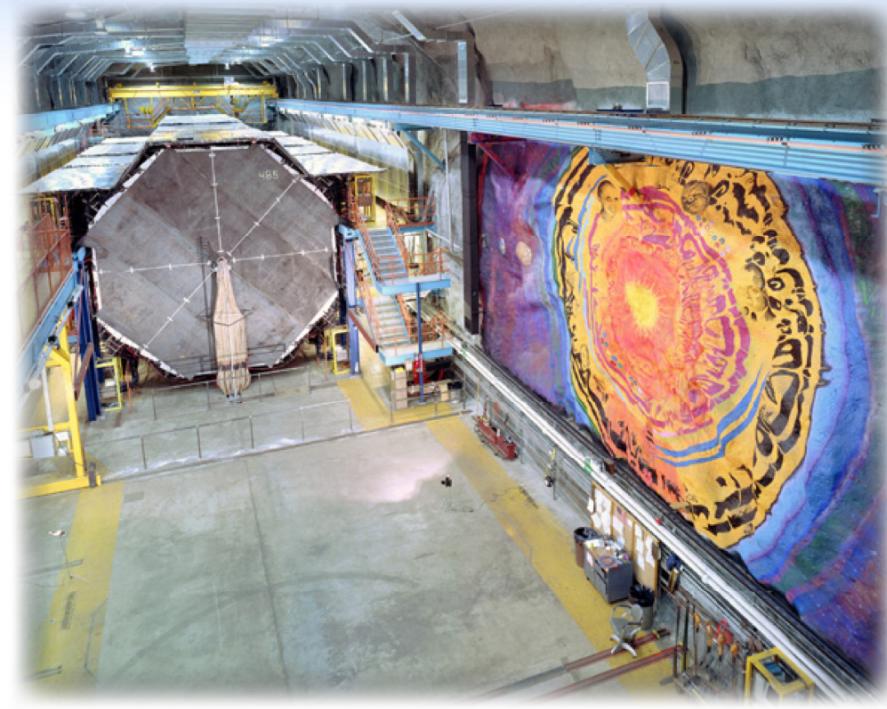


MINOS Search for Sterile Neutrinos

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Harvard University
for the MINOS Collaboration

NuFact '11
Geneva, Switzerland
08/03/2011



MINOS Overview



- **MINOS (Main Injector Neutrino Oscillation Search)**

- ~320 kW NuMI neutrino beam from 120 GeV Main Injector-accelerated protons

- Neutrino energy spectrum measured with two functionally identical iron-scintillator tracking calorimeters:

- Near Detector at Fermilab

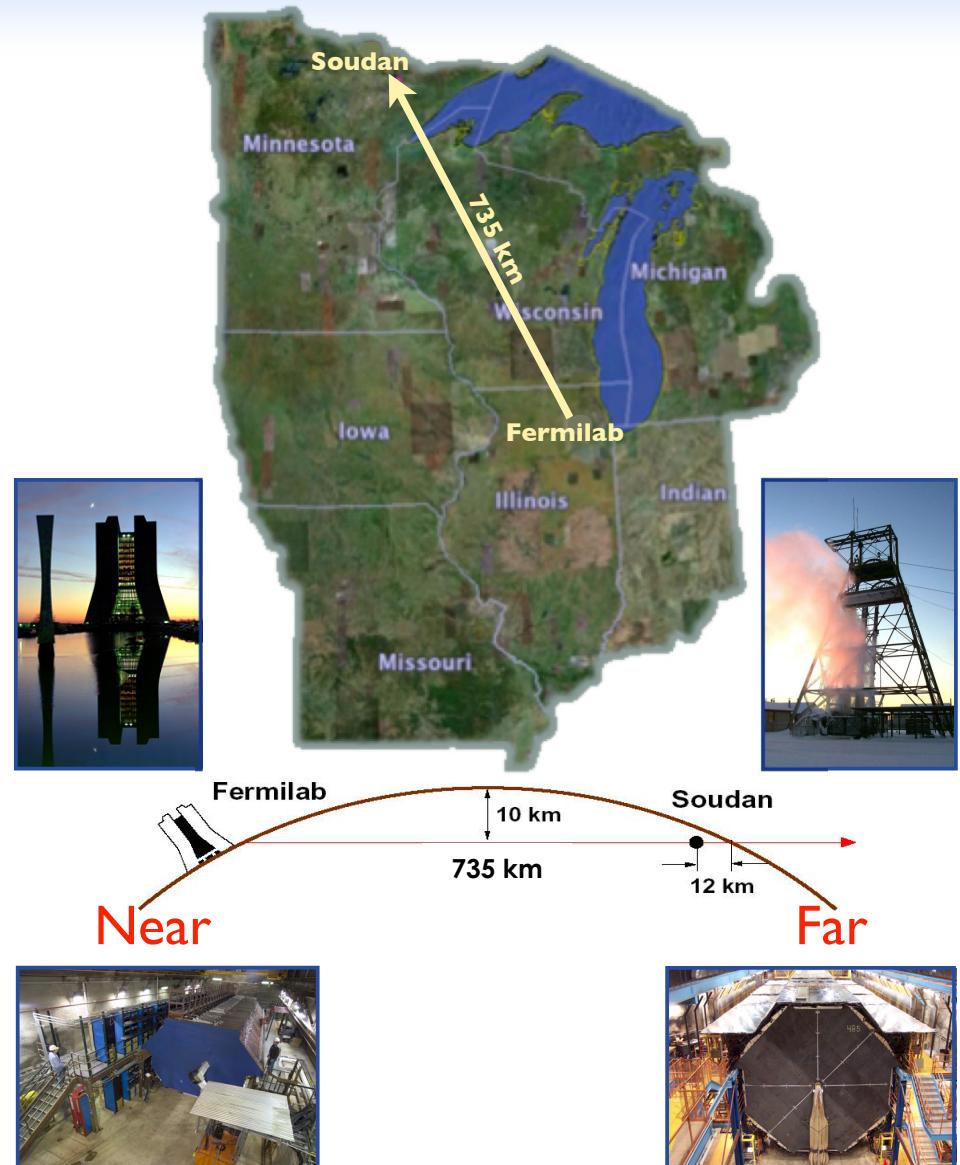
- 1 km away from target,
 - 1 kton mass (27 ton fiducial)

- Far Detector, deep underground in the Soudan mine

- 735 km away

- 5.4 kton mass (4.0 ton fiducial)

- Compare Far Detector observations with extrapolation of Near Detector measurement to study neutrino oscillations



MINOS Physics Goals

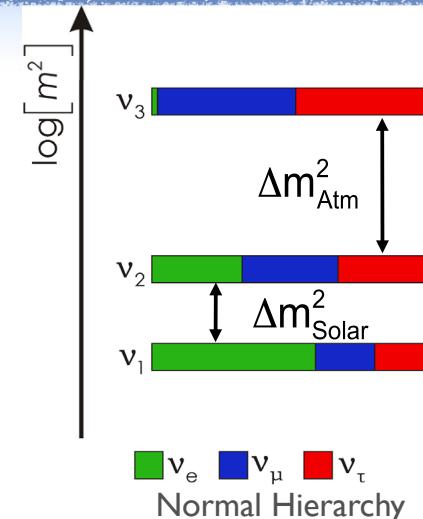


$$U_{PMNS} = \begin{bmatrix} 1 & & & \\ & \boxed{\begin{bmatrix} C_{23} & -S_{23} \\ S_{23} & C_{23} \end{bmatrix}} & & \\ & & \boxed{C_{13}} & 1 \\ & & \boxed{S_{13}e^{-i\delta_{CP}}} & \\ & & & \boxed{1} \end{bmatrix} \begin{bmatrix} & & & \\ & & & \\ & & \boxed{-S_{13}e^{-i\delta_{CP}}} & \\ & & &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

Atmospheric Sector **Unknown** **Solar Sector**

$C_{lk} = \cos\theta_{lk}$

$S_{lk} = \sin\theta_{lk}$



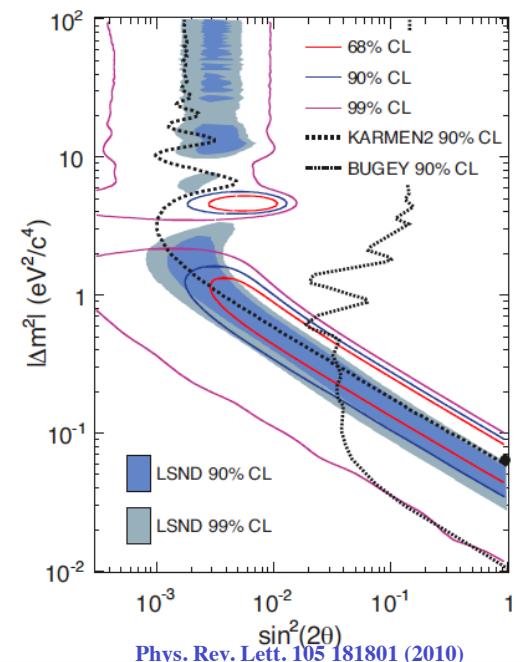
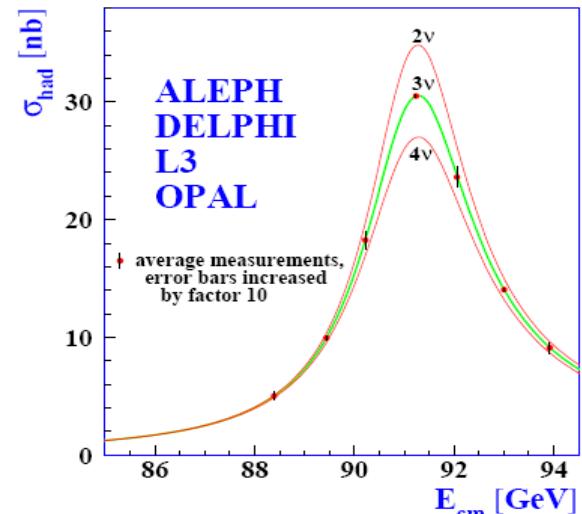
- Look for ν_μ CC disappearance => Perform precision measurements of $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$
- Look for $\bar{\nu}_\mu$ CC disappearance => Measure $|\Delta \bar{m}^2_{32}|$ and $\sin^2(2\bar{\theta}_{23})$
- Look for ν_e CC appearance => Measure θ_{13} - J. Nelson's talk
- Search for sterile neutrino mixing - Look for NC disappearance - This talk

J. Hartnell's
Talk

Sterile Neutrinos



- Preferred explanation for ν_μ CC disappearance is ν_μ oscillating into ν_T
- If θ_{13} is nonzero, a small fraction could be oscillating into ν_e
- Oscillations into a new fourth neutrino flavor are not excluded, but:
 - Measurements of Z^0 width at LEP => only 3 light active neutrinos
 - 4th neutrino flavor has no weak interactions => Sterile neutrino (ν_s)
- Short-baseline experiments, like LSND and MiniBooNE ($\bar{\nu}_\mu$ running) are consistent with a large mass splitting ($\Delta m^2 \sim 1 \text{ eV}^2$), and therefore additional neutrino flavors

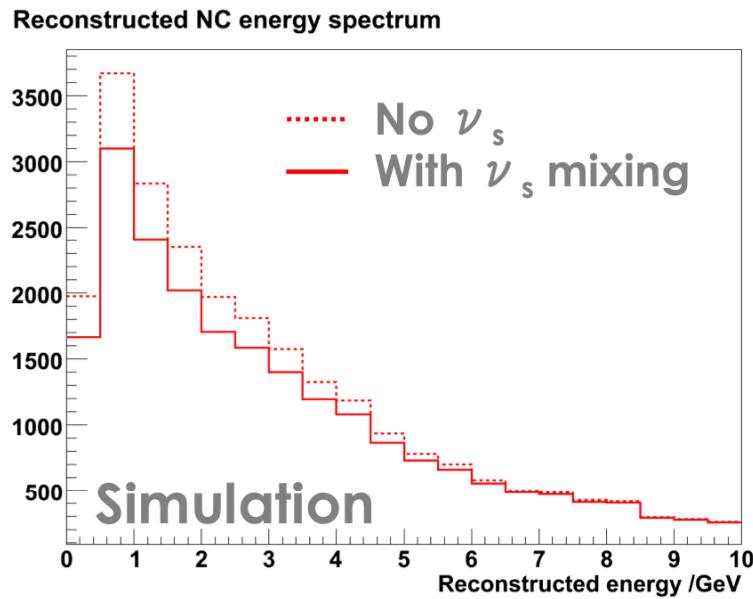
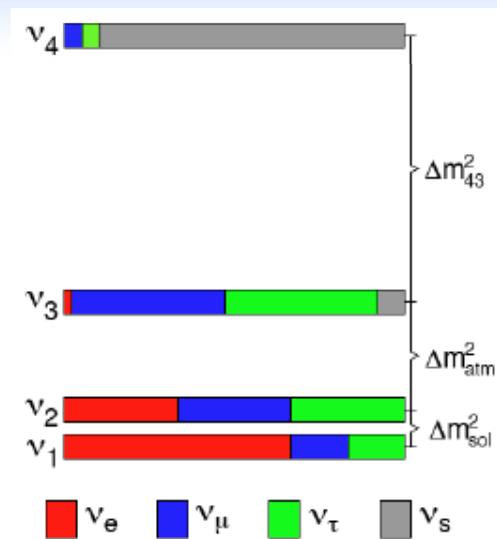


Phys. Rev. Lett. 105 181801 (2010)

Looking for Sterile Neutrinos



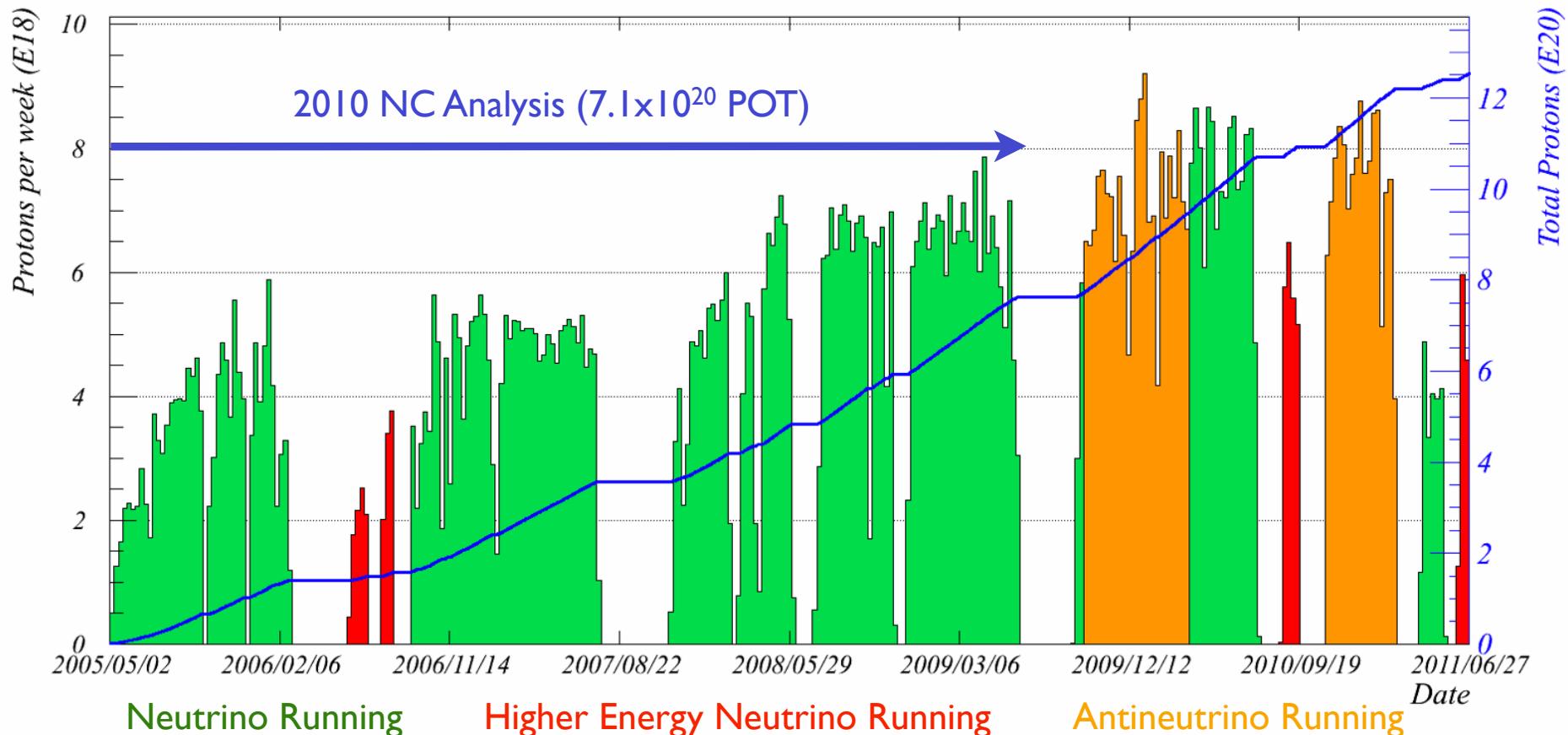
- Active neutrino mixing in MINOS is driven by Δm_{atm}^2
- Neutral current interaction rate is the same for the three active flavors, so standard oscillations do not affect NC interactions
- Oscillations into additional neutrino ν_s may be driven by Δm_{atm}^2 or a new mass scale
- $\nu_\mu \rightarrow \nu_s$ oscillations would reduce number of NC interactions as ν_s do not interact in the detector
- Look for energy-dependent depletion of NC spectrum at Far Detector



Accumulated Beam Data



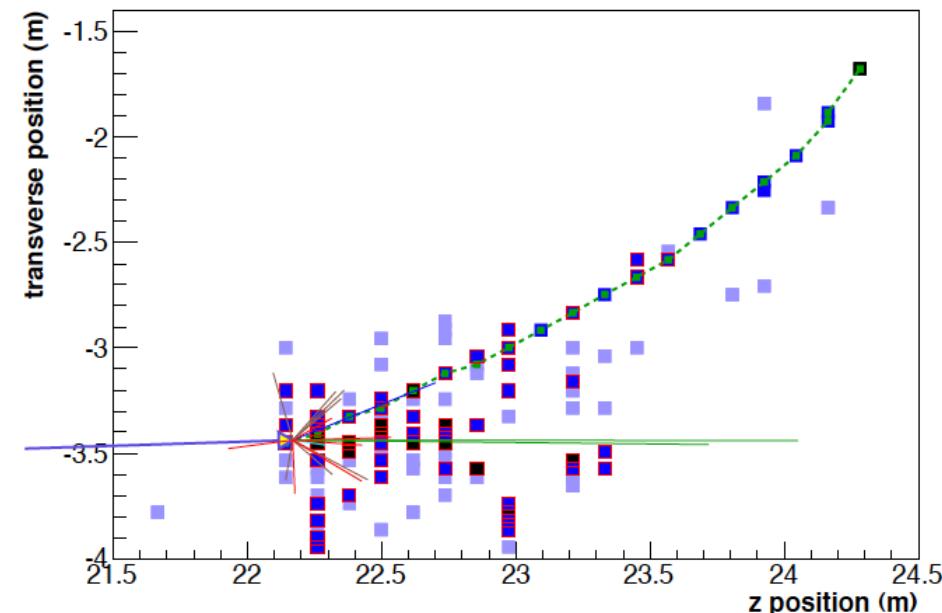
Total NuMI protons to 00:00 Monday 27 June 2011



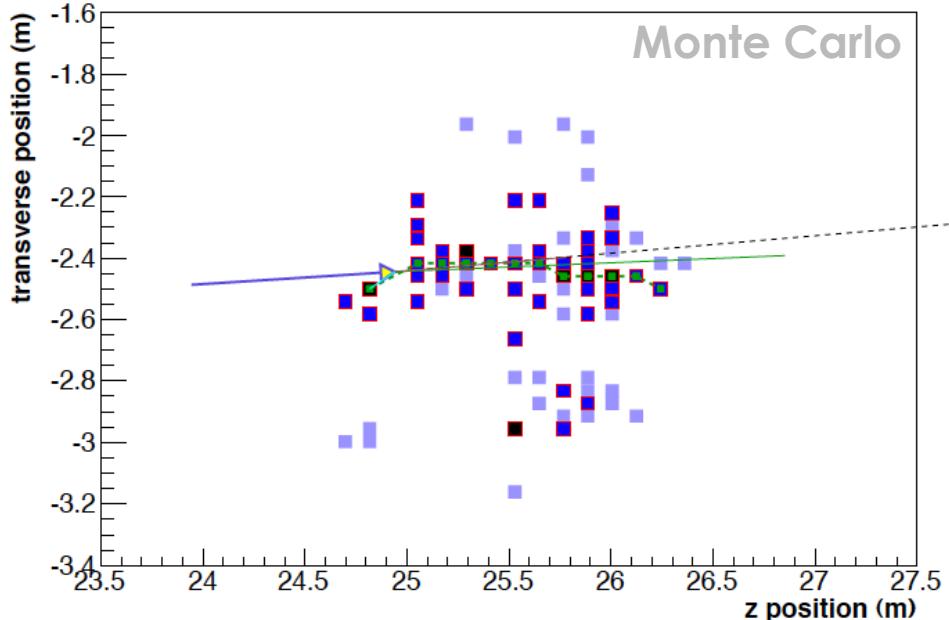
Event Topologies



ν_μ CC Event



NC Event



- **Charged Current ν_μ events**

- long μ track, hadronic activity near event vertex
- neutrino energy from sum of muon energy (range or curvature) and shower energy

$$\frac{\sigma(E)}{E} \approx 5\%(\text{range}), 10\%(\text{curvature})$$

- **Neutral Current events**

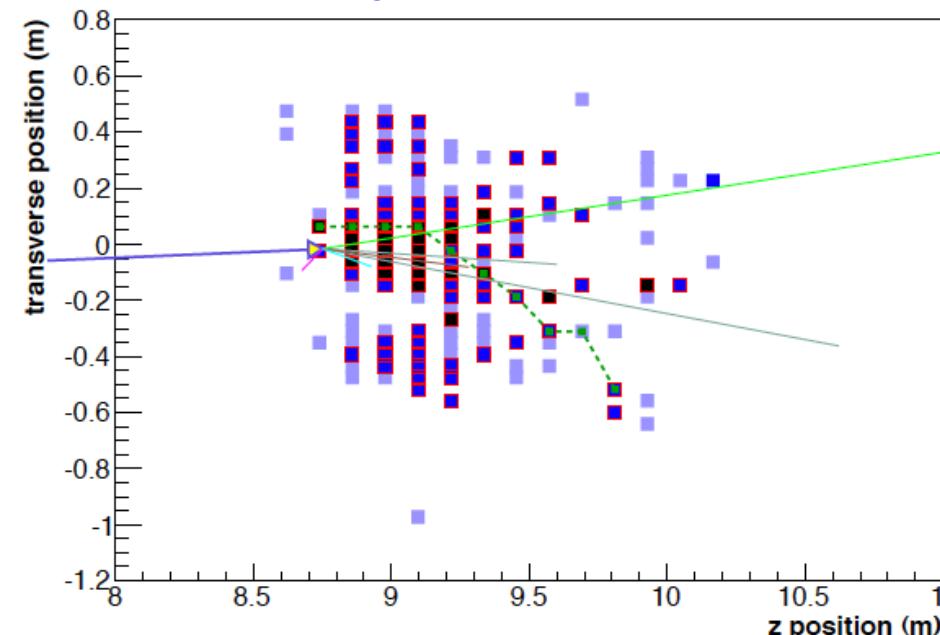
- short, diffuse showers
- shower energy from calorimetric response

$$\frac{\sigma(E)}{E} \approx \frac{56\%}{\sqrt{E}}$$

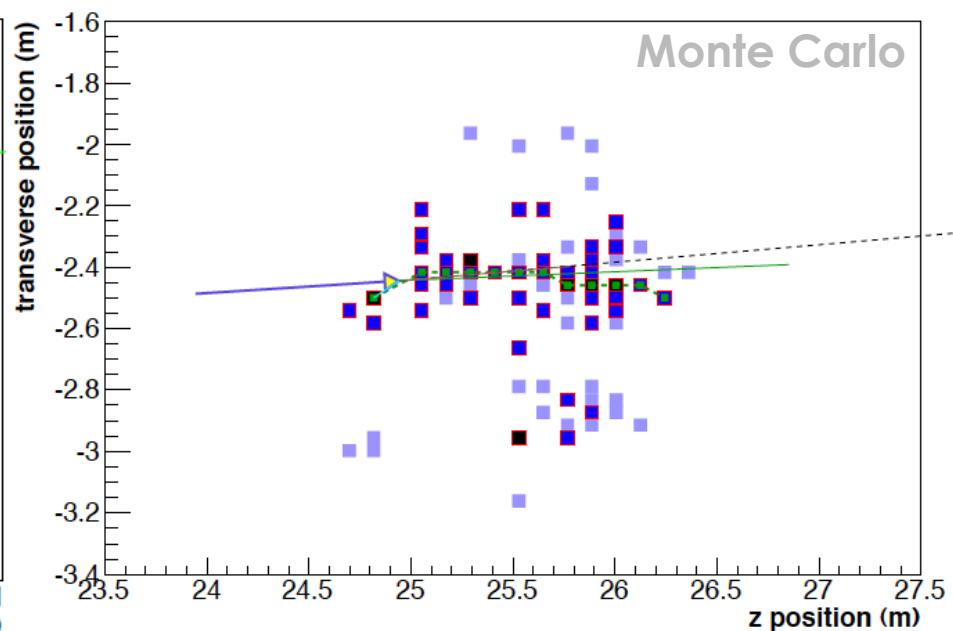
Event Topologies



ν_e CC Event



NC Event



- **Charged Current ν_e events**

- compact shower event with typical electromagnetic profile
- neutrino energy from calorimetric response

$$\frac{\sigma(E)}{E} \approx \frac{22\%}{\sqrt{E}}$$

- **Neutral Current events**

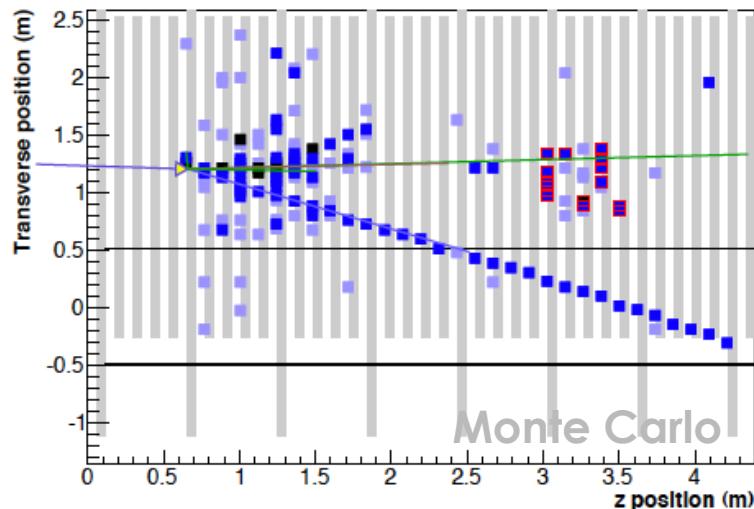
- short, diffuse showers
- shower energy from calorimetric response

$$\frac{\sigma(E)}{E} \approx \frac{56\%}{\sqrt{E}}$$

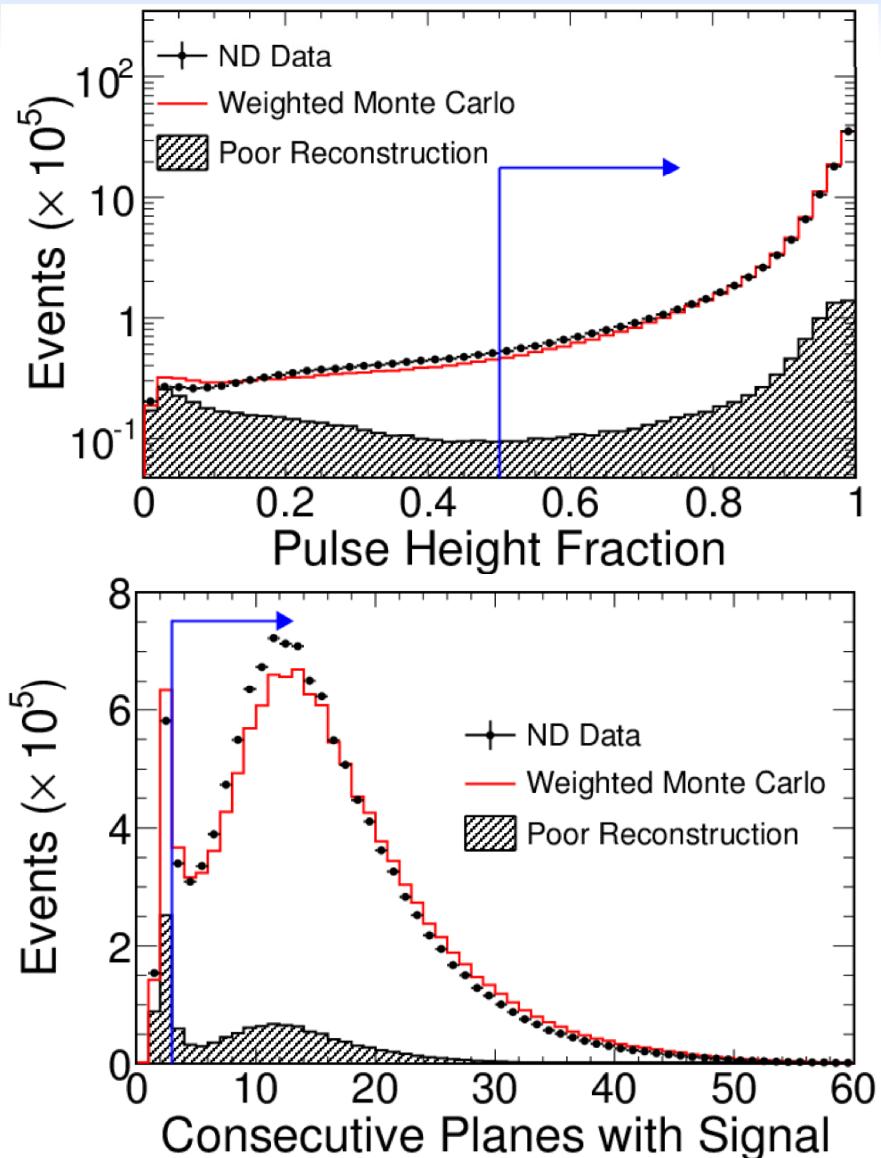
ND Pre-Selection



- High event rate in Near Detector requires time and spatial slicing, and may cause split events



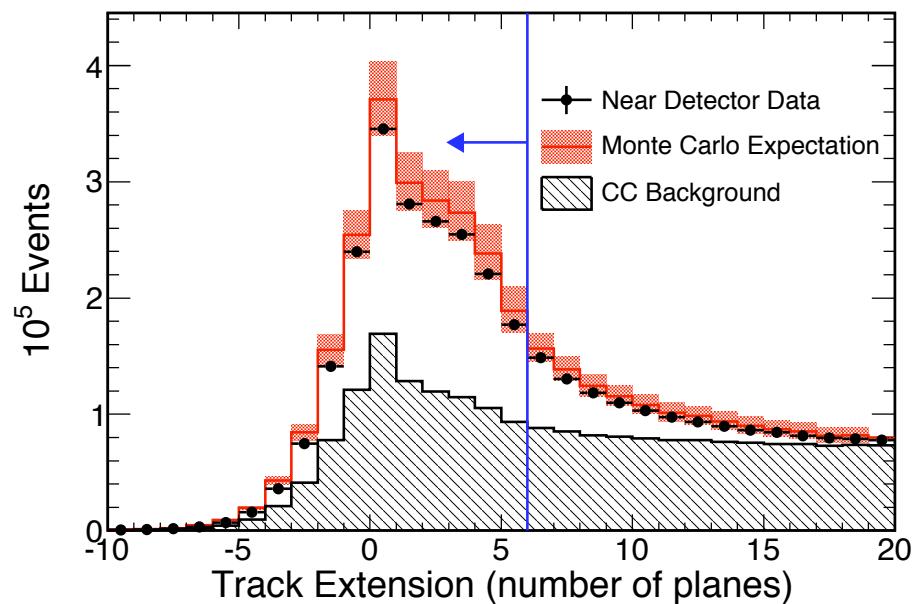
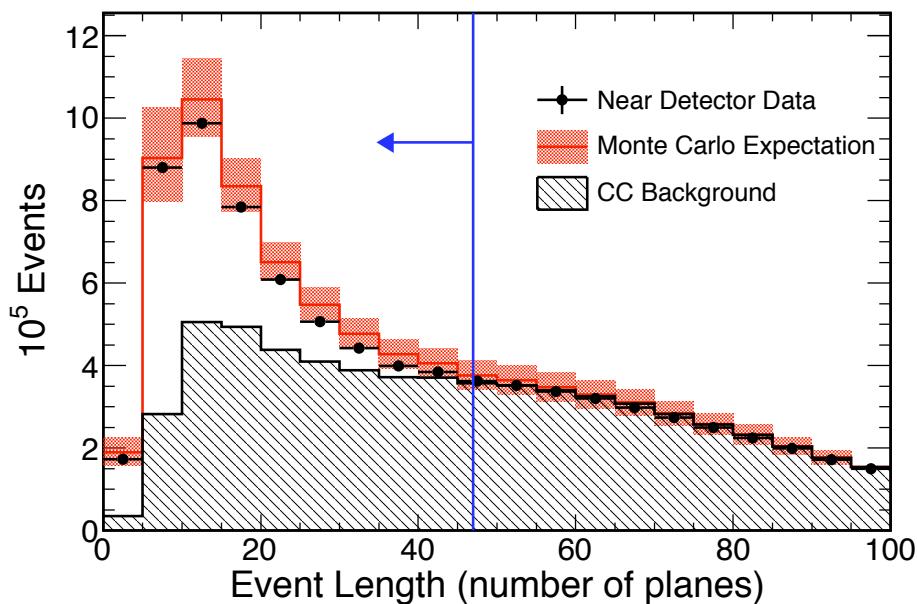
- Mitigated in the analysis by applying pre-selection cuts:
 - Fraction of pulse height in slice > 50%
 - Activity in >3 consecutive planes
- Reduce poorly reconstructed background ($E_{\text{shw_reco}}/E_{\text{shw_true}} < 0.3$) with $E_{\text{reco}} < 1 \text{ GeV}$ from 37% to 11%



NC Event Selection



- NC/CC event separation achieved via cuts on topological variables

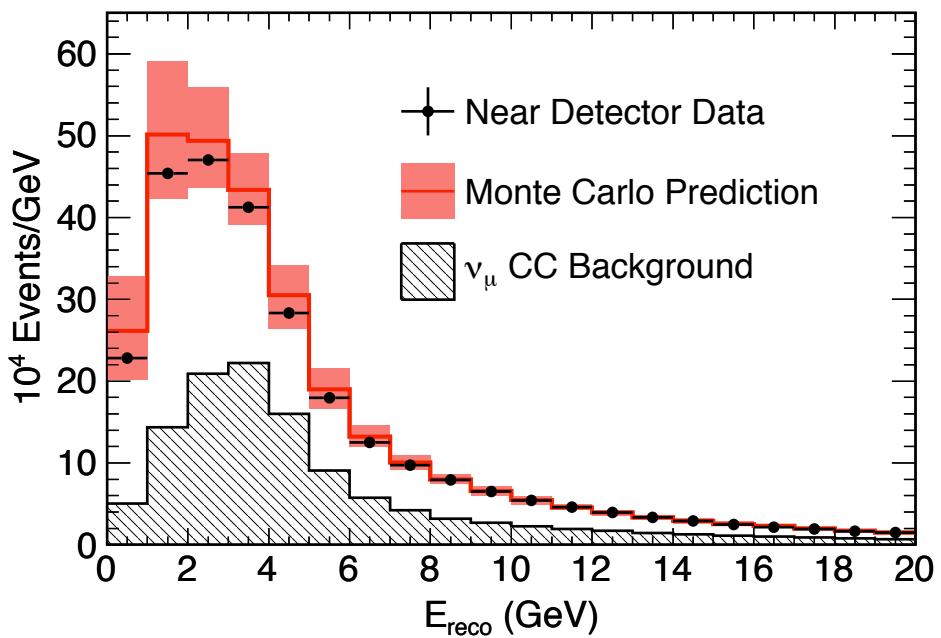
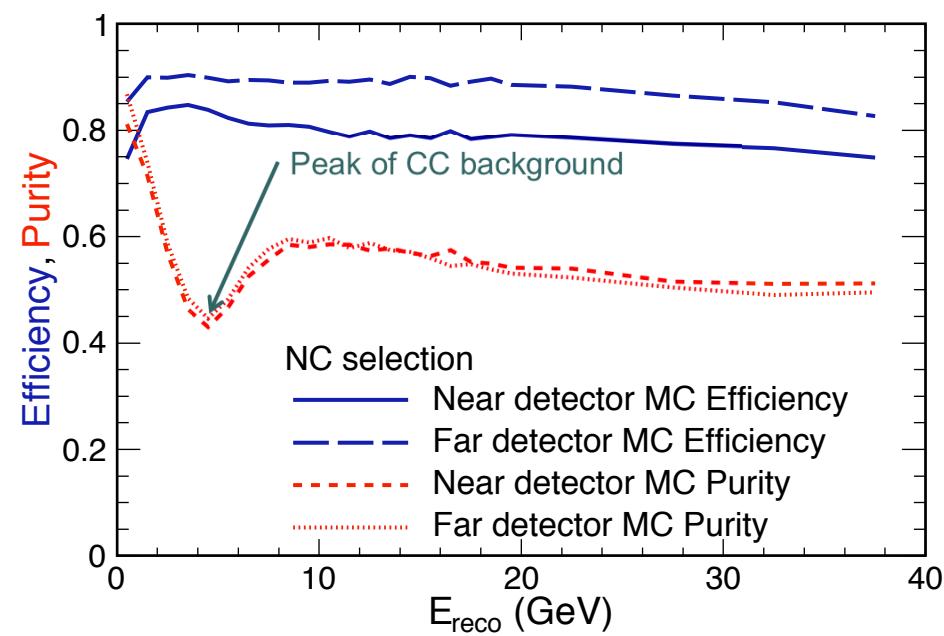


- Discard events with length > 47 planes
 - Same selection applied to data and MC in Far Detector
- Discard events with a track > 6 planes longer than the shower

ND Energy Spectrum



- Main background originates from inelastic (high-y) ν_μ CC events



- NC events selected with 89% efficiency and 61% purity in FD
- Data and MC differences smaller than systematic uncertainties
- 97% of ν_e CC-induced events are classified as NC

Far/Near Extrapolation



- The measured Near Detector energy spectrum is used to predict the Far Detector spectrum via the **Far/Near Ratio** method
- The method uses the ND data without relying on a specific parameterization

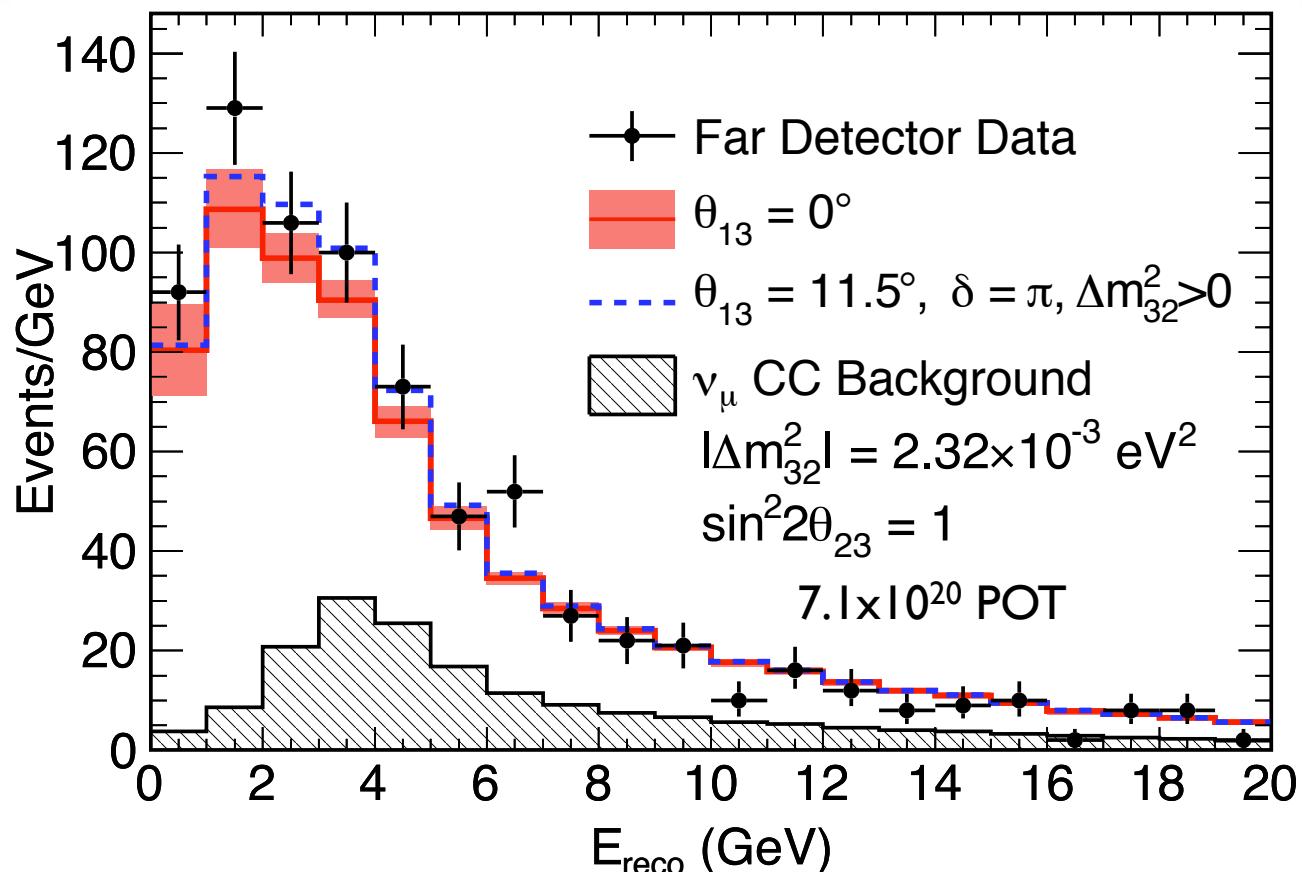
$$FD_i^{predicted} = \frac{FD_i^{MC}}{ND_i^{MC}} ND_i^{Data}$$

- Correct each energy bin in the FD MC using the ND data/MC differences as a scale factor
- Simple, robust to most systematic uncertainties
- FD data spectrum blinded until analysis procedures defined to avoid prediction biases

FD Energy Spectrum



- Results published in PRL
 - Phys. Rev. Lett. 107, 011802 (2011)
- CC background in FD prediction is oscillated at the 2010 MINOS ν_μ CC disappearance best fit values
 - Phys. Rev. Lett. 106, 181801 (2011)
- Blue dashed line shows prediction assuming ν_e appearance at the 2010 MINOS 90% C.L. limit
 - Phys. Rev. D 82, 051102(R) (2010)



No depletion of neutral current events observed

Observed: 802 events
Expected: $754 \pm 28(\text{stat}) \pm 37(\text{syst})$ events

3-Flavor Analysis



- Compare the NC energy spectrum in FD data (7.1×10^{20} POT exposure) with the expectation from standard 3-flavor neutrino oscillation physics using the R statistic

$$R = \frac{N_{data} - \sum B_{CC}}{S_{NC}}$$

Predicted CC background from all flavors ↗
Predicted NC interaction signal ↙

- FD predictions are obtained using the Far/Near Ratio extrapolation method and assume:

- $\Delta m^2_{32} = 2.32 \times 10^{-3} \text{ eV}^2$
- $\sin^2 2\theta_{23} = 1$
- $\Delta m^2_{21} = 7.59 \times 10^{-5} \text{ eV}^2$
- $\theta_{12} = 35^\circ$
- $\theta_{13} = 0 \text{ or } 11.5^\circ$
- $\delta_{CP} = \pi$
- Normal mass hierarchy

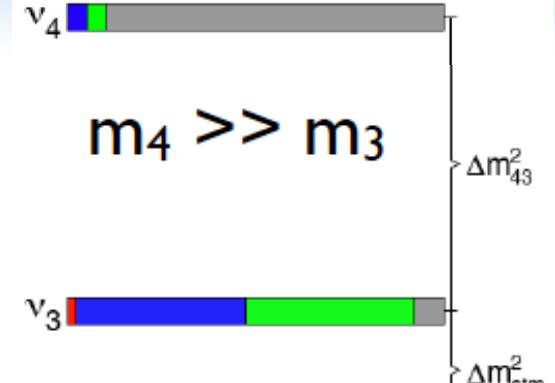
E_{reco} (GeV)	N_{Data}	S_{NC}	$B_{\text{CC}}^{\nu_\mu}$	$B_{\text{CC}}^{\nu_\tau}$	$B_{\text{CC}}^{\nu_e}$
0 – 3	327	248.4	33.2	3.2	3.1 (21.5)
3 – 120	475	269.6	156.0	9.2	31.2 (53.8)
0 – 3		$R = 1.16 \pm 0.07 \pm 0.08 - 0.08(\nu_e)$			
3 – 120		$R = 1.02 \pm 0.08 \pm 0.06 - 0.08(\nu_e)$			
0 – 120		$R = 1.09 \pm 0.06 \pm 0.05 - 0.08(\nu_e)$			

- No NC disappearance $\Rightarrow R=1$

4-Flavor Analysis



- Assume one additional sterile neutrino and an additional neutrino mass scale

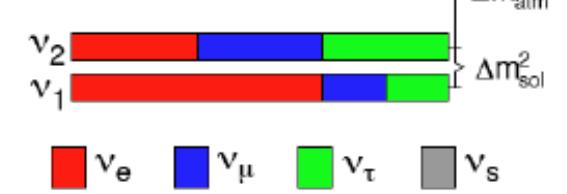


- Extend mixing matrix with extra angles and phases:

$$U = R_{34}(\theta_{34}) R_{24}(\theta_{24}, \delta_2) R_{14}(\theta_{14}) R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta_1) R_{12}(\theta_{12}, \delta_3)$$

- Consider two hypothesis for neutrino mass spectrum

- $m_4 \gg m_3$
- $m_4 = m_1$

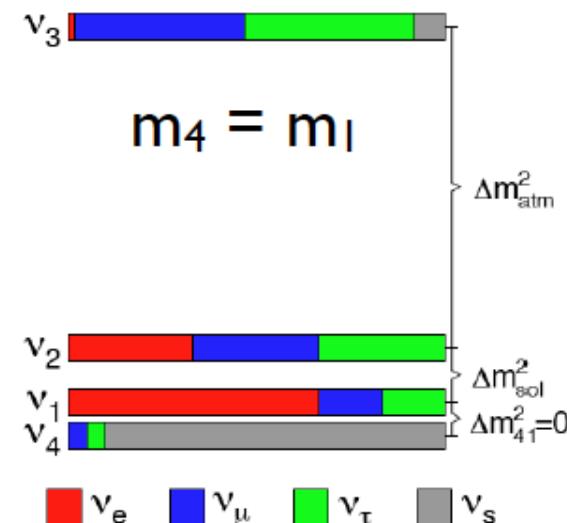


- Oscillation formulae are simplified under the assumptions:

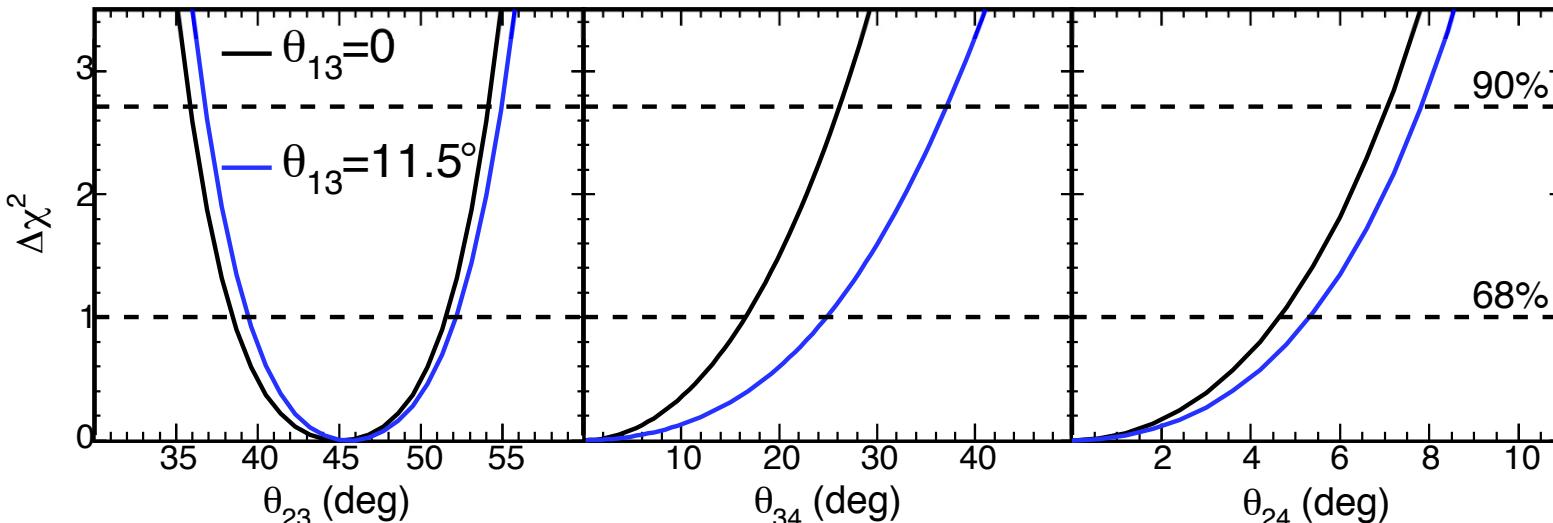
- $|\Delta m^2_{21}| \sim 0, \theta_{14} = 0, \delta_2 = 0$
- For $m_4 \gg m_3$ model, assume rapid oscillations at FD but no observable oscillations at ND $\Rightarrow 0.3 \lesssim \Delta m^2_{43} \lesssim 2.5 \text{ eV}^2$

$$\Rightarrow U = R_{34}(\theta_{34}) R_{24}(\theta_{24}) R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta_1)$$

$$\sin^2(\Delta m^2_{43}) \sim 1/2, \quad \sin(2\Delta m^2_{43}) \sim 0$$



4-Flavor Results



Model	θ_{13}	$\chi^2/\text{d.o.f.}$	θ_{23}	θ_{24}	θ_{34}
$m_4 = m_1$	0	130.4/123	45.0^{+7}_{-7}	...	$0.0^{+17}_{-0.0}$
	11.5	128.5/123	45.6^{+7}_{-7}	...	$0.0^{+25}_{-0.0}$
$m_4 \gg m_3$	0	130.4/122	45.0^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+17}_{-0.0}$
	11.5	128.5/122	45.6^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+25}_{-0.0}$

- 90% C.L. Limits from 1-D $\Delta\chi^2$ projections

$\theta_{34} < 26^\circ$ (37° ν_e) (90% C.L.) (Both models)

$\theta_{24} < 7^\circ$ (8° ν_e) (90% C.L.) ($m_4 \gg m_3$)

- Fraction of ν_μ that may disappear by converting to sterile neutrinos is given by:

$$f_s = \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}}$$

$f_s < 22\%$ (40% ν_e) (90% C.L.)

Most stringent constraint to date!

Other Experiments

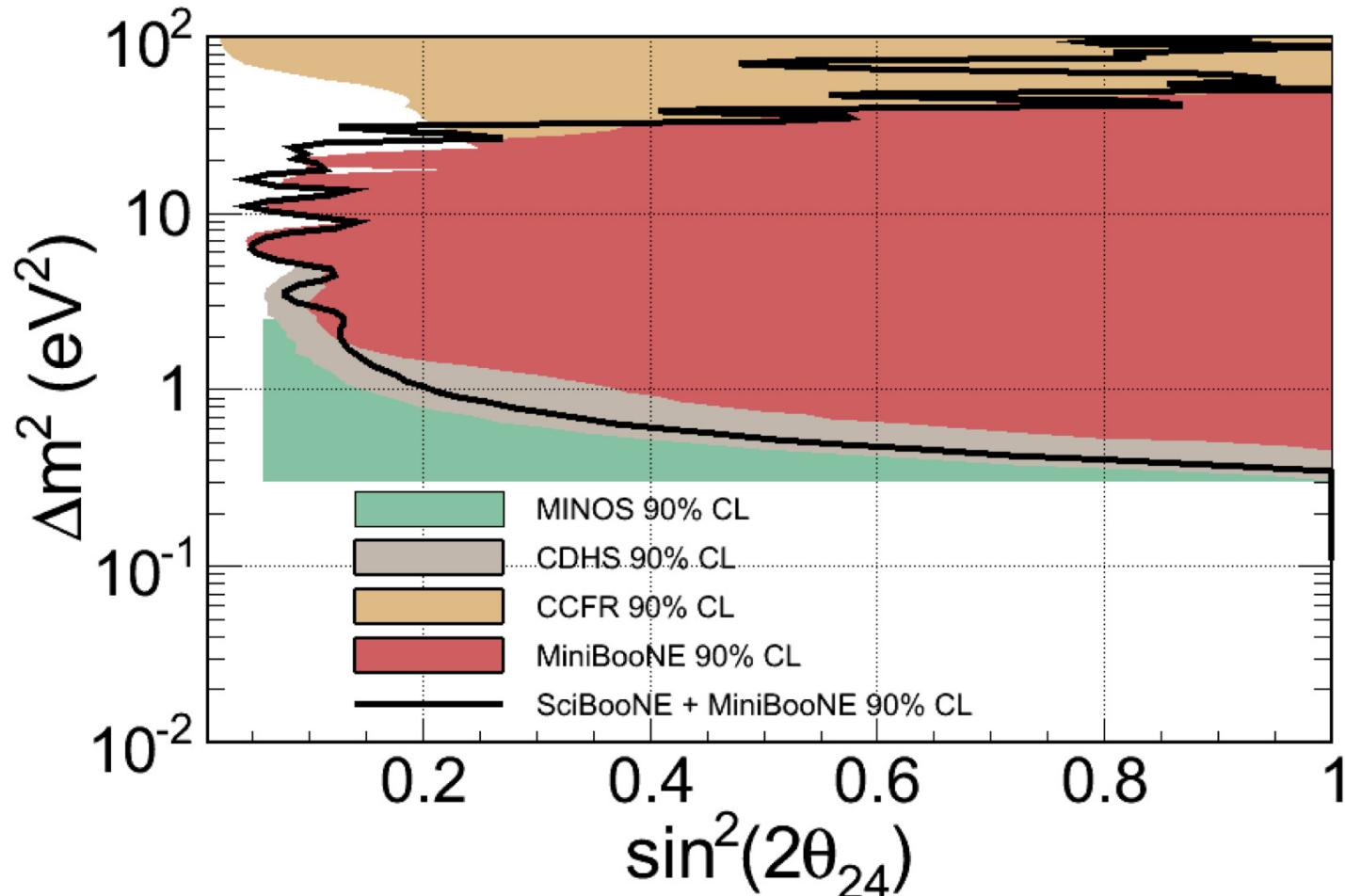


- Different experiments are sensitive to different angles
- Reactor experiments ($\bar{\nu}e$ disappearance): θ_{14}
- MiniBooNE and LSND ($\nu e, \bar{\nu}e$ appearance): $\theta_{14} + \theta_{24}$
- MiniBooNE and LSND, CDHS, CCFR ($\nu_\mu, \bar{\nu}_\mu$ disappearance): θ_{24}
- MINOS (NC and $\nu_\mu, \bar{\nu}_\mu$ disappearance): $\theta_{24} + \theta_{34}$

MINOS θ_{24} Exclusion



- Comparison of MINOS θ_{24} exclusion for $0.3 \leq \Delta m^2_{43} \leq 2.5 \text{ eV}^2$ with ν_μ disappearance contours from other experiments

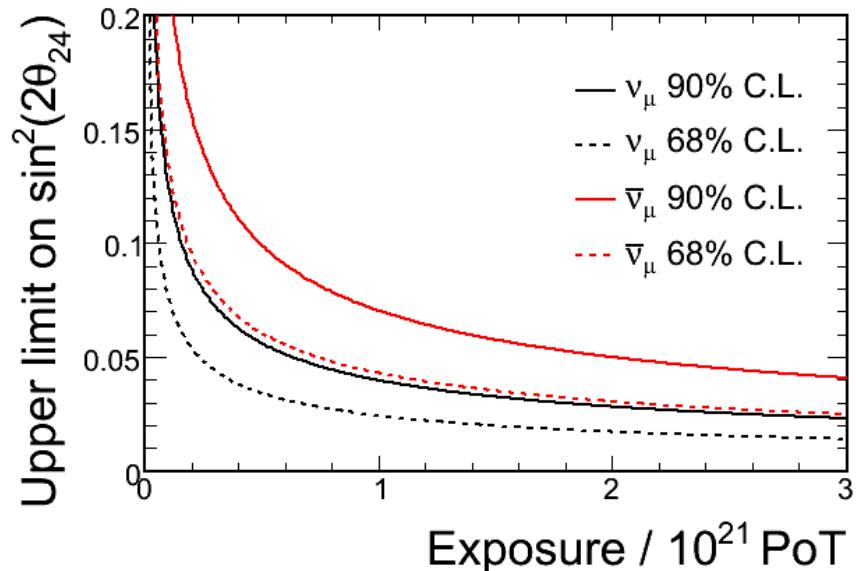


- Recent paper by Hernandez and Smirnov, [arXiv:1105.5946](https://arxiv.org/abs/1105.5946) offers motivation for more sophisticated future analyses

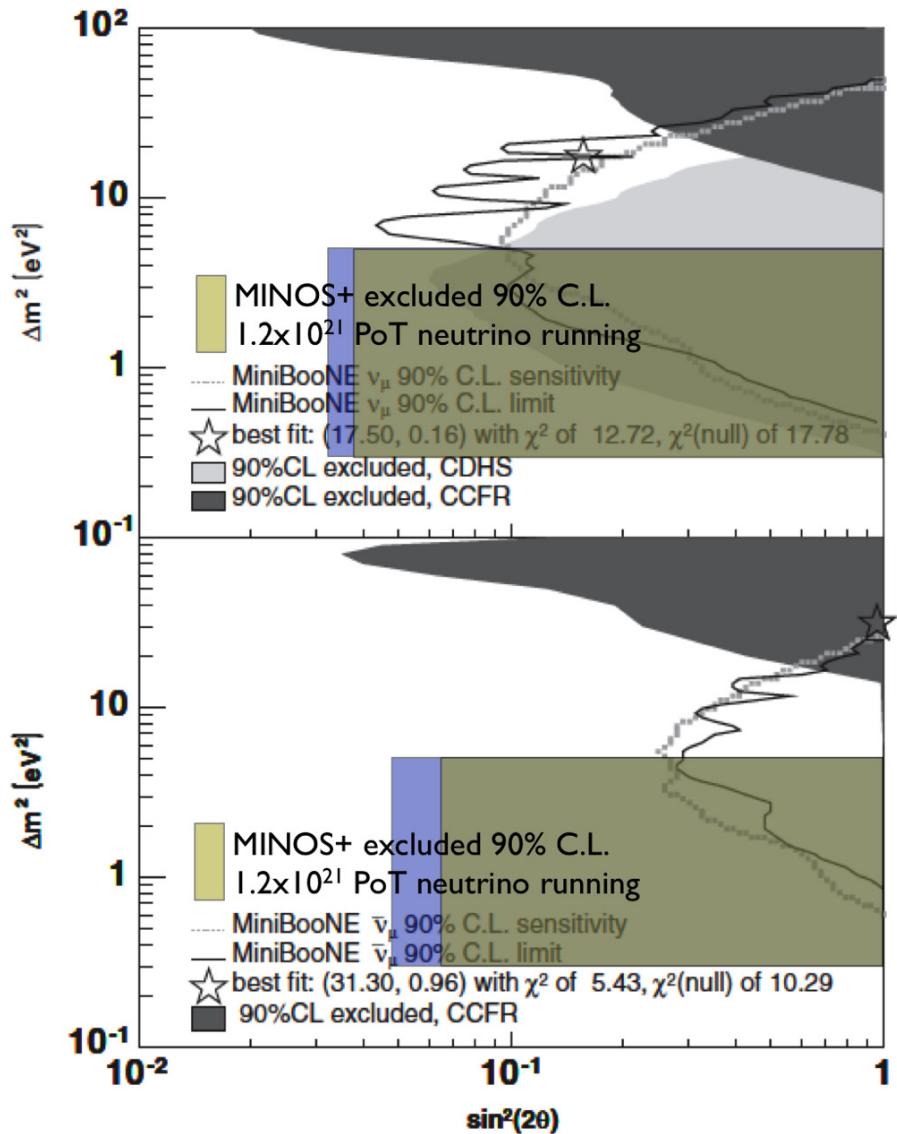
The Future - MINOS+



- Proposal to operate the MINOS detectors during the NOvA run, using the NuMI beam upgraded to 700 kW beam power
 - Starting early 2013
 - Improve present MINOS limits on $\nu_\mu \rightarrow \nu_s$ mixing



- Before MINOS+ era, study NC interactions in dedicated enhanced antineutrino running MINOS data ($\sim 3.0 \times 10^{20}$ POT)



Conclusions



- MINOS is making very important contributions to the body of knowledge on sterile neutrinos
- From observations of neutral current events in a sample of 7.1×10^{20} POT of NuMI neutrino running, MINOS finds:
 - $R = 1.09 \pm 0.06(\text{stat}) \pm 0.05(\text{syst}) - 0.08(\nu_e)$ (0-120 GeV)
 - $\theta_{34} < 26^\circ$ ($37^\circ \nu_e$) (90% C.L.)
 - $\theta_{24} < 7^\circ$ ($8^\circ \nu_e$) (90% C.L.)
 - $f_s < 22\%$ ($40\% \nu_e$) (90% C.L.)

- Phys. Rev. Lett. 107, 011802 (2011)
- arXiv:1104.3922
- Results consistent with no oscillations into sterile neutrinos
- Planning to incorporate ND oscillations in formalism and apply analysis to sample of 3.0×10^{20} POT of enhanced antineutrino running
- Expect future improvements on these limits from MINOS+

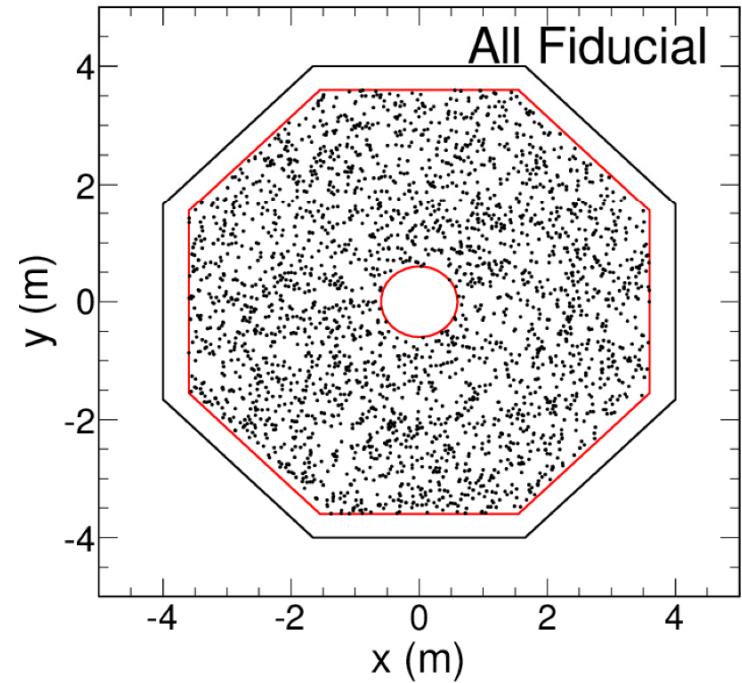
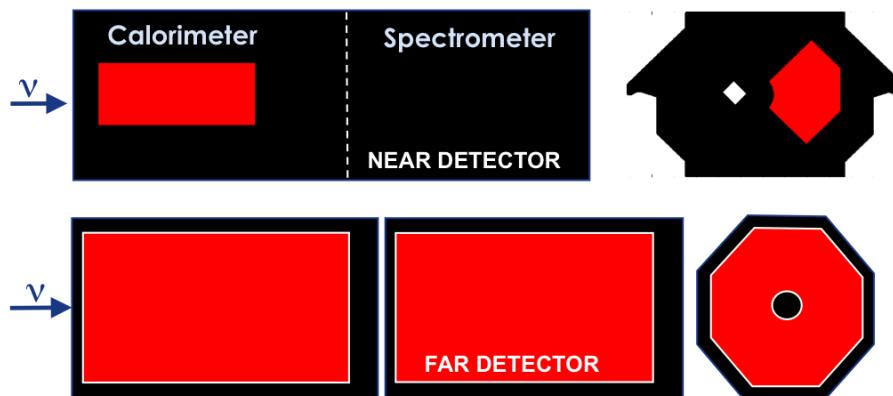


BACKUP

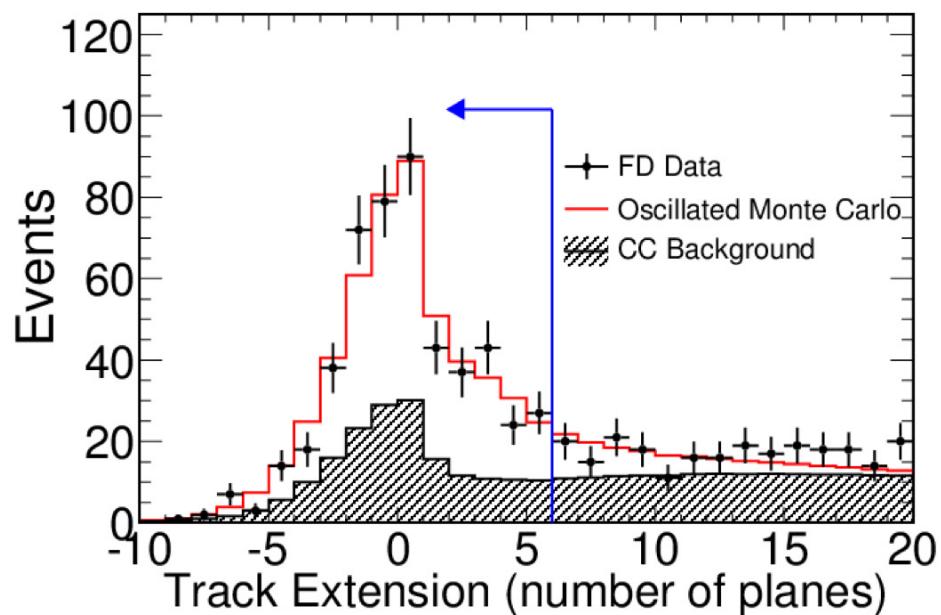
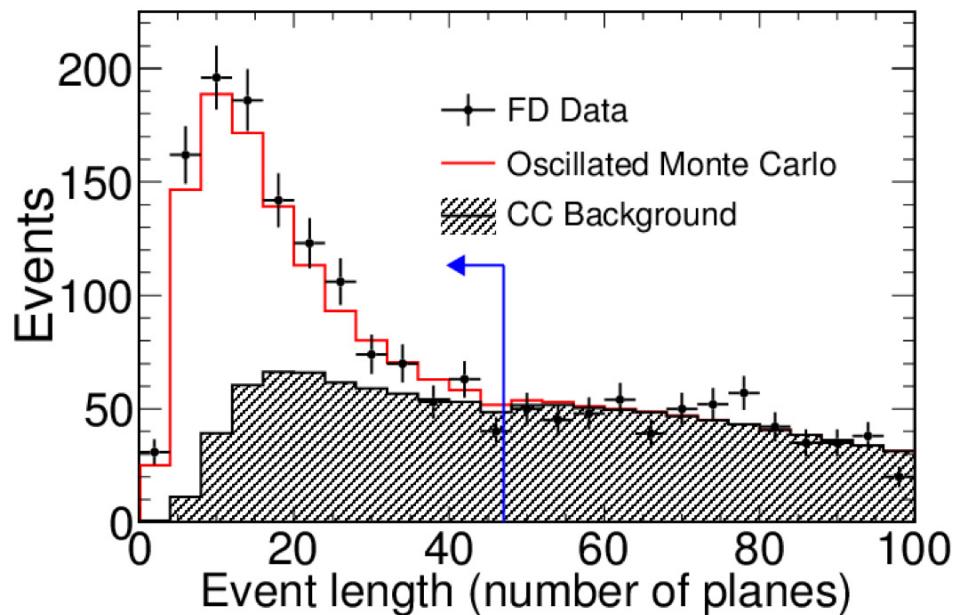
Pre-Selection



- Beam quality and detector quality cuts
- Beam positioning, magnetic horns energized, detectors running within operational parameters
- Cosmics removed using timing and steepness



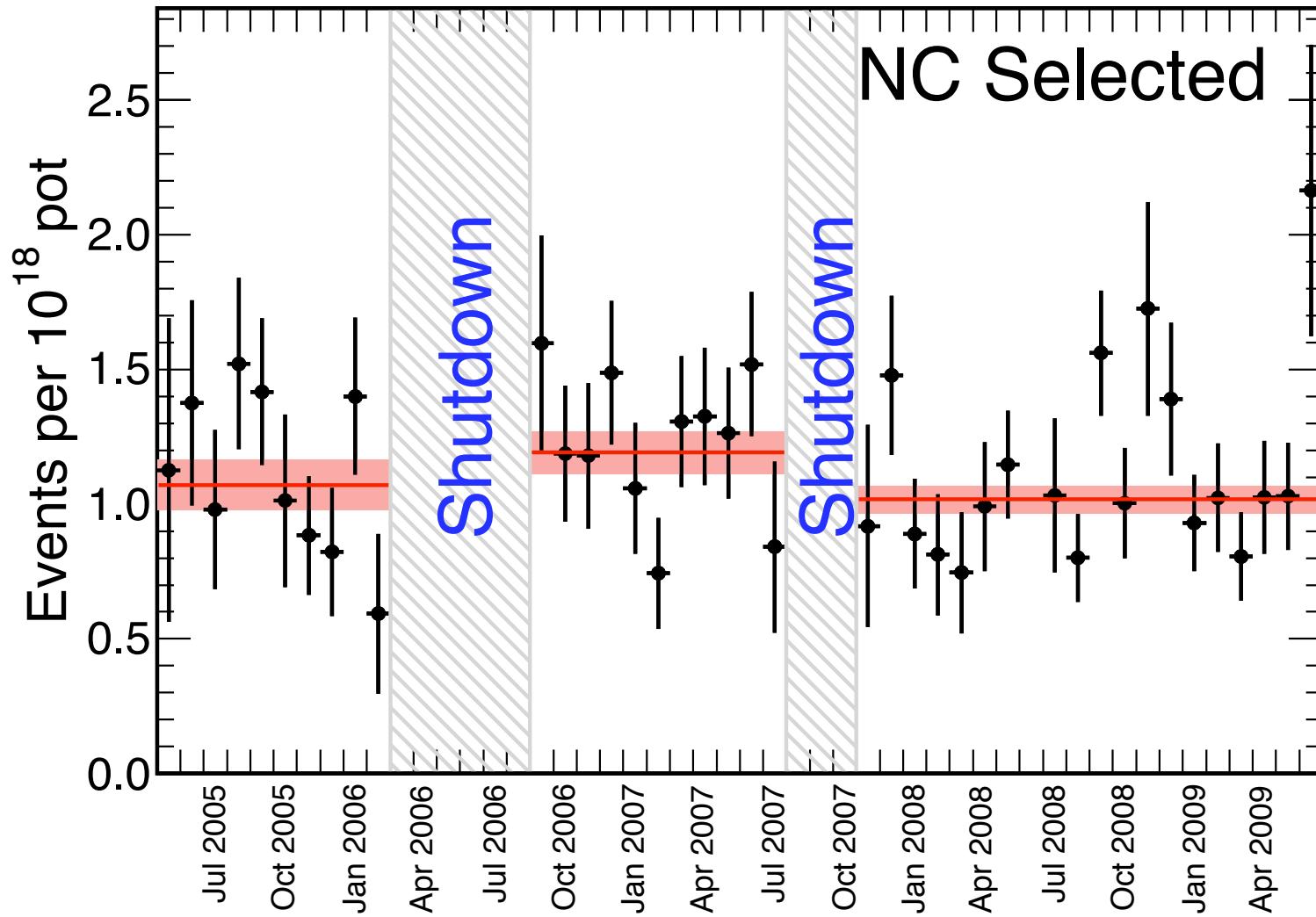
FD NC Selection Variables



FD NC Event Rate



- Rate of NC events selected in FD for each month of data taking





3- Flavor Analysis

- Compare the NC energy spectrum in FD data (7.1×10^{20} POT exposure) with the expectation from standard 3-flavor neutrino oscillation physics.
 - FD predictions are obtained using the Far/Near Ratio extrapolation method

Predicted CC
background
from all flavors

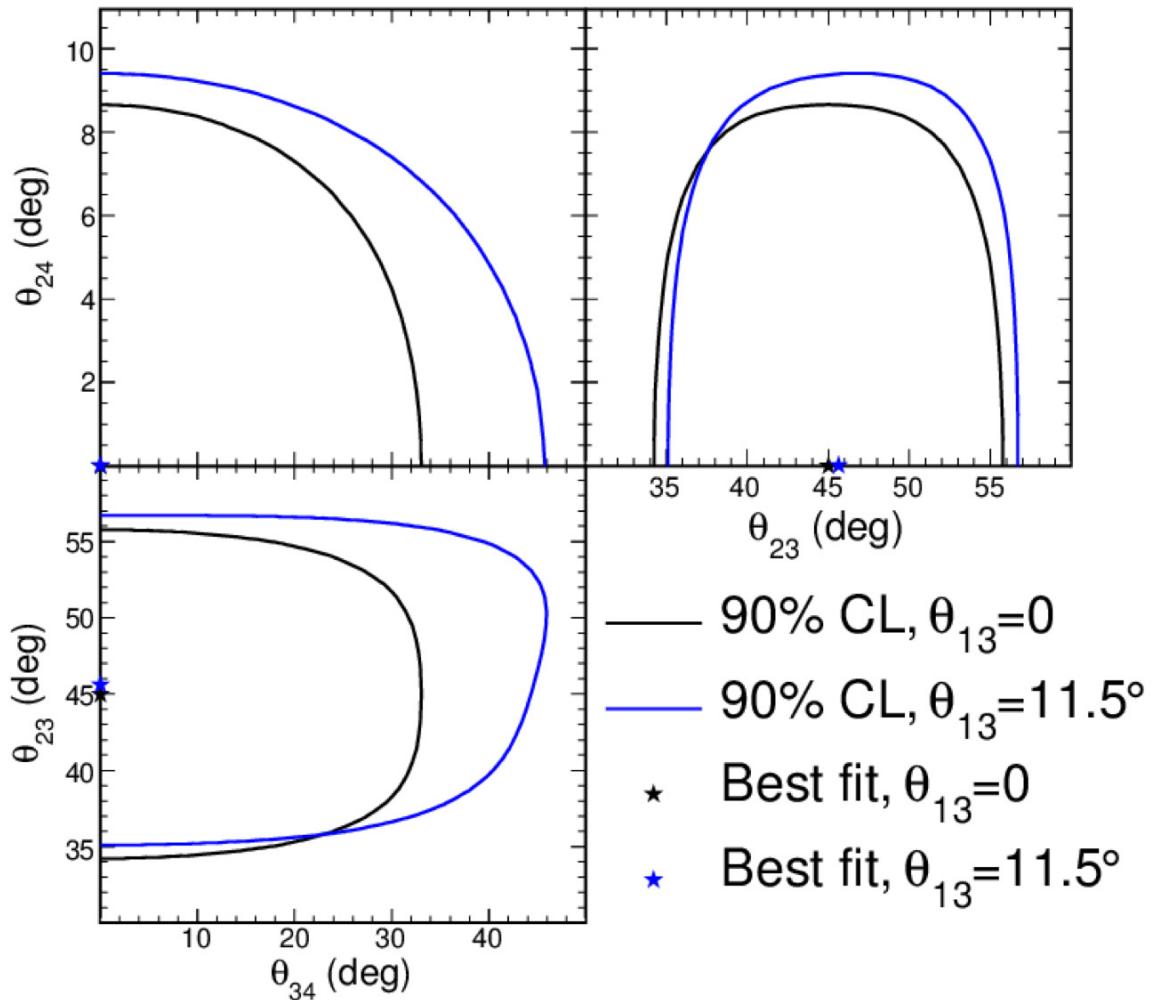
$$R = \frac{N_{data} - \sum B_{CC}}{S_{NC}}$$

Predicted NC
interaction signal

- No NC disappearance $\Rightarrow R=1$

E_{reco} (GeV)	N_{data}	S_{NC}	$B_{\text{CC}}^{\nu_\mu}$	$B_{\text{CC}}^{\nu_\tau}$	$B_{\text{CC}}^{\nu_e}$
0 – 1	92	76.0	3.8	0.3	0.3 (1.4)
1 – 2	129	98.0	8.6	1.1	1.0 (7.6)
2 – 3	106	74.4	20.8	1.8	1.8 (12.6)
3 – 4	100	55.4	30.6	2.1	2.4 (12.7)
4 – 6	120	63.1	42.3	2.9	4.4 (13.4)
6 – 120	255	151.0	87.1	4.3	24.5 (27.8)
0 – 1		$R = 1.15 \pm 0.13 \pm 0.12 - 0.01(\nu_e)$			
1 – 2		$R = 1.21 \pm 0.12 \pm 0.08 - 0.07(\nu_e)$			
2 – 3		$R = 1.10 \pm 0.14 \pm 0.06 - 0.15(\nu_e)$			
3 – 4		$R = 1.17 \pm 0.18 \pm 0.07 - 0.19(\nu_e)$			
4 – 6		$R = 1.12 \pm 0.17 \pm 0.08 - 0.15(\nu_e)$			
6 – 120		$R = 0.92 \pm 0.11 \pm 0.06 - 0.02(\nu_e)$			
0 – 120		$R = 1.09 \pm 0.06 \pm 0.05 - 0.08(\nu_e)$			

Allowed Regions for ν_s Mixing



Systematic Uncertainties



- Normalization: 2.2%
 - Livetime, Near/Far reconstruction efficiency, fiducial mass
- Relative Hadronic Calibration: 2.1%
 - Inter-Detector calibration uncertainty
- Absolute Hadronic Calibration: [$\pm 10\%$, $\pm 6.5\%$]
 - Hadronic Shower Energy Scale($\pm 5.6\%$), Intranuclear rescattering([$\pm 8\%$, $\pm 4\%$])
- Muon energy scale: 2%
 - Uncertainty in dE/dX in MC
- CC Contamination of NC-like sample: $\pm 15\%$
- NC contamination of CC-like sample: $\pm 25\%$
- Cross-section uncertainties:
 - m_A (QE) and m_A (Res): $\pm 15\%$
 - KNO scaling: $\pm 33\%$
- Near Detector NC Selection: $\pm 10\%$ in 0-1 GeV bin
- Far Detector NC Selection: $\pm 5\%$ if $E < 1$ GeV, $< 2.5\%$ if $E > 1$ GeV
- Beam uncertainty: 1σ error band around beam fit results

Effect of largest uncertainties on R

Uncertainty	ΔR (0-120 GeV)
Absolute E_{Hadronic}	0.4%
Relative E_{Hadronic}	0.0%
Normalization	3.2%
CC Background	2.1%
ND Selection	2.7%
FD Selection	2.5%
Total	5.3%

Effect of largest uncertainties on mixing angles in degrees

Uncertainty	$m_4 = m_1$		$m_4 \gg m_3$		
	$\Delta(\theta_{23})$	$\Delta(\theta_{34})$	$\Delta(\theta_{23})$	$\Delta(\theta_{24})$	$\Delta(\theta_{34})$
Absolute E_{Hadronic}	0.2	6.1	0.2	0.8	9.5
Relative E_{Hadronic}	0.3	5.9	0.4	1.2	9.4
Normalization	0.2	11.2	0.0	4.2	6.7
CC Background	0.1	12.1	0.2	0.3	10.0
ND Selection	0.2	15.1	0.4	0.7	13.8
FD Selection	0.1	12.5	0.1	0.7	7.4
Total	0.5	27.0	0.6	4.6	23.8



Oscillation+Decay

- If neutrinos were to decay into a sterile species, NC spectrum would also be affected
- Performed NC+CC fits of a model with neutrino oscillation + neutrino decay

$$P_{\mu\mu} = \cos^4 \theta + \sin^4 \theta e^{-\frac{m_3 L}{\tau_3 E}} + 2 \cos^2 \theta \sin^2 \theta e^{-\frac{m_3 L}{2\tau_3 E}} \cos\left(\frac{\Delta m_{32}^2 L}{2E}\right)$$

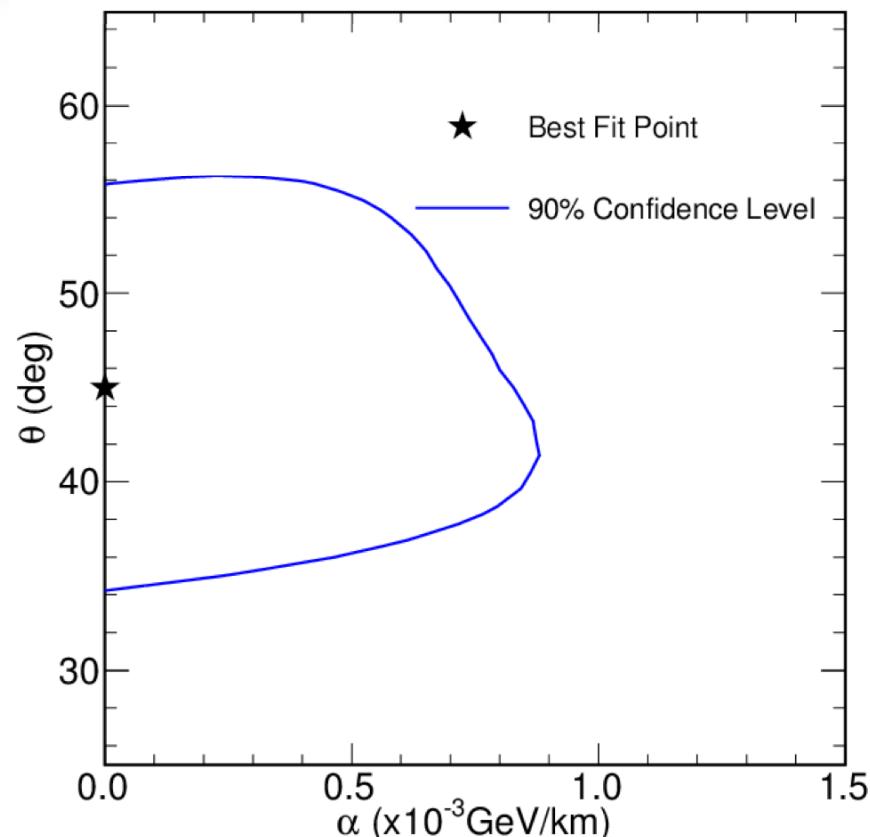
$$P_{\text{decay}} = \left(1 - e^{-\frac{m_3 L}{\tau_3 E}}\right) \sin^2 \theta.$$

M.C. Gonzalez-Garcia, M. Maltoni, Phys. Lett. B **663**, 405 (2008)

	χ^2/DOF	$\alpha (\text{GeV}/\text{km})$	θ
Osc. with Decay	130.7/123	$0.0^{+0.24} \times 10^{-3}$	$45.00^{+7.2}_{-7.2}$
Pure Decay	191.9/124	$2.1^{+1.1}_{-0.2} \times 10^{-3}$	$89.4^{+0.6}_{-31.8}$

NC+CC fits disfavor pure neutrino decay ($\Delta m^2 \rightarrow 0$) at 7.8σ

$$\alpha \equiv \frac{m_3}{\tau_3}$$



- Consistent with no neutrino decay ($\alpha=0$). Can set a limit on neutrino lifetime

$T_3/m_3 > 5.8 \times 10^{-12} \text{ s/eV}$ (90% C.L.)