Current Status of the MINOS and NOν_eA Experiments

Daniel Cronin-Hennessy

Journal Club

Cornell

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Outline

- Introduction
- Soudan Lab/NuMI
- MINOS detector and results
- NOν_eA Status
- Summary

MINOS

Argonne • Arkansas Tech • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab • Harvard • IIT • Indiana • Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary

NOνA

Argonne • Athens • Caltech • Fermilab • College de France • Harvard • Indiana • Michigan State • Minnesota-Twin Cities • Minnesota-Duluth • Rio de Janeiro • South Carolina • Stanford • Texas A&M • Texas-Austin • Tufts • Virginia • William & Mary

symmetry
A joint Fermilab/SLAC publication
dimensions
of
particle
physics
volume 06
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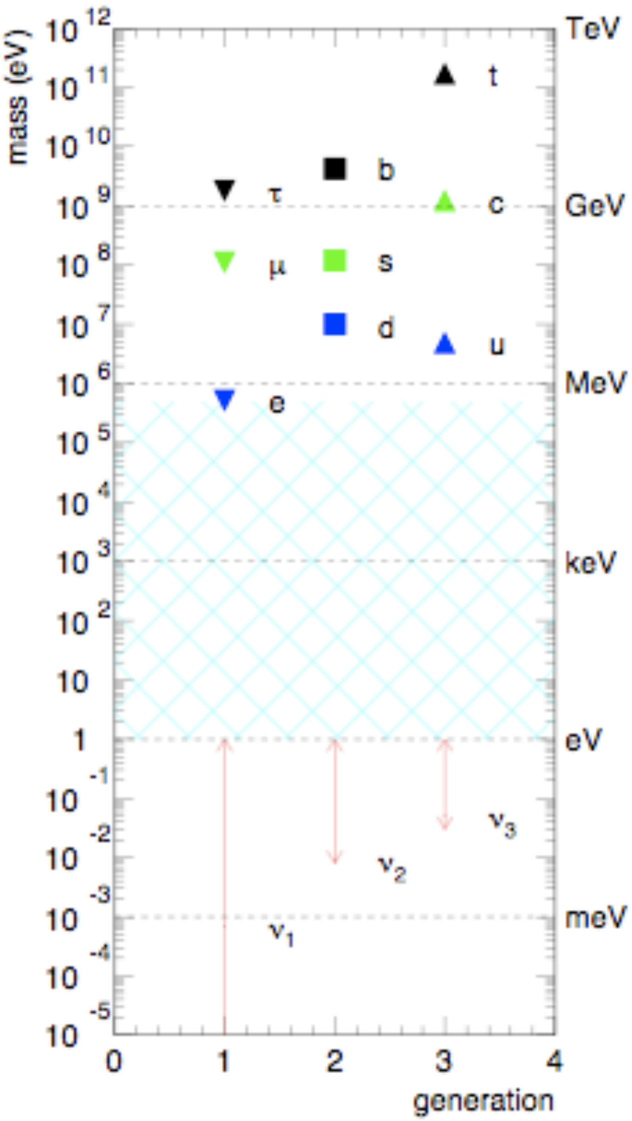
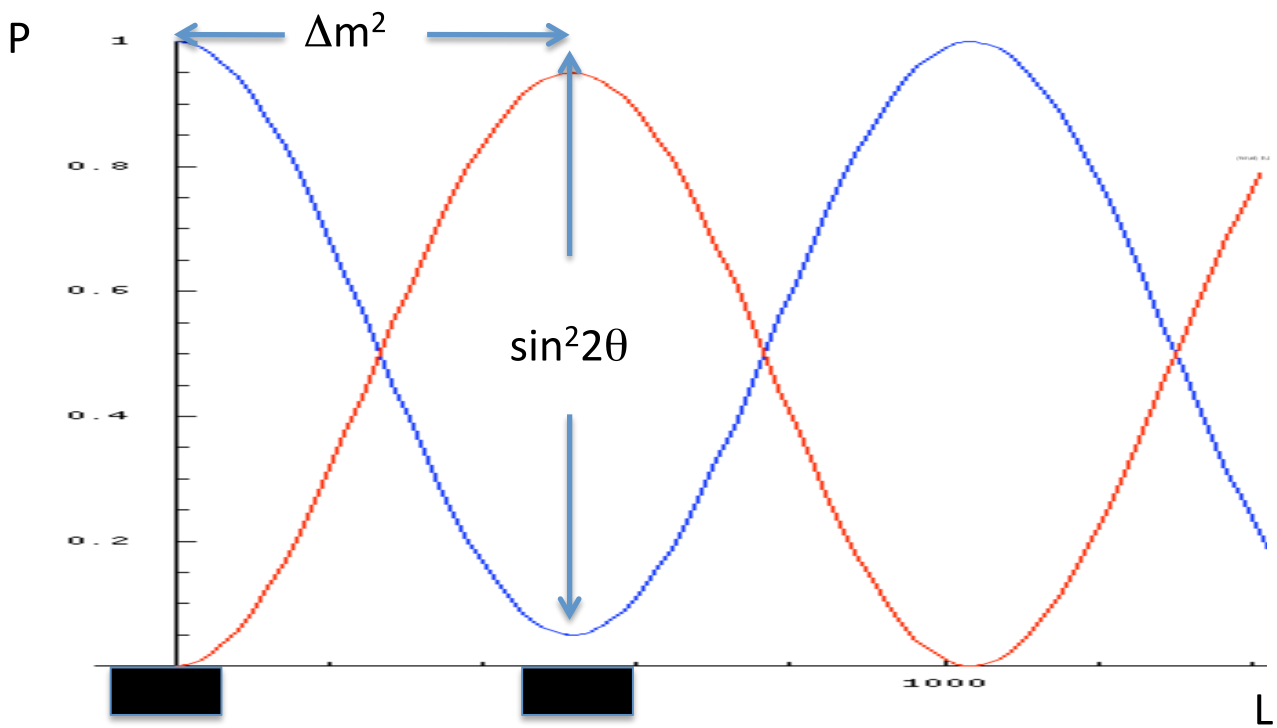
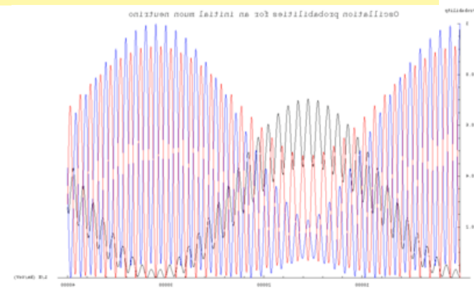
Neutrinos Have Mass



- Neutrino Oscillations: Basic quantum mechanical description of free propagation of a mixed state.
- This is the most simple interpretation of the observations:
  - Solar oscillations ($\nu_e \rightarrow \nu_\mu, \nu_\tau$)
  - Atmospheric ($\nu_\mu \rightarrow \nu_\tau$)
  - Reactor Neutrinos ($\bar{\nu}_e \rightarrow \bar{\nu}_{other}$)
  - Accelerator Neutrinos ($\nu_\mu \rightarrow \nu_{other}$)
- Neutrinos have mass but the masses are not of the same scale as the other fermions.
- We can't help but to ask: Does a different dynamical mechanism govern neutrino mass values?

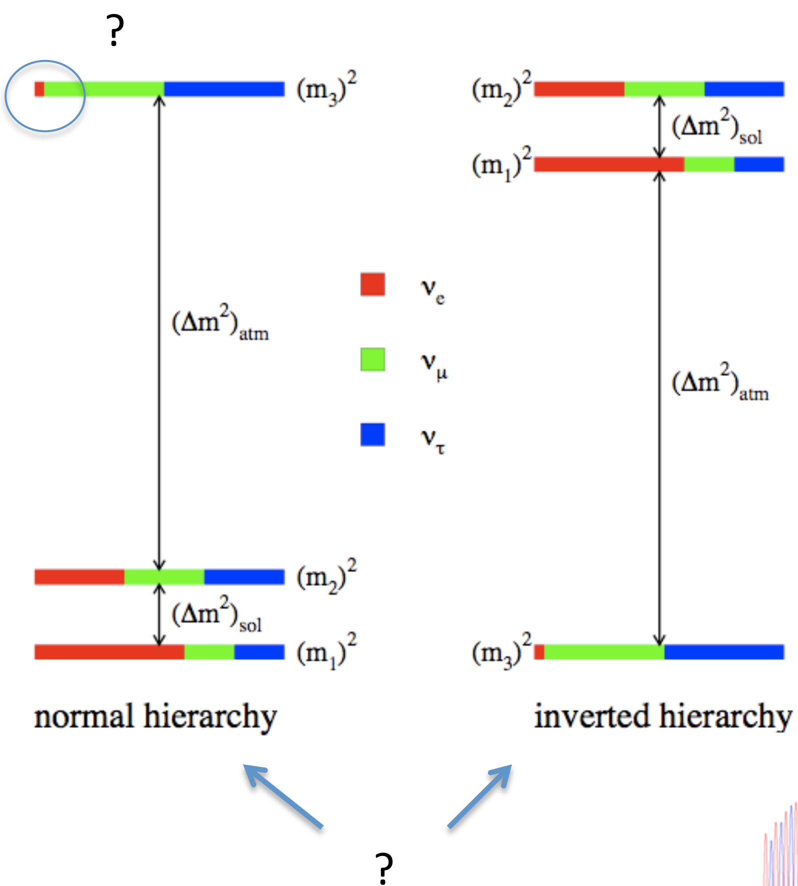
Conceptually Simple





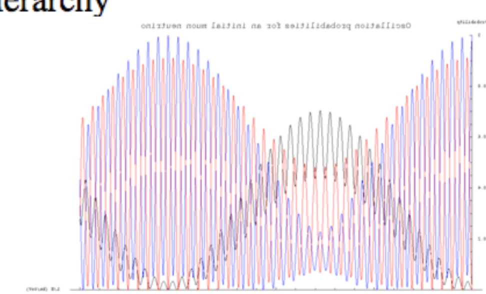
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$

Current Knowledge and Questions

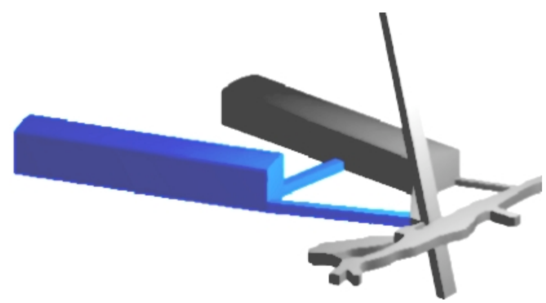


- Two scales of mass-squared differences ($\sim 10^{-3}$ eV^2 and 10^{-5} eV^2)
- $\sin^2 2\theta_{23} \sim 1$ $\sin^2 2\theta_{12} \sim .8$
- $m_2^2 > m_1^2$

- Is $m_3^2 > m_2^2$? (What is the hierarchy?)
- How large $\sin^2\theta_{13}$? (How much ν_e in ν_3?)
- Is θ_{23} > or < $\pi/4$? (Is ν_3 mostly ν_τ or ν_μ?)
- Is δ non-zero? (Do ν and anti-ν oscillate identically? CP violation)
- Are other types of neutrinos involved? ($\nu_{sterile}$)
- Are other mechanisms at work? (ν decay)

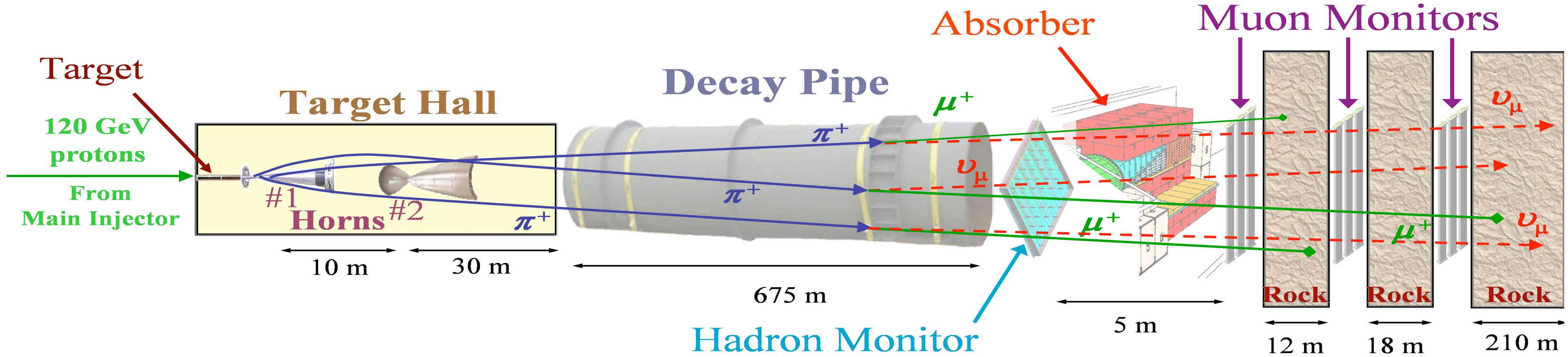


Soudan Underground Laboratory



- Oldest Iron Mine in Minnesota
- Current occupants: MINOS far detector and CDMS II

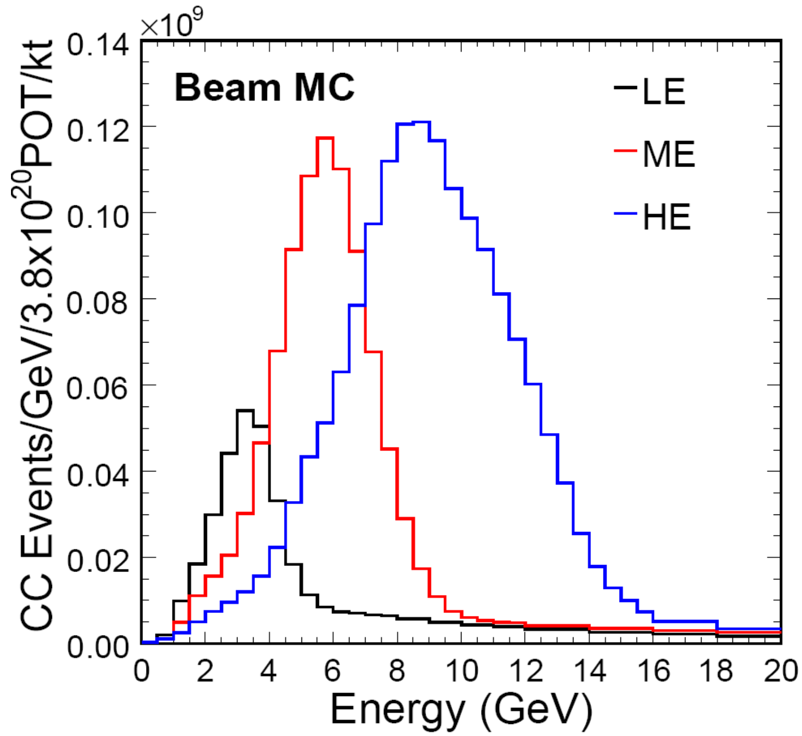
NuMI beam production



- Neutrino beam produced from 120 GeV protons striking a graphite target
  - π and *K* decays produce (LE beam):

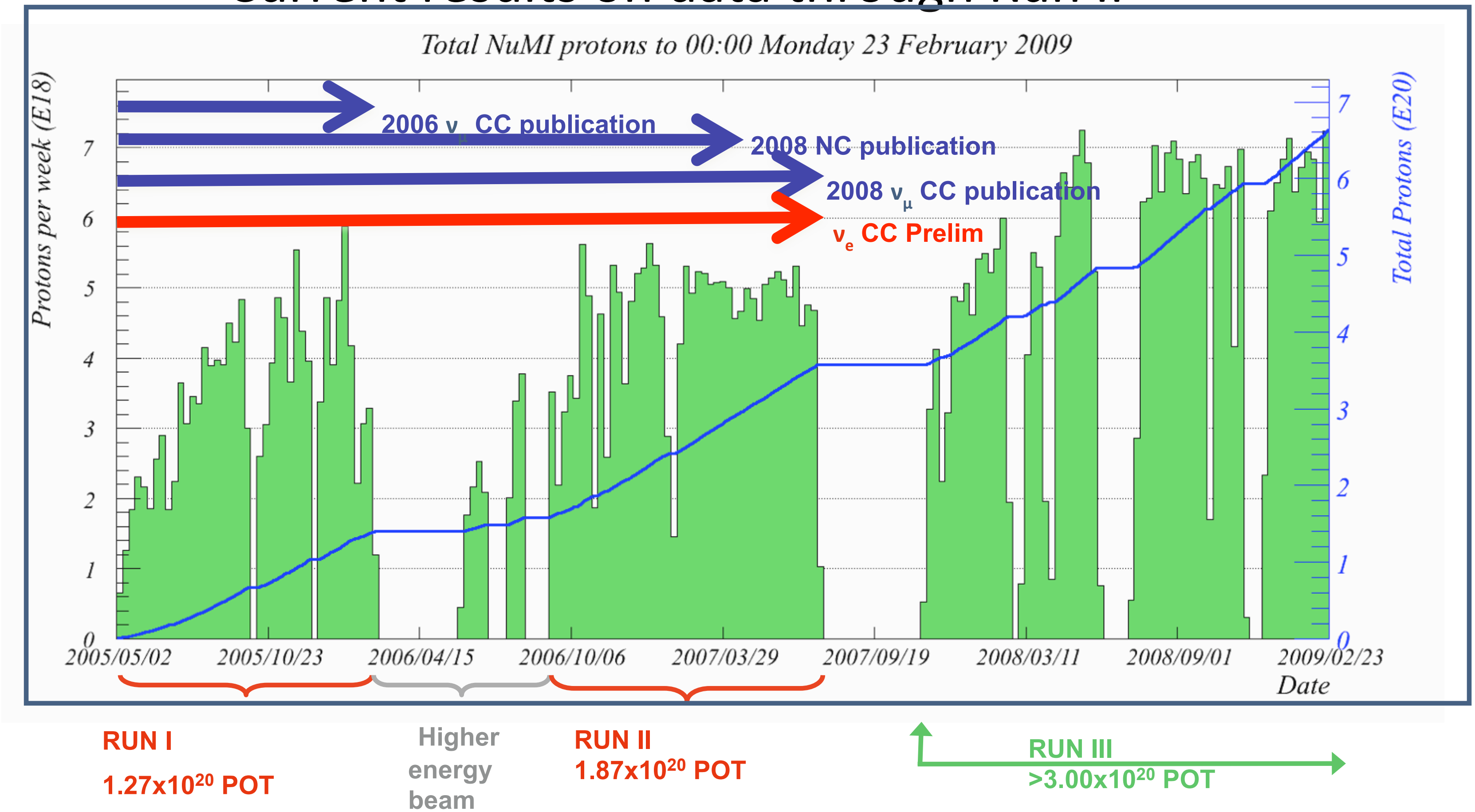
    $$92.9\%\ \nu_\mu\ ,\ 5.8\%\ \overline{\nu}_\mu\ ,\ 1.3\%\ (\overline{\nu}_e + \nu_e)$$
- Beam performance:
  - 10μs spill every 2.2s
  - 2.4×10^{13} POT/spill (Runs 1 & 2) → *3.0×10^{13} (Run 3)*
  - 275 kW beam power
  - $\sim10^{18}$ POTs/day

- Energy tuned by distance between target and 1st horn.



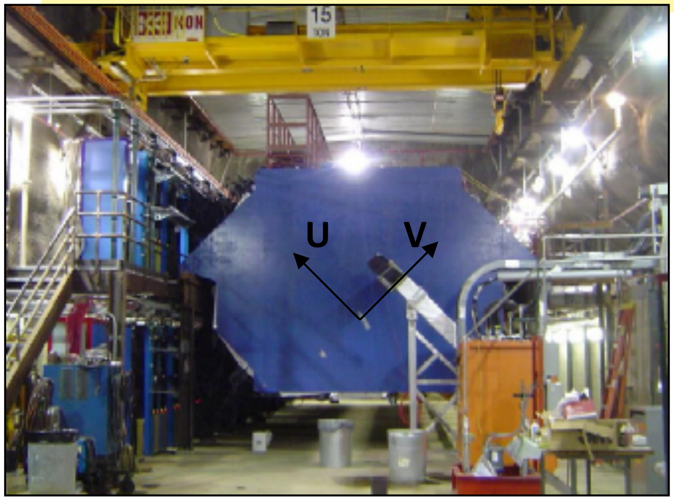
NuMI perfromance

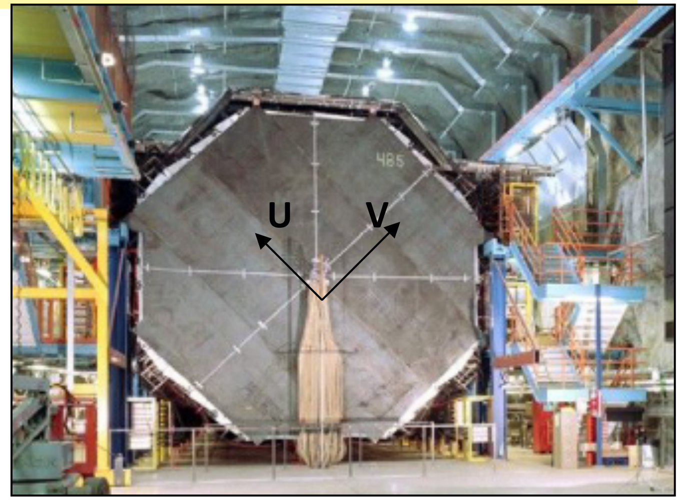
Current results on data through Run II



Results based on Runs I and II: 3.14×10^{20} POT

MINOS Detectors





Near Detector

0.98 kton

1.04 km from target (FNAL)

100 m underground

3.8 × 4.8 × 15 m^3

282 steel planes

153 scintillator planes

Iron and Scintillator tracking calorimeters

(functionally identical detectors)

magnetized steel planes B ≈ 1.2T

Multi-anode PMT readout

GPS time-stamping to synchronize FD data to ND/Beam

Main Injector spill times sent to the FD for a beam trigger

Far Detector

5.4 kton

735.3 km from target (Soudan)

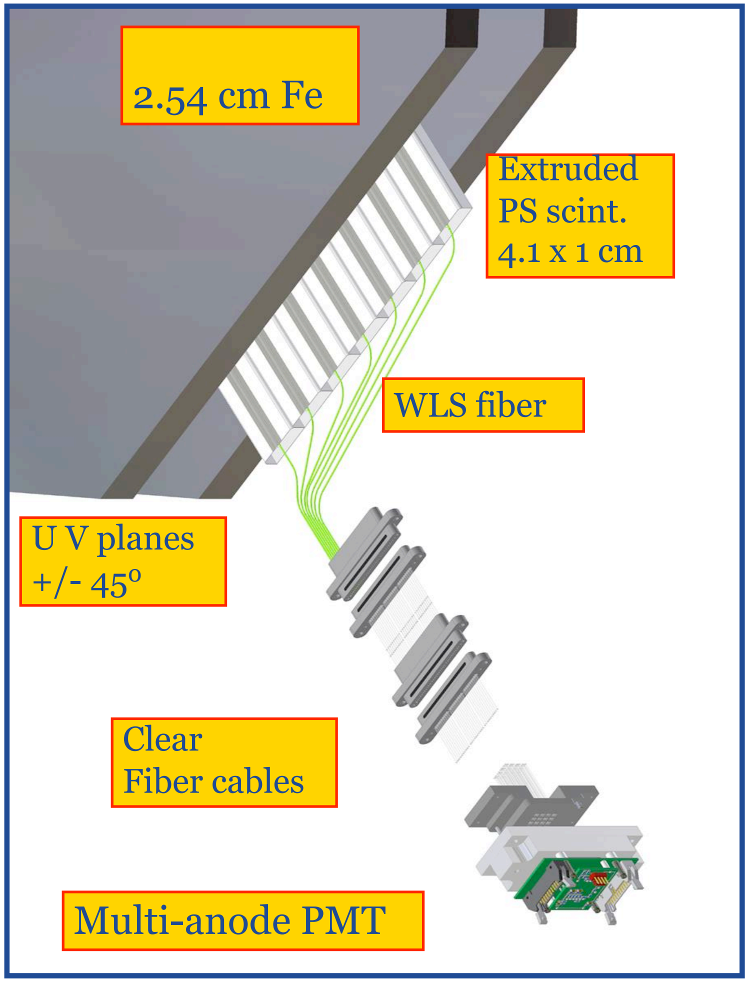
705 m underground

8 × 8 × 30 m^3

486 steel planes

484 scintillator planes

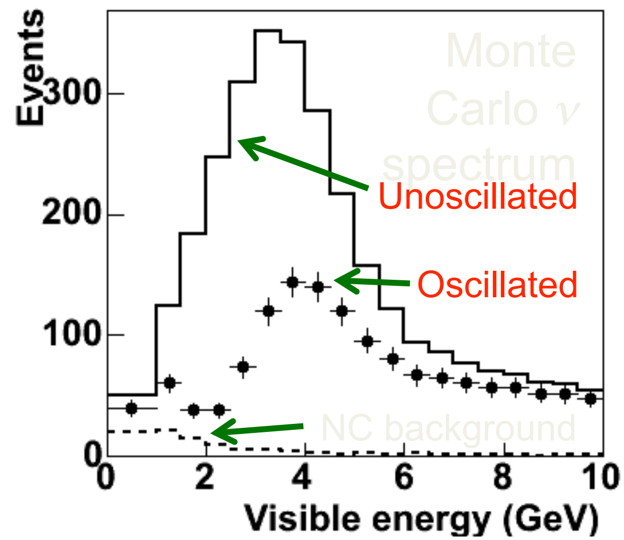
MINOS Technology



- $1 \times 4.1\ cm^2$ scintillator strips
- Multi-anode PMT readout
    - M64 for the ND, M16 for the FD

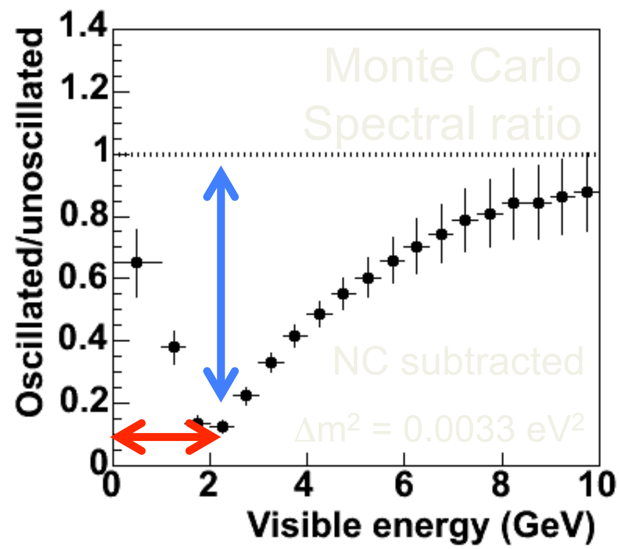
Two-detector ν disappearance

- Produce a high intensity beam of neutrinos at Fermilab
- Measure the energy spectrum at both the near detector & the far detector
- Near spectrum tells you what the far spectrum looks like without oscillation



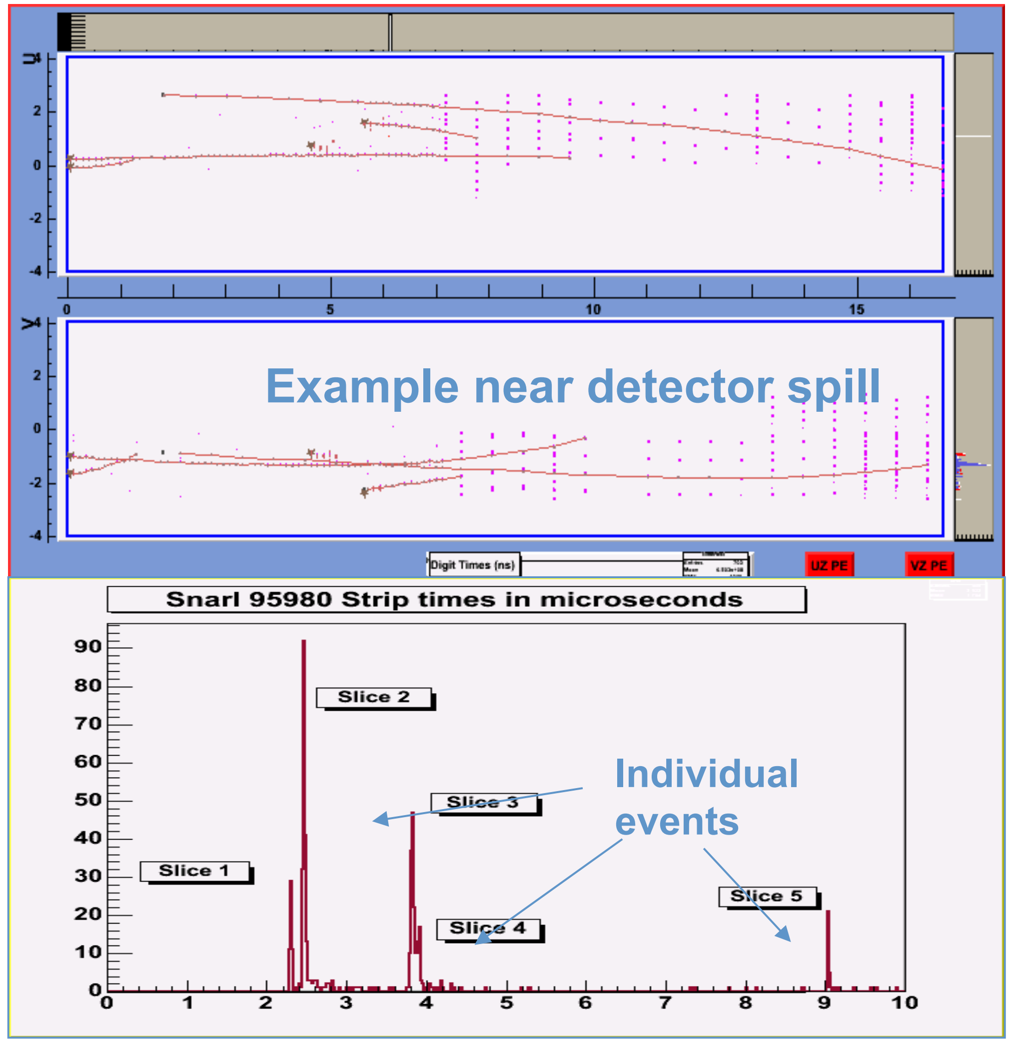
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$

Given L = 735km, oscillation parameters Δm_{23}^2 & $\sin^2 2\theta_{23}$ may be extracted from differences in measured vs. unoscillated energy spectra



Near Detector Events

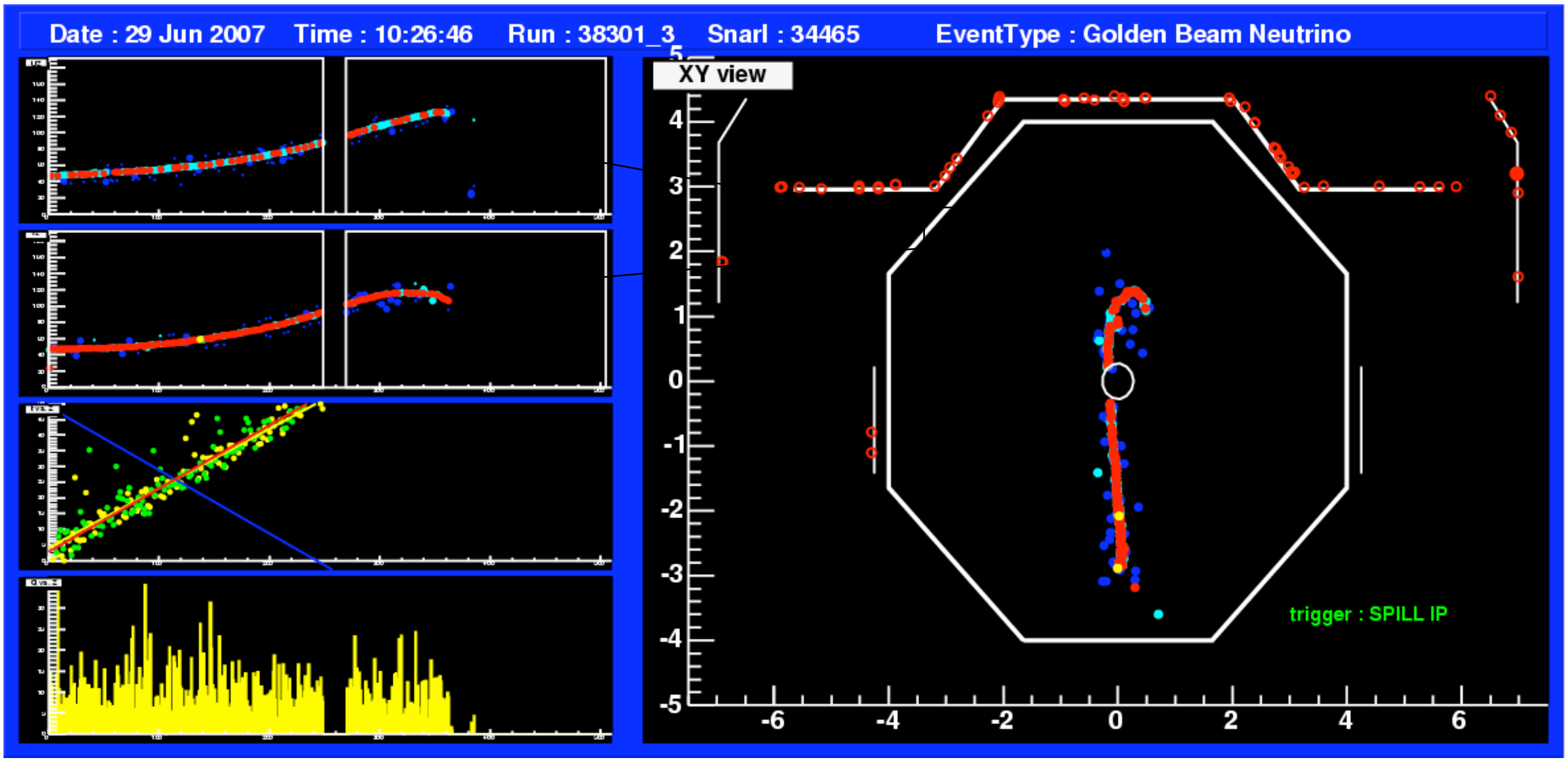
- On average there are 16 interactions per spill in the near detector.
- Events are separated by space and time("slices").



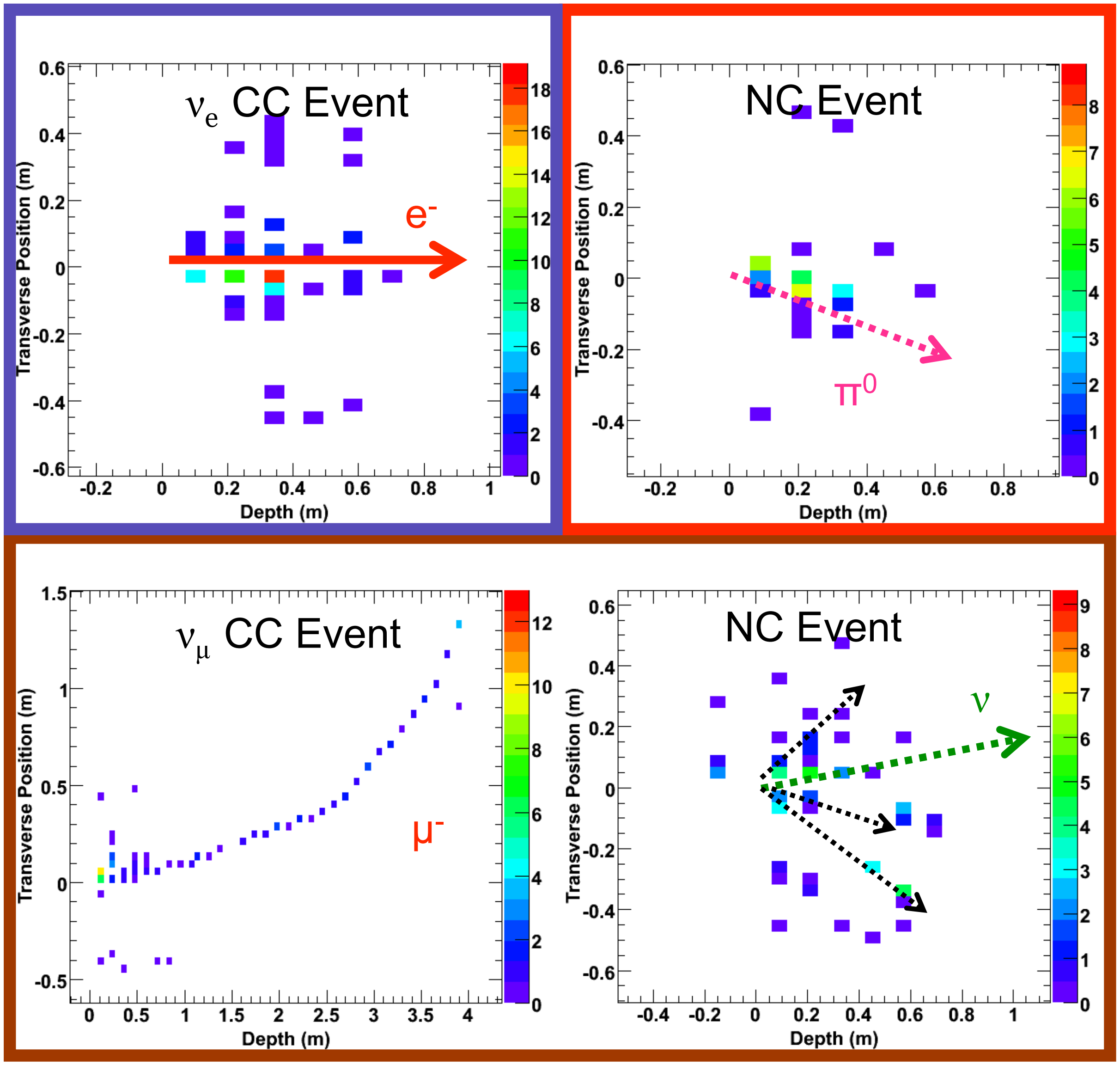
time (μs)

Far detector events

- In the far detector there is 1 event in 10^4 spills.
- Cosmic ray backgrounds are suppressed by direction, rock, and timing.
- Trigger from NuMI (10 μs window every 2.2 sec)

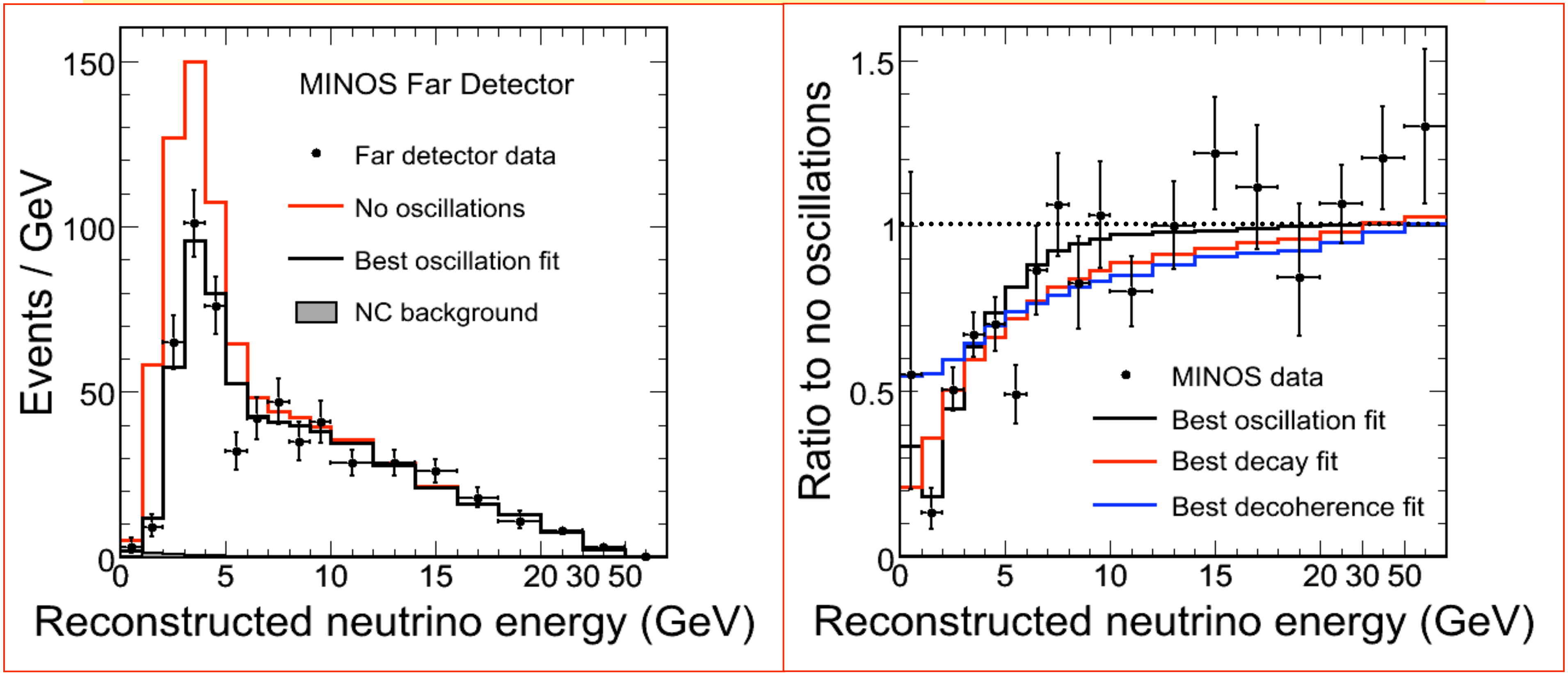


Neutrino Event Topologies



Monte Carlo events

Far Detector ν_μ CC Spectra



- Significant energy-dependent suppression of ν_μ CC events observed
- *Neutrino oscillation favored by 3.7σ over pure decay & 5.7σ over pure decoherence*

81.5% eff, NC contamination is 0.6%, (730 events in oscillation region compared to 936 expected)
Systematics: abs had. energy scale (10.3%), 3.3% unc on N-F extrap.

Result of ν_μ CC Oscillation Fit

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

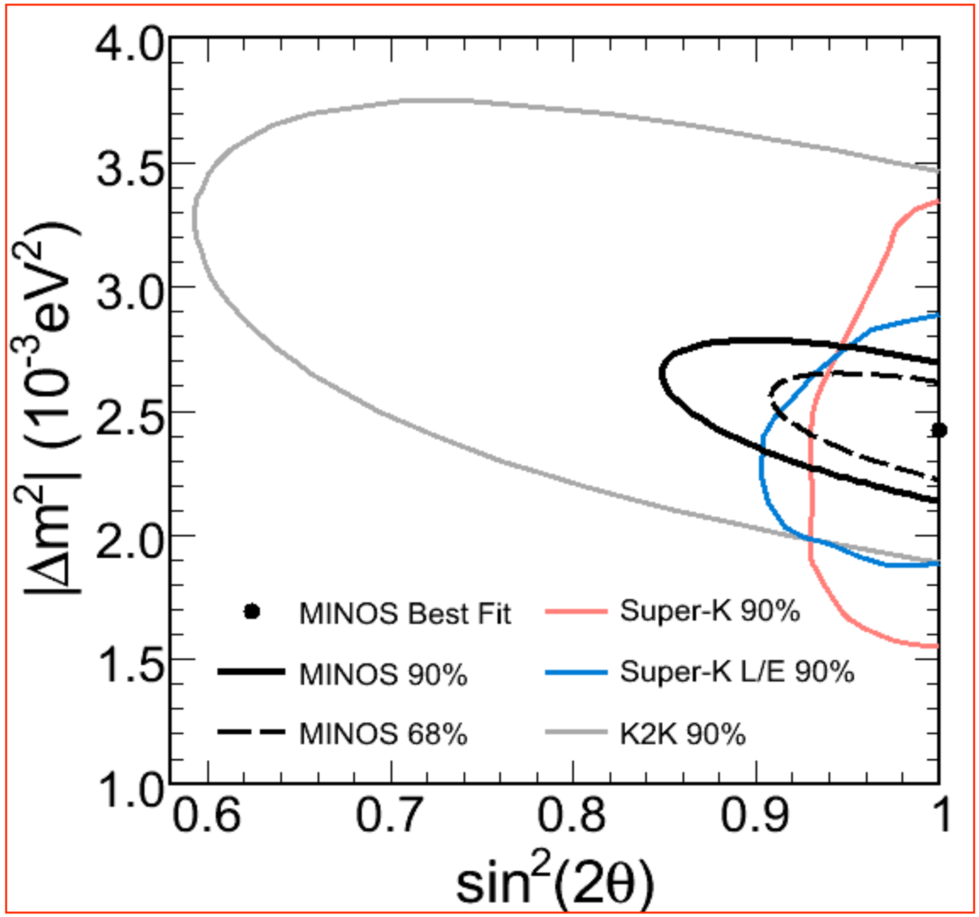
$|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$ (68% c.l.)

$\sin^2 2\theta > 0.90$ (90% c.l.)

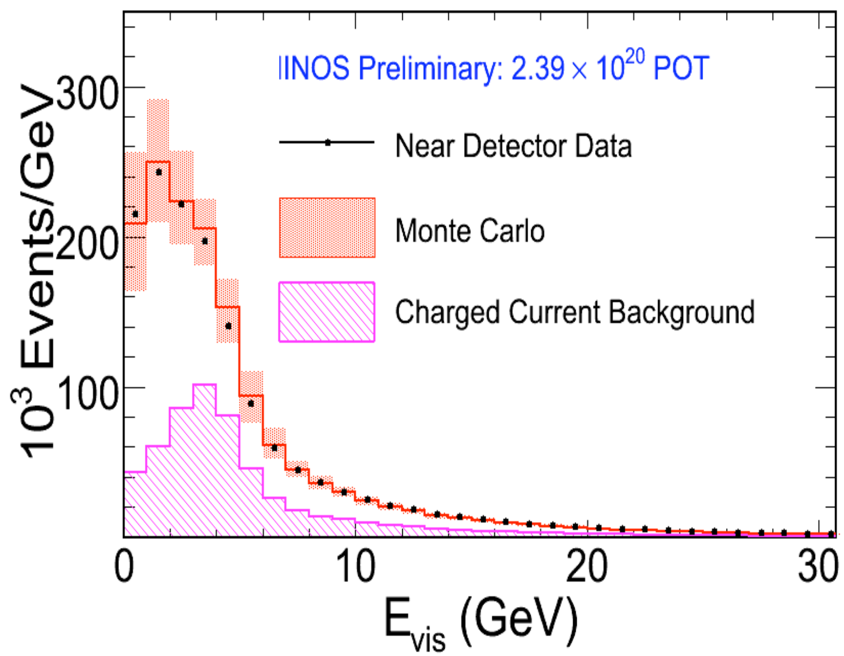
$\chi^2/ndf = 90/97$ (constrained to physical region)

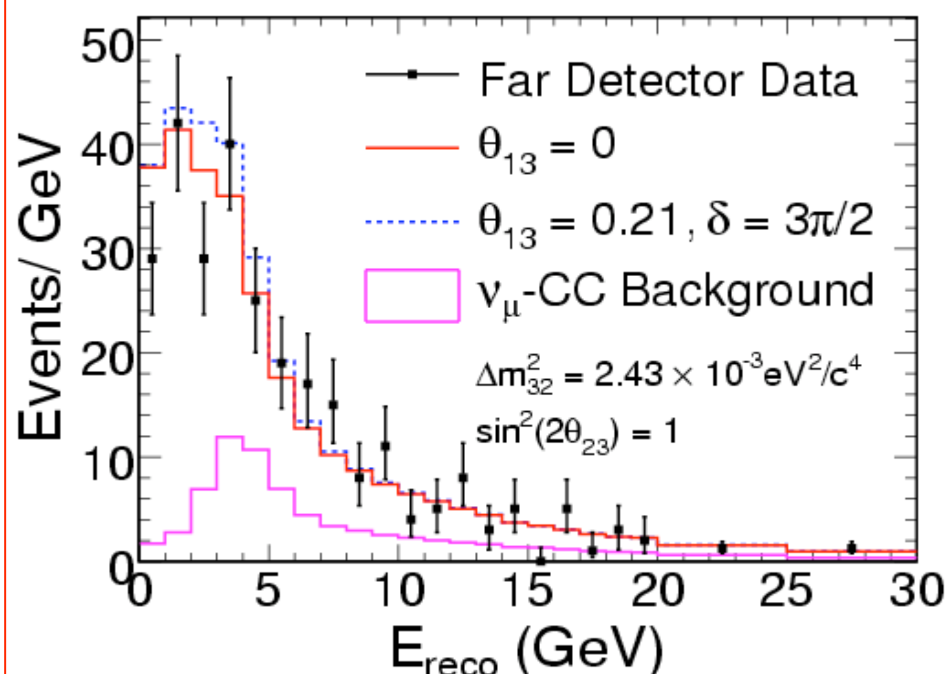
Without constraint $\sin^2 2\theta$ value is 1.07 and $\chi 2$ changes by 0.6.

Physical Review Letters 101 131802 (arXiv:hep-ex/0806.2237)



NC Disappearance/$\nu_{sterile}$ Search





- *Independent* analysis of data through March 2007 (2.46×10^{20} POTs)

$\nu_{sterile}$ NC Analysis Results

- Fit FD spectrum to a 4-neutrino model (3 + 1 sterile) with mixing occurring at one Δm^2

- Oscillation and survival probabilities become:

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

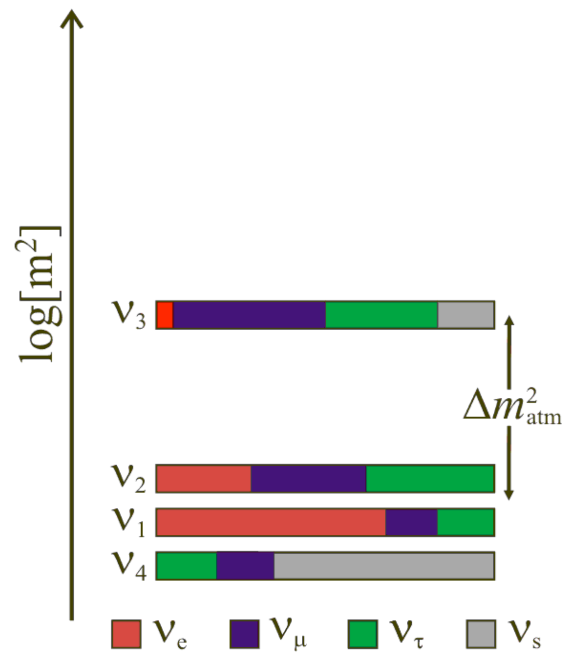
  $P(\nu_\mu \rightarrow \nu_s) = \alpha_s \sin^2(1.27\ \Delta m^2\ L/E)$

- Simultaneous fit to CC & NC energy spectra performed:

  $\boldsymbol{f_s = P(\nu_\mu \rightarrow \nu_s)/[1-P(\nu_\mu \rightarrow \nu_\mu)] = 0.28^{+0.25}_{-0.28}}$ (stat+sys)

  $f_s < 0.68$ *(90% c.l.)*

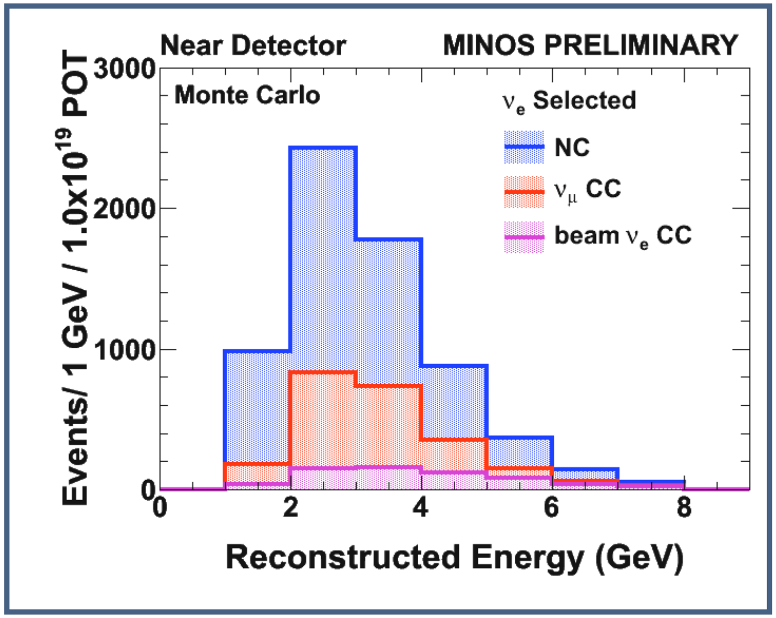
Physical Review Letters 101 221804
(arXiv:hep-ex/0807.2424)

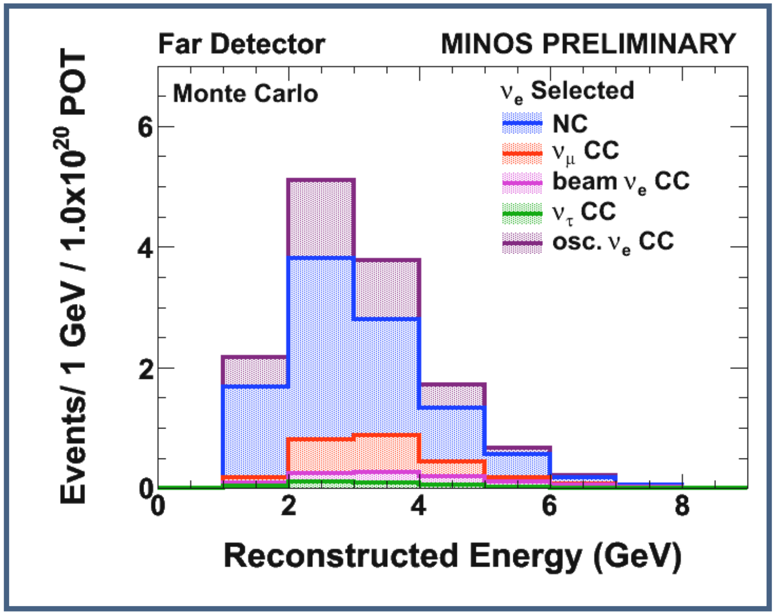


ν_e Appearance in MINOS

- For an appearance measurement there is no signal to extrapolate to the Far Detector.
- However MINOS, dominated by non-active material, is not ideal for electron identification. Backgrounds are substantial. Our background is measured in the near detector and extrapolated to the far detector.
- NC and μ-CC are significant backgrounds. There is also an intrinsic ν_e component to the beam. The energy distribution for the intrinsic ν_e is quite different.
- This is a challenging measurement but simulation suggested that we could expect a limit a little below the existing Chooz limit (on average).
- So we looked.

ν_e Appearance in MINOS





- When selecting ν_e event candidates in the Near Detector we will have a mix of components that do not extrapolate in the same way to the Far Detector.
- Simply extrapolate NC
- ν_μ CC must be oscillated out of the far detector spectrum
- ν_τ CC must be oscillated into the far detector spectrum.
- Then look for the ν_e excess arising from ν_μ to ν_e oscillations in the Far Detector.

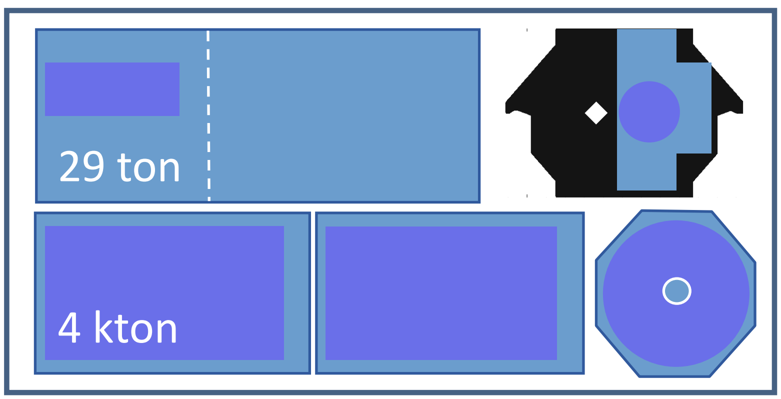
Basic Data Quality Cuts

– Beam quality and detector quality cuts.

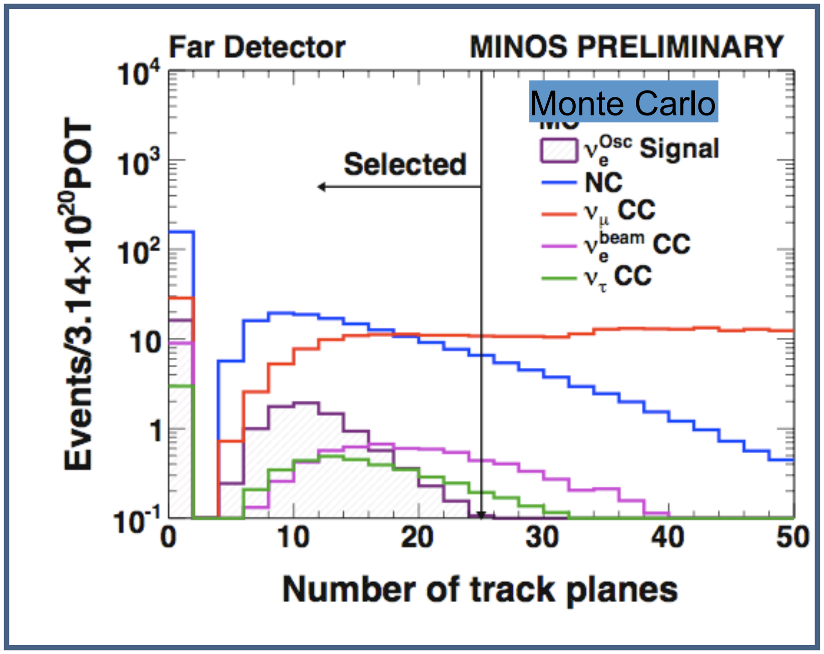
– Fiducial volume cuts:

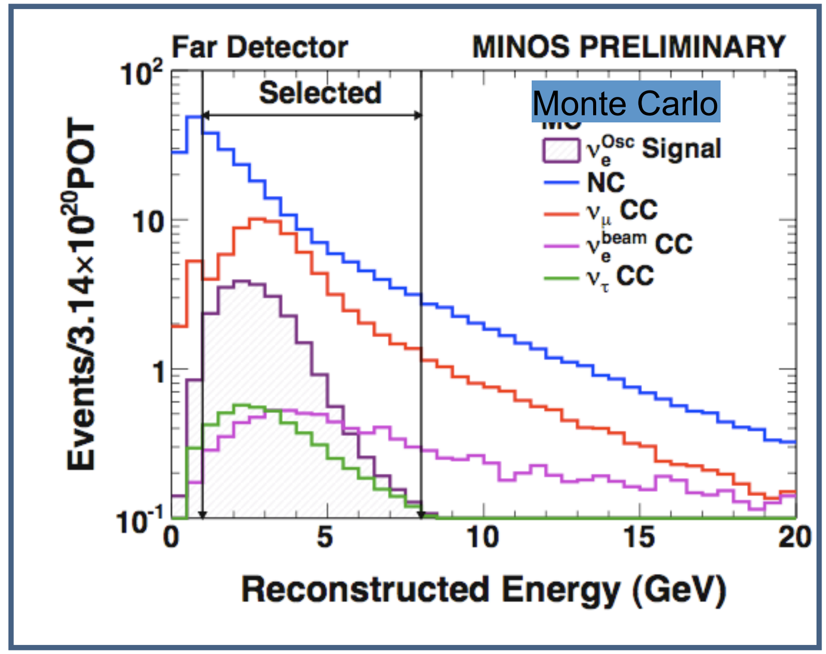
- Near Detector:
  1m < z < 5m , r < 0.8m
- Far Detector:
  0.5 m < z < 14.3 or 16.3m < z < 28m,
  0.5m < r < 3.7m

– Cosmic rejection cuts based on steepness.



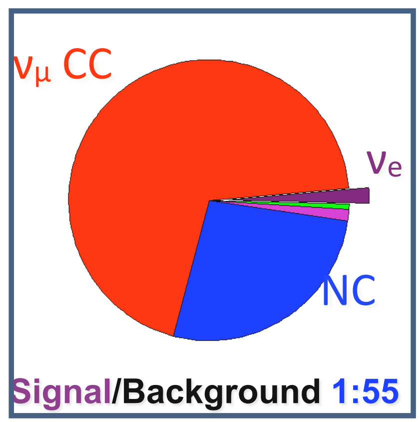
ν_e Preselection Cuts



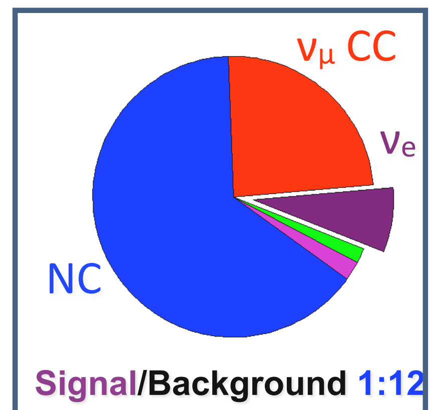


signal at CHOOZ limit

- Preselection requirements:
  - Track length < 25 planes.
  - Reconstructed energy 1-8 GeV.
  - At least one shower and 4 contiguous planes with > 0.5 MIP energy units.



Before

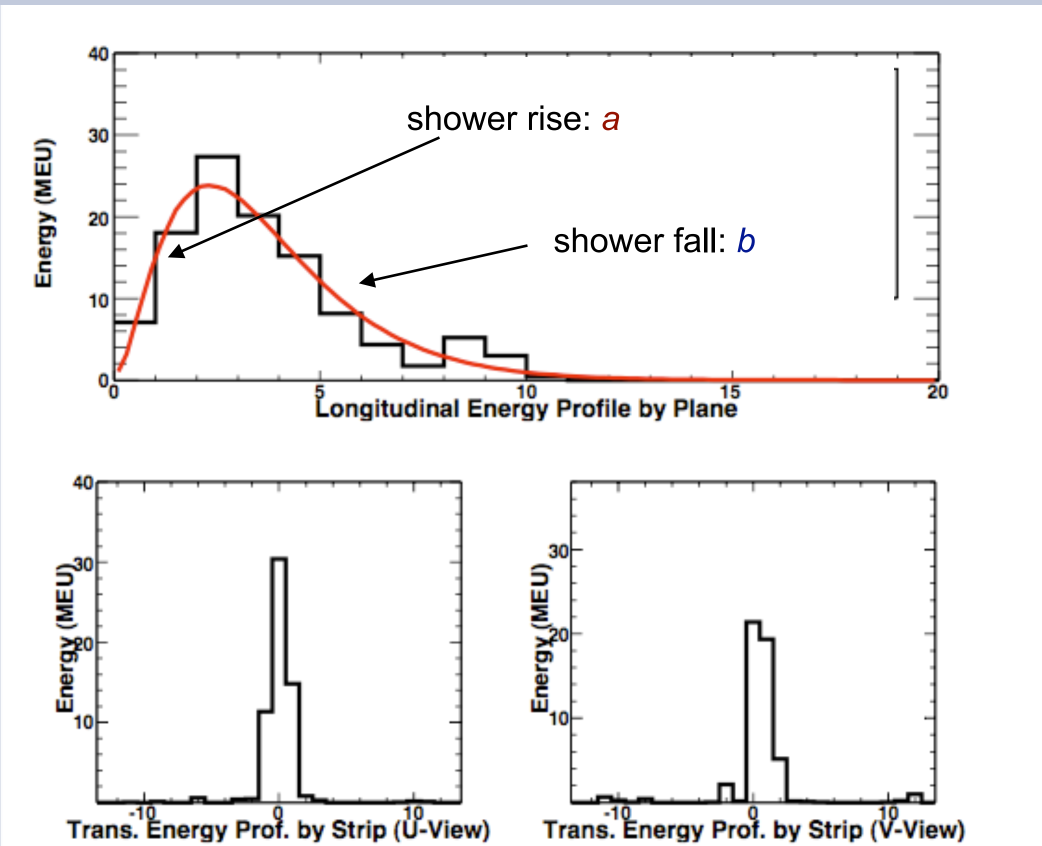


After

Input to Artificial Neural Network (ANN)

Candidates must contain a compact shower and exhibit characteristic EM profile.

Run: 32687 Snarl: 90343
Reco Energy: 4.6 GeV



longitudinal:

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

- fraction of energy deposited within 2,4,6 planes
- longitudinal energy projection

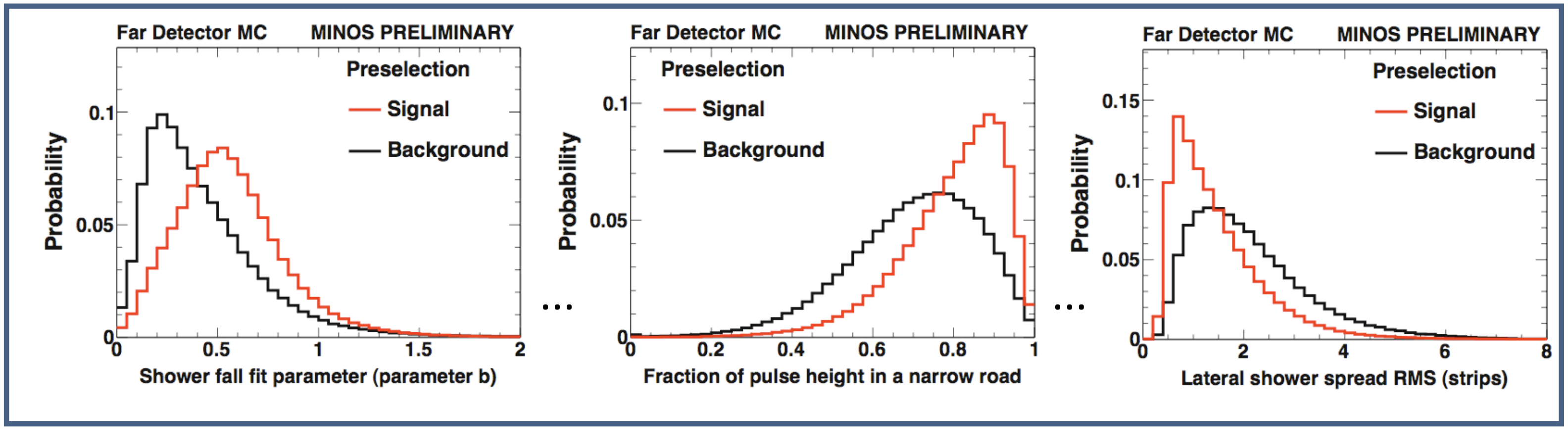
transverse:

- 90% containment radius
- lateral shower spread (RMS)
- fraction of energy deposited within 3 strips along shower axis

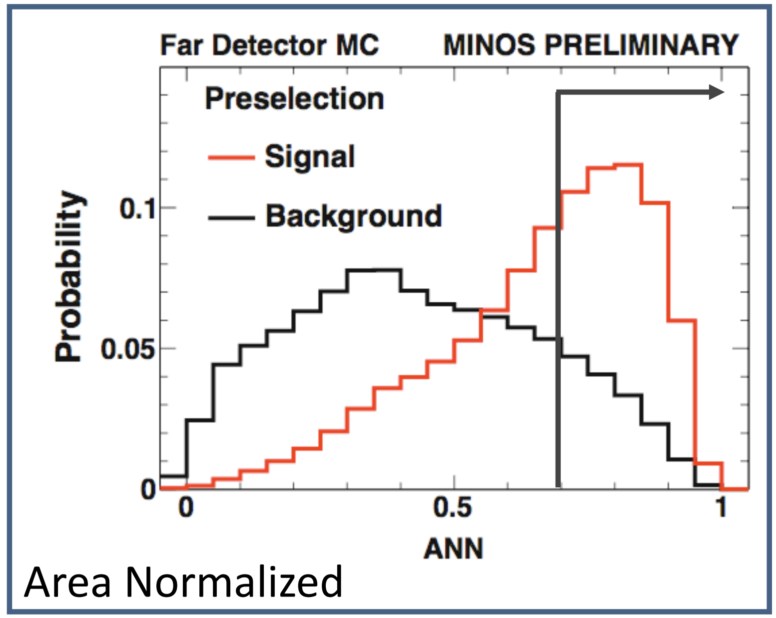
Selecting ν_e events with ANN

event characterization in length, width and shower shape

Examples



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

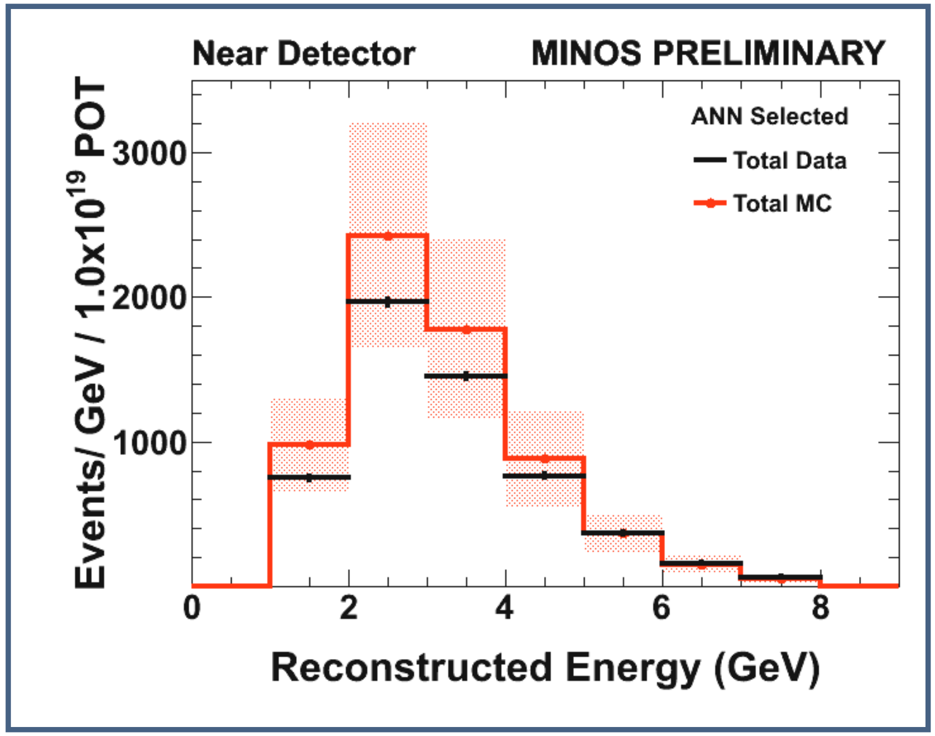


$\Delta m^2_{32}=0.0024\ eV^2,\ \sin^2\theta_{23}=1.0$

ν_e selected Near Detector data

- MC tuned to external bubble chamber data for hadronization models.
  - External data sparse in our kinematic range.

- It is not surprising that the data/MC shows disagreement with the model.
- Discrepancy is within the large uncertainties of the model.
- We have developed **two data-driven methods** to correct the model to match the data.



- The MRCC method uses muon removed ν_μ CC to study the hadronic showers and correct MC.
- The **Horn on/off method** uses the difference in background composition of the two horn configurations.

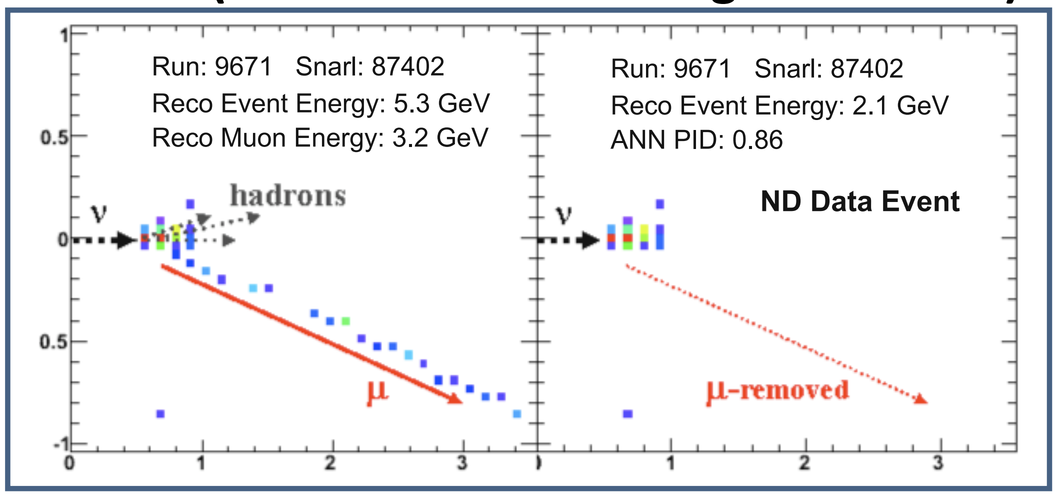
Muon Removal Technique

- Remove the muon track in a selected ν_μ CC event and use the rest as a hadronic shower only event.

- We use events that pass our ν_μ Charged Current event selection, i.e. that have a well defined track.

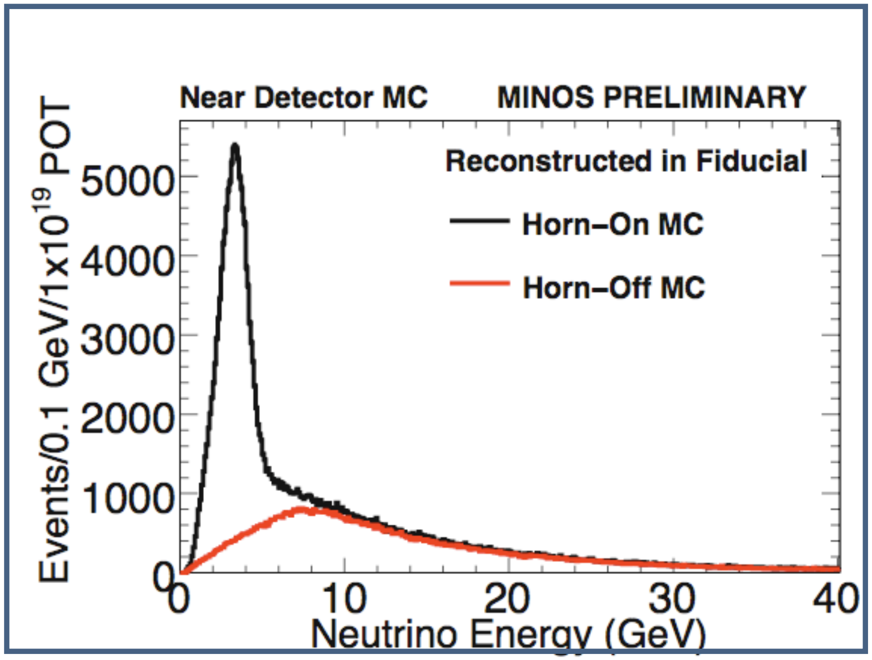
- Well understood ν_μ CC spectra, with well known efficiency and purity from the ν_μ disappearance analysis.

MRCC (Muon Removed Charged Currecnt)



Horn-Off Data

- When beam horns are turned off, the parent pions do not get focused, resulting in the disappearance of the low energy peak in the neutrino energy spectrum.



- The consequence is a spectrum dominated by NC arising from the long tail in true neutrino energy that gets measured in our region of interest in visible energy.

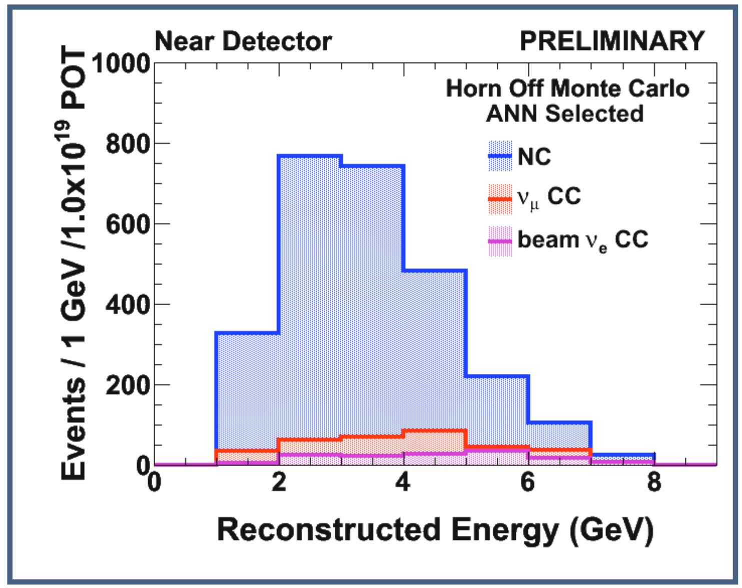
Horn-Off Data

- The **beam ν_e flux** is obtained from the ν_μ CC flux which is constrained by data in the different beam configurations.
- The two main background components can be estimated using the number of data events in the horn on and horn off configurations: $\mathbf{N^{on}}$ and $\mathbf{N^{off}}$.

$$N^{on} = N_{NC} + N_{CC} + N_e \qquad (1)$$
$$N^{off} = r_{NC}*N_{NC} + r_{CC}*N_{CC} + r_e*N_e \qquad (2)$$

from MC:
$r_{NC(CC,e)} = N_{NC(CC,e)}{}^{off}/N_{NC(CC,e)}$

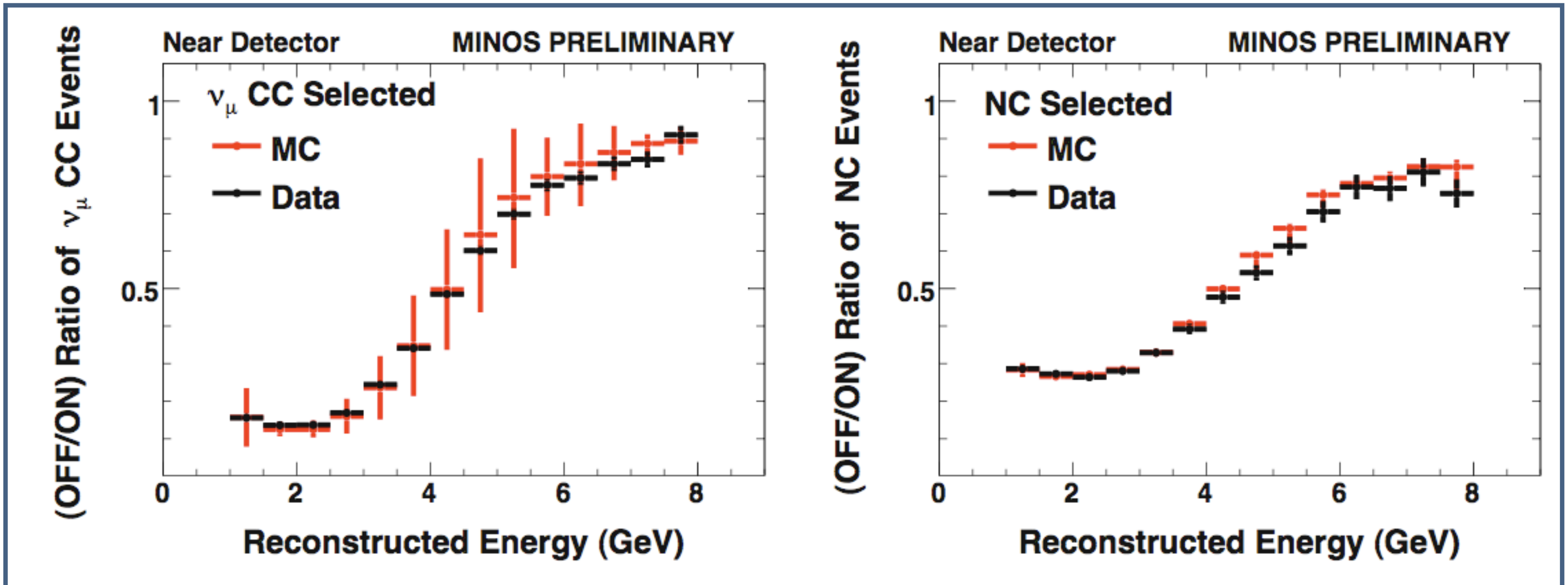
The key is to use the **Horn off/on ratios** for each component to solve:



- Producing **data-driven predictions** for NC and ν_μ CC background for the horn on configuration.

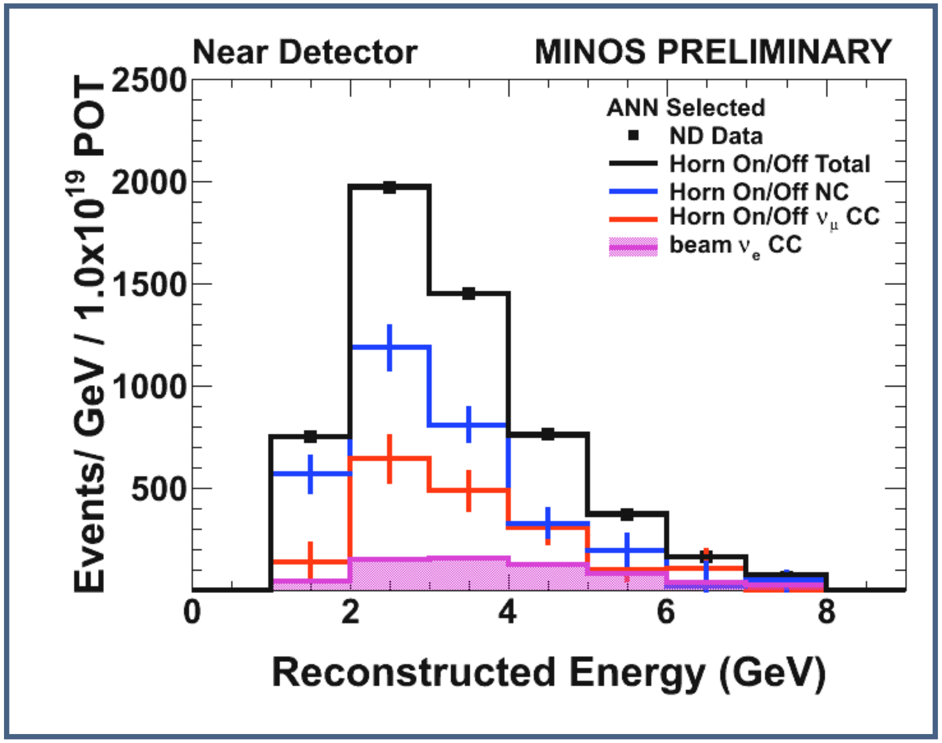
Horn-Off Data

- Horn off/on ratios for ν_μ CC and NC selected events match well between data and MC after fiducial volume cuts.
- Similar ratios are used to solve the horn on/off equations.



MC error statistical plus systematic.

Horn-Off Resuts (ND)



- The NC and ν_μ CC components for the the standard beam configuration are simultaneously solved in the horn on/off method and are by definition equal to the data after beam ν_e subtraction.

FD Background

Data-driven Methods

<table>
<tr><th></th><th>Total</th><th>NC</th><th>ν_μ CC</th><th>ν_τ CC</th><th>ν_e beam</th></tr>
<tr><td>Horn on/off</td><td>27</td><td>18.2</td><td>5.1</td><td rowspan="2">1.1</td><td rowspan="2">2.2</td></tr>
<tr><td>MRCC</td><td>28</td><td>21.1</td><td>3.6</td></tr>
</table>

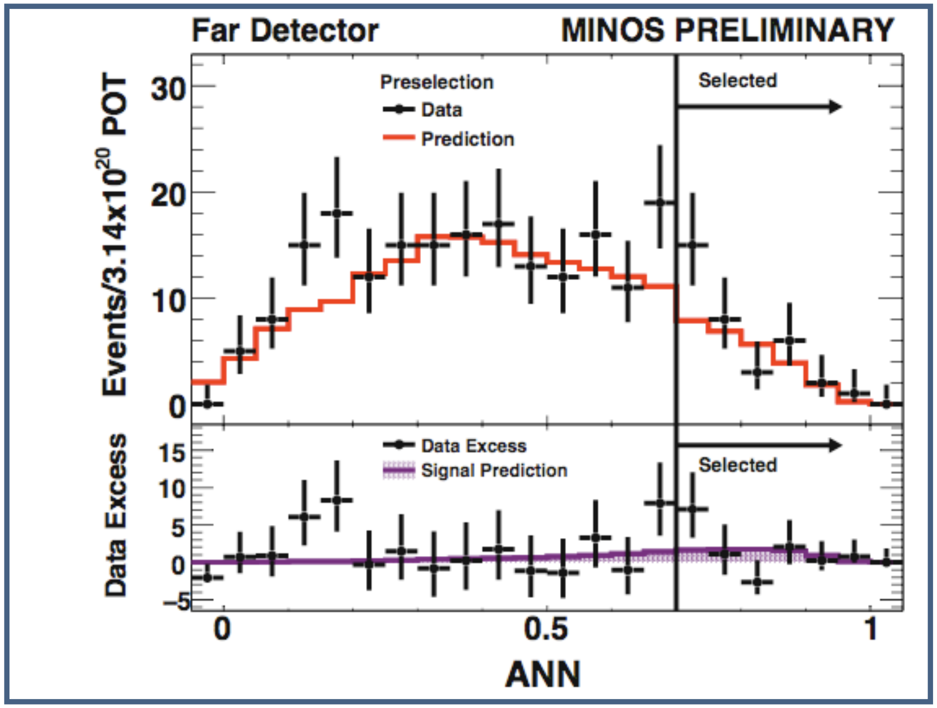
scaled to 3.14 x10^{20} POT

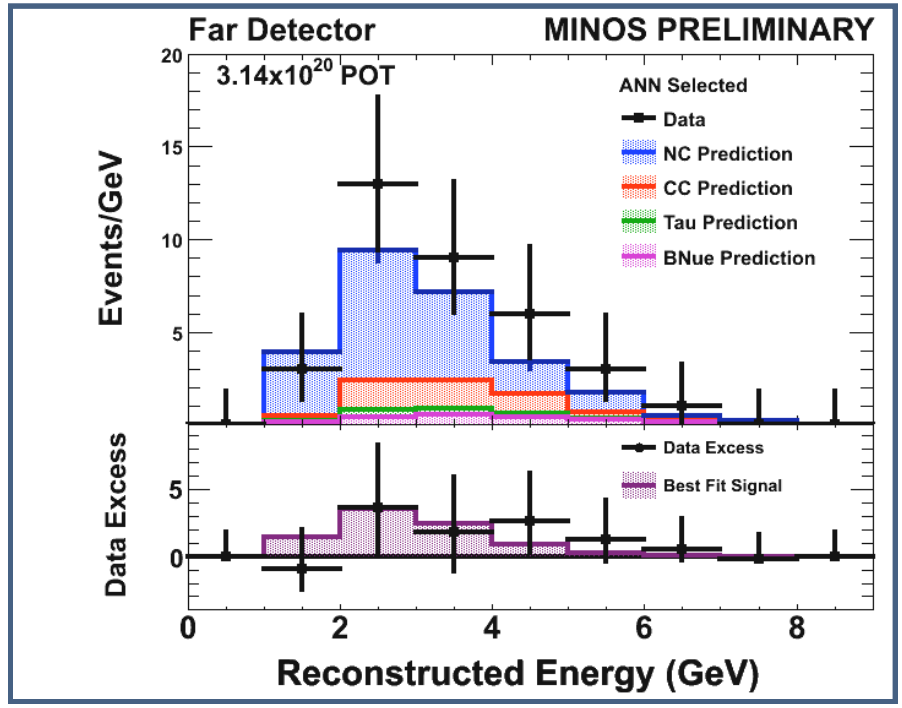
- The two data-driven methods, Horn on/off and MRCC, are in excellent agreement in the Far Detector.
- ~1 event difference is well within errors.

The background prediction at 3.14 x10^{20} POT is: 27±5(stat)±2(sys)

ν_e Selected Far Detector Data

- **We observe a total of 35 events in this sample.**
- **We expect 27±5(stat)±2(sys) background events.**

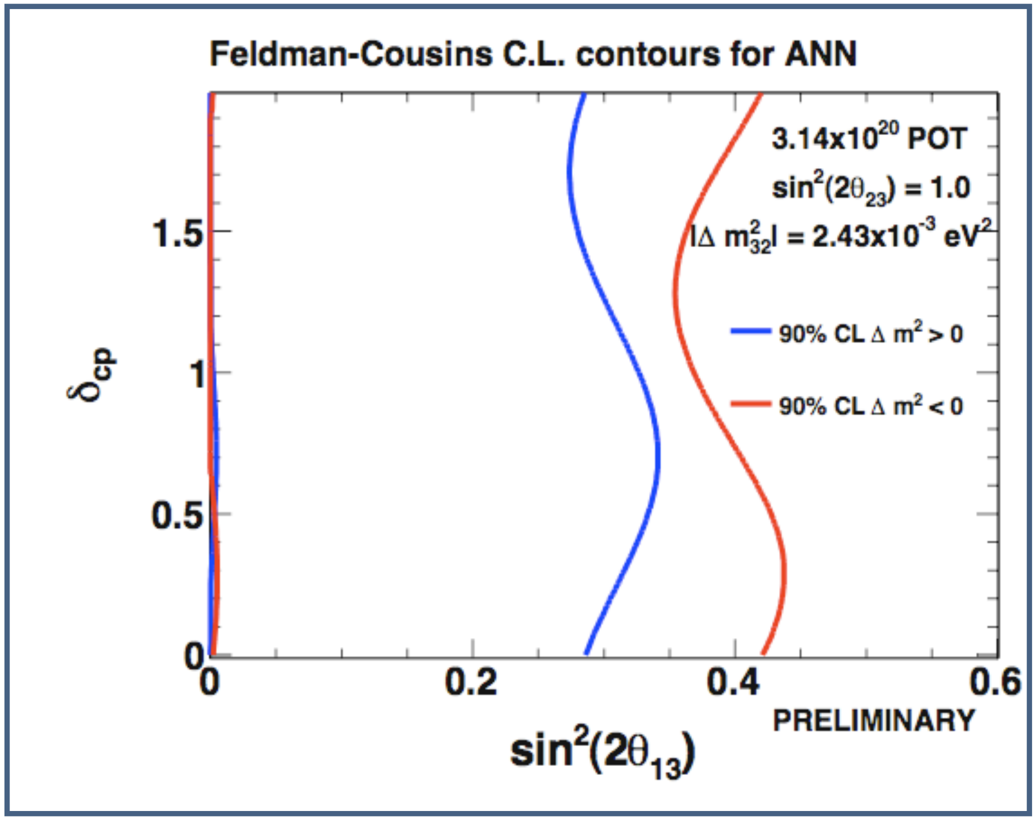




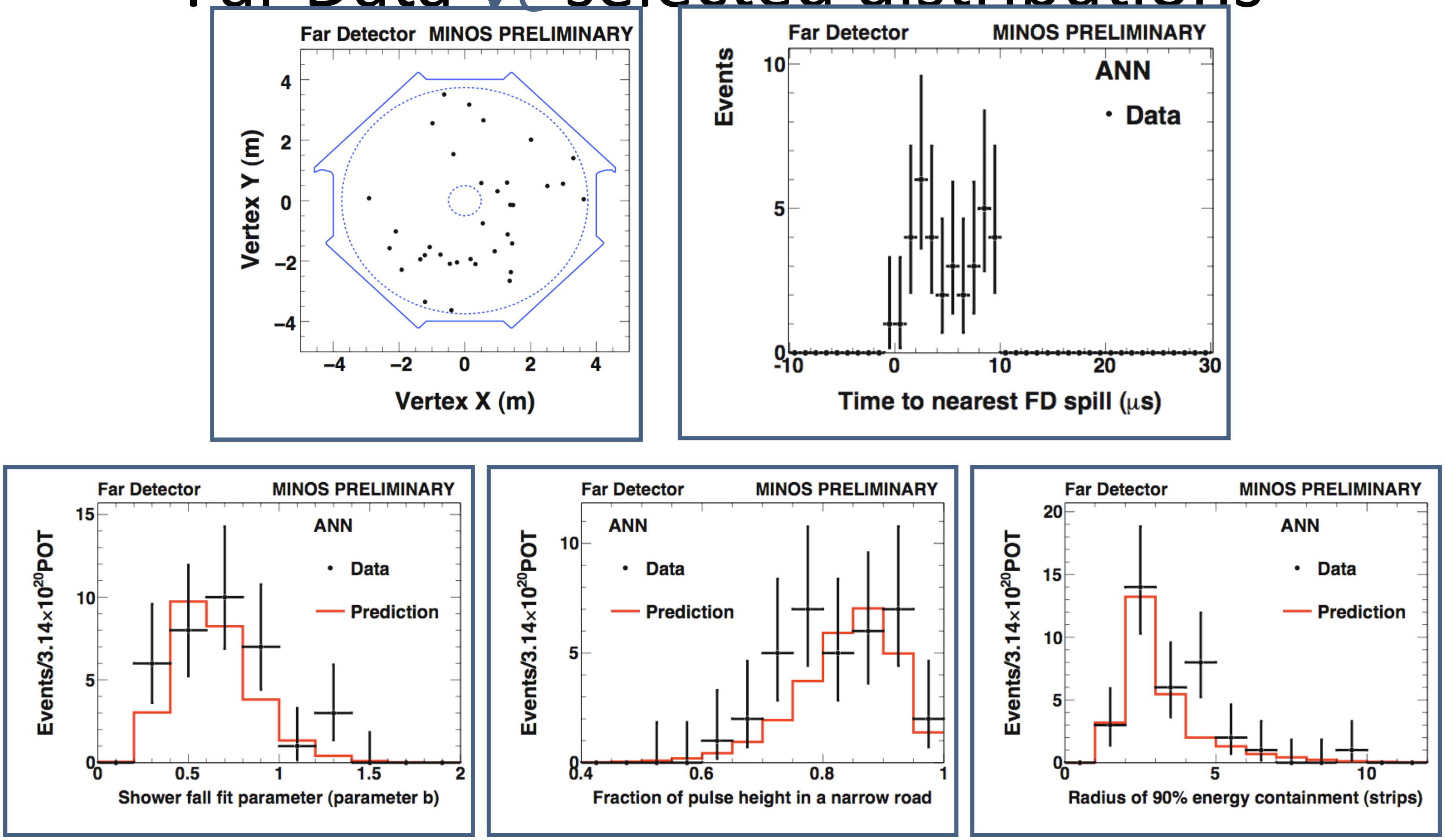
- If we fit the oscillation hypothesis to data, we can obtain the signal prediction for the best fit point.

MINOS 90% CL in $\sin^2 2\theta_{13}$

- Plot shows 90% limits in δ_{CP} vs. $\sin^2 2\theta_{13}$
  - shown at the MINOS best fit value for Δm^2_{32} and $\sin^2 2\theta_{23}$.
  - for both mass hierarchies
- A Feldman-Cousins method was used.

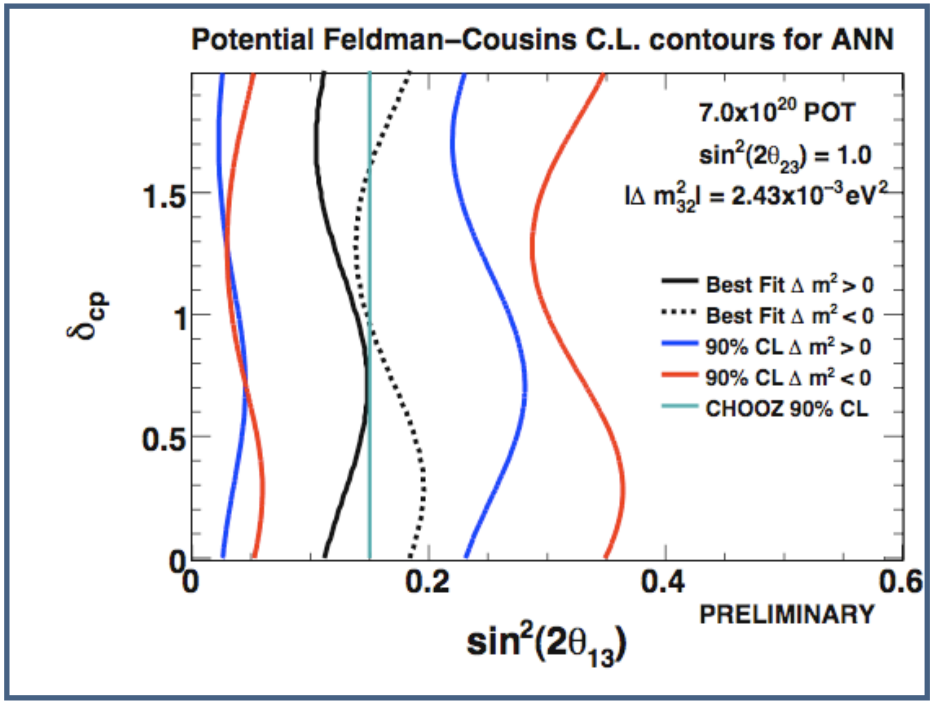


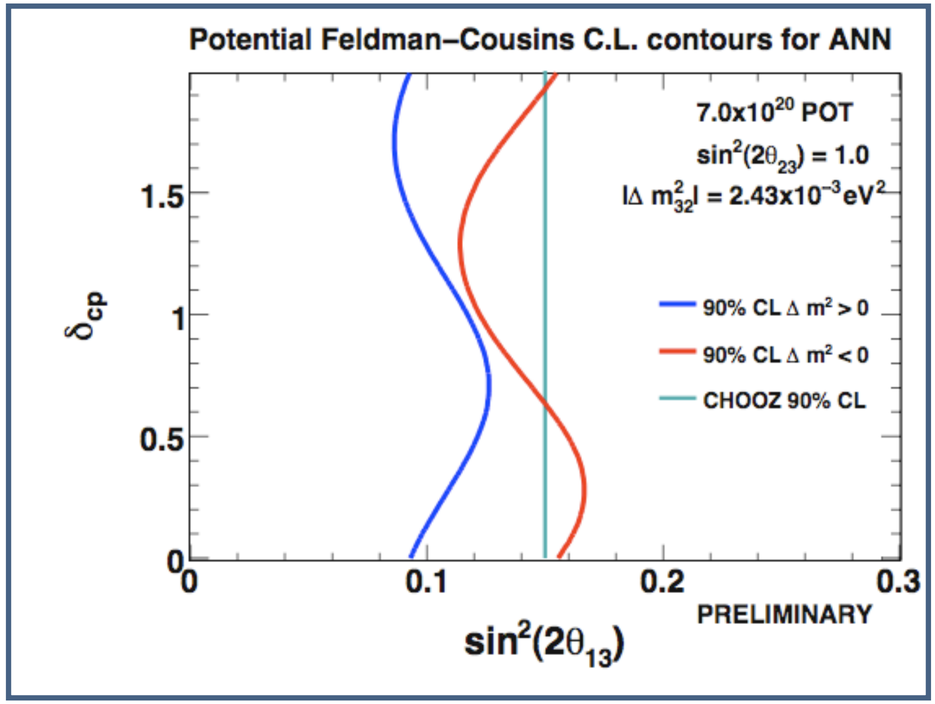
Far Data ν_e selected distributions



Future 90% CL contours

7.0 x10^{20} POT





If data excess persists.

If excess cancels with more data.

NOνA

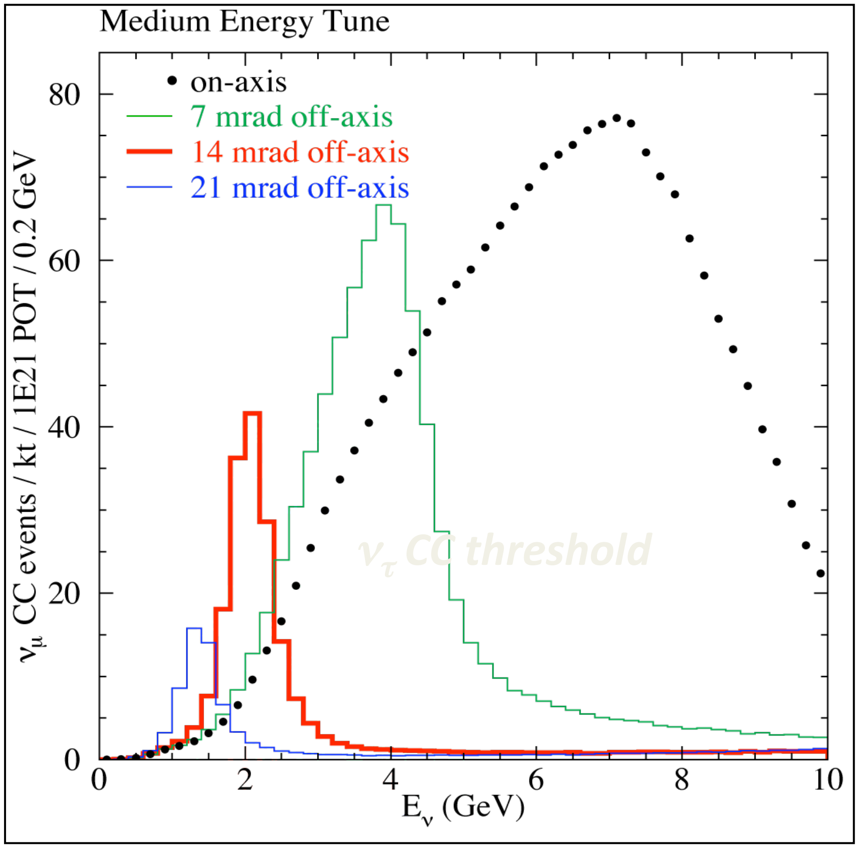
- NuMI Off-Axis electron-Neutrino Appearance Experiment
- NOνA is a second-generation experiment on the NuMI beamline, which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ oscillations.
- Low-Z Detector allows for electron shower development and detection.
  - It will give an order of magnitude improvement over MINOS in measurements of ν_e appearance and ν_μ disappearance.
- NOνA is a "totally active" (73%) tracking liquid scintillator calorimeter
- It is sited off-axis(14 mrad) to take advantage of a narrow-band beam.
- The NOνA project also includes accelerator upgrades to bring the beam power to 700 kW.
- NOνA's unique feature is its long baseline (810 km), which gives it sensitivity to the neutrino mass ordering.
- NOνA is complementary to both T2K and Daya Bay.

NuMI Beam for NOνA

- Intensity will be improved from
- 275 kW to 700+ kW for NOνA

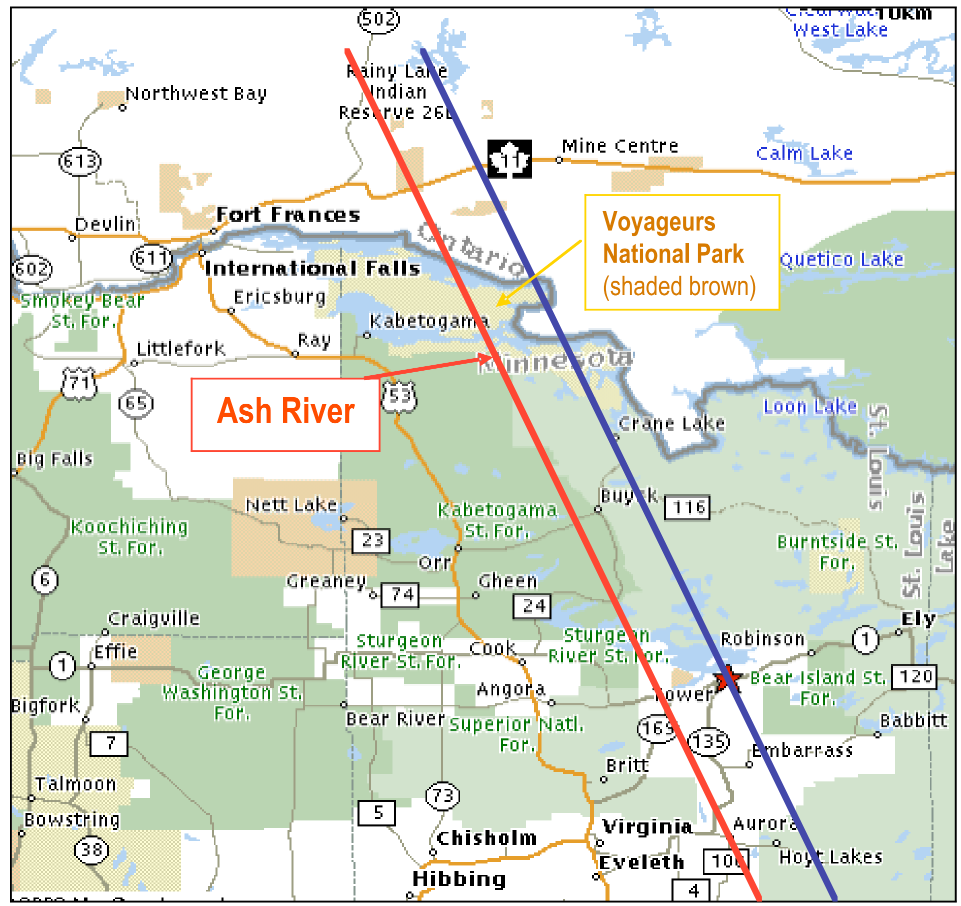
- Beam energy is higher (ME)
  – detectors are *off-axis @810 km*

- Higher flux & lower background.



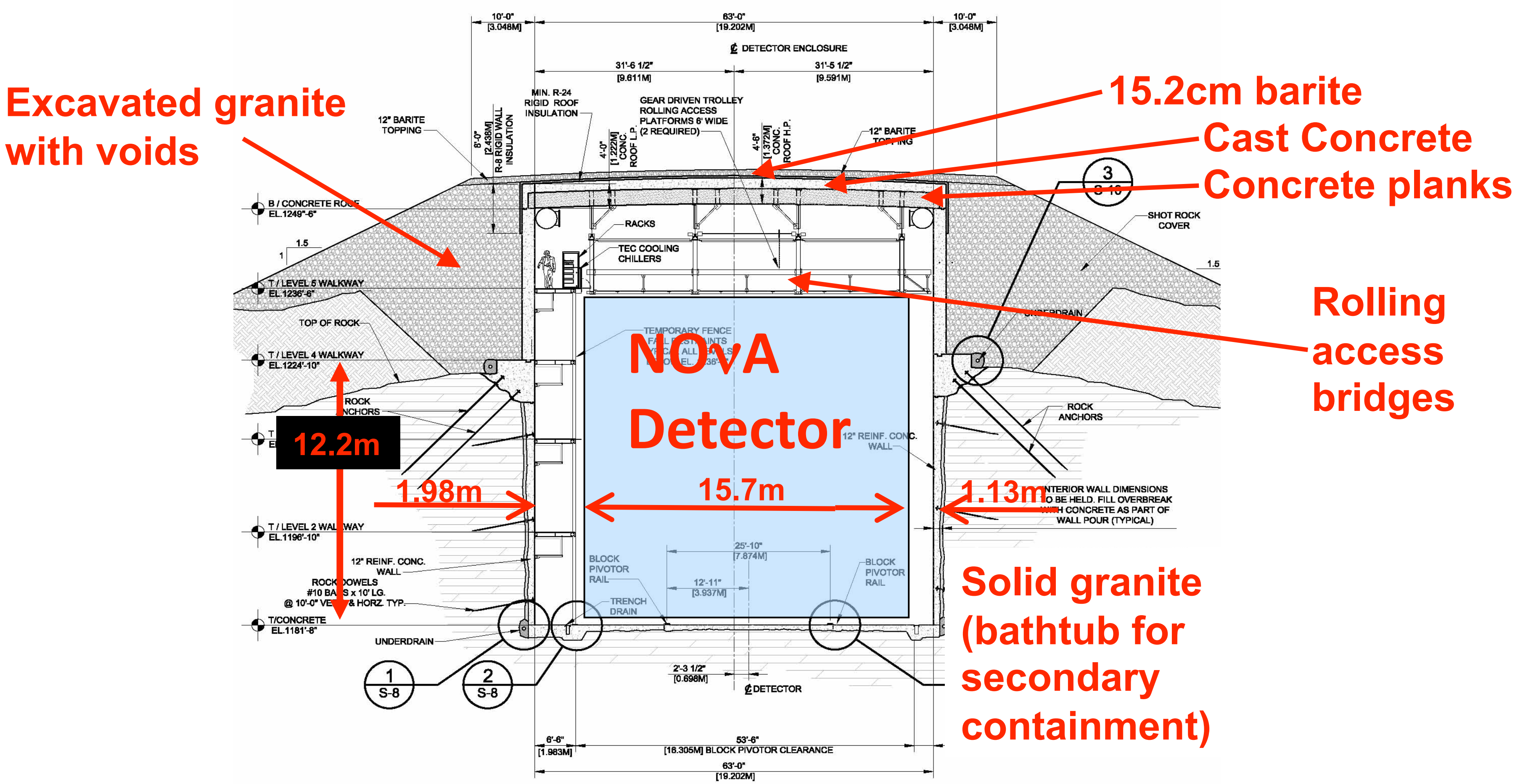
NOνA Site

The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOνA's sensitivity to the mass ordering.

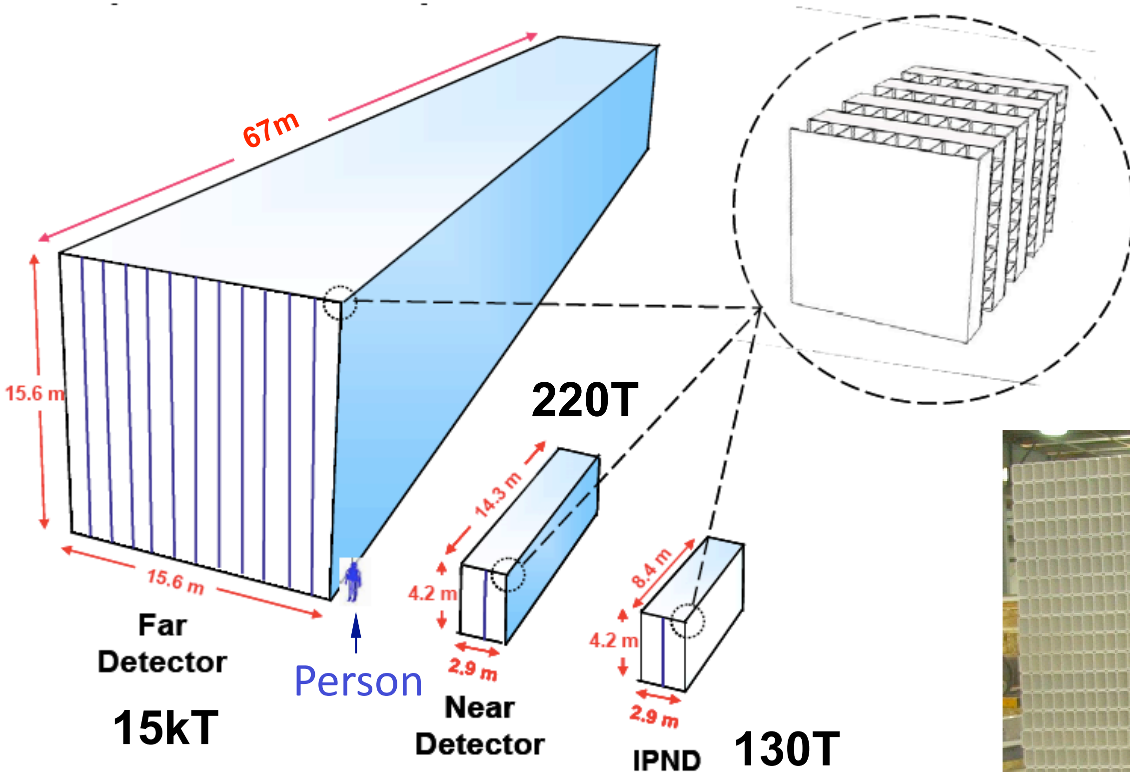


Site and Building

Detector is on the surface.



NOνA Detectors

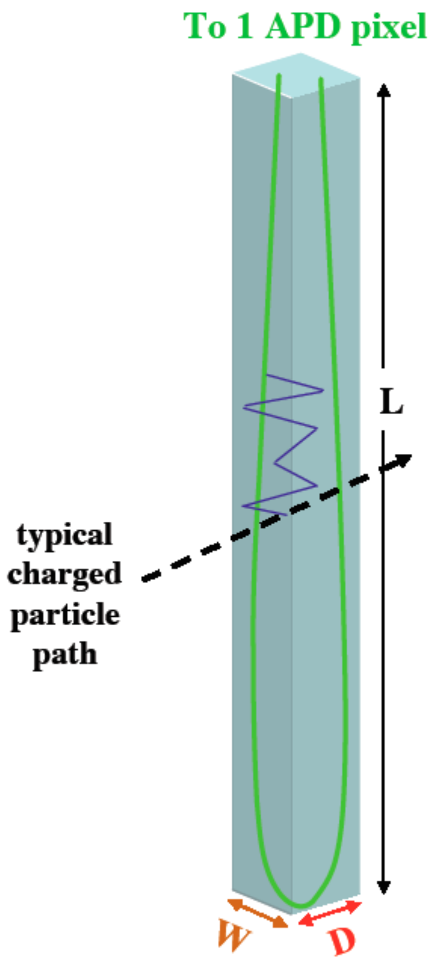


Planes consist of 32 cell PVC extrusions (15% TiO_2)

Planes alternate vertical & horizontal orientation

0.15 X_0 per plane

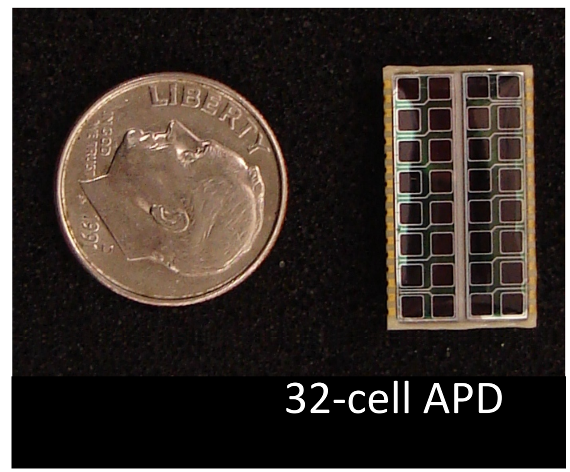
NOνA Basic Detector Element



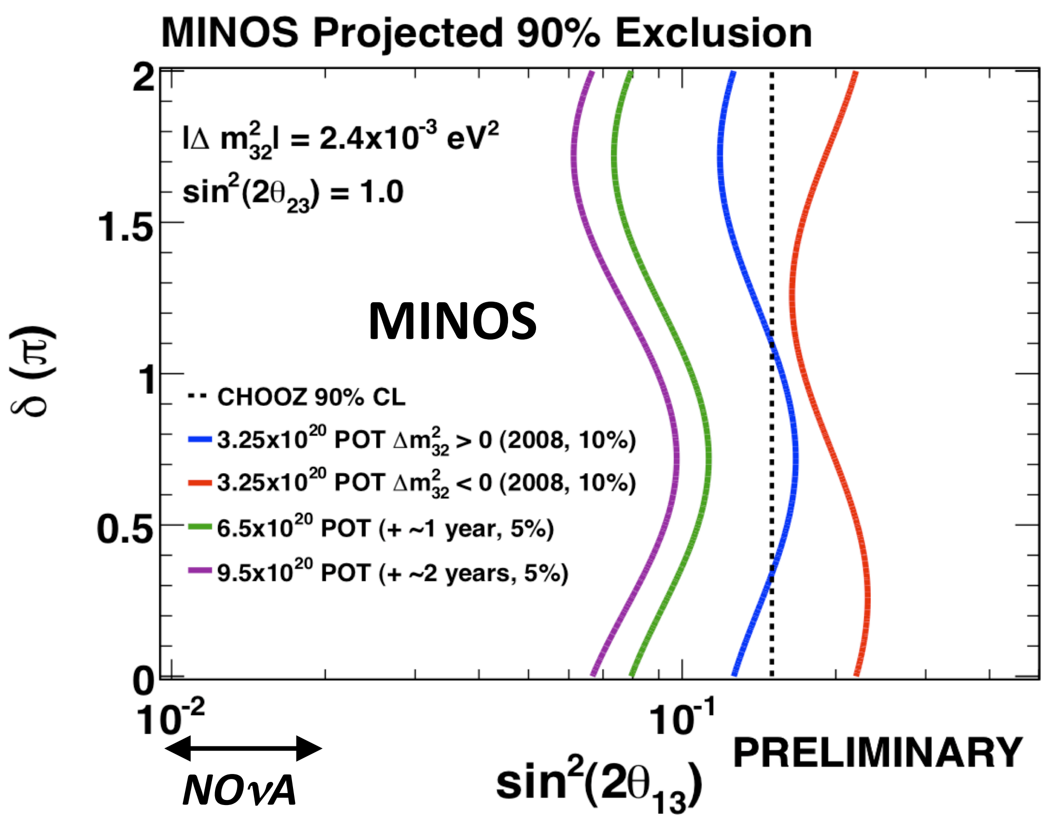
Liquid scintillator in a 4 cm wide, 6 cm deep, 15.7 m long, highly reflective PVC cell.

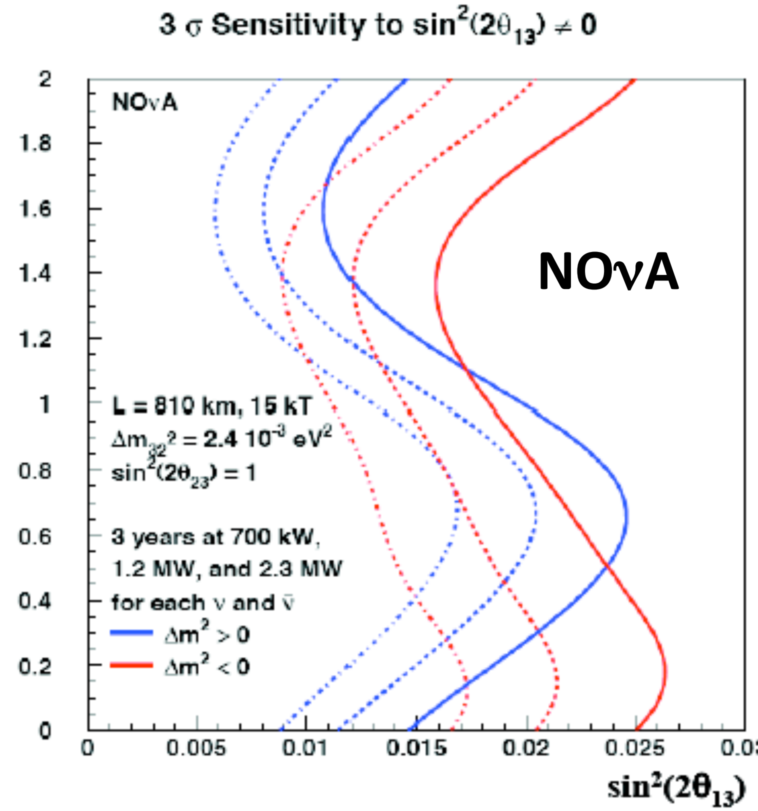
Light is collected in a U-shaped 0.7 mm wavelength-shifting fiber, both ends of which terminate in a pixel of a 32-pixel avalanche photodiode (APD).

The APD has peak quantum efficiency of 85%. It will be run at a gain of 100. It must be cooled to -15°C and requires a very low noise amplifier.



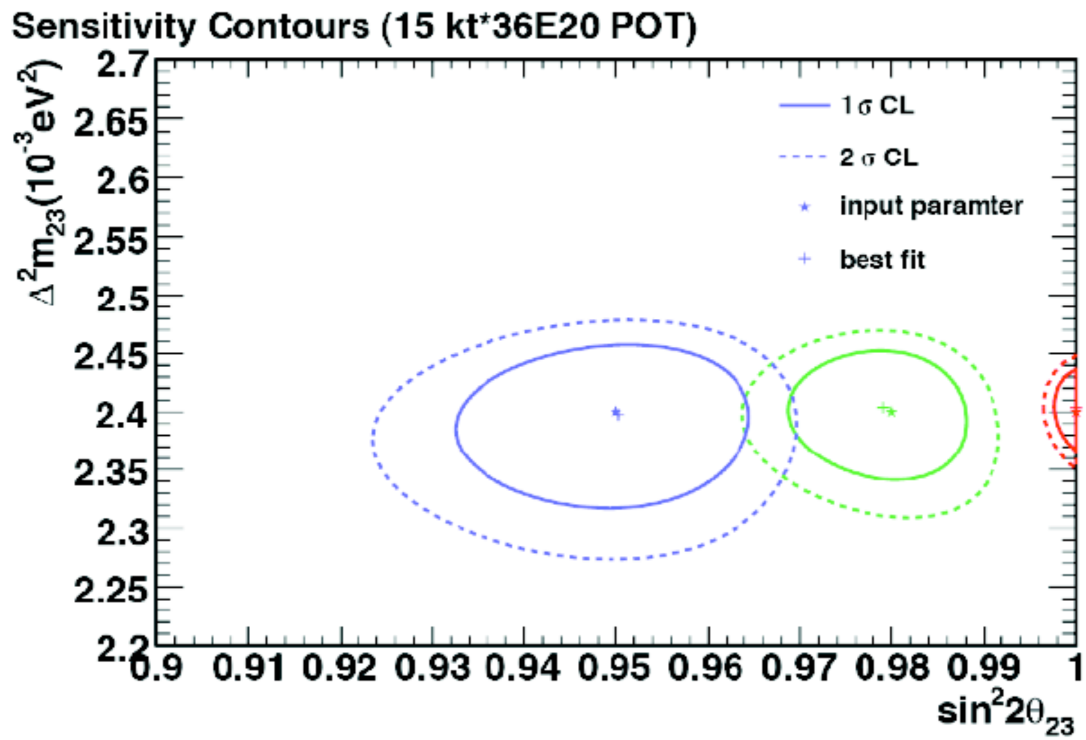
Sensitivity to $\sin^2 2\theta_{13}$





- Assume 3 years neutrino + 3 years anti-neutrino beam

Sensitivity to $\sin^2 2\theta_{23}$



- Assume 3 years neutrino + 3 years anti-neutrino beam
- NOνA can improve the precision of the $\nu_\mu \rightarrow \nu_t$ mixing angle by over an order-of-magnitude over MINOS

Schedule Highlights

- Ash River ground breaking May 1, 2009
- EVMS review May 11-15, 2009
- DOE CD 3b review July 21-23, 2009
- IPND operational March 2010
- Beneficial occupancy far detector building May 2011
- 10-12 month accelerator shutdown July 2011
  - Installation of NOνA Recycler components
  - Near detector cavern excavation
- First 2.5 kT operational August 2012
- Full Far Detector operational December 2013

Summary

- MINOS:
  - World’s most precise measurement of Δm^2_{23} & constraints on sterile neutrinos.
  - 1st results on $\sin^2 q_{13}$ from n_e appearance presented.
  - Factor of 2 increase in statistics coming.
  - Anti-neutrino beam following current run (likely)
  - Many analyses not covered: (Near Detector Physics, anti-neutrino, Rock Interactions, Atmospheric, neutrino Velocity, Global Analysis)

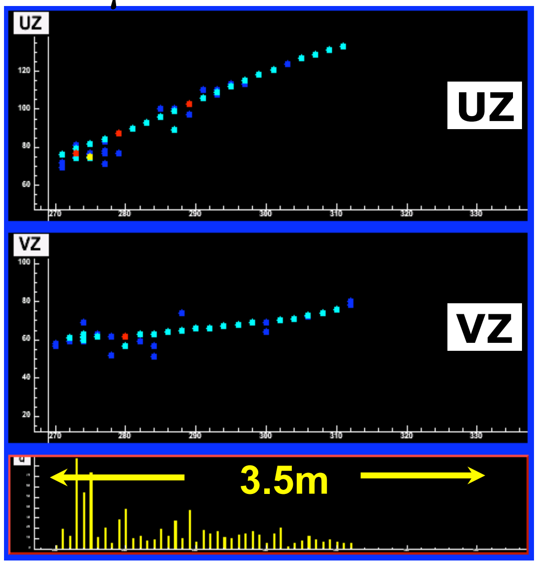
- NOνA:
  - Next generation long-baseline experiment that will yield significantly more precise Δm^2_{23} and $\sin^2 2\theta_{23}$ as well as an order-of-magnitude improvement in sensitivity for $\sin^2 2\theta_{13}$
  - Physics sensitivity is complementary to T2K & reactor experiments

[redacted]

Example event topologies

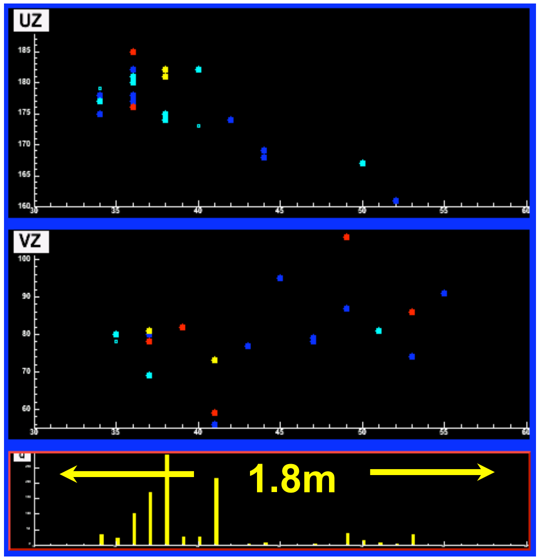
Monte Carlo

ν_μ CC Event



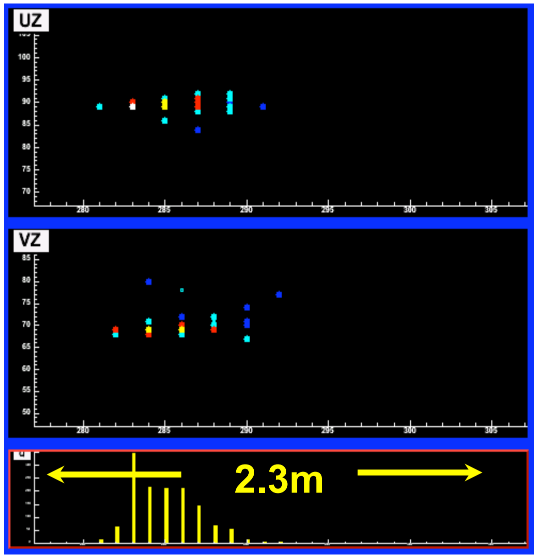
long μ track+ hadronic activity at vertex

NC Event



short event, often diffuse

ν_e CC Event



short, with typical EM shower profile

ν_e appearance result:

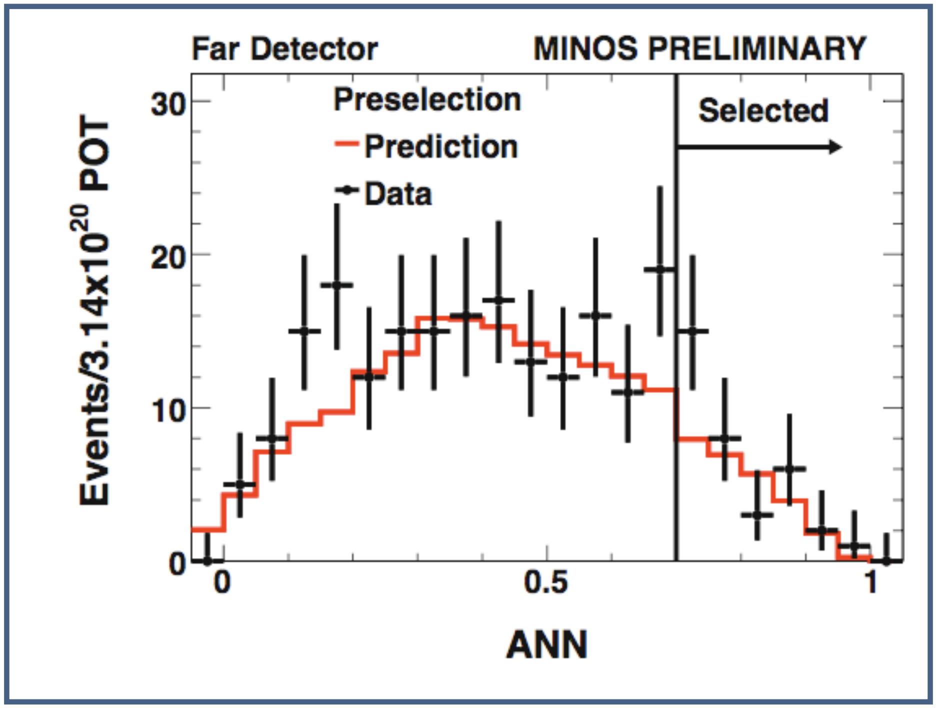
Observation 35 events **Expected Background 27±5(stat)±2(sys)** for 3.14 x 10^{20} POT

MINOS PRELIMINARY

ν_e Selected Far Detector Data

Primary selection method

- Preselected data in the FD as a function of PID compared to the corrected MC.



- **We observe a total of 35 events.**
- **We expect 27±5(stat)±2(sys) background events.**

Results are 1.5 σ above expected background.

ν_e Appearance

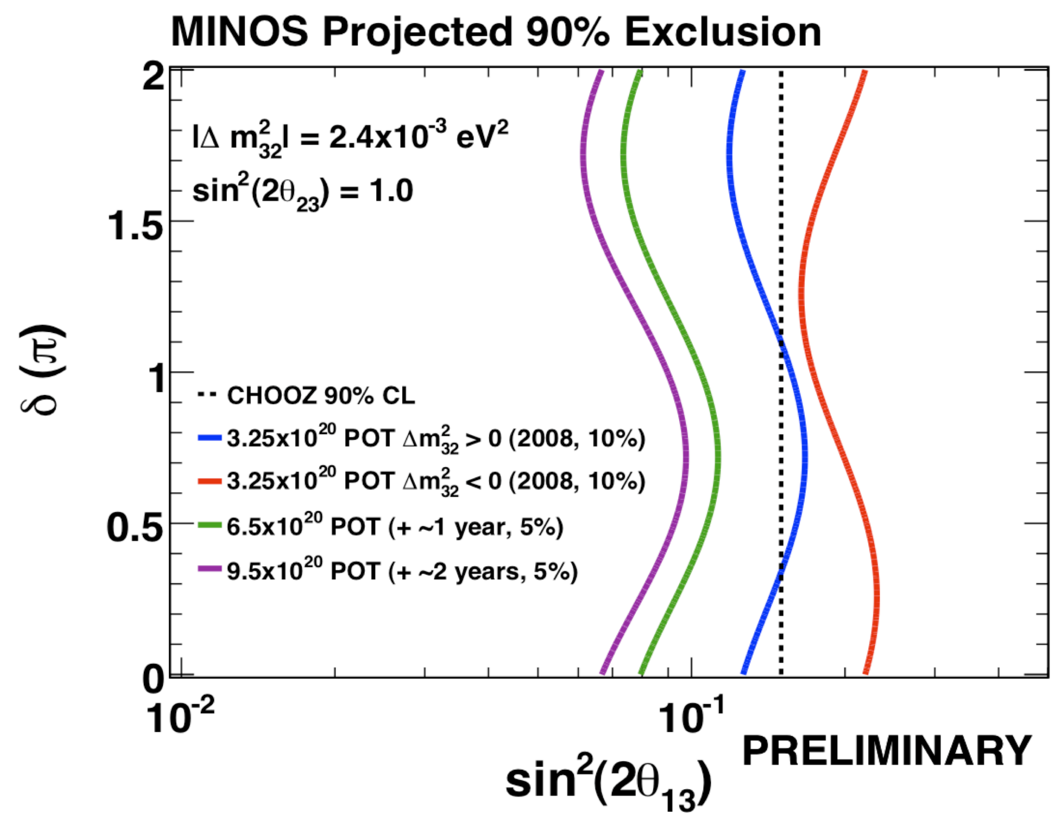
- Measurement of $\sin^2 2\theta_{13}$
  $P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2(1.27\ \Delta m^2_{23}\ L/E)$

- Expect signal/background = 0.3 at the CHOOZ limit for current MINOS exposure

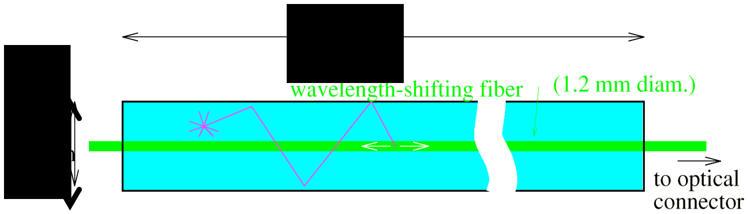
- Data-driven systematic uncertainty: ~10%

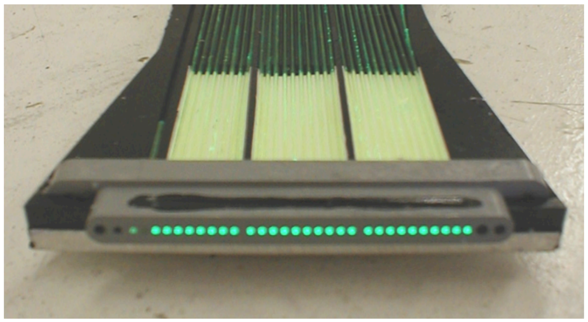
- Hope to improve to 5% systematic uncertainty in the future

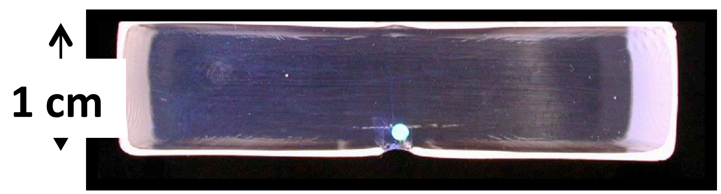
- 1st results expected later this year with sensitivity below the CHOOZ limit



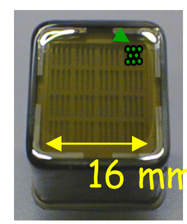
Signal Collection Based on MINOS Active Detector







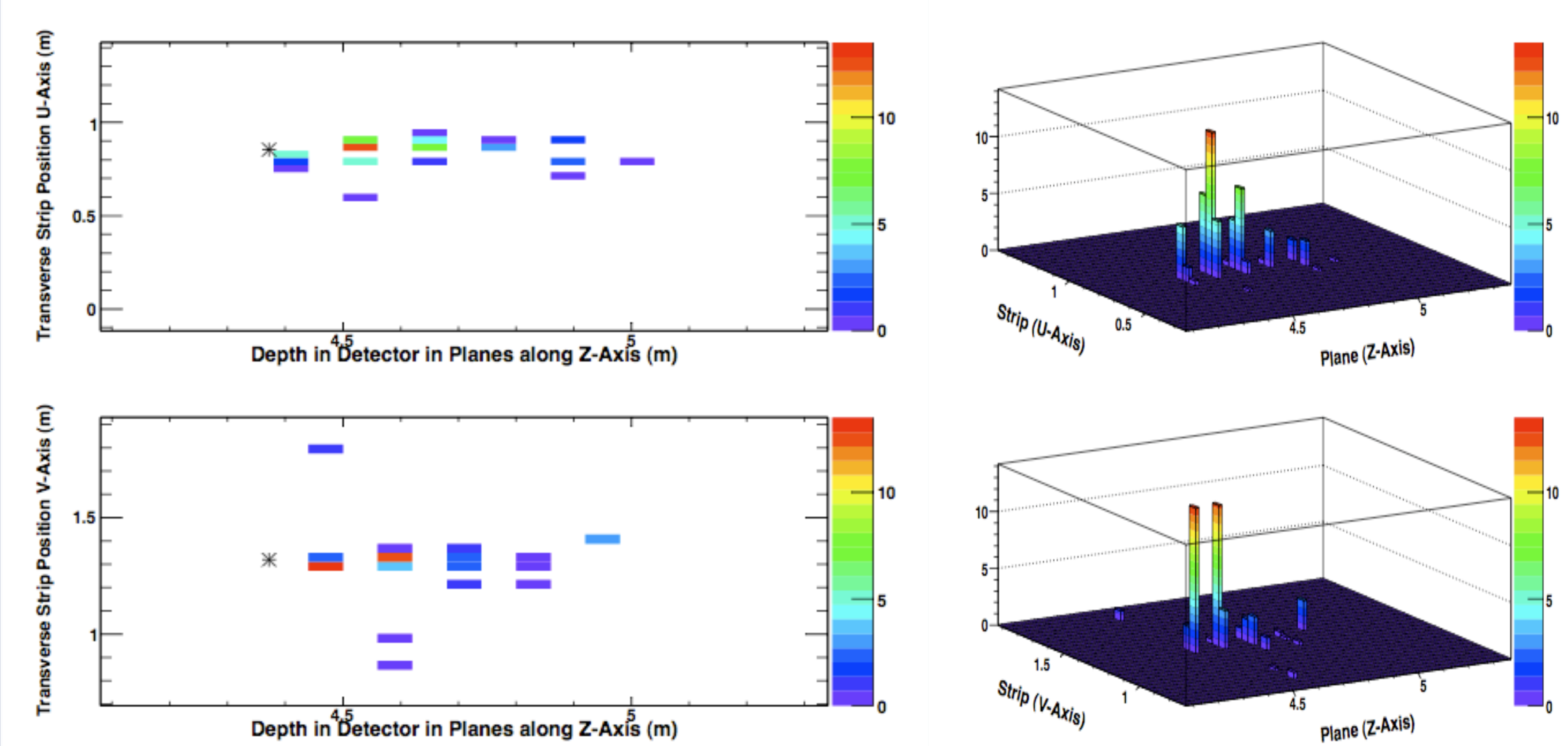
- Plastic Scintillator → Liquid Scintillator
- 8 m length → 15.7 m length
- 1 cm thick → 6 cm thick
- 1.2 mm wavelength shifting fiber → 0.7 mm wls fiber
- Straight fiber read out each side → Looped fiber read out one side
- Hamamatsu multi-anode PMTs → Hamamatsu multi-pixel Avalanche Photodiodes
- 8 cells/pixel multiplexing → 1 cell/ pixel



Candidate ν_e in the FD data

- Typical EM shower characteristics:
  - steel thickness: 2.54cm ~1.44X_0
  - strip width: 4.12cm (Moliere rad ~3.7cm)

Run: 32687 Snarl: 90343
Reco Energy: 4.6 GeV



FD background systematic errors

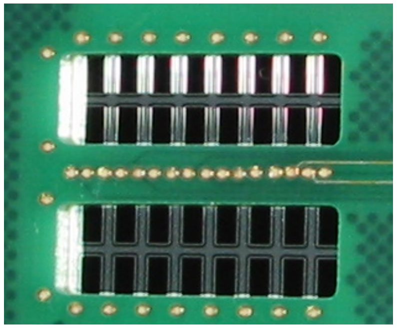
Total errors

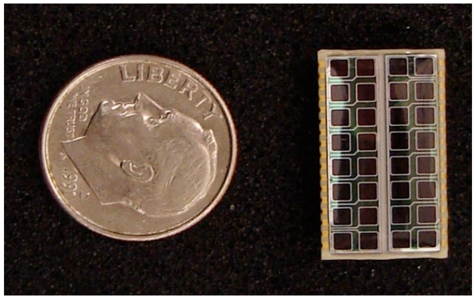
Preliminary Uncertainties	Horn On/Off
(1) Extrapolation	6.4%
(2) Systematic (separation method)	2.7%
(3) Statistical (separation method)	2.3%
Total (sum in quadrature)	7.3%
Statistical error (data)	**19%**

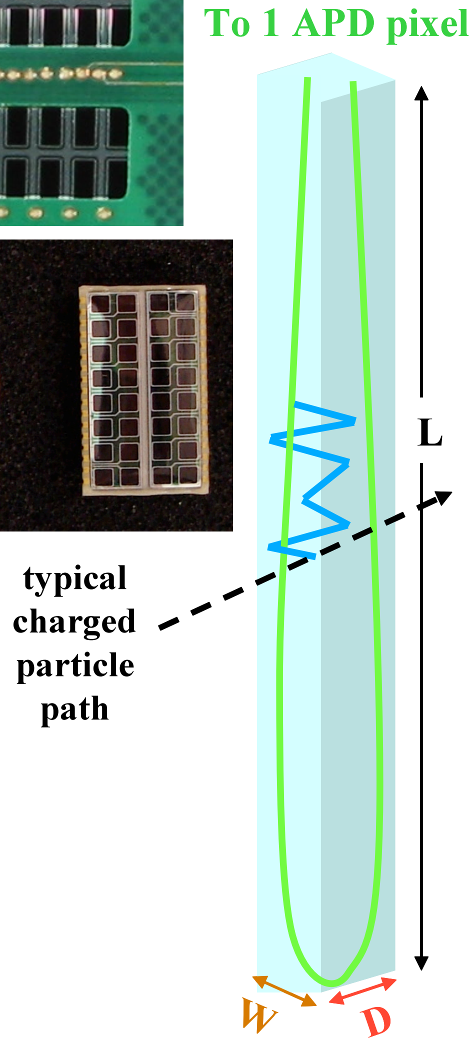
Systematic uncertainties are dominated by error in the extrapolation.
Statistical uncertainties dominate.

NOvA Detector Components

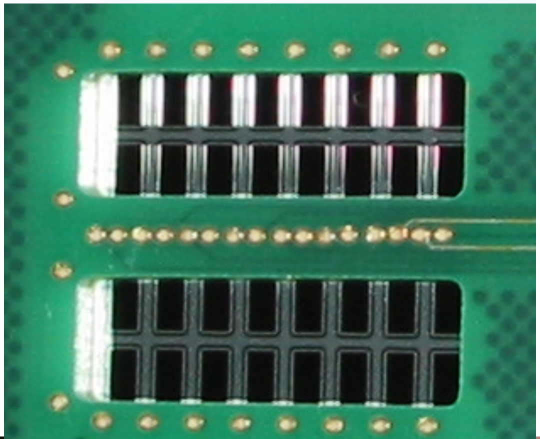
- Liquid scintillator (3 million gallons)
  - Contained in 3.9cm x 6.6 cm cells of length 15.6 meters
  - 3.9 cm as seen by the beam
- Cell walls are rigid PVC (5 kilotons)
  - Loaded with 15% anatase form of titanium dioxide
  - Diffuse reflection at walls keeps light near (within ~ 1 m) particle path
- Looped wavelength-shifting fiber collects light (13,000 km)
  - Fiber diameter 0.7 mm
  - Fiber shifts wavelength to ~ 520-550 nm along the fiber
- Avalanche photodiode (APD) converts light to electrical signal (13,000 devices, ea. 32 pixels)
  - 85% quantum efficiency



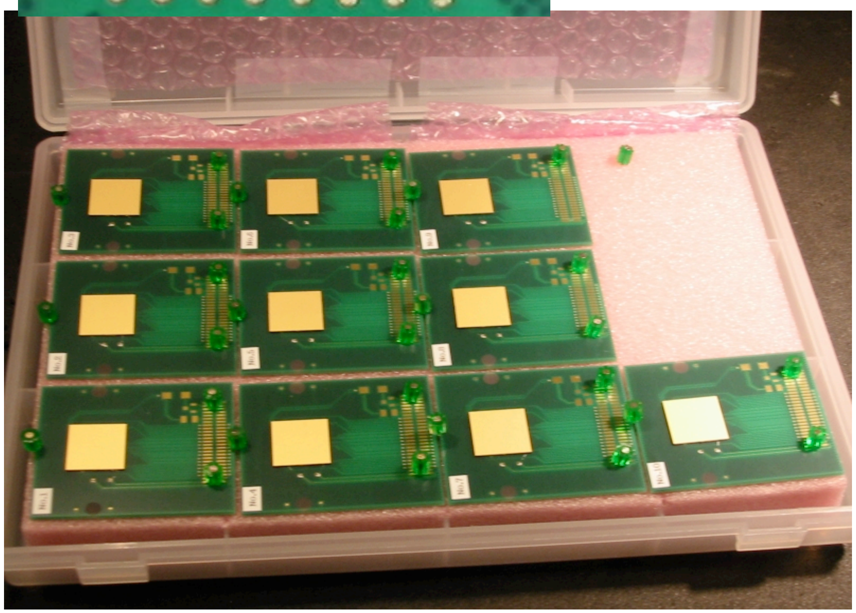


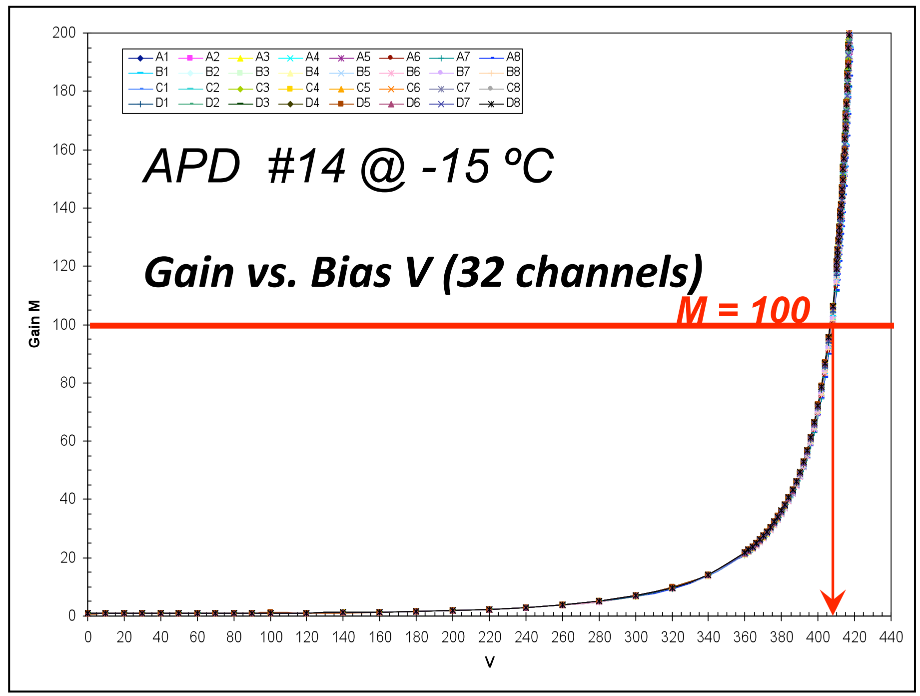


Avalanche Photodiodes



- Silicon solid-state device
- APDs have 85% quantum efficiency @ 520nm
- Operated at gain = 100 biased ~400V
- Low noise (< 2 p.e./channel @ -15 ºC)





Funding: Bust and Boom

- Dec 2007: FY08 Omnibus Funding Bill zeros NOνA funding.
- July 2008: FY08 Supplemental Bill gives NOνA $9M.
- September 2008: CD-2 approved.
- October 2008: CD-3a approved for $24M.
- October 2008: Continuing Resolution gives NOνA $11M.
- February 2009: ARRA (Stimulus) gives NOνA $xxM.
- March 2009: FY09 Omnibus Funding Bill gives NOνA an additional $17M.
- However, no apparent change in schedule.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volume 06
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march 09

NOνA Timeline

- May 2002: 1st Workshop
- April 2005: Fermilab PAC Approval
- April 2006: DOE CD1 Recommendation – “Approve Preliminary Baseline Range”
- May 2007: DOE CD1 Approved
- November 2007: DOE CD2 Review (Cost, Schedule, & Scope Baseline)
  - *Complete* ***Technical Design Report***
- December 17, 2007: US Congress Cuts Most Science Funding including FY08 NOνA
- April 2008: DOE CD2 Review (again) – Approval Recommended
- July 1, 2008: US Congress Passes Emergency Spending Bill
  - *M$9.23 Restored to NOnA Funding – On-Budget Project Activities Can Resume*
- **September 15, 2008: DOE CD2 Approved**
- **CD3b this summer**
- **Detector Construction & Running:**
  - **Expect IPND Data-taking in 2010**
  - **Far Detector Construction late 2011 through 2013**
    – Data can start after first few kT