Analysis of Neutral Current Interactions in MINOS: A Search for Sterile Neutrinos

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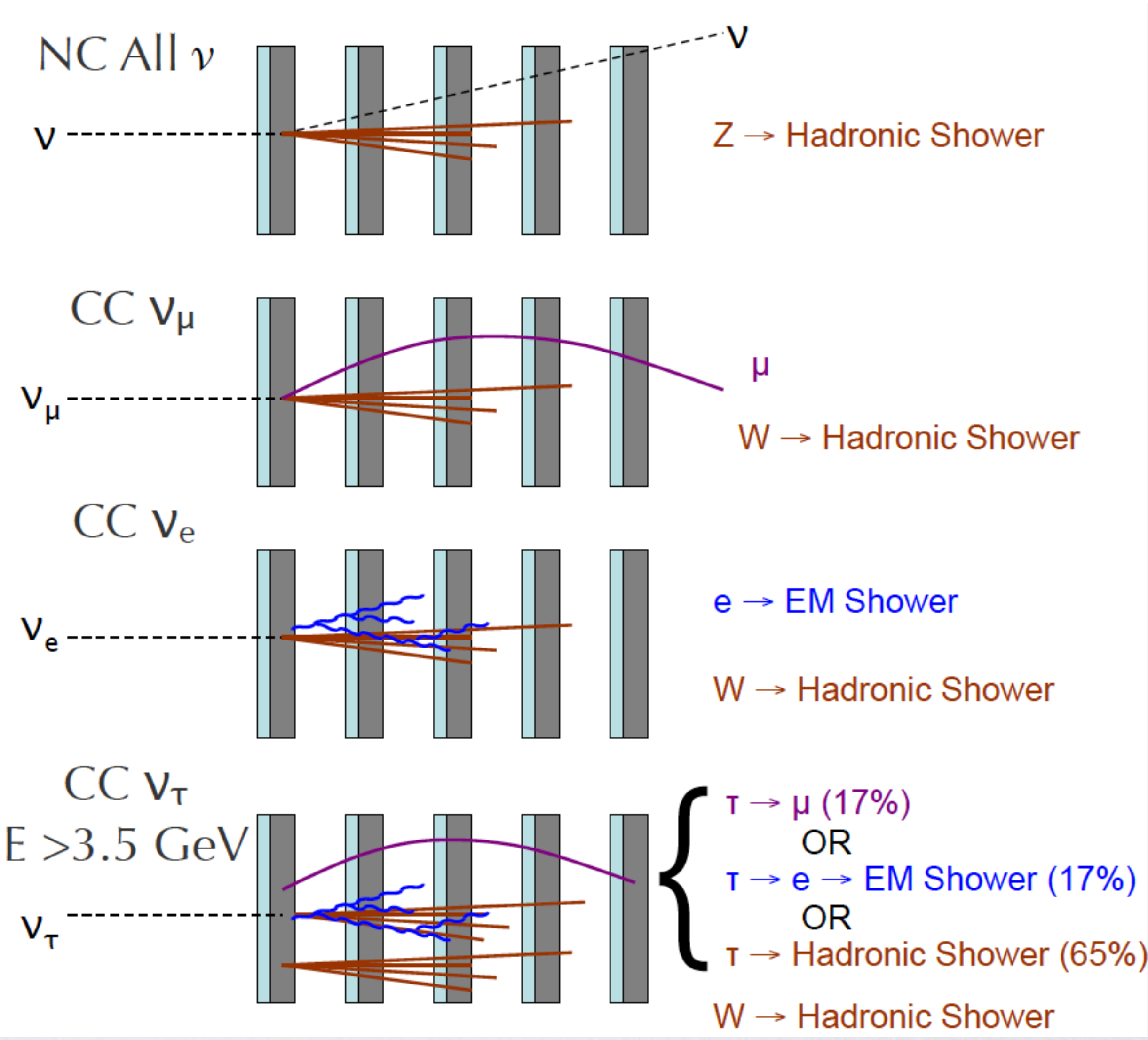
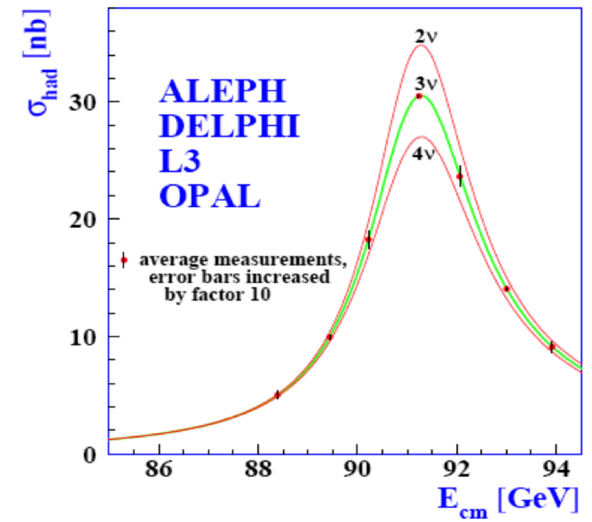
Neutrino Interactions in MINOS

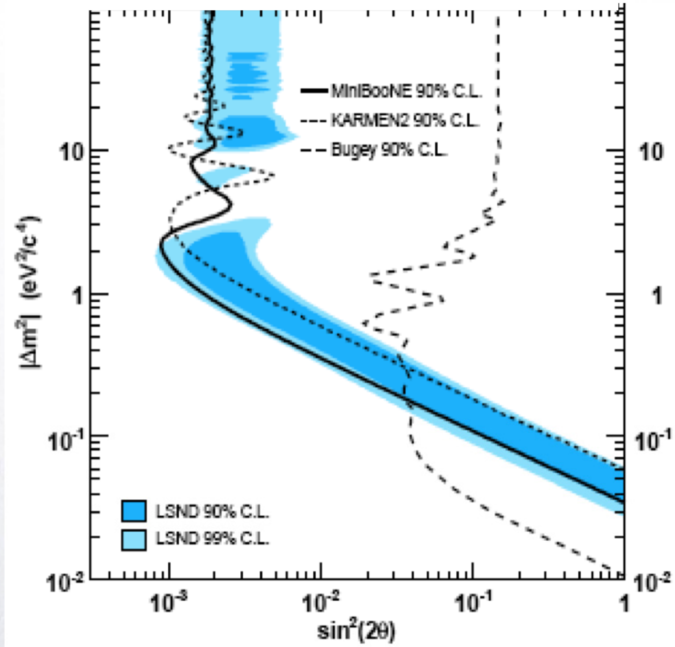
- The MINOS detectors observe both neutral current (NC) and charged current (CC) interactions
- Reconstructed events are composed of tracks and showers
- MINOS is not optimized to measure short showering NC events, but they are interesting!
- NC events allow us to look for sterile neutrinos



Sterile Neutrinos

- Measurements of Z^0 width at LEP => 3 light active neutrinos
  - Any additional neutrinos may not couple to Z^0 => **sterile neutrinos**
- Short baseline LSND experiment suggested a new large mass splitting, possibly explained by an additional neutrino
- MiniBooNE, Bugey and Karmen experiments strongly disfavor oscillations into sterile neutrinos as explanation for LSND signal
- Searches on long baseline experiments for additional massive neutrino(s) still relevant:
  - Dark Matter, Supernovae
  - See-saw mechanism
- **Sterile Neutrinos => New Physics!**





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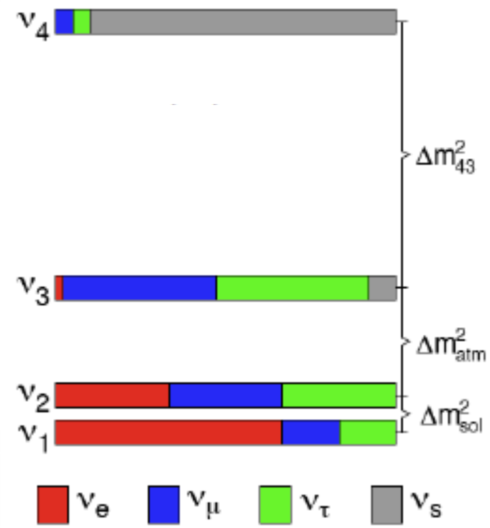
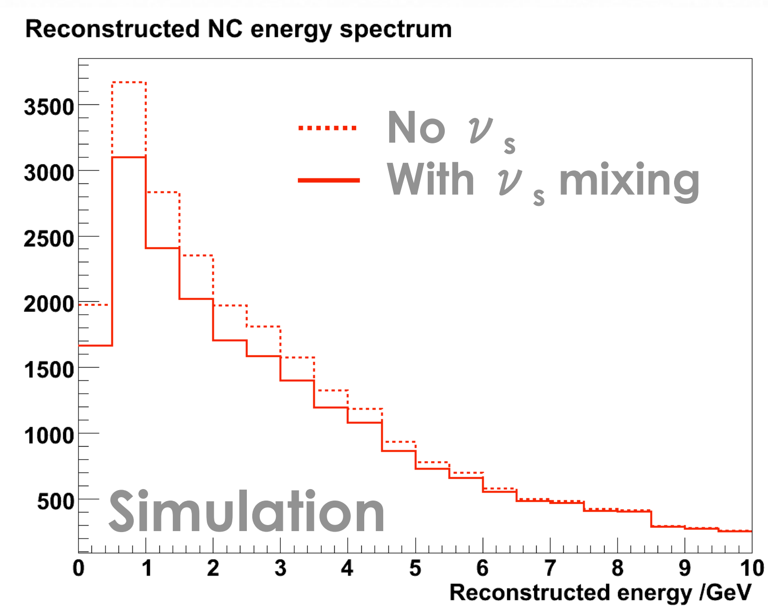
- Standard neutrino oscillations in MINOS are driven by Δm^2_{atm}
  - Neutral current interaction rate is the same for the three active flavors
  - Standard oscillations do not affect NC interactions
- Oscillations into additional neutrino ν_s may be driven by Δm^2_{atm} or a new mass scale
  - ν_s mixing would reduce number of NC interactions as ν_s do not interact in the detector
- Sterile neutrino signal
  - Depletion of NC spectrum at Far Detector
  - Energy-dependent



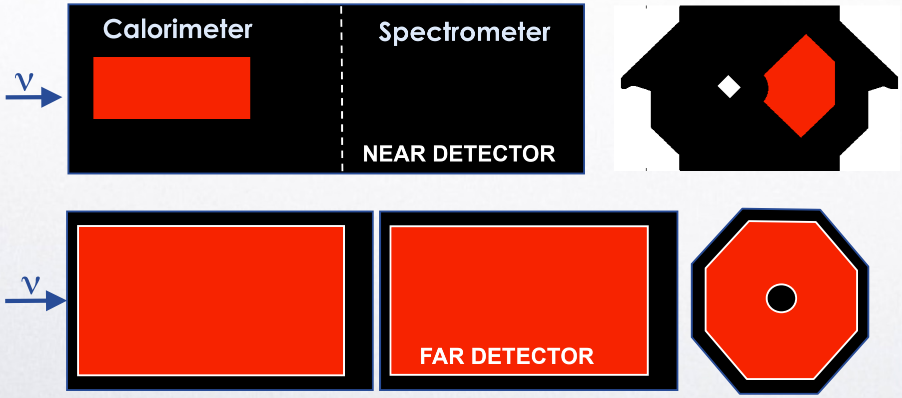


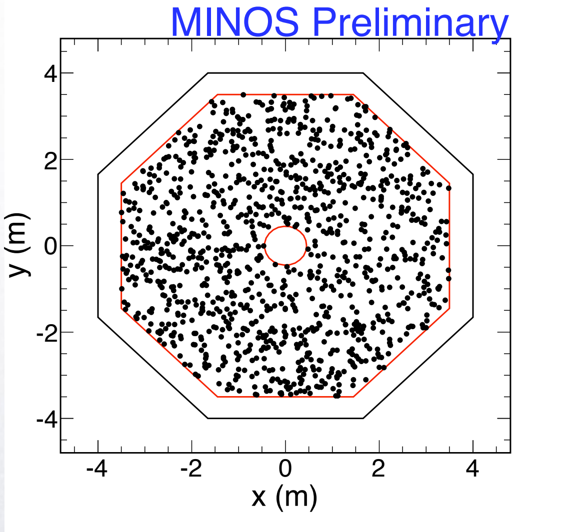
Event Pre-Selection

- Beam quality and detector quality cuts
  - Beam positioning, magnetic horns energized, detectors running within operational parameters

- Cosmics removed using timing and steepness

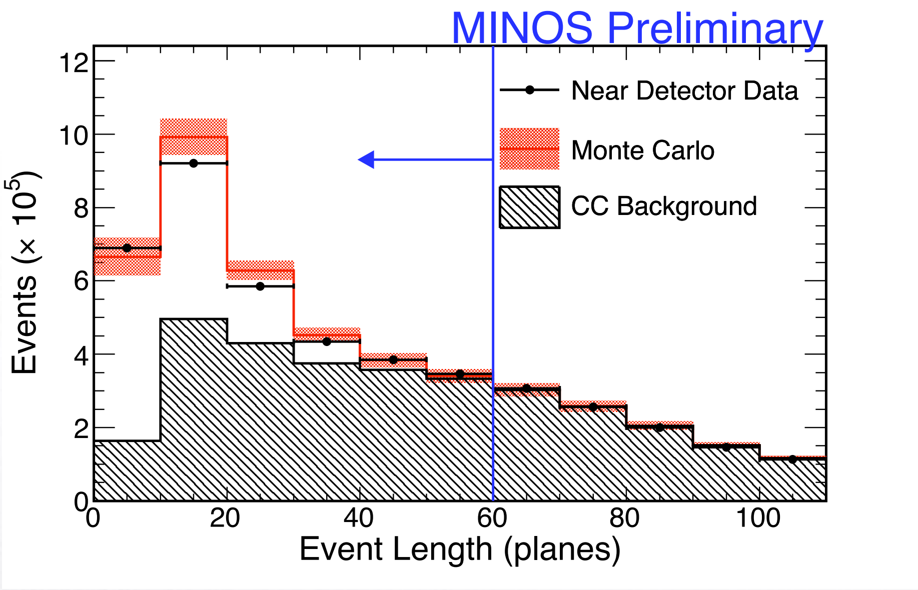
- Event vertex reconstructed within the fiducial volume of the detectors
  - Fiducial volume optimized for containment of hadronic showers

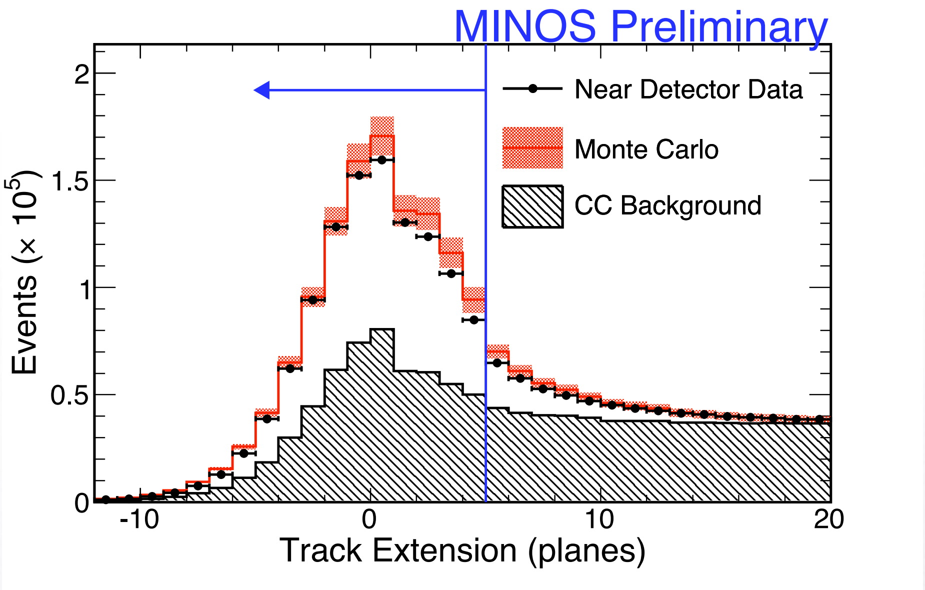




NC/CC Event Separation

- NC event selection achieved via cuts on topological variables
- NC events are typically shorter than CC events
- Expect showers and no tracks or very short tracks reconstructed for NC events



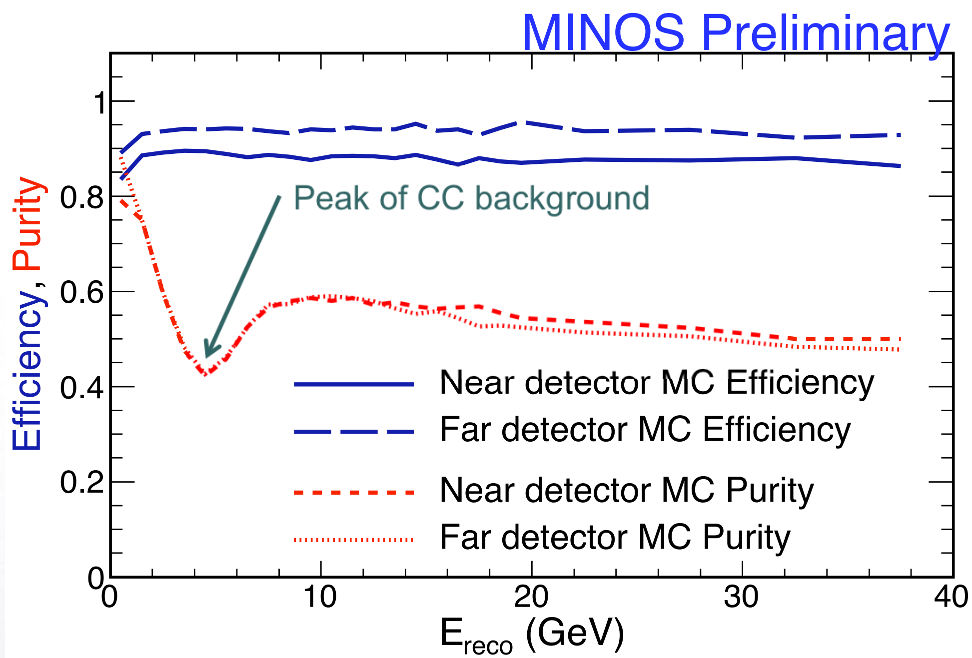


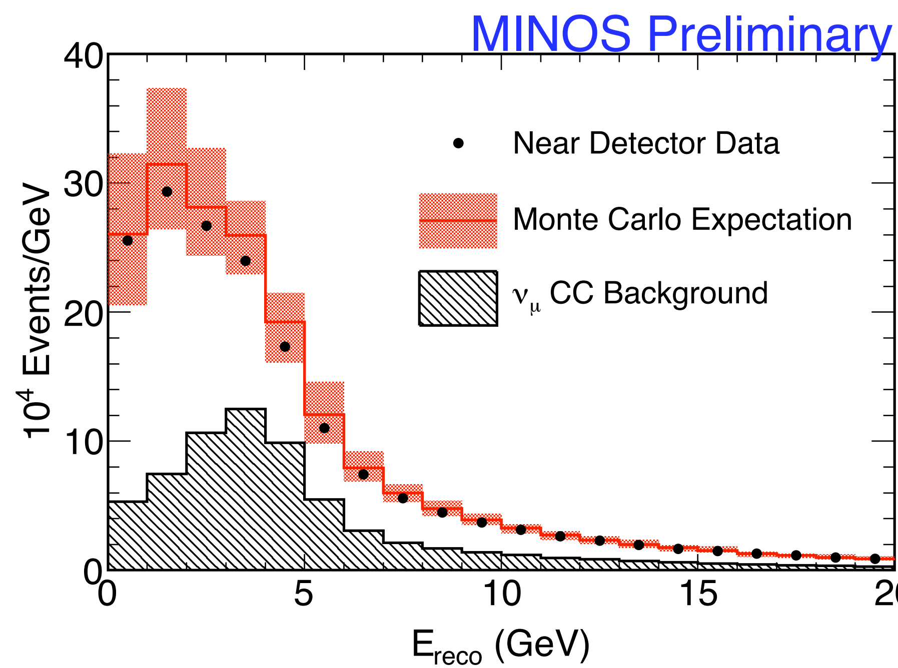
- Discard events with length > 60 planes
- Discard events with a track > 5 planes longer than the shower

- Same selection applied to Far Detector data and MC

NC/CC Event Separation

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





- NC events selected with ~90% efficiency and ~60% purity

- ND reconstructed NC-like energy spectrum
  - Good agreement between data and MC
  - Differences smaller than systematic uncertainties

Three-Flavor Analysis

- Compare the NC energy spectrum measured in the FD data (3.18×10^{20} POT exposure) with the expectation from standard 3-flavor neutrino oscillation physics. FD predictions are obtained using the Far/Near Ratio extrapolation method
- Fix the oscillation parameter values in predictions:
  - $\sin^2 2\theta_{23} = 1$ (SuperKamiokande)
  - $\Delta m^2_{32} = 2.43 \times 10^{-3}$ eV^2 (MINOS CC measurement)
  - $\Delta m^2_{21} = 7.59 \times 10^{-5}$ eV^2, $\theta_{12} = 35°$ (KamLAND + SNO)
  - $\theta_{13} = 0$ or $12°$ (Chooz limit)
  - $\delta_{CP} = 3\pi/2$ (maximal ν_e appearance)
  - Normal mass hierarchy
  - Note: CC ν_e are classified as NC by the analysis
- Make comparisons in terms of the ***R*** statistic:

Predicted CC background from all flavors

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

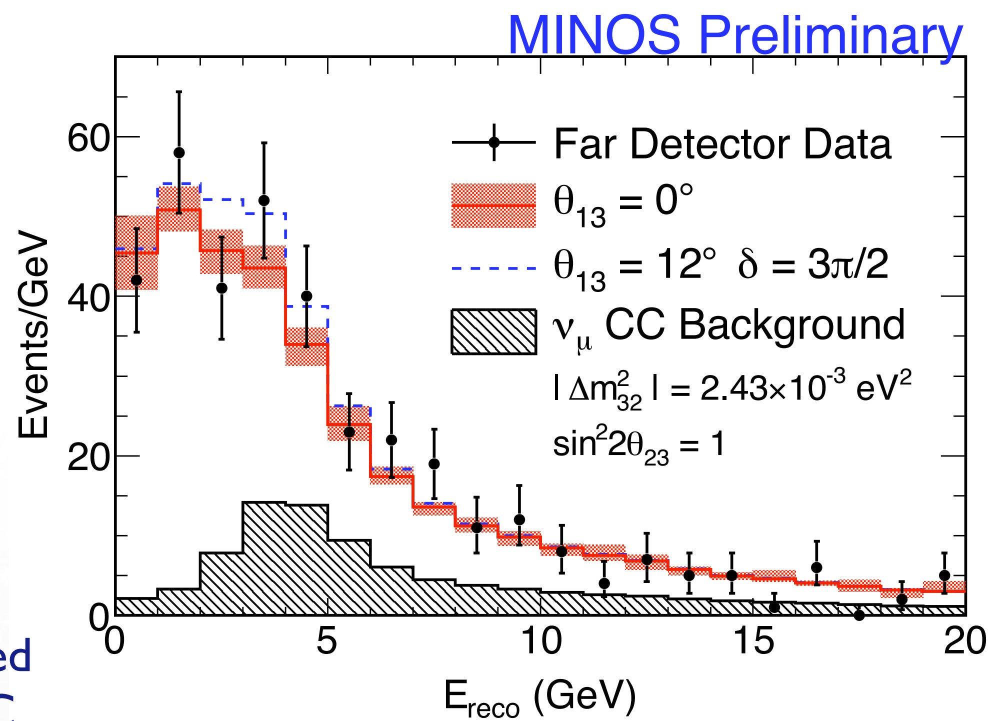
Predicted NC interaction signal

Three-Flavor Analysis

- Plot shows the selected FD NC energy spectrum for data and oscillated MC predictions

- Expect largest NC spectral depletion for E < 3 GeV if sterile mixing is driven by Δm^2_{32}

- Observed 388 data events, expected 377 ± 19.4 ± 18.5 (stat. ± syst.) MC events



Data is consistent with no NC disappearance

E_{reco} (GeV)	N_{Data}	S_{NC}	$B^{\nu_\mu}_{CC}$	$B^{\nu_\tau}_{CC}$	$B^{\nu_e}_{CCn}$
0 – 3	141	125.1	13.3	1.4	2.3 (12.4)
3 – 120	247	130.4	84.0	4.9	16.0 (32.8)
0 – 3	$R = 0.99 \pm 0.09 \pm 0.07 - 0.08(\nu_e)$				
3 – 120	$R = 1.09 \pm 0.12 \pm 0.10 - 0.13(\nu_e)$				
0 – 120	$R = 1.04 \pm 0.08 \pm 0.07 - 0.10(\nu_e)$				

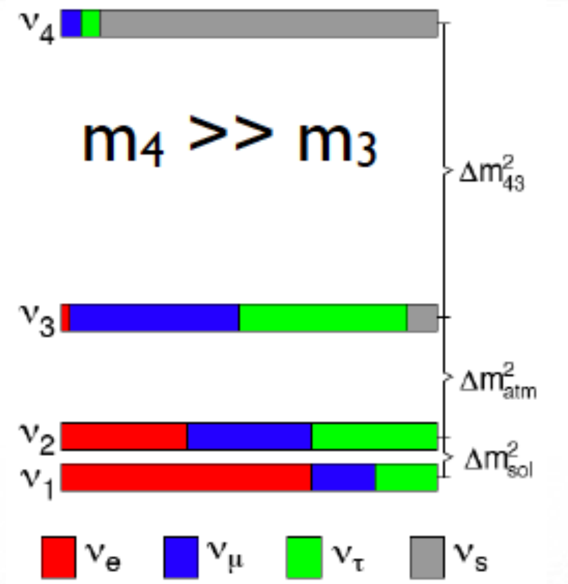
Four-Flavor Analysis

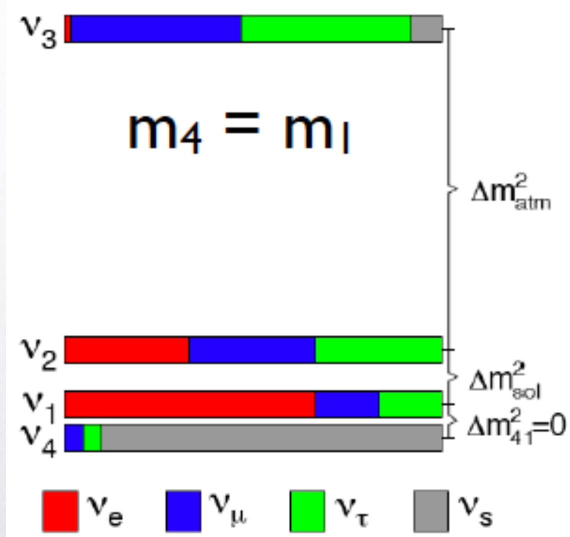
- Assume an additional sterile neutrino and an additional neutrino mass scale
- Extend mixing matrix with extra angles and phases:

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

- Consider two hypothesis for neutrino mass spectrum
  - $m_4 >> m_3$
  - $m_4 = m_1$
- Oscillation formulae are simplified under the assumptions:
  - $|\Delta m^2_{21}| \sim 0$
  - $\theta_{14} = 0$
  - $\delta_2 = 0$

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



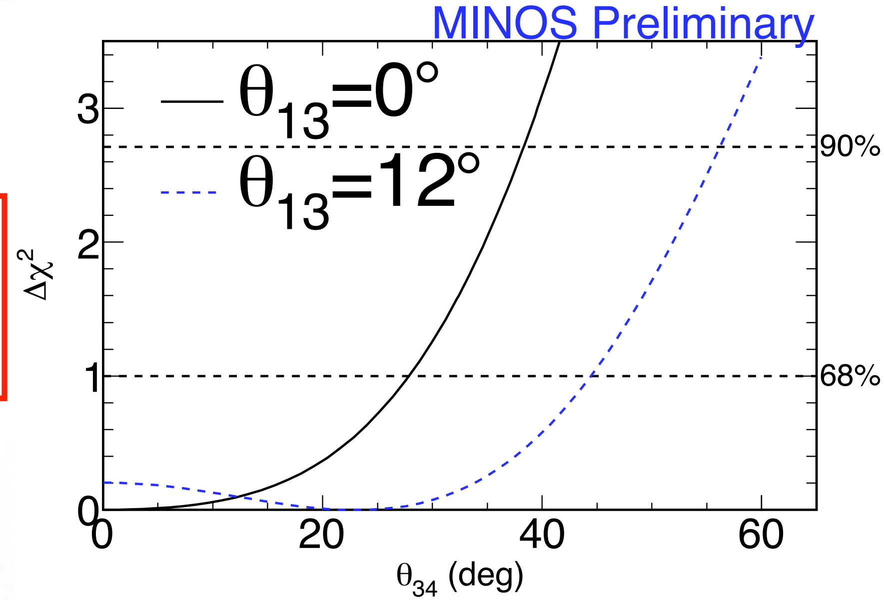


Four-Flavor Analysis

- Plots show 1-D $\Delta\chi^2$ projections for the angles relevant to sterile neutrino mixing

$\theta_{34} < 38°$ ($56°$ ν_e) (90% C.L.) (Both models)

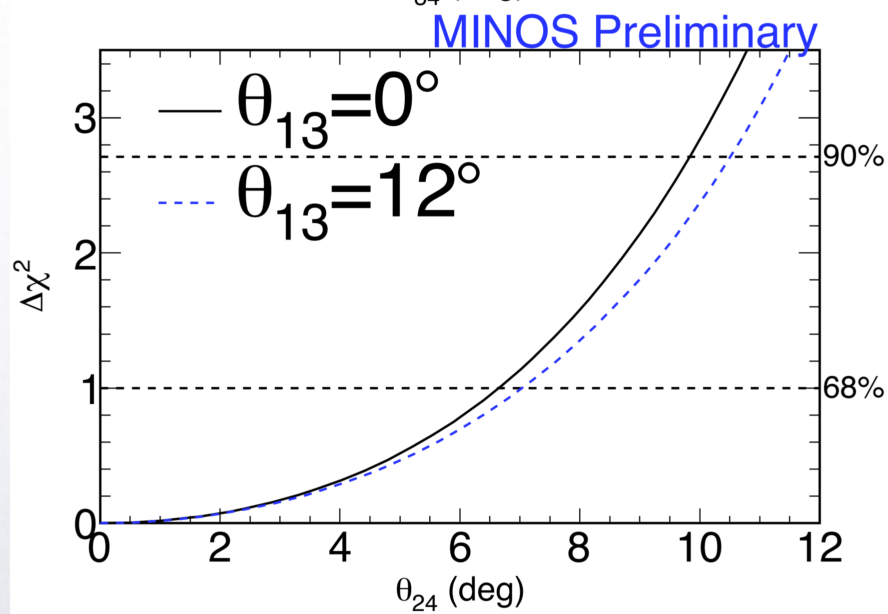
$\theta_{24} < 10°$ ($10.6°$ ν_e) (90% C.L.) ($m_4 >> m_3$)



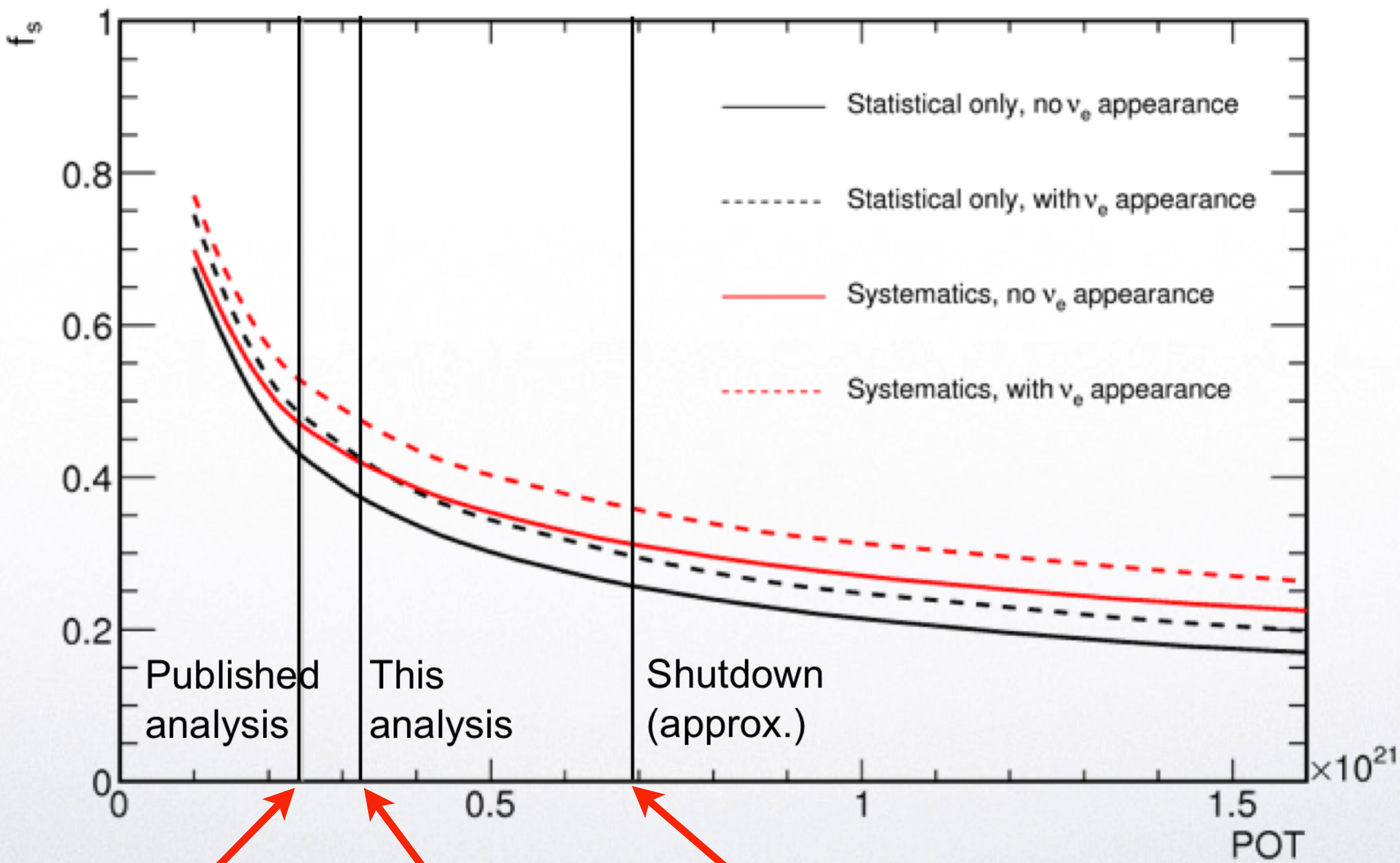
- Fraction of ν_μ that disappear by converting to sterile neutrinos is given by:

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

$f_s < 51\%$ (55% ν_e) (90% C.L.)



- Expect to improve 90% C.L. limit on sterile fraction with increased data exposure



2.46×10^{20} POT

Phys. Rev. Lett. 101, 221804 (2008)

3.18×10^{20} POT

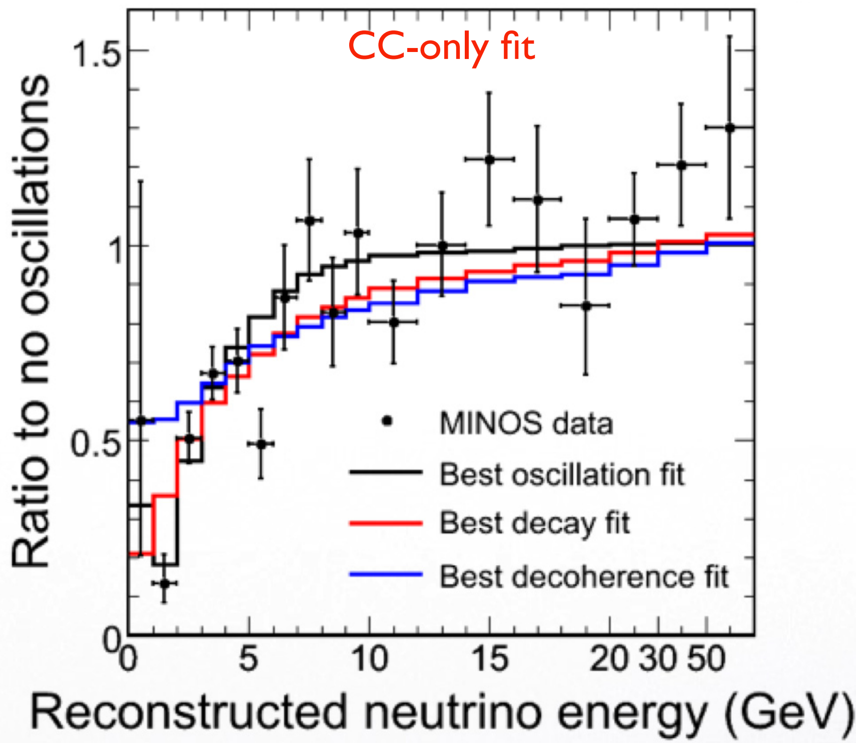
$\sim7\times10^{20}$ POT

Neutrino Decay

- If neutrinos were to decay into a sterile species, NC spectrum would also be affected
- MINOS CC results disfavor pure neutrino decay as an alternative to oscillations at 3.7σ
- Can improve this result by performing joint NC + CC fits to the data using a model with:
  - neutrino oscillations
  - single mass scale decays

$$P_{decay} = \left(1 - e^{-\alpha L/E}\right) \sin^2 \theta$$

NC+CC fits disfavor pure neutrino decay ($\Delta m^2 \rightarrow 0$) at 5.4σ



$\alpha < 1.6\times10^{-3}$ GeV/km (90% C.L.)

$\tau_3/m_3 > 2.1\times10^{-12}$ s/eV (90% C.L)

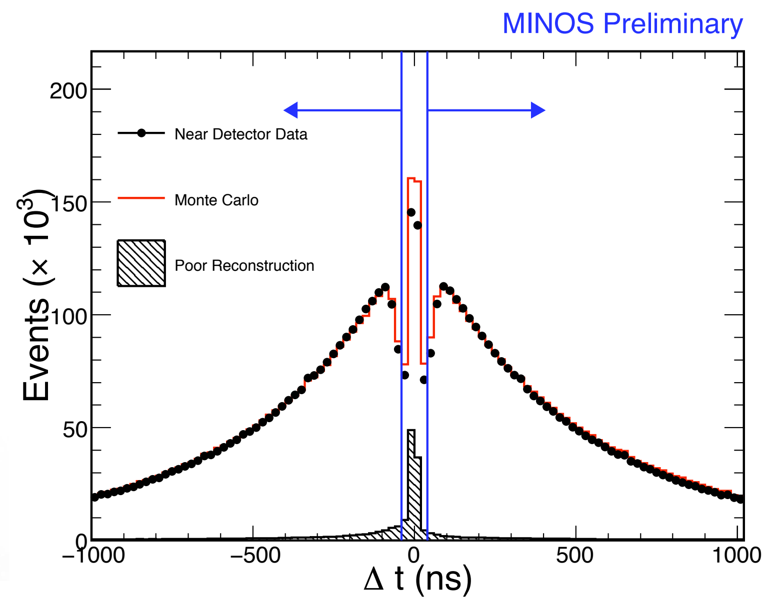
Summary

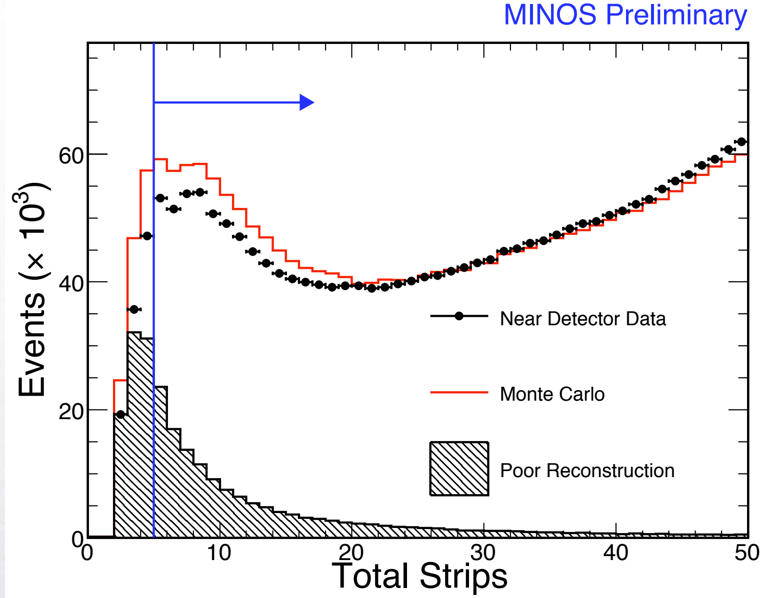
- MINOS has completed an analysis of neutral current interactions using 3.18×10^{20} POT NuMI beam exposure
- Results are consistent with no oscillations into sterile neutrinos
  - $R = 1.04 \pm 0.08 \pm 0.07 - 0.10(\nu_e)$
  - $f_s < 51\%$ (55% ν_e) (90% C.L.)
- Disfavor pure neutrino decay by 5.4σ as an alternative to oscillations
- To be submitted to Phys. Rev. D
- Limits expected to improve with analysis of $\sim 7 \times 10^{20}$ POT data sample.

BACKUP

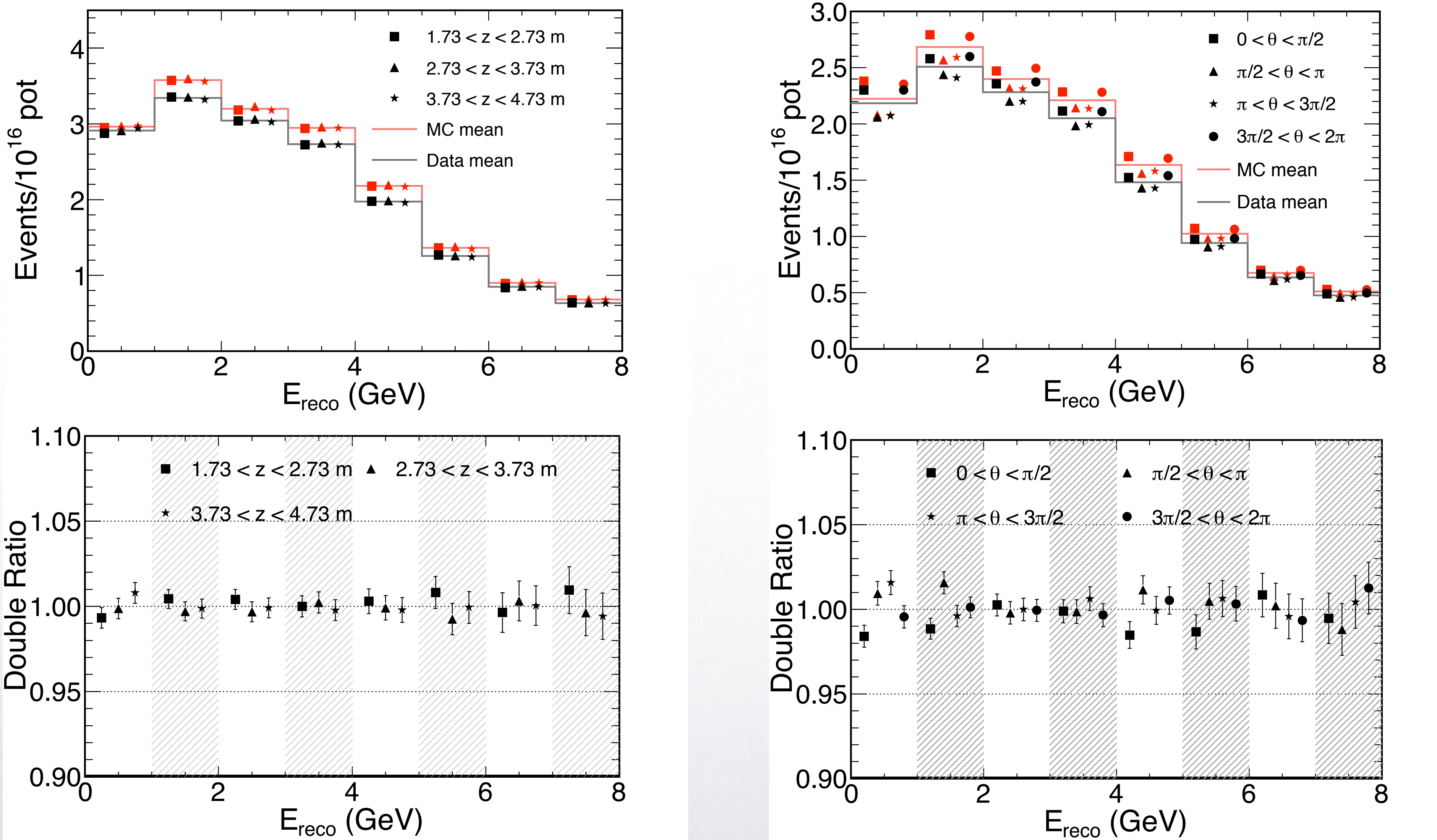
Near Detector Pre-Selection

- High event rate in ND can cause poor event reconstruction
  - Split events
  - Incorrect vertex
- Apply a series of cuts
  - Time and spatial separation
  - Total number of hit strips
  - Event steepness
  - Activity in edge region
- Reduce poorly reconstructed background <1GeV from 34% to 8%



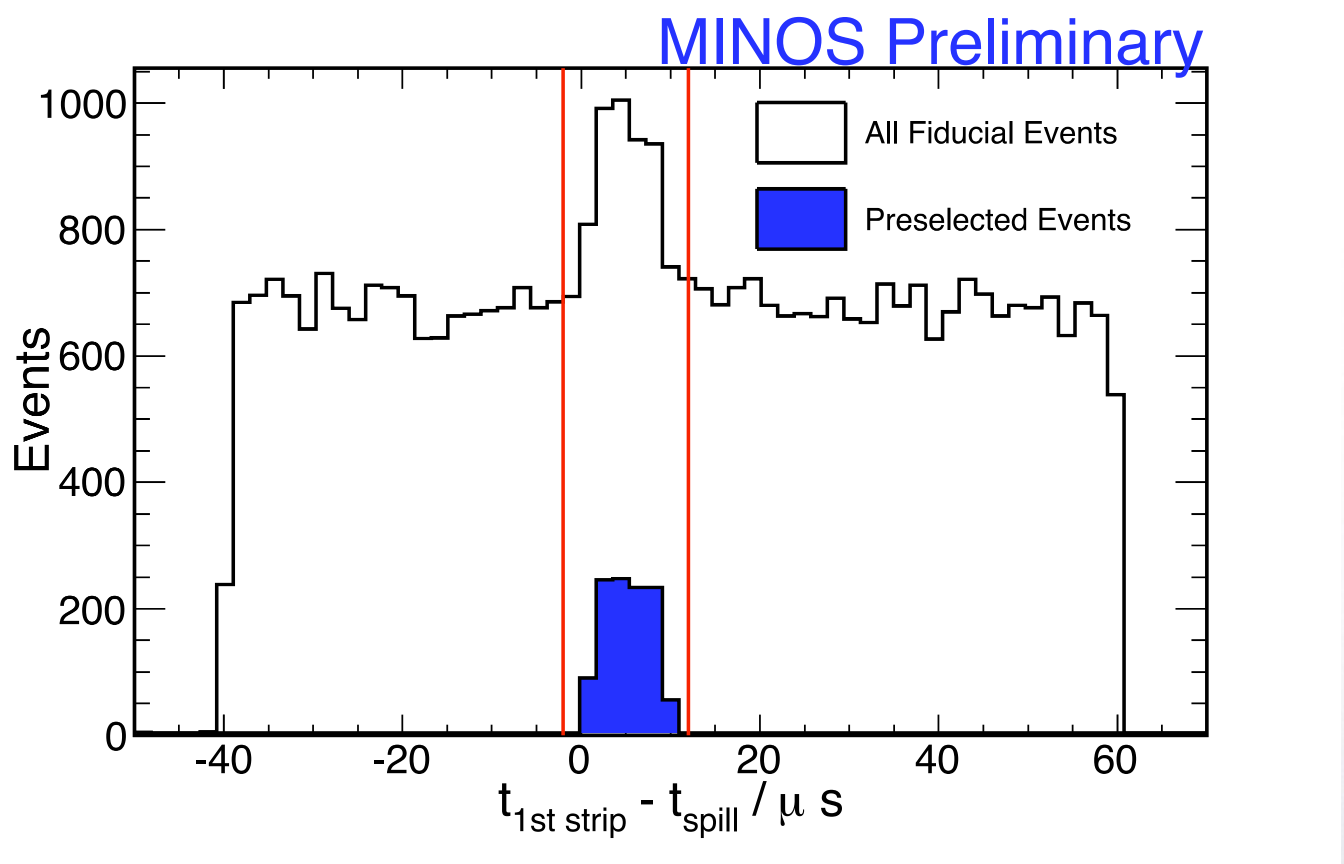


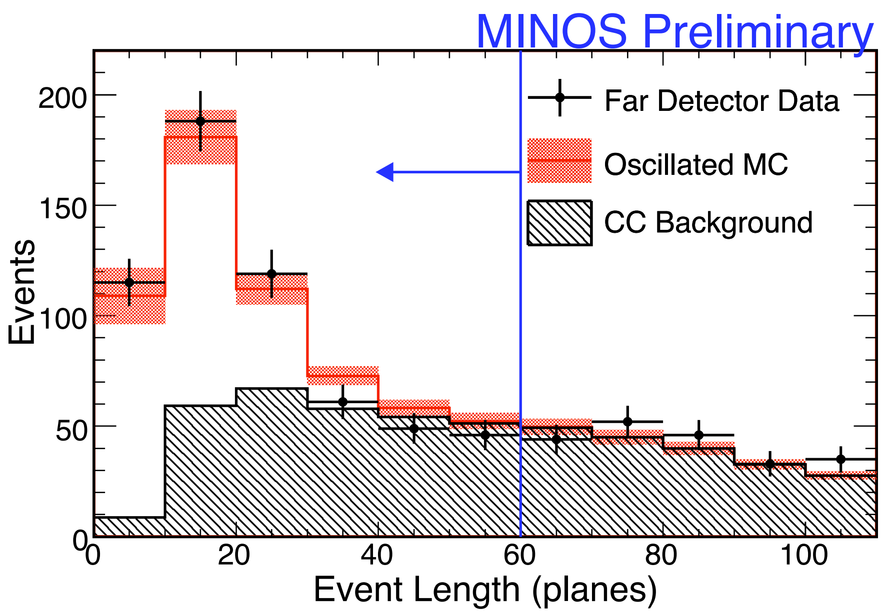
- Compare NC-selected Data/MC in different regions of the ND detector

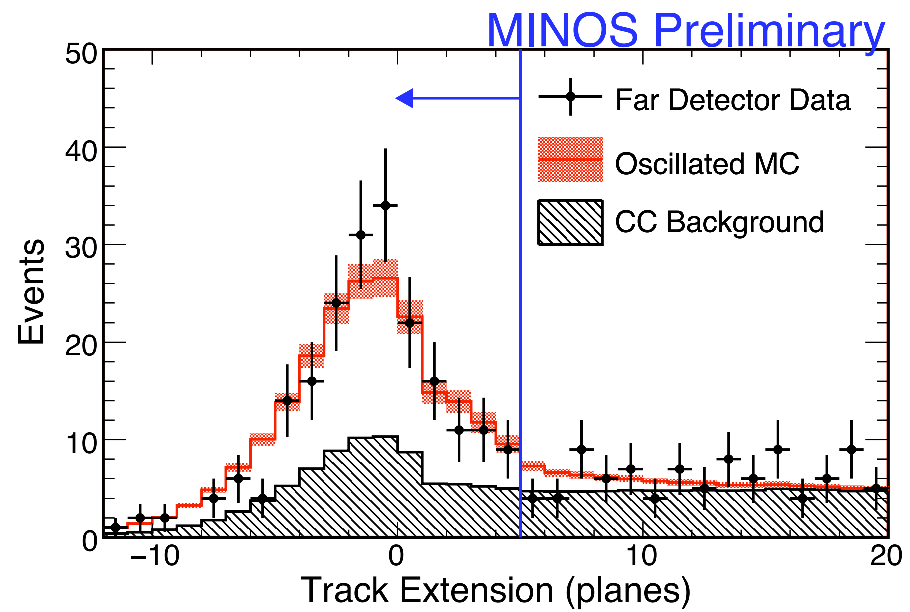


Far Detector Pre-Selection

- Cosmic backgrounds are removed using combination of timing and steepness




MINOS Preliminary
Far Detector Data
Oscillated MC
CC Background
Events
Event Length (planes)
0
20
40
60
80
100
50
150
200


MINOS Preliminary
Far Detector Data
Oscillated MC
CC Background
Events
Track Extension (planes)
−10
0
10
20
30
40
50

Extrapolation to Far Detector

- The measured ND energy spectrum is used to predict the FD energy spectrum via the **Far/Near Ratio** method
- Far/Near Ratio accounts for differences in detector geometry and fiducial volumes without relying on a specific parameterization of the ND data

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

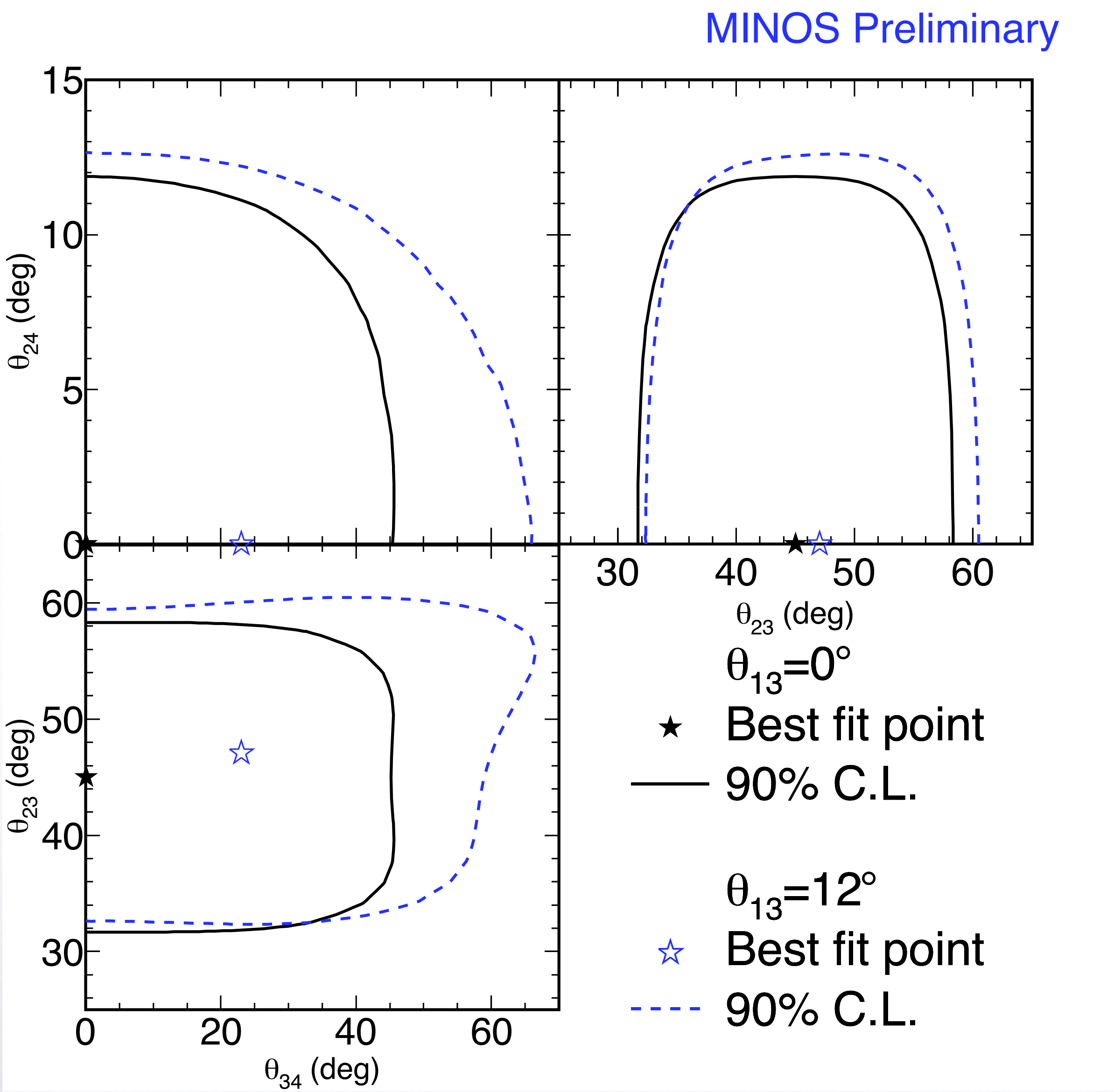
- Apply corrections to each energy bin in the FD MC using the ND data/MC differences as a scale factor
- Robust to most systematic uncertainties on flux and cross-sections
- FD data spectrum blinded until analysis procedures defined to avoid prediction biases

Four-Flavor Results

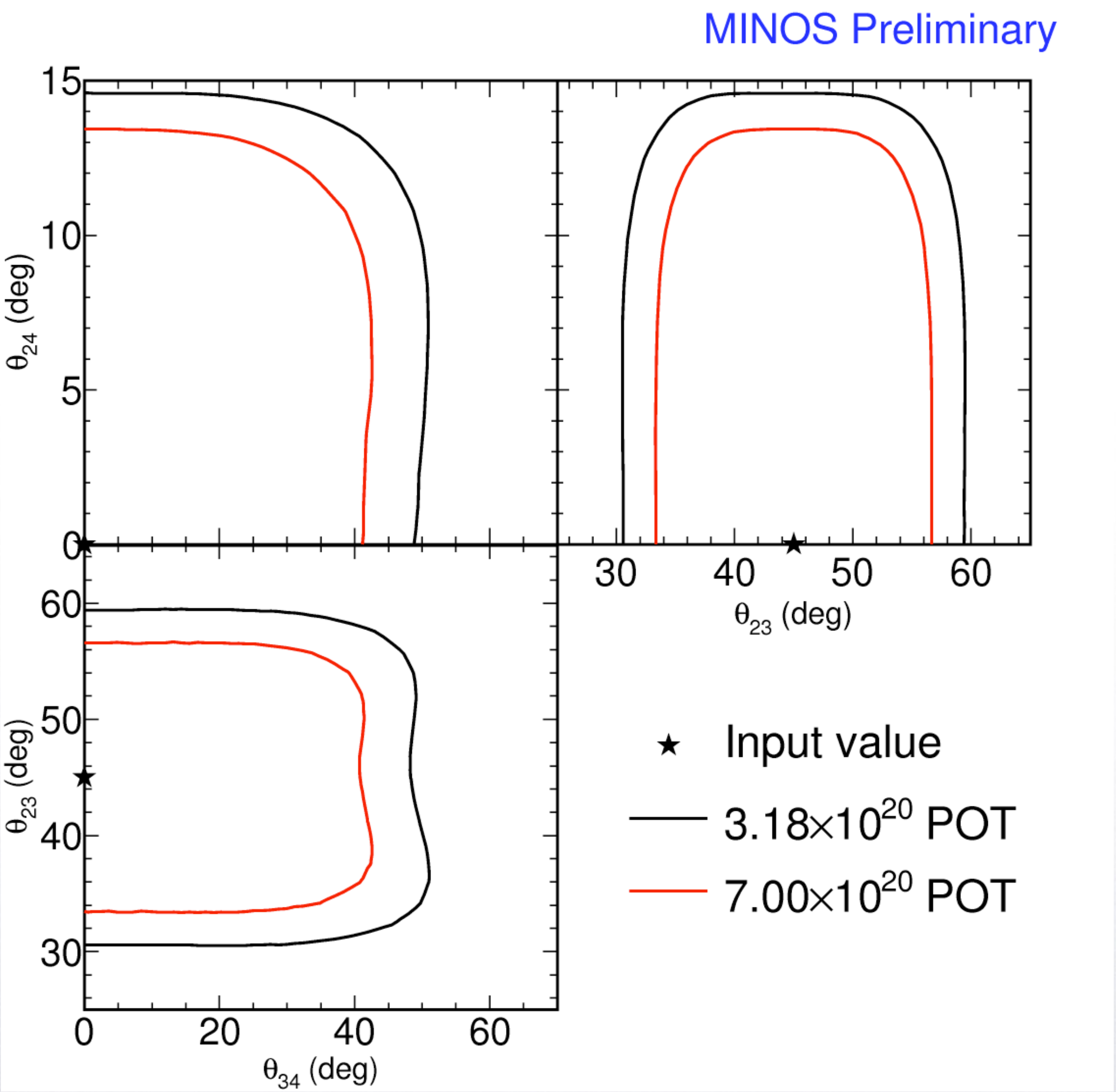
- Best fit points with 1σ errors obtained for the active-sterile oscillation models. Results are shown with and without ν_e appearance at the Chooz limit

Model	θ_{13}	χ^2/D.O.F.	θ_{23}	θ_{24}	θ_{34}	f_s
$m_4 = m_1$	0°	47.5/39	$45.0^{\circ}{}^{+9.0}_{-8.9}$	-	$0.1^{\circ}{}^{+28.7}$	0.51
	12°	46.2/39	$47.1^{\circ}{}^{+8.8}_{-11.0}$	-	$23.0^{\circ}{}^{+22.6}_{-24.1}$	0.55
$m_4 \gg m_3$	0°	47.5/38	$45.0^{\circ}{}^{+9.0}_{-8.9}$	$0.0^{\circ}{}^{+7.2}$	$0.1^{\circ}{}^{+28.7}$	0.52
	12°	46.2/38	$47.1^{\circ}{}^{+8.8}_{-11.0}$	$0.0^{\circ}{}^{+7.2}$	$23.0^{\circ}{}^{+22.6}_{-24.1}$	0.54

Four-Flavor Contours



Four-Flavor Sensititivities

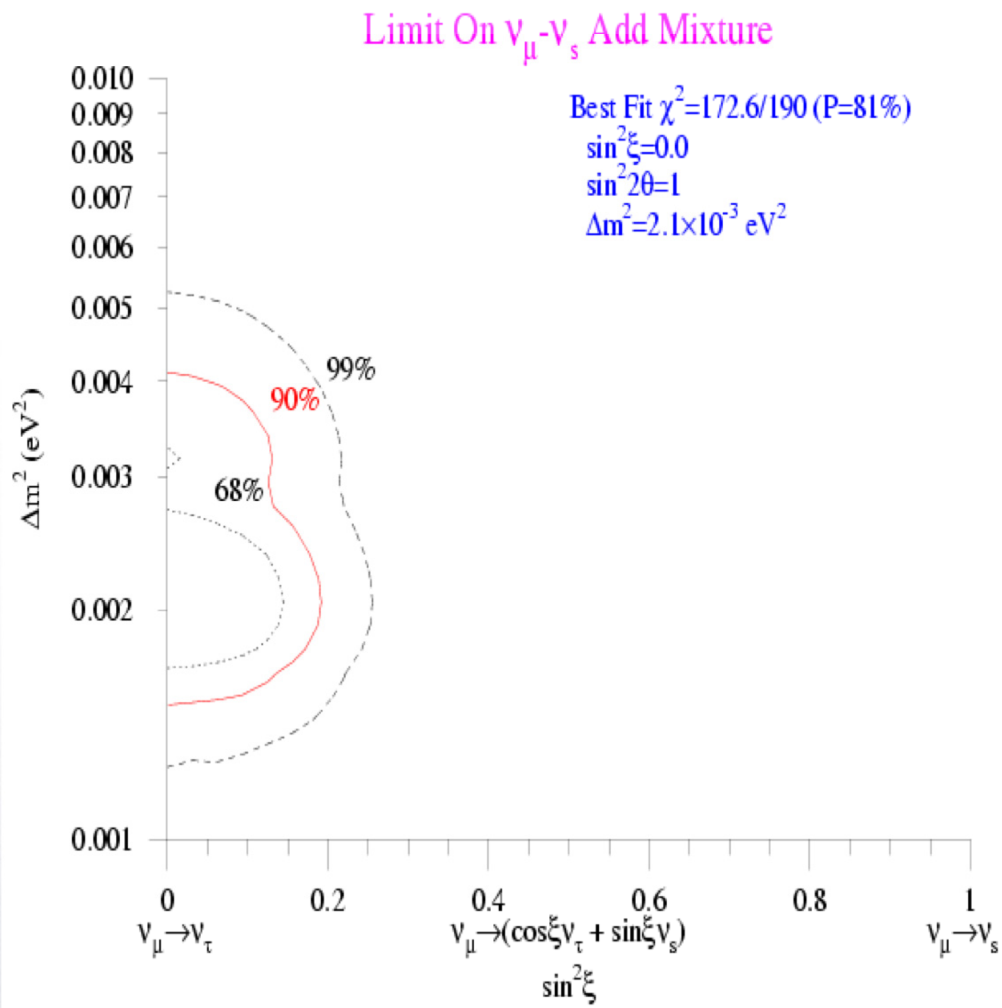


Systematic Errors

- **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

Uncertainty	$m4 \equiv m_1$		$m_4 \gg m_3$			Osc. with decay	
	$\Delta(\theta_{23})$	$\Delta(\theta_{34})$	$\Delta(\theta_{23})$	$\Delta(\theta_{24})$	$\Delta(\theta_{34})$	$\Delta(\alpha)$	$\Delta(\theta)$
Absolute $E_{Had.}$	0.3°	3.6°	0.2°	1.5°	4.5°	2.54×10^{-4}	2.6°
Relative $E_{Had.}$	0.6°	9.9°	0.6°	2.1°	9.9°	0.70×10^{-4}	3.7°
Normalization	0.3°	12.6°	0.1°	5.1°	6.3°	6.25×10^{-4}	0.9°
CC Background	0.1°	9.9°	0.2°	0.3°	9.9°	1.23×10^{-4}	4.0°
ND Selection	0.1°	9.9°	0.2°	0.3°	9.9°	1.15×10^{-4}	3.9°

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