Neutrino Oscillations with MINOS

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for the MINOS collaboration

Introduction

- MINOS physics goals
- NuMI neutrino beam
- MINOS detectors
- Results:
  - Muon neutrino disappearance
  - Muon anti-neutrino analysis (new!)
  - Electron neutrino appearance
- Future plans

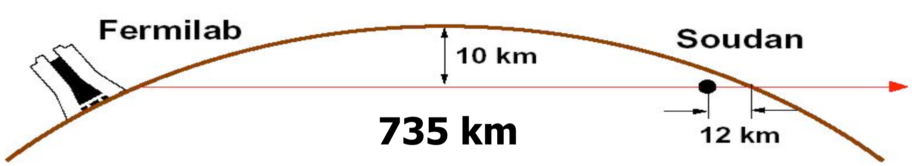
The MINOS Collaboration

28 institutions
140 scientists

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
Harvard • Holy Cross • IIT • Indiana • Minnesota-Twin Cities • Minnesota-Duluth • Otterbein
Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • Warsaw • William & Mary

MINOS Overview

- Main Injector Neutrino Oscillation Search
- Neutrinos at the Main Injector (NuMI) beam at Fermilab
- Two detectors:
- Near detector at Fermilab
  - measure beam composition
  - energy spectrum
- Far detector in Minnesota
  - search for and study oscillations



MINOS Physics Goals

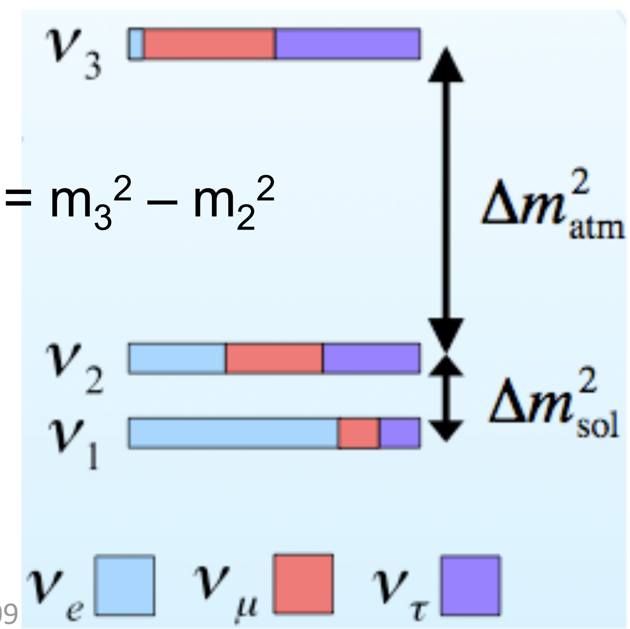
- Test the $\nu_\mu \rightarrow \nu_x$ oscillation hypothesis
  - Measure precisely $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$
  - Compare $\bar{\nu}_\mu$, ν_μ oscillations
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
  - sensitive to θ_{13}
- Other MINOS physics:
  - Search for sterile neutrinos, CPT/Lorentz violation
  - Studies of cosmic rays and atmospheric neutrinos
  - Neutrino interaction studies in the Near detector

ν_e appearance

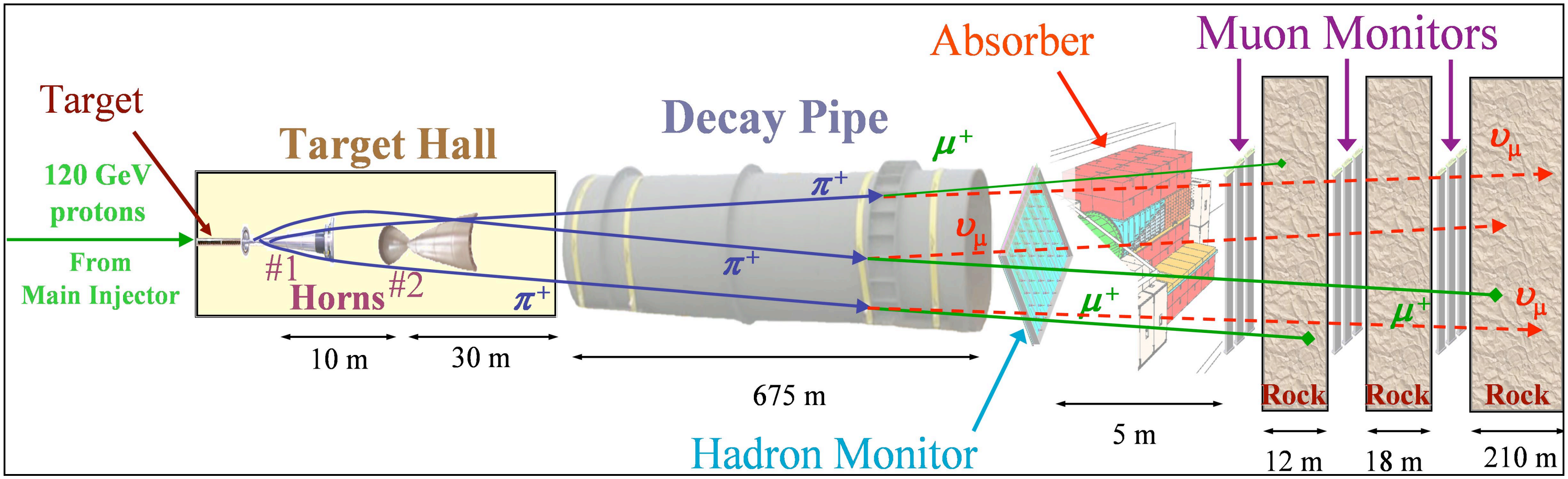
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν_μ disappearance

$\Delta m^2_{32} = m_3^2 - m_2^2$



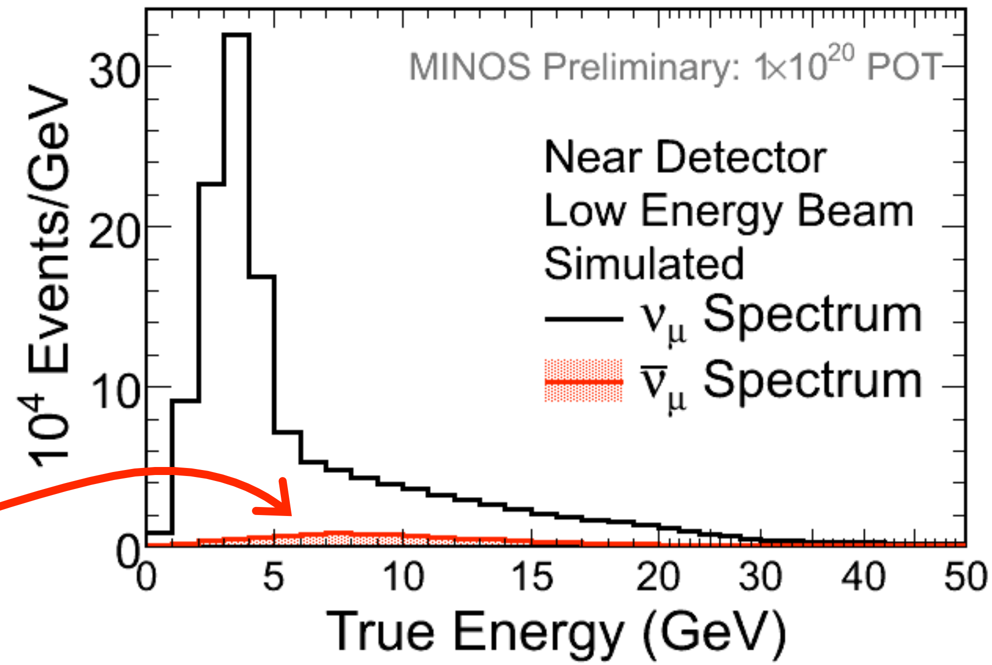
Neutrino Beam (NuMI)

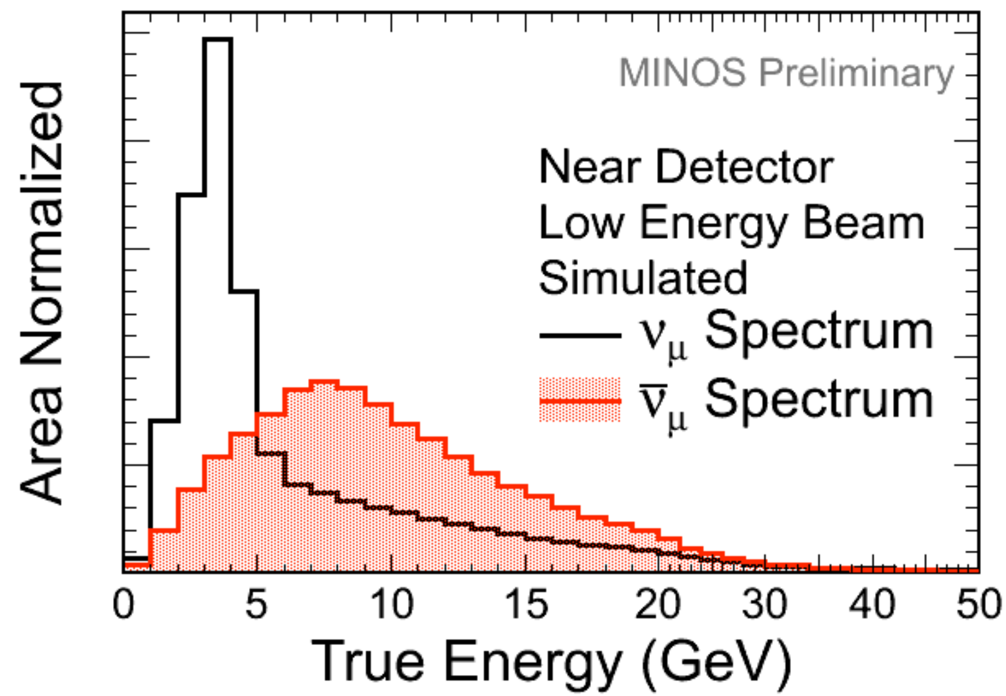


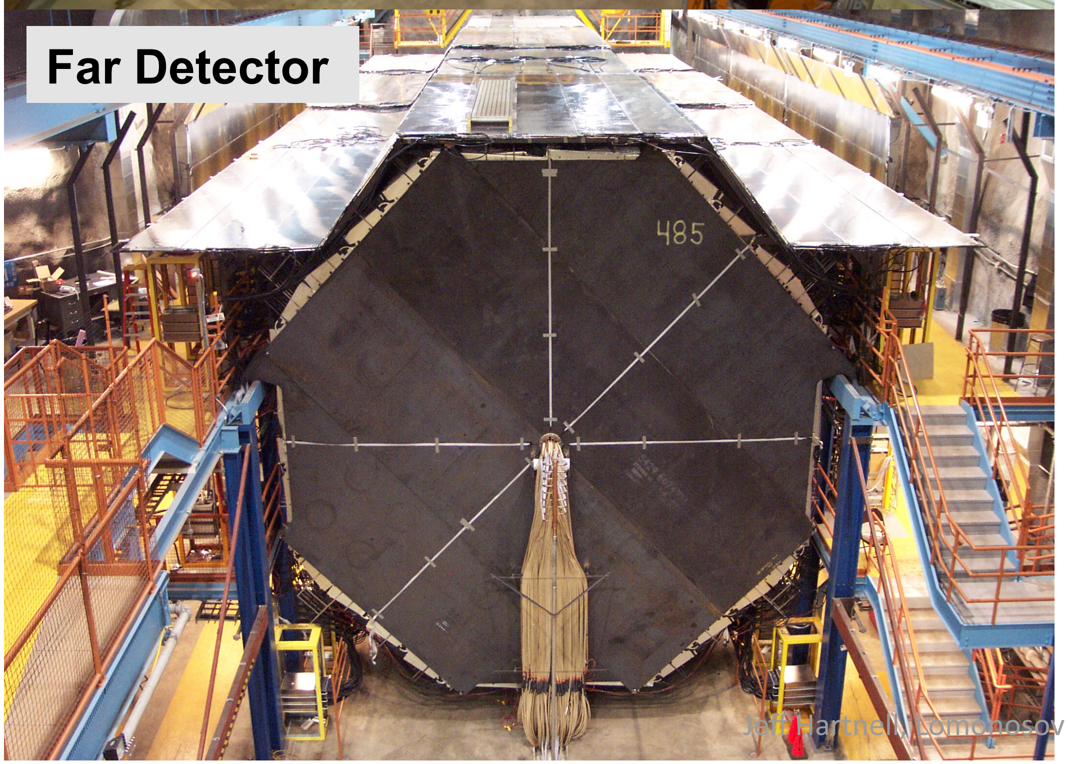
- 120 GeV protons strike target
- 10 µs long pulse of 3×10^{13} protons every 2.2 seconds (275 kW)
- Two magnetic horns focus secondary π/K
  - decay of π/K produce neutrinos
- Variable neutrino beam energy

Beam Flavour Composition

- The charged current interactions in the Near detector comprise of:
  - 91.7% ν_μ
  - 7.0% $\bar{\nu}_\mu$
  - 1.3% ν_e and $\bar{\nu}_e$
- Significant difference in the energy spectrum:
  - ν_μ peak at 3 GeV
  - $\bar{\nu}_\mu$ peak at 8 GeV





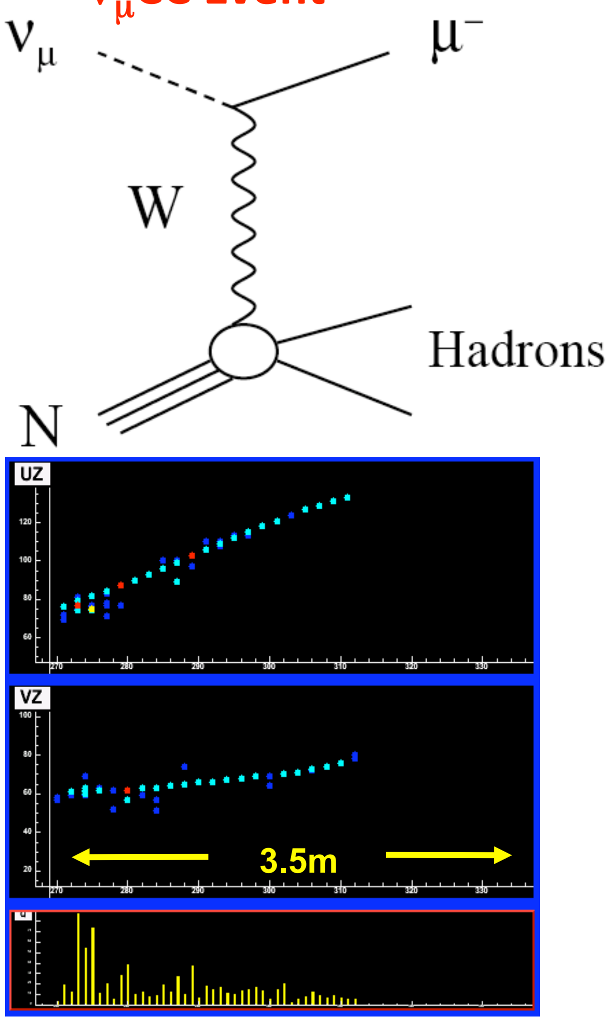


MINOS Detectors

- Massive
  - 1 kt Near detector
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

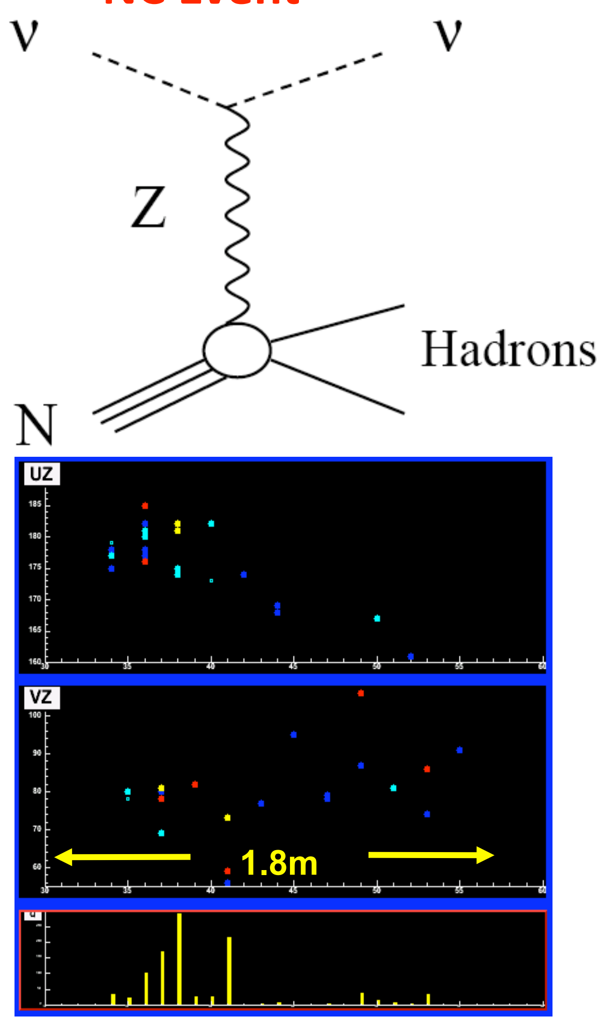
MINOS Event Topologies (MC)

ν_μCC Event



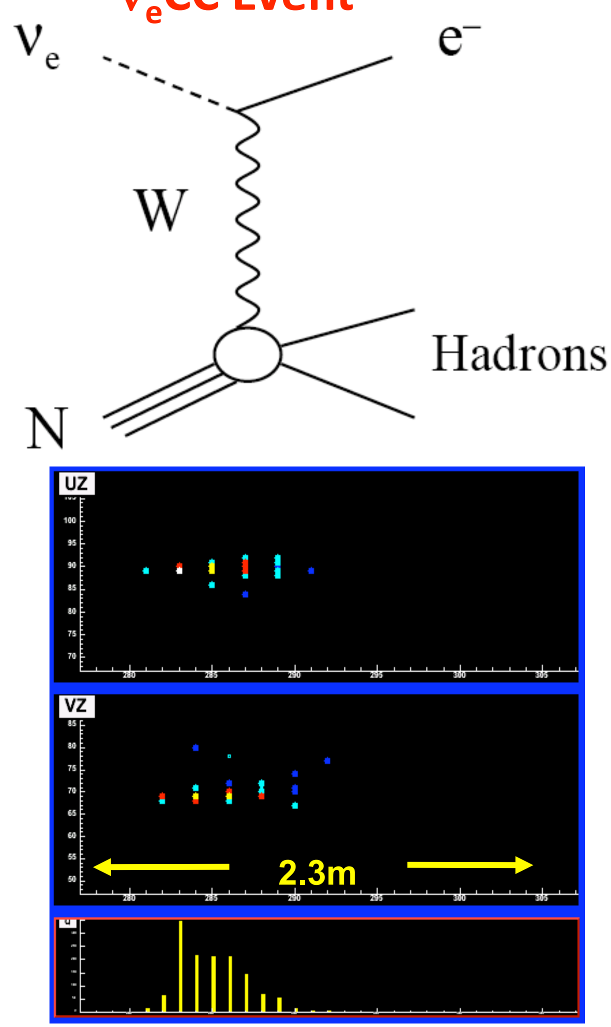
long μ track+ hadronic activity at vertex

NC Event



short event, often diffuse

ν_eCC Event



short, with typical EM shower profile

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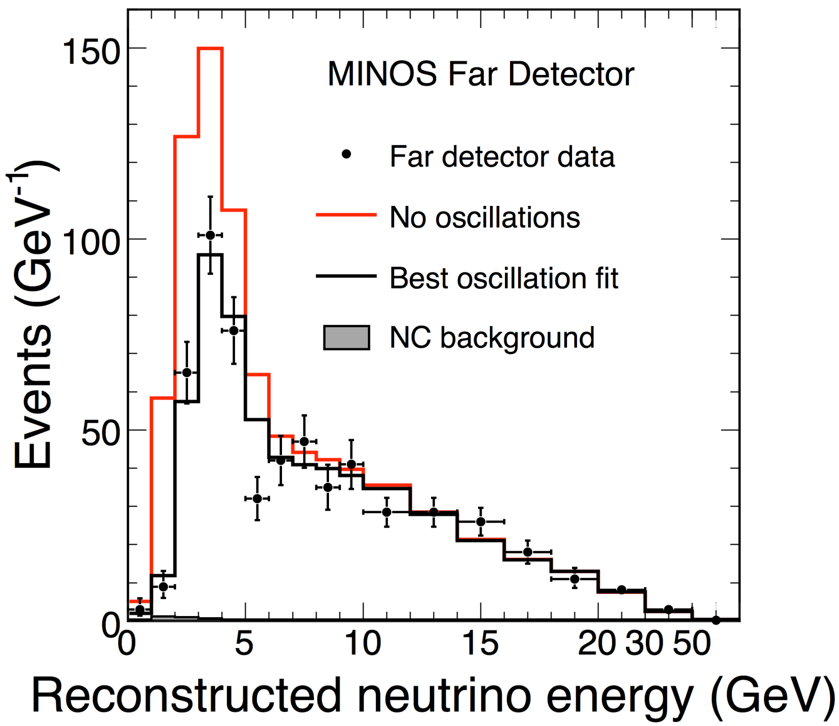
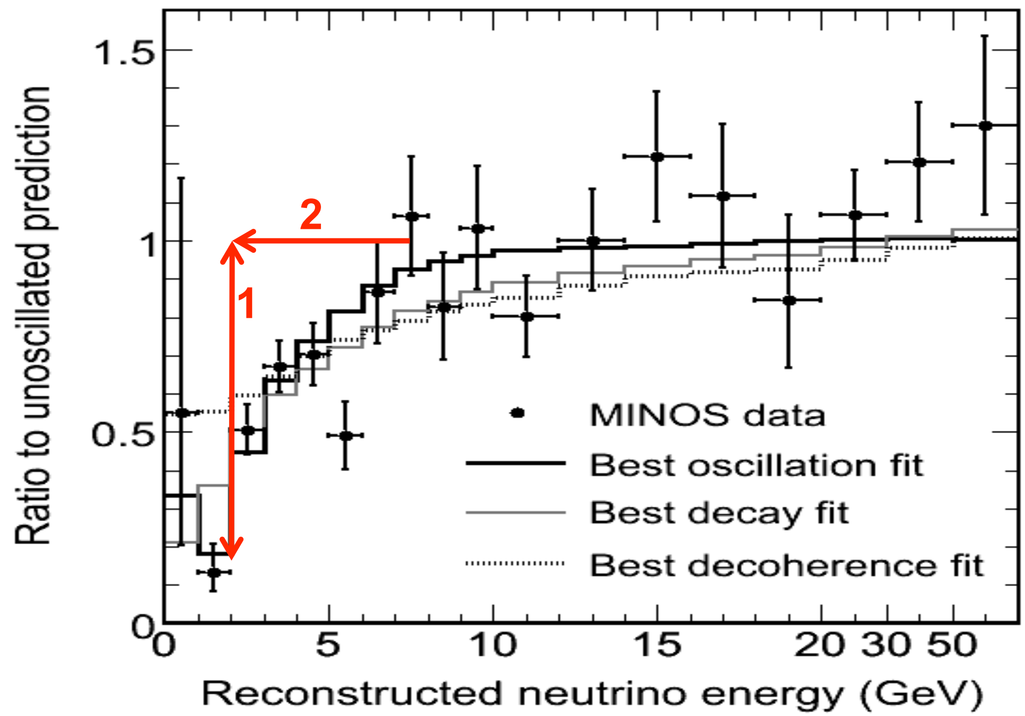
Muon Neutrino Disappearance Analysis

Experimental Approach

- **Two detector experiment** to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimised
  - Measure unoscillated ν_μ spectrum at Near detector
    - extrapolate using MC
  - Compare to measured spectrum at Far detector





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

1 2

Allowed Region

- Energy spectrum fit with the oscillation hypothesis:

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

- Results:

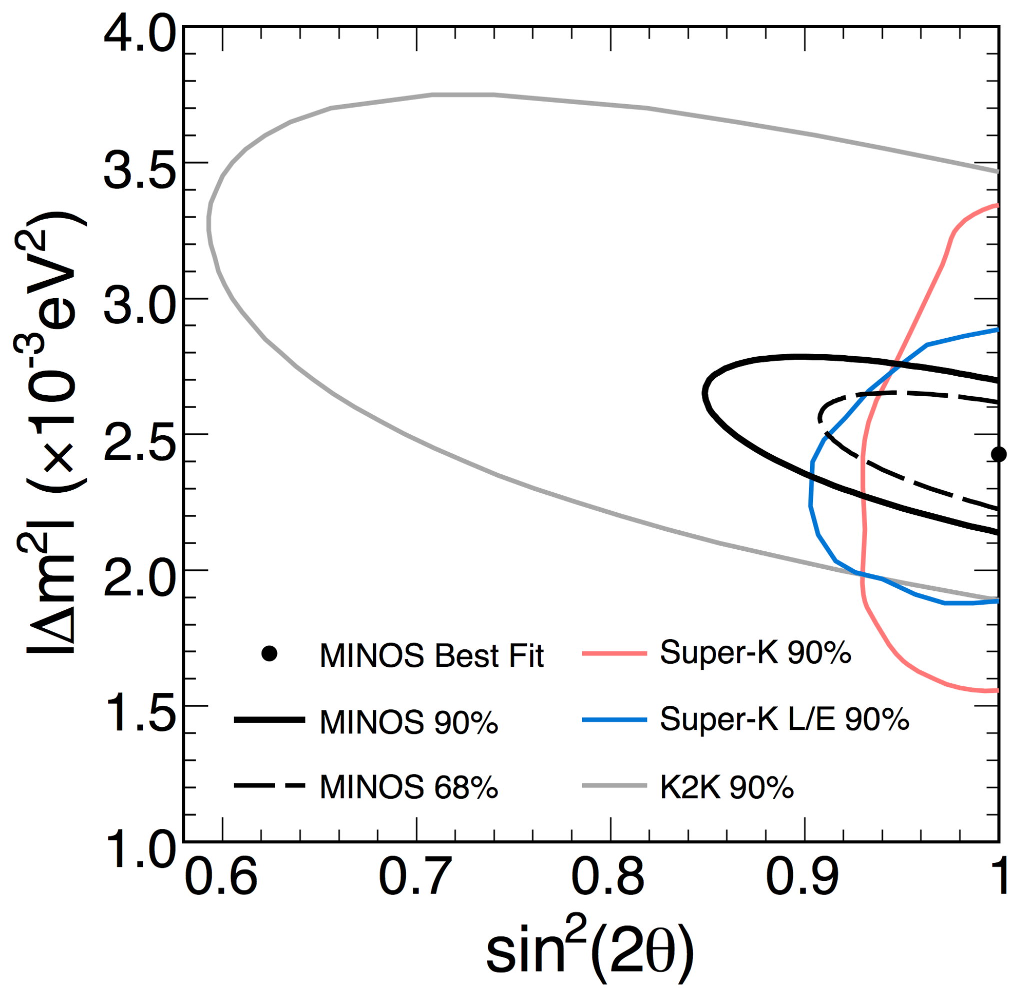
$|\Delta m^2_{32}|=(2.43\pm0.13)\text{x}10^{-3}\ \text{eV}^2$

at 68% C.L.

$\sin^2(2\theta_{23}) > 0.90$

at 90% C.L.

PRL **101** 131802 (2008)



Most precise measurement of $|\Delta m^2_{32}|$ performed to date

What about the Muon Anti-Neutrinos...

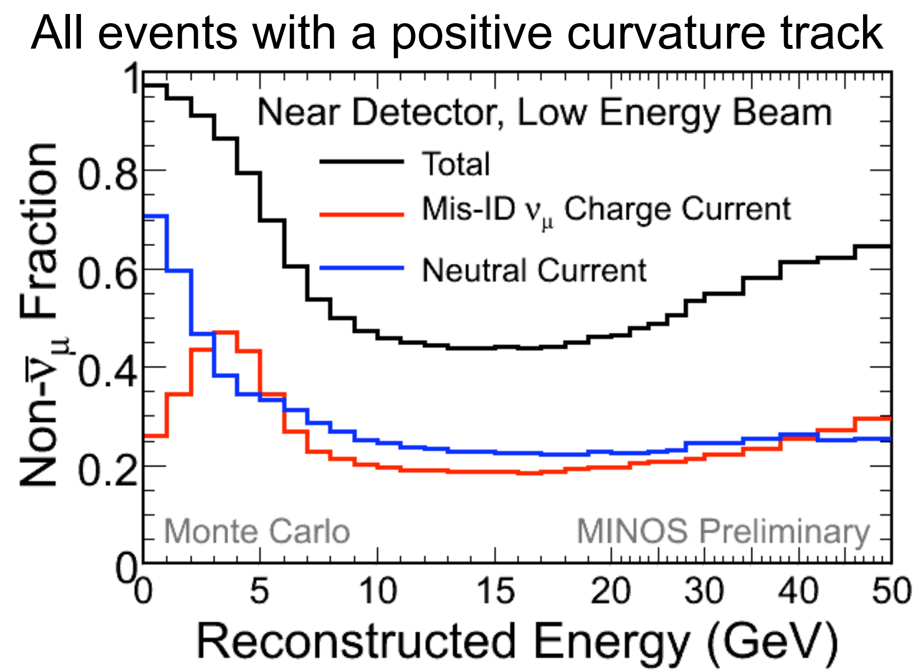
$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons}$$

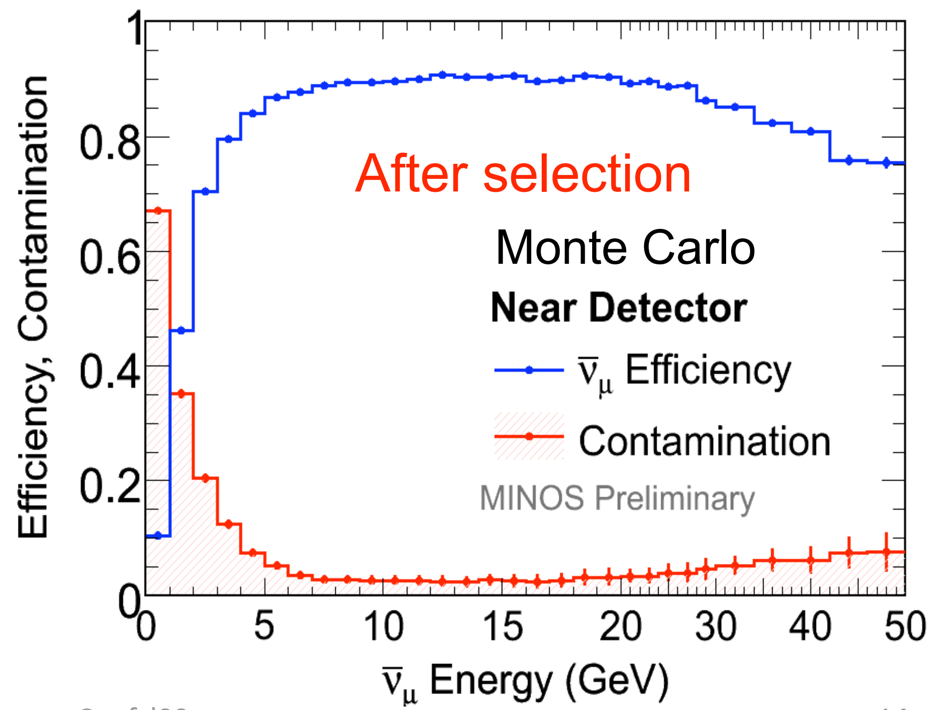
$$\nu_\mu + N \rightarrow \mu^- + \text{hadrons}$$

(NEW: Preliminary results released in May '09)

Selecting $\bar{\nu}_\mu$

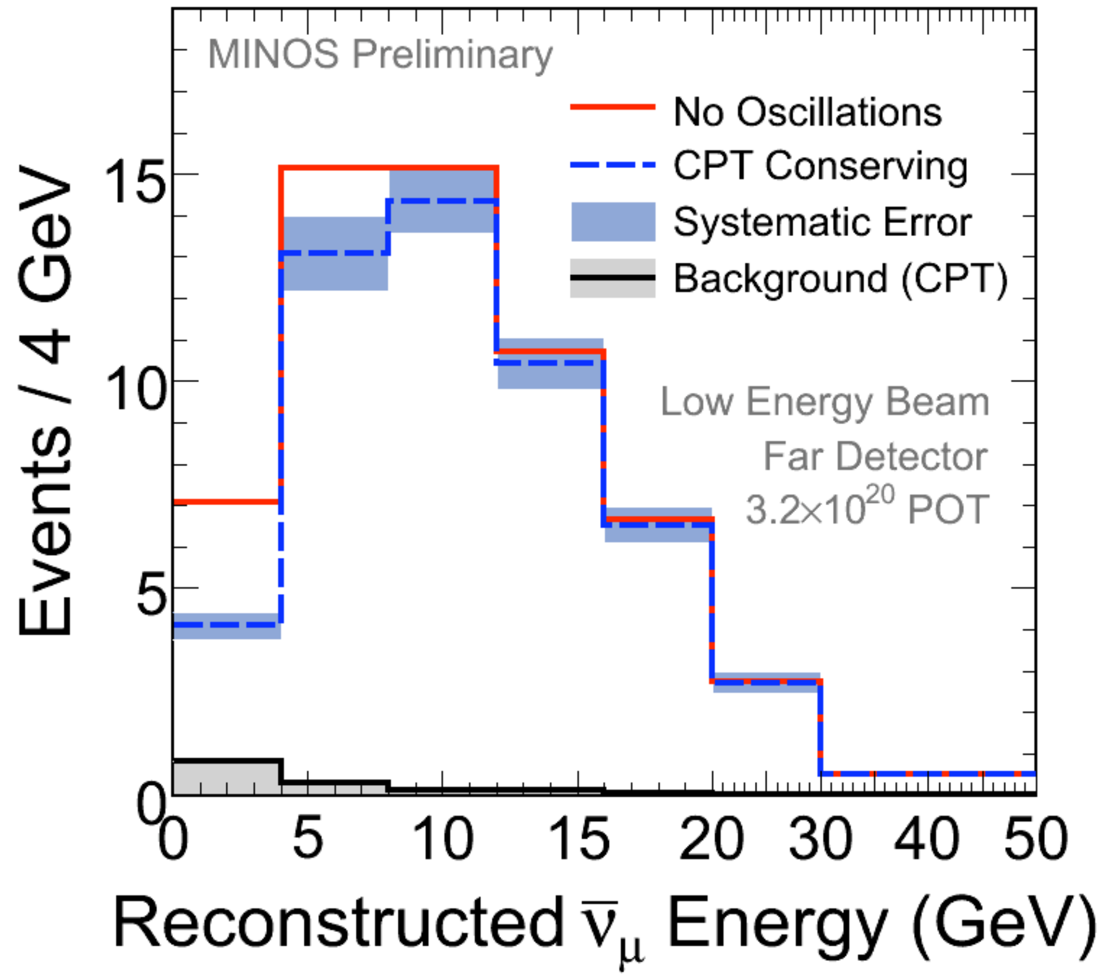
- $\bar{\nu}_\mu$ CC events are 7% of beam
- Searching for $\bar{\nu}_\mu$ CC amongst a large sample of other events:
  - Mis-identified ν_μ CC where μ charge sign is wrong
  - Neutral Current (NC) events where another particle fakes a μ^+ track
- NC events with a track are ~50:50, positive:negative charge sign
- Cut on additional variables to achieve:
  - Efficiency of 87%
  - Contamination of 5%





Predicted Far Detector Spectrum

(follow an analogous procedure as for the muon neutrinos)

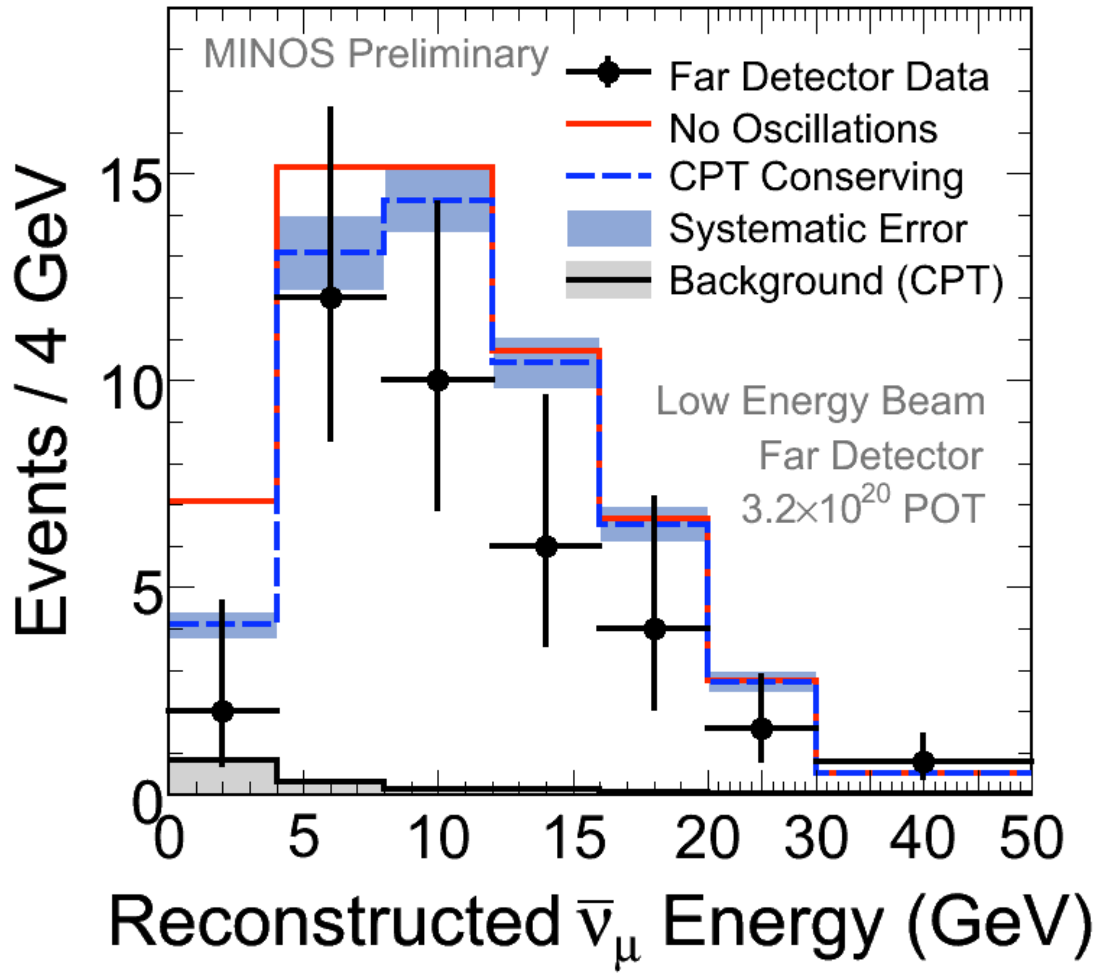


- Predicted events with CPT conserving oscillations:
  - 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - 64.6 ± 8.0 (stat.) ± 3.9 (syst.)

Far Detector Spectrum

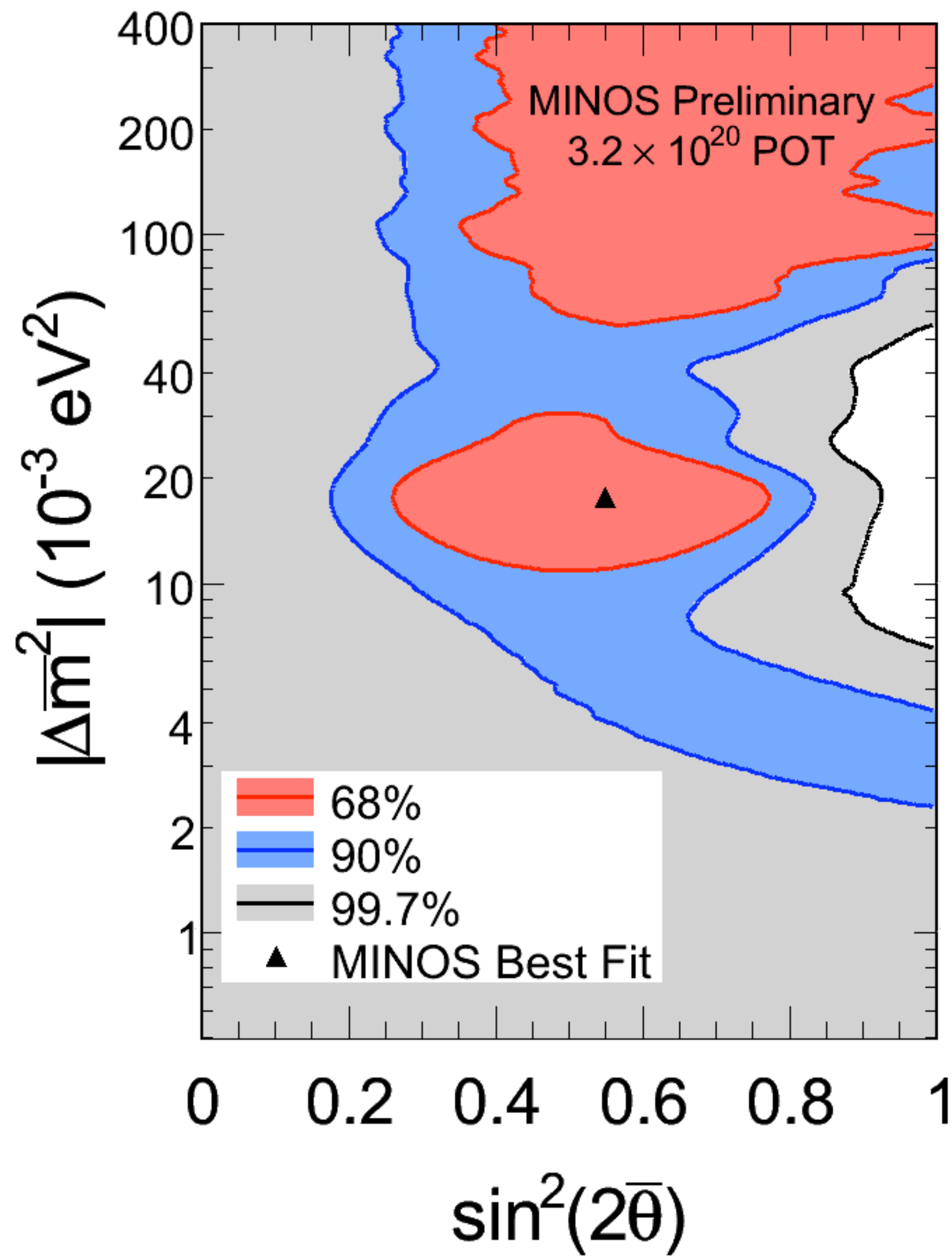
- Observe **42 events** in the Far detector
- First direct observation of $\bar{\nu}_\mu$ in an accelerator long-baseline experiment

- Predicted events with CPT conserving oscillations:
  - 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - 64.6 ± 8.0 (stat.) ± 3.9 (syst.)



Allowed Region

- Null oscillation hypothesis excluded at 99%
- CPT conserving point from the MINOS neutrino analysis is within 90% contour
- $\bar{\nu}_\mu$ best fit is at high value, due to deficit at high energy
- At maximal mixing **exclude**:
  - $(5.0 < \Delta\bar{m}^2 < 81)\mathrm{x}10^{-3}\ \mathrm{eV}^2$ (90% C.L.)



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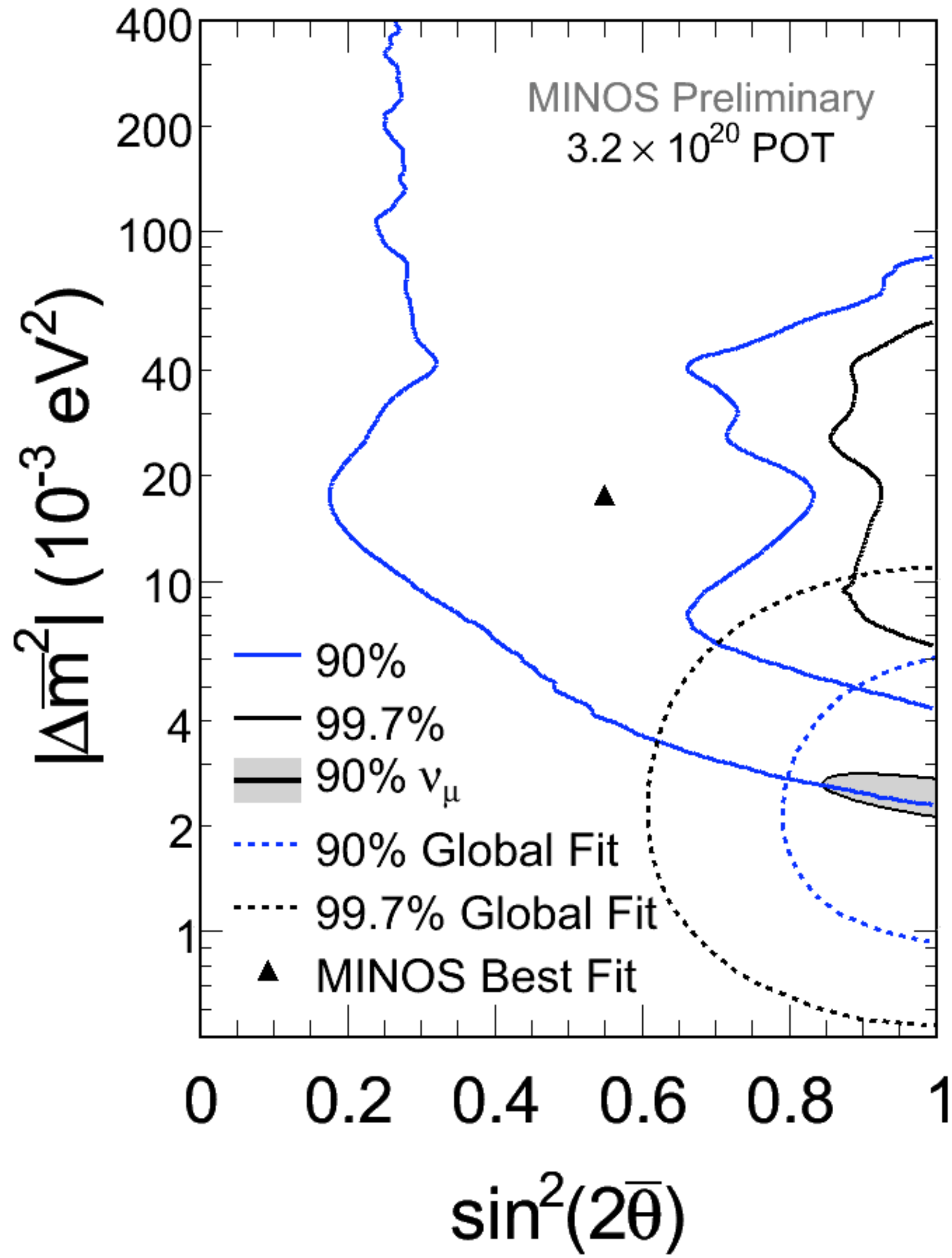
- At maximal mixing **exclude**:
  - $(5.0 < \Delta\bar{m}^2 < 81) \times 10^{-3}$ eV^2 (90% C.L.)
- Dashed lines show global fit to previous data, Super-Kamiokande dominates (SK-I and SK-II)
  - M. C. Gonzalez-Garcia & Michele Maltoni, Phys. Rept. 460 (2008)



Electron Neutrino Appearance Analysis

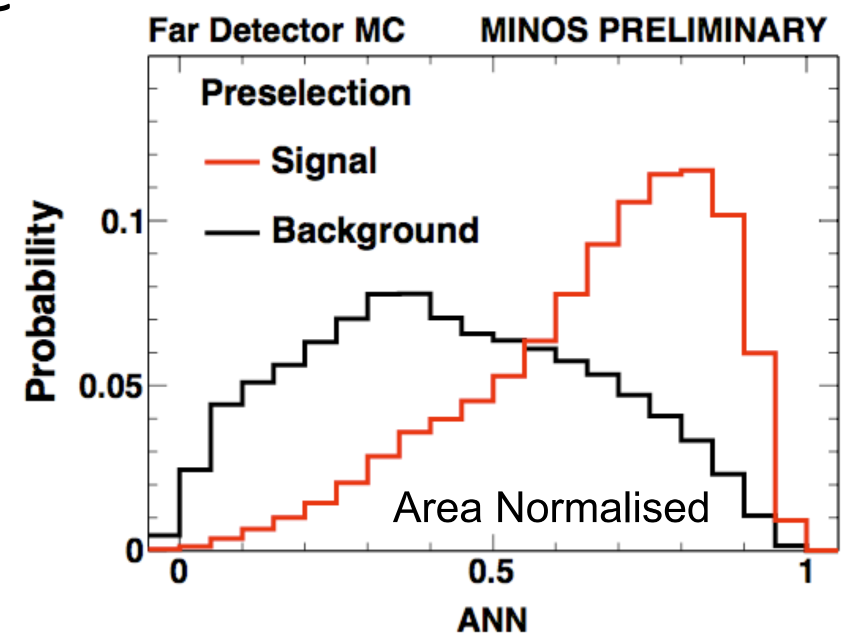
$\nu_\mu \rightarrow \nu_e$ Oscillation Search Overview

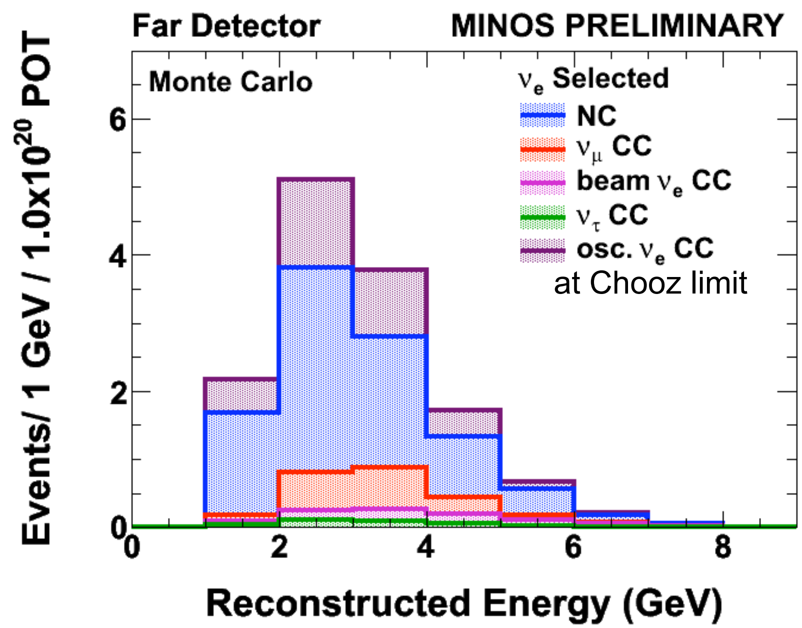
- Sub-dominant neutrino oscillations
  - Look for ν_e appearance at Far detector
    - $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$
      - also CPv and matter effects: not shown here but included in fit
  - Electron neutrino events only 2% of total (at Chooz limit)
- Select events w/ compact shower, typical EM profile
  - MINOS optimised for ν_μ
  - ν_e signal selection is harder
    - Steel thickness 2.5 cm = 1.4 X_0
    - Strip width 4.1cm ~ Molière radius (3.7cm)
- Use the Near detector to determine the background

Selecting ν_e Events

- 11 variables chosen describing length, width and shower shape
- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection >92.3%
  - ν_μCC rejection >99.4%
  - signal/background 1:4

    at Chooz limit
- Primary background from NC events, also
  - high-y ν_μ CC, beam ν_e, oscillated ν_τ at Far detector

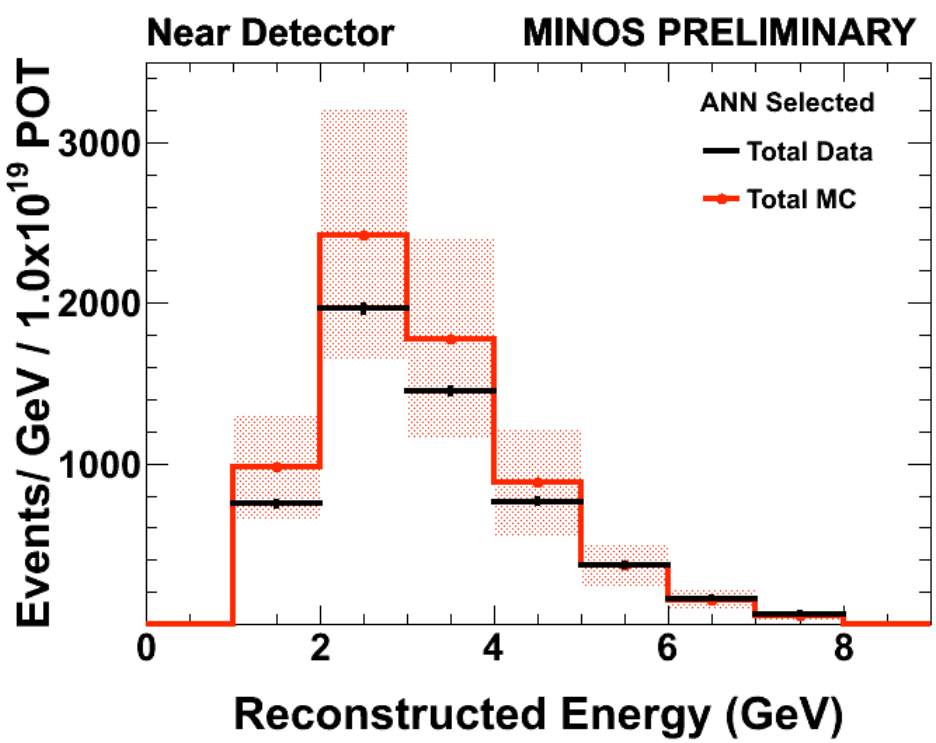




Extrapolation

- *O*(20%) data/MC differences in Near detector
- Use a data driven technique to measure Near detector background and extrapolate to Far detector

- Total systematic error on Far detector prediction is 7.3%
- Far detector statistical error of 19% dominates



Far Detector Energy Spectrum

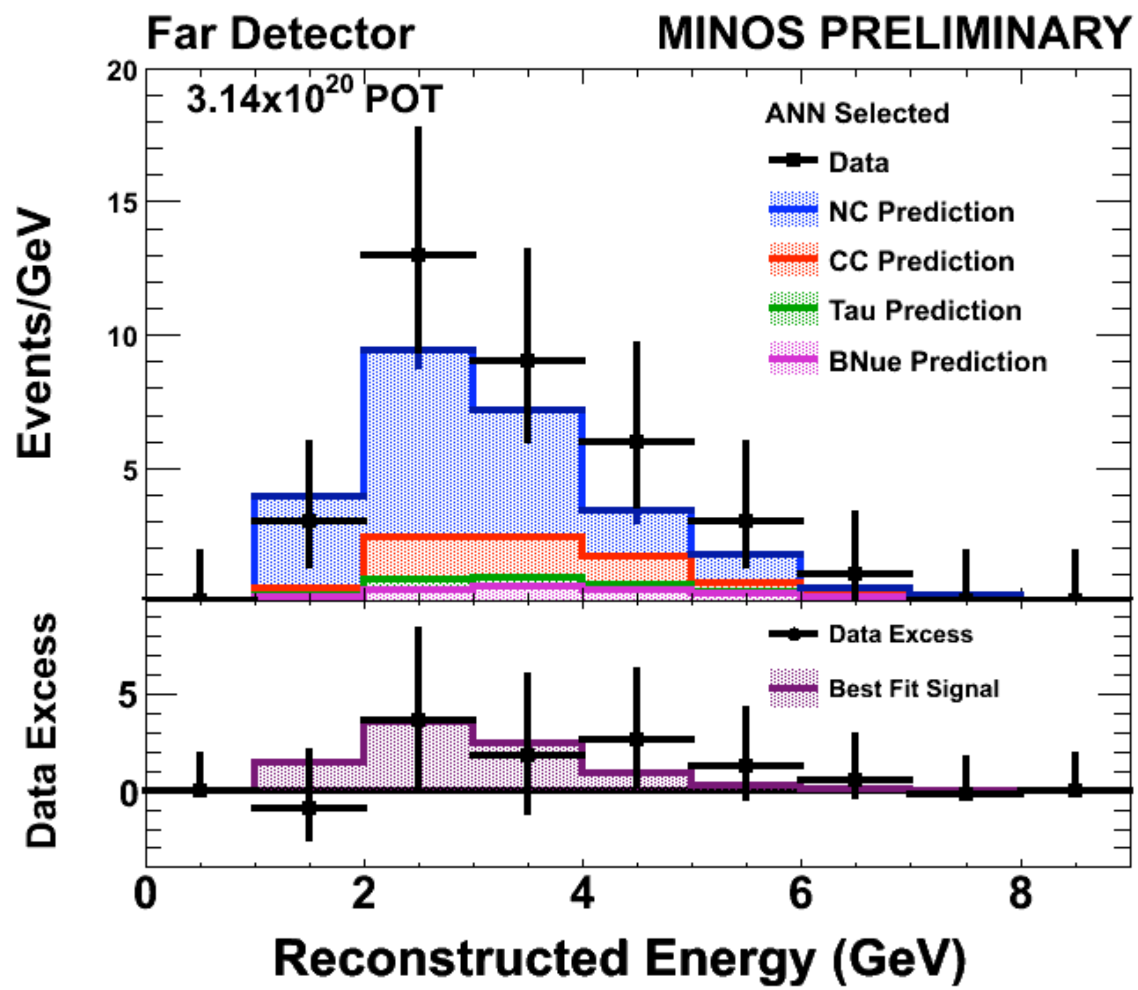
- A blind analysis was performed
- Expected background:

  27 ± 5(stat) ± 2(sys)

- Observed events:

  35

- A 1.5σ excess over background prediction



Fit the data to the oscillation hypothesis, obtain the signal prediction for the best fit point

Allowed Region

- Fit simply to the number of events from 1-8 GeV
- Best fit and 90% C.L. limits are shown:
  - for both mass hierarchies
  - at MINOS best fit value for Δm^2_{32} & $\sin^2(2\theta_{23})$

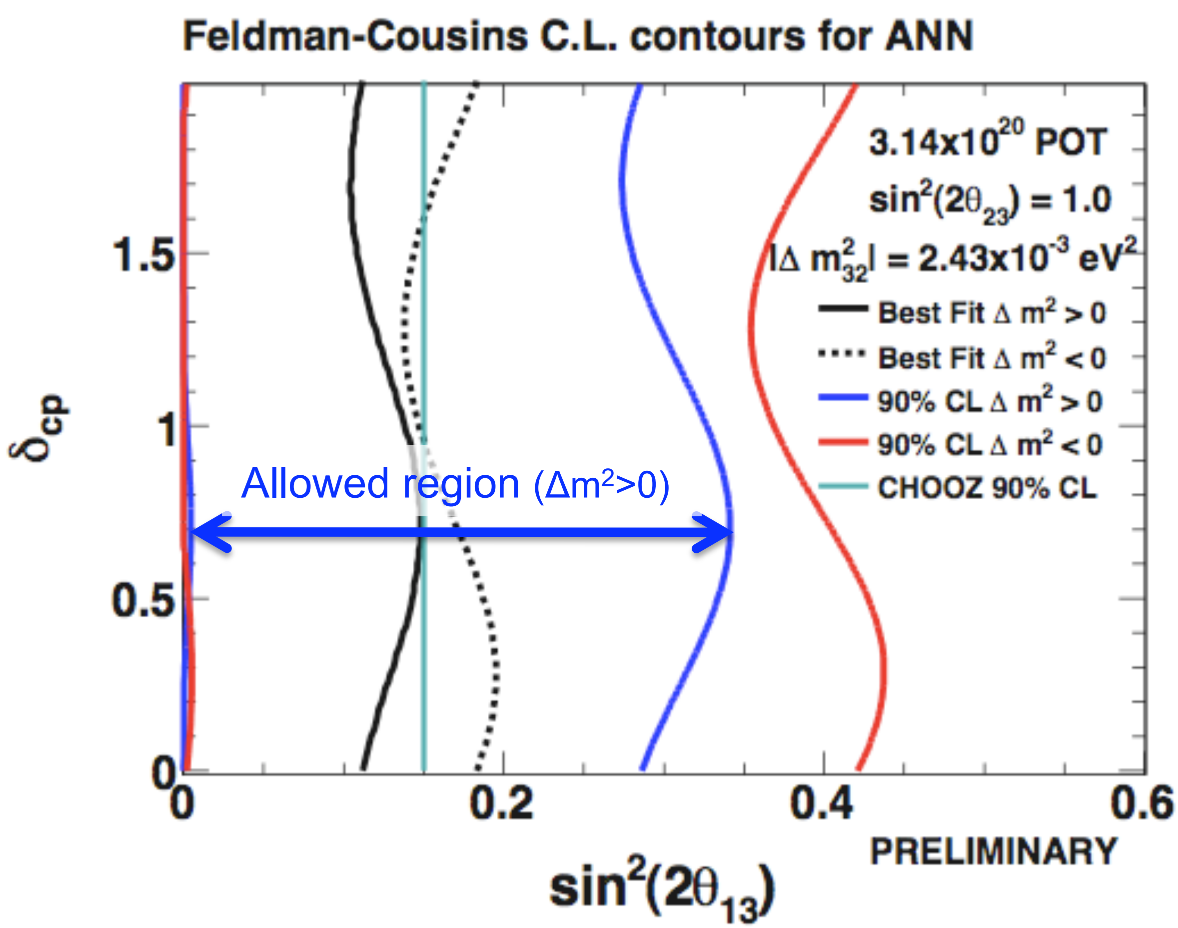
- Results:

Normal hierarchy (δ_{CP}=0):

$\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)

Inverted hierarchy (δ_{CP}=0):

$\sin^2(2\theta_{13}) < 0.42$ (90% C.L.)



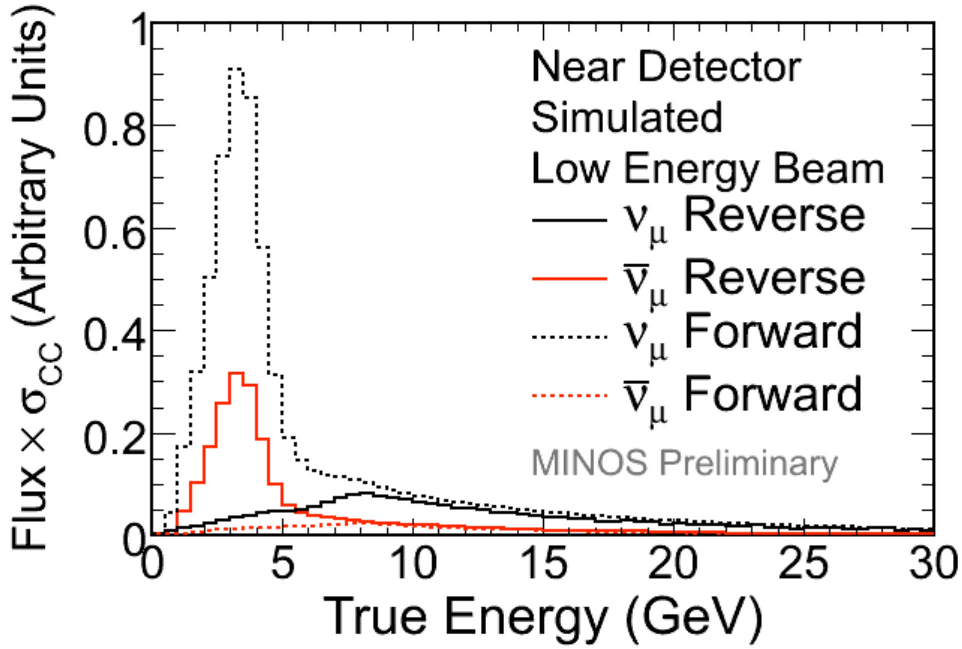
Future plans

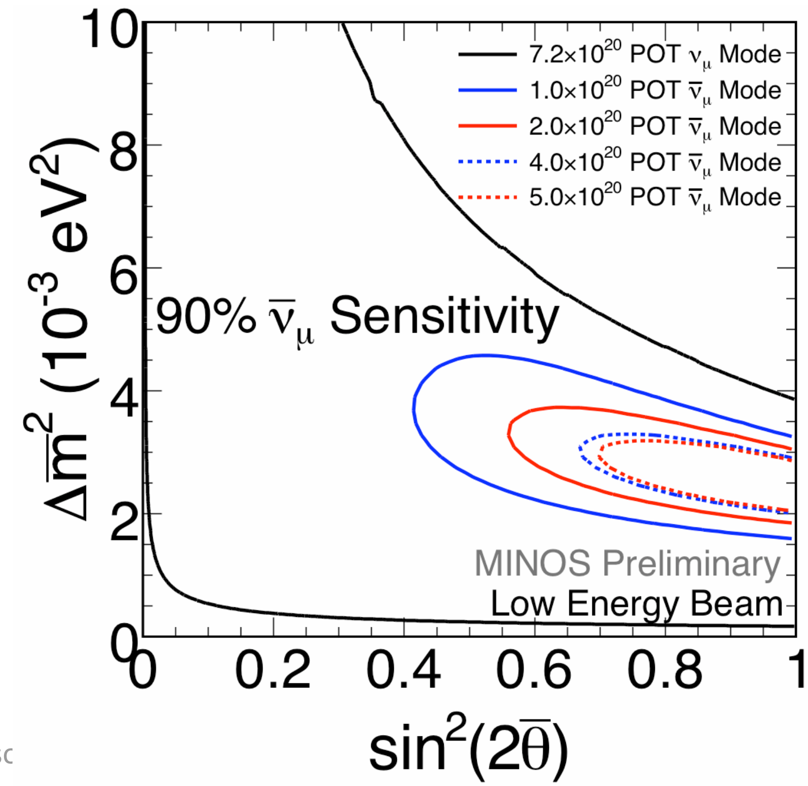
a.) Update all analyses with more than double the data set

b.) Dedicated $\bar{\nu}_\mu$ run

Dedicated $\bar{\nu}_\mu$ Running

- Plan to reverse current in NuMI magnetic horns to focus π^- from September
  - create a $\bar{\nu}_\mu$ beam
- MINOS can directly observe $\bar{\nu}_\mu$ disappearance at 7σ with 5x10^{20} POT
  - rapidly reduce the uncertainty on $\Delta\bar{m}^2_{32}$



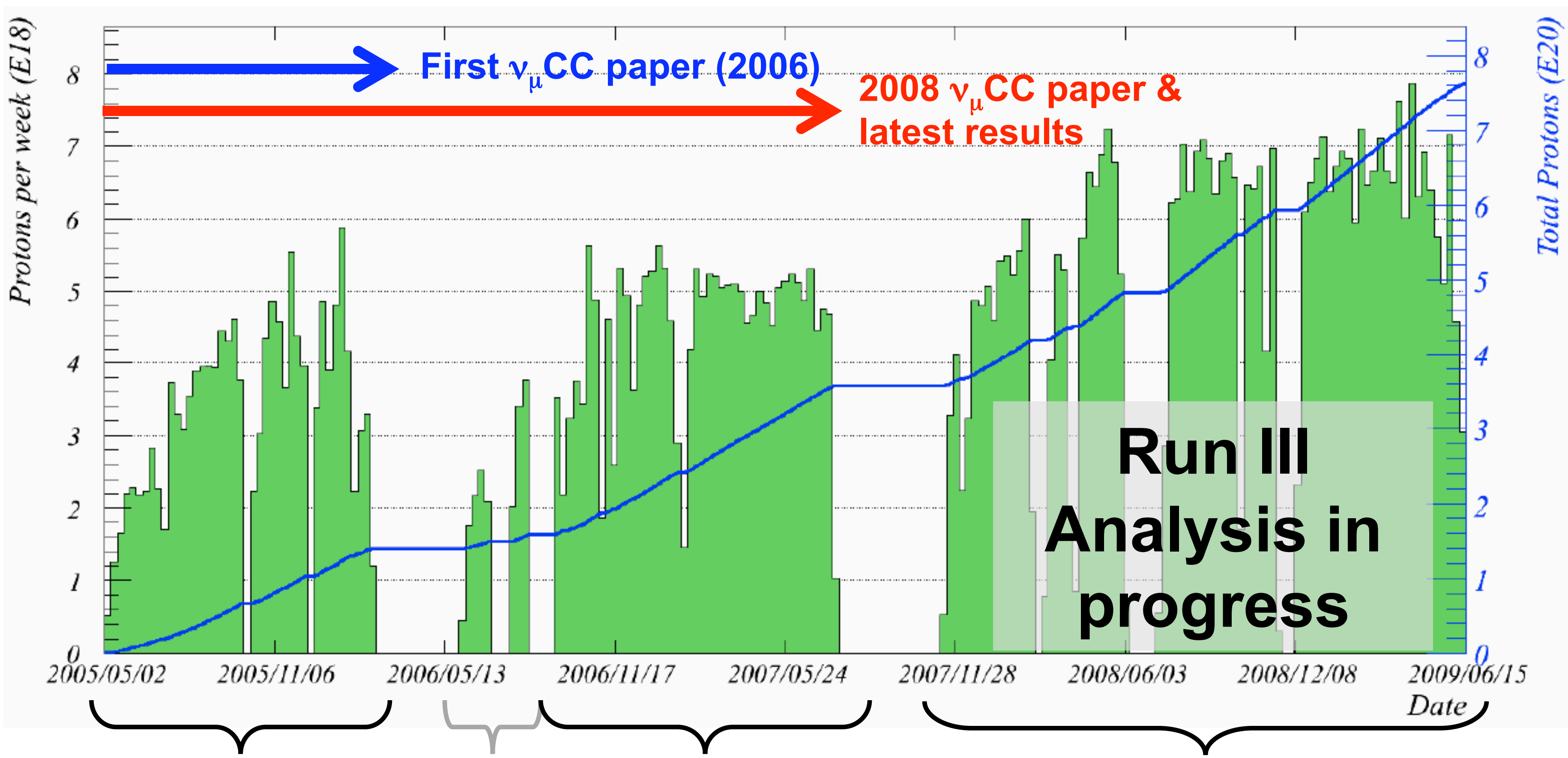


Conclusions

- MINOS has analysed 3.2×10^{20} POT of beam data (>7×10^{20} POT data now taken)
- Search for electron neutrino appearance
  - 1.5 σ excess over background prediction
  - $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.) (normal mass hierarchy, $\delta_{CP}=0$)
- First direct observation of $\bar{\nu}_\mu$ in an accelerator long-baseline experiment
  - At maximal mixing **exclude**: $(5.0 < \Delta\bar{m}^2 < 81) \times 10^{-3}\ \mathrm{eV}^2$ (90% C.L.)
- Muon neutrino disappearance
  - $|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\ \mathrm{eV}^2$ (68% C.L.)
  - $\sin^2(2\theta_{23}) > 0.90$ (90% C.L.)
- Plans for dedicated $\bar{\nu}_\mu$ run

Backup slides

Accumulated Beam Data



RUN I

1.27×10^{20} POT

Higher energy beam

0.15×10^{20} POT

RUN II

1.87×10^{20} POT

RUN III

$\sim 4 \times 10^{20}$ POT

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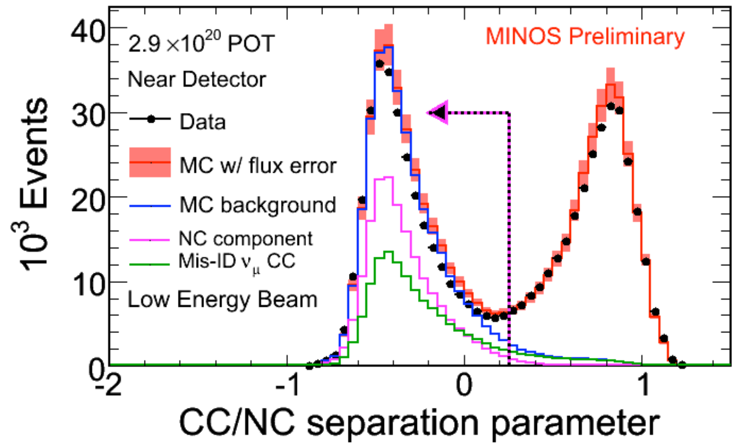
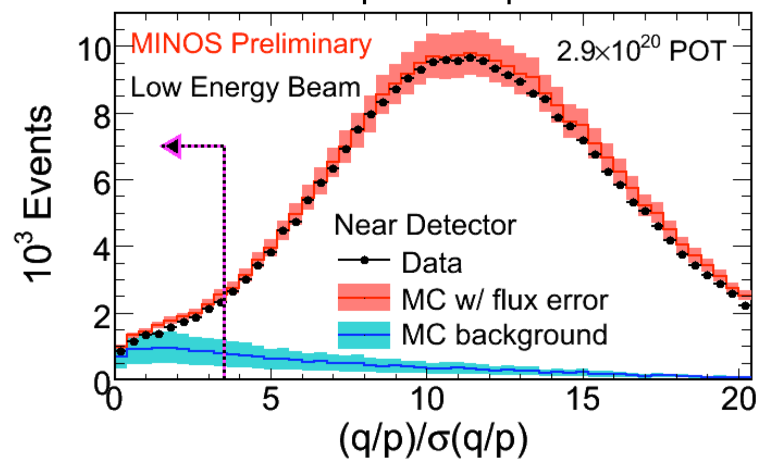
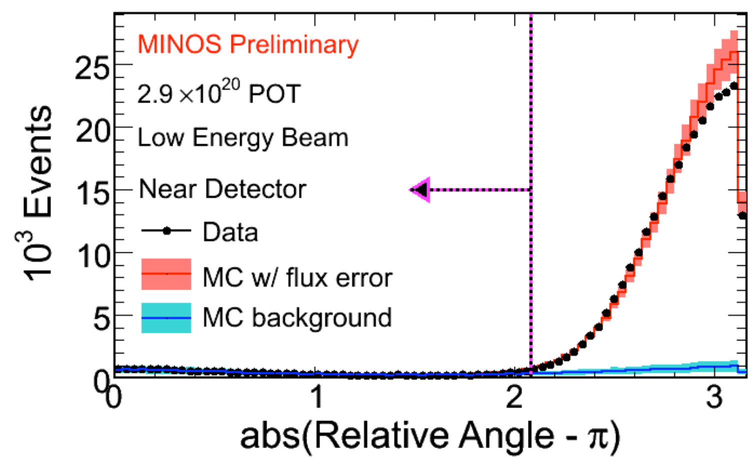
Additional Selection Variables

1) Likelihood based CC/NC separation parameter developed for previous analyses
   - Removes **both** NC and mis-identified ν_{μ} CC events
2) Track fit charge sign significance
3) Relative angle
   – measure of whether the track curves towards or away from the magnetic coil hole, relative to its initial direction







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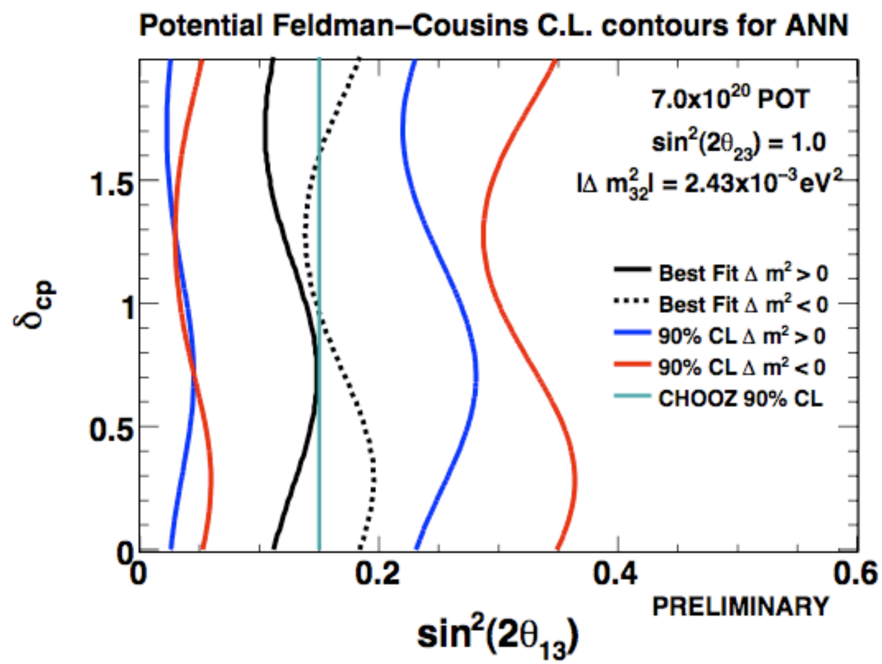
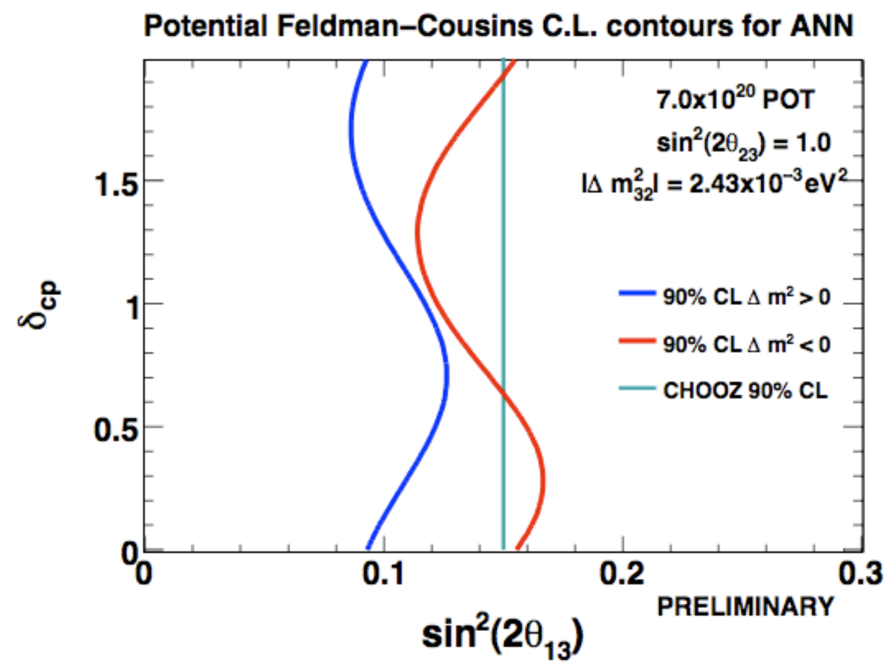
Future 90% CL contours

7.0 $\times 10^{20}$ POT



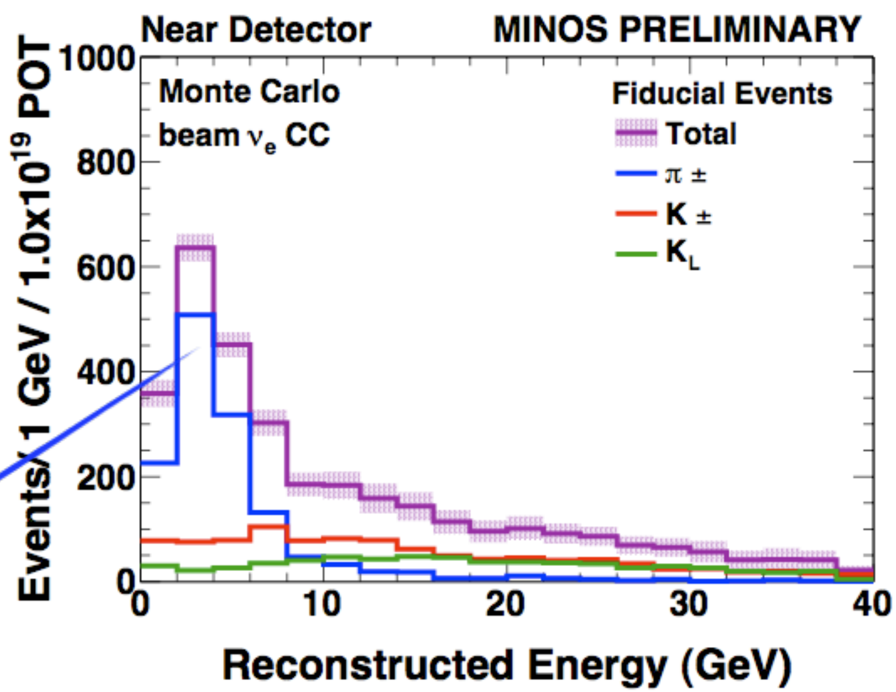


Future measurement if data excess persists.

Future limit if excess cancels with more data.

Beam ν_e component

- Neutrino beam has 1.3% of ν_e contamination from pion and kaon decays.
- Region of interest for the ν_e oscillation analysis, 1-8GeV, dominated by events from secondary muon decays:
- $\pi^+ \rightarrow \mu^+ \nu_\mu$
  $\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$
- Near and Far beam ν_e spectra are constrained by using ν_μ events from several beam configurations.

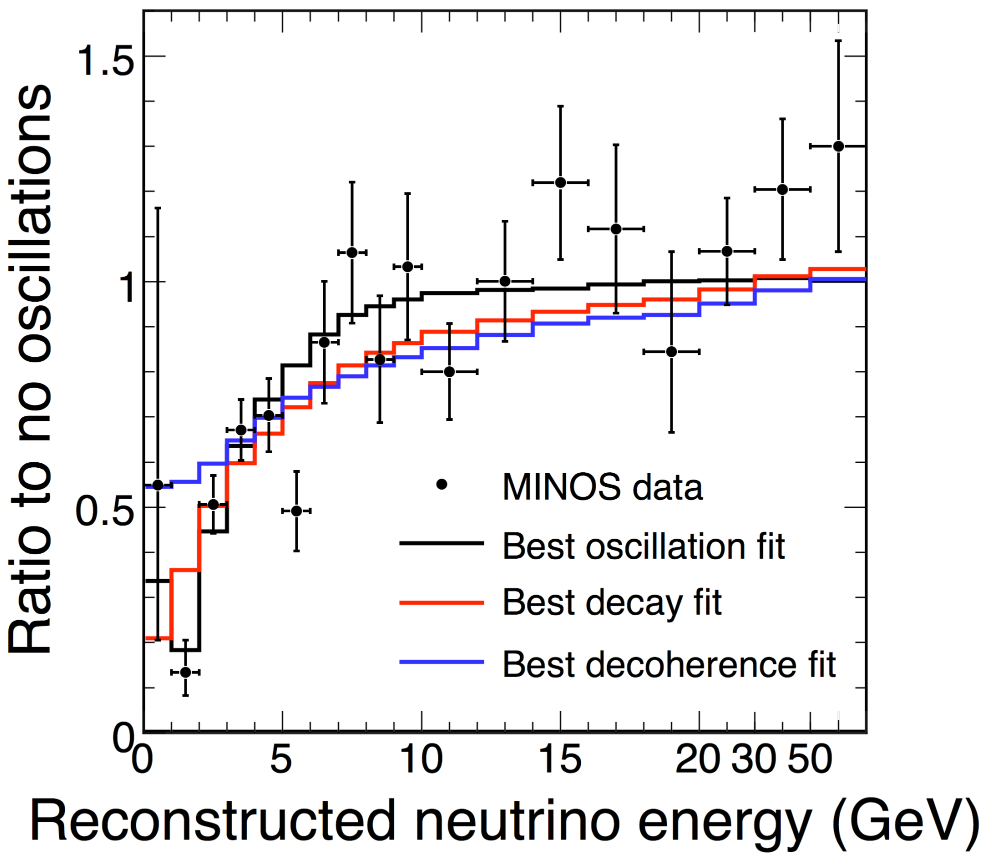


- Uncertainties on the flux in the region of interest are ~10%.

CC Analysis

Alternative Models

Two alternative disappearance models are disfavoured



Decay:

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

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

χ^2/ndof = 104/97

$\Delta\chi^2 = 14$

disfavored at 3.7σ

Decoherence:

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

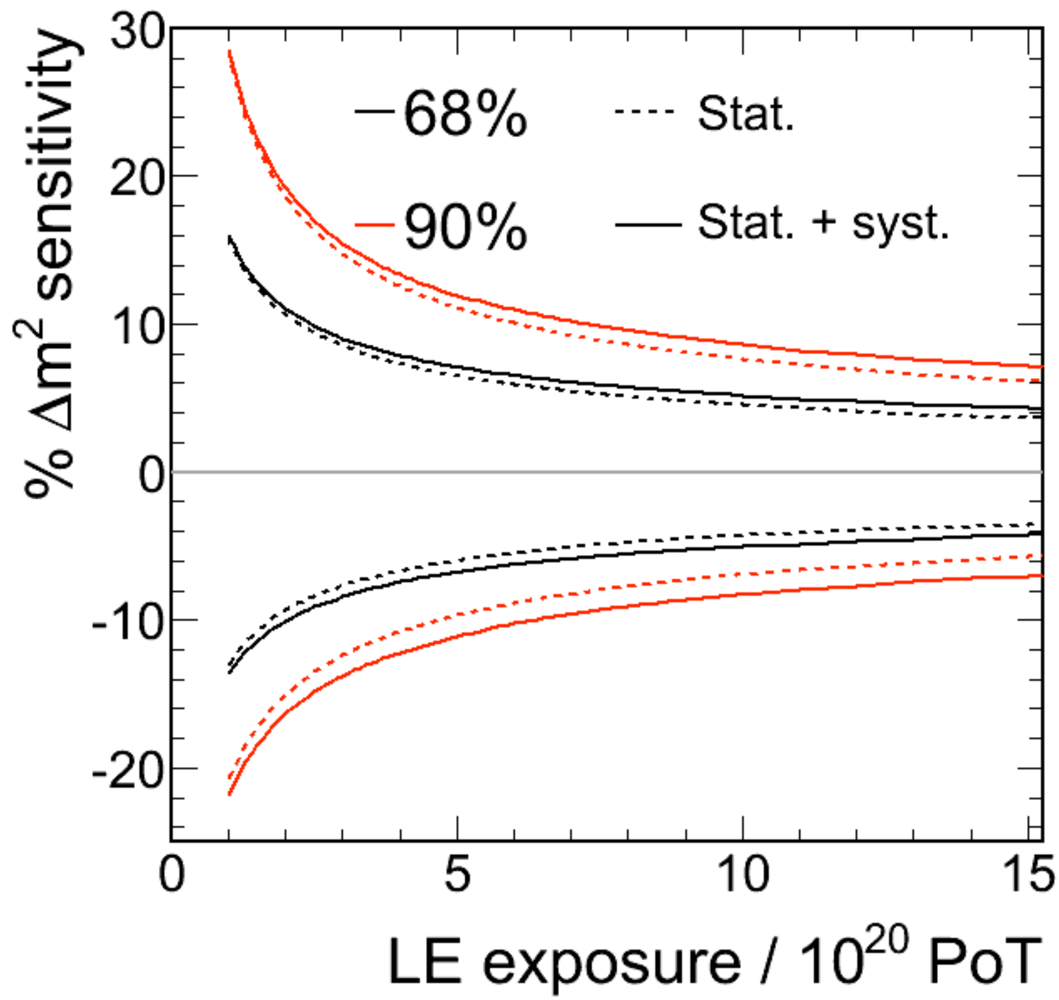
G.L. Fogli *et al.*, PRD67:093006 (2003)

χ^2/ndof = 123/97

$\Delta\chi^2 = 33$

disfavored at 5.7σ

Neutrino Δm^2 sensitivity evolution



Neutral Current Analysis

- Looking for sterile neutrino mixing -

Neutral Current Analysis

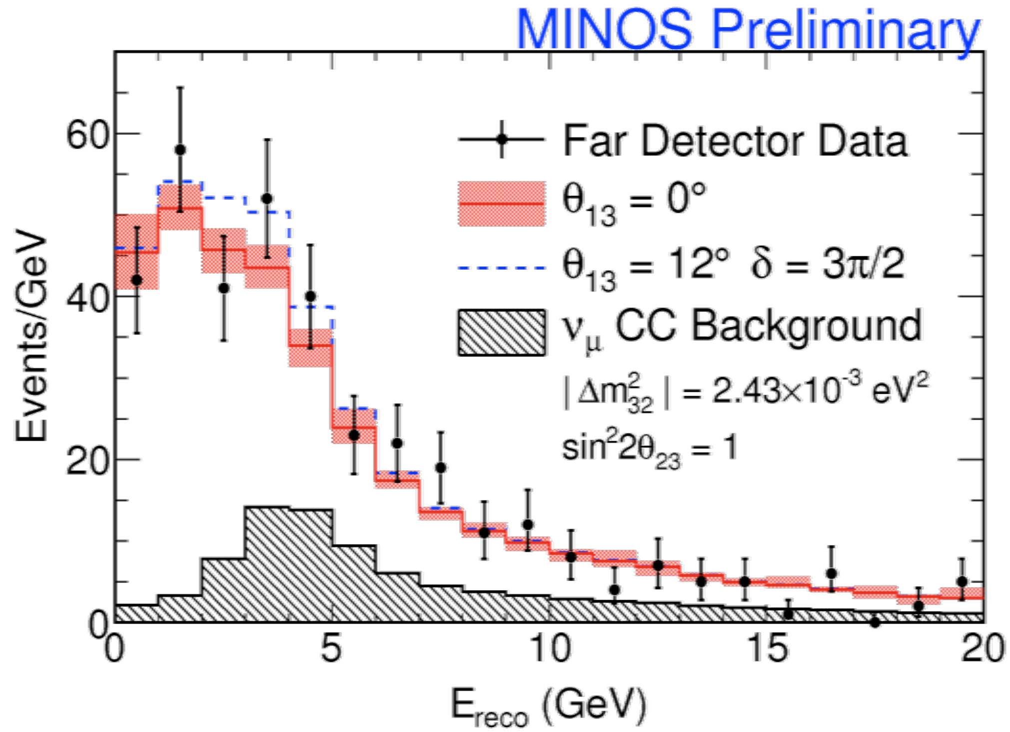
- General NC analysis overview:
  - All active neutrino flavours participate in NC interaction
  - Mixing to a sterile-ν will cause a deficit of NC events in Far Det.
  - Assume one sterile neutrino and that mixing between ν_μ, ν_s and ν_τ occurs at a single Δm^2
- Survival and sterile oscillation probabilities become:

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

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

($\alpha_{\mu,s}$ = mixing fractions)

[Previous result: PRL **101** 221804 (2008)]



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

$$f_s = \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)}$$

$f_s < 0.55$ (90% C.L.)