'Final' MINOS Results

12th September, 2012
NOW 2012 Workshop
Otranto, Lecce, Italy

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University of Oxford

Outline

- MINOS Detectors & the NuMI Beamline
- MINOS Physics Program & Results
- Introduction to MINOS+
- Conclusion

The MINOS Experiment

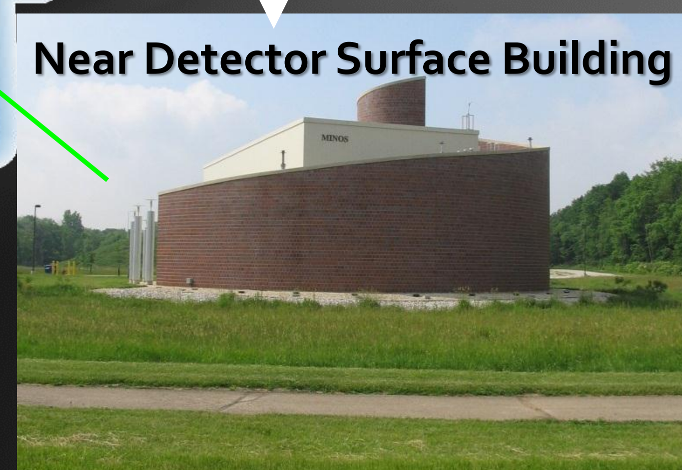
The MINOS Experiment
(Main Injector Neutrino Oscillation Search)

MINOS Is a two detector long base line Neutrino Oscillation experiment

- 735 km baseline from Fermilab to Soudan,MN.


Soudan Entrance Elevators

~734 km


Near Detector Surface Building

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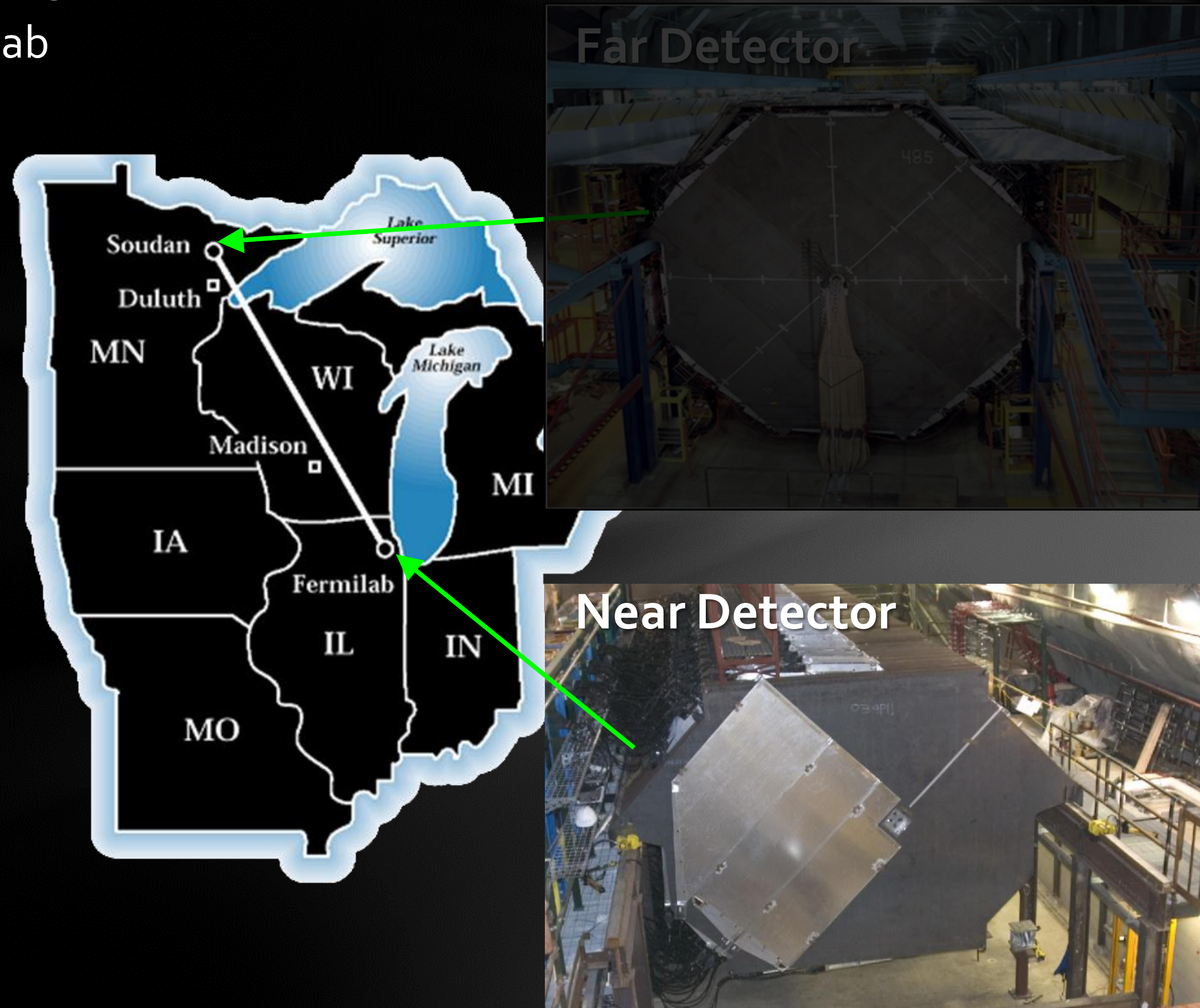
MINOS Near Detector

- Measure beam composition
- Measure ν energy spectrum
- 1km from source and 0.98kton
- $3.8 \times 4.8 \times 17 m^3$
- 100 m underground



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MINOS Near Detector

- Measure beam composition
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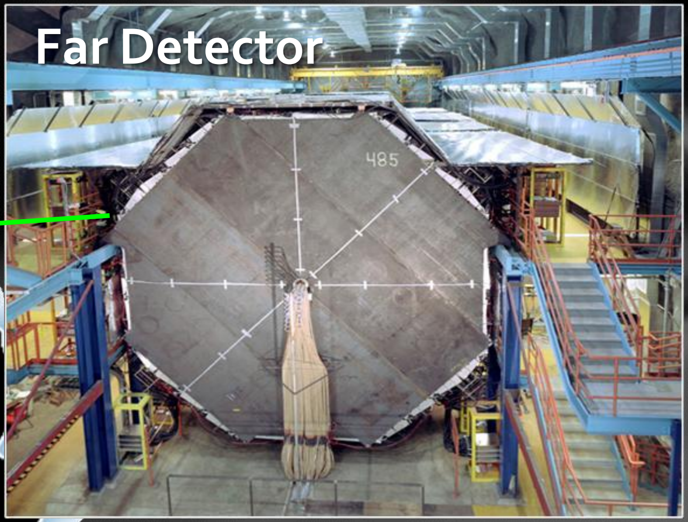
- 1km from source and 0.98kton
- 3.8 x 4.8 x 17 m^3
- 100 m underground

MINOS Far Detector

- Look for evidence of oscillations by comparing spectrum to Near detector
- <u>functionally identical</u> to Near detector
- 735 km from source
- 8 x 8 x 30m^3, 700 m underground, 5.4kton



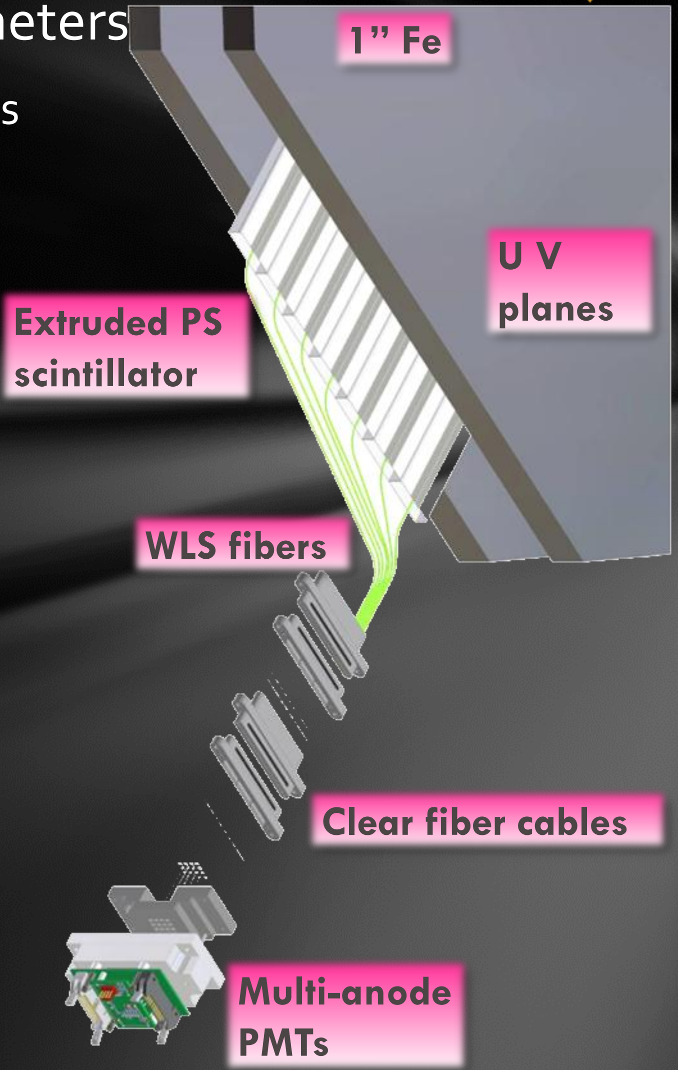
The MINOS Detectors

Detectors are steel-scintillating sampling calorimeters

Having two functionally identical detectors minimizes errors due to beam and neutrino interaction uncertainties

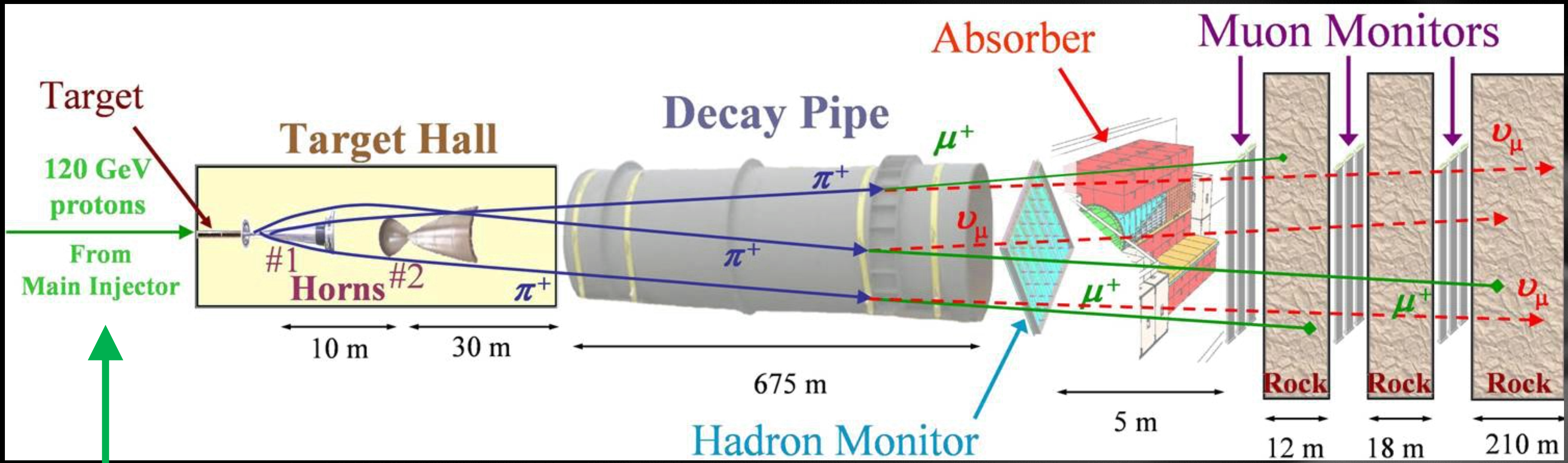
Steel plane absorbers 2.54cm thick
- Average <B>=1.3 Tesla (Toroidal)
- Good muon charge sign identification

Scintillating strips measure 4.1 x 1 cm^2
- strip width is 1.1 Moliere radius
- have embedded wavelength shifting fibers
- subsequent planes are orthogonal to allow for 3-D reconstruction of events.



The NuMI Beamline

Neutrino Production with NuMI
(Neutrinos at the Main Injector)



The Beam

• 120 GeV protons from the Main Injector
•~300 kW beam power

Neutrino Production with NuMI
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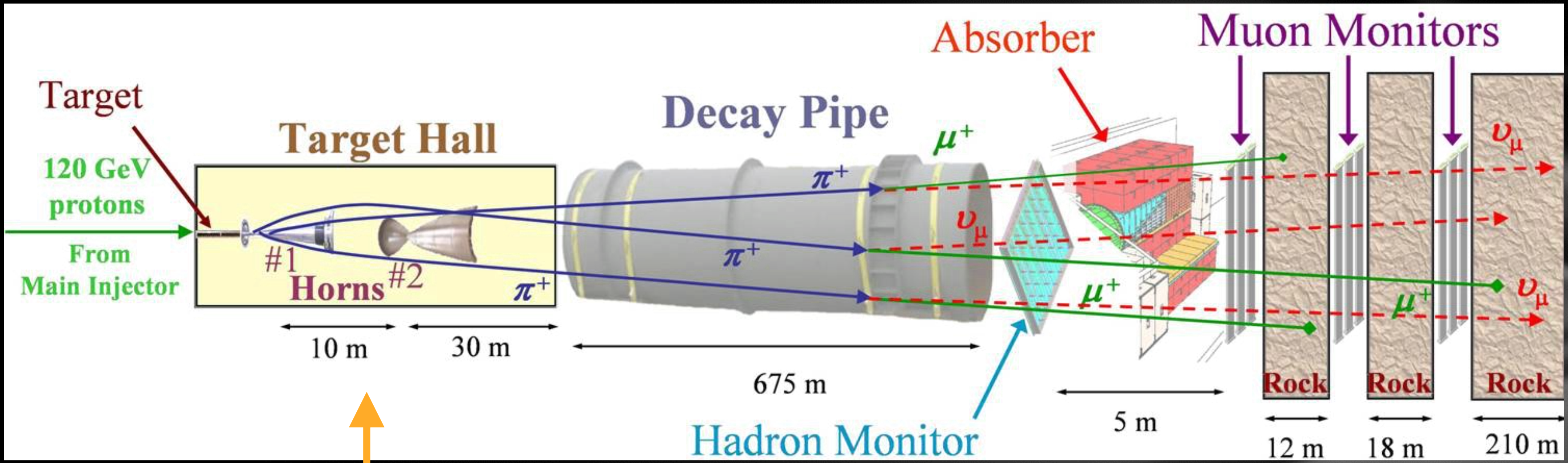

The Target and Production

- Protons strike a graphite target
  - 47 segments, 6.4 x15 x 20mm^3(MINOS)
  - ~95.4 cm long or 1.9 interaction length

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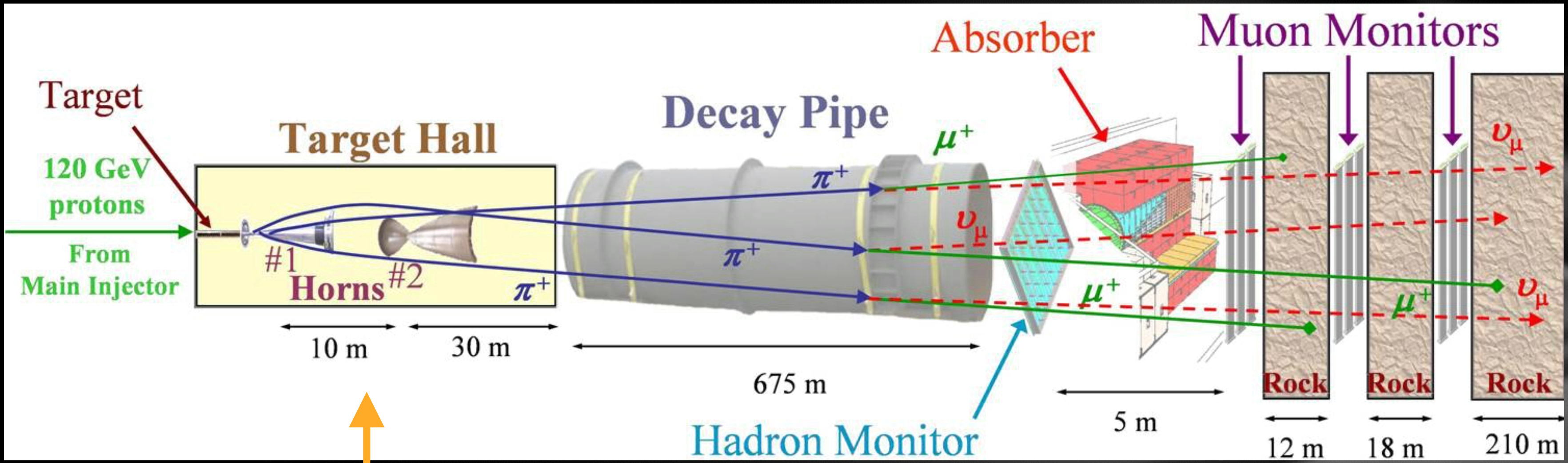
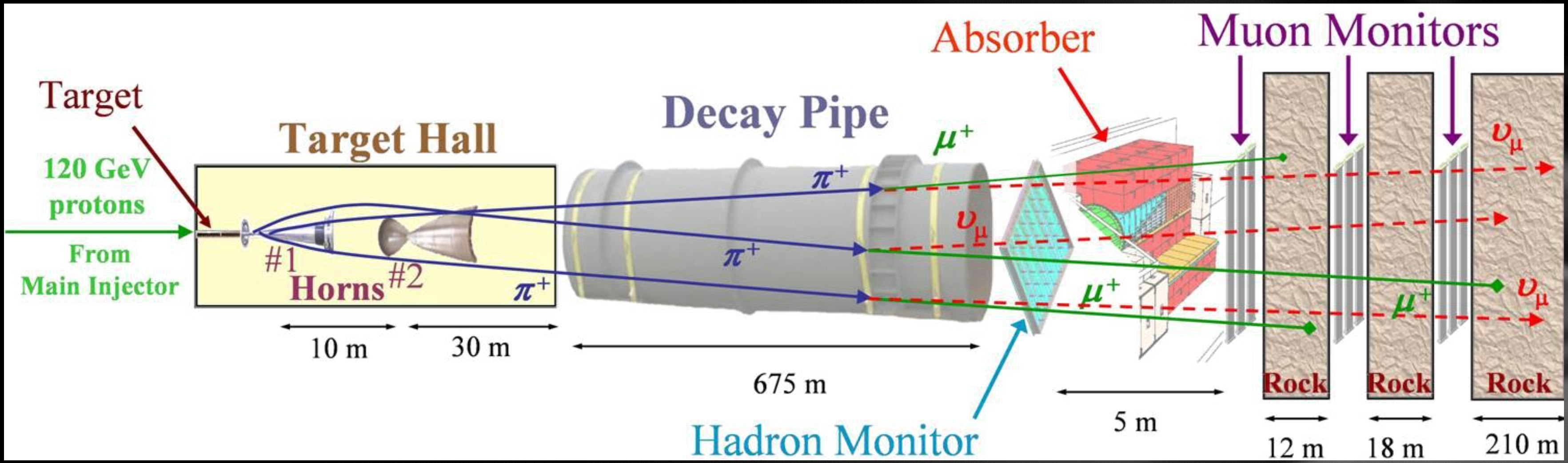


The Target and Production

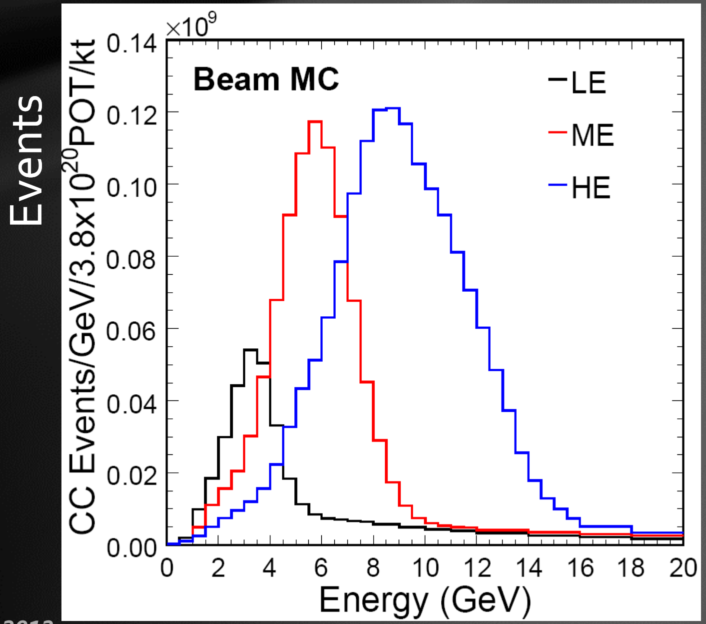
- Protons strike a graphite target
  - 47 segments, 6.4 x15 x 20mm^3(MINOS)
  - ~95.4 cm long or 1.9 interaction length
- Two magnetic focussing horns guide mesons, mostly πs + Ks, down decay pipe
  - Pulsed horn current ~200kA
  - 3T magnetic field

Neutrino Production with NuMI
(Neutrinos at the Main Injector)



The Neutrino Beam

Neutrino energy is tunable by modifying the target position with respect to the horn



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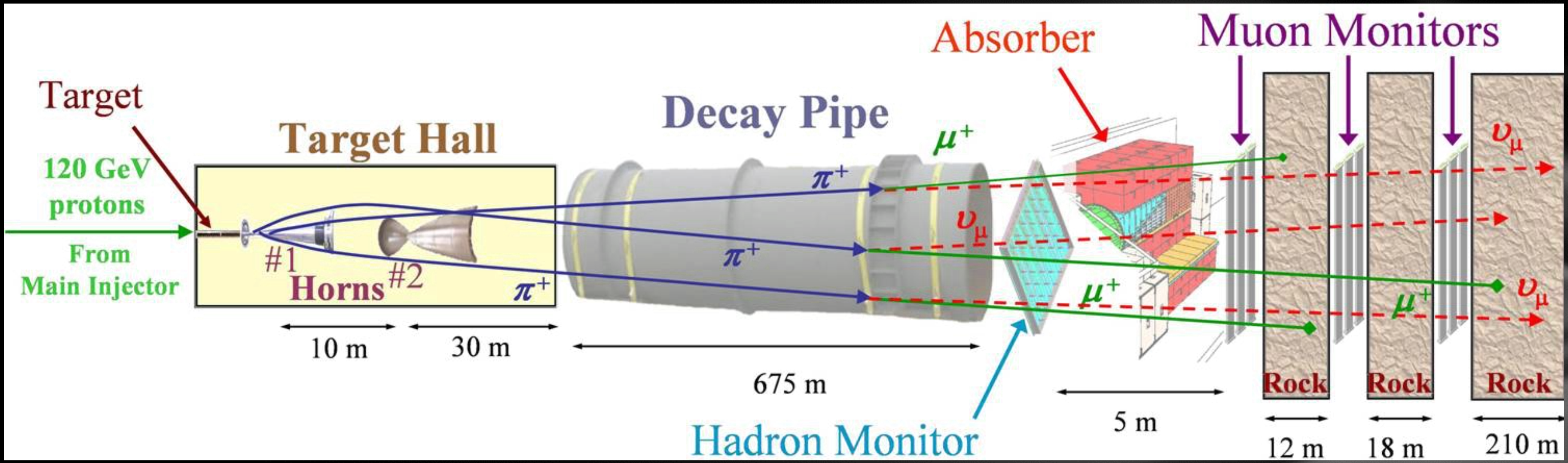

The Neutrino Beam

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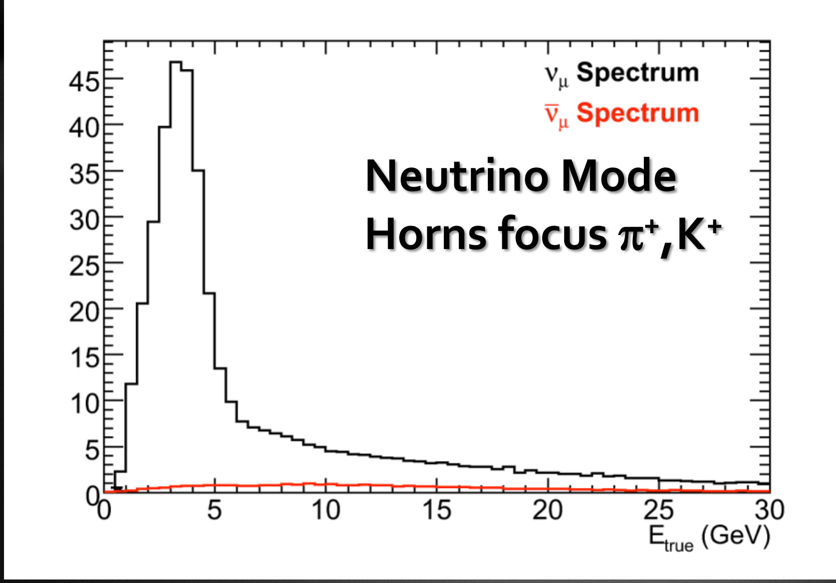
Neutrino beam composition

$$91.7\%\,\nu_\mu, 7.0\%\,\overline{\nu_\mu}, 1.3\%\left(\nu_e+\overline{\nu_e}\right)$$



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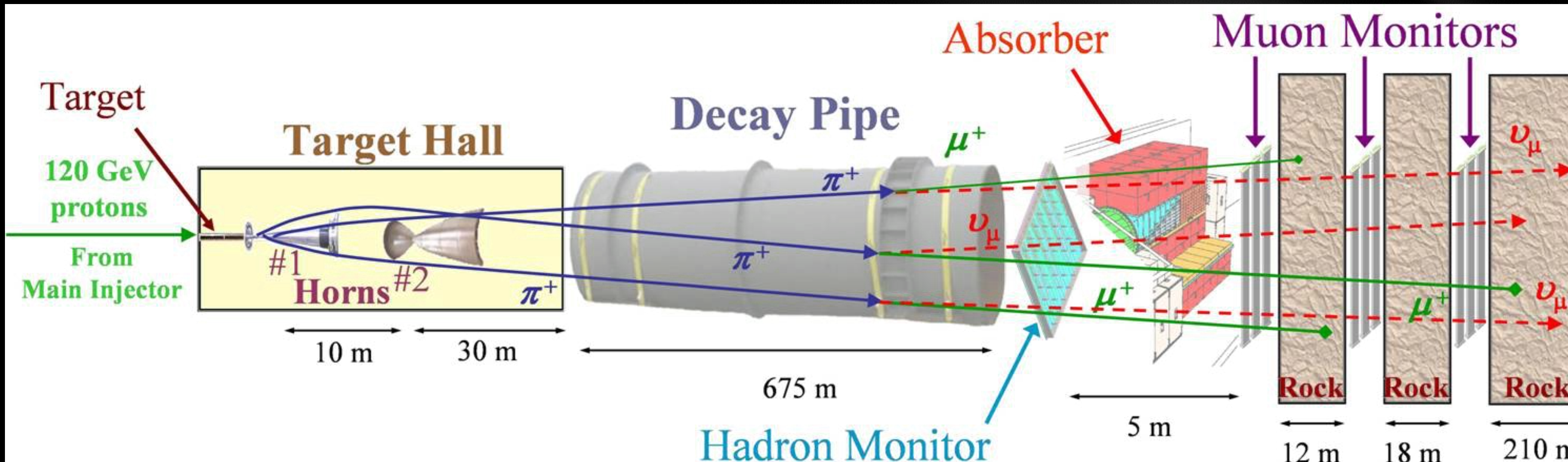


The Neutrino Beam

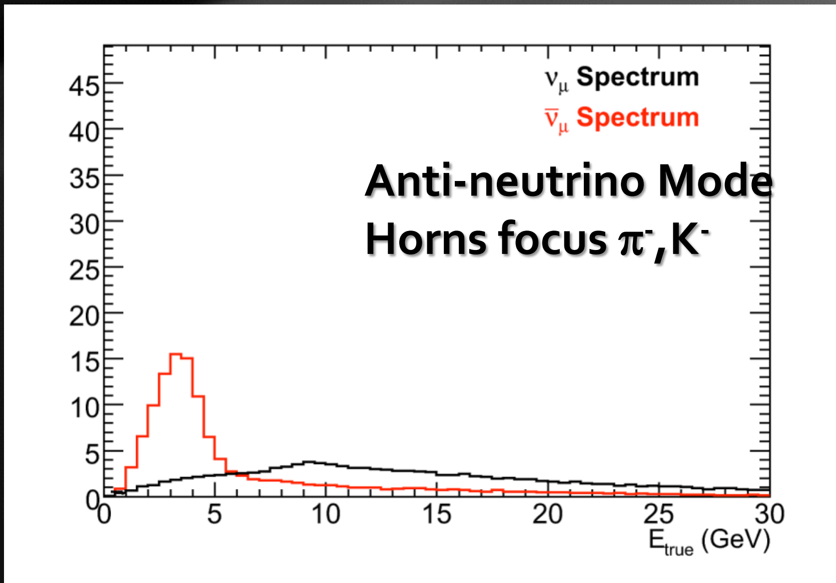
Neutrino energy is tunable by modifying the target position with respect to the horn

Neutrino beam composition

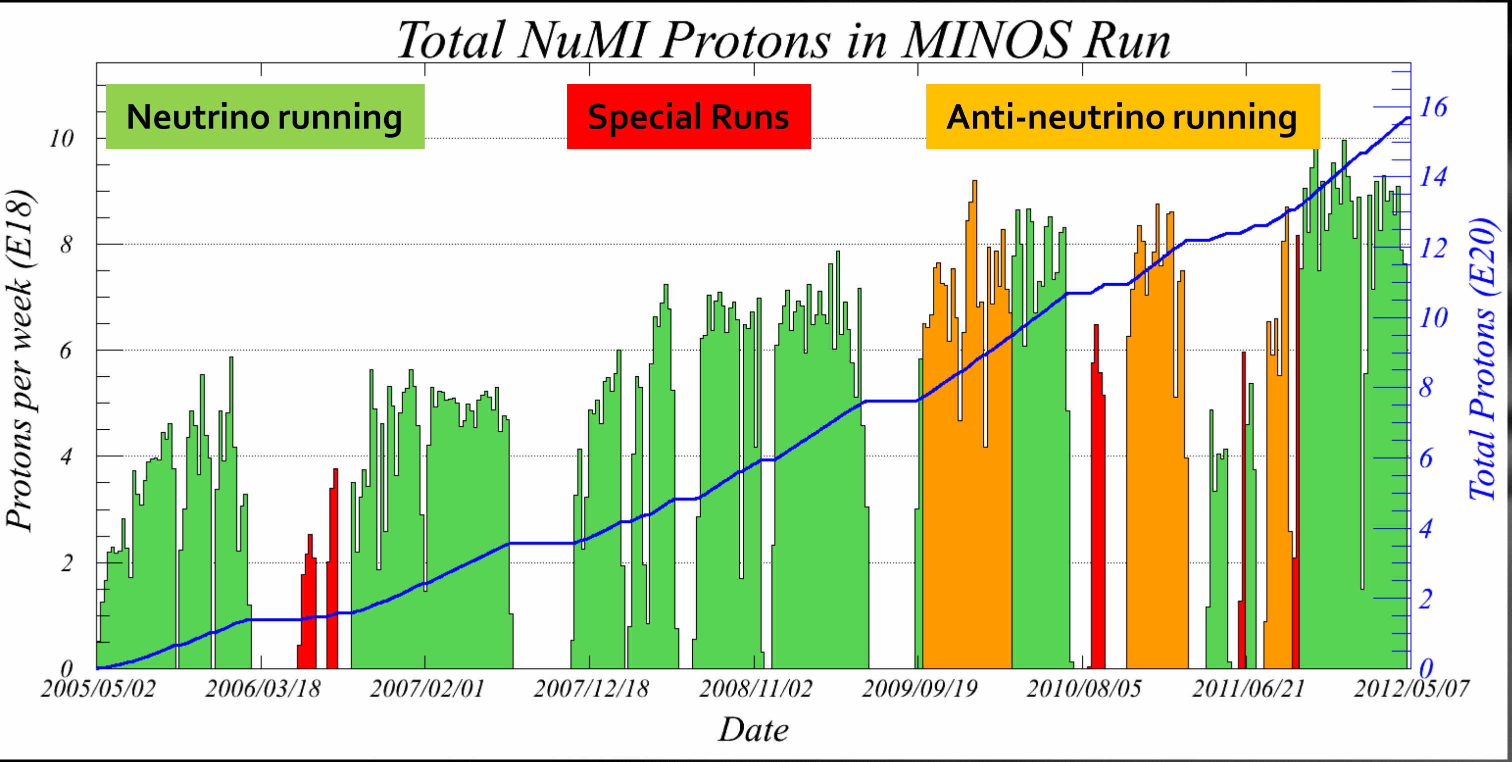
$$91.7\%\,\nu_\mu, 7.0\%\,\overline{\nu_\mu}, 1.3\%\left(\nu_e+\overline{\nu_e}\right)$$

Anti-neutrino beam composition

$$39.9\%\,\overline{\nu_\mu}, 58.1\%\,\nu_\mu, 2.0\%\left(\nu_e+\overline{\nu_e}\right)$$



NuMI Delivered POTs

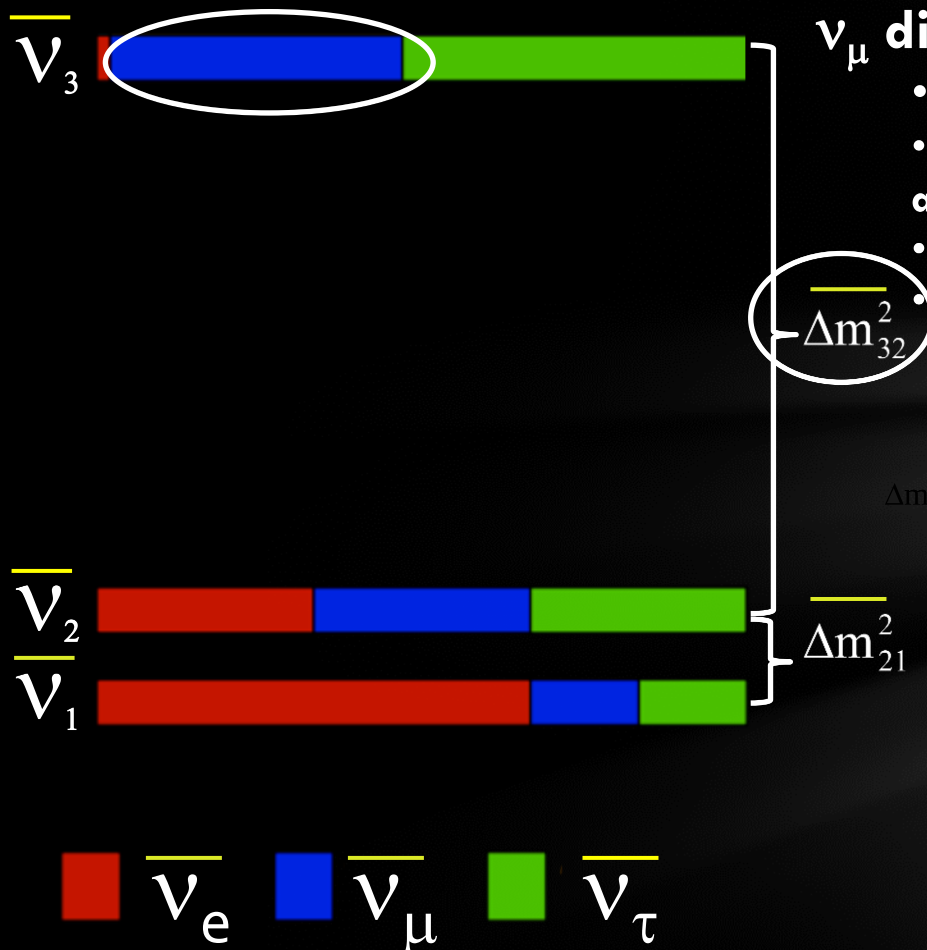


NuMI beam to MINOS ended April 30, 2012.

Accumulated more than 15 x 10^{20} POT

- 10.71 x 10^{20} POT in (LE) neutrino running
- 3.36 x 10^{20} POT in antineutrino running
- Other configurations for beam model and background tuning

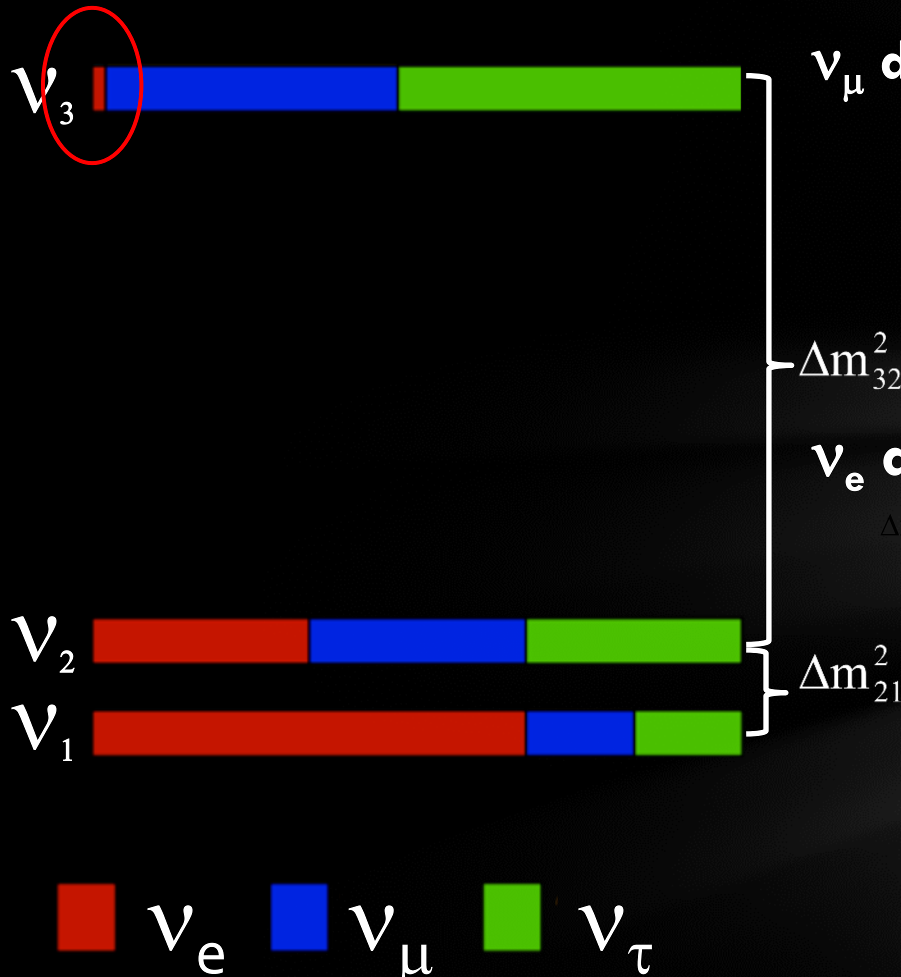
MINOS Physics



ν_μ disappearance & $\overline{\nu_\mu}$ disappearance

- measure Δm^2_{32} and $\sin^2(2\theta_{23})$, $\overline{\Delta m^2_{32}}$ and $\sin^2(\overline{2\theta_{23}})$
- Place limits on other phenomena including decay and decoherence
- measure do $\bar{\nu}$ behave the same as ν?
- Complimentary measurement from atmospheric $\nu/\bar{\nu}$

MINOS Physics



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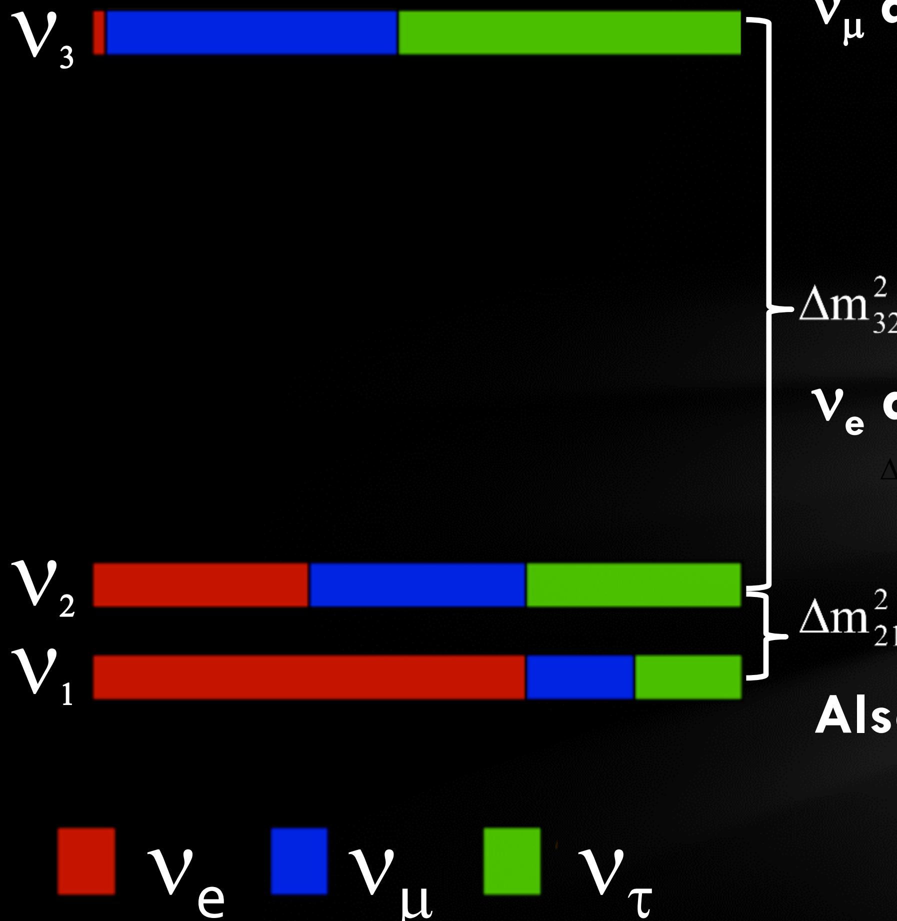
ν_e appearance

- look for ν_e appearance in a ν_μ beam
- measure θ_{13}

MINOS Physics



ν_μ disappearance & $\overline{\nu_\mu}$ disappearance

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- measure do $\overline{\nu}$ behave the same as ν?
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ν_e appearance

- look for ν_e appearance in a ν_μ beam
- measure θ_{13}

Also of Interest

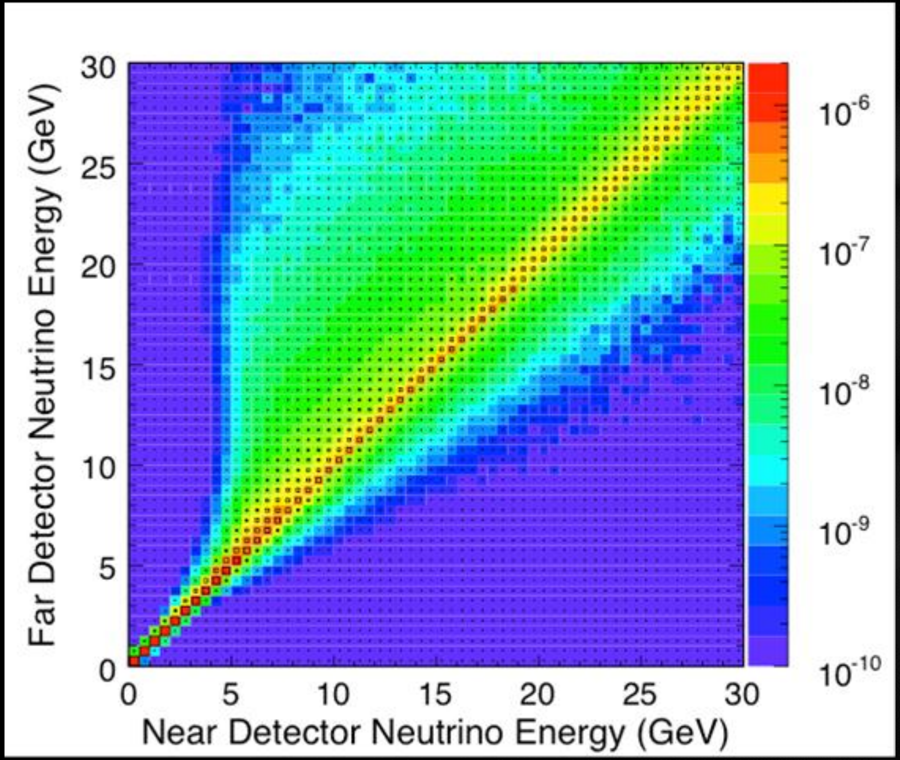
- Neutrino Velocity / Time of Flight
- Disappearance to sterile neutrinos
- Neutrino Interactions & Cross-sections
- Cosmic Rays

ν_μ & $\overline{\nu_\mu}$ Disappearance

Analysis Fundamentals

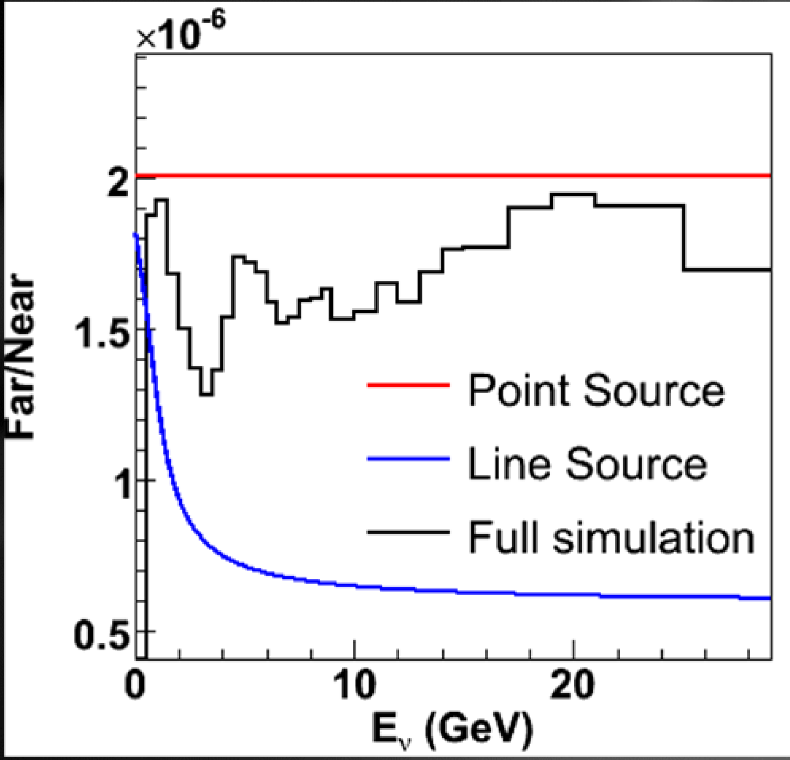
1) Measure neutrino beam spectrum and composition at a Near Detector
2) Predict/"Extrapolate" far detector spectrum

"Beam Matrix" ν_μ and $\bar{\nu}_\mu$ CC analysis



Mesons producing a particular energy at the ND, will produce a range of energies at the FD

"Far over Near" – NC and ν_e



$$F_i^{\text{predicted},\alpha} = N_i^\alpha \times \left(\frac{f_i^\alpha}{n_i^\alpha} \right)$$

Monte-Carlo

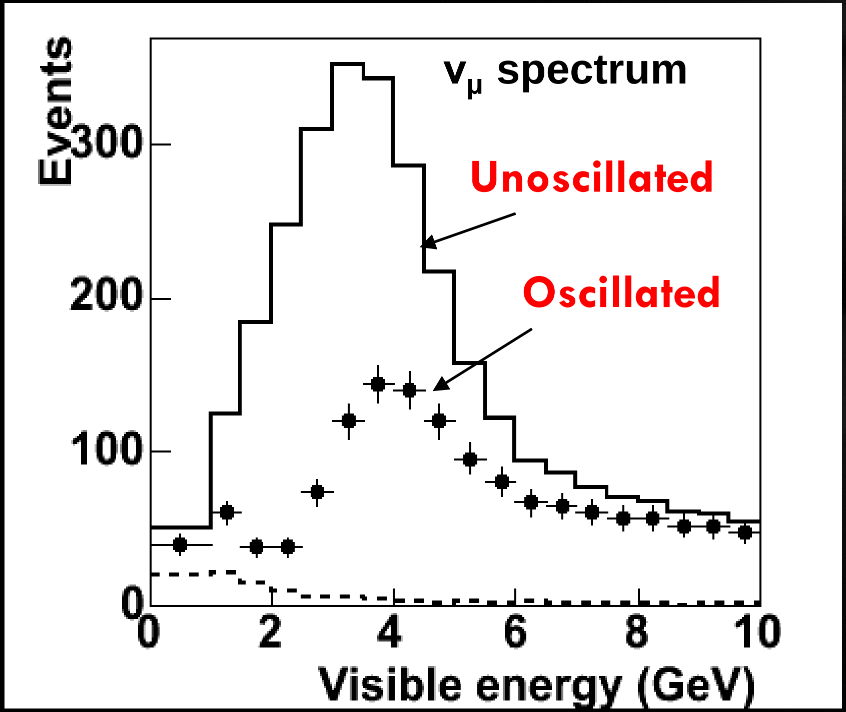
data

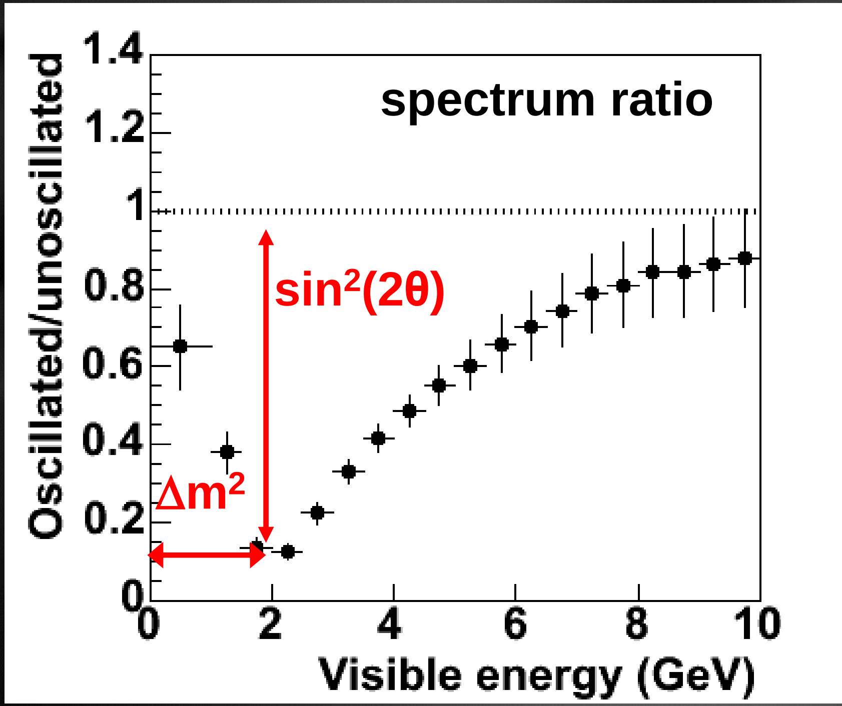
Analysis Fundamentals

1) Measure neutrino beam spectrum and composition at a Near Detector
2) Predict/"Extrapolate" far detector spectrum
3) "Open the box" and compare to different oscillation predictions

In the two flavour approximation

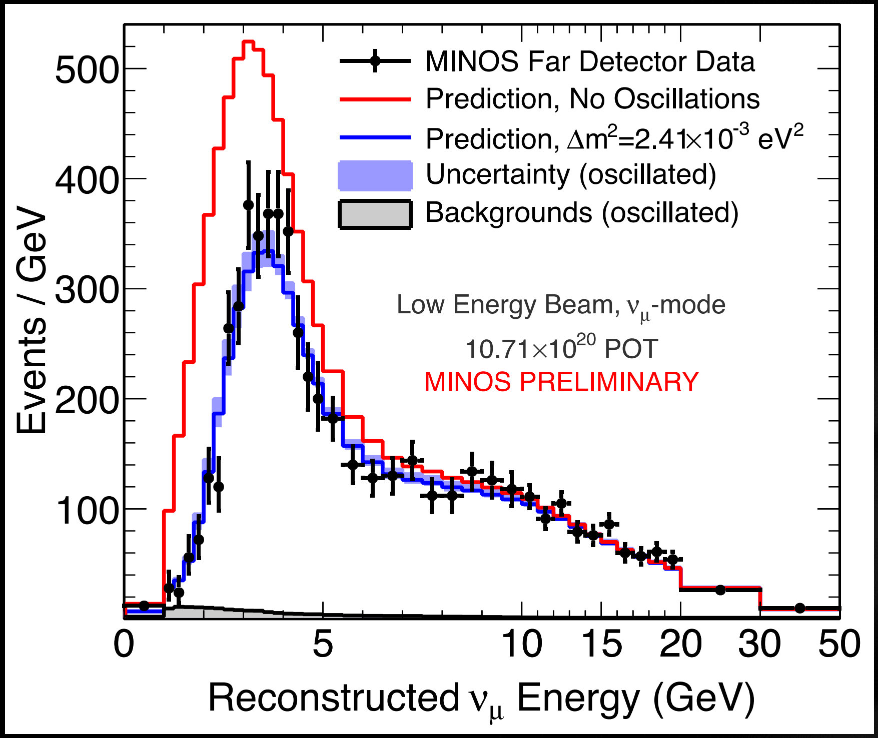
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$

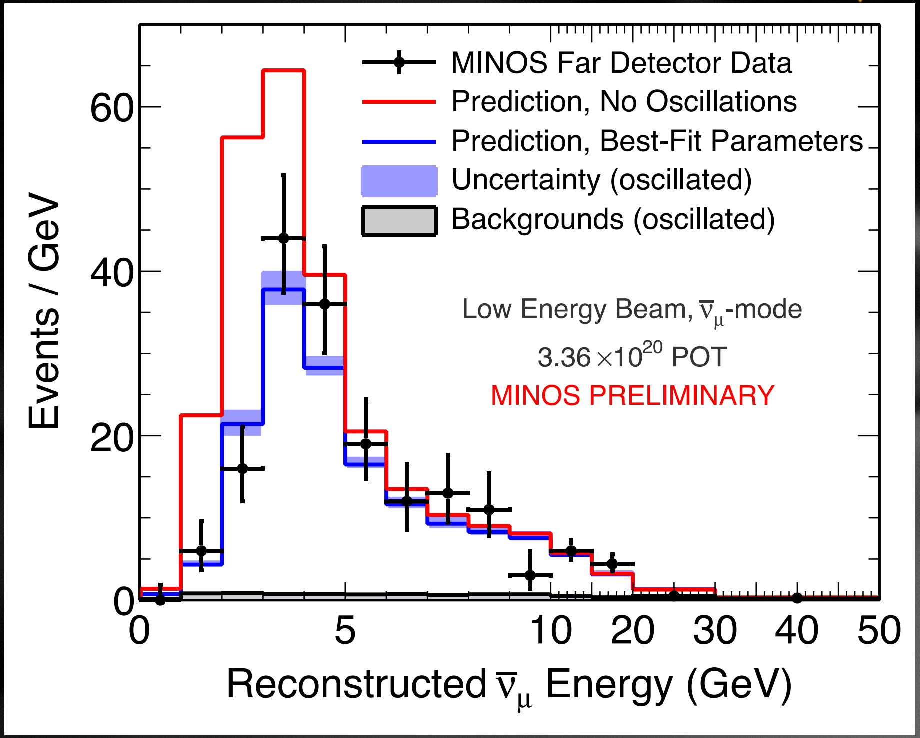




Currently developing full 3-flavour oscillation fits

Neutrino Disappearance





ν_μ disappearance

Expected (no osc.) : 3564

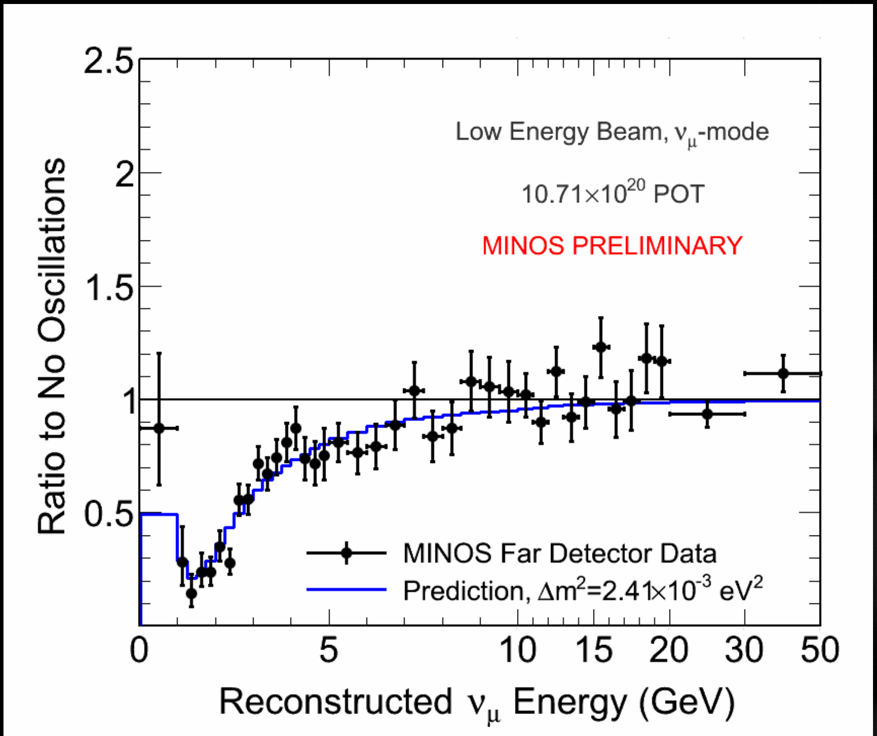
Observed : 2894

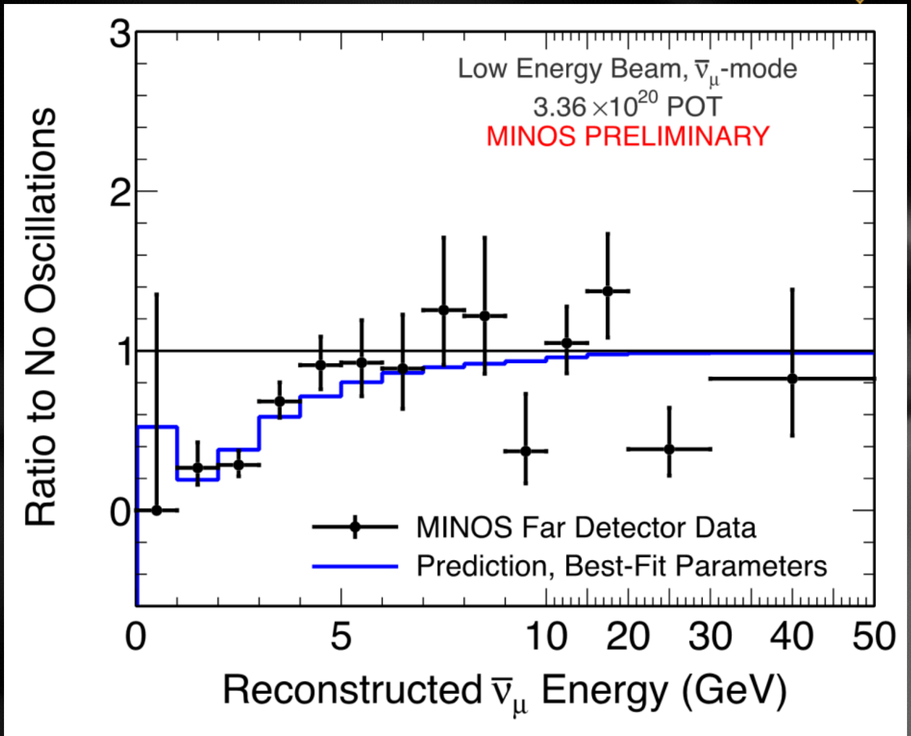
$\overline{\nu_\mu}$ disappearance

Expected (no osc.) : 312

Observed : 226

Neutrino Disappearance





ν_μ disappearance

Expected (no osc.) : 3564
Observed : 2894

$$\left|\Delta m^2\right| = 2.41^{+0.11}_{-0.10}\times10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.94^{+0.04}_{-0.05}$$

$\overline{\nu_\mu}$ disappearance

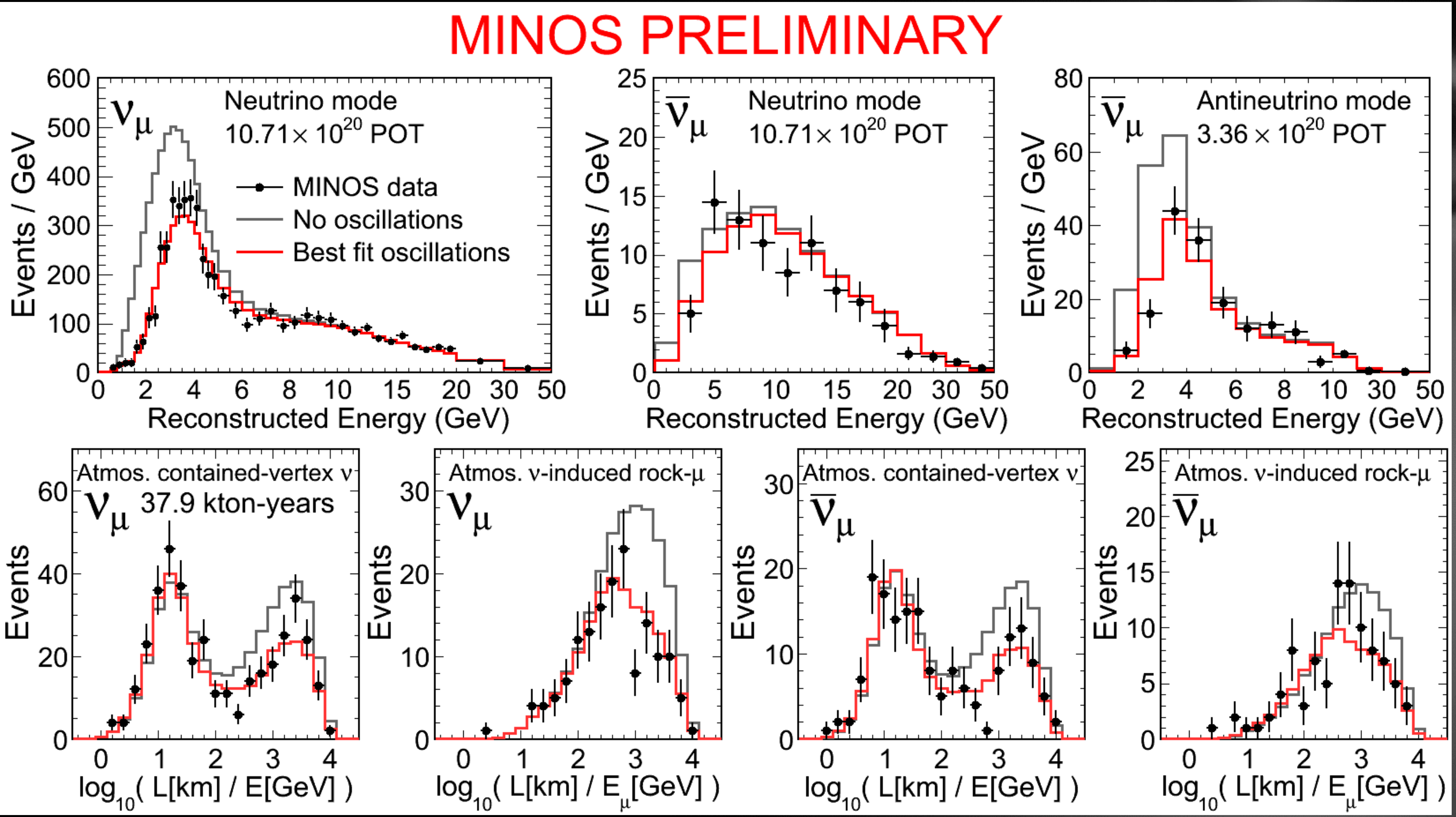
Expected (no osc.) : 312
Observed : 226

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

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

Beam and Atmospheric Data

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



Combined Contours

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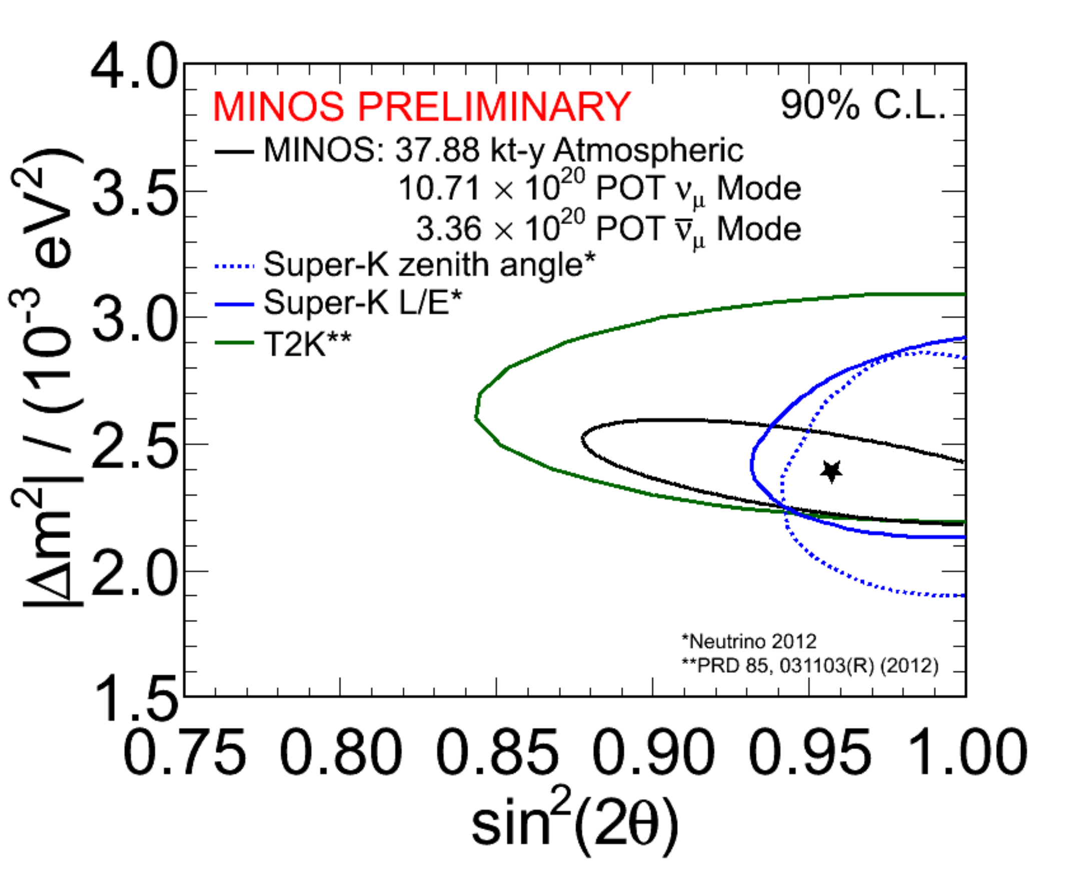


Assuming neutrinos are equivalent to anti-neutrinos

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

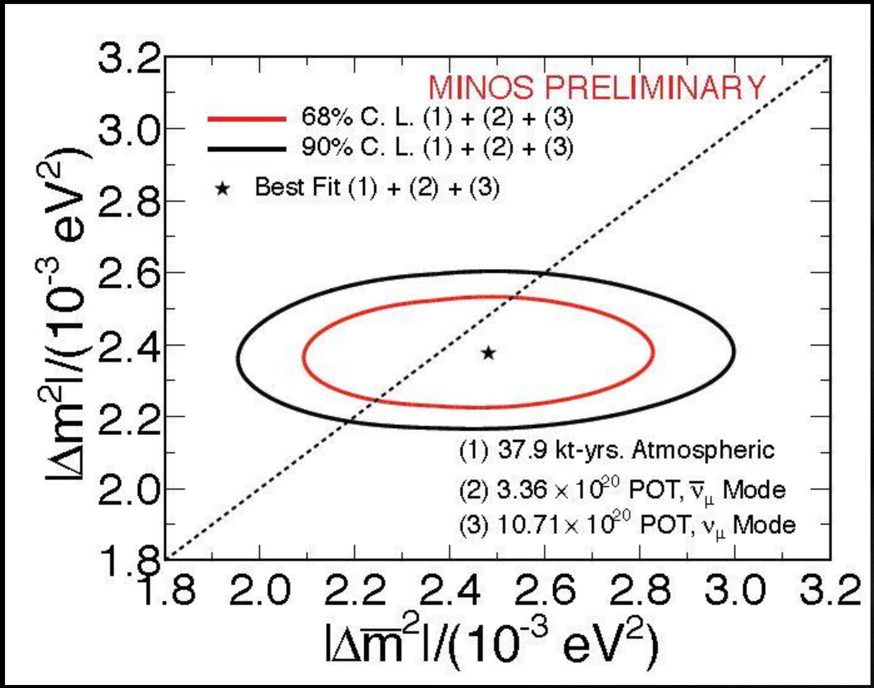
$$\sin^2(2\theta) = 0.957^{+0.035}_{-0.036}$$

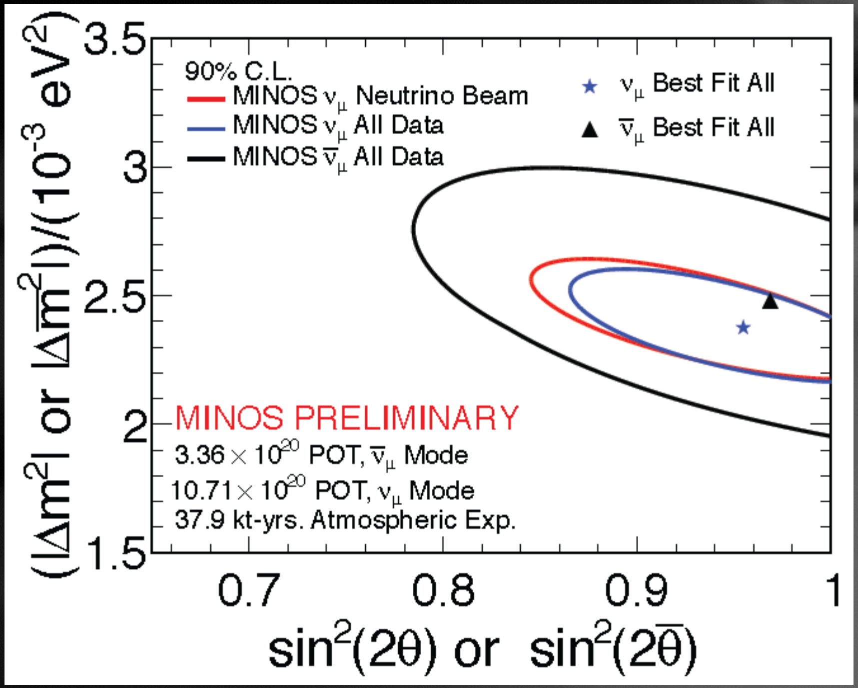
$$\sin^2(2\theta) > 0.90\ (90\%\ \mathrm{C.L.})$$

Now favour non-maximal mixing !

Neutrino vs Anti-neutrinos

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



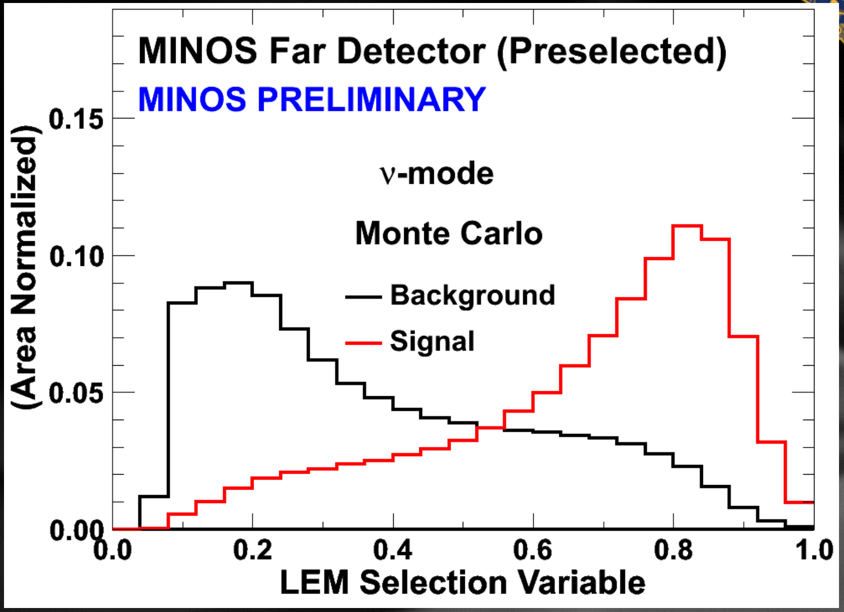


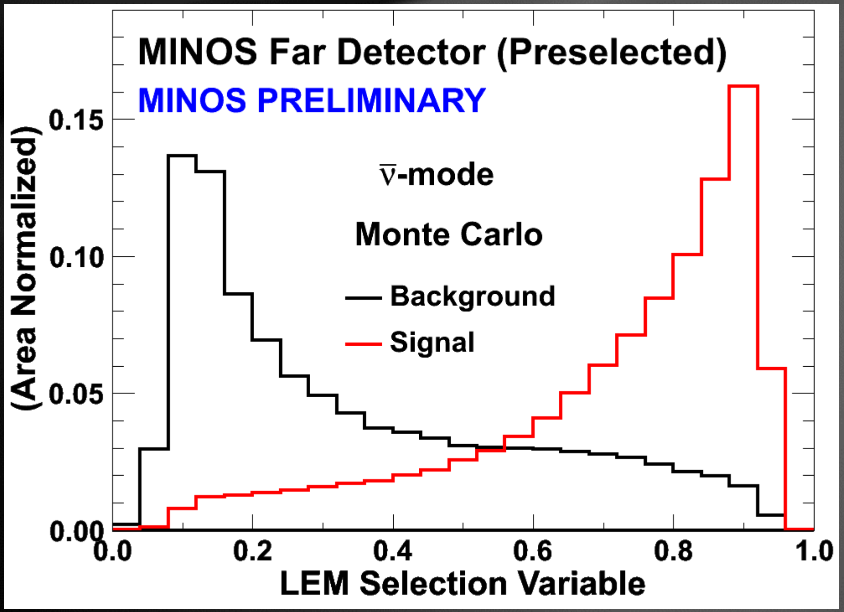
The new data resolves the previous tension between neutrino & antineutrino parameters

ν_e **Appearance**

ν_e Particle ID

- Detector granularity makes it difficult to identify ν_e events in MINOS
- Compare observed event to large library of Monte-Carlo signal and background events
- 3 variables describing best matches + reconstructed energy used as inputs to a neural net→ LEM
- Vary beam configuration to determine composition at ND
  - ➢ components extrapolate to FD differently





ν_e Appearance

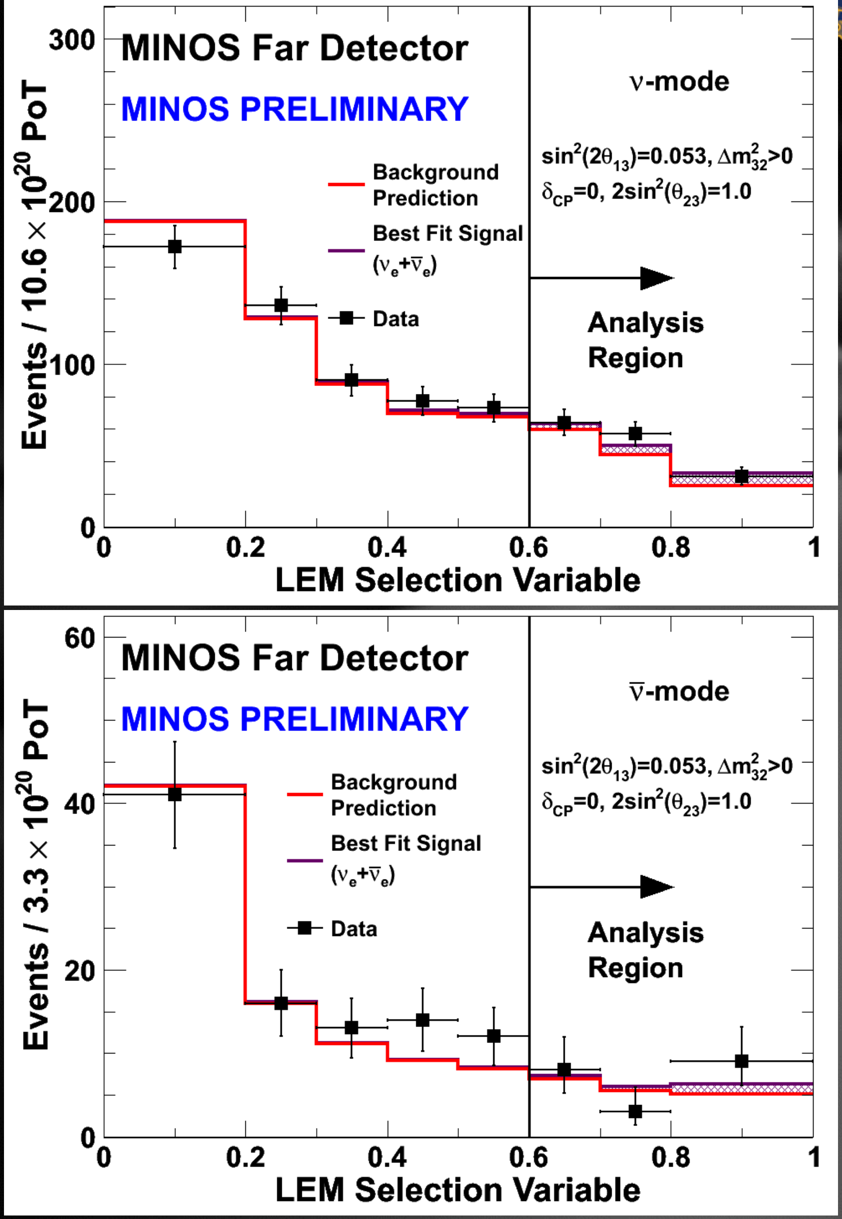
Neutrino Beam

- Expect 128.6(+32.5) events
- Observed: 152 events

Antineutrino Beam

- Expect 17.5(+3.7) events
- Observed: 20 events

Signal prediction for normal hierarchy and $\sin^2(2\theta_{13})=0.1$, $\delta_{CP}=0$



ν_e Appearance

Fitting neutrinos and anti-neutrinos to the same oscillation parameters

Best Fit Parameters (δ=0)

Normal Hierarchy

$$2\sin^2(2\theta_{13})\sin^2\theta_{23} = 0.053$$

$$0.01 < 2\sin^2(2\theta_{13})\sin^2\theta_{23} < 0.12 \text{ at } 90\% \text{ C.L.}$$

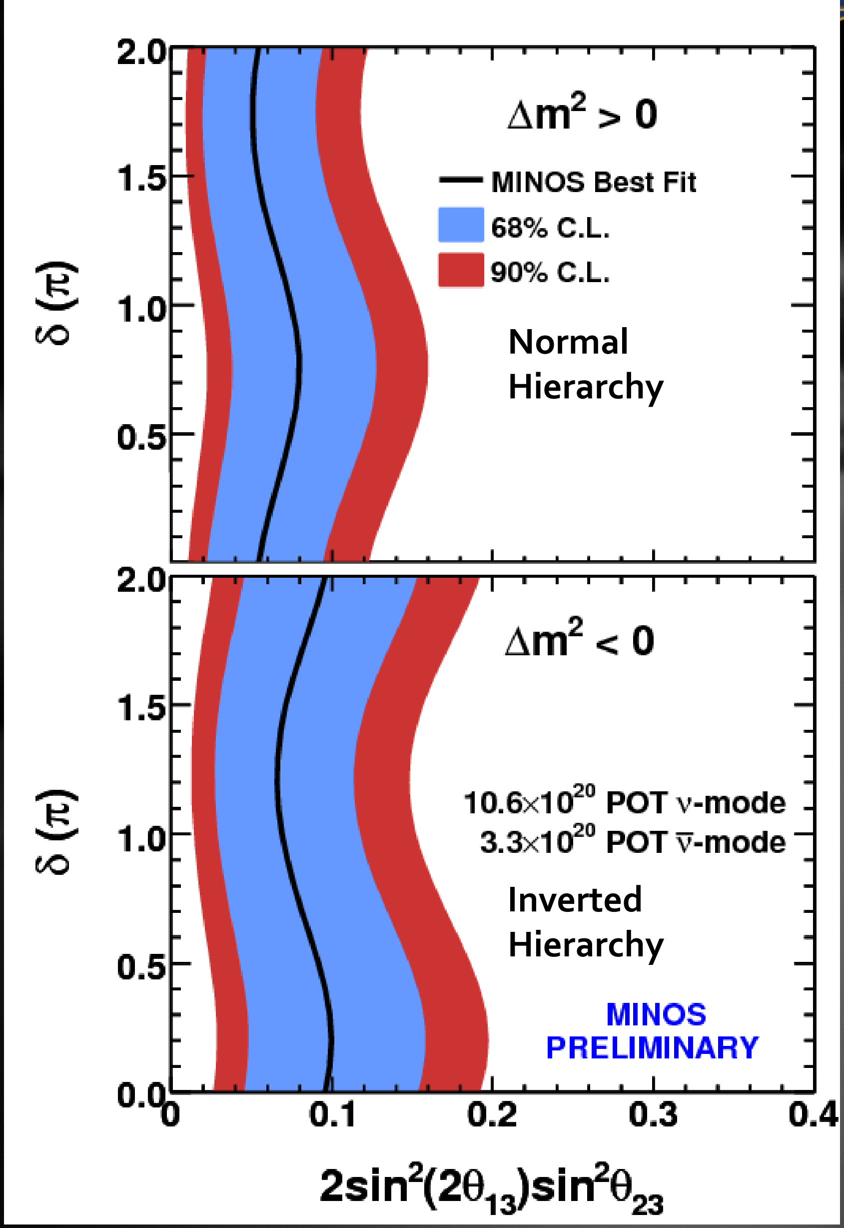
Inverted Hierarchy

$$2\sin^2(2\theta_{13})\sin^2\theta_{23} = 0.094$$

$$0.03 < 2\sin^2(2\theta_{13})\sin^2\theta_{23} < 0.19 \text{ at } 90\% \text{ C.L.}$$

θ_{13}=0 excluded at 96% CL

Using the reactor best fit, we have a slight preference for inverted hierarchy at $-2\Delta\ln L$=0.2



MINOS+

MINOS+

MINOS+ : Running the MINOS experiment in the NOvA beam

700kW beam (vs 350kW), decreased rep rate, and slightly higher energy

~ 4000 ν_μ CC events/year (vs 4000 events total) at the Far Detector

also expecting 80ν_τ CC events/year but lots of background.

Will start in 2013 and run for 3 years (18E20POT+30kton·years).

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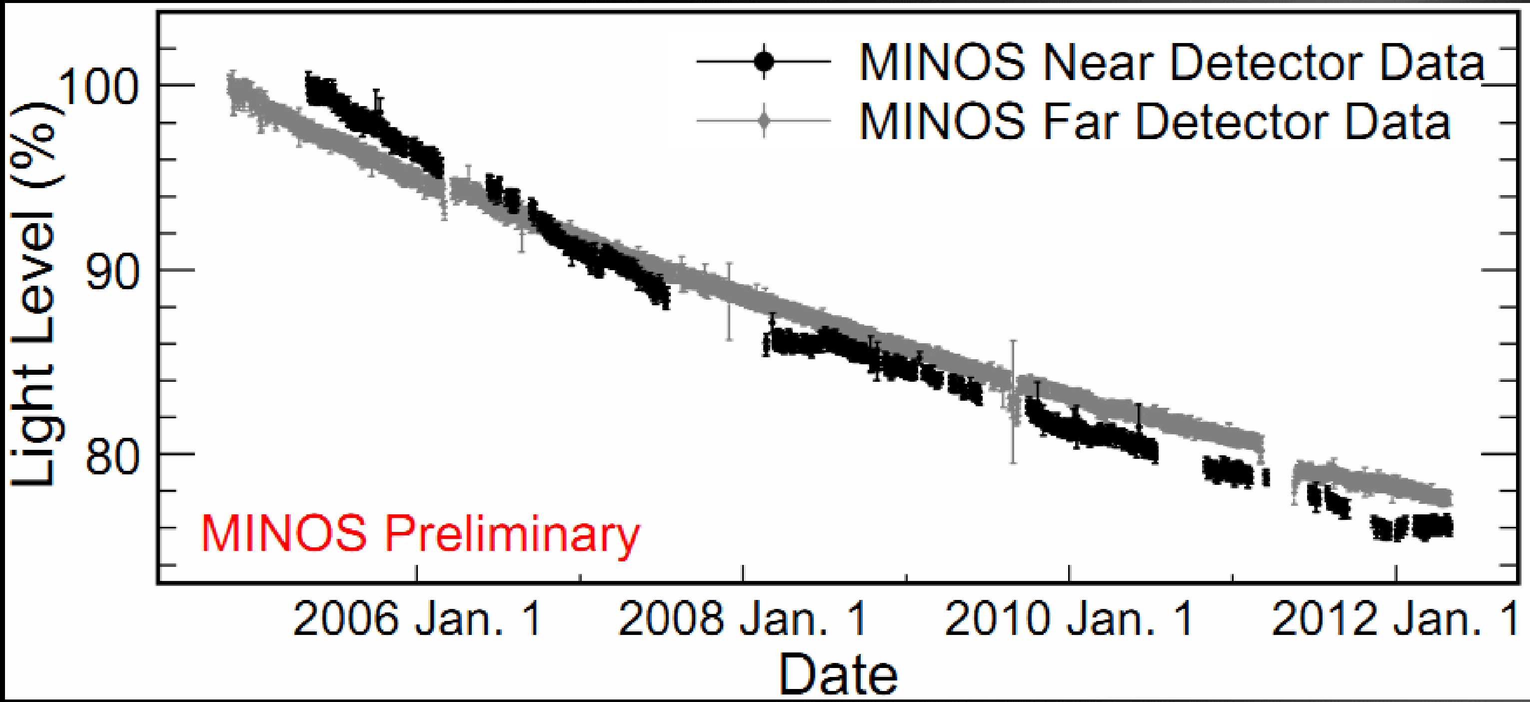
Detectors are, and will continue to be, well behaved

no evidence of track loss due to decreased light level



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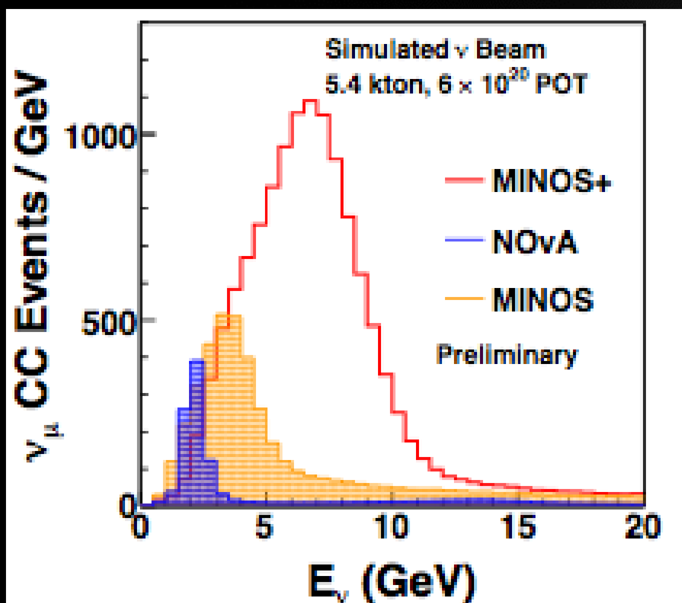
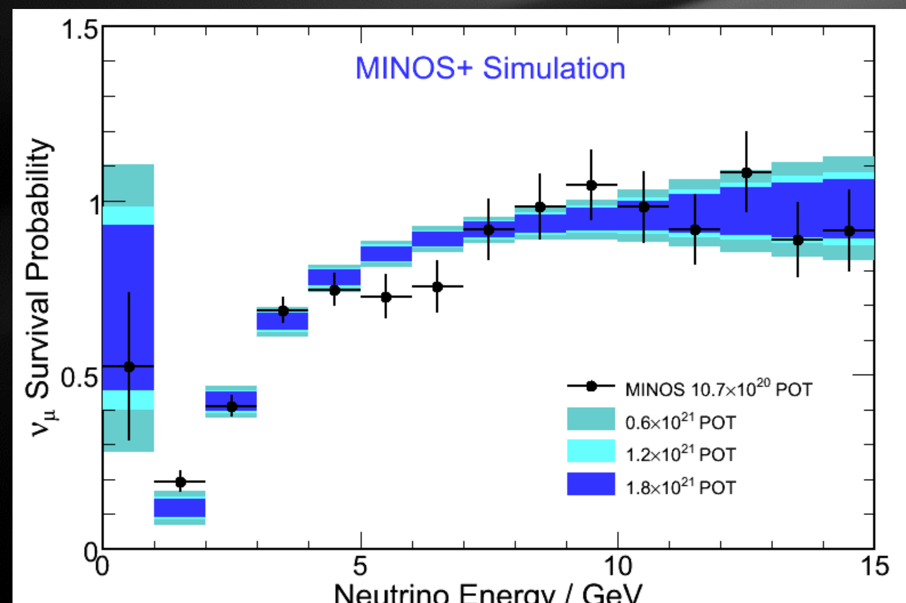
Probe previously unexplored energy region with high statistics & charge determination

high energy "tail" is sensitive to exotic physics: Sterile, NSI, extra dimensions

More precisely measure atmospheric mixing parameters.

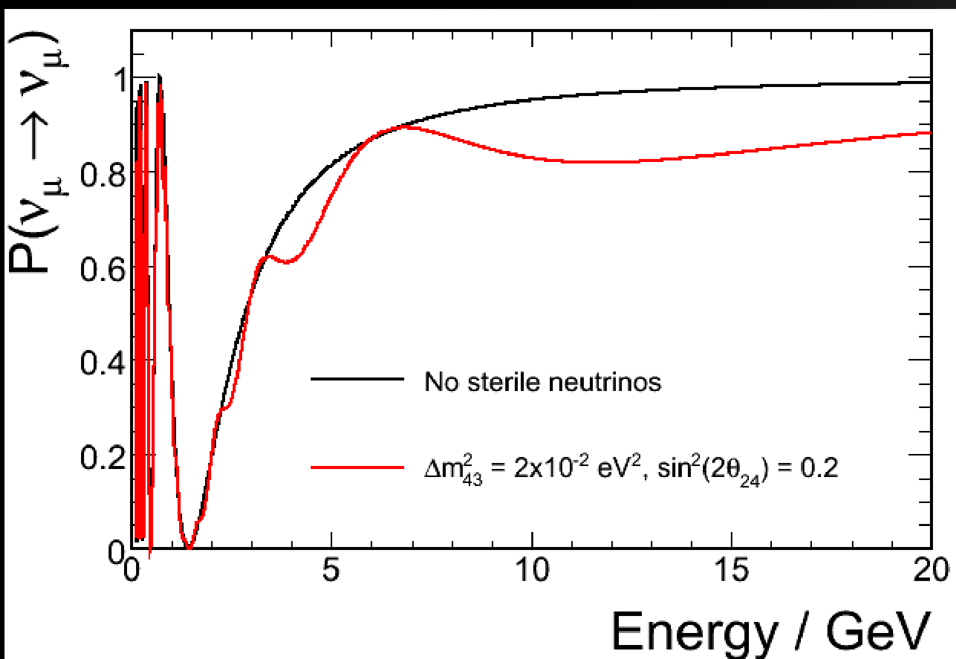


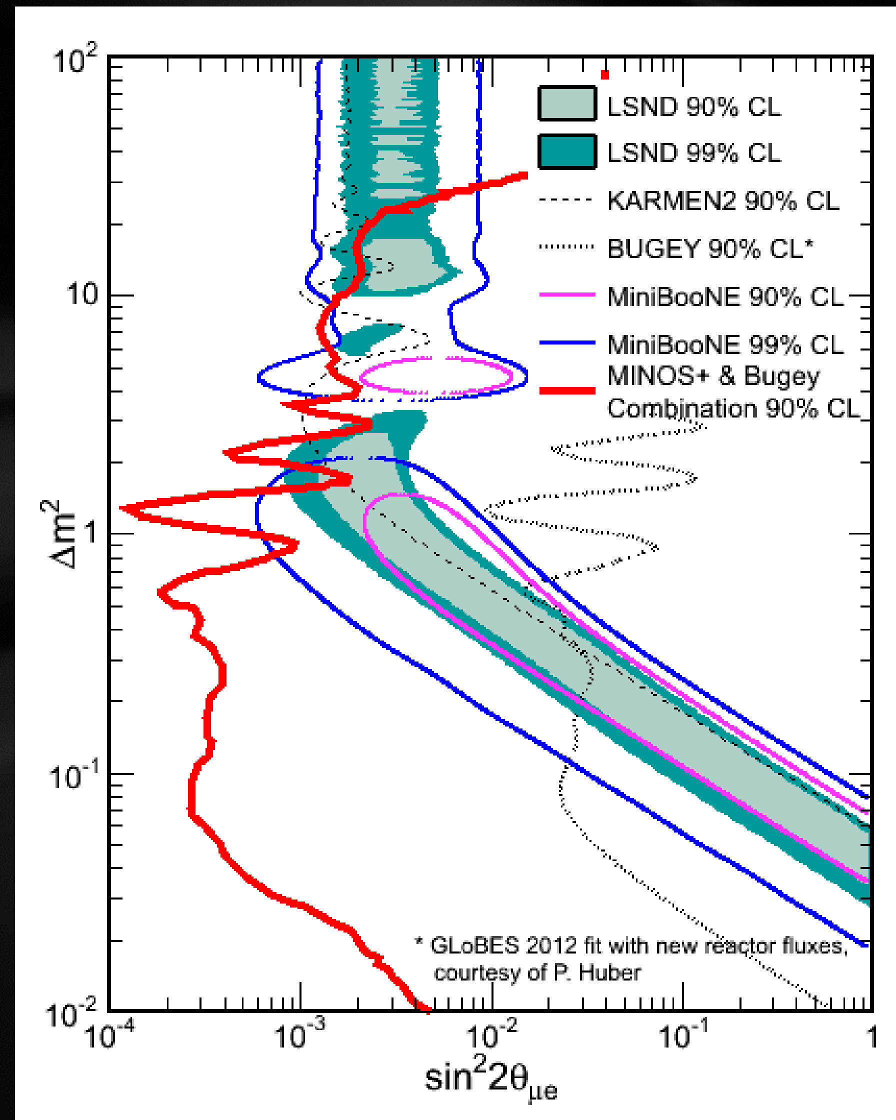


MINOS+

MINOS+ is particularly sensitive to a sterile neutrino which modifies the standard oscillation probabilities at high energy

By using complementary information from sterile neutrino searches at the Bugey reactor experiment and MINOS+ we can almost rule out the allowed low mass LSND region





CONCLUSION

The MINOS experiment has finished a very successful 7 year run, collecting over 15E20 protons on target

Near To Final Results

- ✓ MINOS has produced the most precise measure of the neutrino and anti-neutrino mass splitting
- ✓ Muon neutrino disappearance now favours non-maximal mixing
- ✓ Muon anti-neutrino disappearance is now in good agreement with neutrino disappearance.
- ✓ Electron neutrino appearance exclude $\theta_{13}=0$ at 96% CL
- ✓ Three flavour fit is in progress.

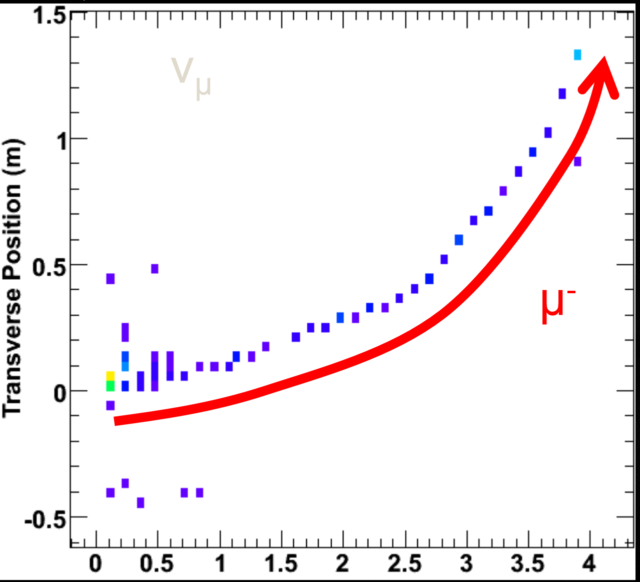
MINOS + will probe oscillation models narrowband beams cannot

http://www-numi.fnal.gov/MinosResults/index.html
http://www-numi.fnal.gov/pr_plots/index.html

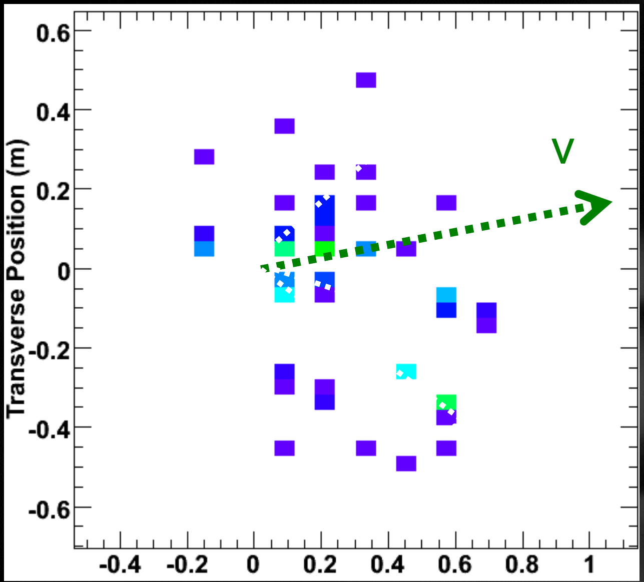
Thank You !

Neutrino Events in MINOS

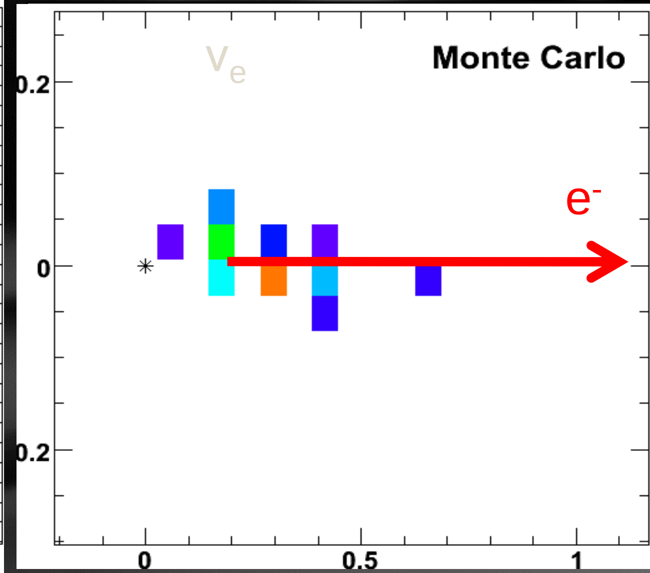
ν_μ Charged Current Event



Neutral Current Event



ν_e CC Event



<u>Charge Current Event</u>

Hadronic shower at vertex + long muon track

<u>Neutral Current Event</u>

Short hadronic shower, quite diffuse

<u>ν_e Charge Current Event</u>

Short track with electromagnetic energy profile

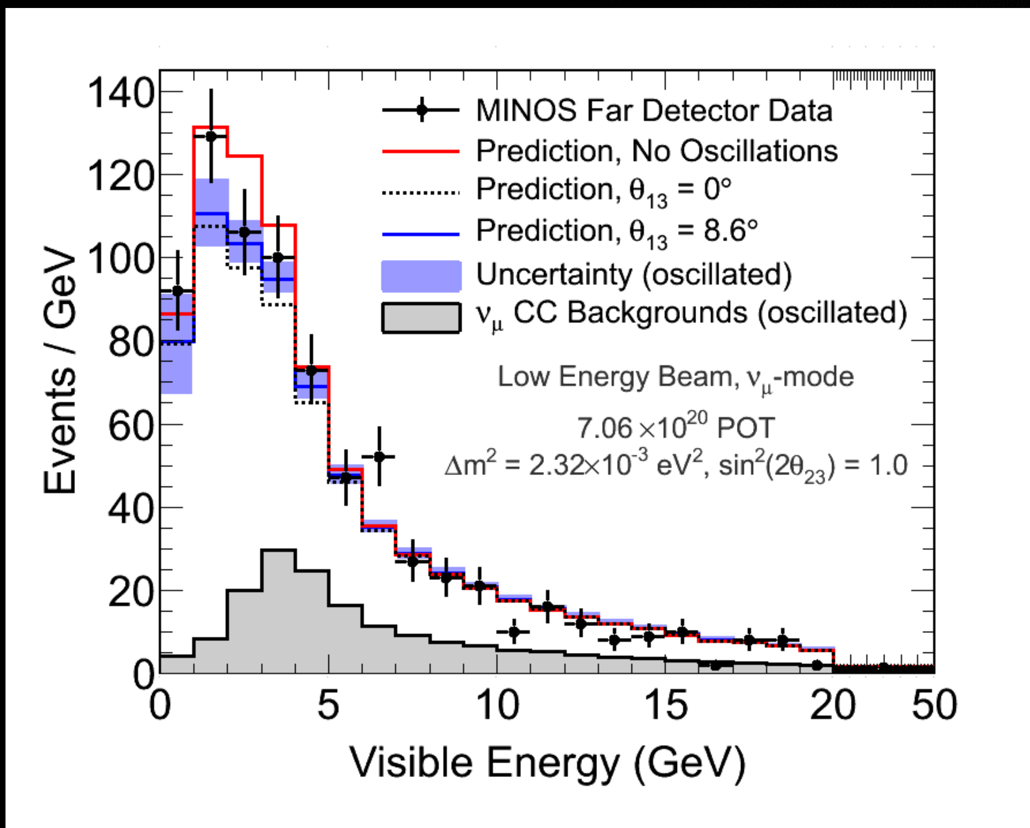
Neutral Current Search

ν_μ to ν_e oscillations will modify the number of showers observed at the Far Detector

→ ν_e CC events may be misinterpreted at Neutral Current events.

MINOS has revisited its NC measure in light of the recent θ_{13} measurement

Constraints on mixing to sterile neutrinos weakens slightly



Full 3 flavour oscillations modelled

E_{reco} (GeV)	N_{Data}	S_{NC}	$B^{\nu_\mu}_{CC}$	$B^{\nu_\tau}_{CC}$	$B^{\nu_e}_{CC}$
0 – 3	327	245.6	32.5	3.2	2.7 (12.4)
3 – 200	476	267.8	157.4	9.3	30.6 (44.7)
0 – 200	803	513.4	190.0	12.5	33.2 (57.0)
0 – 3	$R = 1.14 \pm 0.07 \pm 0.08$				
3 – 200	$R = 0.99 \pm 0.08 \pm 0.06$				
0 – 200	$R = 1.06 \pm 0.06 \pm 0.06$				

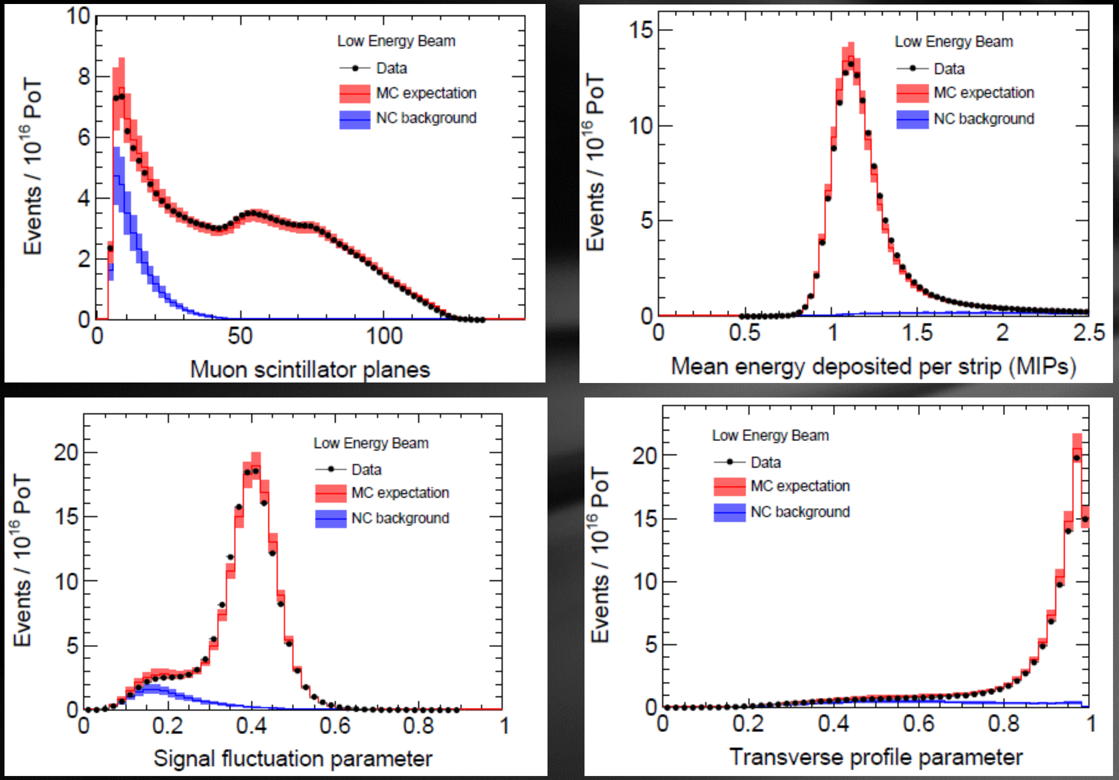
MINOS Particle Identification

CC/NC separation is done using a nearest-neighbour algorithm(kNN) with 4 inputs

- ❑ Track Length(# of planes)

For Hits on the track

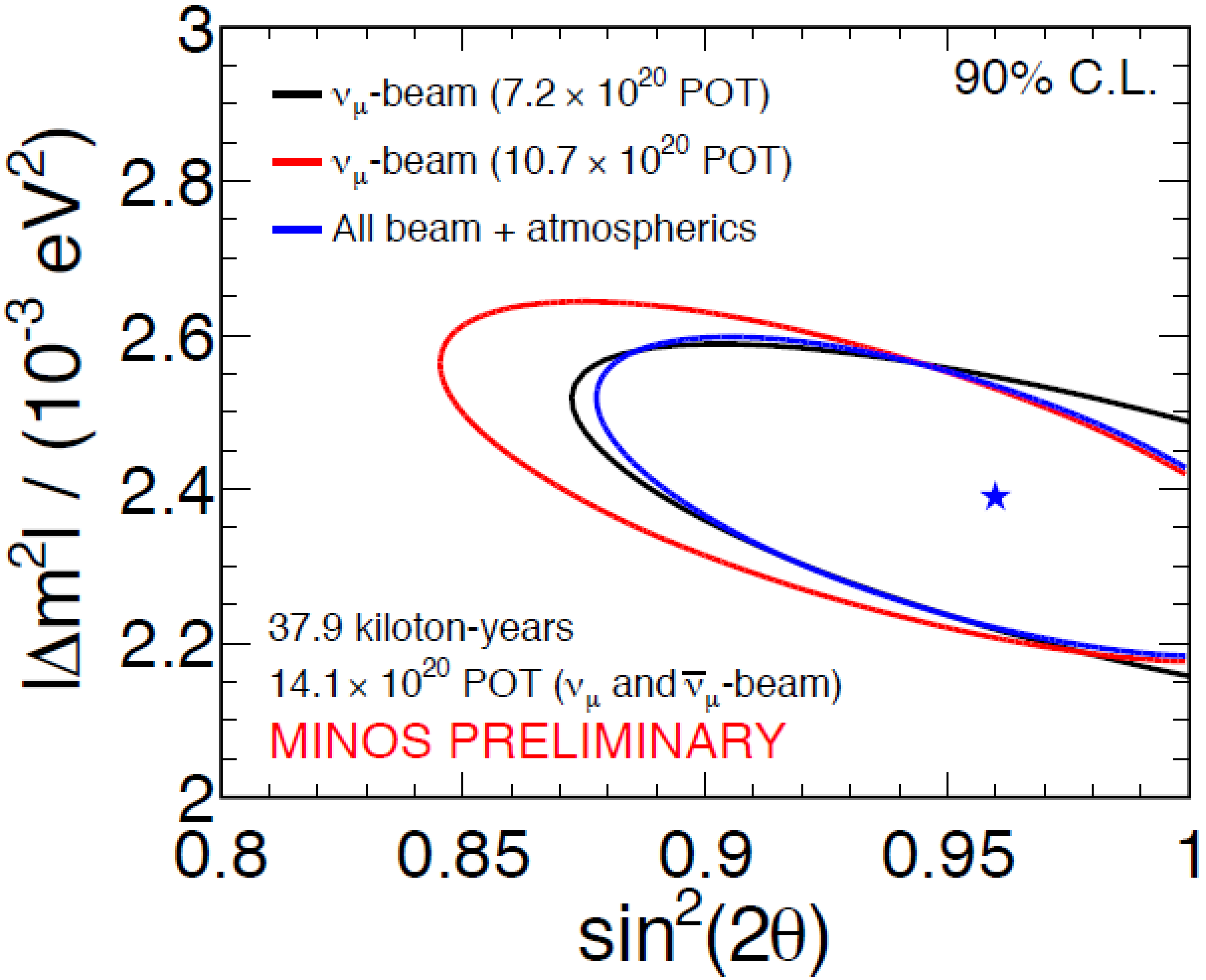
- ❑ Mean Pulse Height
- ❑ Fluctuation in Pulse Height
- ❑ Transverse Track Profile



Anti-neutrino analysis requires an additional selection on muon charge sign !

Contours

Adding in the extra data and the atmospherics



New MINOS neutrino oscillation parameters:

$$\Delta m^2 = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

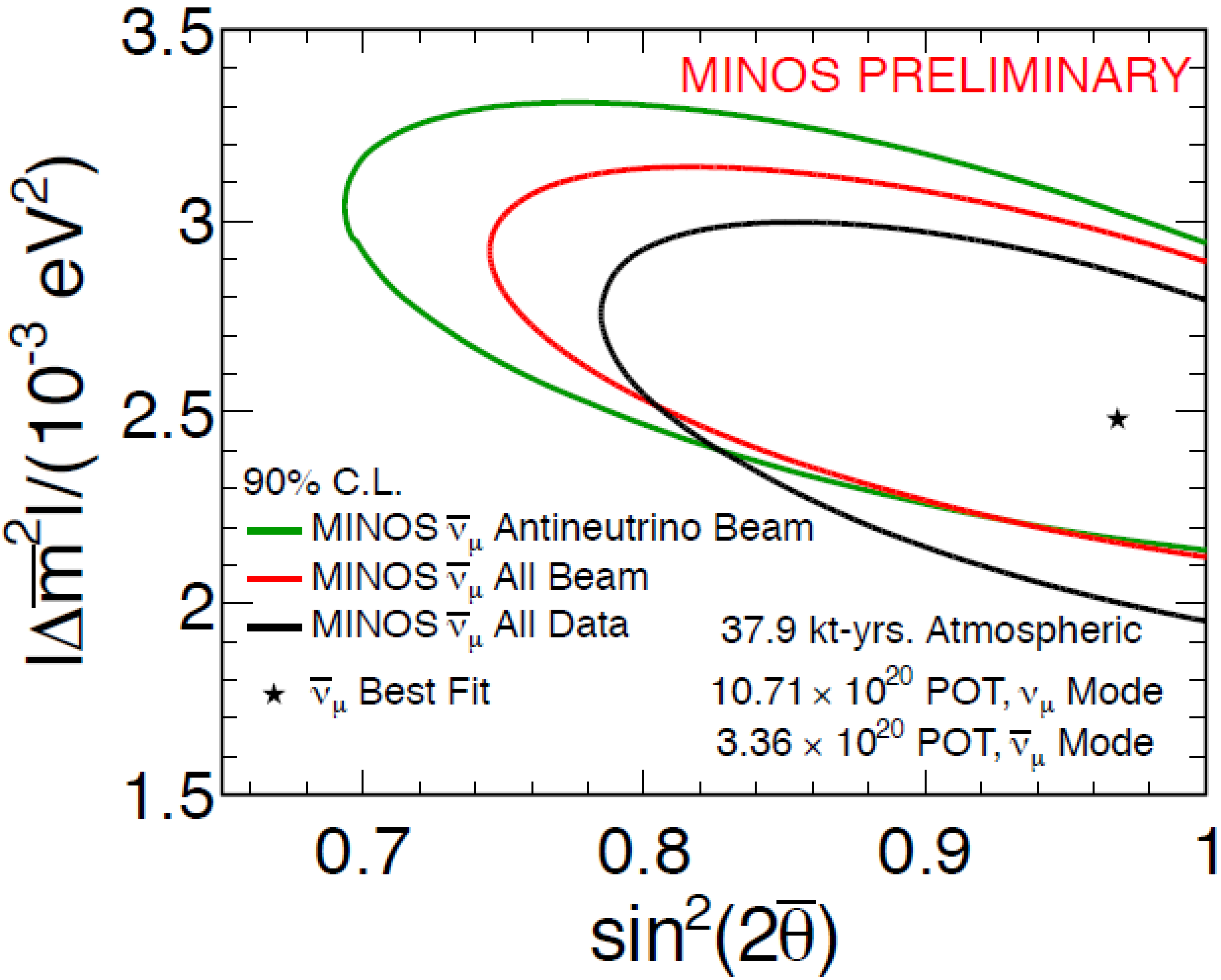
$$\sin^2(2\theta) = 0.96^{+0.04}_{-0.04}$$

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

New

Antineutrino Contours

Beam and Atmospherics



New MINOS antineutrino oscillation parameters:

$$|\Delta\overline{m}^2| = 2.48^{+0.22}_{-0.27} \times 10^{-3} eV^2$$

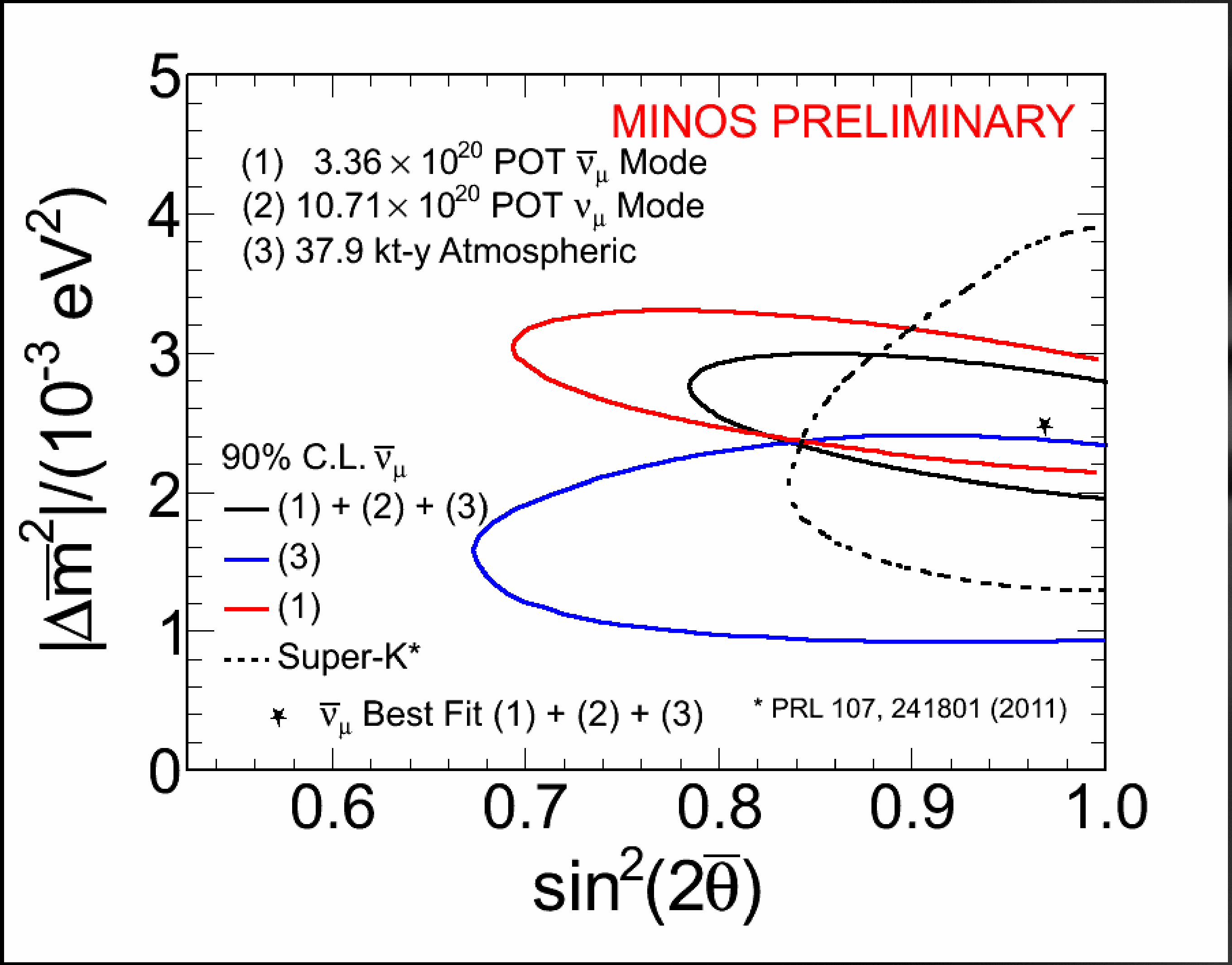
$$\sin^2(2\overline{\theta}) = 0.97^{+0.03}_{-0.08}$$

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

New

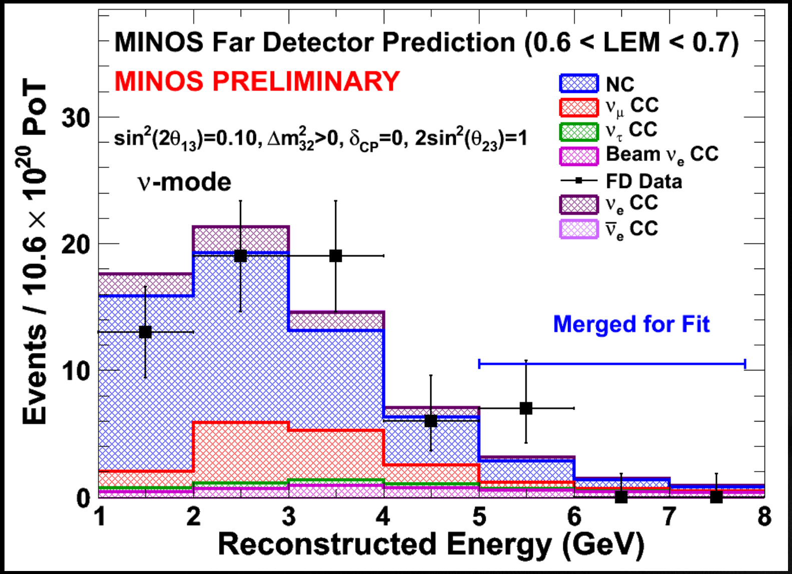
See Poster

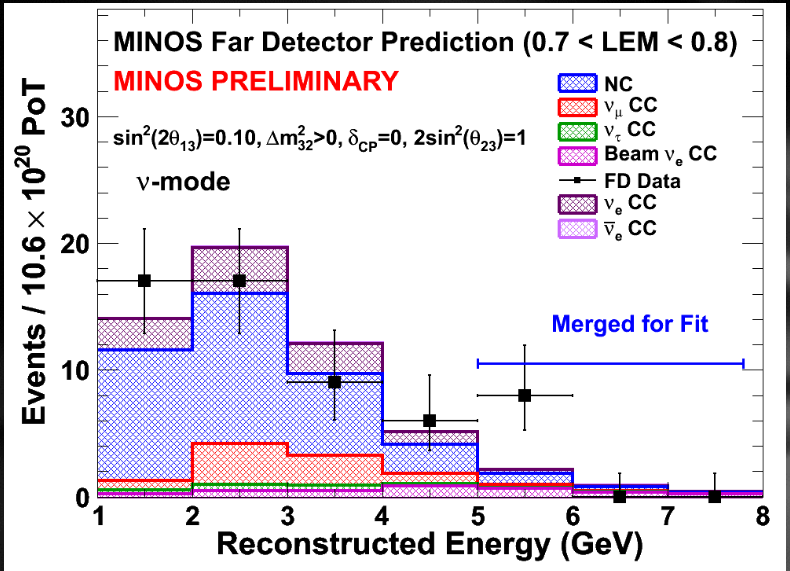
Anti-neutrino Contours

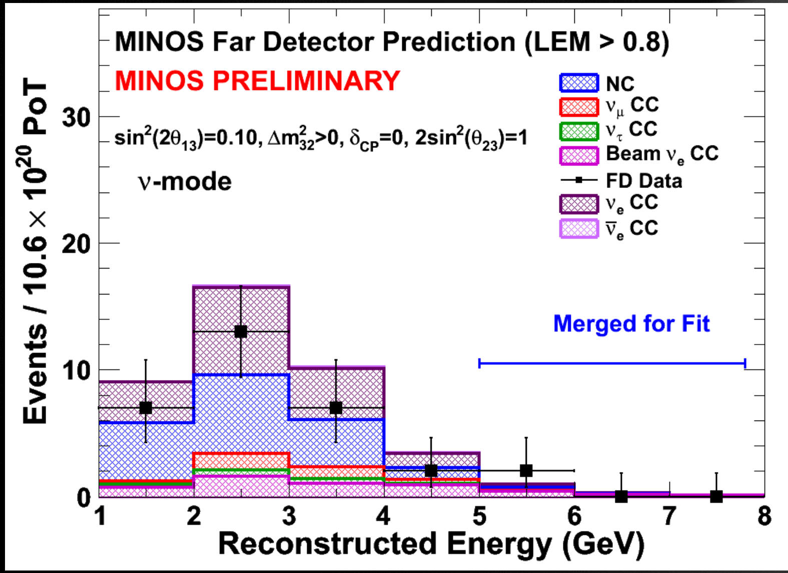


MINOS can identify anti-neutrinos on an event by event basis.

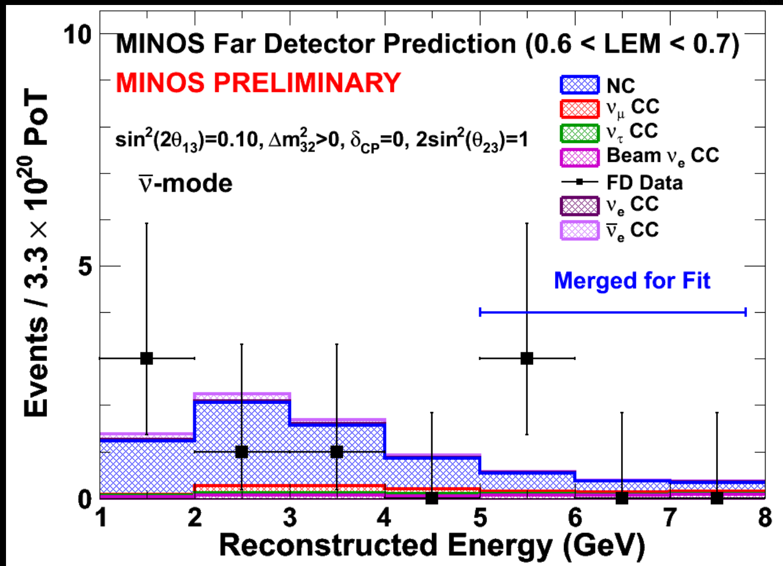
ν_e Appearance Spectrum

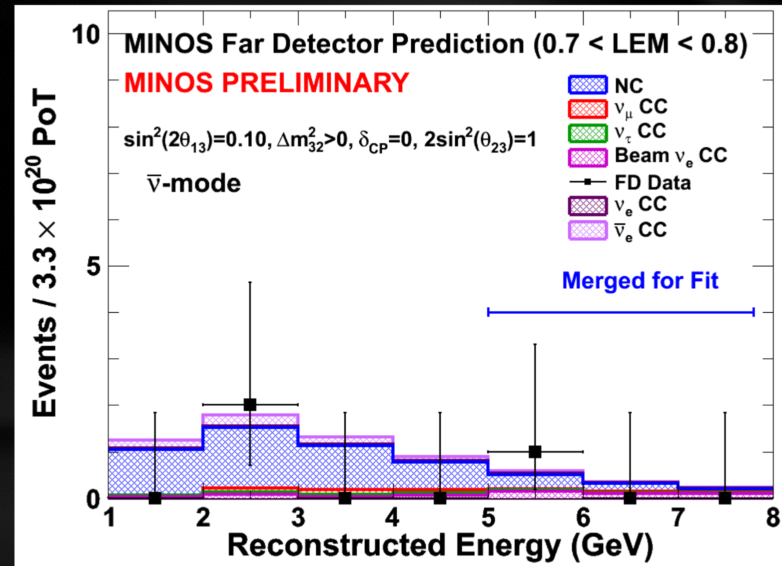


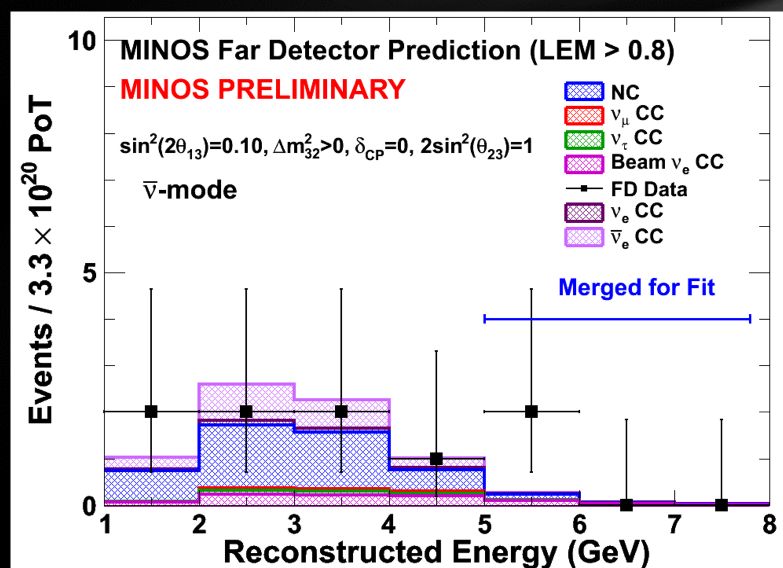




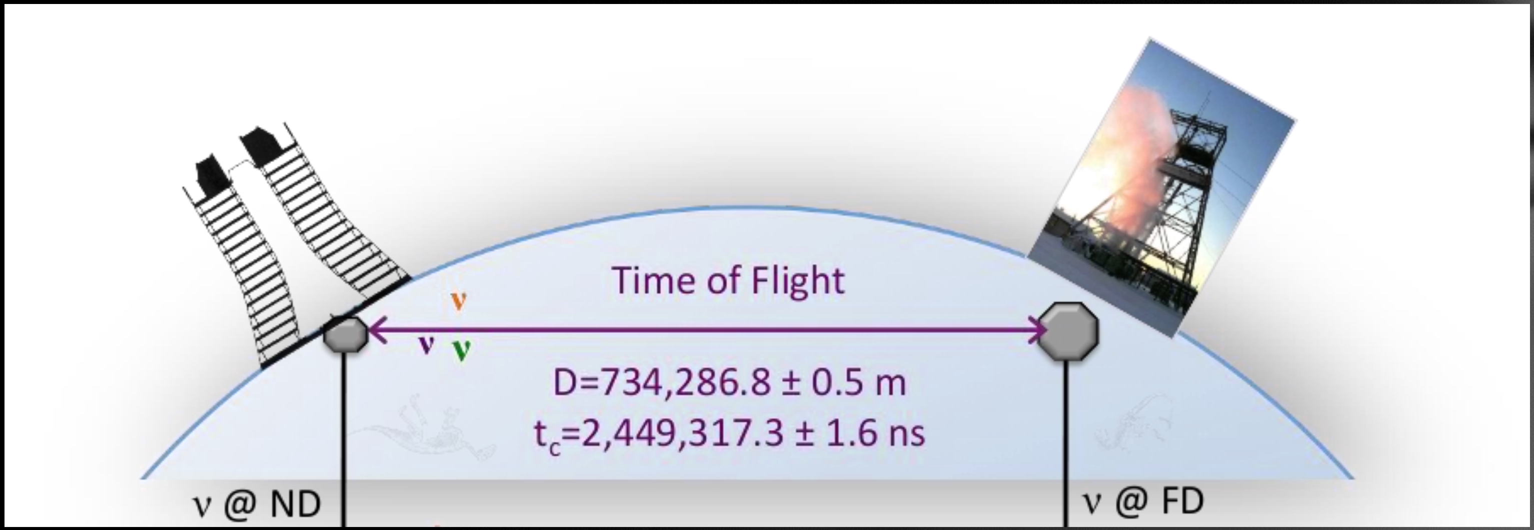
$\overline{\nu}_e$ Appearance Spectrum





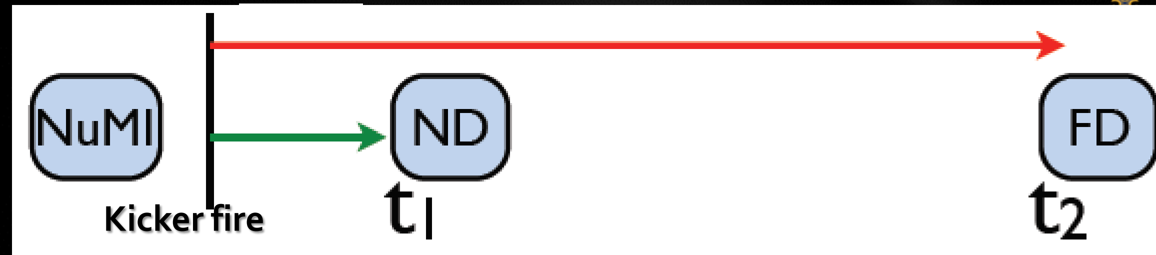


Time Of Flight

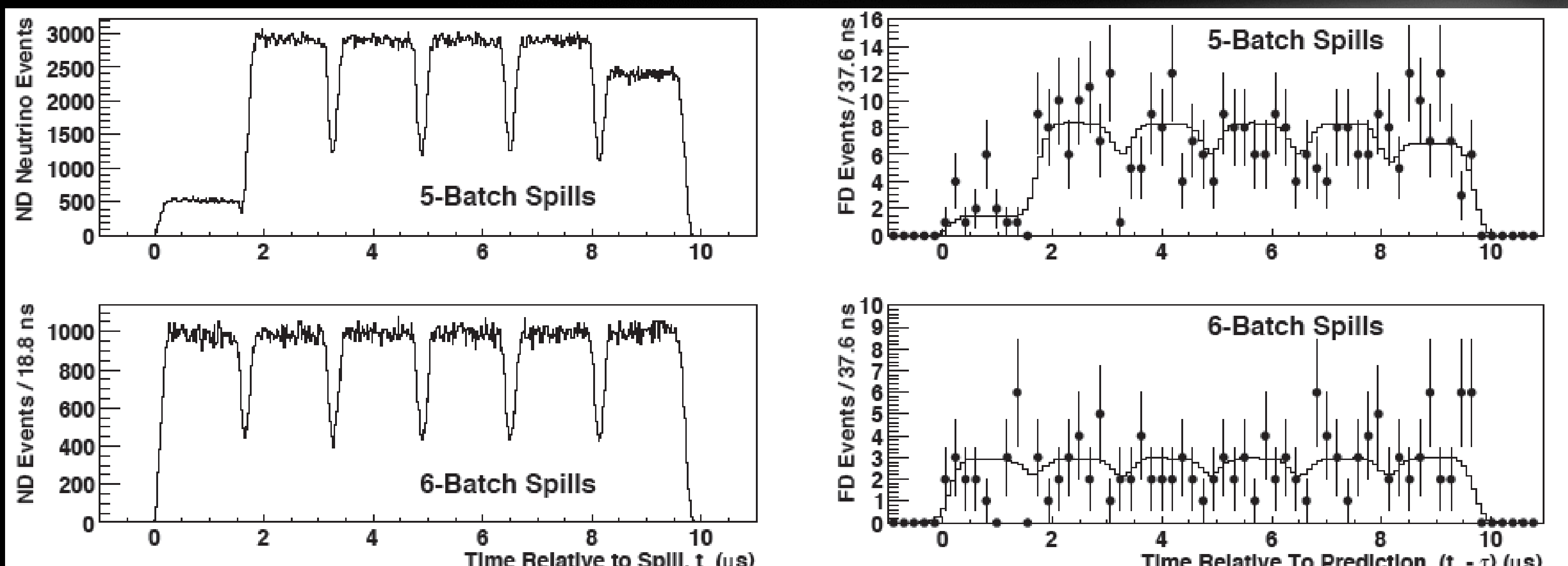


MINOS TOF circa 2007

MINOS made a time of flight measurement in 2007 using 473 events in the far Detector
Phys. Rev D76(2007) 072005



MINOS is a neutrino to neutrino measurement(mitigates beam timing errors)



The MINOS neutrino events mimic the structure of the beam, that is:

- 10 μs spill event 2 seconds with five or six 1.6μs batches with <u>100 ns gaps</u>

MINOS TOF circa 2007

MINOS made a time of flight measurement in 2007 using 473 events in the far Detector
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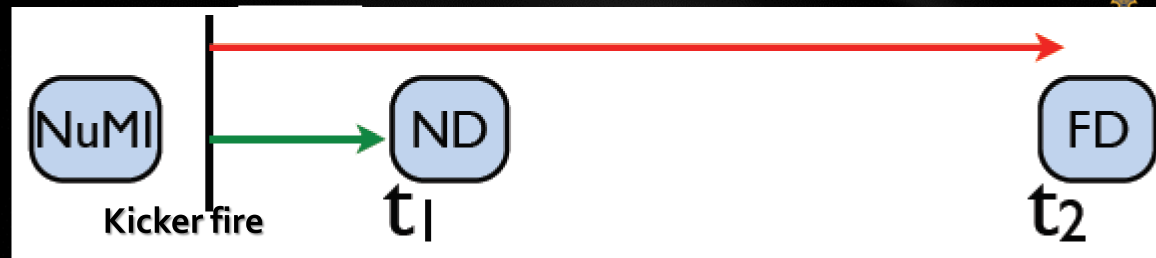


MINOS is a neutrino to neutrino measurement(mitigates beam timing errors)

	Description	Uncertainty (68% C.L.)
A	Distance between detectors	2 ns
B	ND Antenna fiber length	27 ns
C	ND electronics latencies	32 ns
D	FD Antenna fiber length	46 ns
E	FD electronics latencies	3 ns
F	GPS and transceivers	12 ns
G	Detector readout differences	9 ns
	Total (Sum in quadrature)	64 ns

MINOS " 1st " Results

$$\mathrm{TOF}_c - \mathrm{TOF}_\nu = 126 \pm 32(stat.) \pm 64(syst.)ns$$

$$\frac{v-c}{c} = (5.1 \pm 2.9) \times 10^{-5}$$

The measurement is limited by systematic errors, and efforts are underway to reduce all these uncertainties !

MINOS TOF Retrospective

- Added portable detectors for use at both sites: measure muons coincident with MINOS to get relative electronic delays.
- Added multiple good GPS units and careful monitor of time dependence of delays.
- Careful study of existing GPS, ND readout and delays of existing cables

NuMI neutrinos span a 10 us spill

- spill subdivided into 1.619 us batches
- 95 ns gap between batches, 81 bunches/batch

Full spill approach

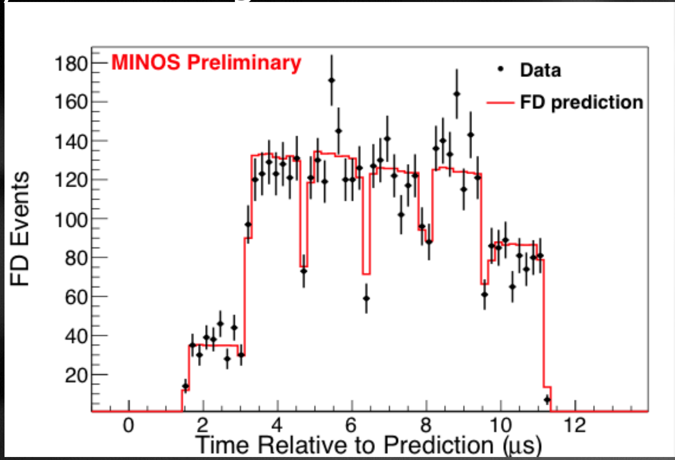
- Use event time within spill distribution in ND to predict FD distribution
- Vary time of flight to match prediction to data

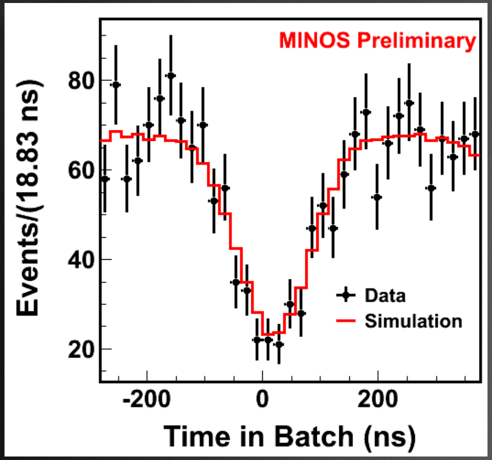
Earlier by 18 ± 11 (stat.) ± 29 (syst.) ns

Wrapped Spill approach

- Measure event time within batch
- Find time of the gap between batches in each detector
- Subtract gap times to find time of flight

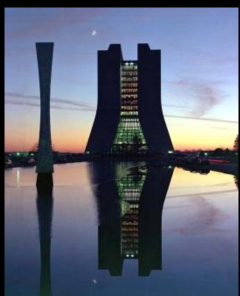
Earlier by 11 ± 11 (stat.) ± 29 (syst.) ns





Cable Delays

The length of the optical fiber connecting the GPS antenna to the GPS receiver underground is the largest systematic error …….. But is also the easiest to reduce



Resurvey to provide more accurate length measurements

Measurements are now complete, with errors on the order of 1-2 ns

~110 m shaft

~700 m shaft

Fibre optic cable

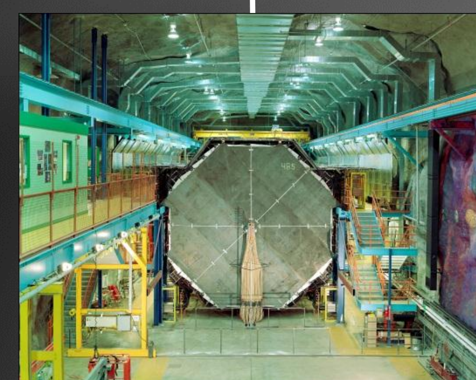
27 ns

Fibre optic cable

46 ns

Near Detector, Fermilab

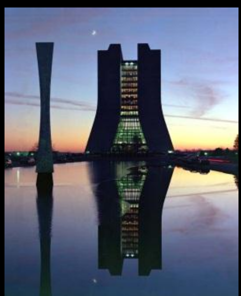
Far Detector, Soudan



GPS timing

- There is currently a 12-25ns uncertainty on inter-detector offset

… and ~100ns random jitter in the system.



Using TWSTT

~110 m shaft

~700 m shaft

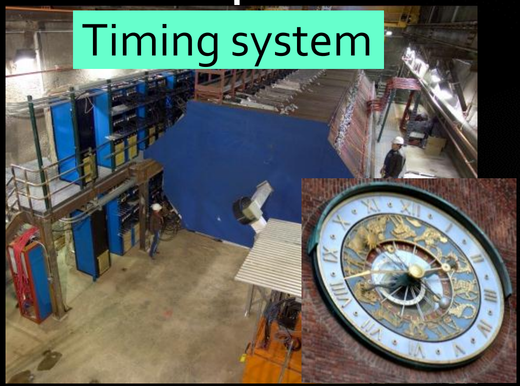
Fibre optic cable

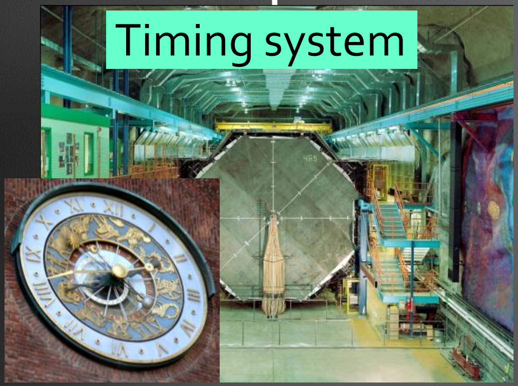
Fibre optic cable

Installed rubidium clocks at each detector

Expecting 1-4ns uncertainty

Systematic uncertainty is expected to decrease from 68ns to 11-18 ns !!





The MINOS Detectors

Detectors are steel-scintillating sampling calorimeters

Having two functionally identical detectors minimizes errors due to beam and neutrino interaction uncertainties

Steel plane absorbers 2.54cm thick

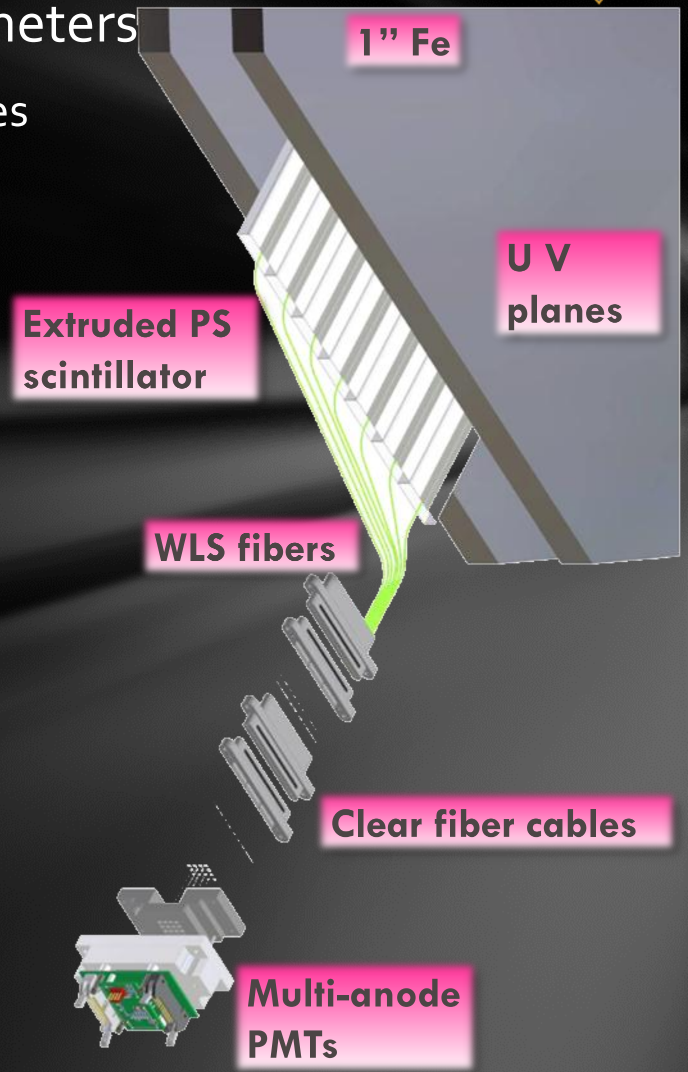
- Average <B>=1.3 Tesla (Toroidal)
- Good muon charge sign identification

Scintillating strips measure 4.1 x 1 cm^2

- strip width is 1.1 Moliere radius
- have embedded wavelength shifting fibers
- alternative planes are orthogonal to allow for 3-D reconstruction of events.

Detector Calibration

- Light injection to monitor hardware+electronics
- Cosmic muons used to monitor scintillator response
- CERN test beam detector set absolute Energy scale

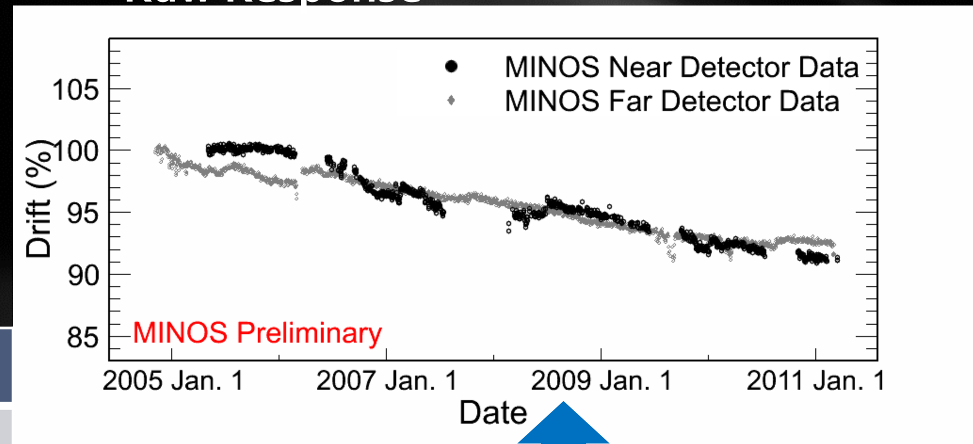


MINOS Detector Behaviour

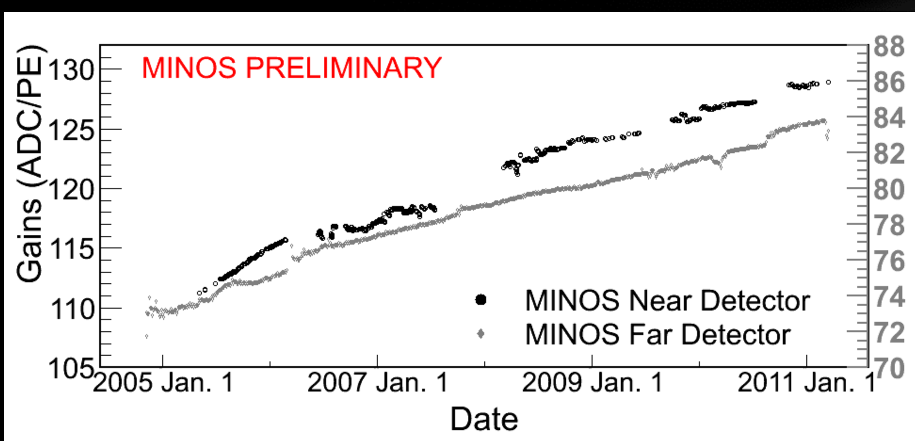
The MINOS Detectors are steel-scintillator calorimeters. The scintillation light is transported along WLS fibers and read out by Hamamatsu Multi-Anode PMTs.

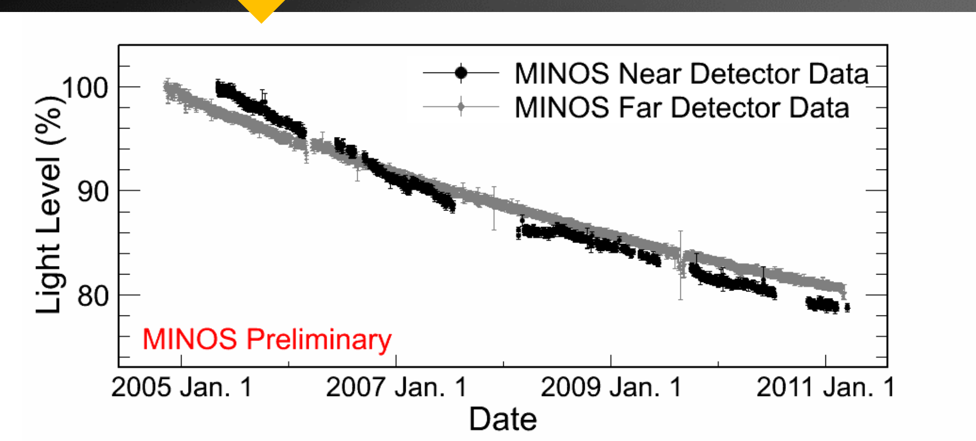
	Near	Far
Gains Increasing By	2.5%/yr	1.8%/yr
Light Level Decreasing By	3.5%/yr	3.0%/yr

Raw Response



$$\text{Light Level}_i = \frac{\text{Detector Drift}_i}{\text{Average Gains}_i}$$

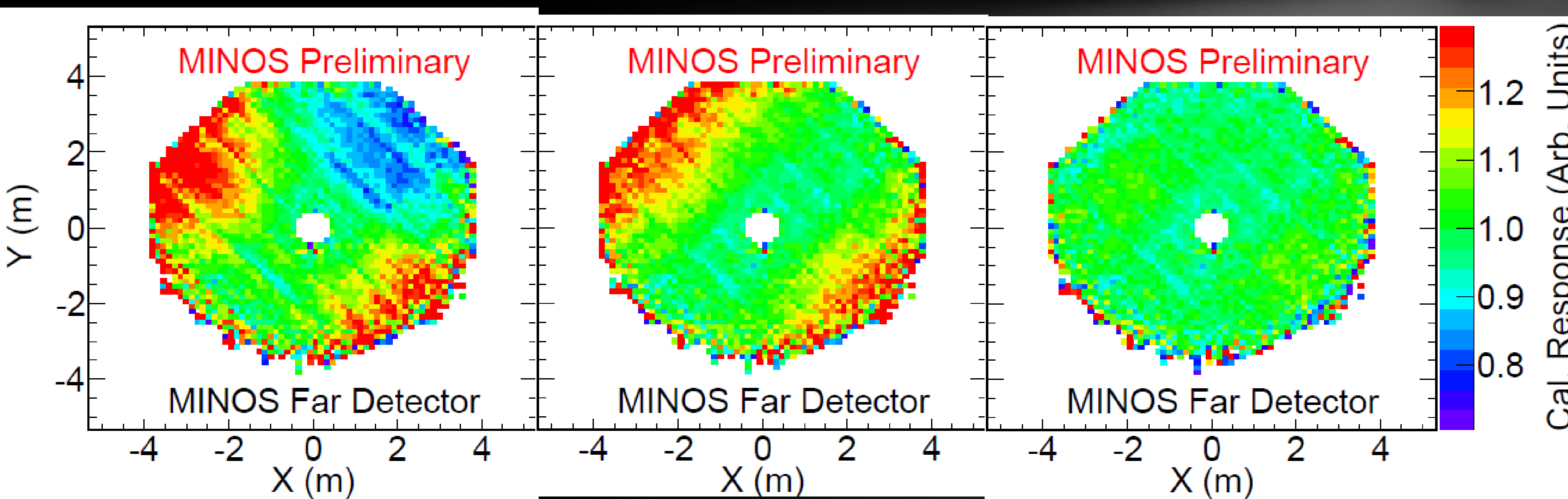




Far Detector Calibration

The scintillating strips at the MINOS far detector are oriented at 45° to the vertical, and 90° with respect to neighbouring planes. Shown below is the calibration of one of these two views
(The NuMI neutrino beam is travelling out of the page)

Pre-Calibration | **Mid-Calibration** | **Post-Calibration Response**



This is the raw response of the detector

This is the response of the detector after all calibrations except the attenuation correction

This is the fully calibrated response of the detector