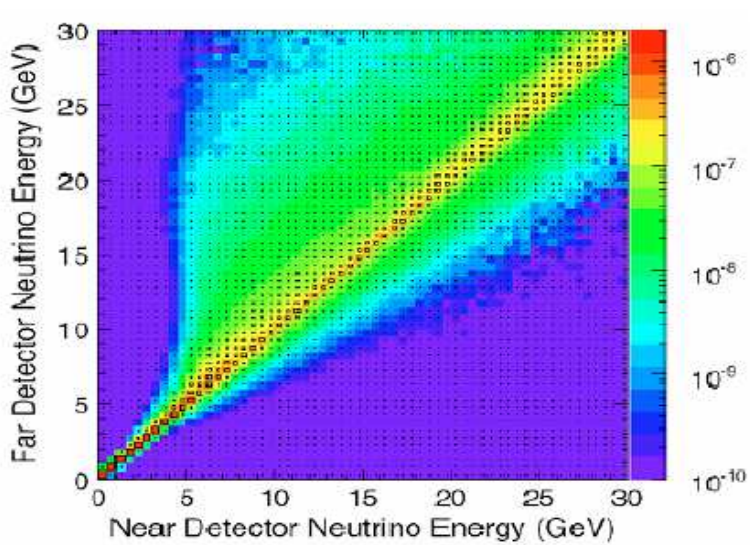
- Use measured Near Detector spectrum to predict Far Detector spectrum.

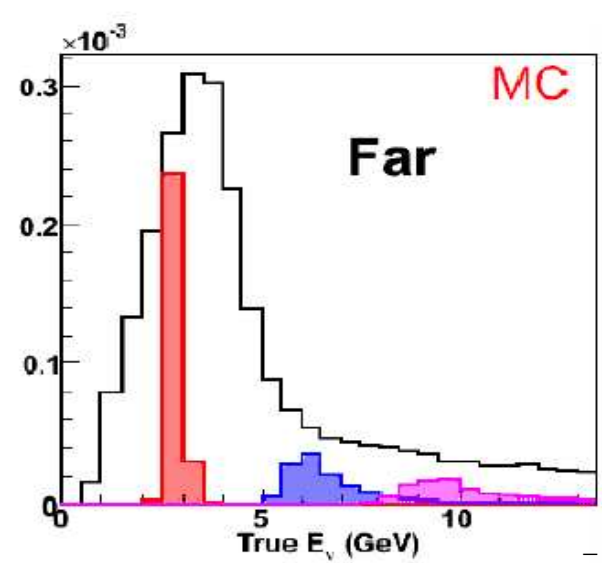


- Near and Far detectors have different acceptance for neutrinos produced from π decay.
  - The Near detector sees a line source, while the far detector sees a point source.

- Extrapolate using **Beam transfer matrix**
  - Encodes geometry of beamline and pion decay kinematics.
  - *Matrix element M_{ij} gives probability of obtaining a FD event of energy E_j given the observation of a ND event of energy E_i.*







Analysis Improvements

- ▶ Refined ND event sample.
  - ▷ More stringent track quality requirement.
- ▶ New shower energy estimator
  - ▷ ∼10% improvement to sensitivity
  - ▷ Same algorithm as used for 2010 ν_μ-CC analysis.

- ▶ Reanalyzed Run IV (1.71$\times 10^{20}$ PoT) data sample with analysis changes before opening the box on the combined sample.
  - ▷ **Parameter shifts are much smaller than uncertainties.**

Run IV w/2010 analysis

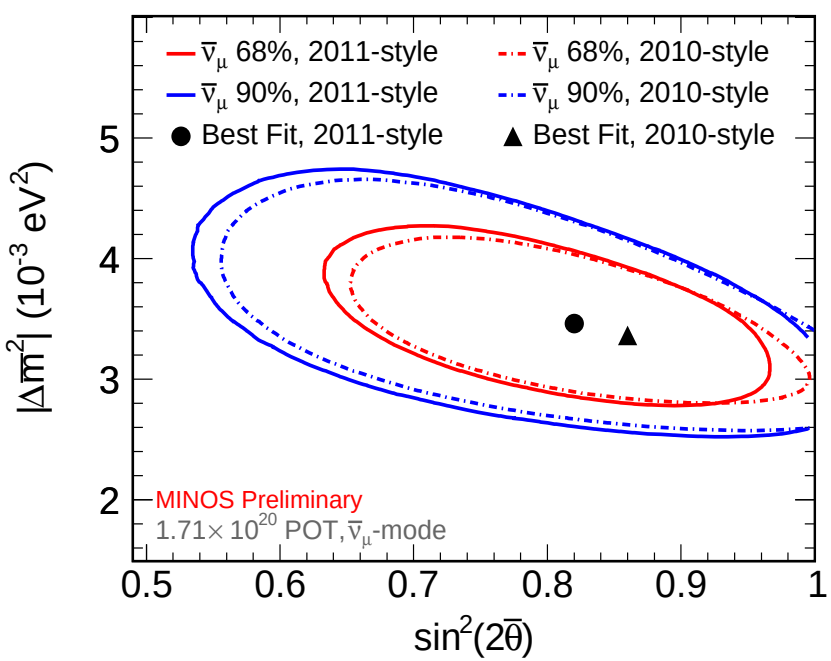
$|\Delta\overline{m}^2_{\rm atm}| = [3.36^{+0.46}_{-0.40}] \times 10^{-3}\ {\rm eV}^2$

$\sin^2(2\overline{\theta}_{23}) = 0.86^{+0.11}_{-0.12}$

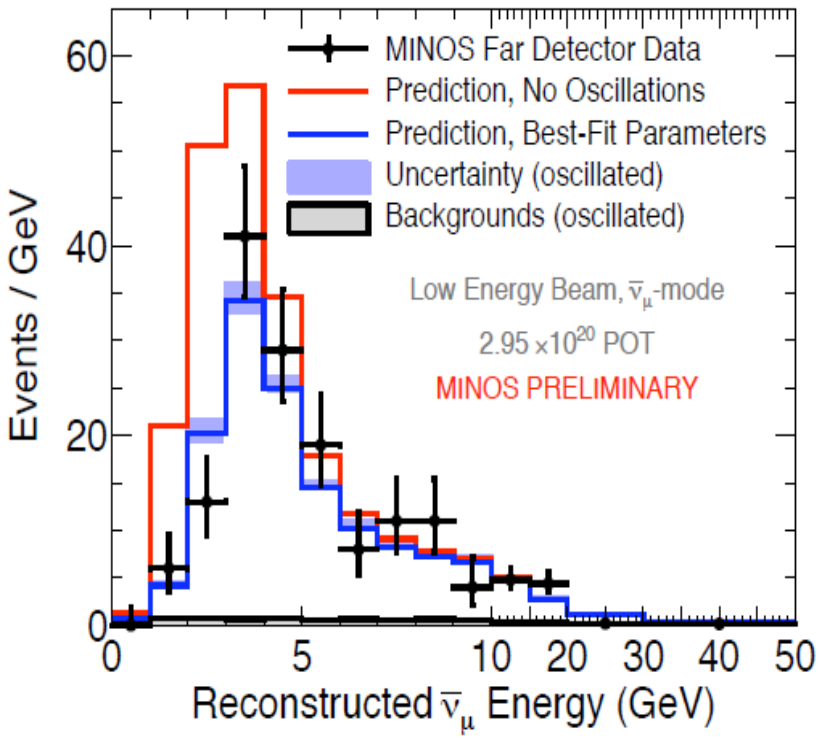
Run IV w/2011 analysis

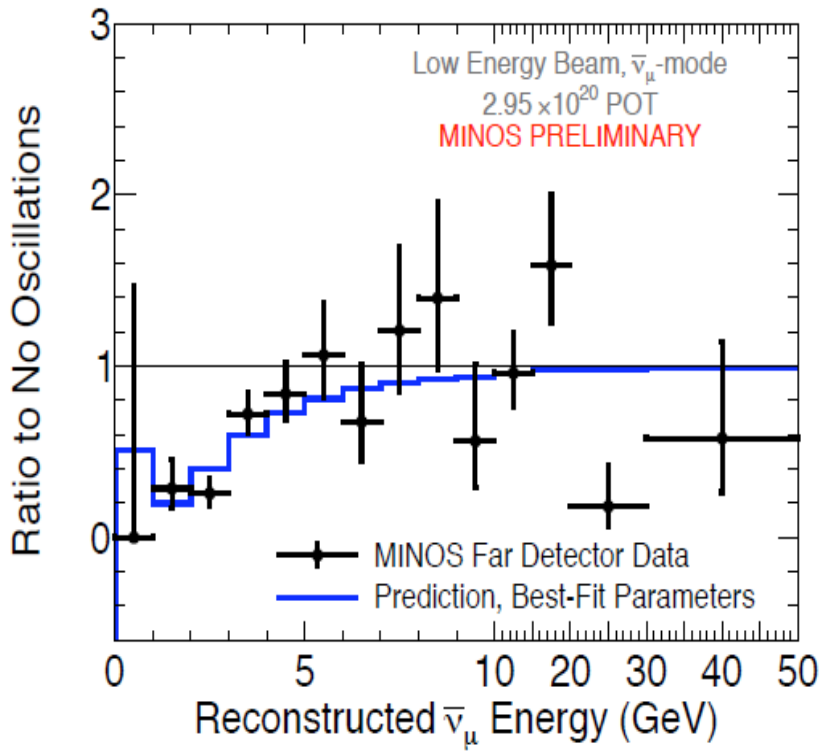
$|\Delta\overline{m}^2_{\rm atm}| = [3.46^{+0.47}_{-0.43}] \times 10^{-3}\ {\rm eV}^2$

$\sin^2(2\overline{\theta}_{23}) = 0.82^{+0.10}_{-0.11}$



2011 Antineutrino Oscillation Results





273 Expected (no oscillation).

193 Observed

- Null-Oscillations excluded at 7.3σ

Best fit:

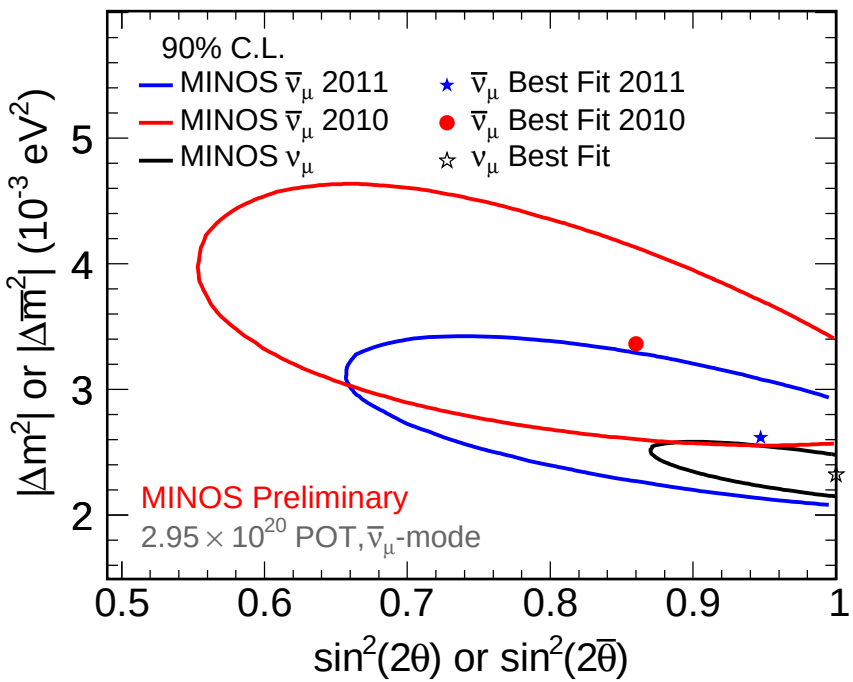
$$|\Delta\overline{m}^2_{\rm atm}| = (2.62^{+0.31}_{-0.28}({\rm stat}) \pm 0.09({\rm syst})) \times 10^{-3}{\rm eV}^2$$

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

Contour Comparisons

Antineutrino Oscillation Parameters
$|\Delta\overline{m}^2_{atm}| = [2.62^{+0.31}_{-0.28}] \times 10^{-3}\ \mathrm{eV}^2$
$\sin^2(2\overline{\theta}_{23}) > 0.75$ at 90% CL.

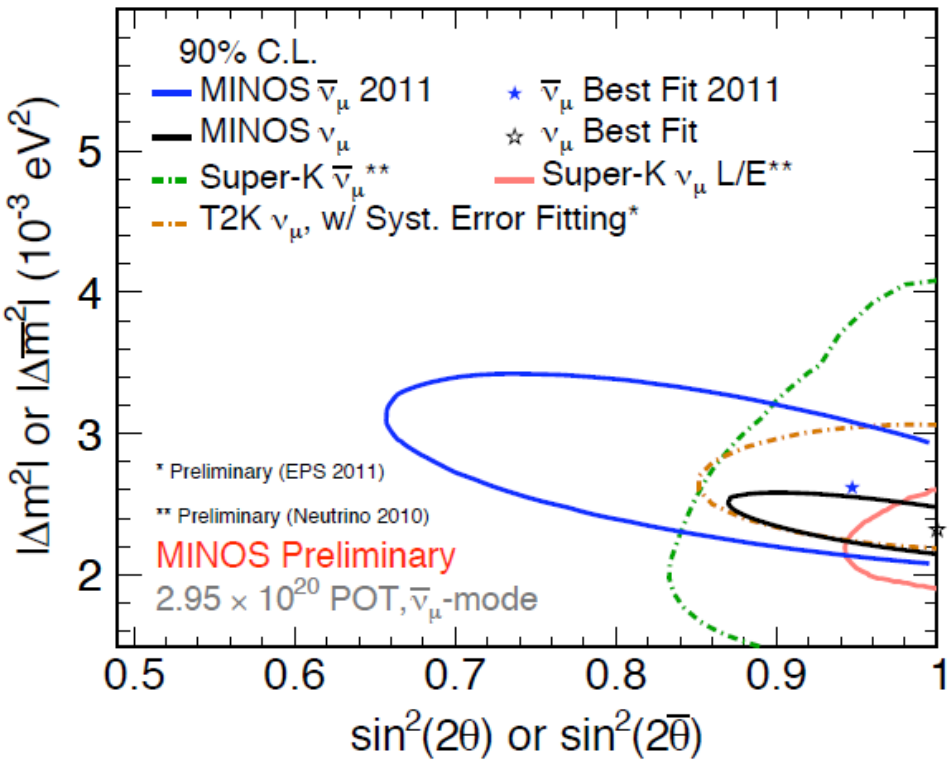
Neutrino Oscillation Parameters
$|\Delta m^2_{atm}| = [2.32^{+0.12}_{-0.08}] \times 10^{-3}\ \mathrm{eV}^2$
$\sin^2(2\theta_{23}) > 0.90$ at 90% CL.



Compatibility with Neutrino Result:

- Assuming identical underlying oscillation parameters, measurements are consistent at the 42% CL.
- Was 2% CL for the 2010 analysis (red curve).

Contour Comparisons

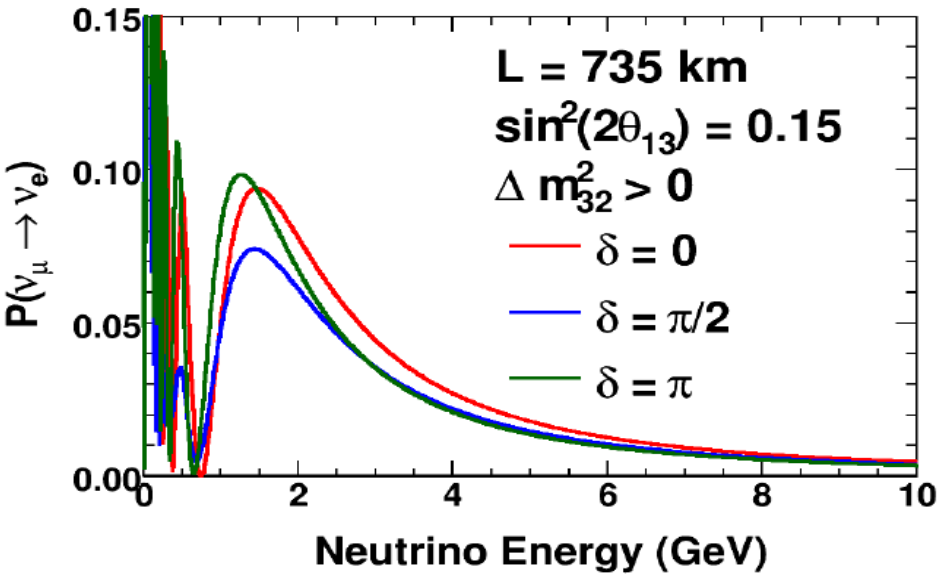


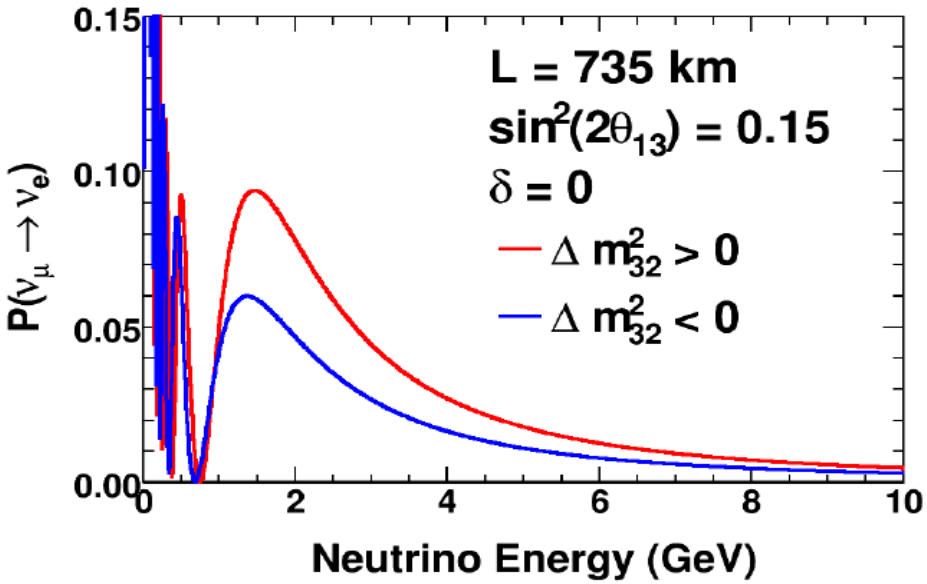
- Comparison with Super-K and T2K ν_μ and $\bar{\nu}_\mu$ results.
- MINOS provides the best constraint on $|\Delta\bar{m}^2_{atm}|$.
- MINOS is currently running in $\bar{\nu}_\mu$, expect further improvement in precision.

Electron Neutrino Appearance

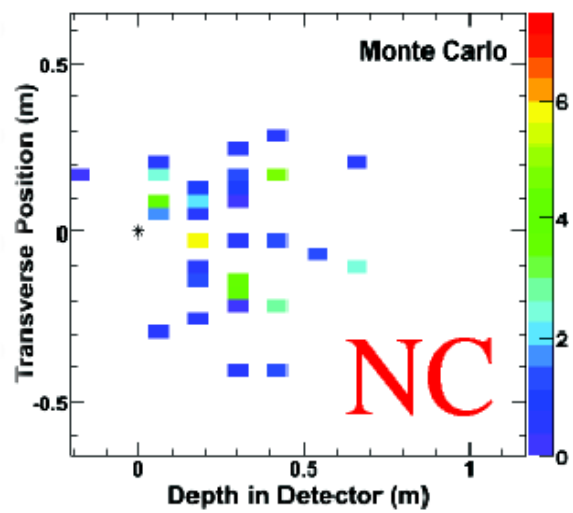
Electron Neutrino Appearance in MINOS

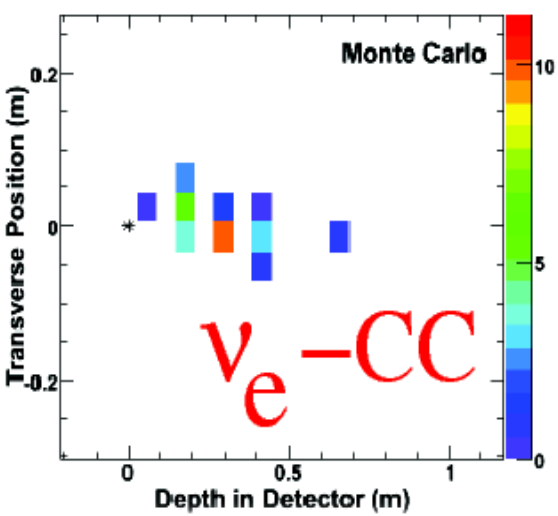
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2 \frac{\Delta m^2_{atm} L}{4E}$$ + smaller terms $(\delta,\ \mathrm{matter\ effects{:}sign}(\Delta m^2))$





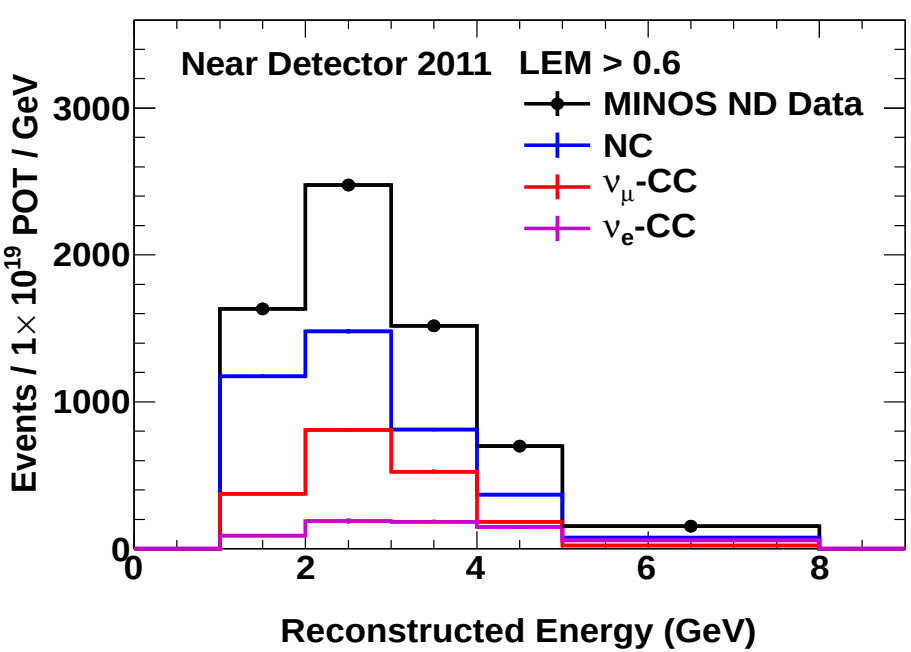
- Signal is small.
- Backgrounds in MINOS:
  - ν_e beam.
  - ν_e-like NC interactions.
  - High-y ν_μ-CC events





ν_e Selection and Background

- **ν_eCC-like sample selection**: NEW Library Event Matching (LEM) technique.
  - Compare each candidate event to library (20M signal and 30M background events).
  - Form discriminant using information from 50 best matches.
  - Based on strip-level information (pattern and pulseheight).
  - Gives 15% improvement in sensitivity over previous technique. (previous ANN technique used high-level reconstructed quantities (Phys. Rev. D 82, 051102 (2010)).
- **Determine Far Detector backgrounds from Near Detector sample**
  - Decompose Near Detector ν_eCC-like event sample into components (NC, Beam ν_e and ν_μ-CC).
    - Fit uses three beam configurations (LE-10, Horn-off and HE).



- Extrapolate each measured background component separately to obtain FD background predictions.

$$F_{\alpha,i} = N_{\alpha,i} \times R^{F/N}_{\alpha,i}$$

FD prediction for component α in bin i

ND data for component α in bin i

Far/Near ratio: Ratio of selected events for component α in bin i using MC

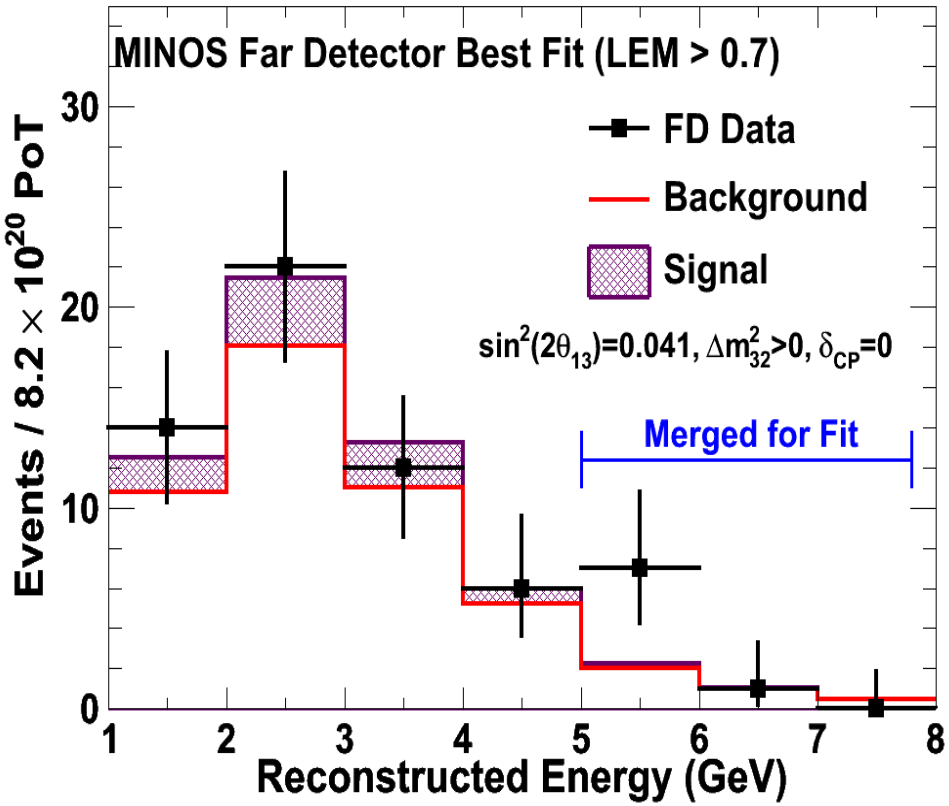
Far Detector Data

Observe 62 events

Background Prediction ($\theta_{13} = 0$)

49.6 $\pm$ 7.0 (stat) $\pm$ 2.7 (syst)

Background Contributions ($\theta_{13} = 0$)	
Component	Events
NC	34.1
ν_μ-CC	6.7
beam ν_e-CC	6.4
ν_τ-CC	2.2



Best fit (for δ=0, $\theta_{23} = \pi/4$, & normal hierarchy).

$$\sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$$

Limit Contours

(for $2\sin^2(\theta_{23})$=1, δ=0, and $|\Delta m^2_{32}|$ = 2.32$\times 10^{-3}$eV^2)

90% Confidence Limits

Normal mass hierarchy: $\sin^2(2\theta_{13}) < 0.12$

Inverted mass hierarchy: $\sin^2(2\theta_{13}) < 0.20$

Best fit:

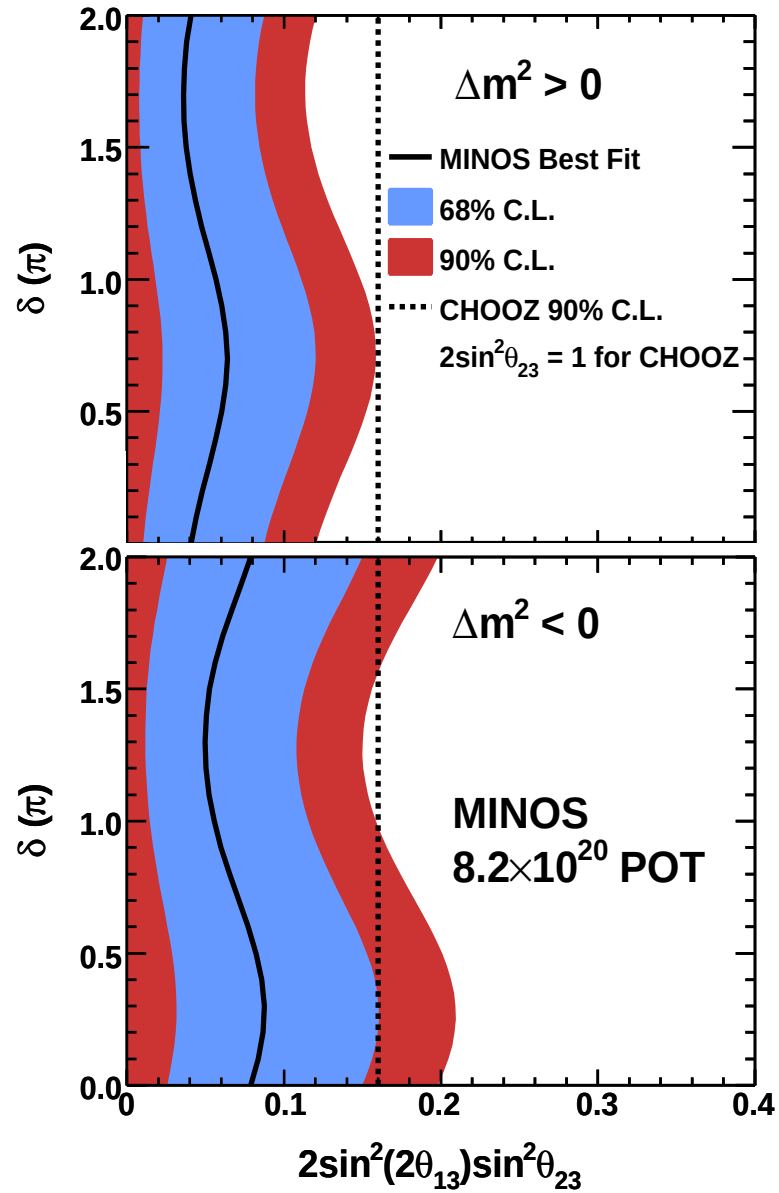
Normal $\sin^2(2\theta_{13}) = 0.04$

Inverted $\sin^2(2\theta_{13}) = 0.08$

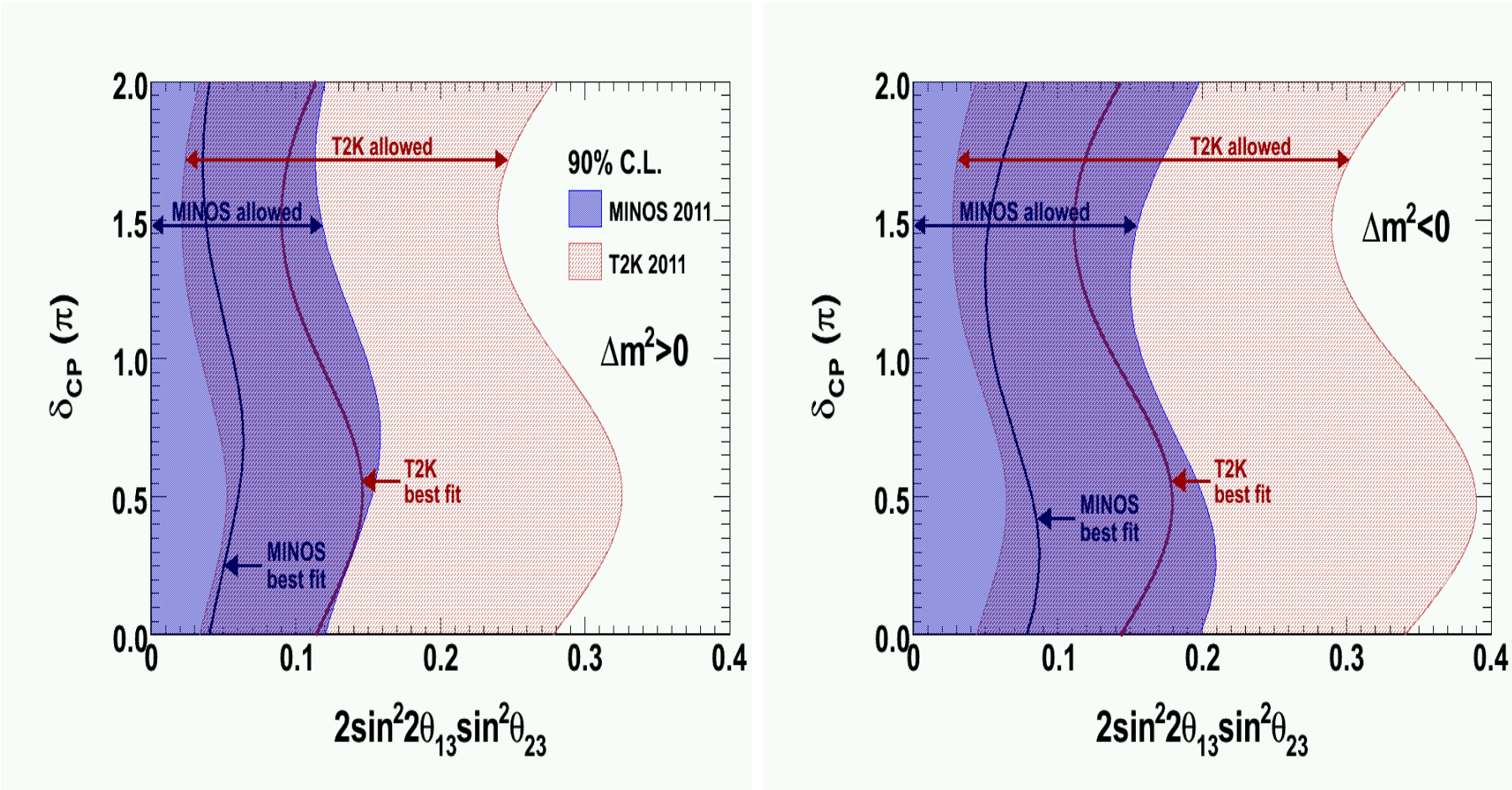
- Most sensitive constraint on θ_{13} to date.

(arXiv:hep-ex/1108.0015 accepted by PRL)

$\sin^2(2\theta_{13}) = 0$ excluded at 89% CL



Overlap of Minos 2011 and T2K



- MINOS significantly constrains the θ_{13} range allowed by T2K.

Summary

- New $\overline{\nu}_\mu$ disappearance result (2.95$\times 10^{20}$PoT RHC mode)

Best fit:
$|\Delta\overline{\mathrm{m}}^2_{\mathrm{atm}}| = (2.62^{+0.31}_{-0.28}(\mathrm{stat}) \pm 0.09(\mathrm{syst})) \times 10^{-3}\mathrm{eV}^2$
$\sin^2(2\overline{\theta}_{23}) = 0.95^{+0.10}_{-0.11}(\mathrm{stat}) + 0.01(\mathrm{syst})$

  - ν_μ and $\overline{\nu}_\mu$ oscillation parameters are consistent at the 42% CL.
  - MINOS provides the best constraint on $|\Delta\overline{\mathrm{m}}^2_{\mathrm{atm}}|$.

- New ν_e appearance result (8.2$\times 10^{20}$PoT FHC mode)

90% Confidence Limits ($\delta = 0$)
Normal mass hierarchy: $\sin^2(2\theta_{13}) < 0.12$
Inverted mass hierarchy: $\sin^2(2\theta_{13}) < 0.20$

  - Most sensitive constraint on θ_{13} to date.
  - MINOS significantly constrains the θ_{13} range allowed by T2K.

Future:

- MINOS is currently running in $\overline{\nu}_\mu$, expect further improvement in precision.
- Stay tuned: MINOS+ plans for future running in NoνA era beam.

Extra Slides

$\overline{\nu}_\mu$ Result Comparisons

Run VII only)

(Exposure 1.24E20 PoT)

$|\Delta\overline{\mathrm{m}}^2_{\mathrm{atm}}| = [2.26^{+0.27}_{-0.29}] \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2(2\overline{\theta}_{23}) > 0.79$ (90% CL)

Run IV only w/2011 analysis

(Exposure 1.71E20 PoT)

$|\Delta\overline{\mathrm{m}}^2_{\mathrm{atm}}| = [3.46^{+0.47}_{-0.43}] \times 10^{-3}\ \mathrm{eV}^2$

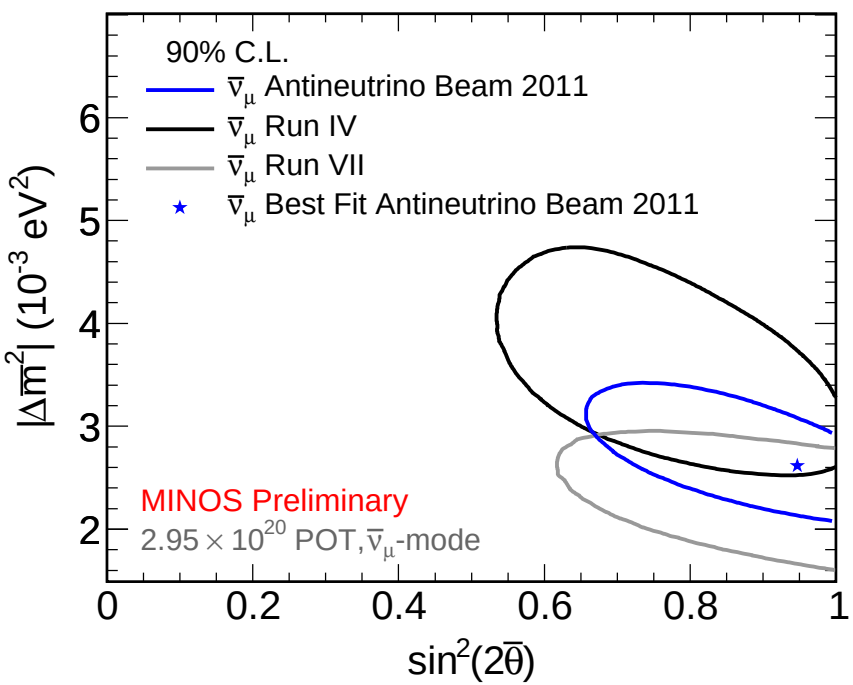
$\sin^2(2\overline{\theta}_{23}) = 0.82^{+0.10}_{-0.11}$

- 90% CL Comparison with Run IV obtained from 2011 reanalysis.
- Results overlap at 90% CL

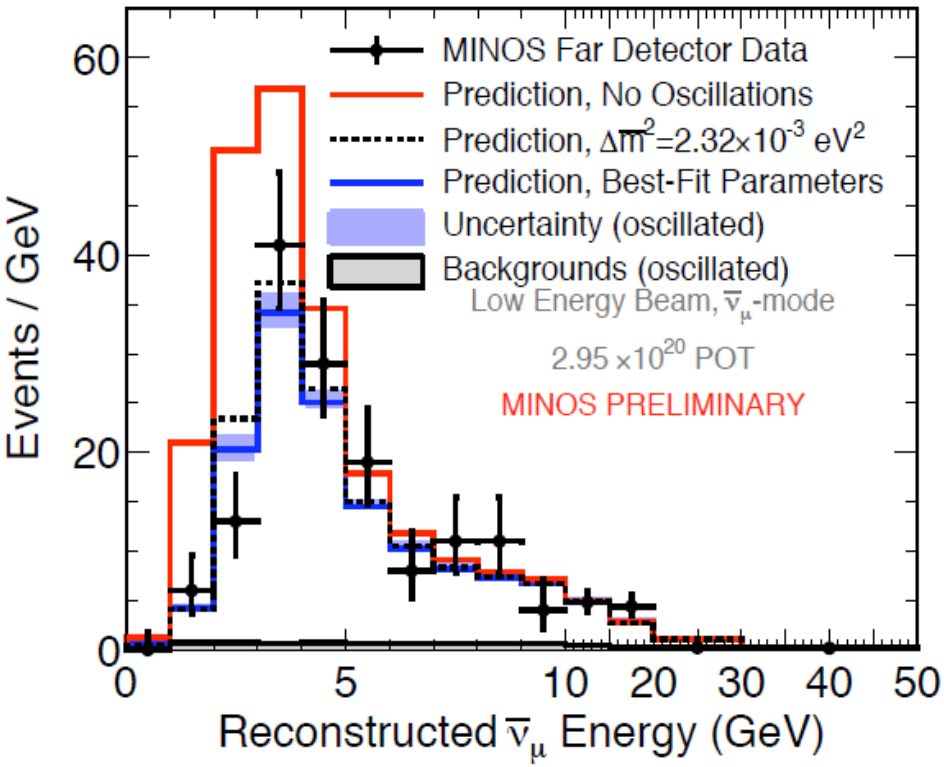
Combined Run IV and VII

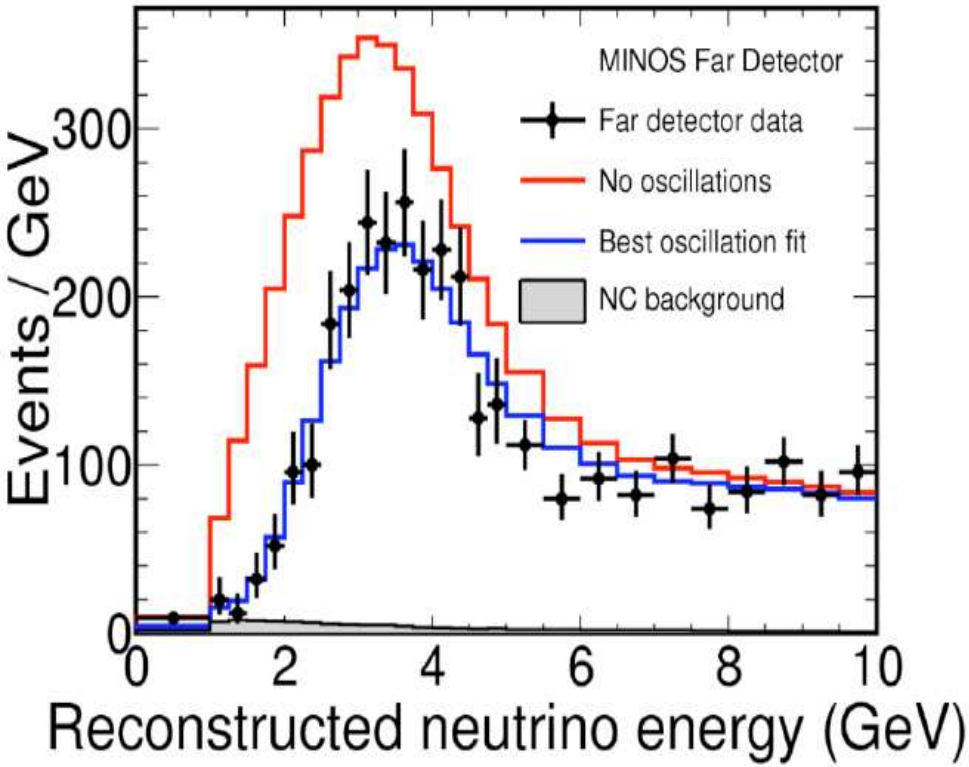
$|\Delta\overline{\mathrm{m}}^2_{\mathrm{atm}}| = [2.62^{+0.31}_{-0.28}] \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2(2\overline{\theta}_{23}) = 0.95^{+0.10}_{-0.11}$



Neutrino vs. Antineutrino





$\overline{\nu}_\mu$ Oscillation Parameters

$|\Delta\overline{\mathrm{m}}^2_{\mathrm{atm}}| = [2.62^{+0.32}_{-0.28}] \times 10^{-3}\ \mathrm{eV}^2$

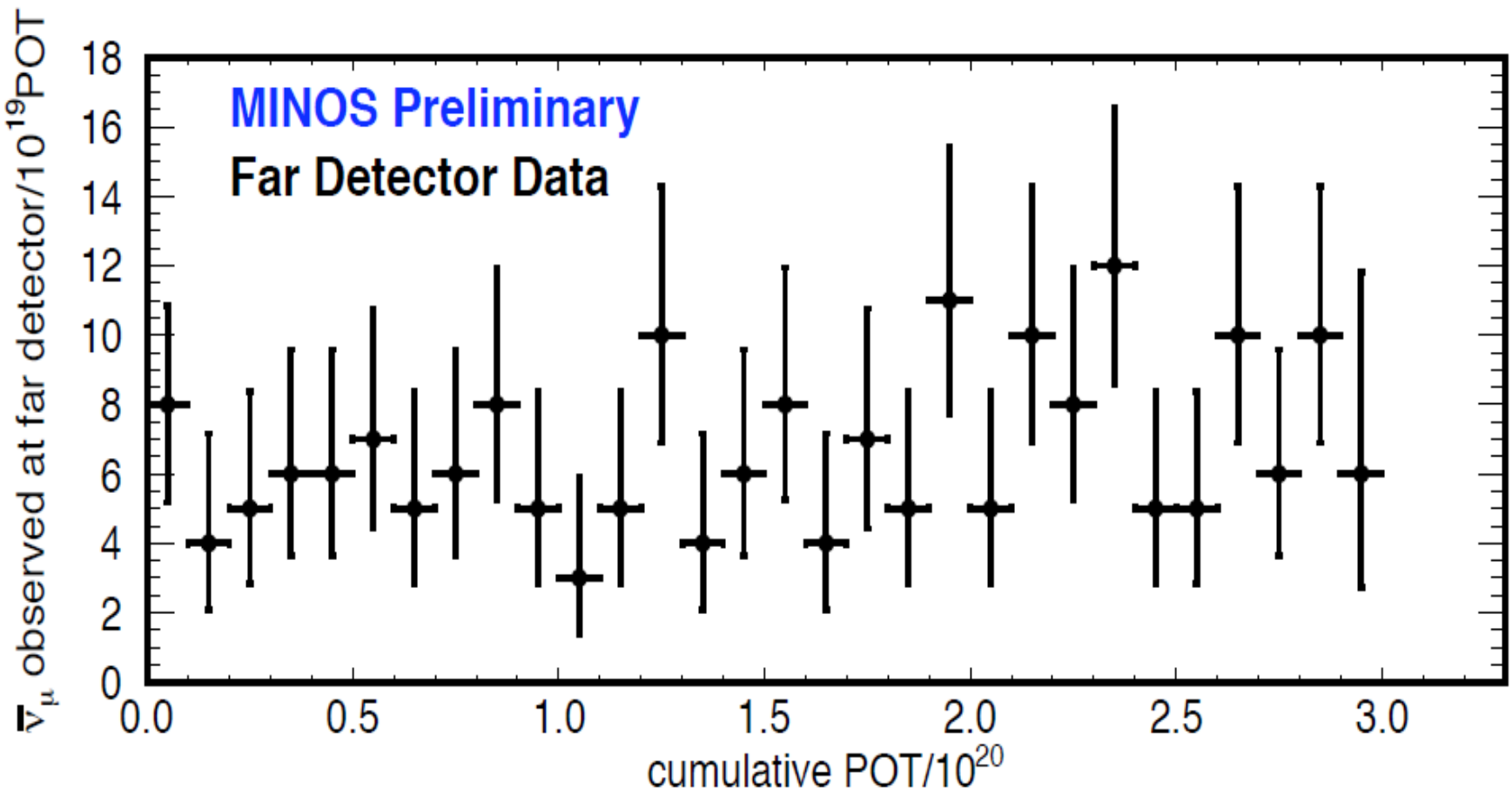
$\sin^2(2\overline{\theta}_{23}) > 0.75$ at 90% CL.

ν_μ Oscillation Parameters

$|\Delta\mathrm{m}^2_{\mathrm{atm}}| = [2.35^{+0.12}_{-0.08}] \times 10^{-3}\ \mathrm{eV}^2$

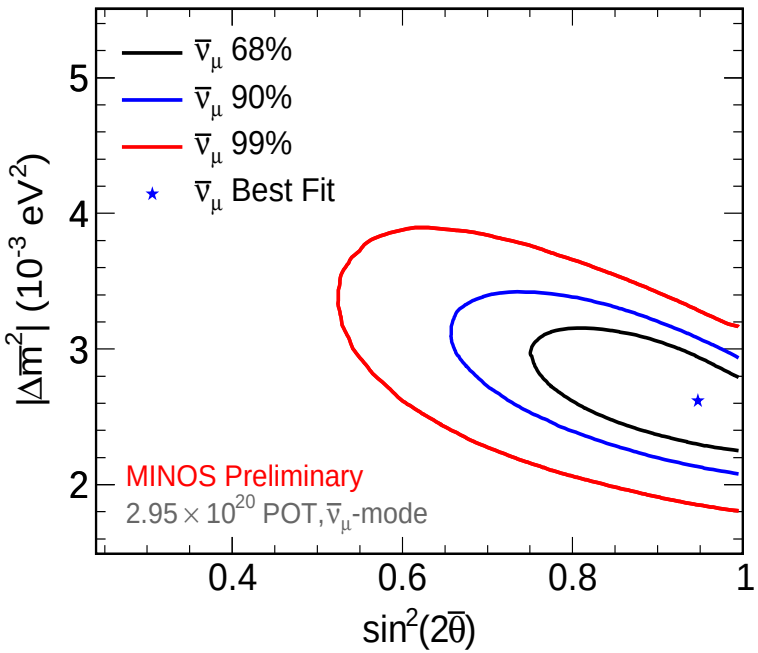
$\sin^2(2\theta_{23}) > 0.91$ at 90% CL.

FD Data Stability

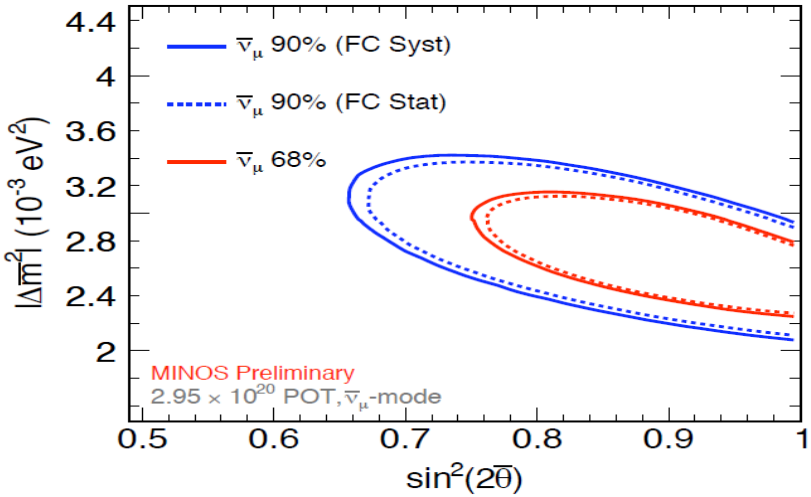


Allowed Regions

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

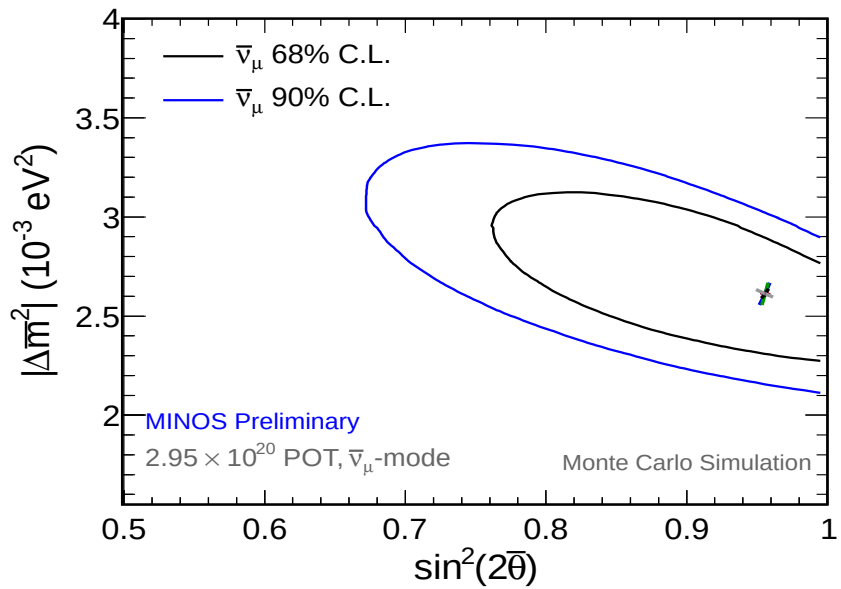


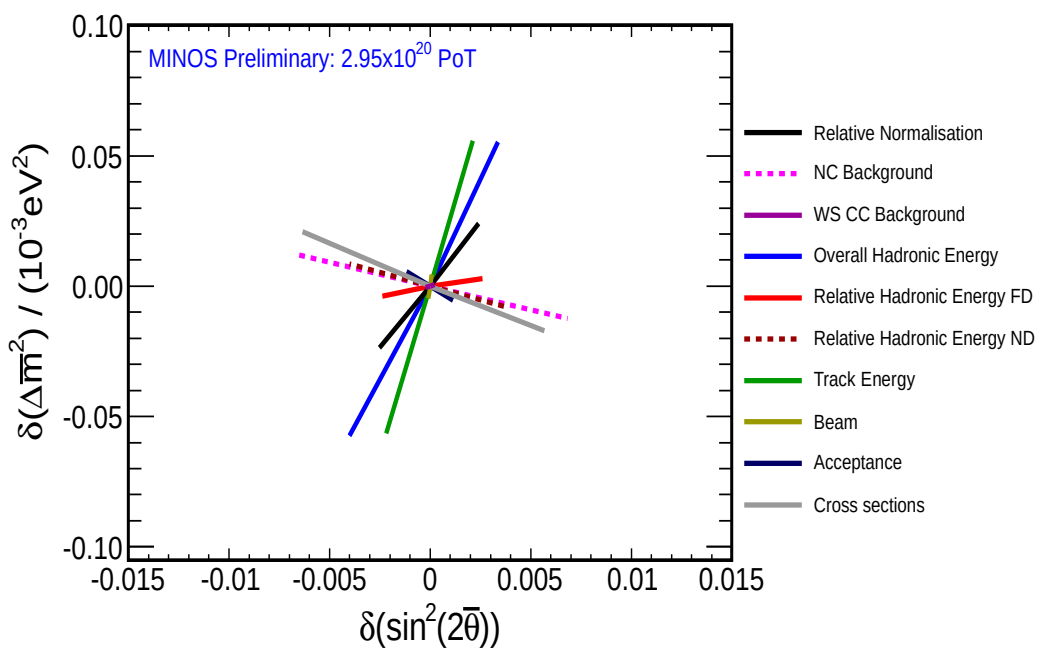
- Contours are Feldman cousins corrected.
- Systematic uncertainties included in the contour.



- Effect of including systematic uncertainties is small. (dotted curves show statistics only contours).
- Result is statistics limited.

$\overline{\nu}_\mu$ Systematic Uncertainties





NC/CC Separation

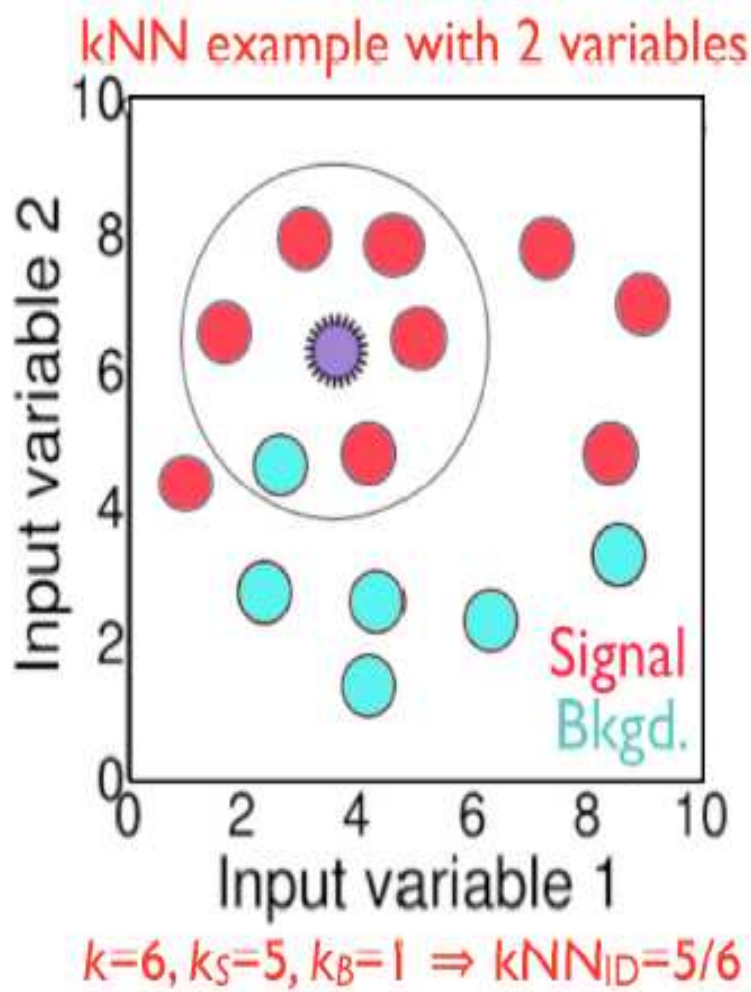
- Charged-current events are selected by tracks which satisfy a multivariant topological ID that uses a k nearest-neighnor algorithm.

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

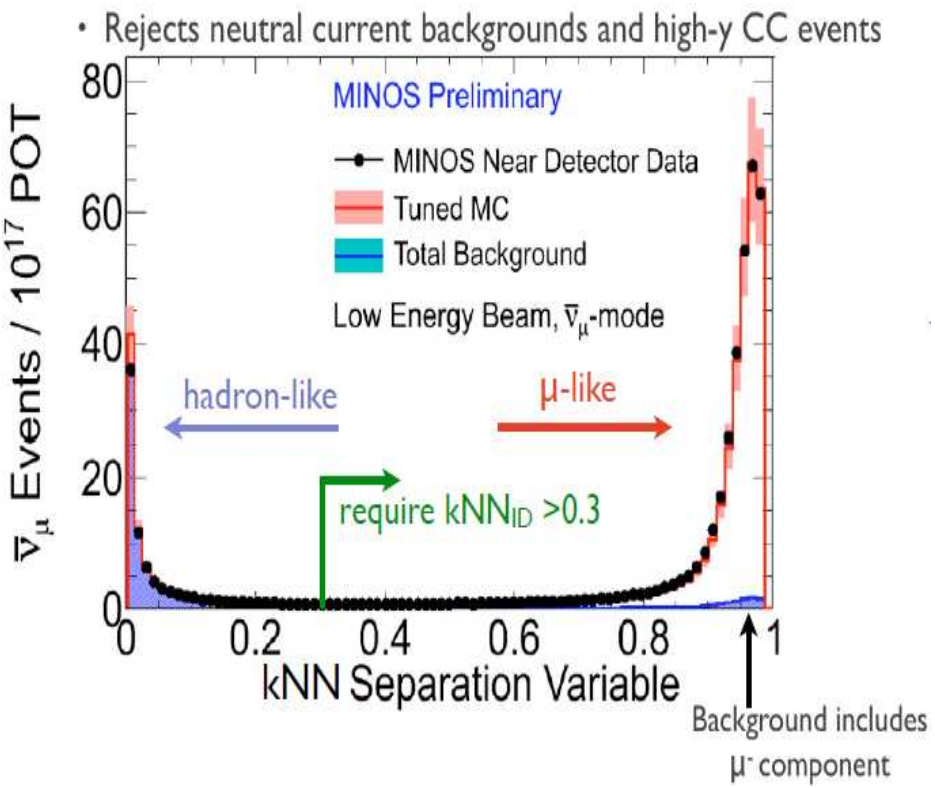
$$D = \left(\sum_{i=1}^{N_{\mathrm{Var}}} |X_i^{MC} - X_i^Q|^2 \right)^{\frac{1}{2}}$$

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

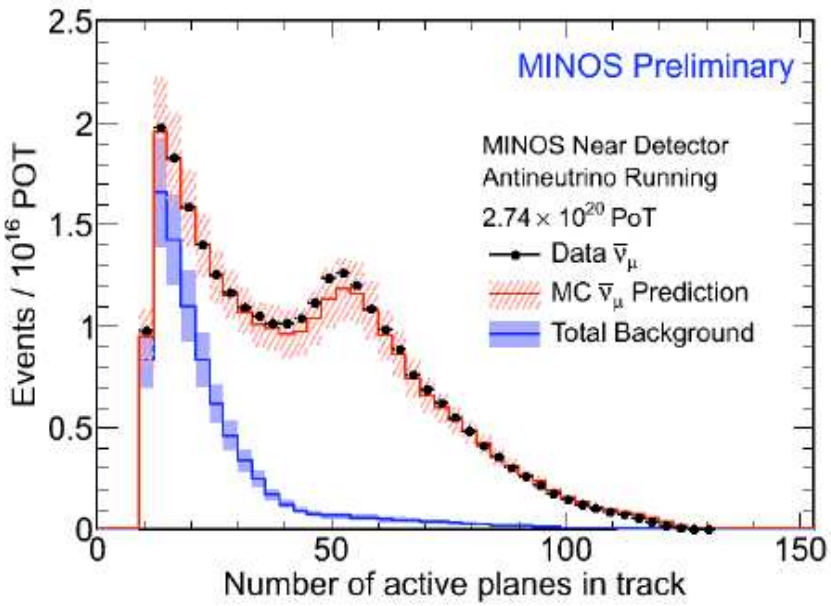
$$\mathrm{kNN_{ID}} = \frac{k_S}{k_S + k_B}$$

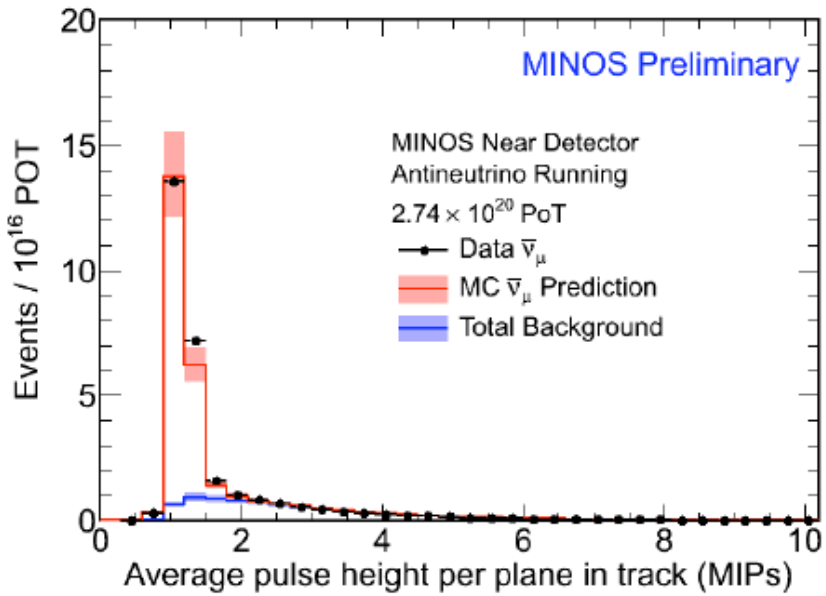


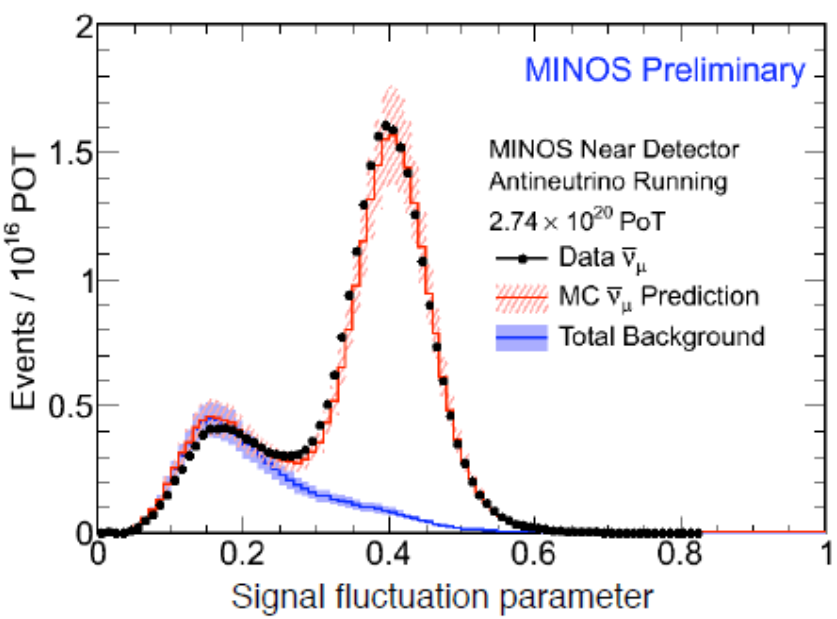
NC/CC Separation (KNN Variable)

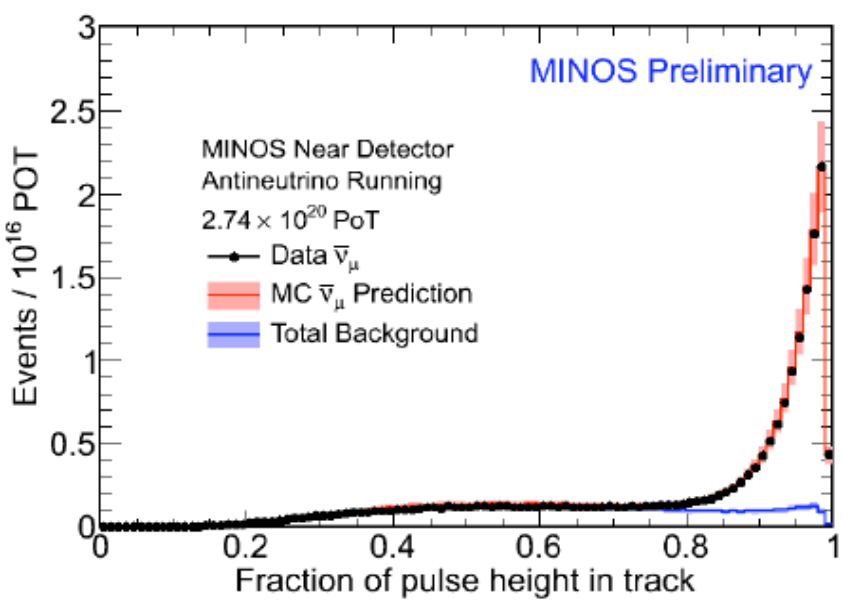


KNN Input Variable Distributions





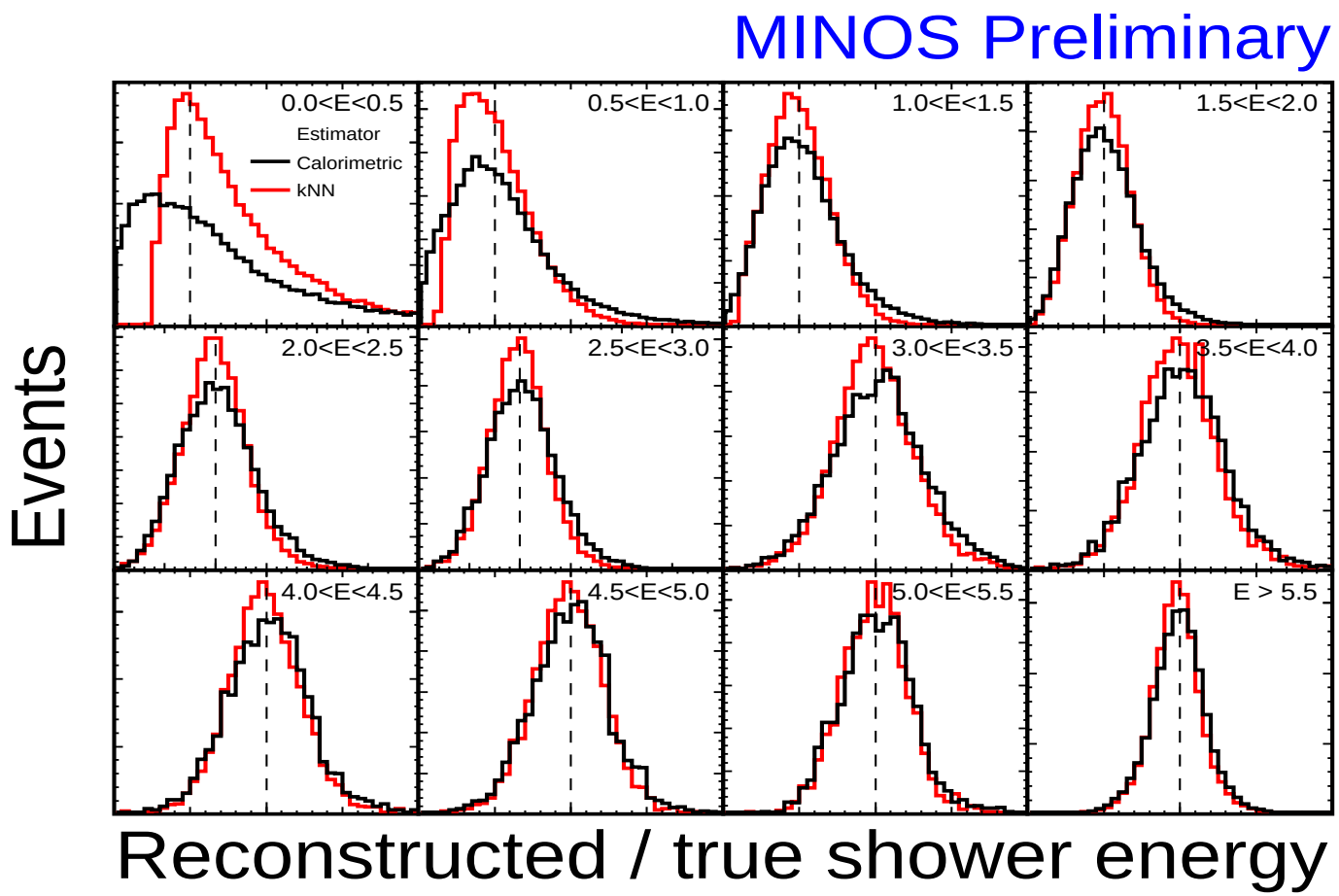




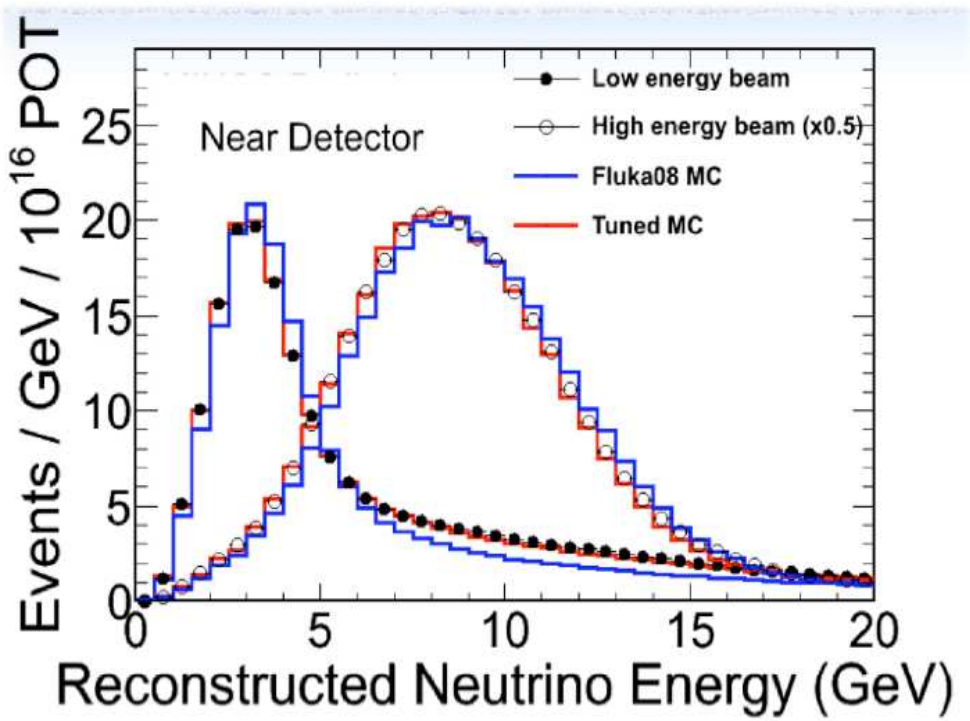
Shower Energy

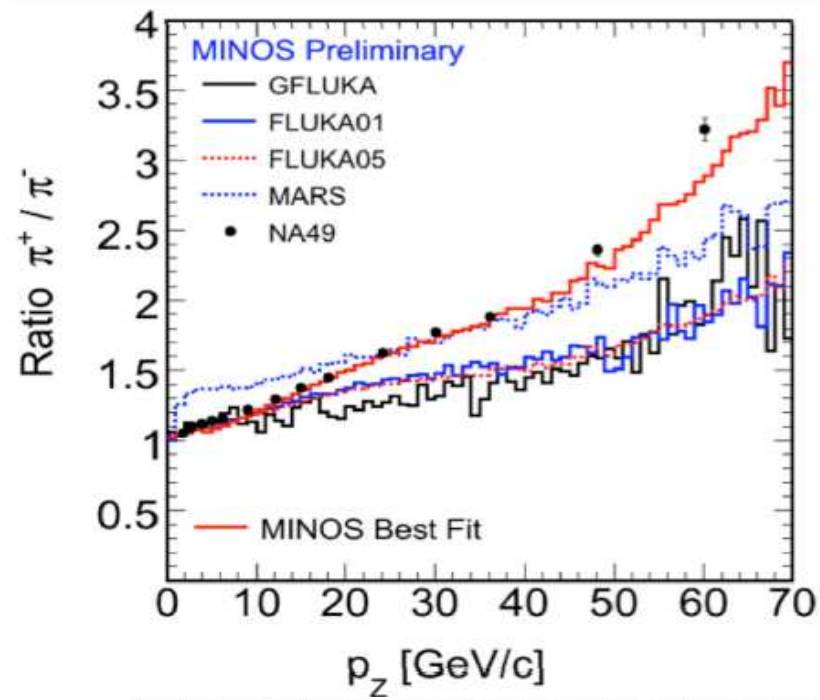
Shower energy computed using the average true hadronic energy of the k nearest-neighbor MC events in 3D space.

- Total energy deposited in 1 m transverse radius around vertex.
- Sum of energy in the two largest showers.
- length of the longest shower.

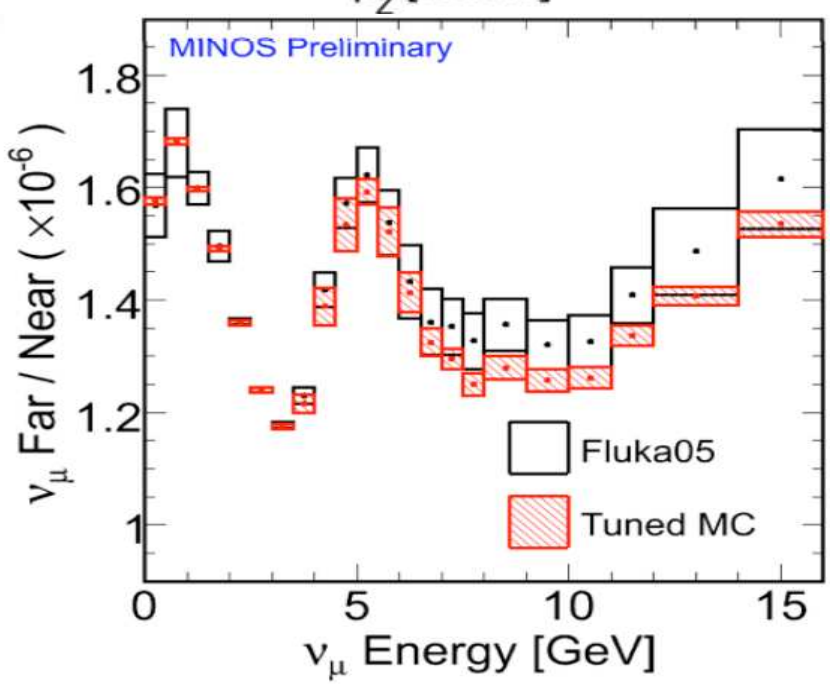


Near Detector Beam Flux Tuning

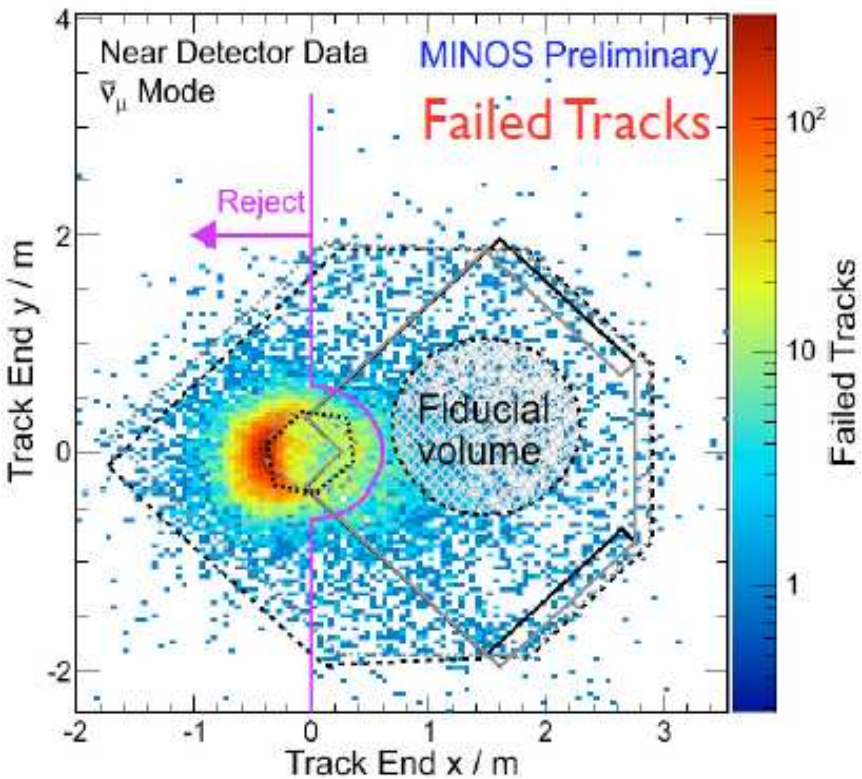




- Beam flux is tune by fitting x_f and p_t distributions with parametric model using several beam configurations.
- External input is used from NA49 π^+/π^- and K/π ratios.
  - Flux model uncertainty is taken into account in predicting the FD spectrum but is among the smallest uncertainties considered.



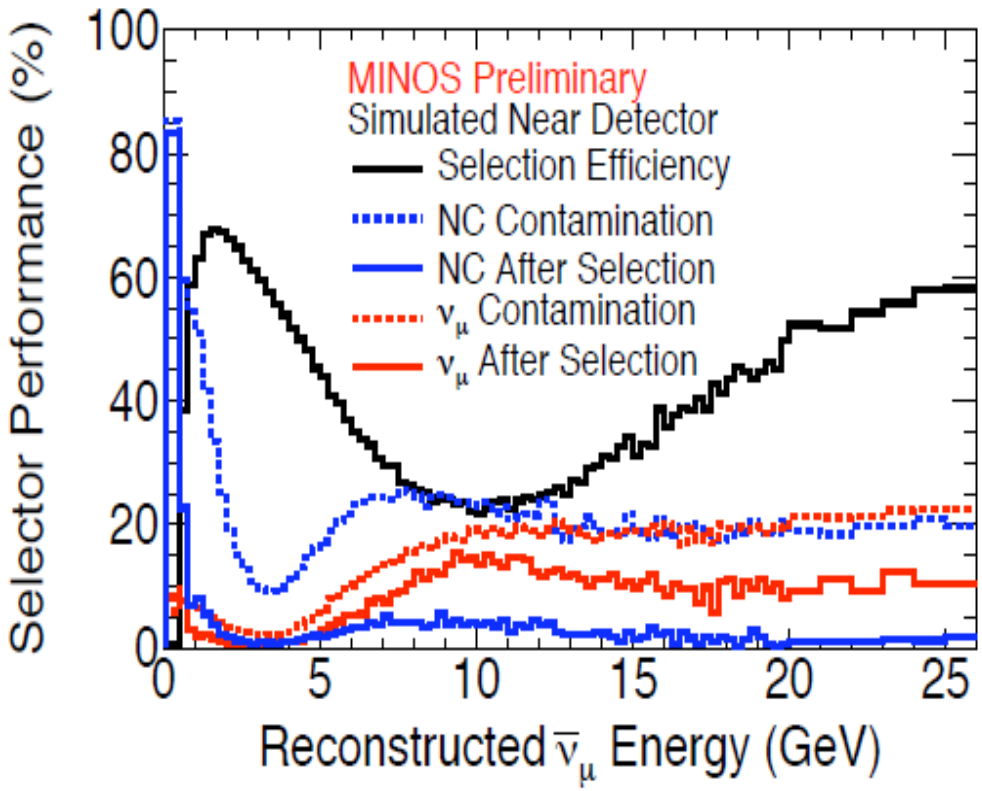
Near Detector Coil Hole Cut

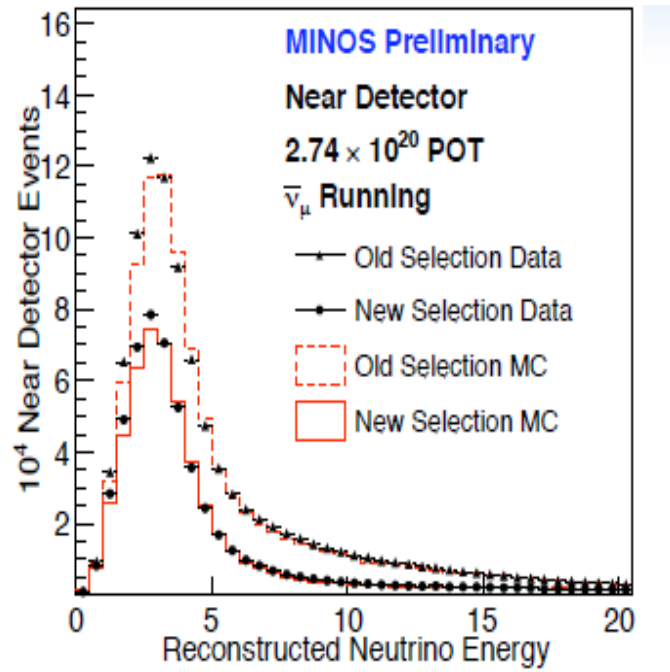


End positions of tracks failed by track fitter

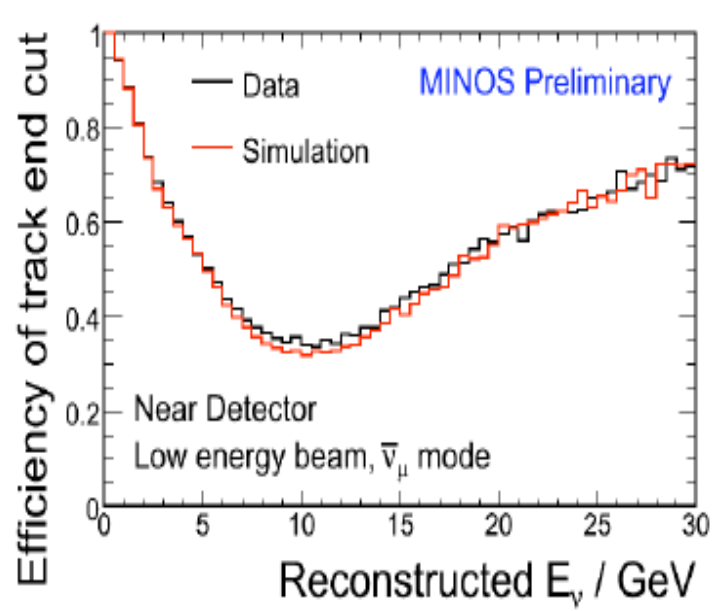
- Track fitter occasionally fails
  - Most failed tracks end near the coil hole.
  - ND coil region is difficult to model (4.2% failures in data, 6.1% in MC)
- New selection removes all tracks ending near or passing through the coil hole.
  - Selection is well modeled in MC
  - After selection only $\sim$1% of tracks fail (both data and MC)
- ND sample is better modeled at the expense of reduced efficiency.

Near Detector 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



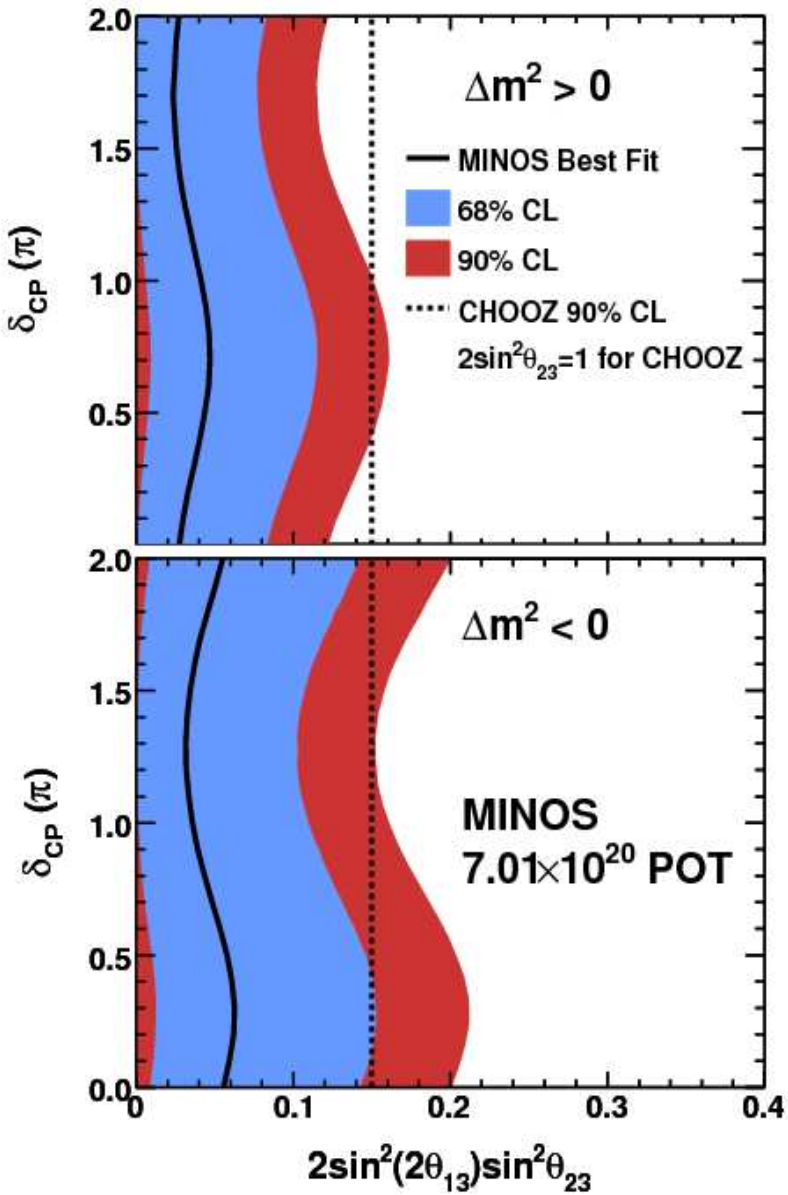
ν_e Appearance 2010 Result

For $2\sin^2(\theta_{23} = 1$, δ=0, and $|\Delta m^2_{32}| = 2.43x10^{-3}$eV^2

Normal mass hierarchy: $\sin^2(2\theta_{13}) < 0.12$

Inverted mass hierarchy: $\sin^2(2\theta_{13}) < 0.20$

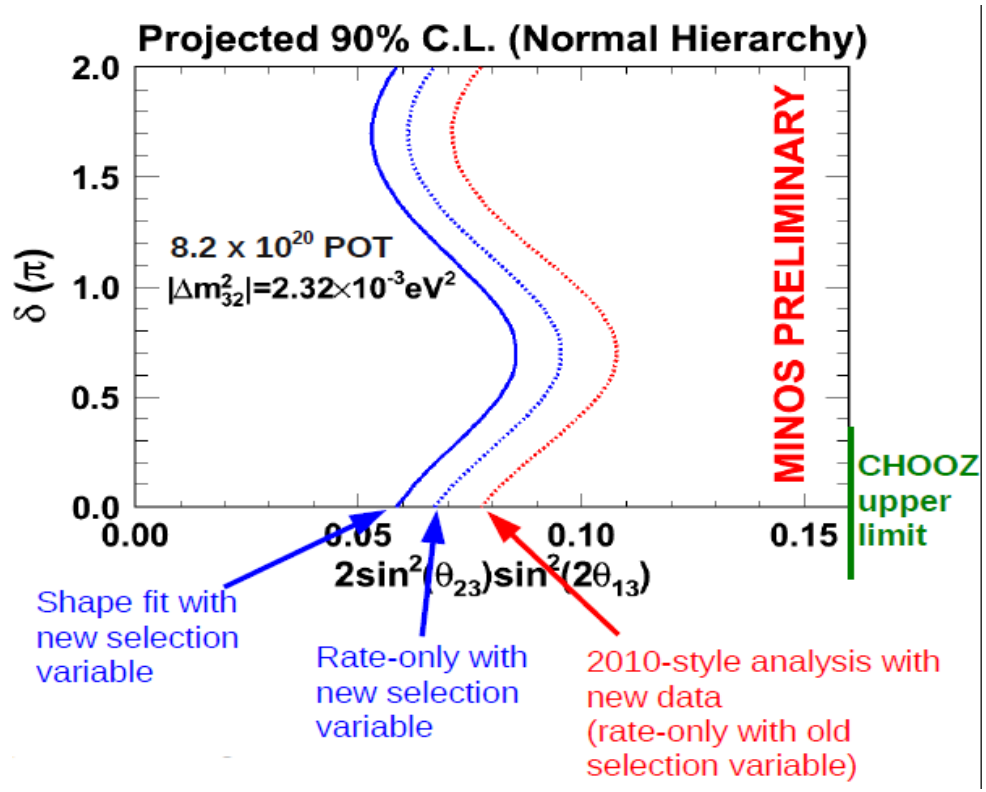
(P. Adamson *et al.*, Phys. Rev. D82 051102 (2010).)



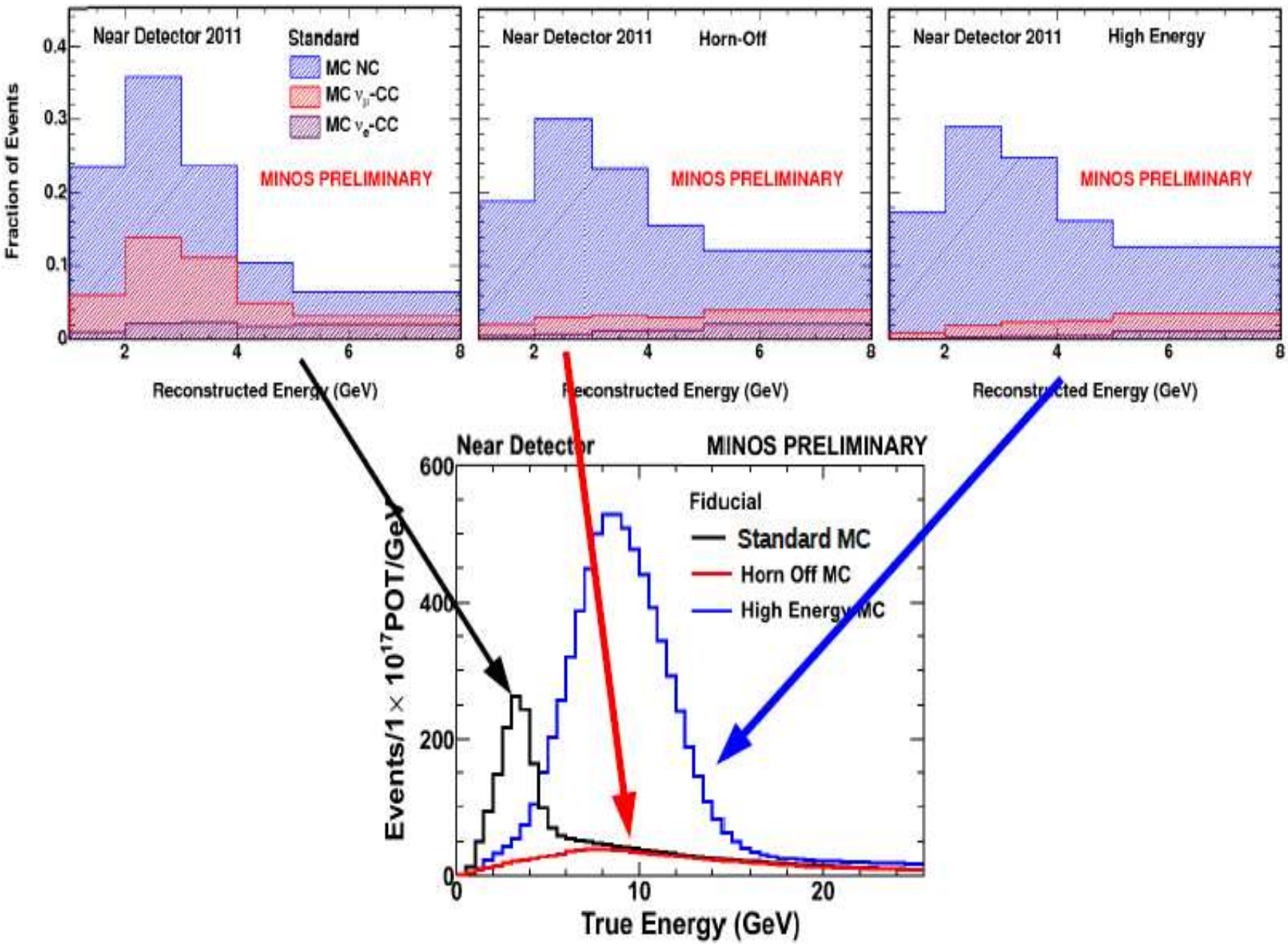
Improvements to ν_e Appearance Analysis

What's new for 2011 analysis

- New selection criterion (LEM)
- New shape fit: 5-energy bins, 3 PID bin
- 12% Increase in sample size (1.2E20 PoT more data).

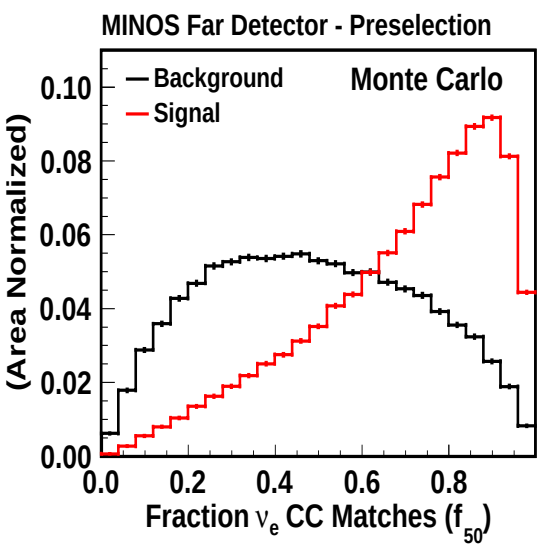


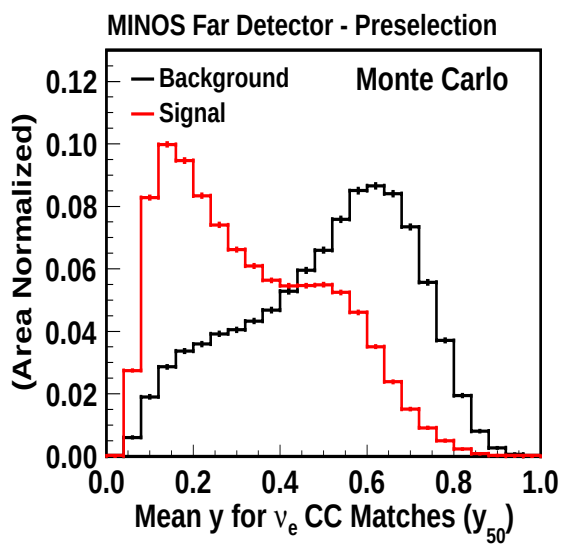
ν_e Background Decomposition

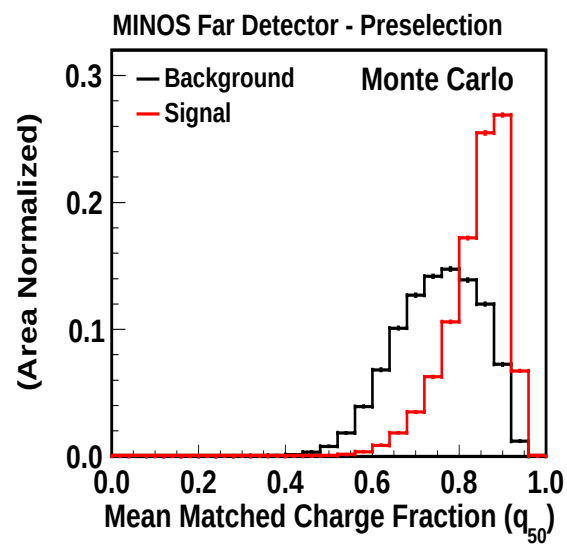


LEM PID Variable

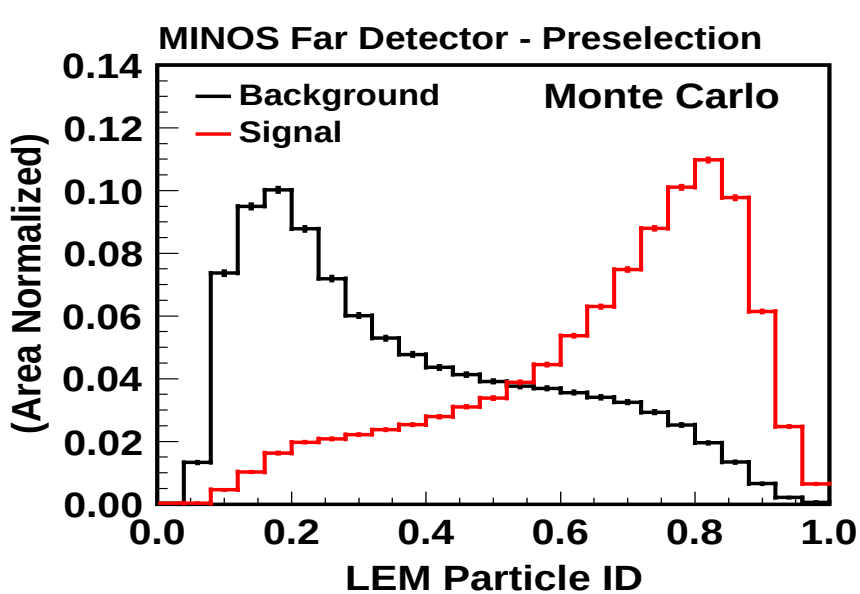
- Each event is compared to the library events (20M signal, 30M background) by calculating the likelihood that the photoelectrons came from the same energy deposition.



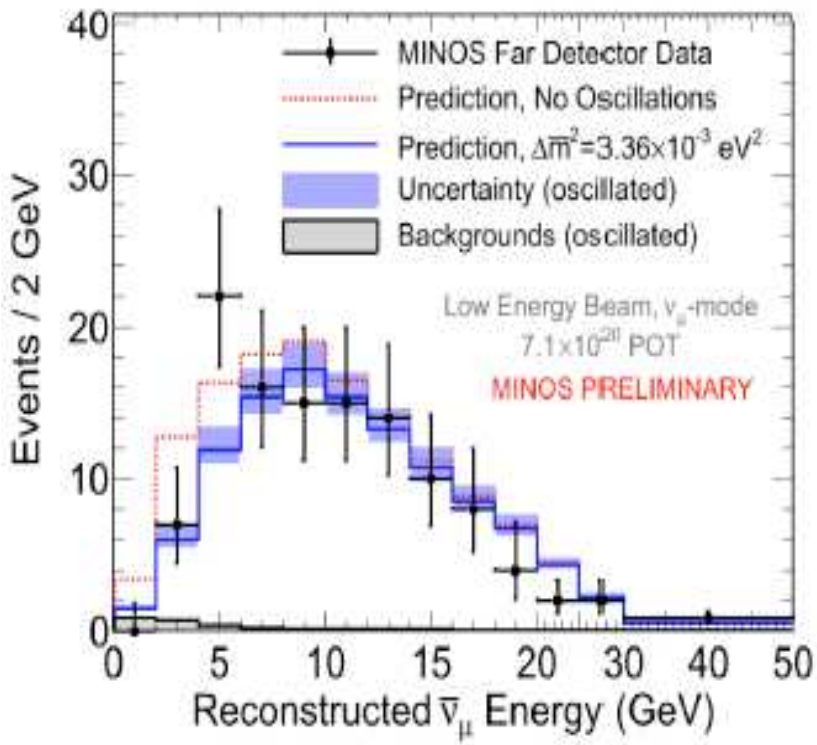


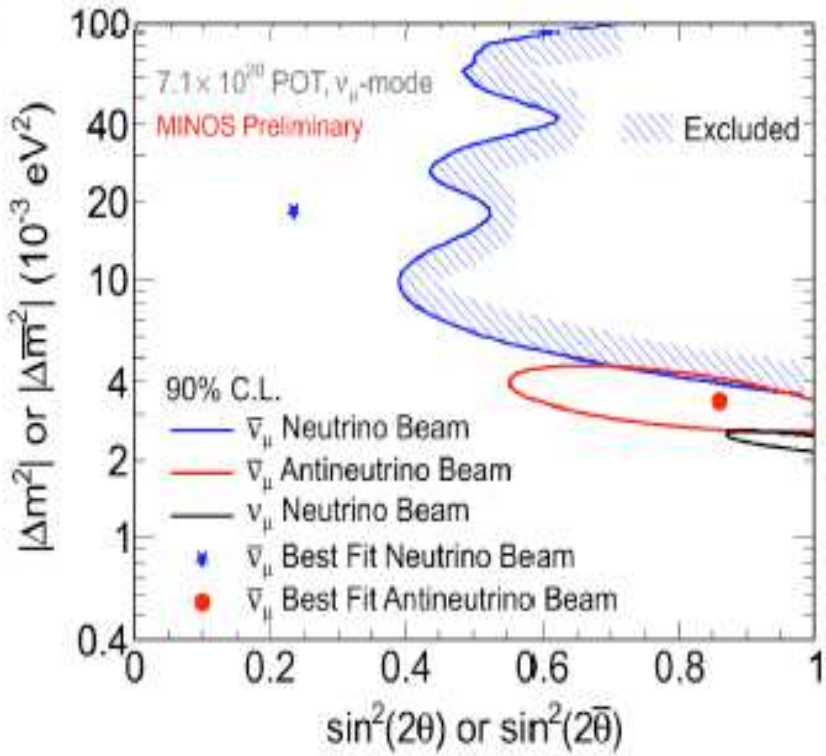


- Use three distributions from the best matches + reconstructed energy as input to a neural net.
- Output is LEM PID ($\sim$ 40% signal efficiency).



Antineutrinos in FHC Mode Beam



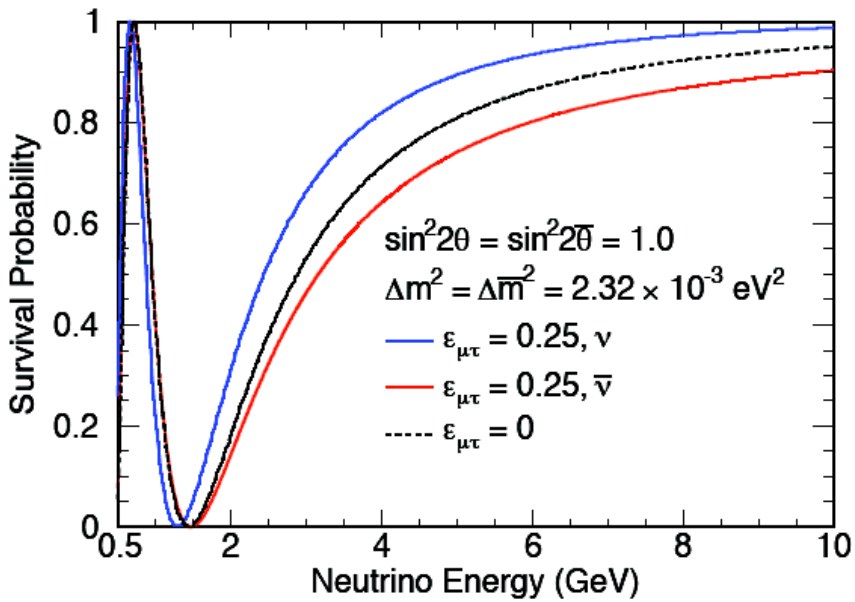


- Analyze 7% antineutrino component of neutrino beam
- Complementary information from higher energy events
- Results consistent with the other MINOS disappearance analysis

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

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

NSI Fit Run IV



- Combined fit to neutrino and antineutrino samples
- Three parameter fit to common oscillation parameters and $\epsilon_{\mu\tau}$

$$\Delta m^2 = 2.57 \pm 0.15 \times 10^{-3}\text{eV}^2.$$
$$\sin^2(2\theta) = 0.98 \pm 0.08$$
$$\epsilon_{\mu\tau} = -0.16 \pm 0.16$$

  - Expect update from combined sample very soon.