MINOS Results

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Neutrino phenomenology

Pontecorvo – Maki – Nakagawa - Sakata (PMNS) matrix

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

3 mixing angles + 1 phase

Weak States

Mass States

$$E^2 = p^2 + m^2$$

Neutrino mixing matrix is similar to quark matrix, but still very different!

$(c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij})$

CP violating

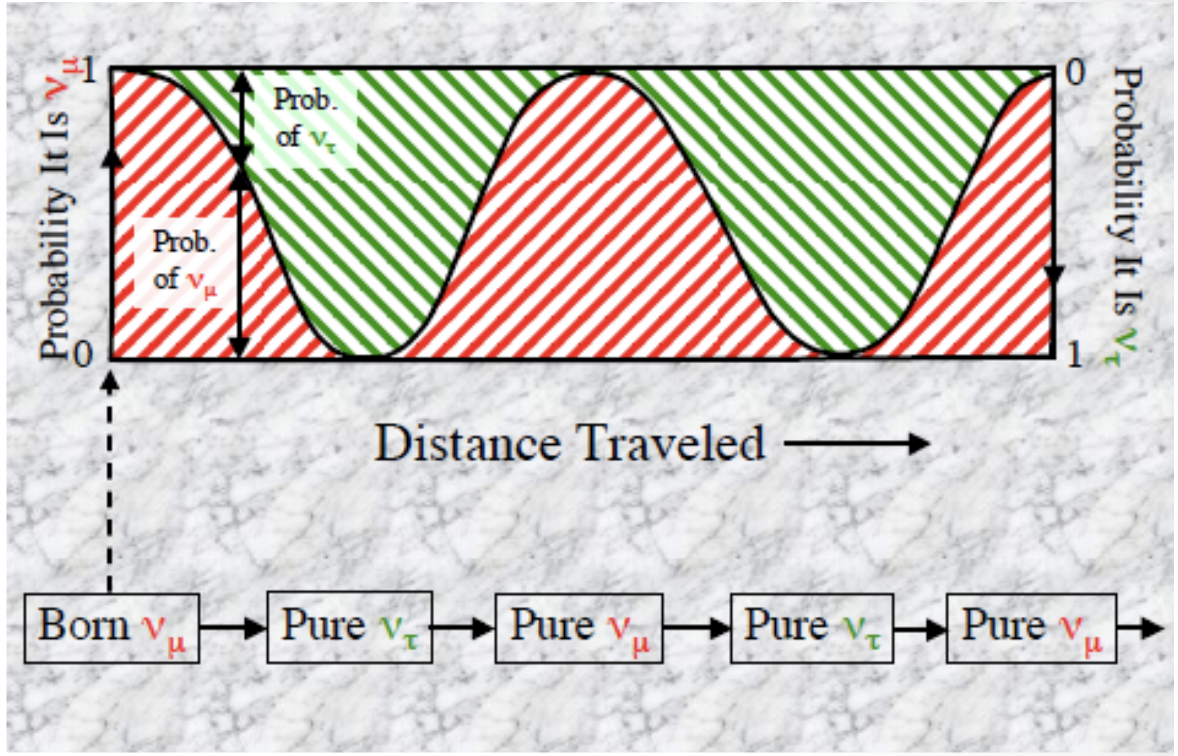
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} \cdot e^{i\delta} \\ & 1 & \\ -s_{13} \cdot e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Solar	Atmospheric	Atmospheric	Majorana
KamLand	Reactor	$\nu_\mu \leftrightarrow \nu_\tau$	Phases
	$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$		$0\nu\beta\beta$

MINOS study area

Neutrino propagation and mixing

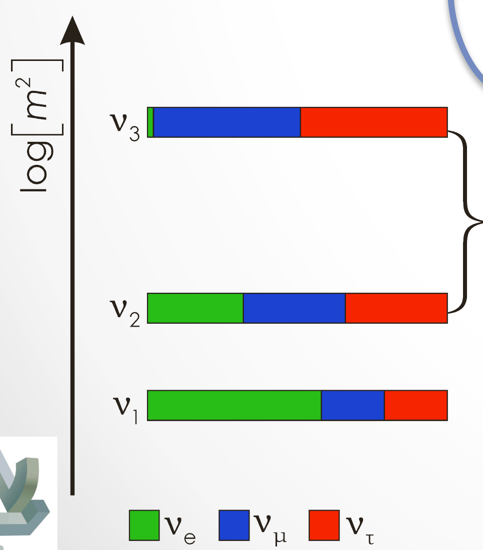
Neutrino born as one weak state flavor, turns into a mixture of weak states as it travels some distance!



In two flavor mode, "Survival probability":

For a neutrino energy E and distance L from the source.

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



$\Delta m^2_{32} = 2.3\text{x}10^{-3}$ eV^2

Largest mass splitting

Require ~ O(500 km/GeV)

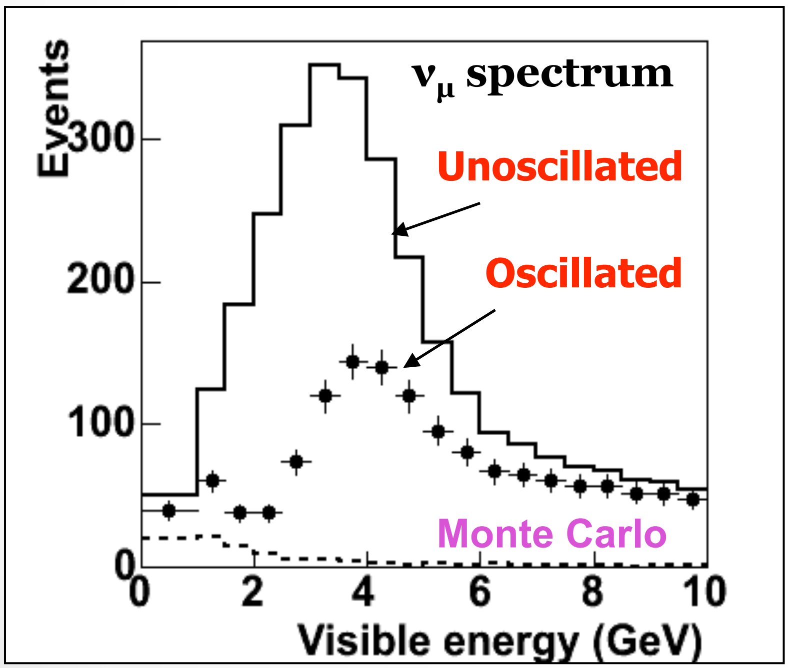
Neutrinos interact as flavor eigenstates $\{\nu_e, \nu_\mu, \nu_\tau\}$ but propagate as mass eigenstates $\{\nu_1, \nu_2, \nu_3\}$

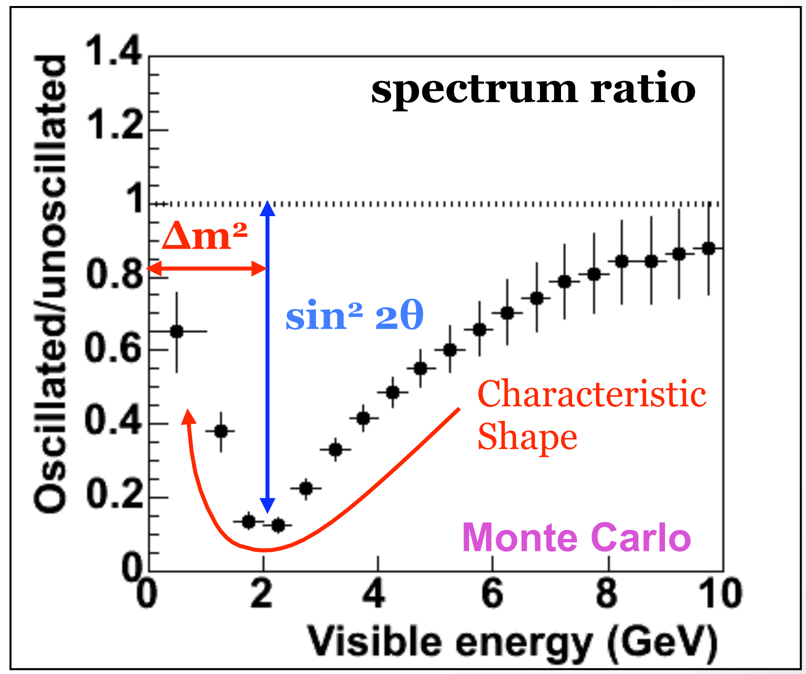
How we obtain oscillations results?

- Look for ν_μ disappearance as a function of neutrino energy.
- Use Near Detector to predict un-oscillated spectrum at Far Detector.
- Compare predictions with measured spectrum to extract oscillation parameters.

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

Example: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2



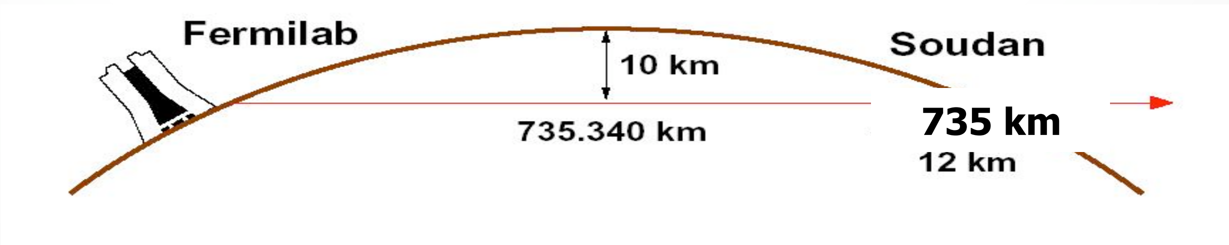


MINOS

- Uses intense beam facility at NuMi, Fermilab
- Two detectors (to mitigate systematics effects)
- Two parabolic magnetic horns, Movable target (➔Energy spectrum)
- Long baseline neutrino oscillation experiment

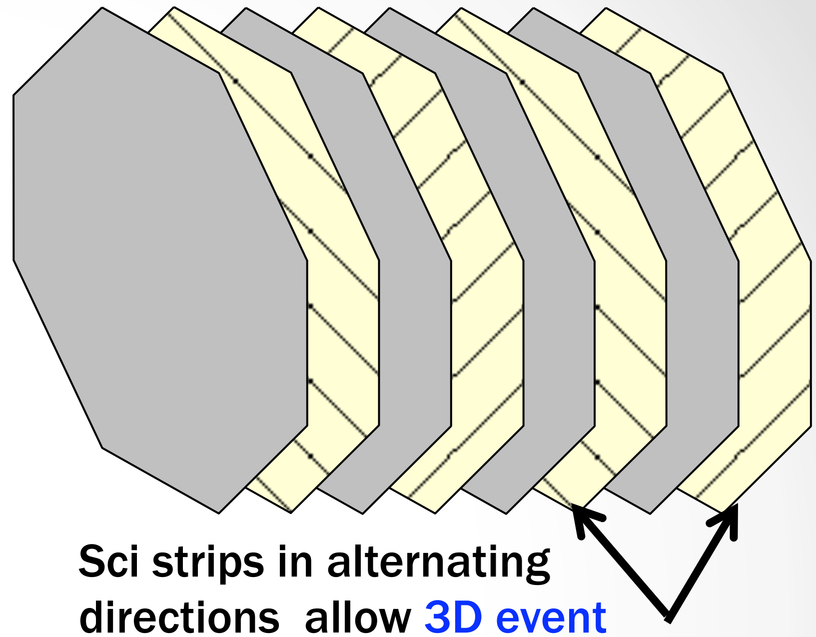
Near Detector at Fermilab
- measure beam composition
- energy spectrum

Far Detector in Soudan, MN
- search for and study neutrino oscillations

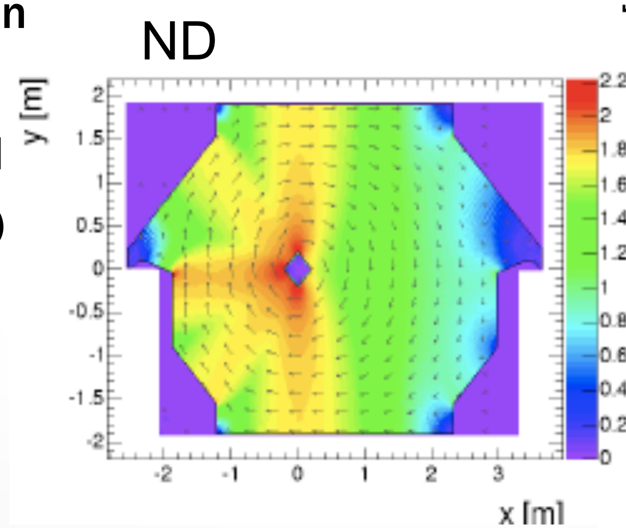


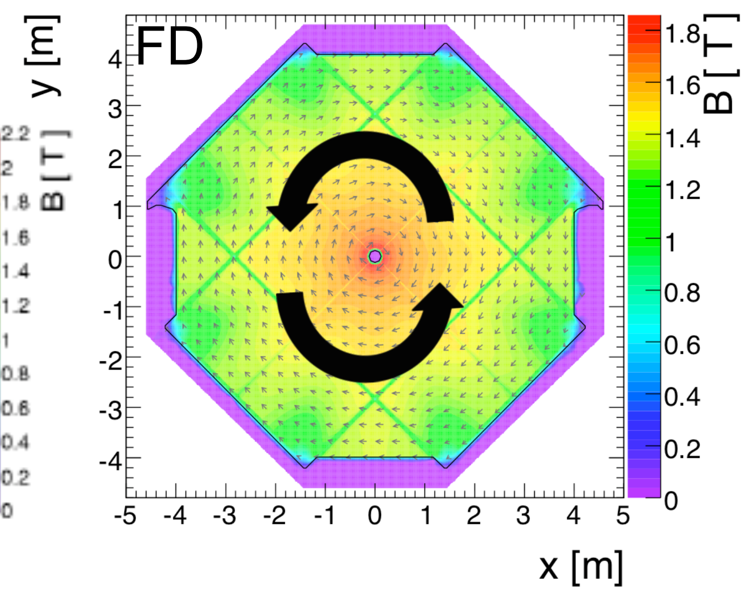
MINOS Detectors

- **Tracking sampling calorimeters**
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 1 cm thick, 4.1 cm wide (1.1 Moliere radius)
  - 1 GeV muons penetrate 28 layers
- **Magnetized**
  - distinguish μ^+ from μ^-
  - muon energy from range/curvature
- **Functionally equivalent**
  - same segmentation
  - same materials
  - same mean B field (1.3 T)
  - massive
    ND: 1 kT
    FD: 5.4 kT



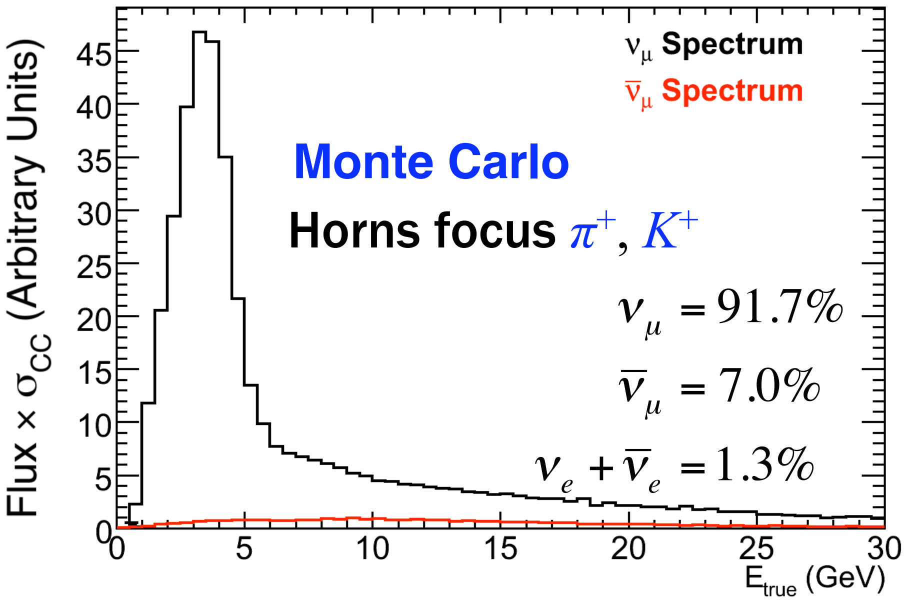
Sci strips in alternating directions allow 3D event reconstruction

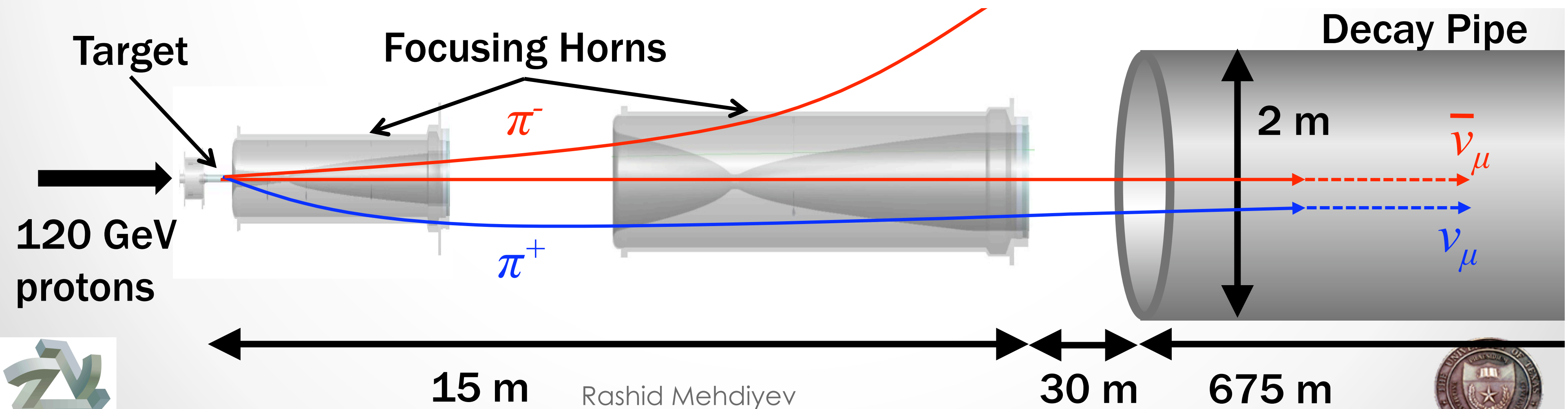




Neutrino mode

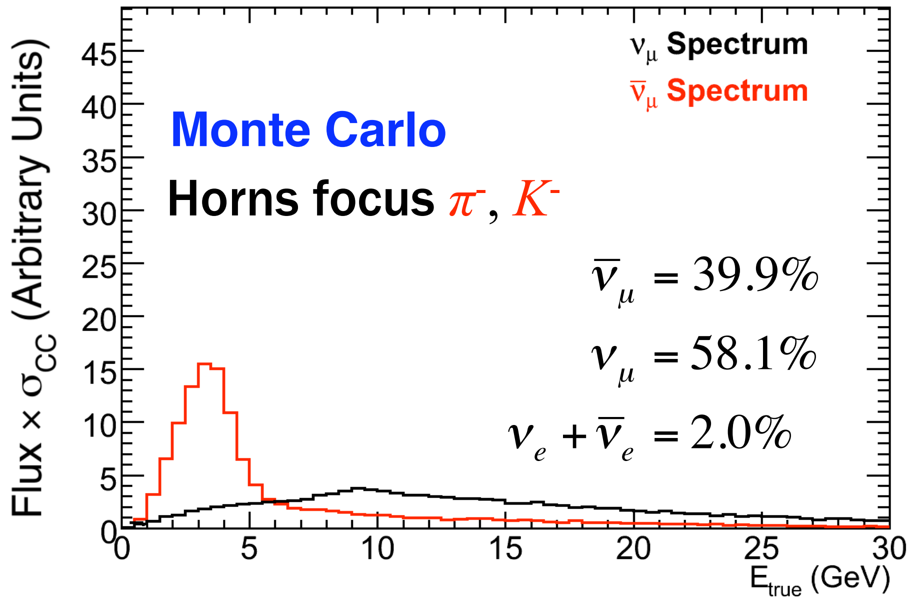
- 120 GeV protons incident on a thick, segmented graphite target
- Magnetic horns focus π^+, K^+ enhancing the ν_μ flux.
- In this neutrino mode we get only about 7% anti-neutrinos.

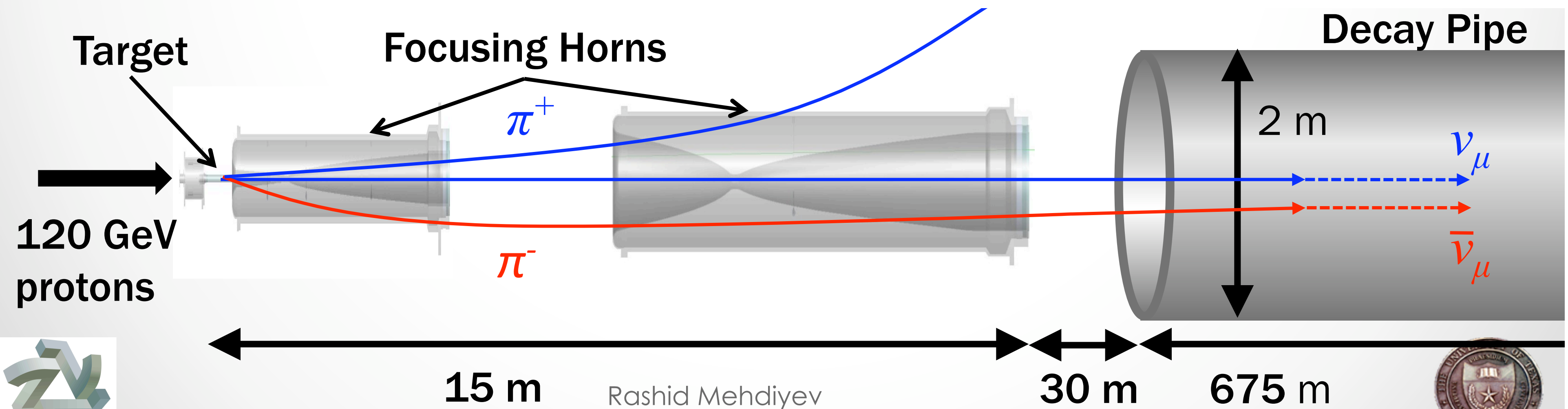




Anti-neutrino mode

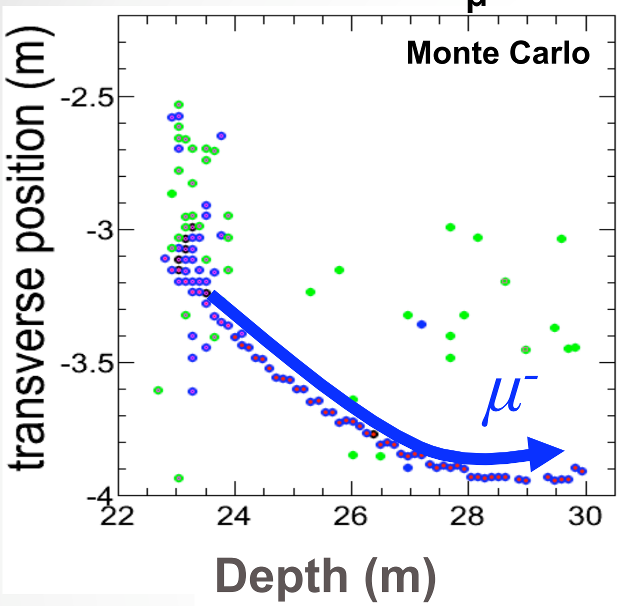
- By reversing the current in the horns we can focus π^{-}' s and K^{-}' s, creating an anti-neutrino beam.
- However, due to a smaller cross-section for anti-ν_μ and less π^{-} 's off the target, the rate of anti-ν_μ events is smaller. There are lots of high energy ν_μ 's.

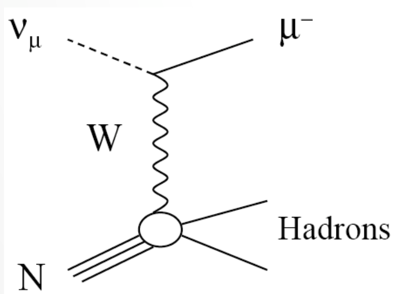




MINOS event topologies

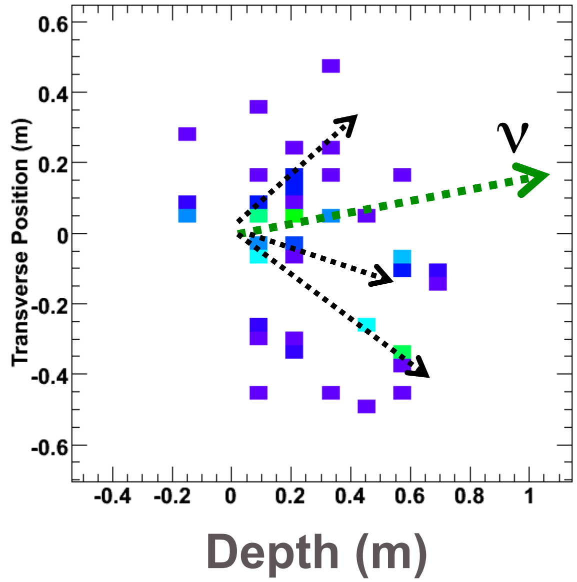
Charged Current ν_μ event

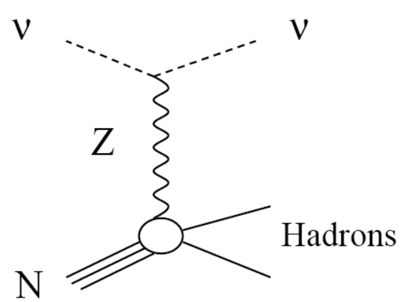




long μ track and hadronic activity near vertex

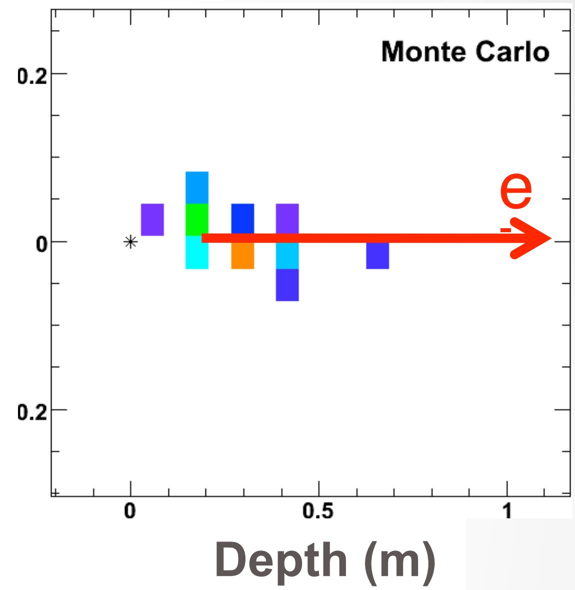
Neutral Current Event

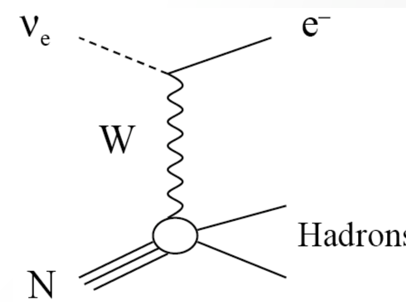




diffuse shower event

Charged Current ν_e event





compact EM shower event

MINOS Results

Beam content

ν_μ disappearance in ν_μ beam

$\nu_\mu = 91.7\%$

$\bar{\nu}_\mu = 7.0\%$

Anti-ν_μ disappearance in ν_μ beam

$\nu_e + \bar{\nu}_e = 1.3\%$

Anti-ν_μ disappearance in anti-ν_μ beam

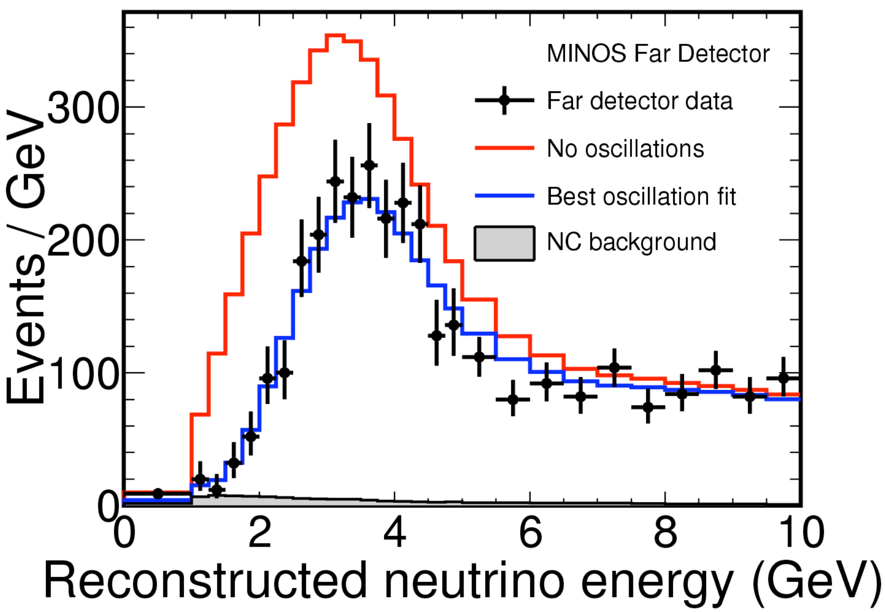
$\bar{\nu}_\mu = 39.9\%$

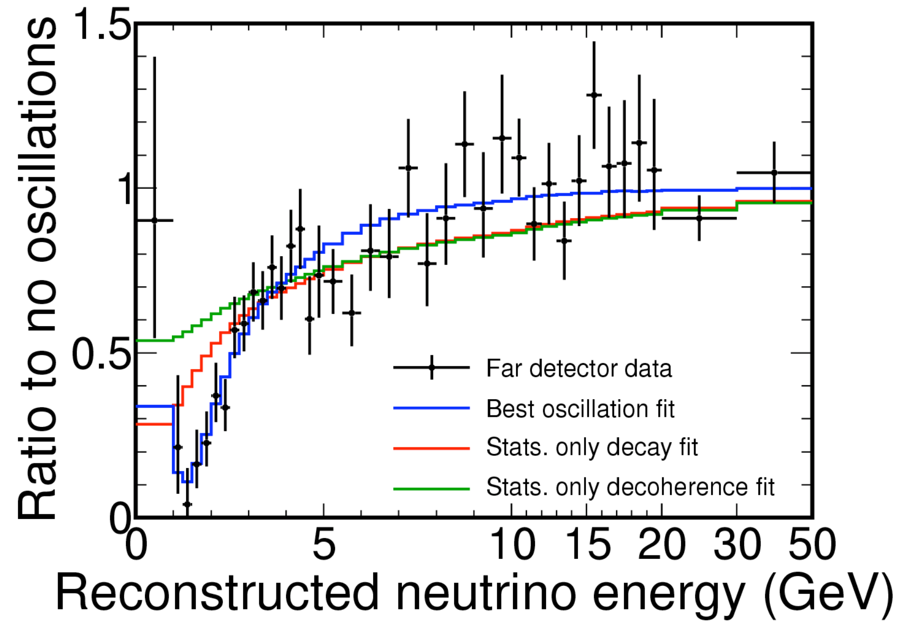
$\nu_\mu = 58.1\%$

ν_μ disappearance in anti-ν_μ beam

$\nu_e + \bar{\nu}_e = 2.0\%$

ν_μ disappearance in MINOS: Far Detector spectra





7.25 x 10^{20} POT

No Oscillations:	2451
Observation:	1986

Disfavored decay (at 7σ)
and decoherence (at 9σ)

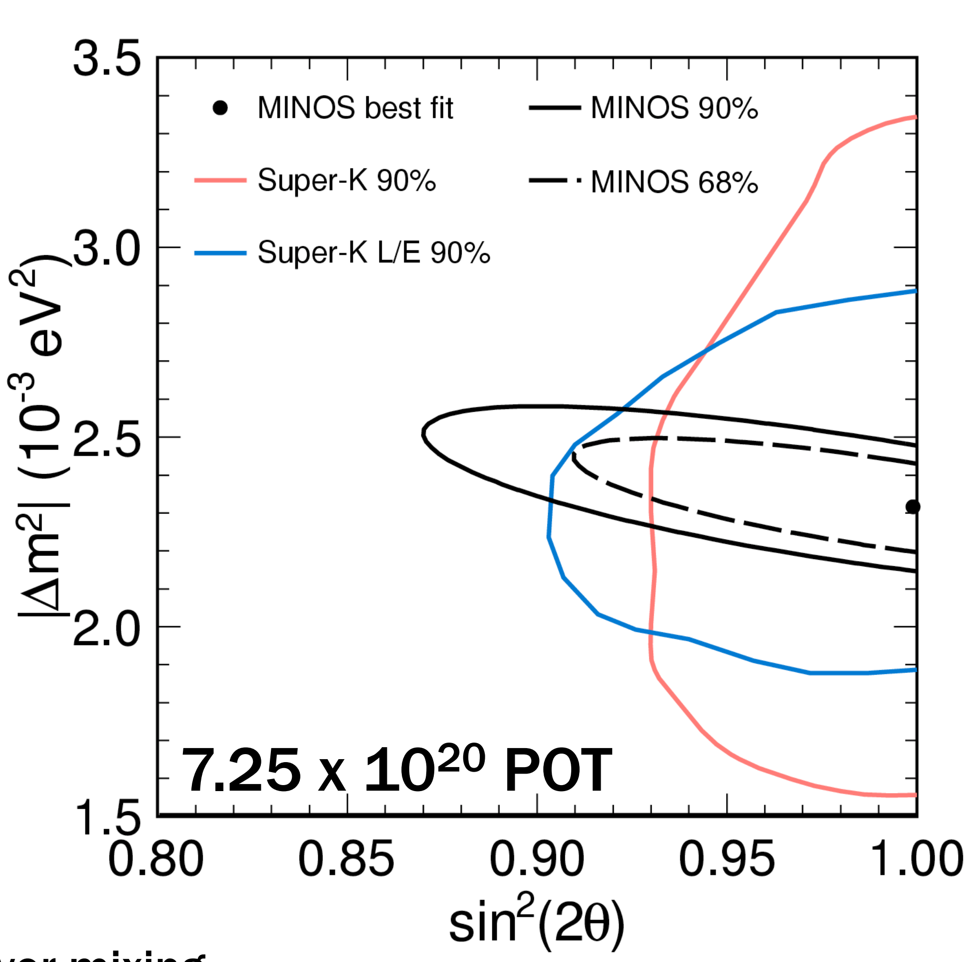
Phys Rev Lett.106.181801

ν_μ disappearance in MINOS: Fit results

$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ eV^2$

$\sin^2(2\Theta) > 0.90$ (90% CL)

Consistent with maximal mixing: $\sin^2(2\Theta) = 1$



Super-K contour uses 2 flavor mixing

MINOS Results

Beam content

ν_μ disappearance in ν_μ beam

Anti-ν_μ disappearance in ν_μ beam

Anti-ν_μ disappearance in anti-ν_μ beam

$\bar{\nu}_\mu = 39.9\%$

$\nu_\mu = 58.1\%$

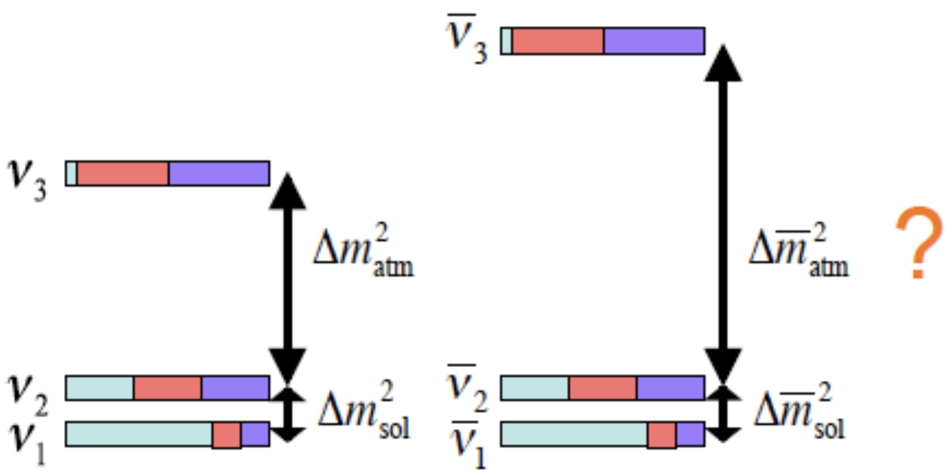
$\nu_e + \bar{\nu}_e = 2.0\%$

ν_μ disappearance in anti-ν_μ beam

What are we trying to answer?

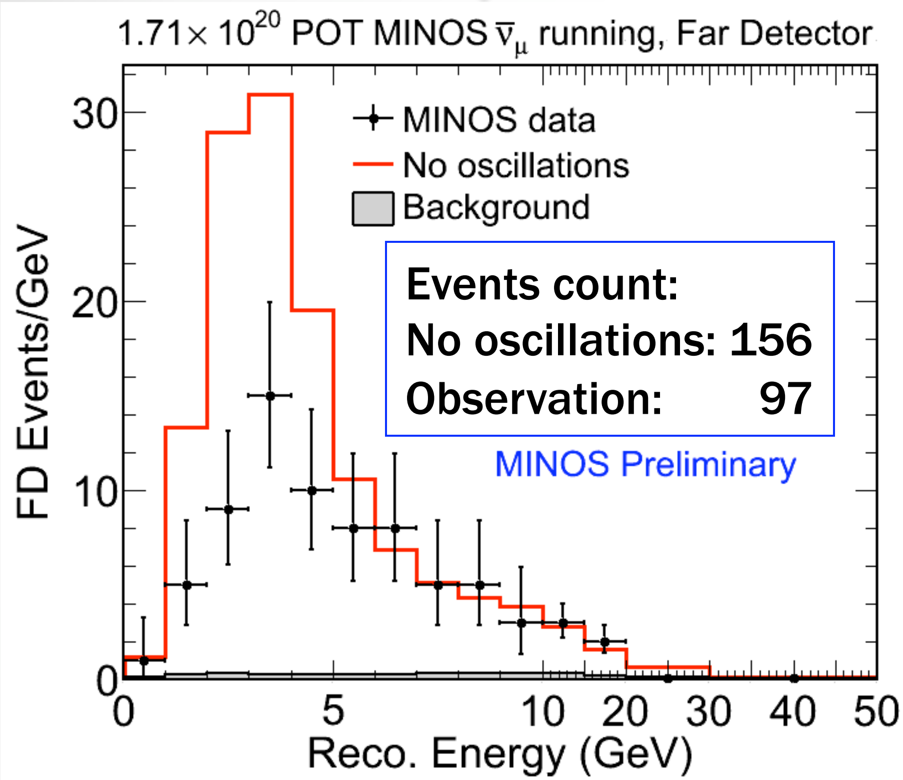
Are survival probability of those are the same or not ?

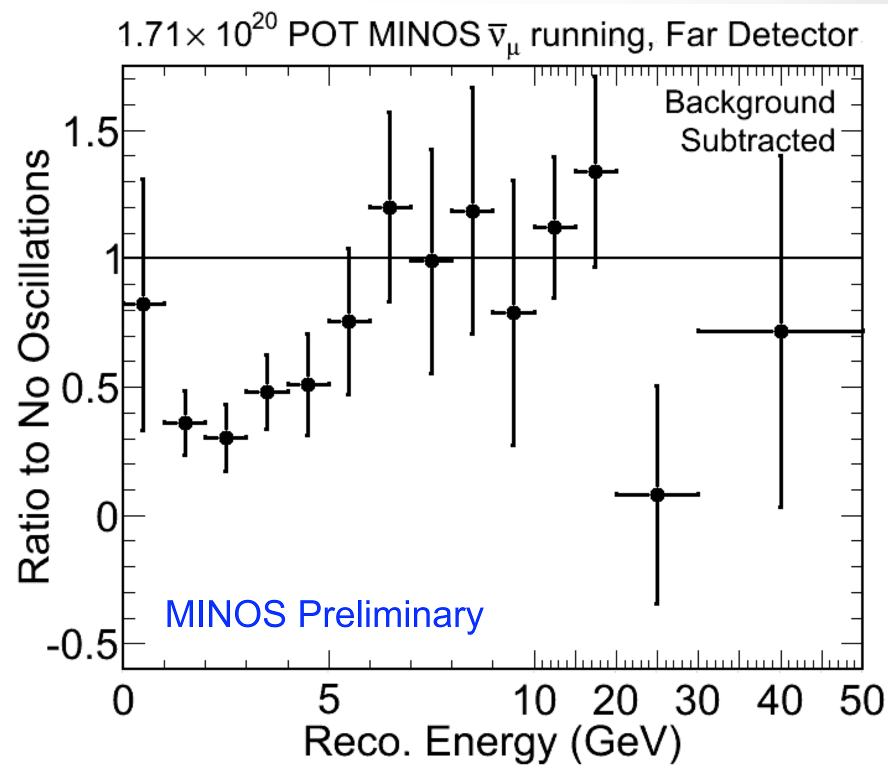
$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right) \overset{?}{=} P(\overline{\nu_\mu} \rightarrow \overline{\nu_\tau}) = \sin^2(2\overline{\theta})\sin^2\left(\frac{1.27\Delta \overline{m}^2 L}{E}\right)$$



Are atmospheric neutrino oscillation parameters the same or, indeed, they are different ?

Anti-ν_μ results in anti-ν_μ beam





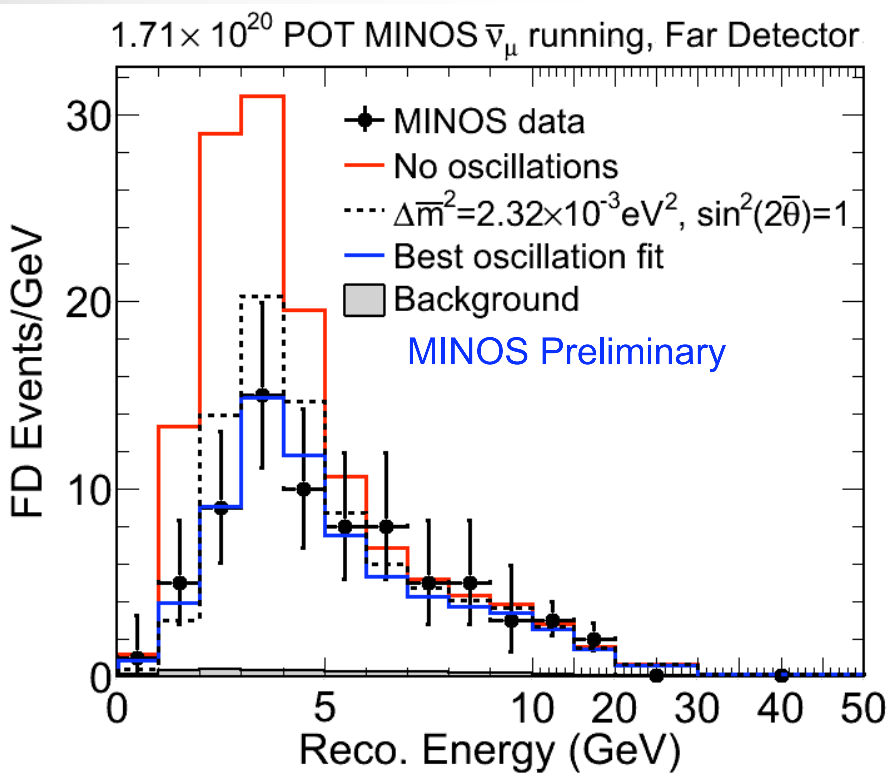
$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.46}_{-0.40}(stat) \pm 0.06(syst) \times 10^{-3}\,\mathrm{eV}^2,$$

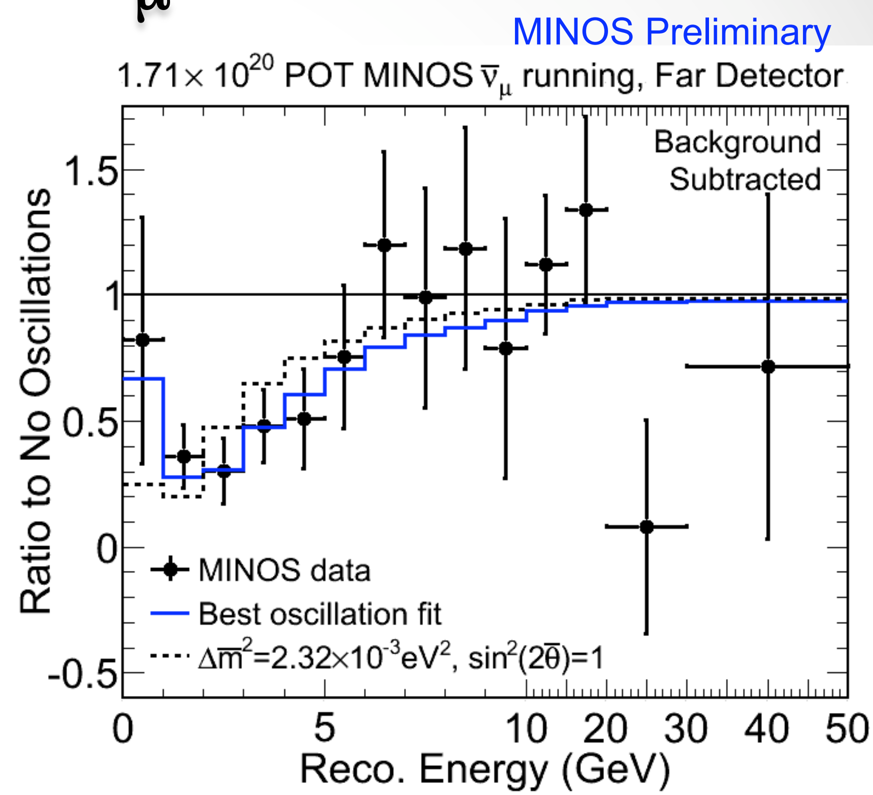
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}(stat) \pm 0.01(syst)$$

The data disfavor no oscillations at the 6.3 standard deviation level.

arXiv:1104.0344

Comparison to ν_μ results





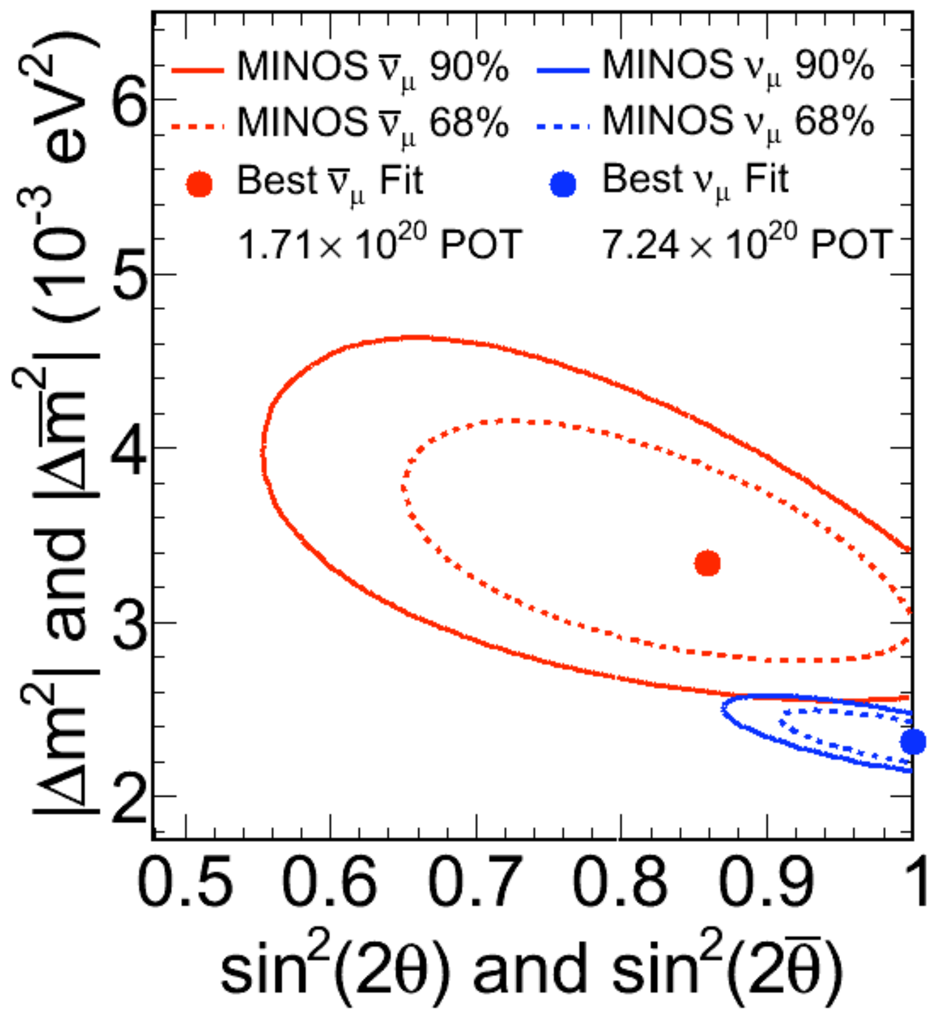
$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.46}_{-0.40}(stat) \pm 0.06(syst) \times 10^{-3}\,\mathrm{eV}^2,$$

$$\sin^2(2\bar{\theta}) = 0.86^{+0.11}_{-0.12}(stat) \pm 0.01(syst)$$

$$\left|\Delta m^2\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2,$$

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

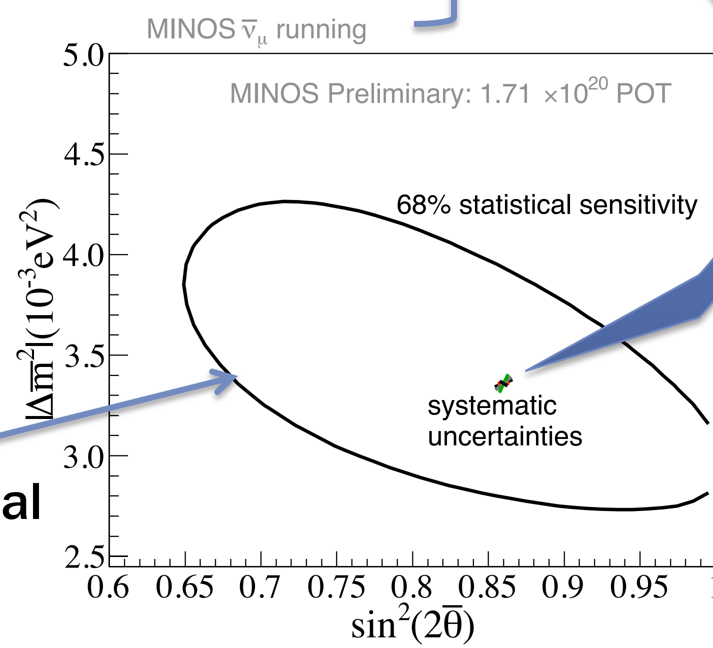
Head to head



Only ~2% probability of common parameters

Anti-ν_μ contours include effects of dominant systematic uncertainties:

- Normalization
- NC background
- Shower energy
- Track energy
- Cross-section



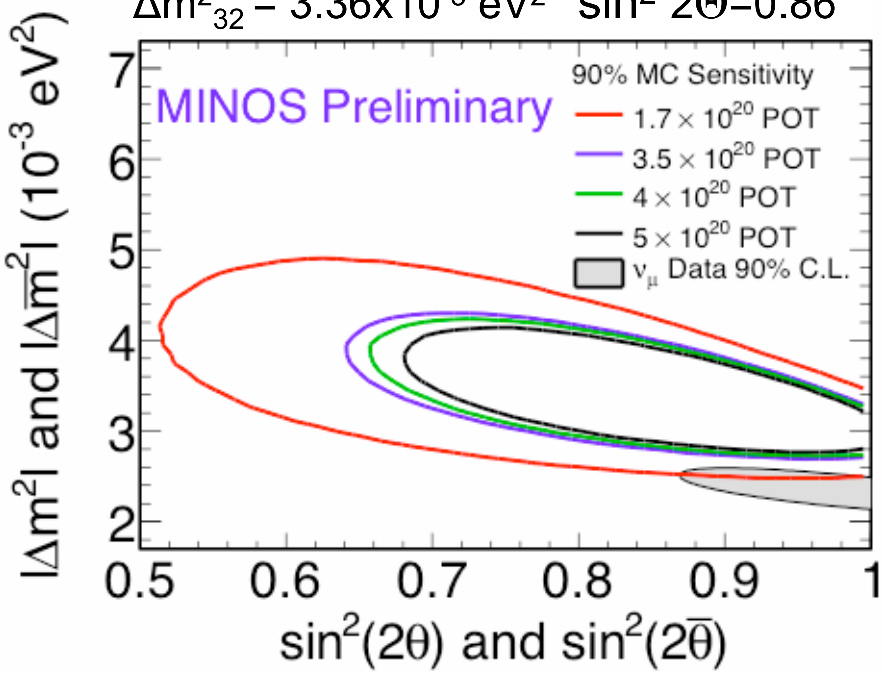
Dominated by statistical uncertainty!

Which way would that go ?

With increase of statistics of anti–ν_μ running (in analysis now!)

IF new results would be similar to the anti-ν_μ parameters

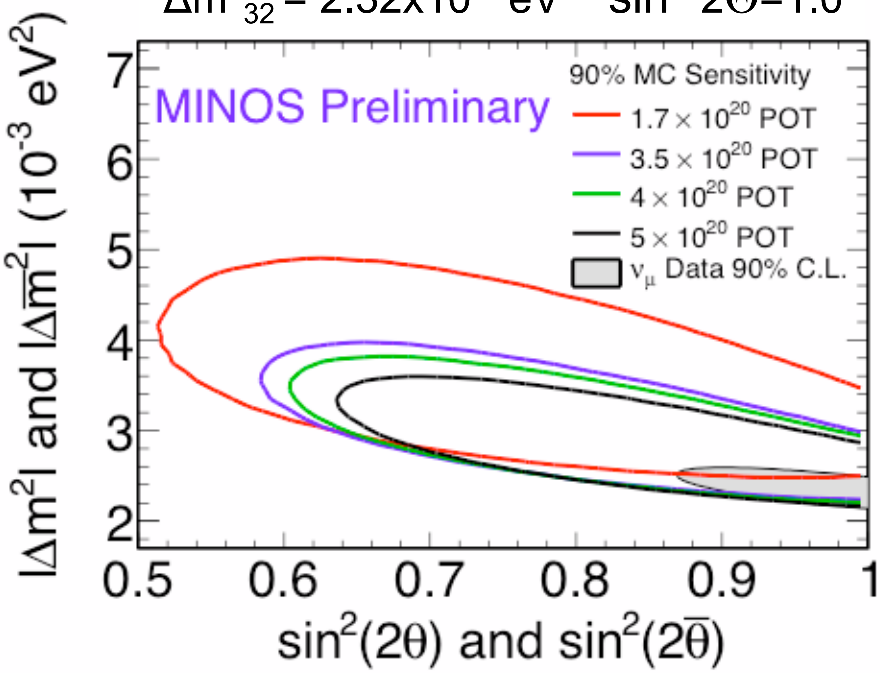
$\Delta m^2_{32} = 3.36\mathrm{x}10^{-3}\ eV^2$ $\sin^2 2\Theta=0.86$



?

IF new results would be similar to CC ν_μ oscillation parameters

$\Delta m^2_{32} = 2.32\mathrm{x}10^{-3}\ eV^2$ $\sin^2 2\Theta=1.0$



With $4\mathrm{x}10^{20}$ POT of anti-neutrino running, a ν_μ - anti-ν_μ difference could be observed at >3σ at the current best fit parameters (green contour above).

MINOS Results

ν_μ disappearance in ν_μ beam

Anti-ν_μ disappearance in ν_μ beam

Anti-ν_μ disappearance in anti-ν_μ beam

ν_μ disappearance in anti-ν_μ beam

Beam content

$\nu_\mu = 91.7\%$

$\bar{\nu}_\mu = 7.0\%$

$\nu_e + \bar{\nu}_e = 1.3\%$

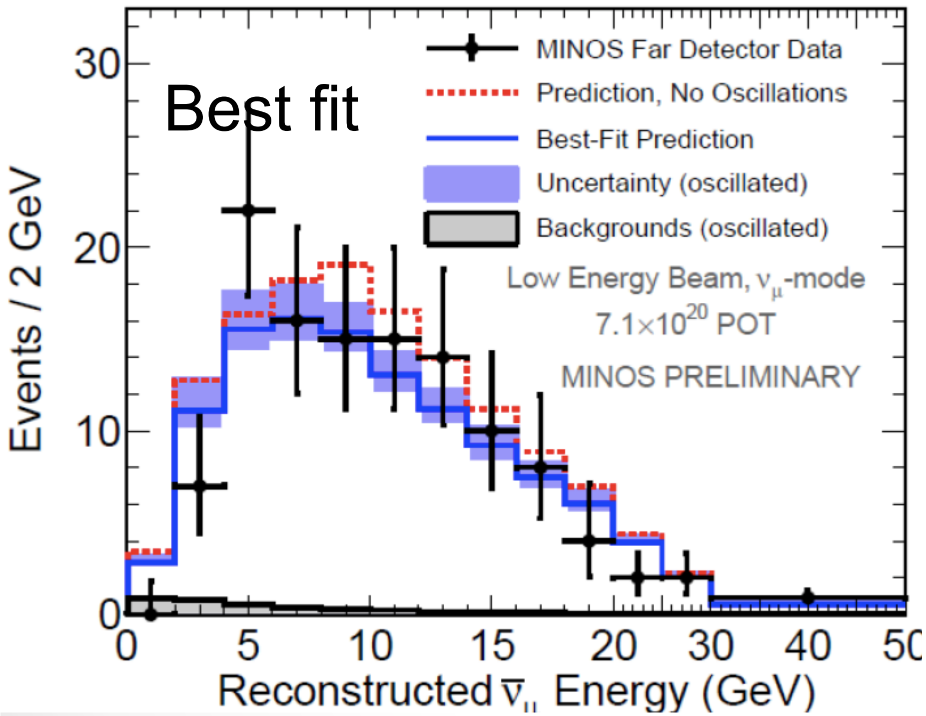
$\bar{\nu}_\mu = 39.9\%$

$\nu_\mu = 58.1\%$

$\nu_e + \bar{\nu}_e = 2.0\%$

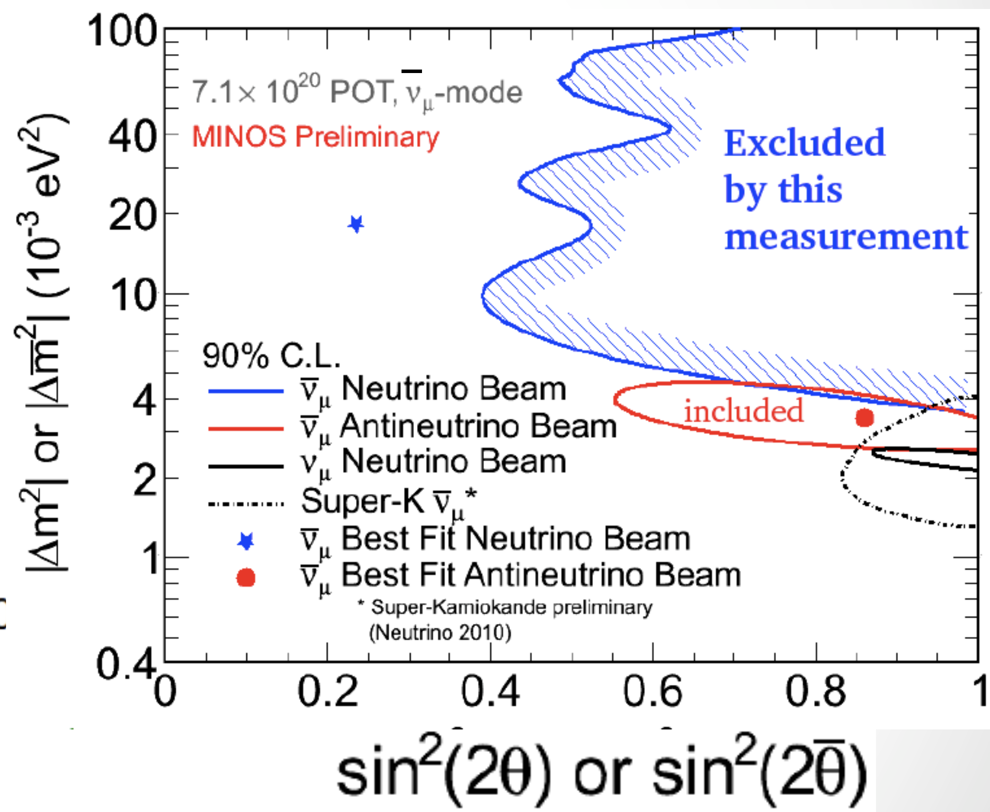
Anti-ν_μ disappearance in MINOS:

Far Detector spectra



No Oscillations:	150
Observation:	130

MINOS 90% C.L. on ν_μ oscillations, from analysis of the anti-neutrino component In MINOS neutrino beam



Under the assumption of maximal mixing, these data constrain $|\Delta \bar{m}^2| < 3.37 \times 10^{-3}$ eV^2 (90% C.L.).

Summary

- MINOS continues providing the important neutrino oscillations parameters:
  - most precise neutrino oscillations data (based on 7.25×10^{20} POT).

$$\left|\Delta m^2\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2(2\theta) > 0.90$$

(90% CL)

  - first direct anti-neutrino oscillation parameters (based on 1.7×10^{20} POT) in dedicated anti-neutrino running mode.

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.46}_{-0.40}(stat) \pm 0.06(syst) \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}(stat) \pm 0.01(syst)$$

(90% CL)

  - obtained new anti-neutrino results in a neutrino running mode. These results are consistent with the other MINOS anti-neutrino results.
- MINOS observes some tension between neutrino and anti-neutrino oscillation parameters.
  - MINOS is increasing statistics in the anti-neutrino dedicated beam
  - Persistence of the difference may be intriguing.

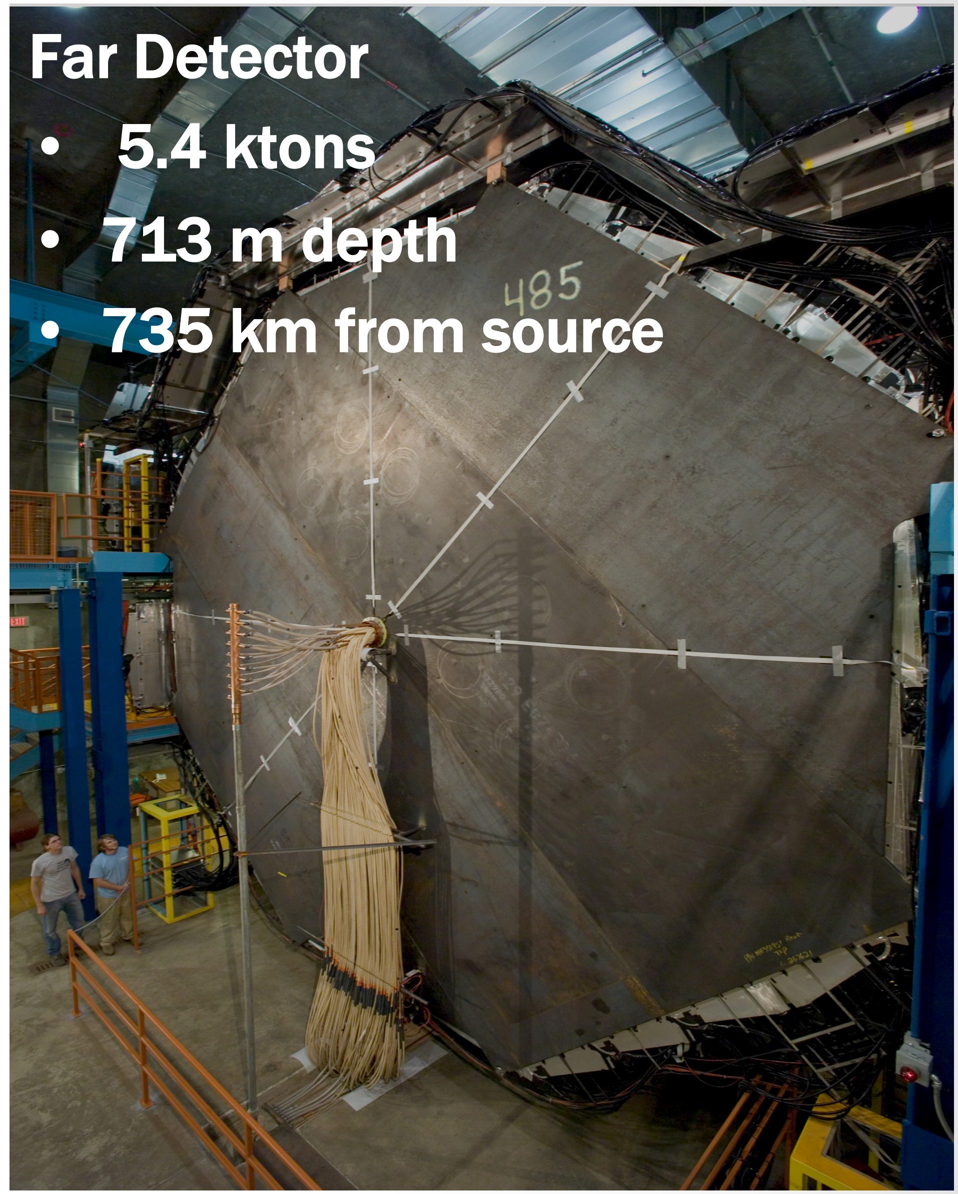
MINOS Collaboration

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
Goias • Harvard • Holy Cross • IIT • Indiana • Iowa State • 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

Back up slides

MINOS Detectors

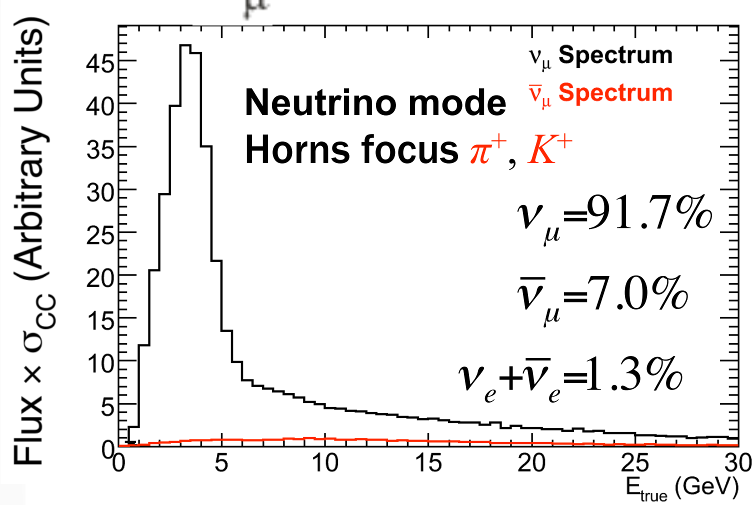
Near Detector
- 1 kton
- 95 m depth
- 1 km from source



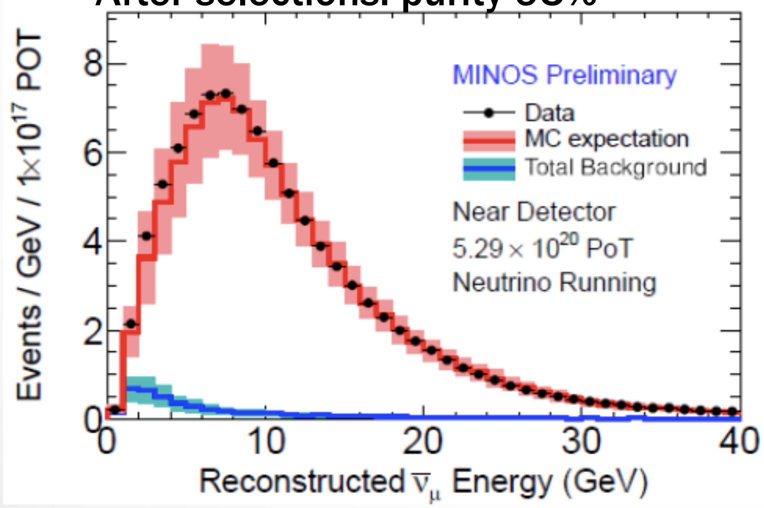
Far Detector
- 5.4 ktons
- 713 m depth
- 735 km from source

Two anti-ν_μ MINOS studies

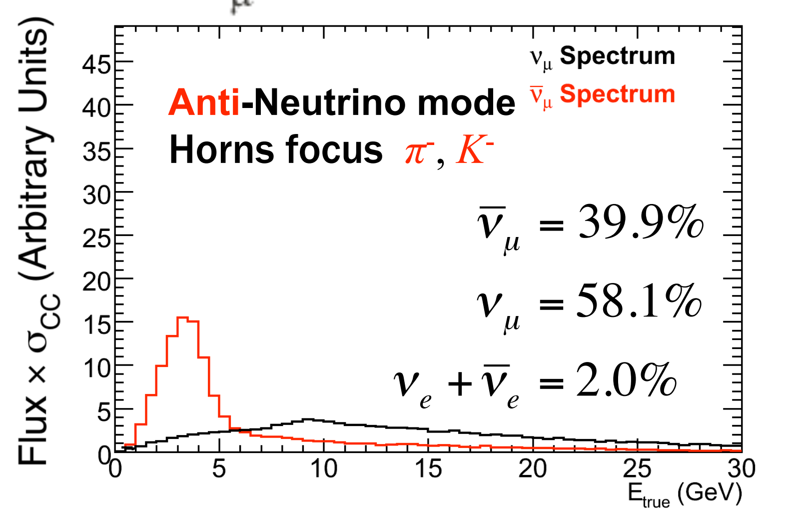
In ν_μ optimized beam



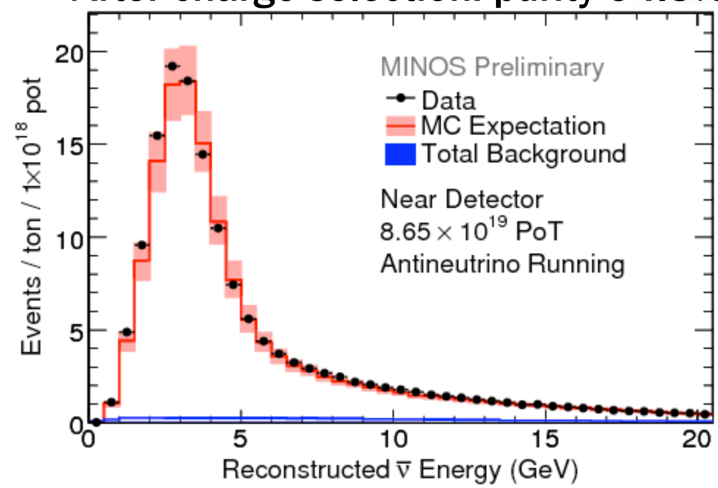
After selections: purity 95%



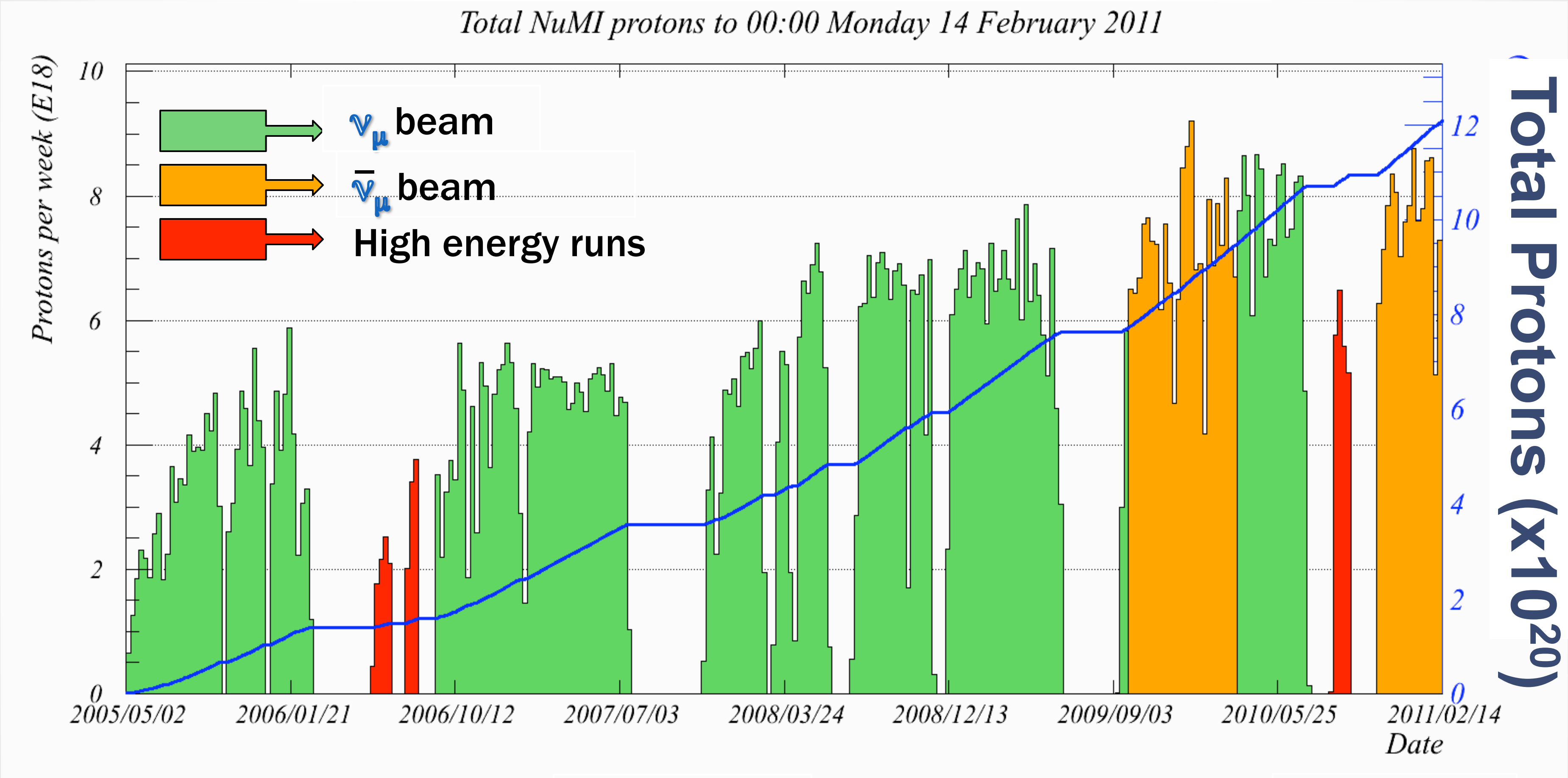
In $\bar{\nu}_\mu$ optimized beam



After charge selection: purity 94.3%



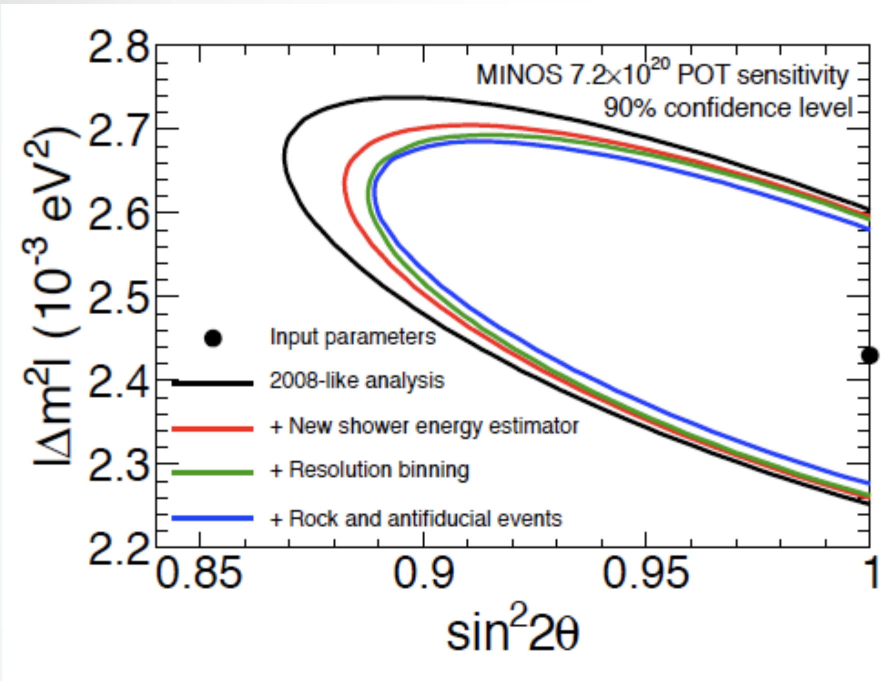
NuMi beam performance



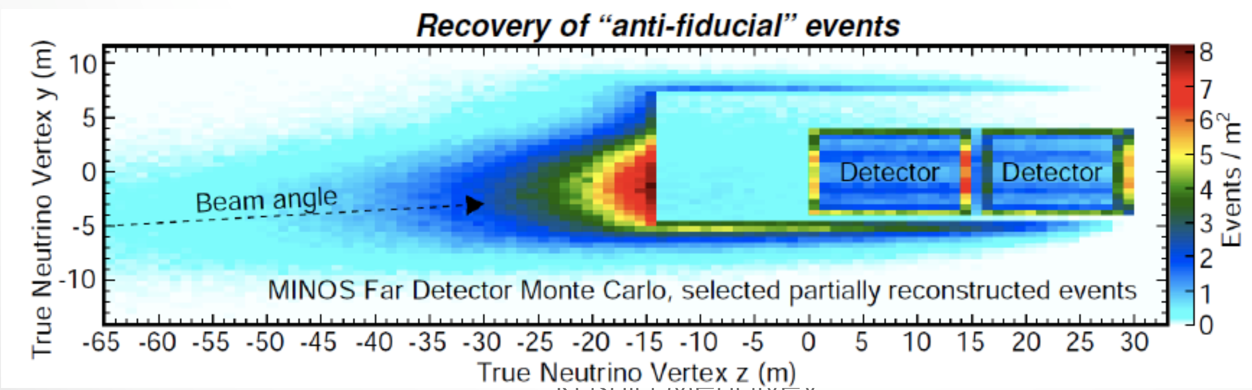
8.0 x 10^{20} POT in ν_μ beam

3.0 x 10^{20} POT in $\bar{\nu}_\mu$ beam

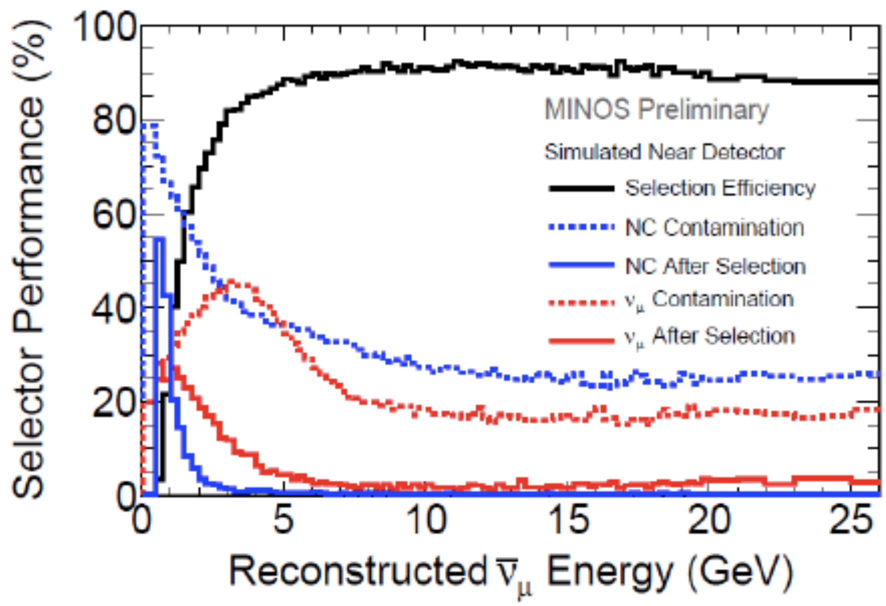
2010 ν_μ analysis improvements



- 2x statistics increase
- new event selection to increase efficiency
- Improved shower energy resolution
- Separate fits in the energy resolution bins
- Inclusion of events which have origin outside of FD fiducial volume.



Event requirements



Anti-neutrinos in the ν_μ beam

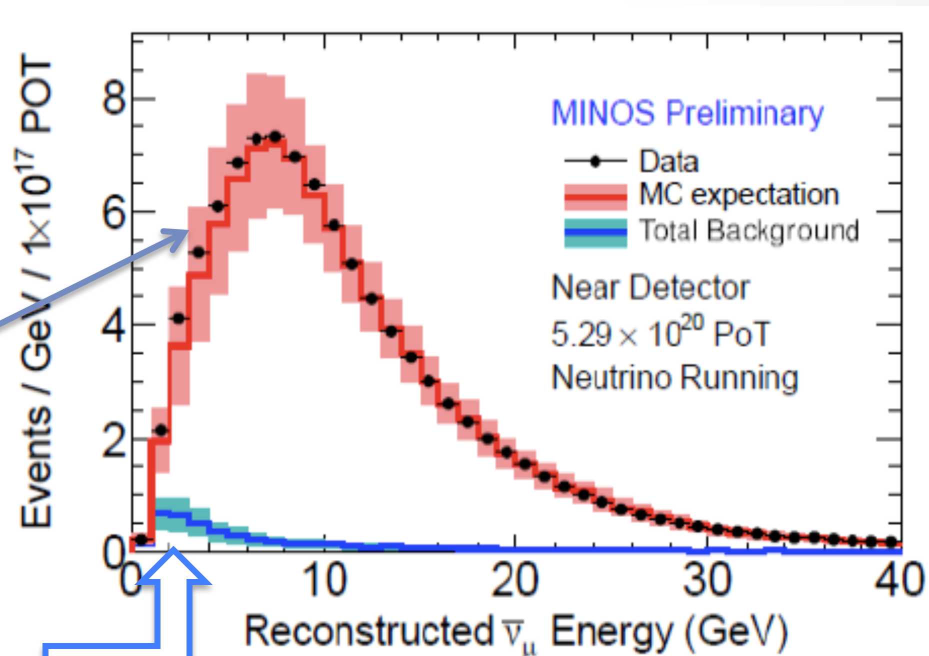
- **Charge cut to select positively charged μ tracks,**
- **3 other variables to improve (efficiency x purity) of the selection.**

- **90% selection efficiency**
- **95% selection purity.**

ν_μ=91.7%

$\overline{\nu}_\mu$=7.0%

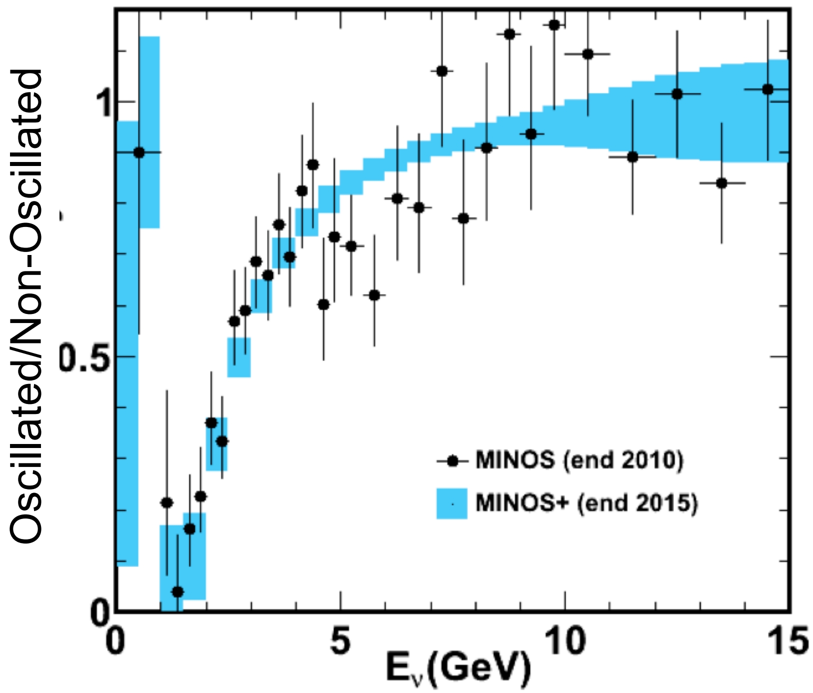
$\nu_e+\overline{\nu}_e$=1.3%



Neutral Current +
Wrong Sign Background

Minos+ ?

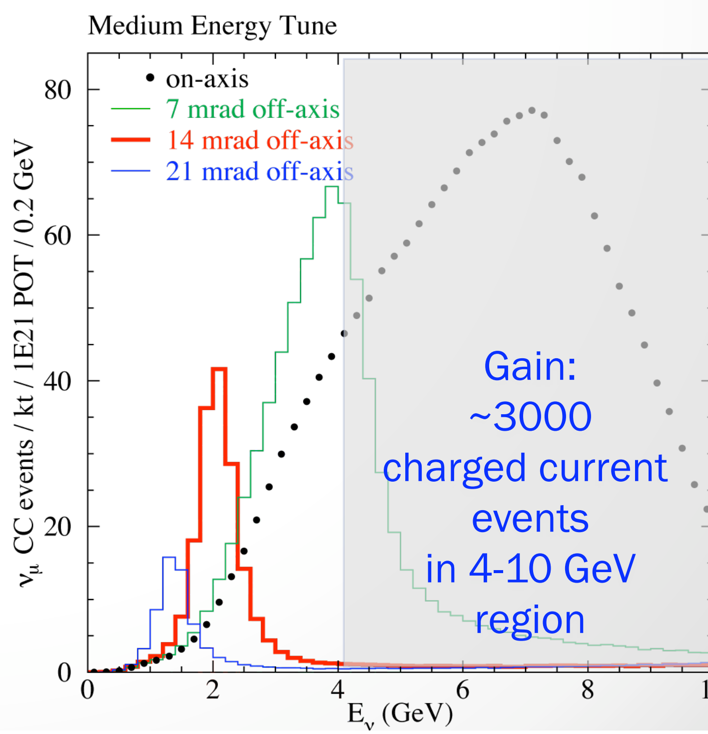
Using NuMi - NOvA beam (on axis)



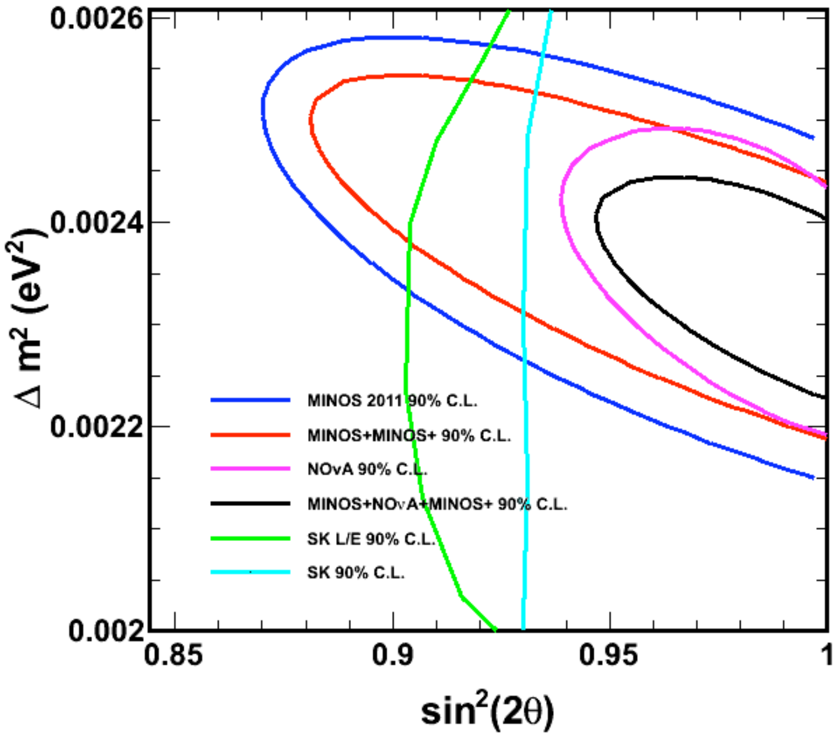
Would allow to reduce statistical uncertainty from 25% to 5% within 3 years of more running (2012-2015).

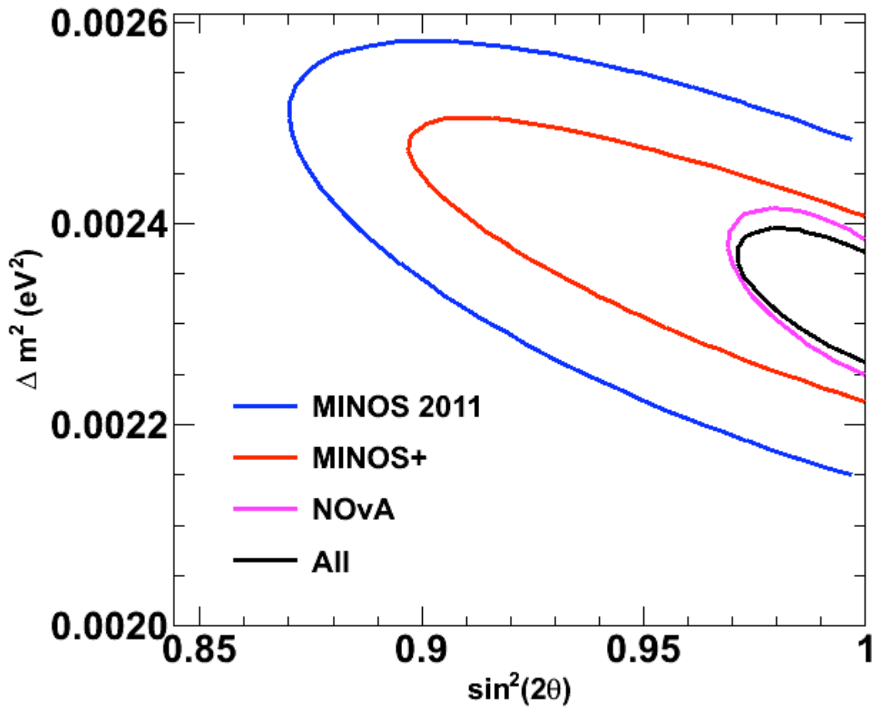
Physics Goals:

- Measure of $\sin^2(2\Theta)$ and Δm^2 with higher precision.
- The same for $\sin^2(2\bar{\Theta})$ and $\Delta\bar{m}^2$
- Study high energy neutrinos
- Search for sterile neutrinos
- Non-standard interactions



Oscillation parameters reach





After one year of MINOS+:

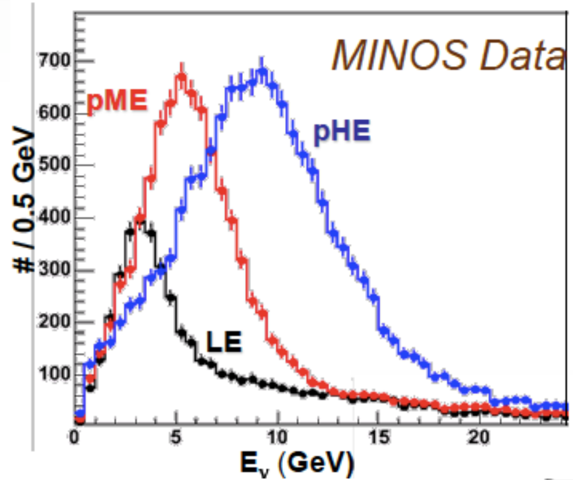
- MINOS continues to dominate Δm^2 measurement
- NOvA is 50% complete

After three years of MINOS+ running:

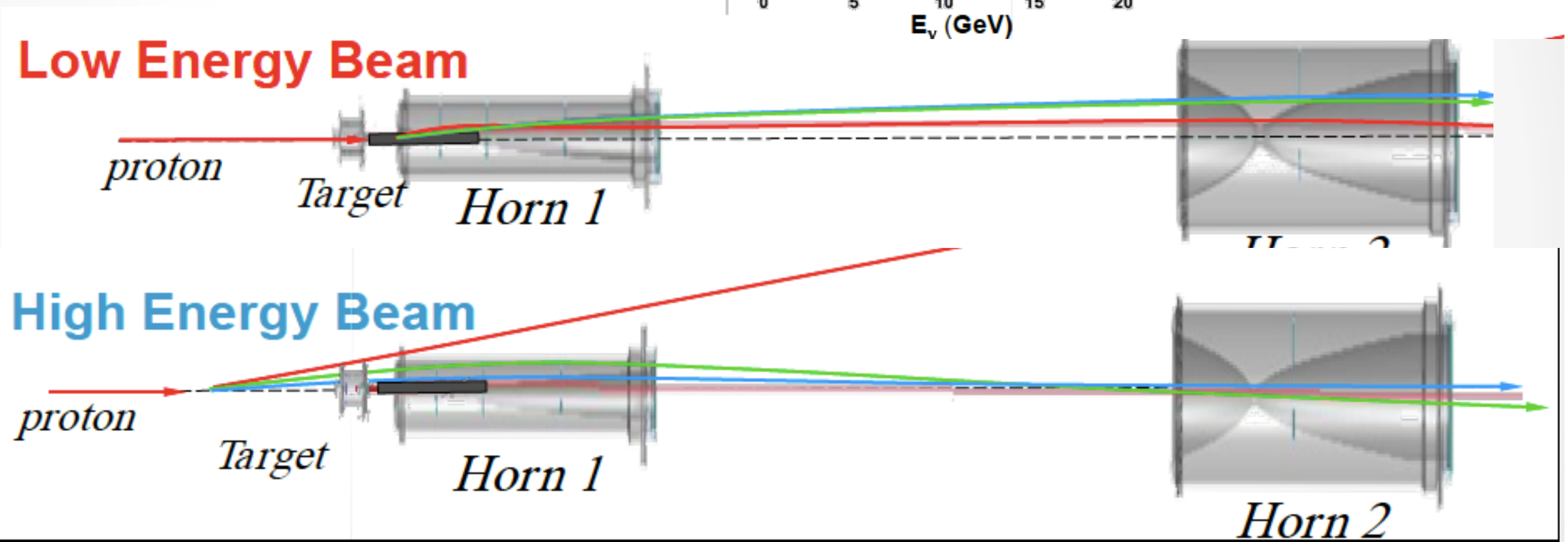
- NOvA complete after first 18 months
- Significant improvements to parameters' accuracy over 3 years period due to MINOS+ running.

MINOS+ would be very supplementary to NOvA and provides unique opportunity to study medium energy neutrinos.

Beam Optics

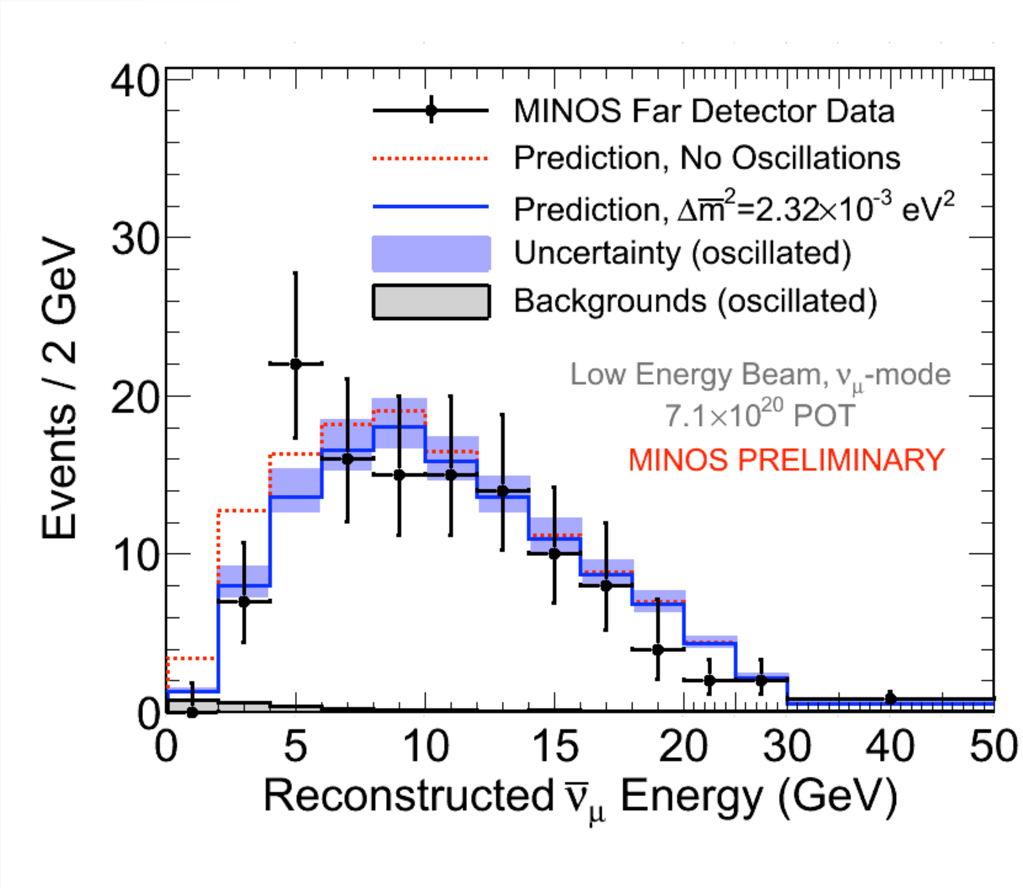


Pions with
p_T=300 MeV/c and
p=5 GeV/c
p=10 GeV/c
p=20 GeV/c

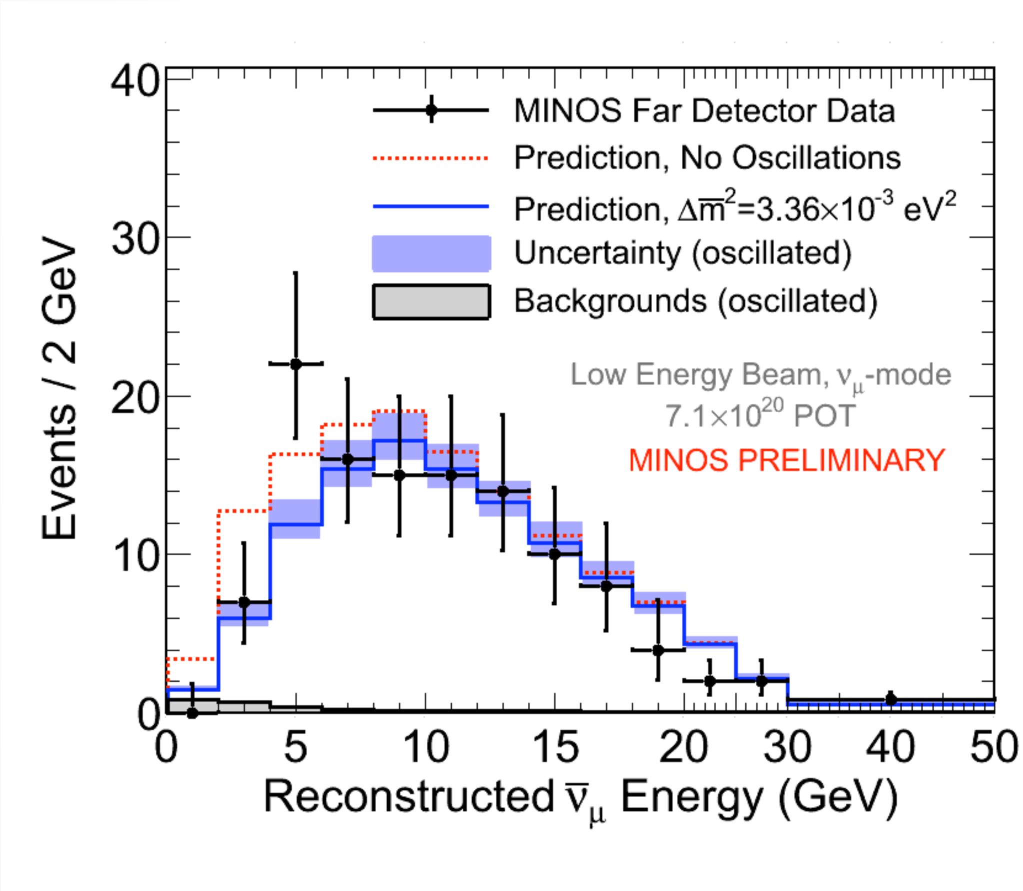


Beam energy change achieved by sliding the target in/out of Horn 1

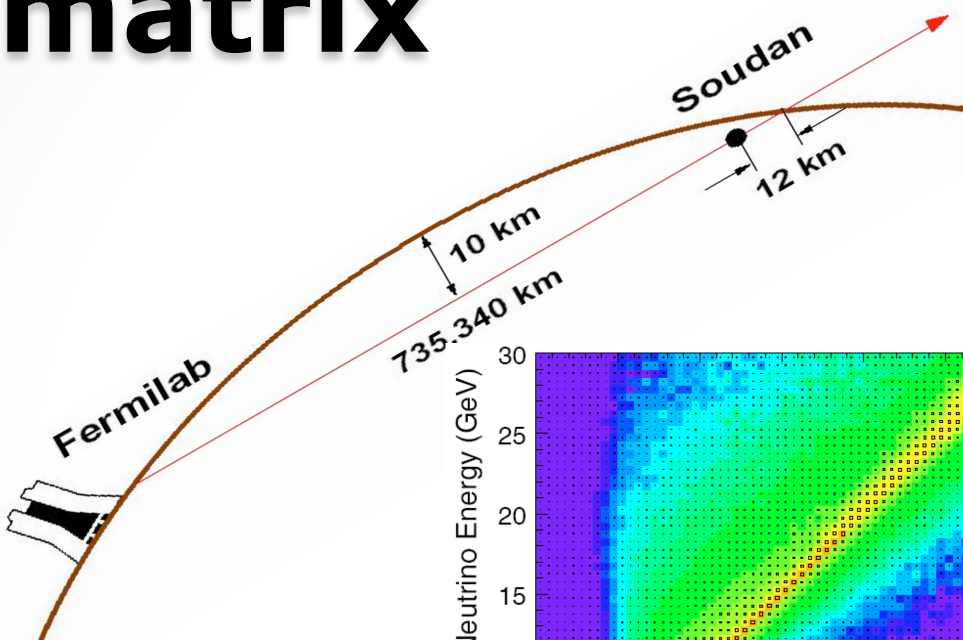
Predictions from ν_μ in ν_μ beam mode

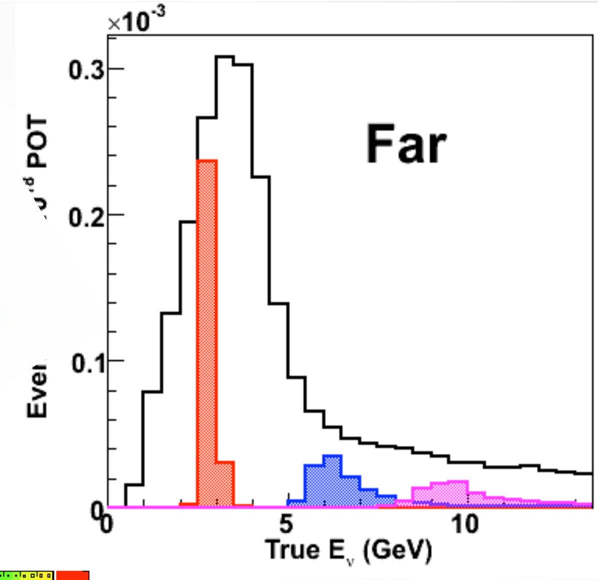


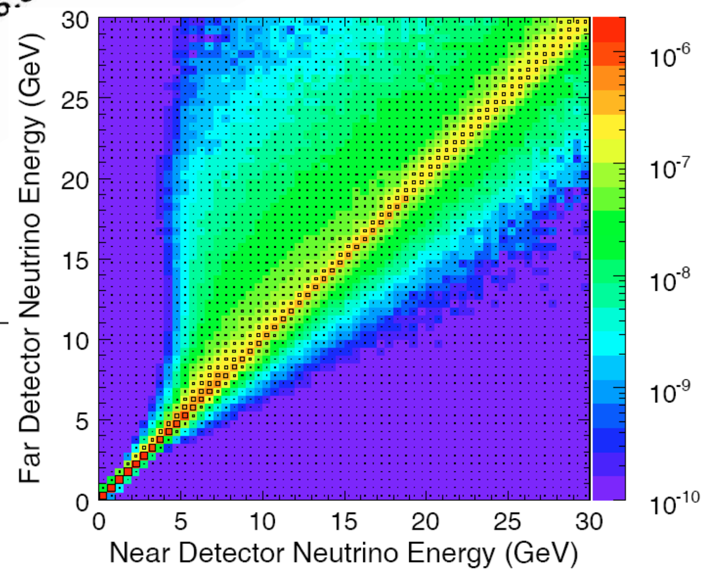
Predictions from ν_μ in $\bar{\nu}_\mu$ beam mode

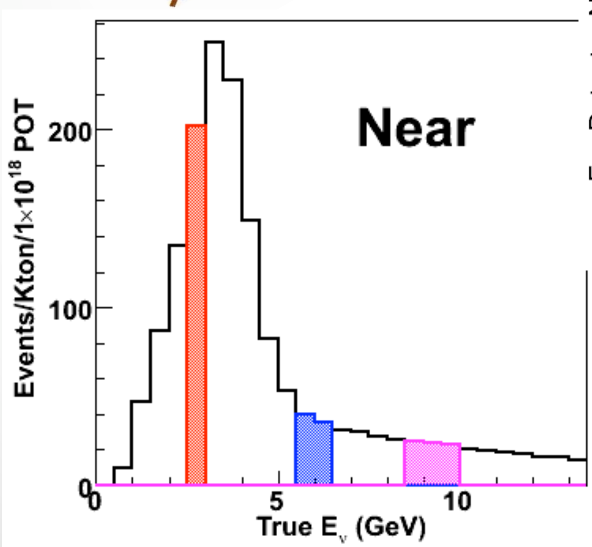


Far/Near matrix



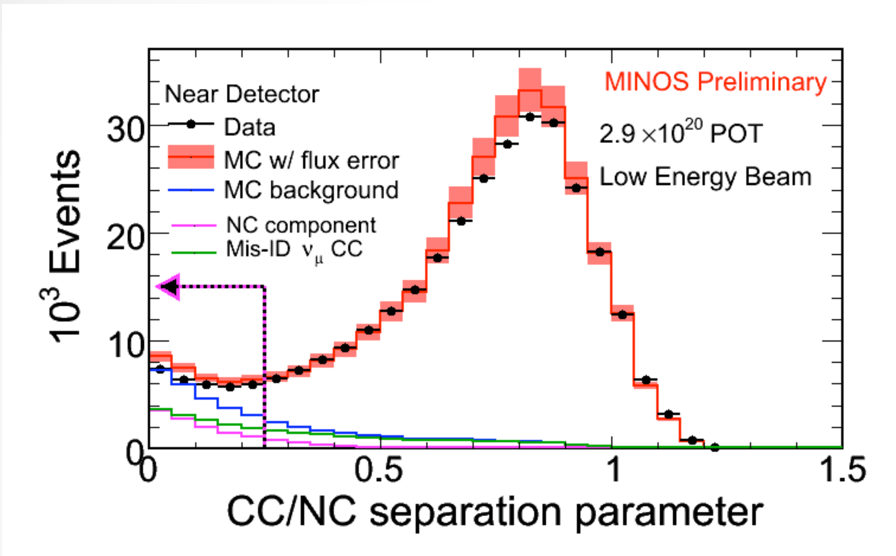


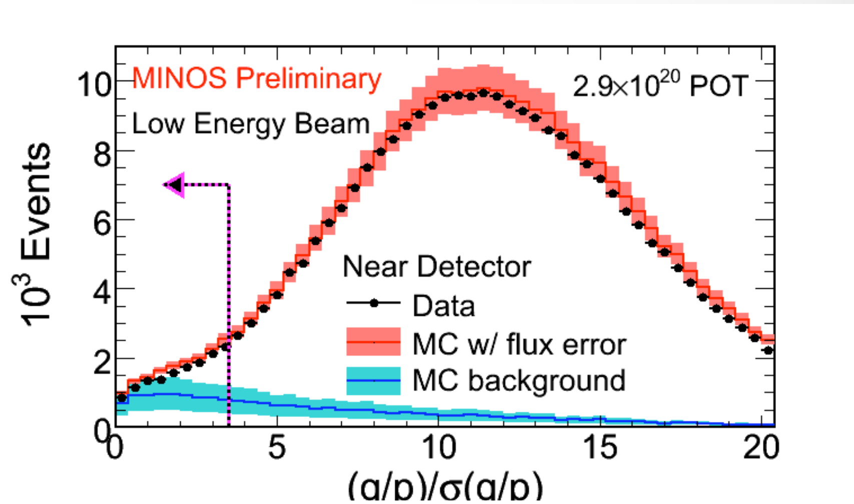


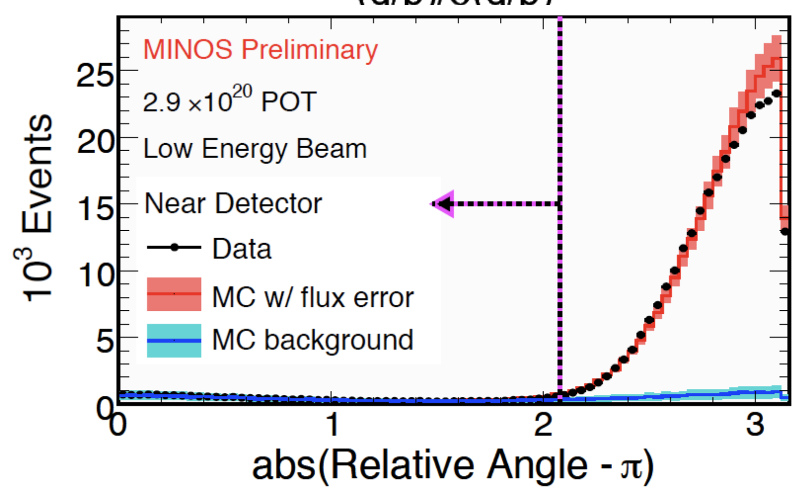


Beam Matrix encapsulates the knowledge of pion two-body decay kinematics & geometry, relates ND with FD spectrum.

Anti-ν_μ event requirements in ν_μ optimized beam

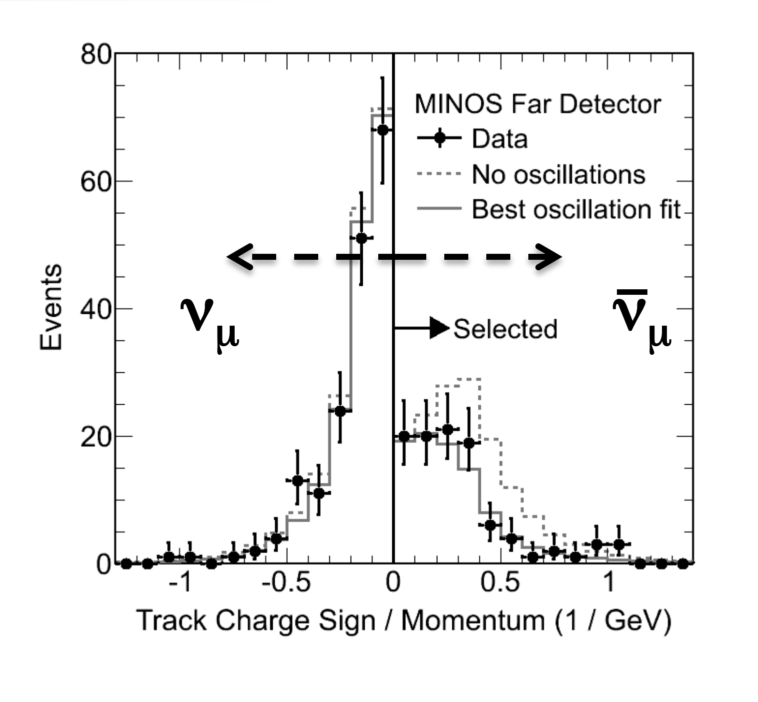


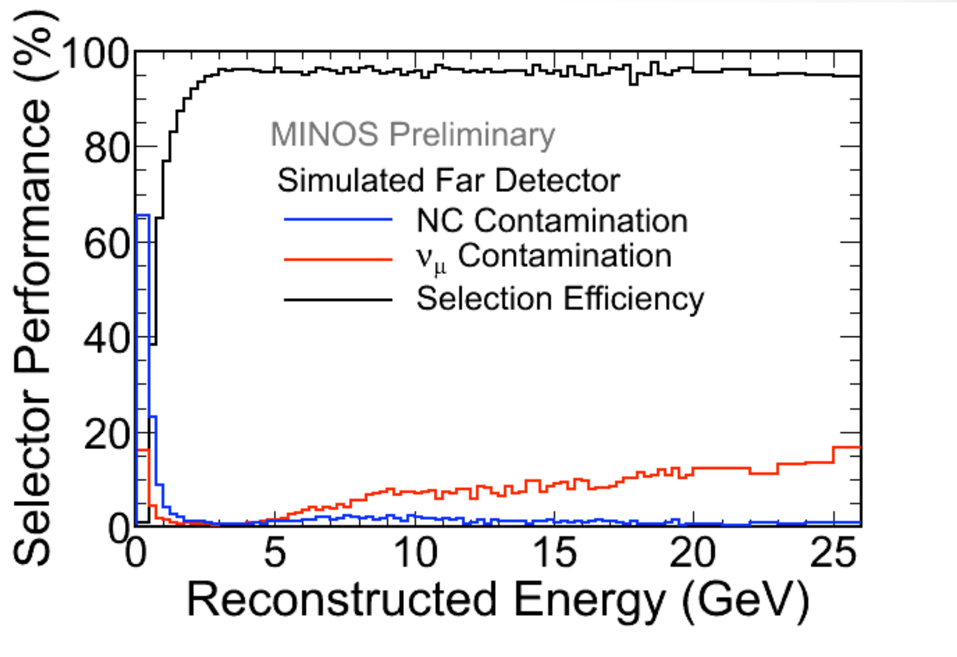




Besides a charge cut, three additional selections used.

Anti-ν_μ selections in anti-ν_μ optimized beam

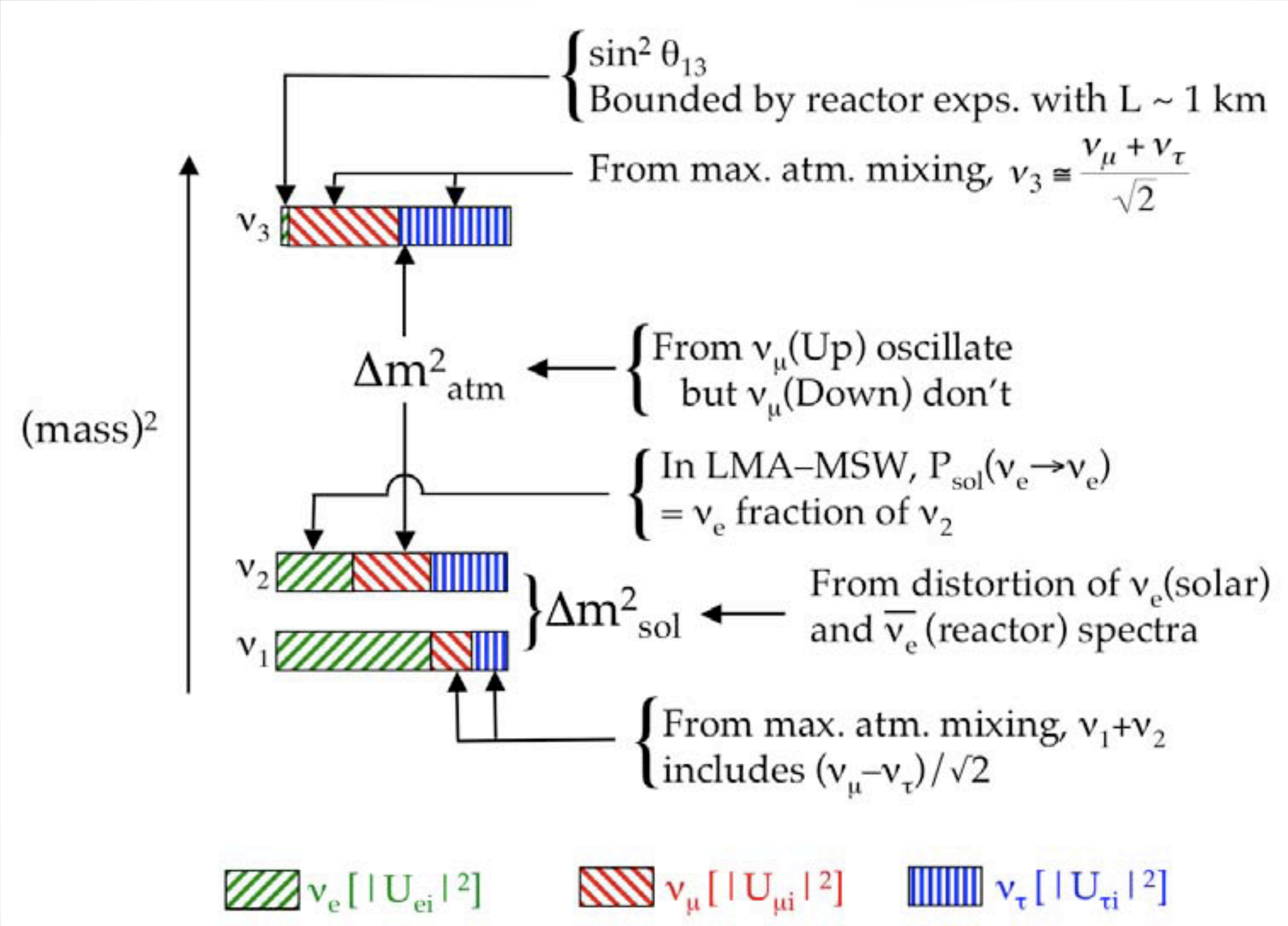




High efficiency and purity

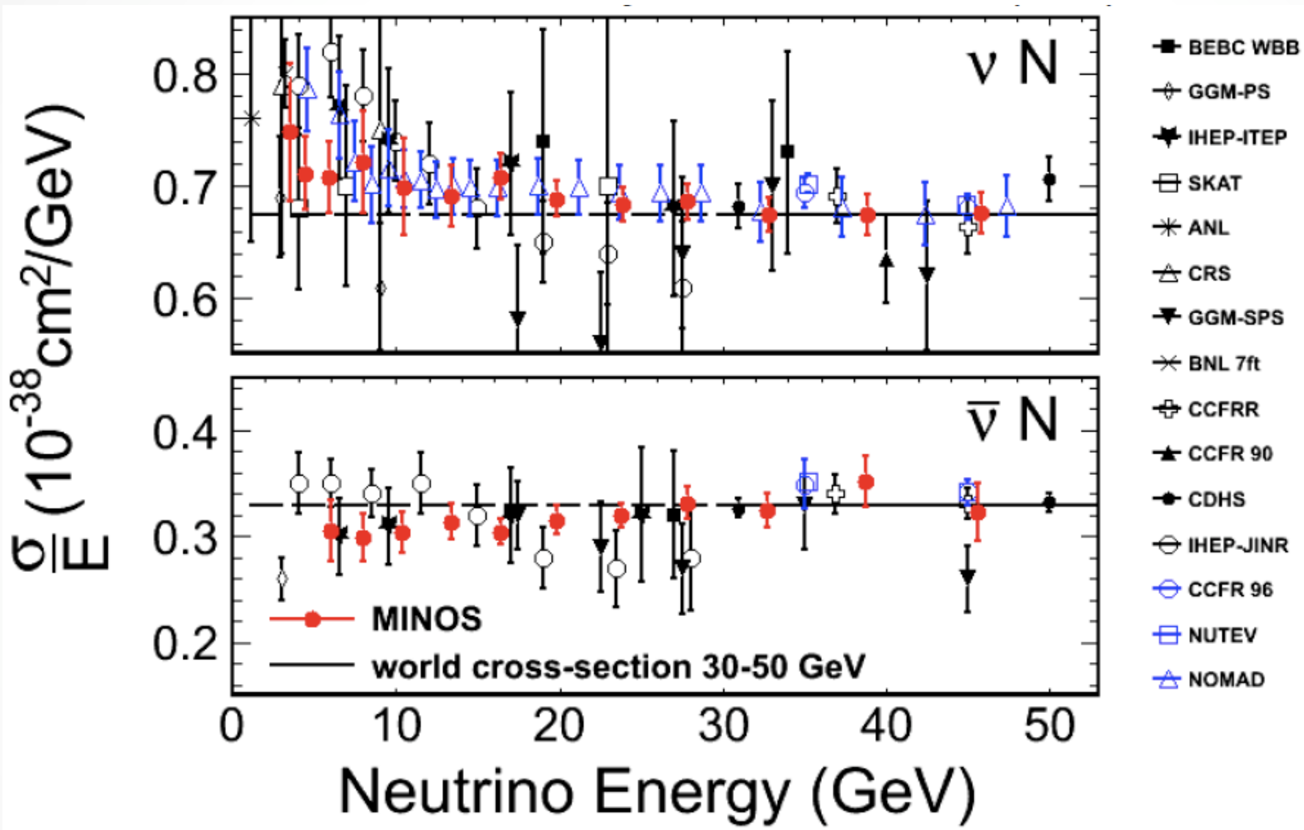
What MINOS does

- High precision measurement of Δm^2_{23} in Charged Current analysis
  - Implying that muon neutrino in MINOS disappear into tau neutrino, MINOS precisely measure flavor oscillation parameters $(\nu_\mu \leftrightarrow \nu_\tau)$
  - This provides a solid discrimination against alternative models such as ν decay, decoherence etc
- Directly compare ν vs anti-ν oscillation parameters.
- Favor or disfavor 4 flavor neutrino theory (with sterile ν) in Neutral Current (NC) analysis.
- Study subdominant $\nu_\mu \leftrightarrow \nu_e$ oscillations
  - Attempt to set limits on θ_{13}
- Study ν interactions and cross sections using the very high statistics accumulated in Near Detector for number of years.
  - Coherent Neutral Current π^0 production.
- Cosmic Ray Physics with both detectors
- Atmospheric Neutrino interactions
- Seasonal variation of neutrino fluxes.



From B.Kayser, 2004

Neutrino production cross-sections



Red points – MINOS measurements

Phys. Rev. D 81, 072002 (2010)

Non-standard interactions?

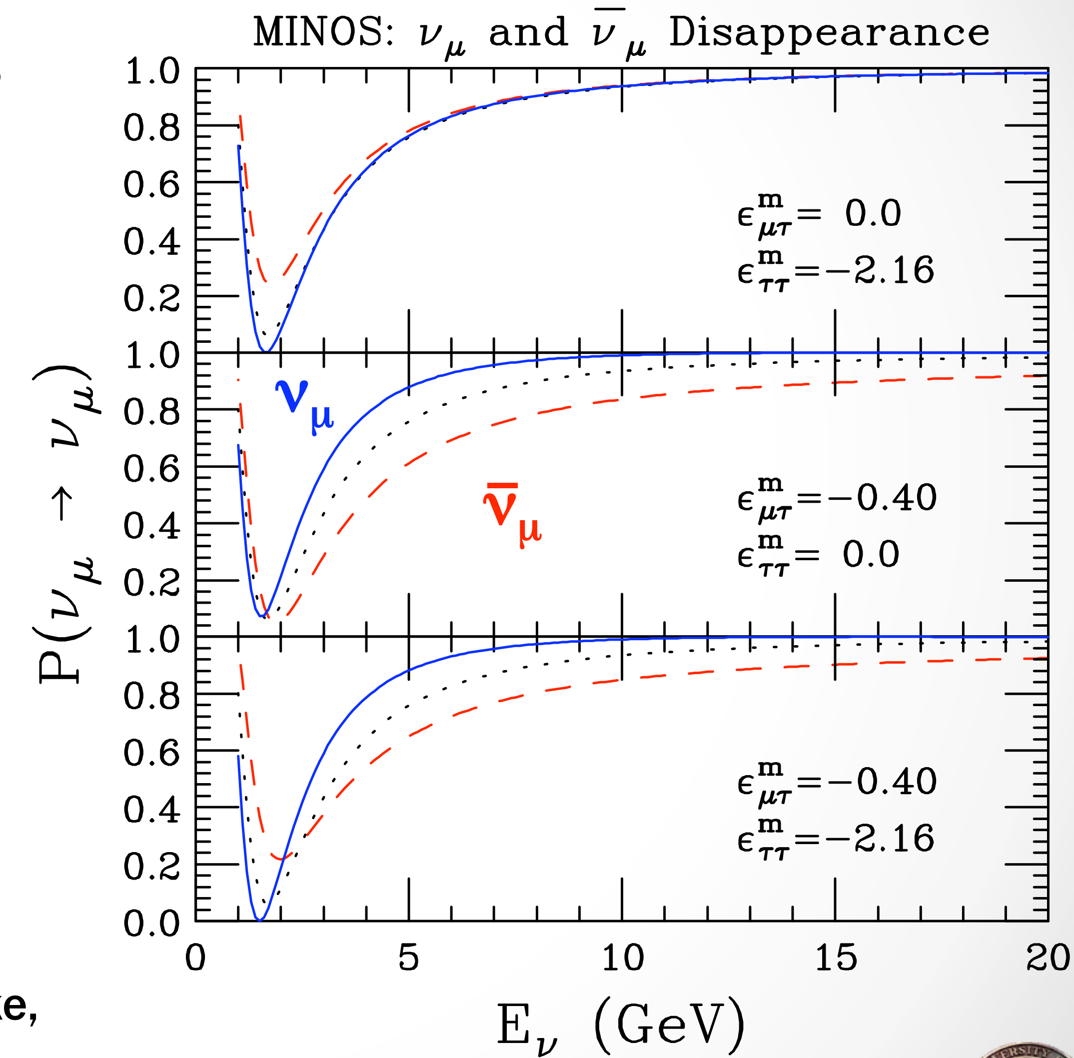
Do we see neutrino non-standard interactions in matter already?

The amplitude and position of survival probability is different for neutrino and anti-neutrino?

Modified survival probability (with maximal mixing):

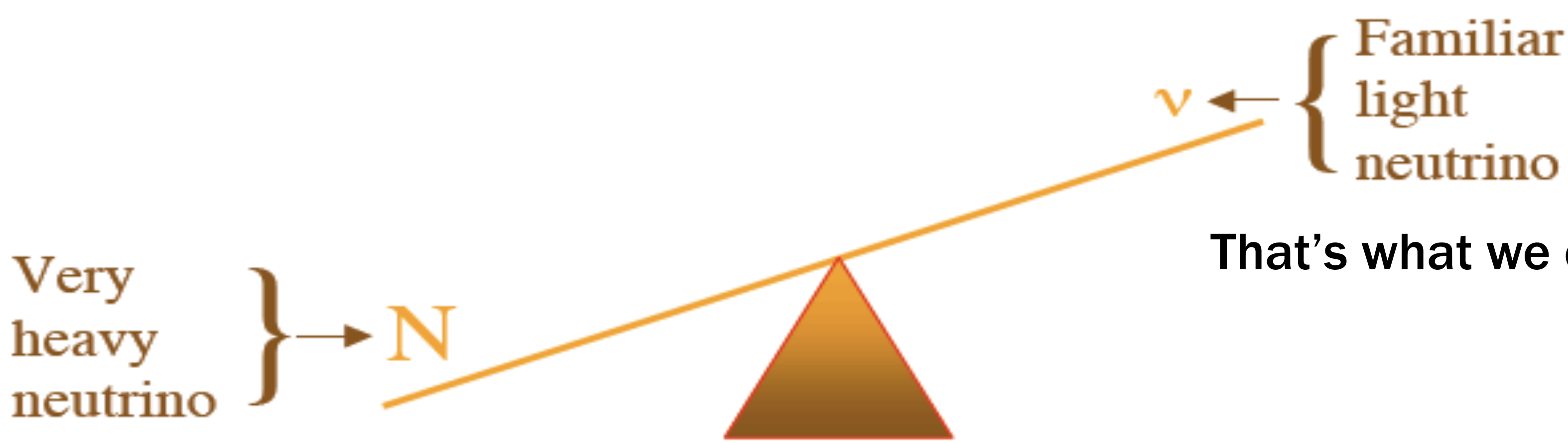
$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2\left(\frac{\Delta m_{23}^2 L}{4E} \pm \epsilon_{\mu\tau} V\, L\right)$$
$$= 1 - \sin^2\left(1.27\frac{\Delta m^2 L}{E} \pm \epsilon_{\mu\tau} V\, L\right)$$

J.Kopp, P.Machado, S.Parke, arXiv:1009.0014 [hep-ph]



Why those neutrino we observe do have a mass?

The See-Saw Relation



That's what we can

We can't observe it (ever)