Search for Flavor Changing Non-standard Interactions with the MINOS+ Experiment

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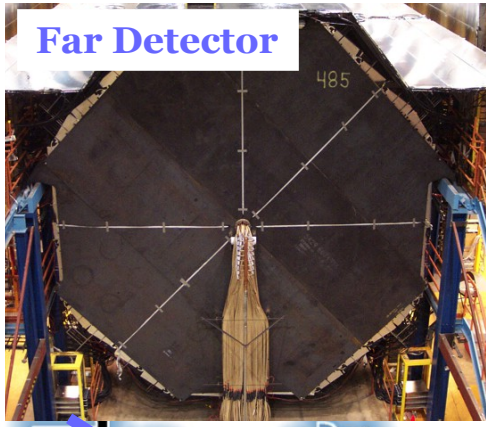
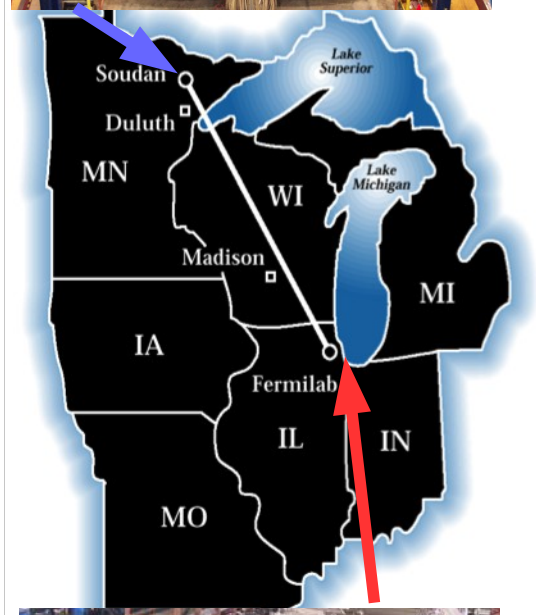
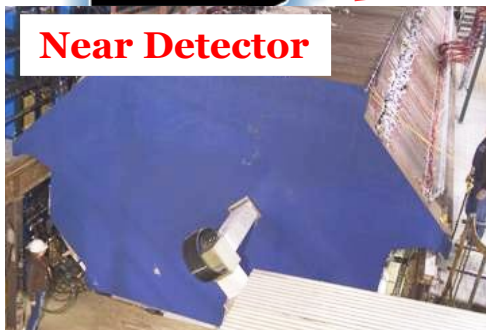
For the MINOS+ Collaboration

Meeting of APS Division of Particles and Fields
University of Michigan, Ann Arbor
August 4, 2015

The MINOS Experiment



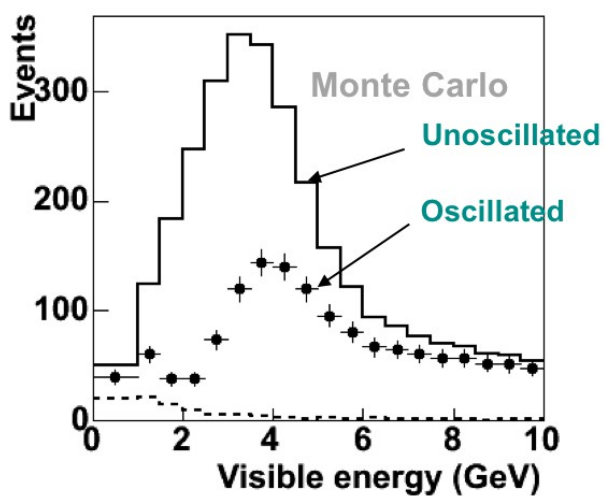


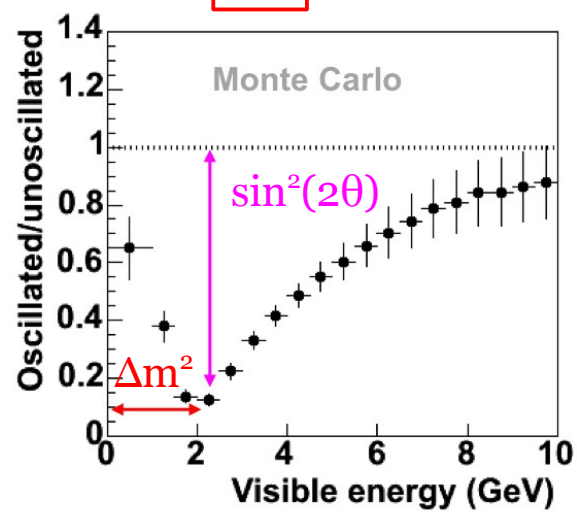


Main Injector Neutrino Oscillation Search

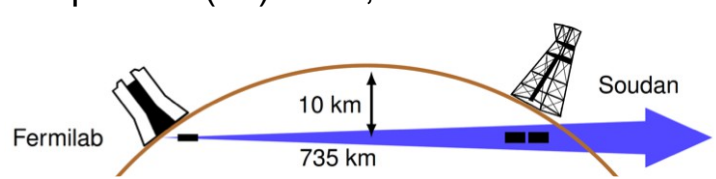
- Located along the NuMI beamline
- Two functionally equivalent detectors 735 km apart
  - Near Detector (ND) at Fermilab
  - Far Detector (FD) at Soudan, MN
- Look for ν_μ disappearance as a function of neutrino energy
  - Use ND to predict unoscillated FD spectrum
  - Compare predicted and measured FD to extract oscillation parameters

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L/E)$$





MC Input: $\sin^2(2\theta) = 1.0$; $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2



The MINOS Detectors

Both Detectors

- Alternating planes of steel and scintillator
- As similar as possible to reduce systematics associated with neutrino flux, cross sections, and detector efficiency
- Toroidal magnetic field of 1.3 T
  - Distinguish μ^+/μ^-
  - Momentum form range/curvature

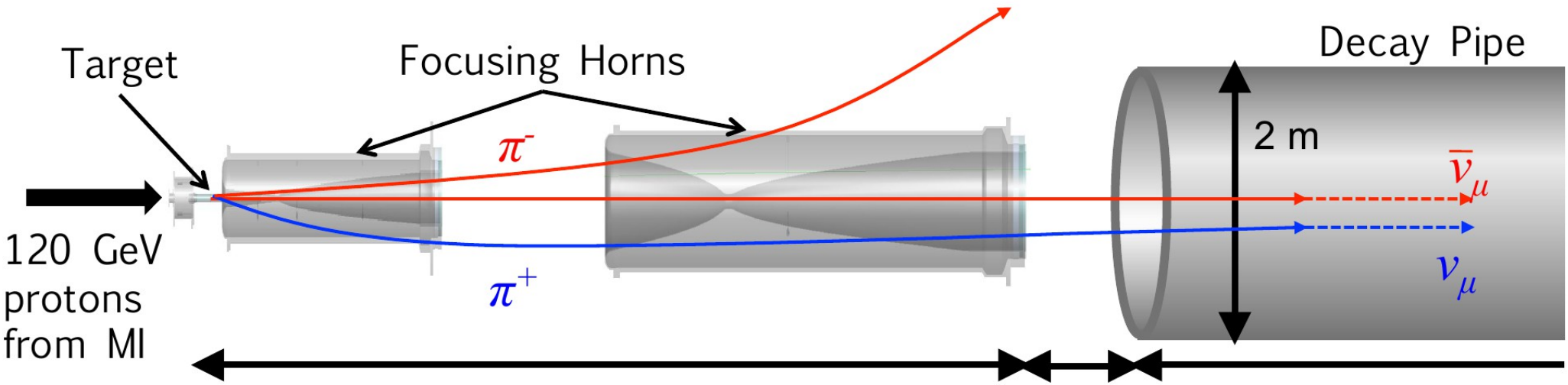
Near Detector at Fermilab

- 1 km from source
- 0.98 kt, 282 planes
- Measure beam composition and energy spectrum

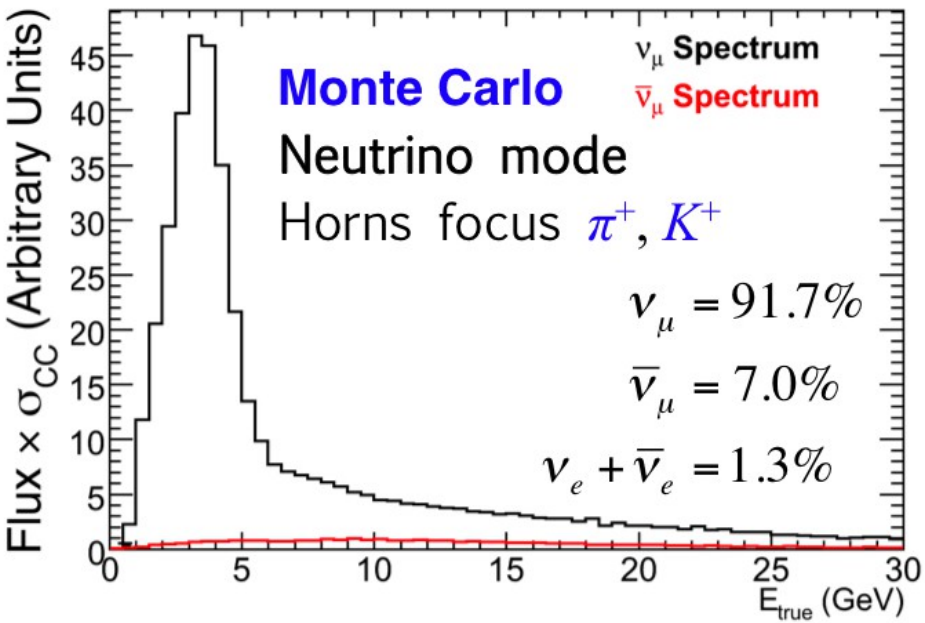
Far Detector at Soudan Mine

- 735 km from source
- 5.4 kt, 486 planes
- Measure energy dependent disappearance/appearance
- Indication of neutrino oscillations

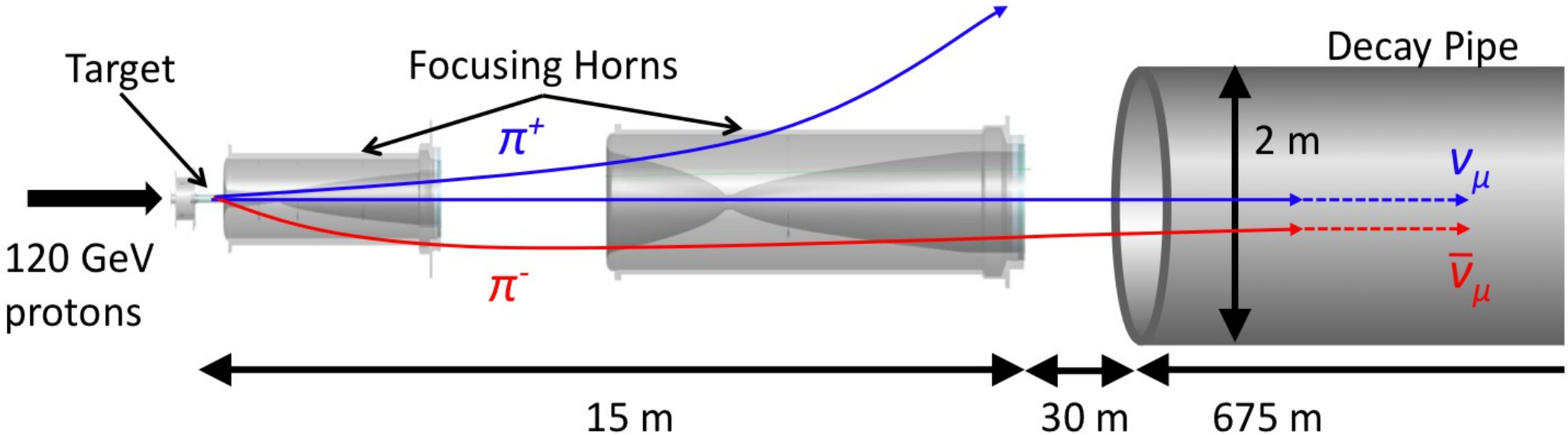
NuMI Beam



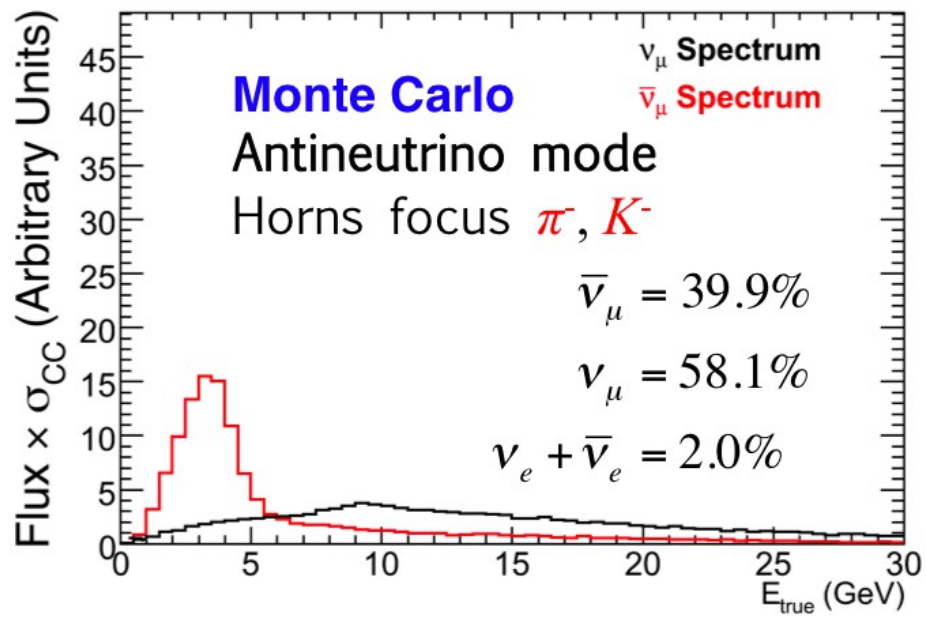
- 120 GeV protons from Main Injector strike graphite target producing hadrons
- Two magnetic horns horns focus π^+ and K^+, enhancing ν_μ flux
- Energy spectrum changed by varying target position
- Nominal configuration ~3 GeV



Antineutrino Beam



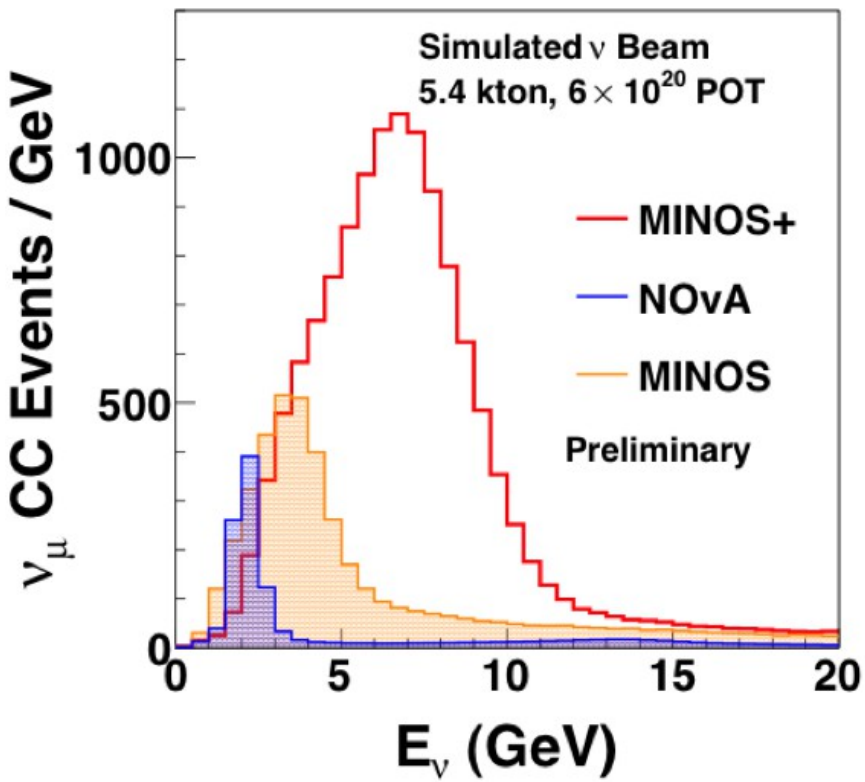
- Reverse horn current to focus π^- and K^-, creating $\bar{\nu}_\mu$ enriched beam
- Due to smaller $\bar{\nu}_\mu$ cross section and less π^- produced, $\bar{\nu}_\mu$ rate is lower and there are many high energy ν_μ



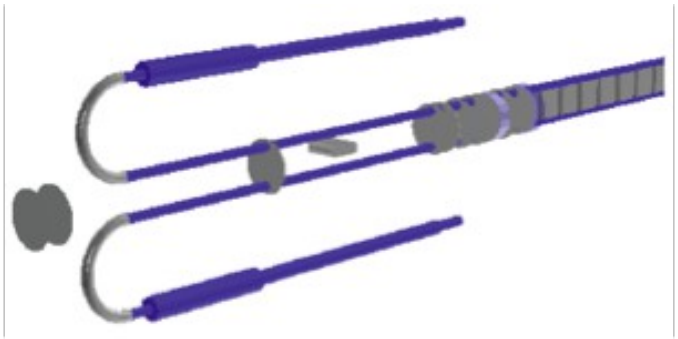
NuMI Beam in the Nova Era

MINOS+ takes advantage of new Medium Energy (ME) beam setting (for NOvA)

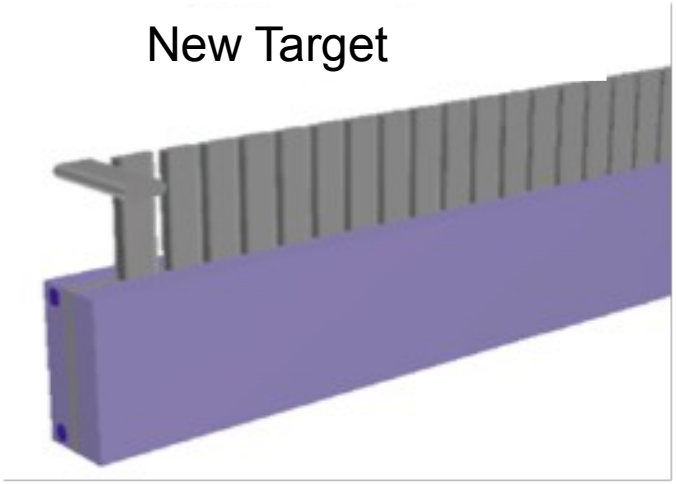
- New target and new Horn 1
- Horn 2 moved 10 m downstream
- Higher intensity, higher energy beam



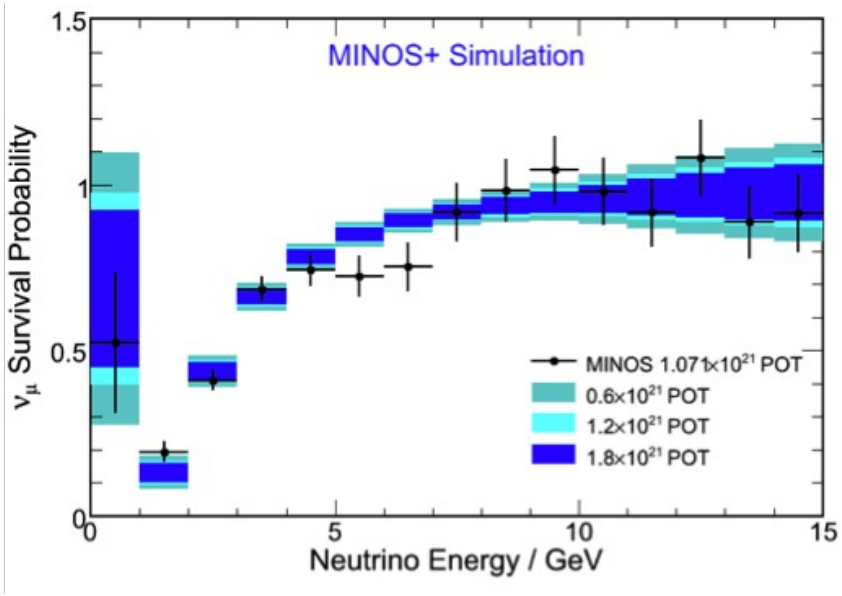
Old Target

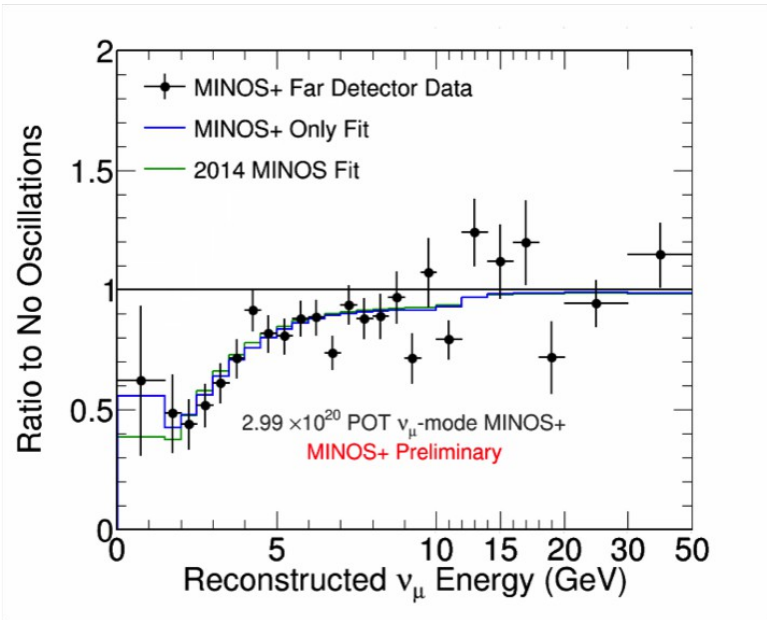


New Target



MINOS+ Physics





Higher Energy: Cross-check existing neutrino oscillation results in higher energy region with using new beam and cross-section systematics

Higher Statistics: Expect ~4000 events/year at FD for improved measurements of standard three-flavor oscillations (in particular, Δm^2_{32})

Enhanced Sensitivity to New Physics:

- Search for light sterile neutrinos
- Search for flavor changing Non-standard Interactions (NSI) in mu-tau and e-tau sectors

Have analyzed first year of MINOS+ beam data (3×10^{20} POT)

- Independent test of MINOS oscillation result
- Combined MINOS and MINOS+ beam data provide significant statistical improvement of standard neutrino oscillation measurement

Non-Standard Interactions

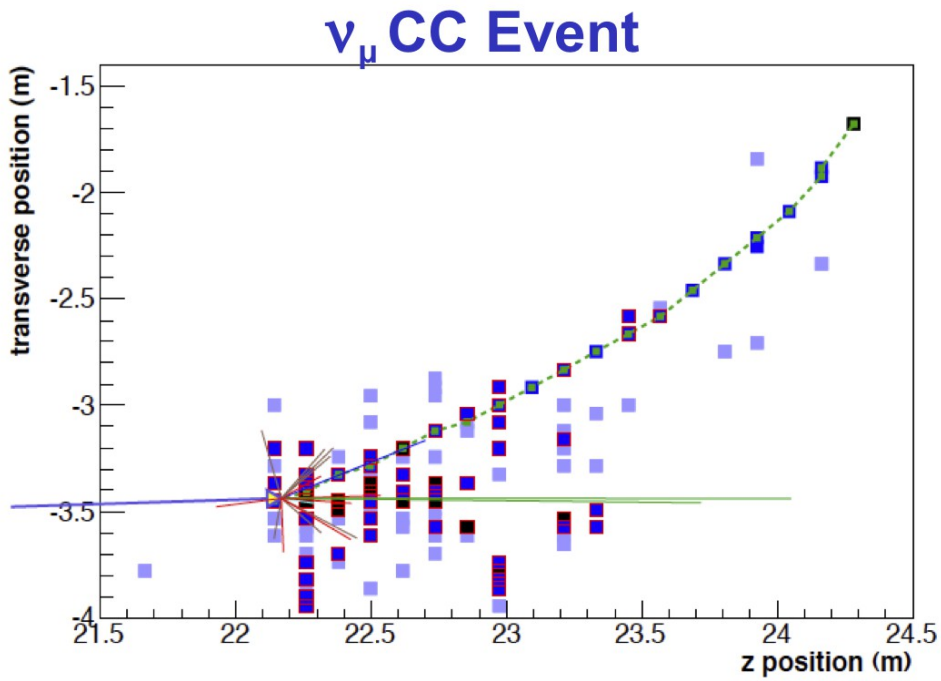
- Coherent forward scattering of neutrinos via interactions with matter as they propagate
- Interactions beyond the standard model
- Flavor conserving or flavor changing

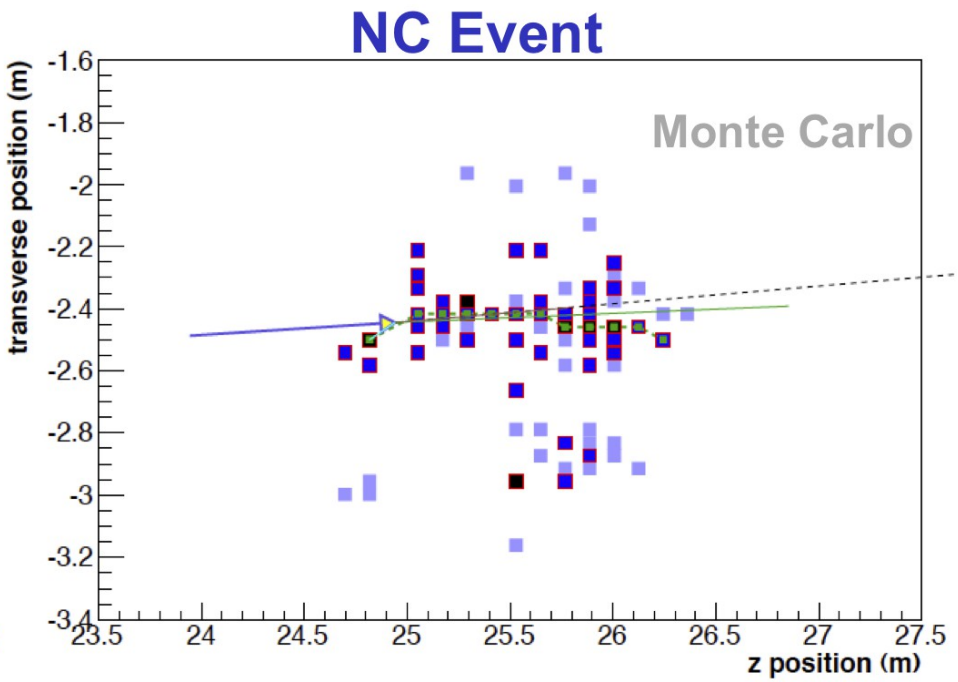
$$H = \underbrace{U_{PMNS} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U_{PMNS}^T}_{\text{Vacuum oscillations}} + \sqrt{2} G_F N_e \underbrace{\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}}_{\text{NSI}}$$

- MINOS is sensitive to flavor changing Non-standard Interactions (NSI) in multiple oscillation modes
  - $\varepsilon_{\mu\tau}$ through ν_μ disappearance
  - $\varepsilon_{e\tau}$ through ν_e appearance

Selecting ν_μ-CC Events

- MINOS event topologies





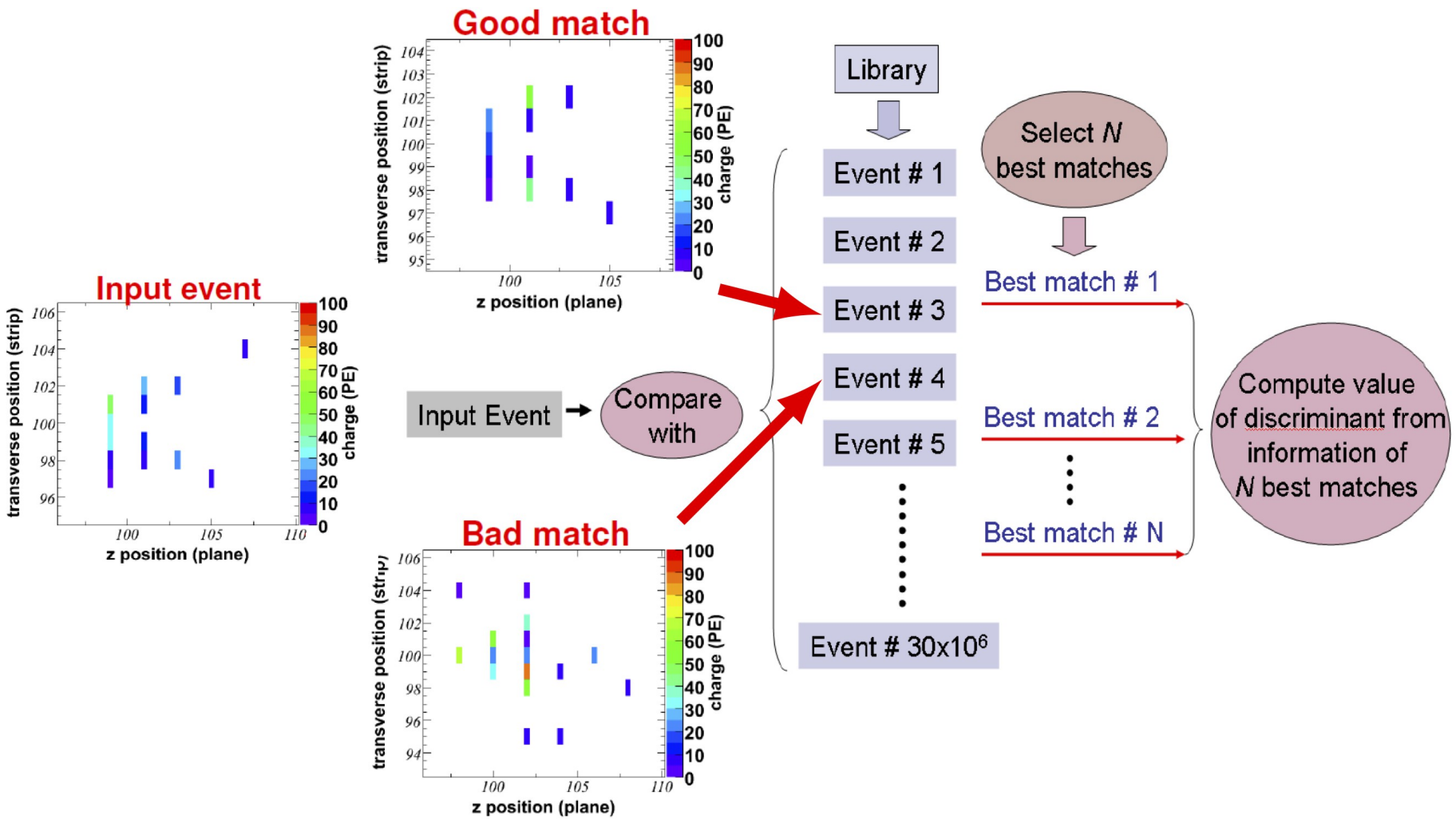
CC Signal Event
- Long track with hadronic activity at vertex
- Total energy = Track + Shower

NC Background Event
- No track
- Main contamination at low energy

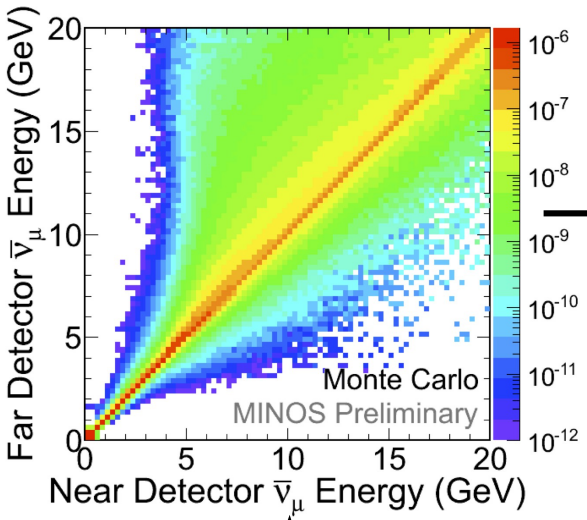
- Use k-Nearest Neighbor (kNN) algorithm to further enrich CC sample

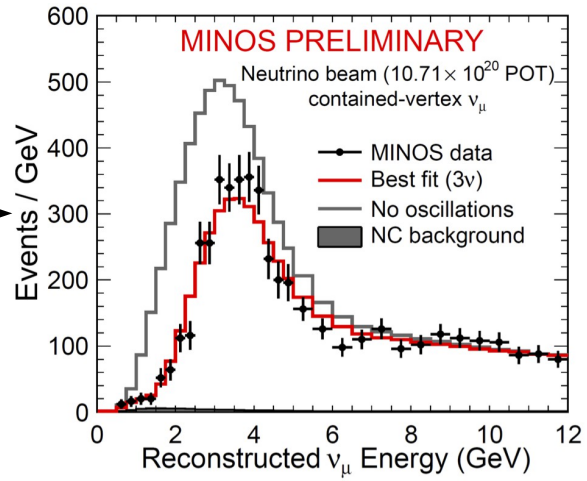
Selecting ν_e-CC Events

Library Event Matcing (LEM)

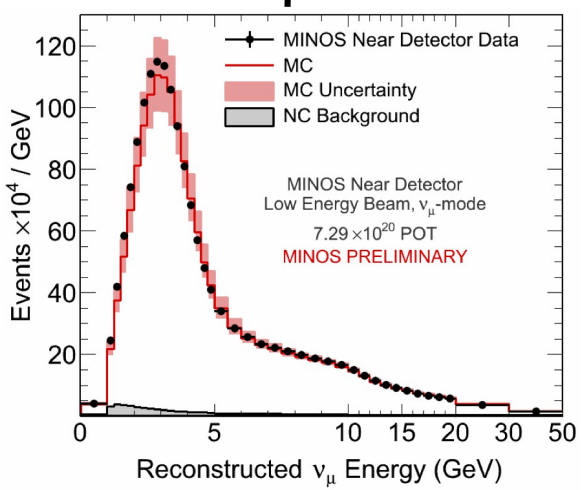


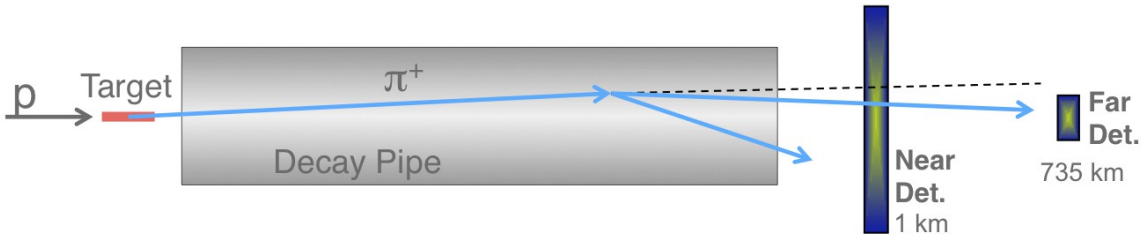
Near to Far Extrapolation



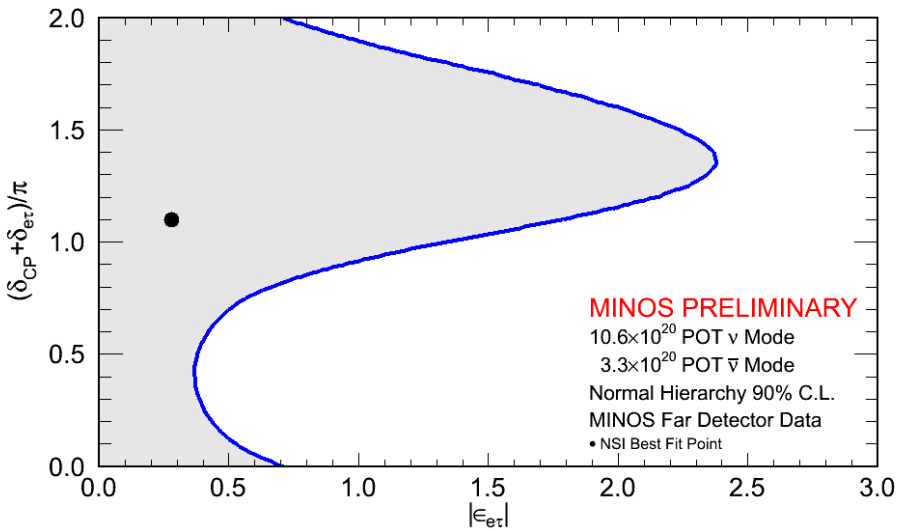


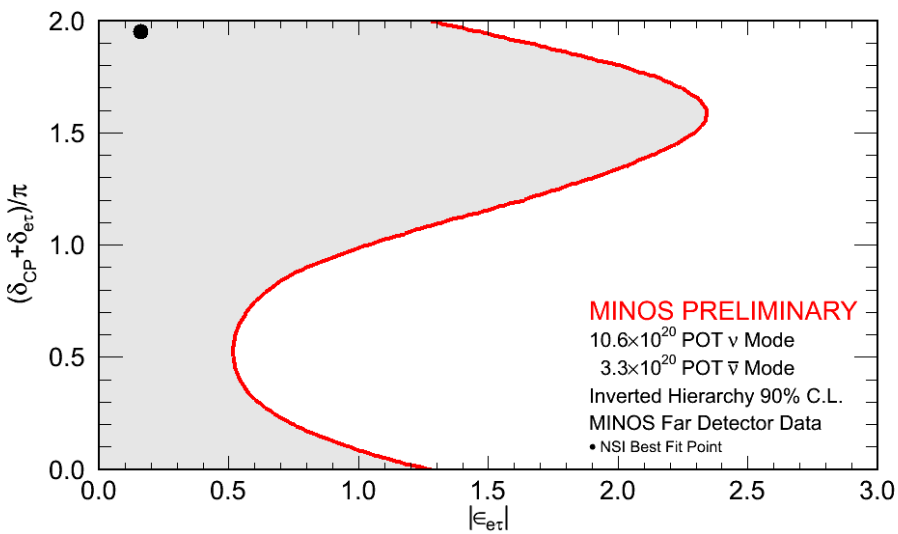
Beam matrix encapsulates knowledge of pion two-body decay kinematics and geometry, relating ND and FD spectra





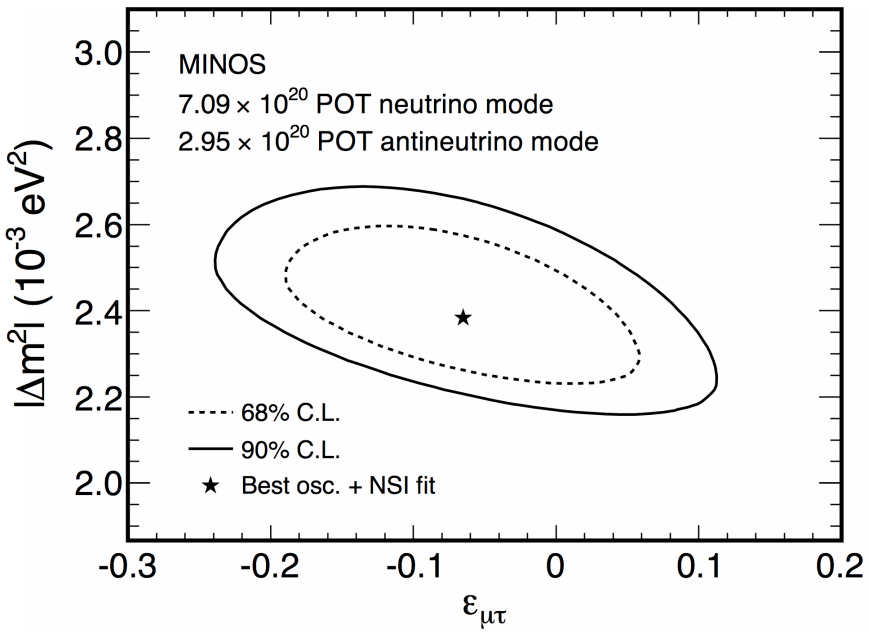
$\varepsilon_{e\tau}$ Results

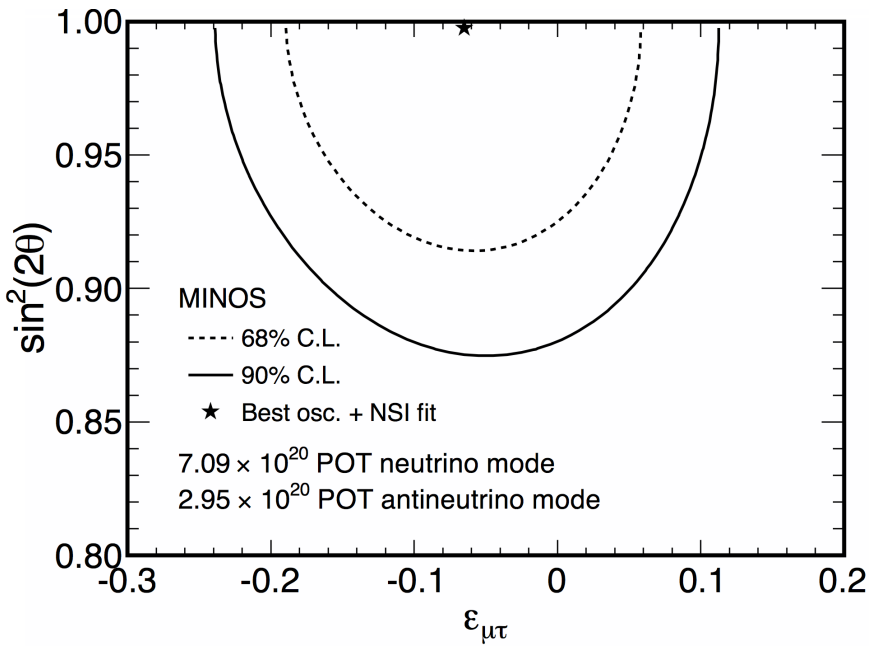




- Presented at Neutrino 2014 in Boston
- $\varepsilon_{e\tau}$ analysis follows NSI formulation from:
  *Friedland, Lunardini, Maltoni, PRD **70**, 111301 (2004)*
  *Coelho, Kafka, Mann, Schneps, Altinok, PRD **86**, 113015 (2012)*
- Uses full MINOS beam data set
- Results consistent with no Non-standard Interactions

$\varepsilon_{\mu\tau}$ Results





- Simultaneous fit to neutrino and antineutrino samples of conventional $\nu_\mu \longrightarrow \nu_\tau$ oscillations with an additional NSI matter effect:

$$\Delta m^2 = 2.39^{+0.14}_{-0.11} \times 10^{-3}\, eV^2$$
$$\sin^2(2\theta) = 1.00^{+0.00}_{-0.06}$$
$$\epsilon_{\mu\tau} = -0.07^{+0.08}_{-0.08}$$

with an allowed range of:

$$-0.20 < \epsilon_{\mu\tau} < 0.07 \quad (90\%\ C.L.)$$

- Within errors result is consistent with no contribution to flavor change from NSI

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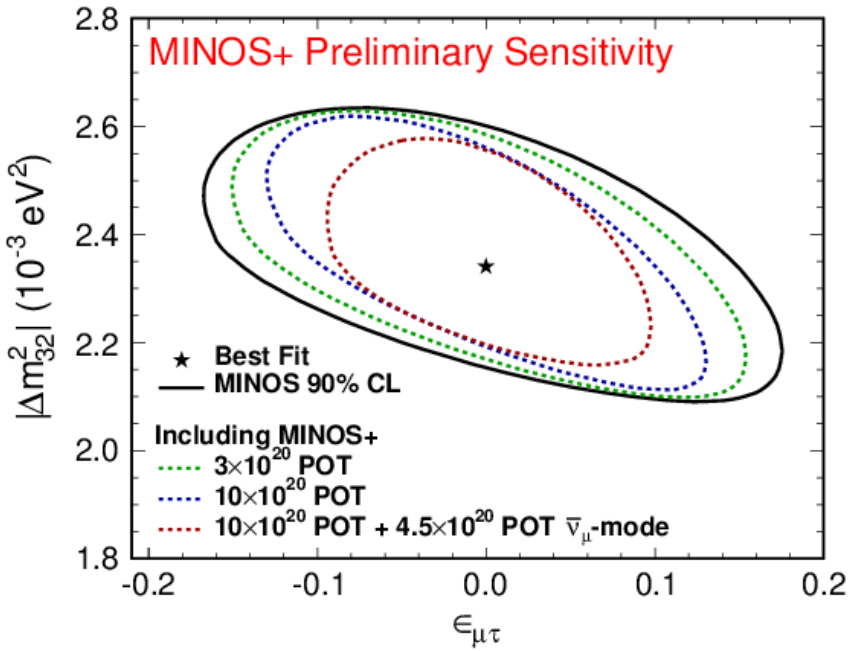
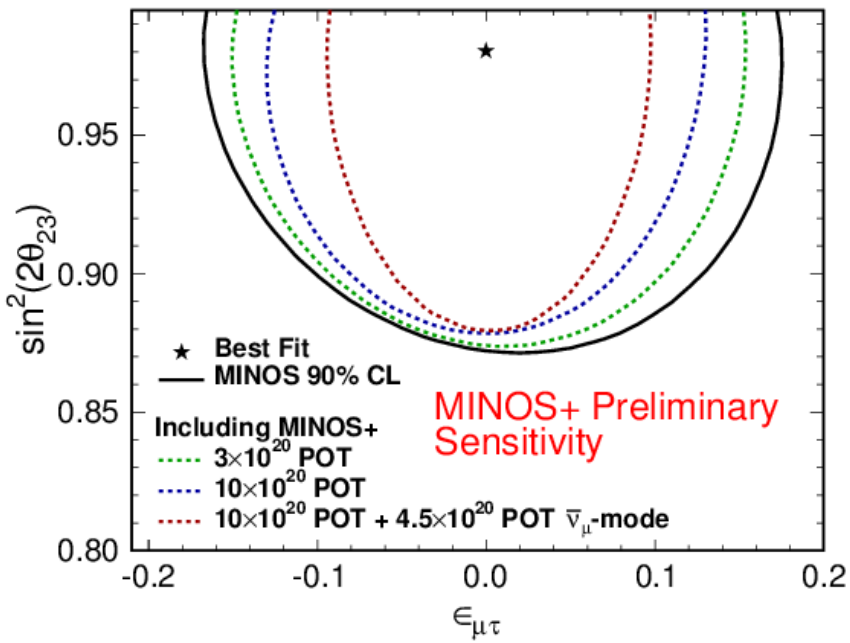
MINOS+ $\varepsilon_{\mu\tau}$ Sensitivity





- Improvement in sensitivity from including complete MINOS beam data set
- Expect further improvement (~17%) from including first year of MINOS+ data
  - Project an improvement of nearly 50% in sensitivity to $\varepsilon_{\mu\tau}$ compared to current limit by including full MINOS+ data set
  - Antineutrino running contributes close to half of this improvement
- Updated result with result with full systematics and 3 flavor NSI will be released soon

Summary

- MINOS+ uses the medium energy NuMI beam and will continue to improve neutrino oscillation measurements

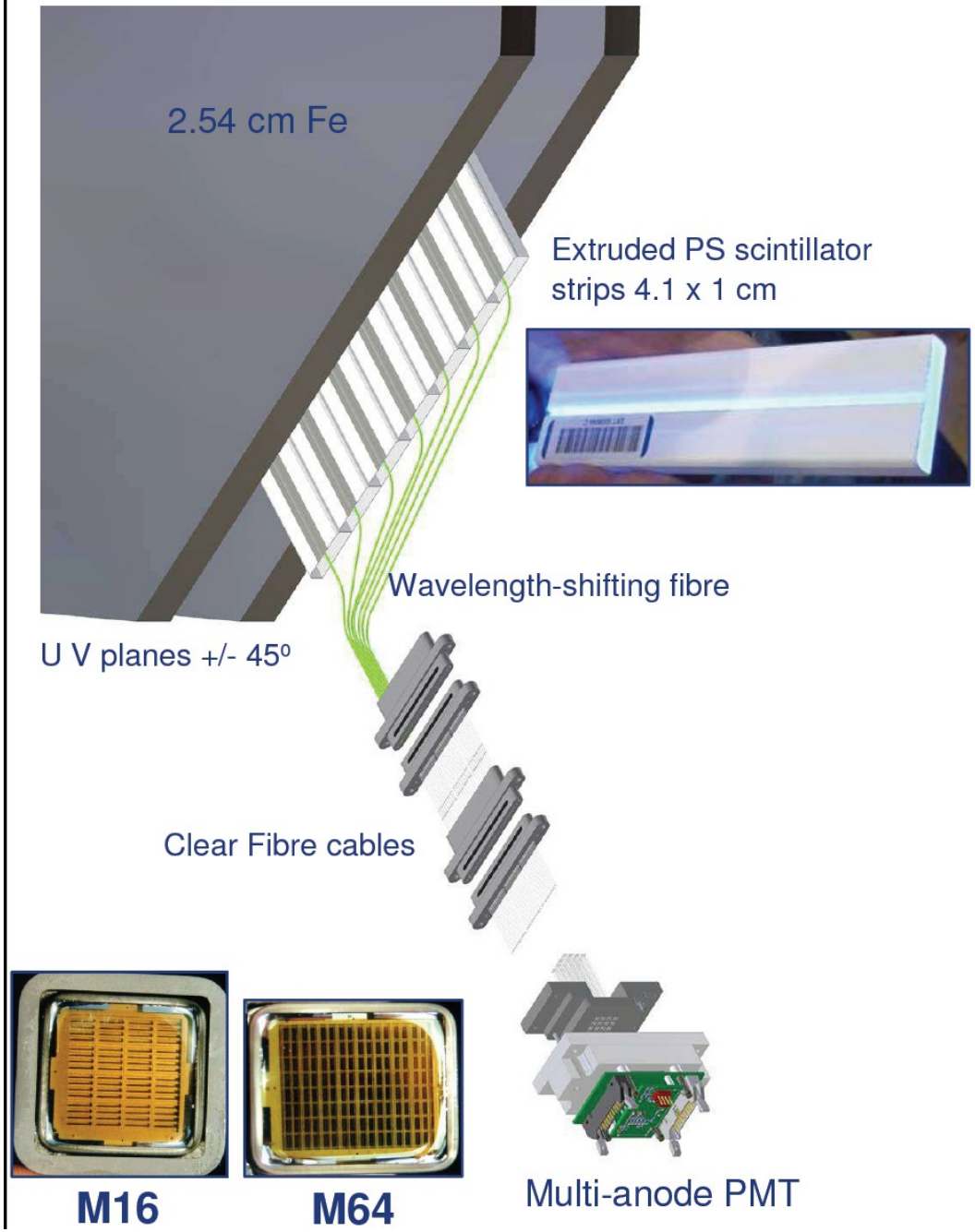
- MINOS+ is sensitive to NSI parameters $\varepsilon_{\mu\tau}$ through ν_μ disappearance and $\varepsilon_{e\tau}$ through ν_e appearance

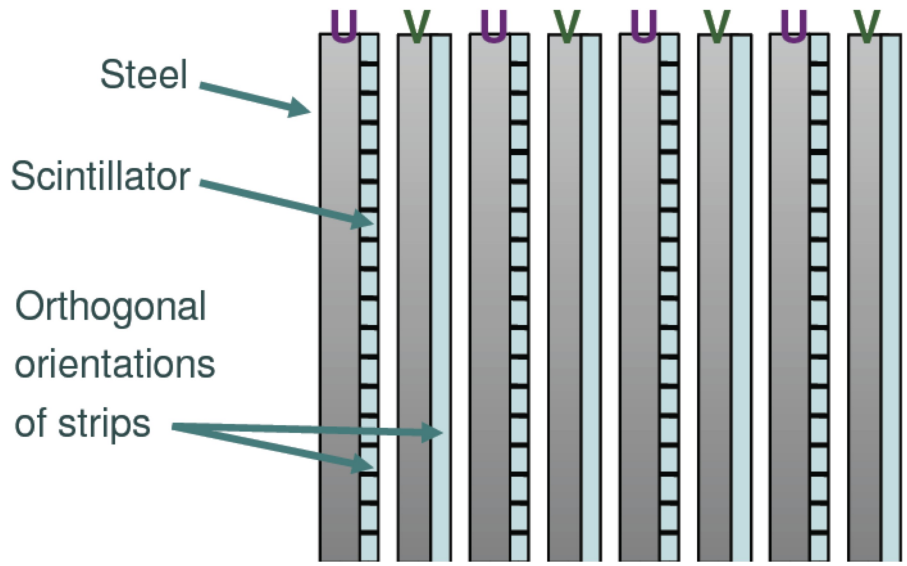
- Studies using MINOS beam data in both sectors are consistent with no NSI

- Sensitivity to NSI parameters will be significantly improved with MINOS+ data

Backup Slides

Detector Technology





Tracking Calorimeters

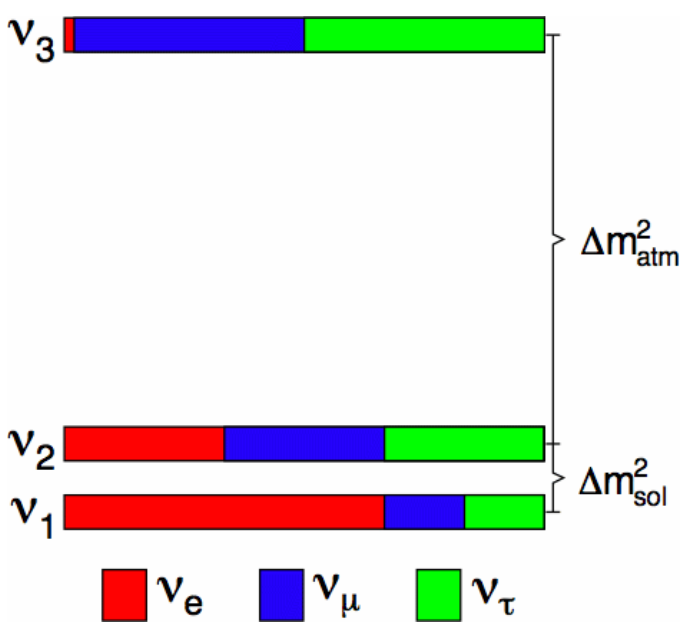
- 2.54 cm thick steel planes
  - 1.4 radiation lengths
- 1 cm thick scintillator planes
  - 1.11 x Moliere radius
  - Segmented into 4.1 cm wide strips
  - Scintillator strips optically coupled to mulit-anode PMTs

Neutrino Oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric, accelerator — $\theta_{13}\approx 9^{o}$ — Solar, reactor

$\theta_{23}\approx 45^{o}$ — $\delta \rightarrow$ CP violating phase — $\theta_{12}\approx 34^{o}$



From solar/reactor:

$$|\Delta m^2_{sol}|\approx 8\times 10^{-5}\,eV^2$$

From atmospheric/accelerator:

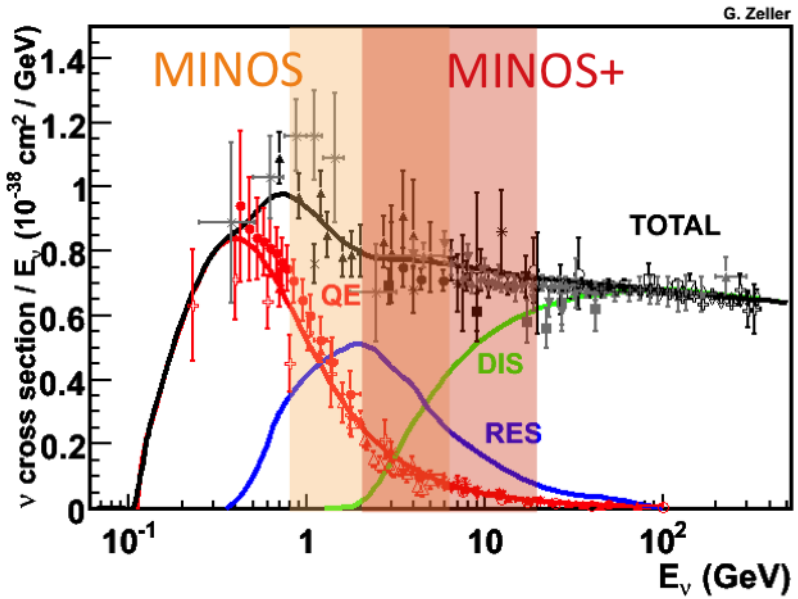
$$|\Delta m^2_{atm}|\approx 2.4\times 10^{-3}\,eV^2$$

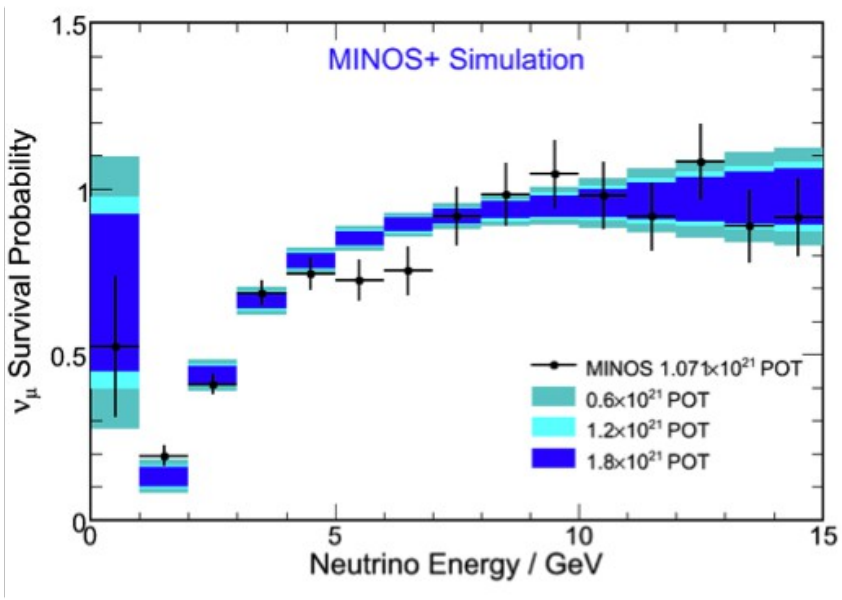
Sign of Δm^2_{atm} unknown

Are neutrinos Majorana?

Is there a fourth sterile neutrino?

MINOS+ Physics





MINOS+ is the next phase of MINOS, using the medium-energy NuMI beam.

Higher Energy: Cross-check existing neutrino oscillation results in higher energy region with using new beam and cross-section systematics

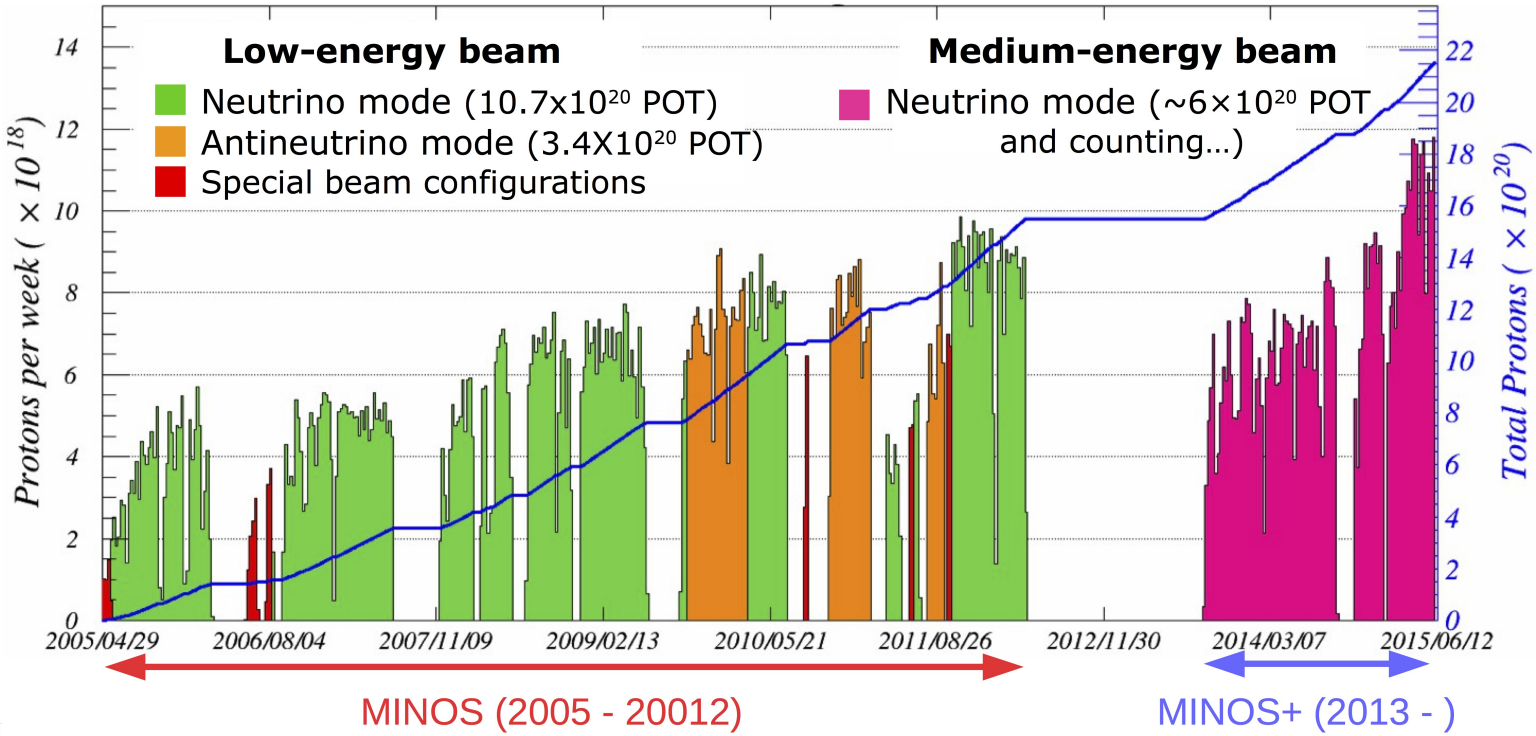
Higher Statistics: Expect ~4000 events/year at FD for improved measurements of standard three-flavor oscillations (in particular, Δm^2_{32})

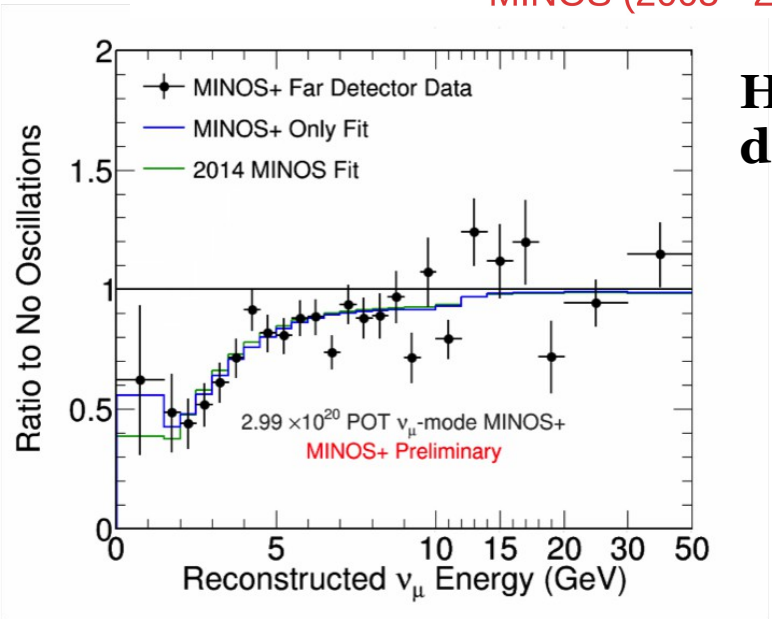
Enhanced Sensitivity to New Physics:

- Search for light sterile neutrinos
- Search for flavor changing Non-standard Interactions (NSI) in mu-tau and e-tau sectors

MINOS & MINOS+ Data

NuMI Protons-on-target (POT)





Have analyzed first year of MINOS+ beam data (3x10²⁰ POT)

- Independent test of MINOS oscillation result
- Combined MINOS and MINOS+ beam data provide significant statistical improvement of standard neutrino oscillation measurement

NSI in the μ-τ Sector

$$P = \cos^2(F_1) + \frac{\cos^2(2\theta)\sin^2(F_1)}{F_2}$$

- In units of GeV, km, eV²

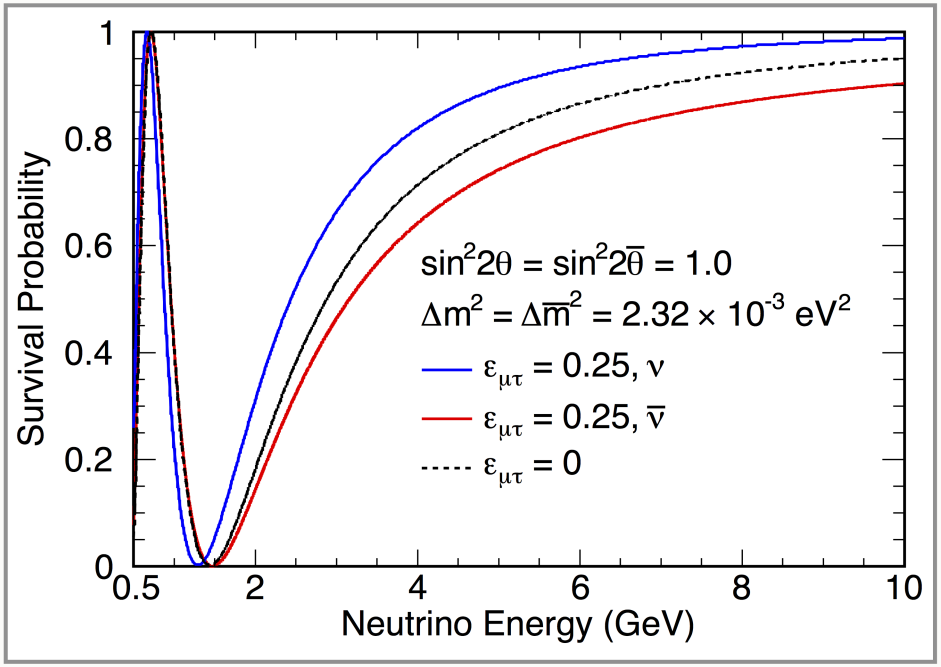
+ for neutrinos
- for antineutrinos

$$F_1 = \sqrt{\left(1.27\frac{\Delta m^2 L}{E}\right)^2 \pm 2\sin(2\theta)\left(1.27\frac{\Delta m^2 L}{E}\right)\epsilon VL + (\epsilon VL)^2}$$

$$F_2 = 1 \pm 2\frac{\sin(2\theta)\epsilon VL}{1.27\frac{\Delta m^2 L}{E}} + \left(\frac{\epsilon VL}{1.27\frac{\Delta m^2 L}{E}}\right)^2$$

$$with \quad \epsilon = 0; \quad F_1 = \left(1.27\frac{\Delta m^2 L}{E}\right), F_2 = 1$$

$$P \rightarrow 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m_{32}^2\frac{L}{E}\right)$$



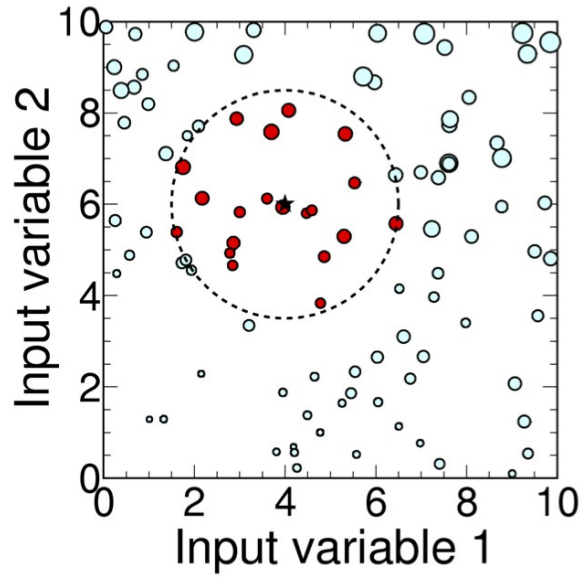
Selecting ν_μ-CC Events

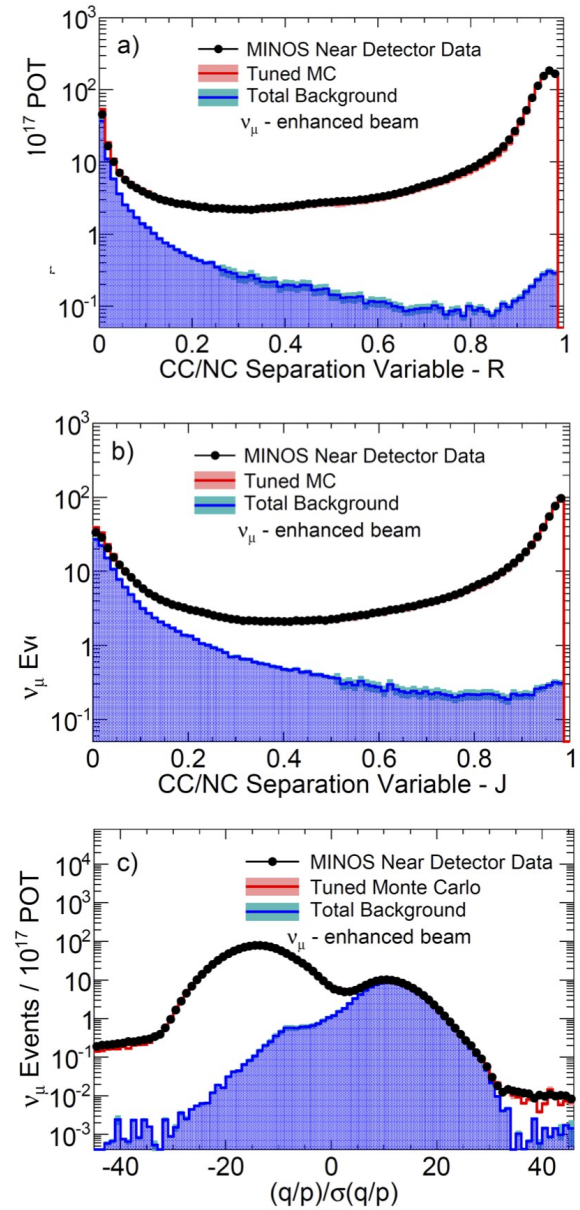
kNN Algorithm

- R input variables
  - # of active planes
  - Mean PH per plane
  - PH fluctuation
  - Transverse profile

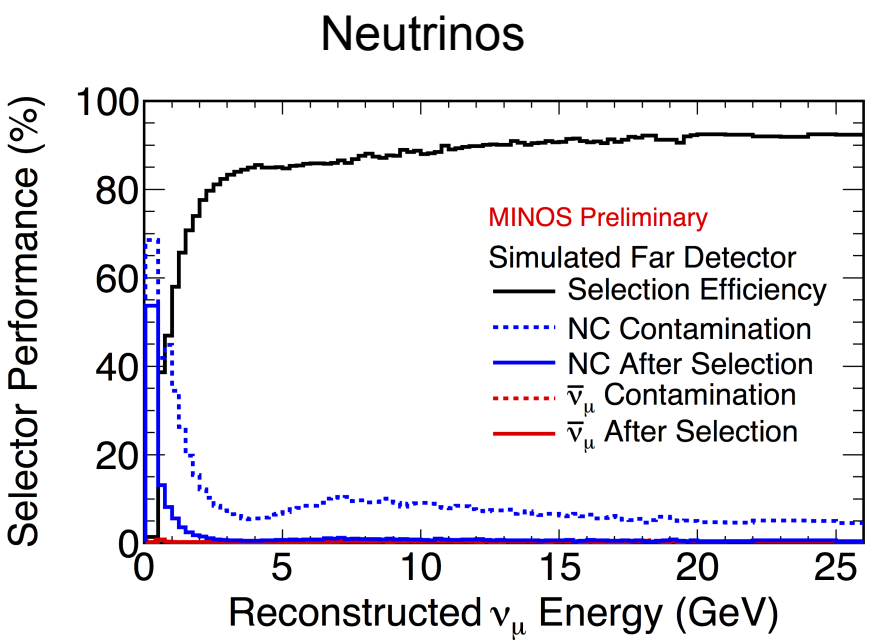
- J input variables
  - # of active planes
  - Track end PH
  - Scattering

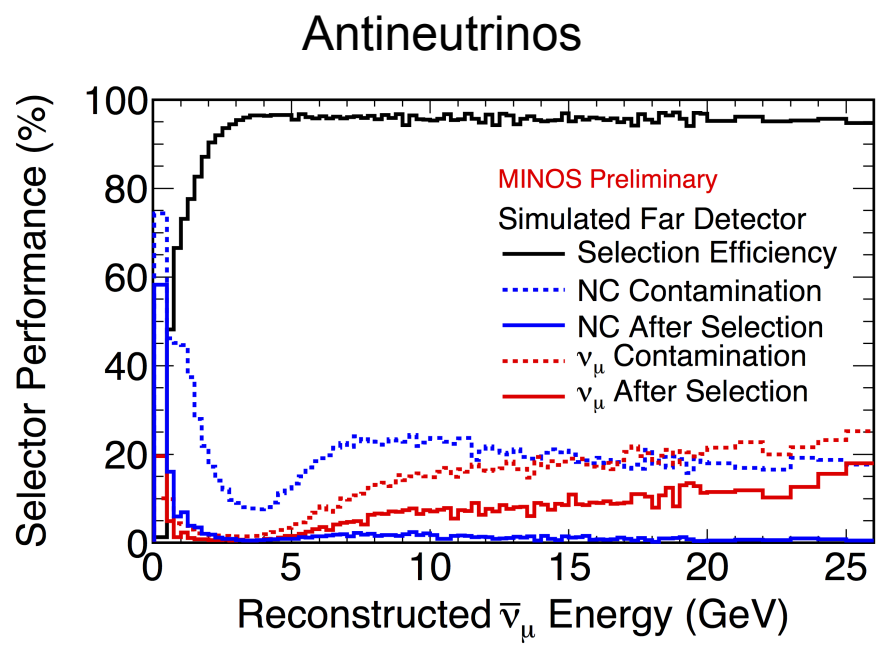
- Select if J > 0.5 || R > 0.25
- Charge determination by curvature



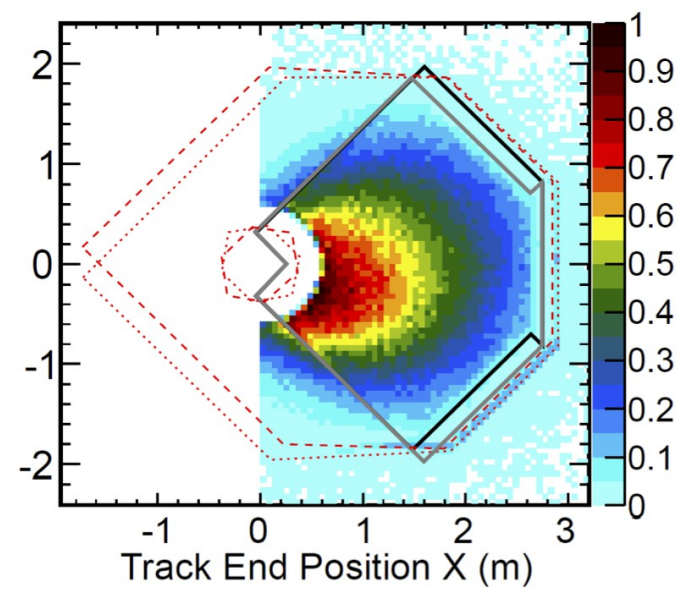


Selection Efficiency



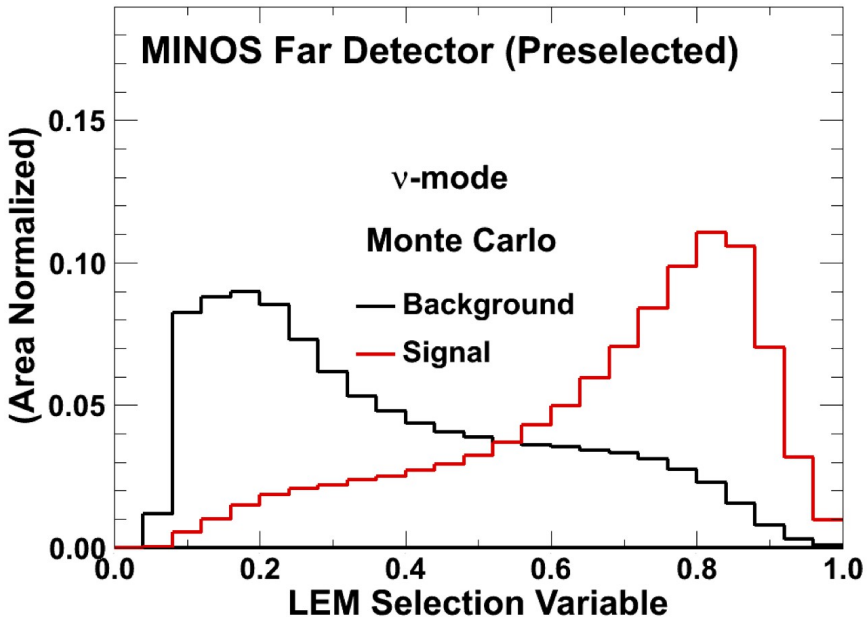


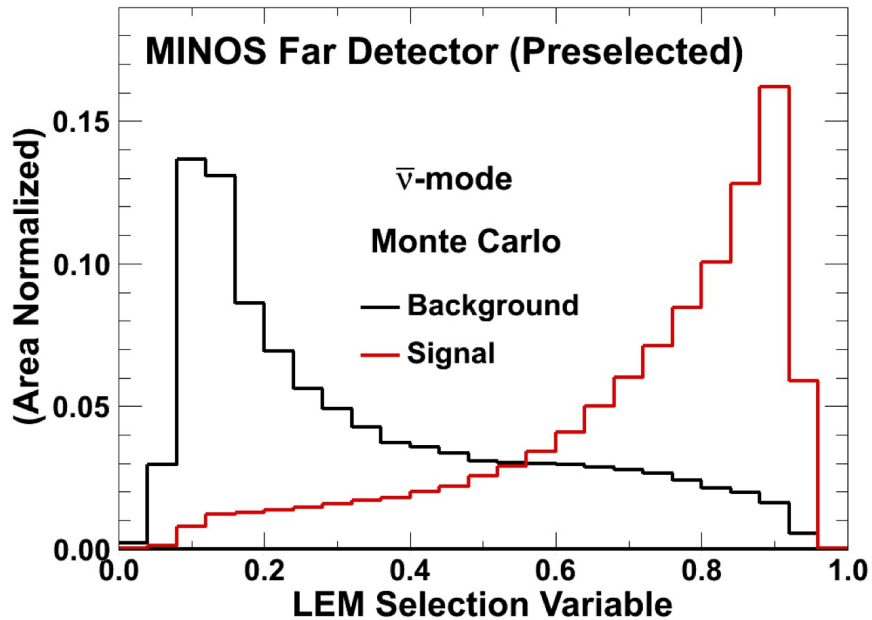
- Second kNN variable improves efficiency at low energy
- Remove tracks near coil hole in ND
  - Improves systematic uncertainty
  - Efficiency less important in ND



Selecting ν_e-CC Events

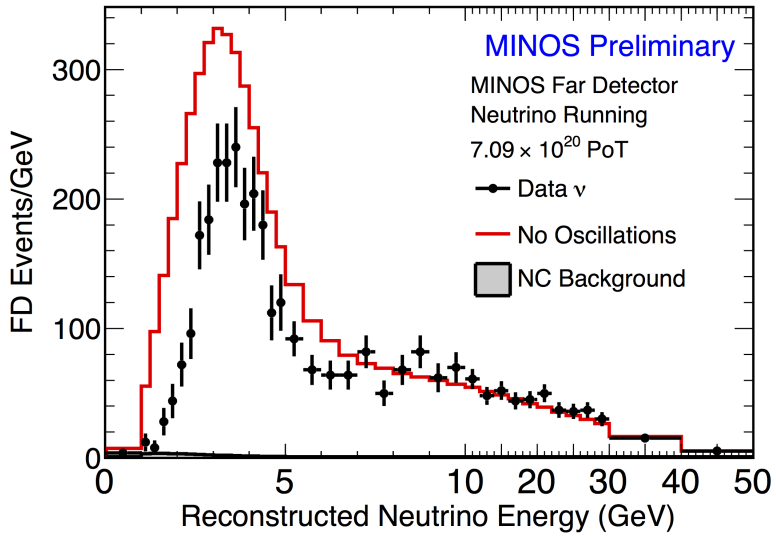
Library Event Matcing (LEM)



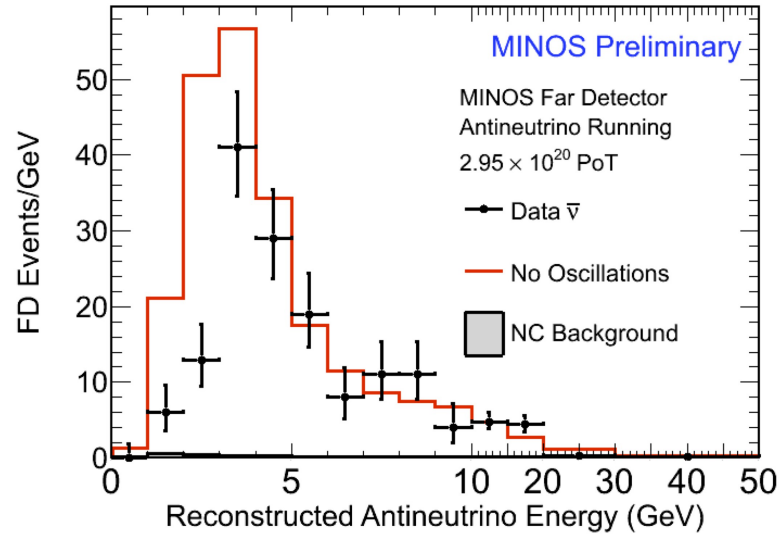


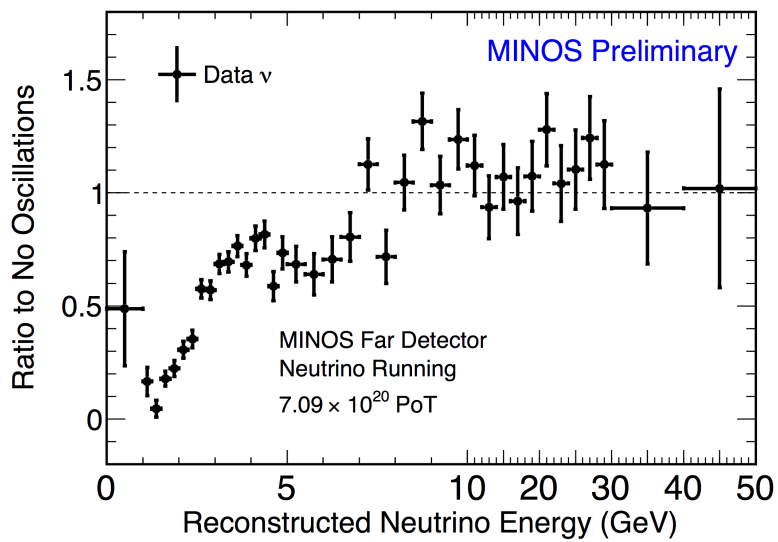
Far Detector Spectra (μτ Sector)

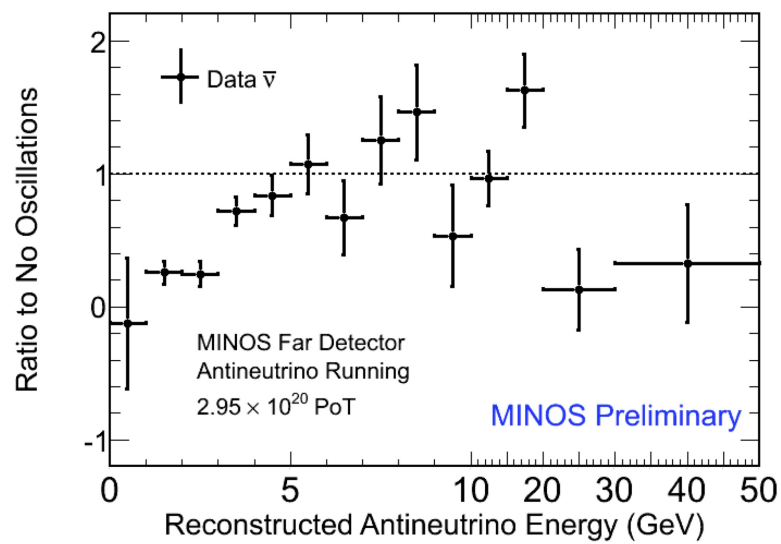
Neutrinos



Antineutrinos

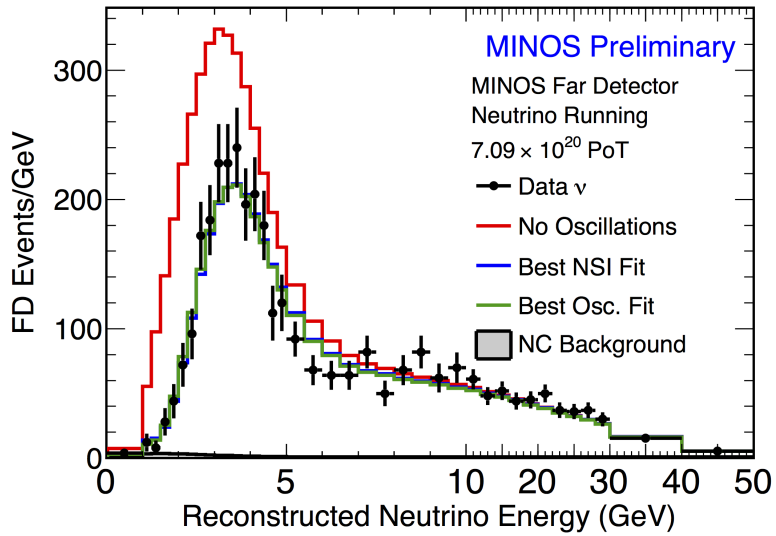


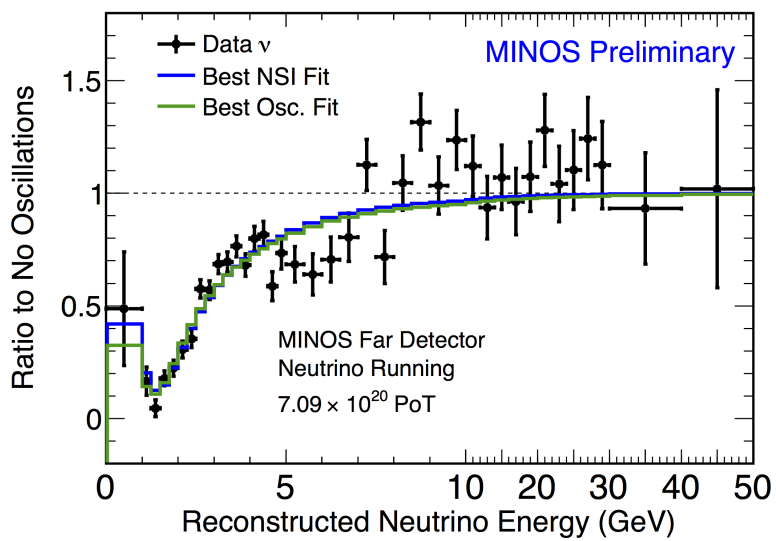




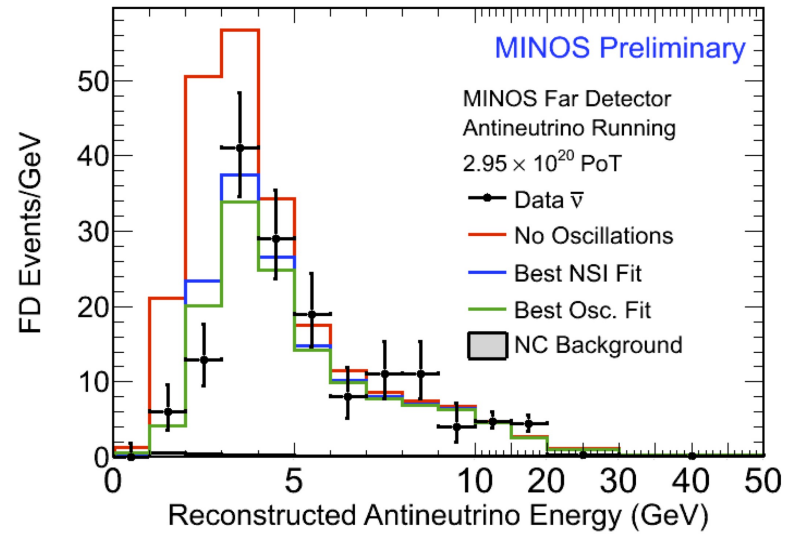
Far Detector Spectra After Fit

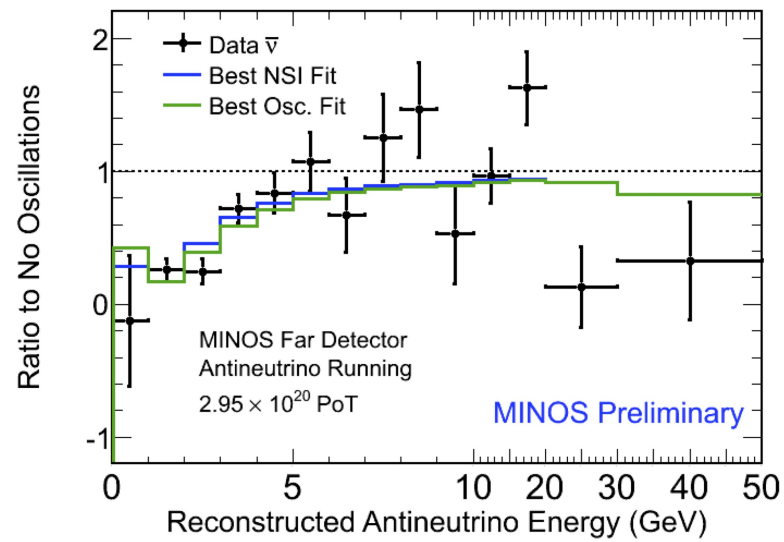
Neutrinos



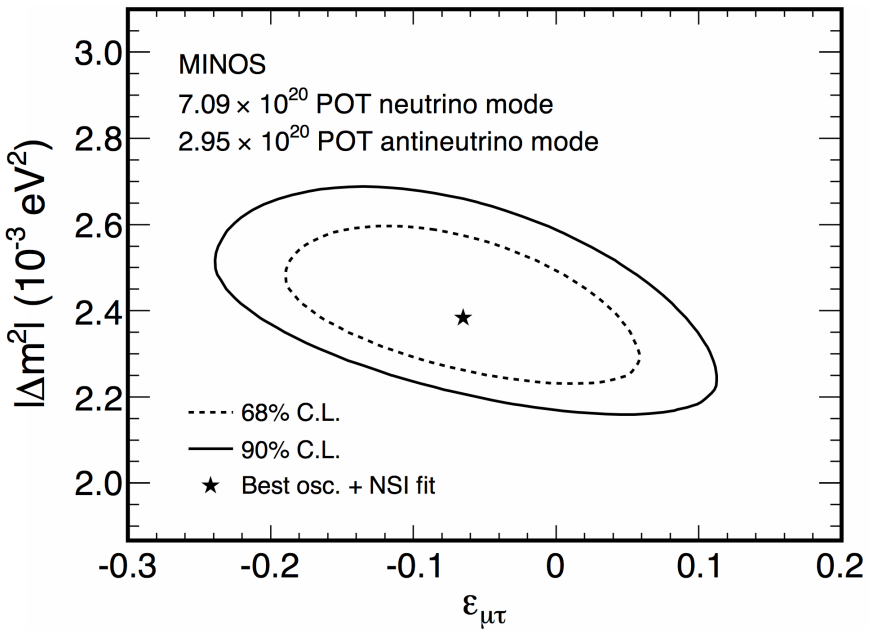


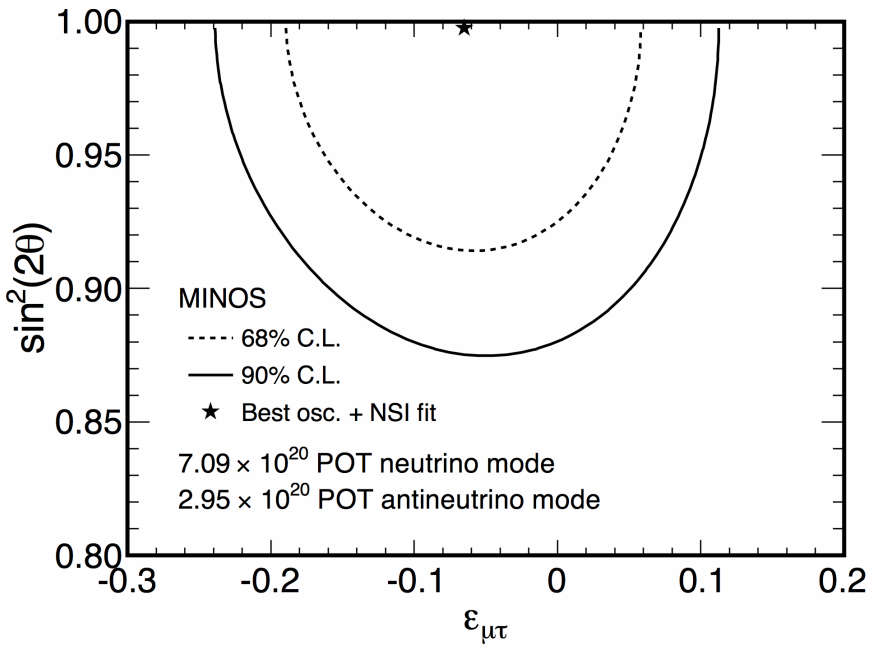
Antineutrinos

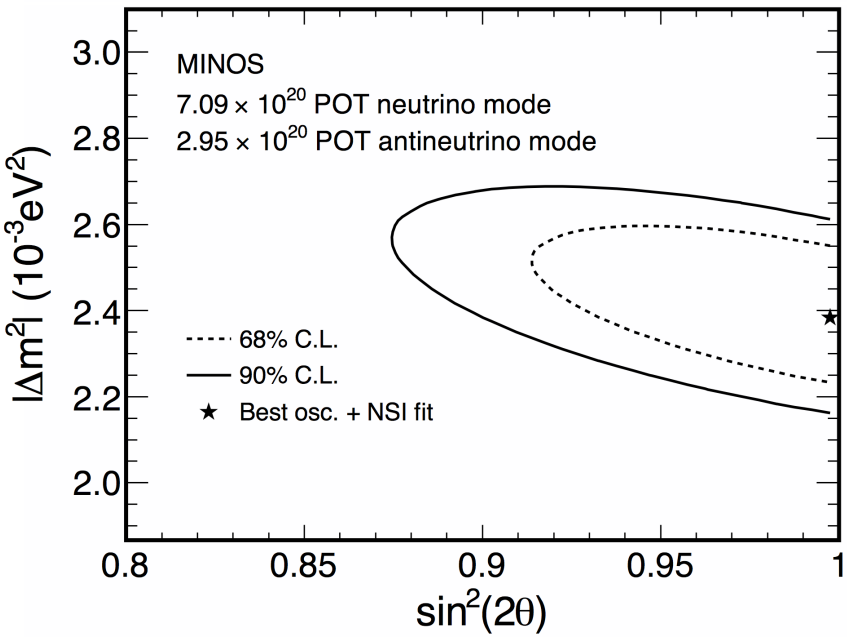




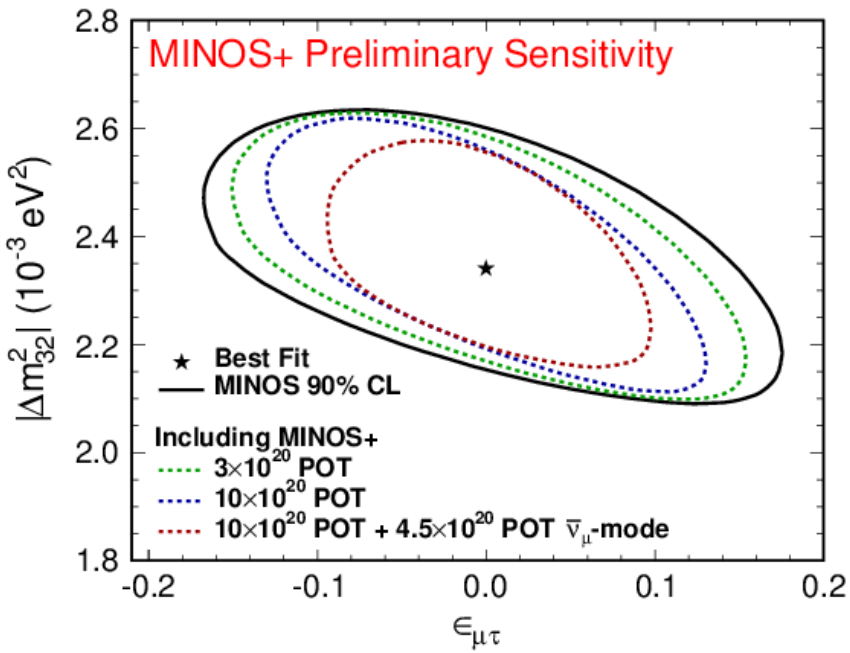
$\varepsilon_{\mu\tau}$ Contours

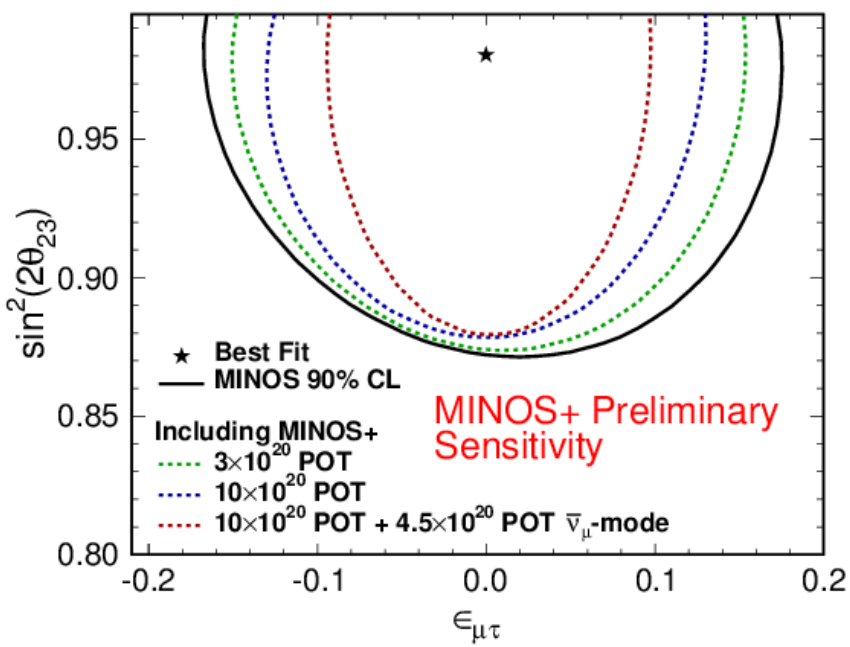


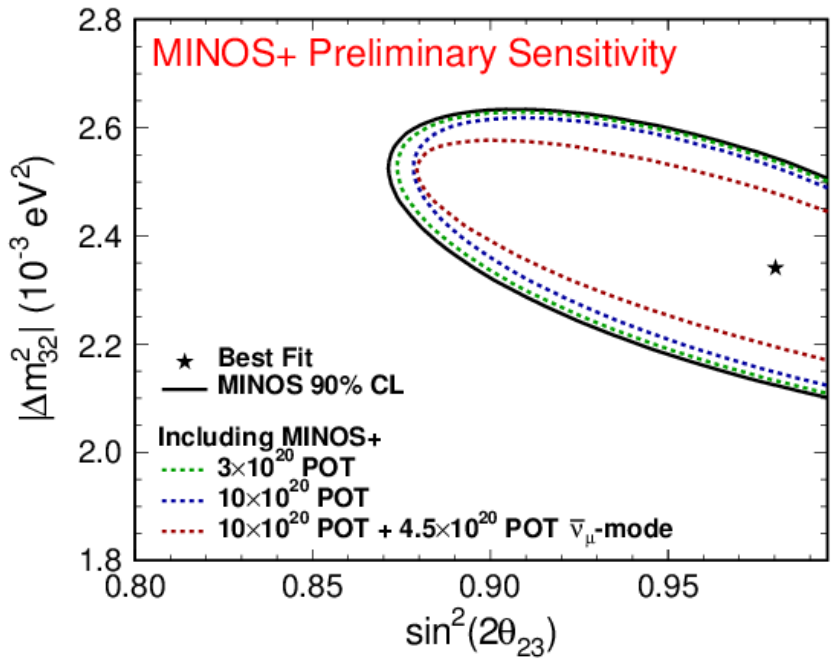




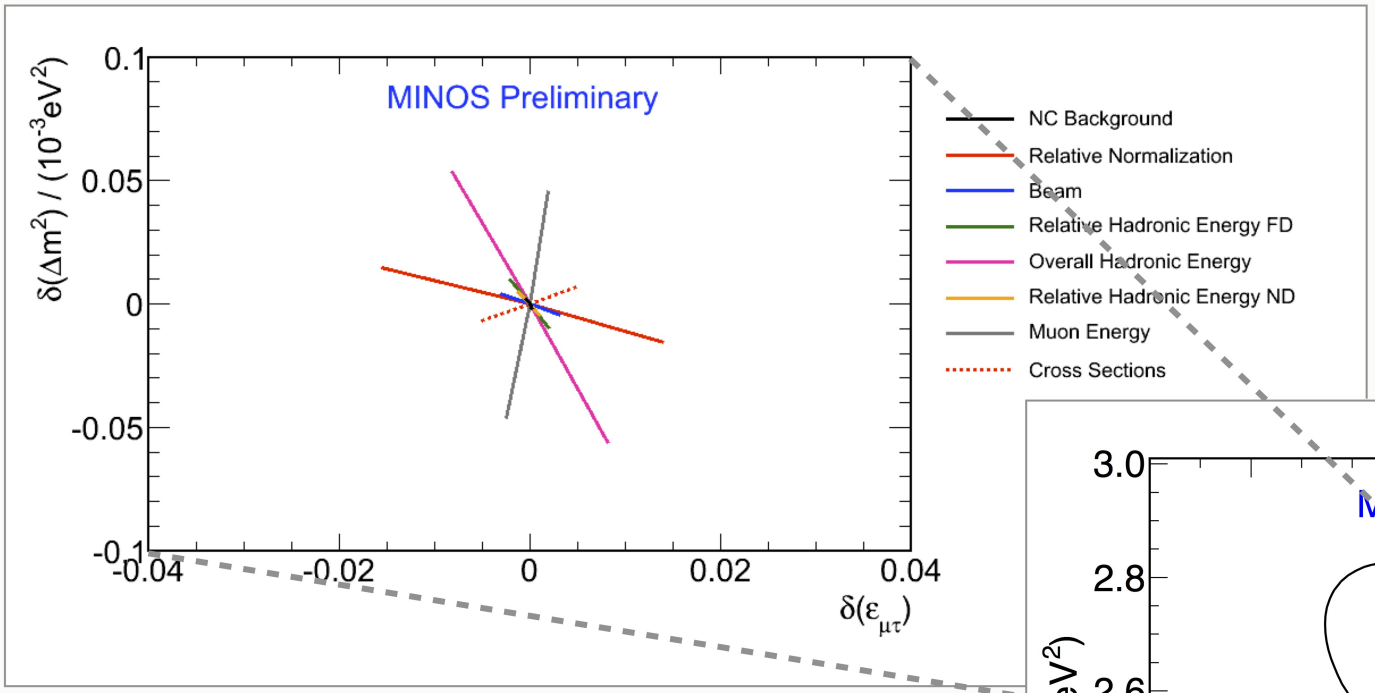
$\varepsilon_{\mu\tau}$ Future Sensitivity Contours

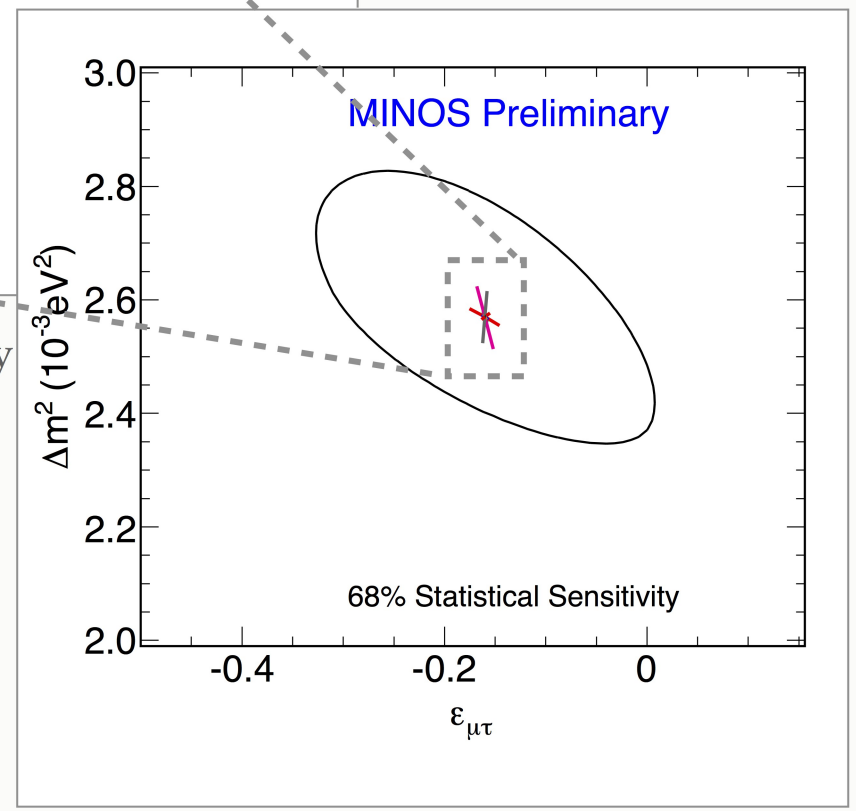






$\varepsilon_{\mu\tau}$ Systematic Uncertainties

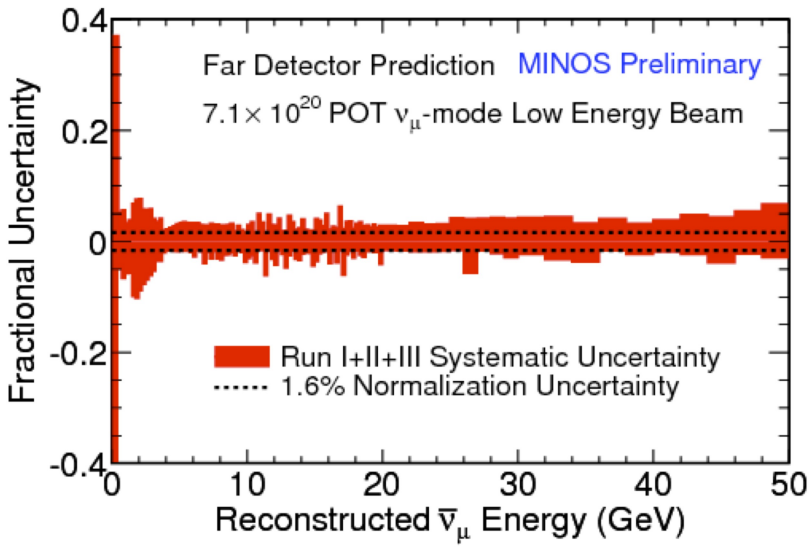


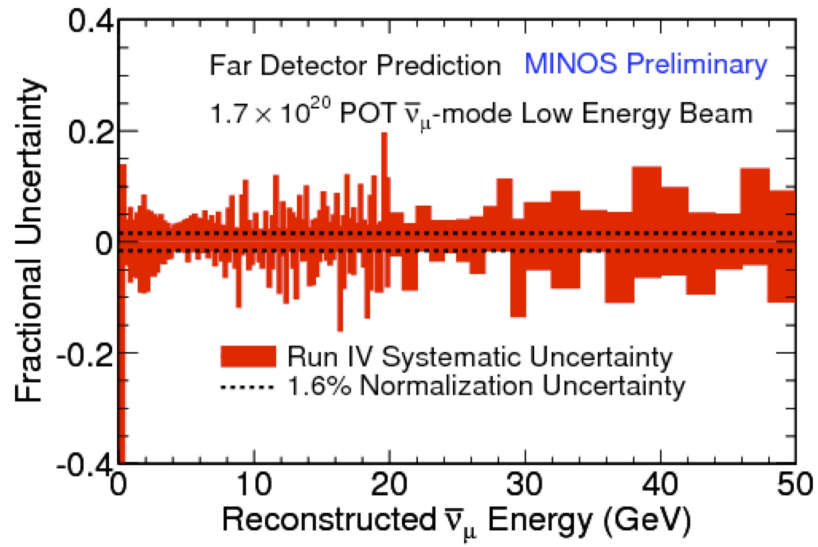


- Star plot shows effect of each systematic uncertainty on the measurement.
- Right: Size of systematics compared to statistical uncertaintly.
- Overall statistics limited but the neutrino sample is much larger than the antineutrino: Account for systematics in the fit

$\varepsilon_{\mu\tau}$ Systematic Uncertainties

- Bands show the effect of four most significant systematics: Muon energy scale, hadronic energy scale, normalization, and neutral current background





- Include these four systematics in fit as nuisance parameters