NuMI

MINOS

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MINOS Neutrino Oscillation Results and the new NOνA experiment

Alec Habig, for the MINOS & NOνA Collaborations

Univ. of Birmingham, Oct. 20 2010

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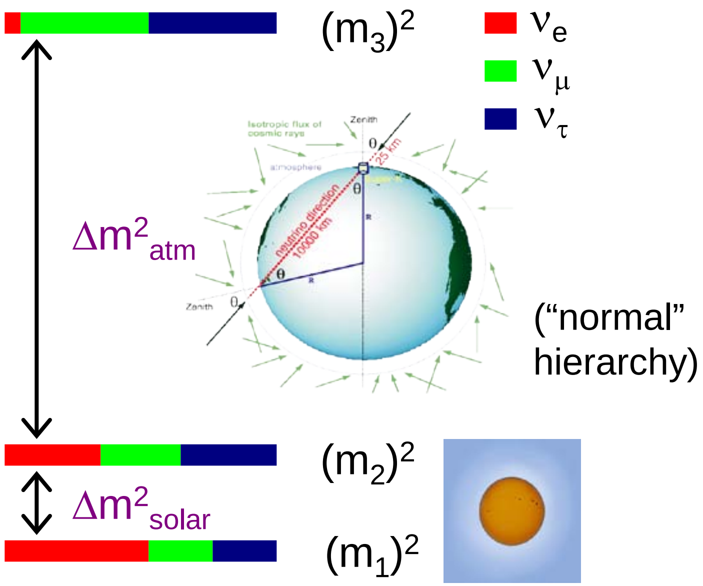
Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL
Warsaw • William & Mary

30 institutions
121 physicists

ν flavor mixing

- ν are leptons, interact only weakly
  - interact as flavor eigenstates $\{\nu_e, \nu_\mu, \nu_\tau\}$
  - but propagate as mass eigenstates $\{\nu_1,\nu_2,\nu_3\}$
- Different m’s make mass states slide in and out of phase as they travel
  - So a ν created as one flavor might be detected as another later



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

$$\boxed{U_{e3}\equiv \sin\theta_{13}e^{-i\delta}}$$

$$\boxed{\sin^2(2\theta_{23})\equiv 4|U_{\mu 3}|^2\left(1-|U_{\mu 3}|^2\right)}$$

Useful Approximations:

ν_μ Disappearance (2 flavors):

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

ν_e Appearance:

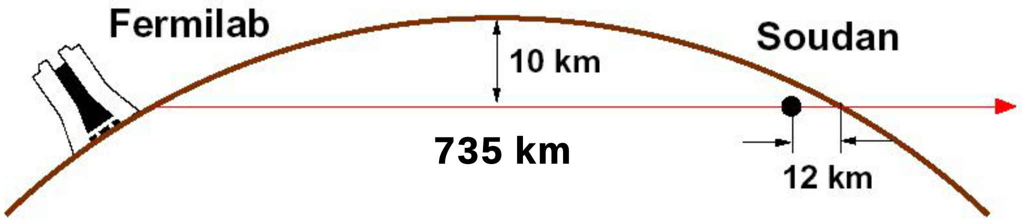
$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31}L/E)$

Where L, E are experimentally optimized and θ_{23}, θ_{13}, Δm^2_{32} are to be determined

MINOS

Main Injector Neutrino Oscillation Search

- Investigate atmospheric sector ν_μ 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



MINOS Physics Goals

- Precise (~10%) measurement of Δm^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, ν decay, etc
- Directly compare ν vs $\overline{\nu}$ oscillations (a test of CPT and odd stuff)
  - MINOS is first large underground detector with a magnetic field for μ^+/μ^- tagging
- Investigate the flavor-independent ν flux
  - The “Neutral Current” (NC) analysis, checking for sterile ν
- Search for subdominant $\nu_\mu \leftrightarrow \nu_e$ oscillations
  - The “ν_e” analysis, a shot at measuring θ_{13}
- Study ν interactions and cross sections using the very high statistics Near Detector data set
- Cosmic Ray Physics with both detectors

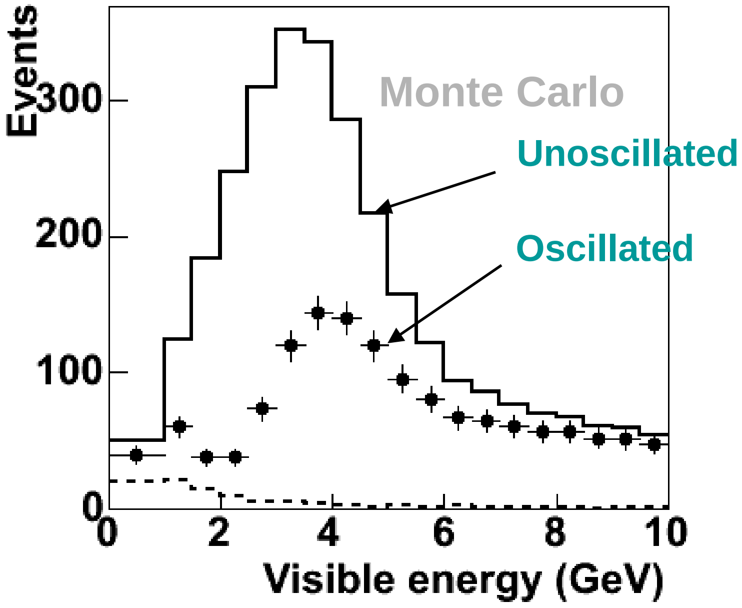
This Talk

ν_μ Disappearance Methodology

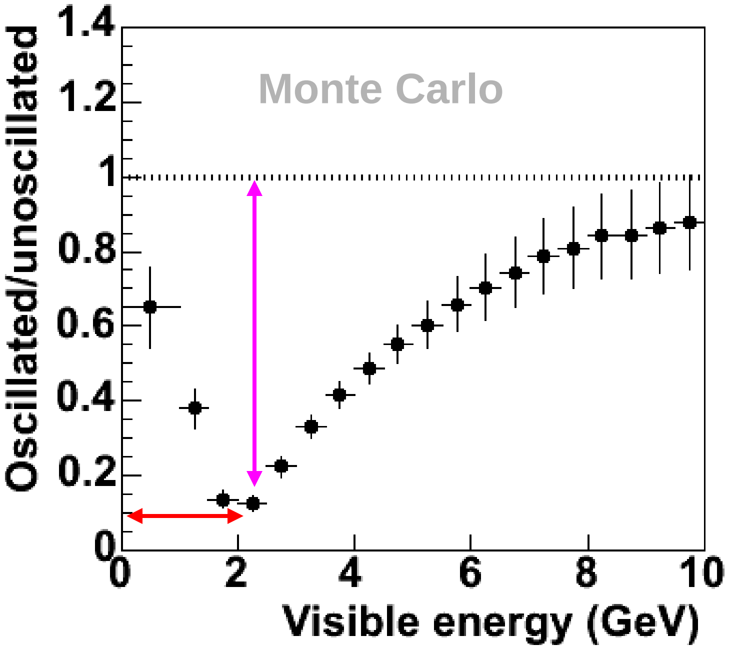
- Measure ν_μ flux at Near Det, see what's left at Far Det
- Simulated results plotted as F/N ratio
  - Position of dip gives Δm^2
  - Depth of dip gives $\sin^2 2\theta$

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

- Spectral ratio shapes would differ in alternative models



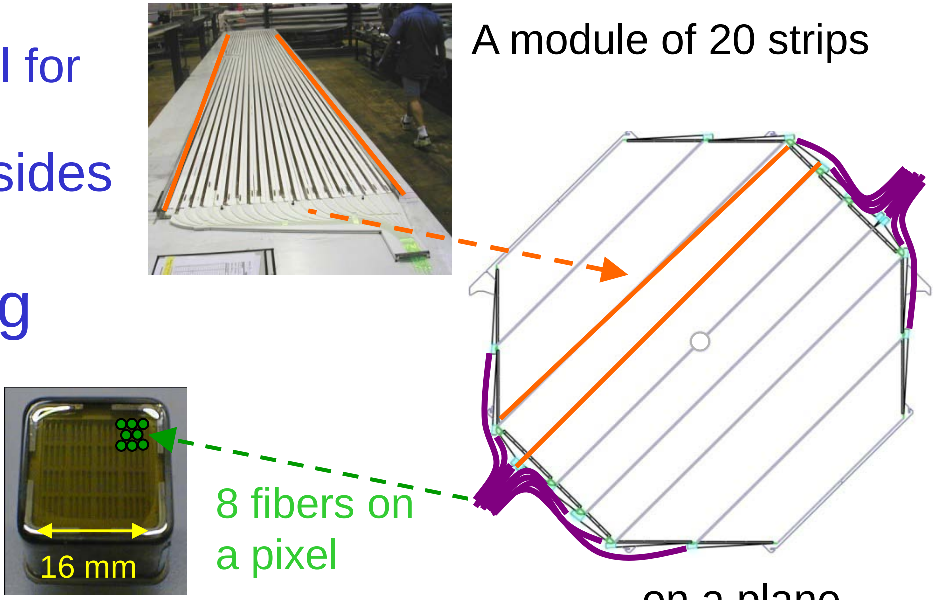
ν_μ spectrum



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

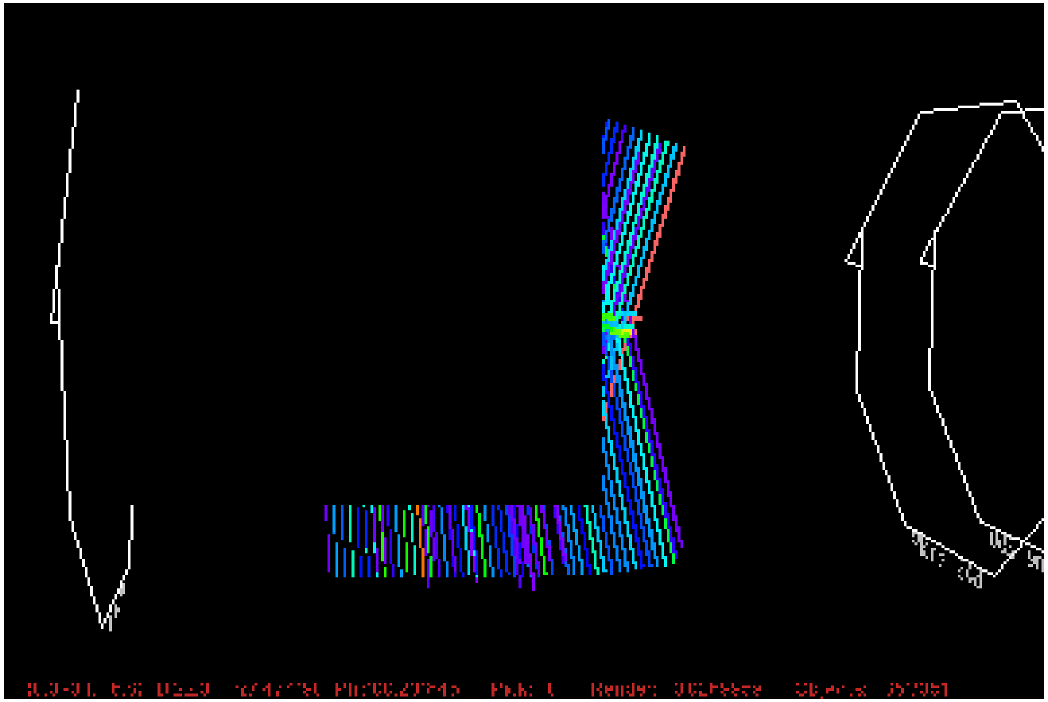

A module of 20 strips

8 fibers on a pixel

…on a plane

M16 PMT

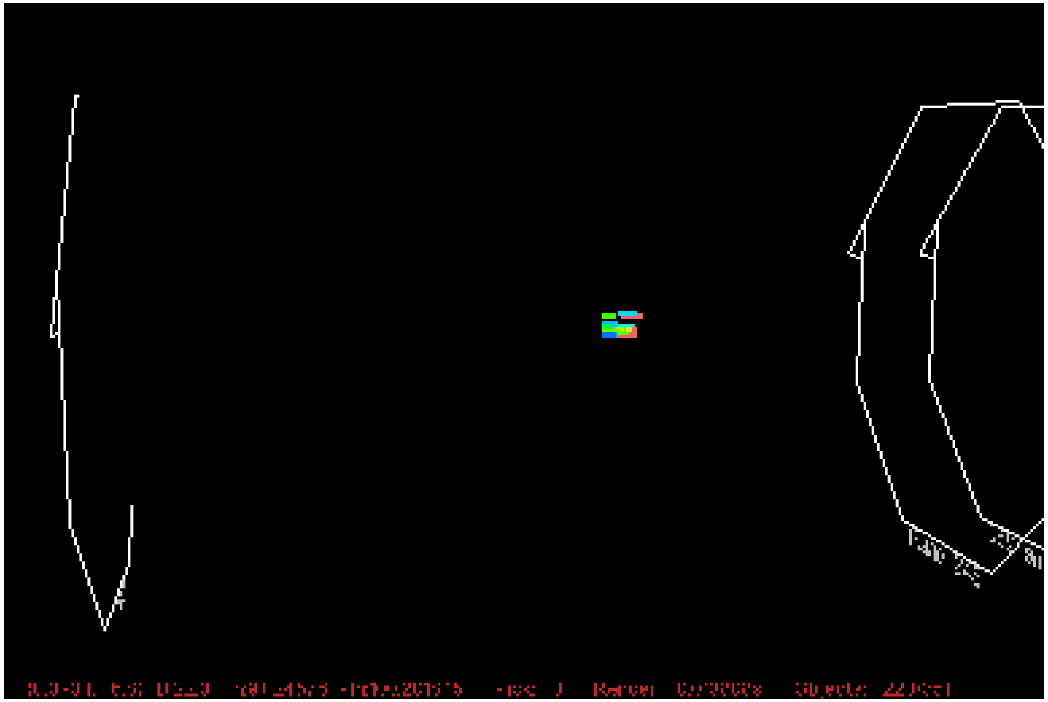
3D Reconstruction



- Take all the “U” view lit-up strips
  - Cross with all the “V” view lit-up strips
  - X marks the spot(s)

See live events at http://www.soudan.umn.edu

3D Reconstruction

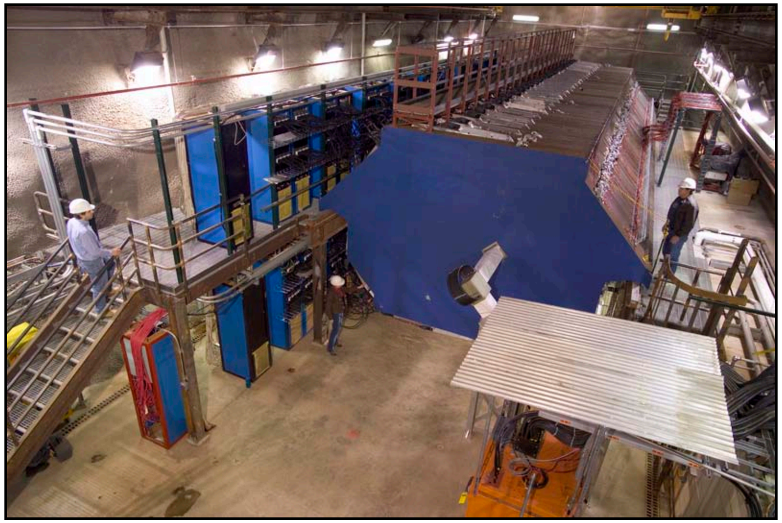


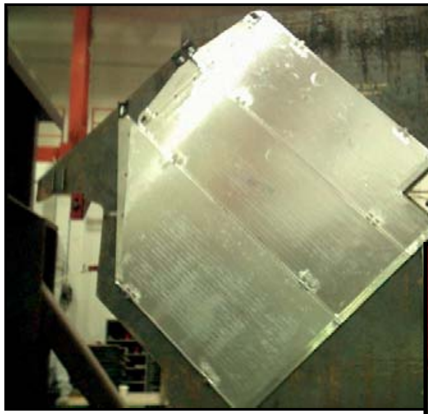
See live events at
http://www.soudan.umn.edu

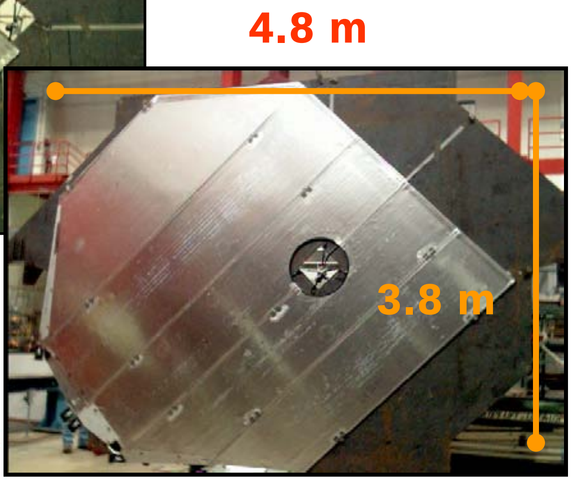
- This is a real ν_μ interaction from the beam
  - μ^- appears inside detector,
  - cruises along through many planes,
  - curving in the magnetic field,
    - Curvature tells us momentum…
  - stops.
    - …so does range

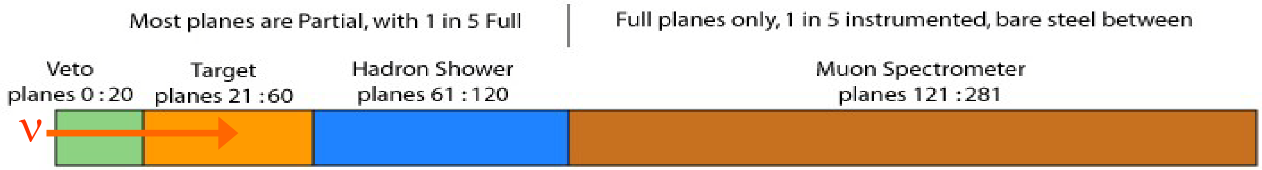
Near Detector

- 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









Most planes are Partial, with 1 in 5 Full | Full planes only, 1 in 5 instrumented, bare steel between

Veto planes 0 : 20

Target planes 21 : 60

Hadron Shower planes 61 : 120

Muon Spectrometer planes 121 : 281

NuMI Beam

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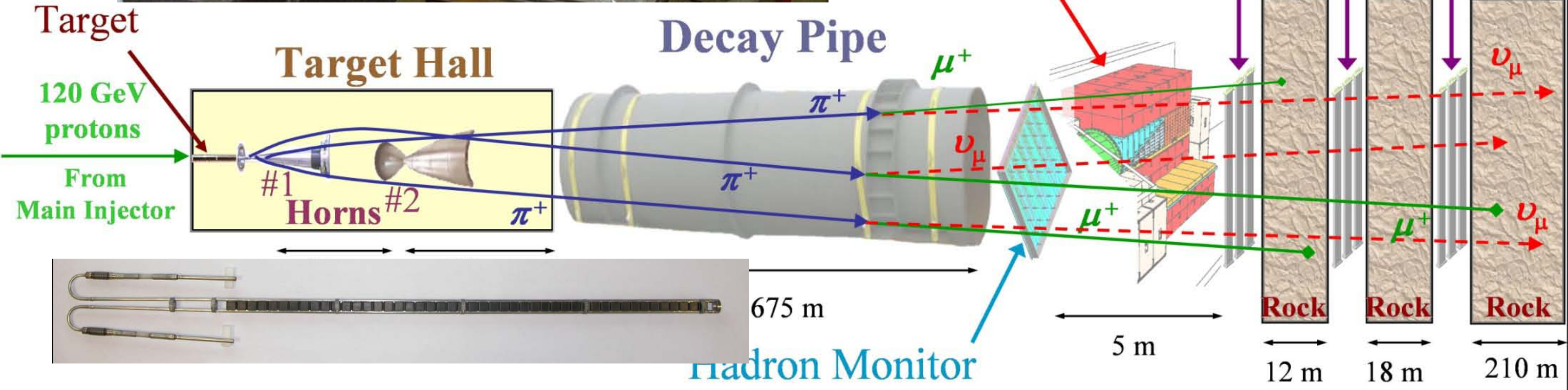
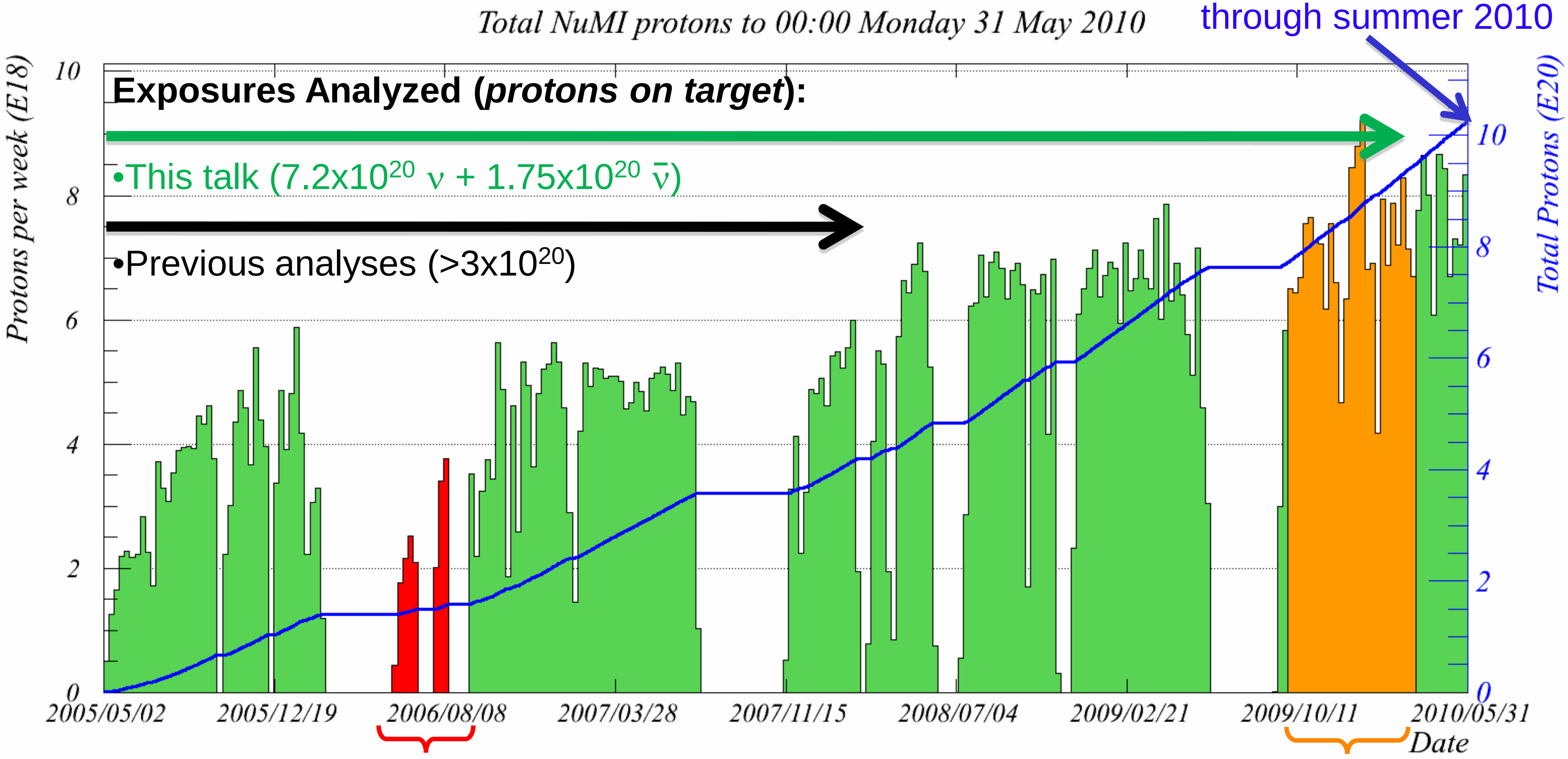


Beam Data Analyzed

1.07×10^{21} POT total
through summer 2010



Exposures Analyzed (*protons on target*):

- This talk (7.2×10^{20} ν + 1.75×10^{20} $\bar{\nu}$)
- Previous analyses ($>3 \times 10^{20}$)

HE beam:
0.15×10^{20} POT

Far Det
>98% live!

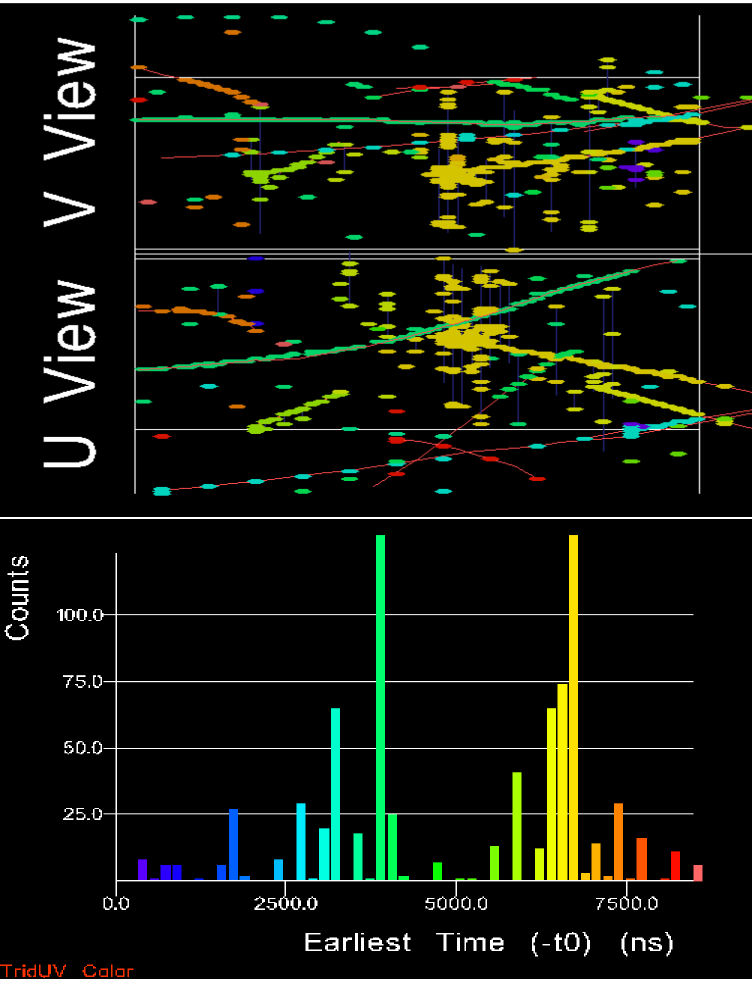
Anti-nu beam:
1.75×10^{20} POT

Near Detector Data

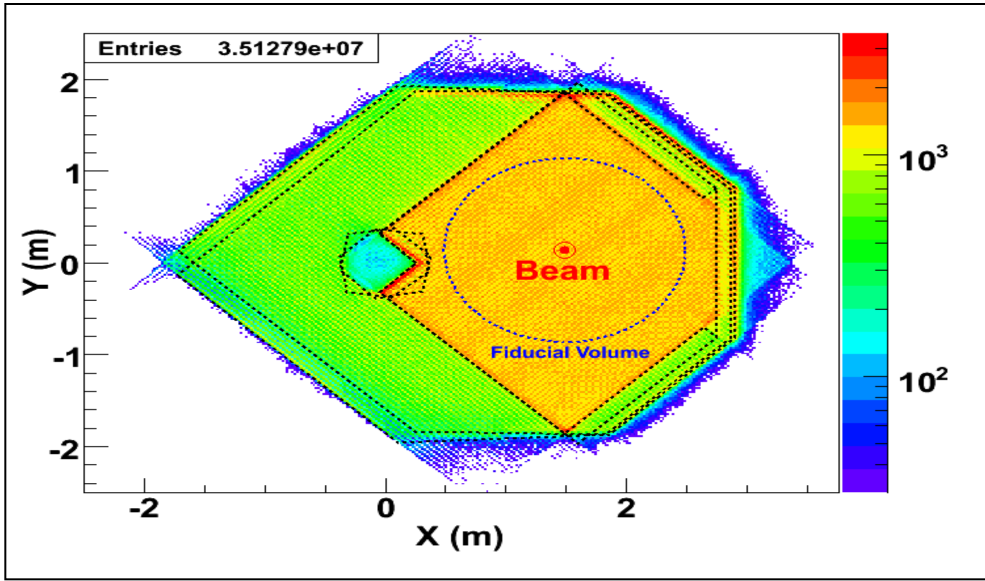
- How do data look in the Near Detector, where we have ~unlimited statistics? (*10^7 ν per 10^{20} pot)*
- If we understand things there, we can then look at the Far Detector data where the oscillation physics is happening, so:
  - Examine ND closely
  - Compare ND data/MC
  - "Blind" analysis done

Lots of ν in the Near Detector

- A mean of 3 ν interactions per spill (in 8 or 10 μs), up to 10
- Typical 250kW beam makes 10^4 ν/day in ND
- Near Detector Electronics gates for 19 μs during the entire spill
  - Digitizes continuously every 19 ns, no dead time
- Separate events using timing and topology
- Below: ~35 x 10^6 events for 1.27 x 10^{20} POT image the ND's internal structure with ν!



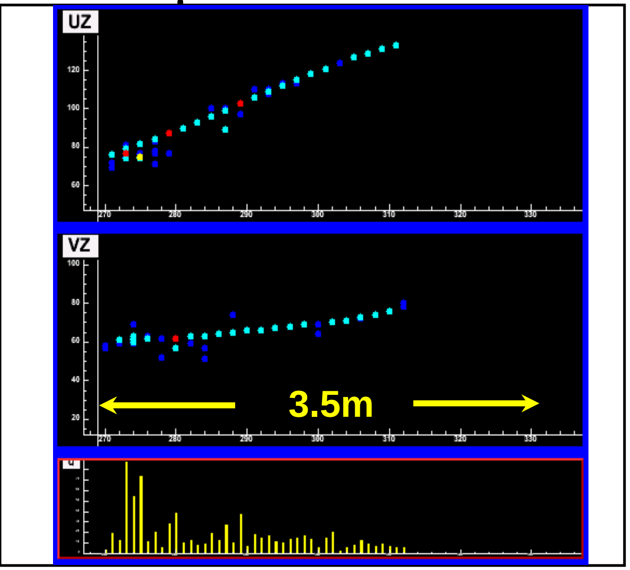
A typical 6-event spill, colored by time



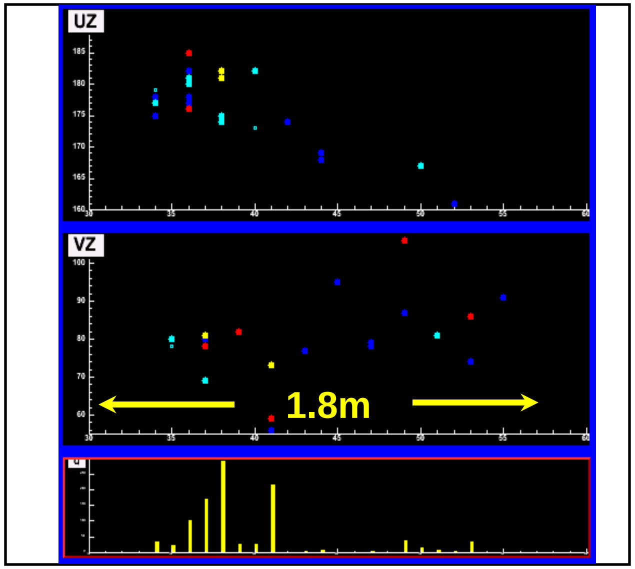
What sort of ν Interaction?

Monte Carlo

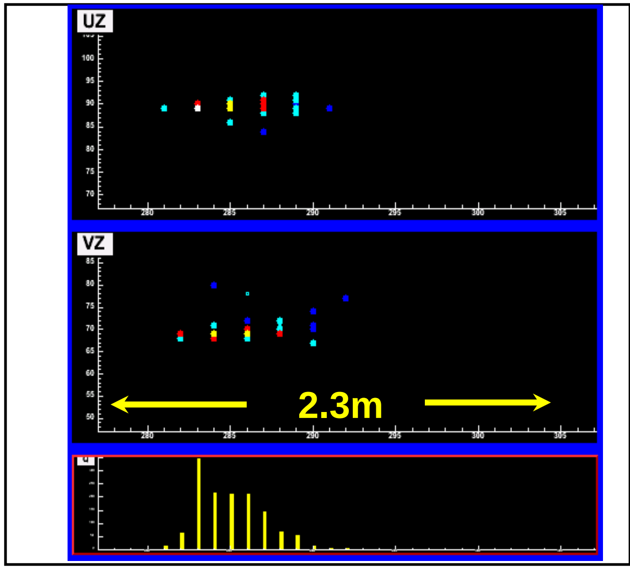
ν_μ CC Event



NC Event



ν_e CC Event



Long μ track + hadronic activity at vertex

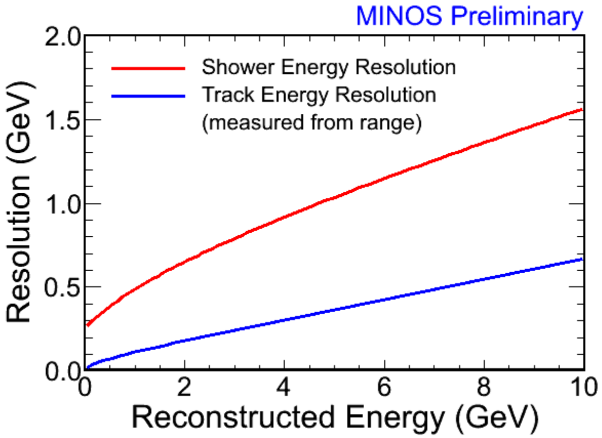
Short event, often diffuse

$$E_\nu = E_{shower} + E_\mu$$

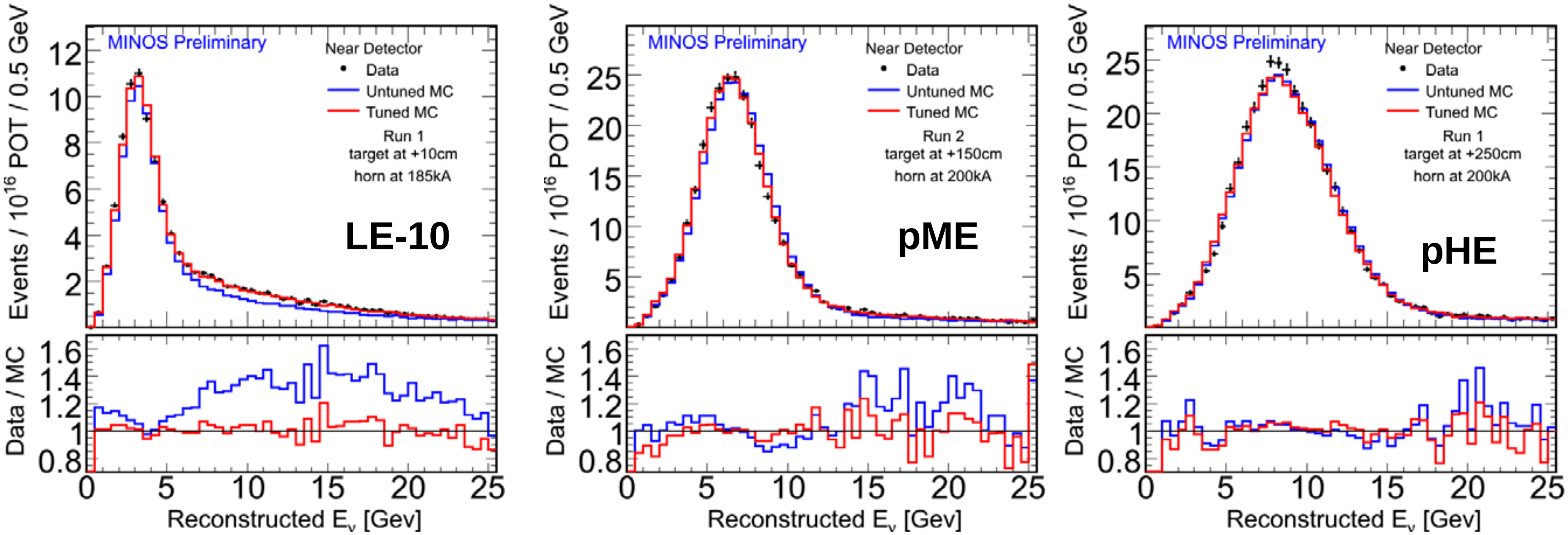
40.4%/√E +8.6% +257MeV/E

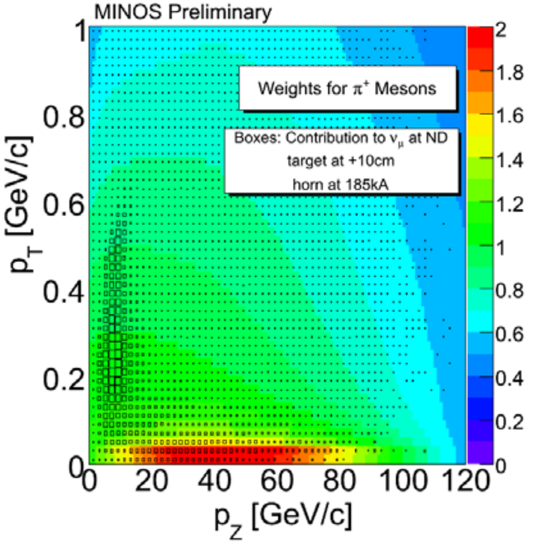
(hadronic)

5.1%/√E +6.9% range



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

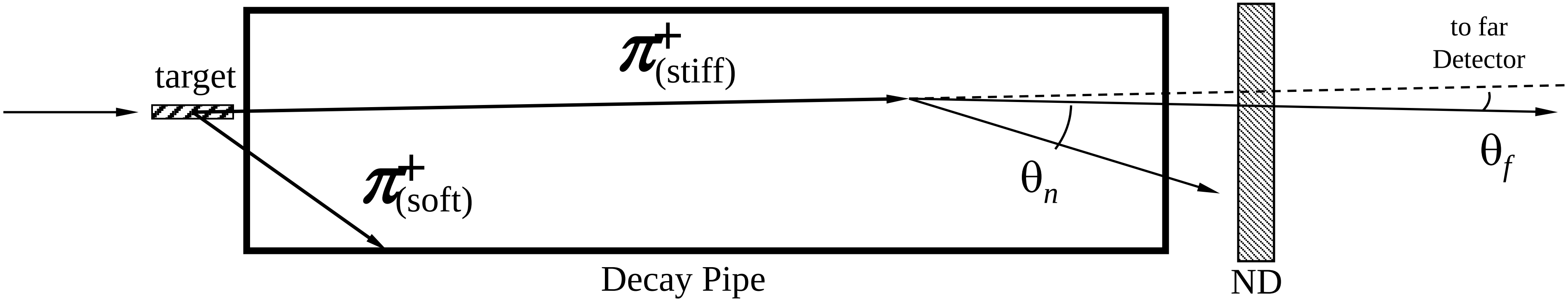
MC tuned by fitting to hadronic x_F and p_T over 9 beam configurations (3 shown here, from older Fluka05-based work)

Do we understand things?

- Data/MC agreement between low-level quantities tells us the modeling and reconstruction are OK
- Data/MC agreement between high-level quantities (Energy, kinematics, PID) is:
  - within the expected systematic uncertainties from:
    - cross-section modeling
    - beam modeling
    - calibration uncertainties
  - improved after applying beam reweighting on the x_F and p_T of parent hadrons in the Monte Carlo

What is Expected in Soudan?

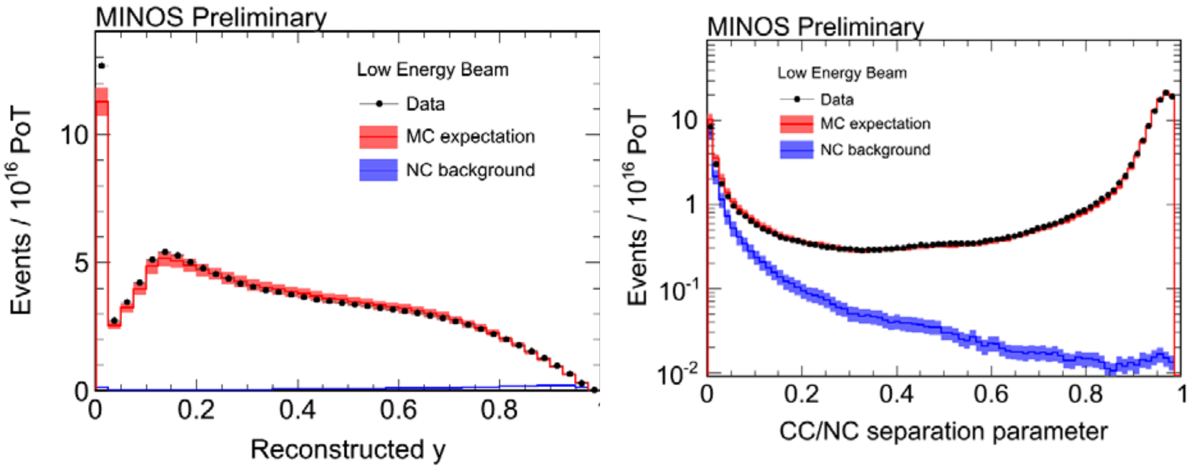
- Measure Near Detector E_ν spectrum
- To first order the beam spectra at Soudan is the same as at Fermilab, but:
  - Small but systematic differences between Near and Far
  - Use Monte Carlo to correct for energy smearing and acceptance
  - Use our knowledge of pion decay kinematics and the geometry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



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

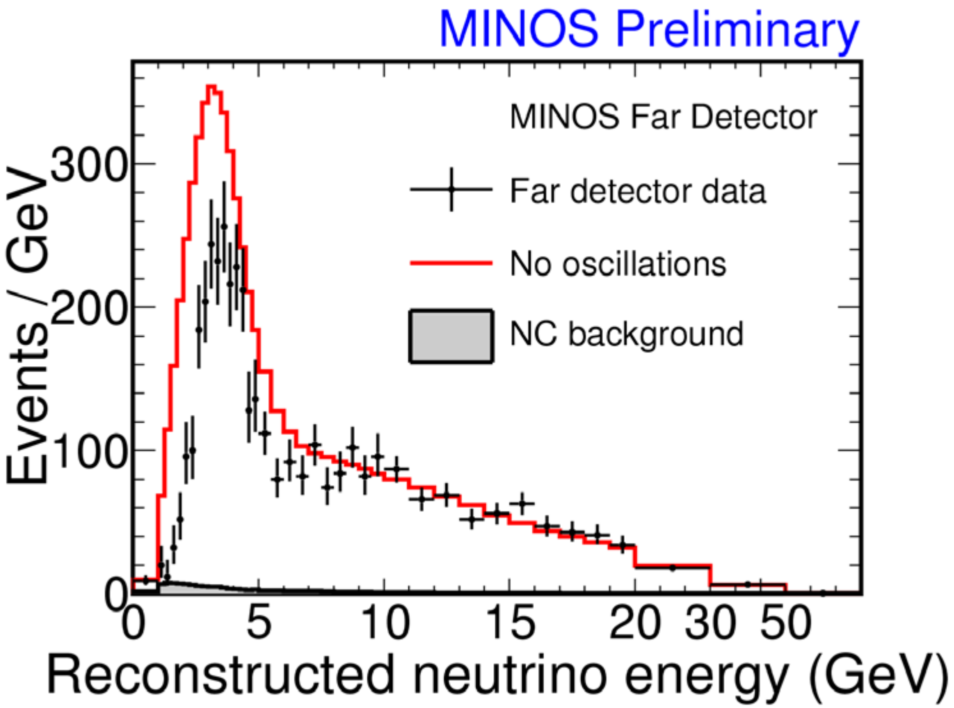
On to the Far Detector…

- “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

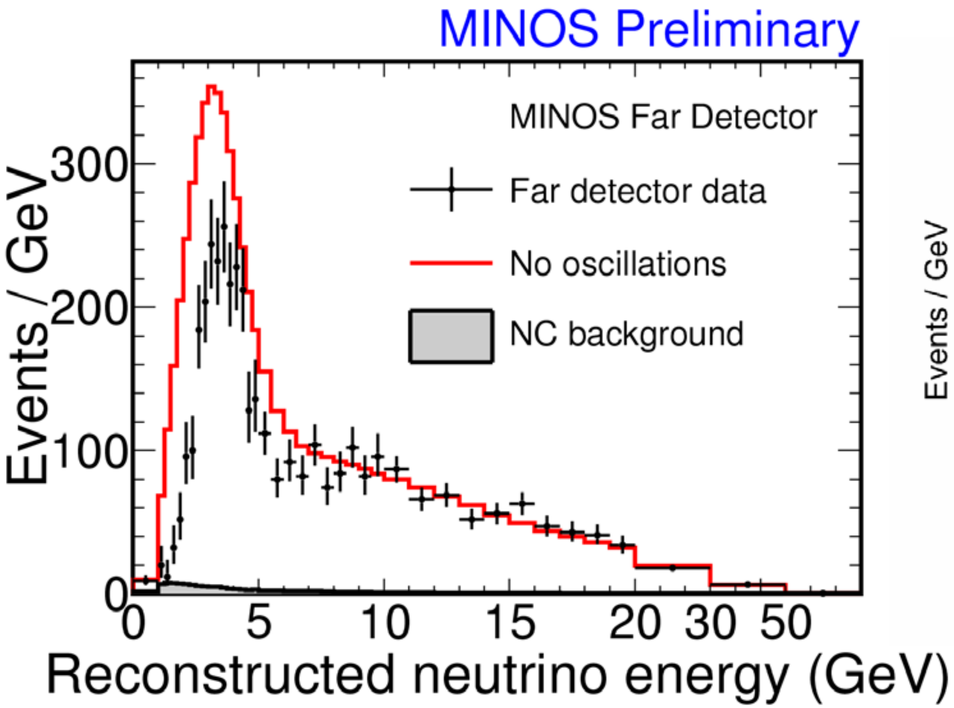


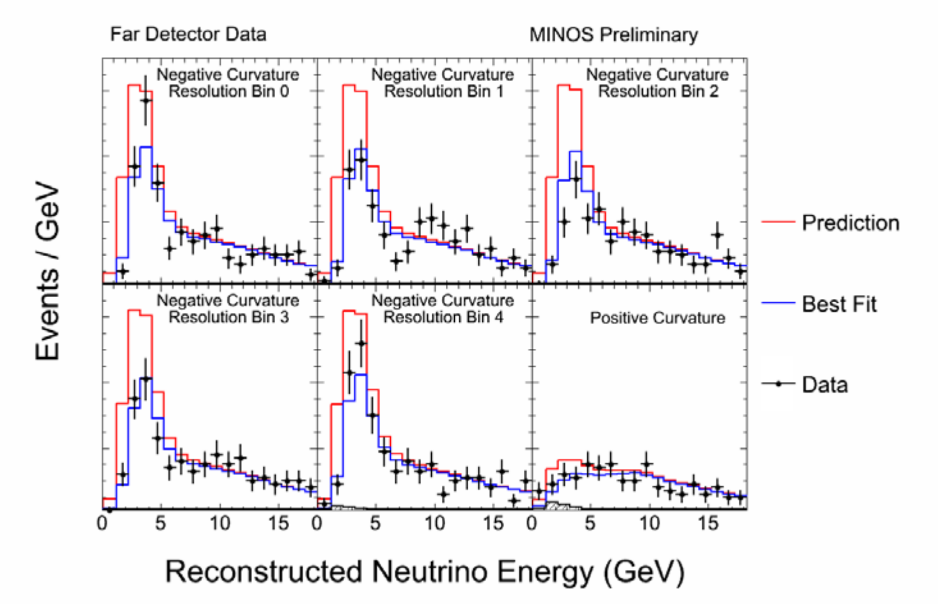
Expect 2451 without oscillations

includes ~1 CR μ, 8.1 rock μ, 41 NC, ~3 ν_τ BG

See only 1986 in the FD.

Spectrum





Expect 2451 without oscillations

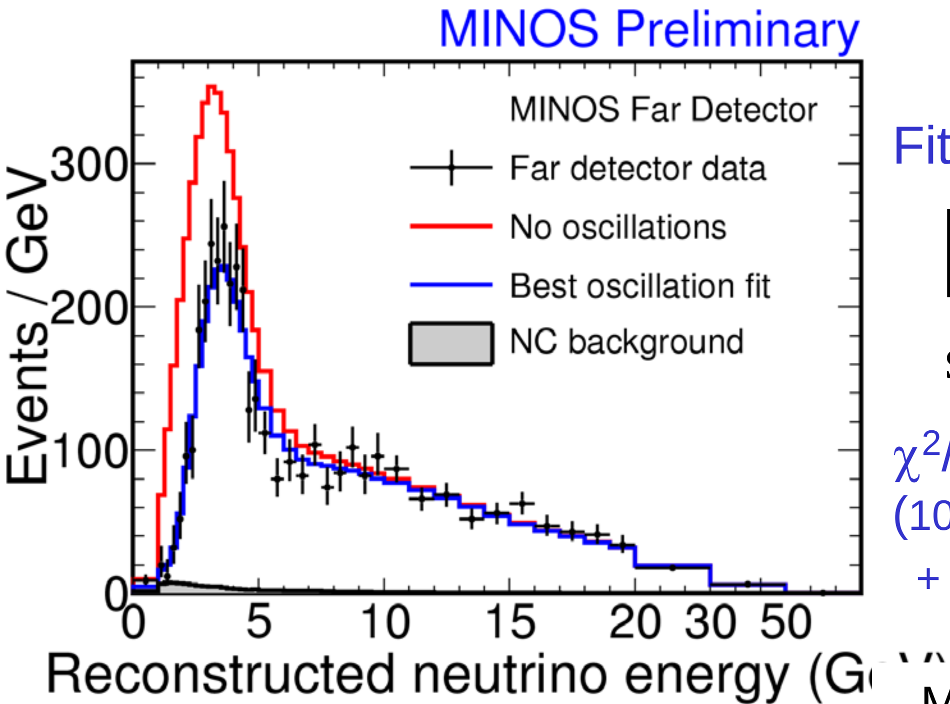
includes ~1 CR μ, 8.1 rock μ, 41 NC, ~3 ν_τ BG

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



Fit for oscillation parameters:

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

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

χ^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 μ, 8.1 rock μ, 41 NC, ~3 ν_τ BG

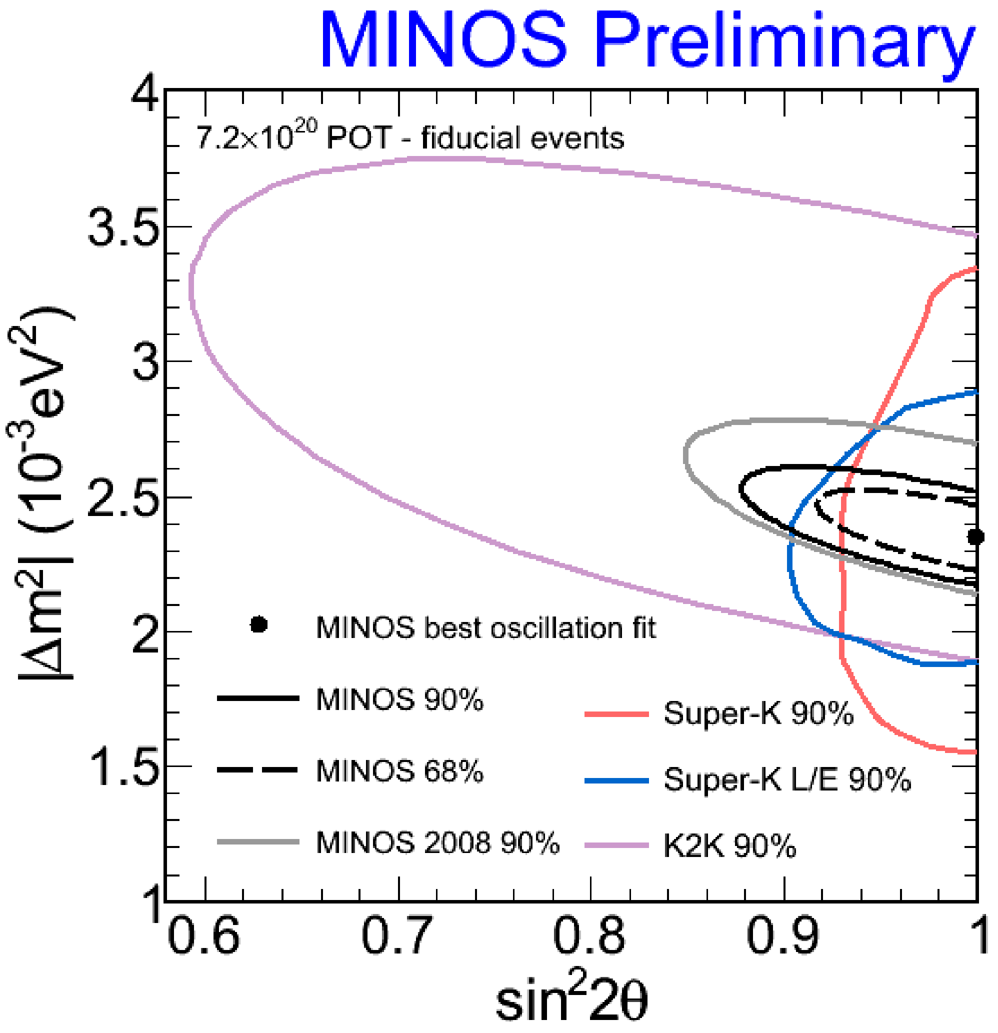
See only 1986 in the FD.

$$o_i = \text{observed}$$

$$e_i = \text{expected}$$

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

Allowed Region



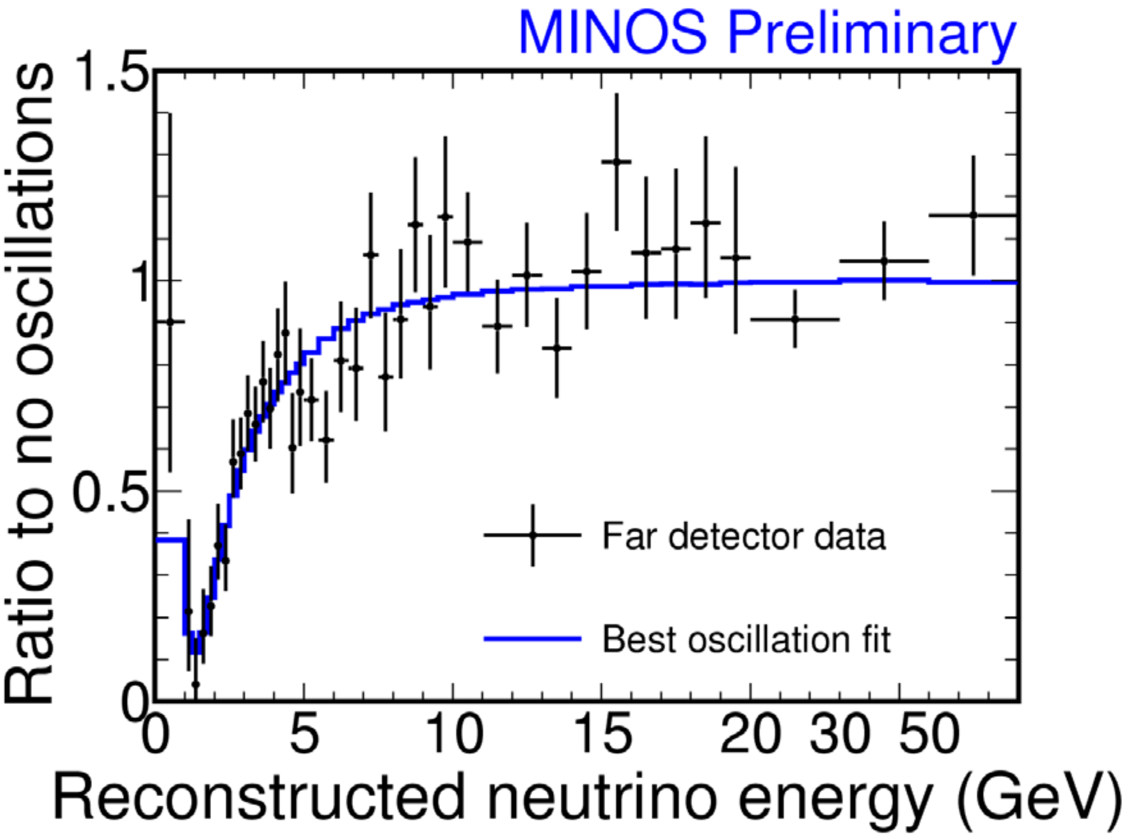
- Fit includes systematic penalty terms
- Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$
  - Best physical fit: $|\Delta m|^2 = 2.35 \times 10^{-3}\ \text{eV}^2$ $\sin^2(2\theta) = 1.00$
  - Unconstrained: $|\Delta m|^2 = 2.34 \times 10^{-3}\ \text{eV}^2$ $\sin^2(2\theta) = 1.007$

Earlier results are in:

Phys.Rev. Lett. 101:131802, 2010

Alternative ν_μ Disappearance Models

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

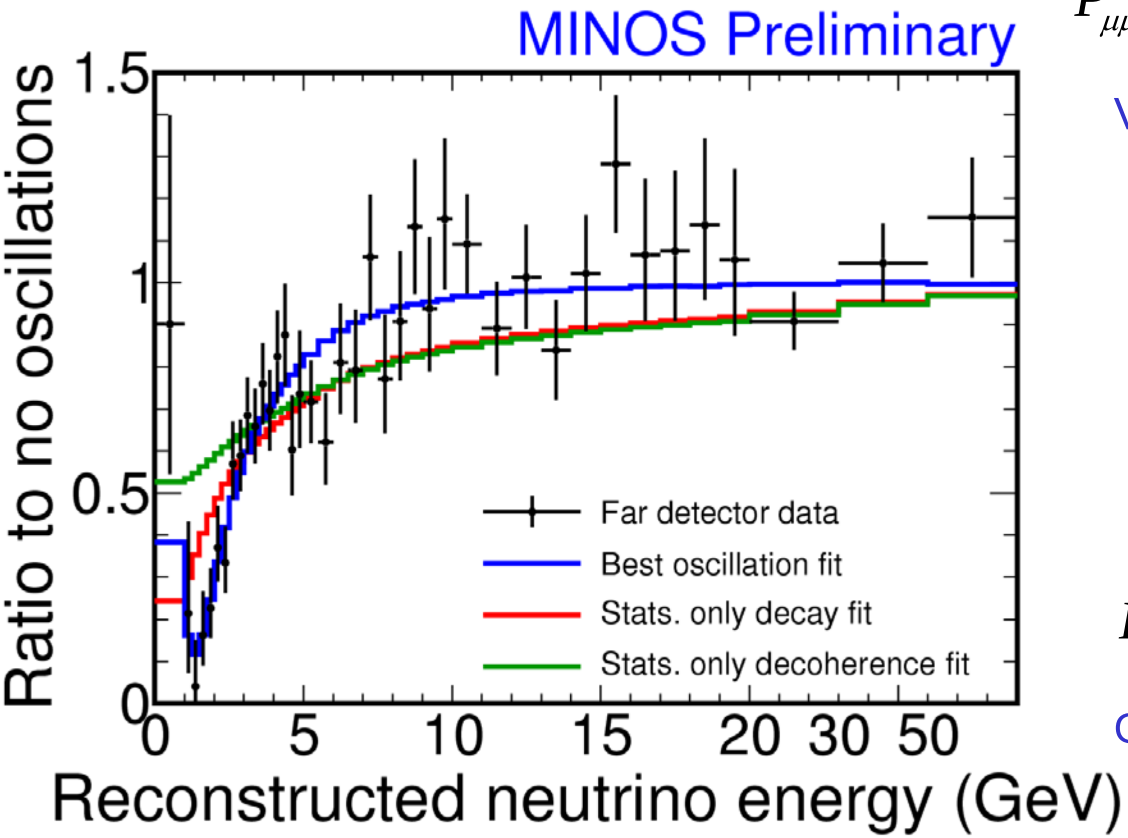


$$P_{\mu\tau} = \sin^2 2\theta_{23} \sin^2 (1.27 \Delta m^2_{32} L / E)$$

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

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

Alternative ν_μ 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)

χ^2/ndof = 2165.81/2298

$\Delta\chi^2$ = 46.3

disfavored at 6.8σ

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)

χ^2/ndof = 2197.59/2298

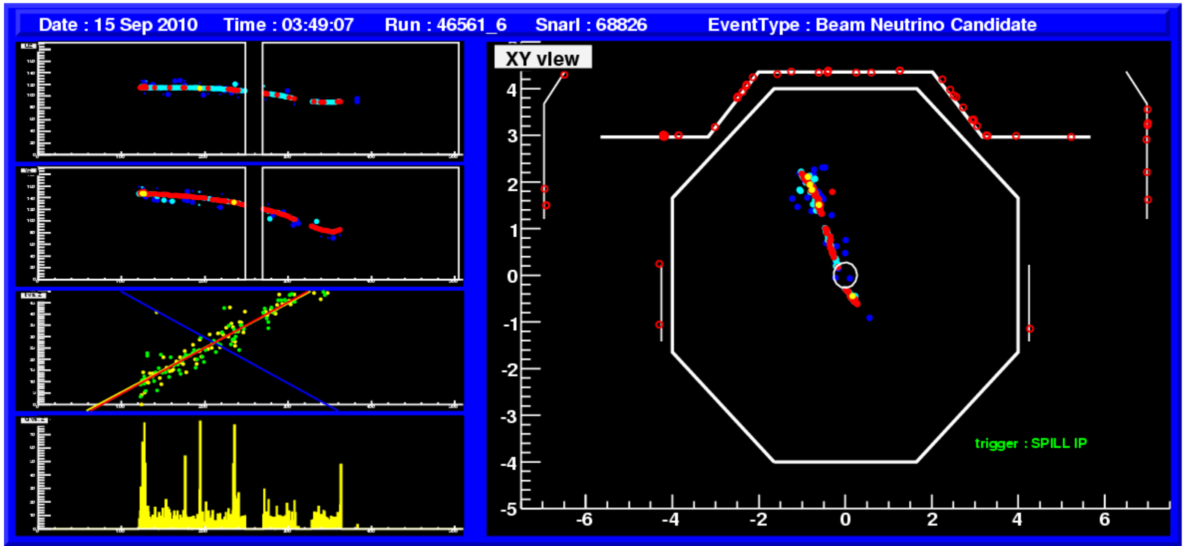
$\Delta\chi^2$ = 78.1

disfavored at 8.8σ

$\bar{\nu}_\mu$

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

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

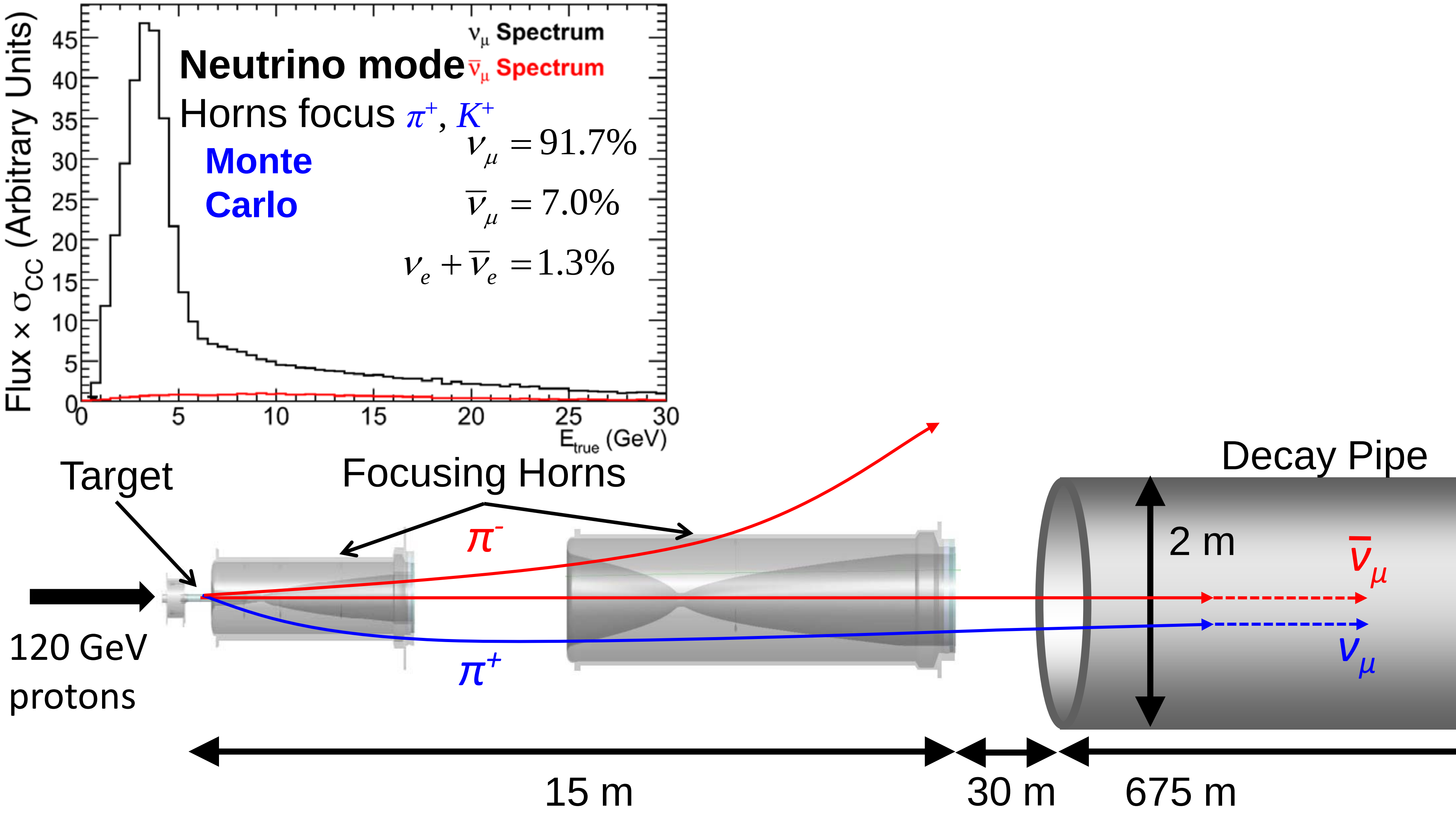


Date : 15 Sep 2010 Time : 03:49:07 Run : 46561_6 Snarl : 68826 EventType : Beam Neutrino Candidate

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

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

Neutrino Mode



Neutrino mode

Horns focus π^+, K^+

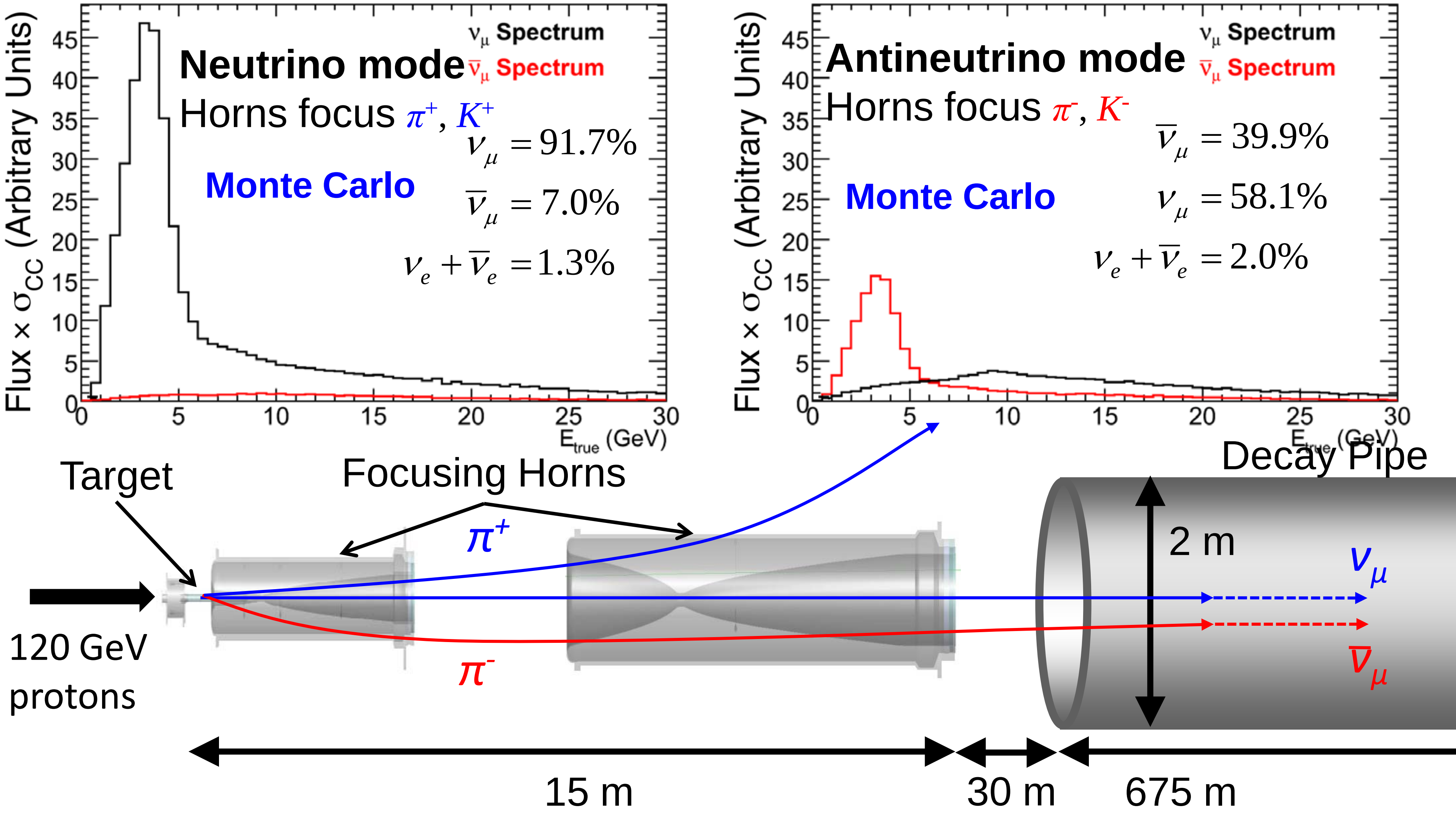
Monte Carlo

$$\nu_\mu = 91.7\%$$

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

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

Anti-neutrino Mode



Neutrino mode

Horns focus π^+, K^+

Monte Carlo

$$\nu_\mu = 91.7\%$$
$$\overline{\nu}_\mu = 7.0\%$$
$$\nu_e + \overline{\nu}_e = 1.3\%$$

Antineutrino mode

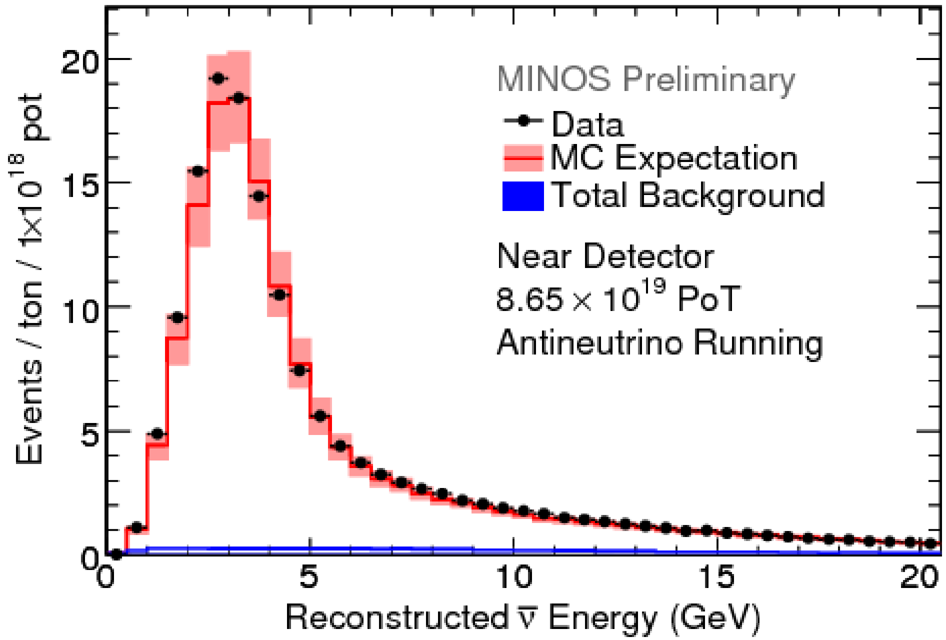
Horns focus π^-, K^-

Monte Carlo

$$\overline{\nu}_\mu = 39.9\%$$
$$\nu_\mu = 58.1\%$$
$$\nu_e + \overline{\nu}_e = 2.0\%$$

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

- Same analysis done as ν_μ 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% ν_μ)
  - 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)

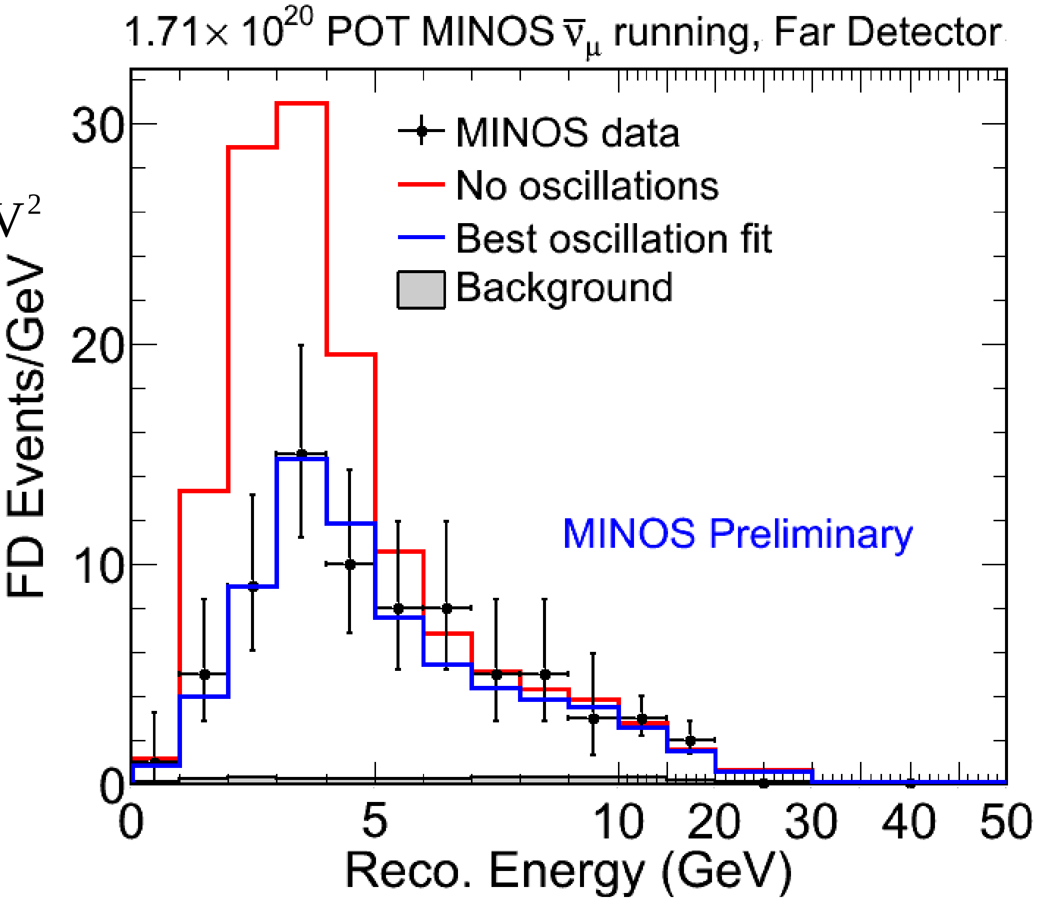


$\bar{\nu}_\mu$ Results

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

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

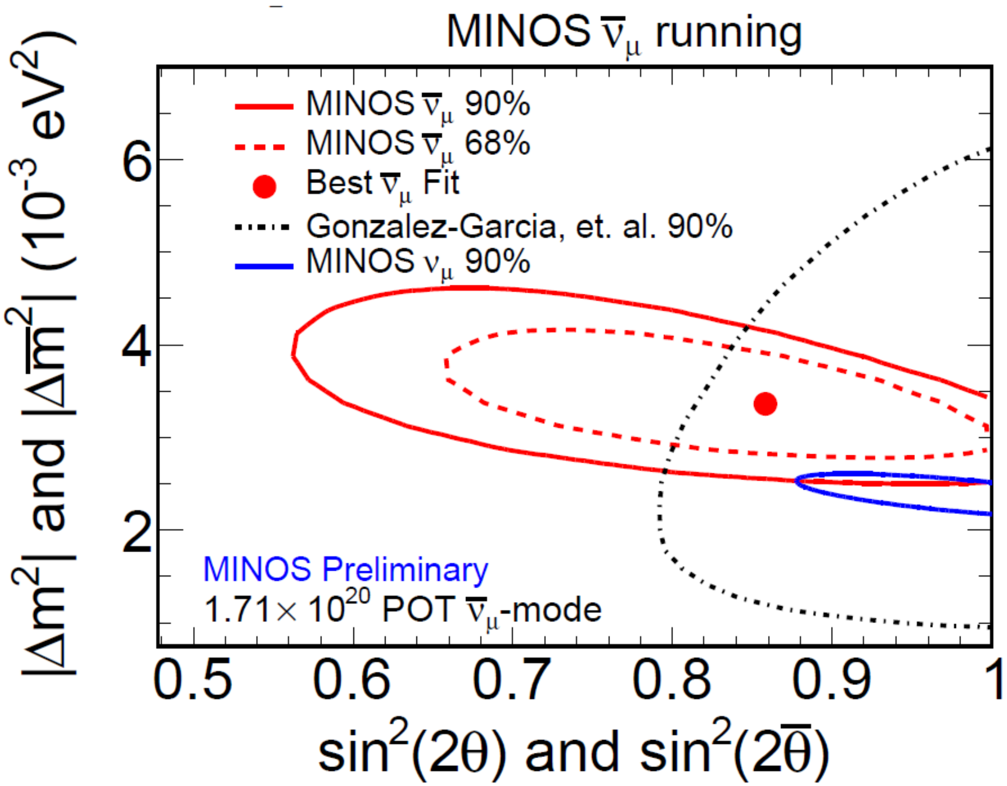
$$\sin^2(2\overline{\theta}) = 0.86 \pm 0.11(stat) \pm 0.01(syst)$$



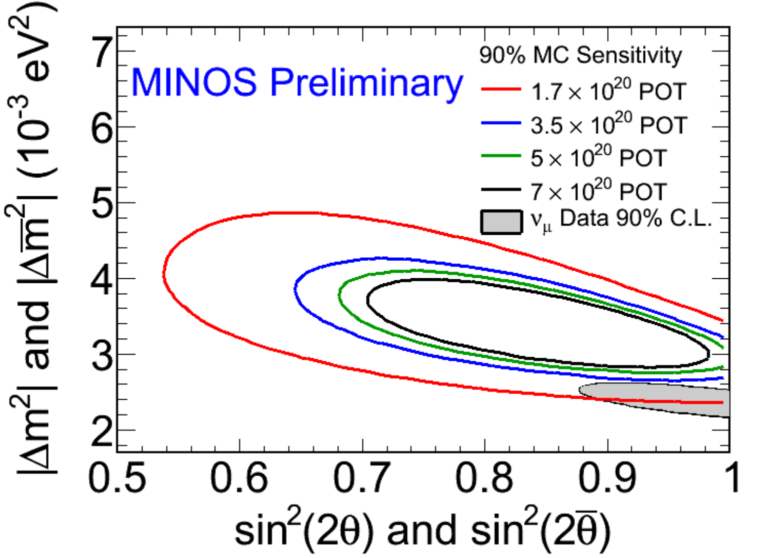
- Completely dominated by low statistics
  - Includes additional 30% uncertainty on the ν_μ background
- Plan to double anti-nu statistics after initial Minerva run

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

- Interestingly, oscillation parameters differ from the ν_μ results at a not terribly significant level, ~2σ



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

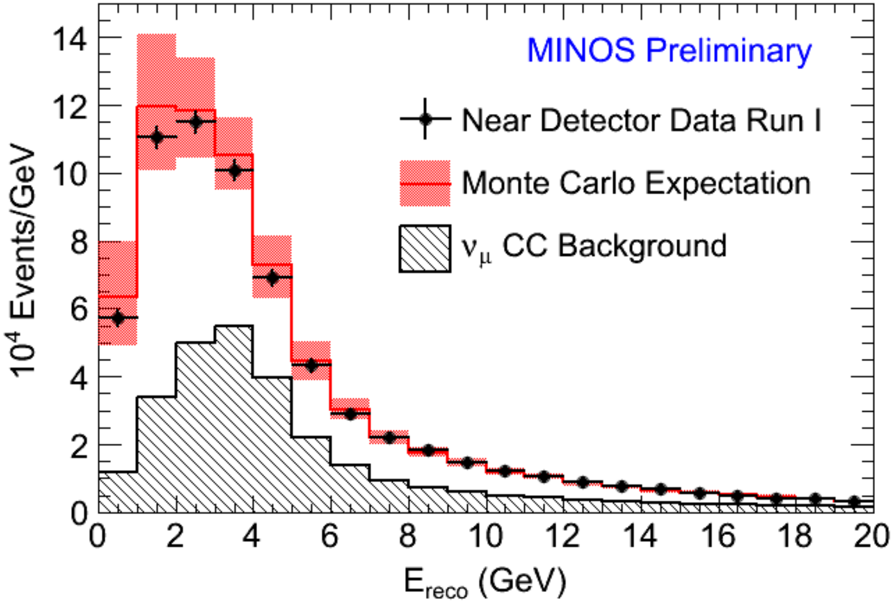


Global fit from Gonzalez-Garcia & Maltoni, *Phys. Rept.* 460 (2008), SK data dominates

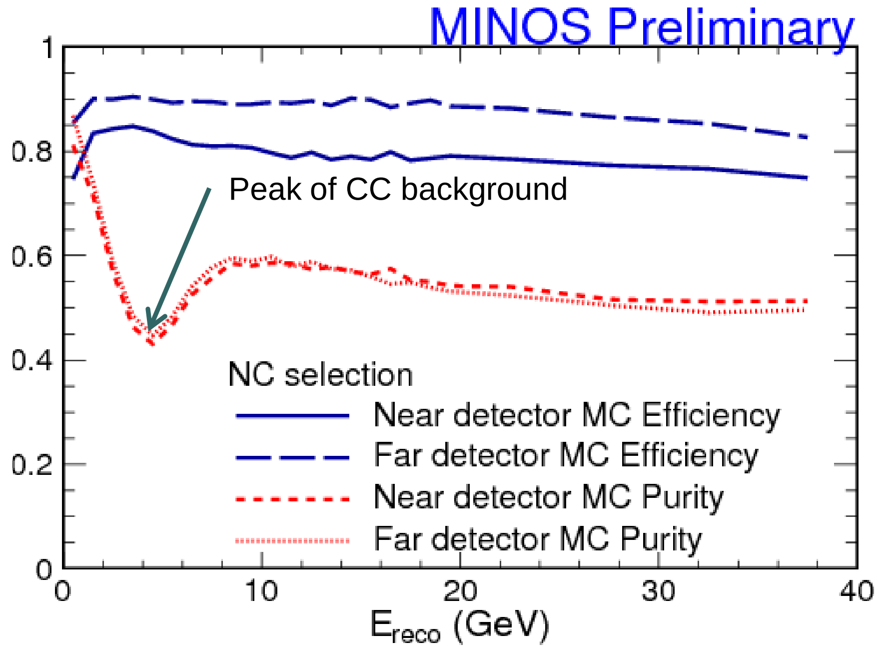
So what <u>are</u> the ν_μ disappearing to?

- For ν oscillations in this “atmospheric” sector, we like to blame ν_μ oscillating to ν_τ,
  - Most ν below τ production threshold
  - Few τ that aren’t produce very messy decays which get rejected by our analysis
- Some very well might be going to ν_e as well, depending on the currently unknown θ_{13} (known to be less than 0.21 from Chooz)
- A fourth, sterile neutrino could also be the culprit
  - By definition, ν_s interact with nothing save gravity

NC Spectrum



ND NC Data



89% Efficient, 61% Pure

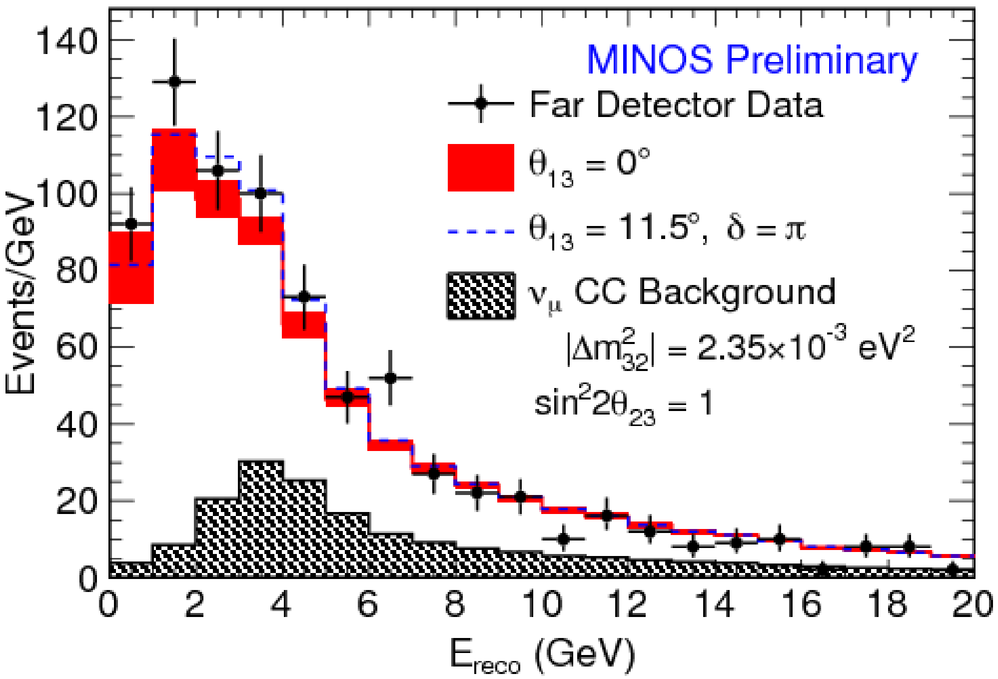
- NC events can be used to search for sterile neutrino component in FD
  - via disappearance of NC events at FD
  - If oscillation is confined to active neutrinos instead, NC spectrum will be unchanged

NC Analysis Results – 3-flavor Rate

- FD NC energy spectrum for Data and oscillated MC predictions
    - Form ratio R, data are consistent with no ν_μ disappearing to νs
- Simultaneous fit to CC and NC energy spectra yields the fraction of ν_μ that could be oscillating to ν_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

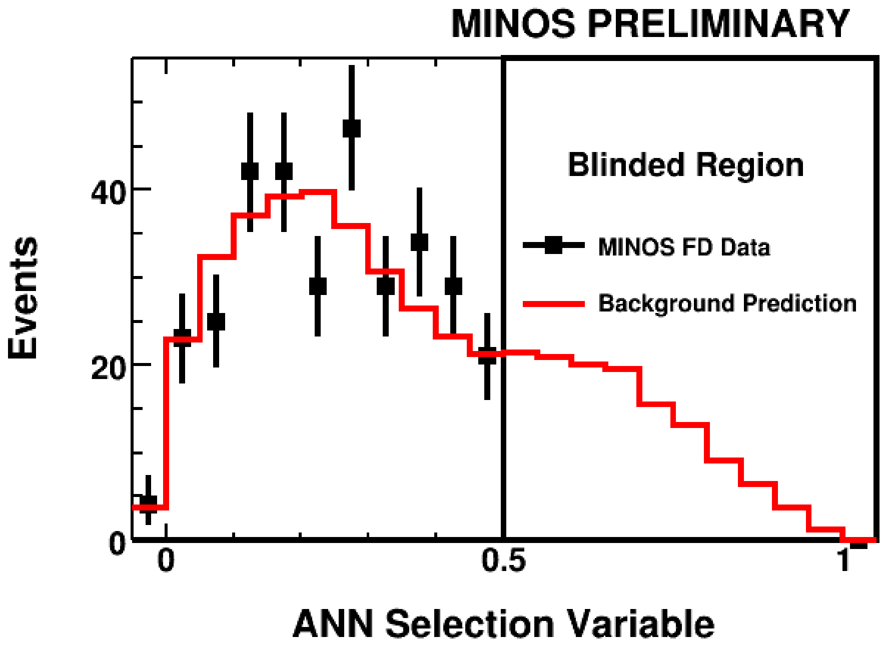
Earlier results are in: Phys.Rev.D81:052004, 2010

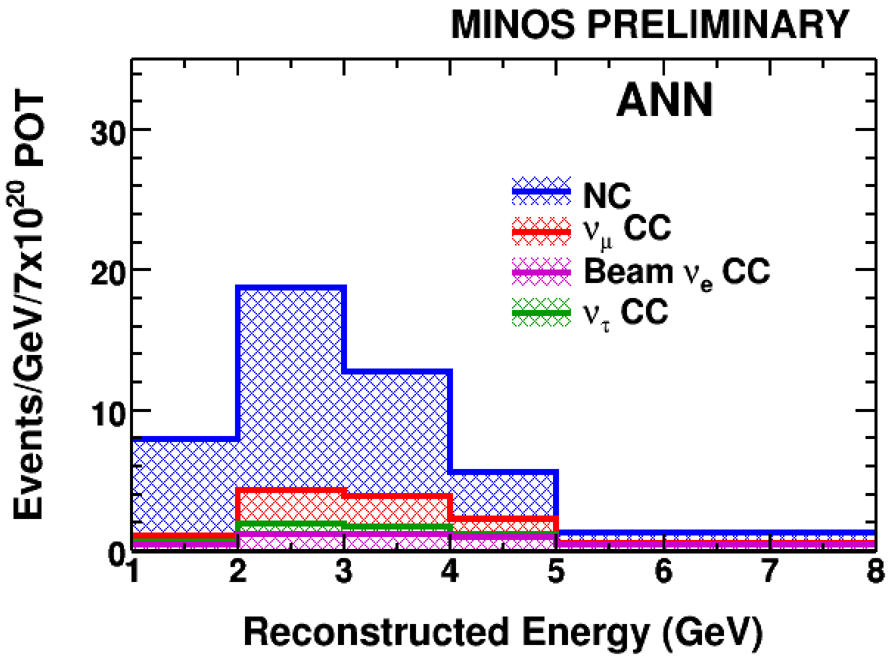
ν_e Appearance

- Are some of the disappearing ν_μ re-appearing as ν_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 δ 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

ν_e Appearance Results

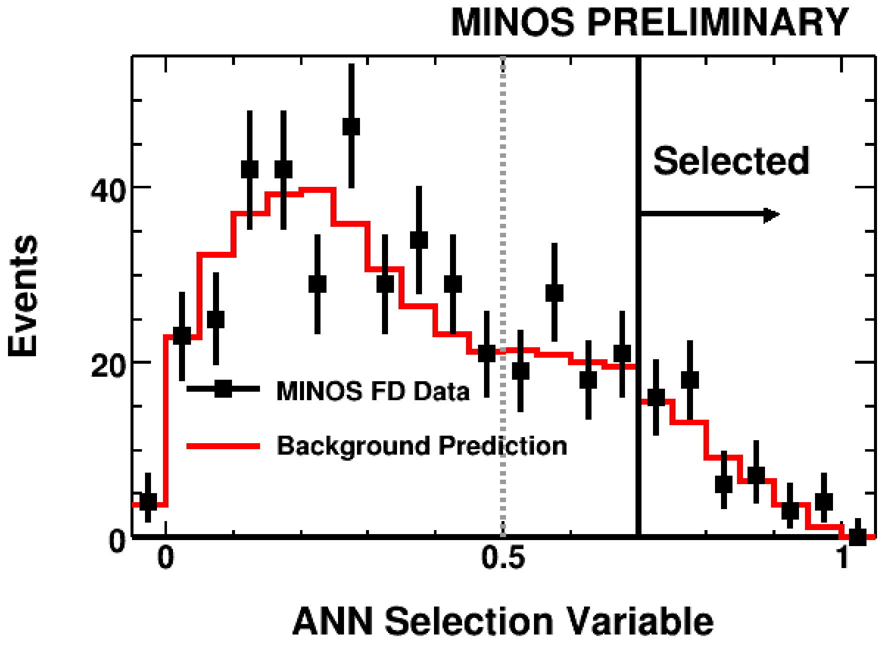
- FD background prediction:
  - **49.1±7(stat)±2.7(sys)**

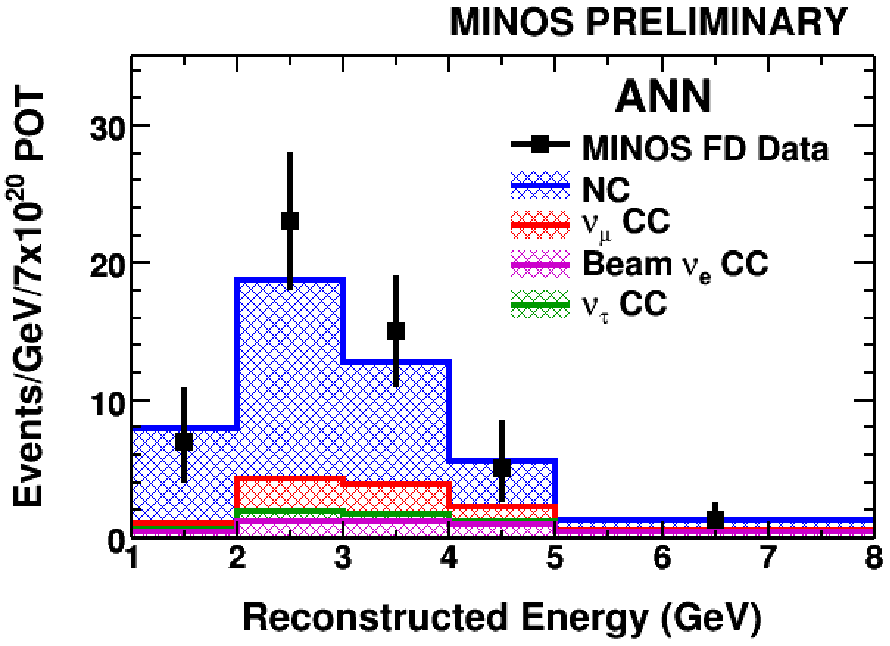




ν_e Appearance Results

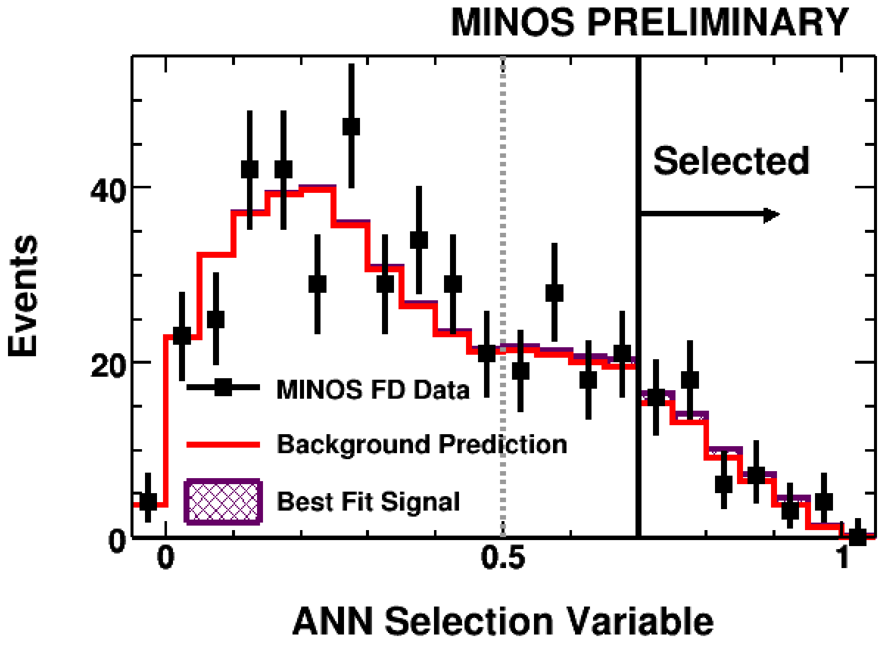
- FD background prediction:
  - **49.1±7(stat)±2.7(sys)**
- Observed:
  - **54**

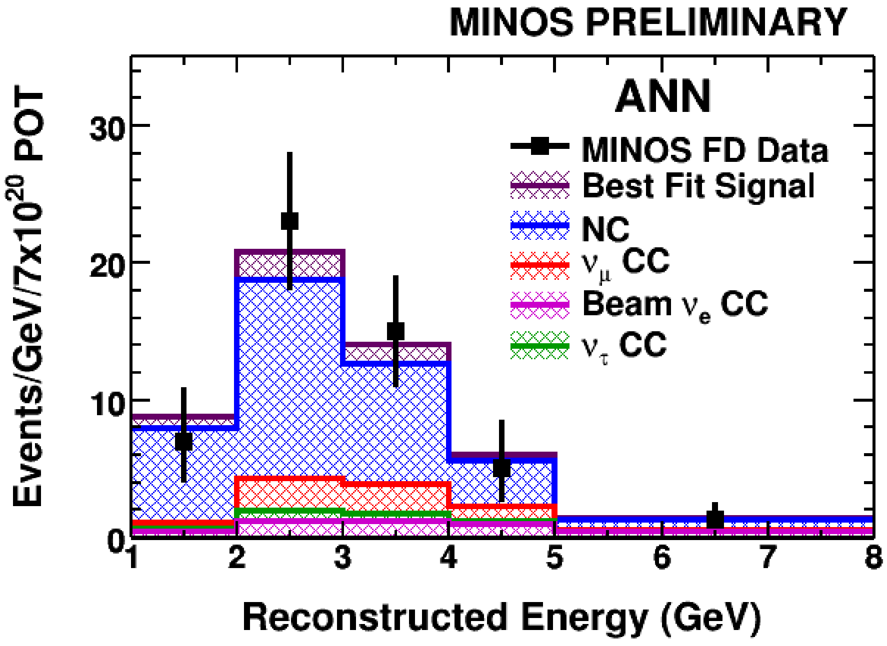




ν_e Appearance Results

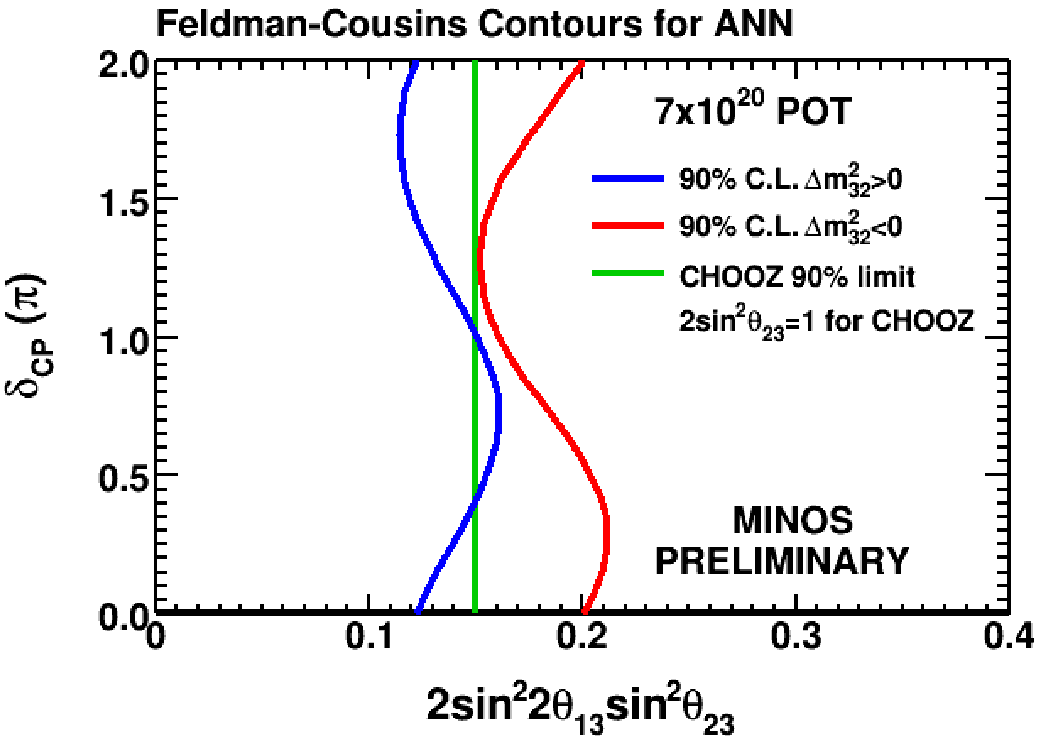
- FD background prediction:
  - **49.1±7(stat)±2.7(sys)**
- Observed:
  - **54** (0.7σ excess)





ν_e Appearance Results

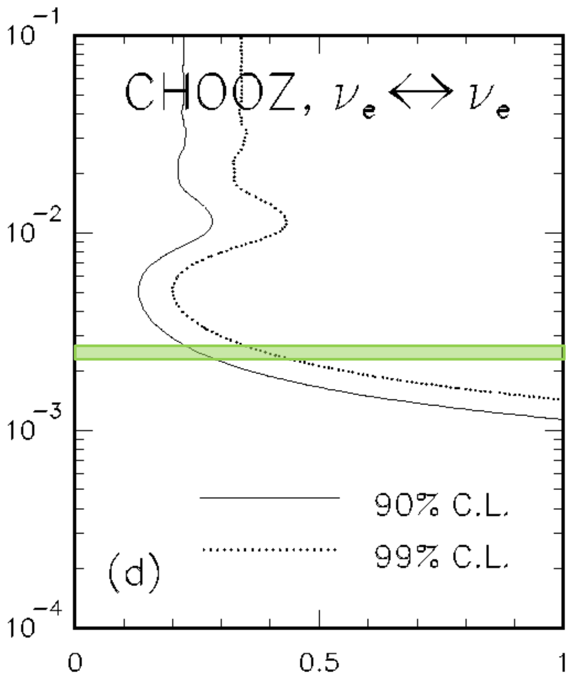
- No significant excess seen, find allowed upper limits using F-C approach
  - For both Normal and Inverted mass hierarchies
  - Normal hierarchy (δCP=0):
    - $\sin^2(2\theta_{13}) < 0.12$ (90% C.L.)
  - Inverted hierarchy (δCP=0):
    - $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)



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

ν_e disappearance

- The next frontier for neutrino experiments:
  - Try to find θ_{13}, since we know the other two θ
- Reactor experiments tackle this problem by getting a “beam” of anti-ν_e and seeing if any go missing
  - Detect the positron from the same reaction as Reines and Cowan used to discover the ν
  - Slightly dependent on atmospheric parameters over the current narrow MINOS bounds
- The Chooz experiment saw nothing, has the current best limit of $\sin^2 2\theta_{13} < 0.17$



ν_e disappearance

- Three experiments are racing to improve on this in the next few years:
  - Double Chooz, Daya Bay, RENO
  - Will be up to an order of magnitude more sensitive with enough time
- But this disappearance is insensitive to CP-violating δ and the neutrino mass hierarchy

ν_e appearance

- How about starting off with no ν_e and seeing if any pop up after some L/E?
  - This isn't simply the converse of the reactor case
- Back to the oscillation approximations we use for ν_μ disappearance:
  - Note that while experimentally θ_{23} is close to $\pi/4$, if it's not exactly $\pi/4$ we can't tell if it's > or <
  - And that "≈" wipes away a lot more terms which result from multiplying out the mixing matrix properly

<u>Useful Approximations:</u>

ν_μ Disappearance (2 flavors):

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

ν_e Appearance:

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

Where L, E are experimentally optimized and θ_{23}, θ_{13}, Δm^2_{32} are to be determined

ν_e appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$\underset{-}{(+)}\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \qquad \Delta = \Delta m^2_{31} L/(4E) \qquad A = \underset{+}{(-)} G_f n_e L/(\sqrt{2}\Delta)$$

Thanks to Greg Pawloski for typesetting this beast!

- Note there are θ_{23} terms that are not squared, introducing sensitivity to $\theta_{23} > \pi/4$ or $< \pi/4$
- CP-violating δ is present
- Matter effects are in there (30% for NOνA!), differ in sign for ν and anti-ν, so a comparison could allow sorting out the mass hierarchy
- But if θ_{13} is near zero, we learn nothing (all terms→0)

So What Might We Learn?

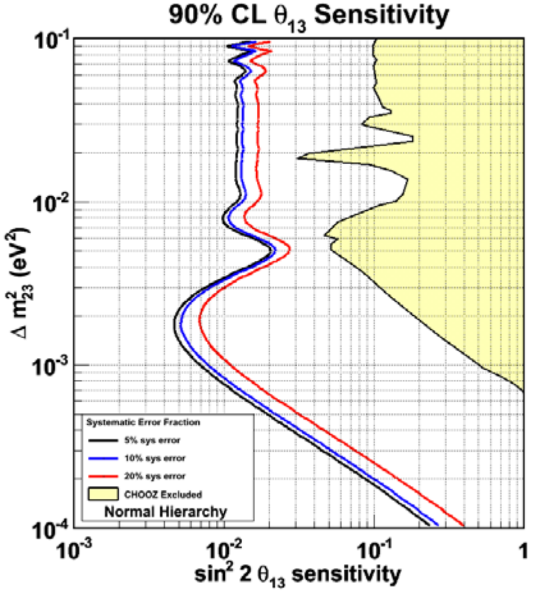
- ⊙ Does the ν_3 mass state have a ν_e component?
  - – Is $\theta_{13} \neq 0$?   (*without which nothing else works*)
- ⊙ Is there CP violation in the lepton sector?
  - – Is $\delta_{CP} \neq 0$?
- ⊙ Is the ν_3 mass state more massive than ν_1 and ν_2 (*normal hierarchy*) or less massive (*inverted hierarchy*)?
  - – Absolute mass values need β and $\beta\beta$ decay experiments to nail down
- Does the ν_3 mass state have a larger ν_μ or ν_τ component?
  - – Is $\theta_{23} \neq \pi/4$?

In my biased opinion, that's 2.5 of the fundamental 4 things
we don't yet know about the standard model, the Higgs mass being the 4th.

T2K

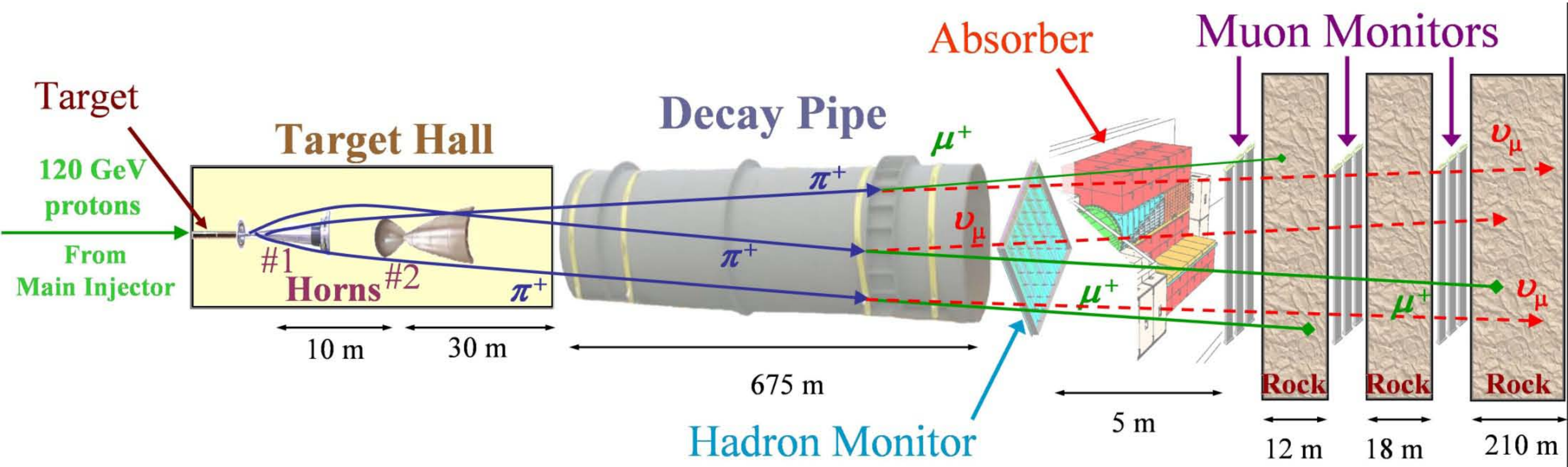
- The first dedicated ν_e long-baseline experiment
  - Uses an off-axis, narrow-band beam
    - 2.5^o off-axis, 600 MeV peak, goal of 750 kW
  - Far Detector is the existing Super-K detector, with its very large mass and good particle ID
  - Operating now at 50 kW, first ν seen in SK in Feb. 2010!
- 0.75MW x 5×10^7sec (=3.75MW$\times10^7$sec)
  - Sensitive to appearance $\sin^2 2\theta_{13}$ down to 0.018 (3σ), 0.008 (90%CL)

Takashi Kobayashi, Neutrino 2010, Athens, June 2010



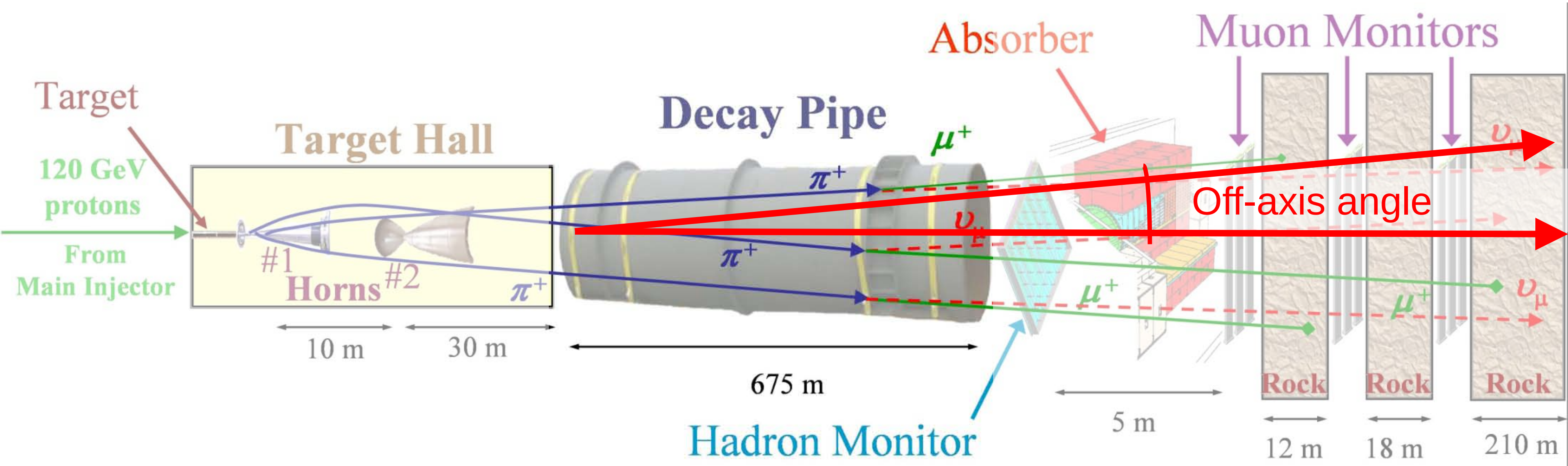
Off-Axis?

- What is this, and how does it help get a narrow-band beam?
- Let’s start with how to make a beam of ν_μ, using the NuMI beam which will supply NOνA:



The pions decay

- Pions decay into like-charge muons and muon neutrinos (here, $\pi^+ \rightarrow \mu^+ + \nu_\mu$)
  - The 675m long, 2m wide, Helium filled decay pipe is a decay length for a 10 GeV pion
  - Viewed from off-axis, pion energy is a function of angle, from π decay kinematics



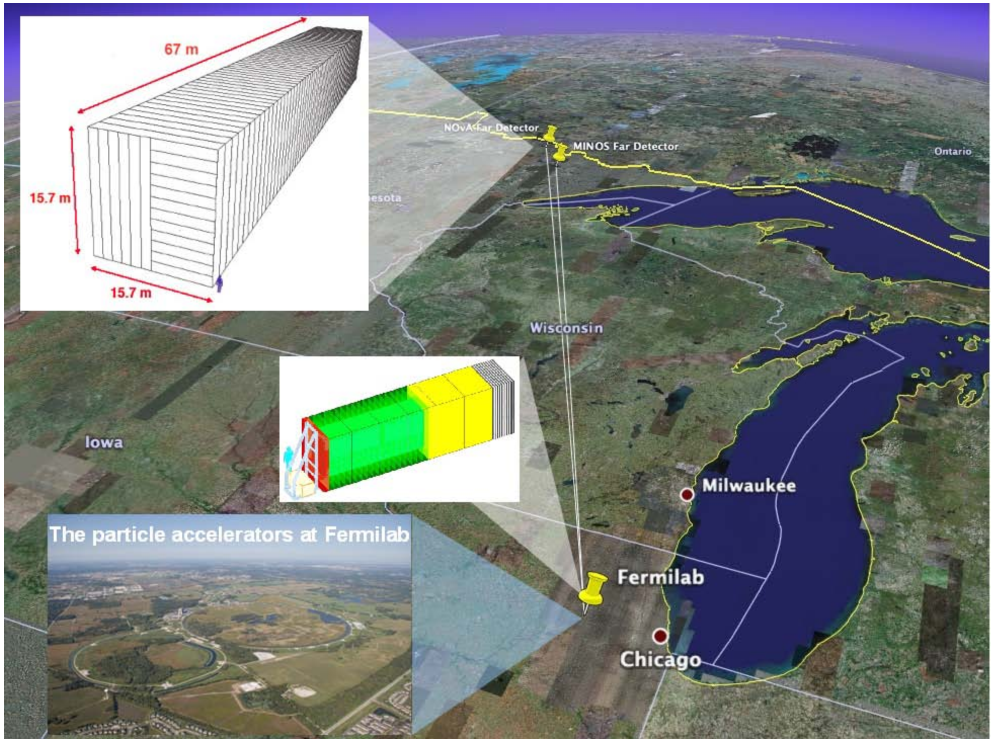
The NOνA Experiment

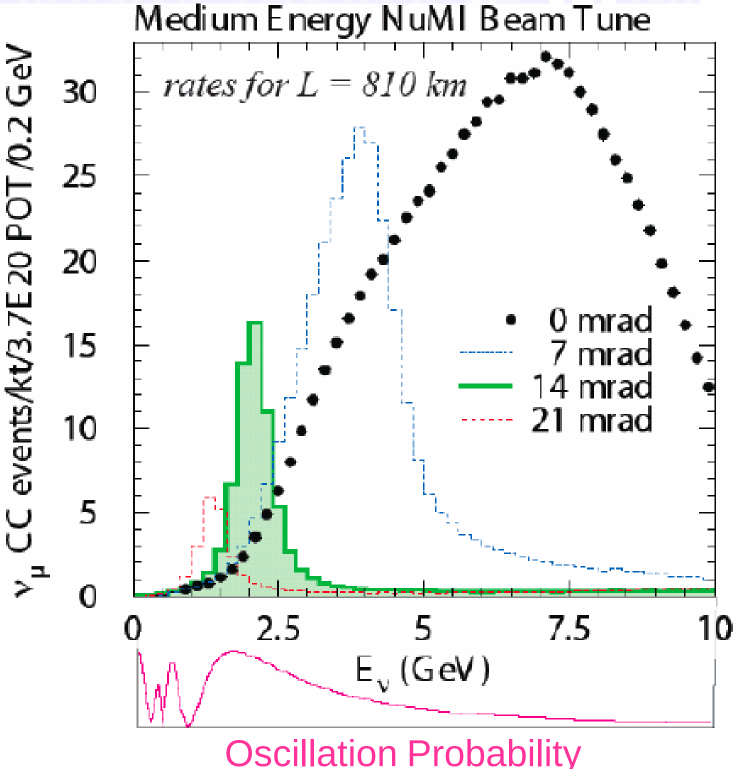
The NuMI Off-axis ν_e Appearance collaboration is 180 Scientists and Engineers from 27 Institutions:

Argonne • Athens • Caltech • UCLA • Fermilab • Harvard
Iowa State • Indiana • Lebedev • Michigan State
Minnesota, Duluth • Minnesota, Minneapolis • INR, Moscow
TU München • SUNY Stony Brook • Northwestern
South Carolina • SMU • Stanford Tennessee • Texas A&M
Texas, Austin • Texas, Dallas • Tufts • Virginia
William and Mary • Wichita State

A narrow-band, long-baseline ν_μ beam

- 810 km away, 14 mrad off-axis, the beam spectra is narrow and at a good L/E for oscillation physics
- Current NuMI beam operates routinely at up to 400 kW
  - NOνA upgrades will put it to 700 kW in 2012 (*NOνA plots*), up to 2.3 MW eventually (*“Project X”*)
  - Plans are to run in both neutrino and anti-neutrino modes



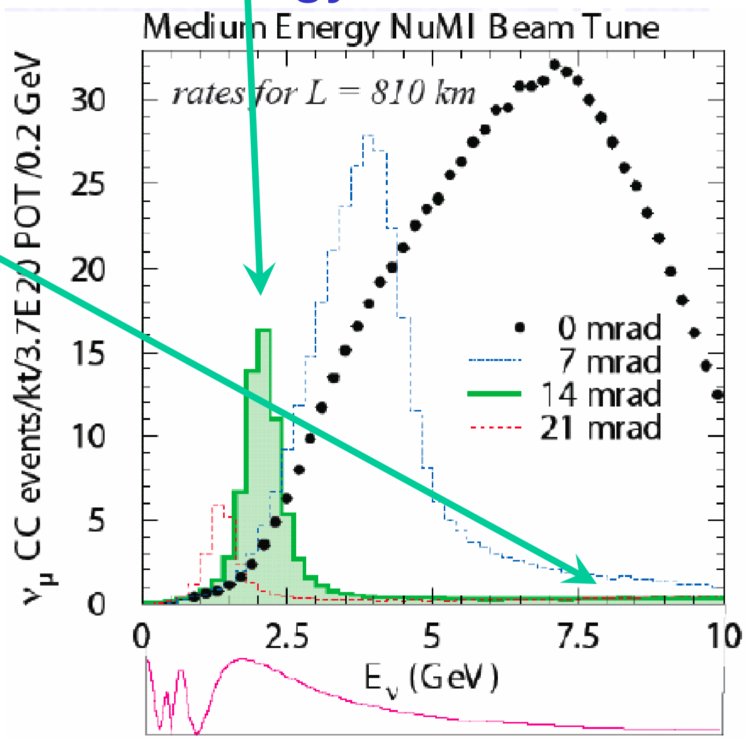


NuMI

MINOS

Narrow? So What?

- This off-axis trick sacrifices intensity for a narrow range in energy. How does this help?
- ν_e charged current interactions from here produce electron showers of about this same energy
- Other interactions (*eg*, neutral currents, hadronic debris from ν_μ interactions) up here produce lower energy showers which can be confused with the ν_e signal
- So, a narrow band beam cuts background



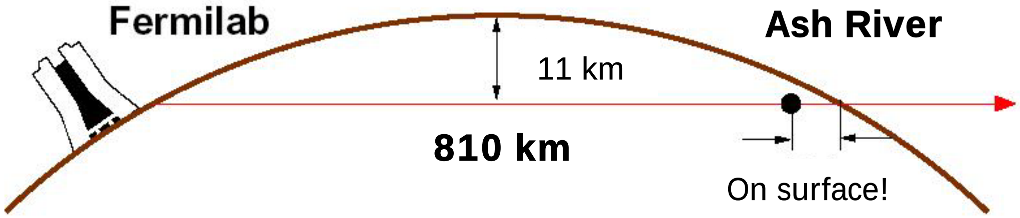
Oscillation Probability

But Why?

- Between the reactor experiments and T2K, won't we know θ_{13} already by the time this fancy beam powers up at 700kW in 2012/13?
  - Perhaps, especially if it's at a large (and interesting!) value, rather than a painfully small one
- So why bother with Yet Another θ_{13} Experiment?

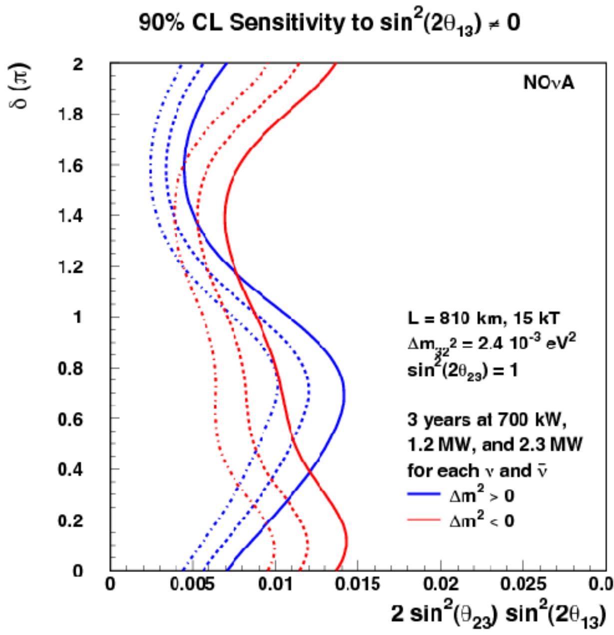
Matter Effects!

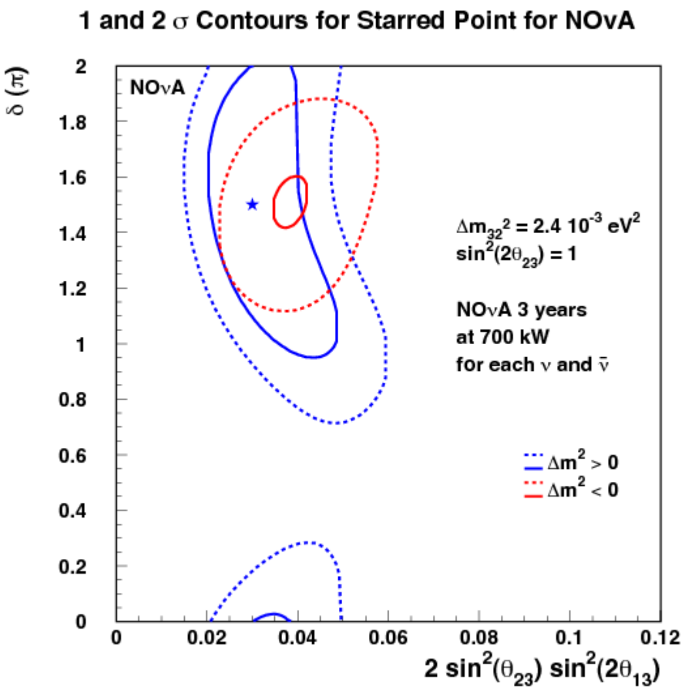
- The longer baseline crosses underground length than the T2K beam, as well as more dense rock due to its depth
  - This enhances any CP-violating delta’s effects
- Comparing T2K and NOνA results with their different beams would allow even further disentangling of the various effects



Projected Sensitivity

- Measuring θ_{13} and δ_{CP}:
  - Sensitivities to θ_{13} comparable to T2K, an order of magnitude better than current experiments
  - Comparing the ν and anti-ν data can close the contours



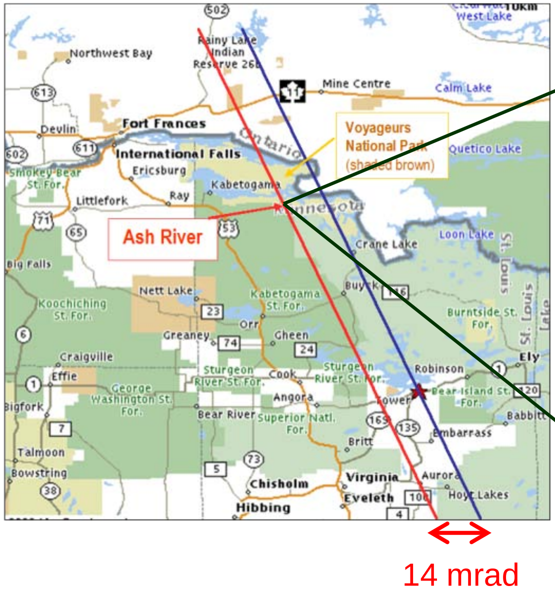


The Detectors

- All this assumes we can reduce systematics by comparing similar Near and Far detectors, like MINOS does
- Plus, going off-axis greatly reduces the total flux, so we need to make up for this intensity by providing as large a target mass as possible
  - And there's no handy mine 810km off-axis, so this large detector must be on the surface
- How do we accomplish this?

Ash River

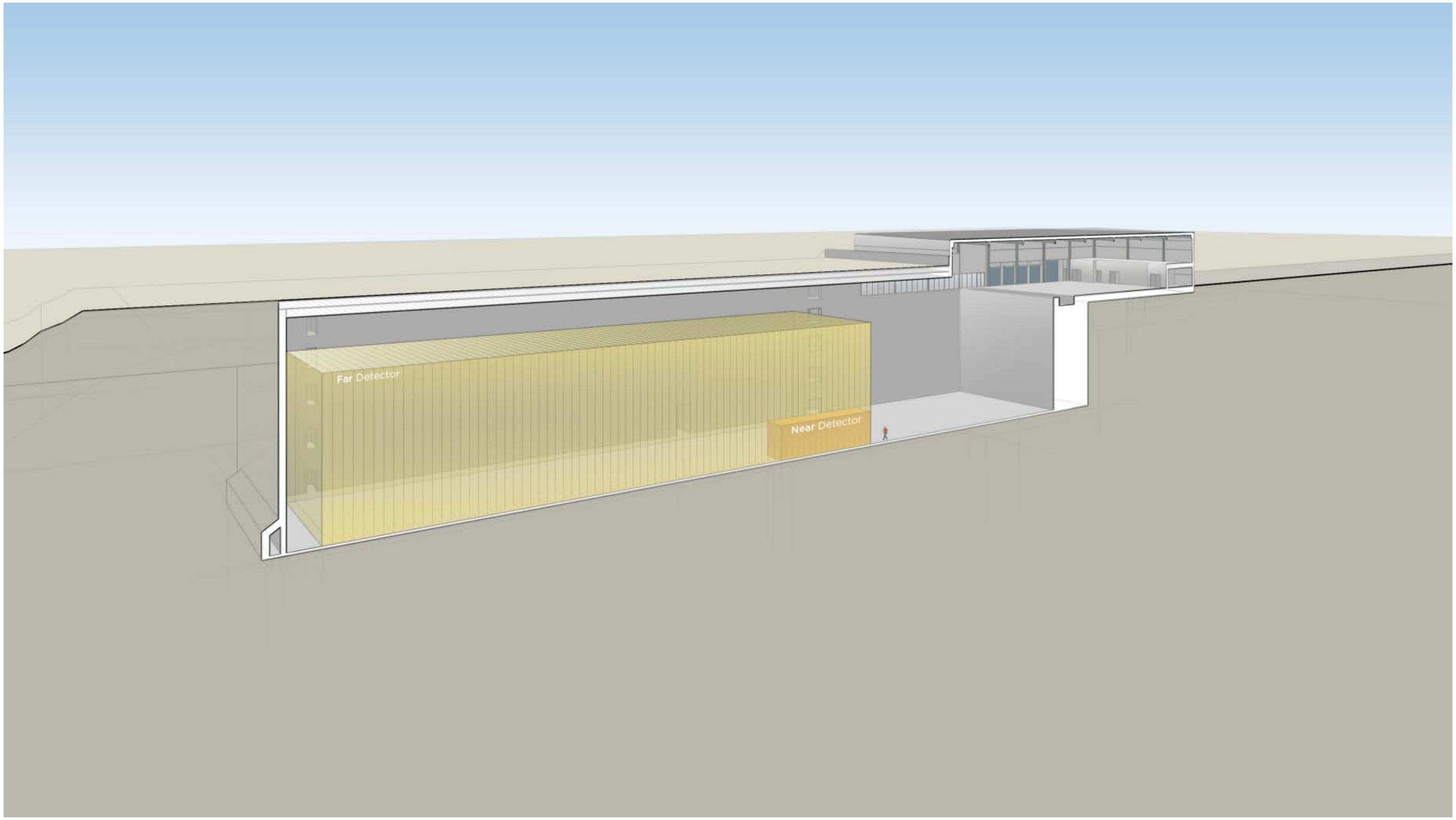
- The NuMI beam's direction is set – so look for the longest baseline available at the appropriate off-axis angle
- A greenfield site on the last road in the US, just across from Voyageurs Natl. Park



NuMI

MINOS

Building

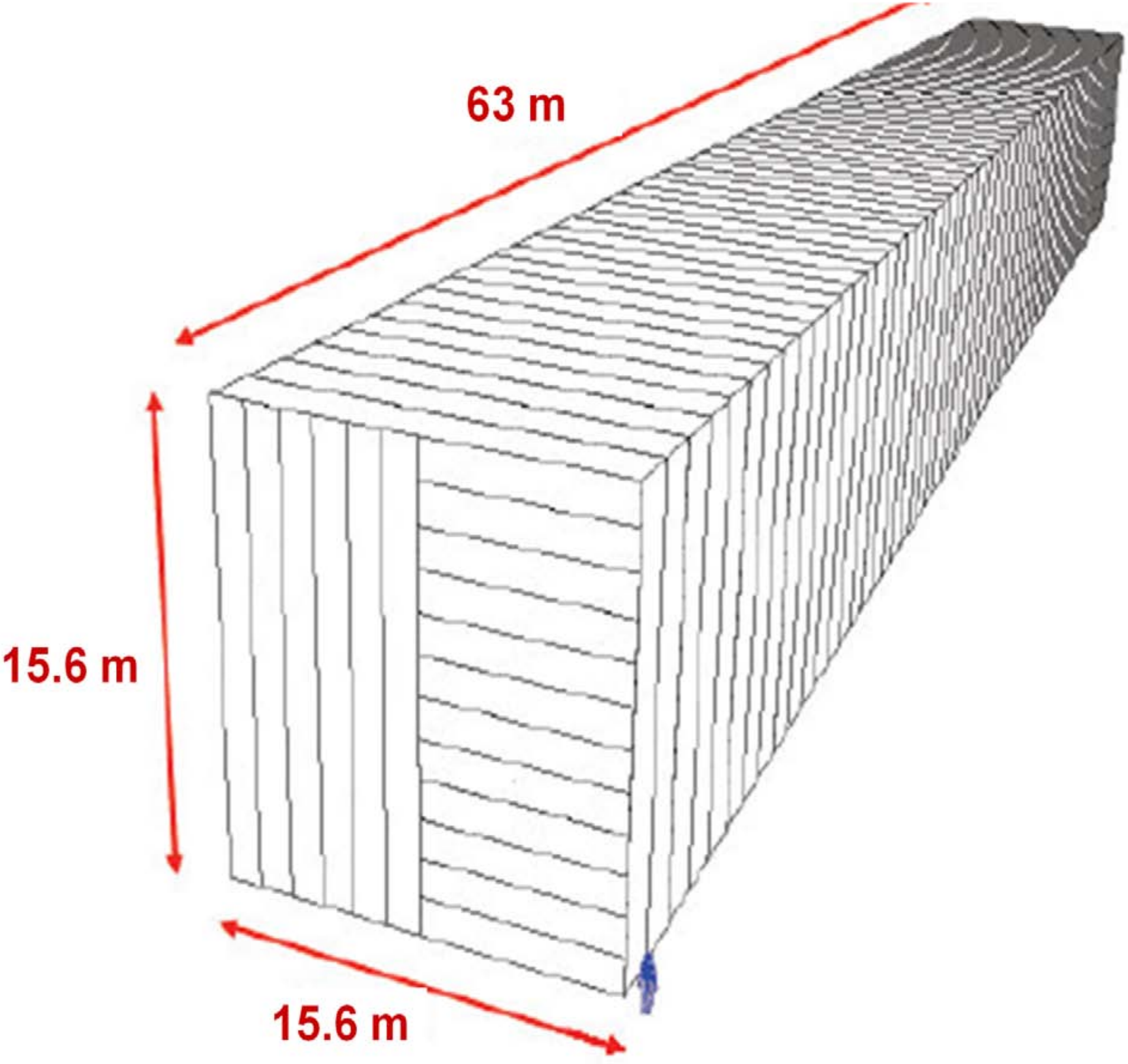


NuMI

MINOS

Far Detector

- That’s big! 14 kt of detector, “totally active” (ok, except for the PVC cell walls).
  - If things don’t go overbudget, we could spend contingency to make it 15kt (67m long)

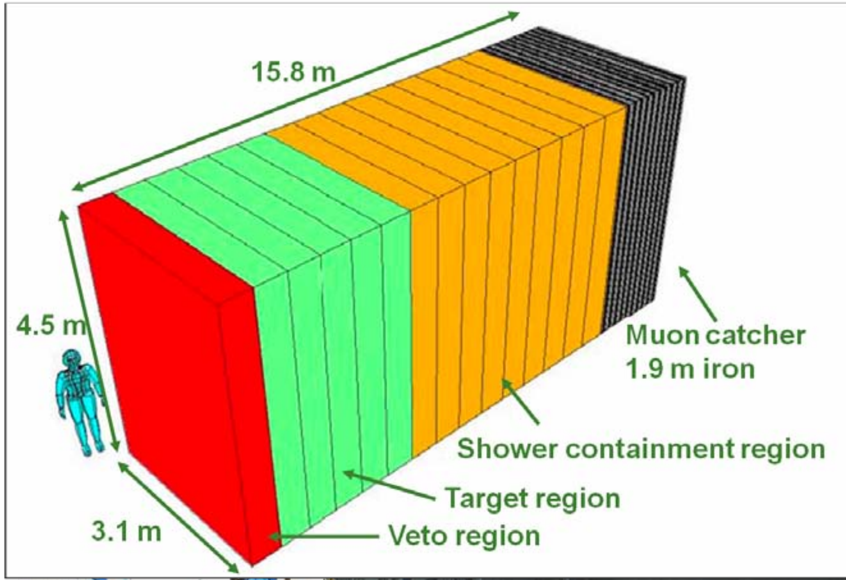


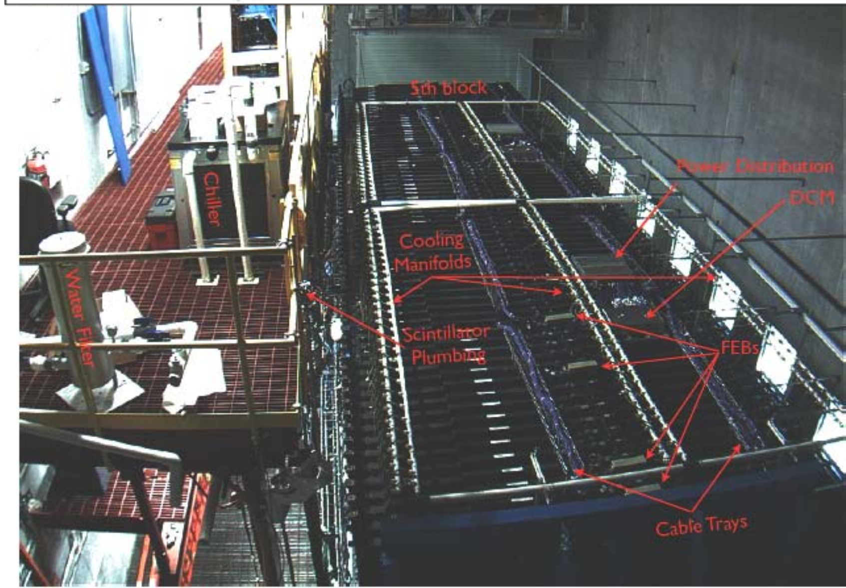
Fun Scales

NOνA in Soldier Field, Chicago (61,500 seat home of the NFL Bears)

Near Detector

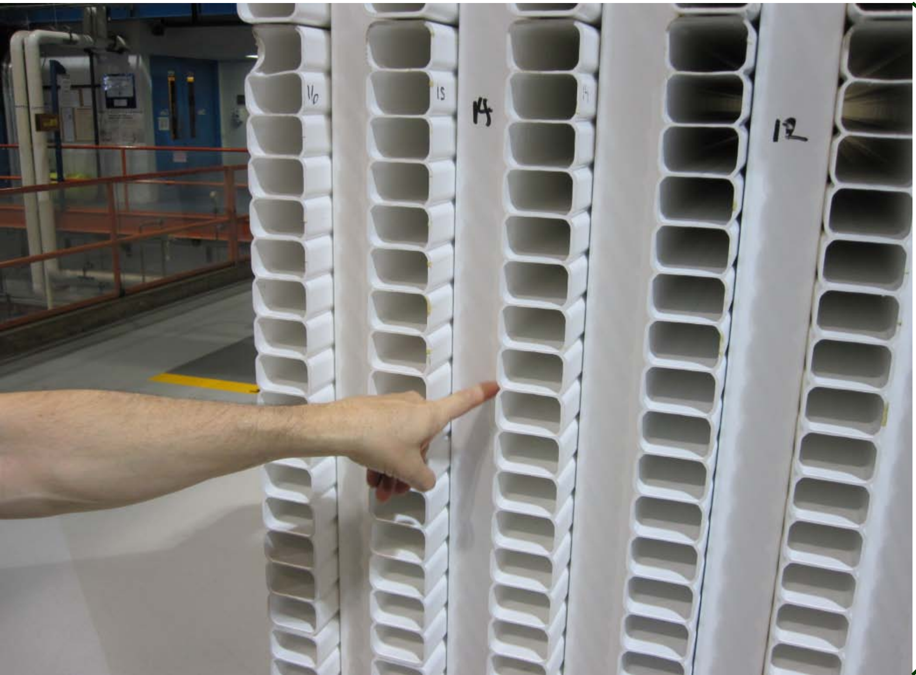
- The Near Detector will watch the NuMI beam at Fermilab from 100m underground, off-axis near the MINOS Near Detector.
  - Being built now on surface as a prototype and beam test through 2011
  - Later moved underground.
  - 225 tons
    (130t totally active, 24t fid.)
  - Blocks are 2 modules wide by 3 modules tall (Ash River is 12x12)

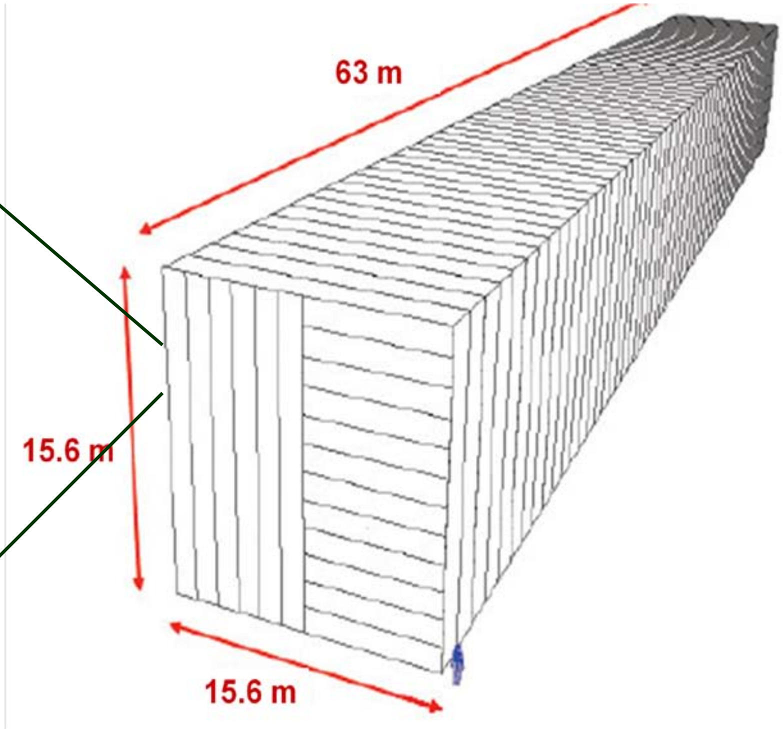




Cells

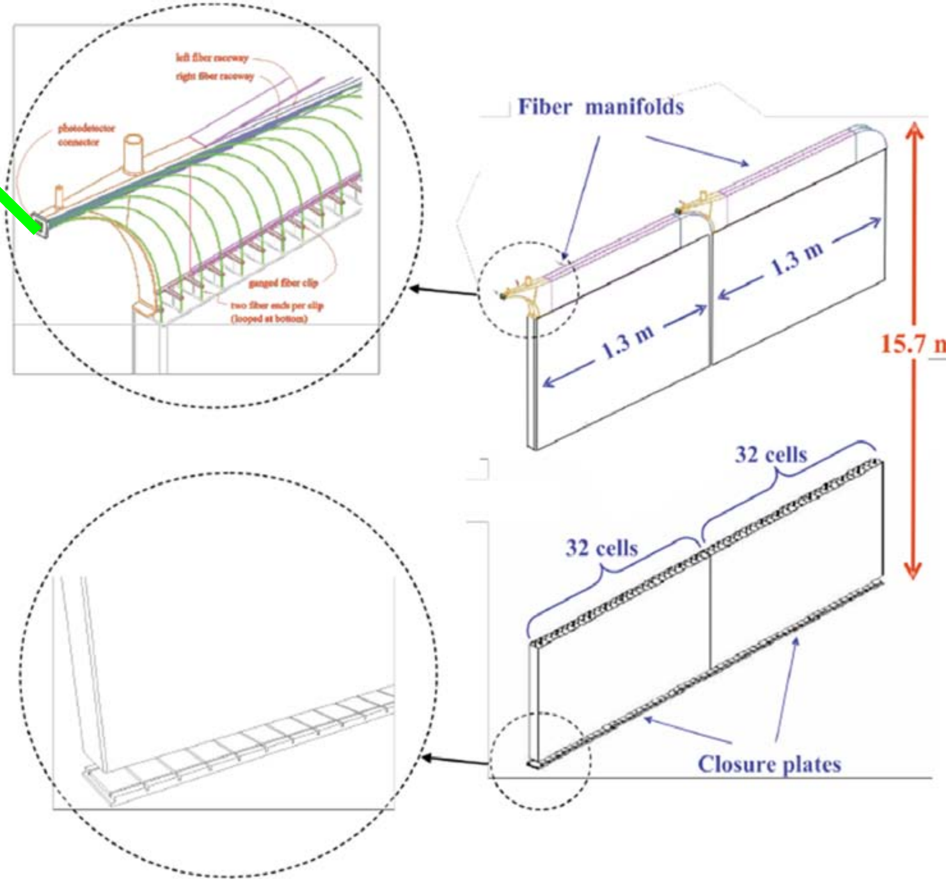
- NOνA composed of highly reflective (15% TiO_2) extruded PVC cells filled with liquid scintillator.
  - Alternating horizontal and vertical layers provide stereo views.

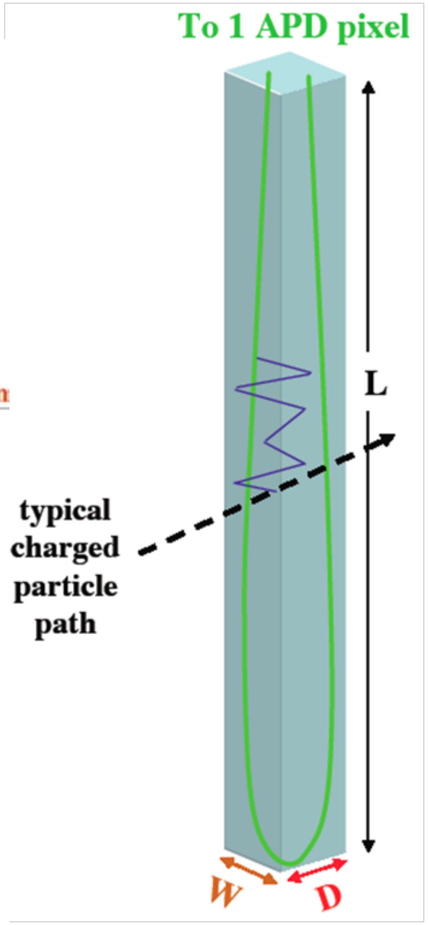




Getting the Light Out

- A loop of wavelength shifting fiber in each cell pipes the scintillation light out to the readout.





Rate and Triggering

- Cosmic Ray data rate for this large surface detector is ~700 MB/s
  - Would need LHC-level data handling
- So to first order, throw away everything that’s not within a beam spill window
  - 10 μs every 1.3 seconds
  - Use GPS timestamps, as does MINOS
  - Cosmics, Supernovae, etc use other trigger schemes

Status and Schedule

- Near Detector On the Surface ("NDOS") coming together now
- Far Detector
  - building done spring 2011
  - assembly underway
  - First 2.5kT operational in winter 2011/12
  - NuMU upgrades 2011-13
  - Complete for full physics in 2013
- Run 3 years each in nu, anti-nu modes

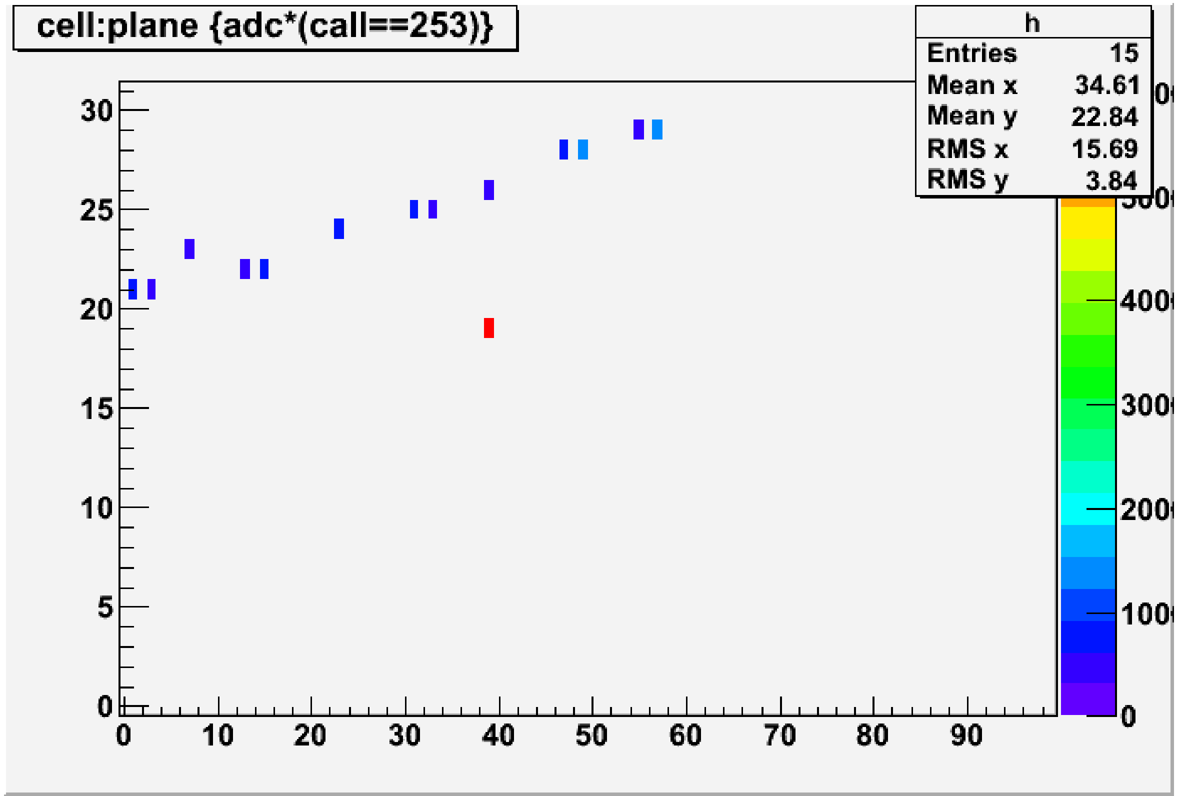
5of 6 blocks
completed
in new building,
filling now!
(4 of 6 filled)

NuMI

MINOS

It works!

- As of this Monday, first cosmic ray event seen during commissioning!
  - Really raw, but hot off the presses



NuMI

MINOS

MINOS Summary

- The first 7×10^{20} POT of NuMI beam data have been analyzed:
  - ν_μ 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 ν_μ disappearance models are disfavored:
    - Neutrino decay: 6.8σ Decoherence: 8.8σ
  - Direct $\overline{\nu}_\mu$ CC measurement shows they oscillate too, perhaps ~2σ differently than ν_μ
  - The Neutral Current data spectrum places limits on sterile neutrino participation, $f_s < 0.22$ (90% c.l.)
  - Negligible 0.7σ excess seen in ν_e appearance channel, improves on the CHOOZ limit
    - $\sin^2(2\theta_{13}) < 0.12$ (90% C.L.) (for normal mass hierarchy, $\delta_{CP}=0$)

This work was supported by the U.S. Department of Energy, the U..K. Science and Technology Facilities Council, and the State and University of Minnesota. We gratefully acknowledge the Minnesota Department of Natural Resources for allowing us to use the facilities of the Soudan Underground Mine State Park.
This researcher was directly supported by NSF RUI grant # 0970111.

NOνA Summary

- NOνA will probe θ_{13} parameter space to an order of magnitude more precision than current knowledge
  - Later that other experiments, but with more sensitivity to δ_{CP} and the sign of θ_{23}
  - Off-axis, long, deep beam enhances matter effects
  - Totally Active Near and Far detectors
- Construction underway
  - Civil at Far site
  - Prototyping/beam test at Near site
- Physics in 2013!

`http://www-nova.fnal.gov`

This research is supported by NSF RUI grant #0970111.
NOνA is funded by the U.S. Department of Energy and National Science Foundation, and the State and University of Minnesota.