NuMI

MINOS

UNIVERSITY OF MINNESOTA

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# MINOS Neutrino Oscillation Results


Alec Habig, for the MINOS Collaboration


Tau 2010

Manchester, Sept. 17 2010

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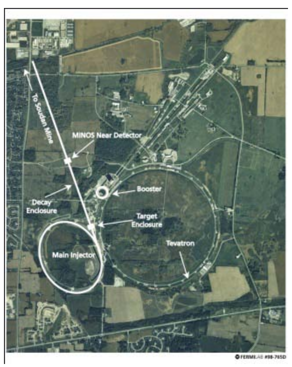
Texas-Austin • Tufts • UCL
Warsaw • William & Mary

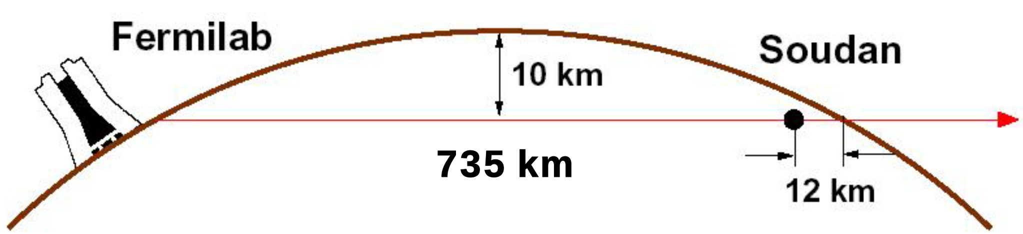
30 institutions
121 physicists

# MINOS

## Main Injector Neutrino Oscillation Search

- Investigate atmospheric sector $\nu_\mu$ oscillations using intense, well-understood NuMI beam
- Two similar magnetized iron-scintillator calorimeters
  - Near Detector
    - 980 tons, 1 km from target, 100 m deep
  - Far Detector
    - 5400 tons, 735 km away, 700 m deep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# Physics Goals

- Precise (~10%) measurement of $\Delta m^2_{23}$
  - The “Charged Current” (CC) analysis
  - Precisely measure $\nu_\mu \leftrightarrow \nu_\tau$ flavor oscillation parameters, provide high statistics discrimination against alternatives such as decoherence, $\nu$ decay, etc
- Directly compare $\nu$ vs $\bar{\nu}$ oscillations (a test of CPT and odd stuff)
  - MINOS is first large underground detector with a magnetic field for $\mu^+/\mu^-$ tagging
- Investigate the flavor-independent $\nu$ flux
  - The “Neutral Current” (NC) analysis, checking for sterile $\nu$
- Search for subdominant $\nu_\mu \leftrightarrow \nu_e$ oscillations
  - The “$\nu_e$” analysis, a shot at measuring $\theta_{13}$
- Study $\nu$ interactions and cross sections using the very high statistics Near Detector data set
- Cosmic Ray Physics with both detectors

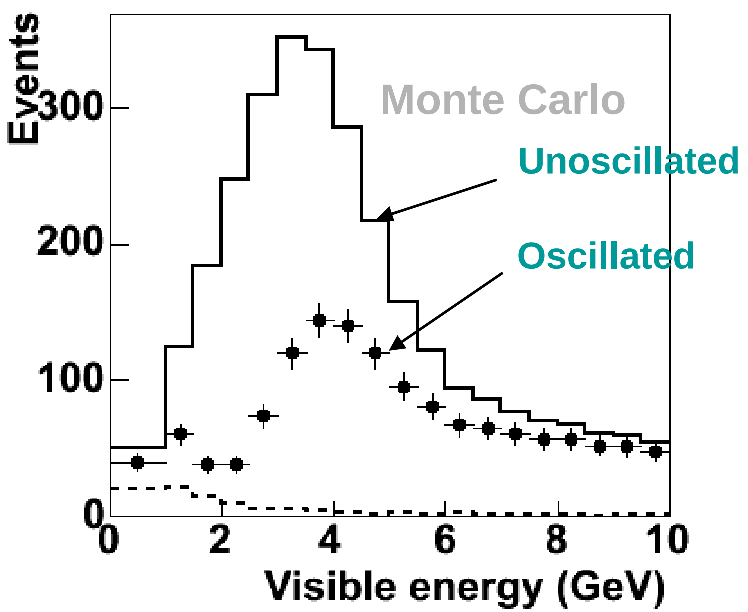
This Talk

# $\nu_\mu$ Disappearance Methodology

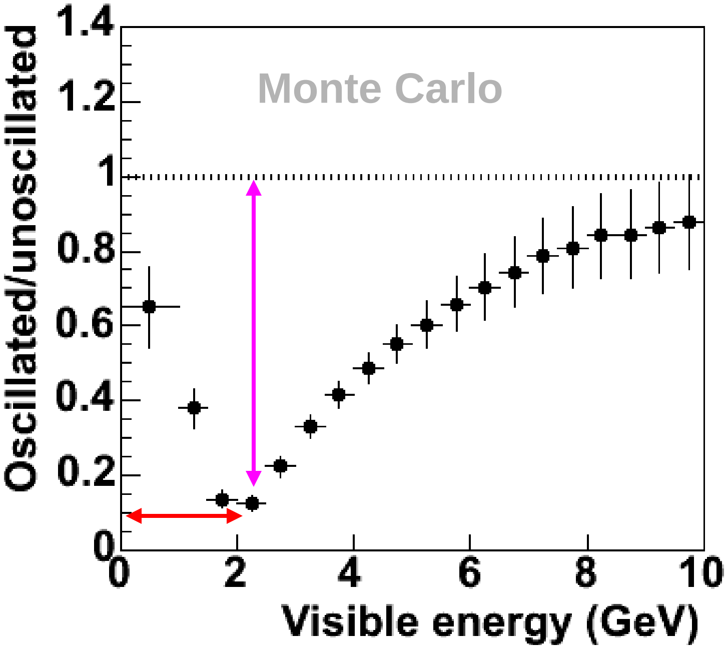
- Measure $\nu_\mu$ flux at Near Det, see what's left at Far Det
- Simulated results plotted as F/N ratio
  - Position of dip gives $\Delta m^2$
  - Depth of dip gives $\sin^2 2\theta$

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

- Spectral ratio shapes would differ in alternative models



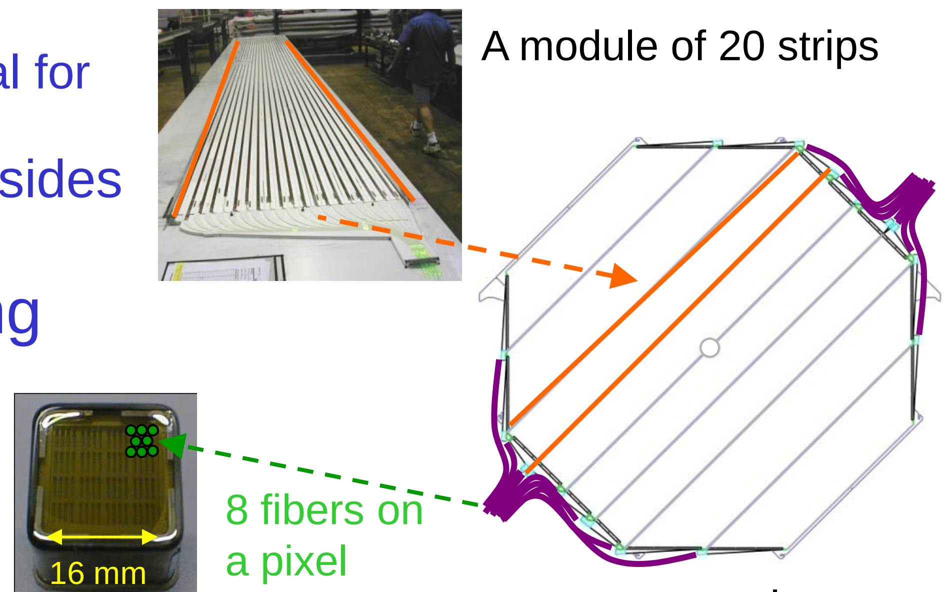

$\nu_\mu$ spectrum




Spectrum ratio

# Far Detector

- 486 planes, 5400 tons total
  - Each is (1” steel + 1 cm plastic scintillator) thick
  - 8 m diameter with torodial ~1.5 T B-field
  - 31 m long total, in two 15 m sections
  - 192 scintillator strips across
    - Alternating planes orthogonal for stereo readout
  - Scint. CR veto shield on top/sides
- Light extracted from scint. strips by wavelength shifting optical fiber
  - Both strip ends read out with Hamamatsu M16 PMTs
  - 8x multiplexed

M16 PMT

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# Near Detector

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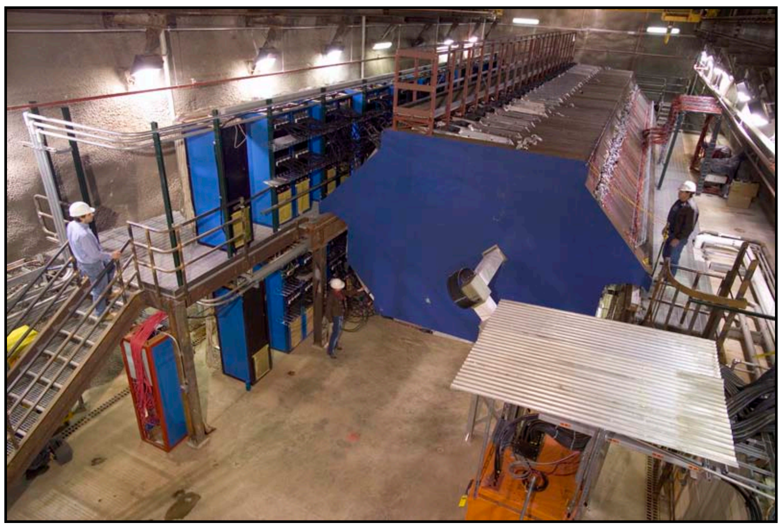
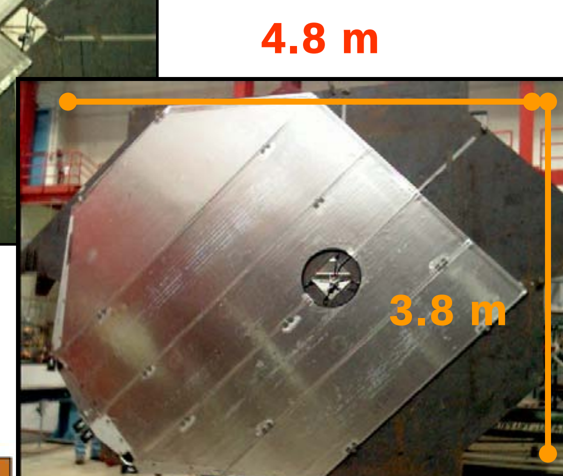
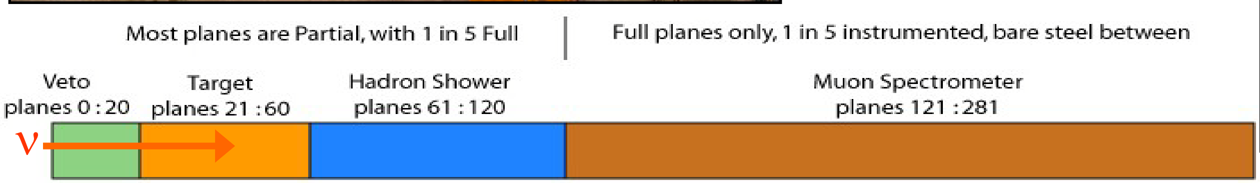
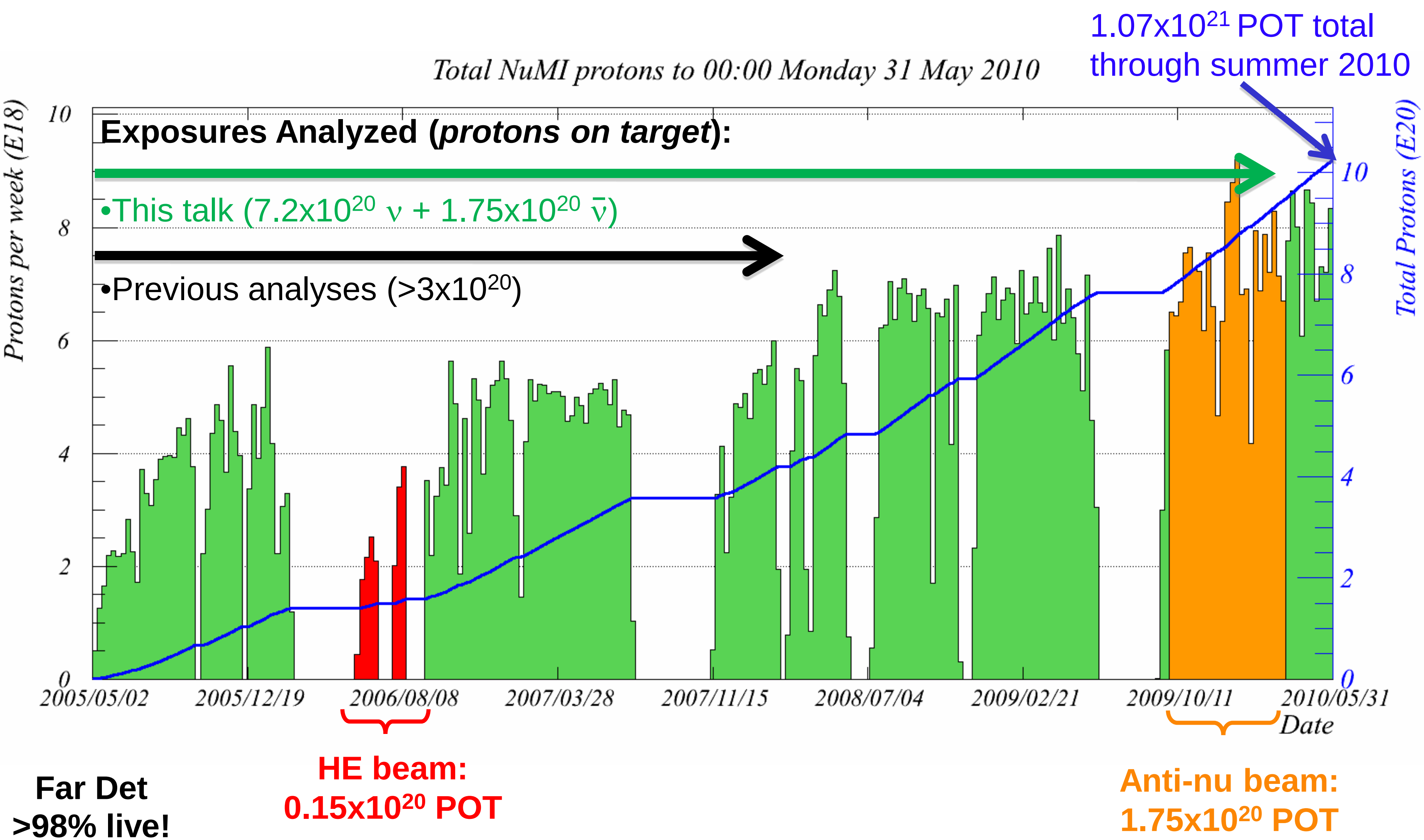
- 282 planes, 980 tons total
  - Same 1” steel,1 cm plastic scintillator planar construction, B-field
  - 3.8x4.5 m, some planes partially instrumented, some fully, some steel only
  - 16.6 m long total
- Light extracted from scint. strips by wavelength shifting optical fiber
  - One strip ended read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





# Beam Data Analyzed

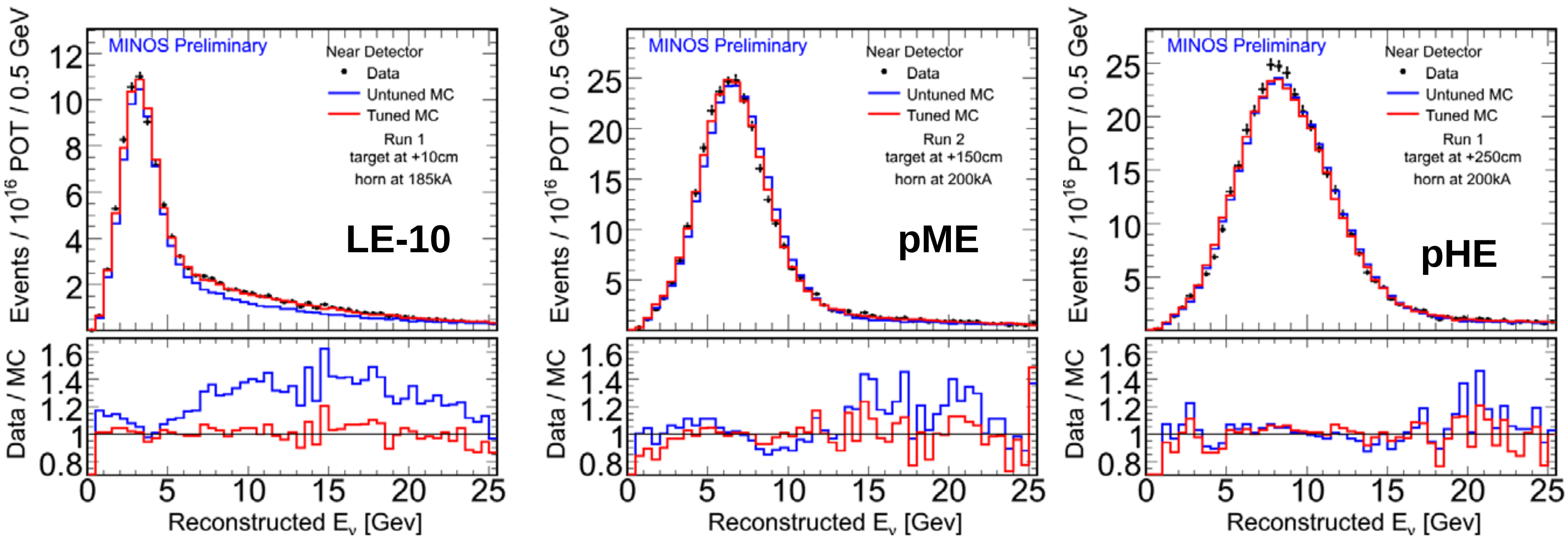


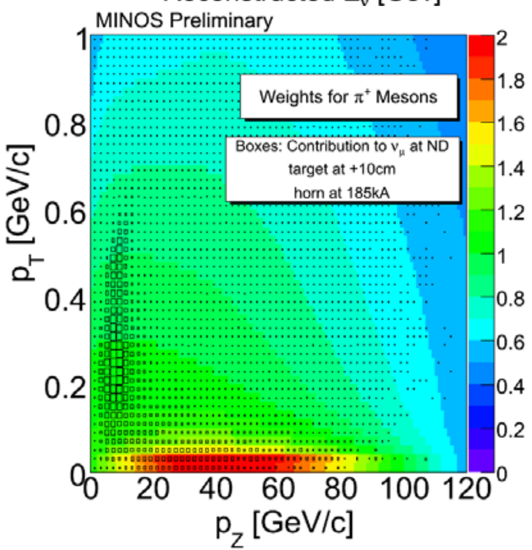

**Far Det >98% live!**

# Near Detector Data

- How do data look in the Near Detector, where we have ~unlimited statistics? (*$10^7$ $\nu$ per $10^{20}$ pot)*
- If we understand things there, we can then look at the Far Detector data where the oscillation physics is happening, so:
  - Examine ND closely
  - Compare ND data/MC
  - "Blind" analysis done

# Reconstructed Beam Spectrum




Weights applied as a function of hadronic $x_F$ and $p_T$.

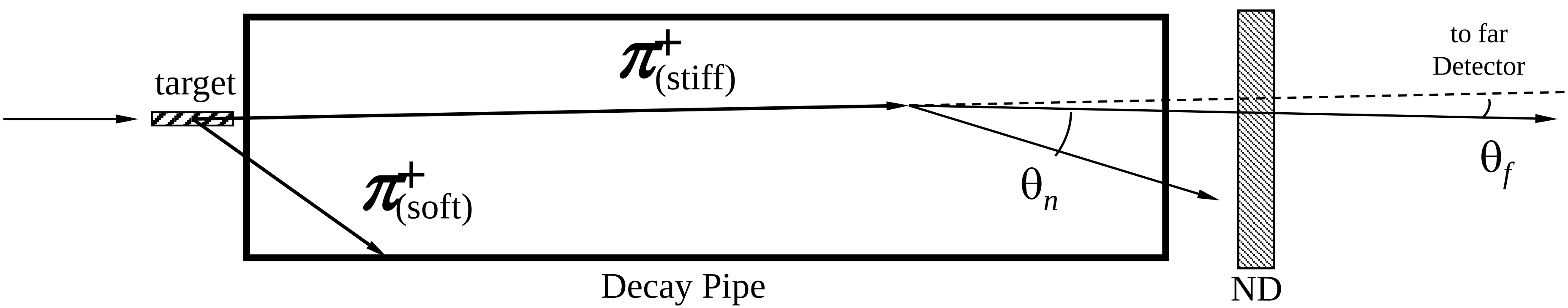
MIPP data on MINOS target will be used to refine this in the future, NA49 and Harp results also used

Discrepancies between data and Fluka08 Beam MC vary with beam setting: so source is due to beam modeling uncertainties rather than cross-section uncertainties

MC tuned by fitting to hadronic $x_F$ and $p_T$ over 9 beam configurations (3 shown here, from older Fluka05-based work)

# What is Expected in Soudan?

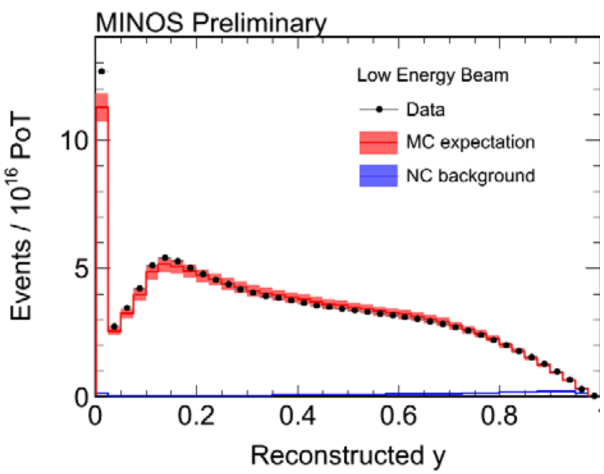
- Measure Near Detector $E_\nu$ spectrum
- To first order the beam spectra at Soudan is the same as at Fermilab, but:
  - Small but systematic differences between Near and Far
  - Use Monte Carlo to correct for energy smearing and acceptance
  - Use our knowledge of pion decay kinematics and the geometry of our beamline to predict the FD energy spectrum from the measured ND spectrum

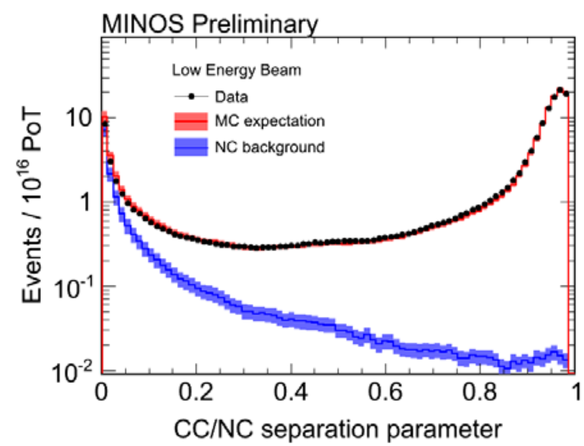



$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 \qquad E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

# On to the Far Detector…

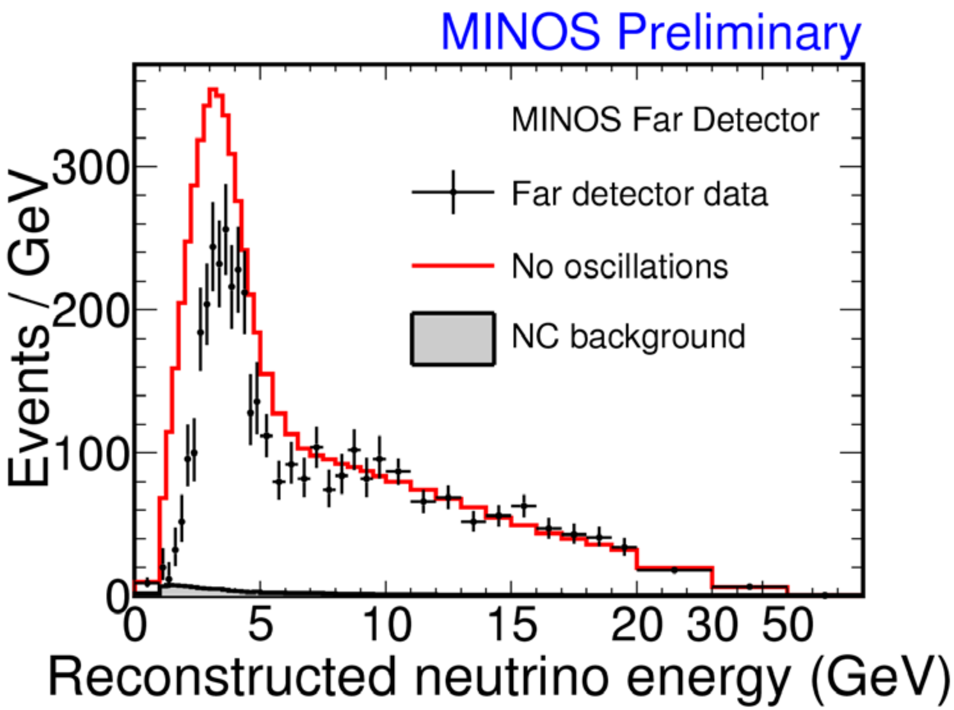
- “Blind” analysis
  - Only after understanding the Near Detector, reconstruction, selected non-oscillation Far Detector parameters, and early pHE (*ie*, non-oscillating) beam data did we “open the box”
  - Data “re-blinded” when developing new analyses, analysis improvements, and adding new data




Two of zillions of such plots…

# Spectrum

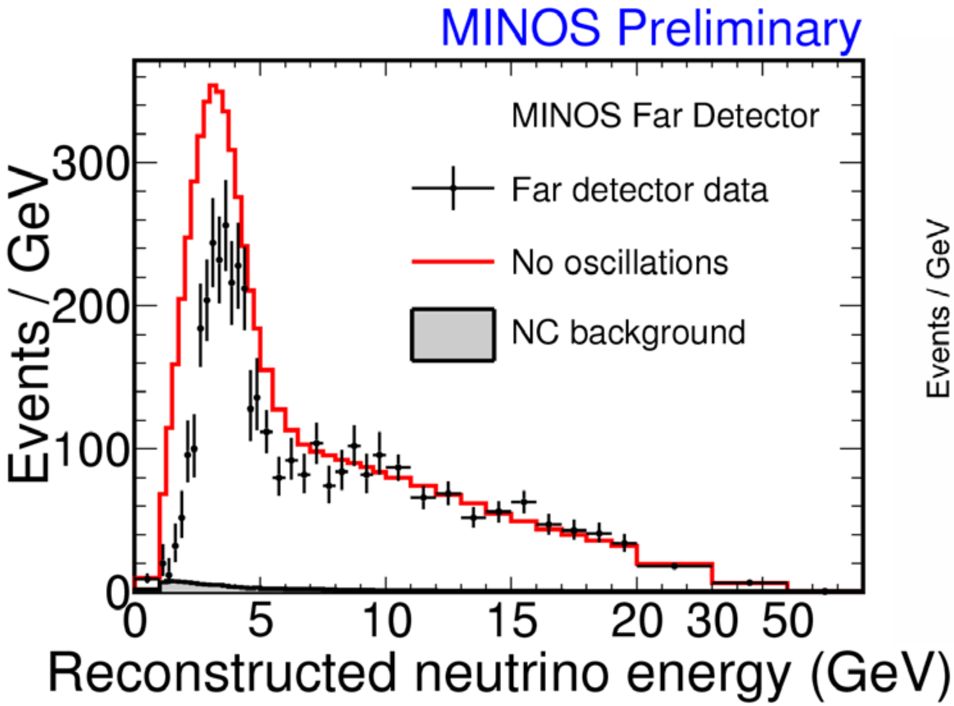


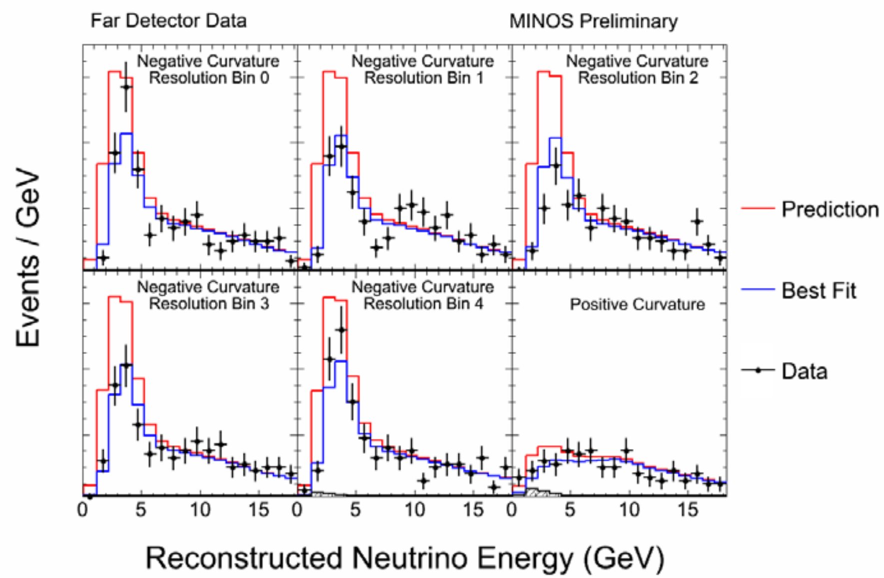

Expect 2451 without oscillations

includes ~1 CR μ, 8.1 rock μ, 41 NC, ~3 $\nu_\tau$ BG

See only 1986 in the FD.

# Spectrum




Expect 2451 without oscillations

includes ~1 CR $\mu$, 8.1 rock $\mu$, 41 NC, ~3 $\nu_\tau$ BG

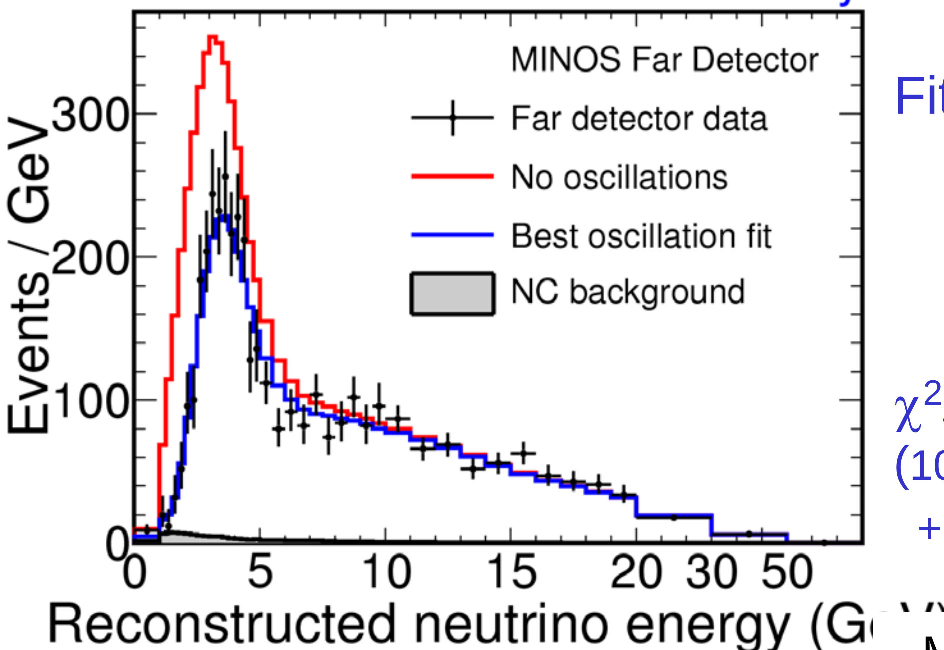
See only 1986 in the FD.

Split up sample into five bins by energy resolution, to let the best resolved events carry more weight (plus a sixth bin of wrong-sign events)

Fit everything simultaneously…

# Spectrum

MINOS Preliminary




Fit for oscillation parameters:

$$|\Delta m^2_{32}| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\Theta_{23} = 1.00_{-0.05}$$

$\chi^2$/ndf = 2119.51/2298

(100 bins x 4 spectra x 5 resolutions,

+ 100 bins x 3 spectra for PQ, – 2)

Measurement errors are 1σ, 1 DOF

Expect 2451 without oscillations

includes ~1 CR $\mu$, 8.1 rock $\mu$, 41 NC, ~3 $\nu_\tau$ BG

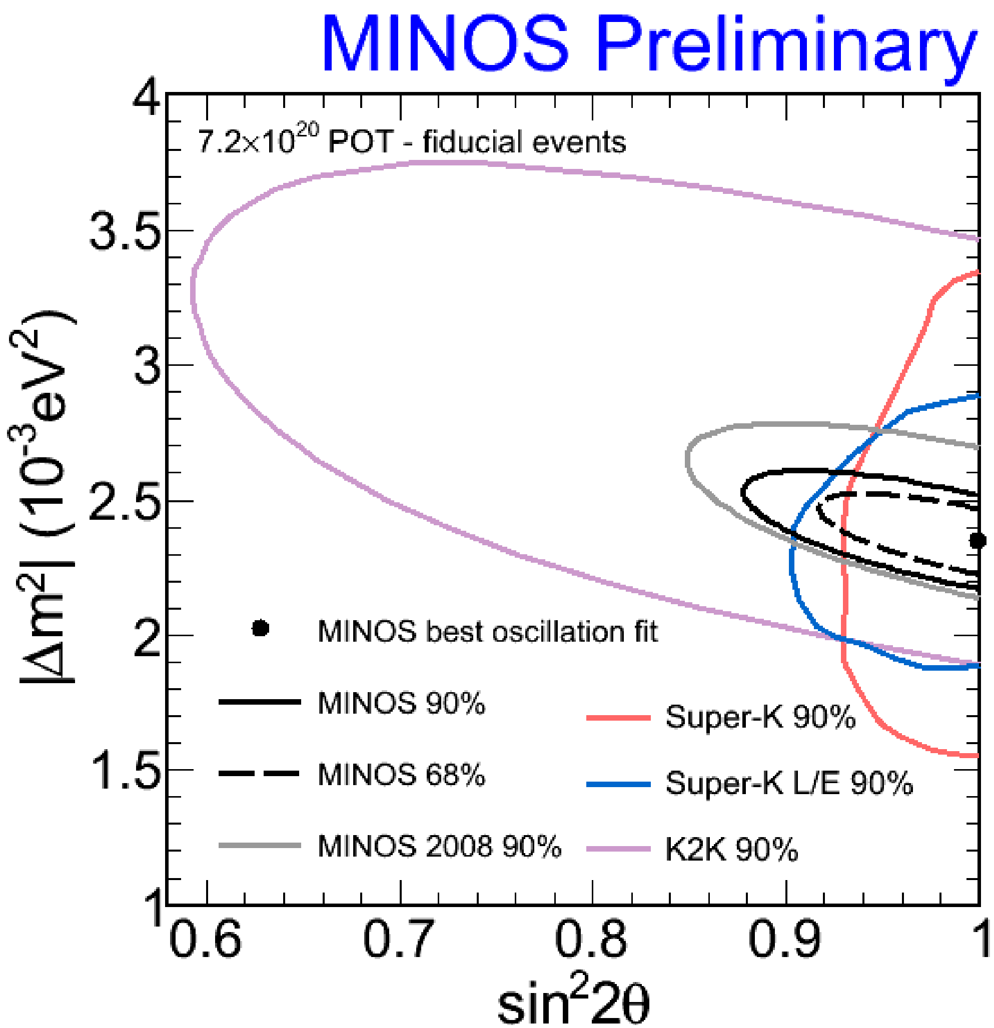
See only 1986 in the FD.

$$o_i = \text{observed}$$

$$e_i = \text{expected}$$

$$\chi^2(\Delta m^2, \sin^2 2\theta, \alpha_j, \ldots) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i) + \sum_{j=1}^{nsyst} \Delta\alpha_j^2 / \sigma_{\alpha_j}^2$$

# Allowed Region



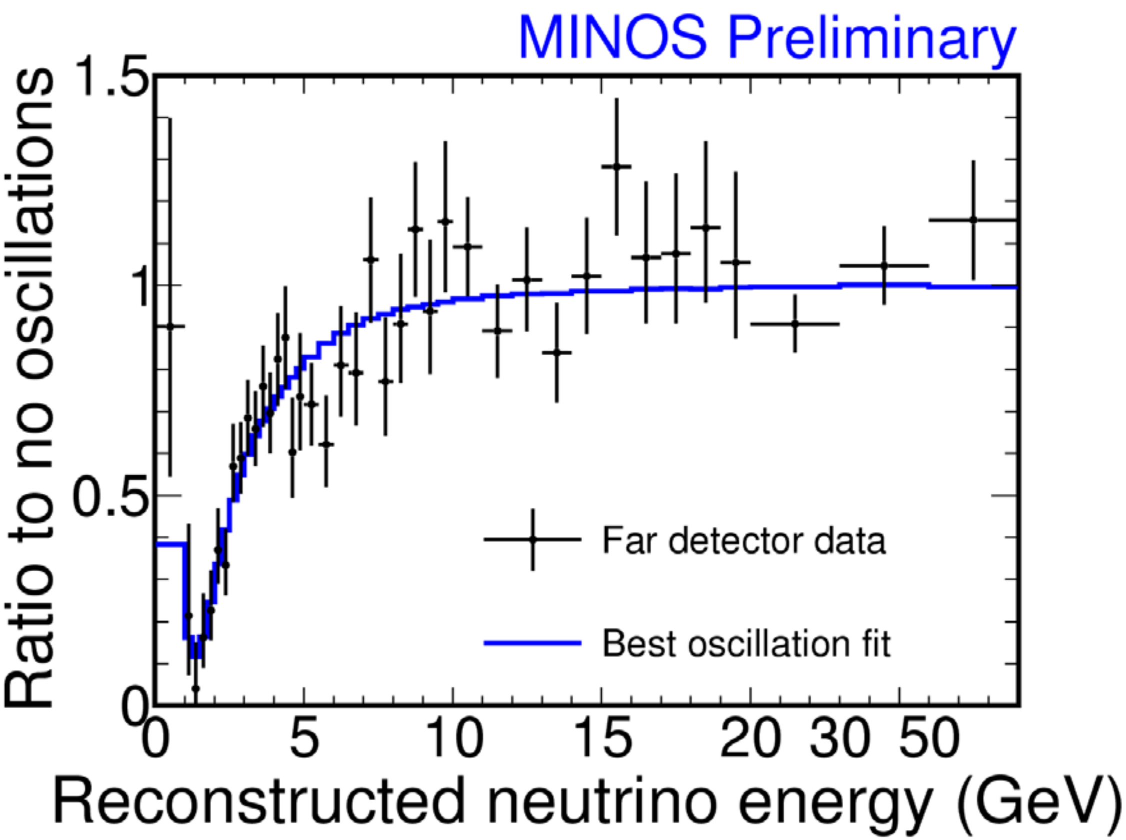

- Fit includes systematic penalty terms
- Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$
  - Best physical fit:
    $|\Delta m|^2 = 2.35 \times 10^{-3}\ eV^2$
    $\sin^2(2\theta)=1.00$
  - Unconstrained:
    $|\Delta m|^2 = 2.34 \times 10^{-3}\ eV^2$
    $\sin^2(2\theta)=1.007$

Earlier results are in:

Phys.Rev. Lett. 101:131802, 2010

# Alternative $\nu_\mu$ Disappearance Models

## $\nu_\mu \leftrightarrow \nu_\tau$ Oscillations:

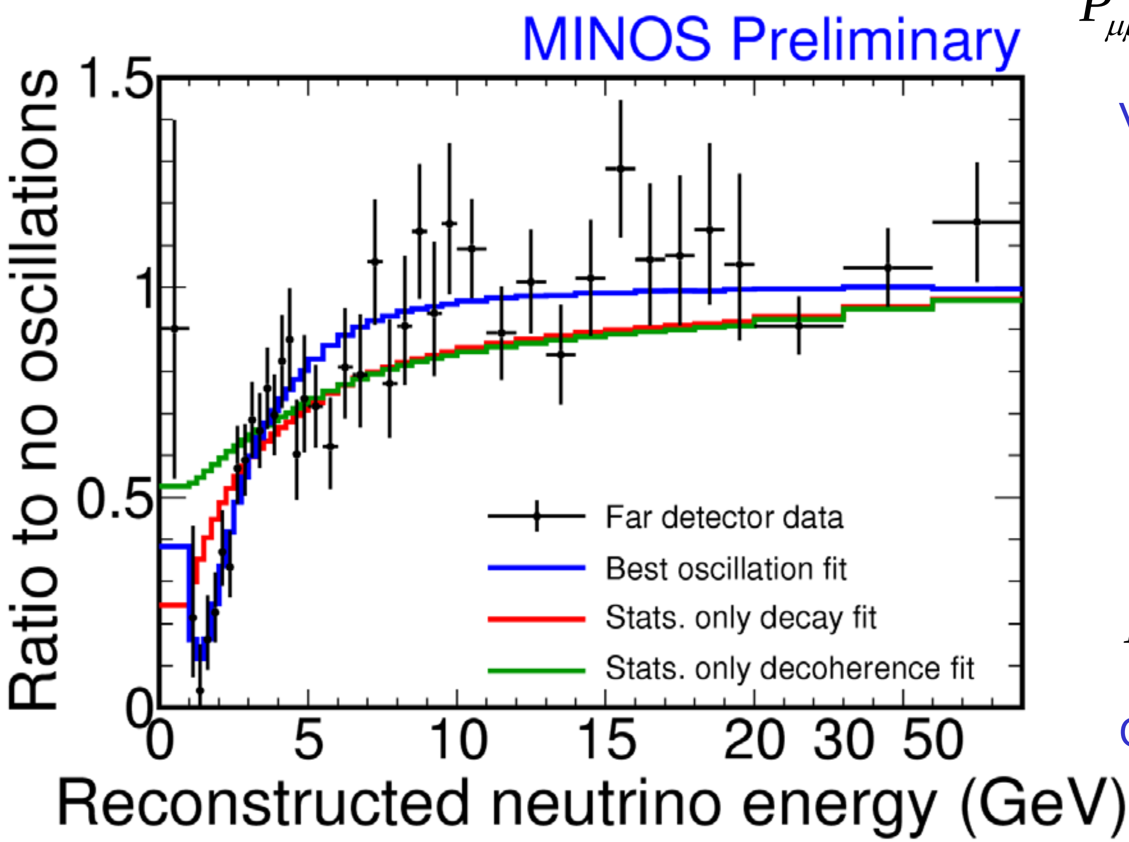



$$P_{\mu\tau} = \sin^2 2\theta_{23} \sin^2(1.27\Delta m_{32}^2 L / E)$$

$$\left|\Delta m_{32}^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\Theta_{23} = 1.00_{-0.05}$$

# Alternative $\nu_\mu$ Disappearance Models




## Decay:

$$P_{\mu\mu} = \left(\sin^2\theta + \cos^2\theta \exp(-\alpha L/E)\right)^2$$

V. Barger *et al.*, PRL82:2640(1999)

$\chi^2$/ndof = 2165.81/2298

$\Delta\chi^2 = 46.3$

disfavored at 6.8$\sigma$

c

## Decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

G.L. Fogli *et al.*, PRD67:093006 (2003)

$\chi^2$/ndof = 2197.59/2298

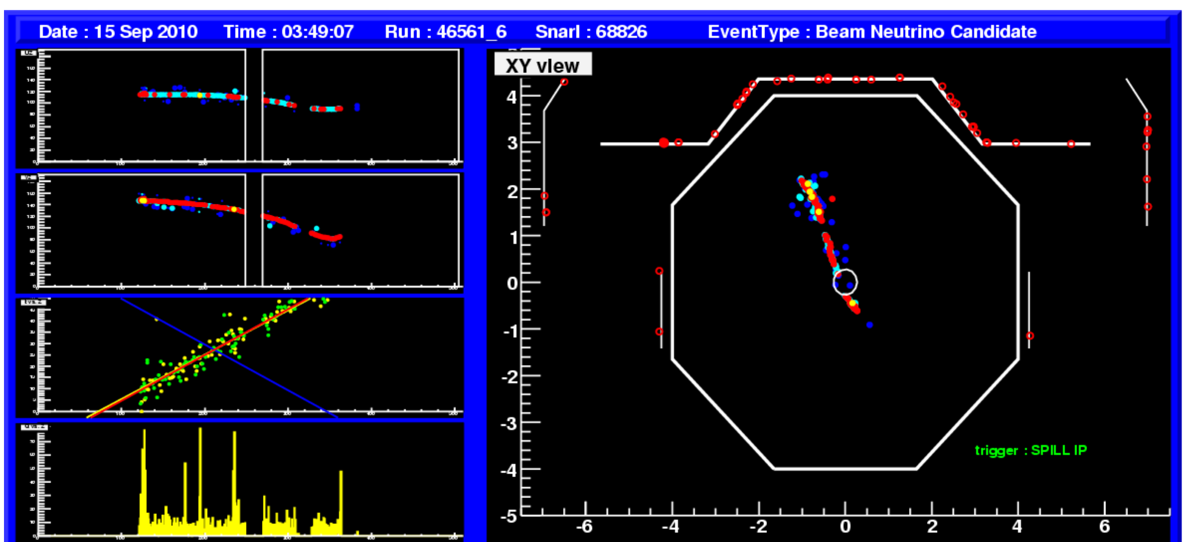
$\Delta\chi^2 = 78.1$

disfavored at 8.8$\sigma$

# $\bar{\nu}_\mu$

- MINOS is the first oscillation experiment able to tell $\bar{\nu}_\mu$ from $\nu_\mu$ on an event by event basis
  - Due to $\mu$ charge-sign separation from the detectors' magnetic fields
- Do $\nu_\mu$ oscillate the same way as $\bar{\nu}_\mu$?

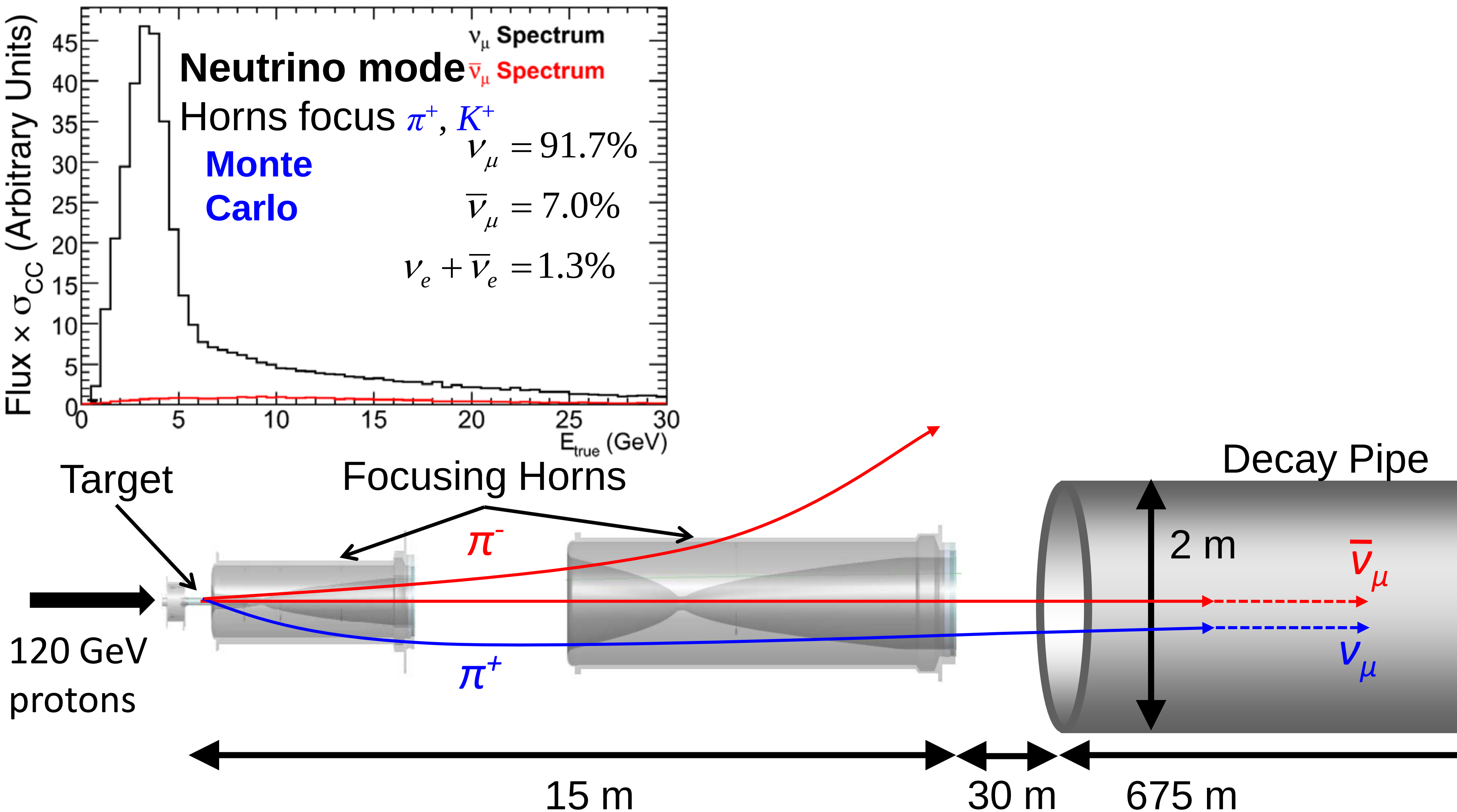
$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\bar{\theta}_{23})\sin^2\left(1.27\Delta\bar{m}^2_{23}\frac{L}{E}\right)$$



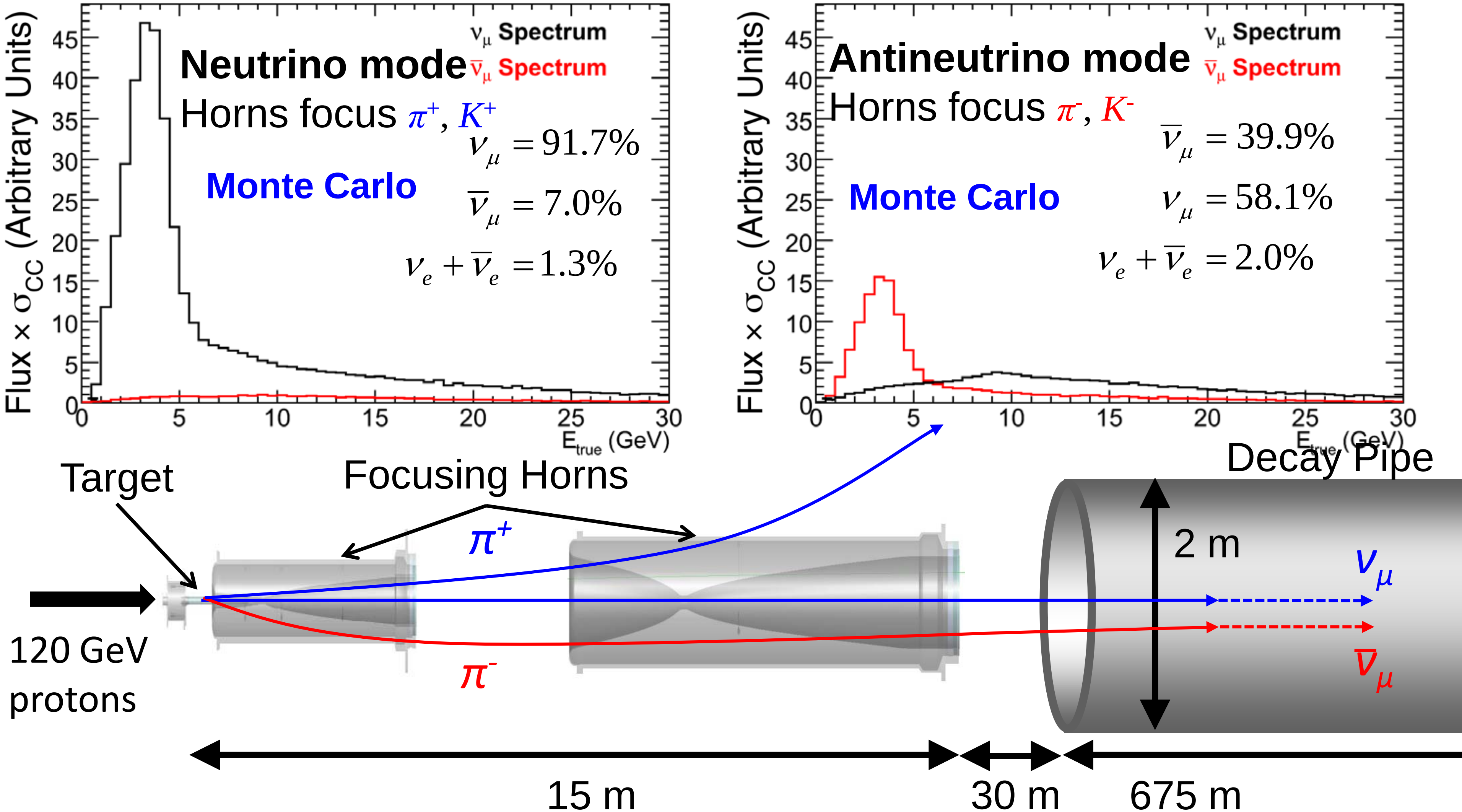

A typical (*ie*, the most recent one when I made this slide) higher energy $\nu_\mu$ CC interaction.

Curvature is obvious, even with this fairly stiff muon – lower energy events in the oscillation region are even easier.

# Neutrino Mode

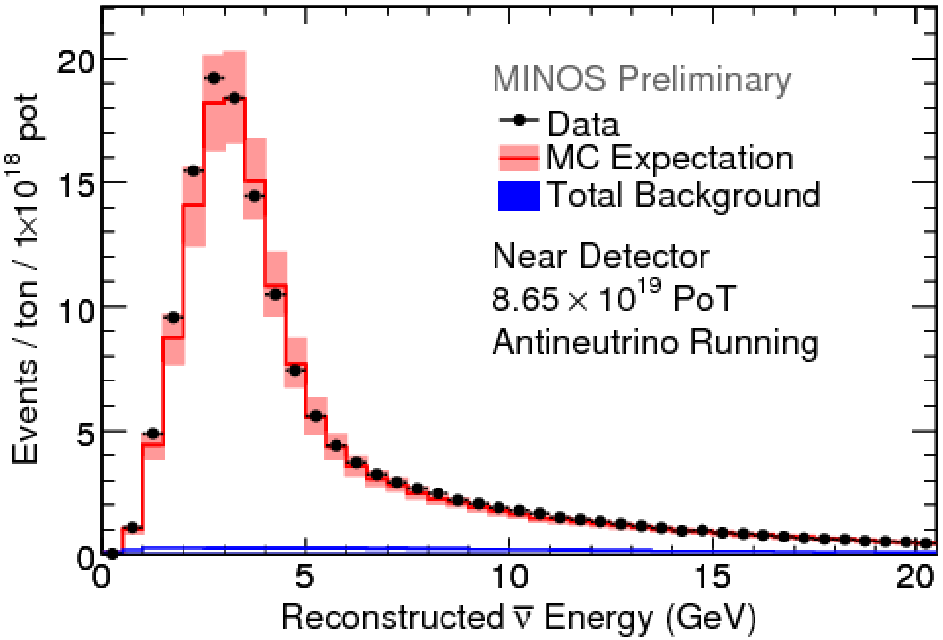


# Anti-neutrino Mode



# $\bar{\nu}_\mu$ Analysis

- Same analysis done as $\nu_\mu$ disappearance
  - At low energies where oscillations occur (<6 GeV), curvature is obvious: antinu sample is 93.5% efficient and 98% pure (BG is 51% NC, 49% $\nu_\mu$)
  - Lower anti-hadron production and anti-nu interaction cross sections make for much lower statistics, about 2.5x less events per-pot
- Same great MC, data agreement (albeit with lower statistics)

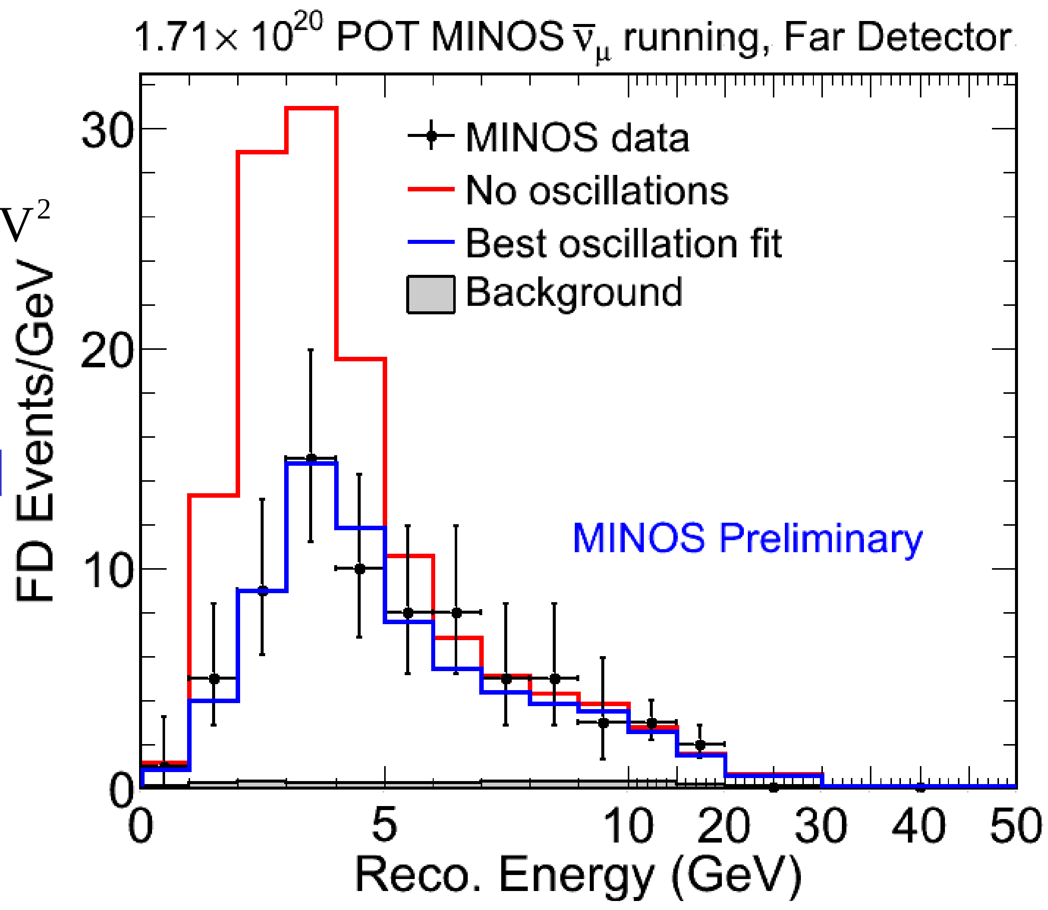


# $\bar{\nu}_\mu$ Results

- 97 events seen, 155 expected (no osc)
- No- oscillations scenario disfavored at 6.3σ
- Same sort of oscillation fit yields:

$$|\overline{\Delta m^2}| = 3.36^{+0.45}_{-0.40}(stat) \pm 0.06(syst) \times 10^{-3}\,\mathrm{eV}^2$$

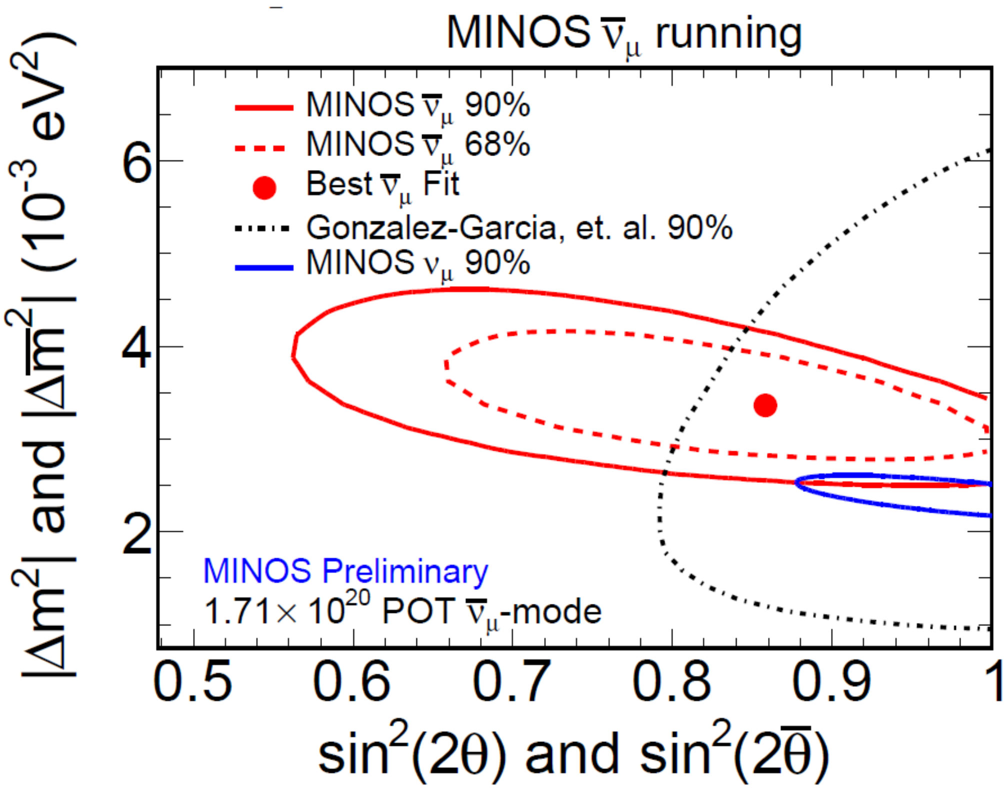
$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11(stat) \pm 0.01(syst)$$



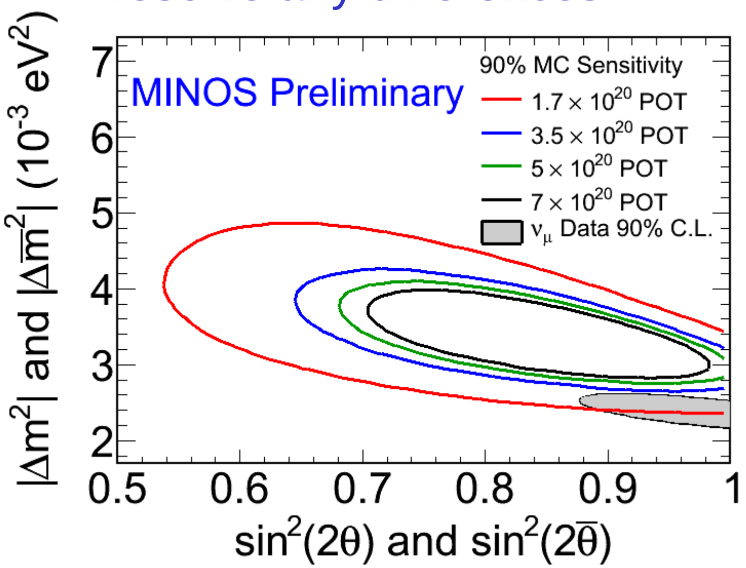

- Completely dominated by low statistics
  - Includes additional 30% uncertainty on the $\nu_\mu$ background
- Plan to double anti-nu statistics after initial Minerva run

# $\bar{\nu}_\mu$ Results

- Interestingly, oscillation parameters differ from the $\nu_\mu$ results at a not terribly significant level, ~2$\sigma$




MC Sensitivity studies show doubling the data should better resolve any differences:




Global fit from Gonzalez-Garcia & Maltoni, *Phys. Rept.* 460 (2008), SK data dominates

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# So what are the $\nu_\mu$ disappearing to?

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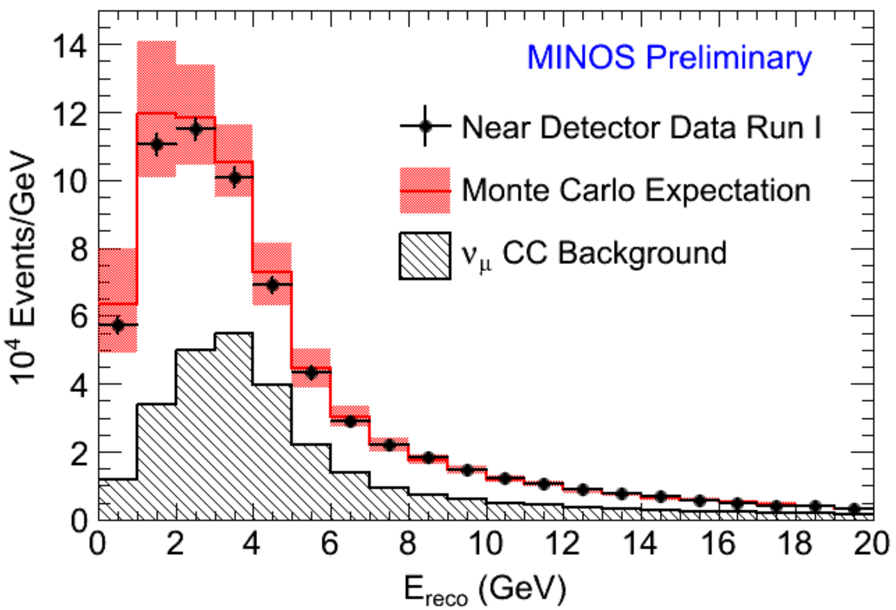
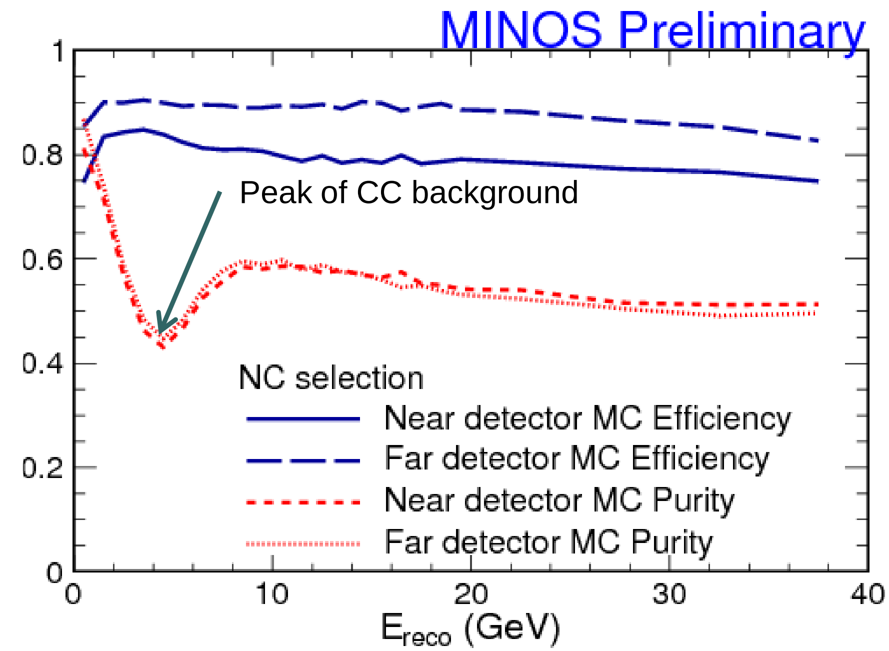
- For $\nu$ oscillations in this "atmospheric" sector, we like to blame $\nu_\mu$ oscillating to $\nu_\tau$,
  - Most $\nu$ below $\tau$ production threshold
  - Few $\tau$ that aren't produce very messy decays which get rejected by our analysis
- Some very well might be going to $\nu_e$ as well, depending on the currently unknown $\theta_{13}$ (known to be less than 0.21 from Chooz)
- A fourth, sterile neutrino could also be the culprit
  - By definition, $\nu_s$ interact with nothing save gravity

# NC Spectrum




ND NC Data




89% Efficient, 61% Pure

- NC events can be used to search for sterile neutrino component in FD
  - via disappearance of NC events at FD
  - If oscillation is confined to active neutrinos instead, NC spectrum will be unchanged

# NC Analysis Results – 3-flavor Rate

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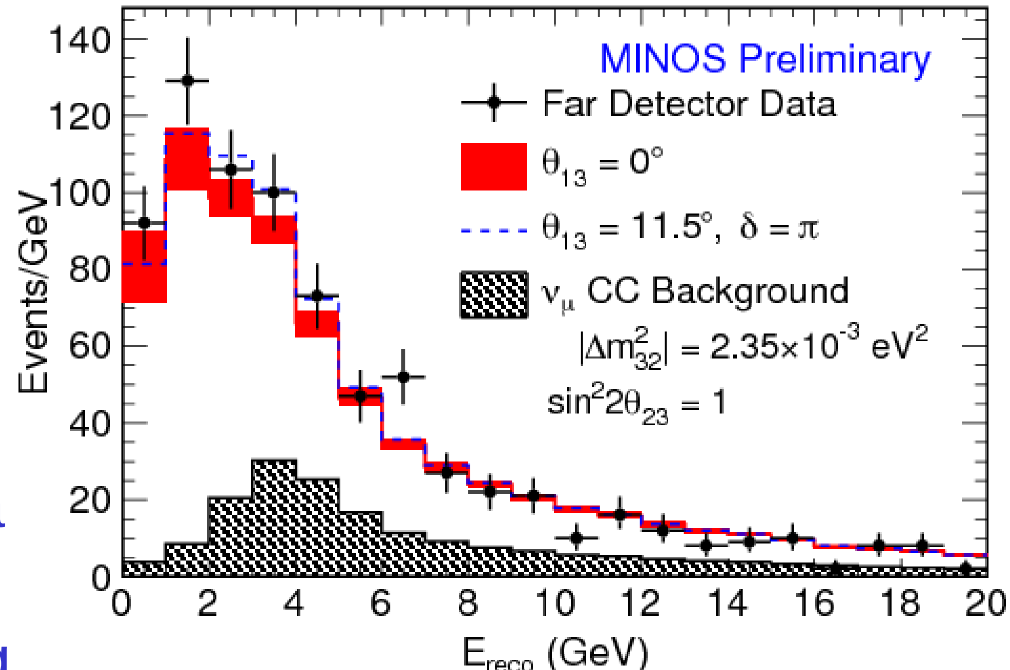
- FD NC energy spectrum for Data and oscillated MC predictions
  - Form ratio R, data are consistent with no $\nu_\mu$ disappearing to $\nu s$
- Simultaneous fit to CC and NC energy spectra yields the fraction of $\nu_\mu$ that could be oscillating to $\nu_s$:

$$f_s = \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)}$$

$f_s < 0.22 \quad (0.40\nu_e)@(90\%\ \text{C.L.})$




$$R \equiv \frac{N_{Data} - B_{CC}}{S_{NC}}$$

| | $R$ ± stat ± syst |
|---|---|
| $\theta_{13}$=0 | 1.09 ± 0.055 ± 0.053 |
| $\theta_{13}$=11.5° | 1.01 ± 0.055 ± 0.058 |

Earlier results are in:

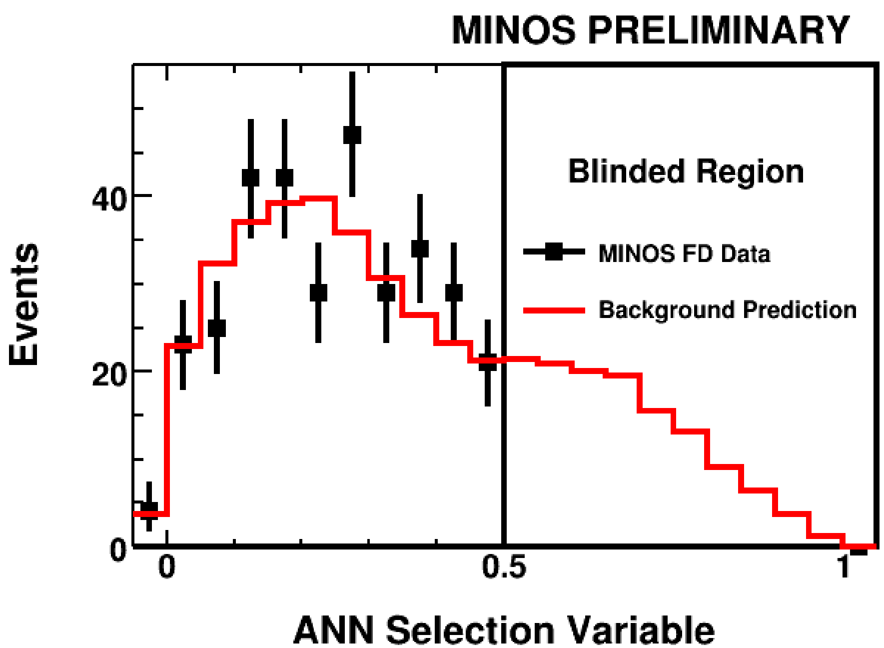
Phys.Rev.D81:052004, 2010

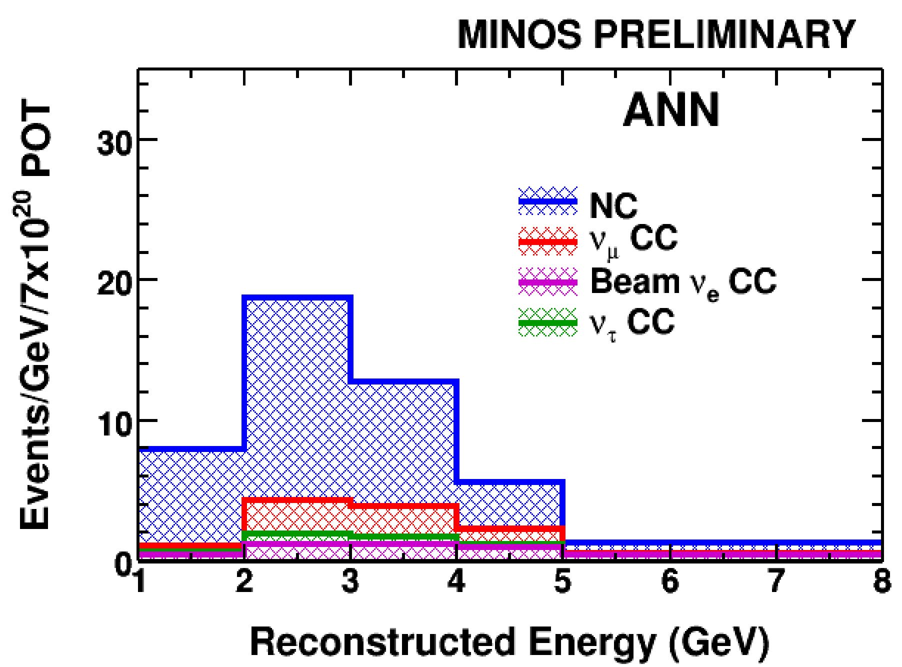
# $\nu_e$ Appearance

- Are some of the disappearing $\nu_\mu$ re-appearing as $\nu_e$?
  - $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$
    - Plus CP-violating $\delta$ and matter effects, included in fits
- Need to select events with compact shower
  - MINOS optimized for muon tracking, limited EM shower resolution
    - Steel thickness 2.5 cm = 1.4 $X_0$
    - Strip width 4.1cm ~ Molière radius (3.7cm)
  - At CHOOZ limit, expect a ~2% effect
    - Do blind analysis – establish all cuts, backgrounds, errors first
    - Crosscheck in three sidebands
    - Only then look at the data to see what pops out

# $\nu_e$ Appearance Results

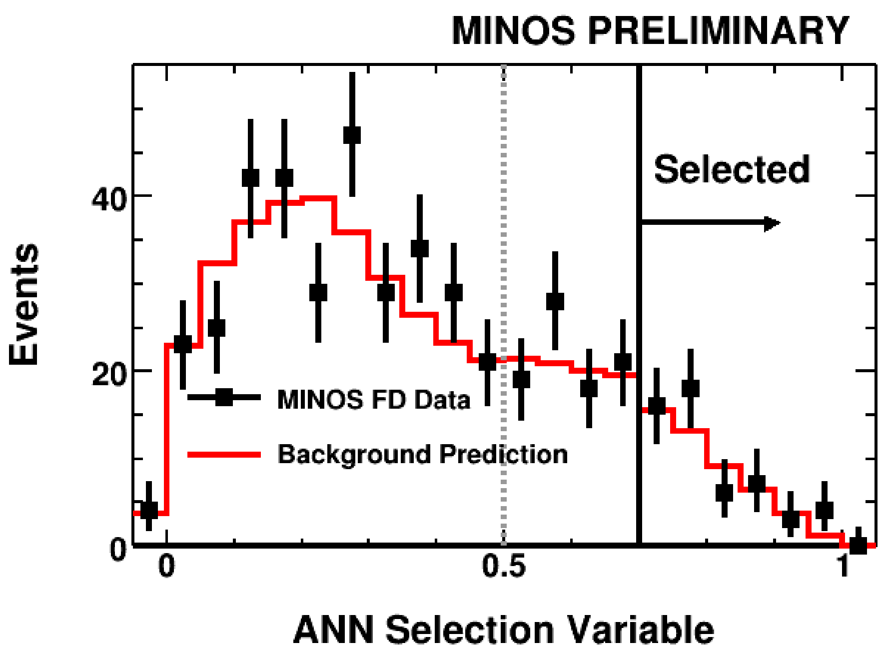
- FD background prediction:
  - **49.1±7(stat)±2.7(sys)**

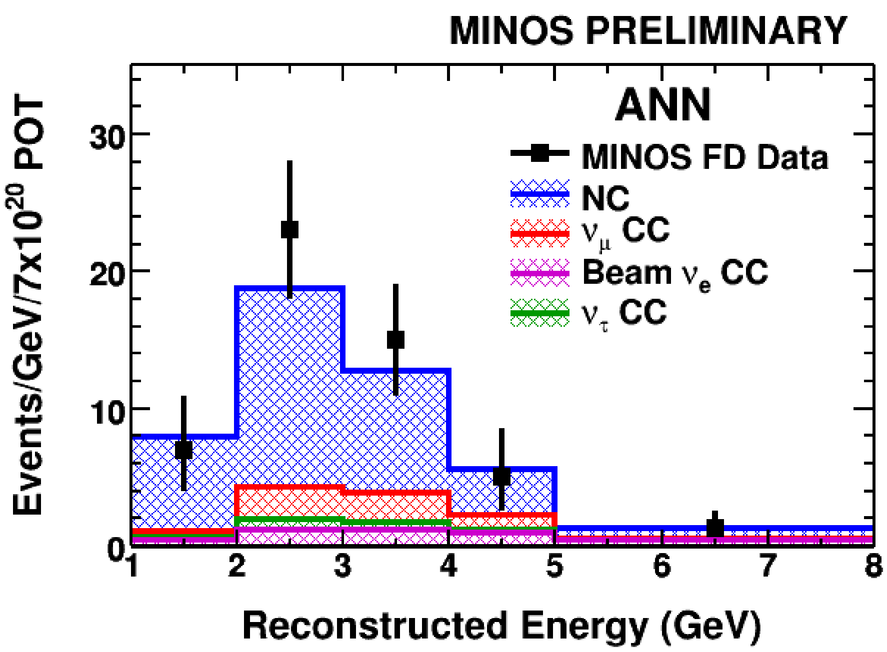


# $\nu_e$ Appearance Results

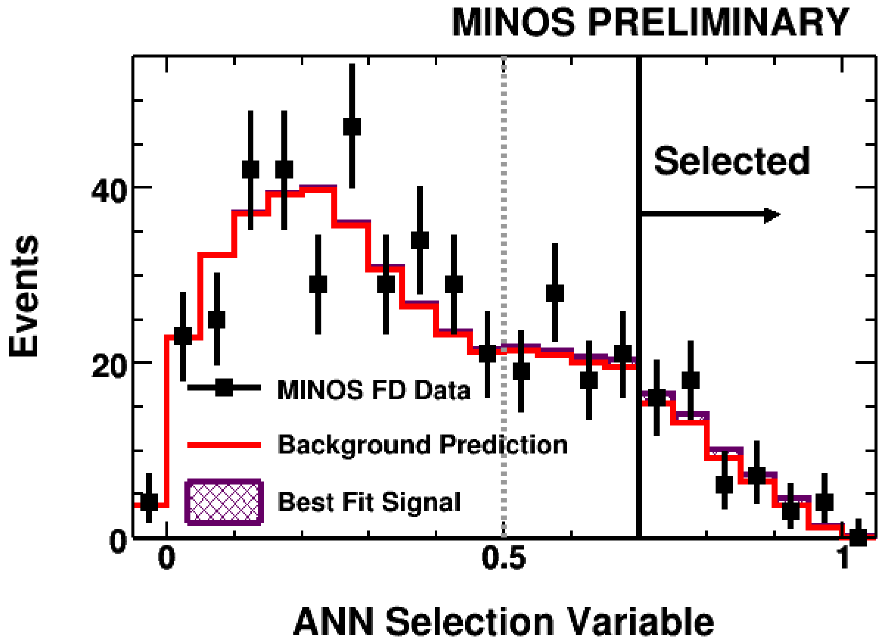
- FD background prediction:
  - **49.1±7(stat)±2.7(sys)**
- Observed:
  - **54**

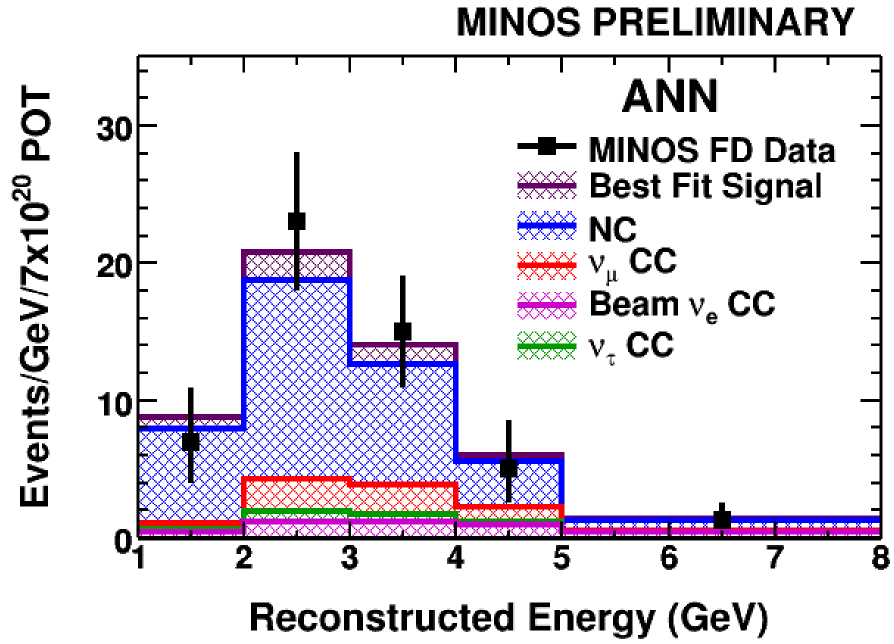


# $\nu_e$ Appearance Results

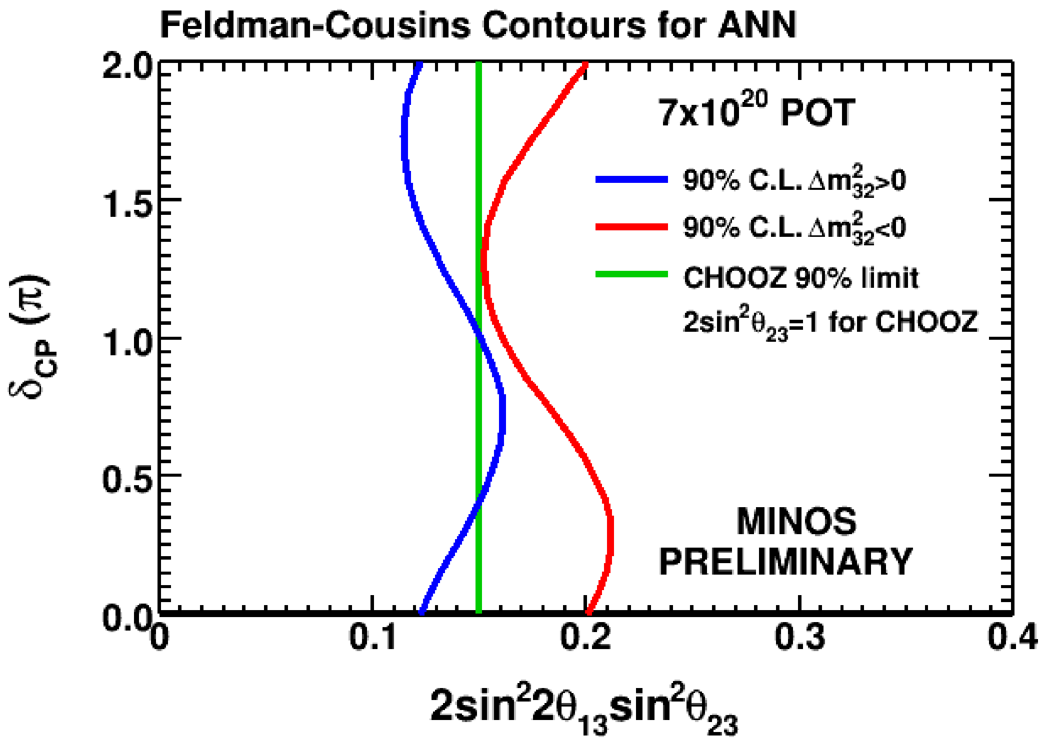
- FD background prediction:
  - **49.1±7(stat)±2.7(sys)**
- Observed:
  - **54** (0.7σ excess)



# $\nu_e$ Appearance Results

- No significant excess seen, find allowed upper limits using F-C approach
  - For both Normal and Inverted mass hierarchies
  - Normal hierarchy (δCP=0):
    - $\sin^2(2\theta_{13}) < 0.12$ (90% C.L.)
  - Inverted hierarchy (δCP=0):
    - $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)




A paper about this:
arXiv:1006.0996 [hep-ex]

# $\nu_e$ Appearance Results

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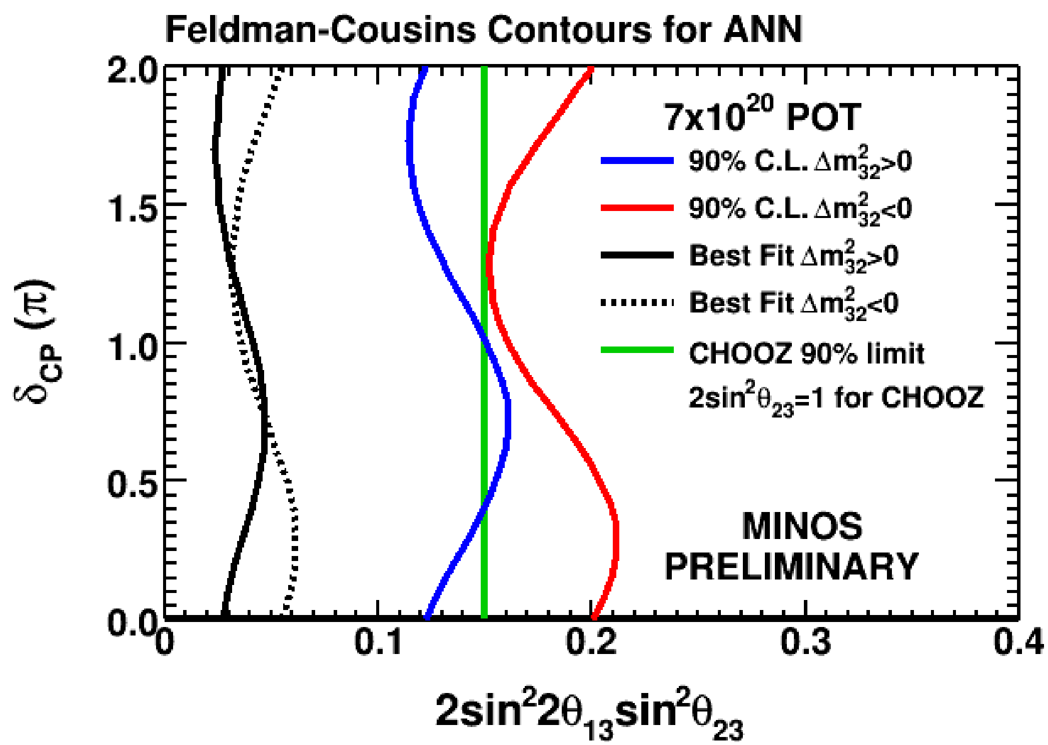
  - Inverted hierarchy (δCP=0):
    - $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)
- If you care to interpret a 0.7σ excess as a signal, the black line is the best fit




A paper about this:
arXiv:1006.0996 [hep-ex]

NuMI

MINOS

# Summary

- The first $7\times10^{20}$ POT of NuMI beam data have been analyzed:
  - $\nu_\mu$ disappearance oscillations are consistent with standard neutrino oscillations with the following parameters:

$$\left|\Delta m^2_{32}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\Theta_{23} = 1.00_{-0.05}$$

  - Alternative $\nu_\mu$ disappearance models are disfavored:
    - Neutrino decay: $6.8\sigma$ Decoherence: $8.8\sigma$
  - Direct $\overline{\nu}_\mu$ CC measurement shows they oscillate too, perhaps ~$2\sigma$ differently than $\nu_\mu$
  - The Neutral Current data spectrum places limits on sterile neutrino participation, $f_s < 0.22$ (90% c.l.)
  - Negligible $0.7\sigma$ excess seen in $\nu_e$ appearance channel, improves on the CHOOZ limit
    - $\sin^2(2\theta_{13}) < 0.12$ (90% C.L.) (for normal mass hierarchy, $\delta_{CP}=0$)

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