# Recent results from MINOS experiment

Jarek Nowak
University of Minnesota

# Overview

- Introduction
- The NuMI Project: MINOS
  - Beam & Detectors
  - Muon Neutrino Disappearance
  - Neutral Current Events
  - Electron Neutrino Appearance
- Outlook

# Neutrino Mixing

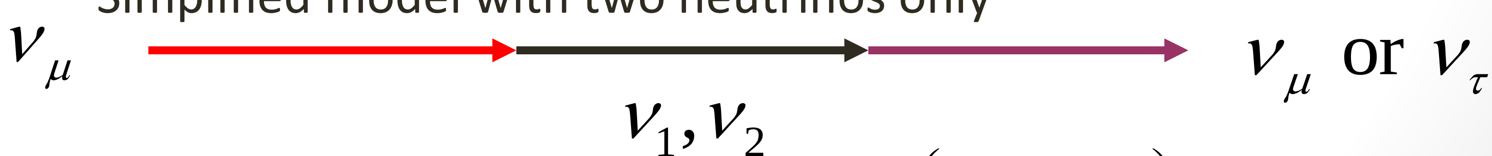
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Assume that neutrinos do have mass:
  - mass eigenstates $\neq$ weak interaction eigenstates
  - Analogue to CKM-Matrix in quark sector!

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, $\theta_{ij}$ = mixing angle and $\Delta m_{ij}^2$ = mass$^2$ difference

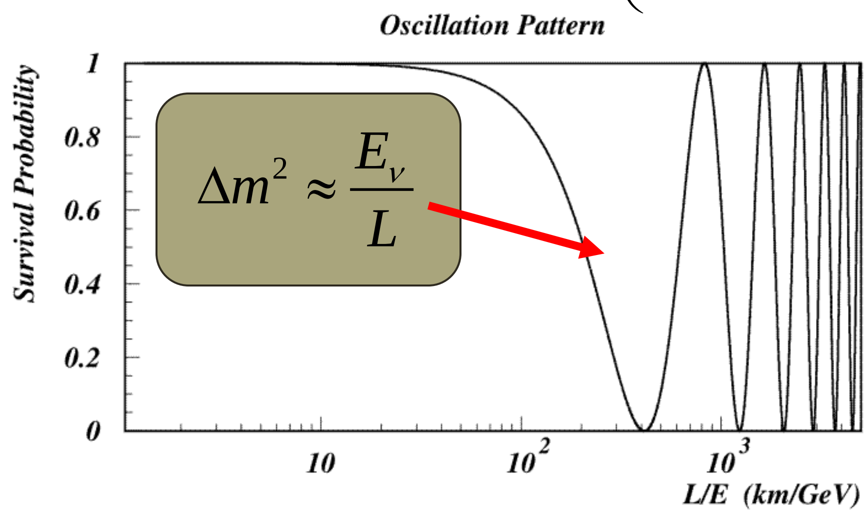
- Neutrino is produced in weak eigenstate
- It travels a distance L as a mass eigenstate
- It will be detected in a (possibly) different weak eigenstate
- Simplified model with two neutrinos only




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

# Oscillation Signature

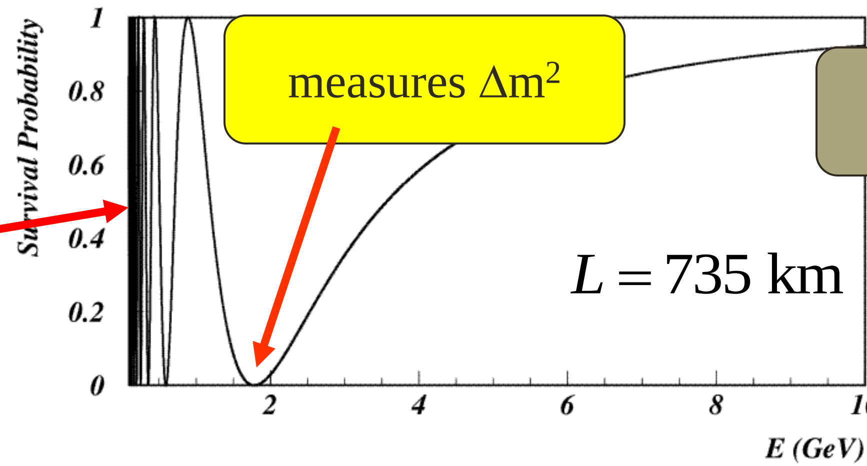
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E_\nu}\right)$$




$$\Delta m^2 \approx \frac{E_\nu}{L}$$

$$\Delta m^2 = 3\times10^{-3}\,eV^2$$

$$\sin^2 2\theta = 1$$




measures $\Delta m^2$

No effect!

Smeared by resolution P ~ 1/2

$L = 735$ km

# The MINOS Collaboration

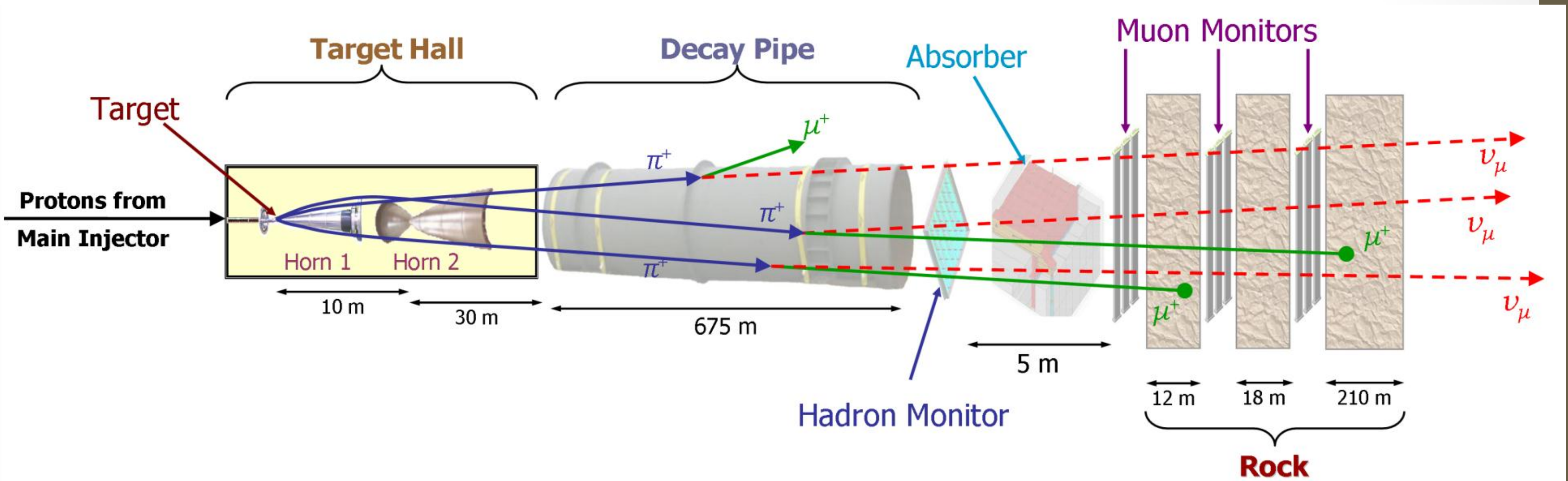

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas
Fermilab • Harvard • IIT • Indiana • Minnesota-Duluth • Minnesota-Twin Cities
Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford
Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary

# Experimental Setup

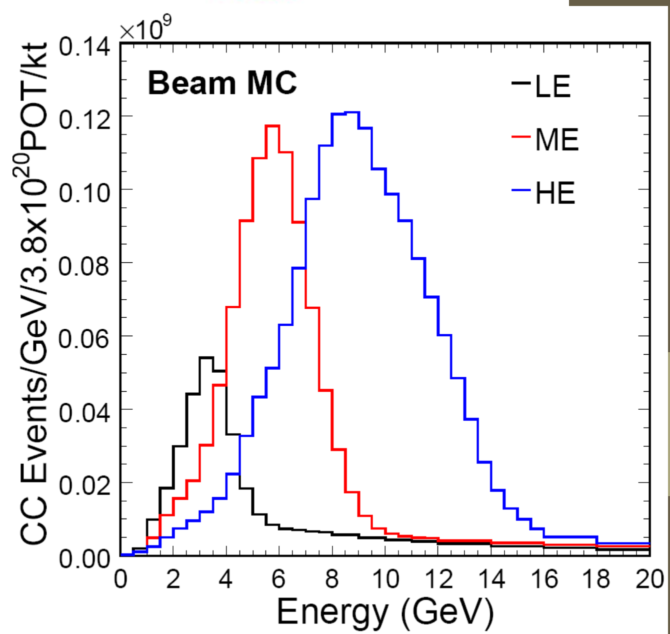


- **MINOS**
  **(Main Injector Neutrino Oscillation Search)**
  - A long-baseline neutrino oscillation experiment
  - Near Detector at Fermilab to measure the beam composition
  - Far Detector deep underground in the Soudan Underground Lab, Minnesota, to search for evidence of oscillations

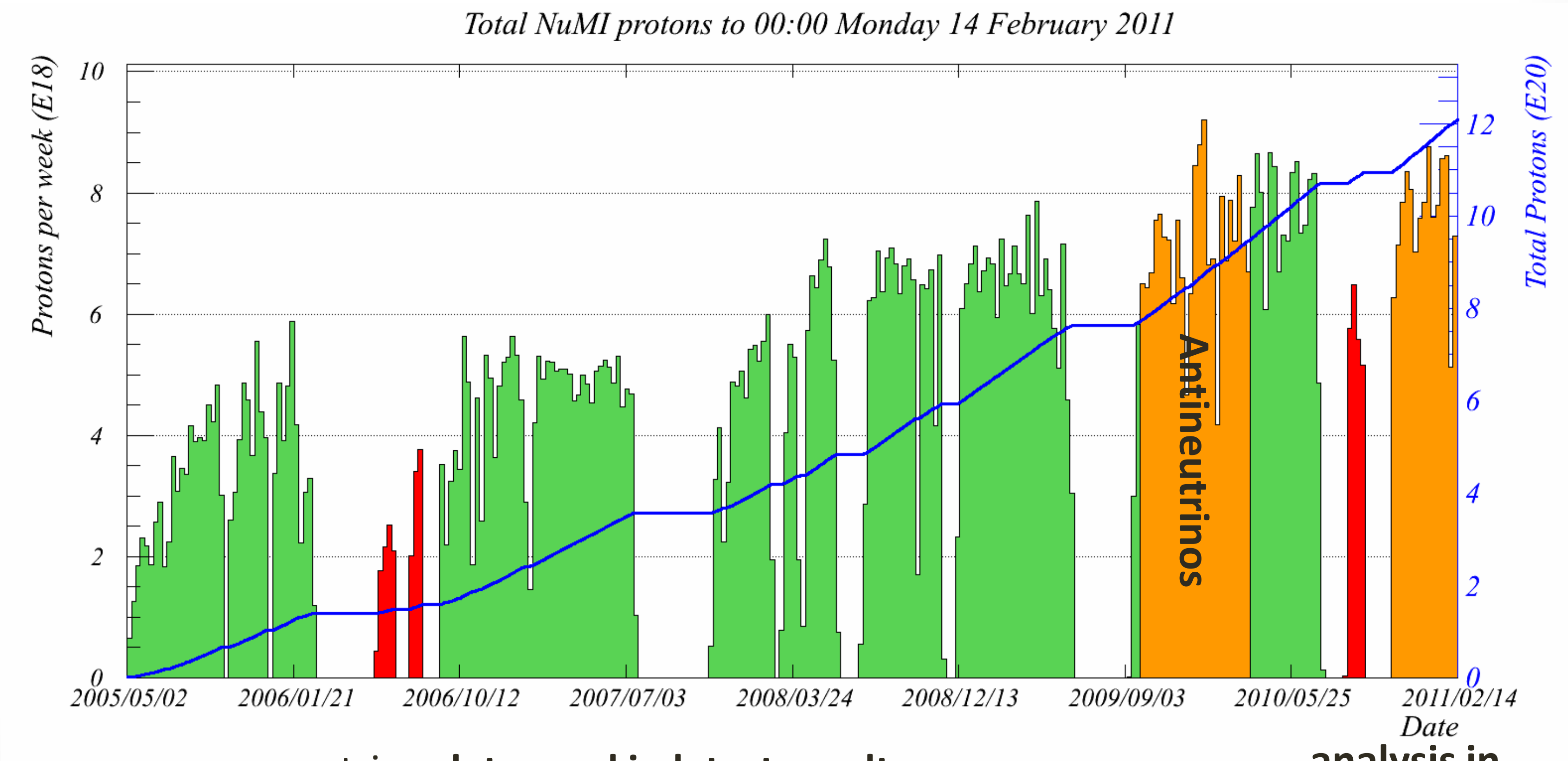

# Making Neutrinos (II)




- Neutrinos from the Main Injector (NuMI)
- 10 μs spill of 120 GeV protons every 2.2 s
- 250 kW typical beam power
- 2.5 $\times 10^{13}$ protons per pulse
- Neutrino spectrum changes with target position



# Beam Data Analyzed

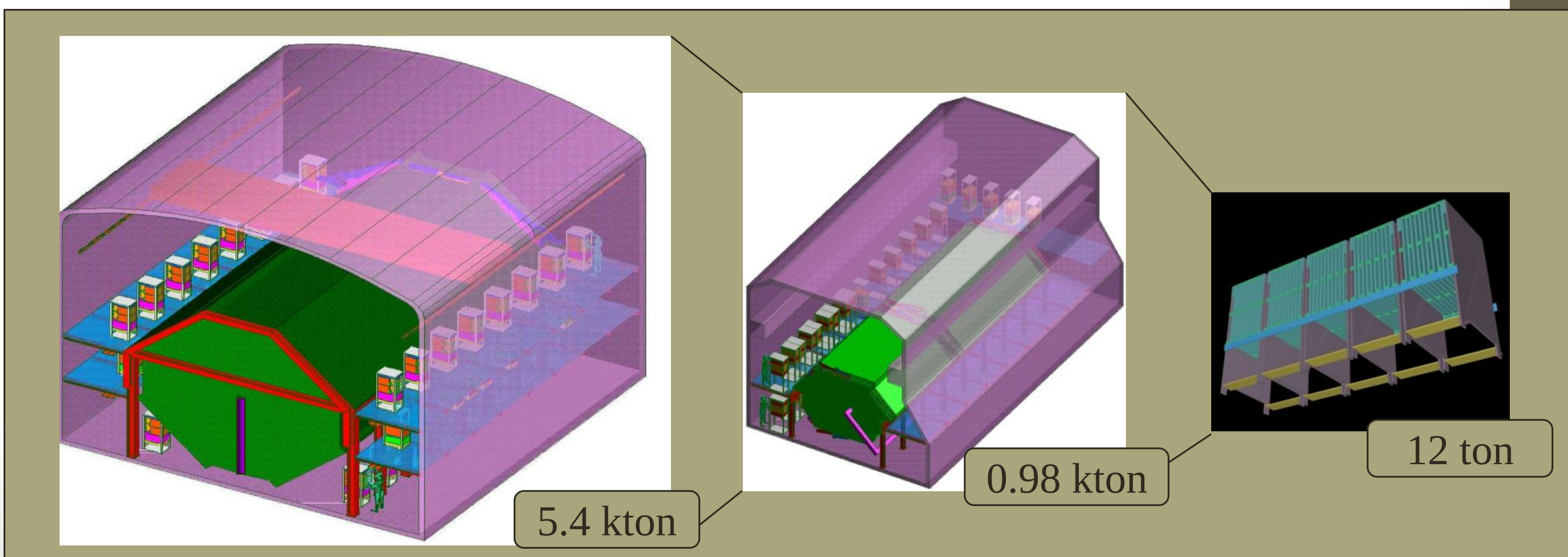



neutrino **data used in latest results**

**analysis in progress**

# MINOS Detectors

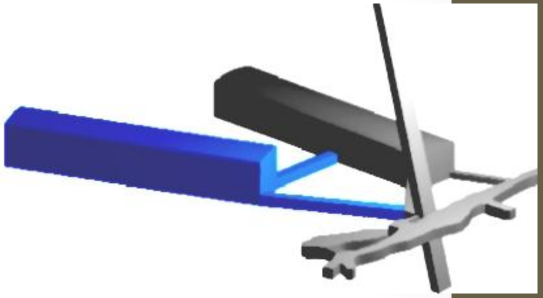
- 3 MINOS Detectors
  - Near Detector @ FNAL (ND)
  - Far Detector @ Soudan (FD)
  - Calibration Detector @ CERN (CalDet)
- Magnetised steel scintillator tracking calorimeters
  - functionally identical




6/6/2011

# Soudan Underground Lab



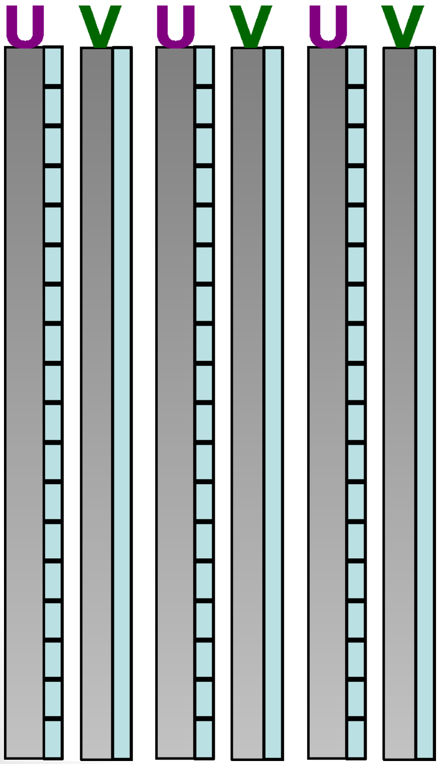




- former iron mine, now a state park, home of
  - Soudan-1 & 2 , CDMS-II , and MINOS experiments

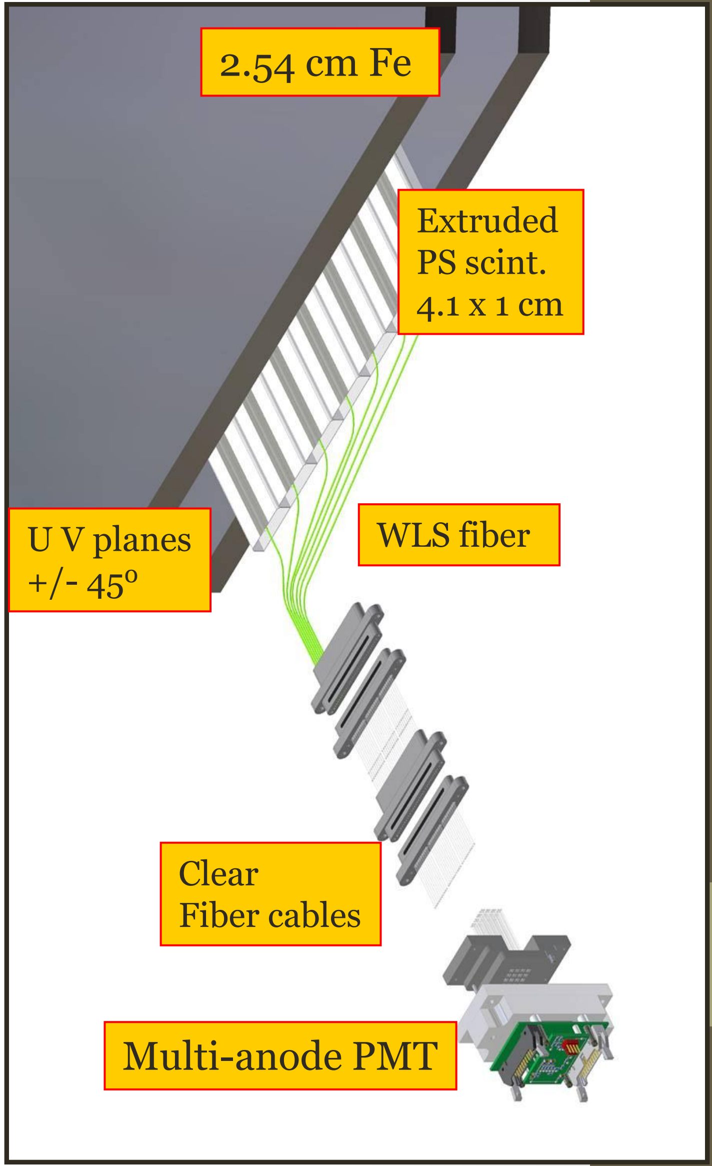
# Detector Construction (I)

# Detector Technology

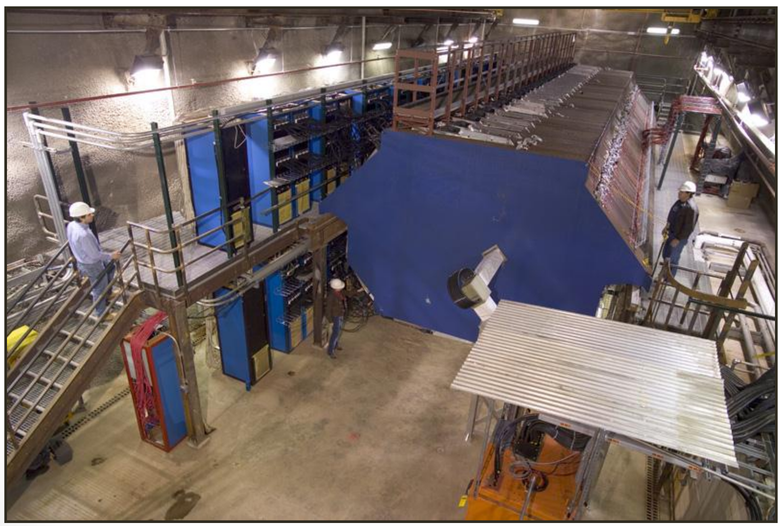

**Near and Far Detectors are functionally identical:**

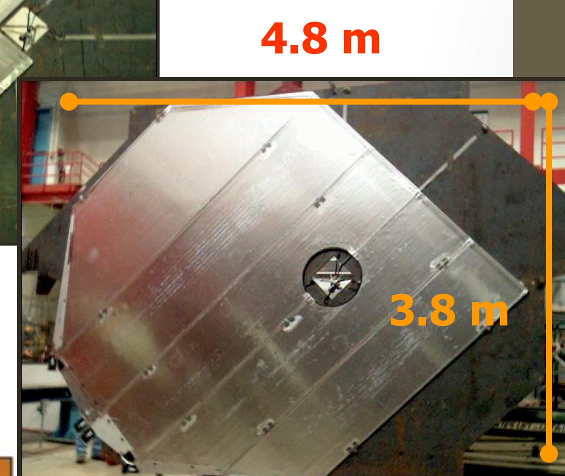
- 2.54cm thick magnetised steel plates
- co-extruded scintillator strips
- orthogonal orientation on alternate planes – U,V
- optical fibre readout to multi-anode PMTs



# Near Detector

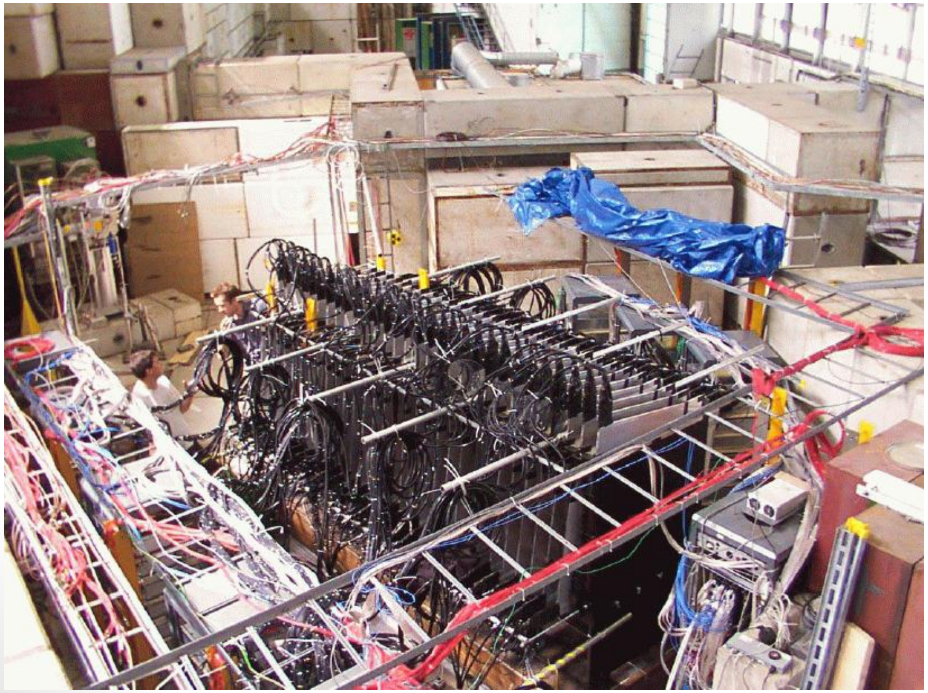
- 282 planes, 980 tons total
  - Same 1” steel,1 cm plastic scintillator planar construction, B-field
  - 3.8x4.5 m, some planes partially instrumented, some fully, some steel only
  - 16.6 m long total
- Light extracted from scint. strips by wavelength shifting optical fiber
  - One strip ended read out with Hamamatsu M64 PMTs, fast QIE electronics
  - No multiplexing upstream, 4x multiplexed in spectrometer region

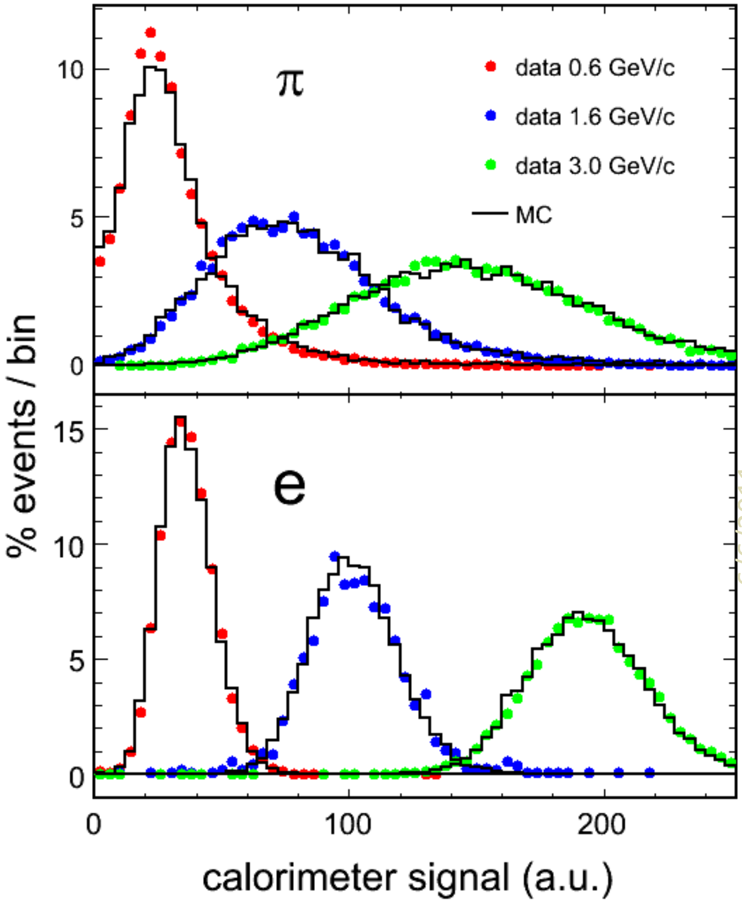


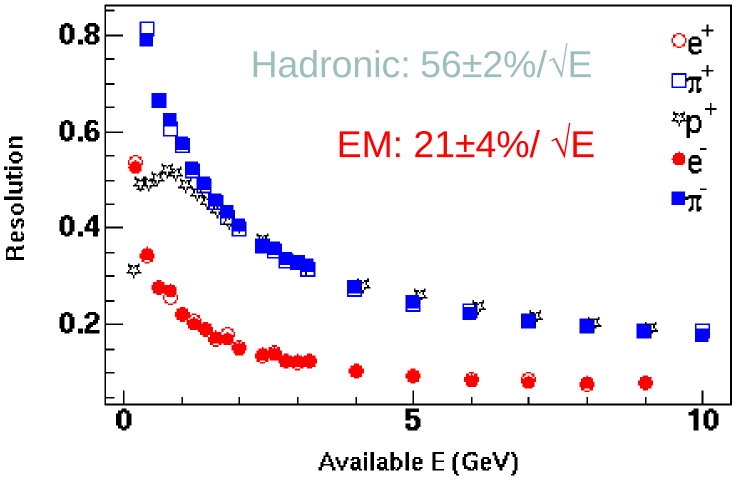



# Calibration Detector

- 60-plane 'micro-MINOS'
  - has taken data at T7 & T11 test beam lines at CERN during 2001, 2002, 2003
- Instrumented with both Near and Far Detector electronics
  - To provide cross-calibrations
  - Energy uncertainties: 3% relative, and 1.9% (ND) & 3.5% (FD) absolute



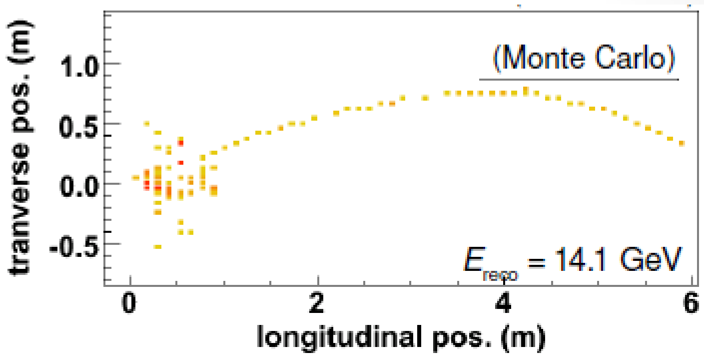


# Neutrino events

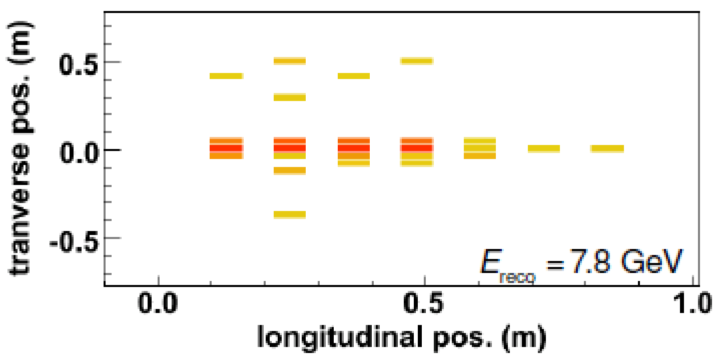
## $\nu_\mu$ charged current

- Clear signature in MINOS: *long track*
- If $\mu$ track is very short, event can be mistaken for NC or $\nu_e$ CC



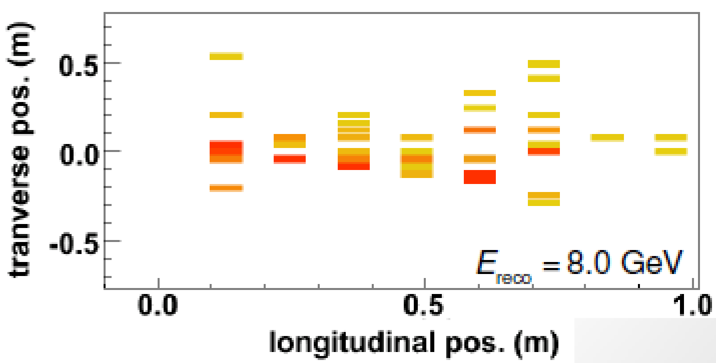

## $\nu_e$ charged current

- $\nu_e$ is small component of initial flux
- Electron leaves characteristic deposition pattern: *compact shower*




## neutral current

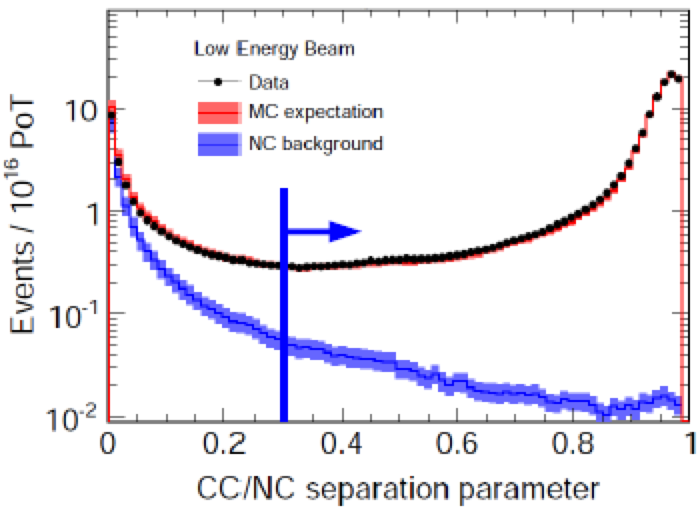
- Esp. with $\pi^0$, hard to distinguish from $\nu_e$ CC
- Energy more transversely distributed

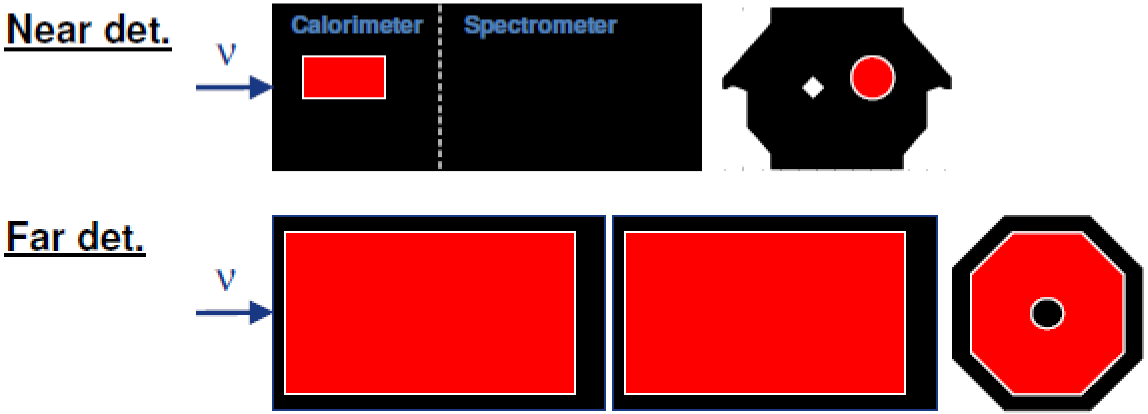


# Muon neutrino disappearance

- Start by measuring $\nu_\mu$ charged current rate in **near detector**
- ***First stage of selection:***
  - **Fiducial volume** (below)
  - Beam **timing**, **cosmic** removal
  - How "**track-like**" is the event? →
- ***New for 2010 analysis:***
  - Recover **short-track** events
    *(second kNN discriminant and no muon charge cut)*

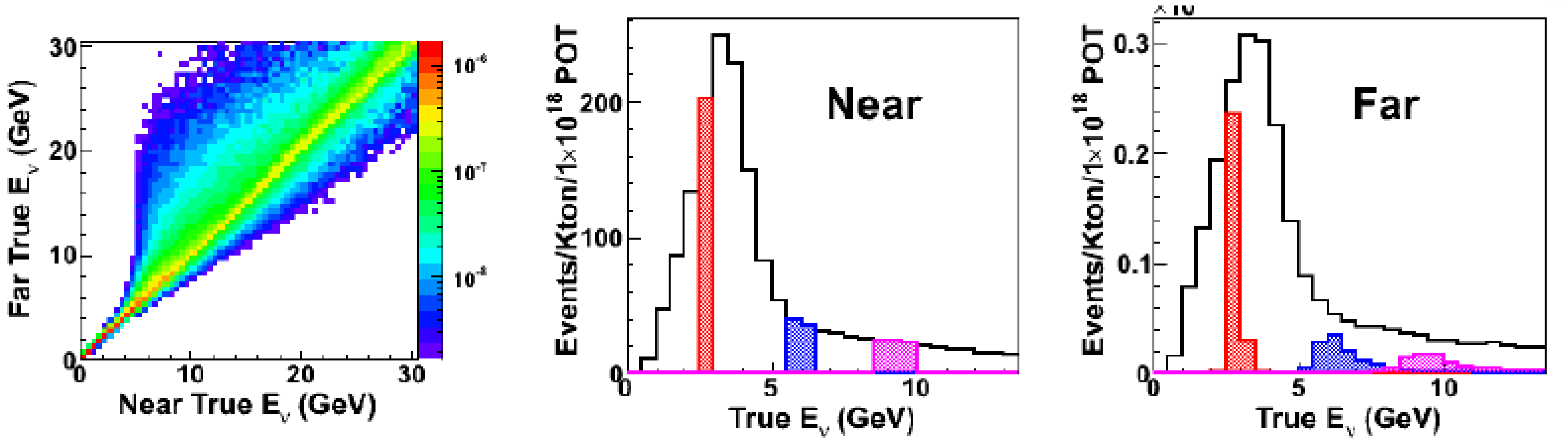
*kNN* **selector**



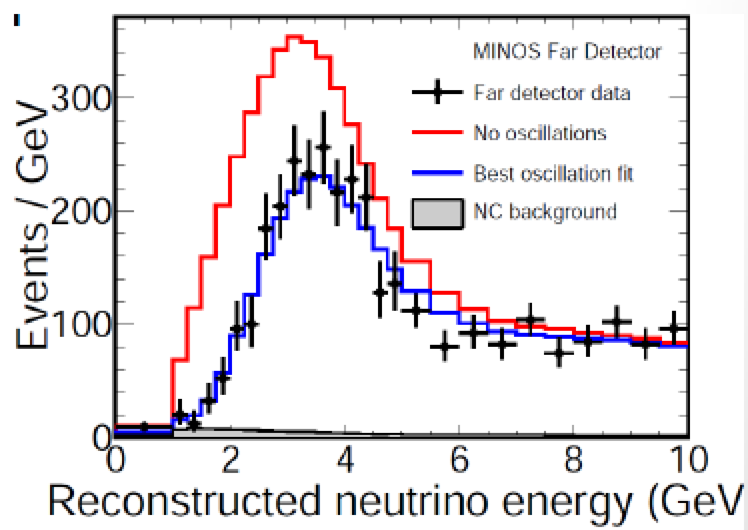

**Fiducial regions (in red)**

- Convert the measured near detector energy spectrum into a prediction for a far detector.
- MC includes: beam geometry, solid angle of the detector , difference between detectors, etc



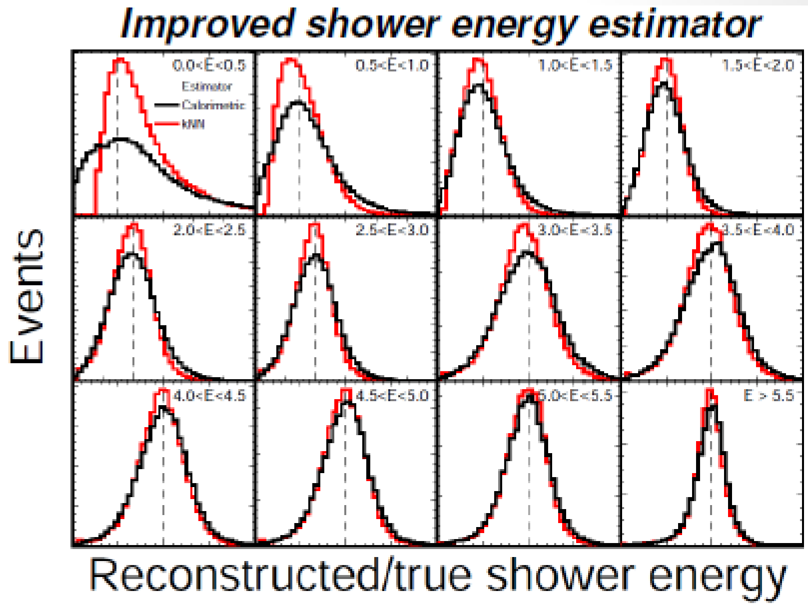

- The deficit of the muon neutrinos

at the far detector is noticeable

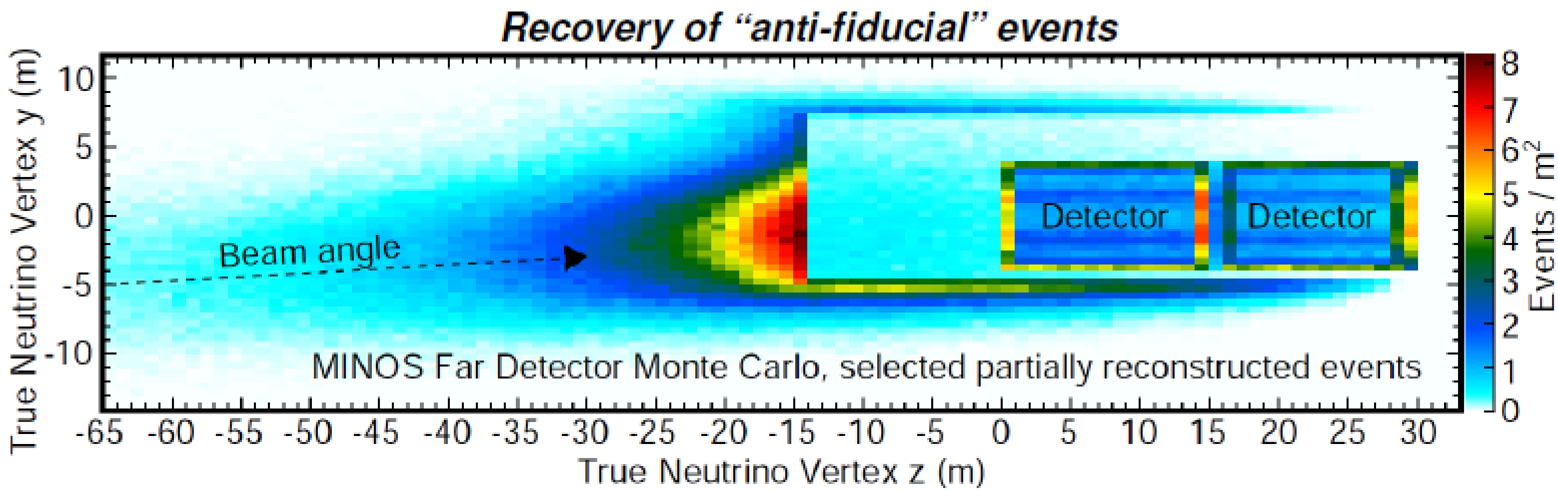


# Improvements in the analysis

- Double the data since 2008
- Improved shower energy reconstruction
- Updated beamline simulation



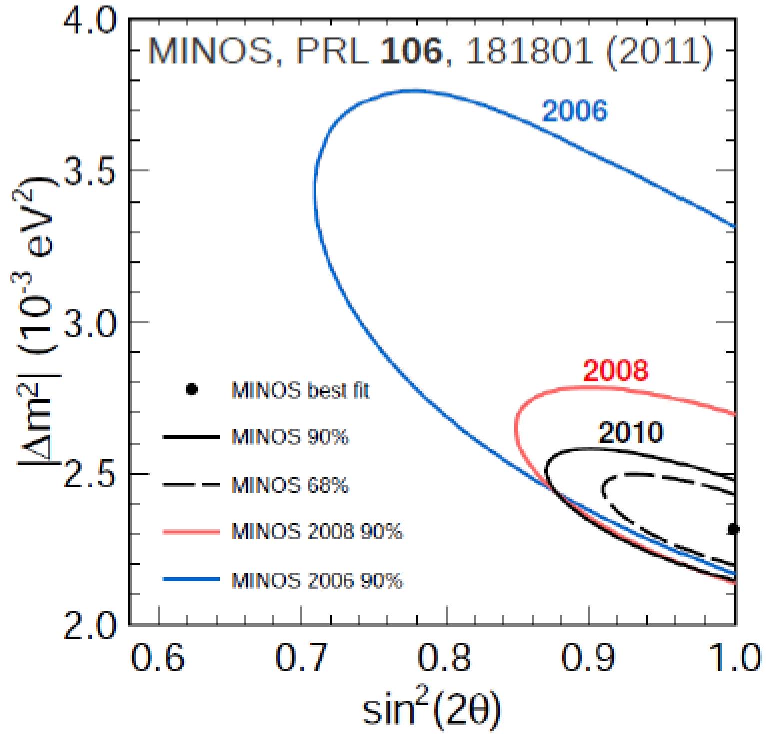

- Recovery of the antifiducial events (neutrino interactions outside the detector)

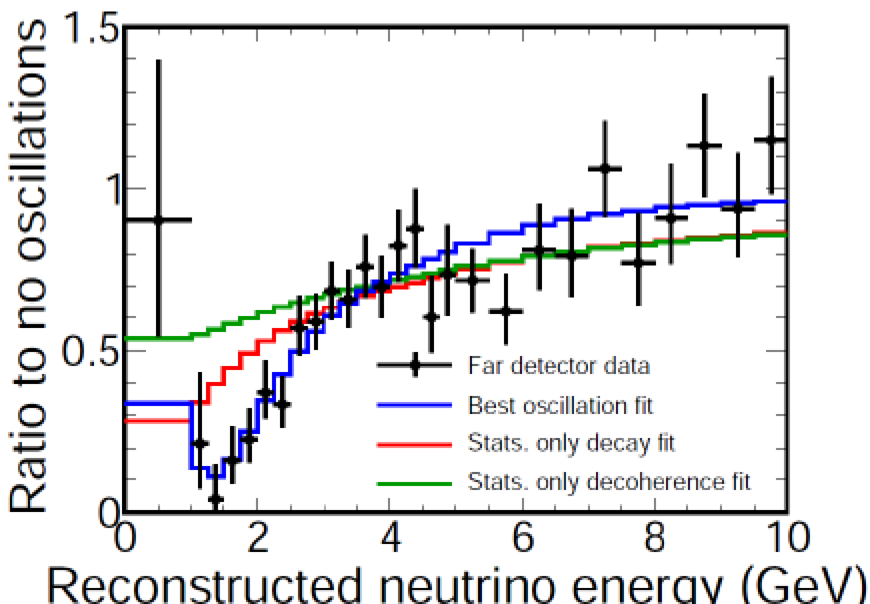


$$\Delta m^2_{\rm atm} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\ {\rm eV}^2$$

- The most precise measurement of atmospheric parameters.

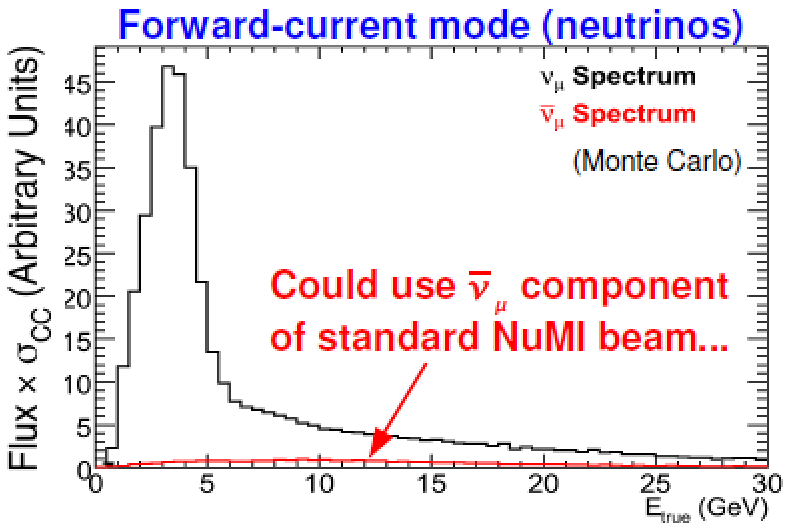
Other interpretations are disfavored

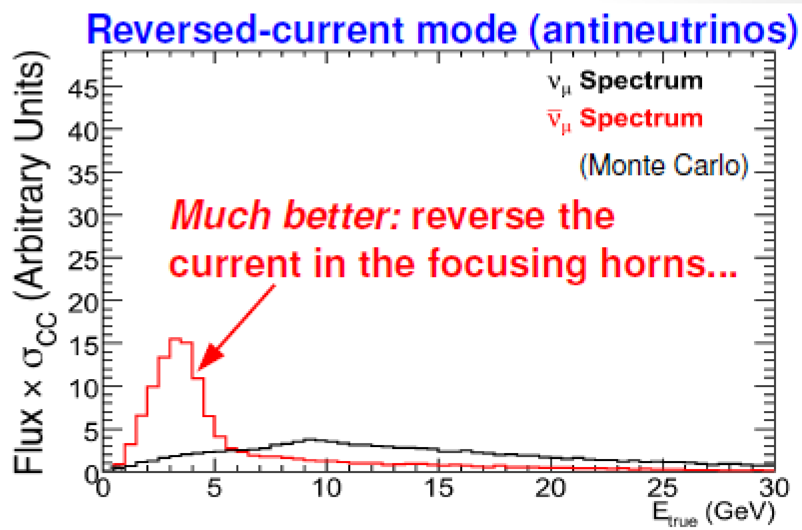


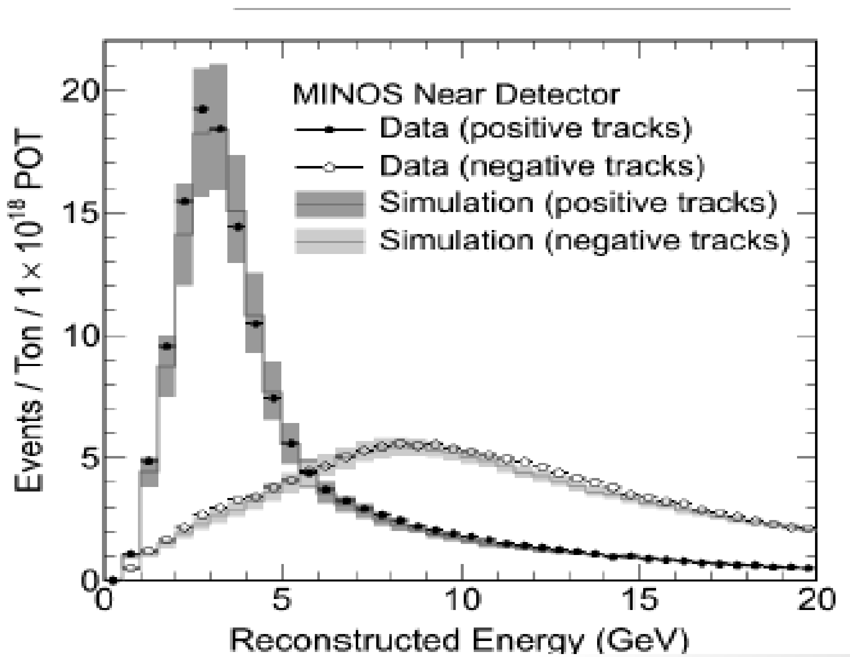

| Source of systematic uncertainty | $\delta(\Delta m^2)$ $(10^{-3}\,{\rm eV}^2)$ | $\delta(\sin^2(2\theta))$ |
|---|---|---|
| (a) Hadronic energy | 0.051 | $< 0.001$ |
| (b) $\mu$ energy (range 2%, curv. 3%) | 0.047 | 0.001 |
| (c) Relative normalization (1.6%) | 0.042 | $< 0.001$ |
| (d) NC contamination (20%) | 0.005 | 0.009 |
| (e) Relative hadronic energy (2.2%) | 0.006 | 0.004 |
| (f) $\sigma_\nu(E_\nu < 10$ GeV) | 0.020 | 0.007 |
| (g) Beam flux | 0.011 | 0.001 |
| (h) Neutrino-antineutrino separation | 0.002 | 0.002 |
| (i) Partially reconstructed events | 0.004 | 0.003 |
| Total systematic uncertainty | 0.085 | 0.013 |
| Expected statistical uncertainty | 0.124 | 0.060 |

# ANTINEUTRINO DATA



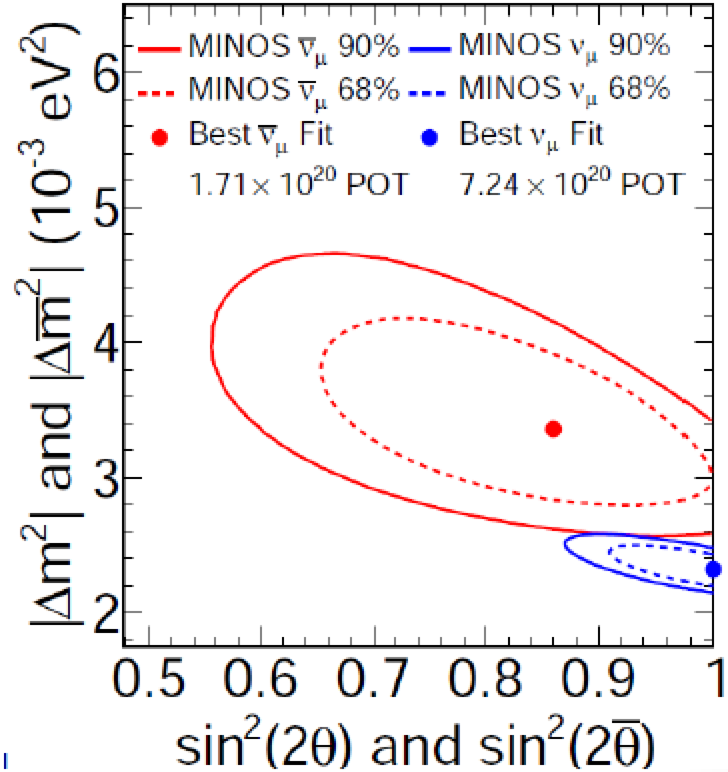

- In the reverse horn current running antineutrino flux is dominant.
- MINOS can select particle charge.
- Neutrino/antineutrino separation well-modelled.



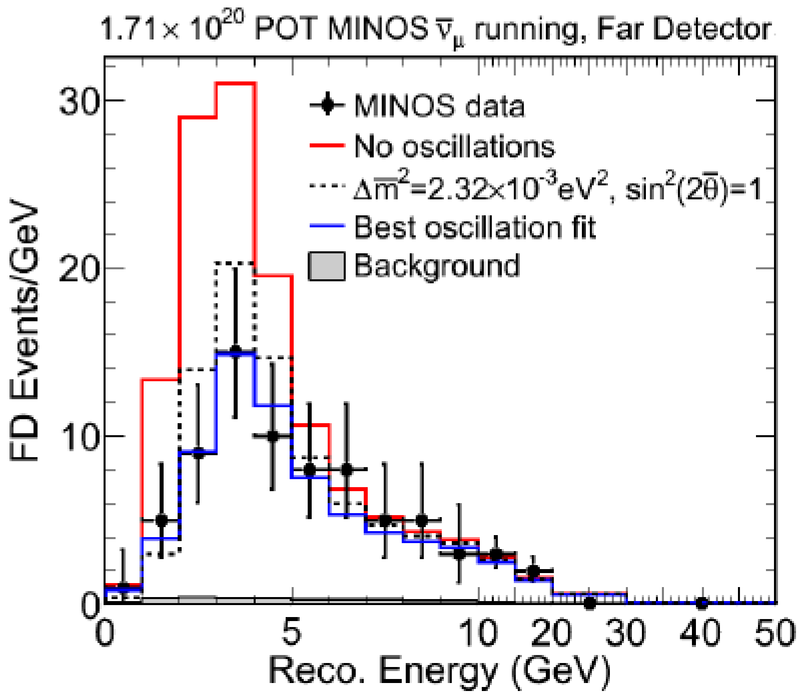

6/6/2011

MINOS, arXiv:1104.0344 (2011)

$$\Delta\overline{m}^2_{\rm atm} = (3.36^{+0.46}_{-0.40})\times 10^{-3}\ {\rm eV}^2$$
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}$$




- Neutrino/antineutrino compatibility only at the 2%C.L.
- Antineutrino disappearance signal at 6.3 σ.




Neutrino oscillation well describes this result

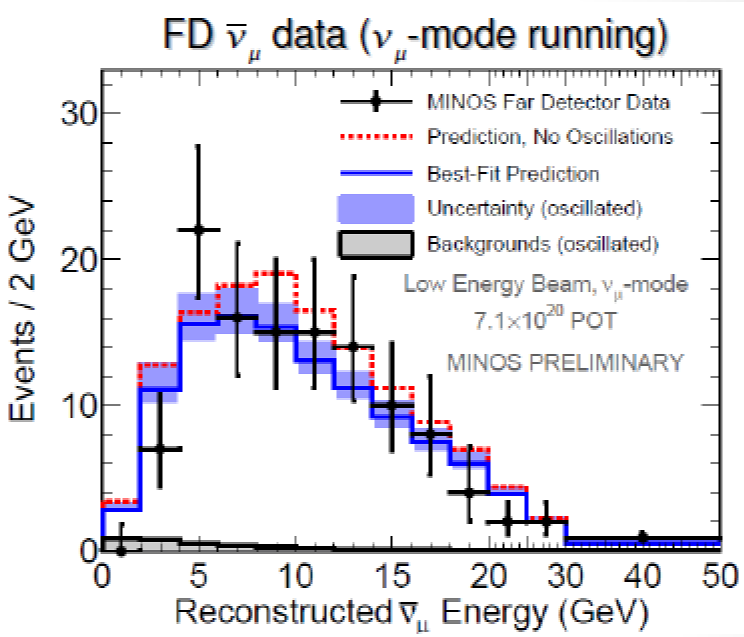
measurement statistically limited

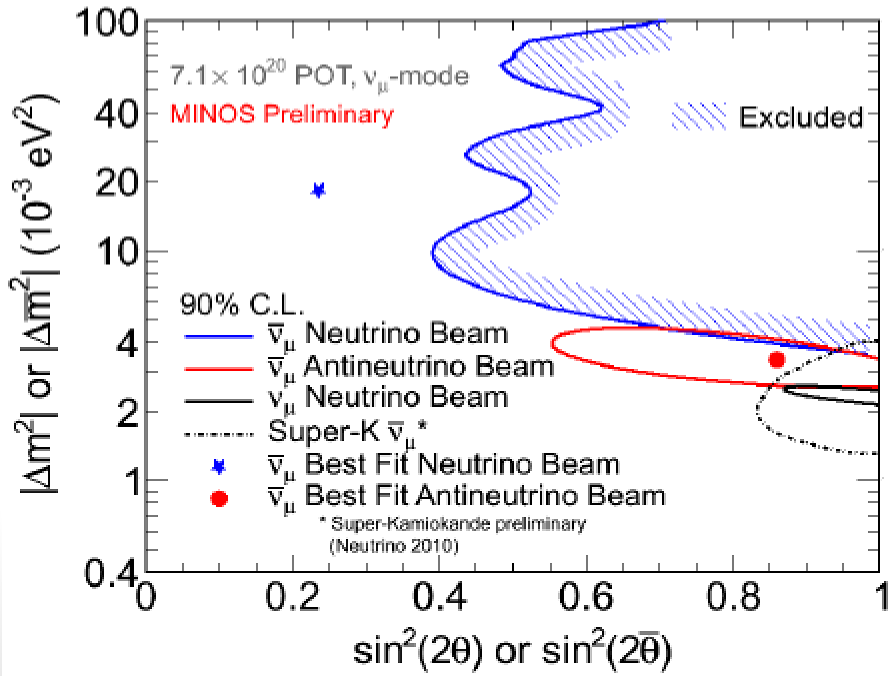
# Antineutrino in FHC

- The antinuetrino contamination

In the forward horn current mode.

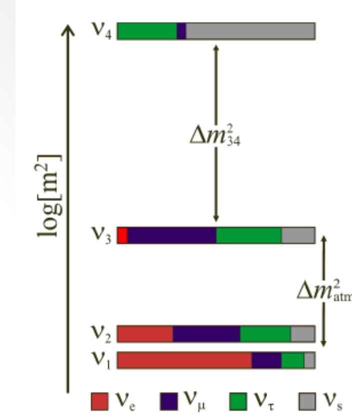
- Higher energies of antineutrinos
- Results consistent with RHC.



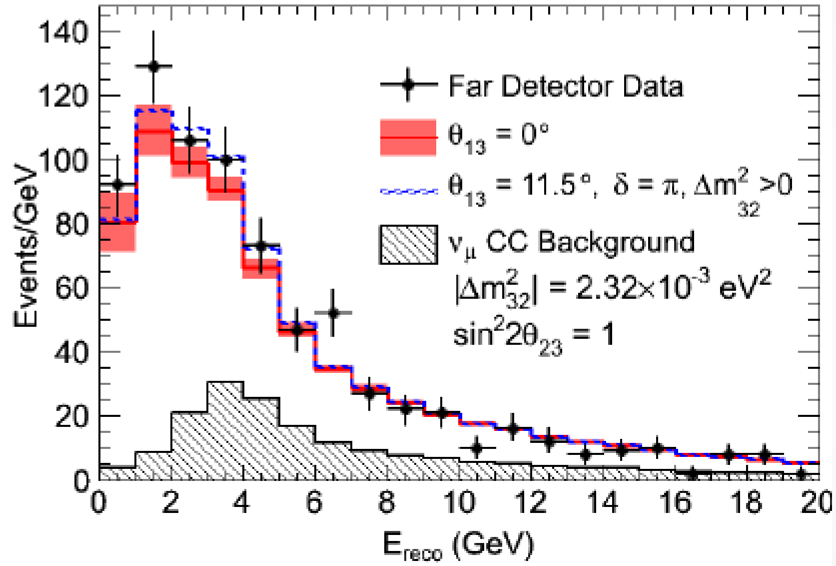



# Sterile neutrinos

**7.07e20POT**




- Select only event with no muon tracks
- Electron neutrino appearance is an additional source of uncertainty




**DATA CONSISTEN WITH NO STERILE NEUTRINOS**

$$R = \frac{\text{(observed)} - \text{(expected CC bg)}}{\text{expected NC}}$$

**0-120 GeV:**

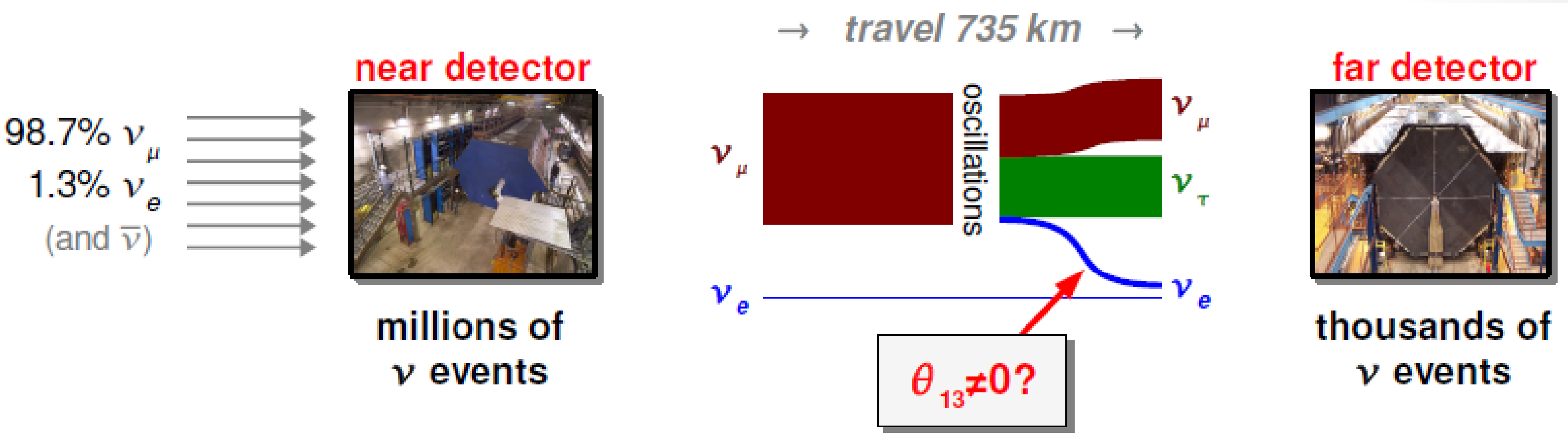
$$R = 1.09 \pm 0.06_{stat} \pm 0.05_{syst} - 0.08_{\nu_e}$$

**0-3 GeV:**

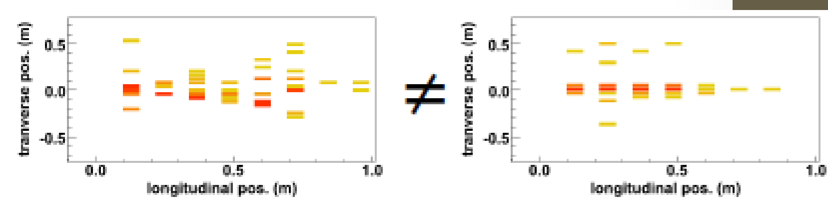
$$R = 1.16 \pm 0.07_{stat} \pm 0.08_{syst} - 0.08_{\nu_e}$$

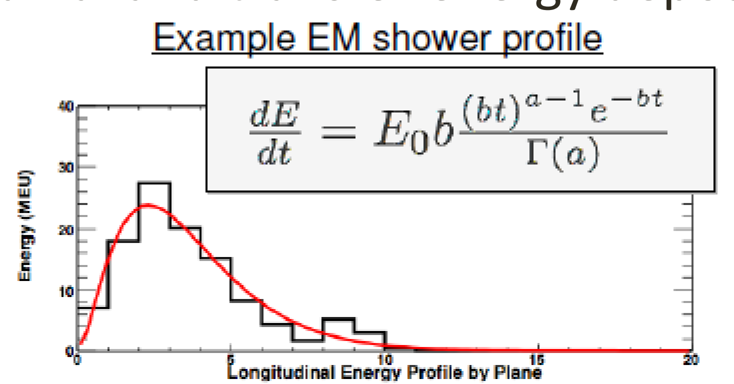
$$f_s = \frac{P(\nu_\mu \to \nu_s)}{P(\nu_\mu \to \nu_{e,\tau,s})} < 0.22 \text{ (90\% C.L.)}$$

# Electron neutrino appearance




- Selection of the non-track events (showers).
- ANN used to clasify the electron neutrino interaction topology.
- 11 variables from longitudinal and transfer energy deposition. (e.g shower width metric)



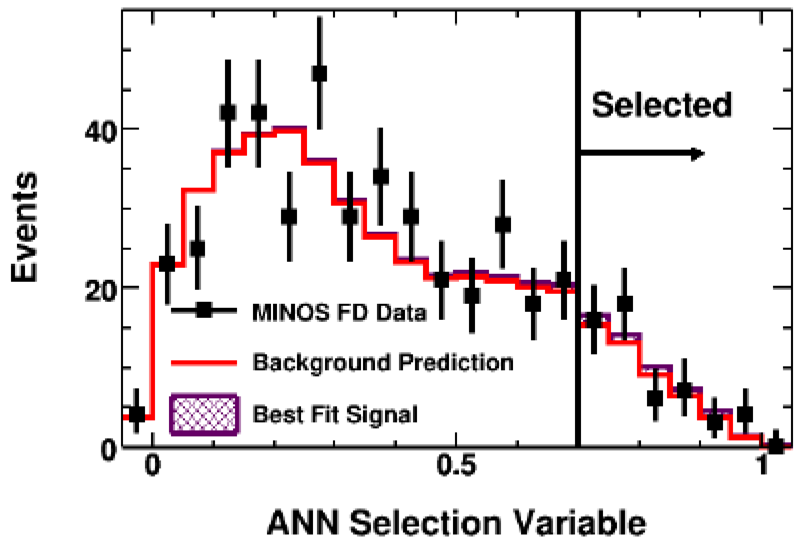

6/6/2011

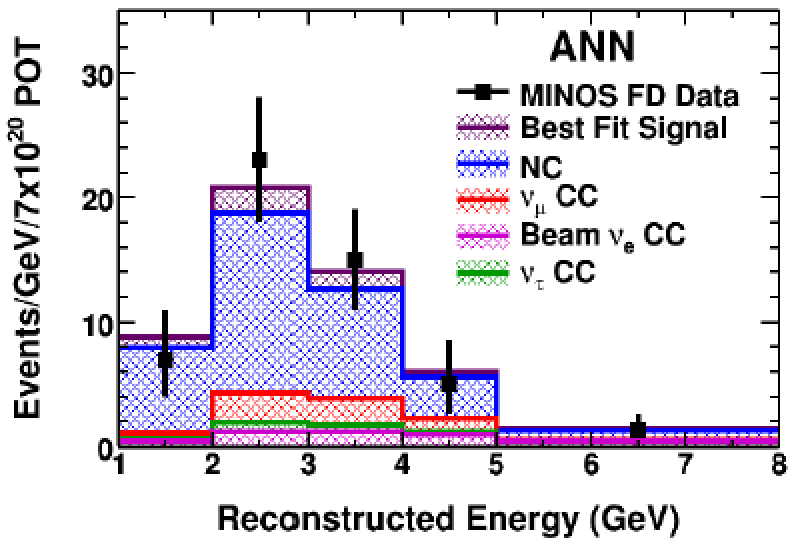
# Results from 2010 (7e20 pot)

***$\nu_e$ charged current candidate events:***

*background expectation:* **49.1 ± 7.0(stat.) ± 2.7(syst.)**
*observed:* **54**

**(0.7$\sigma$ excess)**

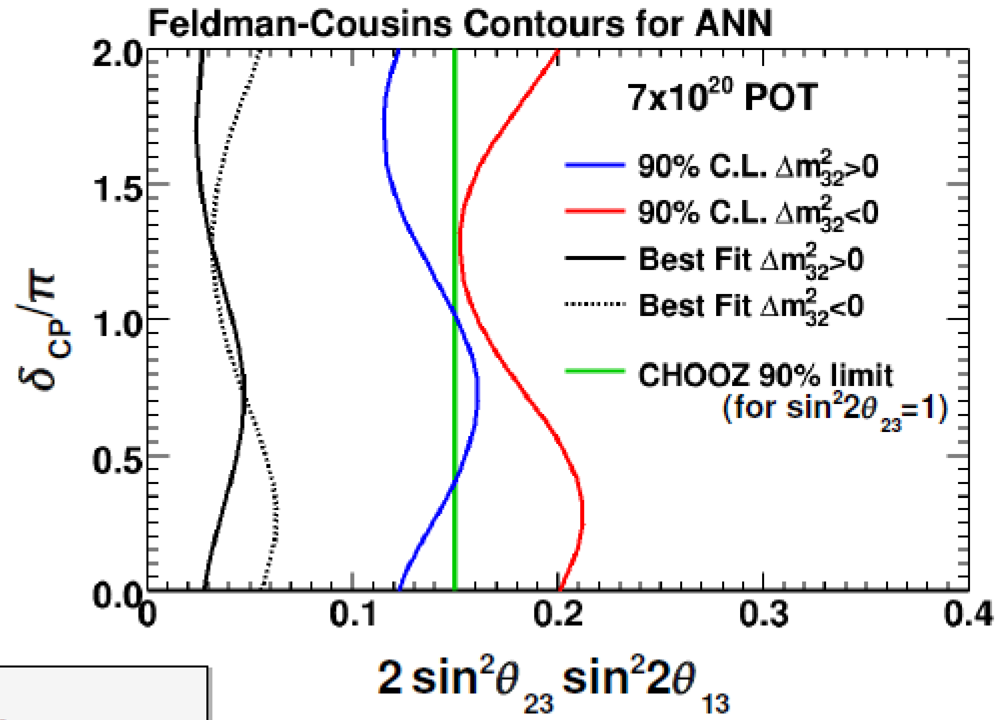


# Limits for the missing parameters

**$\sin^2(2\theta_{13})$ allowed range** depends on **CP-phase $\delta$** and **mass hierarchy** [sign($\Delta m^2$)]

90% C.L. allowed ranges →




MINOS, PRD **82**, 051102 (2010)

***Representative 90% C.L. limits:***

→ *put* $\delta_{CP}=0$, $\theta_{23}=\pi/4$

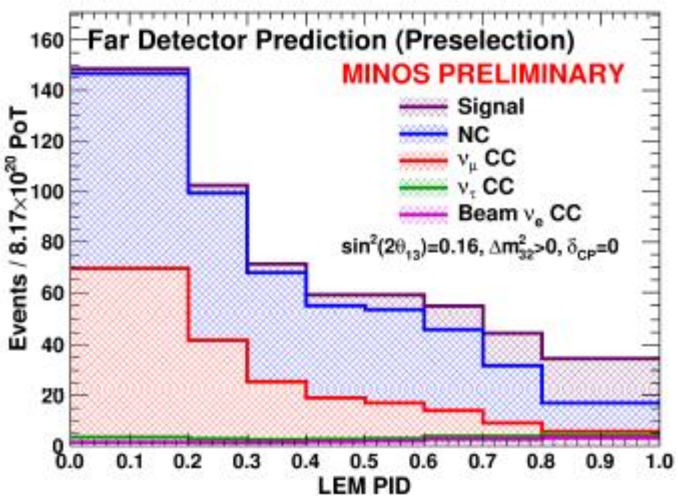
**normal hier.** ⇒ $\sin^2 2\theta_{13} < 0.12$

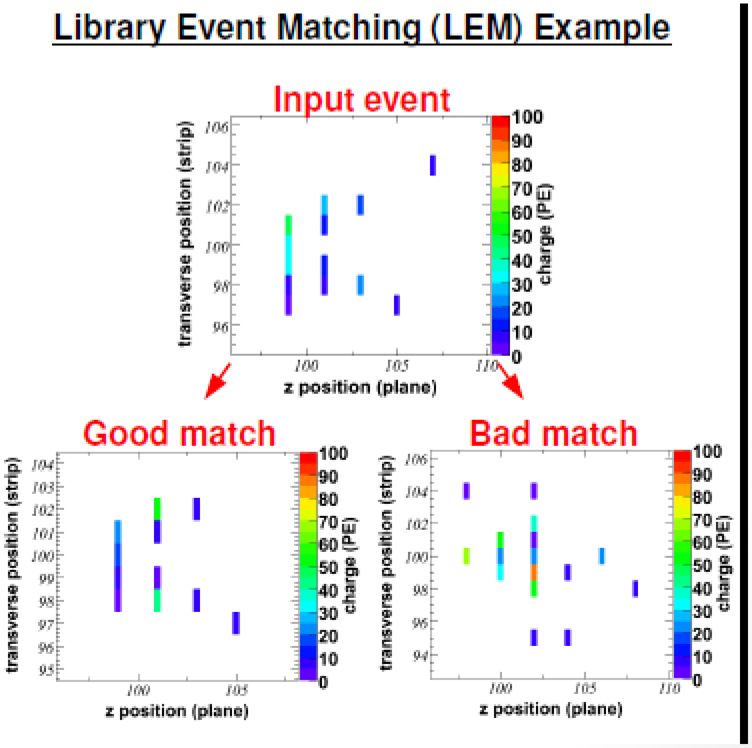
**inverted hier.** ⇒ $\sin^2 2\theta_{13} < 0.20$

*(other oscillation parameters' uncertainties taken into account)*

# Updates for 2011 analysis (8.2e20 pot)

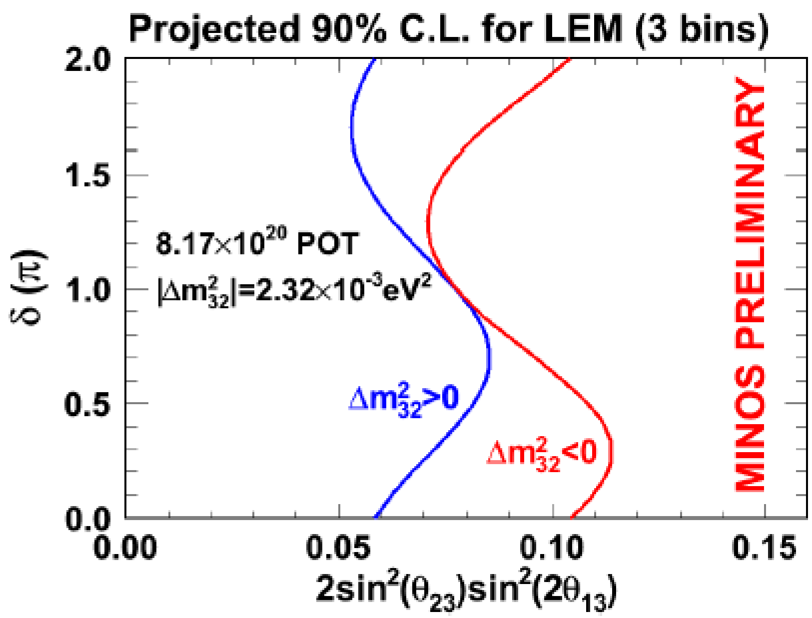
- Higher statistics (not huge improvement)
- A new selector ("Library Event Matchig")
  - Compares input to large library of simulate events.



# Updates for 2011 analysis (8.2e20 pot)

- **30% improvement** in $\sin^2(2\theta_{13})$ sensitivity over 2010 result
- 24% improvement from the **analysis upgrades** alone
  *(roughly half from new selector, half from fitting)*
- ***Below:*** **preliminary 90% C.L. sensitivity** for $8.17\times10^{20}$ p.o.t. analysis




Look for a new $\theta_{13}$ result this summer.

# Summary

- New muon neutrino disappearance results
  - Precise measurement of mass-splitting
- High-purity antineutrino measurment
  - Only 2% C.L agreement with neutrinos
  - New results this summer
- No evidence for missing into sterile neutrinos
  - $f_s$ <0.22 @90% C.L
- Many other results
  - Atmospheric neutrnos, cosmic rays
  - Cross sections
  - Beyond standard model physics searches
- MINOS future: MINOS+, running in NOvA era.