Neutral Current Event Rates in MINOS

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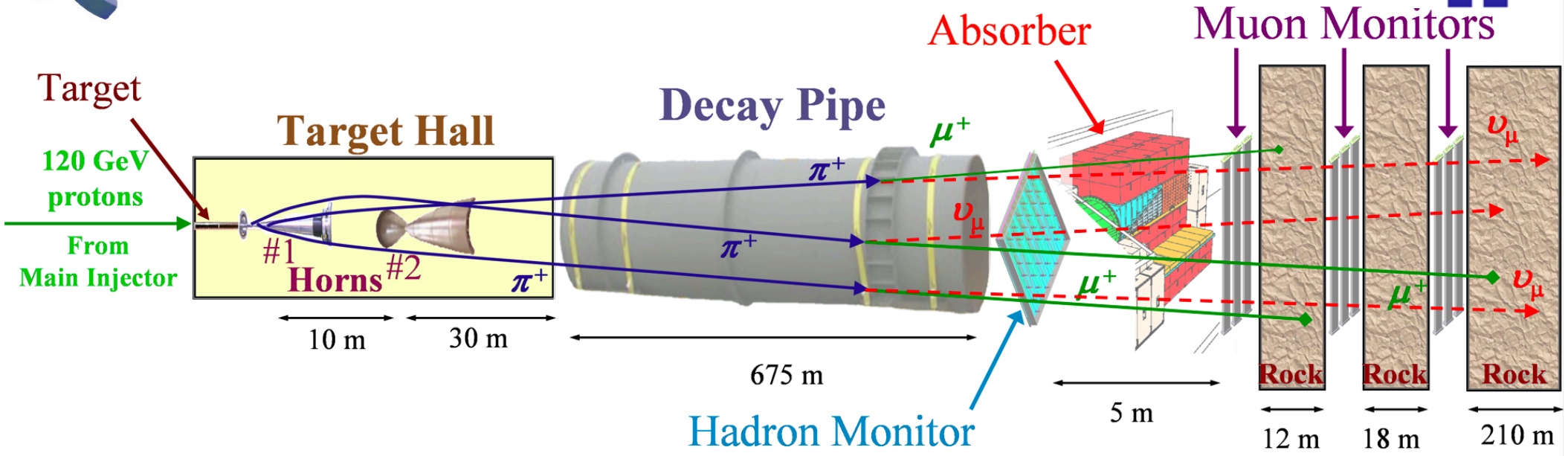
April 2008

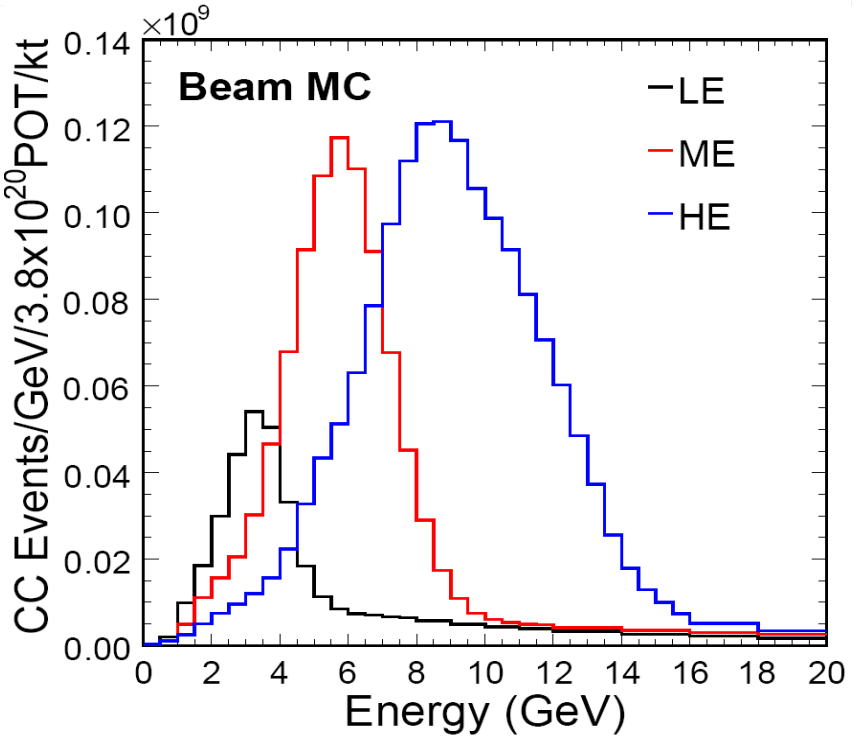
Outline

- Introduction to NuMI/MINOS
- Neutral Current Event Selection
- Neutral Current Prediction at Far Detector
- Three Flavor Results
- Four Flavor Results
- Conclusions

Neutrinos at the Main Injector Beam

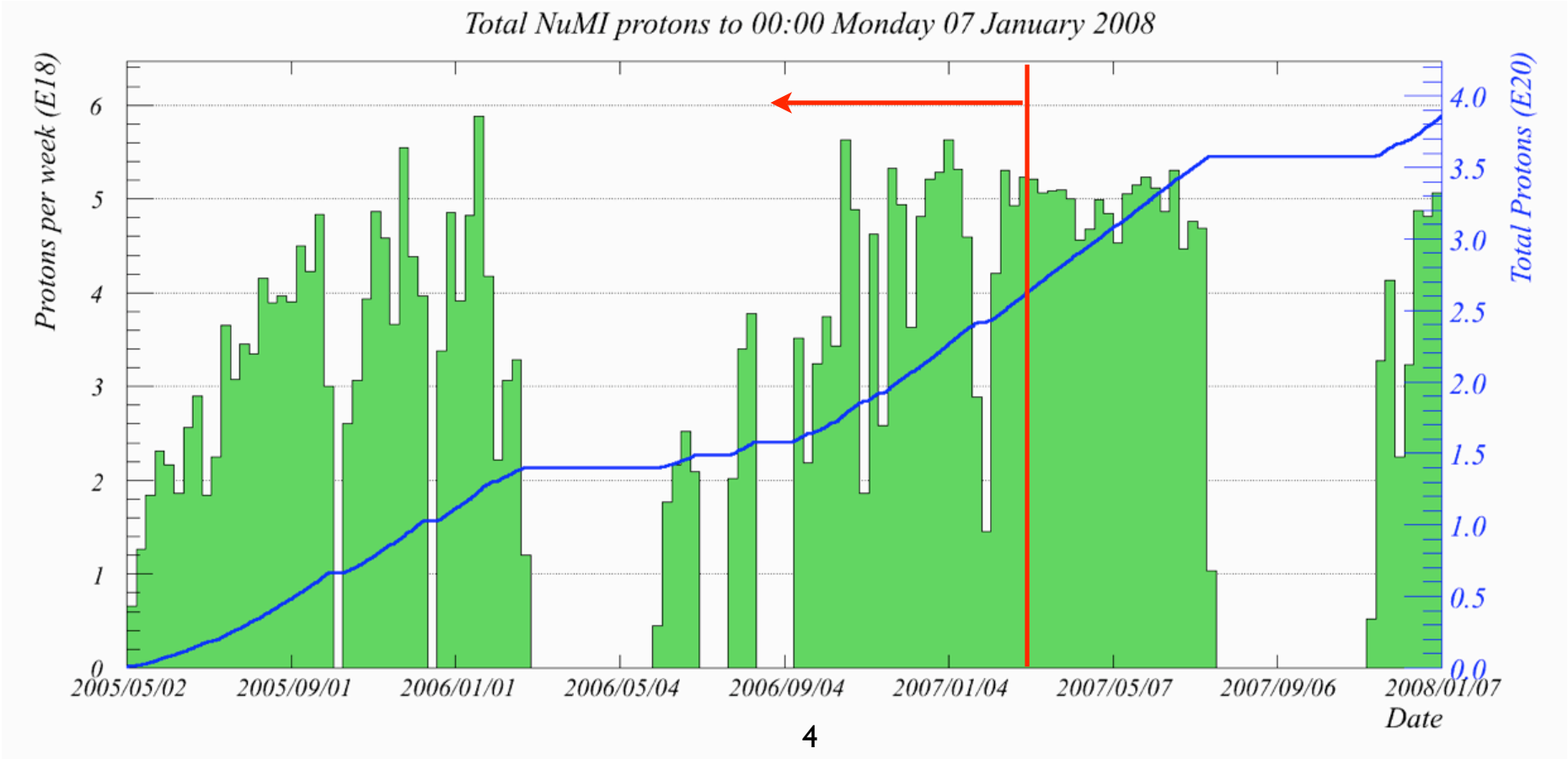


- 120 GeV protons strike graphite target
- Magnetic horns focus produced pions and kaons, pions and kaons decay into muons and neturinos
- Target position adjusts to change beam energy
- 10 μs spill as fast as once every 2 seconds
- 2.5 x 10^{20} POT/year



NuMI Beam Performance

- Data taken from May 2005 - April 2007, 2.46 x 10^{20} POT FD exposure
- Consistently good beam intensity delivered
- Large gaps mainly to accelerator shutdowns



MINOS Overview

- Main Injector Neutrino Oscillation Search is a long baseline neutrino oscillation experiment
- Beam of neutrinos produced using Main Injector at Fermilab
- Measure the neutrinos on site with the near detector
- Measure them again using far detector 735 km away in Soudan Mine
- MINOS main goal is to make a precision measurement of Δm^2_{32}
- Looking for sterile neutrinos, ν_e appearance in the beam and has made measurements on atmospheric ν_μ and $\overline{\nu}_\mu$

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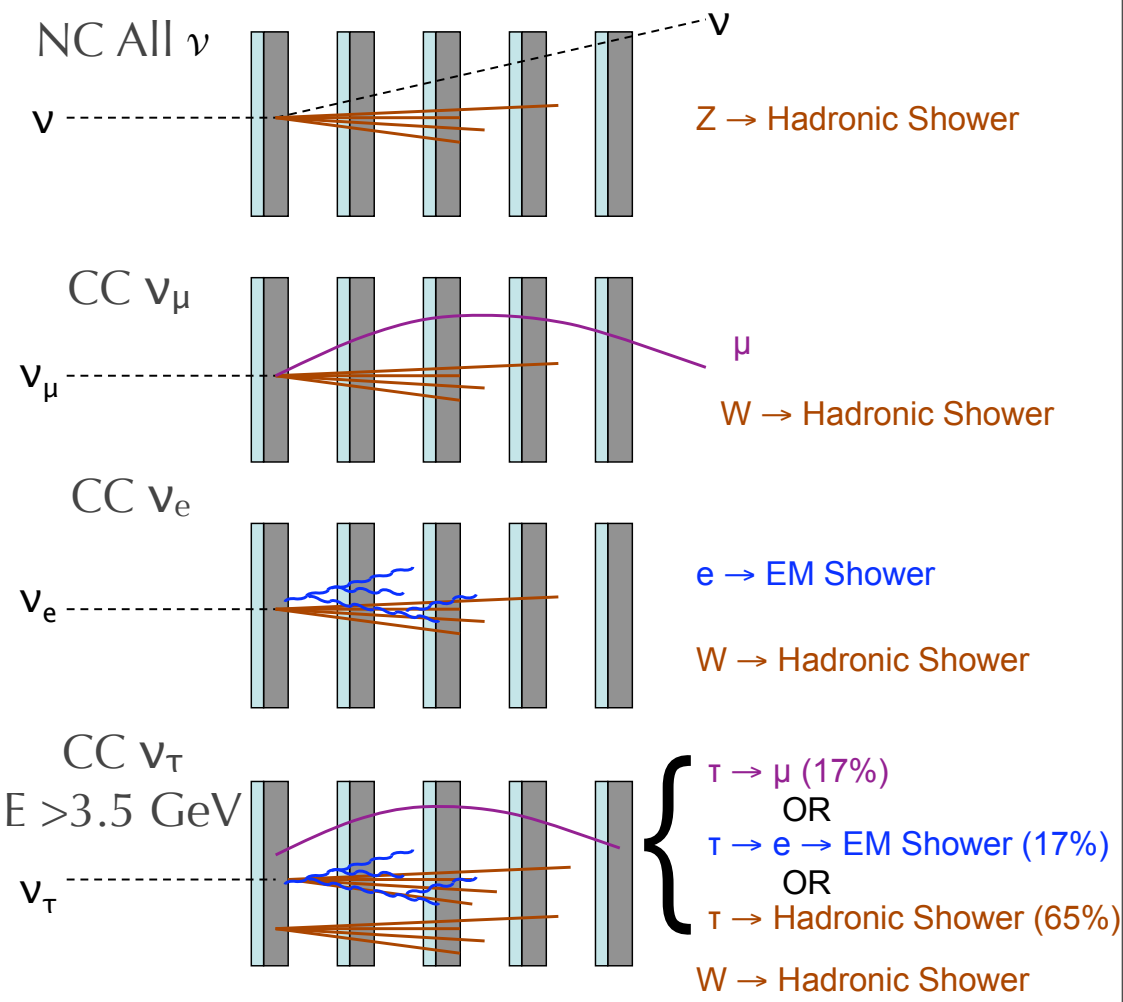
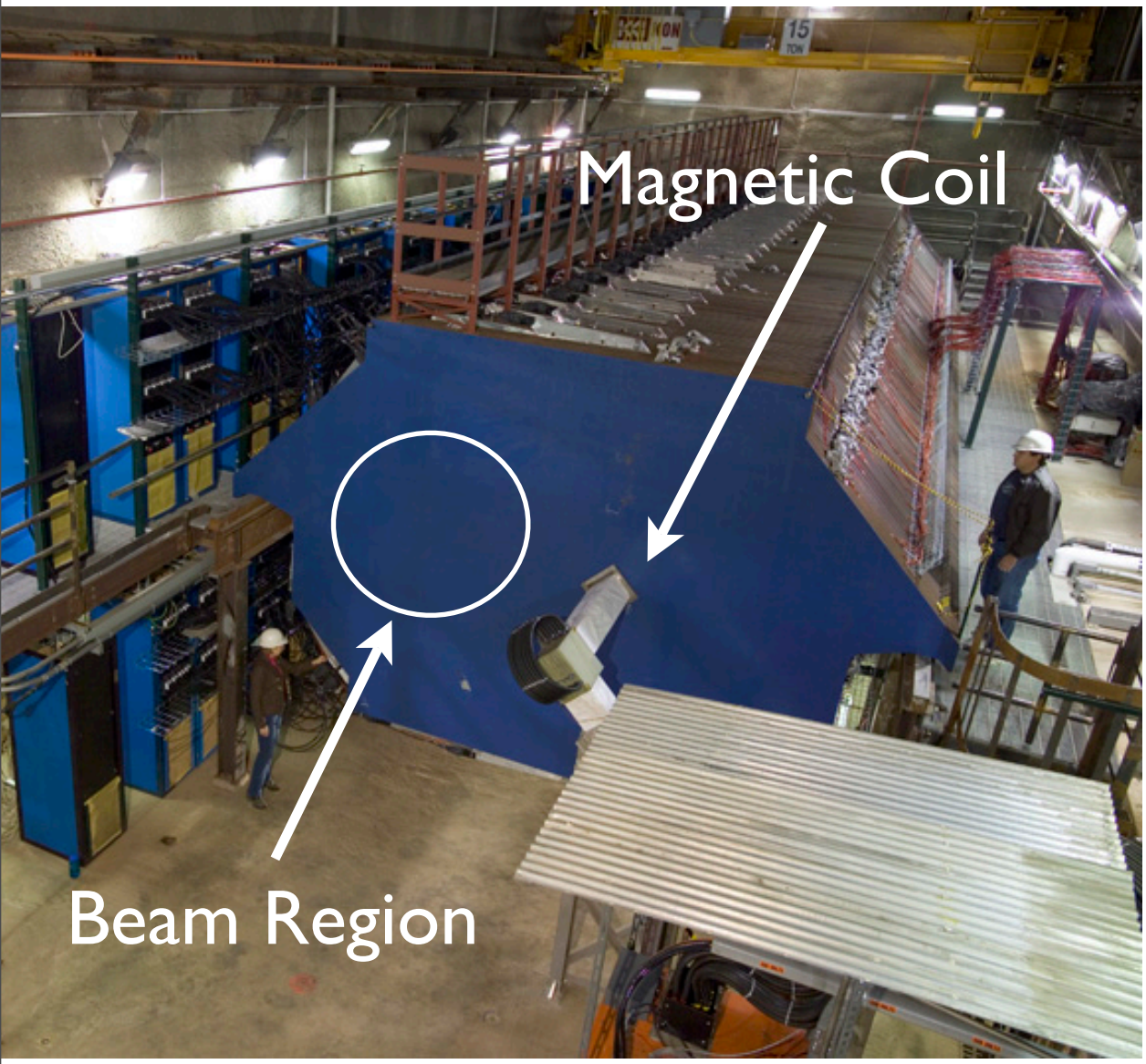
Neutrino Interactions in MINOS

- Detectors are alternating planes of steel and plastic scintillator
- Magnetic field in detectors for charge identification
- MINOS can observe both neutral current (NC) and charged current (CC) interactions
- Reconstructed events are made of tracks and showers
- EM Rad. length = 0.7 steel planes
- Hadronic Int. length = 7 planes
- 2 GeV muon range = 50 planes

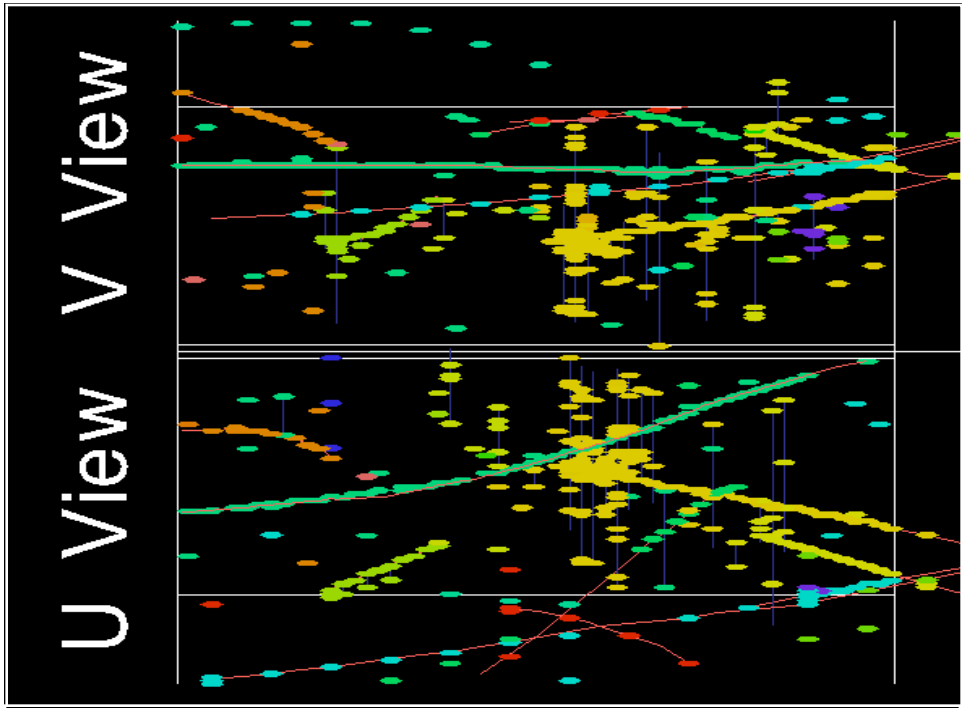


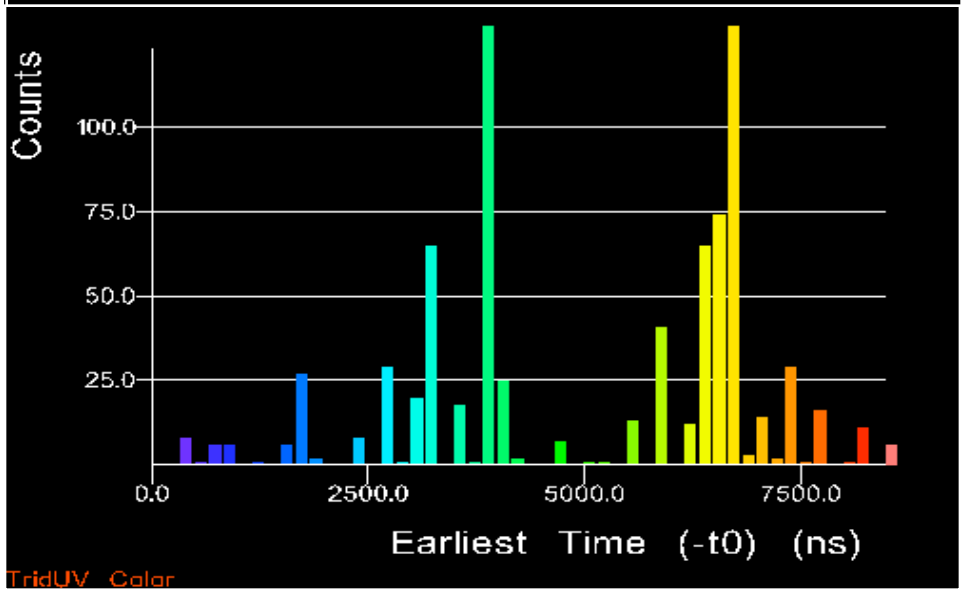
Near Detector



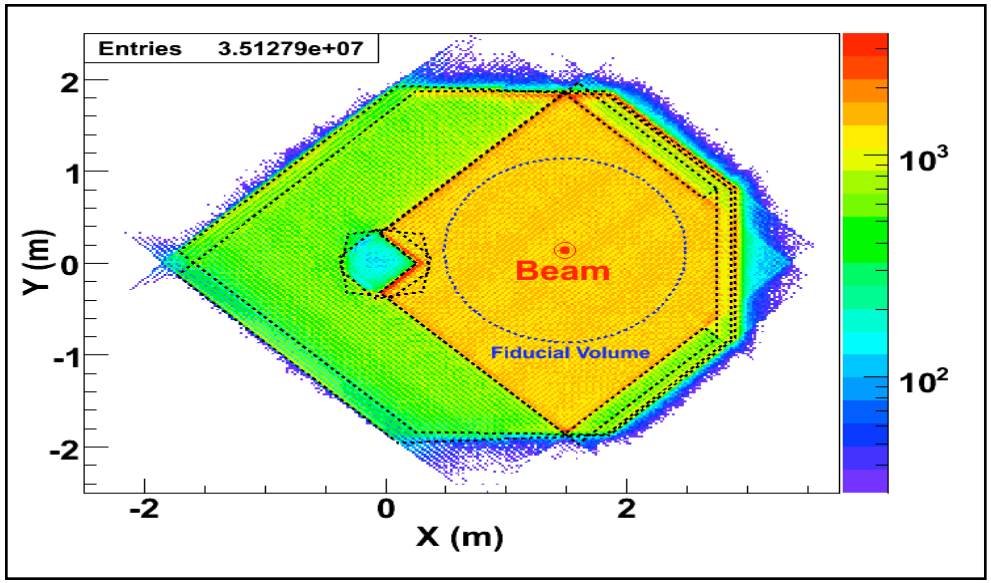
- 980 tons
- 4.8 m x 3.8 m squashed octagon, 282 planes
- 2 sections
  - Calorimeter, every plane instrumented
  - Spectrometer, every 5th plane instrumented
- Front end electronics designed for fast readout to handle high instantaneous neutrino rates

Neutrino Interactions in the Near Detector

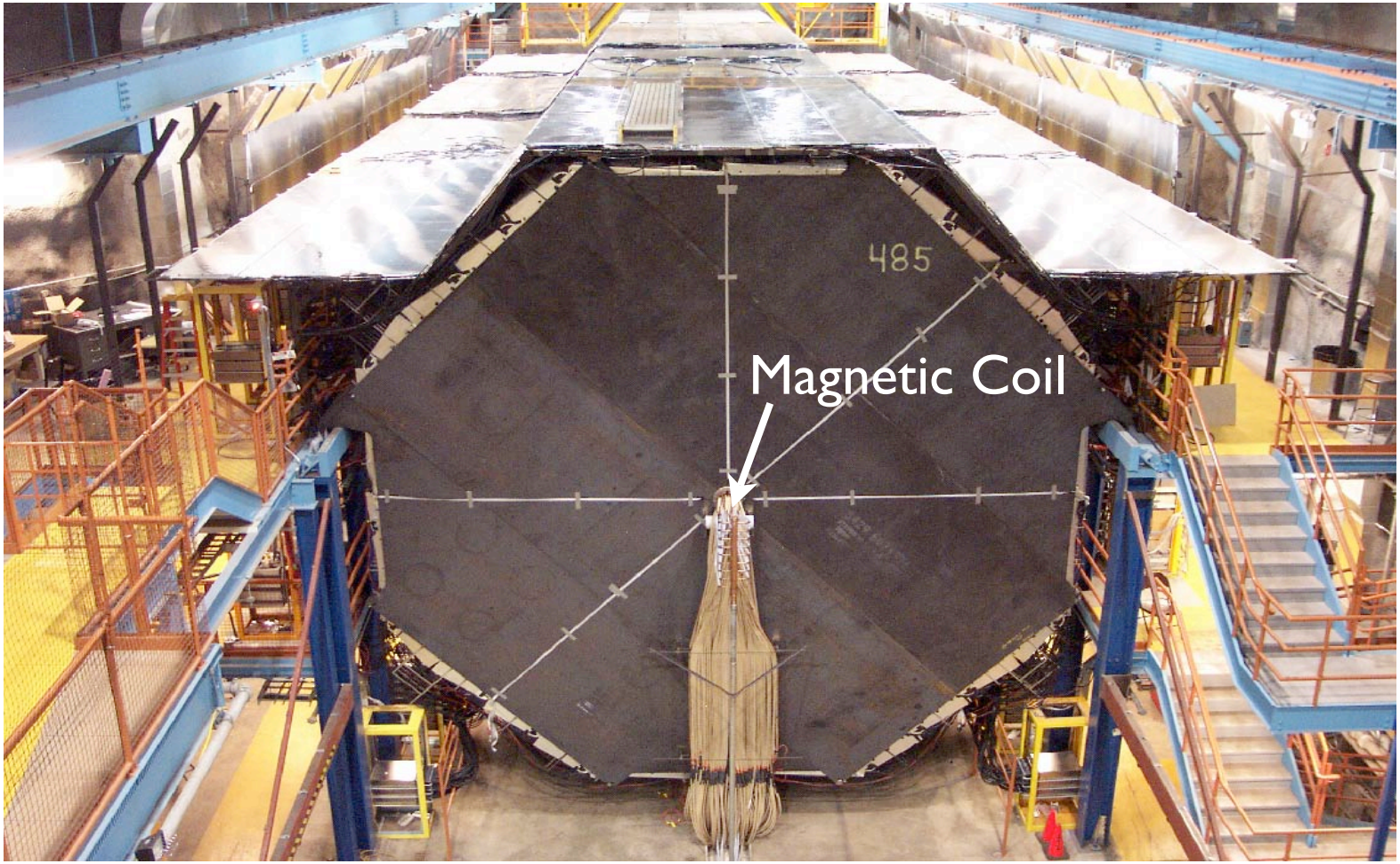




- This display shows activity in the detector for 1 spill
- Separate the events based on topology and timing information
- 3 interactions on average, but up to 10 events per spill possible in the near detector
- ~35 x 10^6 events for 1.27 x 10^{20} POT

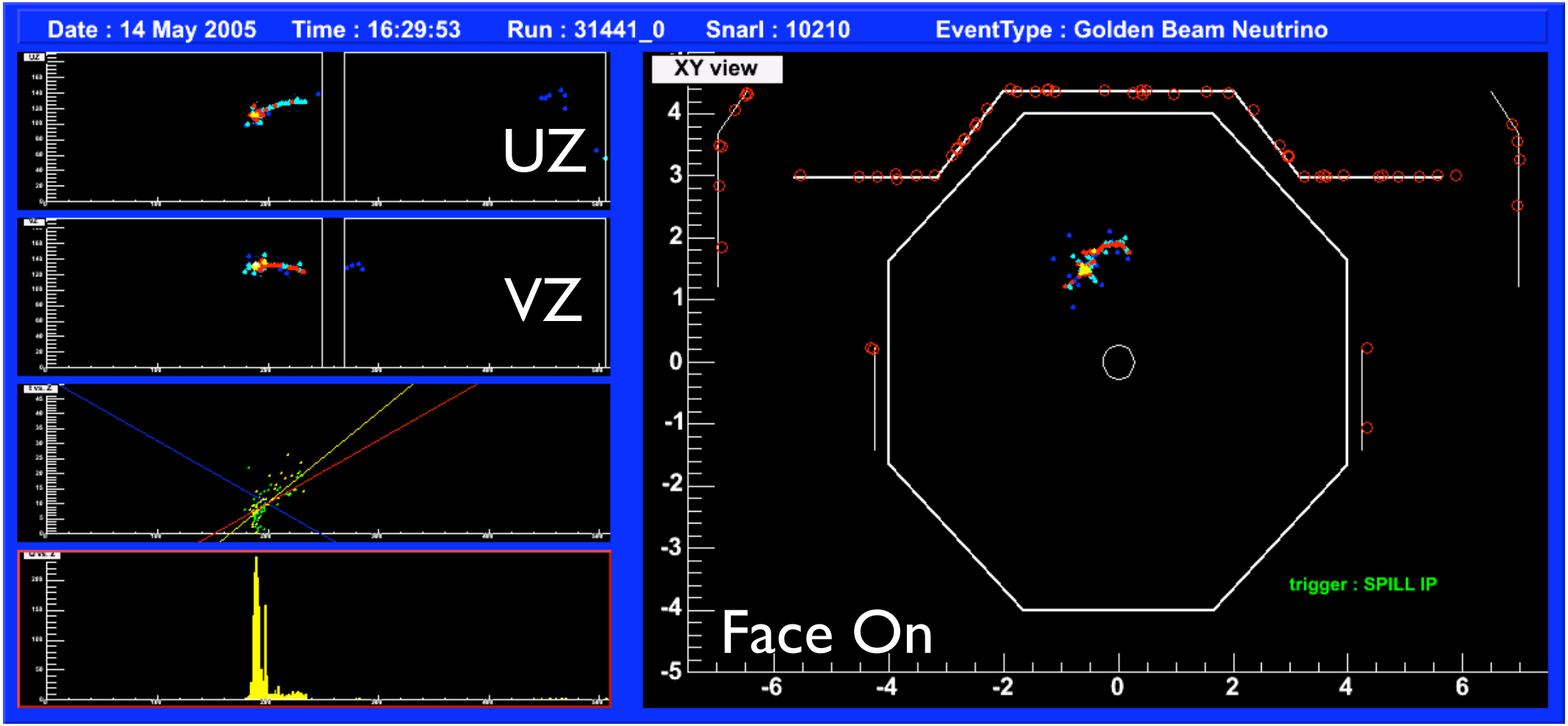


Far Detector



- 5.4 kT, 8 m octagon, 484 instrumented planes, 2 supermodules
- Front end electronics capable of good timing resolution
- ~3 beam neutrino events/day (CC + NC)

Neutrinos in the Far Detector



- Interaction is well away from edges of detector
- Outgoing muon curving towards coil hole

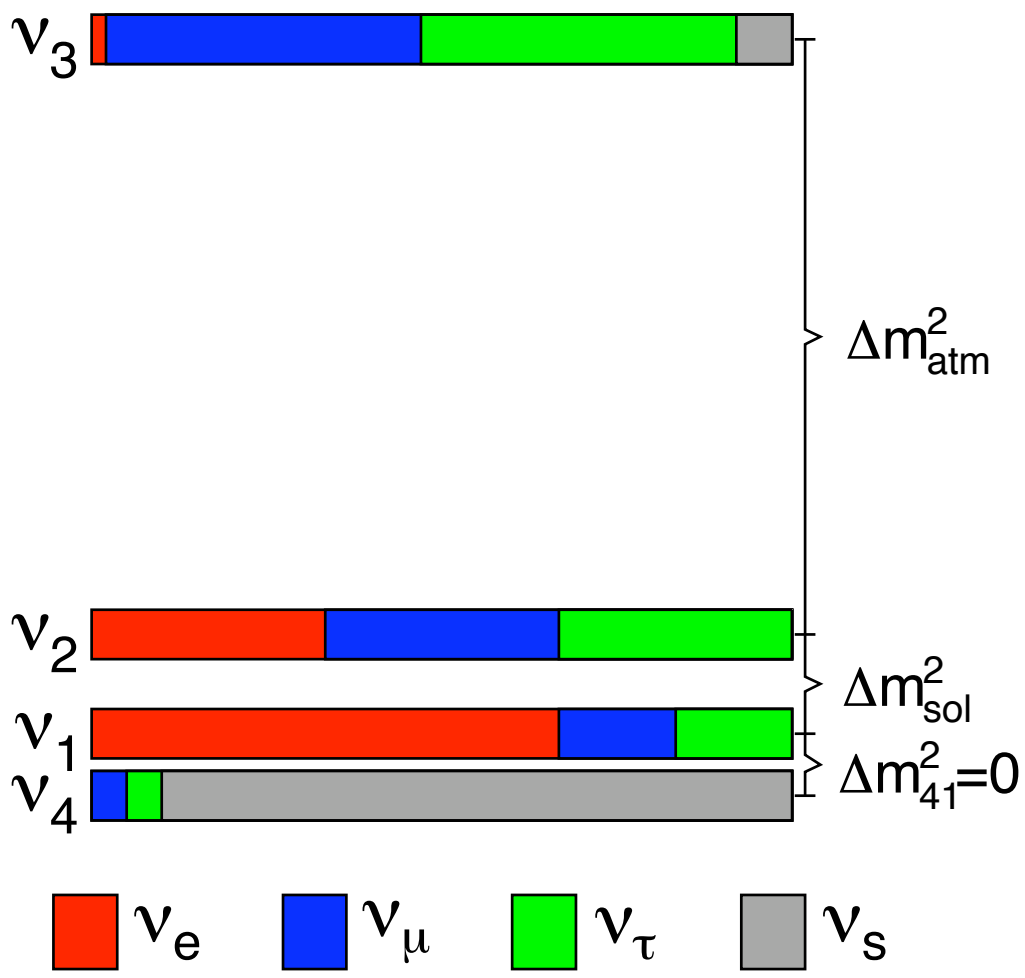
The MINOS Collaboration

Argonne - Athens - Benedictine - Brookhaven - Caltech - Cambridge - Campinas - Fermilab - College de France - Harvard - IIT - Indiana - Minnesota - Minnesota-Duluth - Oxford - Pittsburgh - Rutherford - Sao Paulo - South Carolina - Stanford - Sussex - Texas A&M - Texas - Tufts - University College London - William & Mary - Wisconsin

27 institutions, 175 scientists, funded by DOE, NSF, STFC

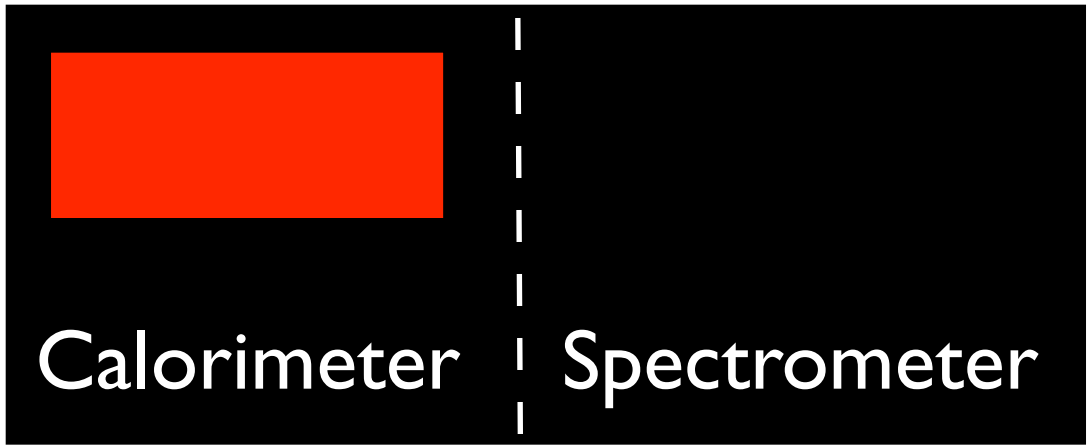
Search for Sterile Neutrinos

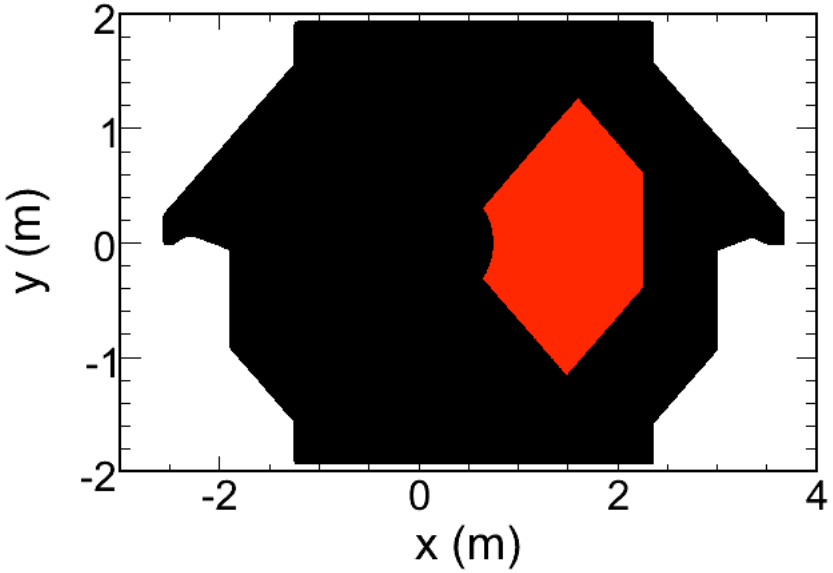
- Total neutrino event rate should be constant for NC events in 3 flavor mixing
- Deficit in expected rate could indicate presence of sterile neutrinos
- Sterile neutrinos do not couple to the W or Z bosons
- They provide a way to generate neutrino mass though see-saw mechanism
- The presence of sterile neutrinos would indicate at least one more mass eigenstate



Possible 4 Flavor Model

Near Detector Event Selection

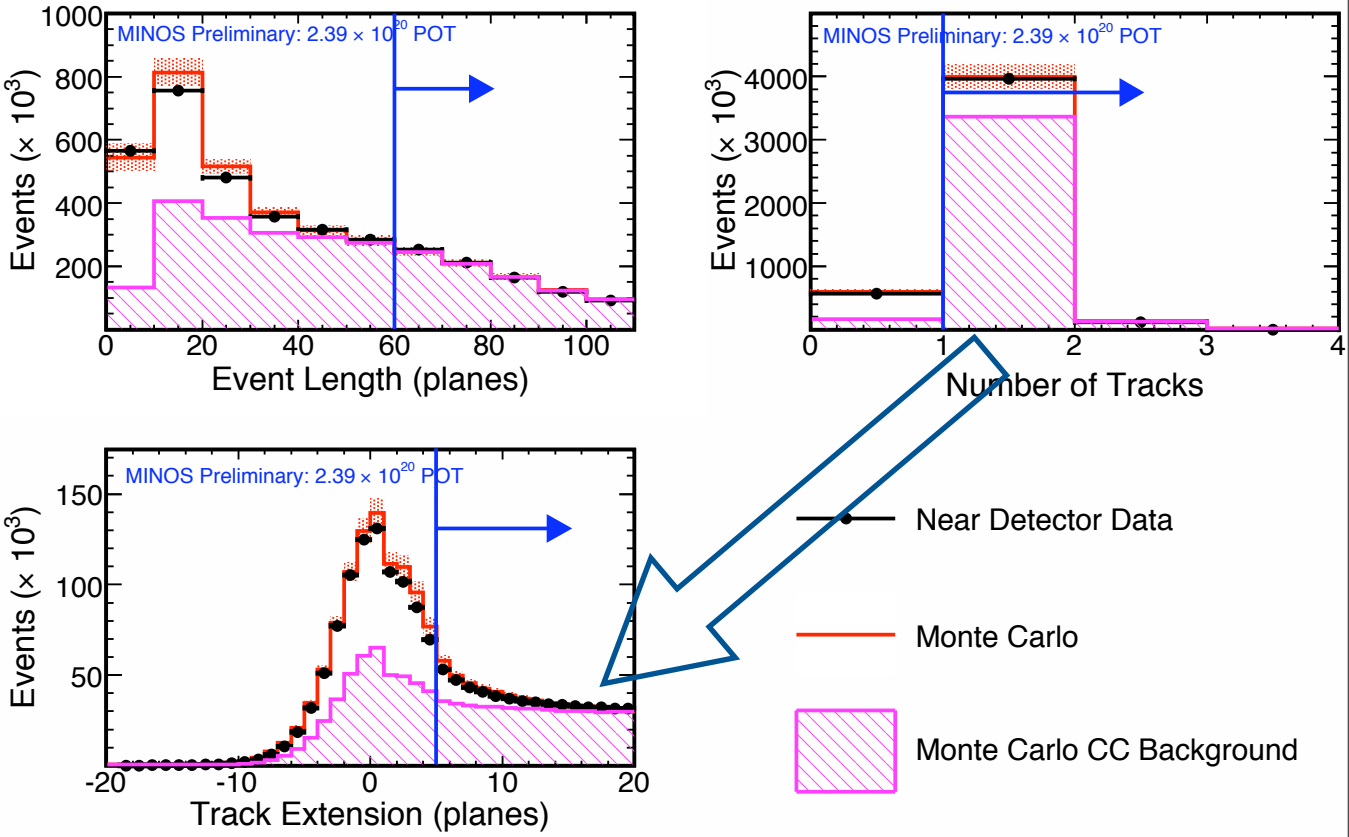




- Use events recorded when beam and detector operating within nominal parameters
- Fiducial volume:
  - Vertex 20 planes from front of detector, 40 planes from start of spectrometer
  - Vertex at least 50 cm from edge of outline of partially instrumented plane
  - Ensures hadronic showers are fully contained in active volume

Identifying NC-like Events

- NC events span fewer planes than CC events
- Expect large showers in NC events, no tracks
- Apply 3 selection criteria
  - Events crossing > 60 planes → CC
  - Remaining events without a track → NC
  - Remaining events with track extension < 5 → NC
- Main background from inelastic ν_μ-CC events



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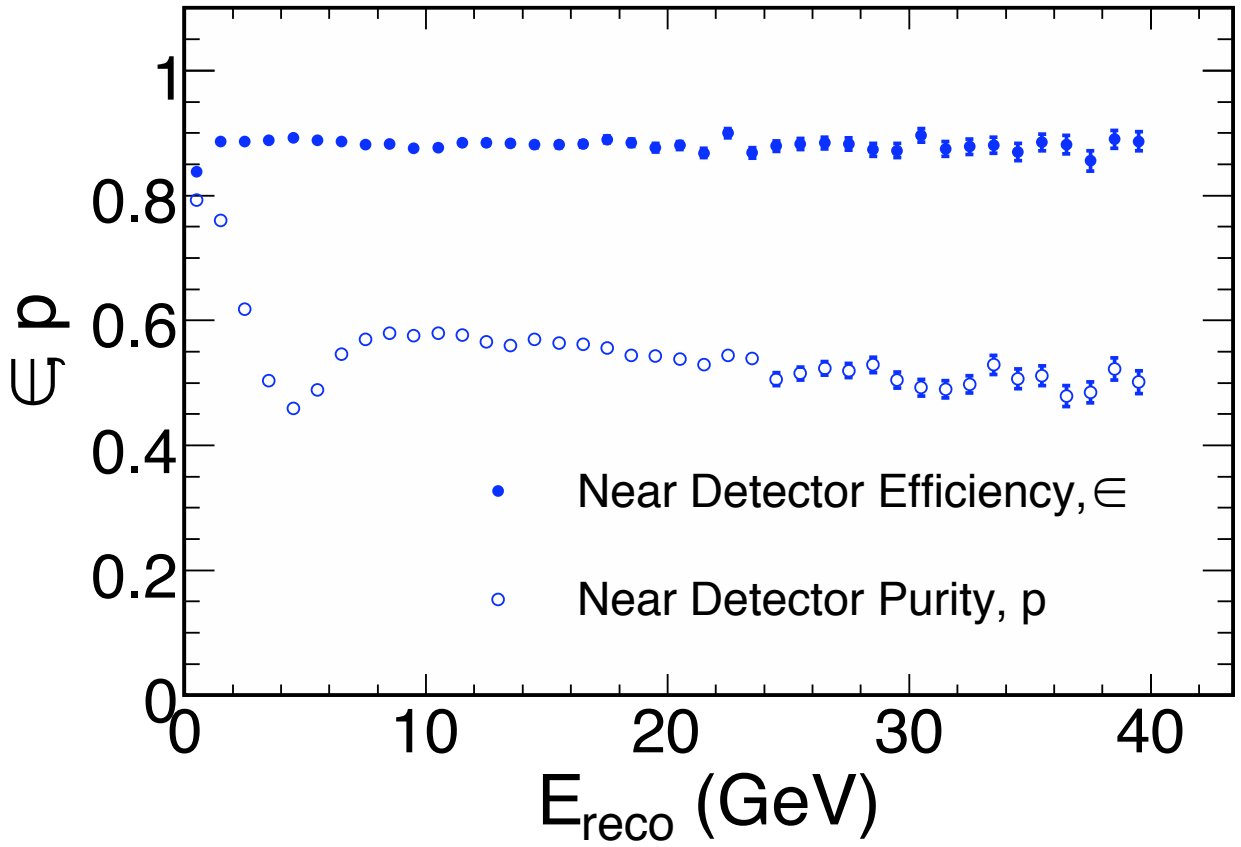
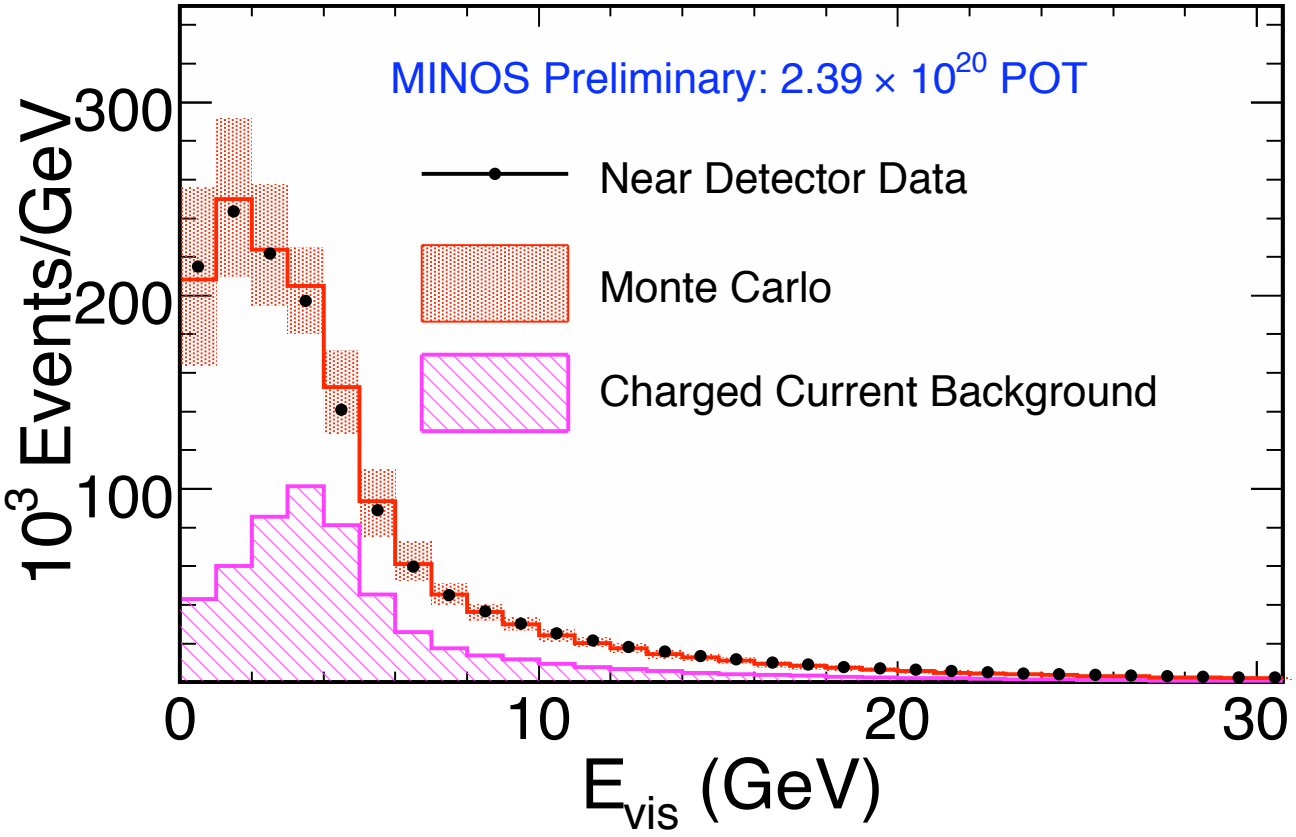


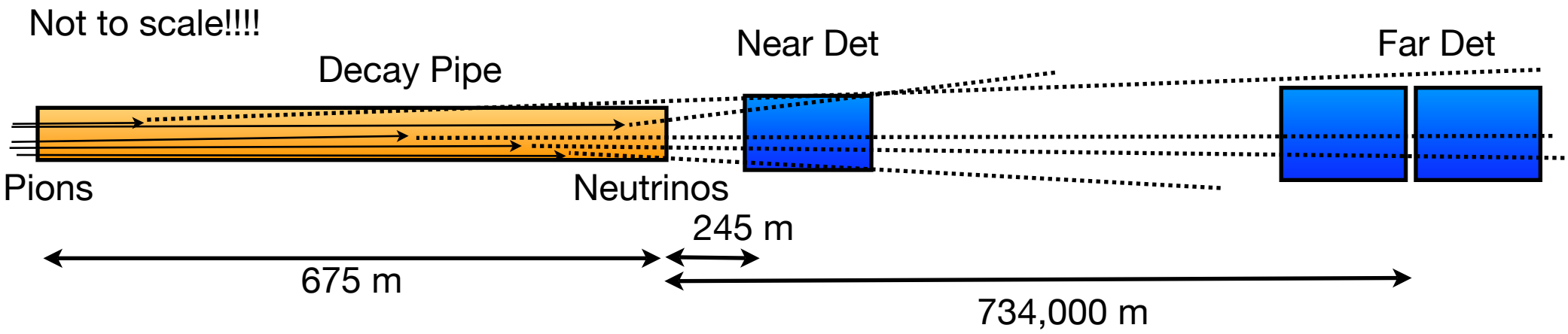
Near Detector Neutral Current Spectrum



- Energy spectrum from near detector shown
- CC background is about 50% of total events
- Use this spectrum to predict spectrum at far detector

Extrapolation to Far Detector

- Use near detector to predict far detector spectrum
- Near and far detectors see different spectra of neutrinos
  - Beam is a line source at the near detector
  - Beam is a point source at the far detector
- Near detector sees more low energy neutrinos from large angle pion decays near the end of the decay pipe



Extrapolating to the Far Detector

- Ratio of events in a given bin in FD relative to ND is same for data and MC

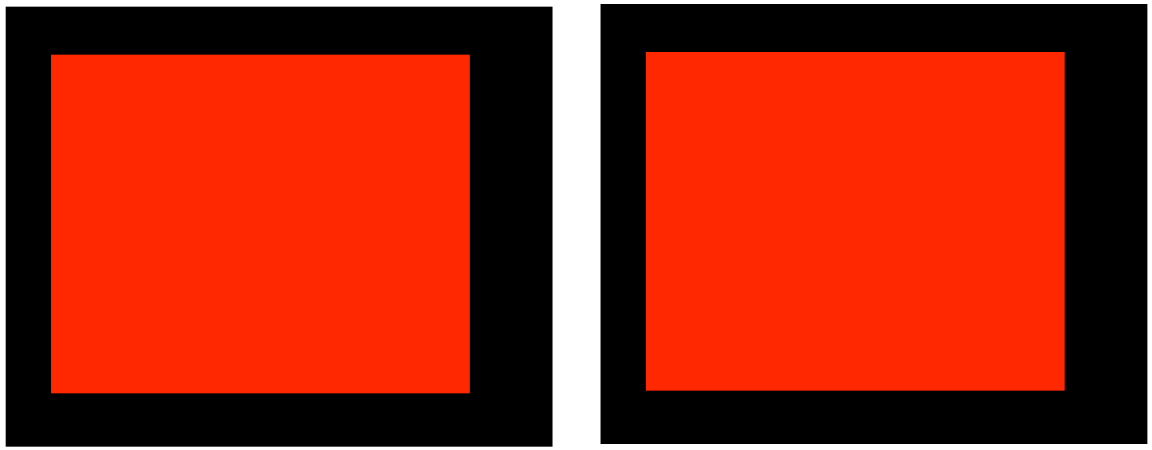
$$F_i^{predict} = N_i^{Data} \frac{f_i^{MC}(osc)}{n_i^{MC}}$$

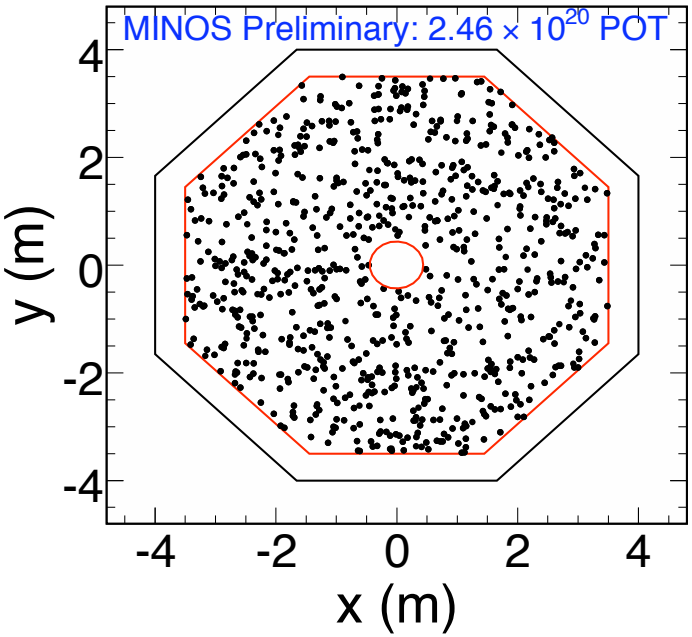
- Use ratio to cancel systematic uncertainties
- Effectively a bin by bin fit of MC to the data
- Makes prediction robust against uncertainties with energy dependence

Blind Analysis

- The analysis of NC-like events was blind
- Unknown algorithm used to hide >30% of events in far detector
- Near detector data are open
- Develop techniques to identify NC-like events and extrapolation to far detector before looking at far detector events
- Collaboration decided analysis was ready to open the box

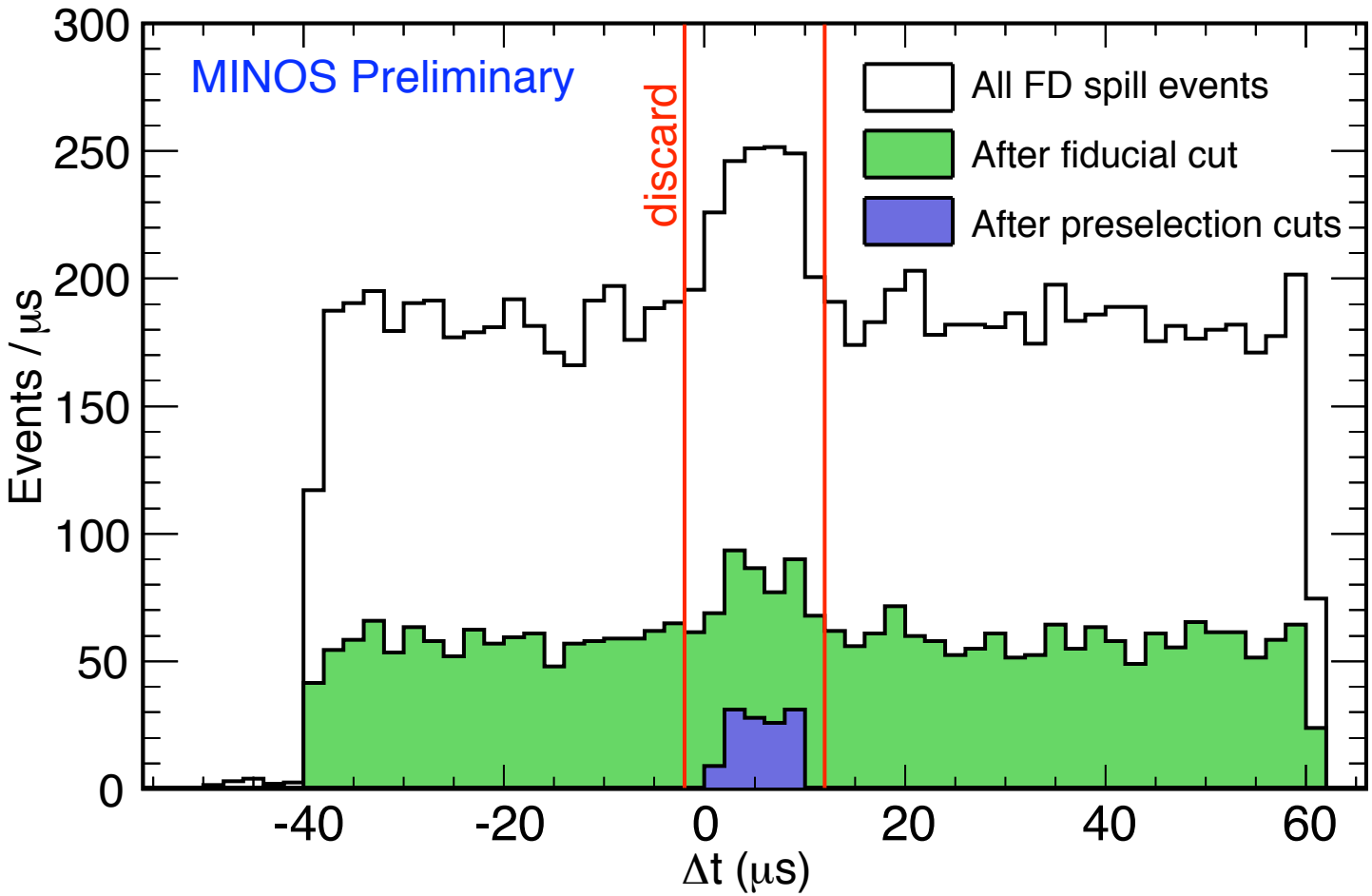
Far Detector Event Selection





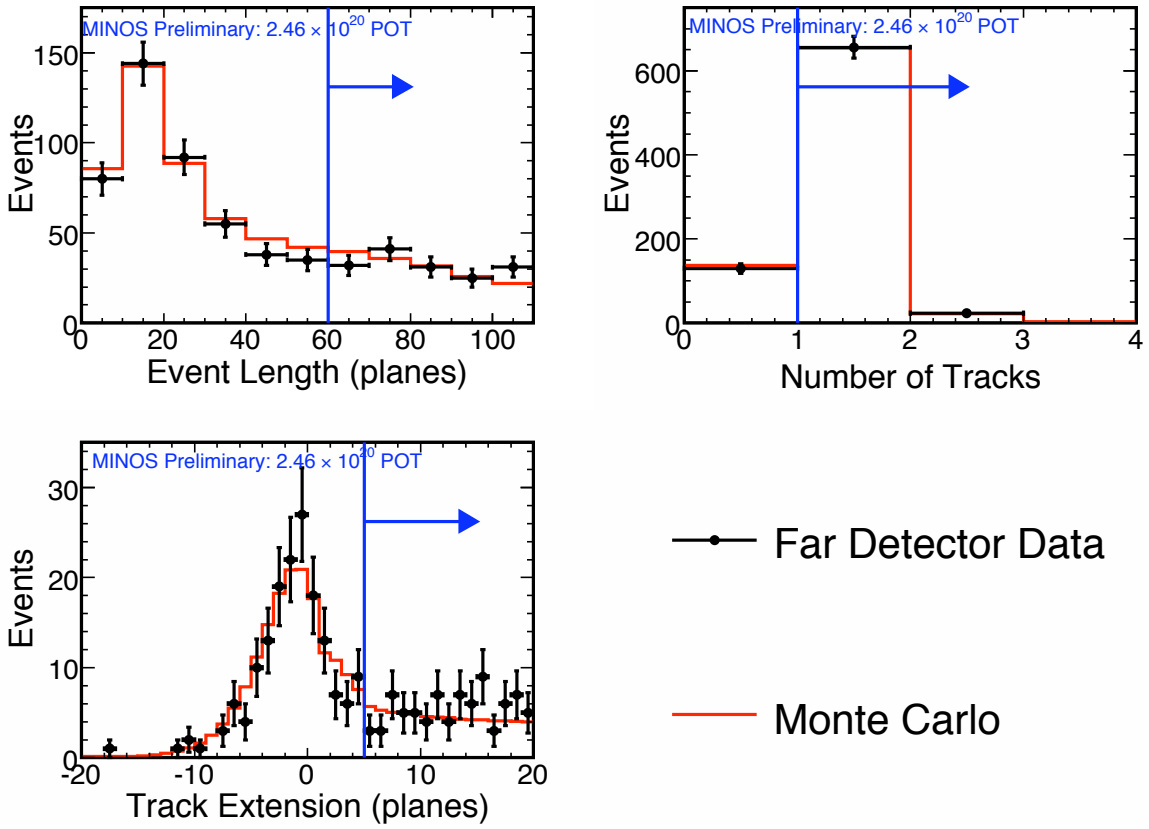
- Use events recorded when beam and detector operating within nominal parameters
- Fiducial volume:
  - Vertex 5 planes from front of each supermodule, 17 planes from end
  - Vertex at least 50 cm from outside edge of detector, 45 cm from center
  - Ensures hadronic showers are fully contained in active volume

Far Detector Event Selection



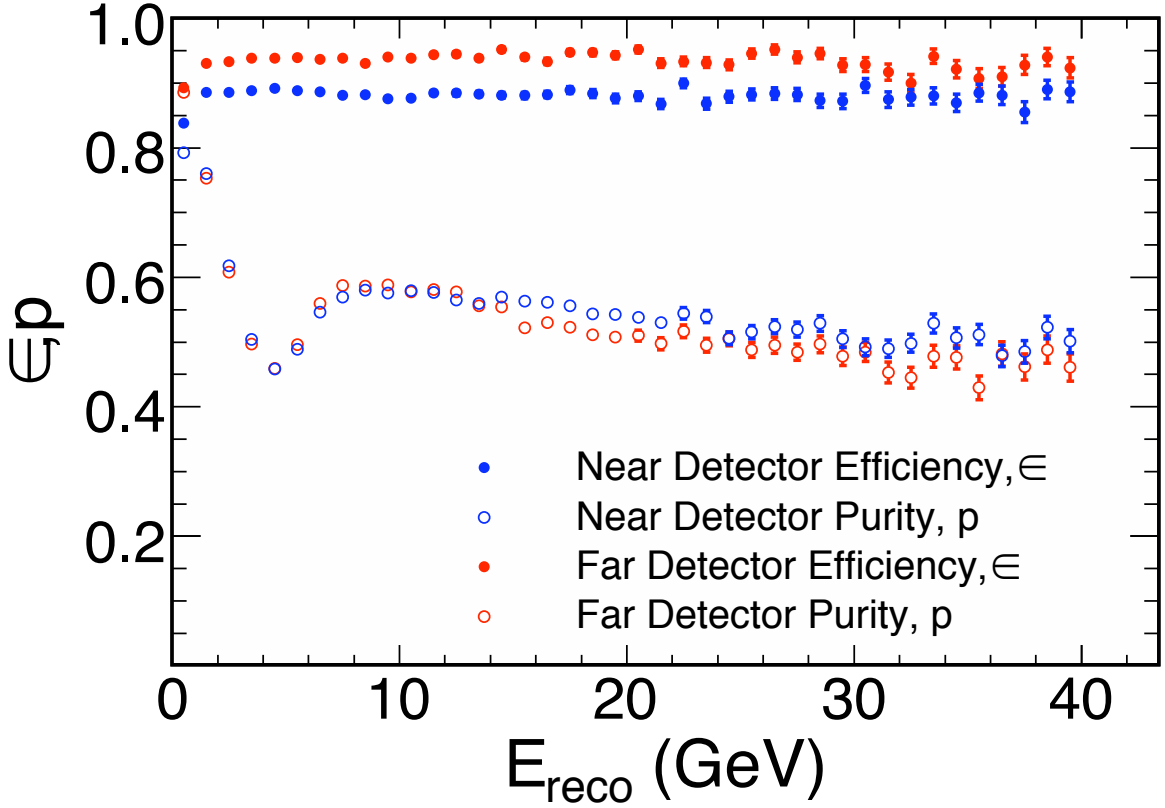
- Potential backgrounds from cosmic rays, noise, reconstruction failures
- Series of cuts remove each
- Most hits read out in FD during beam spills are due to noise
- Timing information from beam is final step in event selection

Far Detector Data



- NC events selected using same cuts as ND
- Monte Carlo prediction made assuming mixing between 3 active flavors
  - $\Delta m^2_{32} = 2.38 \times 10^{-3}$ eV^2
  - $\sin^2 2\theta_{23} = 1$
- Similar efficiencies and purities in both detectors

Far Detector Data



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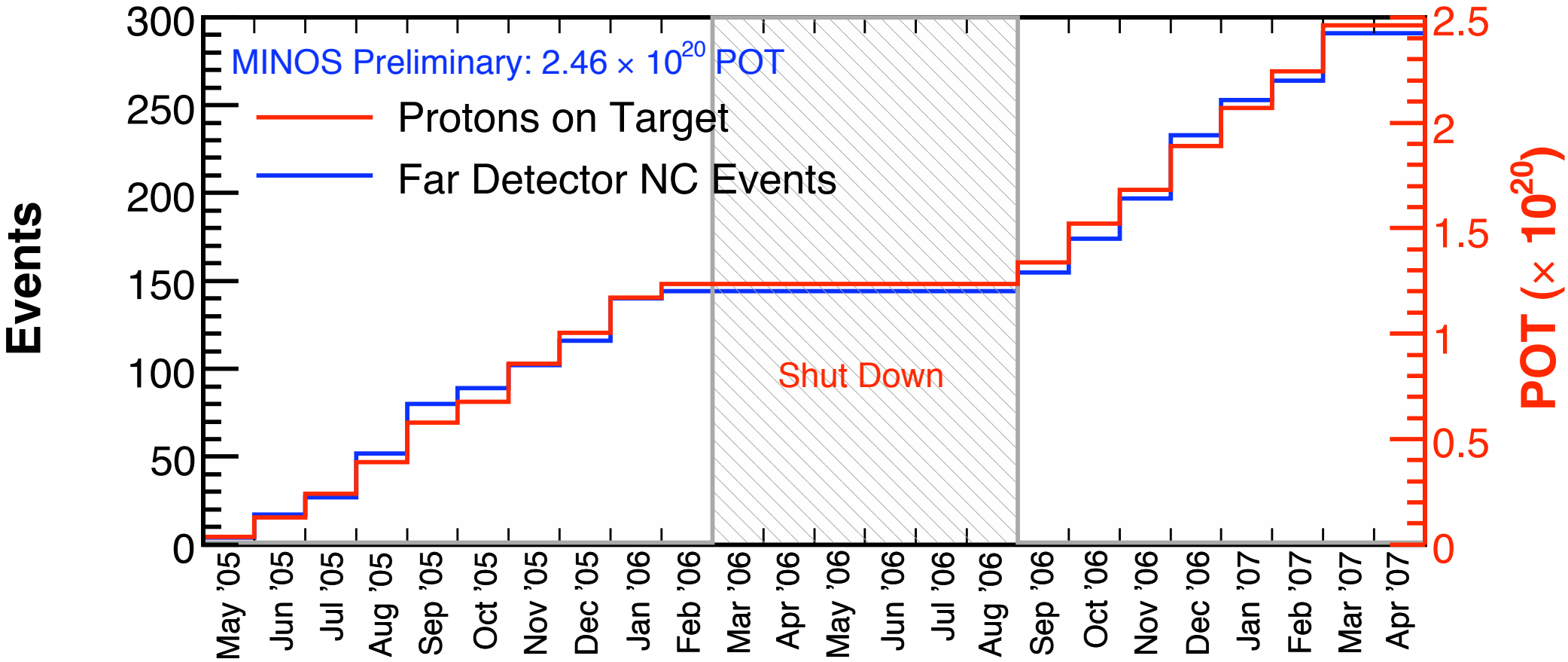
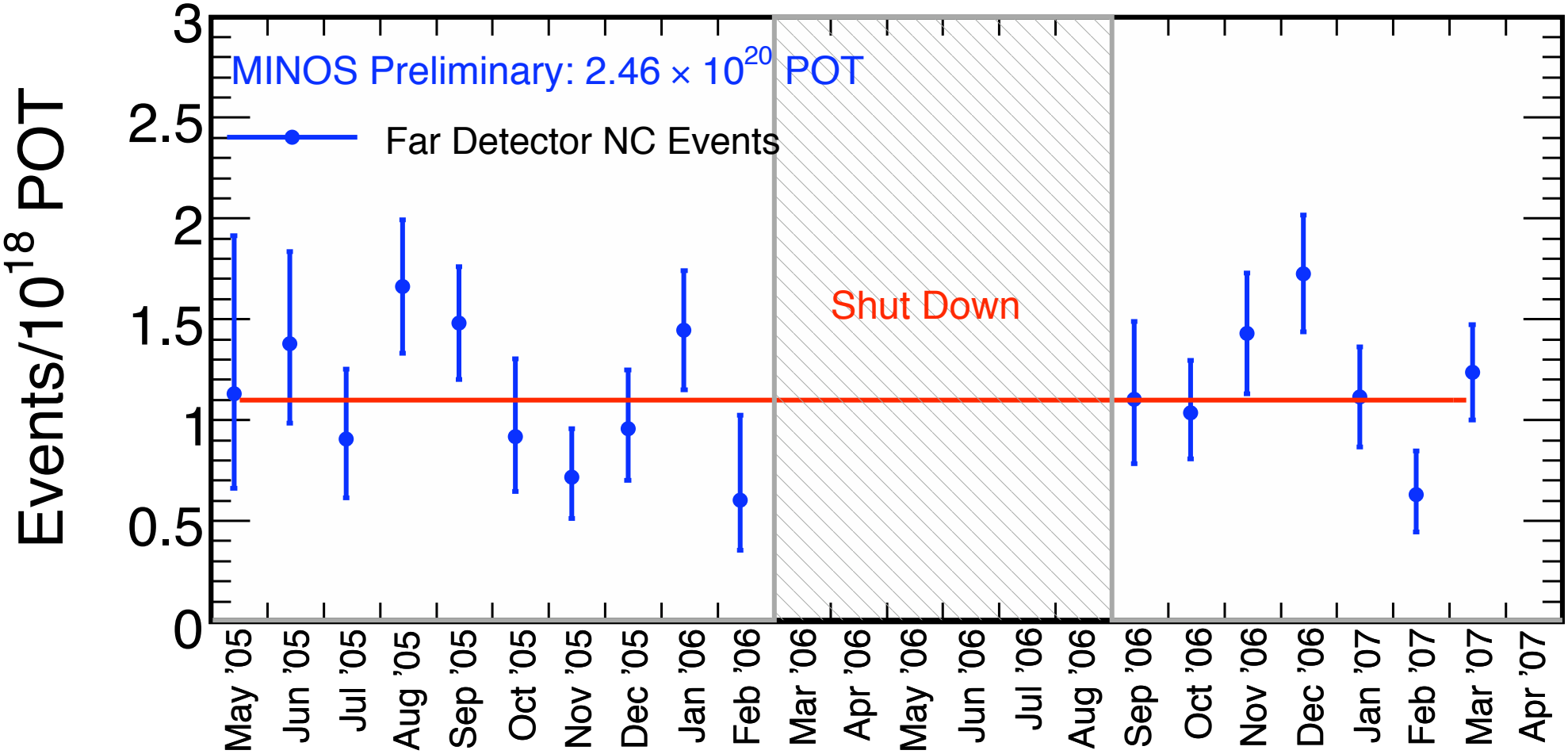
Far Detector NC-like Event Collection



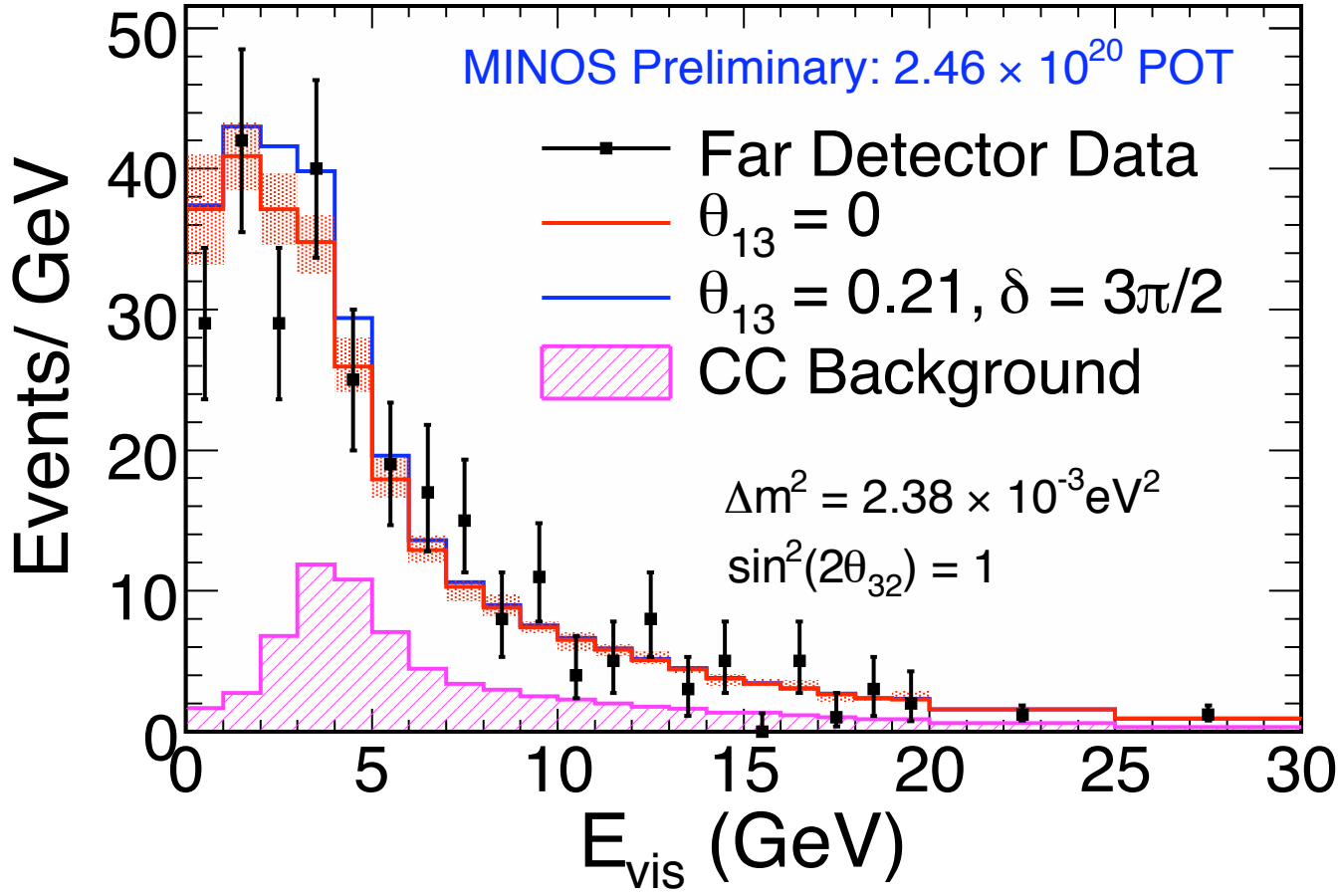
- Number of NC-like events recorded follows number of POT collected

Far Detector NC-like Event Rate



- Number of NC-like events is constant over time
- Average of 1.1 events per 10^{18} POT (~1 every 10^4 spills)

Three Flavor Analysis



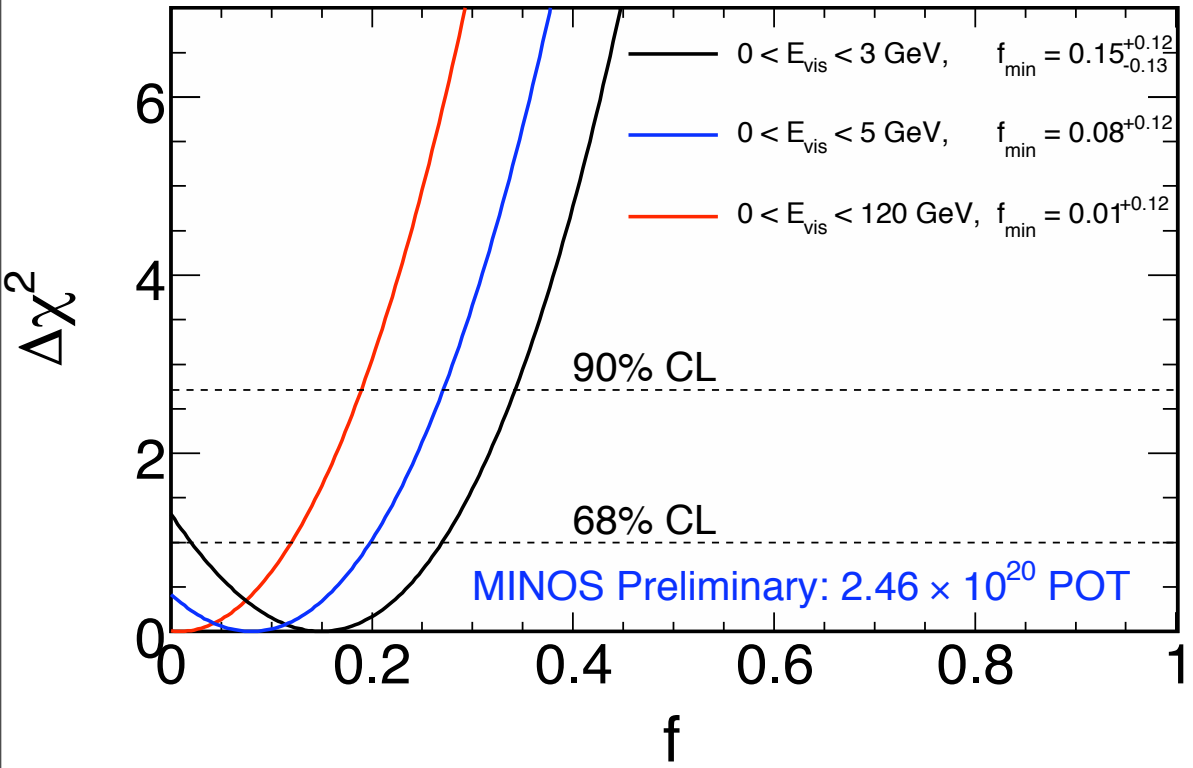
- Test data for consistency with 3 flavor mixing
- ν_e CC events identified as NC-like with nearly 100% efficiency
- Compare data to predictions with and without ν_e appearance in beam

Three Flavor Analysis

Energy (GeV)	Data	MC $\theta_{13} = 0$	σ $\theta_{13} = 0$	MC $\theta_{13} = 0.21, \delta = 3\pi/2$	σ $\theta_{13} = 0.21, \delta = 3\pi/2$
0 - 3	100	115.2±7.7	1.15	122.1±8.8	1.56
0 - 5	165	175.9±10.5	0.42	191.3±12.3	1.42
0 - 120	291	292.6±15.0	0.01	311.5±16.6	0.79

- Table shows observed and expected events for 3 energy ranges
- Systematic uncertainties shown
- Data and Monte Carlo agree to within 1-2σ for all energy ranges

Disappearance Fraction



Background from CC interactions

$$1 - f = \frac{N_{Data} - B_{CC}}{S_{NC}}$$

Signal of NC interactions

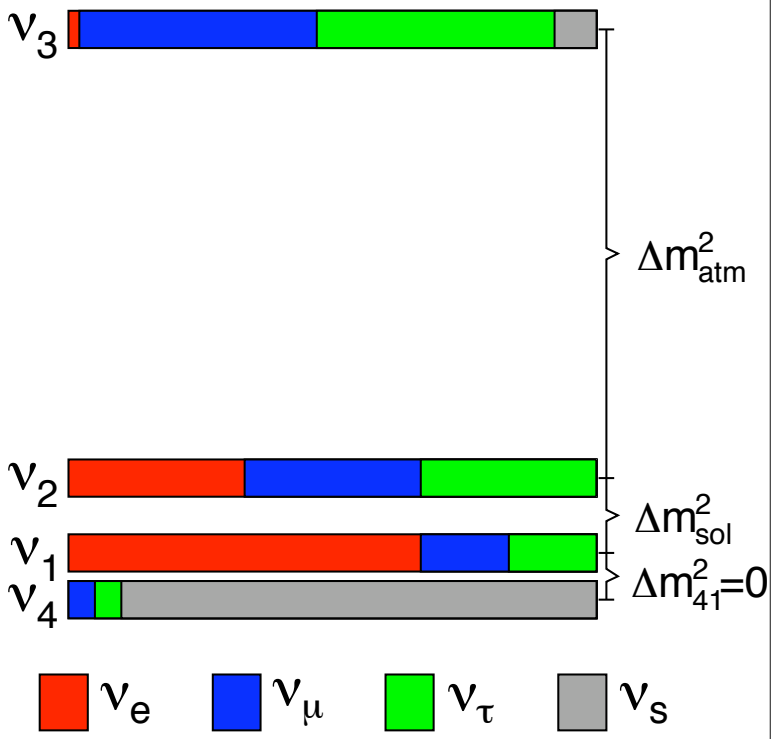
- Expect largest disappearance for E < 3 GeV if active flavors convert to sterile states with Δm^2_{32}
- Table shows uncertainties in *f*
- f < 35% at 90% CL for that energy range

	0 – 3 GeV
Absolute E_{had}	±0.00
Relative E_{had}	±0.03
Normalization	±0.04
ND selection	±0.02*
ν_μ CC background	$^{+0.04}_{-0.05}$
Total:	$^{+0.06}_{-0.07}$

ND Event selection only affects E < 1 GeV

Four Flavor Analysis

- Compare data to model with 1 sterile neutrino
- Set 4th mass eigenstate to be degenerate with 1st
- Assume no sterile component in 1st or 2nd and $\Delta m^2_{21} = 0$
- Amount of mixing between active and sterile neutrinos is $|U_{s3}|^2$
- Energy scale for mixing is Δm^2_{atm}

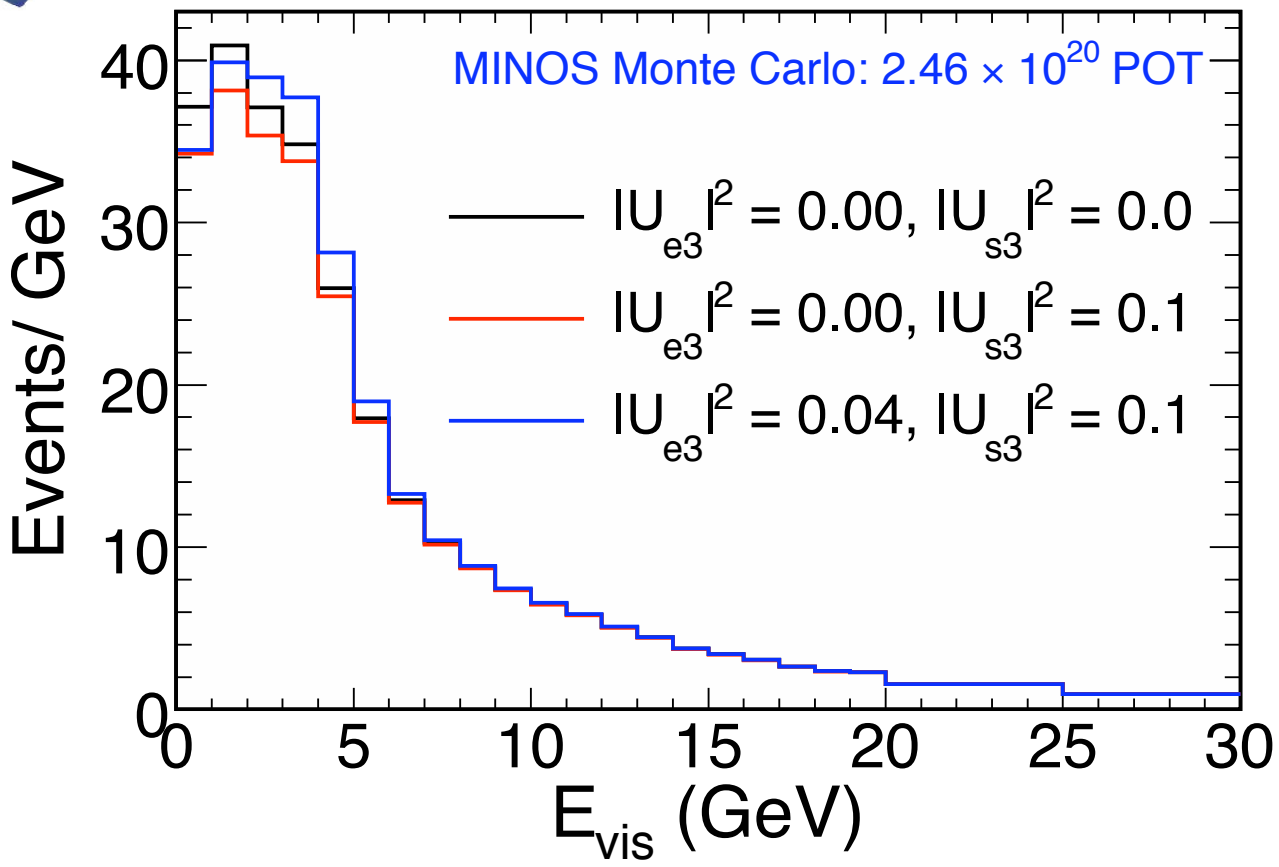


$$
\begin{aligned}
P_{\nu_\mu \to \nu_\mu} &= 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)\sin^2(1.27\Delta m^2_{31}L/E) \\
P_{\nu_\mu \to \nu_e} &= 4|U_{\mu 3}|^2|U_{e3}|^2\sin^2(1.27\Delta m^2_{31}L/E) \\
P_{\nu_\mu \to \nu_s} &= 4|U_{\mu 3}|^2|U_{s3}|^2\sin^2(1.27\Delta m^2_{31}L/E) \\
P_{\nu_\mu \to \nu_\tau} &= 1 - P_{\nu_\mu \to \nu_\mu} - P_{\nu_\mu \to \nu_e} - P_{\nu_\mu \to \nu_s}
\end{aligned}
$$

$$
U = \begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{bmatrix}
$$

Fit Fix

Four Flavor Analysis- MC Prediction

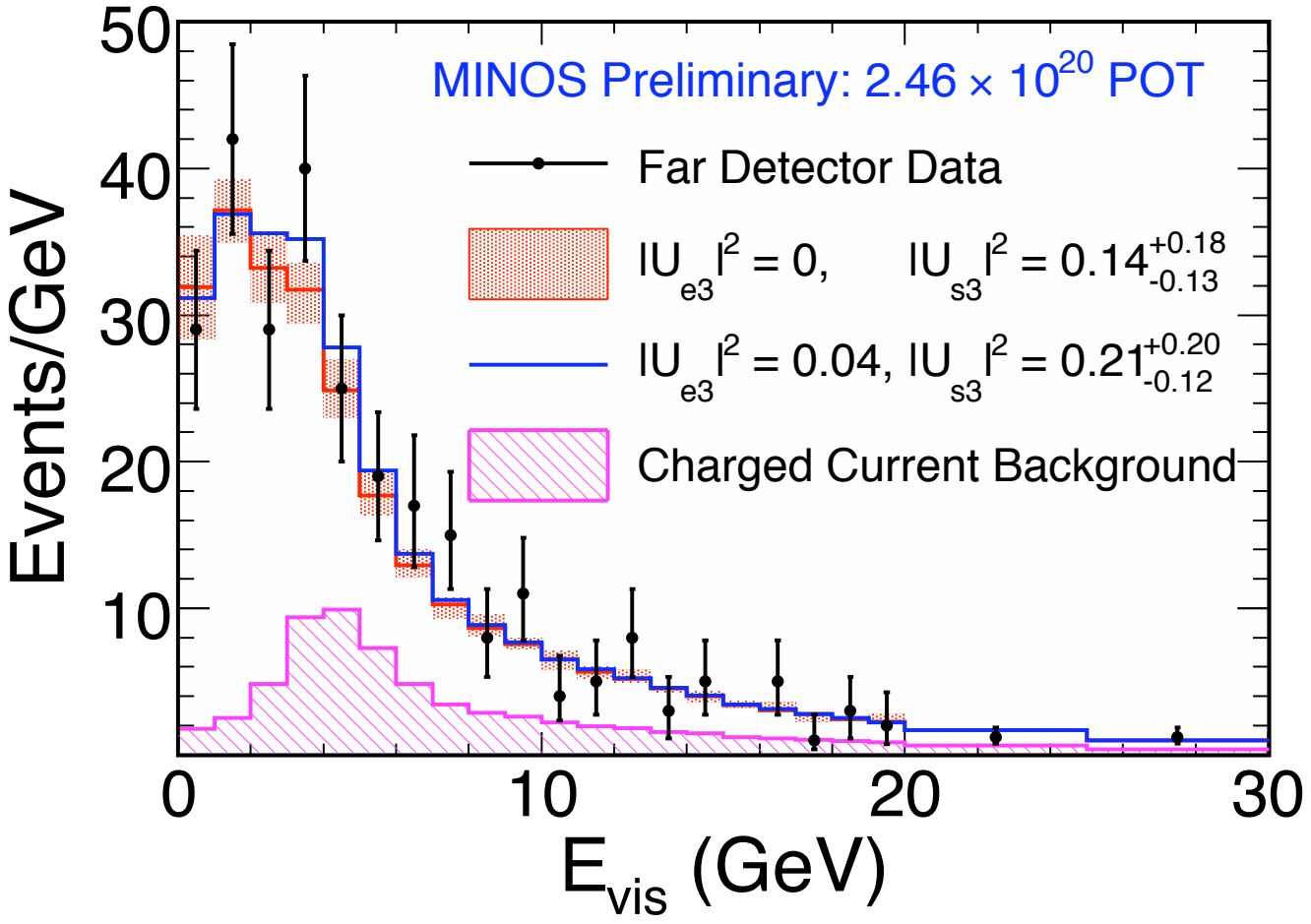


$\Delta m^2_{32} = 2.38 \times 10^{-3}$ eV^2

$|U_{\mu 3}|^2 = 0.5$

- Plot shows far detector expectations for different mixing scenarios
- Sterile neutrino causes largest depletion in 0-3 GeV range
- ν_e appearance has largest effect in 1-5 GeV range

Four Flavor Analysis - Data



- Use largest systematic uncertainties as nuisance parameters in fit

$$\chi^2 = 2\sum_i e_i - o_i + o_i \ln\frac{o_i}{e_i} + \sum_j \frac{\epsilon_j^2}{\sigma_j^2}$$

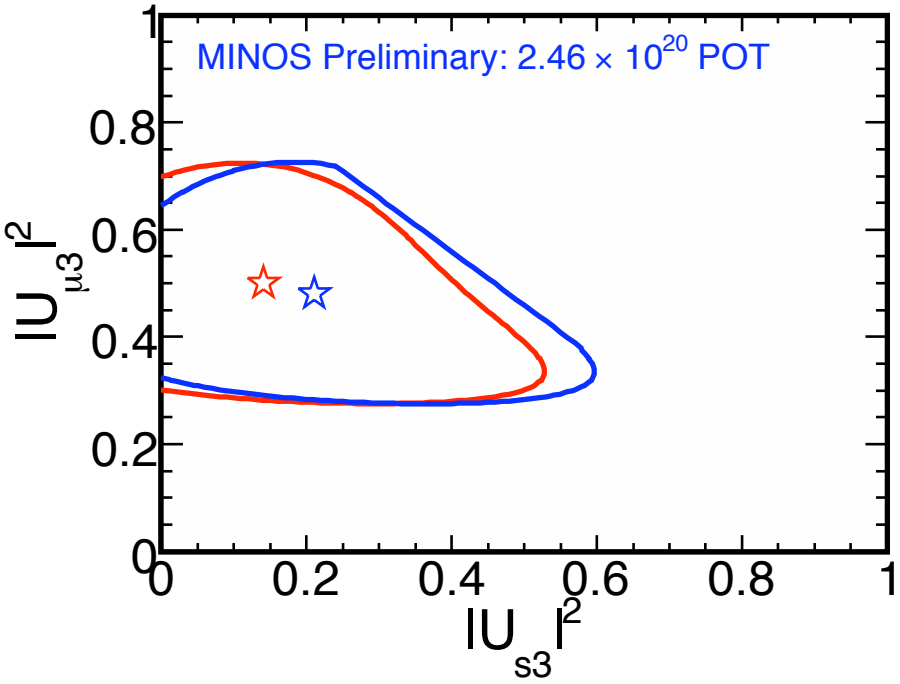
- χ^2/ndf = 47/43 for both scenarios

Measurement of $|U_{s3}|^2$

Far Detector $\quad \Delta_{41} \equiv 0$

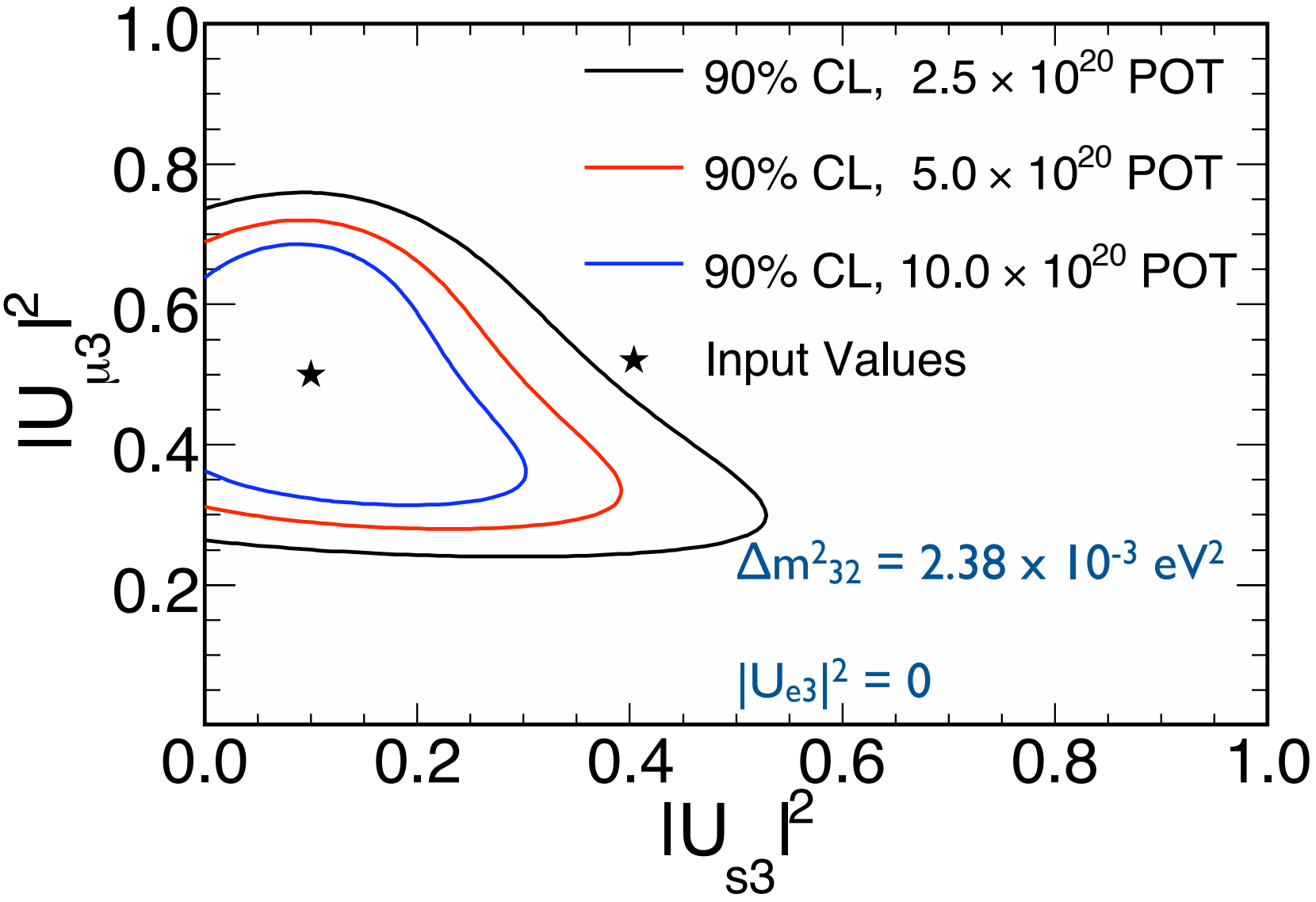
$|U_{e3}|^2 = 0$ $\quad$ $|U_{\mu 3}|^2 = 0.50^{+0.16}_{-0.15}$ $\quad$ $|U_{s3}|^2 = 0.14^{+0.18}_{-0.13}$

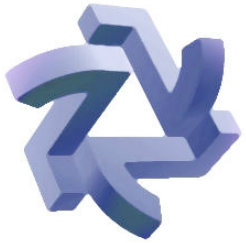
$|U_{e3}|^2 = 0.04$ $\quad$ $|U_{\mu 3}|^2 = 0.48^{+0.18}_{-0.12}$ $\quad$ $|U_{s3}|^2 = 0.21^{+0.20}_{-0.12}$



- 90% contours with and without ν_e appearance shown
- Including ν_e appearance causes contour to run up to unitarity bound
- Results for $|U_{s3}|^2$ are consistent with *f* values from 3 flavor analysis

Sensitivity to $|U_{s3}|^2$

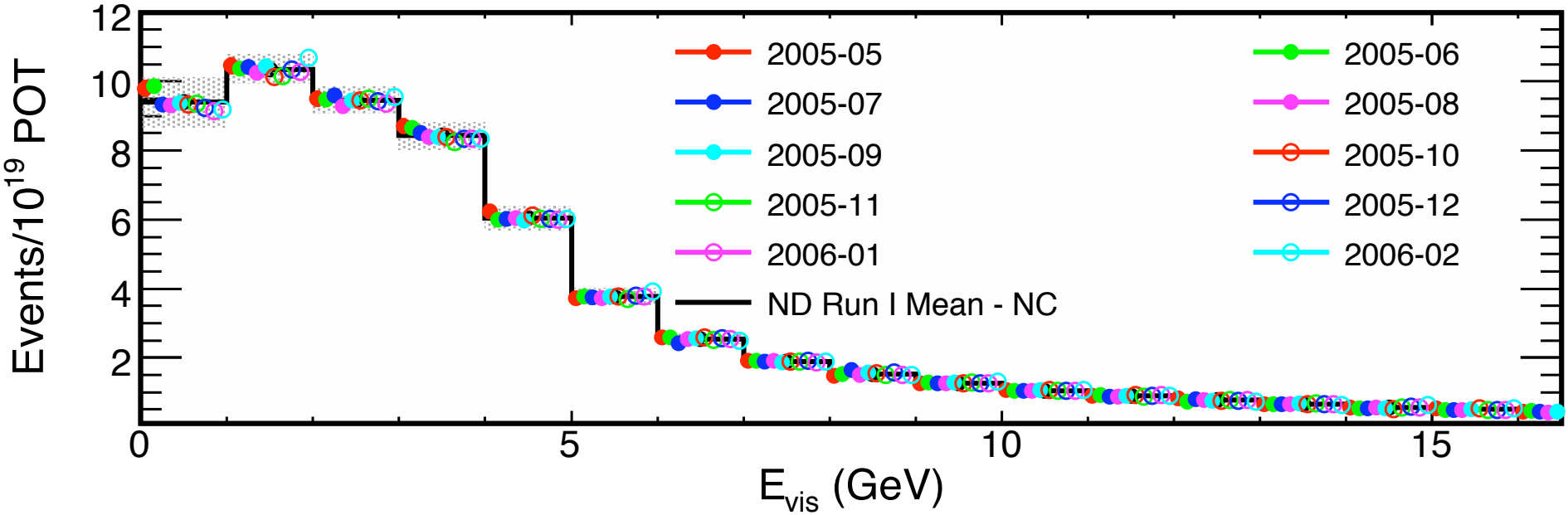


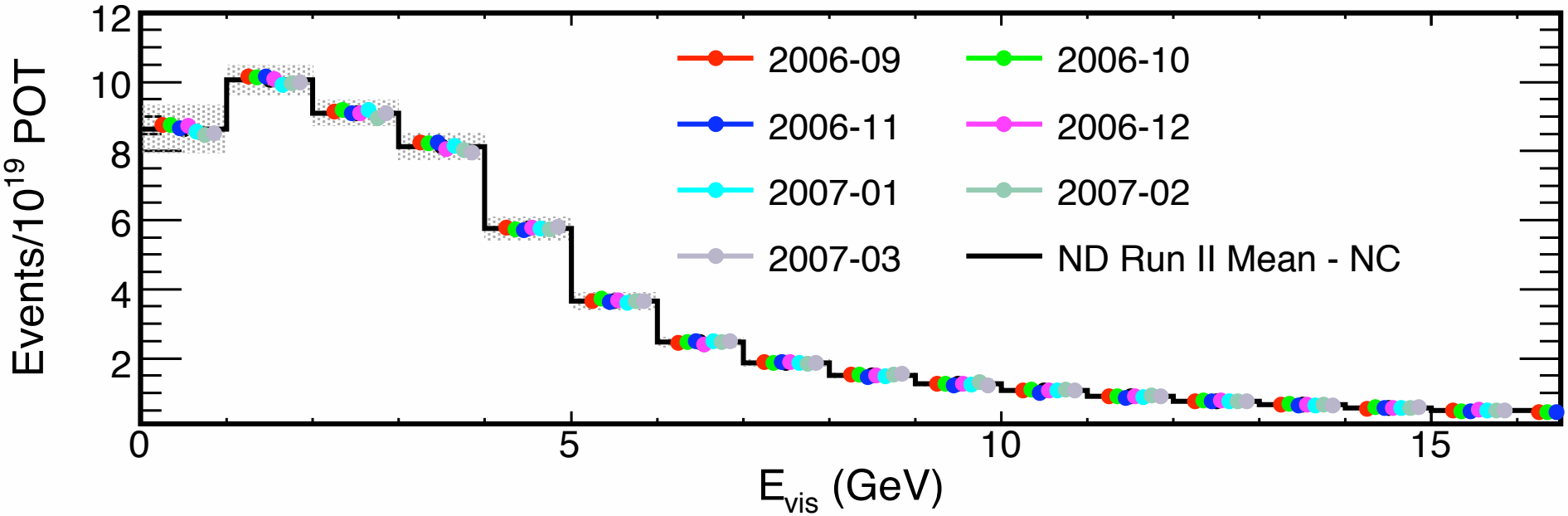


Conclusions

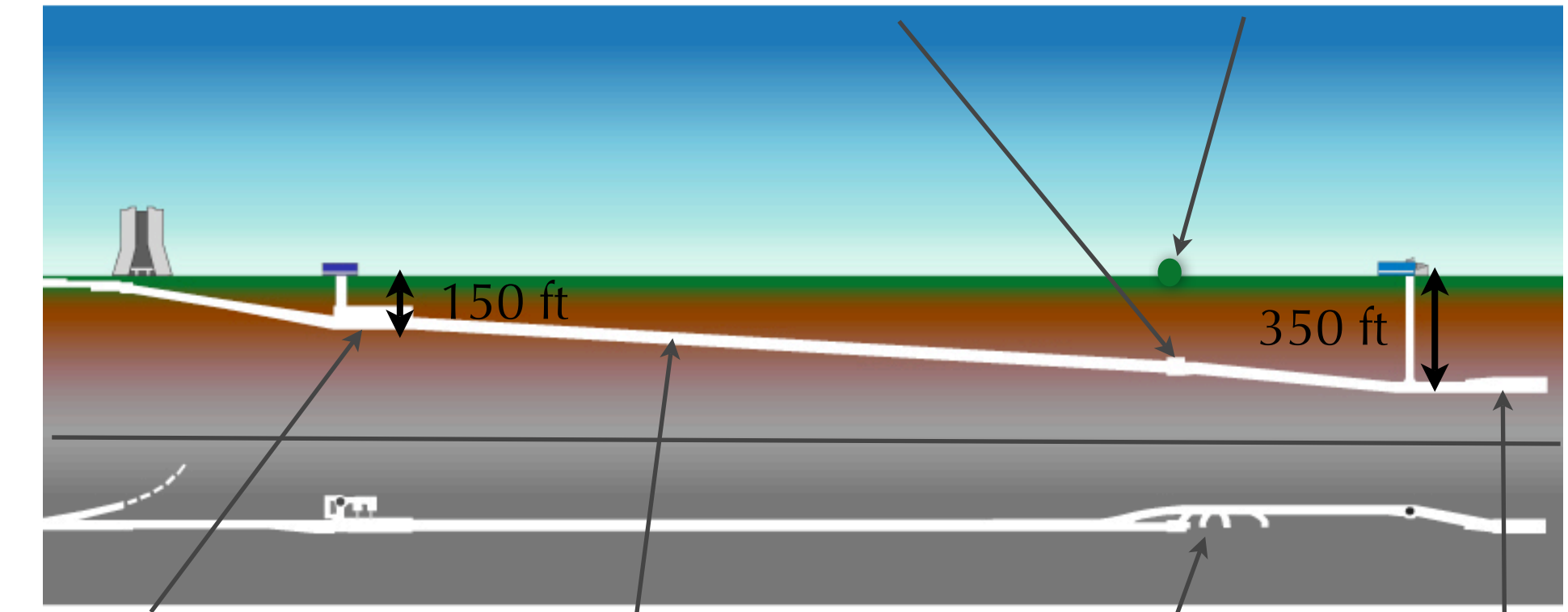
- MINOS has completed the analysis of the NC-like events in the far detector
- Rate comparison between near and far detectors
  - Data are consistent with mixing between active flavors
  - Disappearance fraction f < 35% at 90% CL for E < 3 GeV
- Fit for sterile component in 4 flavor mixing matrix
  - Consistent with rate measurement
  - $|U_{s3}|^2 = 0.14^{+0.18}_{-0.13}$

Near Detector Stability





Neutrinos at the Main Injector Layout



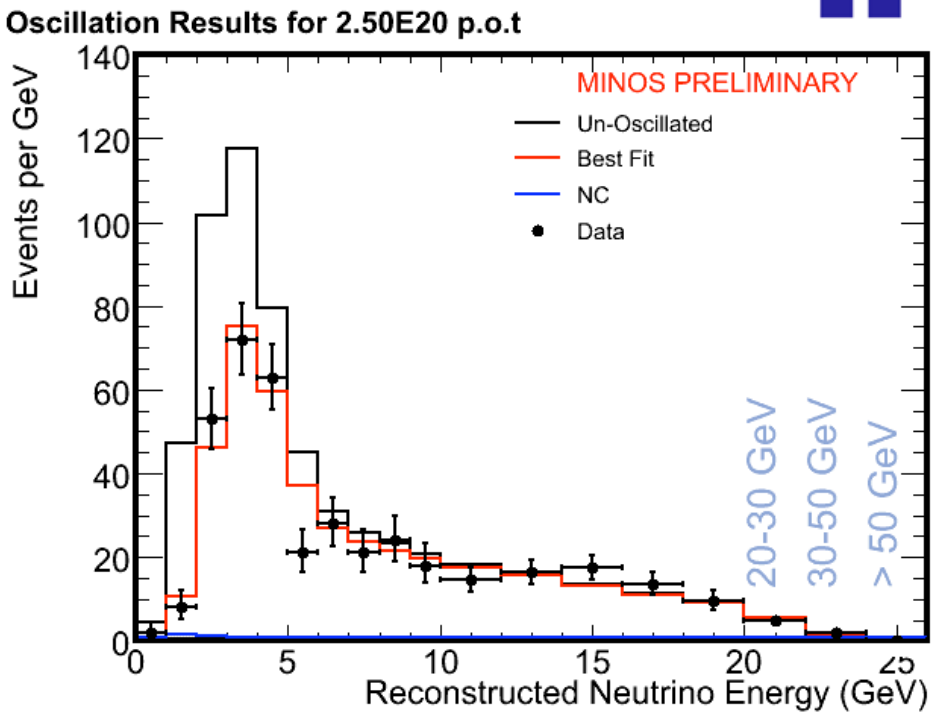
The CC Analysis

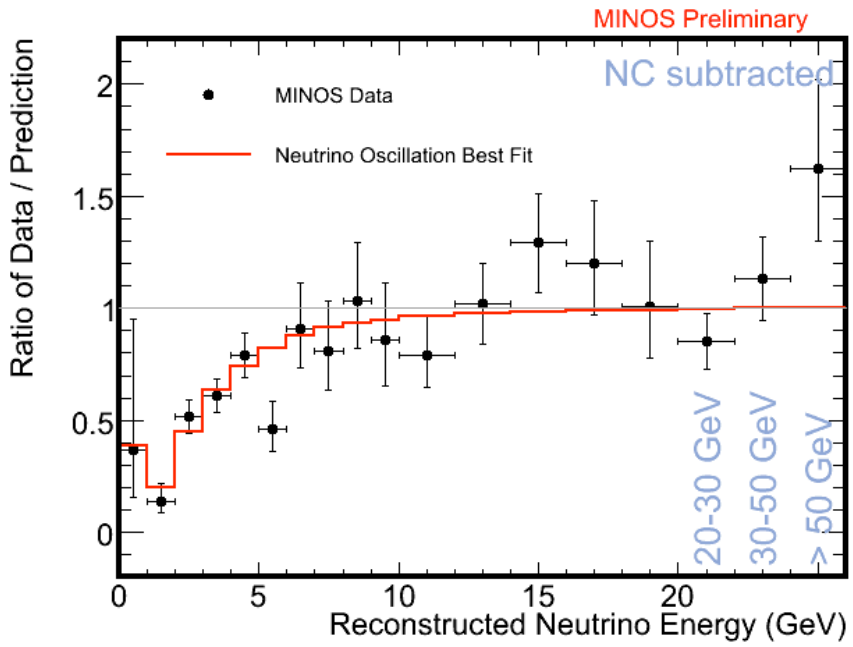
- CC like events used to determine Δm^2_{32}
- CC events easy to identify thanks to the muon in the interaction
- Deficit of CC events observed at far relative to near
- Far spectrum shown at top
- Best fit values shown below

$$\left|\Delta m^2_{32}\right| = 2.38^{+0.20}_{-0.16} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\Theta_{23} = 1.00_{-0.08}$$

$$\frac{\chi^2}{N_{DoF}} = \frac{41.2}{32}$$





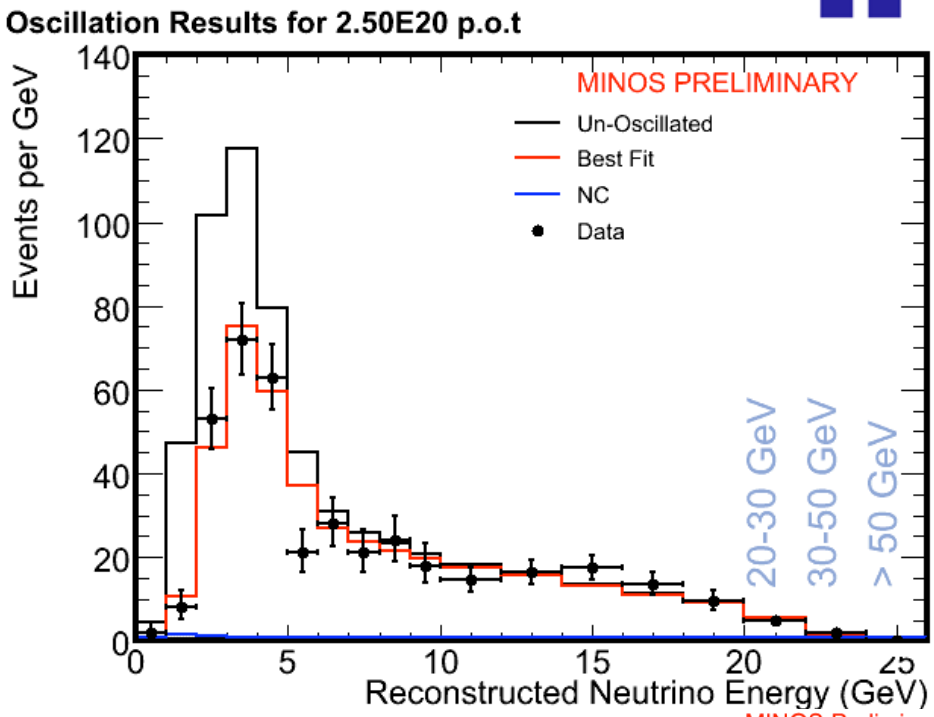
The CC Analysis

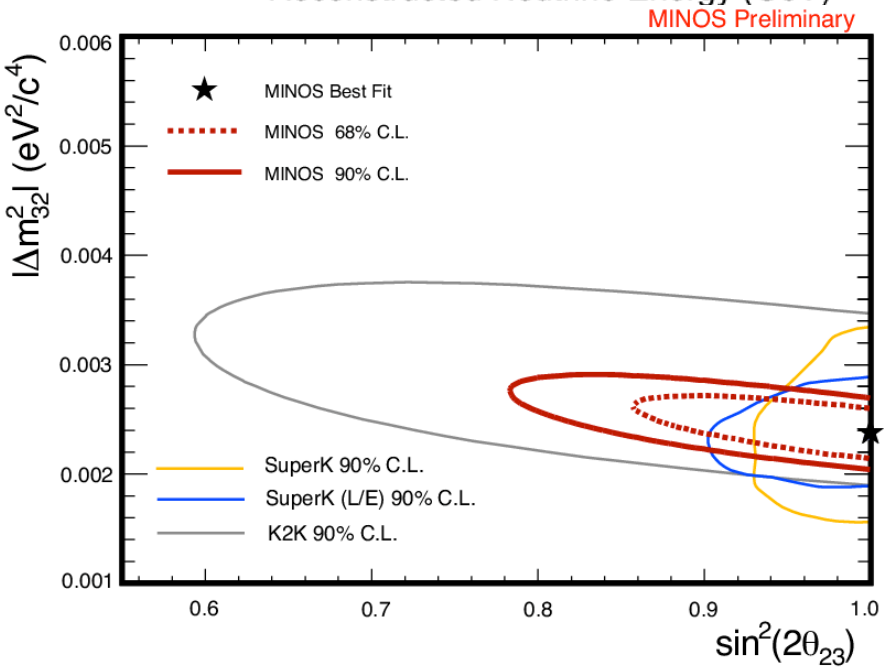
- CC like events used to determine Δm^2_{32}
- CC events easy to identify thanks to the muon in the interaction
- Deficit of CC events observed at far relative to near
- Far spectrum shown at top
- Best fit values shown below

$$\left|\Delta m^2_{32}\right| = 2.38^{+0.20}_{-0.16} \times 10^{-3}\ \mathrm{eV}^2$$

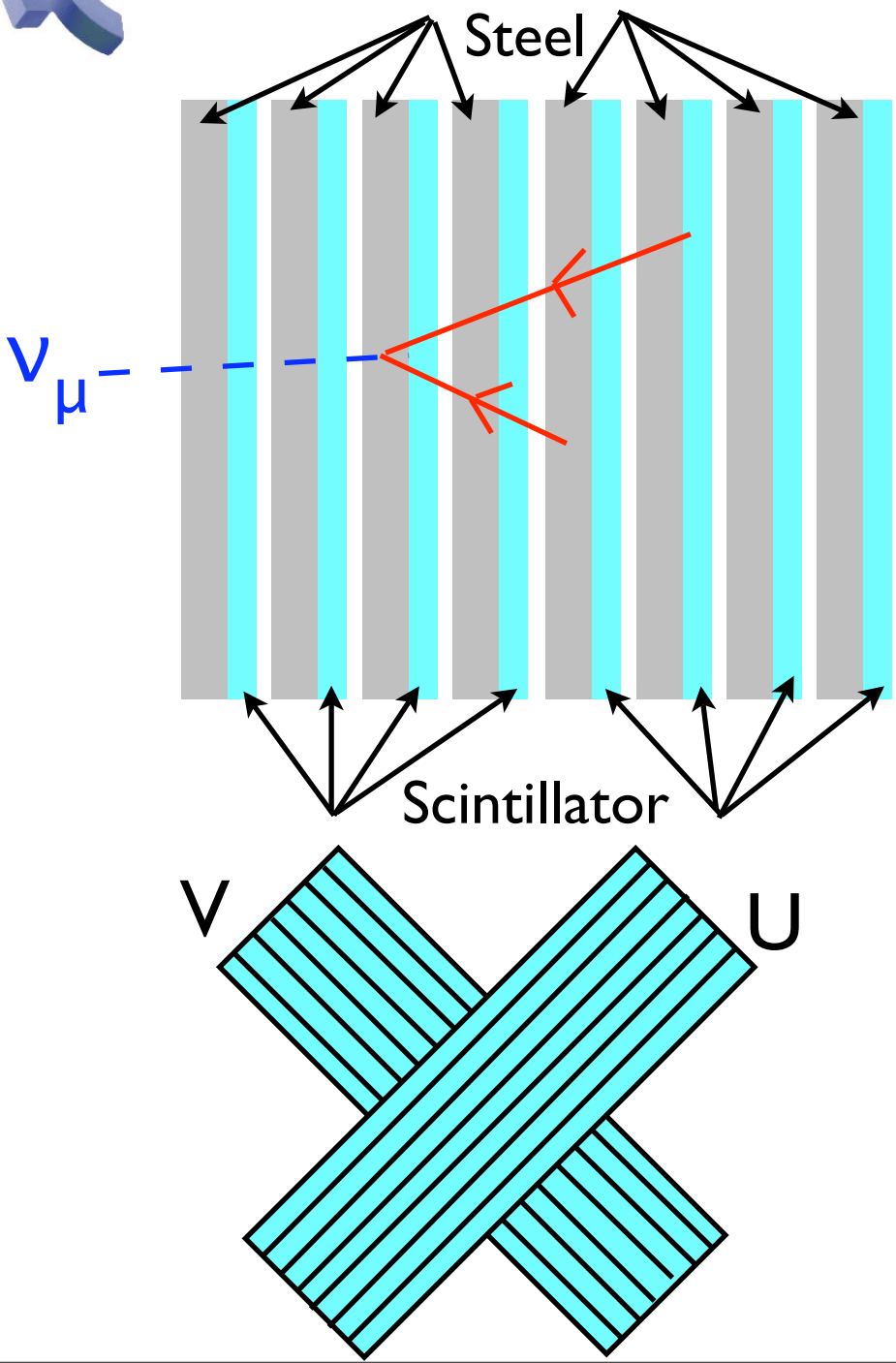
$$\sin^2 2\Theta_{23} = 1.00_{-0.08}$$

$$\frac{\chi^2}{N_{DoF}} = \frac{41.2}{32}$$



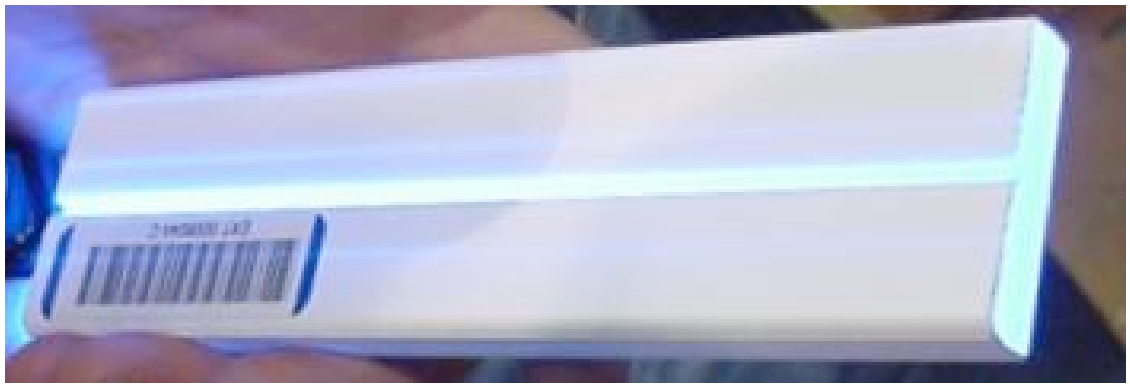


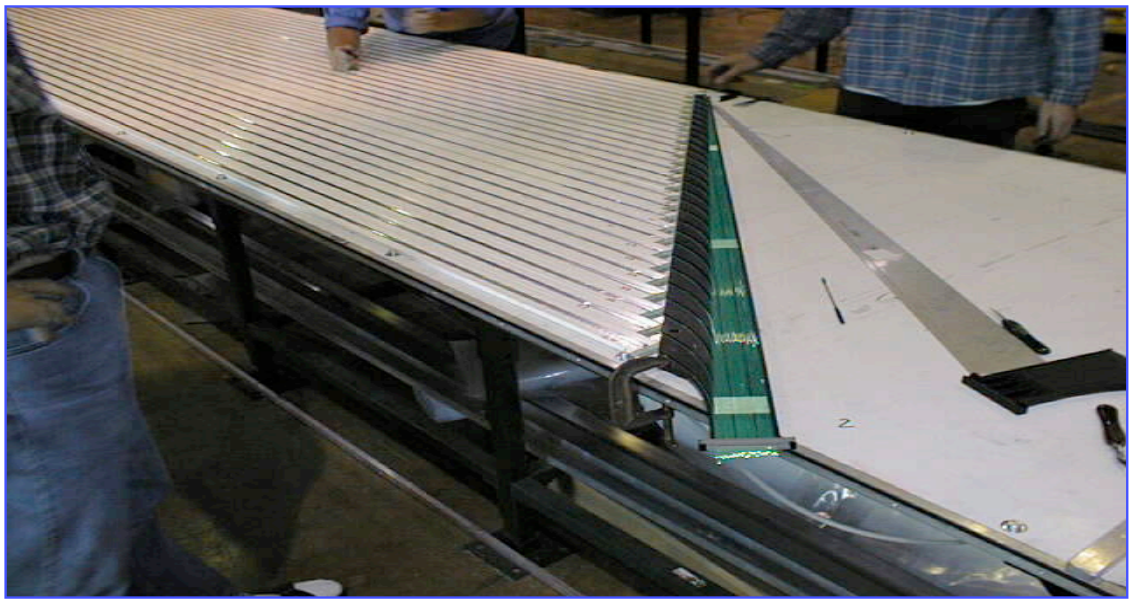
MINOS Detectors



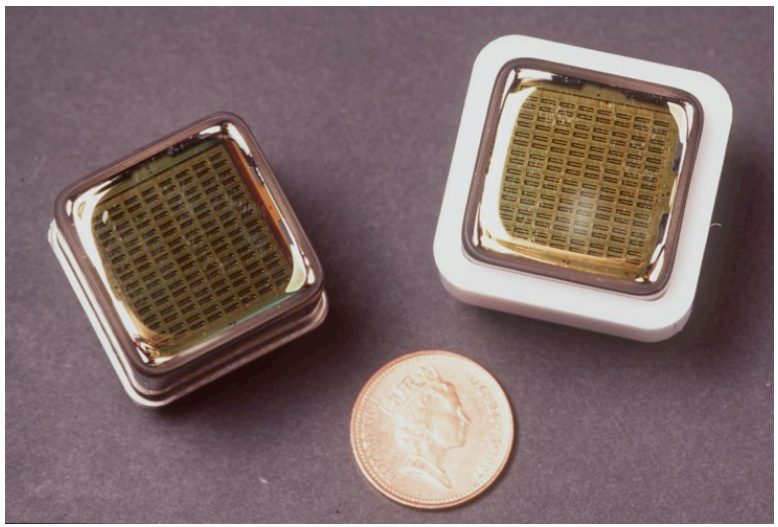
- The MINOS detectors are made of alternating layers of
  - steel - 2.54 cm thick
  - scintillator - 1 cm thick
  - air - 2.42 cm span
- Magnetic field of ~ 1.3 T
- Scintillator alternates orientation to provide 2D position information
- Plane position provides the third dimension

MINOS Detectors





- Strips of scintillator collected in aluminum cases and mounted to the steel
- Wavelength-shifting (green) fiber used to collect scintillation light
- Clear fiber used to bring signal to photomultiplier tubes (PMTs)
- PMTs have pixels to read out signals from multiple strips



Calibration of MINOS

- CalDet - 60 plane "mini-MINOS" was placed in front of test beams at CERN to determine absolute energy calibration
- Hadron Shw Res=55%/√E
- EM Shw Res=23%/√E
- Stopping cosmic ray muons provide strip-to-strip and Near/Far calibrations
- LED system injects light into fibers to monitor time stability and linearity of response
- Current uncertainties: 1.9% uncertainty on absolute energy scale in Near Det, 3.5% uncertainty on absolute energy scale in the Far, 3% near-far relative