New Results from MINOS

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for the MINOS collaboration

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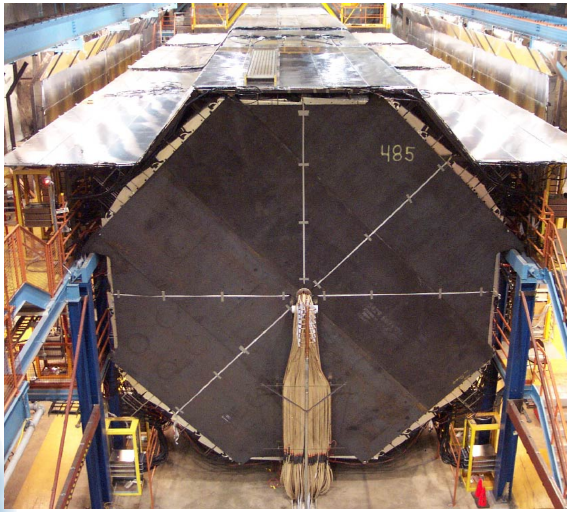
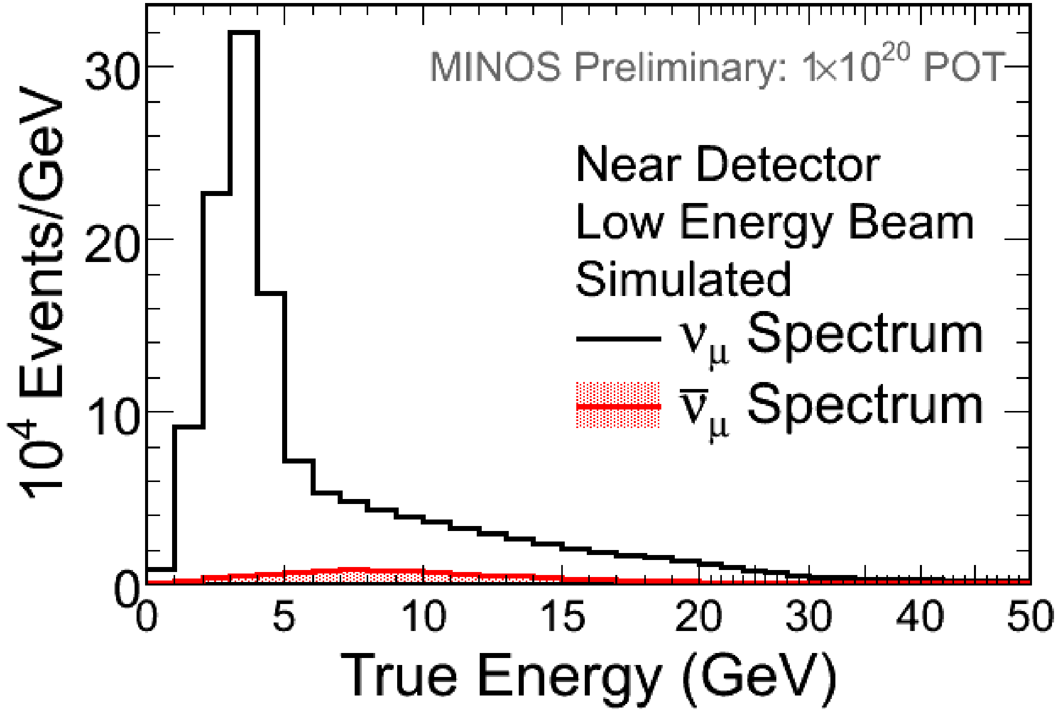
The MINOS Experiment

- A long-baseline accelerator neutrino oscillation experiment
- ν_μ produced at Fermilab
- 1 kt near detector at Fermilab
- 5.4 kt far detector in northern MN, 735 km away
- Functionally identical magnetized detectors:
  - Alternating planes of steel & solid scintillator
  - 3D reconstruction via alternating scintillator orientation



NuMI Beam

- 120 GeV protons incident on a graphite target
- In our normal mode:
  92% ν_μ 7% $\bar{\nu}_\mu$ 1% $\nu_e+\bar{\nu}_e$
- Can also run in antineutrino-mode
- Beam exposure measured in protons-on-target (POT)
  - 7.1×10^{20} POT of neutrinos in Runs I-III
  - 1.7×10^{20} POT of anti-neutrinos in Run IV
  - 0.6×10^{20} POT *and counting* of neutrinos in Run V
- Most analyses have looked at the first 3.2×10^{20} POT so far
  - Plan to have 7.1×10^{20} POT analyses ready for Neutrino 2010 (June)



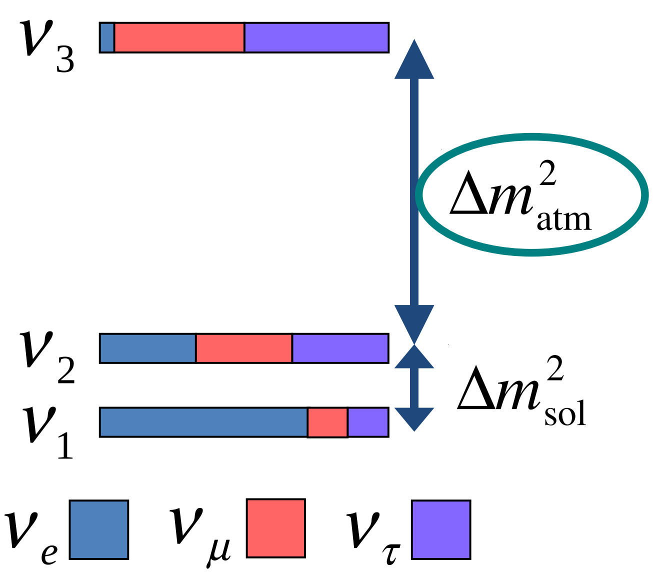
Physics Goals

- ν_μ CC disappearance
  - Precision measurement of $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$
- $\bar{\nu}_\mu$ CC disappearance
  - Tests CPT conservation
  - Measure $\bar{\nu}$ parameters $|\Delta \bar{m}^2_{23}|$ and $\sin^2 2\bar{\theta}_{23}$
- Neutral current event disappearance
  - Signature of sterile neutrinos or decay
- ν_e appearance
  - Sensitive to θ_{13}, δ_{CP}

ν_e appearance

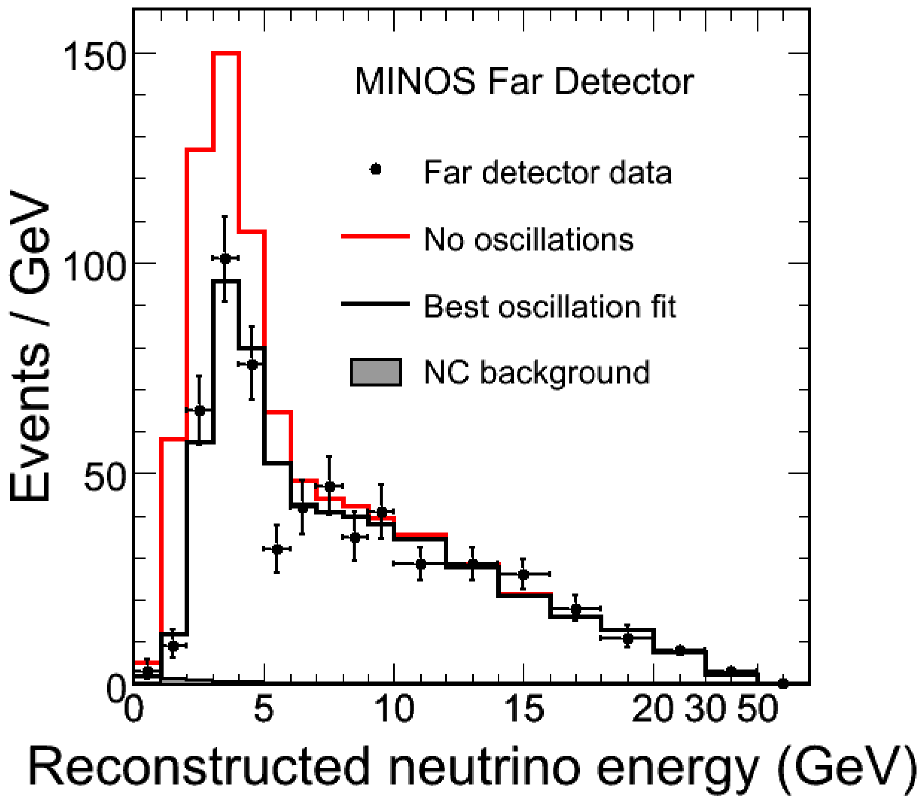
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

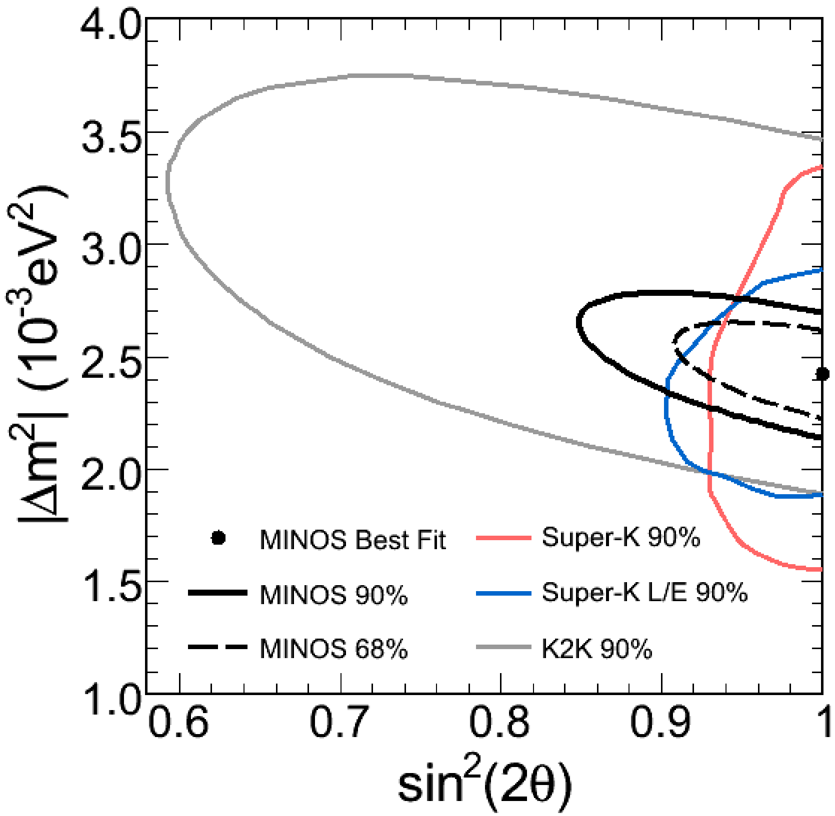
ν_μ disappearance



Neutrino Disappearance

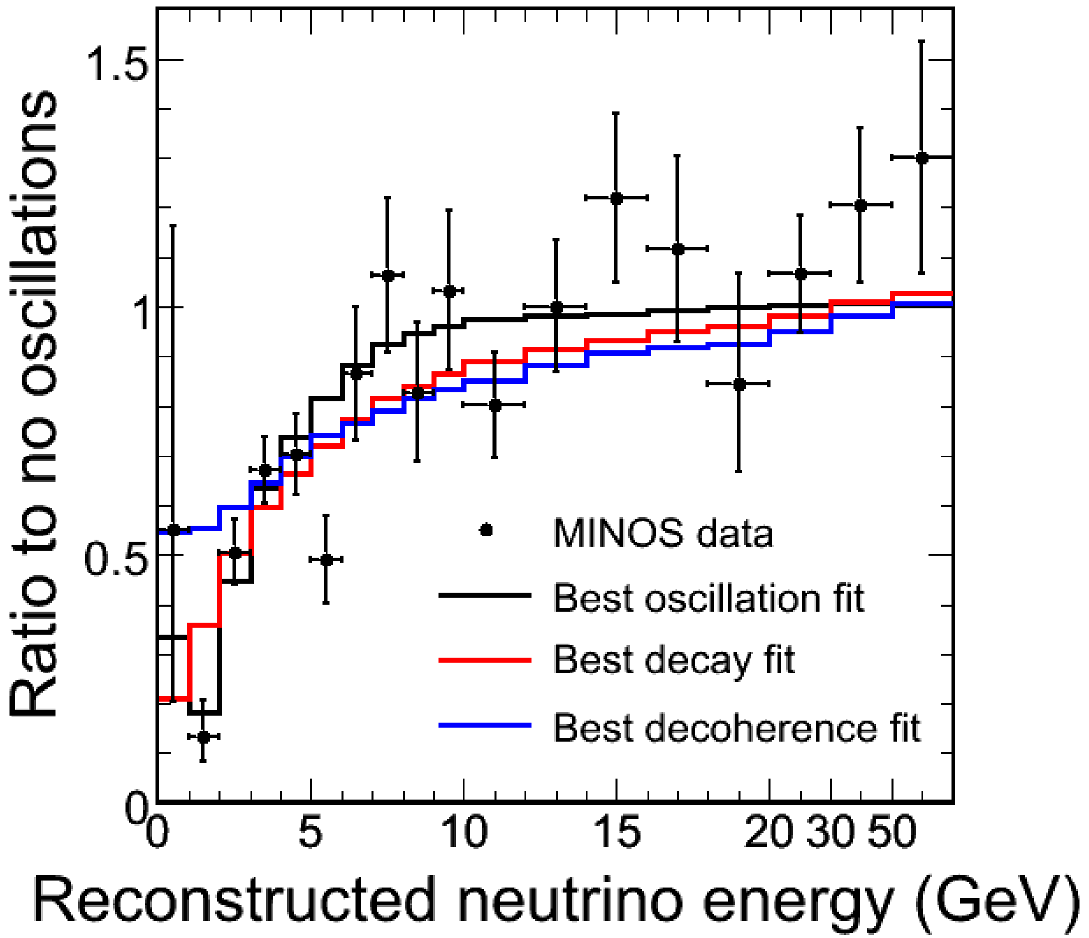
- With 3.2×10^{20} POT, expect 1065±60 (syst) without oscillations
- Observed 848: Best fit $|\Delta m^2| = 2.43\times10^{-3}$ eV^2, $\sin^2 2\theta = 1.0$
  - Backgrounds: 0.7 cosmic, 2.3 rock μ, 5.9 NC, 1.5 ν_τ appearance
  - PRL **101** 131802 (2008)





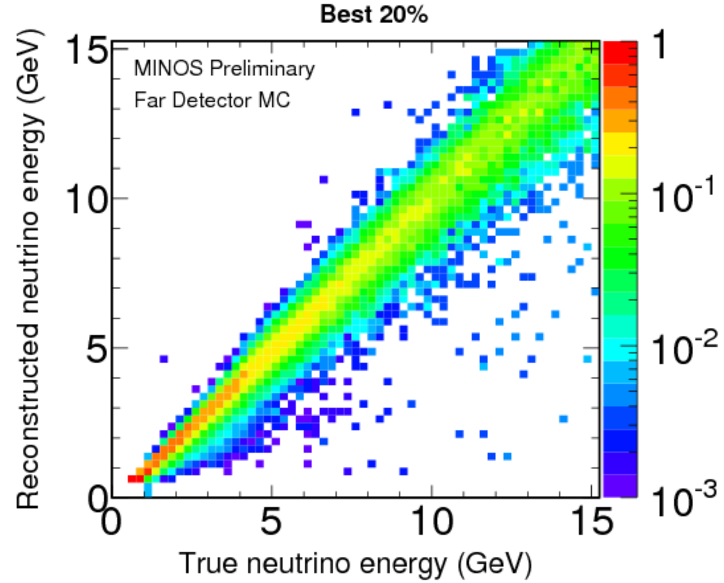
Neutrino Disappearance

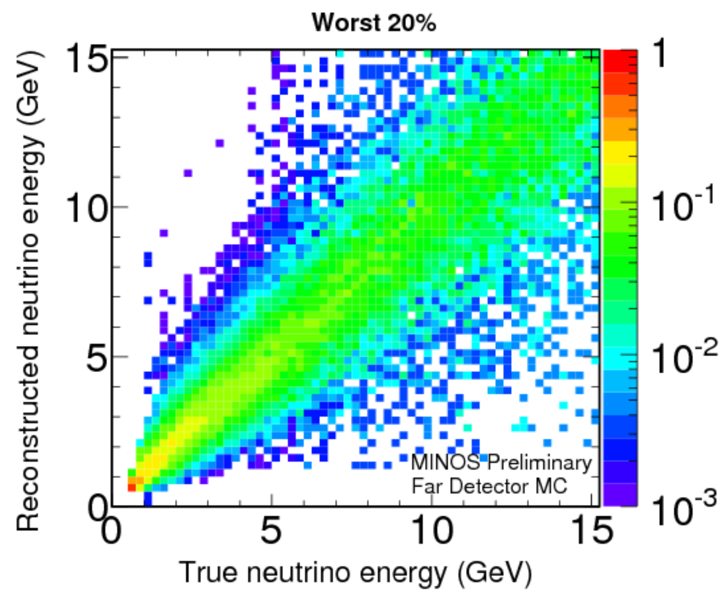
- Discriminate between models of ν disappearance
- Decay
  - Barger *et al.*, PRL **82** 2640 (1999)
  - Disfavored at **3.7σ** with respect to oscillation
  - Including NC events (see later) ⇒ **5.2σ**
- Decoherence
  - Fogli *et al.*, PRD **67** 093006 (2003)
  - Disfavored at **5.7σ** with respect to oscillation

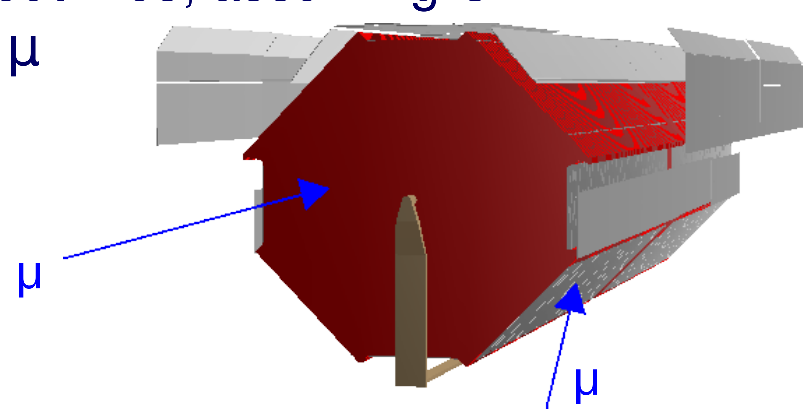


Neutrino Disappearance

- 7.1×10^{20} POT analysis this summer
  - 2.2 times the exposure of last publication
- Analysis improvements:
  - Improved reconstruction & Monte Carlo
  - Reduced systematics
  - Improved particle ID
  - Improved shower energy estimation
  - Separation of events by resolution
  - Inclusion of:
    - Antineutrinos, assuming CPT
    - Rock μ



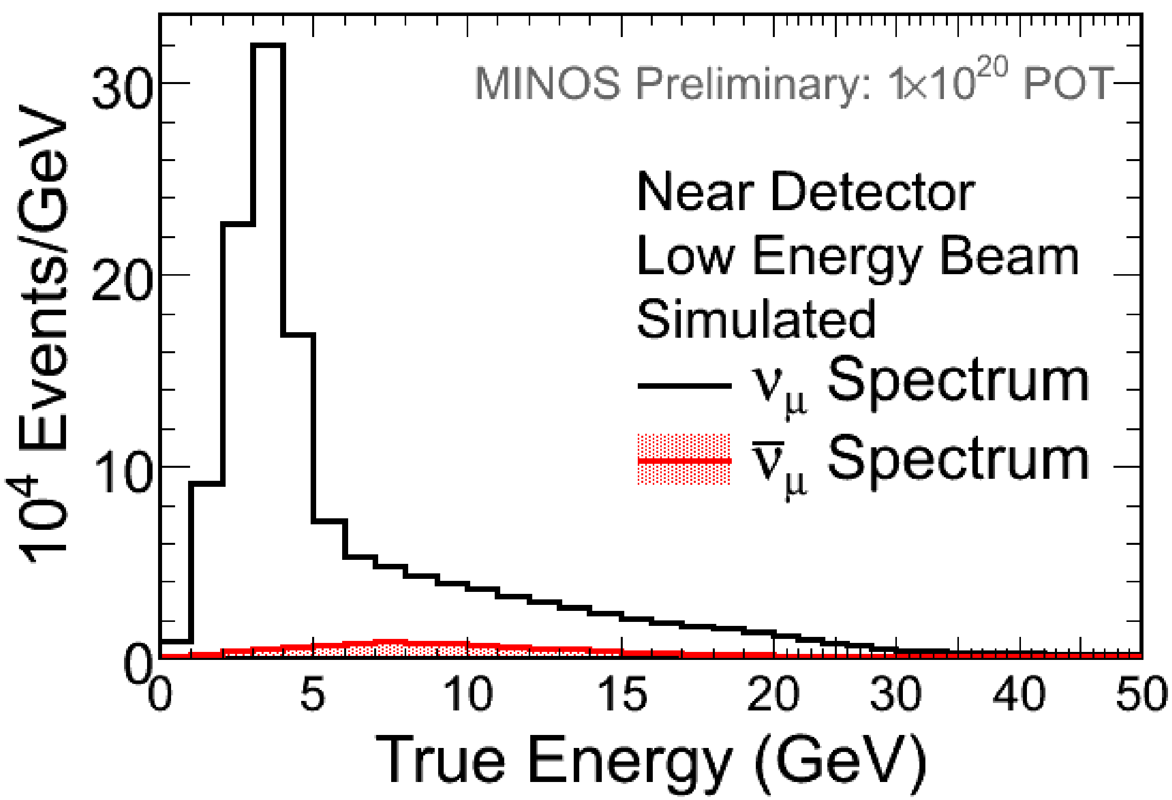




Antineutrino Disappearance

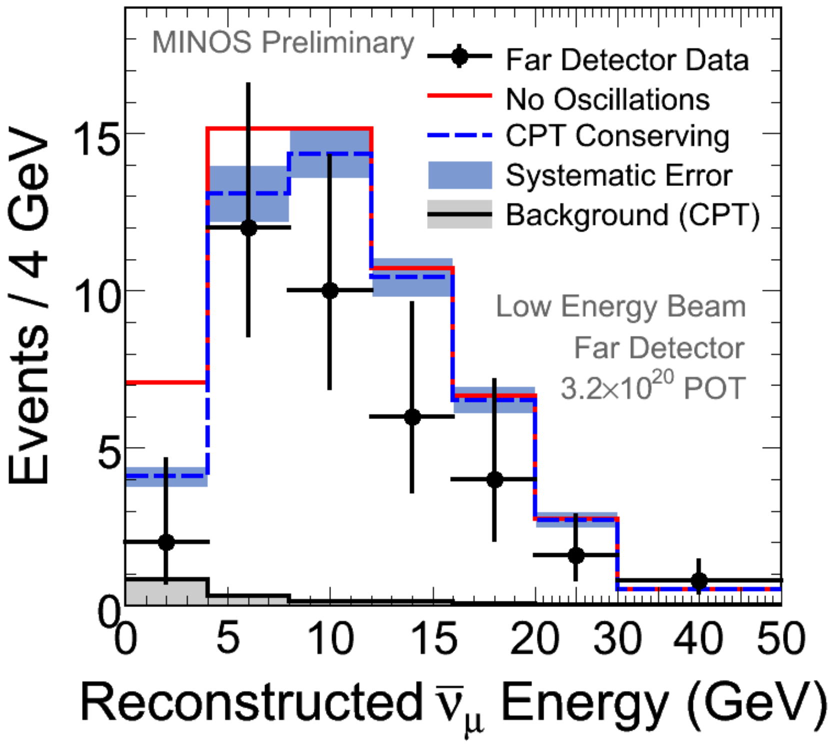
- We have analyzed $\bar{\nu}$ in 3.2×10^{20} POT ν-mode data
- 1.7×10^{20} POT $\bar{\nu}$-mode analysis in progress

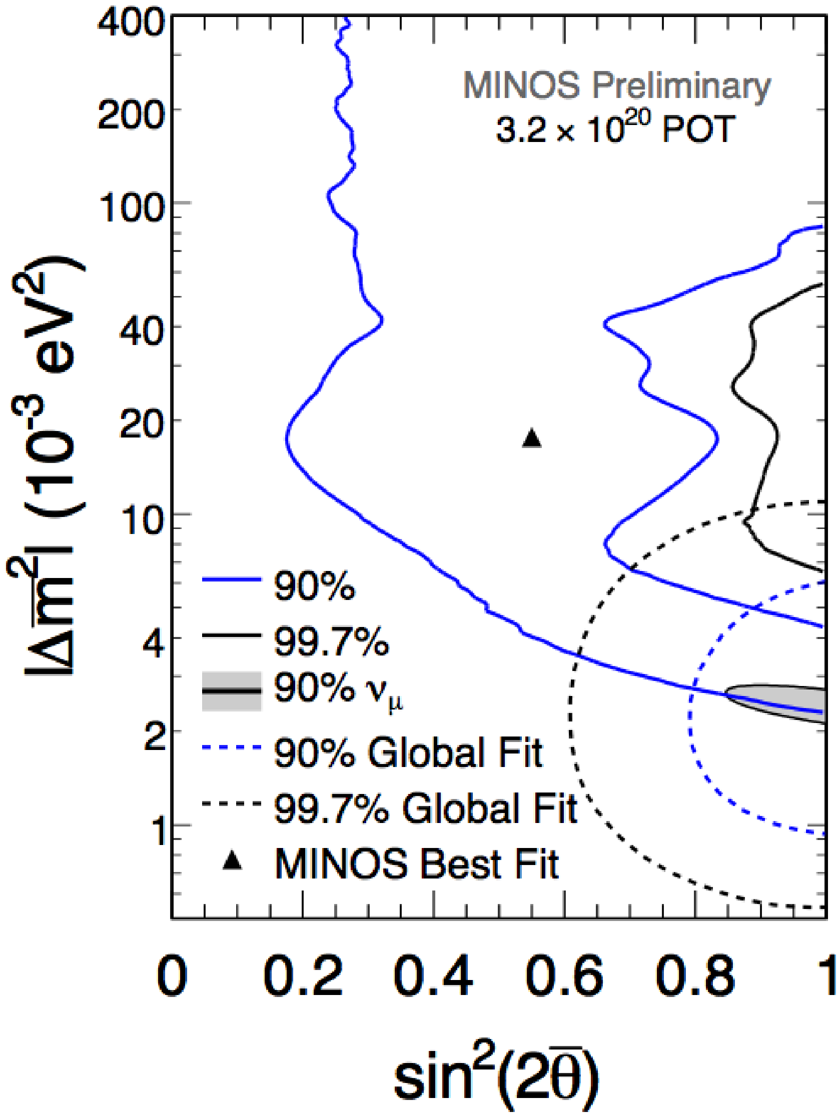
- ν-mode: 7% $\bar{\nu}_\mu$
- Challenges to an analysis of these:
  - $\bar{\nu}$ have ~⅓ the cross-sections of ν
  - $\bar{\nu}$ produced in ν-mode are on average higher energy



Antineutrino Disappearance

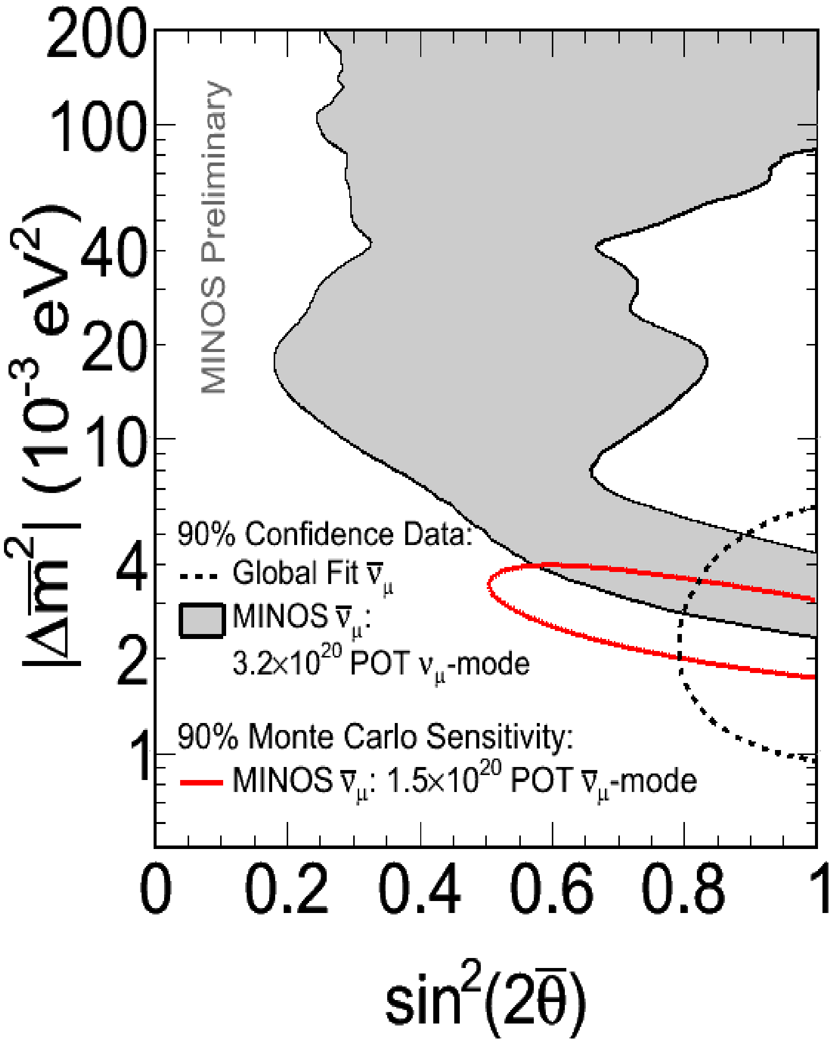
- CPT predicts: 58.3±3.6 (syst) events
  - Observed **42**: 1.9σ deficit
  - No oscillation excluded at 99%
  - CPT-conservation allowed at 90%
- Improves on previous global fit
  - Gonzalez-Garcia, Maltoni
    Phys Rept **460** 1 (2008)



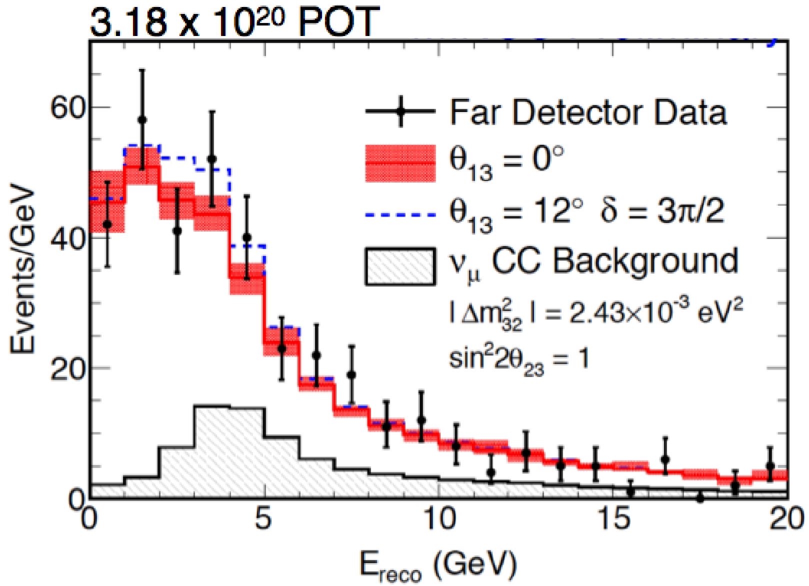


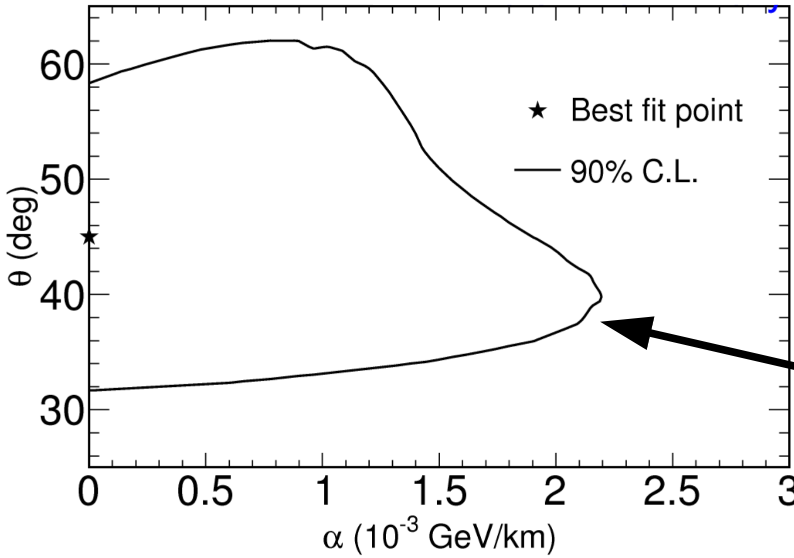
Antineutrino Disappearance

- Have collected 1.7×10^{20} POT of dedicated $\bar{\nu}$ running
- Analysis coming this summer
- Sensitivity at CPT-conserving point shown



Neutral Current Event Disappearance





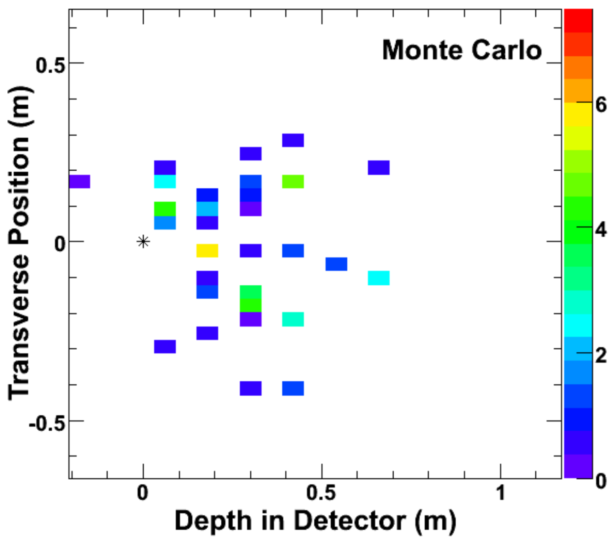
- Deficit ⇒ neutrino decay or mixing with sterile flavor $\boldsymbol{\nu}_s$
- 3.2×10^{20} POT analyzed so far
  - PRD **81** 052004 (2010)
- No significant deficit observed
  - Fraction of disappeared ν_μ converting to ν_s < 52% (90% CL)
  - Several 4-neutrino models consistent with no sterile mixing:
    - $\theta_{24} < 11°$; $\theta_{34} < 56°$ (90% CL)
  - Joint decay/oscillation fit constrains neutrino lifetime
    - $\tau_3/m_3 > 2.1\times10^{-12}$ s/eV (90% CL)

Electron Neutrino Appearance

- A sub-dominant oscillation mode controlled by θ_{13}

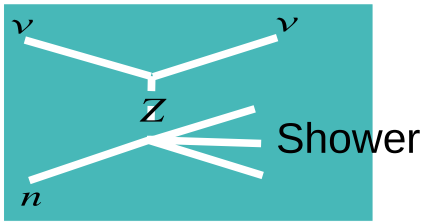
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.267\Delta m^2_{31}L/E)$$

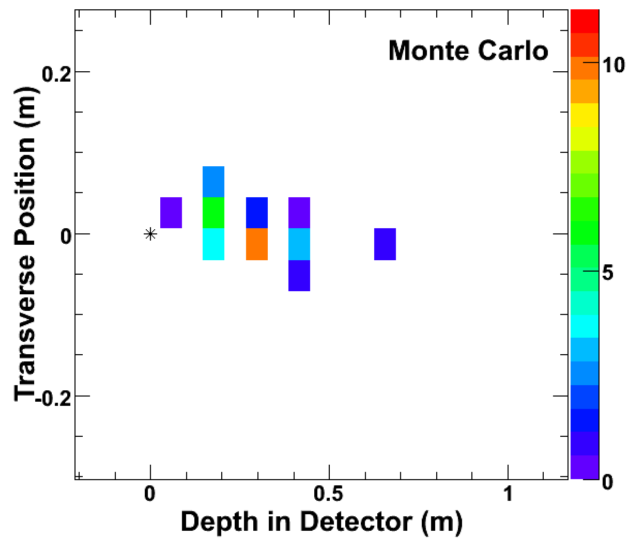
- Chooz: $\sin^2 2\theta_{13} < 0.15$
  - Expect few % appearance at most
- Select events with compact shower, typical EM profile
  - Use an artificial neutral net (ANN)
  - 42% signal efficiency



Hadronic Shower

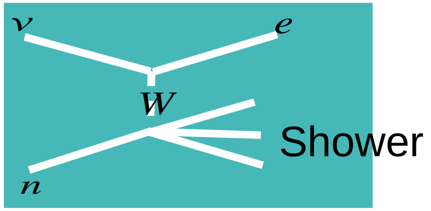
Neutral Current Event





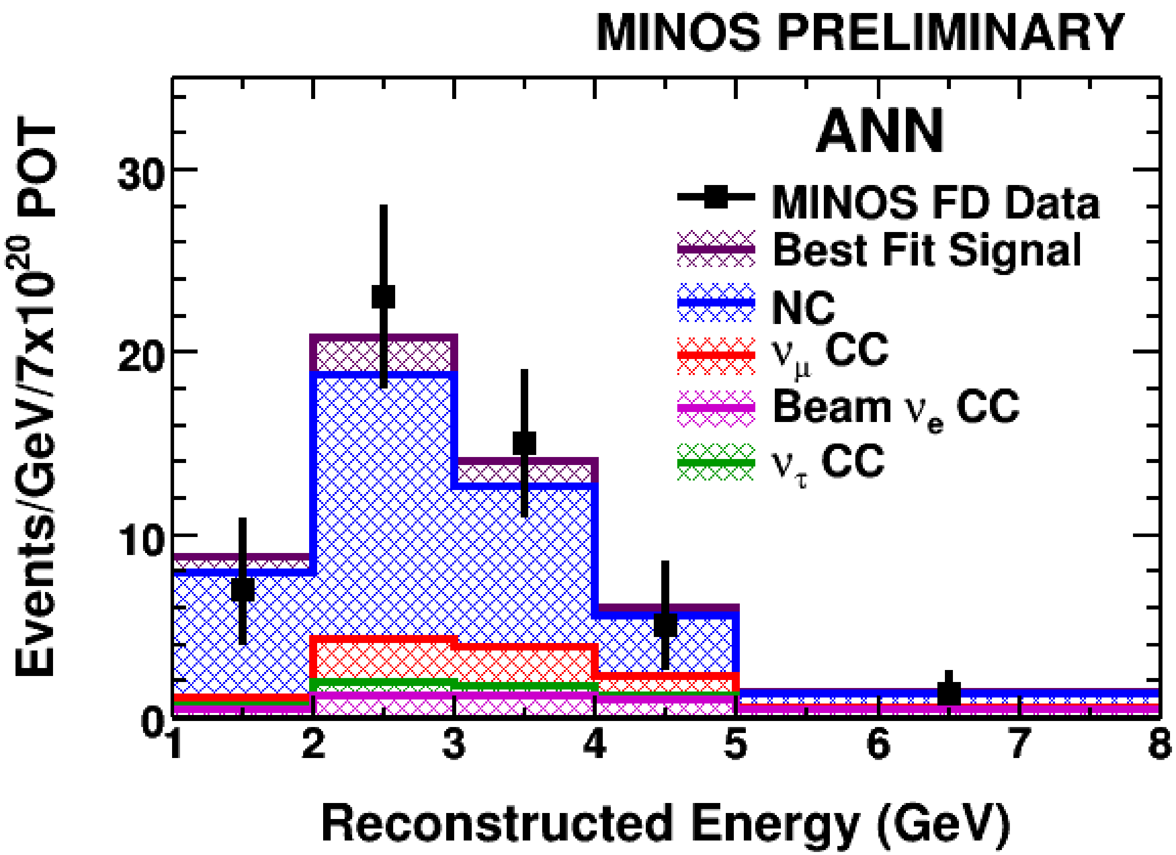
EM Shower

Charged Current ν_e Event



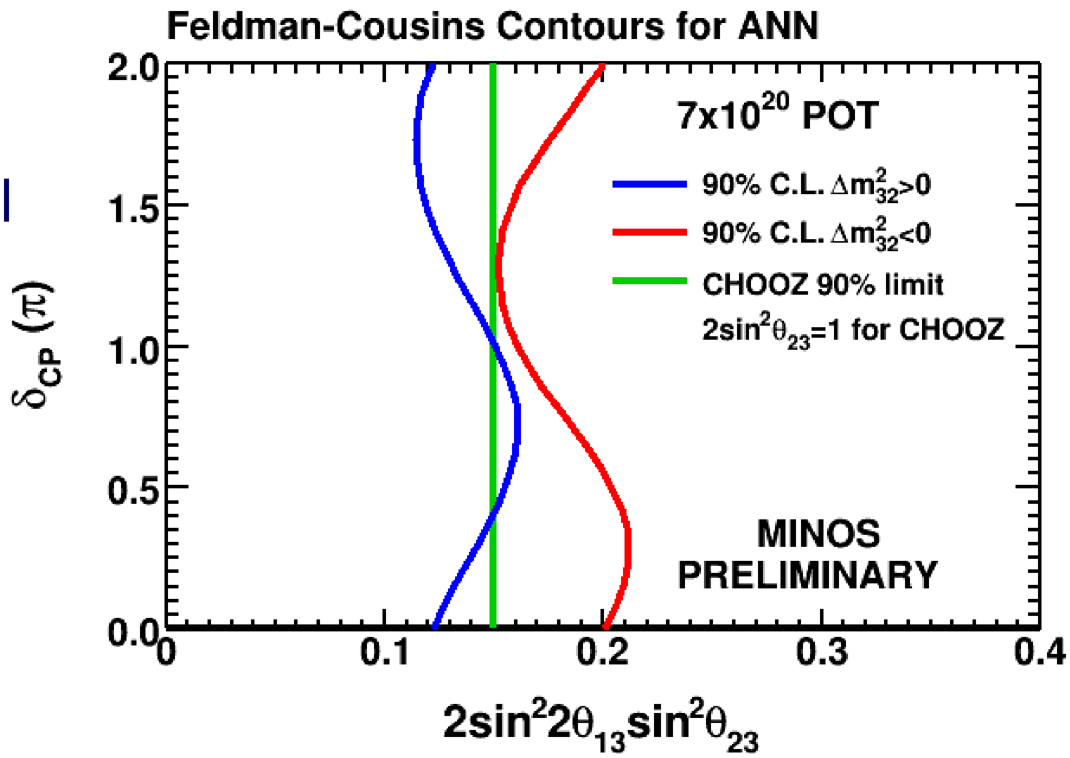
Electron Neutrino Appearance

- With $7{\times}10^{20}$ POT:
  - If $\theta_{13} = 0$, predict 49.1 ± 2.7 (syst) events, observed 54
  - Dominant background is NC



Electron Neutrino Appearance

- First experiment with result beyond the Chooz limit
- For $\delta_{CP} = 0$, $\sin^2 2\theta_{23} = 1$:
  - $\sin^2 2\theta_{13} < 0.12$ (0.20) for normal (inverted) mass hierarchy
- Difficult analysis, but still statistics-limited. Future plans:
  - Addition of Run IV $\bar{\nu}$ data (1.7×10^{20} POT)
  - Addition of Run V ν data (0.6×10^{20} POT and counting)
  - Improved NC/ν_e discrimination



Summary

- ν_μ disappearance
  - World leading measurement of $|\Delta m^2_{23}|$
- $\bar{\nu}_\mu$ disappearance
  - First long-baseline measurement of $|\Delta \bar{m}^2_{23}|$, $\bar{\theta}_{23}$
- Neutral current disappearance
  - Constraints put on sterile neutrino mixing and decay
- ν_e appearance
  - First results below the Chooz limit
- Most analyses planning to have new results ready for Neutrino 2010

Backup

Electron Neutrino Appearance

Neutrinos and Physics Motivation

- There are **3 generations of neutrino**: ν_e, ν_μ, ν_τ
- **neutrinos have mass and they oscillate**
- neutrino oscillations are governed by the PMNS matrix

PMNS mixing matrix (Pontecorvo-Maki-Nakagawa-Sakata):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak Eigenstates — PMNS Matrix — Mass Eigenstates

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

ij=12	=>	solar terms
ij=23	=>	atmospheric terms
ij=13	=>	**unknown terms**
δ	=>	**CP violating phase**

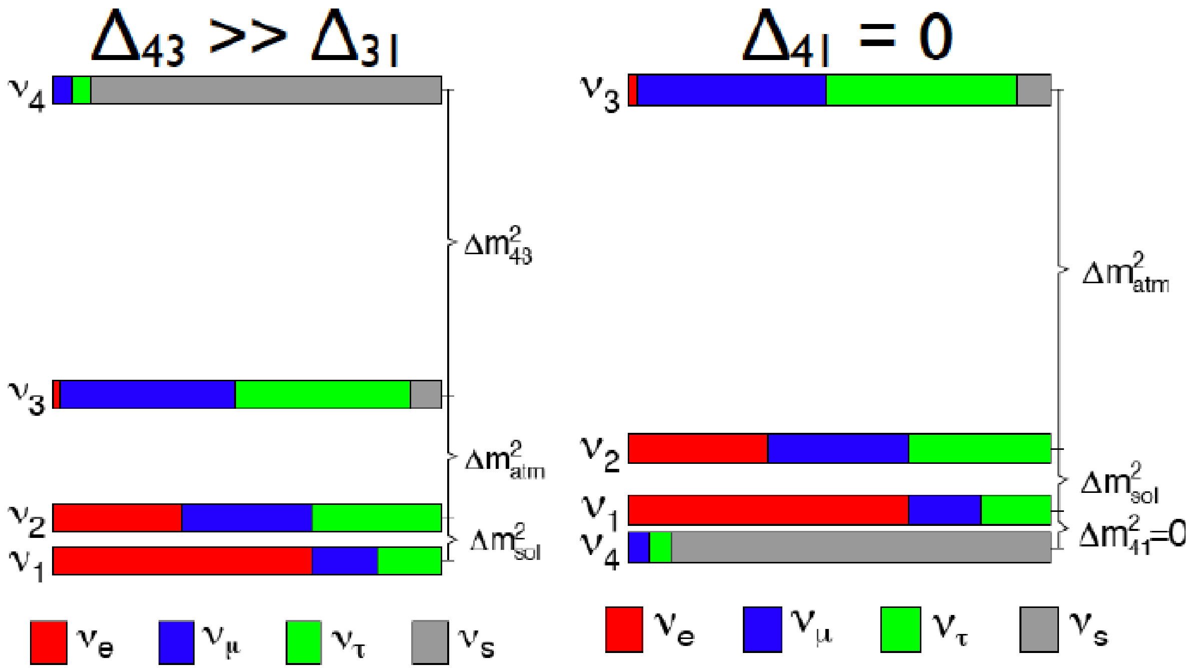
Analysis Results - Four-Flavor Model

- Will consider the same sterile neutrino oscillation models with three active and one sterile neutrinos studied in the PRD:

    1) m4 >> m3

    2) m4 = m1

- Take into account possible ν_e appearance with two sets of fits:
    - $\theta_{13} = 0$
    - $\theta_{13} = 0.20$, $\delta_{CP} = \pi$ (from MINOS 90% C.L. limit for $\Delta m^2>0$)

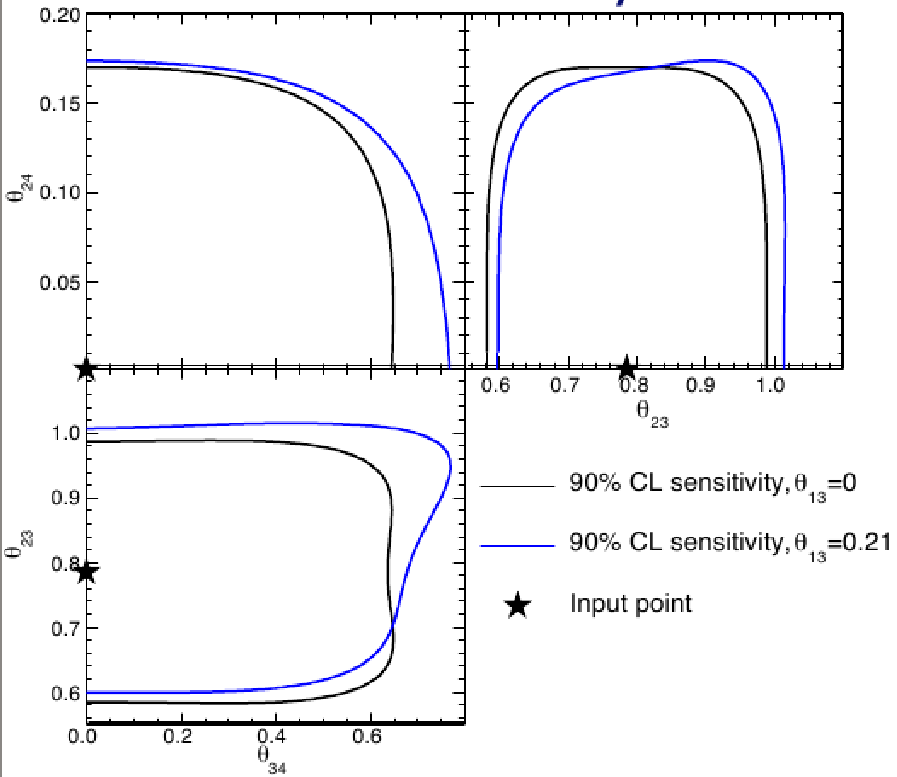


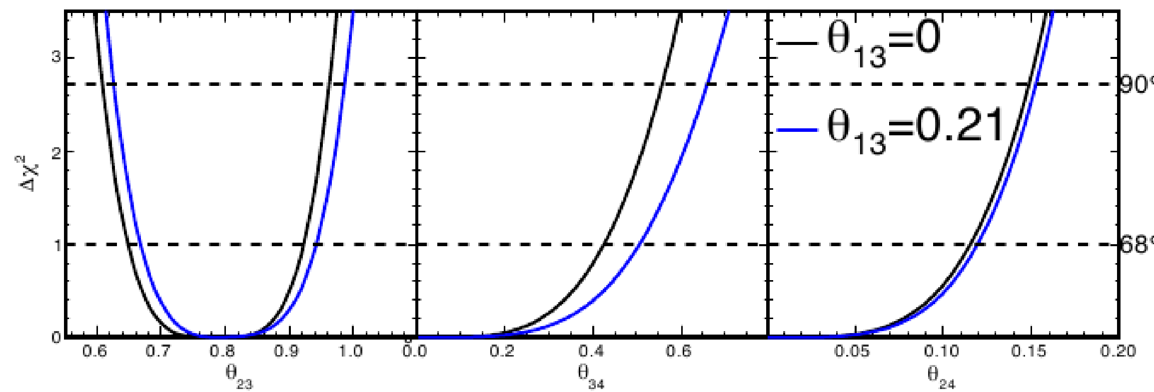
- Will also calculate fraction of active neutrinos that may oscillate into a sterile neutrino for each model

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

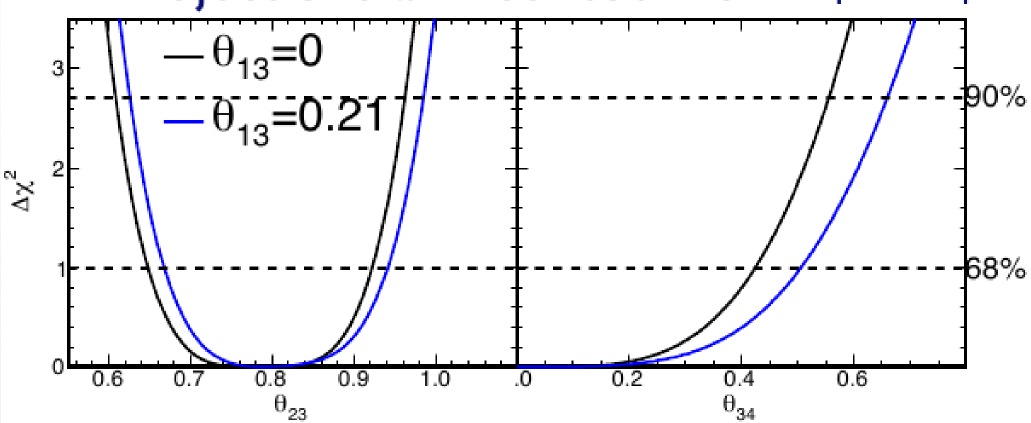
Analysis Results - Four-Flavor Model

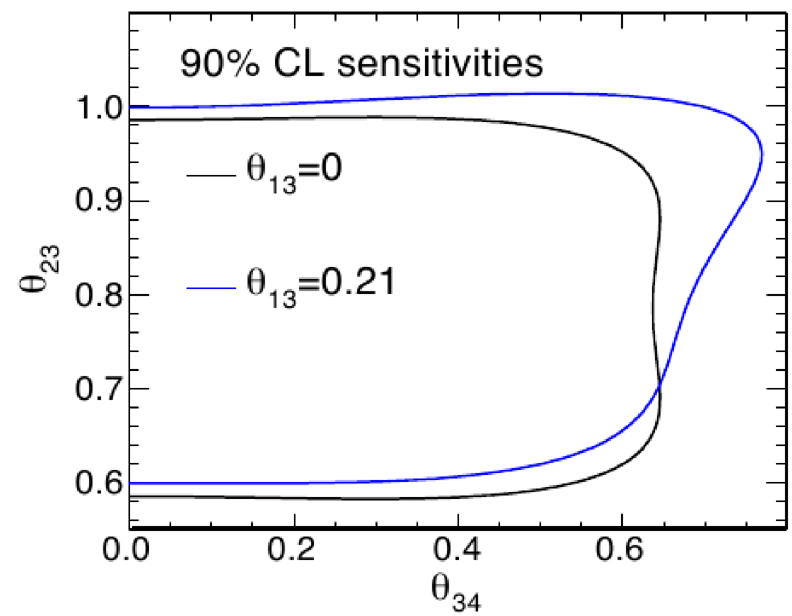
- Statistical sensitivity contours and projections for $m_4 >> m_3$





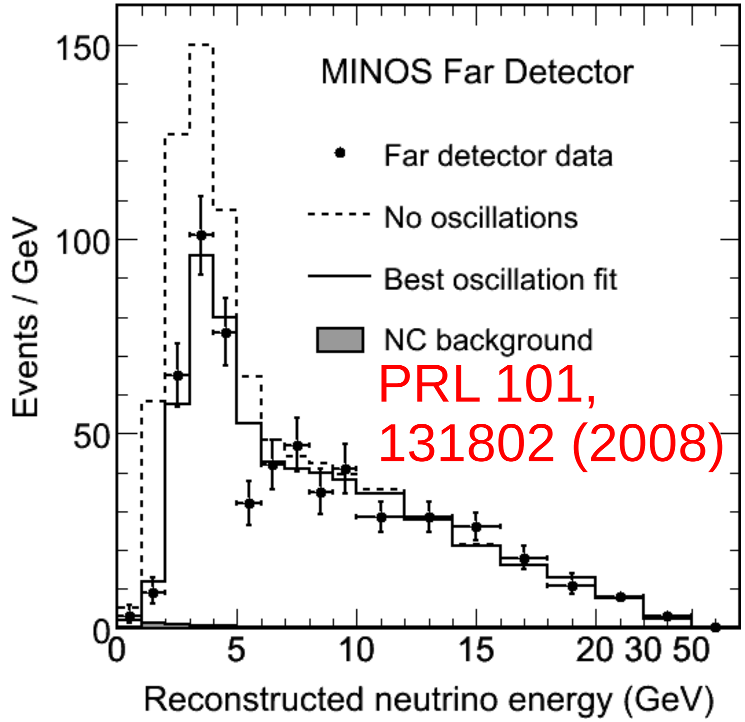
- Projections and contour for m_4 = m

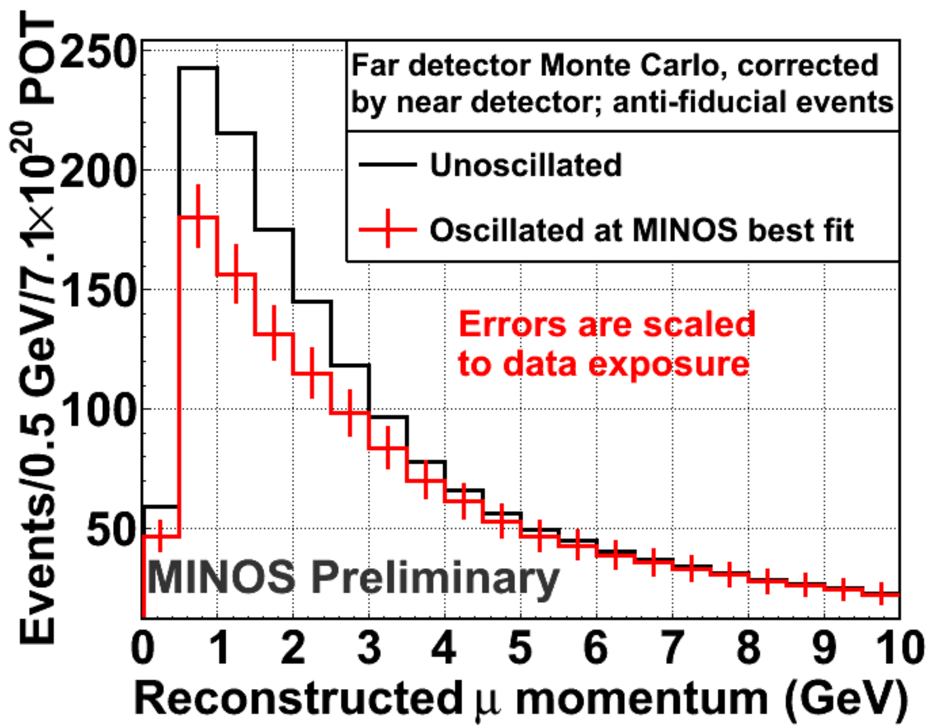


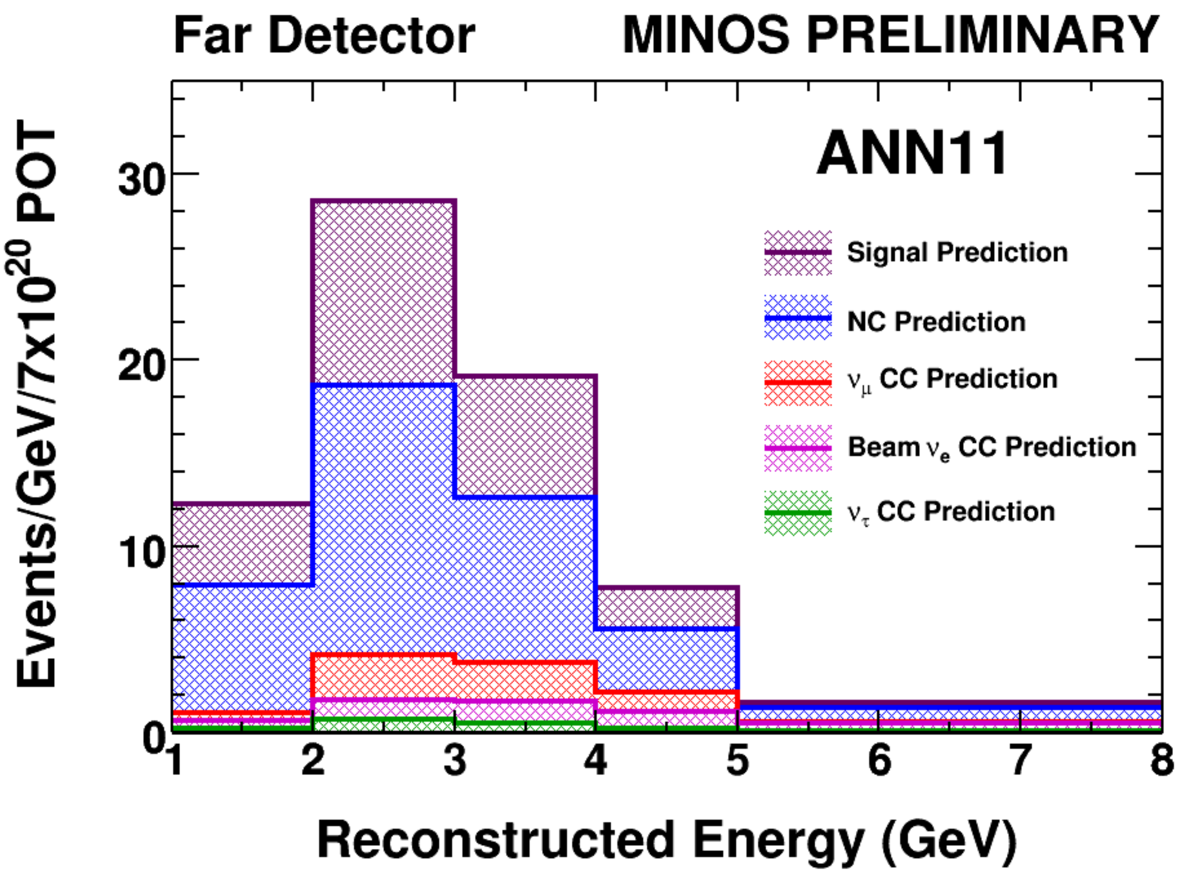


Rock Muons

- Depth of oscillation deficit⇒$\sin^2 2\theta$
  - High E neutrinos reconstructed as low E muons form a **background**
- Location of deficit⇒Δm^2
  - Also partially masked by high energy feed-down
  - But <u>total magnitude</u> of deficit alone gives a strong constraint
  - Strength of this analysis
- Splitting events into several categories isolates the stronger parts of the signal



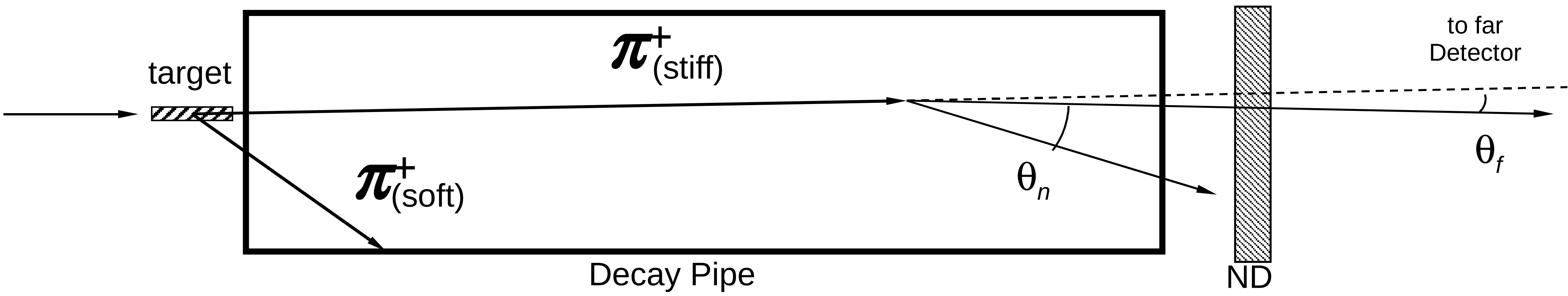




Expected signal at **Chooz limit**: **24 events** => **3.2σ signal** at this limit

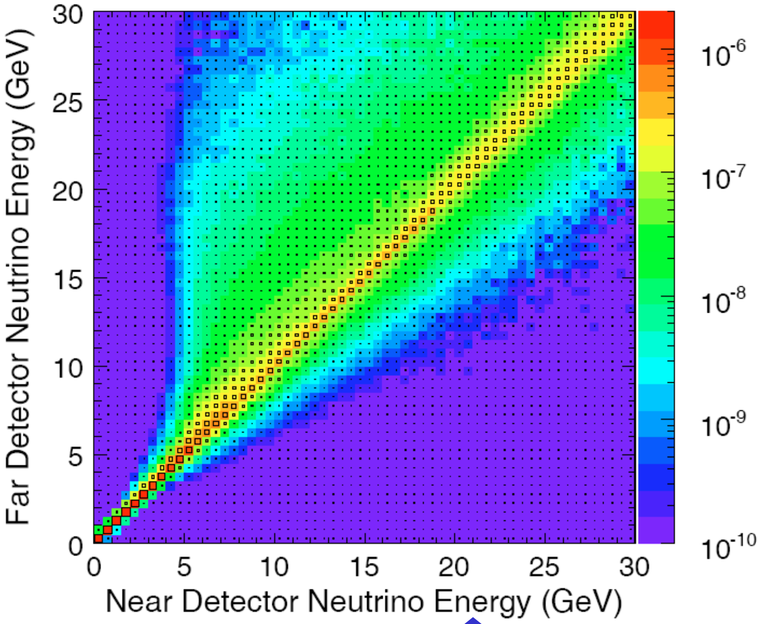
What is Expected in Soudan?

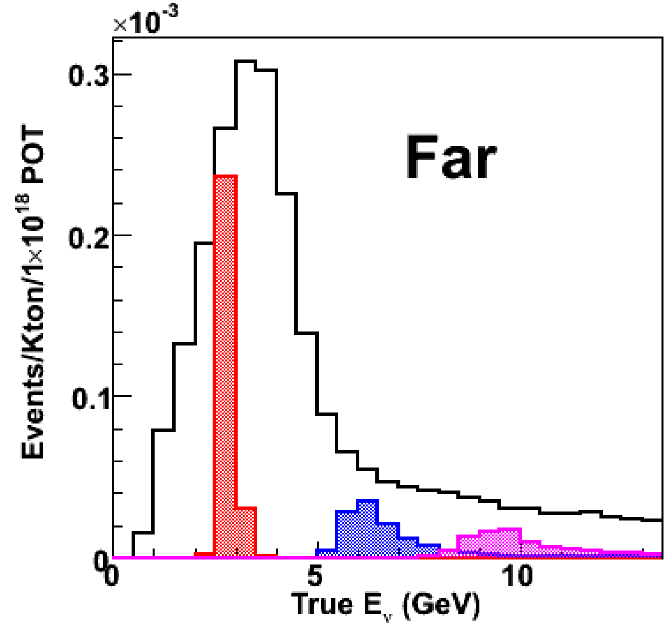
- Measure Near Detector E_ν spectrum
- To first order the beam spectra at Soudan is the same as at Fermilab, but:
  - Small but systematic differences between Near and Far
  - Use Monte Carlo to correct for energy smearing and acceptance
  - Use our knowledge of pion decay kinematics and the geometry of our beamline to predict the FD energy spectrum from the measured ND spectrum

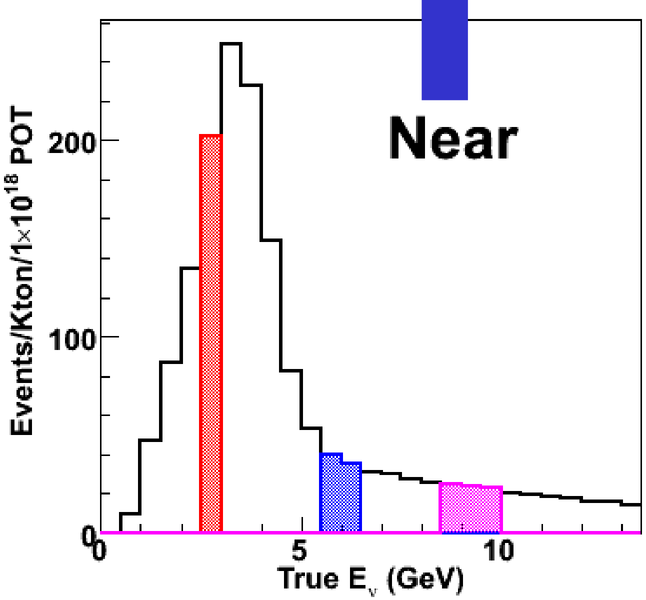


$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 \qquad E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

Far/Near Extrapolation







- Beam Matrix encapsulates the knowledge of pion 2-body decay kinematics & geometry
- Beam Matrix provides a very good representation of how the Far Detector spectrum relates to the near one
- PDF of a E_ν bin @ Near Det as it spreads to the Far Det