MINOS experiment at Fermilab

Tom Kafka for the MINOS Collaboration

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27 institutions
140 physicists

MINOS topics

This talk

- The experiment
- ν oscillations in the NuMI beam:
  (1) ν_μ disappearance
  (2) ν_e appearance
  (3) ν NC disappearance (sterile ν mixing)
  (4) $\bar{\nu}_\mu$ disappearance
- Summary

Other topics

- Atmospheric ν oscillations
- Non-oscillation topics:
  - ν cross sections
  - Quasi-elastic reactions
  - ν-nucleus coherent reactions
- Cosmic-ray μ measurements:
  - Charge ratio
  - Seasonal variations
  - Sudden stratospheric warming

MINOS & neutrino mixing

Three-neutrino mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric ν — Not measured yet — Solar ν

MINOS:

$\nu_\mu/\bar{\nu}_\mu$ disappearance — ν_e appearance — N/A

$$U_3 = R_{23}(\theta_{23})\, R_{13}(\theta_{13},\delta_{CP}) R_{12}(\theta_{12})$$

Four-neutrino mixing:

$$U_4 = R_{34}(\theta_{34})\, R_{24}(\theta_{24},\delta_2)\, R_{14}(\theta_{14})\, R_{23}(\theta_{23})\, R_{13}(\theta_{13},\delta_1) R_{12}(\theta_{12})$$

MINOS: ν NC disappearance/ν_s mixing

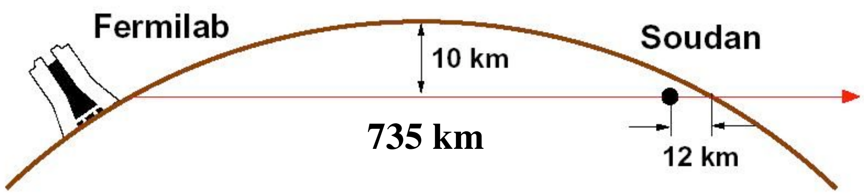
MINOS experiment

MINOS (***M**ain **I**njector **N**eutrino **O**scillation **S**earch*) – a long-baseline neutrino oscillation experiment.

NuMI (***Neu**trinos at the **M**ain **I**njector*) beam provided by 120 GeV protons from the Fermilab Main Injector.

Near Detector (@ 1 km) at Fermilab to measure the beam composition and energy spectrum.

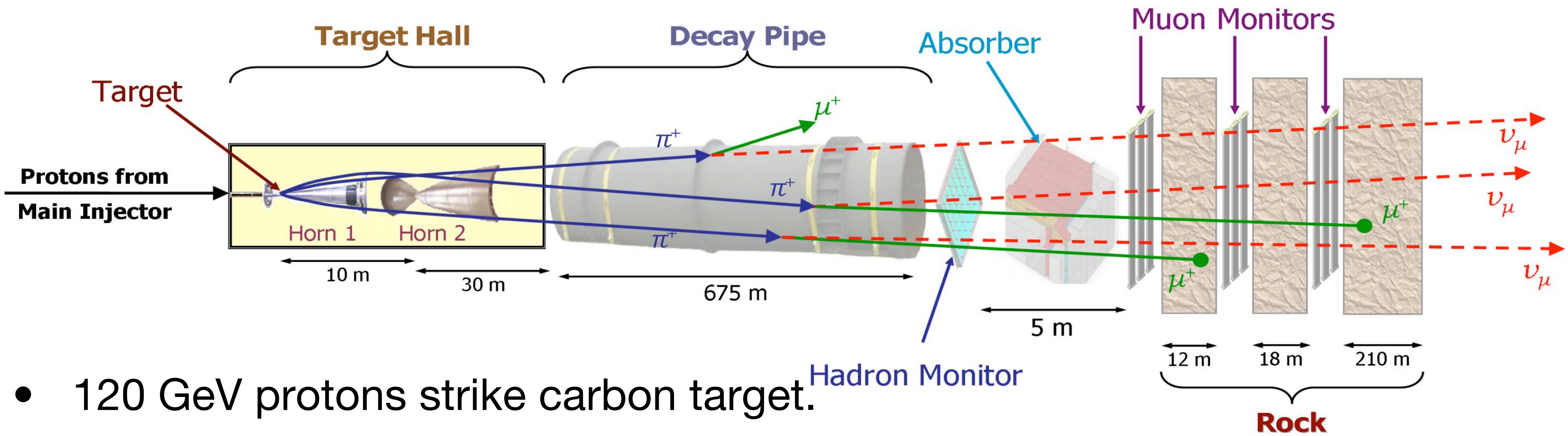
Far Detector (@ 735 km) deep underground in the Soudan Mine, Minnesota, to search for evidence of oscillations.



Far Det., 5.4 kton

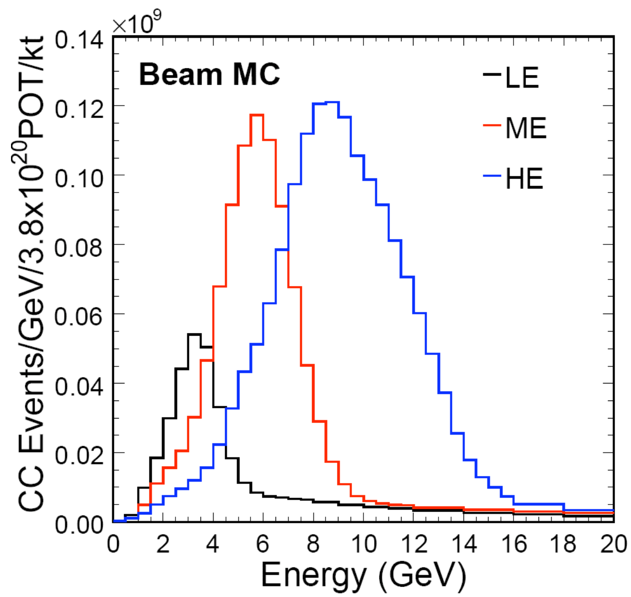
Near Det.
1 kton

NuMI beam



- 120 GeV protons strike carbon target.
- 10 µs long pulse of 3×10^{13} protons every 2.2 seconds (275 kW).
- Two magnetic horns focus secondary π/K; decays of π/K produce neutrinos.
- Move target and/or horns to vary neutrino beam energy.
- In Low-Energy (LE) beam:

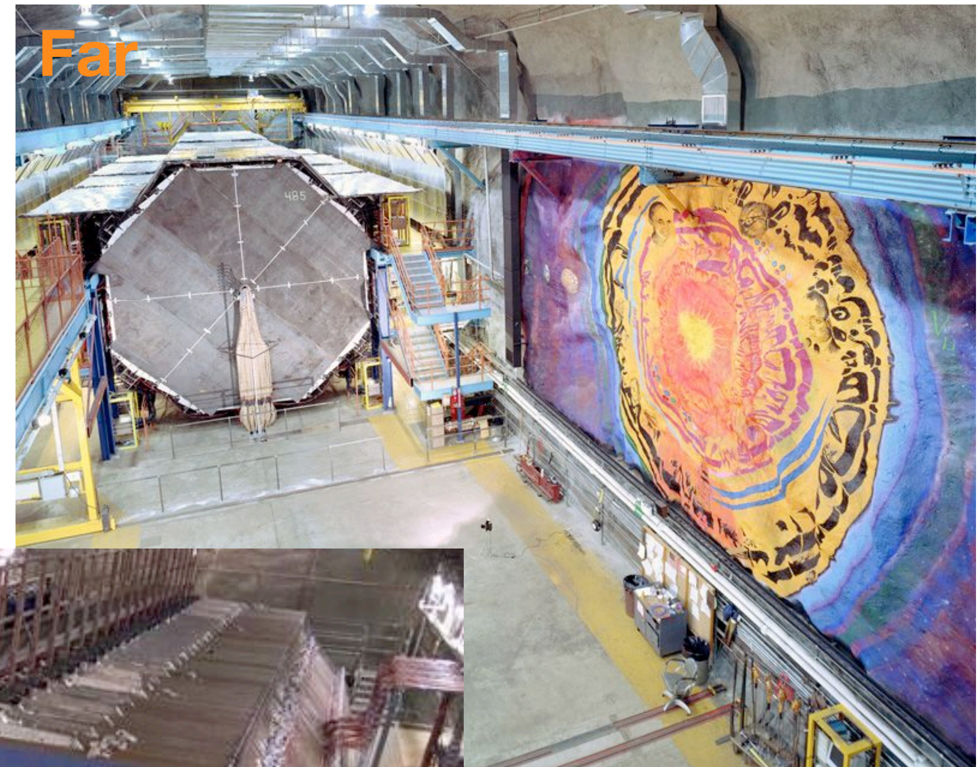
$$91.7\% \ \nu_\mu, \ 7.0\% \ \bar{\nu}_\mu, \ 1.3\% \ \nu_e + \bar{\nu}_e$$



MINOS detectors

- **Near** and **Far** detectors
  are magnetized (1.3 T),
  functionally identical.

- 1-inch thick octagonal steel planes,
  alternating with planes of
  4.1 cm × 1 cm scintillator strips,
  up to 8 m long.



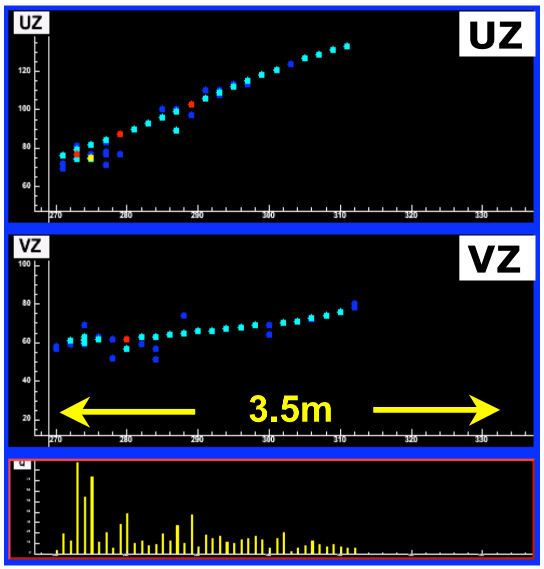
Near:
~ 1kton,
282 squashed octagons,
partially instrumented.

Far:
5.4 kton,
486 8-m octagons,
fully instrumented.

MINOS event topologies

ν_μ charged-current ev.

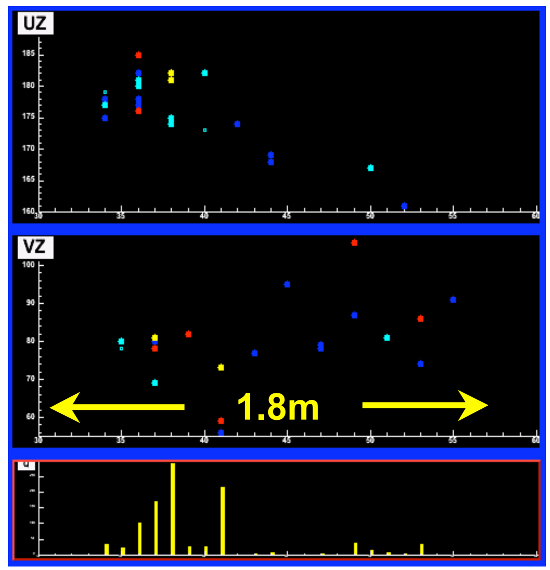
$$\nu_\mu + Fe \rightarrow \mu + X$$



Long μ track & hadronic activity at vertex

Neutral-current ev.

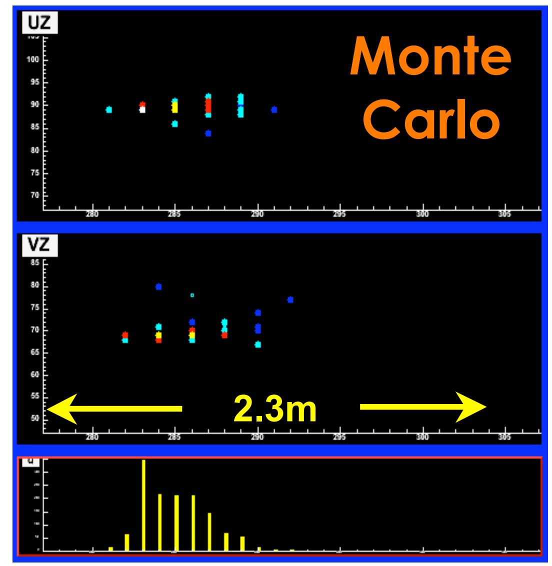
$$\nu + Fe \rightarrow \nu + X$$



Short event, often diffuse

ν_e CC event

$$\nu_e + Fe \rightarrow e + X$$



Short, with typical EM shower profile

CC: $E_\nu = E_{hadrons} + E_{lepton}$

NC: $E_\nu \approx E_{hadrons}$

Common to all analyses:

Exposure:

$3+ \times 10^{20}$ POT

Neutrino flux:

MC flux adjusted to fit data in the Near Detector.

Basic cuts:

Beam quality and detector quality cuts

- Beam positioning, magnetic horns energized, detector running within operational parameters

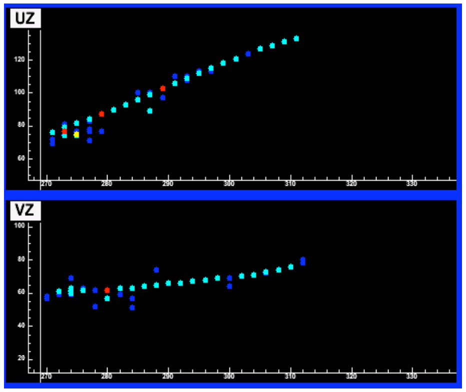
Event vertex reconstructed within the fiducial volume of the detector.

Blind analysis:

FD spectra were analyzed only ***after*** the analysis procedure was finalized and basic data integrity checks were performed.

Next:

Analysis underway of a larger data set already on hand, 7×10^{20} POT.



$$\nu_\mu + Fe \rightarrow \mu^- + X$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

(1) ν_μ CC disappearance

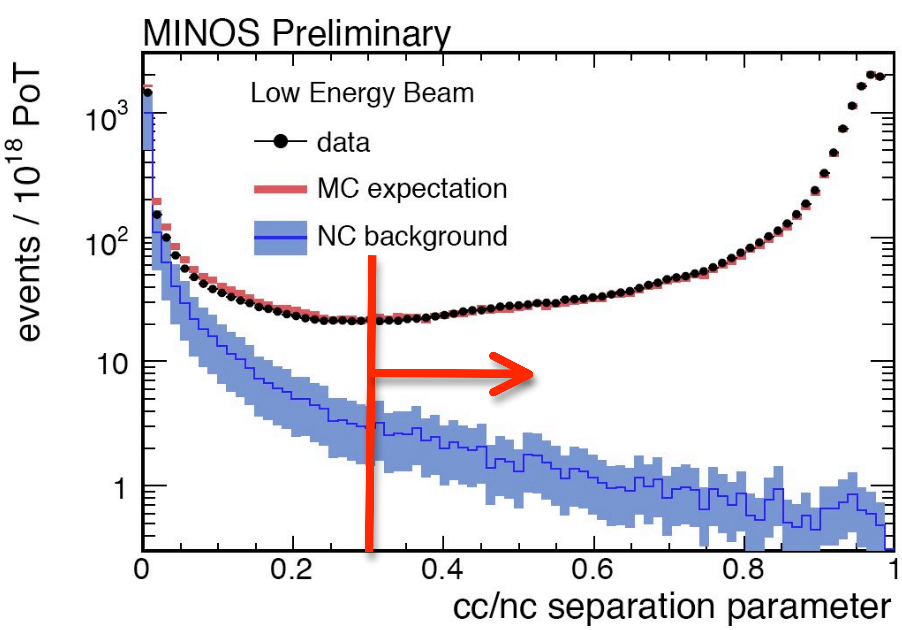
- $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Measure Δm^2_{32}, $sin^2 2\theta_{23}$
- ν decay, decoherence, …

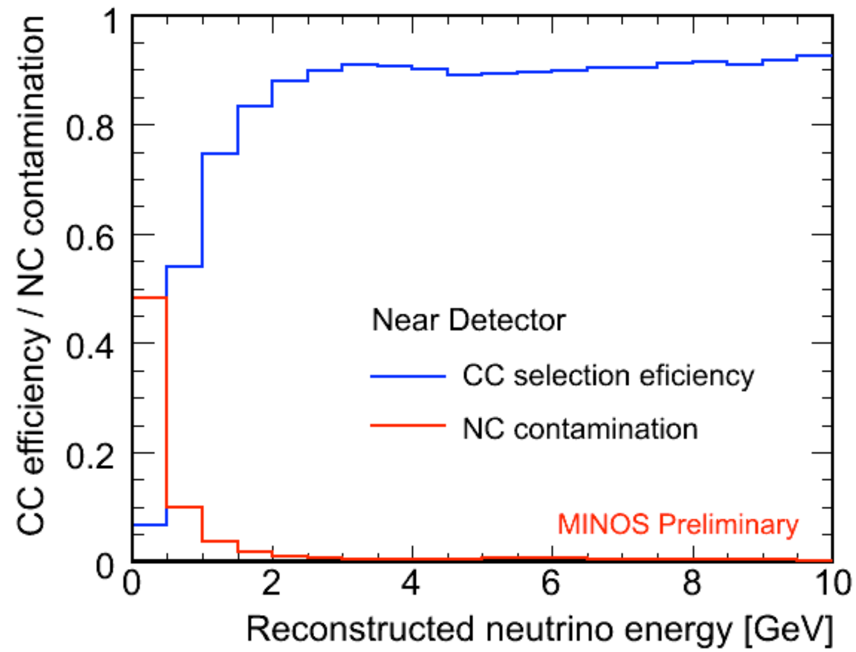
ν_μ CC event selection

Need to separate ν_μ charged-current (CC) and neutral-current (NC) interactions

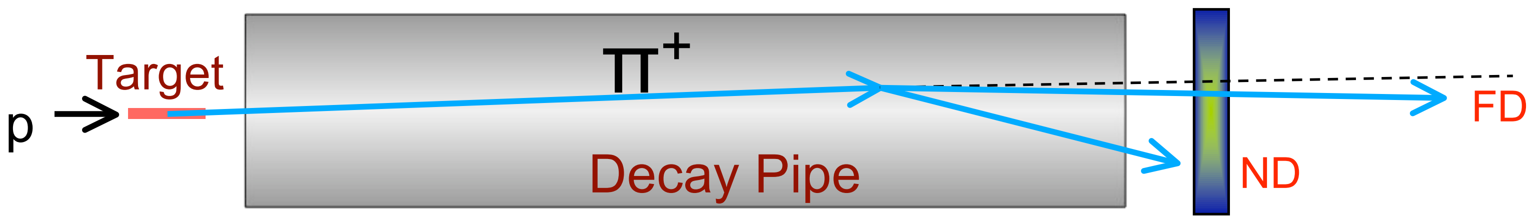
Four variables combined using a *k*-nearest-neighbors algorithm

- Event length (Track length for ν_μ CC);
- Mean pulse height per plane along the track;
- Transverse energy deposition profile of the track;
- Pulse height fluctuations along the track.





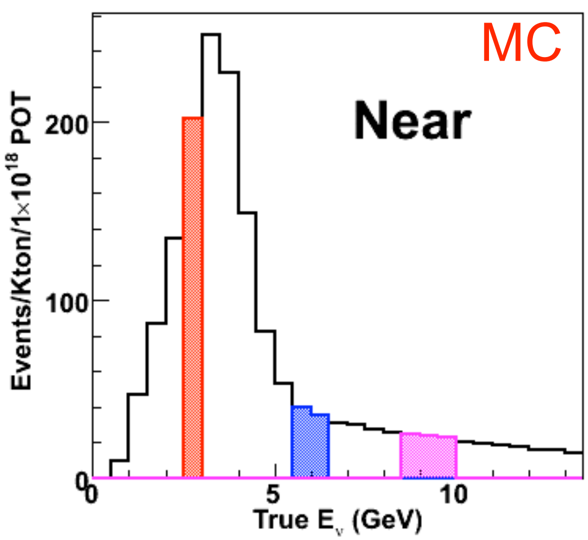
ν_μ beam extrapolation

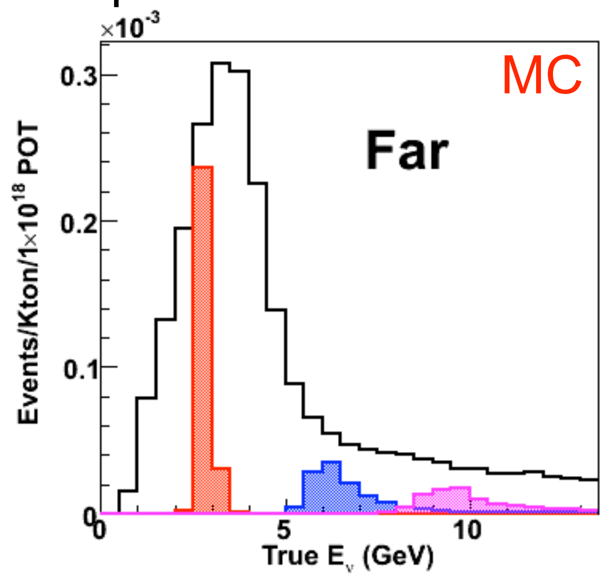


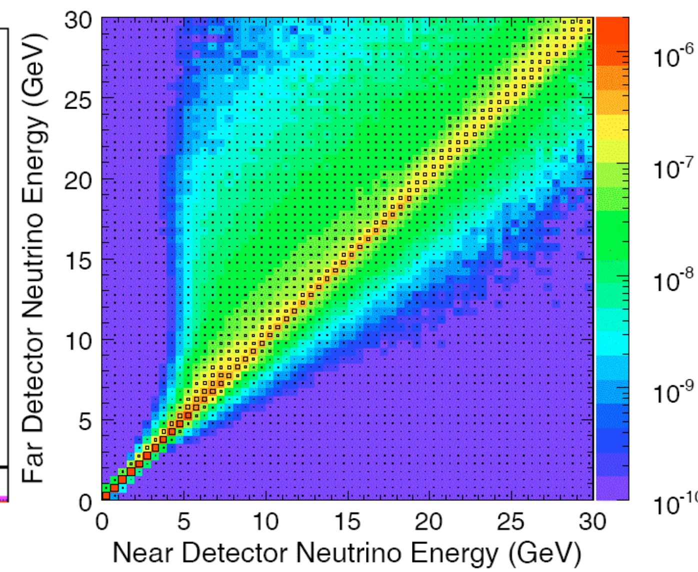
The observed Near-Det. energy spectrum is extrapolated to the Far-Det.:

The energy spectra at the two detectors differ by ~20% due to meson decay kinematics, beamline geometry and detector acceptance.

Using Monte Carlo, encode these differences into a beam transfer matrix used to convert ND to FD spectrum





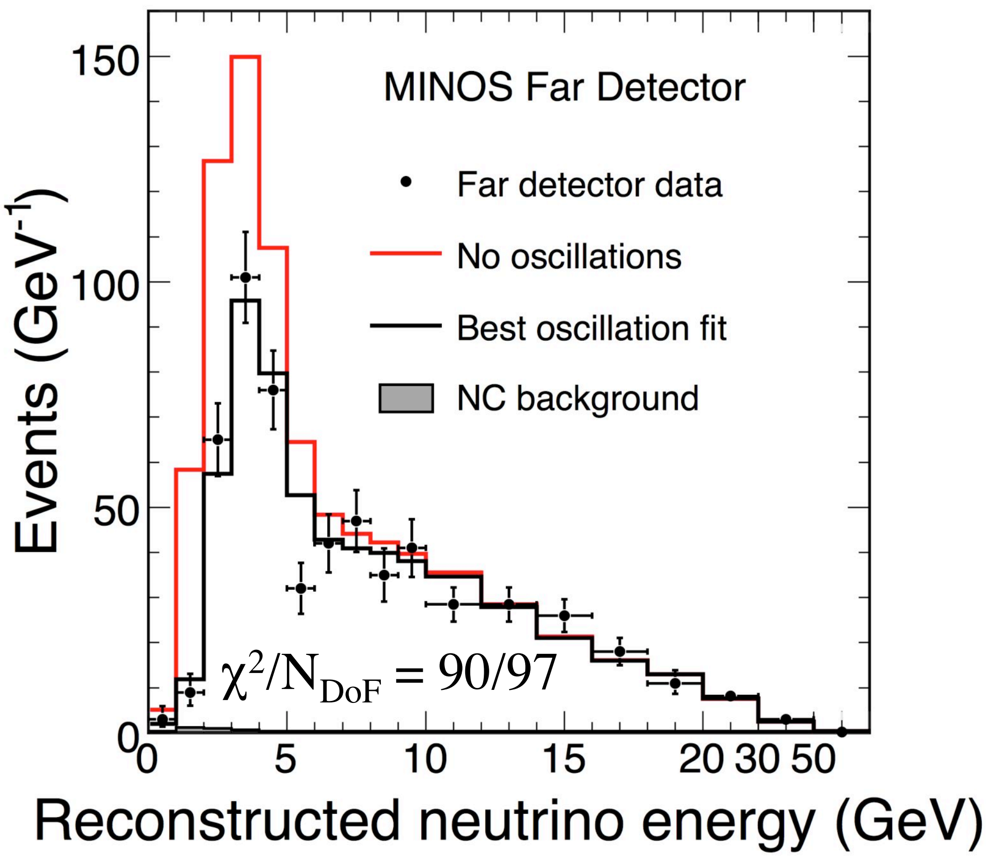


ν_μ CC disappearance

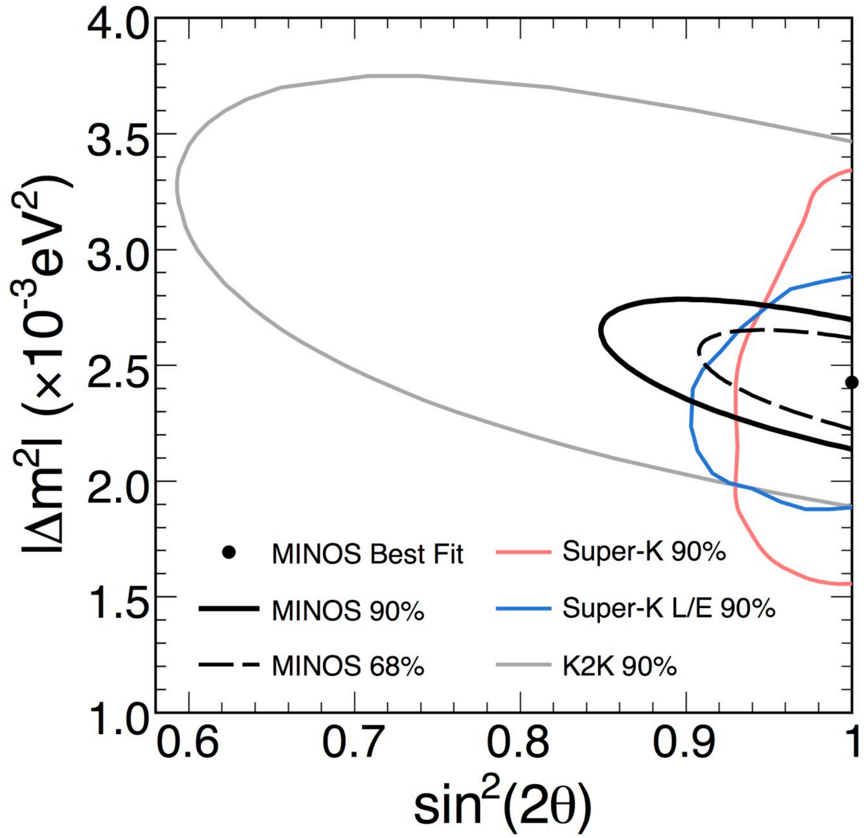
- 3.36×10^{20} POT
- Use both LE and HE beam.
- Blind analysis.
- Expected 1065 ± 60 with no osc.;
- Observed 848 events.
- Energy spectrum fit with the oscillation hypothesis

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

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_\tau)$$



$\nu_\mu \rightarrow \nu_\tau$ oscillations - Allowed region



Best fit

- $|\Delta m_{32}^2|$ =(2.43±0.13)x10^{-3} eV^2 (68% C.L.)
- $\sin^2(2\theta_{23}) > 0.95$ (68% C.L.), 0.90 (90% C.L.)
- χ^2/N_{DoF} = 90/97

Phys. Rev. Lett. ***101****, 131802 (2008)*

ν_μ CC disappearance – Alternative models

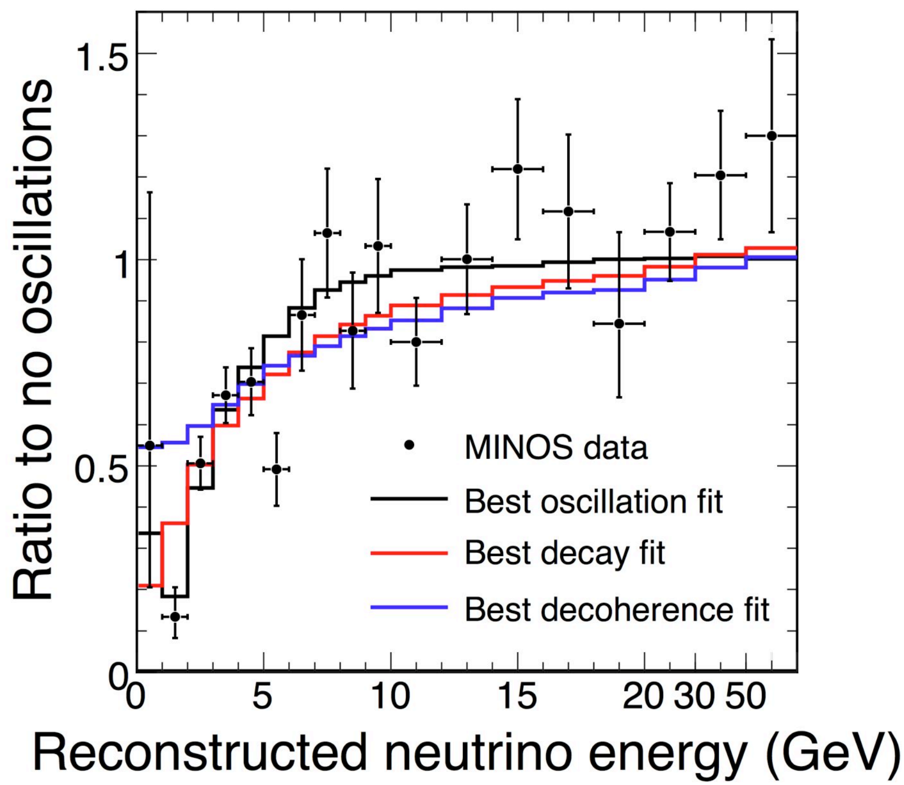
Two alternative disappearance models are disfavored:

[1] Decay without oscillations:

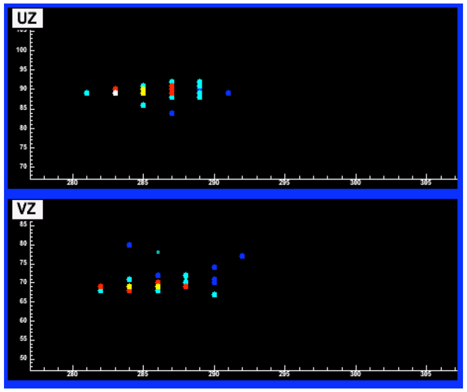
$\chi^2/\text{ndof} = 104/97$
$\Delta\chi^2 = 14$
disfavored at 3.7σ
(*5.4σ* if combine CC & NC)

[2] Decoherence:

$\chi^2/\text{ndof} = 123/97$
$\Delta\chi^2 = 33$
disfavored at 5.7σ



[1] V. Barger *et al.*, PRL **82**, 2640 (1999)
[2] G.L. Fogli *et al.*, PRD **67**, 093006 (2003)



$$\nu_e + Fe \rightarrow e + X$$

$$\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix}$$

(2) ν_e appearance

- Search for $\nu_\mu \rightarrow \nu_e$ oscillations
- Aim to measure $\sin^2 2\theta_{13}$

ν_e appearance

- Select ν_e CC candidate events in the MINOS detectors.
- Measure the background applying ν_e selection to events in the Near Detector.
- Extrapolate the number of background events to the Far Detector taking into account $\nu_\mu \rightarrow \nu_\tau$ oscillations.
- Look for an excess of ν_e events in Far Detector data.

ν_e appearance – event selection

Preliminary cuts:

- Track length < 25 planes
- Reconstructed energy 1-8 GeV.
- At least one shower

Improve Signal:Background from 1:55 to 1:12

(signal at CHOOZ limit assumed)

Multivariate methods devised to select shower topology:

Artificial **N**eural **N**etworks (ANN) *(Primary method)*

- 11 input variables describing length, width and shower shape.
- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection >92.3%
  - CC rejection >99.4%
  - Signal/Background 1:4

Library **E**vent **M**atching (LEM) *(Secondary method)*

- Compare each input event to a large library of MC ν_e CC and NC events.

ν_e appearance – backgrounds

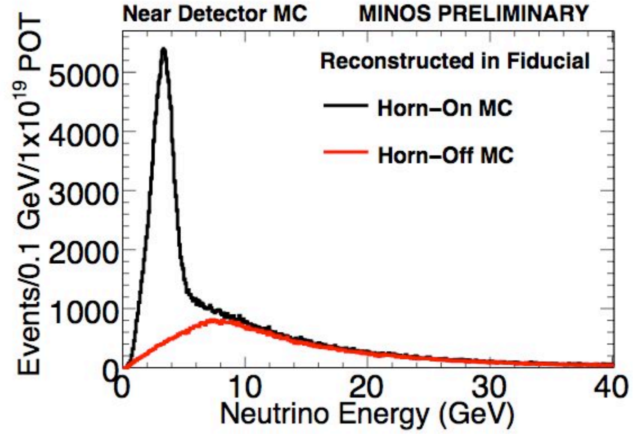
Backgrounds:

- ν **N**eutral-**C**urrent events (with π^0)
- ν_μ **C**harged-**C**urrent events (with π^0 and short μ track = high *y*)
- ν_e intrinsic to the NuMI **b**eam

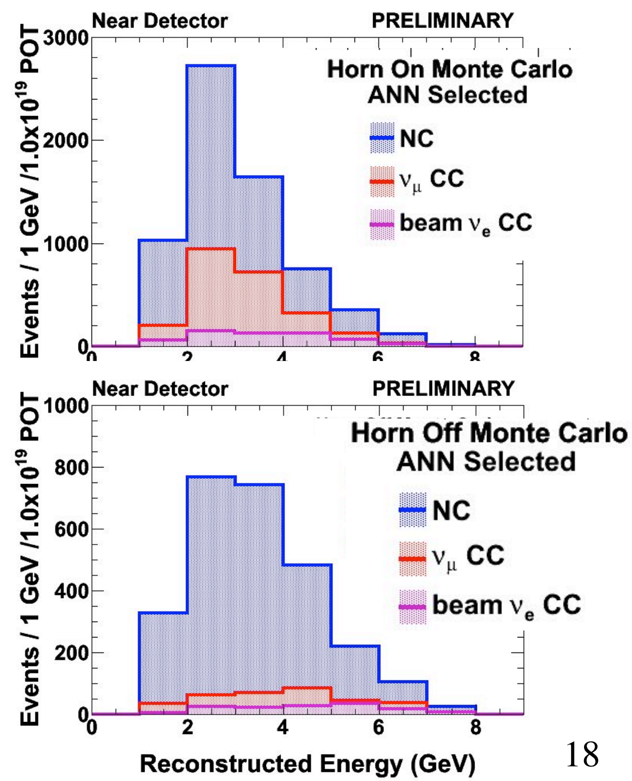
Use data based method(s) to determine the background components:

(1)Horn-Off (Primary method)

(2)Muon-**R**emoved **CC** (Secondary method)

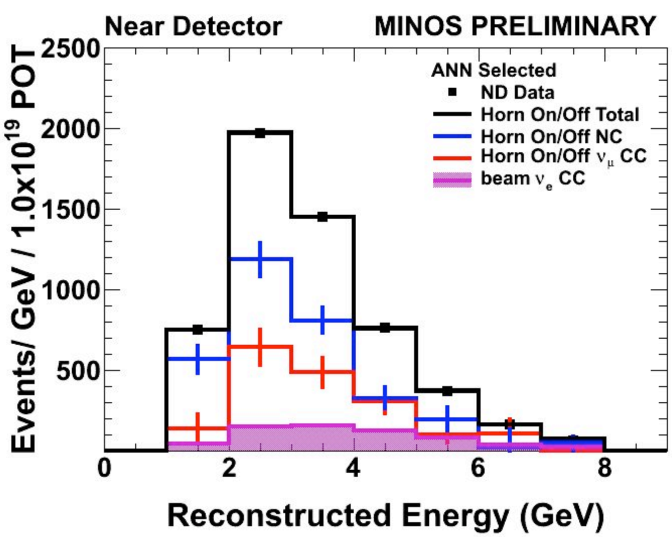


Horn-Off and **Horn-On** ν beams have very different energy distributions and very different NC vs CC composition in ND



ν_e appearance – backgr'd results

- Calculate event rates $N_{NC}^{data\_on}$ and $N_{CC}^{data\_on}$ in terms of N^{data_on} and N^{data_off} from data and ratios $N_{NC(CC,e)}^{MC\_off}/N_{NC(CC,e)}^{MC\_on}$ from MC (modeled satisfactorily).
- Number of beam ν_e is obtained from MC flux (constrained by ν_μ CC data).
- Resulting bkgnd composition in ND: (57±5)% NC, (32±7)% CC, (11±3)% b. ν_e



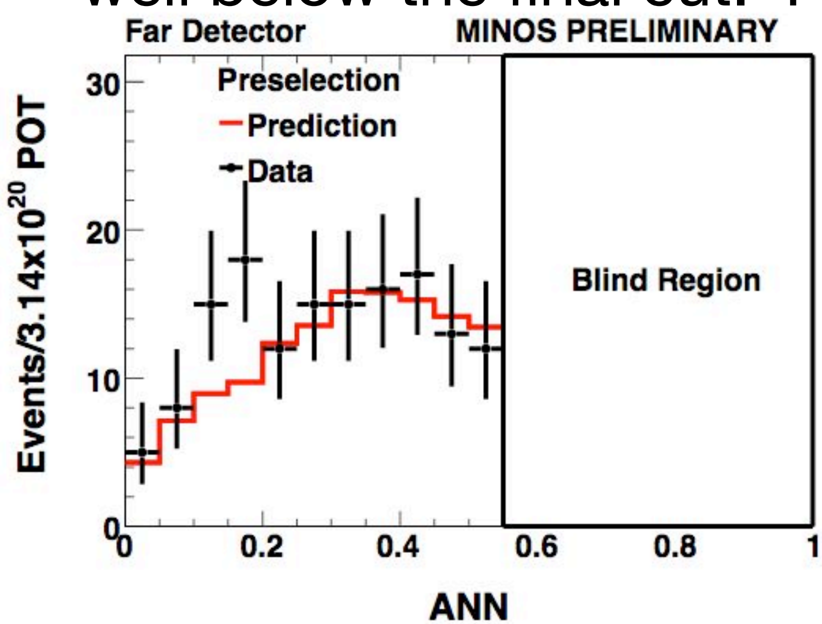
- Propagate background from Near to Far Detector (using "Far/Near" method).
- Extensive study of systematic effects:
  -> Total systematic error 7.3 %
  cf. statistical error of 19 %

The background prediction in the Far Detector is:

27±5(stat)±2(sys) (at 3.14 x10^{20} POT)

ν_e appearance – blind analysis

- Choose final event selection algorithm based on side bands only. Then OPEN THE BOX.
- *Example of a side band:* Region of Particle-ID (PID) parameter well below the final cut. Finding no significant disagreement.

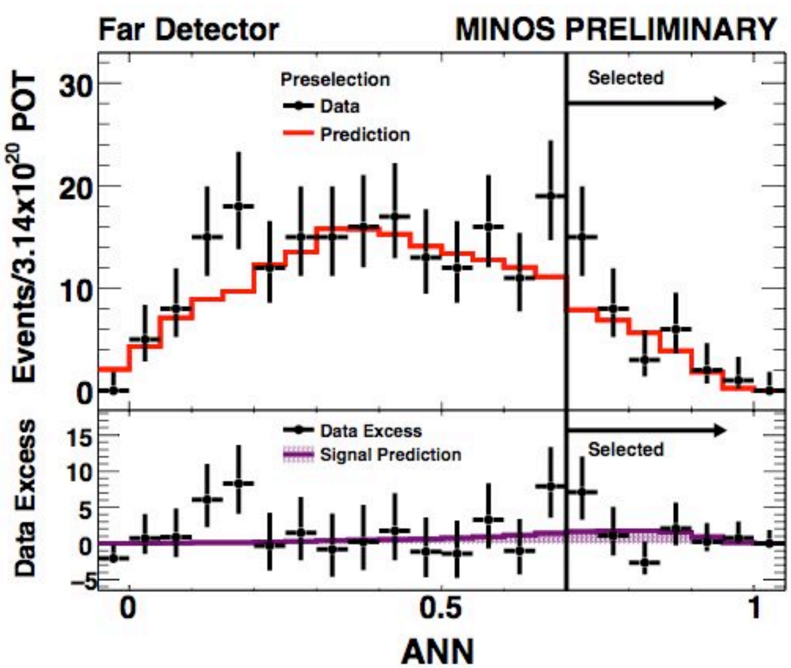


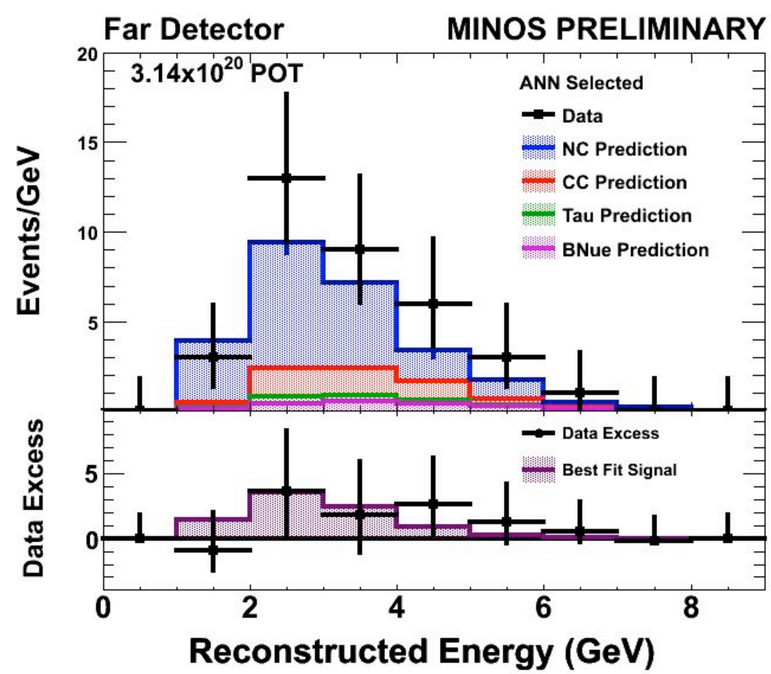
- Observe 146 events.
- Expect 132±12(stat)±8(sys) events.

Note: PID cut established prior to "Box" opening by maximizing the Figure of Merit, *FOM = Signal/*$\sqrt{}$*(Background +* σ^2_{syst}*)*

ν_e – results for 3.14 x10^{20} POT

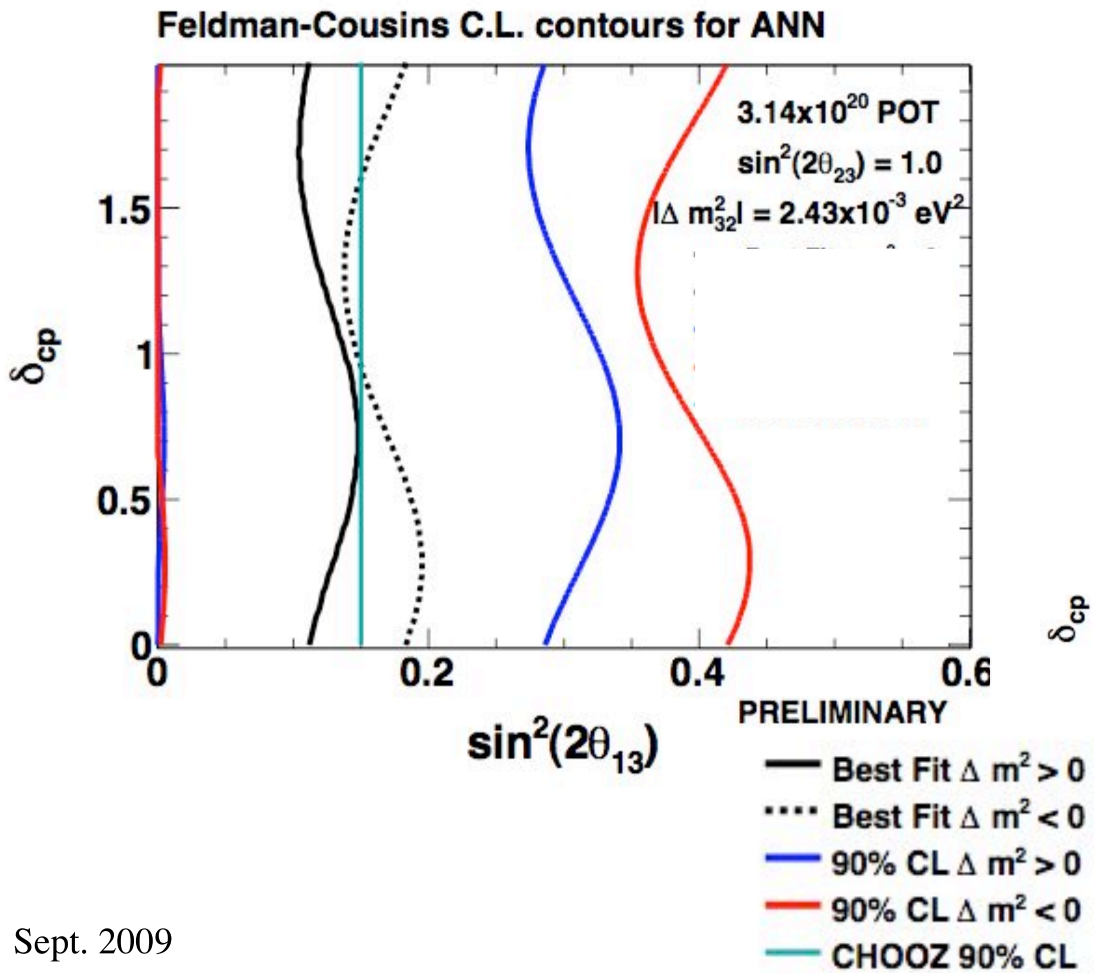
- Observe 35 events in FD after selection.
- Expect 27±5(stat)±2(sys) background events.
  - ∴ 'Excess' of 1.5σ



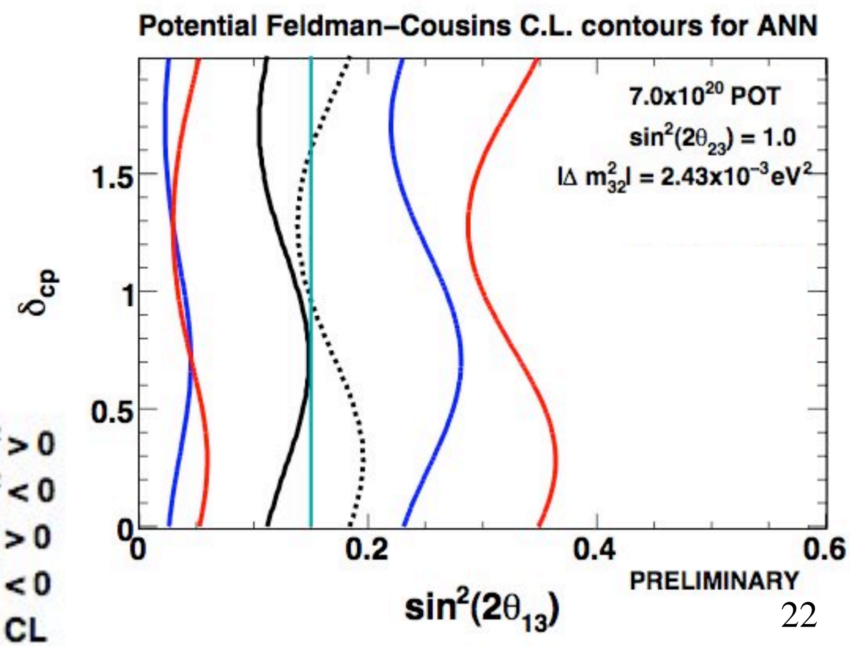


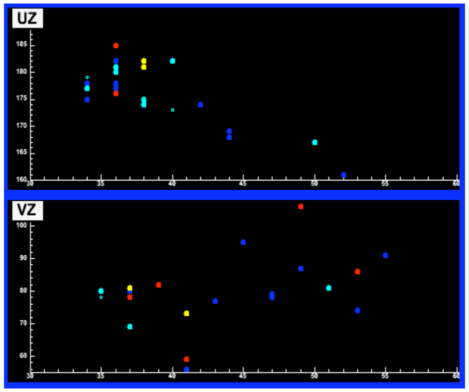
ν_e appearance – δ_{CP} vs. $\sin^2 2\theta_{13}$

- Fit the oscillation hypothesis to our data for 3.14 x10^{20} POT
- Display best fit & 90% CL contours obtained using Feldman-Cousins method.
- Use MINOS best fit from ν_μ CC

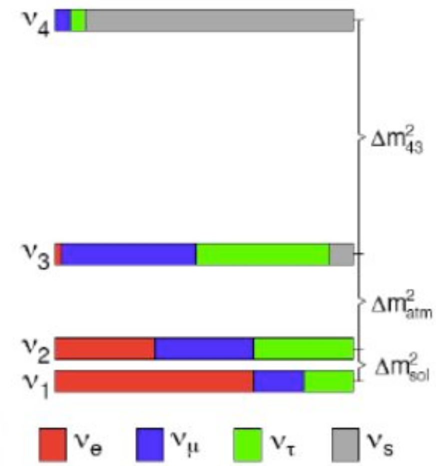


Next: 7 x10^{20} POT;
"if excess persists"





$$\nu + Fe \rightarrow \nu + X$$



(3) ν NC disappearance

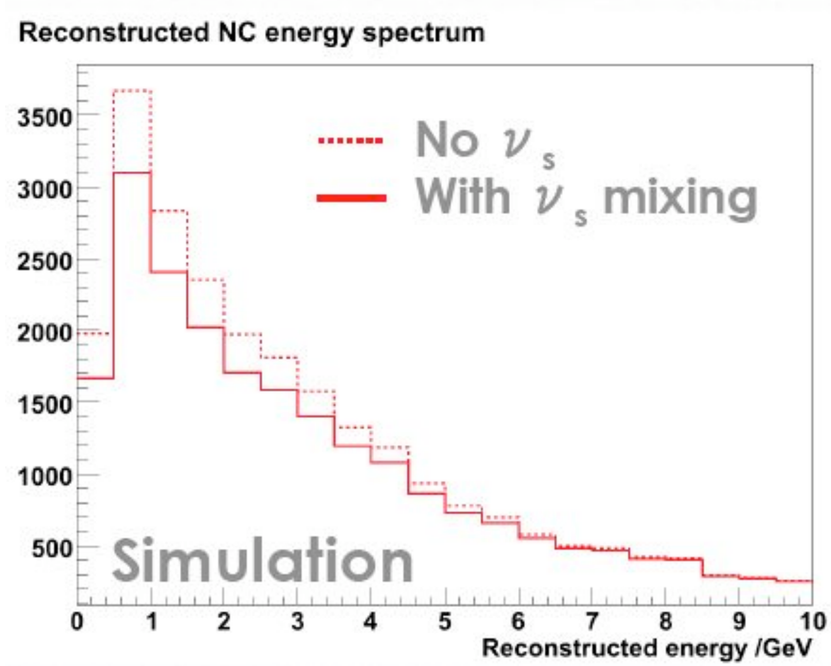
- Look for dearth of Neutral-Current events at the Far Detector as a possible indication of sterile neutrino mixing.
- Consider ν oscillations with ν decay.

Sterile neutrino footprints

- NC interaction rates are the same for all active ν flavors.
- Oscillations among active flavors don't affect NC spectrum.
- Sterile neutrinos would not interact in the detector.
- Sterile ν signal:

Energy-dependent depletion of Far-Detector NC spectrum

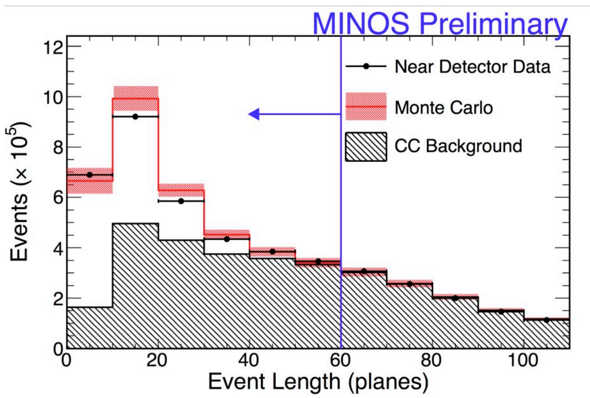
This analysis:
- Cut based, very simple selections,
- CC background straightforward to estimate.

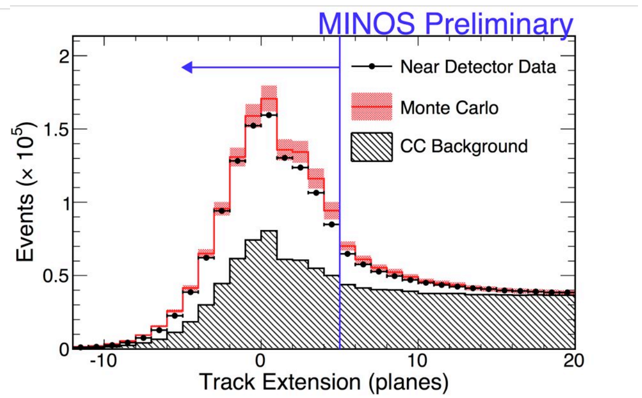


NC event selection

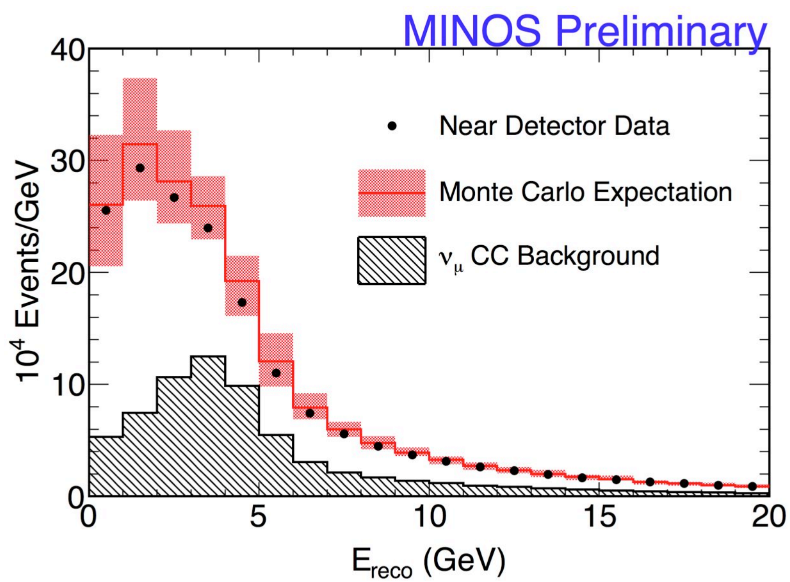
NC = shower topology, no long tracks

- Event length < 60 planes
- No tracks extending > 5 planes beyond the shower





∴ Efficiency ~ 90%
Purity ~ 60%



Near-det. Data & MC agree within errors.

- *Extrapolate:* "Far/Near" method

$$FD_i^{predicted} = \frac{FD_i^{MC}}{ND_i^{MC}} ND_i^{data}$$

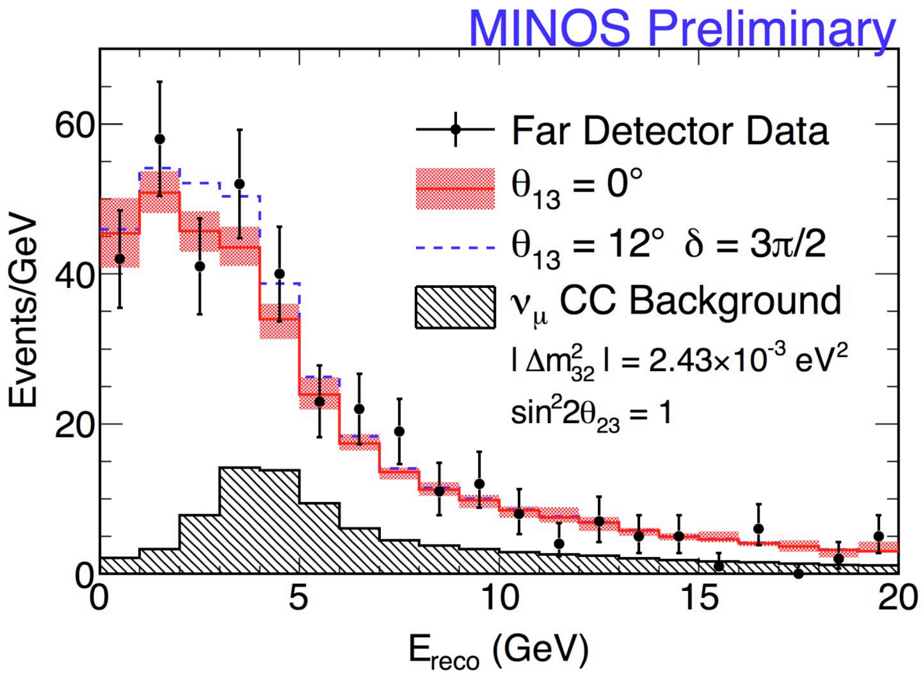
NC at the Far Detector

Beam exposure: 3.18×10^{20} POT
Observe: 388 data events
Expect:
377 ± 19.4(stat) ± 18.5(syst)

$$R \equiv \frac{N_{data} - \Sigma B_{CC}}{S_{NC}},$$

B_{CC} – Predicted CC background

S_{NC} – Predicted NC signal



R = 1.04±0.08±0.07 (no ν_e app.)

= 0.94±0.08±0.07 (with ν_e at CHOOZ limit)

∴ Data is consistent with no NC disappearance.

Oscillations with decay

- If neutrinos were to decay into a sterile species, NC spectrum would also be affected.
- Perform joint NC + CC fits to the LE-beam data using a model with concurrent
  - neutrino oscillations ($\nu_\mu \to \nu_\tau$),
  - subdominant single mass scale decays.
- Assume normal ordering, $m_3 >> m_2 \sim m_1$; ν_3 can decay with lifetime τ_3 .

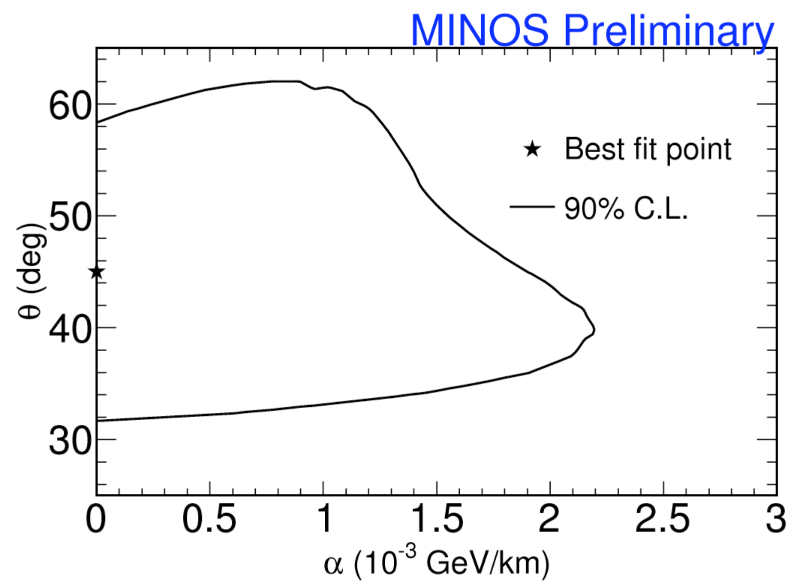
$$P_{\mu\mu} = \cos^4\theta + \sin^4\theta e^{-\frac{\alpha L}{E}} +$$

$$2\cos^2\theta\sin^2\theta e^{-\frac{\alpha L}{2E}}\cos\left(\frac{\Delta m_{32}^2 L}{2E}\right)$$

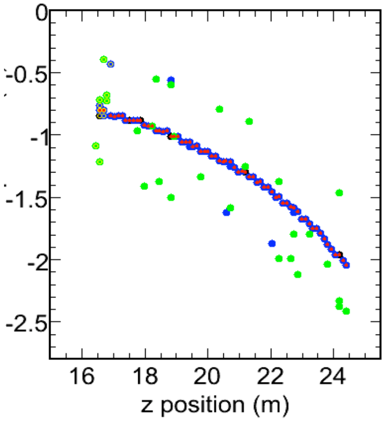
$$P_{decay} = \left(1 - e^{\frac{\alpha L}{E}}\right)\sin^2\alpha, \quad \text{where} \quad \alpha = m_3/\tau_3$$

$\therefore$ $\alpha < 1.6\text{x}10^{-3}$ GeV/km (90% C.L.)

$\tau_3/m_3 > 2.1\text{x}10^{-12}$ s/eV (90% C.L)



Consistent with maximal mixing, θ = 45°, and no neutrino decay.



$\overline{\nu}_\mu + Fe \rightarrow \mu^+ + X$

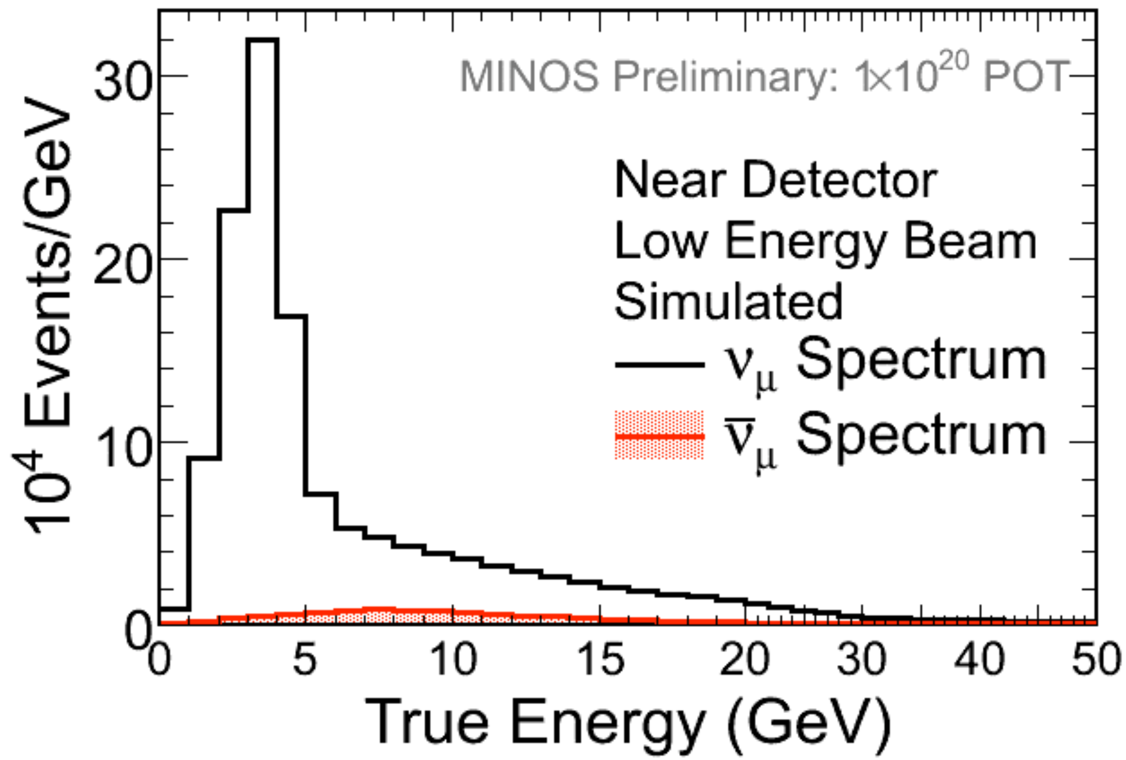
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\overline{\theta}_{23} & \sin\overline{\theta}_{23} \\ 0 & -\sin\overline{\theta}_{23} & \cos\overline{\theta}_{23} \end{pmatrix}$$

(4) $\overline{\nu}_\mu$ disappearance/appearance

- $\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$ oscillations
- $\nu_\mu \rightarrow \overline{\nu}_\mu$ appearance

Antineutrinos in MINOS

- Magnetic field -> separate the 7% $\overline{\nu}_\mu$ component of the forward-horn-current beam.
- Peak @ 3 GeV for ν_μ
  8 GeV $\overline{\nu}_\mu$



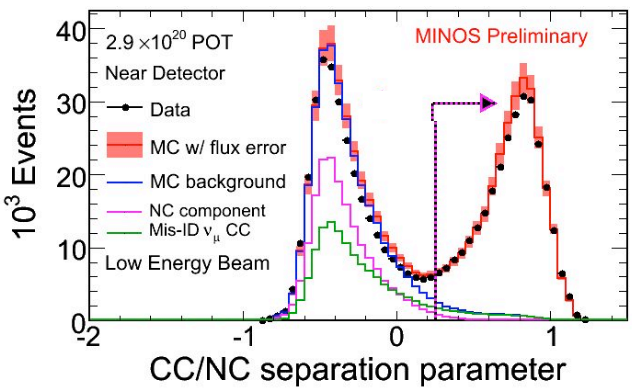
Backgrounds:

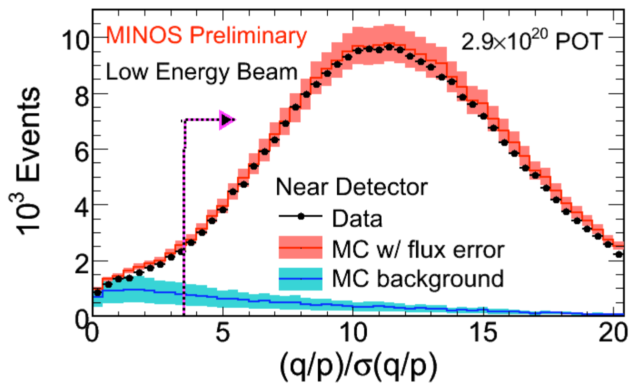
- Misidentified ν_μ CC (μ^- as "μ^+")
- NC (π^+ as "μ^+", π^+:π^-= 50:50)

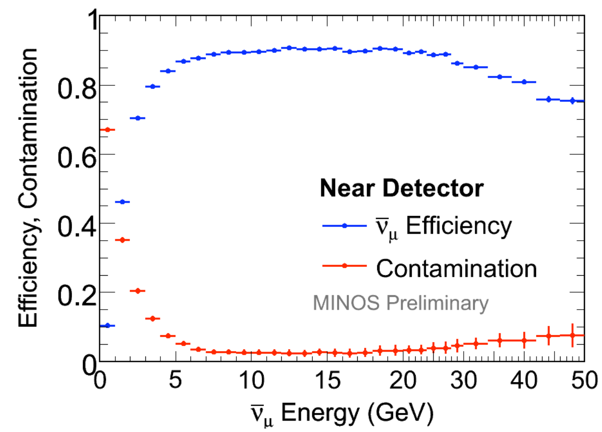
Antineutrinos in MINOS - selection

Event selection:

- Basic cuts – same as previous ν_μ CC
- Cut harder on CC/NC separation parameter
- Track-fit charge sign significance, *q/p/σ(q/p)*
- Relative angle (away or toward mag. coil)







• *Efficiency & contamination:*

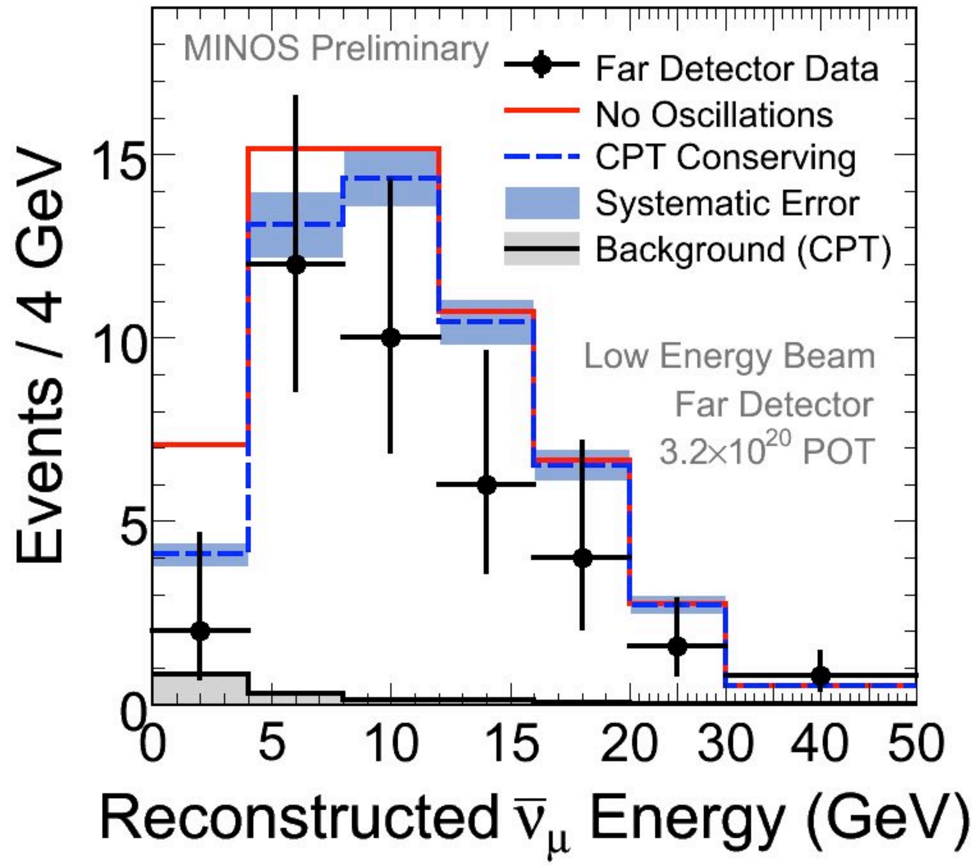
>80%   <5% for *p*>5 GeV/*c*

• *Near to Far extrapolation*

via Beam Matrix method, like ν_μ

Antineutrinos at the Far Detector

- ***Predict:***
  - Null oscillations:
    64.6 ± 8.0 (stat.) ± 3.9 (syst.)
  - CPT conserving oscillations:
    58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- ***Observe:***
  42 events



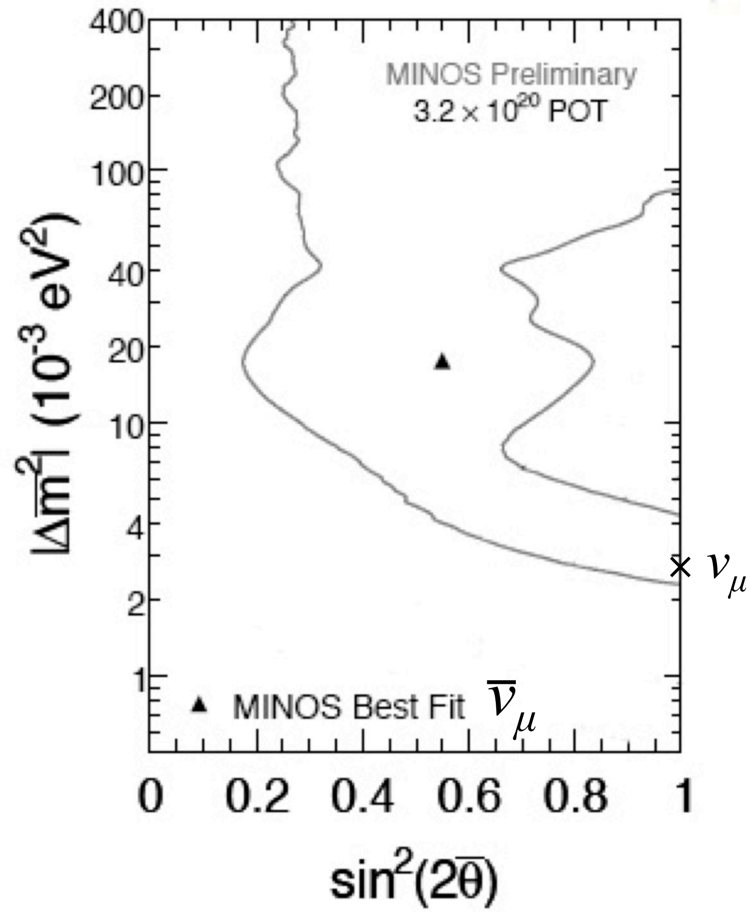
- First direct observation of $\bar{\nu}_\mu$ disappearance in an accelerator LB expt.
- Observe 1.9σ deficit wrt ν_μ -> Extensive checks did not yield any evidence for a bias.

Antineutrino oscillations

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$

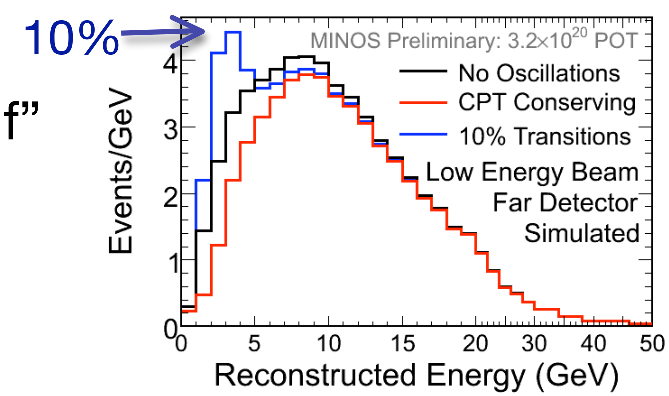
- Contours obtained using Feldman-Cousins technique, including systematics.
- CPT conserving best fit from $\nu_\mu \rightarrow \nu_\tau$ analysis lies within the 90% CL contour.
- Probability of observing the present $\bar{\nu}_\mu$ result if the CPT conserving value were true is 5.2%.
- At maximal mixing we exclude

$$(5.0 < \Delta\bar{m}^2 < 81) \times 10^{-3}\ \mathrm{eV}^2\ (90\%\ \mathrm{C.L.})$$



$\nu_\mu \rightarrow \bar{\nu}_\mu$

"What if"

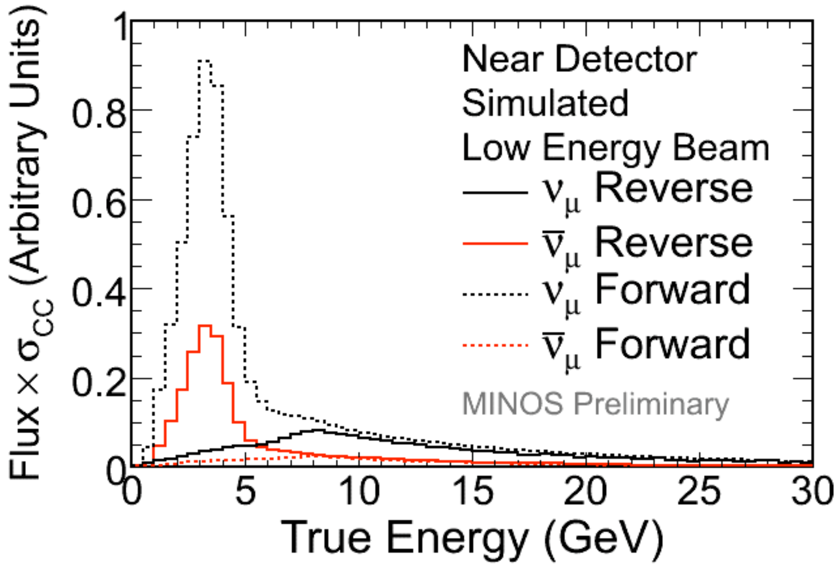


$$P(\nu_\mu \rightarrow \bar{\nu}_\mu) = \alpha \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

(θ and Δm^2 set to CPT conserving values)

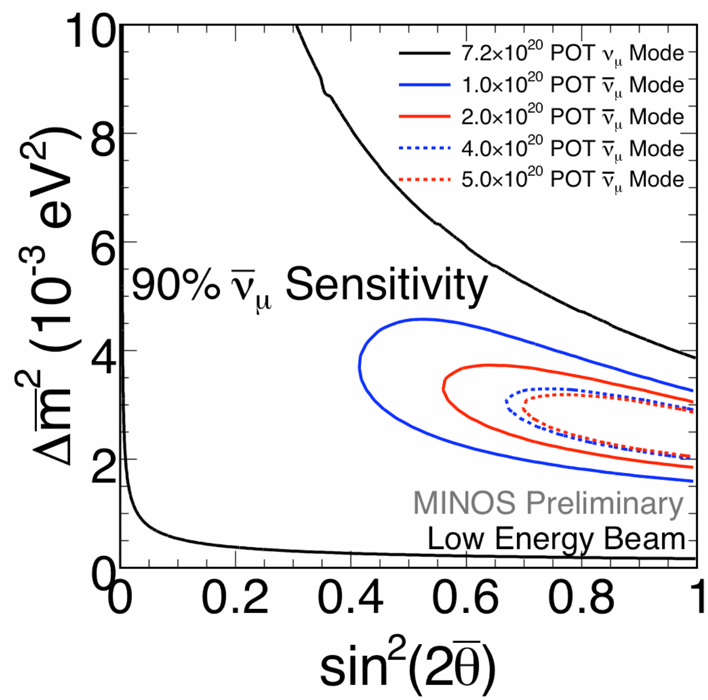
$\alpha < 2.6\%$ at 90% CL

Dedicated $\overline{\nu}_\mu$ running



- Reverse current in the NuMI focusing horns.
- Obtain a greatly enhanced $\overline{\nu}_\mu$ sample below 5 GeV (incl. the oscillation maximum).
- Data taking began earlier this month.

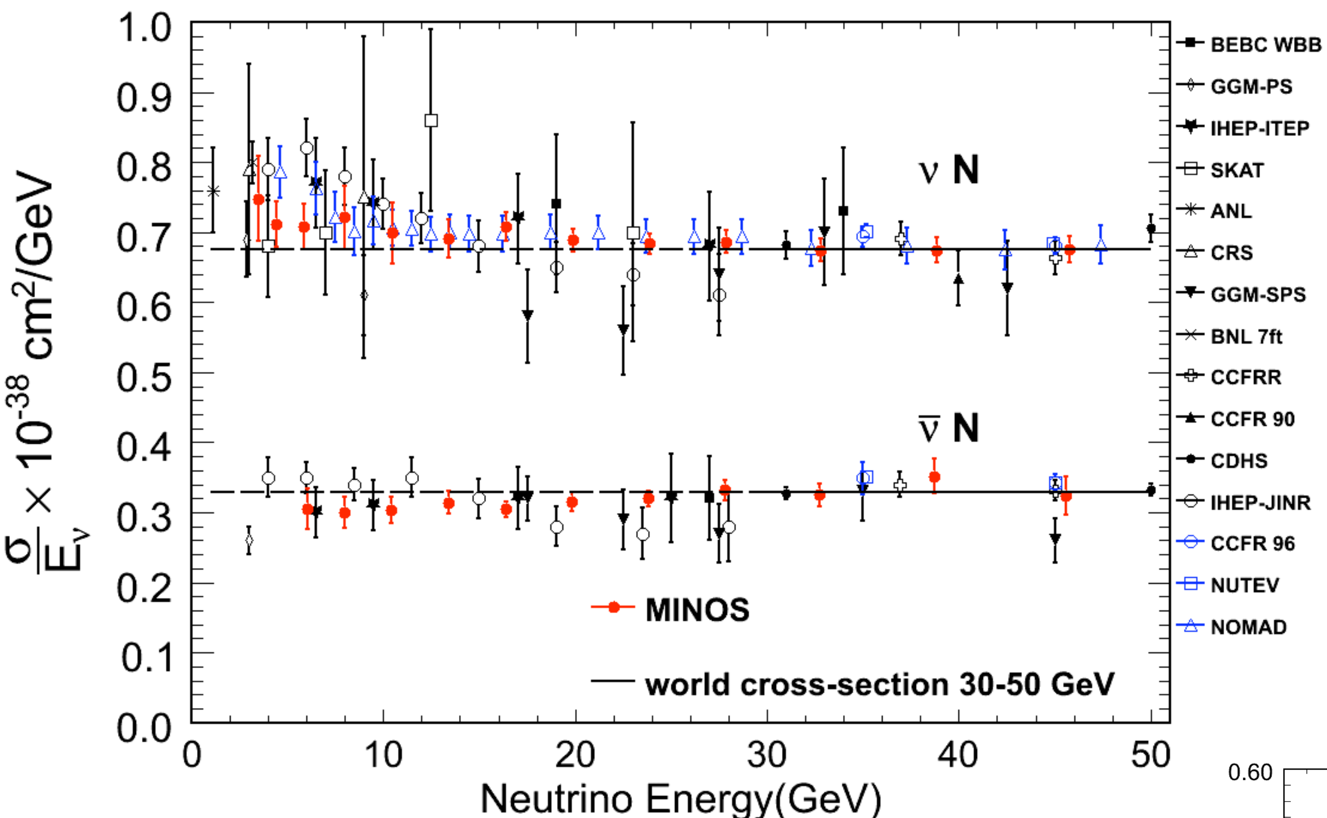
Will enable a more precise measurement of the $\overline{\nu}_\mu$ oscillation parameters than possible with forward horn current (7% $\overline{\nu}_\mu$).

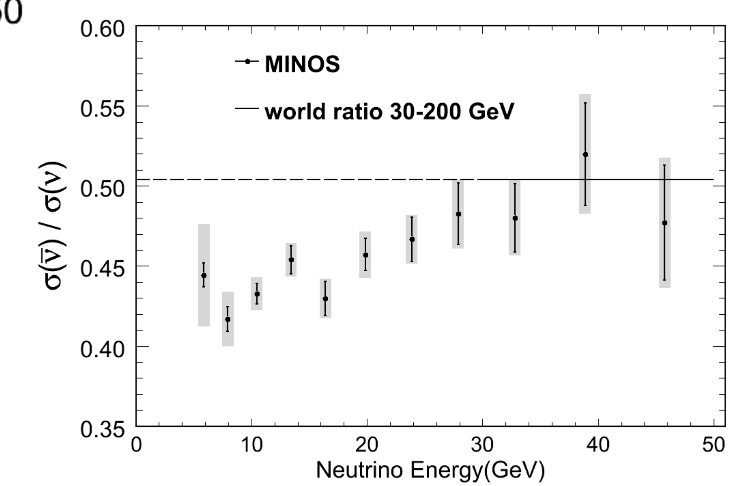


Non-oscillation physics in the MINOS Near Detector

An example: Measurement of cross sections for ν_μ-nucleus and $\bar{\nu}_\mu$-nucleus interactions.

MINOS Near Det. Physics: σ(νN)





MINOS summary

- *ν_μ disappearance:*

  $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters @ 68% C.L. :

  $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2, $\sin^2(2\theta) > 0.95$

- *ν_e appearance:*

  MINOS can probe θ_{13} at/below the CHOOZ limit;

  1.5 σ excess, wait for results from double the data set.

- *ν NC disappearance:*

  NC rate @ FD consistent with active ν flavor mixing only,

  $R = 1.04 \pm 0.08 \pm 0.07$ (when set $\theta_{13}=0$).

- *$\bar{\nu}_\mu$ disappearance:*

  Observe $\bar{\nu}_\mu$ disappearance with low statistics;
  dedicated $\bar{\nu}_\mu$ run in progress.