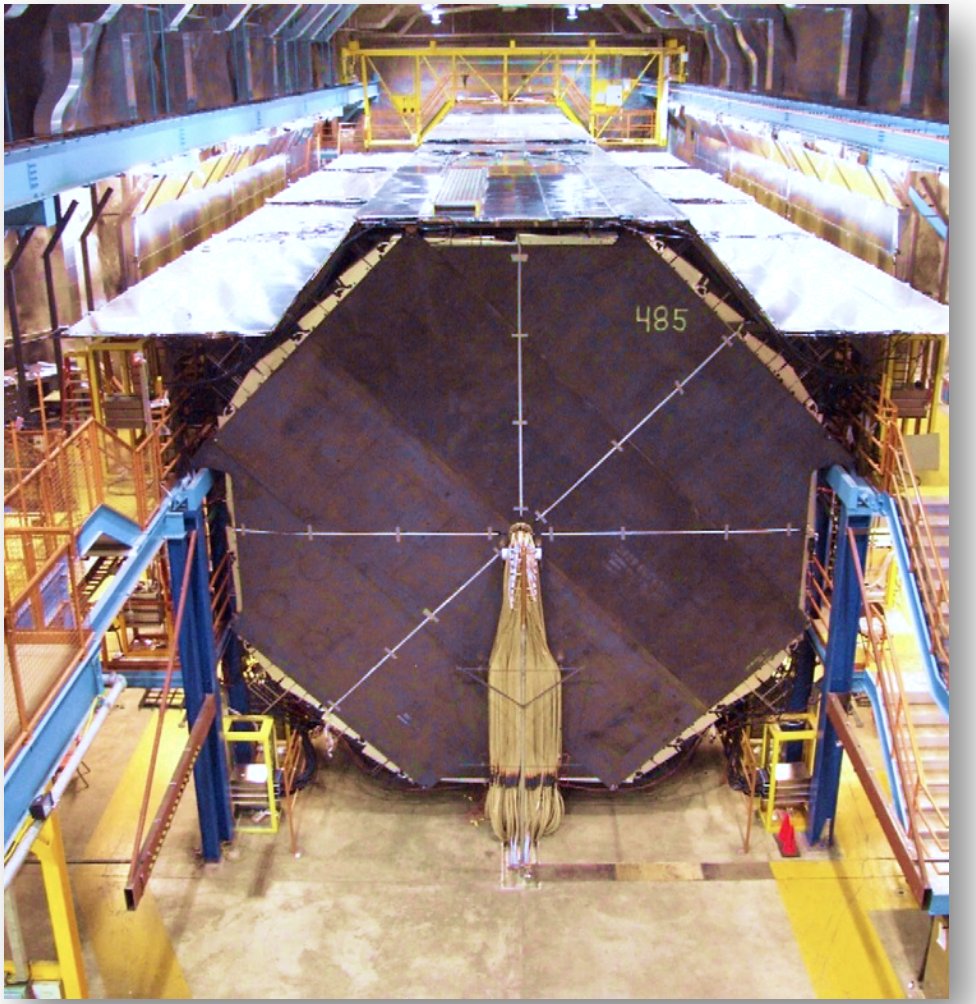
New Results from MINOS

Jeff Nelson

William & Mary

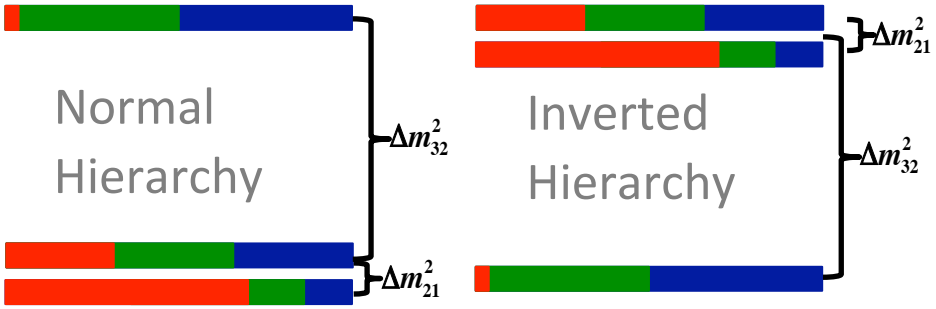


Fermilab User's Meeting
June, 12th 2012

MINOS physics goals

- Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis for atmospheric neutrino disappearance
  - > Measure precisely $|\Delta m^2_{32}|$ and $\sin^2 2\vartheta_{23}$
- Test exotic models
  - Decay, decoherence, sterile neutrinos, velocity
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations
- Compare ν to $\bar{\nu}$ oscillations
- Atmospheric neutrinos
- Neutrino interaction physics
- Cosmic ray physics

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



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

Useful Approximations

ν_μ disappearance (2 flavors):

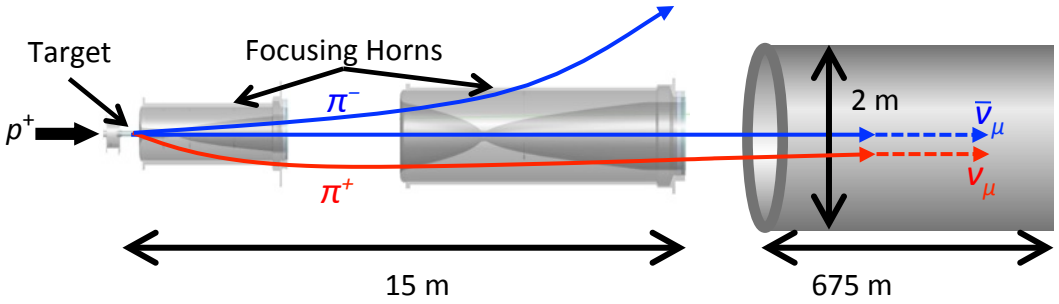
$$P(\nu_\mu \rightarrow \nu_x) = 1 - \sin^2 2\vartheta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$$

ν_e appearance (first order):

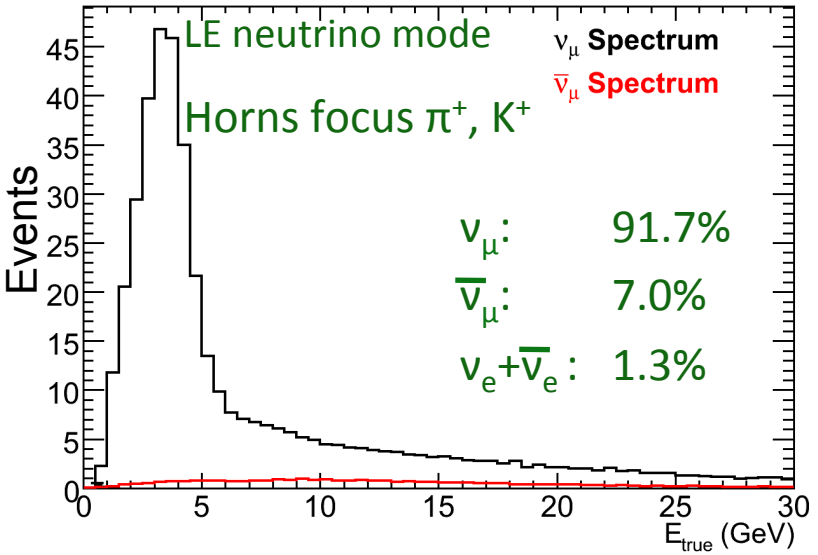
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \vartheta_{23} \sin^2 2\vartheta_{13} \sin^2(1.27 \Delta m^2_{31} L/E)$$

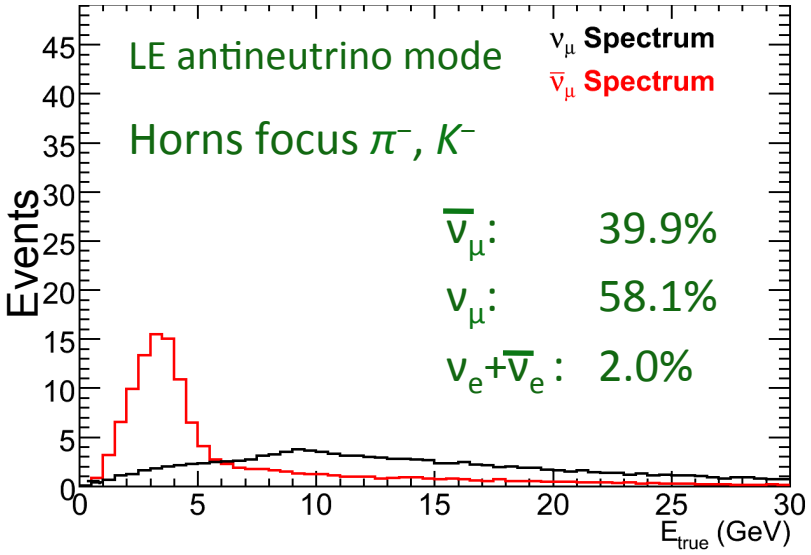
where ***L, E*** are experimental parameters & ϑ_{23}, ϑ_{13}, Δm^2_{32} are to be determined

Producing the NuMI neutrino beam

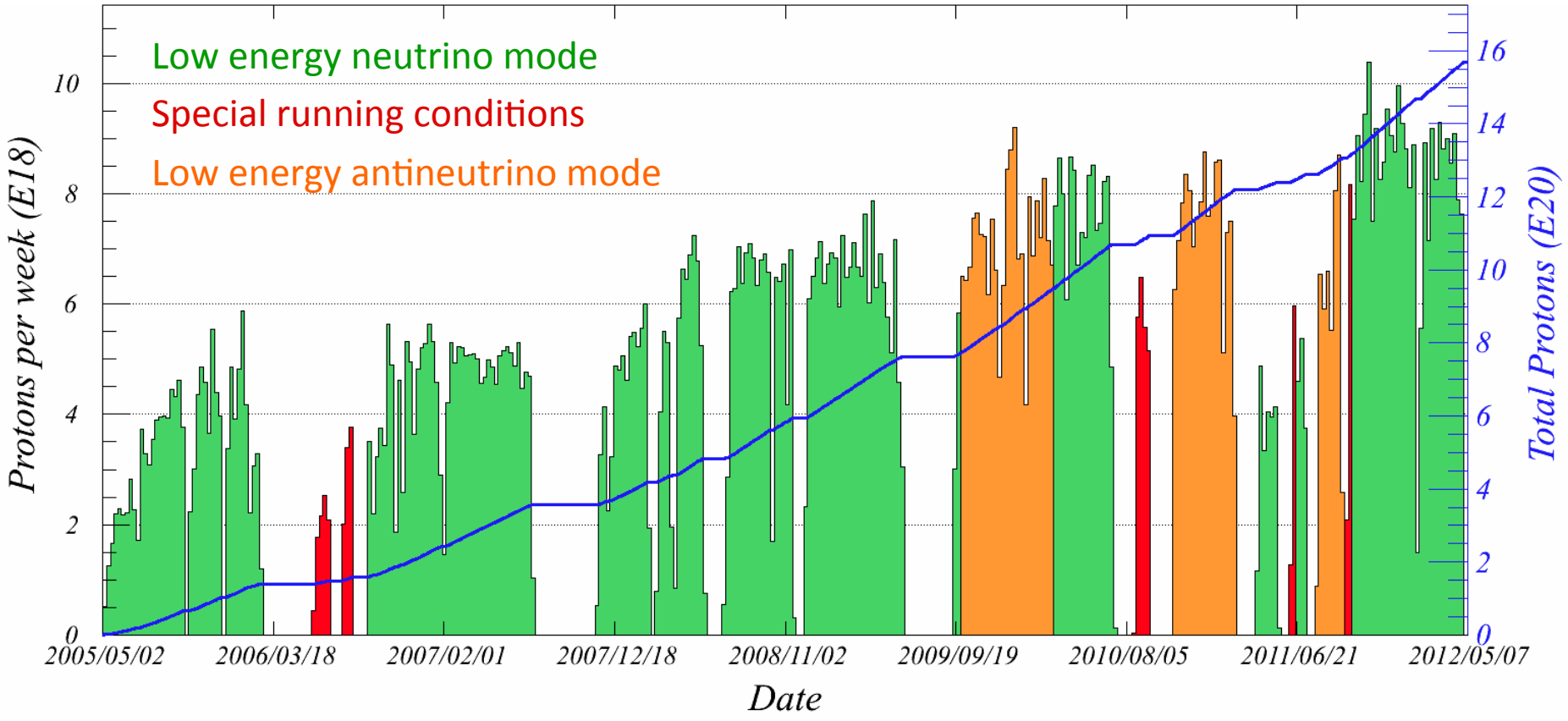


- 120 GeV protons strike target
  - > 10 us pulse every 2.2 s
  - > Typical running at 340 kW
  - > 3.5×10^{13} protons/pulse
- 2 magnetic horns focus secondary π/K
  - > Moveable target & horn provides variable beam energy
  - > Majority of running in low-energy tune
  - > Can focus positives (neutrino mode) or negatives (antineutrino mode)





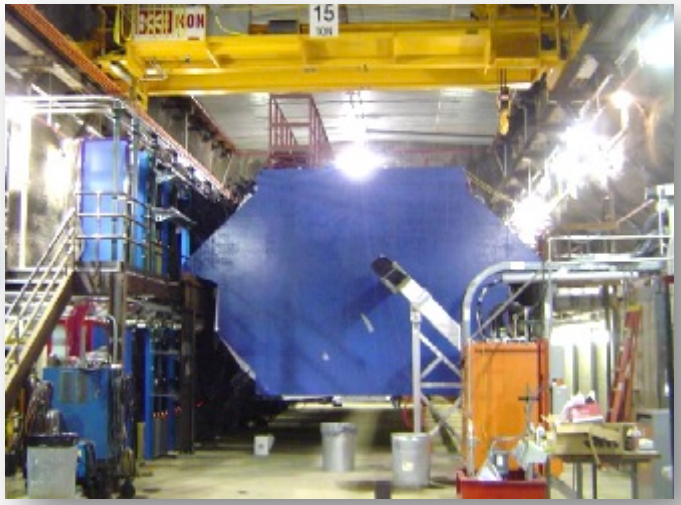
The MINOS LE exposure (2005-2012)
Thanks for all the protons!



15.6 × 10^{20} protons on target [POT]

MINOS: 2 magnetized iron-scintillator tracking calorimeters

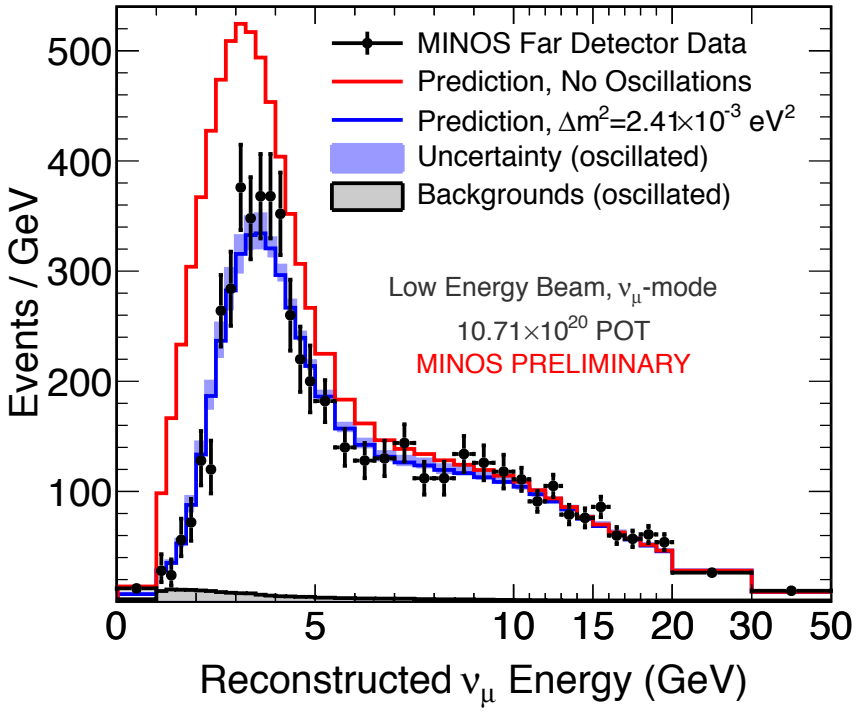
NIMA **596** 190 (2008)

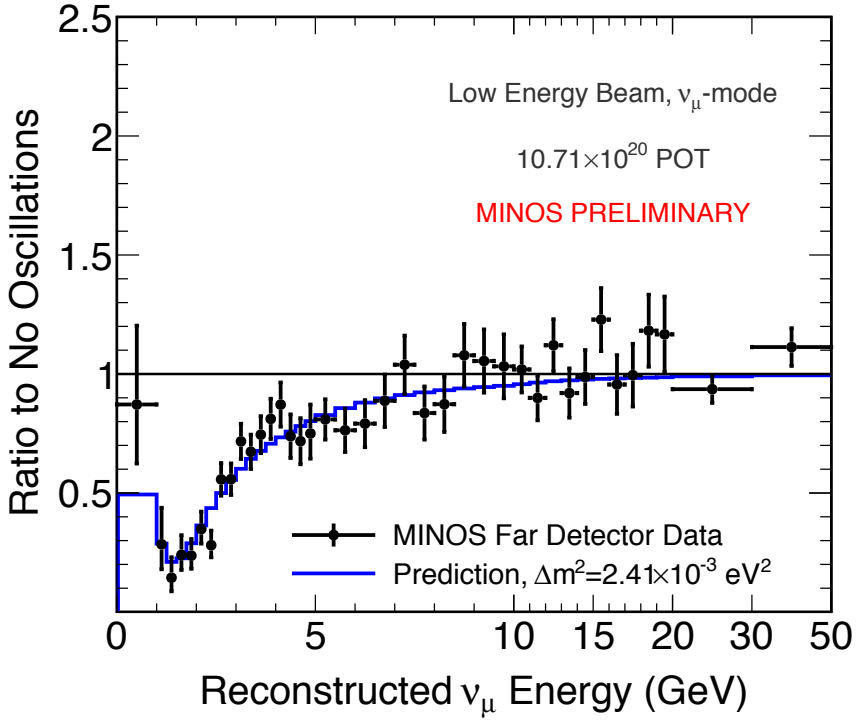


Functionally equivalent

- Magnetized steel planes <B> = 1.3 T
- 1 × 4.1 cm^2 scintillator strips
- 2.54 cm steel sheets
- Moliere radius = 3.7 cm
- Sampling = 1.4 radiation lengths

Muon neutrino oscillation results





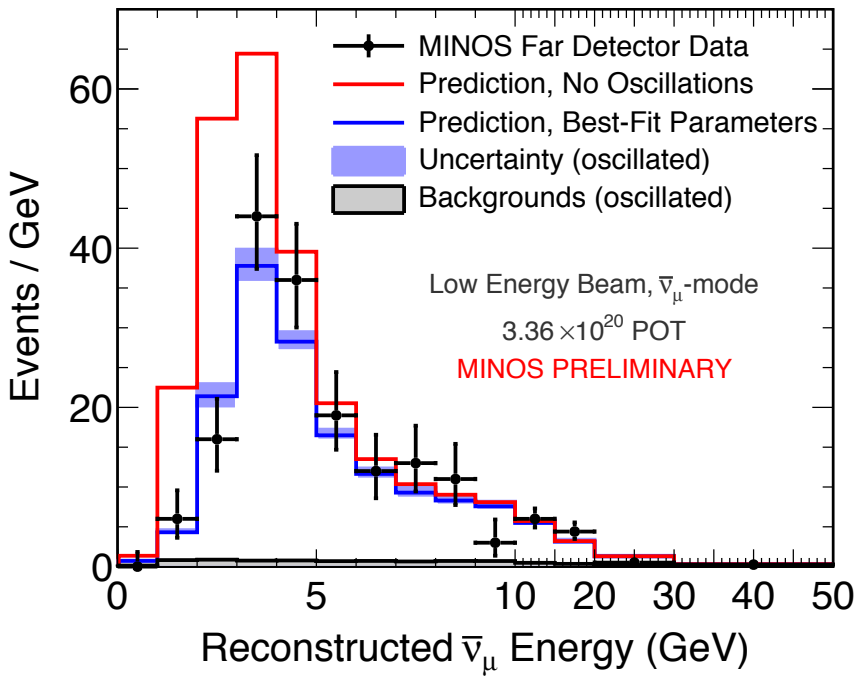
Observed: 2894

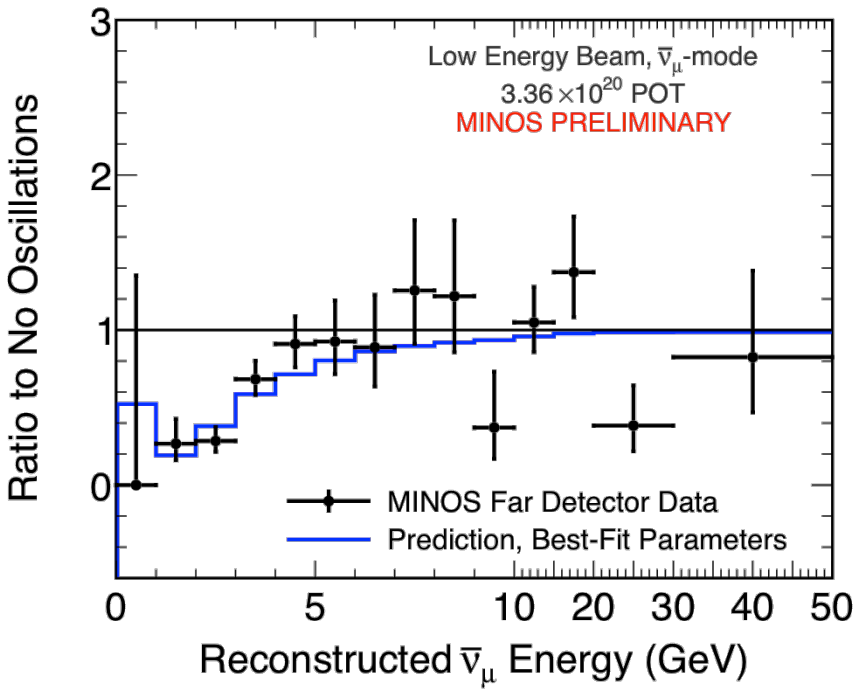
Predicted (no oscillations): 3564

$$\left|\Delta m^2\right| = 2.41^{+0.11}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.937^{+0.044}_{-0.047}$$

Muon antineutrino oscillation results





Observed: 226

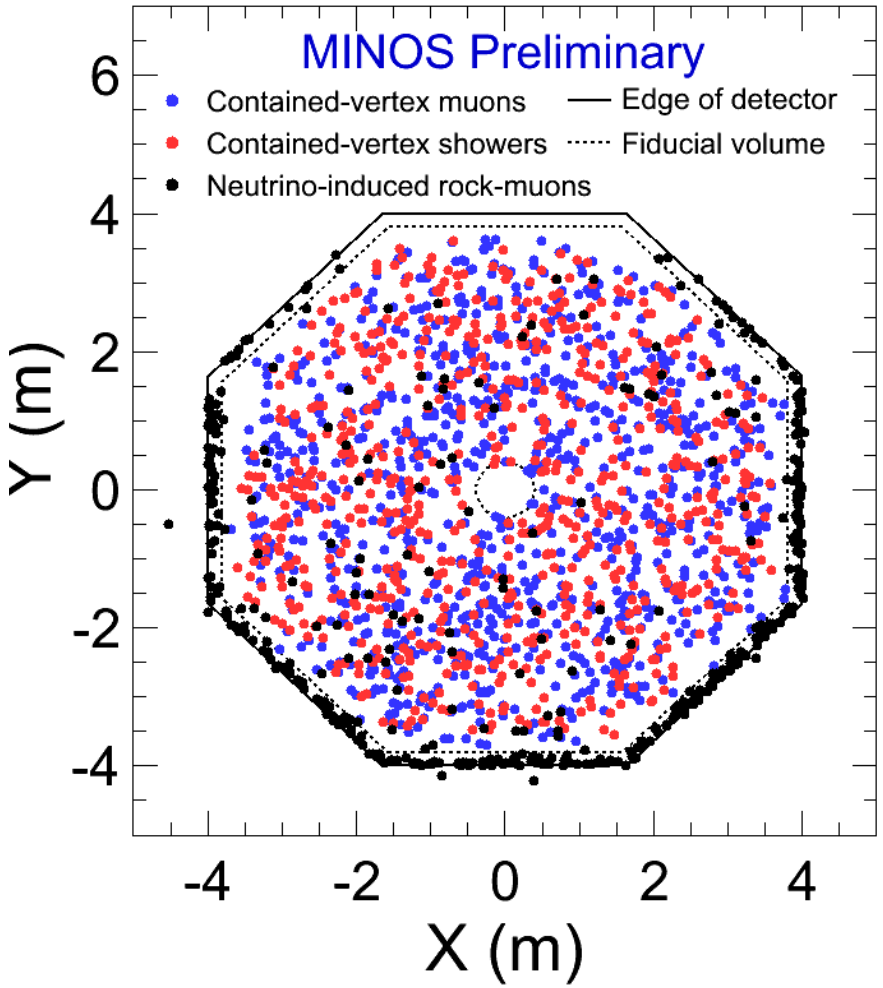
Predicted (no oscillations): 312

$$\left|\Delta\bar{m}^2\right| = 2.64^{+0.28}_{-0.27}\times10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.78 \text{ (90\% C.L.)}$$

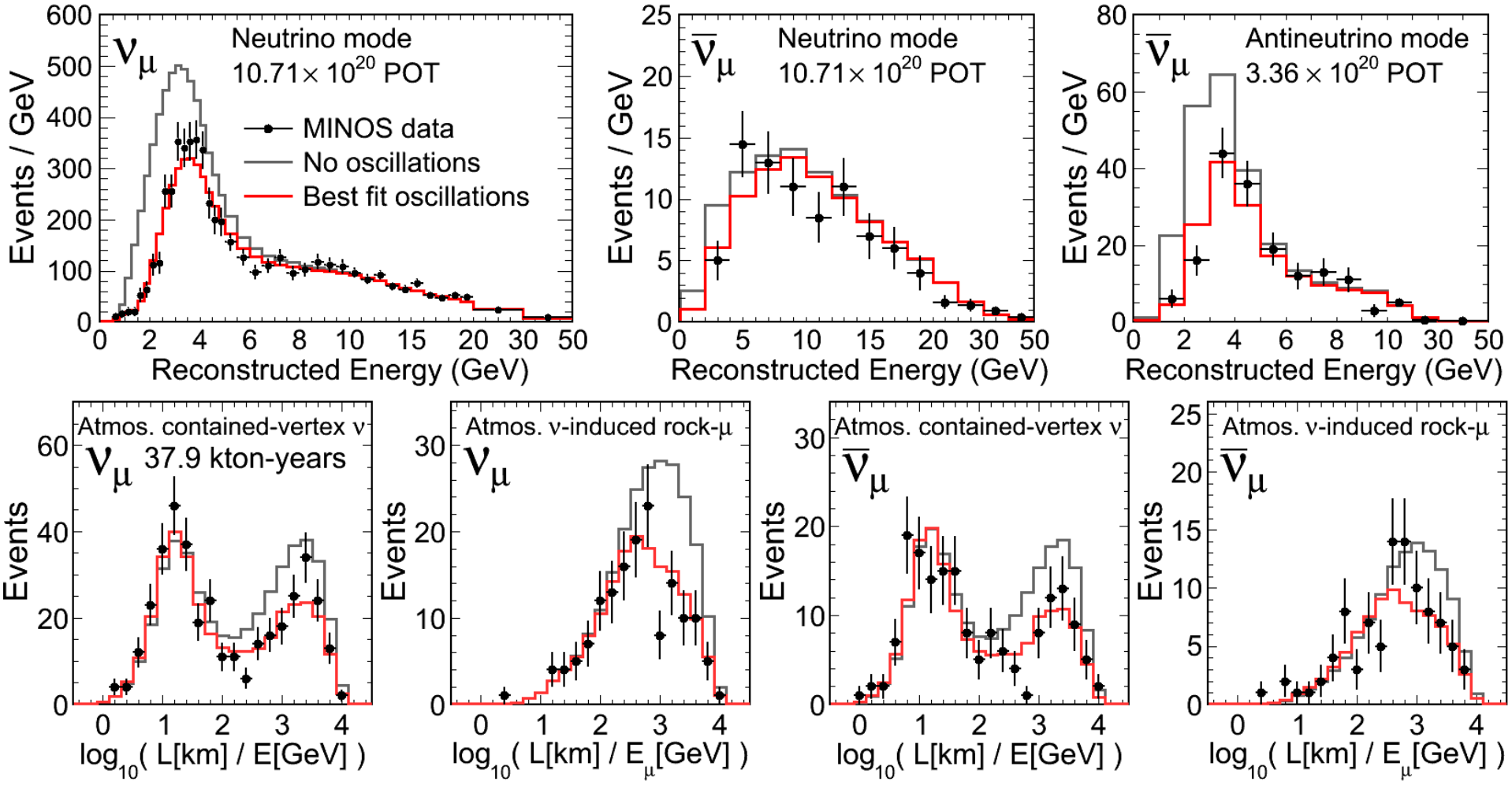
MINOS atmospheric neutrinos & antineutrinos

- Magnetized far detector with scintillator veto shield on top and sides
  - > Located 705m underground (2070 mwe)
  - > Event-by-event muon charge identification
- 2553 live-days or 37.9 kt-yrs
- Observed events
  - > 905 contained-vertex muons
  - > 466 neutrino-induced rock-muons
    - Charged-current muon neutrino interactions
  - > 701 contained-vertex showers
    - Mainly charged-current electron neutrino & neutral-current interactions



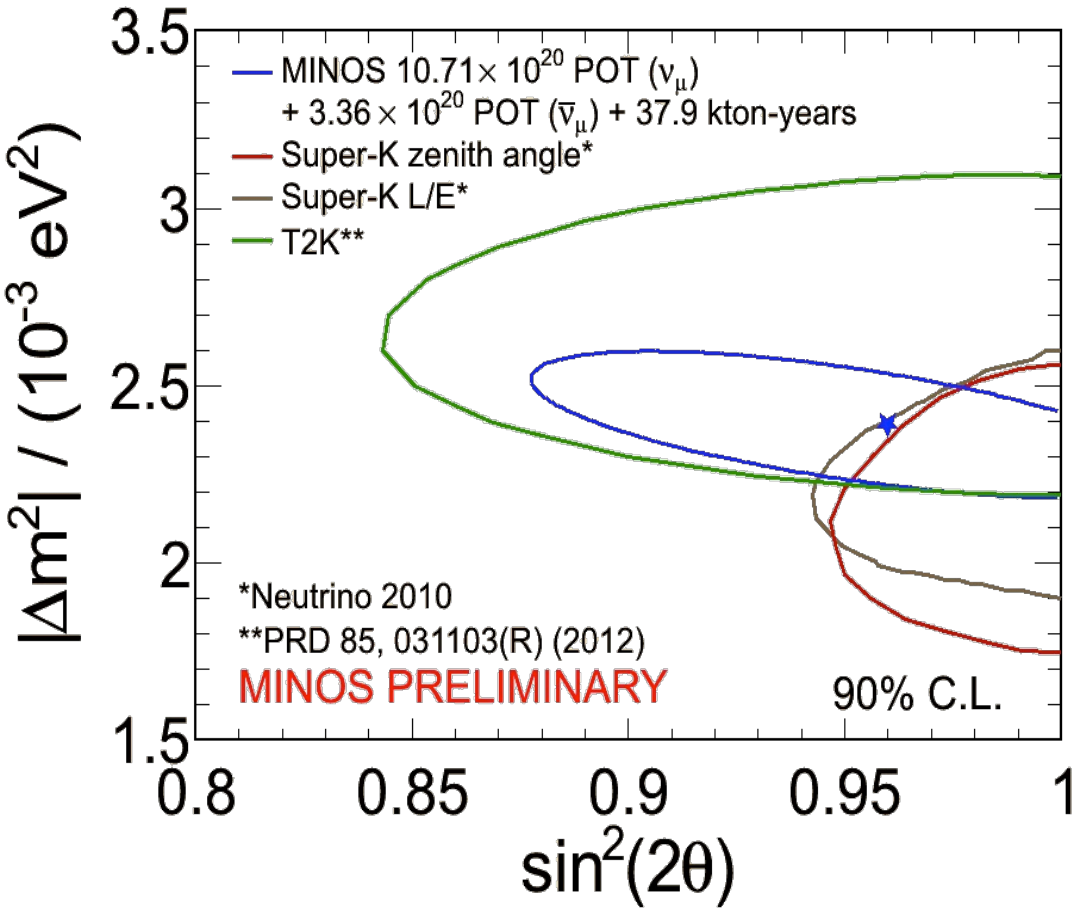
MINOS beam & atmospheric neutrinos & antineutrinos combined in a fit

MINOS PRELIMINARY



MINOS full-exposure results vs the world's results

2-flavour oscillation parameters Δm^2 and $\sin^2 2\theta$ are determined by applying a maximum likelihood fit to the MINOS beam and atmospheric neutrino data



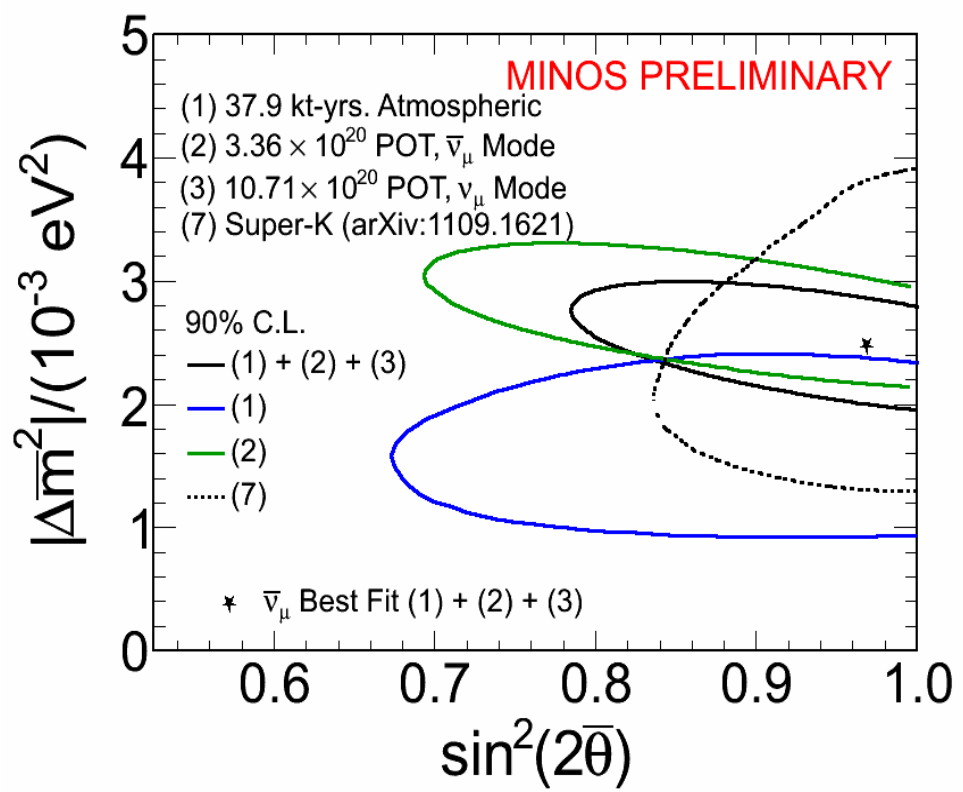
$$\left|\Delta m^2\right| = 2.39^{+0.09}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.957^{+0.035}_{-0.036}$$

$$\sin^2(2\theta) > 0.90 \text{ (90\% C.L.)}$$

MINOS full-exposure results neutrinos vs antineutrinos

Extended fit allows different oscillation parameters for neutrinos and antineutrinos, and confidence limits are placed on the antineutrino oscillation parameters



$$\left|\Delta\bar{m}^2\right| = 2.48^{+0.22}_{-0.27} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.83 \text{ (90\% C.L.)}$$

$$\left|\Delta m^2\right| = 2.39^{+0.09}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

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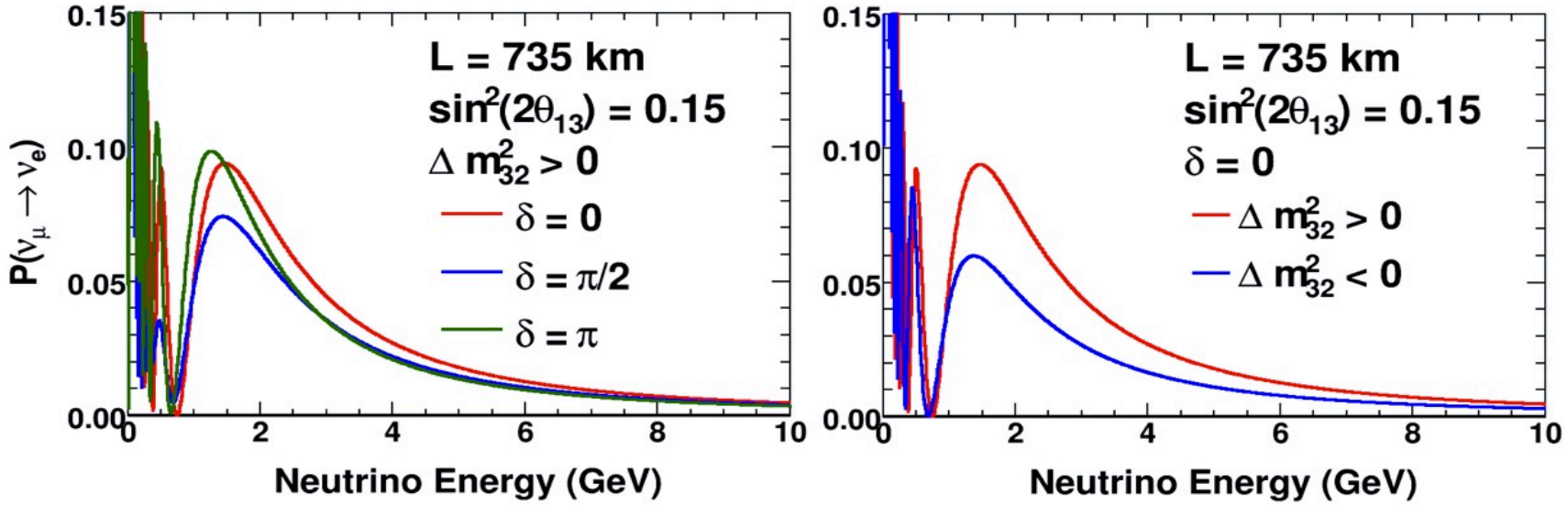
$$\sin^2(2\theta) > 0.90 \text{ (90\% C.L.)}$$

The new data resolves the tension between neutrino & antineutrino parameters

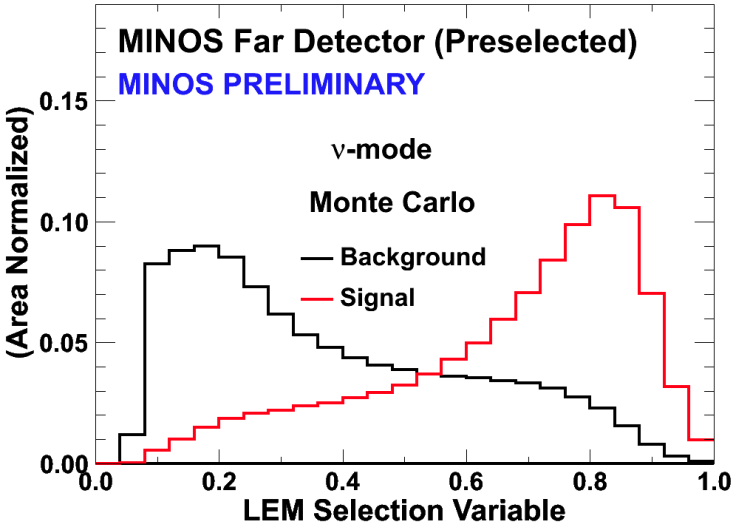
3-flavor oscillation phenomenology

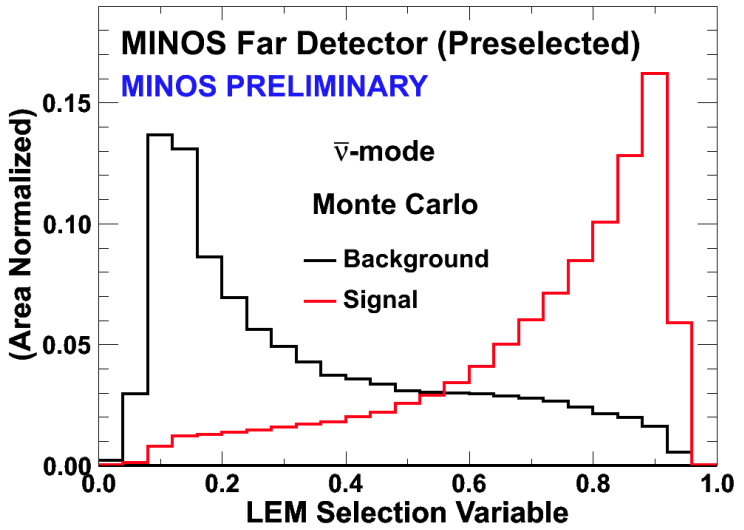
- Super-K / MINOS tell us $|\Delta m^2_{32}| \approx 3\times10^{-3}\ \text{eV}^2$ $\theta_{23}\approx45°$
- SNO / Kamland tell us $\Delta m^2_{21} \approx 8\times10^{-5}\ \text{eV}^2$ $\theta_{12}\approx34°$
- DC+RENO+DB tell us $\theta_{13} \approx 9°$
- Examples of the effects of the higher order terms for MINOS



Search for electron appearance in MINOS

- Due to the coarse sampling we cannot identify electrons in an event-by-event basis
- Particle ID discriminator
  - > Library Event Matching (LEM)
  - > An ANN informed by properties of similar MC library events as defined by a charge overlap algorithm
- Define a signal region for events with LEM>0.6 for a binned fit
  - > Optimal counting analysis is LEM>0.7





Appearance of electrons
10.6×10^{20} POT (ν mode) + 3.3×10^{20} ($\bar{\nu}$ mode)

ν mode

Observe 88 events *

Expected

69.1 (background)

26.0 (signal**)

$\bar{\nu}$ mode

Observe 12 events *

Expected

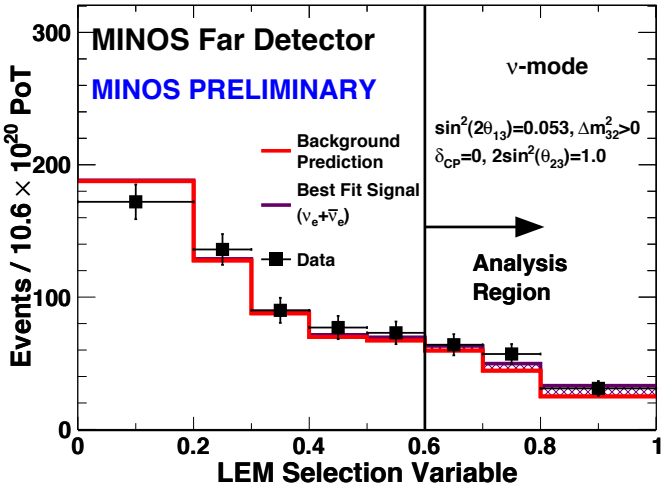
10.5 (background)

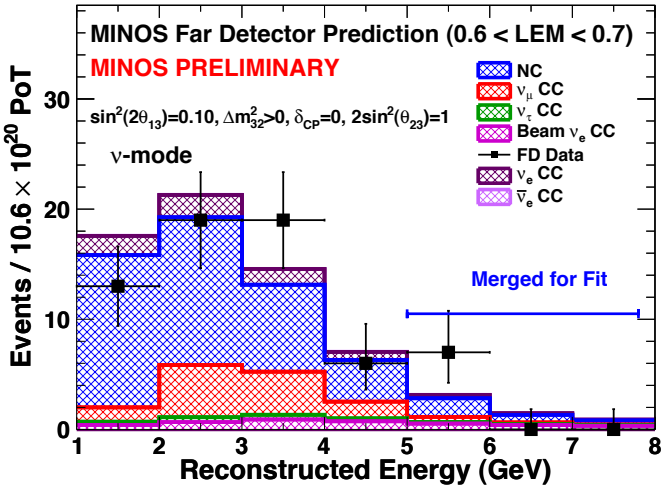
3.1 (signal**)

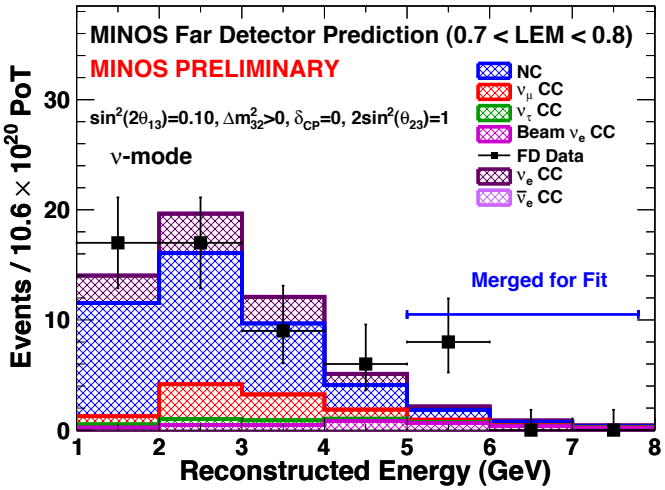
Fit to 15 LEM/energy bins

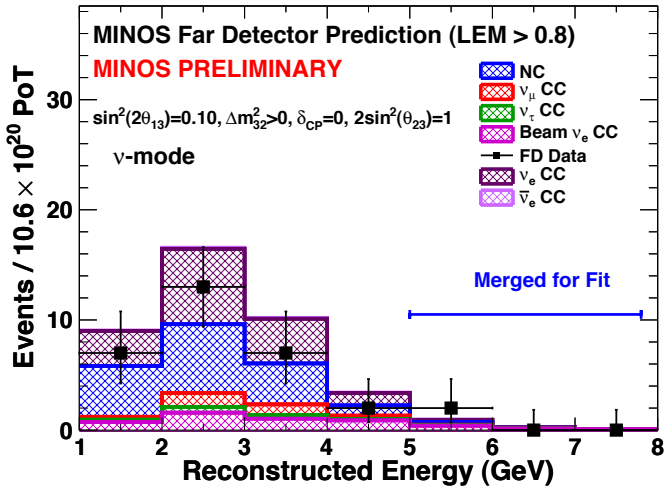
* for LEM>0.7

** assuming $\sin^2(2\theta_{13})=0.1$, $\delta=0$, $\Delta m^2>0$









Results for appearance of electrons with both ν and $\bar{\nu}$ running combined

for $\delta_{CP} = 0, \quad \sin^2(2\theta_{23}) = 1,$

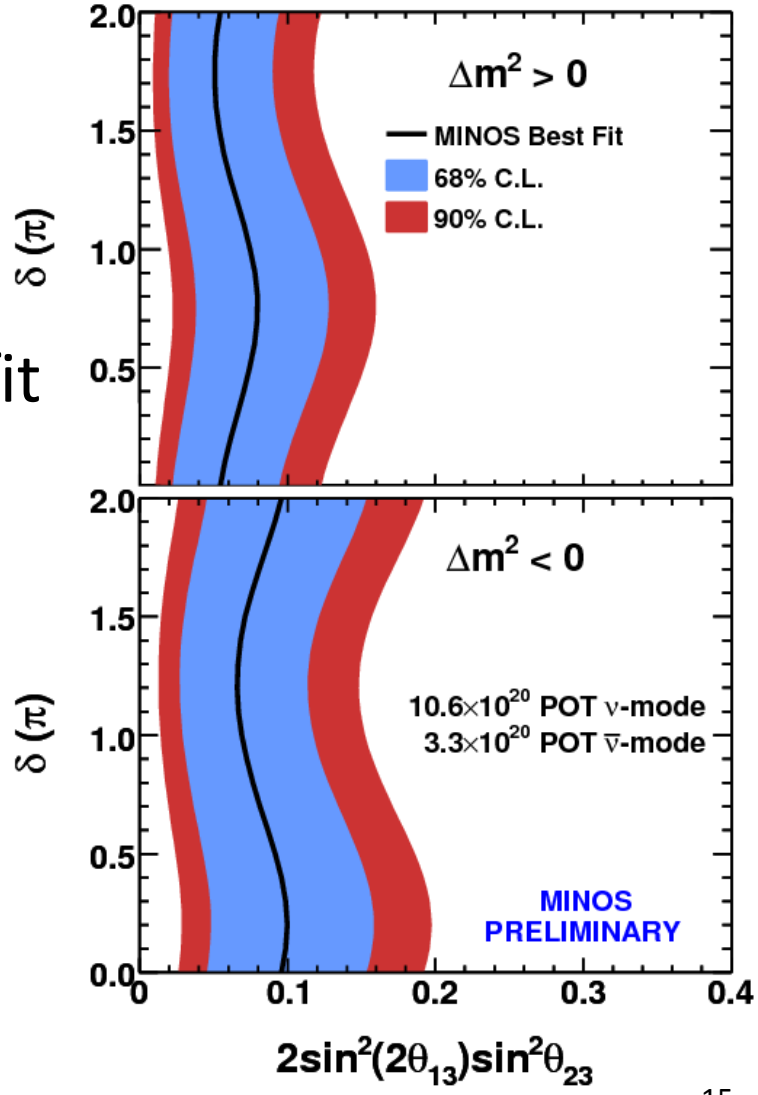
with normal (inverted) hierarcy

$\sin^2(2\theta_{23}) = 0.053 \quad (0.094)$ at best fit

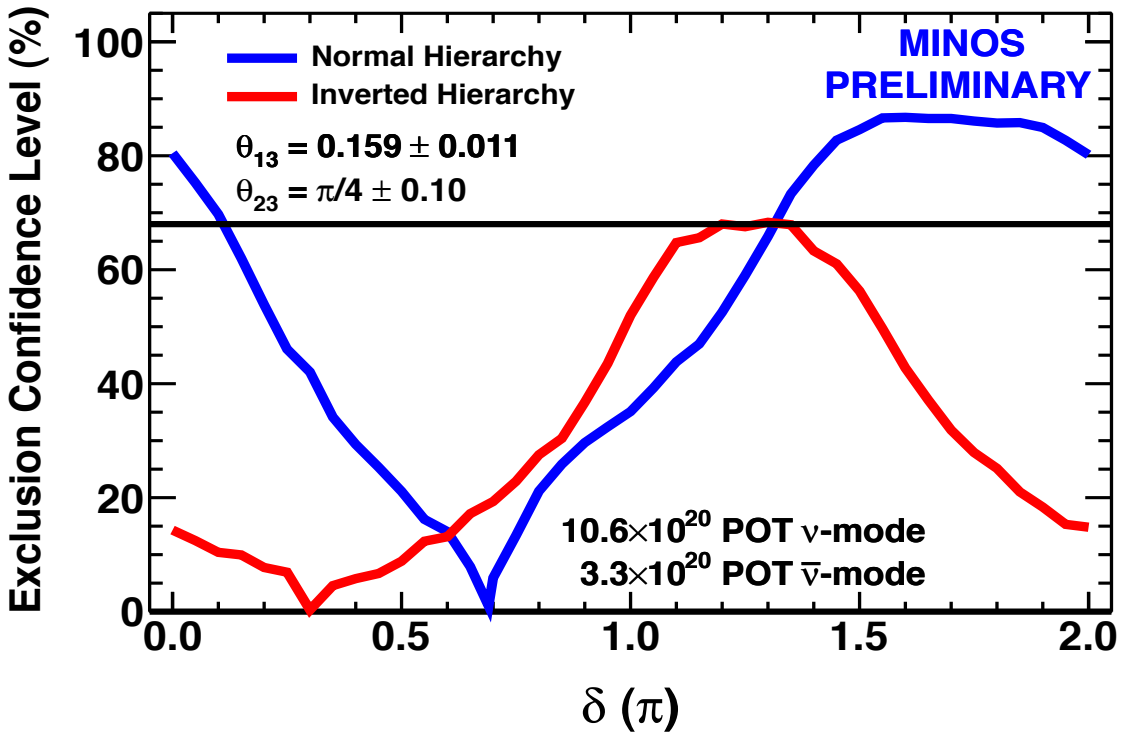
$0.01 < \sin^2(2\theta_{23}) < 0.12$ at 90% C.L.

$(0.03 < \sin^2(2\theta_{23}) < 0.19)$

$\sin^2(2\theta_{23}) = 0$ excluded at 96% C.L.

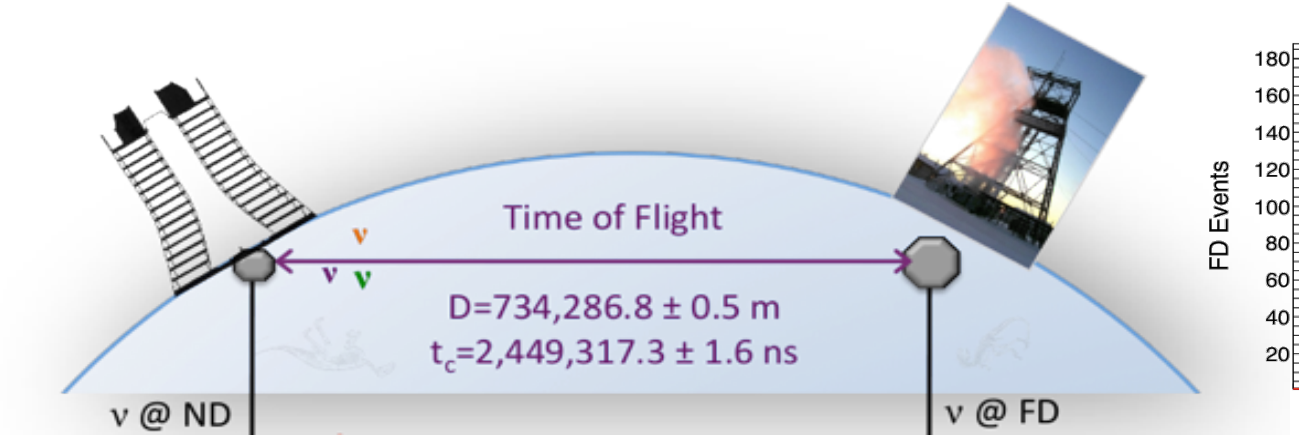


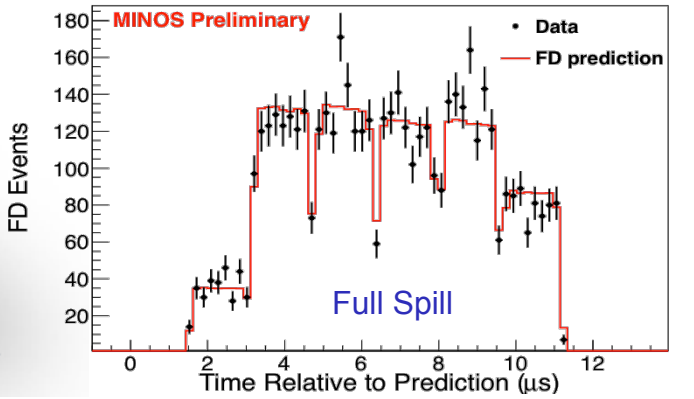
Delta and the hierarchy



- For this plot we look at C.L. wrt the best fit in each hierarchy
  (i.e. assume the hierarchy and see what is consistent with the data)
- Sensitivity to hierarchy: In pseudo experiments, we get the hierarchy right 60% of the time (compare to 50% by chance)
- With θ_{13} from reactor experiments, our data slightly favor inverted hierarchy $-2\Delta\ln L=0.2$

Measure the neutrino velocity by time of flight between the 2 detectors



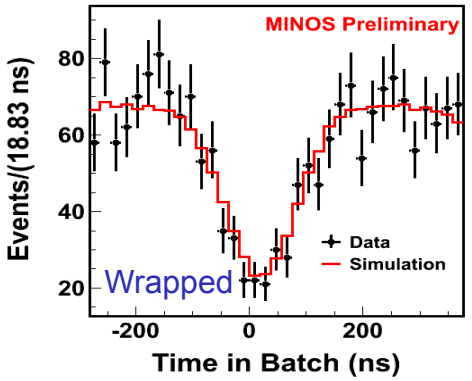


- Initial result after first year of data indicated neutrinos arrived at FD earlier than expected

  -126 ± 32 (stat.) ± 64 (syst.) ns[†]

- We revisited this analysis with a factor of 8 more events & refined systematic errors

  -15 ± 11 (stat.) ± 29 (syst.) ns



- New timing system will greatly reduce the errors in the last 11 weeks of collected data (box to be opened) & during MINOS+ running

[†]Phys. Rev. D76 (2007) 072005

New TOF results: quoted in ns difference WRT speed of light over ~730km

Previously reported results

- MINOS[1] −126 ± 32 (stat.) ± 64 (syst.)
- OPERA[2] −57.8 ± 7.8 [+8.3, -5.9]

New results reported at Neutrino 2012

- MINOS −15 ± 31
- OPERA +1.6 ± 1.1 [+6.1, −3.7]
- Borexino +2.7 ± 1.2 ± 3
- ICARUS +5.1 ± 1.1 ± 5.5
- LVD +2.9 ± 0.6 ± 3

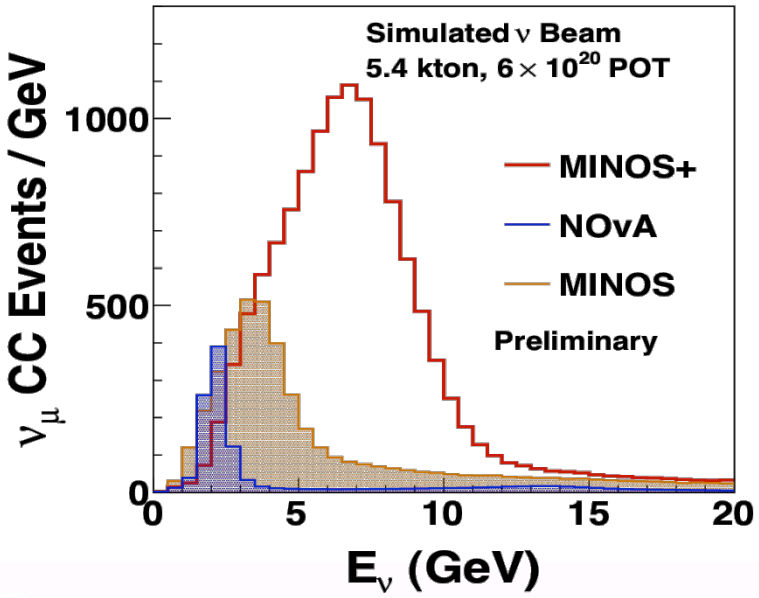
CNGS

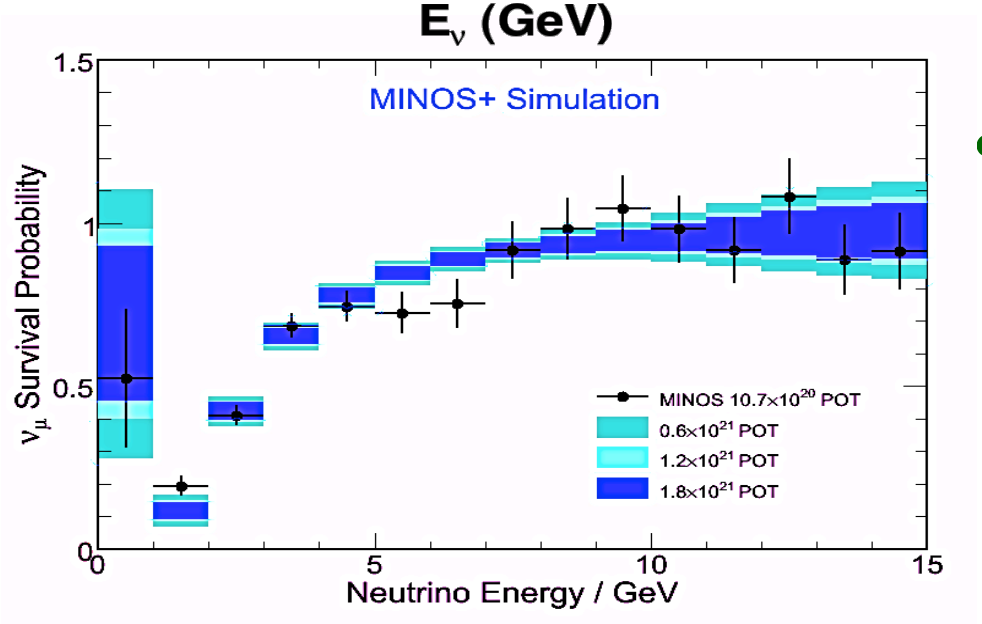
- All consistent with the speed of light

[1] Phys. Rev. D76 (2007) 072005

[2] arxiv1109.4897v2

MINOS+
medium-energy beam exposure

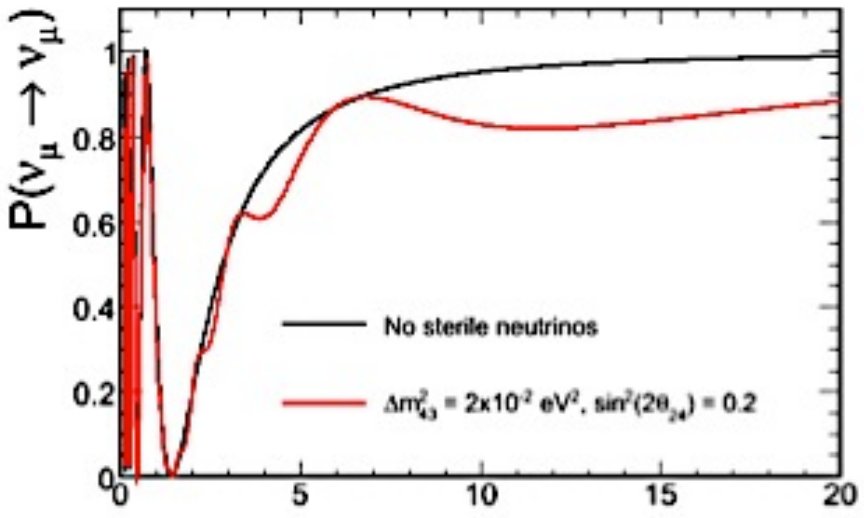


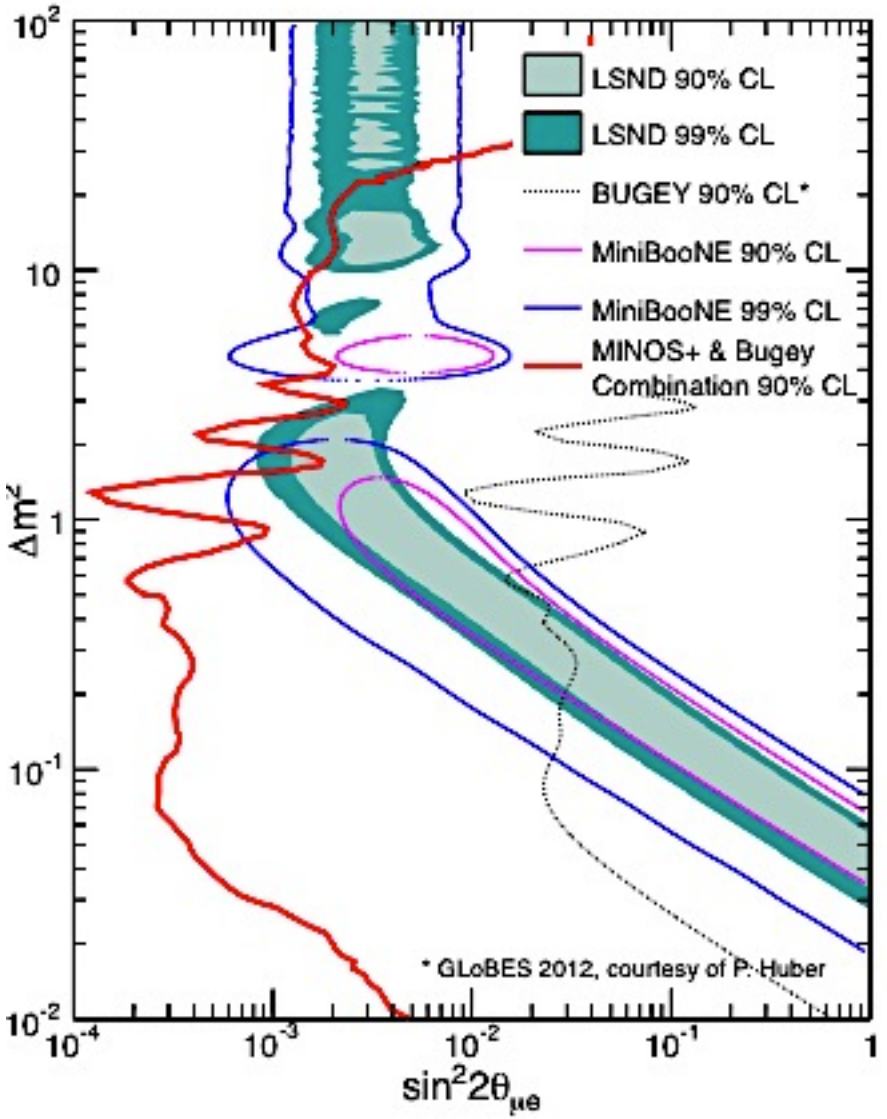


- MINOS will continue to run in the NOvA era
  - > On-axis ME beam peaks above the oscillation dip
- We get a flood of events
  - > Roughly 4000 far detector ν_μ CC events/year
- Unique test of oscillation paradigm
  - > Sensitivity to exotic signals

MINOS+ sensitivity

Using complementary information from Bugey and MINOS+ we can almost rule out all of the low mass LSND region





Summary of new MINOS results

- MINOS has completed its low-energy running after 1.56×10^{21} POT

muon neutrino disappearance

$$\left|\Delta m^2\right| = 2.39^{+0.09}_{-0.10}\times10^{-3}\,\text{eV}^2$$

$$\sin^2(2\theta) = 0.957^{+0.035}_{-0.036}$$

$$\sin^2(2\theta) > 0.90 \text{ (90\% C.L.)}$$

muon antineutrino disappearance

$$\left|\Delta \bar{m}^2\right| = 2.48^{+0.22}_{-0.27}\times10^{-3}\,\text{eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.83 \text{ (90\% C.L.)}$$

electron neutrino appearance

$$0.01\ (0.03) < \sin^2(2\theta_{13}) < 0.12\ (0.19) \text{ at 90\% C.L.}$$

$$\text{for } \delta_{CP} = 0,\ \sin^2\left(2\theta_{23}\right) = 1, \text{ normal (inverted) hierarchy}$$

$$\sin^2(2\theta_{13}) = 0 \text{ excluded at 96\%}$$

- Neutrino velocity is consistent with the speed of light
- MINOS+ has an exciting program based on NuMI medium-energy running