Newest Results from MINOS

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International Workshop on Next Nucleon decay and Neutrino detectors
NNN 08

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The MINOS Collaboration

Argonne • Arkansas Tech • Athens • Benedictine • Brookhaven • Caltech
Cambridge • Campinas • Fermilab • Harvard • IIT • Indiana • Minnesota-Duluth
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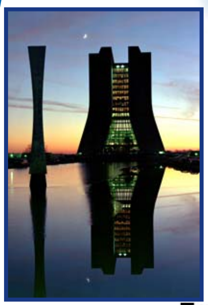
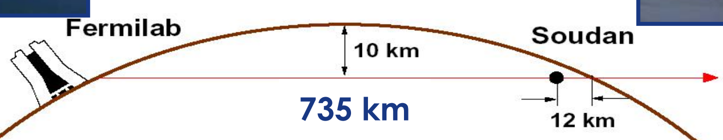
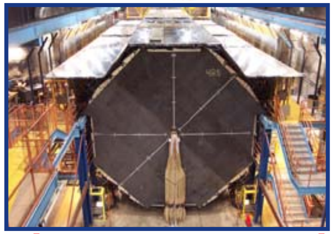
The MINOS Experiment





1 kton – 100 m deep



5.4 kton – 714 m deep

- **MINOS (Main Injector Neutrino Oscillation Search)**
  - Long-baseline neutrino oscillation experiment
- **Basic concept**
  - Create a neutrino beam provided by 120 GeV protons from the Fermilab Main Injector
  - Measure energy spectrum at the Near Detector, at Fermilab
  - Measure energy spectrum at the Far Detector, 735 km away, deep underground in the Soudan Mine.
  - Compare Near and Far measurements to study neutrino oscillations

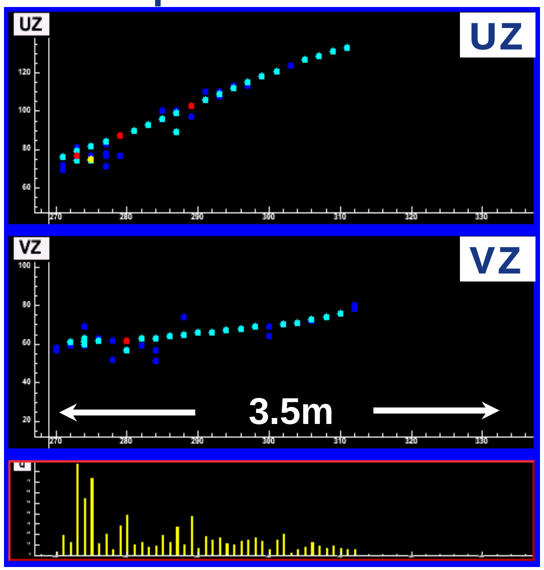
MINOS Physics Goals

- Precise measurements of $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$ via ν_μ disappearance
- Search for or constrain exotic physics such as sterile ν
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Compare ν, $\bar{\nu}$ oscillations
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections using the high statistics Near Detector data set

Event Topologies

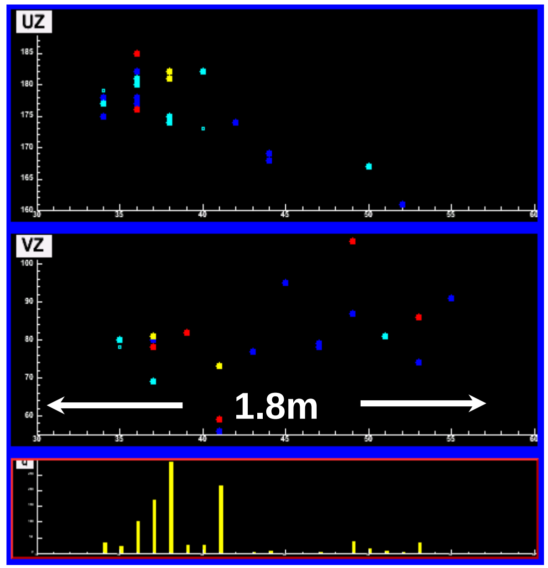
Monte Carlo

ν_μ CC Event



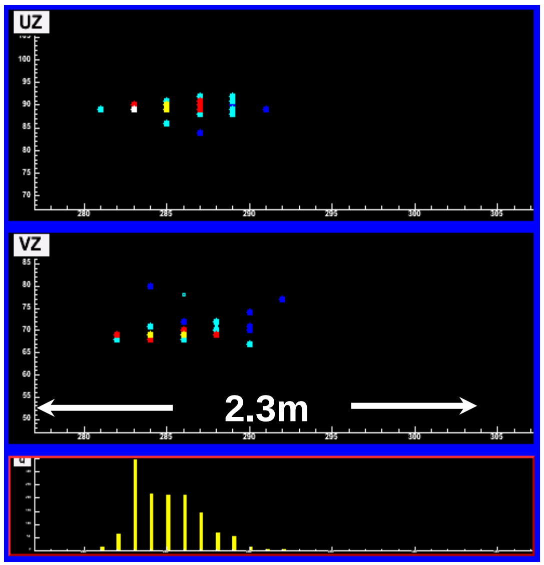
long μ track & hadronic activity at vertex

NC Event



short event, often diffuse

ν_e CC Event



short, with typical EM shower profile

Energy resolution

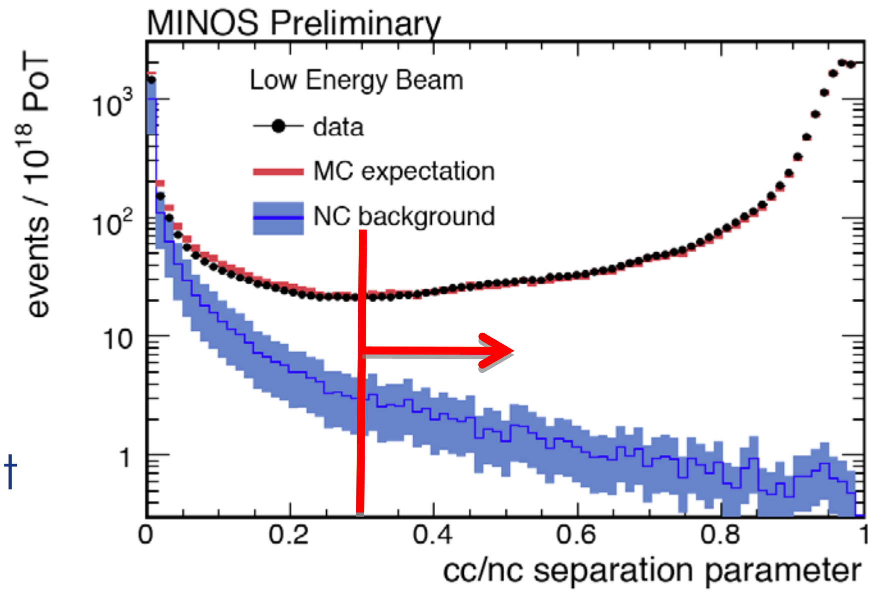
- $\pi^\pm$: 55%/$\sqrt{E(GeV)}$
- $\mu^\pm$: 6% range, 10% curvature

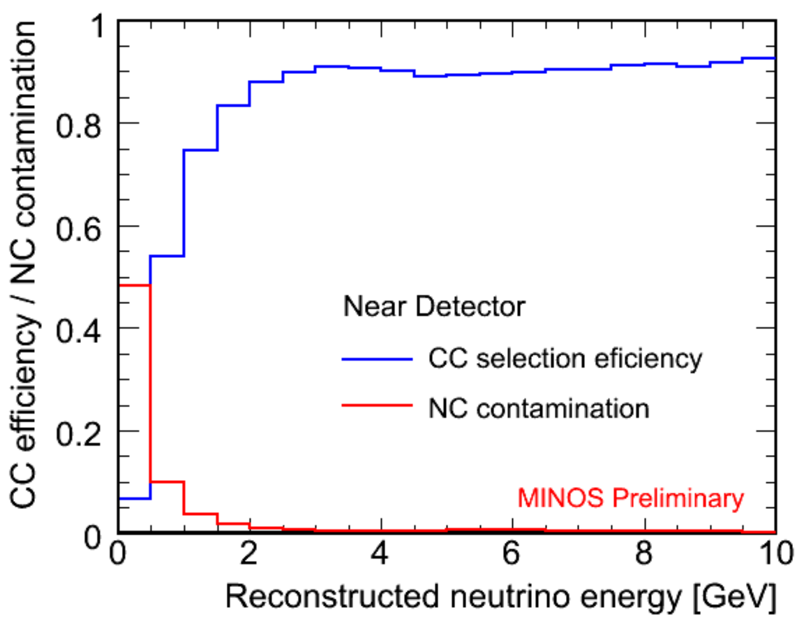
Charged Current Analysis of 3.36×10^{20} POT of MINOS Data

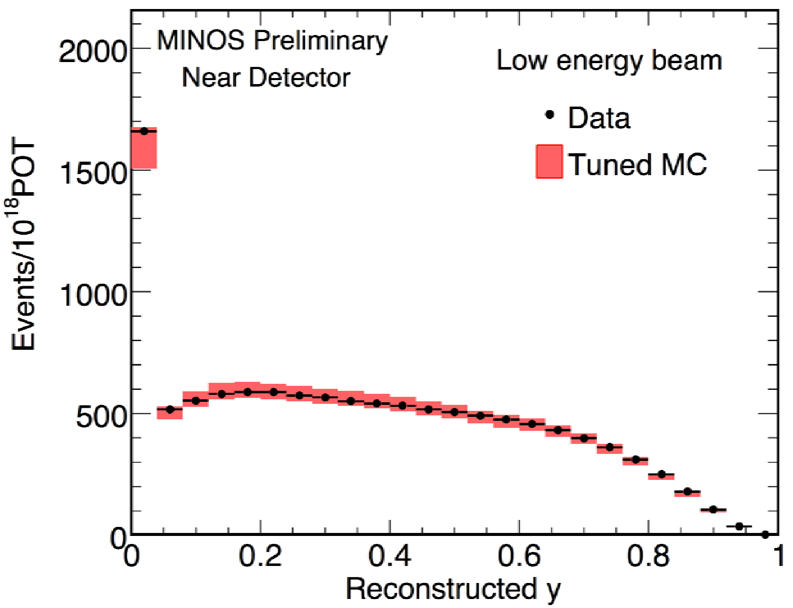
- Precision measurement of $|\Delta m^2|$ and $\sin^2 2\theta$ -

CC Event Selection

- CC / NC Event classification is performed with a k-nearest neighbor (kNN) based algorithm with four inputs:
    1. Track length (planes)
- For hits belonging to the track:
    2. Mean pulse height/plane
    3. Fluctuation in pulse height
    4. Transverse track profile

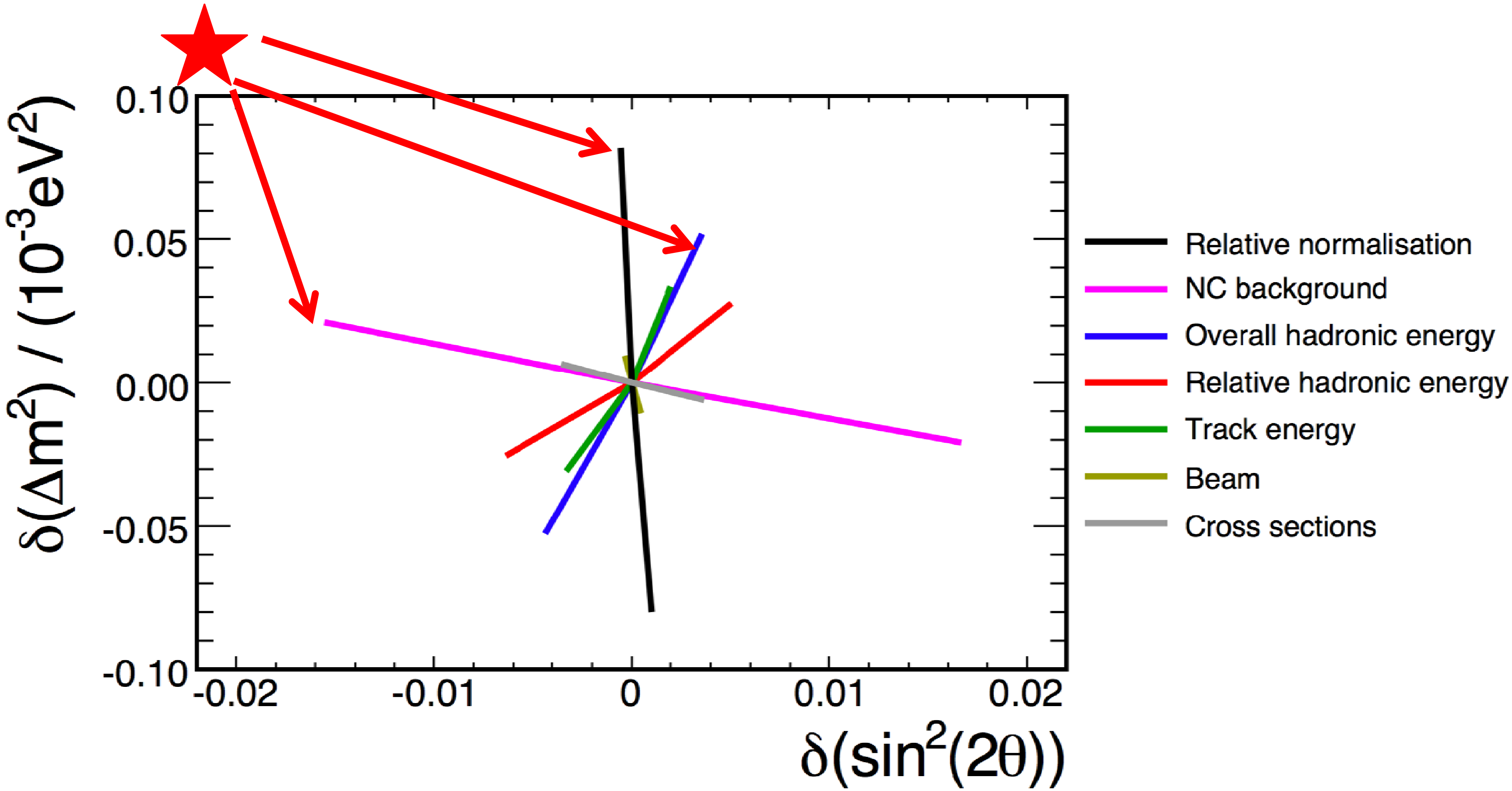






Systematic Uncertainties

- The impact of different sources of systematic uncertainty is evaluated by fitting modified MC in place of the data:



★ *The three largest shifts are included as nuisance parameters in the oscillation fit.*

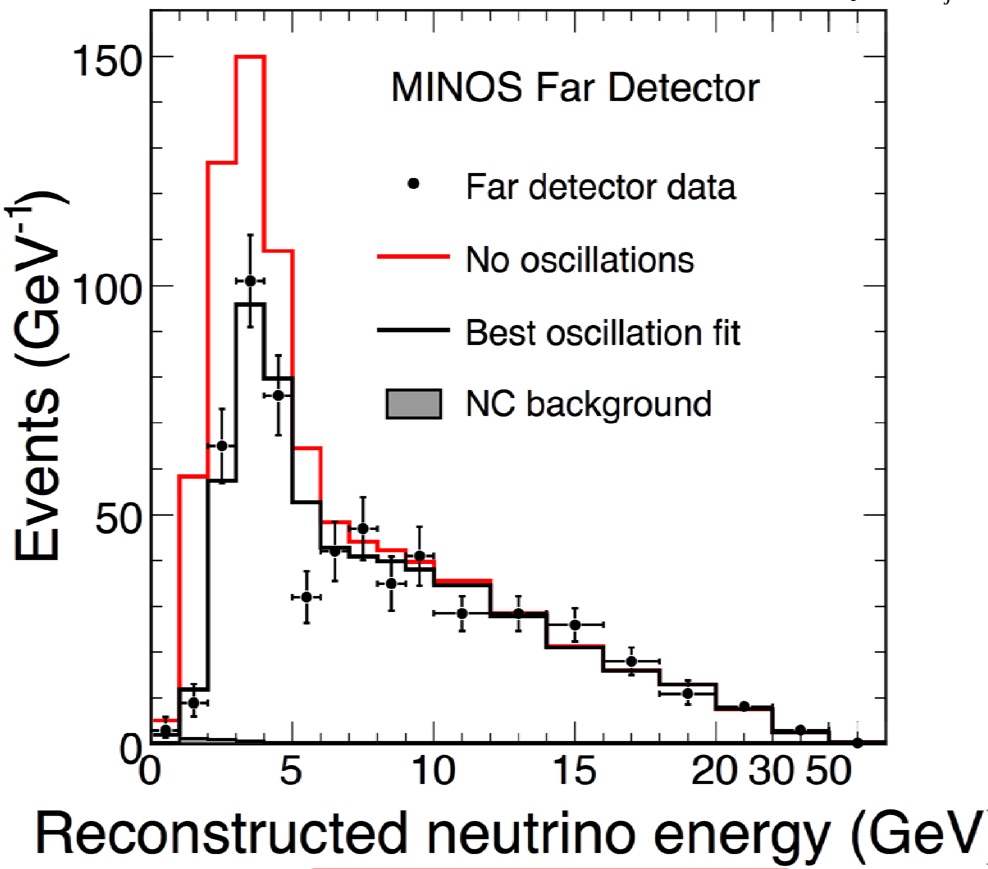
CC Energy Spectrum Fit

$$\chi^2 = \sum_{nbins}(2(e_i - o_i) + 2\, o_i \ln(o_i/e_i)) + \sum_{nsys}\frac{\Delta s_j^2}{\sigma_{s_j}^2}$$

- Fit the energy distribution to the oscillation hypothesis:

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

- Including the three largest sources of systematic uncertainty as nuisance parameters
  - Absolute hadronic energy scale: 10.3%
  - Normalization: 4%
  - NC contamination: 50%



Best Fit:
$|\Delta m^2| = 2.43\times10^{-3}$ eV^2
$\sin^2(2\theta) = 1.00$

Allowed Regions

$|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$ (68% C.L.)

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

$\chi^2/ndof = 90/97$

Fit is constrained to the physical region.

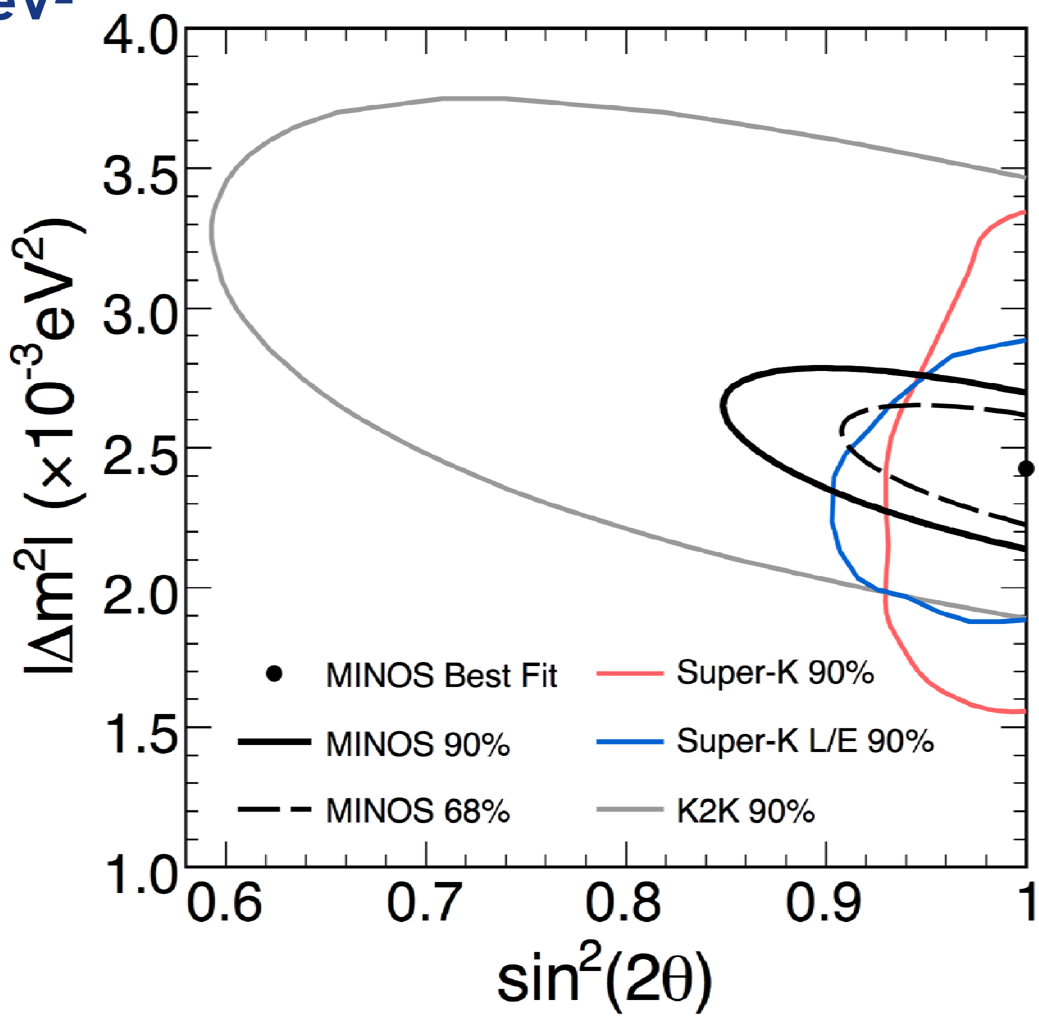
Unconstrained:

$|\Delta m|^2 = 2.33 \times 10^{-3}\ eV^2$

$\sin^2(2\theta) = 1.07$

$\Delta\chi^2 = -0.6$

Accepted by PRL:
arXiv:hep-ex/0806.2237



Most precise measurement of $|\Delta m|^2$ performed to date!

Alternative Hypotheses

Decay:

$$P_{\mu\mu} = \left[\sin^2\theta + \cos^2\theta \;\exp(-\alpha L/E)\right]^2$$

V. Barger *et al.*, PRL82:2640(1999)

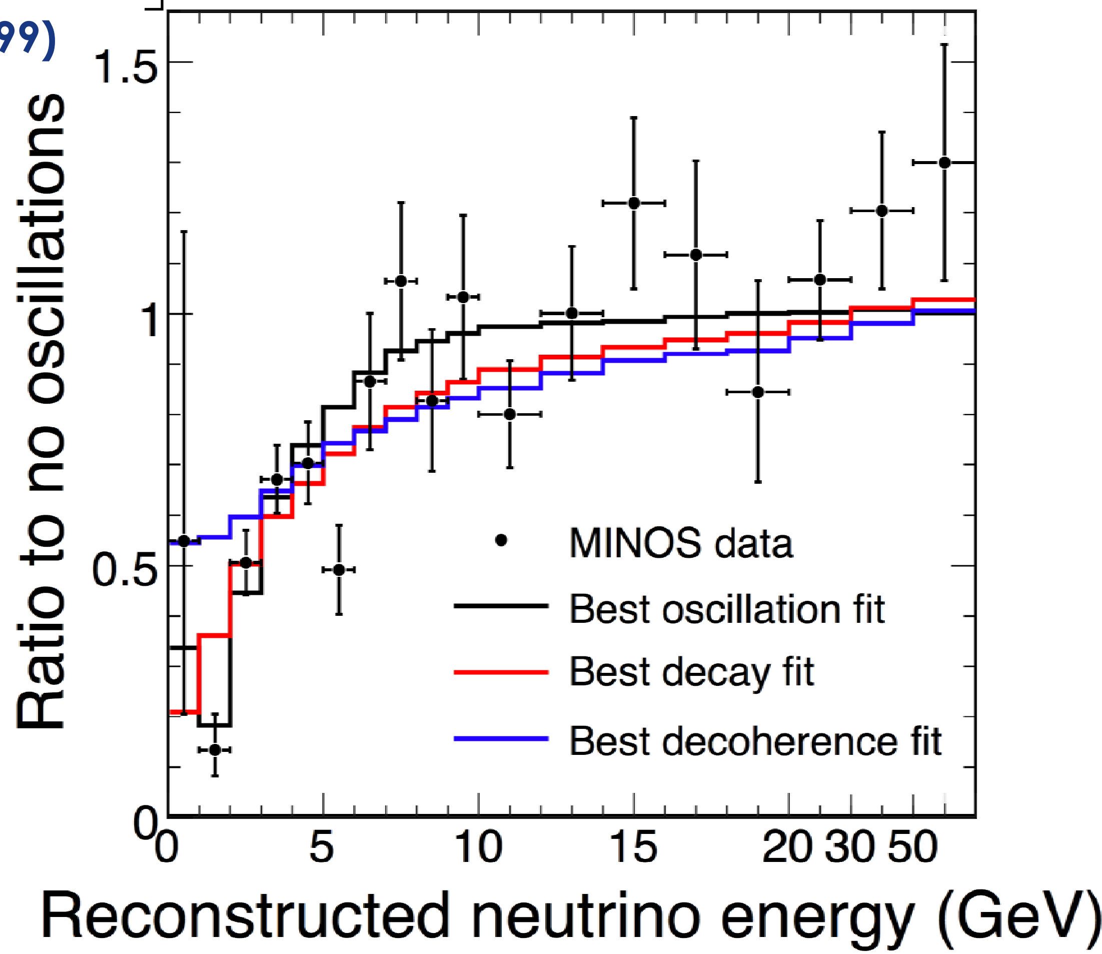
χ^2/ndof = 104/97
$\Delta\chi^2$ = 14
disfavored at 3.7σ

Decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

G.L. Fogli *et al.*, PRD67:093006(2003)

χ^2/ndof = 123/97
$\Delta\chi^2$ = 33
disfavored at 5.7σ

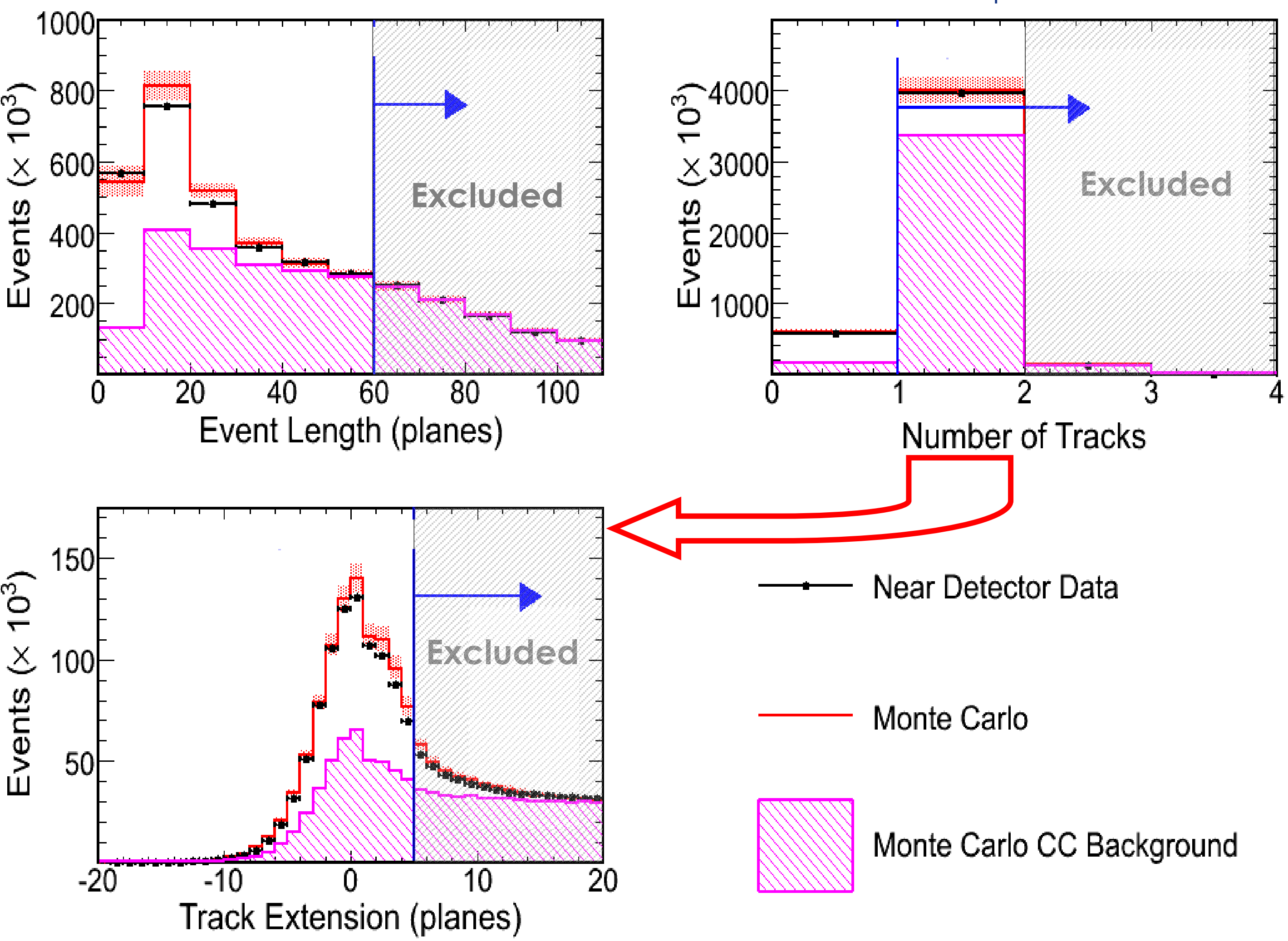


Neutral Current Analysis of 2.46×10^{20} POT of MINOS Data

- Looking for sterile neutrino mixing -

NC / CC Event Separation

- NC events are typically shorter than CC events
- Expect showers and no tracks or very short tracks reconstructed for NC events
- Main background from inelastic (high-y) ν_μ CC events



- Event classified as NC-like if:
  - event length < 60 planes
  - has no reconstructed track or
  - has one reconstructed track that does not protrude more than 5 planes beyond the shower

NC Analysis Results - Rate

- Compare the NC energy spectrum with the expectation of standard 3-flavor oscillation physics
  - Depletion of Far Detector NC spectrum may indicate sterile neutrino mixing

- Fix the oscillation parameter values
  - $\sin^2 2\Theta_{23} = 1$
  - $\Delta m^2_{32} = 2.43\times10^{-3}\ eV^2$

    } From MINOS 2008 CC measurement
  - $\Delta m^2_{21} = 7.59\times10^{-5}\ eV^2$, $\Theta_{12} = 0.61$ from KamLAND+SNO
  - $\Theta_{13} = 0$ or 0.21 (normal MH, $\delta=3\pi/2$) from CHOOZ Limit
    - N.B. CC ν_e are classified as NC by the analysis

- Make comparisons in terms of the ***R*** statistic:

$$R \equiv \frac{N_{Data} - B_{CC}}{S_{NC}}$$

Predicted CC background from all flavors (B_{CC})

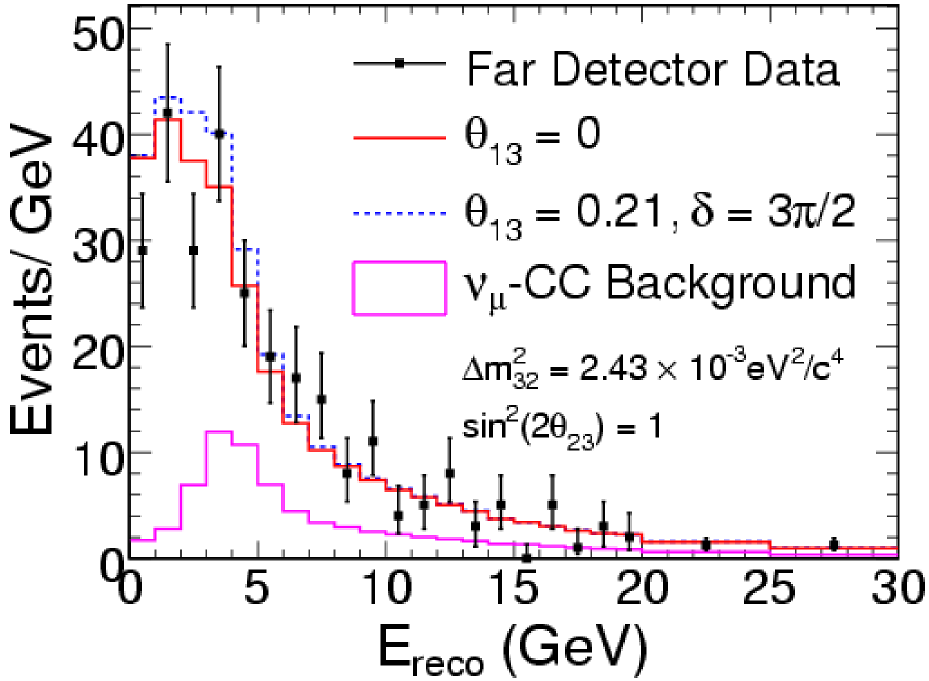
Predicted NC interaction signal (S_{NC})

- For different energy ranges
  - 0-3 GeV
  - 3-120 GeV
  - All events (0-120 GeV)

NC Analysis Results - Rate

- Plot shows the selected FD NC energy spectrum for Data and oscillated MC predictions
- Expect largest NC disappearance for E < 3 GeV if sterile mixing is driven by Δm^2_{32}
- Depletion of total NC event rate (1-***R***) < 17% at 90% C.L. for the 0-120 GeV range

MINOS Far Detector NC Spectrum



Data is consistent with no NC deficit at FD and thus with no sterile neutrino mixing

$E_{\rm reco}$ (GeV)	$N_{\rm Data}$	$S_{\rm NC}$	$B^{\nu_\mu}_{\rm CC}$	$B^{\nu_\tau}_{\rm CC}$	$B^{\nu_e}_{\rm CC}$
$0-3$	100	101.1	11.2	1.0	1.8 (9.3)
$3-120$	191	98.0	64.2	3.5	11.8 (24.6)
$0-3$	$R = 0.85 \pm 0.10 \pm 0.07$			$(0.78 \pm 0.10 \pm 0.07)$	
$3-120$	$R = 1.14 \pm 0.14 \pm 0.10$			$(1.02 \pm 0.14 \pm 0.10)$	
$0-120$	$R = 0.99 \pm 0.09 \pm 0.07$			$(0.90 \pm 0.09 \pm 0.08)$	

NC Analysis Results – f_s Fit

- Assume one sterile neutrino and that mixing between ν_μ, ν_s and ν_τ occurs at a single Δm^2

- Survival and sterile oscillation probabilities become:

$$P(\nu_\mu - \nu_\mu) = 1 - \alpha_\mu \sin^2(1.27\Delta m^2 L/E)$$

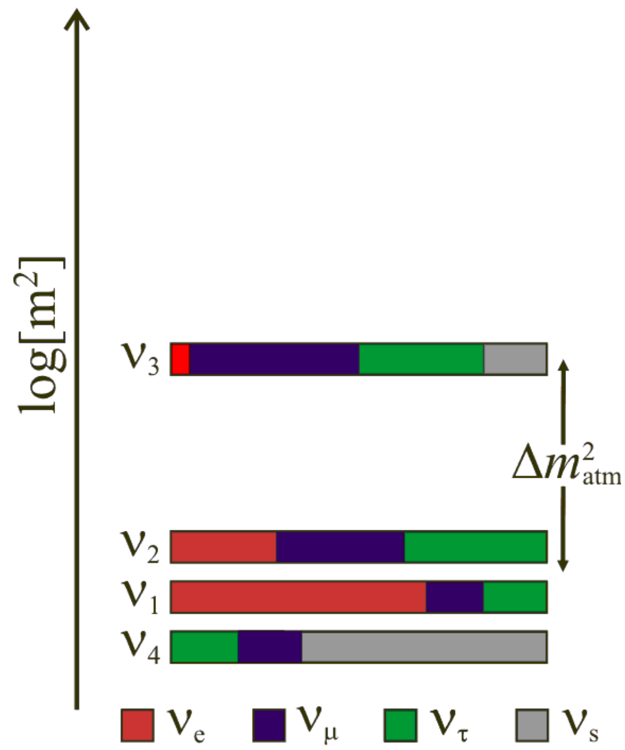
$$P(\nu_\mu - \nu_s) = \alpha_s \sin^2(1.27\Delta m^2 L/E)$$

- Simultaneous fit to CC and NC energy spectra yields the fraction of ν_μ that oscillate to ν_s:

$$f_s = \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)} = 0.28^{+0.25}_{-0.28}(\text{stat.+syst.})$$

$$f_s < 0.68 \quad (90\%\ \text{C.L.})$$

Submitted to PRL (arXiv:hep-ex/0807.2424)

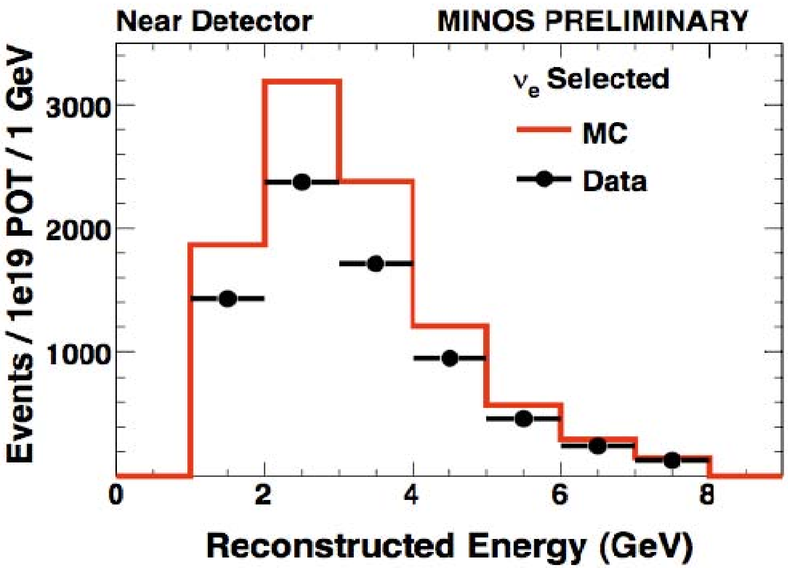


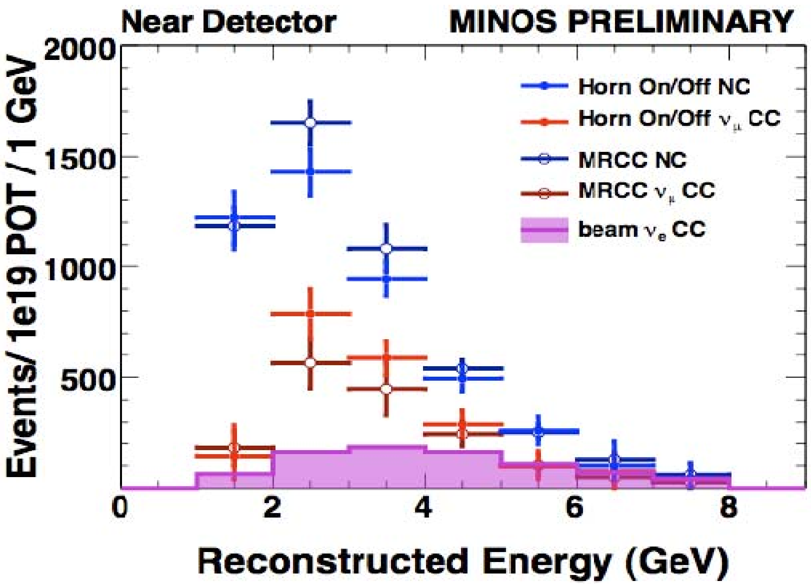
ν_e Appearance Analysis

- Constraining θ_{13} -

ν_e Selection

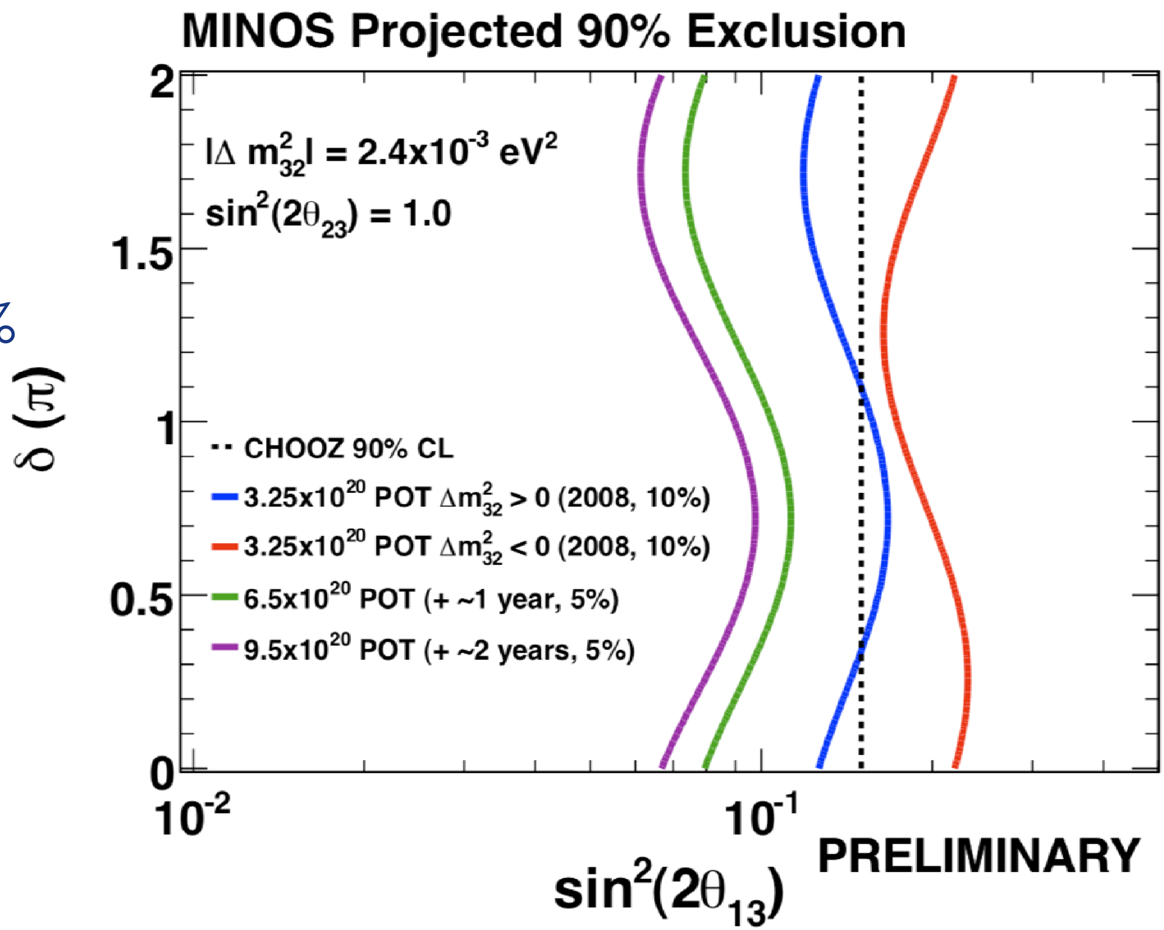
- NC and short ν_μ CC events are the dominant backgrounds
- Neural Network ν_e selection algorithm based on characteristics of electromagnetic showers
- MC tuned to bubble chamber experiments for hadronization models
- Data/MC comparisons show disagreements due to hadronic model
- Correct the model to match the data using data-driven methods in ND
- Background predictions from two methods agree within statistical uncertainty





Future θ_{13} Limits

- Expect 12 signal and 42 bg events at the CHOOZ limit for the current exposure
- Data-driven systematics are hoped to drop to 5% in future years
- Inverted hierarchy shown only for lowest exposure for simplicity
- MINOS can improve the CHOOZ limit on **θ_{13}** by a factor of 2!

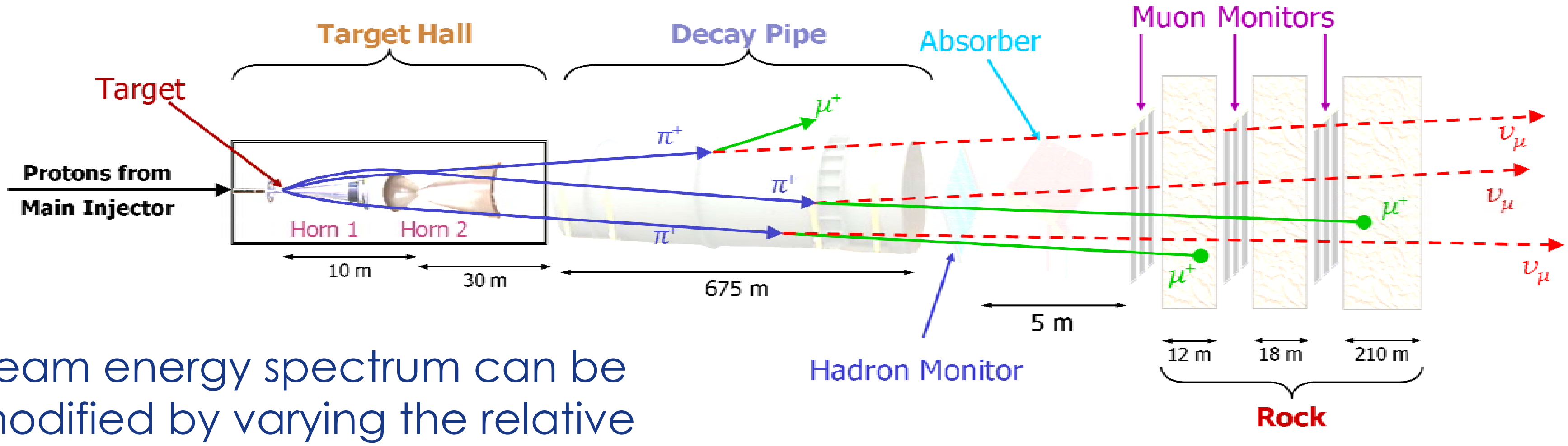


Summary and Conclusions

- The MINOS Experiment is making several contributions to our understanding of Neutrino Physics
- New measurement of atmospheric oscillation parameters from ν_μ disappearance:
  - $|\Delta m|^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% C.L.)
  - $\sin^2(2\theta) > 0.90$ (90% C.L.)
  - **Decay** and **decoherence** models are **disfavored** at **3.7σ** and **5.7σ**, respectively
- New results from search for oscillations into sterile neutrinos:
  - 1-***R*** < 17% at 90% C.L., 0 < E < 120 GeV
  - $f_s < 0.68$ (90% C.L.)
  - Consistent with no sterile neutrino mixing
- First results on ν_e appearance expected later this year and have sensitivity below the CHOOZ limit.

Backup Slides

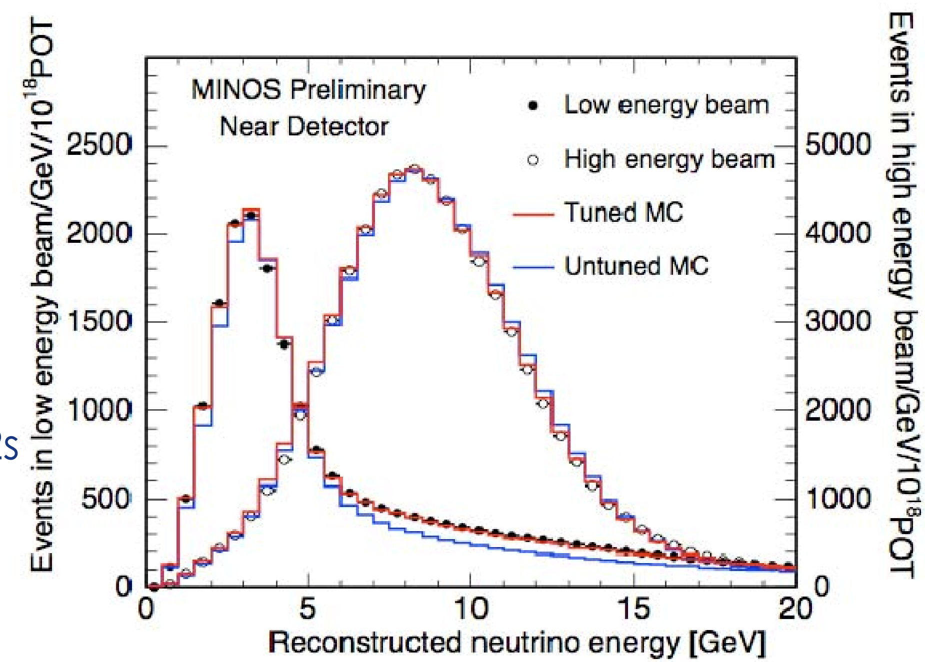
The NuMI Neutrino Beam



- Beam energy spectrum can be modified by varying the relative positions of target and horns.
- Beam composition in the LE configuration:

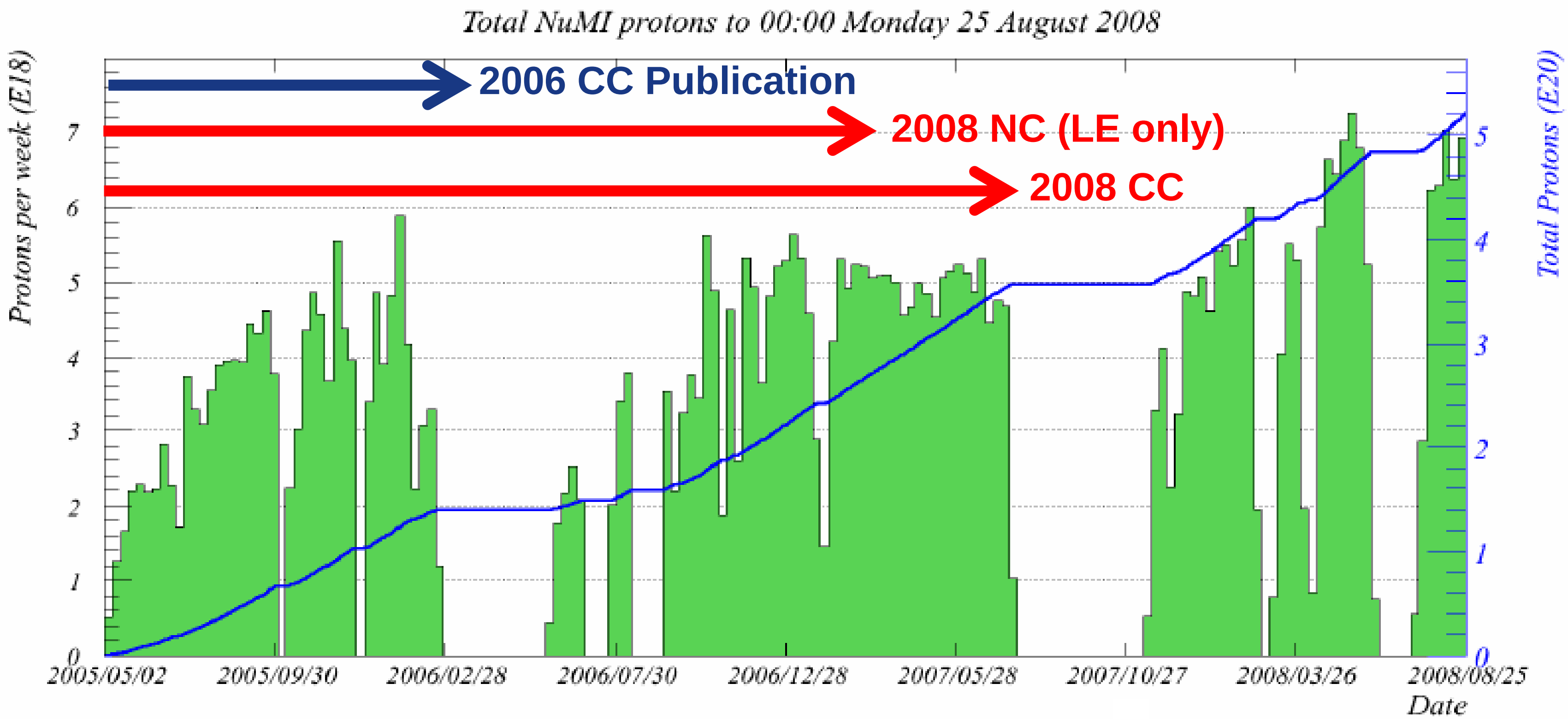
$$92.9\%\ \nu_\mu,\ 5.8\%\ \overline{\nu}_\mu,\ 1.3\%\ \nu_e + \overline{\nu}_e$$

- Beam performance:
  - 10μs spill of 120 GeV protons every 2.2s
  - Intensity: 3.0×10^{13} POT/spill
  - 0.275 MW beam power
  - 10^{18} POT/day



Accumulated Beam Data

Many thanks to Fermilab's Accelerator Division



RUN I - 1.27x10^{20} POT

Higher energy beam

0.15×10^{20} POT

RUN IIa

1.23×10^{20} POT

RUN IIb

0.71×10^{20} POT

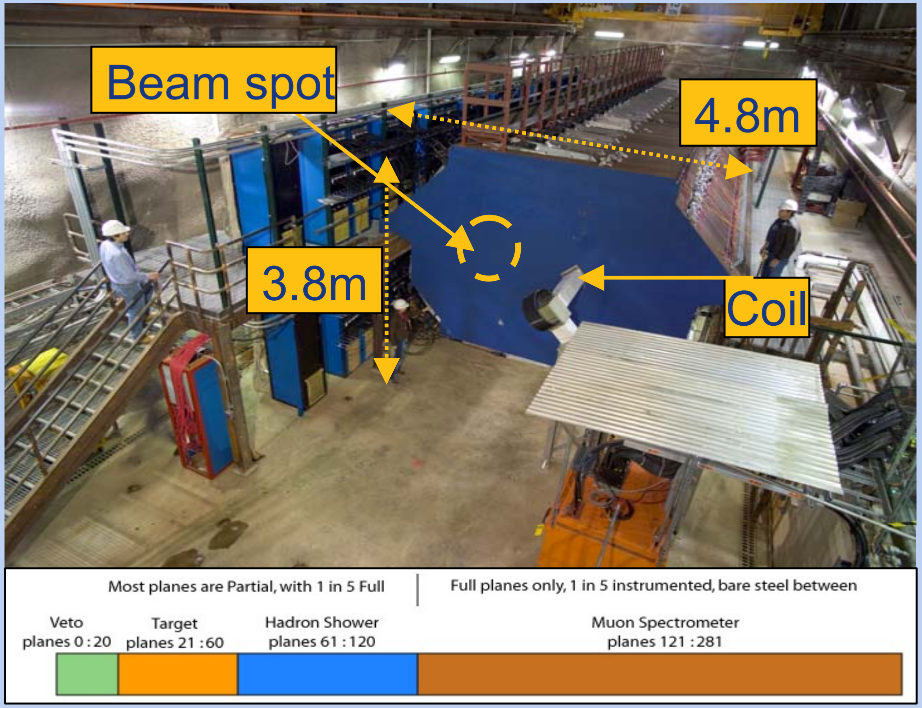
RUN III

1.2×10^{20} POT

The MINOS Detectors

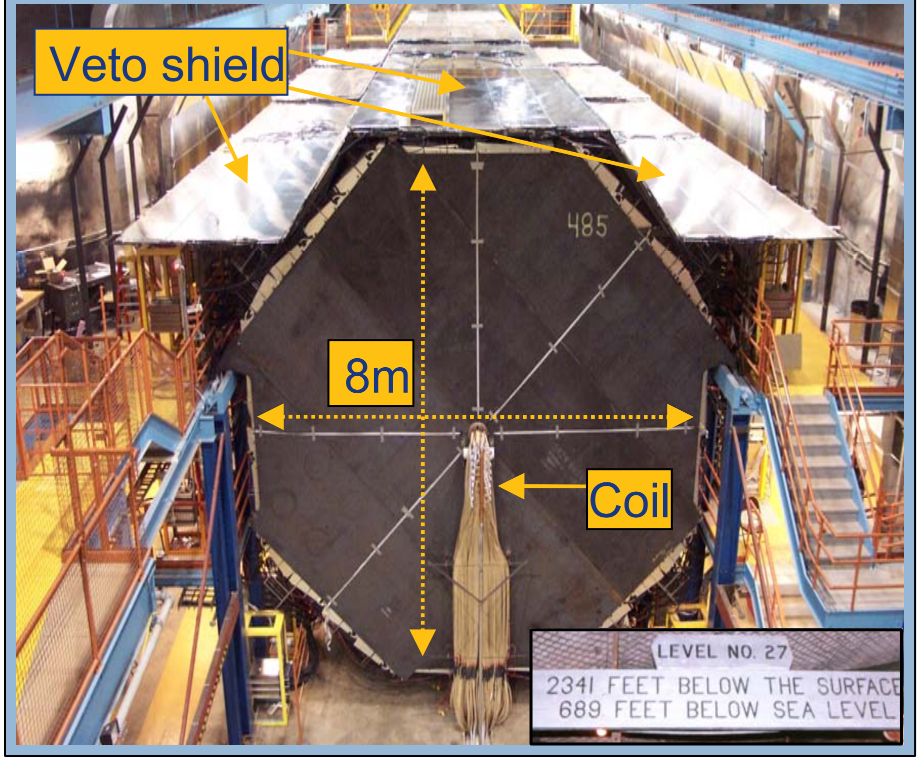
Near Detector

- Located 1km downstream of the target
- ~1kt (980t) total mass
- Shaped as squashed octagon ($4.8\times3.8\times15m^3$)
- Partially instrumented (282 steel, 153 scintillator planes)
- Fast QIE readout electronics, continuous sampling during beam spill



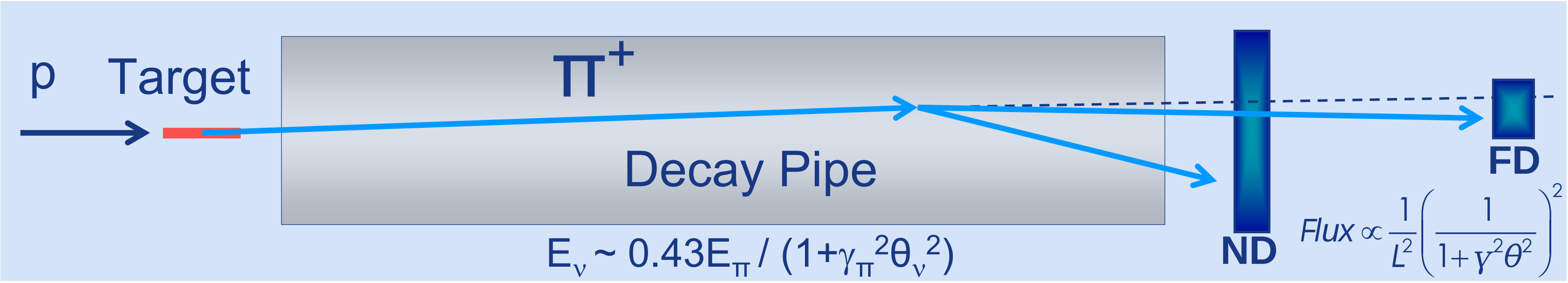
Far Detector

- Located 735km away in Soudan mine, MN
- 5.4kt, 2 supermodules
- Shaped as octagonal prism ($8\times8\times30m^3$)
- 486 steel planes, 484 scintillator planes
- Veto shield (scintillator modules)
- Spill times from Fermilab for beam trigger

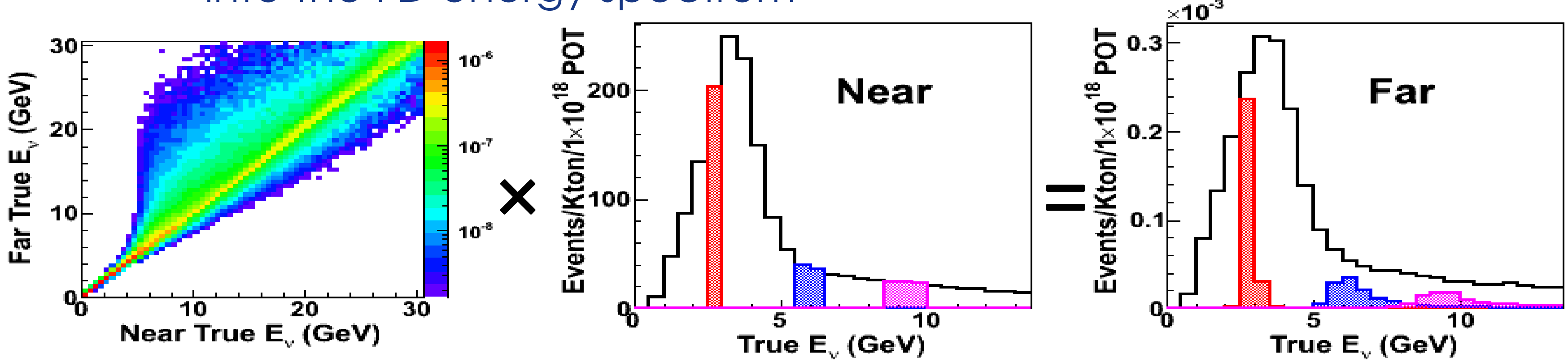


Near to Far Extrapolation

- Far detector energy spectrum without oscillations is not the same as the Near detector spectrum



- Start with near detector data and extrapolate to the far detector
  - Use Monte Carlo to provide corrections due to energy smearing and acceptance
  - Encode pion decay kinematics and the geometry of the beamline into a **beam transport matrix** used to transform the ND spectrum into the FD energy spectrum

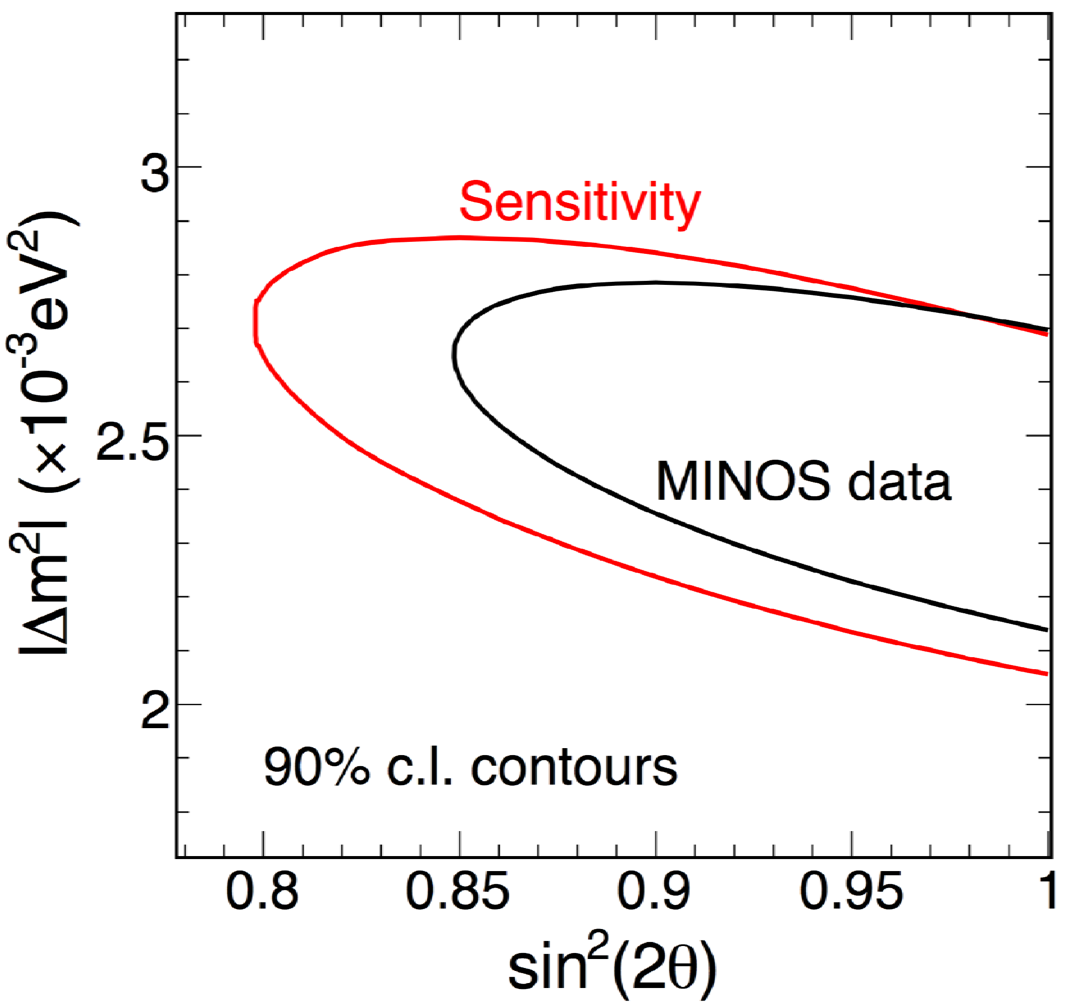


Data Sensitivity

For a true value at the best fit point of:

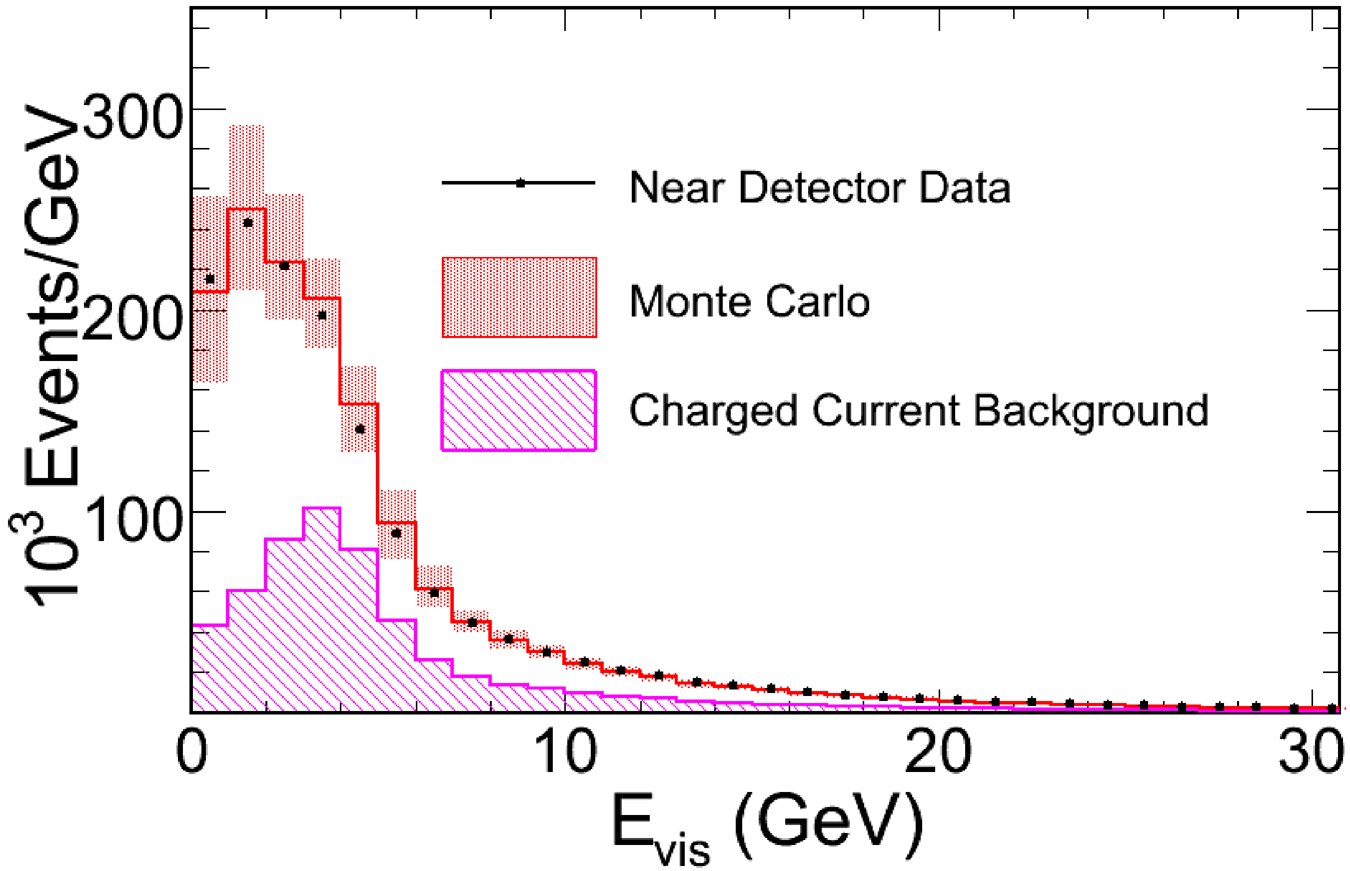
$|\Delta m^2| = 2.43\text{x}10^{-3}\ eV^2$
$\sin^2(2\theta) = 1.00$,

26.5% of unconstrained fits have a fit value of $\sin^2(2q) \geq 1.07$.



Neutral Current NC Energy Spectrum

- NC selected Data and MC energy spectra for Near Detector



- Good agreement between Data and Monte Carlo
- Discrepancies much smaller than systematic uncertainties
- NC events are selected with 90% efficiency and 60% purity

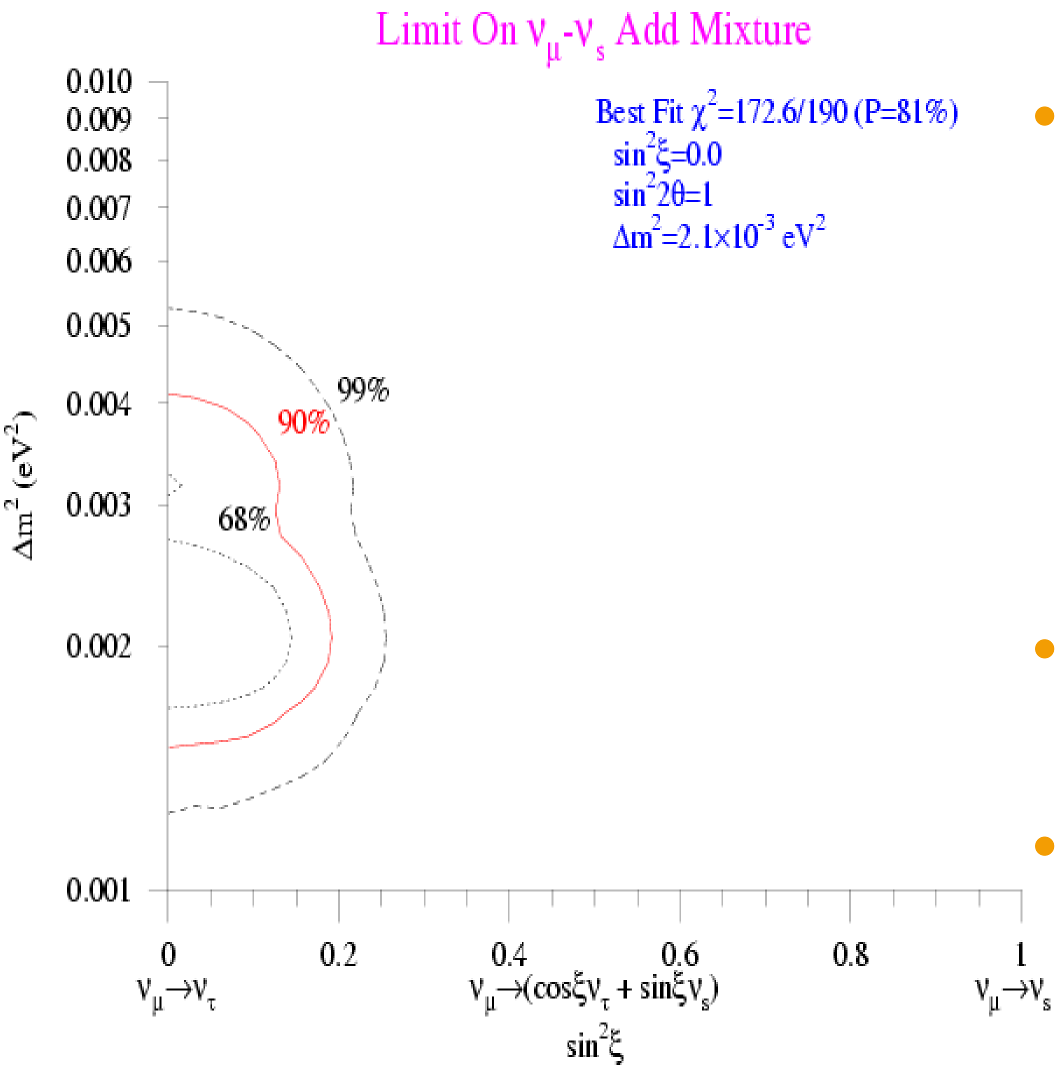
Systematic Errors

- **Relative Normalization:** ±4%
  - POT counting, Near/Far reconstruction efficiency, fiducial mass
- **Relative Hadronic Calibration:** ±3%
  - Inter-Detector calibration uncertainty
- **Absolute Hadronic Calibration:** ±11%
  - Hadronic Shower Energy Scale(±6%), Intranuclear rescattering(±10%)
- **Muon energy scale:** ±2%
  - Uncertainty in dE/dX in MC
- **CC Contamination of NC-like sample:** ±15%
- **NC contamination of CC-like sample:** ±25%
- **Cross-section uncertainties:**
  - m_A (qe) and m_A (res): ±15%
  - KNO scaling: ±33%
- **Poorly reconstructed events:** ±10%
- **Near Detector NC Selection:** ±8% in 0-1 GeV bin
- **Far Detector NC Selection:** ±4% if E < 1 GeV, <1.6% if E > 1 GeV
- **Beam uncertainty:** 1σ error band around beam fit results

	$0-3$ GeV	$3-120$ GeV
Absolute E_{had}	$\pm < 0.01$	± 0.05
Relative E_{had}	± 0.03	± 0.04
Normalization	± 0.04	± 0.08
Near detector selection	± 0.02	–
ν_μ-CC background	± 0.03	± 0.01
Total:	± 0.07	± 0.10

Effect of the most relevant systematic uncertainties on ***R***

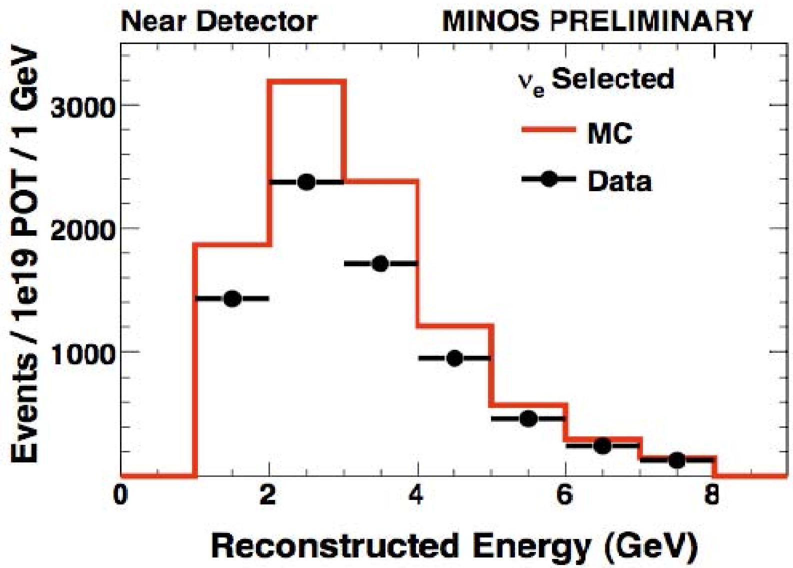
ν_μ to $\nu_{sterile}$ in SuperK



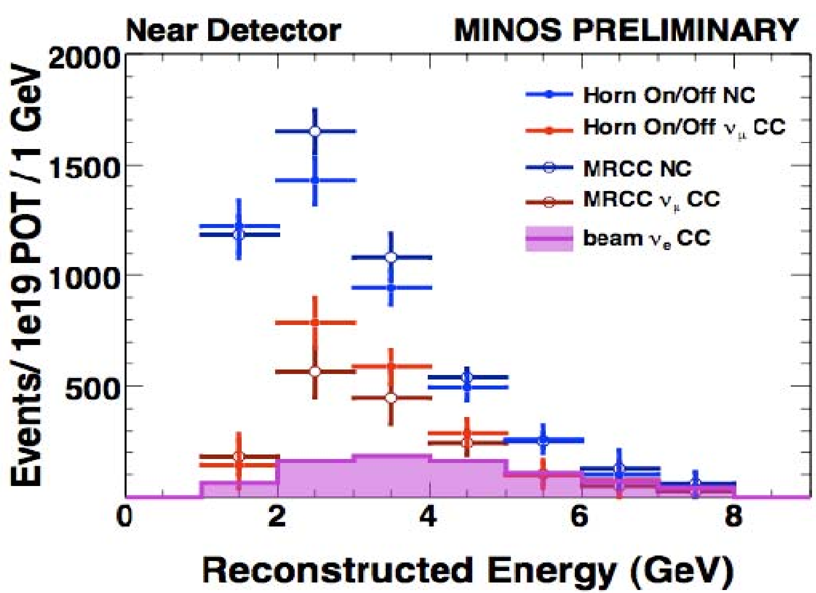
- High energy ν experience matter effects which suppress oscillations to sterile ν
  - Matter effects not seen in up-μ or high-energy PC data
  - Reduction in neutral current interactions also not seen
  - constrains ν_s component of ν_μ disappearance oscillations
- Pure ν_μ->ν_s disfavored
  - ν_s fraction < 20% at 90% c.l.
- Result published only in conference proceedings

ν_e Selection

- Neural Network ν_e selection algorithm based on characteristics of electromagnetic showers
- MC tuned to bubble chamber experiments for hadronization models
- Data/MC comparisons show disagreements due to hadronic model

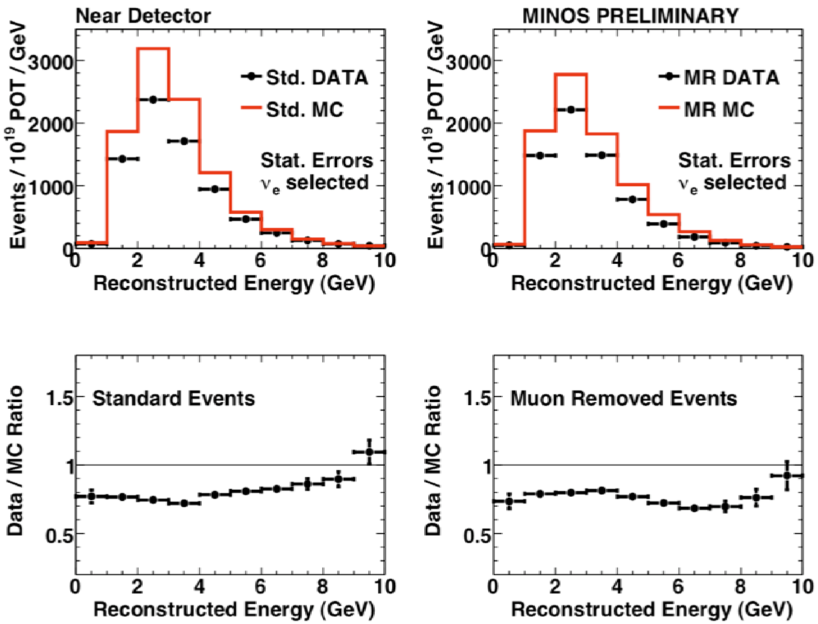


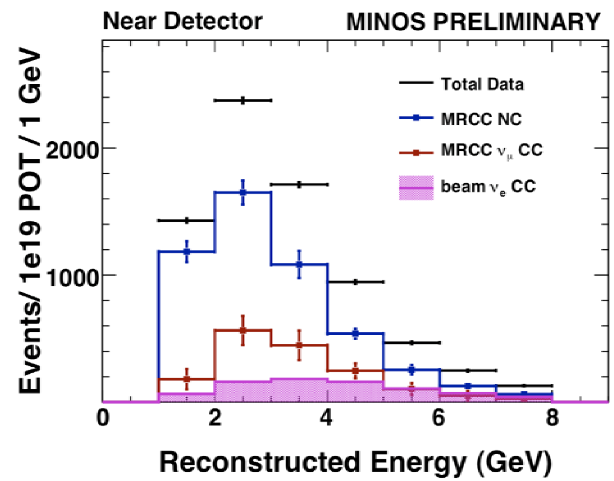
- Developed two data-driven methods to correct the model to match the data
- Muon Removed CC Events (**MRCC**)
  - Use well understood ν_μ CC data sample with removed track hits to correct **NC** event number
  - **Beam ν_e** known from MC, subtract from **NC** component to obtain **ν_μ CC**
- Horns on/off
  - pions are not focused with horns off and energy spectrum peak disappears
  - Estimate **NC** and **ν_μ CC** from differences between horns on/off data samples and MC
- Extrapolate each background to FD to obtain data-driven sensitivities



Muon Removal

- >20% Data/MC discrepancy in both the standard ν_e and the muon removed CC samples
- Comparisons of standard Data and MC shower topological distributions disagree in the same way as does MRCC data with MRCC MC
  - So MC hadronic shower production/modeling is a major contribution to the disagreement.
  - Kinematic phase space of MRCC and selected NC events matches well, but MRCC and selected CC events do not.
- The MRCC sample is thus used to make ad-hoc correction to the model to NC events per bin
  - Beam ν_e from MC, CC events are the remainder





Horn on / off Method

- After applying ν_e selection cuts to Near Detector data, the composition of the selected events is quite different with the NuMI focusing horns on or off.

$$N_{on} = N_{NC} + N_{CC} + N_e \quad (1)$$
$$N_{off} = r_{NC}*N_{NC} + r_{CC}*N_{CC} + r_e*N_e \quad (2)$$

from MC:

$$r_{NC(CC,e)} = N_{NC(CC,e)}^{off}/N_{NC(CC,e)}^{on}$$

- Get horn on/off ratios from MC, then solve for NC and CC backgrounds in bins of energy, get beam ν_e from the beam MC (a well understood number)
  - Independent of hadronic modeling