First Results from Analysis of Neutral Current Neutrino Interactions in MINOS

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Wine & Cheese Seminar
Fermilab

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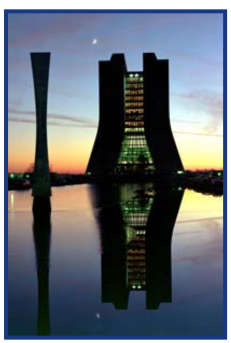
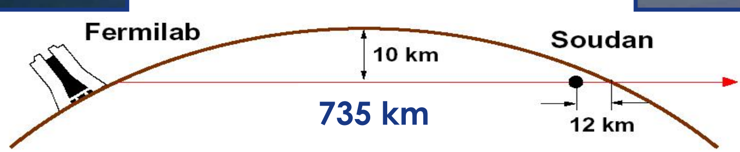
Outline

- Introduction
- Overview of the MINOS Experiment
  - NuMI Beam
  - MINOS Detectors
- Near Detector and Far Detector Data Selection
- Near to Far Extrapolation of Neutral Current Energy Spectrum
- Results using NuMI Beam Exposures of
  - 2.39×10^{20} Protons-on-Target in the Near Detector (up to 03/2007)
  - 2.46×10^{20} Protons-on-Target in the Far Detector (up to 03/2007)
- Summary and Outlook

The MINOS Experiment





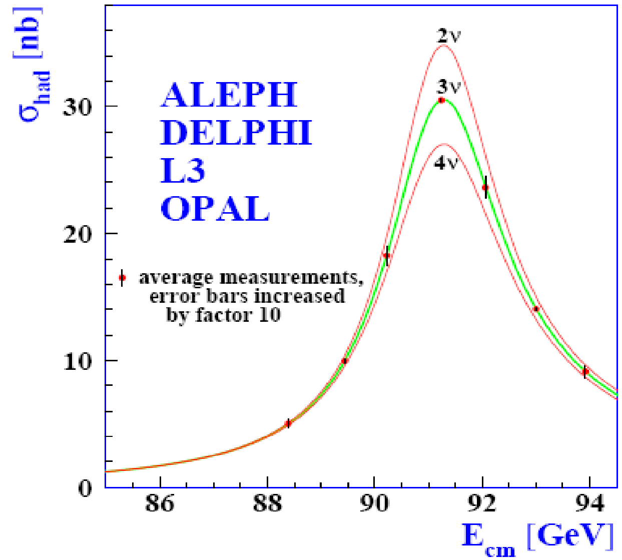
- **MINOS (Main Injector Neutrino Oscillation Search)**
  - Long-baseline neutrino oscillation experiment
  - Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector
- **Basic concept**
  - Measure energy spectrum at the Near Detector, at Fermilab
  - Measure energy spectrum at the Far Detector, 735 km away, deep underground in the Soudan Mine.
  - Compare Near and Far measurements to study neutrino oscillations

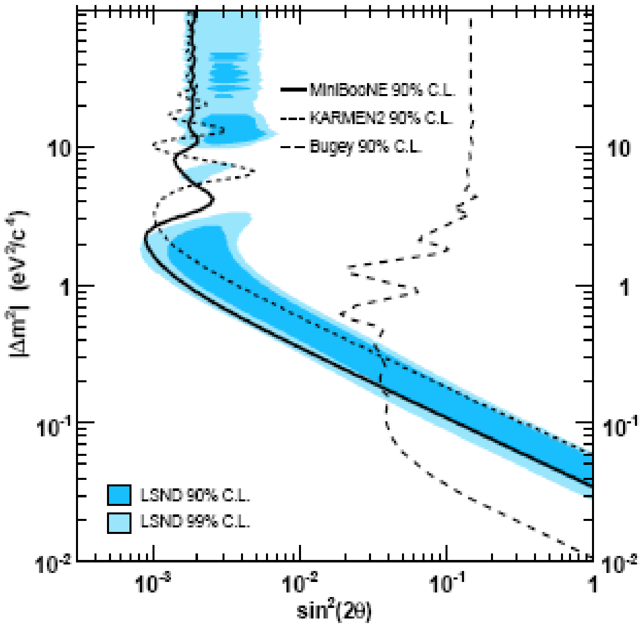
MINOS Physics Goals

- Precise measurements of $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$ via ν_μ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Compare ν, $\bar{\nu}$ oscillations
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections using high statistics Near Detector data set
- **Search for or constrain exotic physics such as sterile ν**

Sterile Neutrinos

- Measurements of Z^0 width at LEP exclude more than 3 light active neutrinos
  - A 4th neutrino cannot couple to Z^0
  - Cannot participate in weak interactions – sterile neutrino
- LSND results suggested the existence of a fourth neutrino with large mass splitting
- Earlier findings (Bugey, Karmen) combined with recent results from MiniBooNE strongly disfavor sterile neutrinos as an explanation for LSND
- Additional massive neutrinos could still
  - be possible dark matter candidates
  - help determine seesaw mass scale
- **Sterile neutrinos => new physics!**

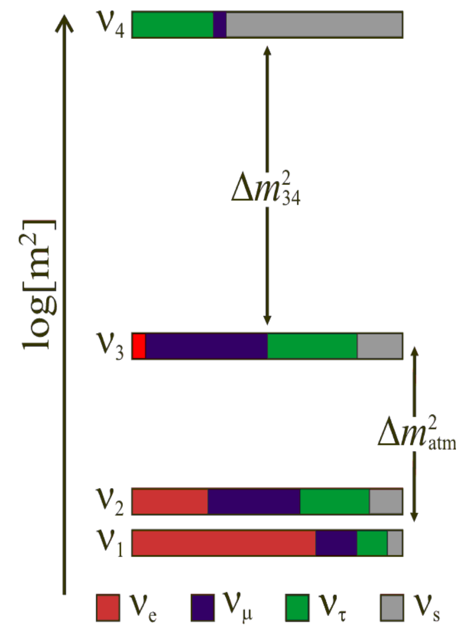




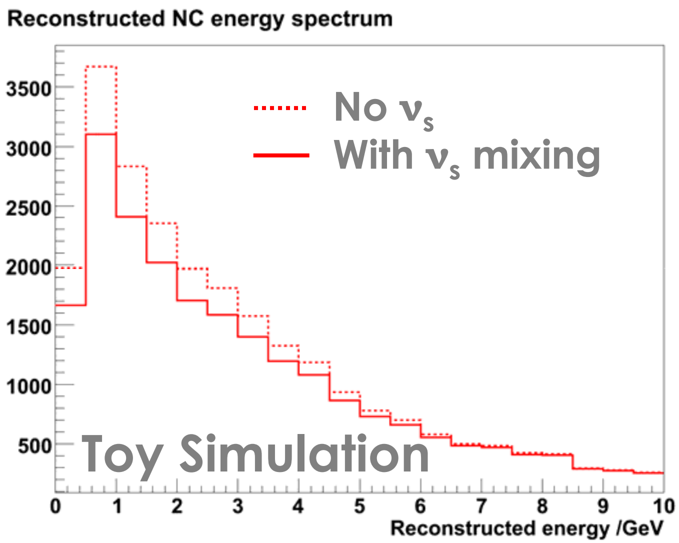
Phys. Rev. Lett. 98, 231801 (2007)

Looking for Sterile Neutrinos in MINOS

- Oscillations in MINOS are driven by Δm^2_{32}
  - Oscillation is between ν_μ and ν_τ
  - No effect on neutral current (NC) interactions



- Add a 4[th] neutrino
  - Extra mass ν_4, extra flavor ν_s
  - Oscillations can now occur between ν_μ and ν_s
    - driven by Δm^2_{32}
    - driven by a new mass scale



- Oscillations into ν_s affect number of observed NC interactions as ν_s do not interact in the detector

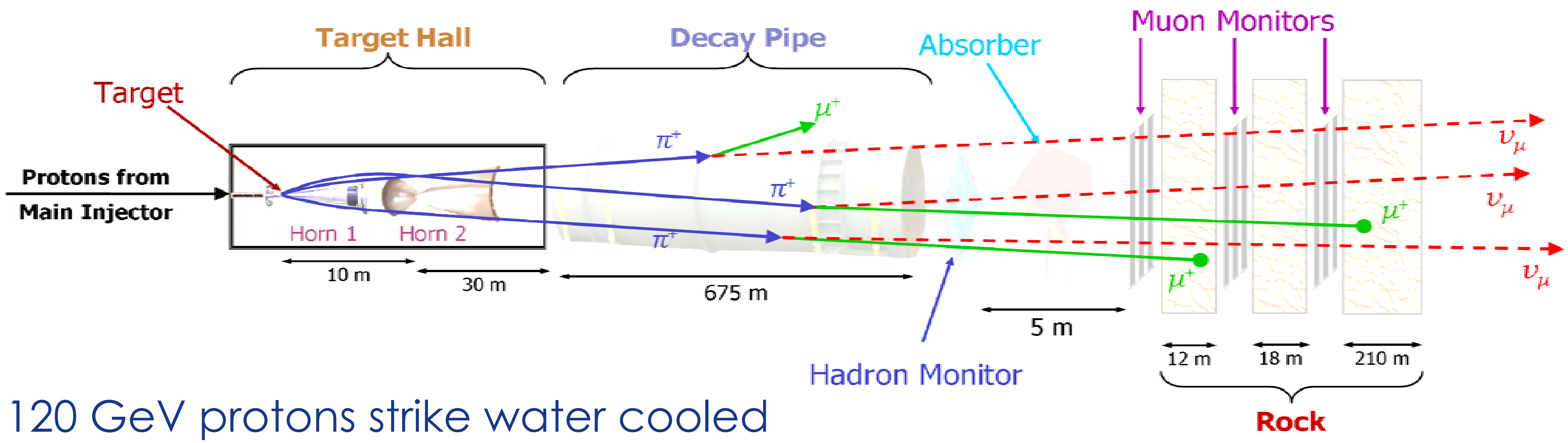
- Look for NC disappearance at the Far Detector
  - Sterile neutrino mixing would deplete NC Energy spectrum

Overview of the MINOS Experiment

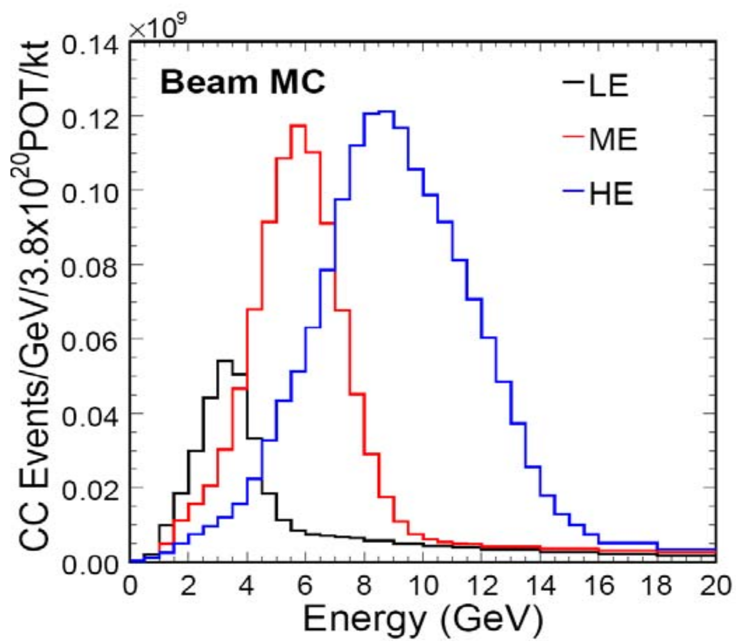
The MINOS Collaboration

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

The NuMI Neutrino Beam

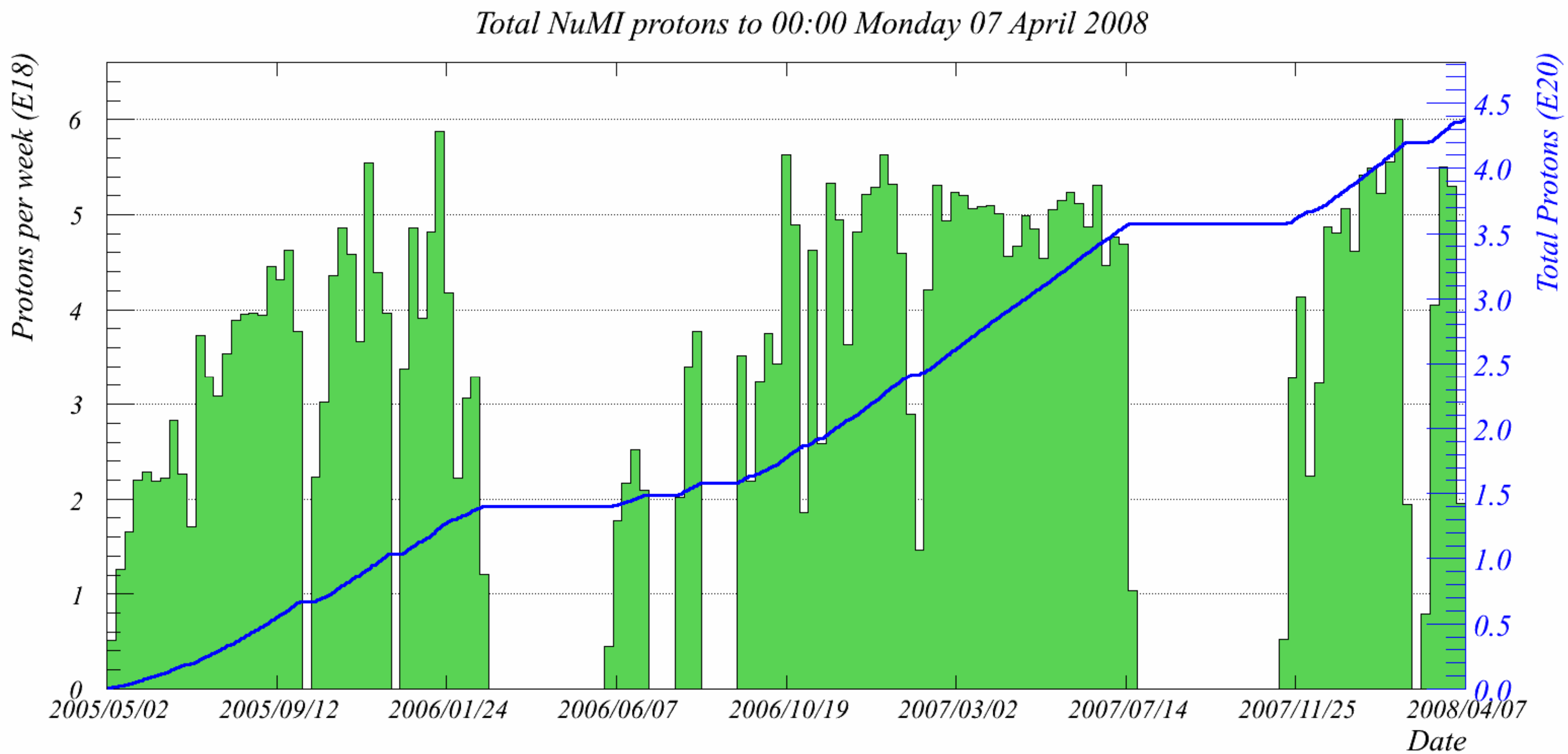


- 120 GeV protons strike water cooled graphite target, producing kaons, pions
- 2 parabolic magnetic horns focus secondaries, which decay into muons, neutrinos
- Beam energy spectrum can be tuned by varying the relative positions of target, horns
- Performance
  - 10μs spill of 120 GeV protons every 2.4s
  - Intensity: 2.4×10^{13} POT/spill
  - 0.2 MW average beam power



Accumulated Beam Data

Many thanks to Fermilab's Accelerator Division



RUN I - 1.24×10^{20} POT (LE) (PRL Publication ν_μ disappearance)

Higher energy beam

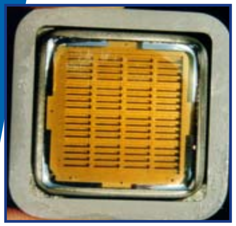
RUN IIa 1.22×10^{20} (LE) POT (new)

RUN IIb $\sim 0.75 \times 10^{20}$ POT (not included)

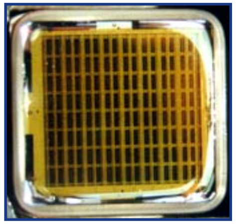
RUN III $>0.9 \times 10^{20}$ POT (current)

This Analysis: Run I + Run IIa => 2.46×10^{20} POT (LE Beam only)

MINOS Detector Technology



M16



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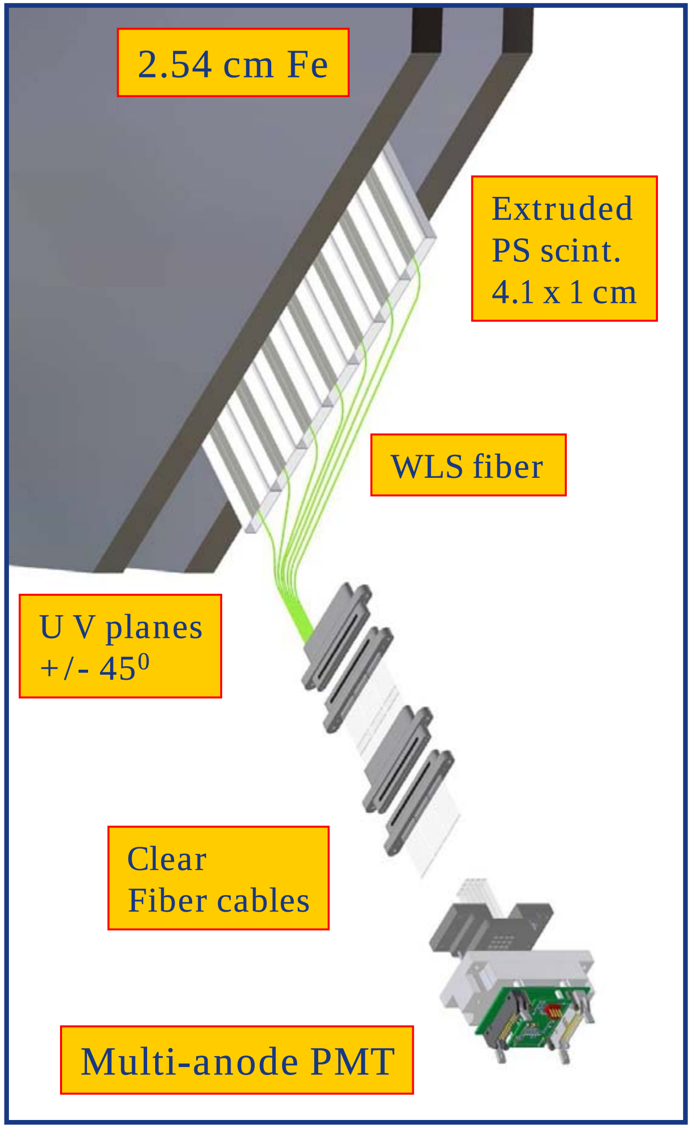
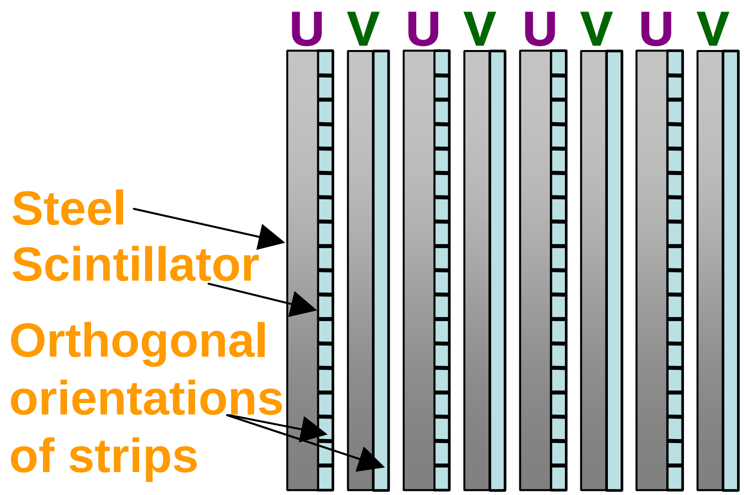
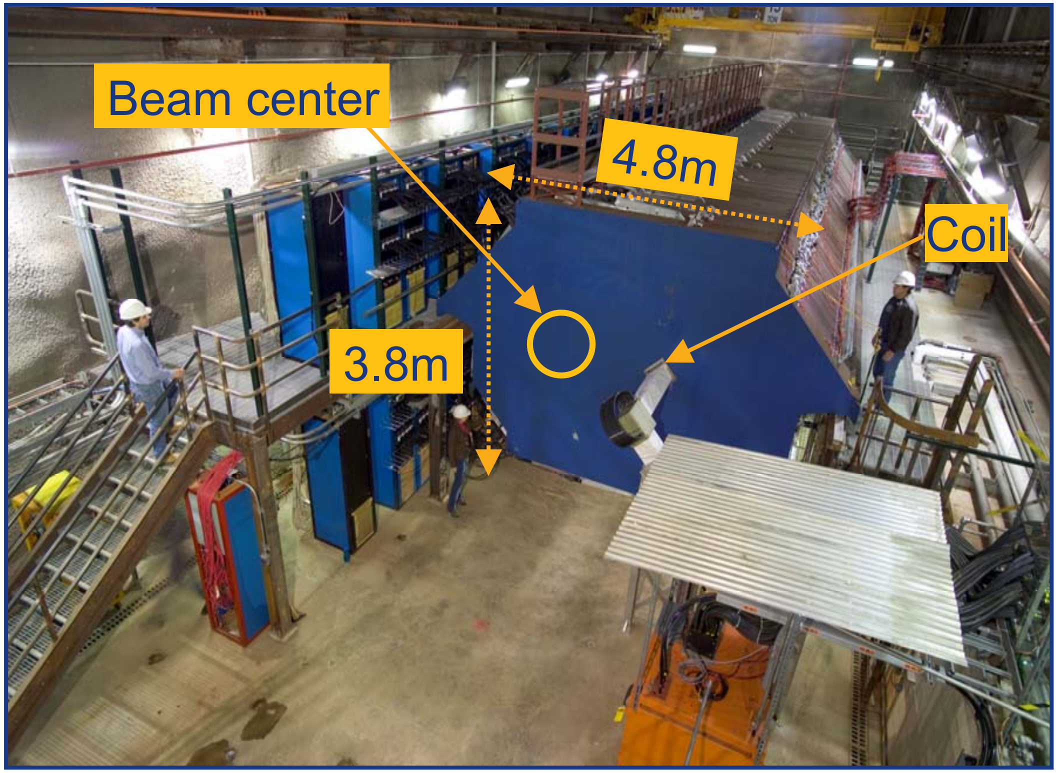


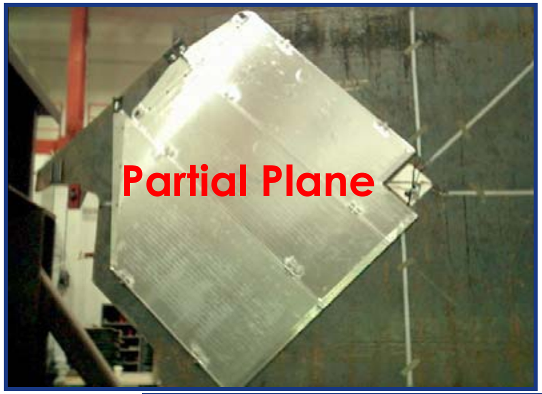
- **MINOS Near and Far Detectors are functionally identical:**
  - 2.54cm thick magnetized steel plates (B~1.3T)
  - co-extruded polystyrene scintillator strips
  - orthogonal orientation on alternate planes – U,V
  - optical fiber readout to multi-anode PMTs



The MINOS Near Detector

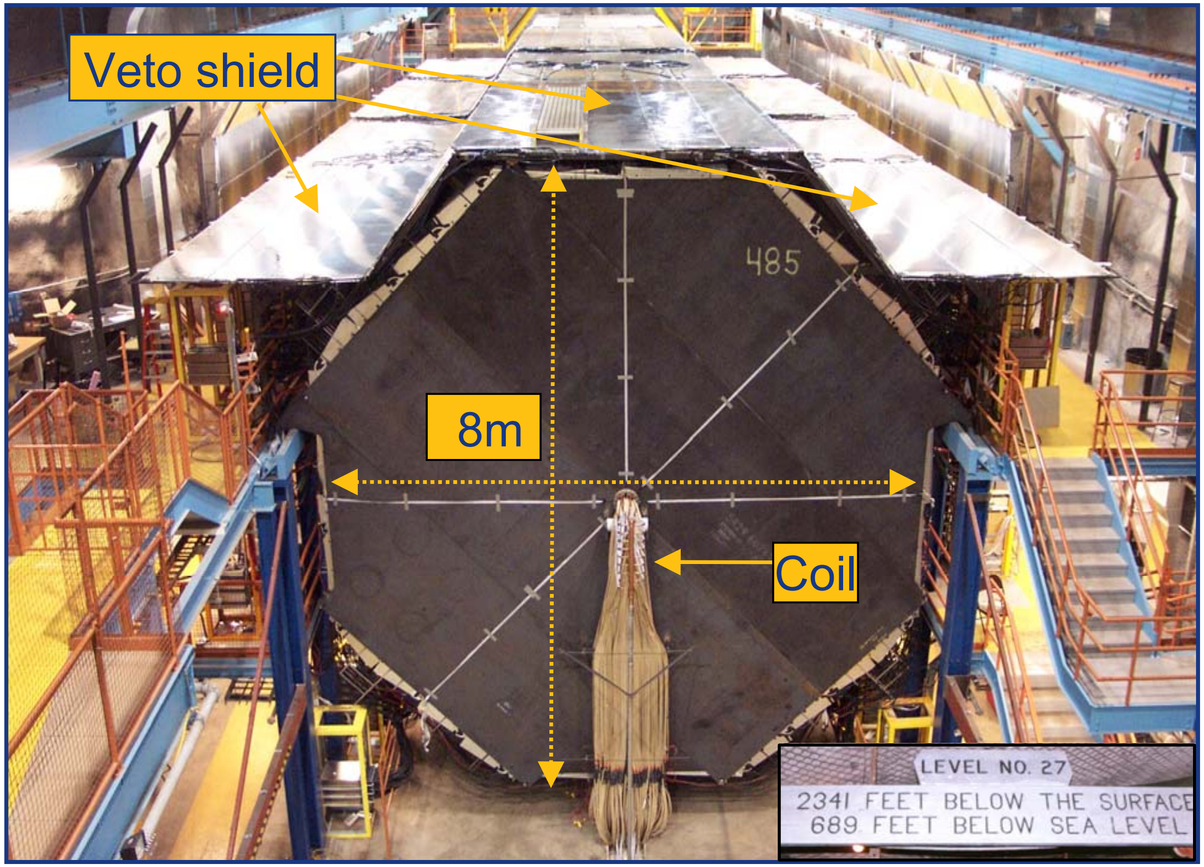
- Located 1km downstream of the target
- ~1kt (980t) total mass
- Shaped as squashed octagon (4.8×3.8×15m^3)
- Partially instrumented (282 steel, 153 scintillator planes)
- Uses both partial and full scintillator planes
- Fast QIE readout electronics, continuous sampling during beam spill



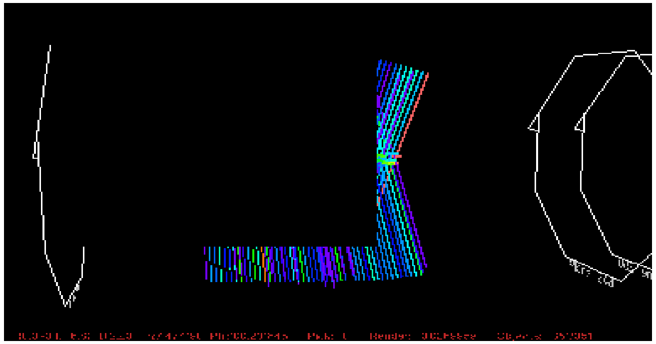


The MINOS Far Detector

- Located 735km away at the Soudan mine, MN
- 5.4kt, 2 supermodules
- Shaped as octagonal prism ($8\times8\times30m^3$)
- 486 steel planes, 484 scintillator planes
- Veto shield (scintillator modules)
- Spill times from Fermilab for beam trigger



Beam neutrino interaction from real FD data



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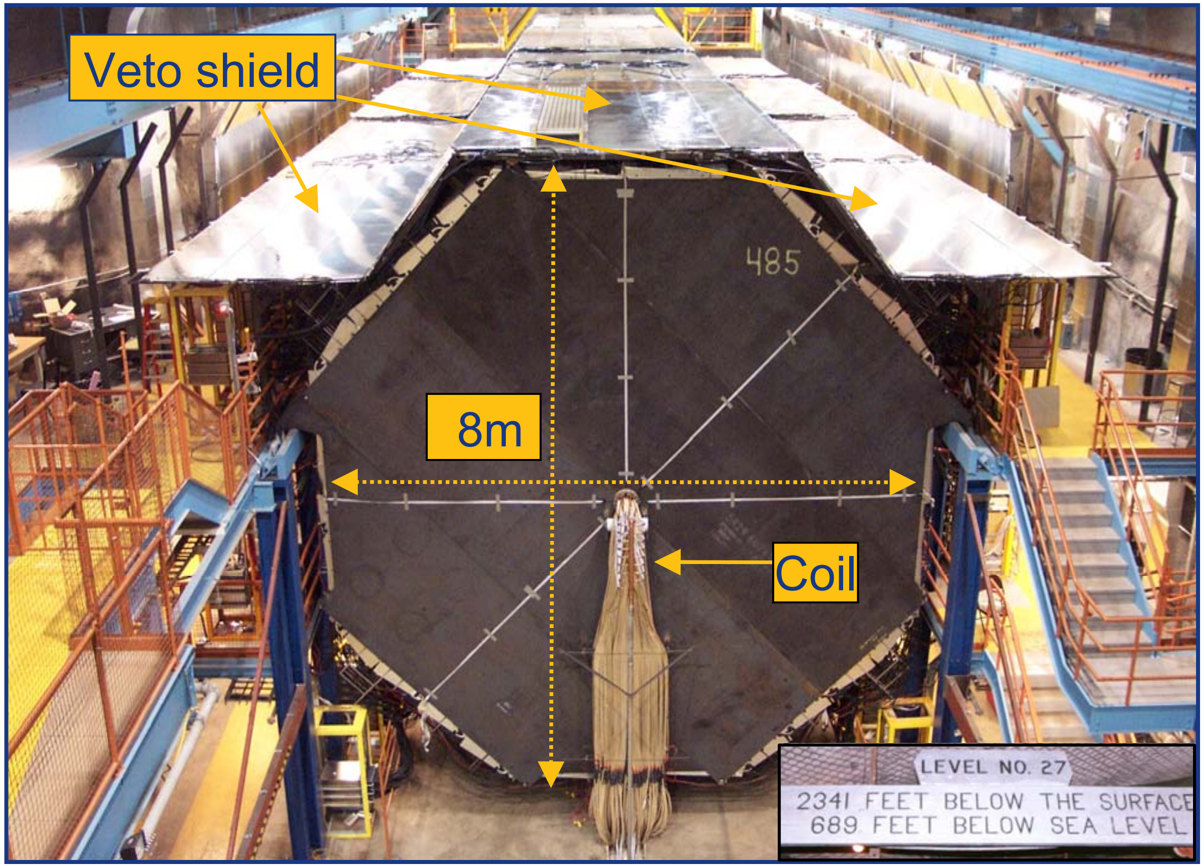
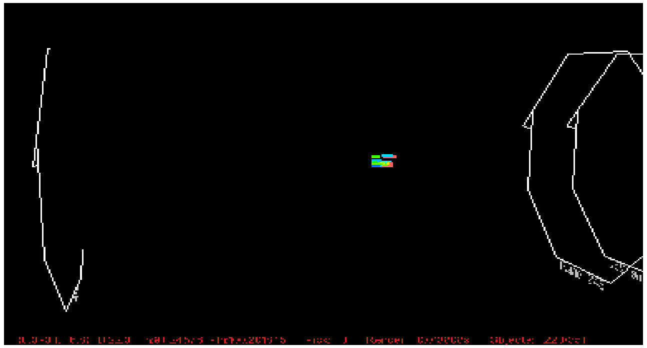
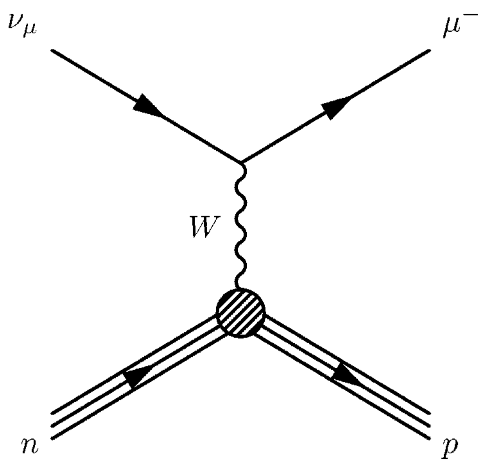


Reconstructed beam neutrino interaction from real FD data

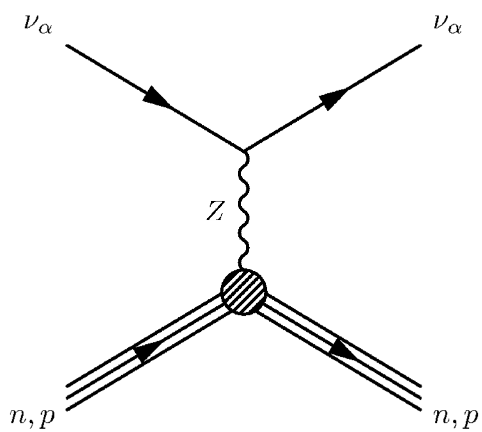


Event Topologies

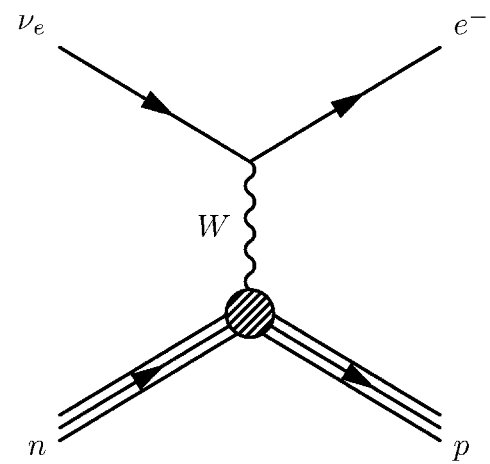
ν_μ CC Event



NC Event



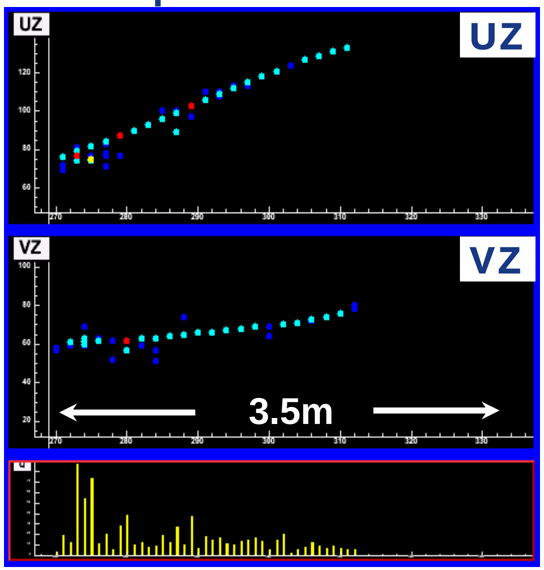
ν_e CC Event



Event Topologies

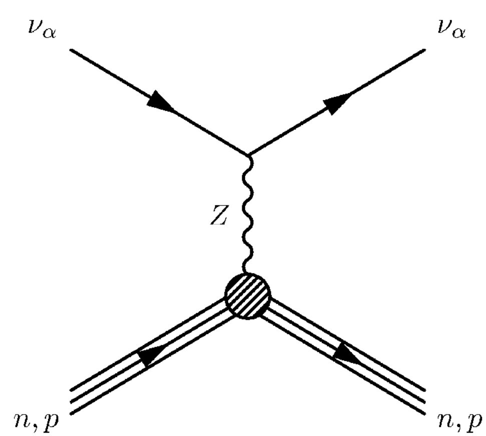
Monte Carlo

ν_μ CC Event



long μ track & hadronic activity at vertex

NC Event



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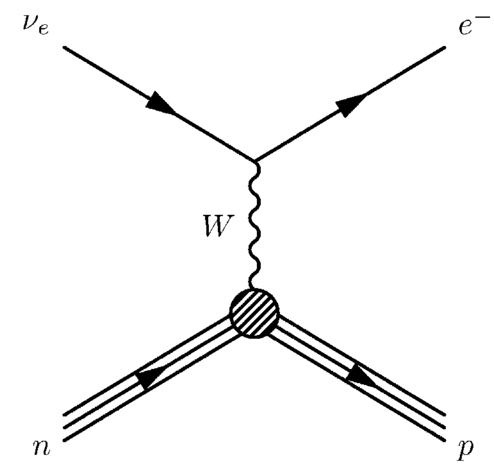

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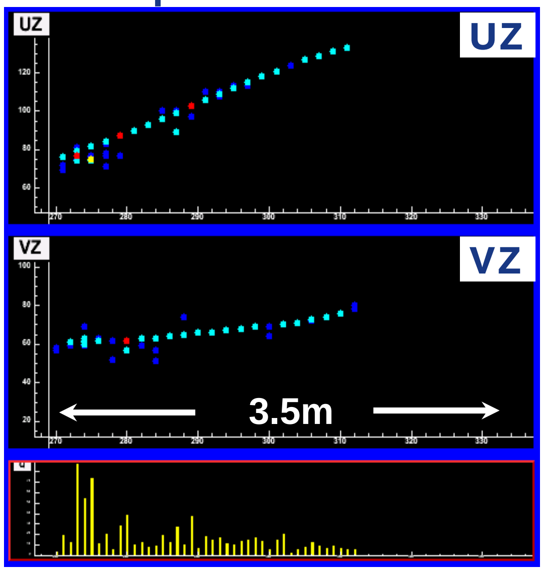

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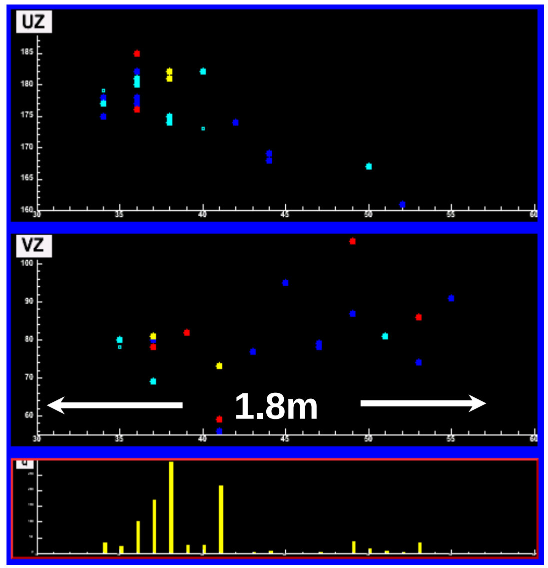
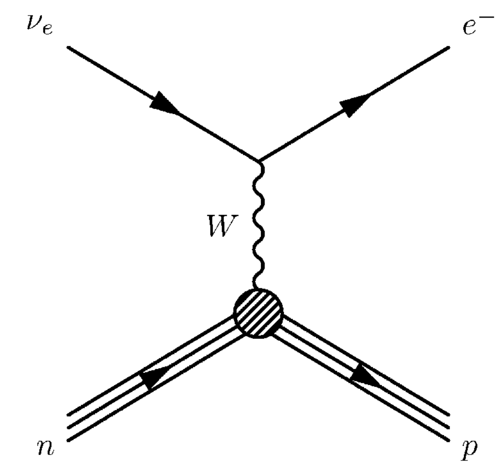


short event, often diffuse

ν_e CC Event



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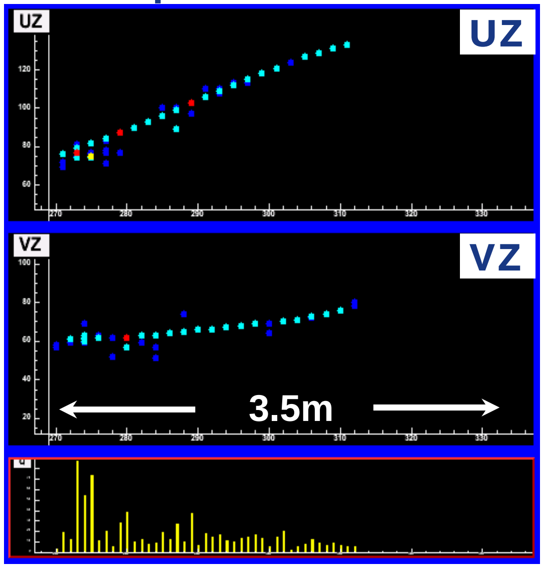

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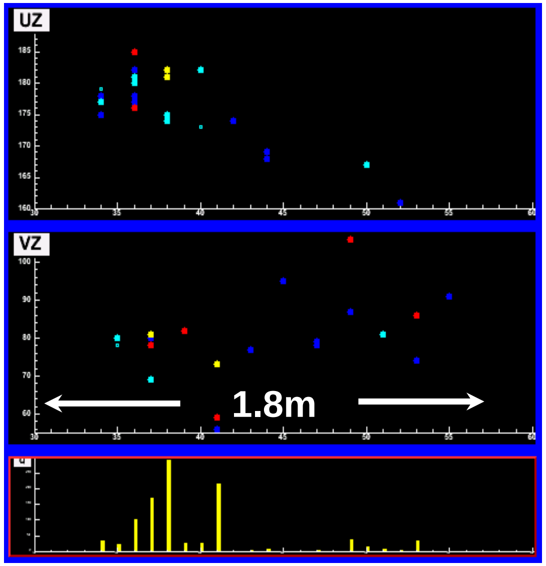

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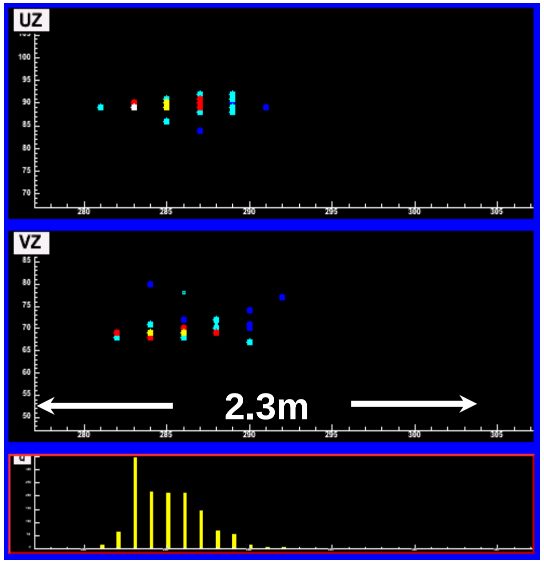
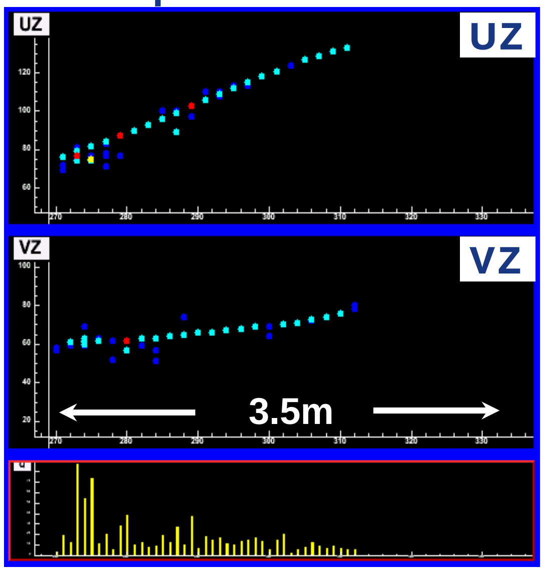


short, with typical EM shower profile

Event Topologies

Monte Carlo

ν_μ CC Event



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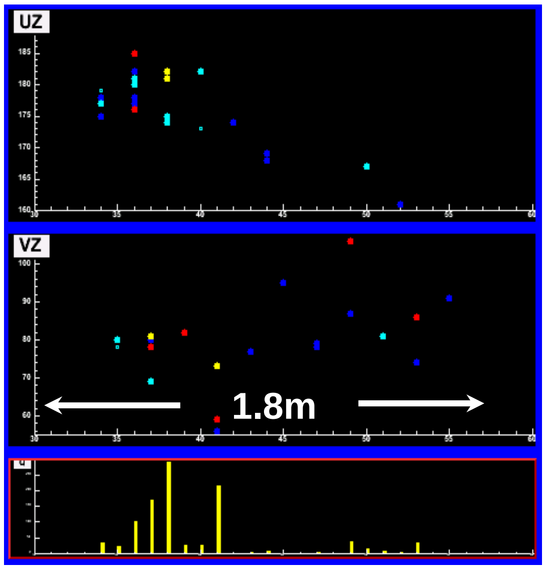

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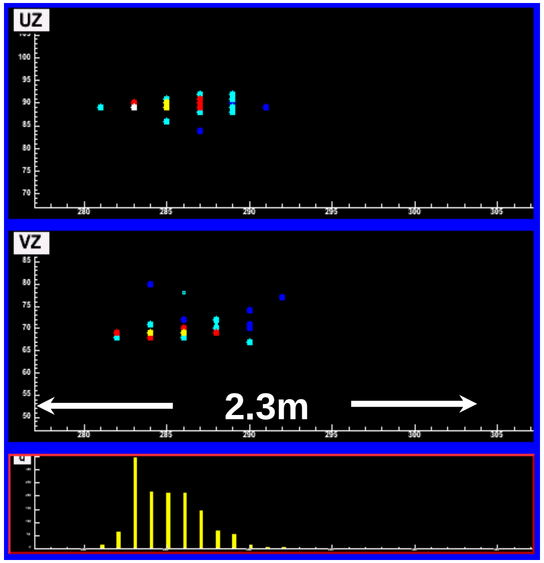
ν_e CC Event



short, with typical EM shower profile

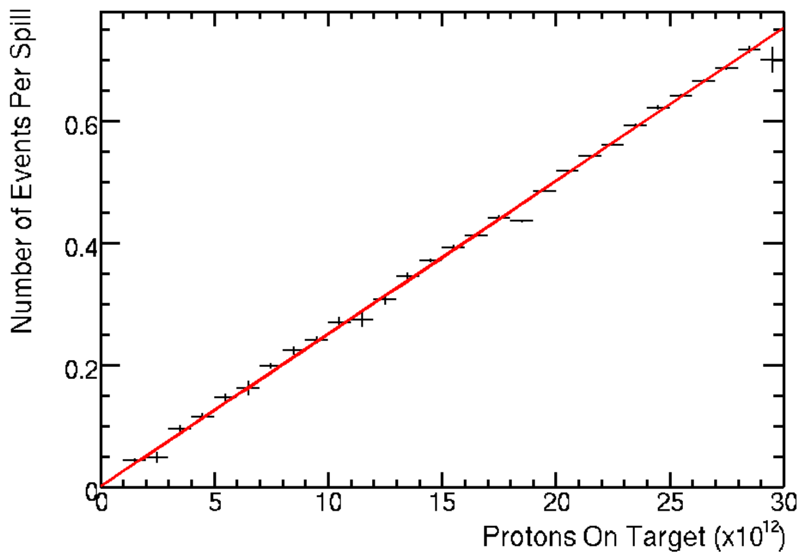
Energy resolution

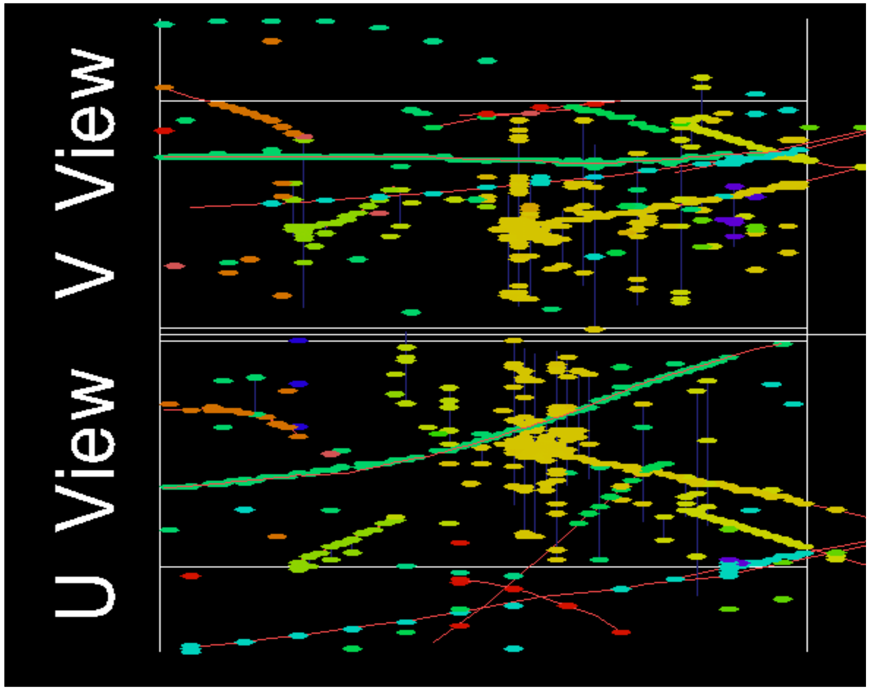
- $\pi^\pm$: 55%/$\sqrt{E(\mathrm{GeV})}$
- $\mu^\pm$: 6% range, 10% curvature

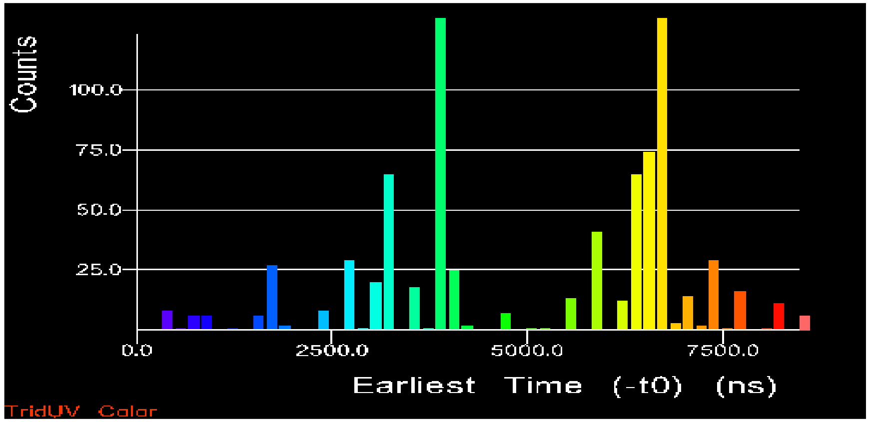
Near Detector Data Selection

Near Detector Spill

- Multiple events in ND per Main Injector spill
  - Over $1x10^7$/year fiducial events collected
- Events are separated using topology and timing
  - Color in display indicates time
  - Blue hits are early, red are late
- Linear increase in event rate with beam intensity

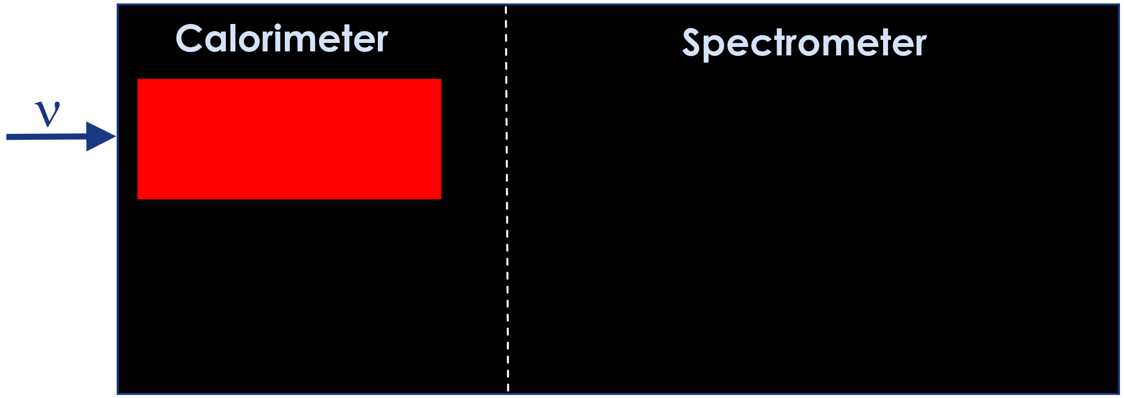


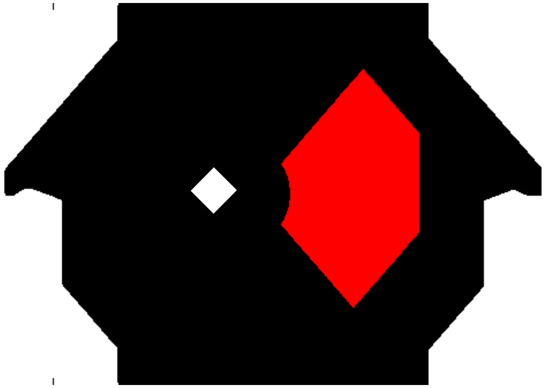




Event Pre-Selection Cuts

- Beam quality and detector quality cuts
  - Beam positioning, magnetic horns energized, detector running within operational parameters
- Event vertex reconstructed within the fiducial volume of the detector
  - Transverse vertex position > 50 cm away from the edge of a partial plane or its outline on a full plane
  - 30 planes < z < 80 planes





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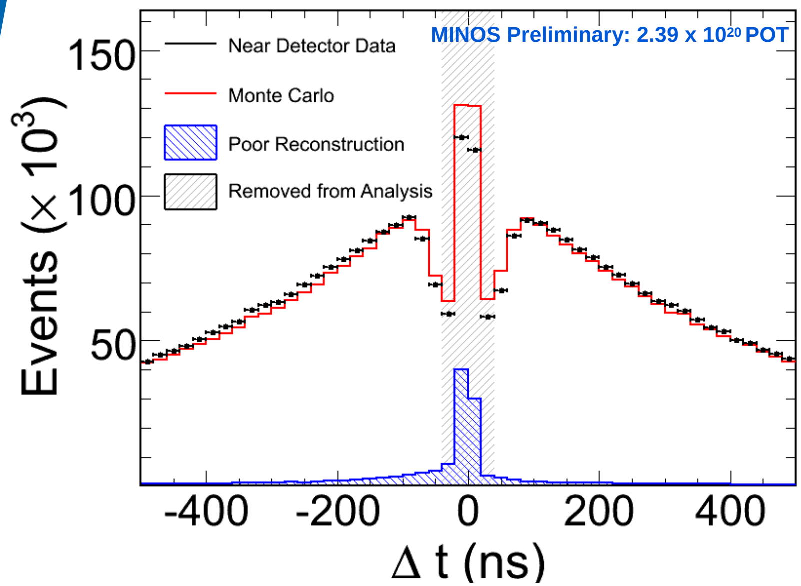
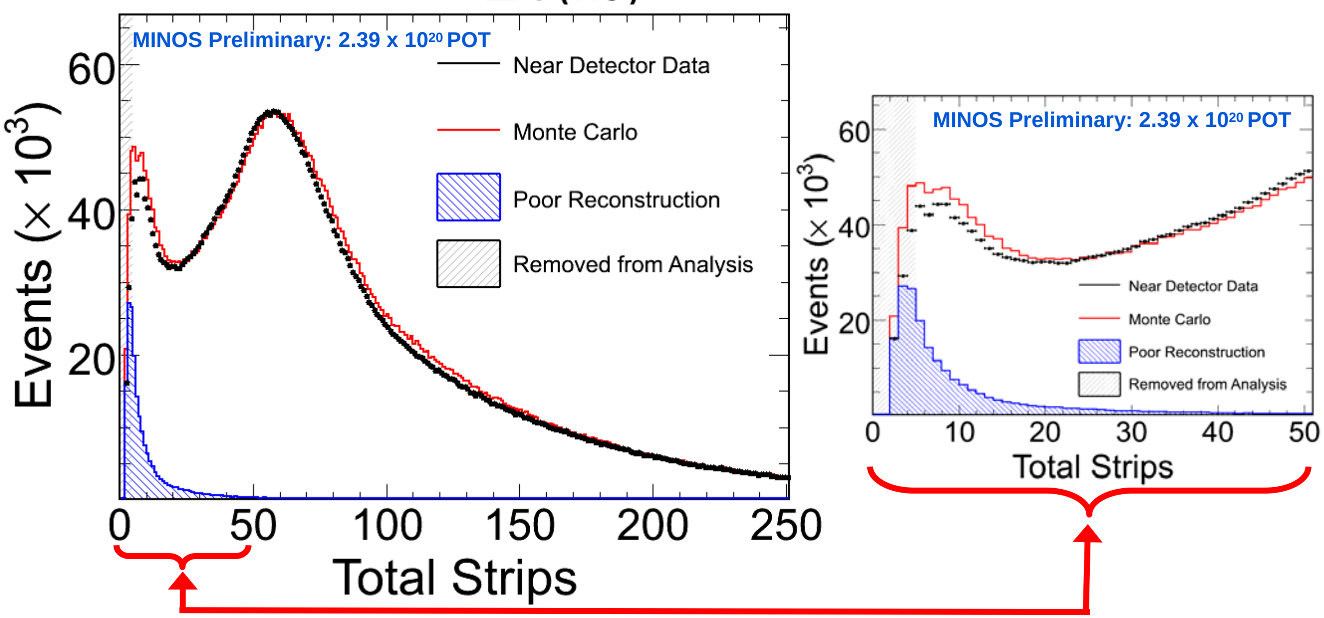


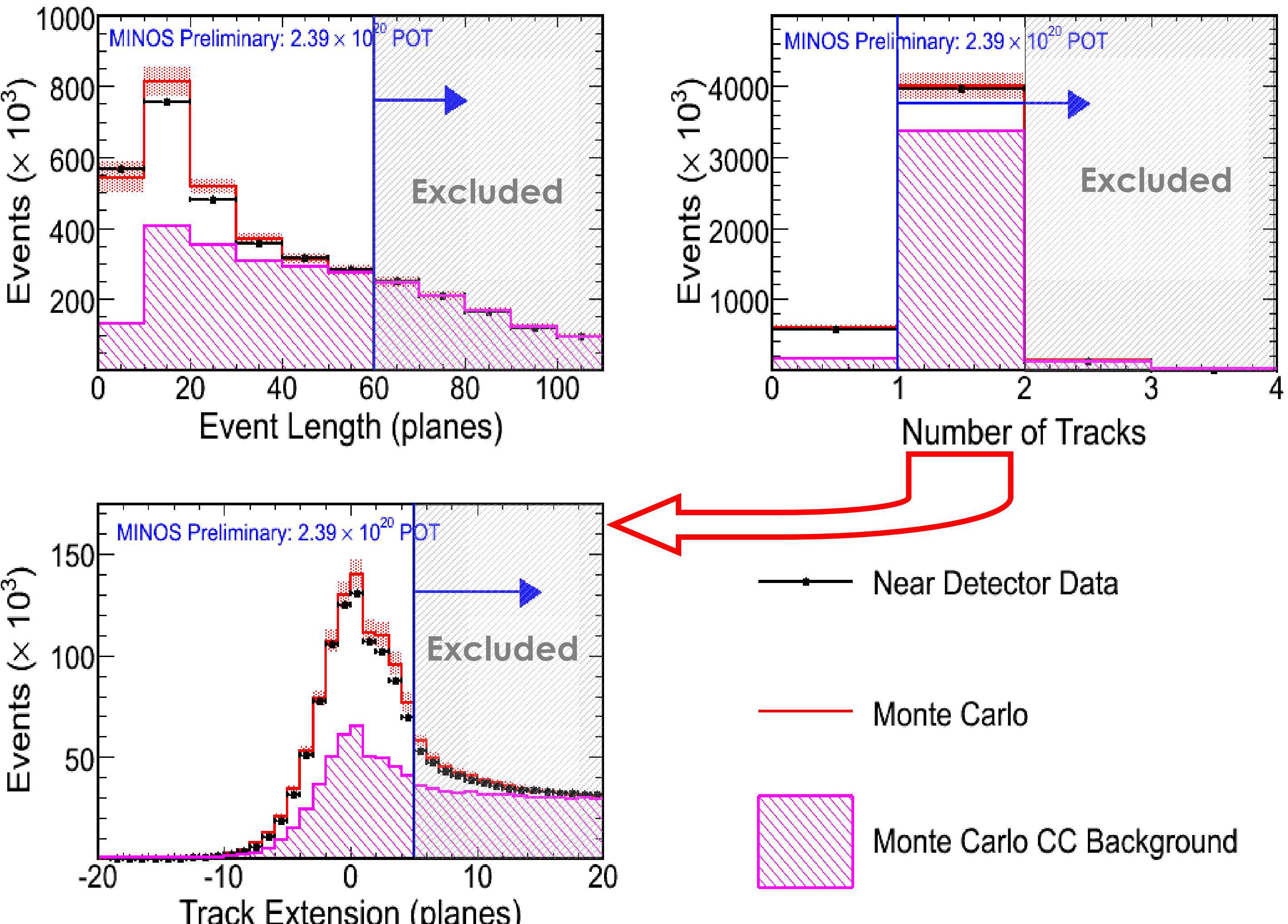
- High rate of neutrino interactions in ND can cause reconstruction failures
  - Split events from a single neutrino interaction
  - Event with vertex erroneously reconstructed inside fiducial volume
- A large fraction of these events can be eliminated via a series of cuts



- Cuts on time and spatial separation between events
- Cut on total number of event strips
- Event steepness cut
- Veto on activity in partially instrum. region

Near Detector NC Event Selection

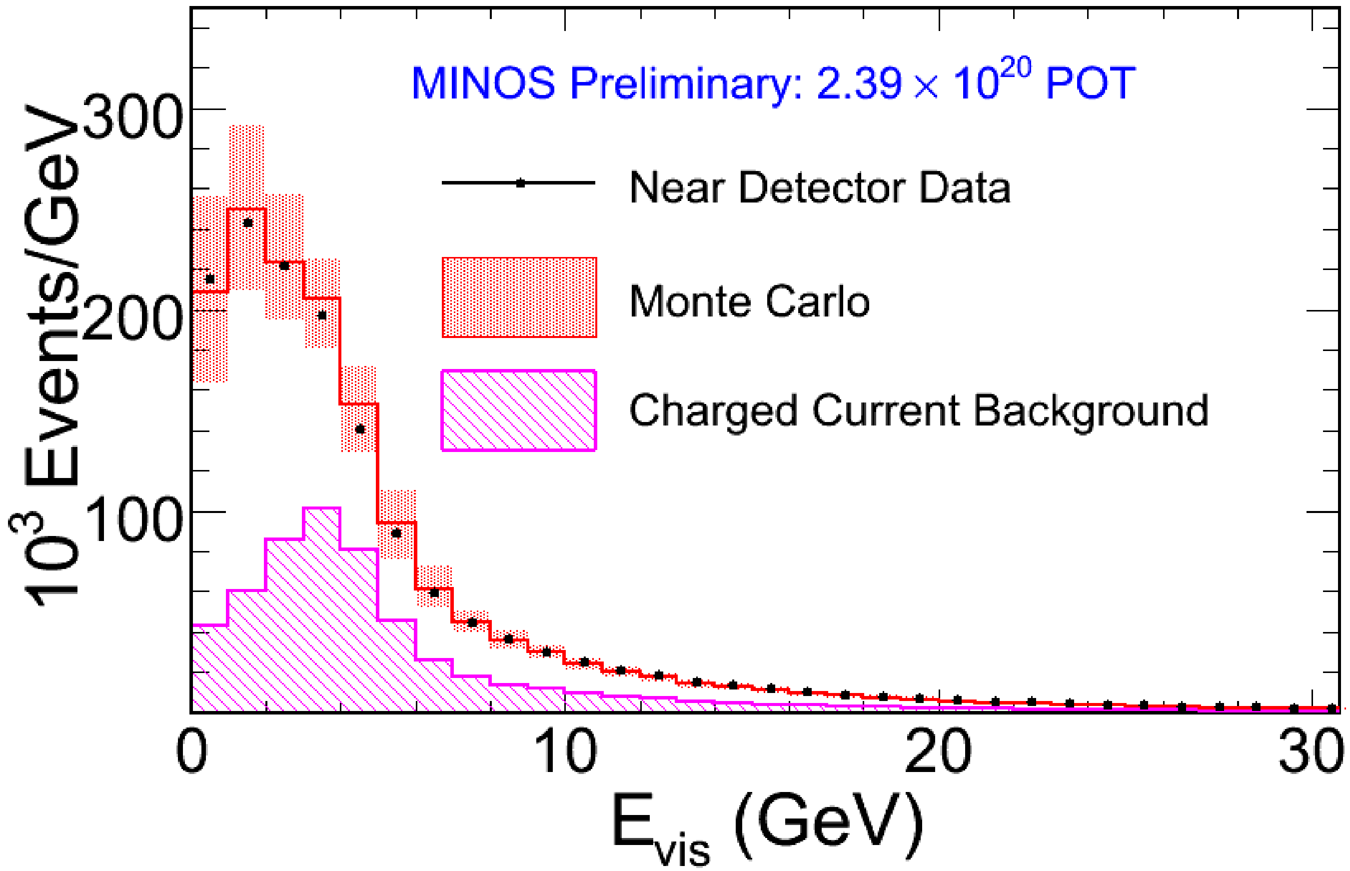
- Final neutral current event selection proceeds via cuts on three variables
- Error envelopes shown reflect systematic uncertainties due to cross-section modeling and beam modeling



- Event classified as NC-like if:
  - event length < 60 planes
  - has no reconstructed track or
  - has one reconstructed track that does not protrude more than 5 planes beyond the shower

Neutral Current Energy Spectrum

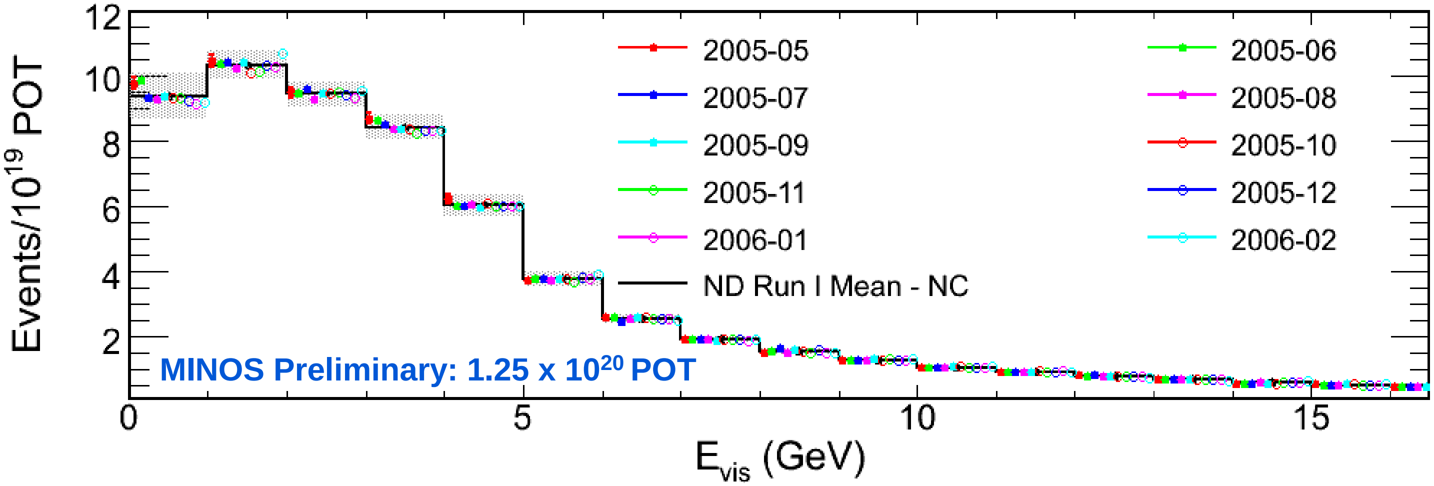
- NC selected Data and MC energy spectra for Near Detector

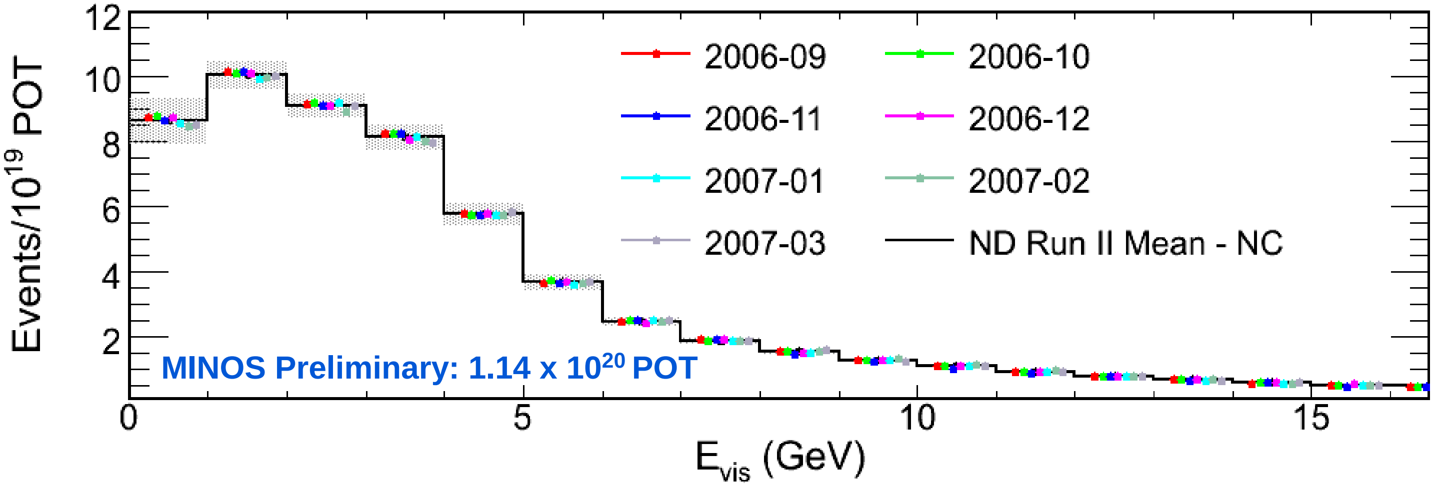


- Good agreement between Data and Monte Carlo
- Discrepancies much smaller than systematic uncertainties
- NC events are selected with 90% efficiency and 60% purity

Near Detector Data Stability

- NC events selected for each month of MINOS data taking





- Changes from month to month are much smaller than the uncertainty due to beam and selection systematics.

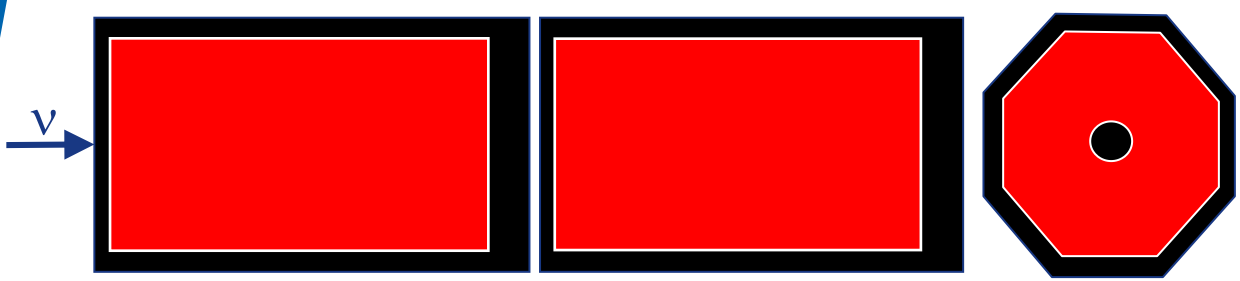
Far Detector Data Selection

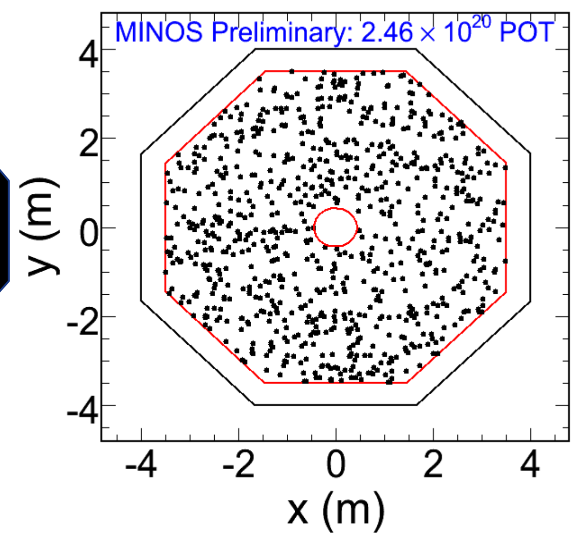
Blind Analysis

- The MINOS collaboration employed a blinding procedure for its Neutral Current Analysis
- Unknown fraction of the FD events was hidden according to an unknown function based on event length and energy
- The open fraction of FD data was used to perform data quality checks
- All Near detector data was kept open. Used to study beam properties, cross-sections and detector systematics
- Once final analysis and event selection cuts were decided upon, the "Box" was opened
  - Final analysis and cuts were applied to complete FD data sample
  - No re-tuning of cuts or analysis changes made after box opening

Event Pre-Selection Cuts

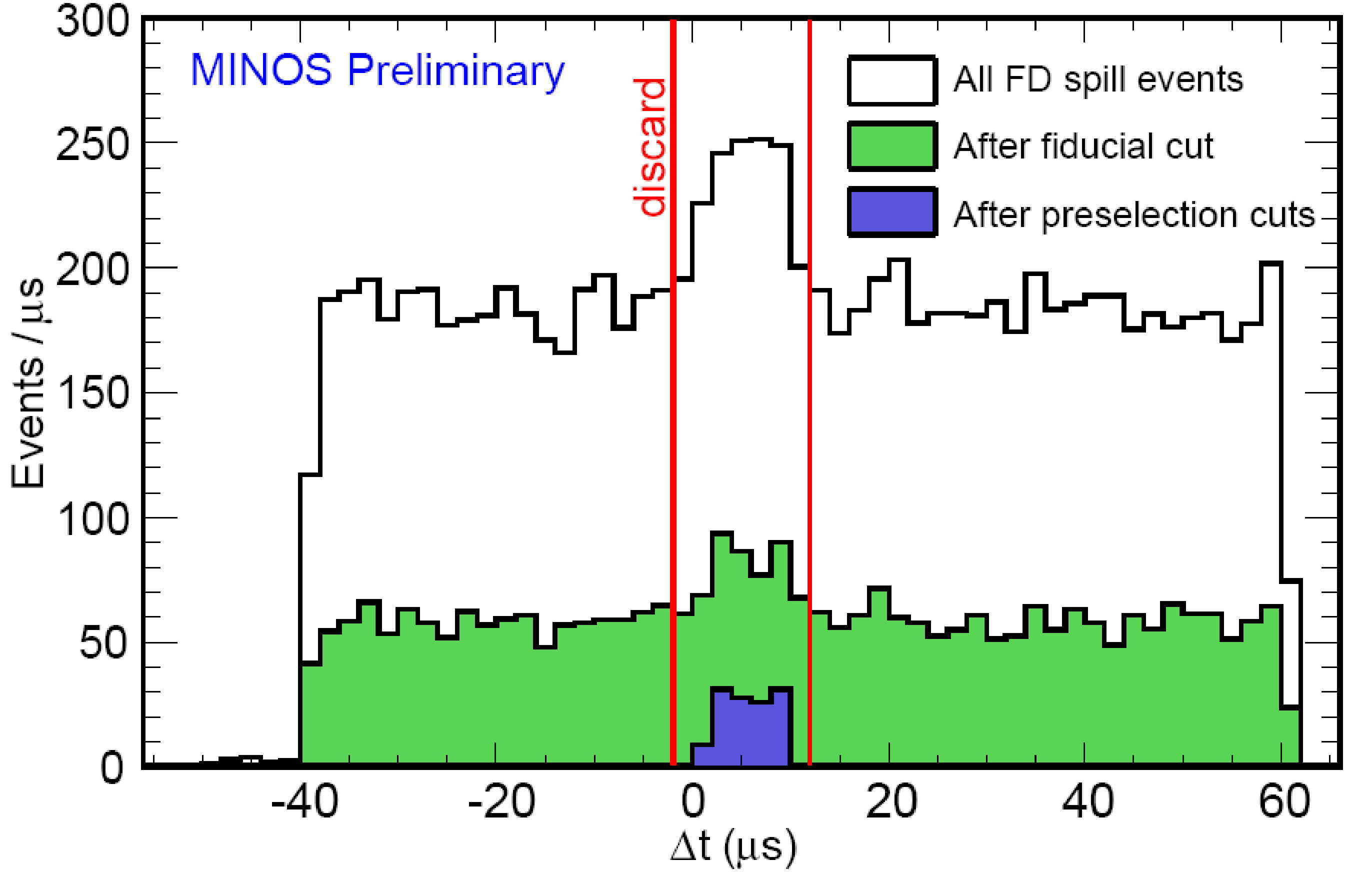
- Beam quality and detector quality cuts
  - Beam positioning, magnetic horns energized, detector running within operational parameters
- Event vertex reconstructed within the fiducial volume of the detector
  - Transverse vertex position > 50 cm from the edge of the detector and > 45 cm from the center of the detector (avoid uninstrumented coil hole region)
  - Longitudinal vertex position more than 25 cm from the front and at least 1m from the back of each super-module





Event Pre-Selection Cuts

- Noise sources
  - detector noise, cosmics, split events
- Series of cuts used to eliminate each one
  - Associated systematic uncertainty included in analysis



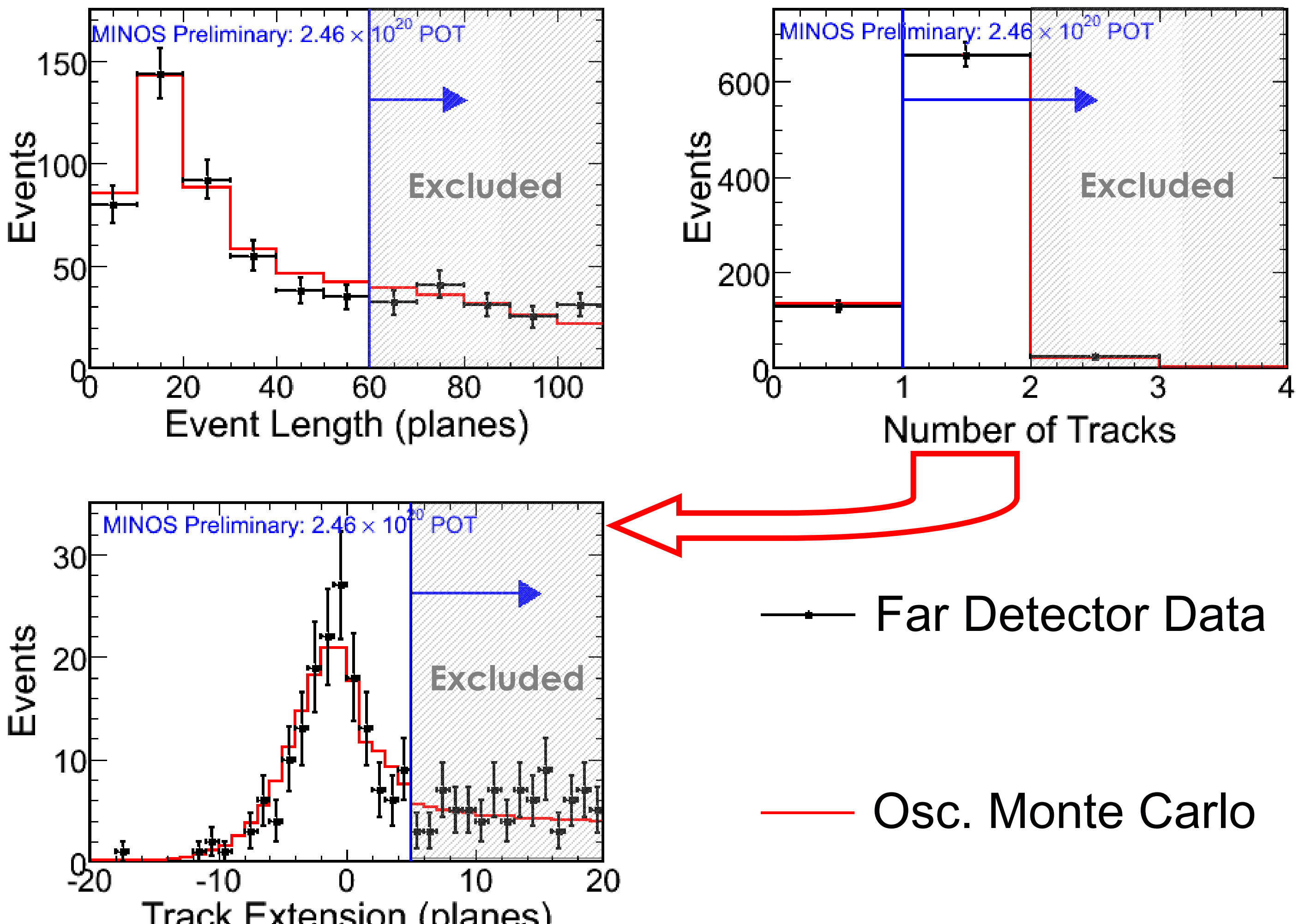
Breakdown of FD Pre-Selected Events

- Effect of pre-selection cuts on FD events

	Cut	Events	Surviving Fraction
	All Fiducial Events	26476	100%
Pre-Selection Cuts	Detector Noise	961	3.6%
	Cosmics	875	3.3%
	Timing	857	3.2%

Far Detector NC Selection

- The FD NC selection uses the same variables as the ND selection, with identical cut values
- MC oscillated with MINOS CC best fit: $\Delta m^2 = 2.38 \times 10^{-3}\ eV^2$, $\sin^2(2\theta_{23})=1$



Breakdown of FD Selected Events

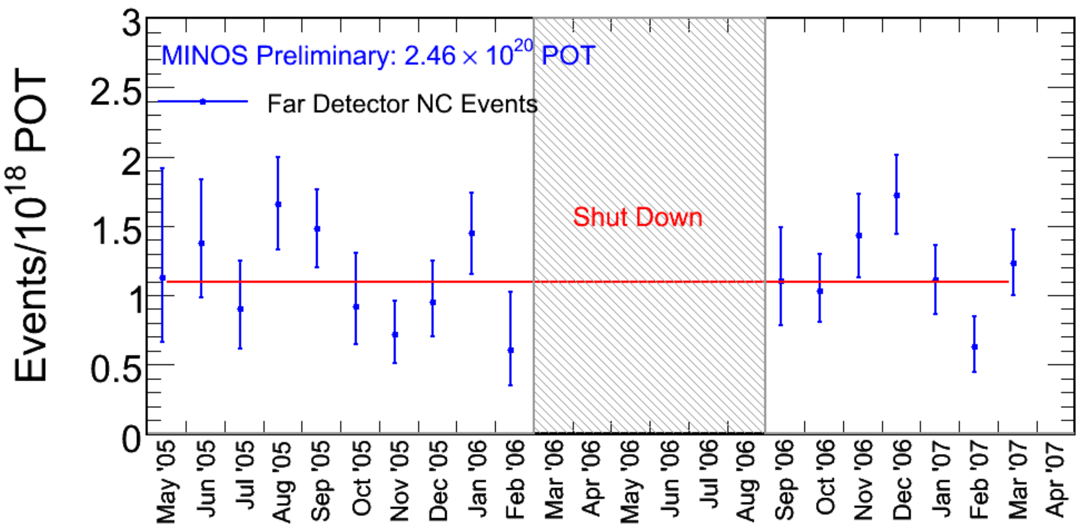
- Effect of NC selection cuts on Far Detector events

	Cut	Events (Data)	Surviving Fraction (Data)	Surviving Fraction (Osc. MC)
	All Pre-Selected Events	857	100%	100%
NC Selection Cuts	Event Length	463	54.0%	55.1%
	Number of Tracks	455	53.1%	54.0%
	Track Extension	291	34.0%	34.7%

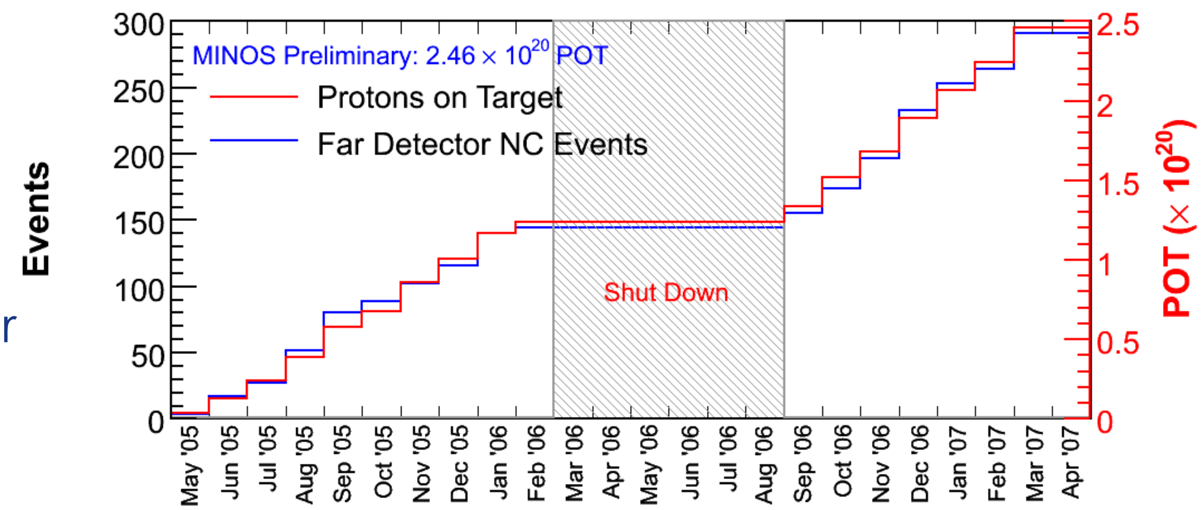
Far Detector Data Stability

- Event rate vs time

  NC selected events in the FD divided by number of POT

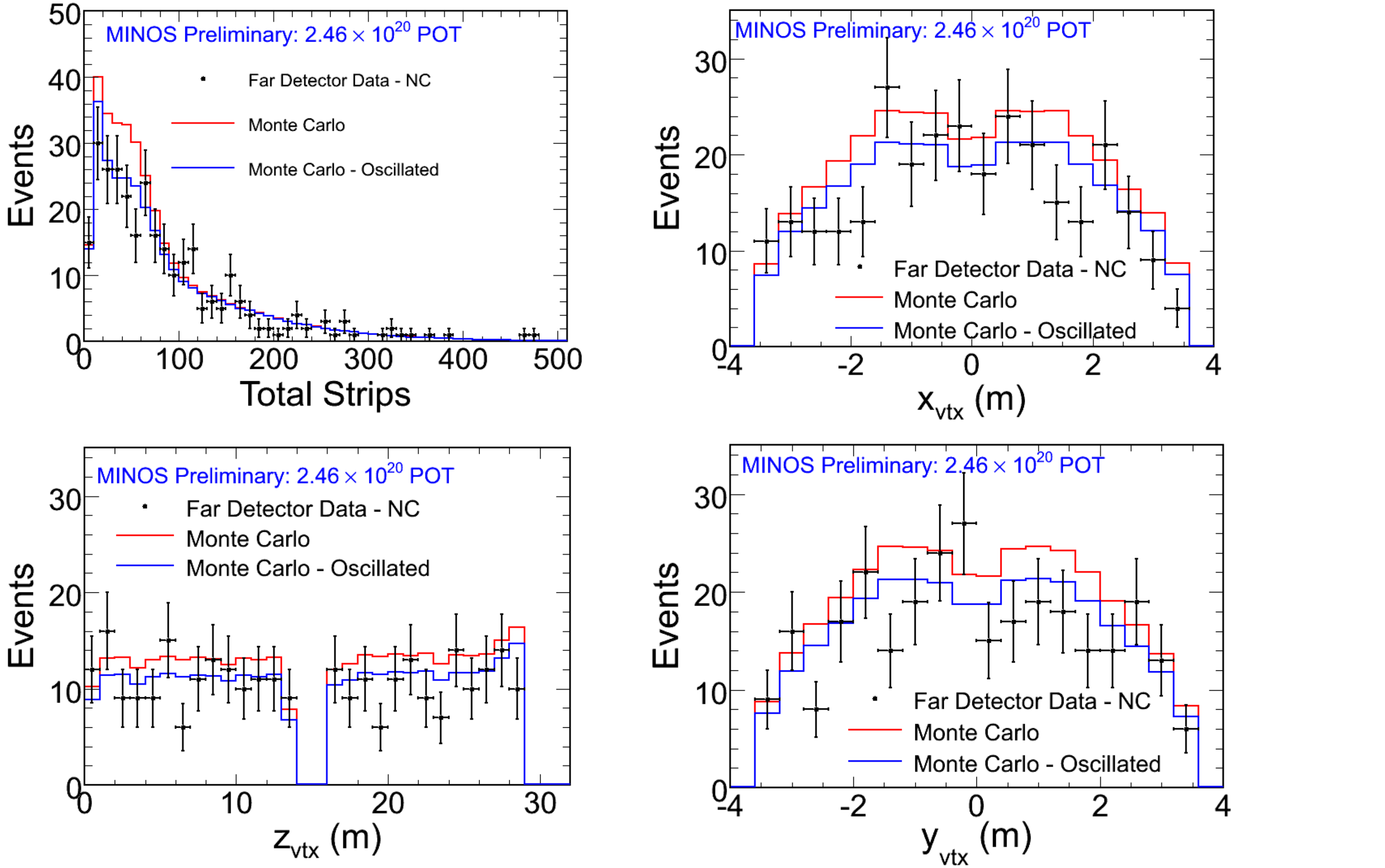


- Integral number of NC selected events in the FD compared with accumulated POT
- NC selected events per month proportional to accumulated POT

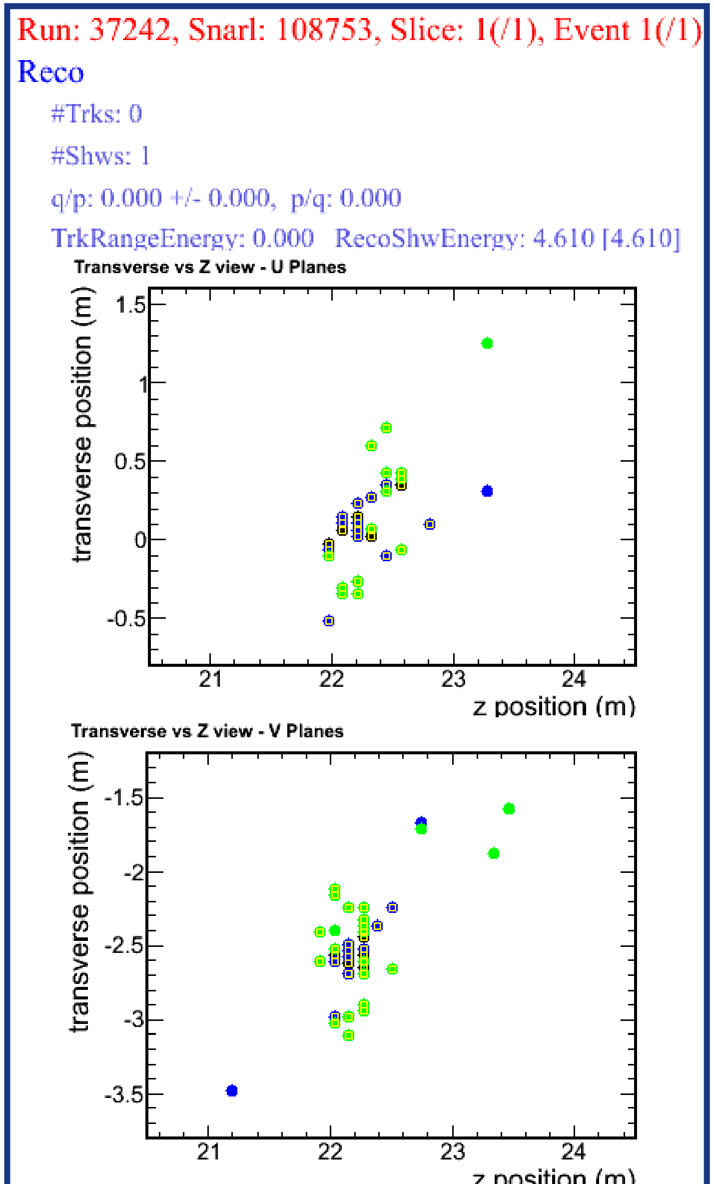


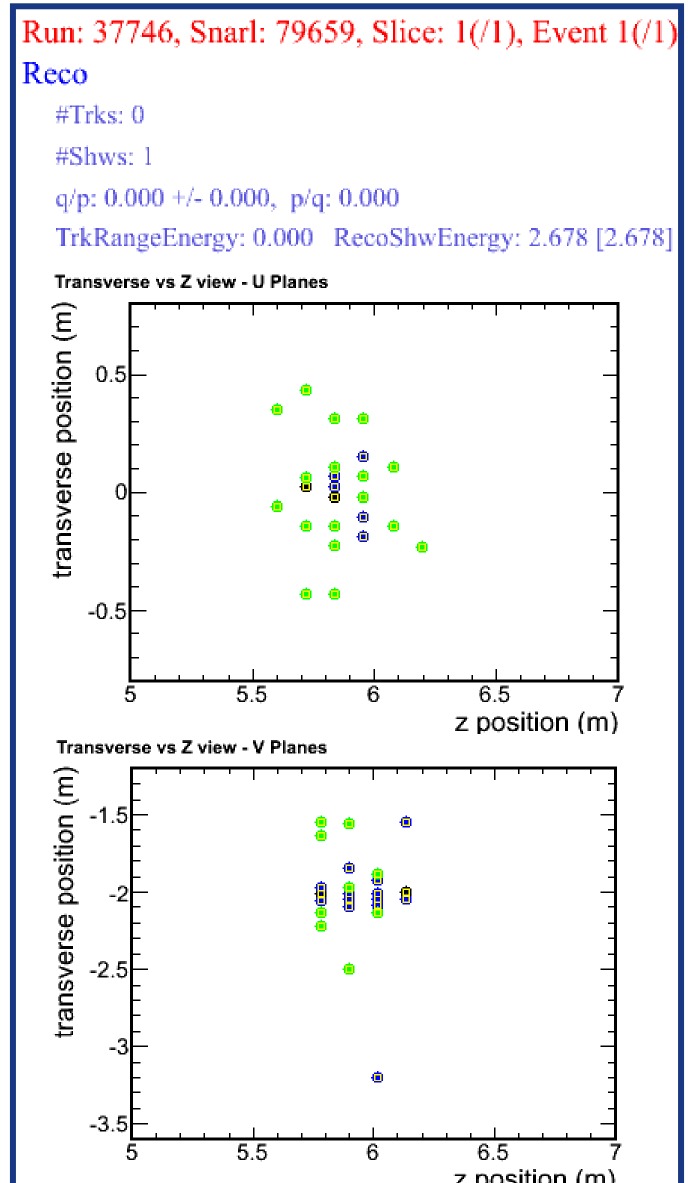
Far Detector Data Quality Plots

- Data and MC distributions of selected NC Events in the Far Detector
- MC oscillated with MINOS CC best fit: $\Delta m^2 = 2.38 \times 10^{-3}$ eV^2, $\sin^2(2\theta_{23})=1$



NC Selected Events in Far Detector Data

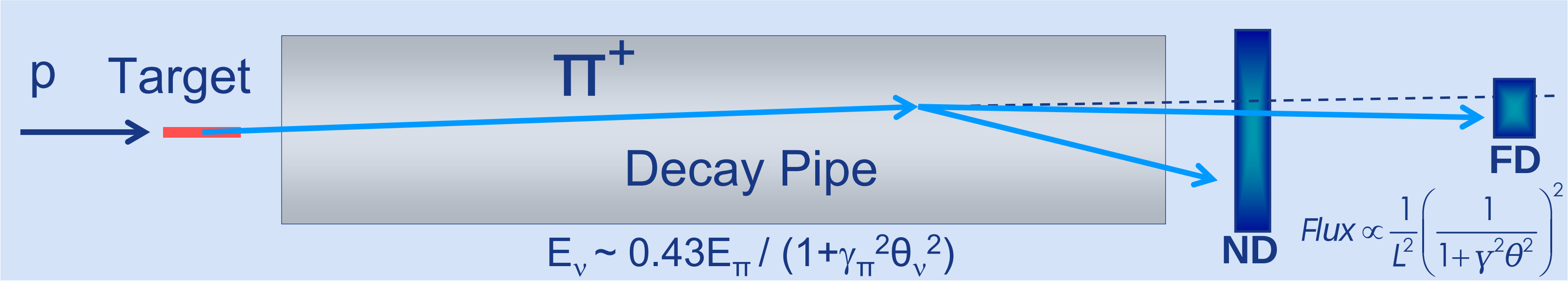




Near to Far Extrapolation of the Neutral Current Energy Spectrum

Far Detector MC Prediction

- Far detector energy spectrum without oscillations is not the same as the Near detector spectrum
  - Decay angles for neutrinos to reach detector are different for ND and FD ⇒ different energy spectrum



- We use the measured ND energy spectrum to predict the unoscillated FD energy spectrum
  - Near to Far extrapolation makes use of Monte Carlo to correct for energy smearing and acceptance differences

Far / Near Ratio Method

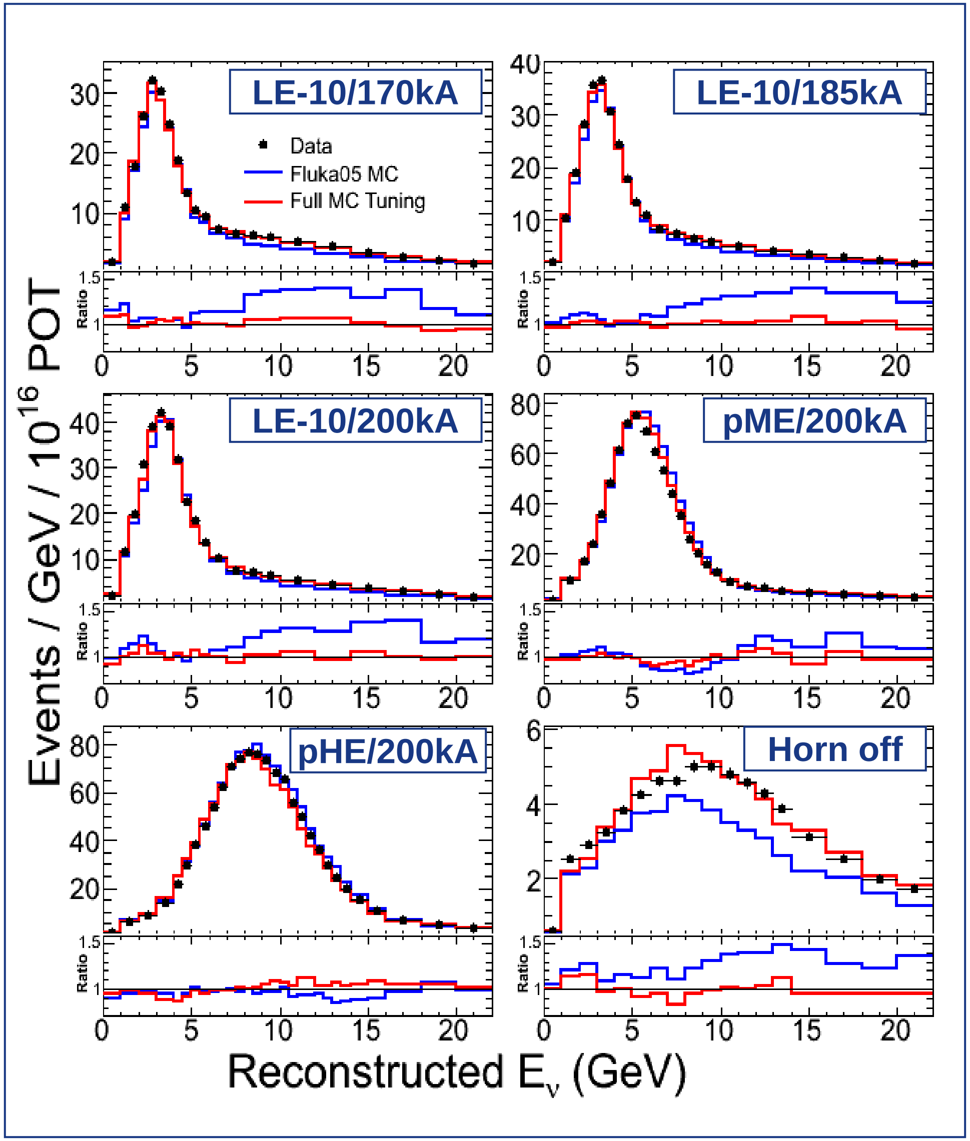
- An approach that uses the ND data in a non-parameterized way is provided by the F/N ratio method:

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

- For every event that passes FD NC selection, a reconstructed energy vs true energy 2D histogram is created
  - Oscillation weights are calculated for bins of true Energy
  - For each bin of true energy, the reconstructed energy projection is multiplied by the corresponding oscillation weight
  - Prediction is obtained by multiplying each bin by N_i^{Data}/N_i^{MC}
- Simple, makes no assumptions about ND Data parameterization, robust to systematic errors

Hadron Production Tuning

- Use tuning of hadron production in CC events to provide flux corrections for Monte Carlo
- Parameterize Fluka2005 prediction as a function of x_F and p_T
- Perform fit which reweights neutrino parent pion x_F and p_T to improve data/MC agreement



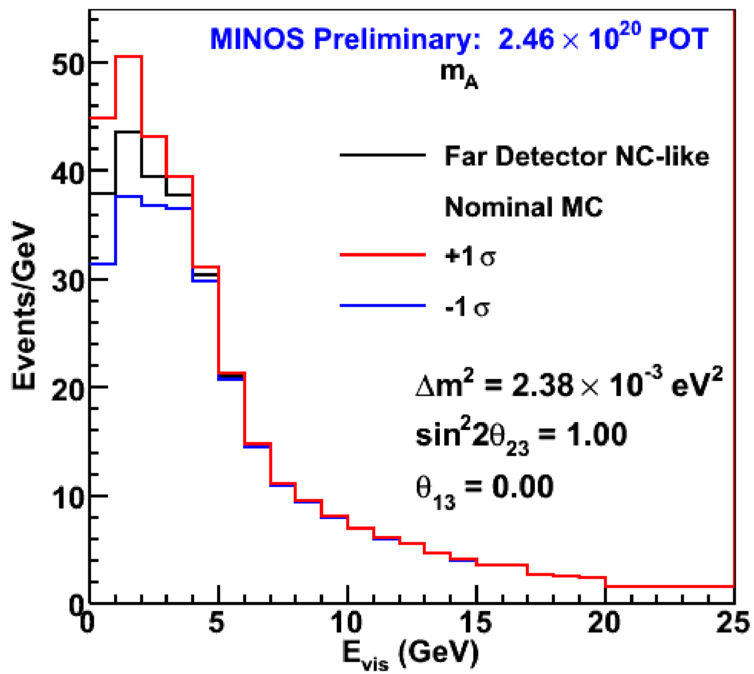
Results from Neutral Current Analysis of 2.46×10^{20} POT of MINOS Data

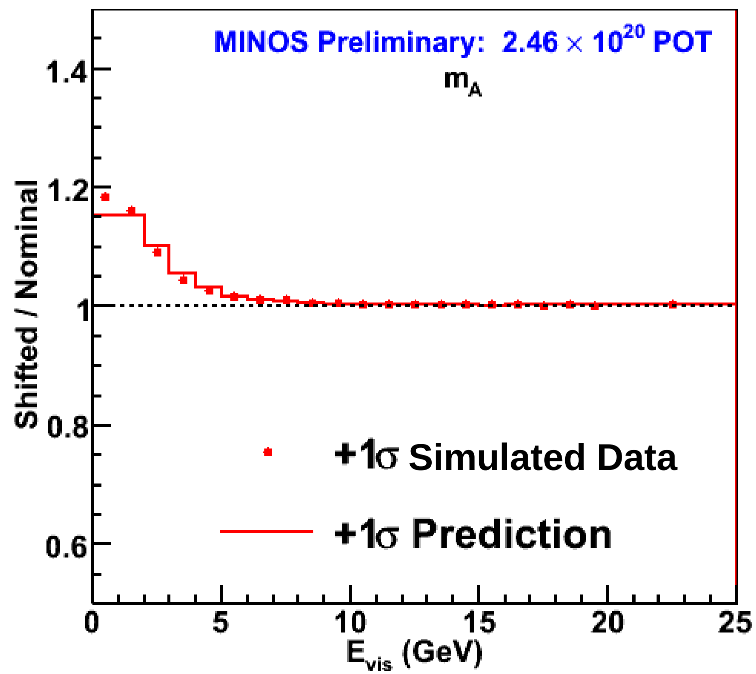
Systematic Errors

- **Normalization**: ±4%
  - POT counting, Near/Far reconstruction efficiency, fiducial mass
- **Relative Hadronic Calibration:** ±3%
  - Inter-Detector calibration uncertainty
- **Absolute Hadronic Calibration:** ±11%
  - Hadronic Shower Energy Scale(±6%), Intranuclear rescattering(±10%)
- **Muon energy scale:** ±2%
  - Uncertainty in dE/dX in MC
- **CC Contamination of NC-like sample:** ±15%
- **NC contamination of CC-like sample:** ±25%
- **Cross-section uncertainties:**
  - m_A (qe) and m_A (res): ±15%
  - KNO scaling: ±33%
- **Poorly reconstructed events:** ±10%
- **Near Detector NC Selection:** ±8% in 0-1 GeV bin
- **Far Detector NC Selection:** ±4% if E < 1 GeV, <1.6% if E > 1 GeV
- **Beam uncertainty:** 1σ error band around beam fit results

Systematic Errors

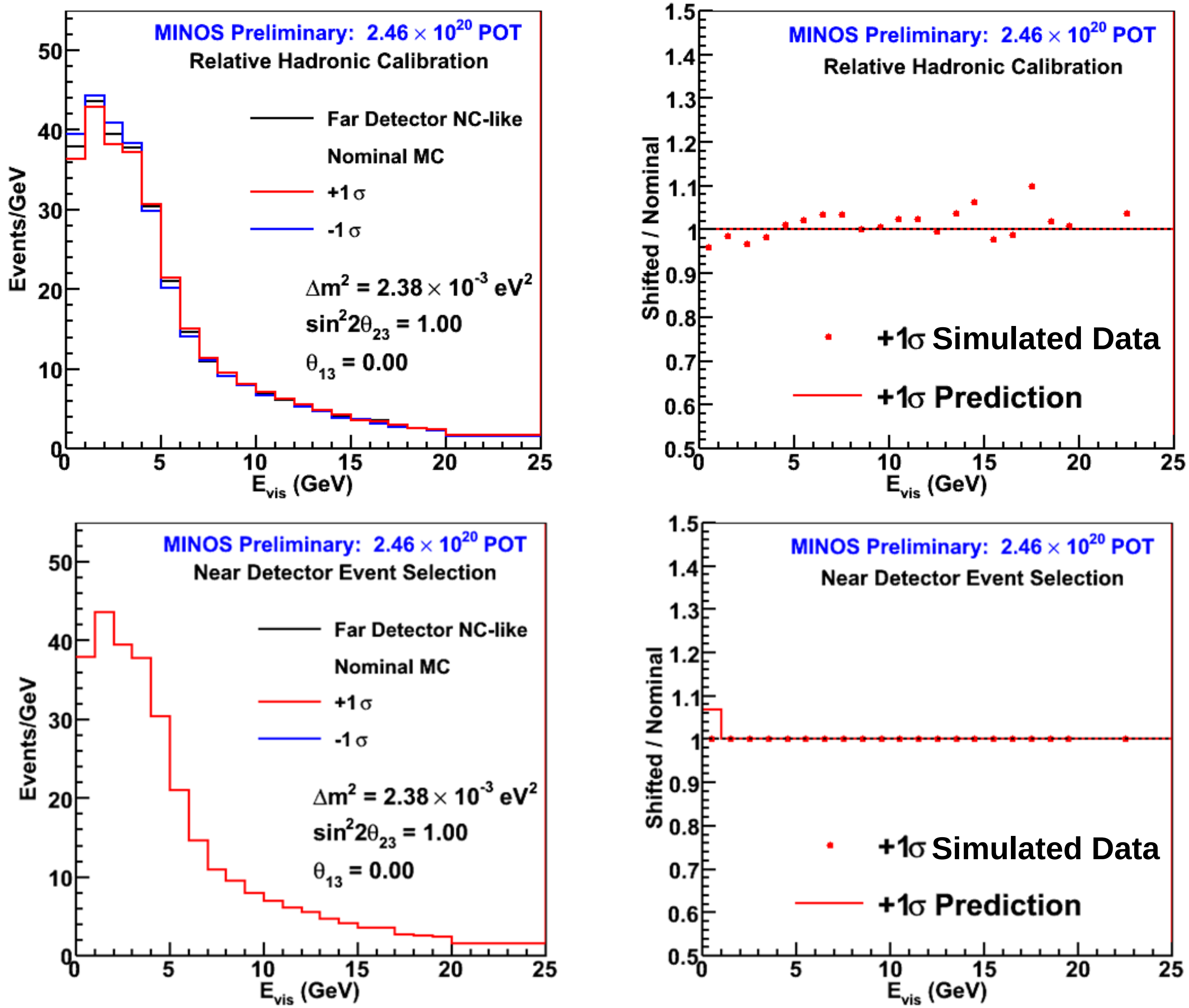
- Systematic errors studied using simulated Far Detector data histograms with oscillation parameters $\Delta m^2 = 2.38 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$
- Left plot displays magnitude of shift in FD simulated data compared to nominal
- Ratio plots show shifted/nominal ratio for FD simulated data, overlaid with shifted/nominal MC FD prediction
  - Displays ability of F/N extrapolation method to reproduce systematic shift





- F/N extrapolation method is robust to absolute systematic errors, which shift the energy spectra in both Near and Far detectors
- Most relevant systematics are relative, where shifts only applied to one detector

Systematic Errors



3-Flavor Analysis

- Compare the NC energy spectrum with the expectation of standard 3-flavor oscillation physics

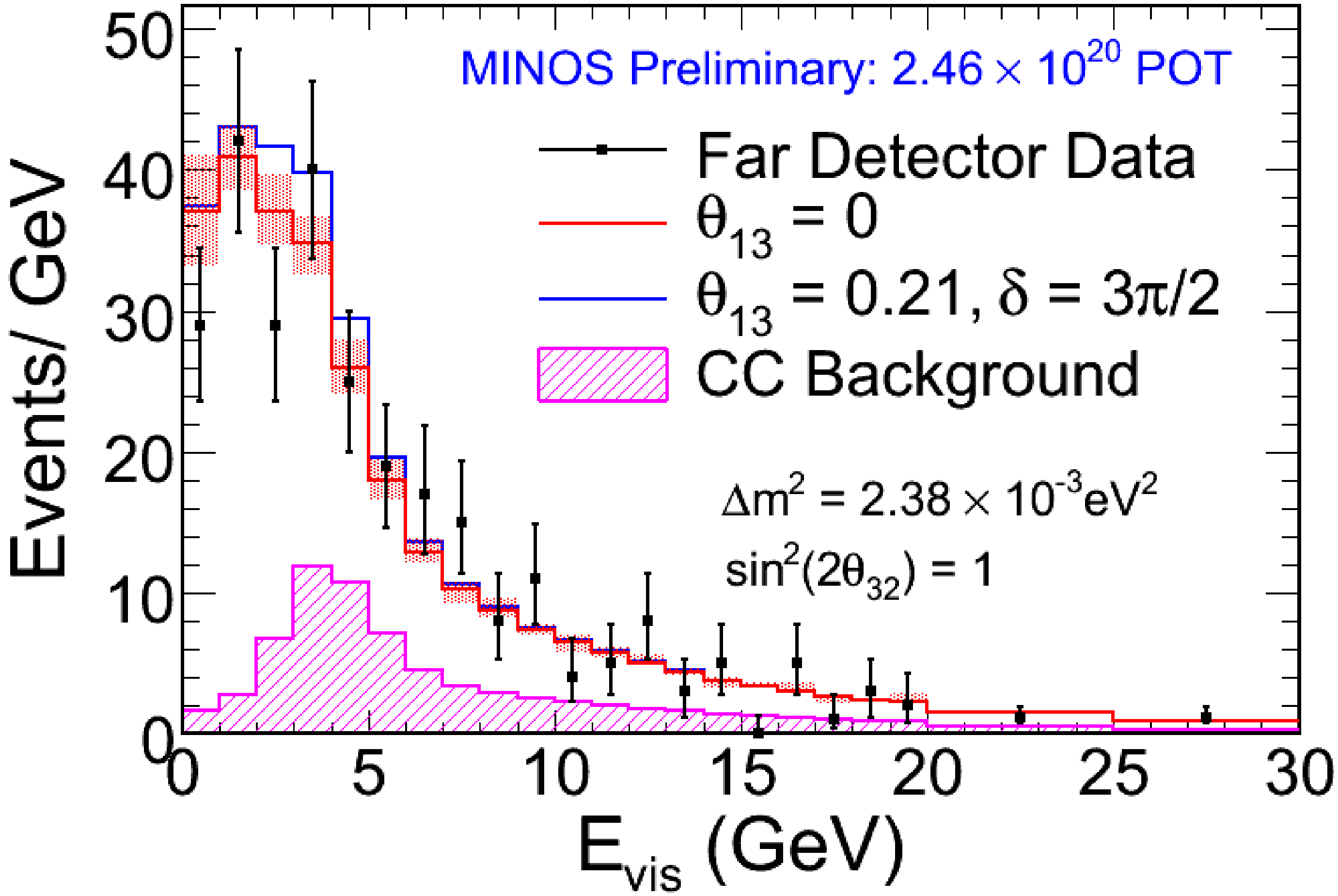
- Pick the oscillation parameter values
  - $\sin^2 2\Theta_{23} = 1$ } From MINOS CC measurement
  - $\Delta m^2_{32} = 2.38\times10^{-3}\ eV^2$ } From MINOS CC measurement
  - $\Delta m^2_{21} = 7.59\times10^{-5}\ eV^2$, $\Theta_{12} = 0.61$ from KamLAND+SNO
  - $\Theta_{13} = 0$ or 0.21 (normal MH, $\delta=3\pi/2$) from CHOOZ Limit
  - Note that CC ν_e are classified as NC by the analysis

- Make comparison in terms of number of events in different energy ranges
  - 0-3 GeV
  - 0-5 GeV
  - All events (0-120 GeV)

- Result is #σ (dis-)agreement

3-Flavor Far Detector Energy Spectrum

- Far Detector reconstructed energy spectra for NC-like events.
- Oscillation parameters are fixed. MC predictions with Θ_{13}=0 and Θ_{13} at the CHOOZ limit are shown.



3-Flavor Results and Significance

- Comparisons between observed Data and MC Prediction
- Significance is given by

$$Sig. = \frac{Data - MC}{\sqrt{MC + \sigma_{sys}^2}}$$

Energy Range (GeV)	Data	MC $\Theta_{13} = 0$	Sig. (σ) $\Theta_{13} = 0$	MC $\Theta_{13} = 0.21$ $\delta = 3\pi/2$	Sig. (σ) $\Theta_{13} = 0.21$ $\delta = 3\pi/2$
0-3	100	115.16 ± 7.67	1.15	122.09 ± 8.42	1.56
0-5	165	175.92 ± 10.42	0.65	191.26 ± 11.88	1.42
0-120	291	292.63 ± 15.02	0.10	311.54 ± 16.28	0.89

- For the 0-3 GeV reconstructed energy range, a 1.15σ difference between Data and Osc. Monte Carlo is observed in the case where $\Theta_{13} = 0$

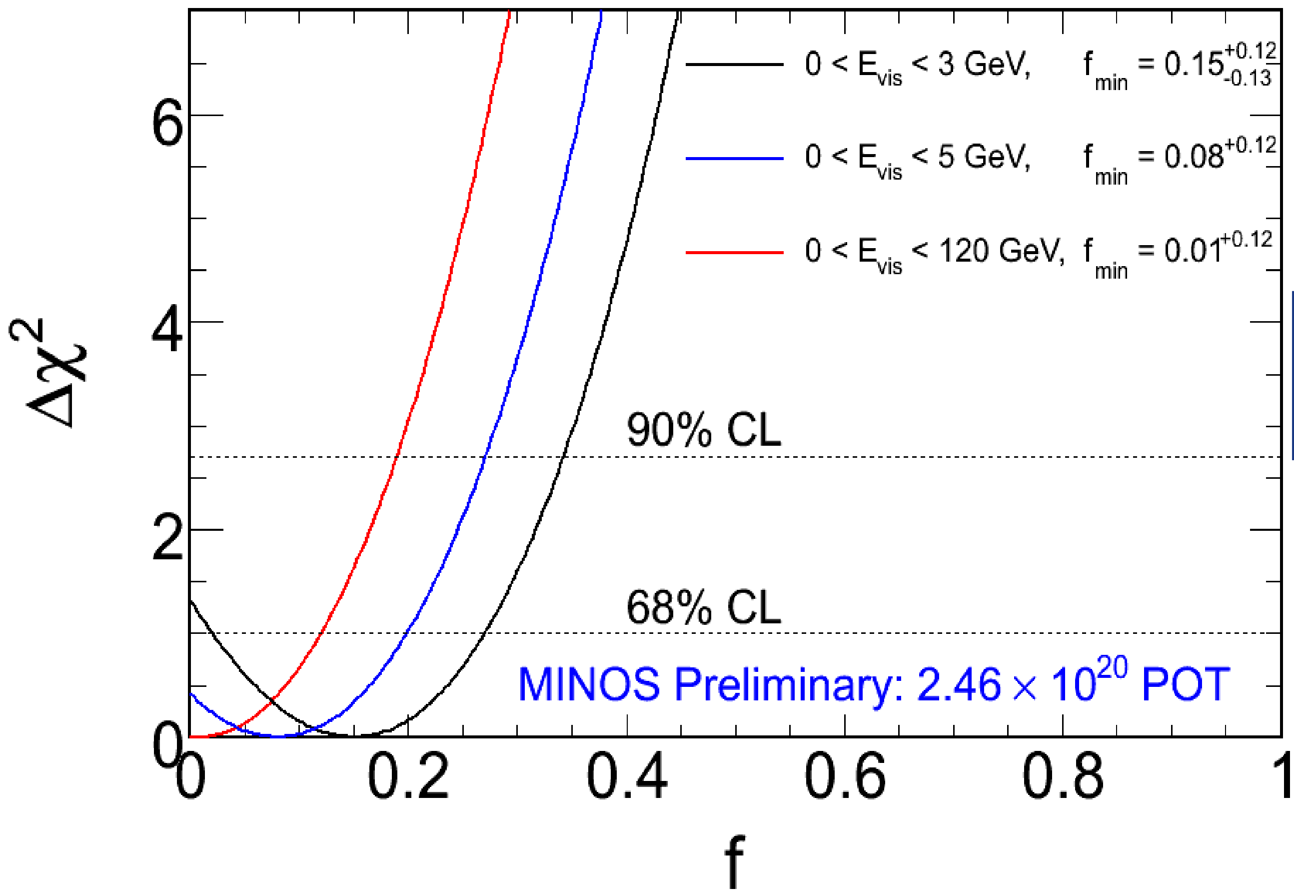
NC Disappearance Fraction

- The expected total number of events is given by

$$MC = NC\,(1 - f) + CC\,\nu_\mu + CC\,\nu_e + CC\,\nu_\tau\,,$$

where *f* is the fraction of total neutral current events that disappear

- Calculate χ^2 for values of *f* between 0 and 1 (fixed $\Theta_{13} = 0$)



$$\chi^2 = \frac{(Data - MC)^2}{MC + \sigma_{sys}^2}$$

For $E_{vis} < 3$ GeV: *f* < 0.35, 90% C.L.

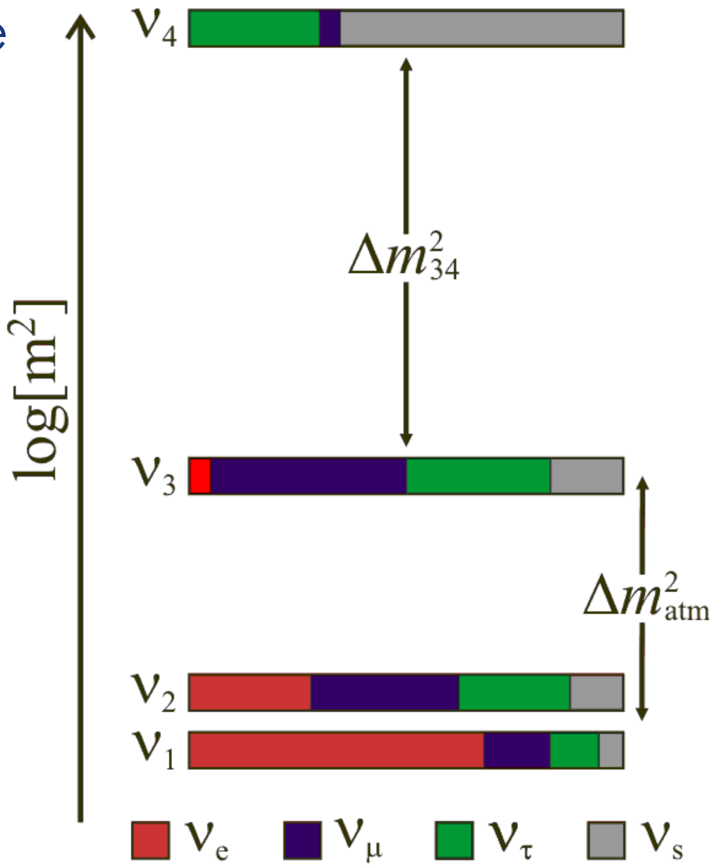
For $E_{vis} < 120$ GeV: *f* < 0.17, 90% C.L.

4-Flavor Analysis

- Assume there is an additional sterile neutrino and an additional mass scale

- Mixing matrix is extended to:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



- Parameters ($\Delta m^2_{21} \sim 0$)
  - $|U_{s3}|^2$, $|U_{s4}|^2$, $|U_{\mu 4}|^2$, Δm^2_{41} and Φ_{43}

4-Flavor Model

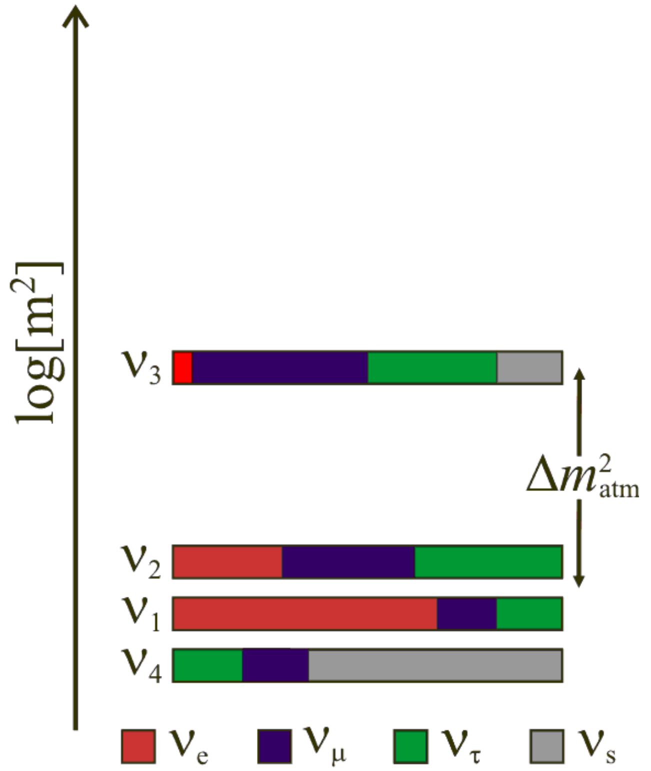
- Assume $\Delta m^2_{41} = 0$
  - Oscillation at single mass scale
  - Oscillation probabilities simplify to:

$$P_{\nu_\mu \to \nu_\mu} = 1 - 4|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right) \Delta_{31}^2$$

$$P_{\nu_\mu \to \nu_e} = 4|U_{\mu 3}|^2 |U_{e3}|^2 \Delta_{31}^2$$

$$P_{\nu_\mu \to \nu_s} = 4|U_{\mu 3}|^2 |U_{s3}|^2 \Delta_{31}^2$$

$$P_{\nu_\mu \to \nu_\tau} = 1 - P_{\nu_\mu \to \nu_\mu} - P_{\nu_\mu \to \nu_e} - P_{\nu_\mu \to \nu_s}$$



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

$$\Delta_{31}^2 = \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

- Fit for Δm^2_{31}, $|U_{\mu 3}|^2$ and $|U_{s3}|^2$
- Joint fit of NC and CC spectra
- Fix $|U_{e3}|^2 = 0$ and 0.04 (CHOOZ limit)

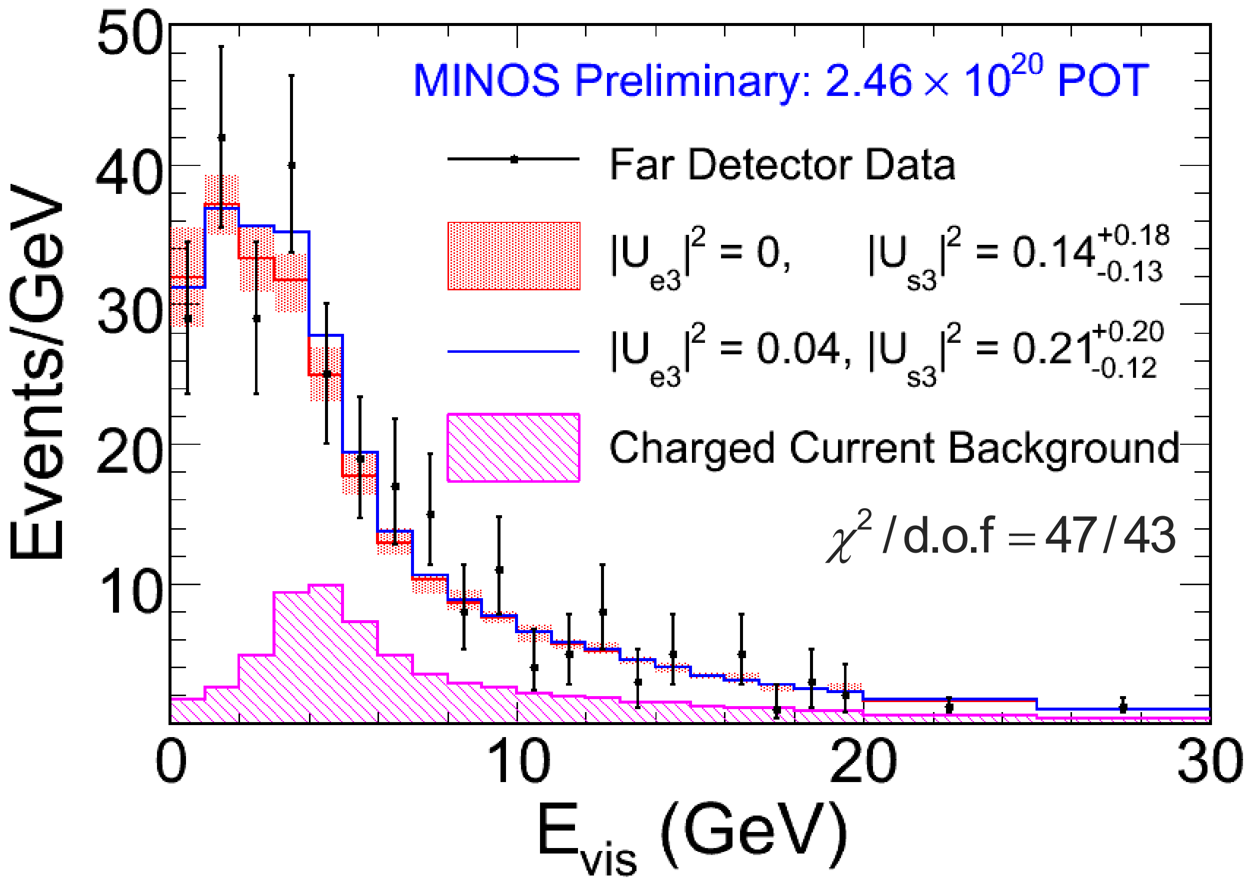
4-Flavor Systematic Shifts

- Systematic shifts in the fitted parameters are computed using MC simulated data histograms oscillated with $|U_{\mu 3}|^2 = 0.5$, $|U_{s3}|^2 = 0.2$

Uncertainty	Shift in $|U_{s3}|^2$	Shift in $|U_{\mu 3}|^2$
m_A	0.01	0.00
KNO	0.01	0.00
Beam uncertainties	0.00	0.01
Absolute Hadronic Calibration	0.01	0.02
Relative Hadronic Calibration	0.04	0.02
Muon Energy Scale	0.01	0.01
Normalization	0.06	0.03
CC Background in NC Spectrum	0.03	0.01
NC Background in CC Spectrum	0.01	0.02
Near Detector Selection	0.04	0.01
Poorly Reconstructed Events	0.00	0.00
Far Detector Selection	0.02	0.00
Total (sum in quadrature)	0.09	0.05
Statistical Sensitivity	0.18	0.18

4-Flavor Fit Results

- Best fit energy spectrum for 2.46×10^{20} POT
- Largest systematic uncertainties included in the fit

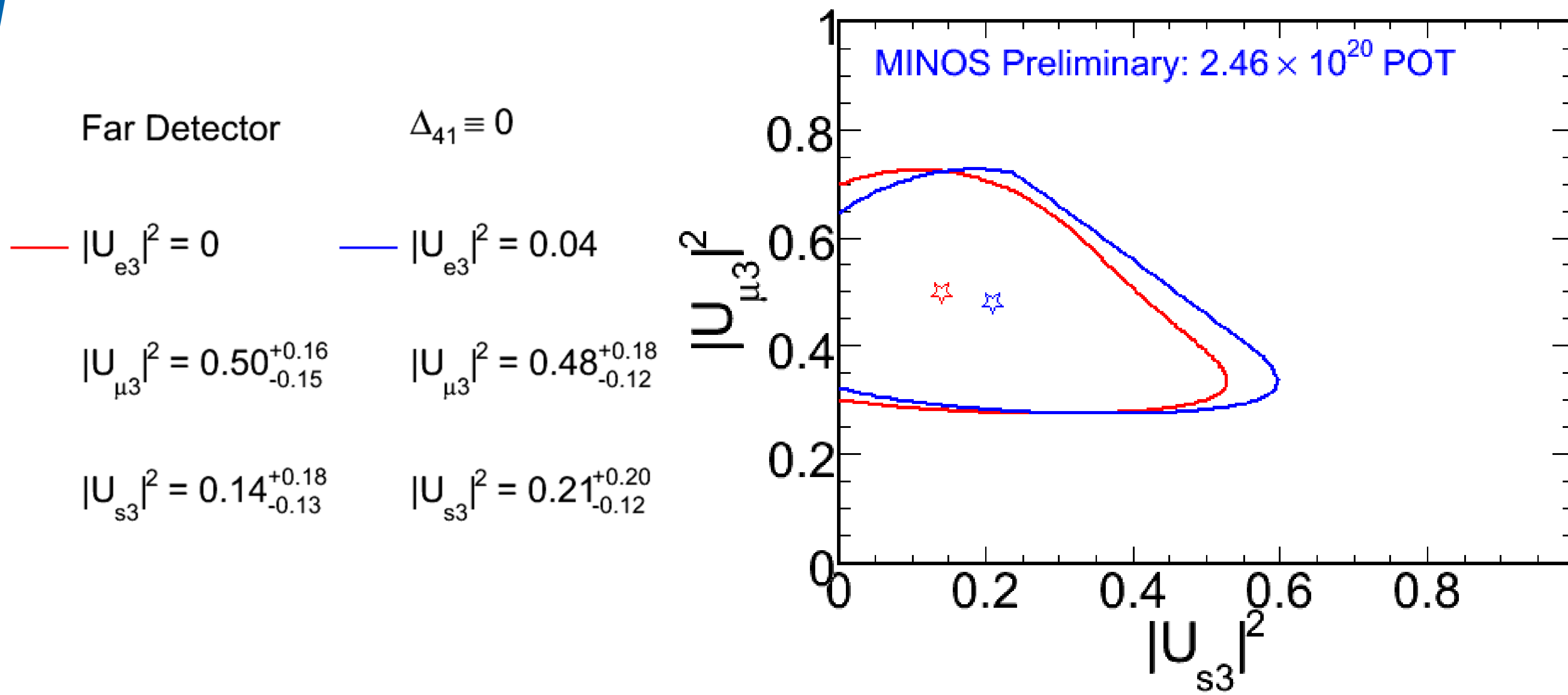


$$\chi^2 = \sum_{i=1}^{nbins}\left[2\left(e_i - o_i\right) + 2o_i \ln\left(o_i/e_i\right)\right] + \sum_{j=1}^{nsys} \Delta s_j^2 / \sigma_{s_j}^2$$

← **Penalty terms for systematic uncertainties**

4-Flavor Fit Contour

- 90% C.L. contour for the fits to $|U_{s3}|^2$ and $|U_{\mu3}|^2$
- Showing both cases: $|U_{e3}|^2 = 0$ and $|U_{e3}|^2 = 0.04$ (CHOOZ limit)



Summary

- MINOS has completed an analysis of neutral current neutrino interactions in 2.46×10^{20} POT of NuMI beam exposure

- From 3-flavor analysis:

  E < 3 GeV, *f* < 0.35 to 90% C.L.

  – Results consistent with no sterile neutrino admixture.

- 4-flavor analysis best fit values:

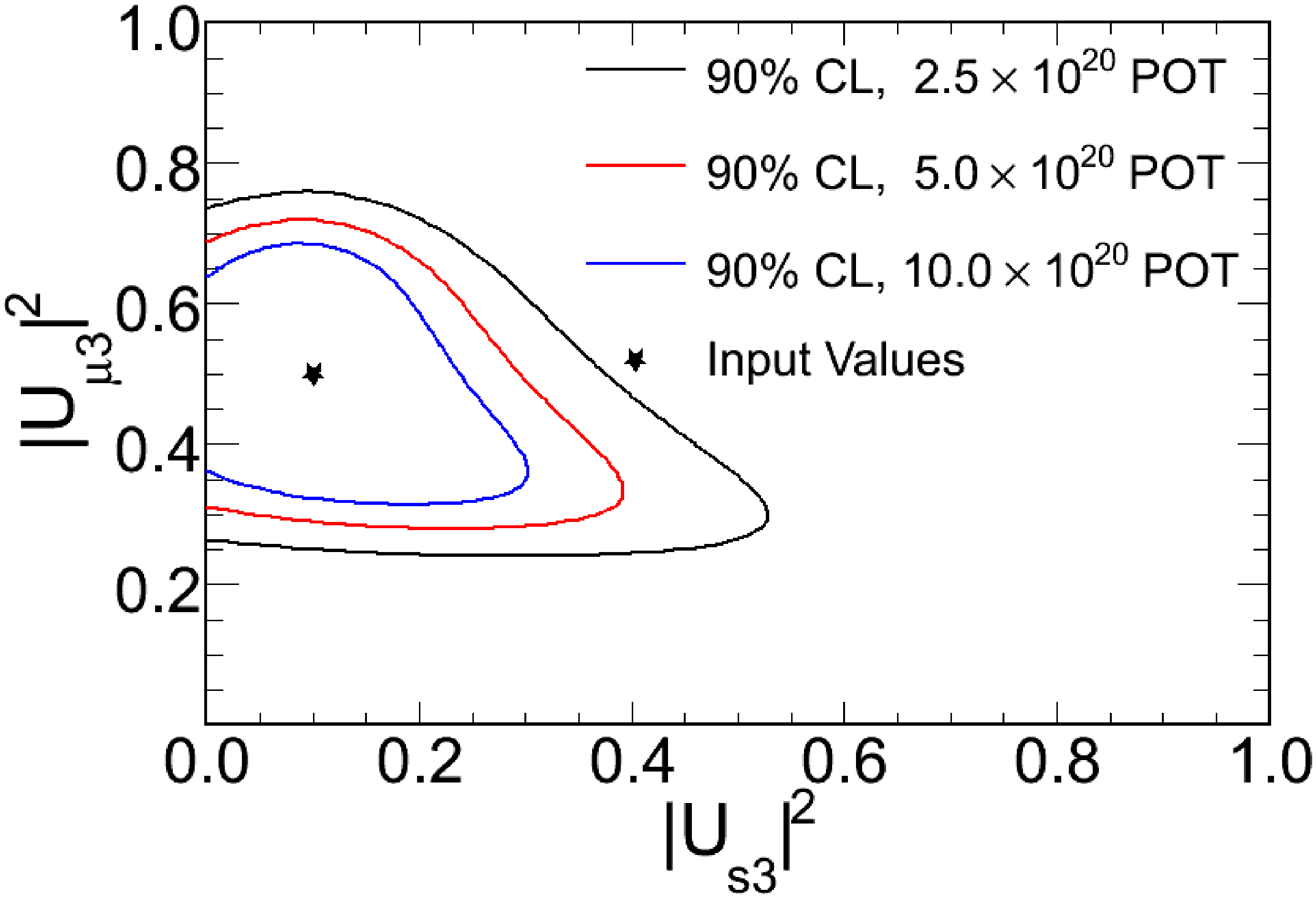
$$|U_{s3}|^2 = 0.14^{+0.18}_{-0.13}, \quad \text{for } |U_{e3}|^2 = 0 \qquad (\text{no } \nu_e \text{ admixture})$$

$$|U_{s3}|^2 = 0.21^{+0.20}_{-0.12}, \quad \text{for } |U_{e3}|^2 = 0.04 \quad (\nu_e \text{ admixture})$$

- Measurement statistically limited. Substantially more protons will improve results significantly

Outlook

- 90% C.L. sensitivity curves for different NuMI beam exposures
- Input values of oscillation parameters
  - $|U_{\mu 3}|^2 = 0.5$, $|U_{s3}|^2 = 0.1$, $\Delta m^2_{32} = 2.38 \times 10^{-3}\ eV^2$, $|U_{e3}|^2 = 0$
- Only MC events are used



Acknowledgements

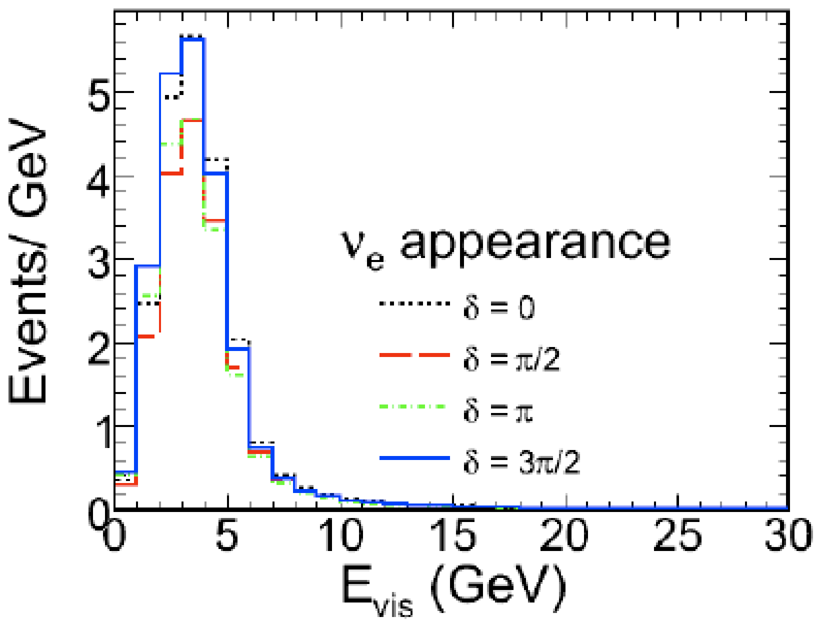
- On behalf of the MINOS Collaboration, I would like to express our gratitude to the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the experiment

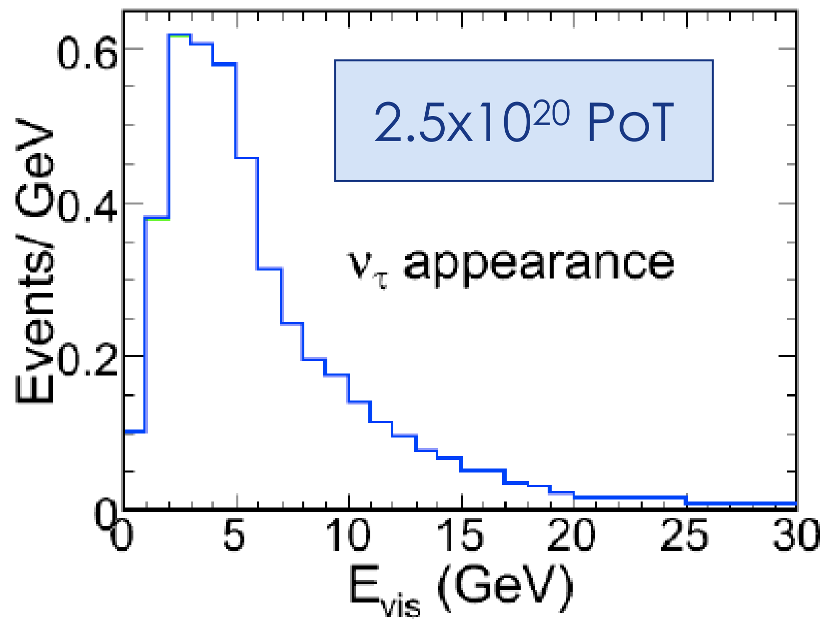
- We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and the Minnesota DNR for hosting us.

Backup Slides

Tau & Electron Events

- How Sensitive is the NC Analysis to tau or electron neutrino appearance?
  - not a great deal
  - 20 electron and 5 tau events





Systematic Errors

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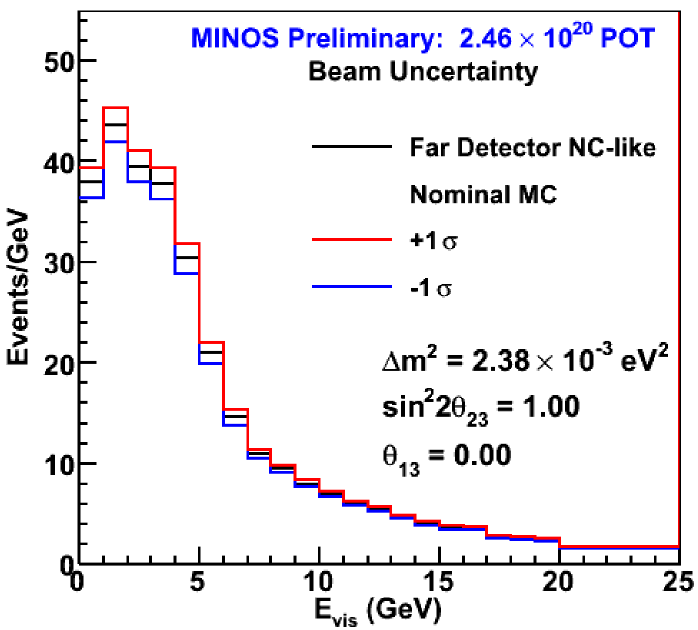
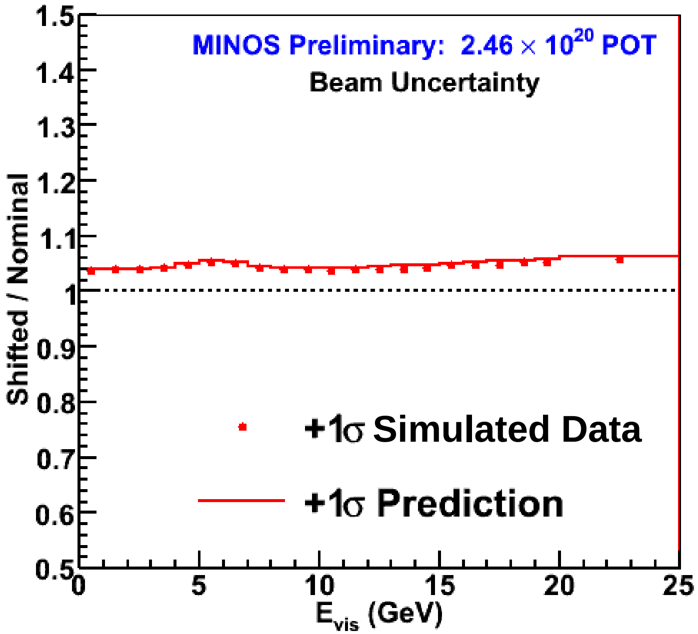
  - Displays ability of F/N extrapolation method to reproduce systematic shift

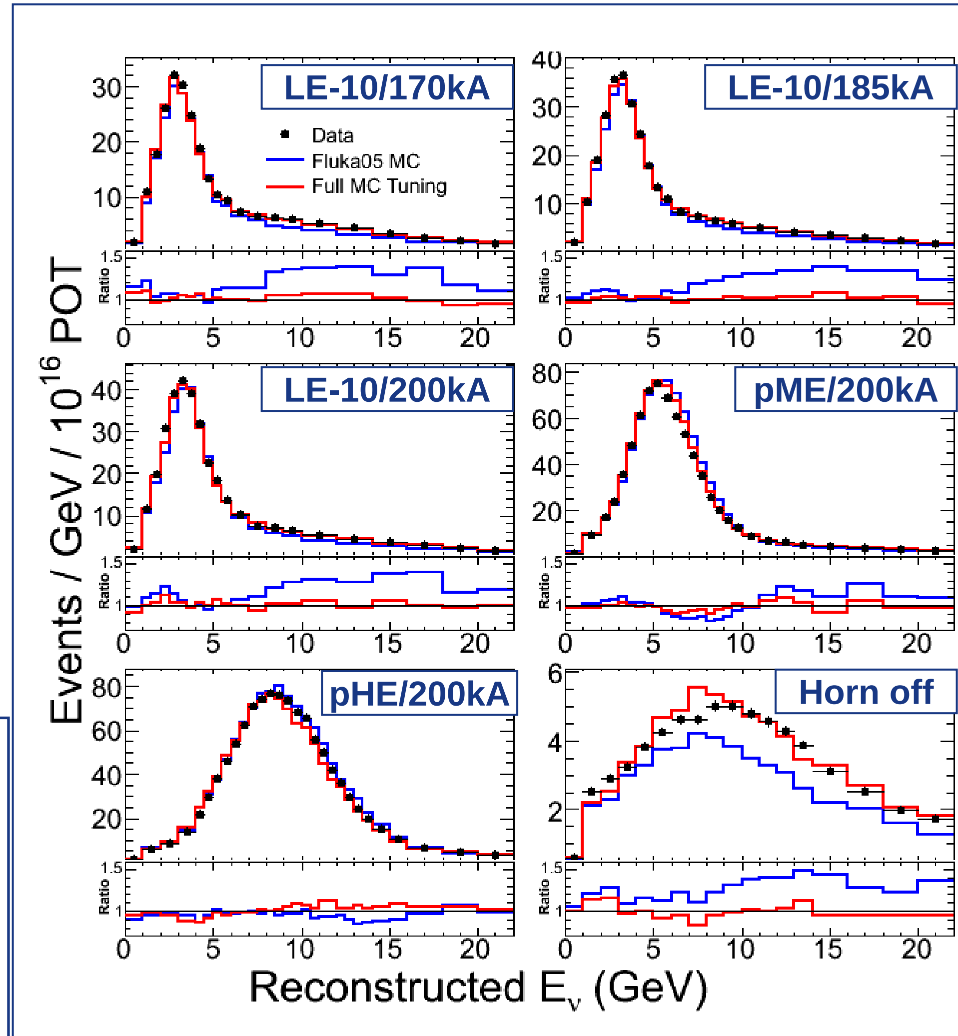


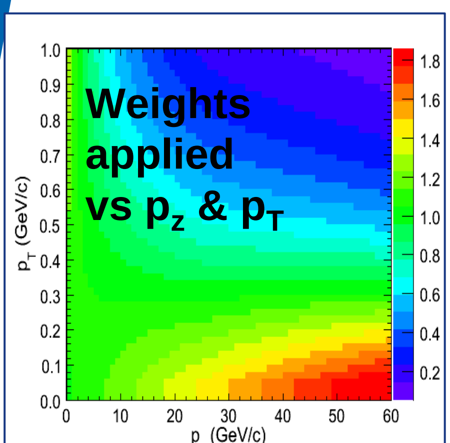


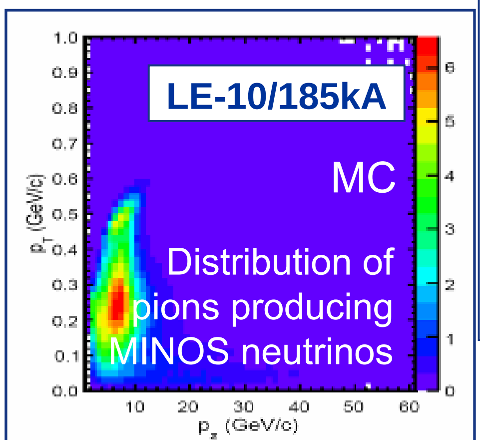
- F/N extrapolation method is robust to absolute systematic errors, which shift the energy spectra in both Near and Far detectors
- Most relevant systematics are relative, where shifts only applied to one detector

Hadron Production Tuning

- Parameterize Fluka2005 prediction as a function of x_F and p_T
- Perform fit which reweights neutrino parent pion x_F and p_T to improve data/MC agreement
- Horn focusing, beam misalignments included as nuisance parameters in fits
- Small changes in x-section, neutrino energy scale, NC background also allowed

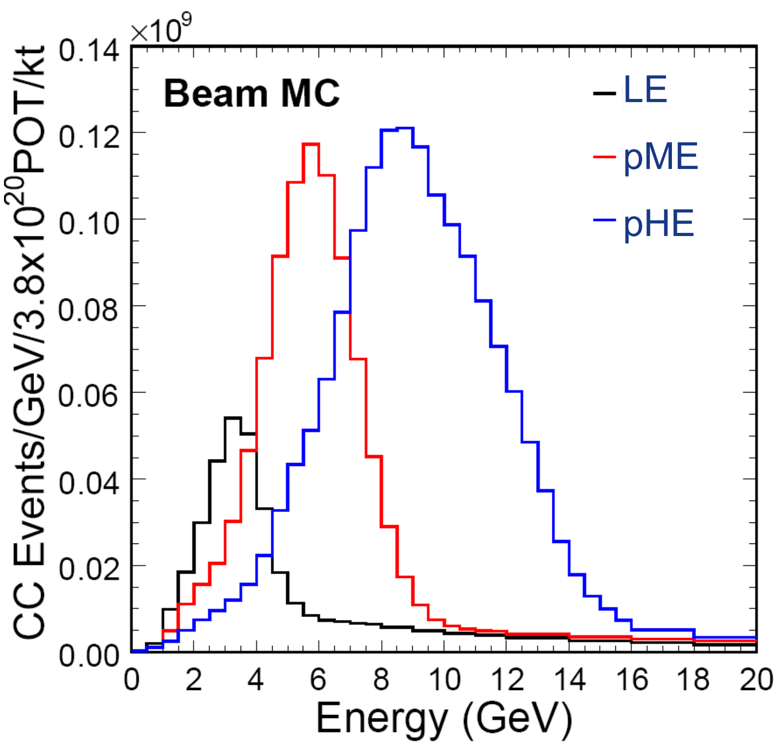






NuMI Beam Composition

- Movable target relative to horns allows beam energy tuning
- **Currently running in the LE-10 configuration**
- ~1.5 ×10[19] POT in pME and pHE configurations early in the run for commissioning and systematics studies



$$98.7\%\ \nu_\mu + \bar{\nu}_\mu \left(5.8\%\ \bar{\nu}_\mu\right)$$

$$1.3\%\ \nu_e + \bar{\nu}_e$$

Beam	Target z position (cm)	FD Events per 1 × 10[20] POT
LE-10	-10	390
pME	-100	970
pHE	-250	1340

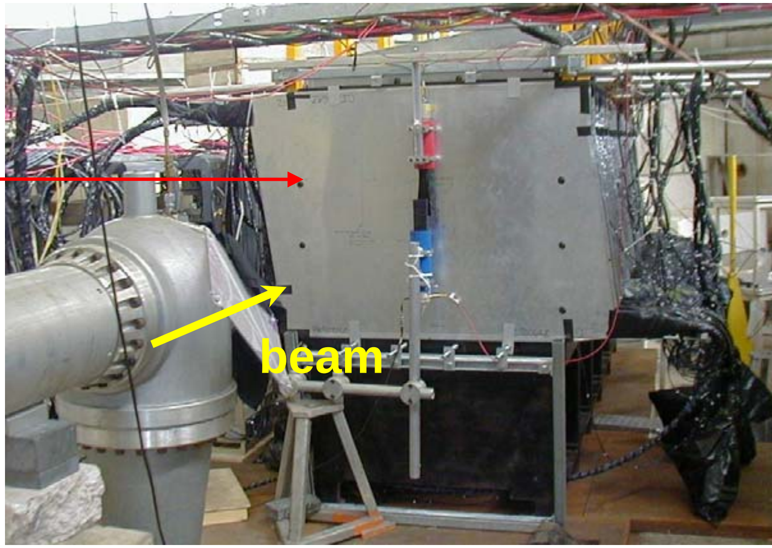
Events expected in fiducial volume

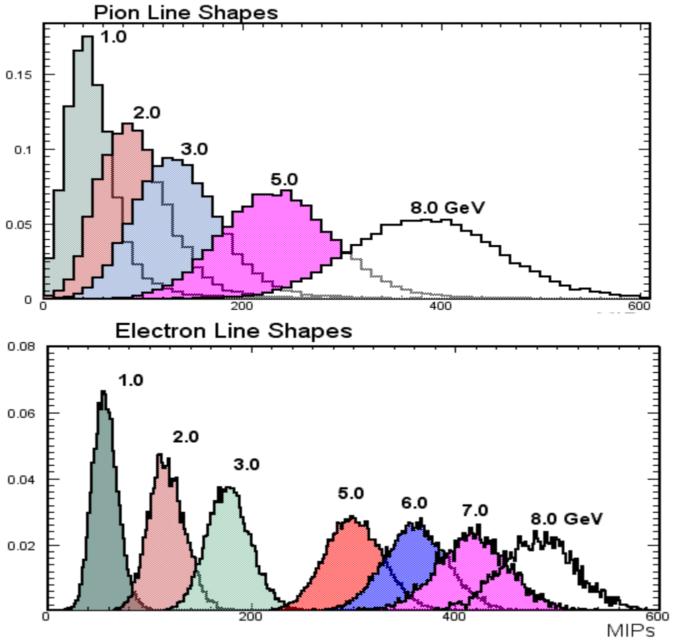
The MINOS Calibration Detector

- Help understand energy response to reconstruct E_ν

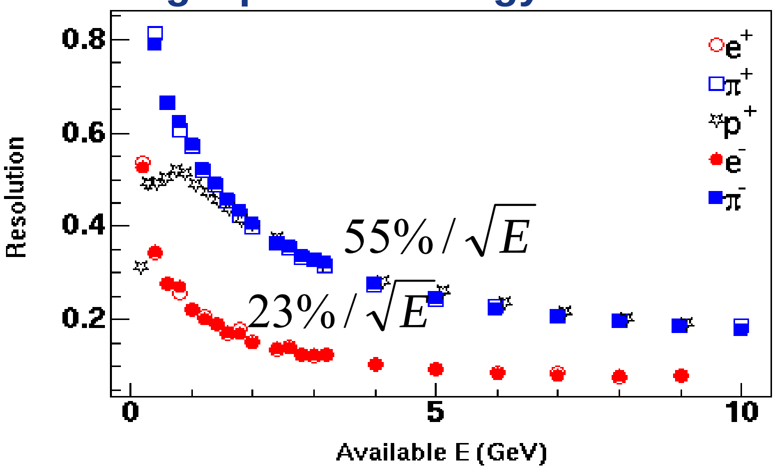
  $$E_\nu = p_\mu + E_{had}$$

- Measured in a CERN test beam with a "mini-Minos"
  - operated in both Near and Far configurations
  - Study e/μ/hadron response of detector
  - Test MC simulation of low energy interactions
  - **Provides absolute energy scale for calibration**



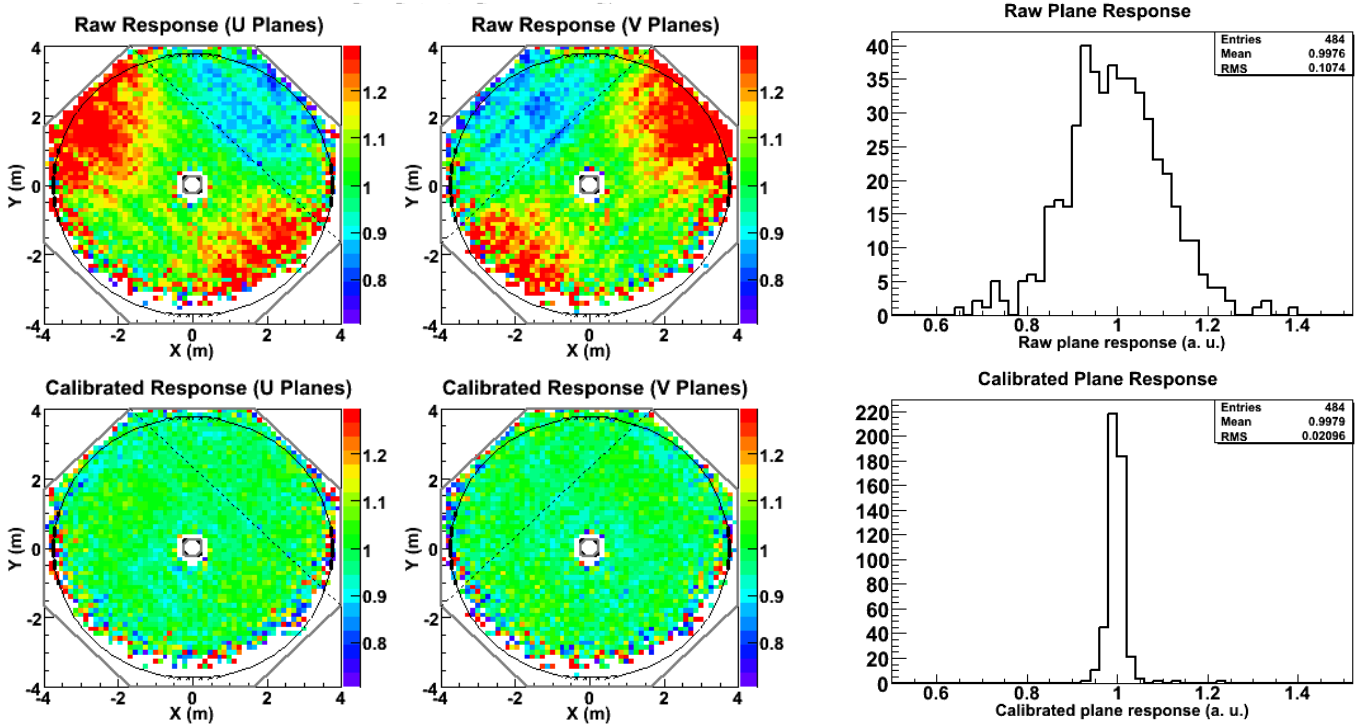


Single particle energy resolution



The MINOS Calibration

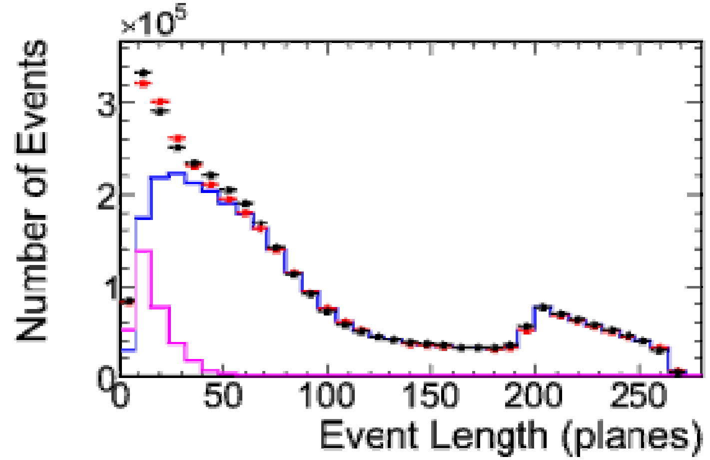
- Calibration of ND and FD :
  - Calibration detector (overall energy scale)
  - Light Injection system (PMT gain+Linearity)
  - Cosmic ray muons (strip to strip and detector to detector)
- Energy scale calibration:
  - **3.1 % absolute error in ND**
  - **2.3 % absolute error in FD**
  - **3.8 % relative**

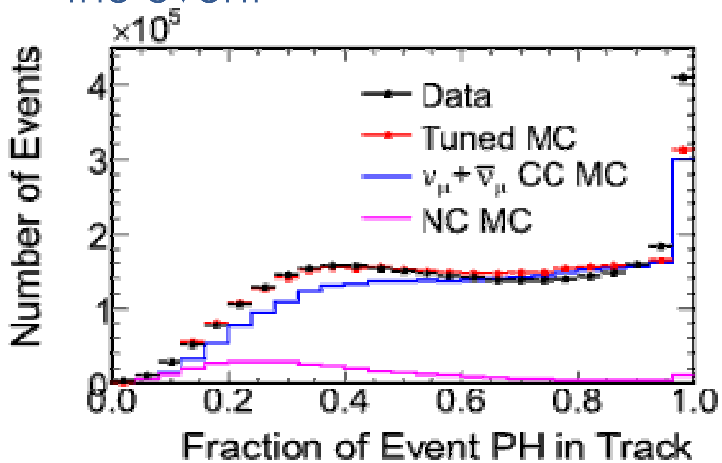


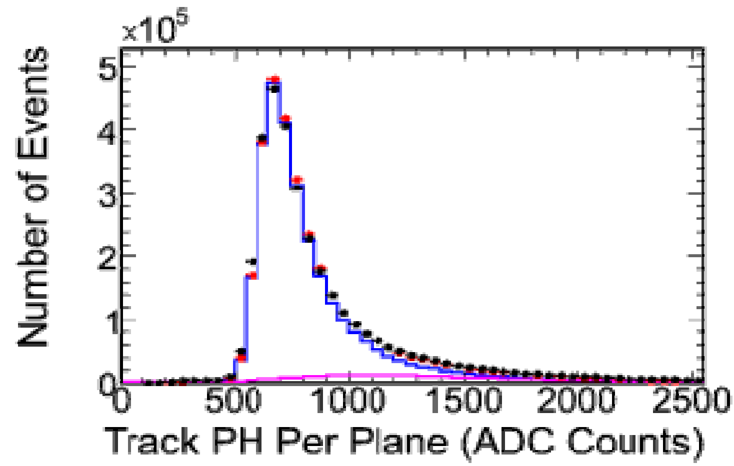
CC Event Selection

- Selection of CC events to be used in the final NC analysis fit employs a likelihood based procedure with probability density functions (PDFs) for three low level variables
  - **Event length**
    - Related to p_μ
  - **Fraction of event PH in track**
    - Related to inelasticity of CC events
  - **Track pulse height per plane**
    - Related to track dE/dx
  - Probability $\mathbf{P_\mu}$ $\mathbf{(P_{NC})}$ is the product of the three **CC (NC)** PDFs at the value of these variables taken by the event

Near Detector





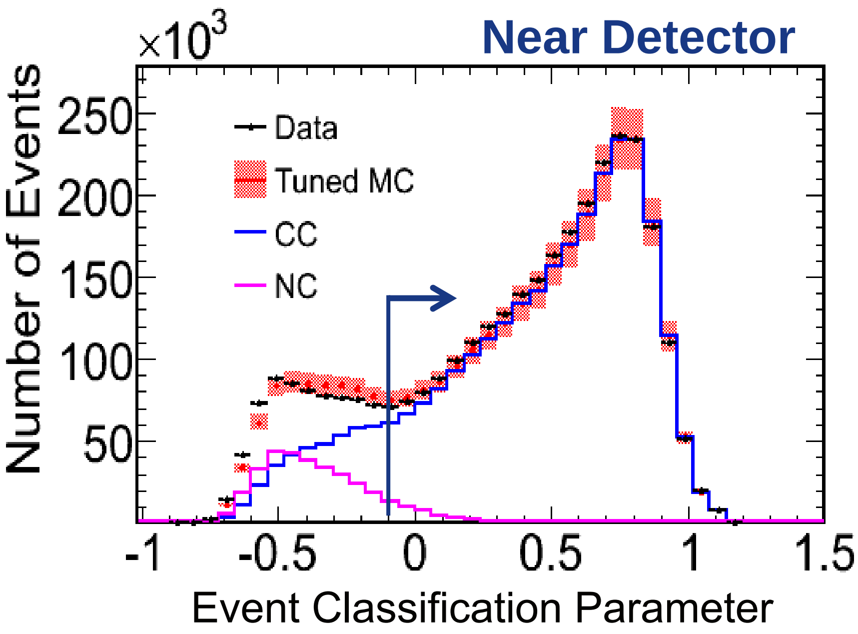


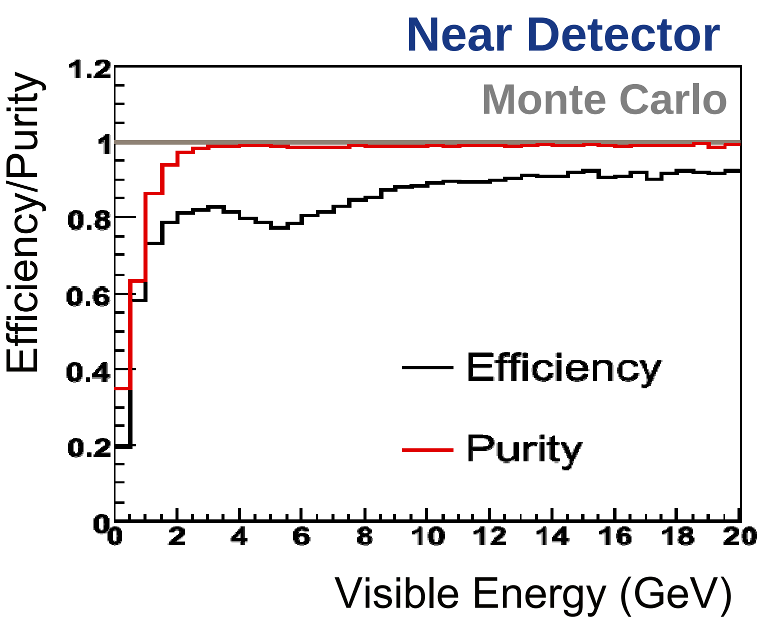
CC Event Selection

- Particle ID (*PID*) parameter obtained from the likelihood procedure is defined as:

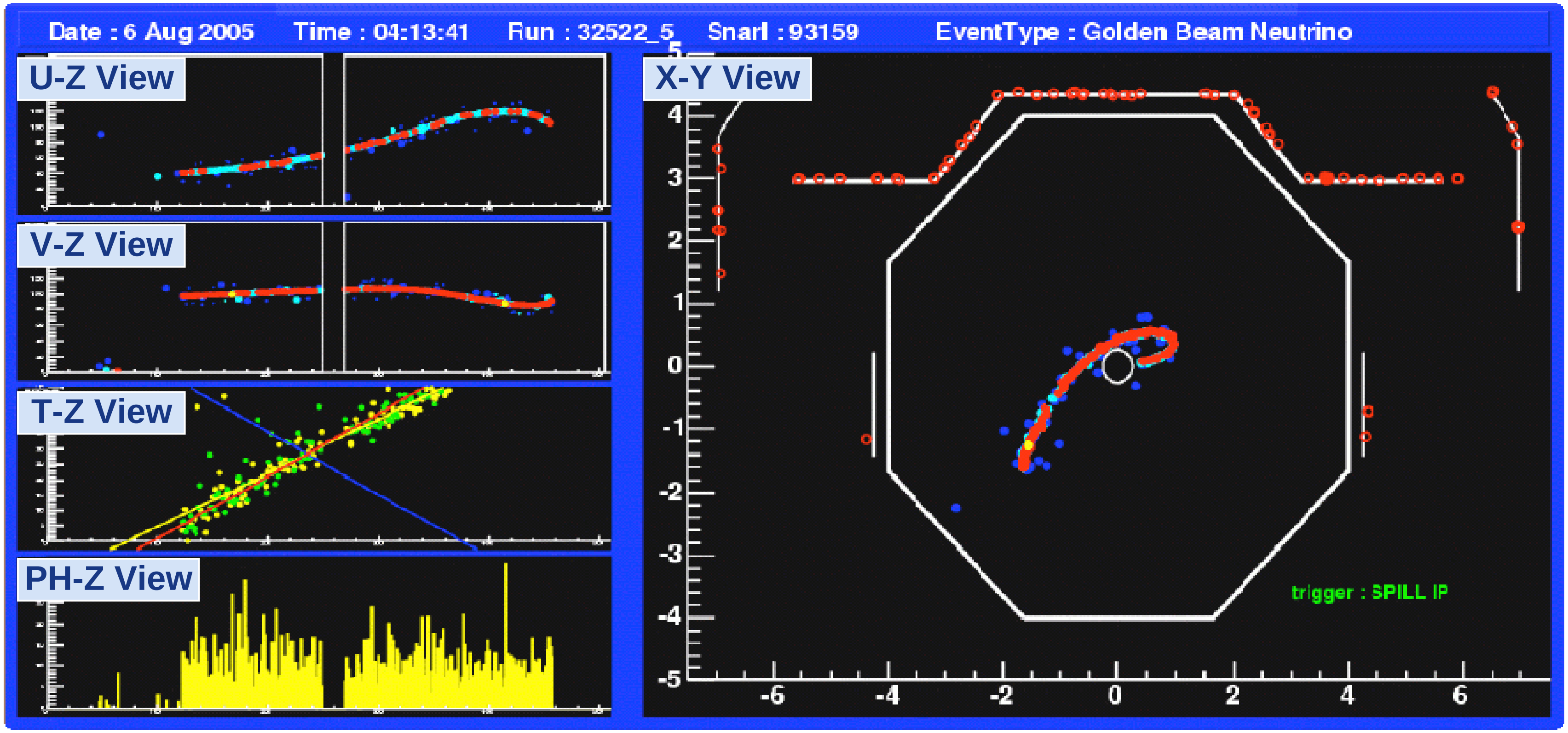
$$PID = -\sqrt{-\log(P_{\mu})} + \sqrt{-\log(P_{NC})}$$

- CC-like events are defined by *PID* > −0.2 in the FD (> −0.1 in the ND)
  - NC contamination limited to low energy bins (below 1.5 GeV)
  - High purity selection. Efficiency mostly flat as a function of visible





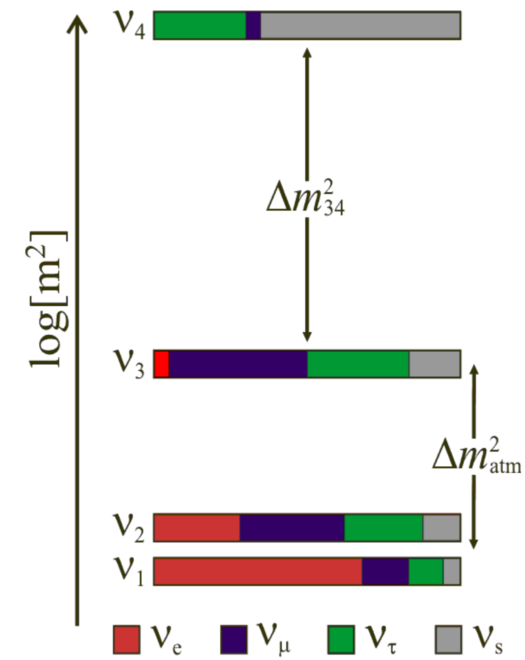
Far Detector Event



- Typical FD ν_μ CC event
  - Spatial information – used for track reconstruction
  - Timing information – used in atmospheric ν analysis to distinguish up/down events
  - Charge information – used for calorimetry

4-Flavor Analysis

- Assume there is an additional sterile neutrino and an additional mass scale and $\Delta m^2_{21} = 0$



- Parameters
  - 3-Flavor: Δm^2_{31}, $|U_{\mu 3}|^2$
  - 4-Flavor: $|U_{s3}|^2$, $|U_{s4}|^2$, $|U_{\mu 4}|^2$, Δm^2_{41}

- Oscillation probabilities are:

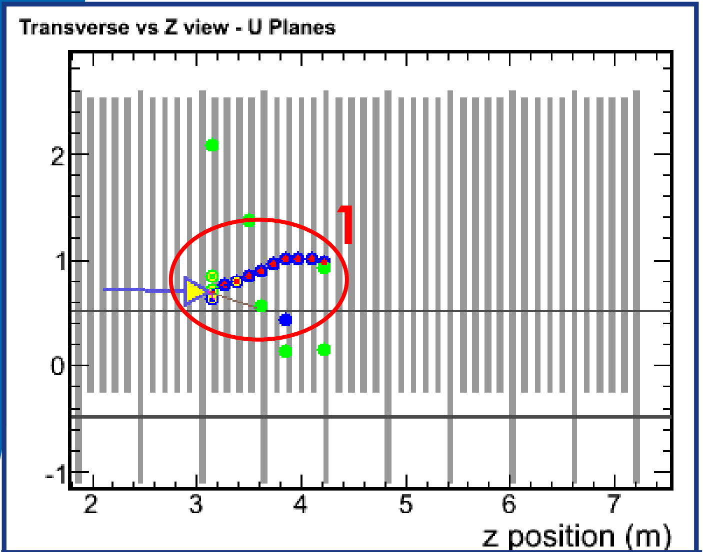
$$P_{\nu_\mu \to \nu_\mu} = 1 - 4\left[|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2\right)\Delta^2_{31} + |U_{\mu 3}|^2 |U_{\mu 4}|^2 \Delta^2_{43} + |U_{\mu 4}|^2 \left(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2\right)\Delta^2_{41} \right]$$

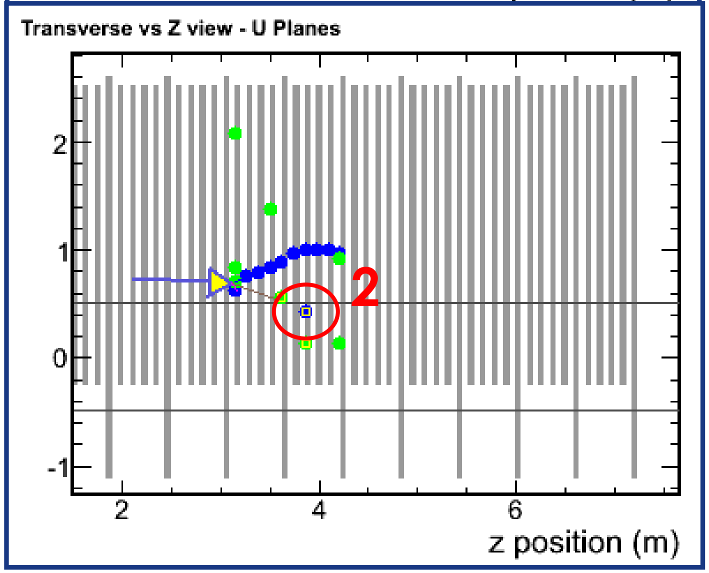
$$P_{\nu_\mu \to \nu_\alpha} = 4\left[\begin{array}{l} |U_{\mu 3}|^2 |U_{\alpha 3}|^2 \Delta^2_{31} + |U_{\mu 4}|^2 |U_{\alpha 4}|^2 \Delta^2_{41} \\ +2|U_{\mu 3}||U_{\alpha 3}||U_{\alpha 4}||U_{\mu 4}|\Delta_{31}\Delta_{41}\Gamma_{43}\cos\phi^{34}_{\mu\alpha} - 2|U_{\mu 3}||U^*_{\alpha 3}||U_{\alpha 4}||U^*_{\mu 4}|\Delta_{31}\Delta_{41}\Gamma_{43}\sin\phi^{34}_{\mu\alpha} \end{array} \right]$$

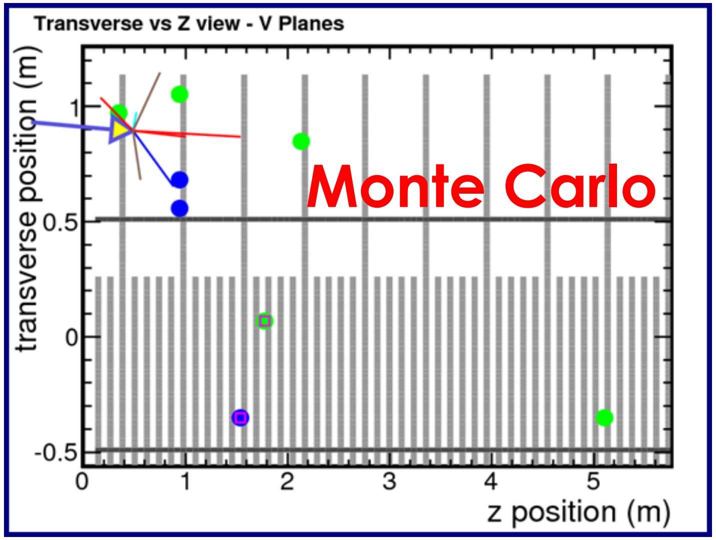
where $\Delta_{ij} = \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right)$, $\Gamma_{ij} = \cos\left(\frac{\Delta m^2_{ij} L}{4E}\right)$, and $\phi^{34}_{\mu\alpha} = -\arg\left[U^*_{\mu 3} U_{\alpha 3} U_{\mu 4} U^*_{\alpha 4}\right]$

Event Pre-Selection Cuts

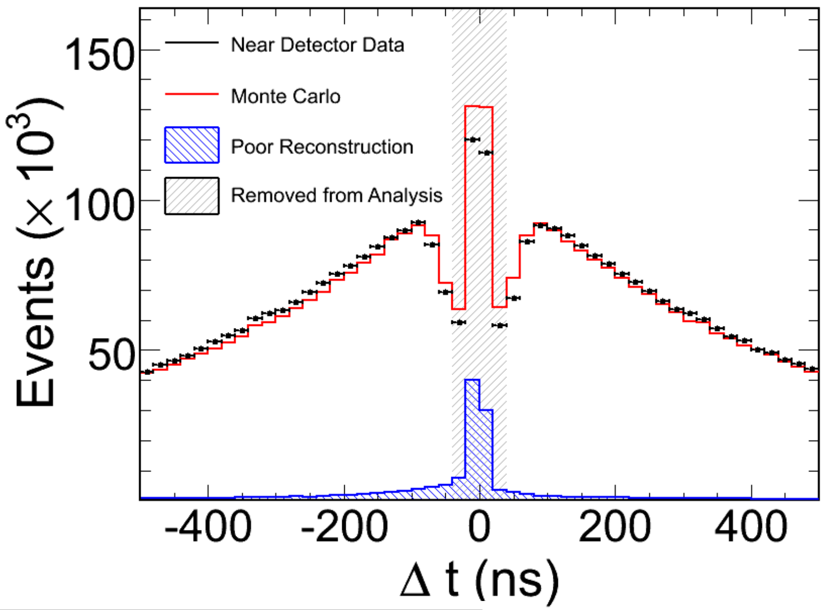
- High rate of neutrino interactions in ND can cause reconstruction failures
  - Split events from a single neutrino interaction
  - Event with vertex erroneously reconstructed inside fiducial volume
- A large fraction of these events can be eliminated via a series of cuts



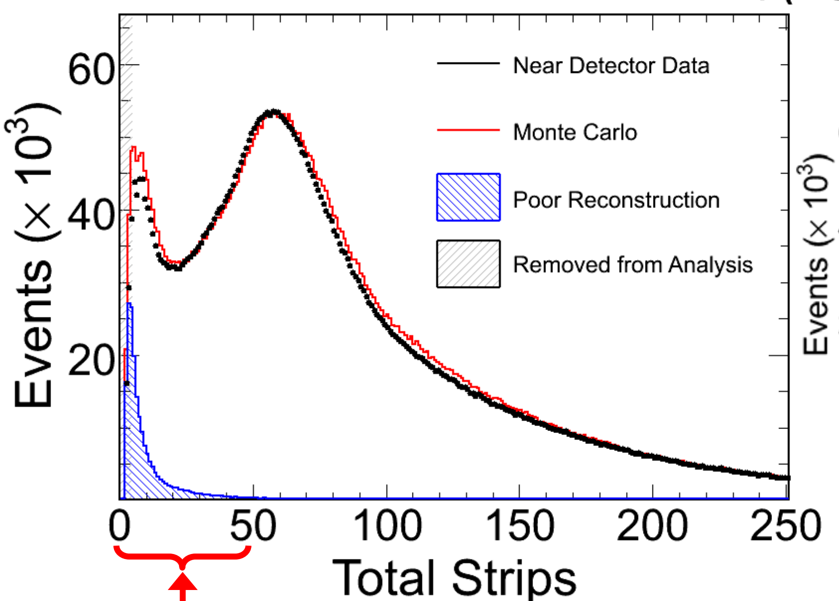


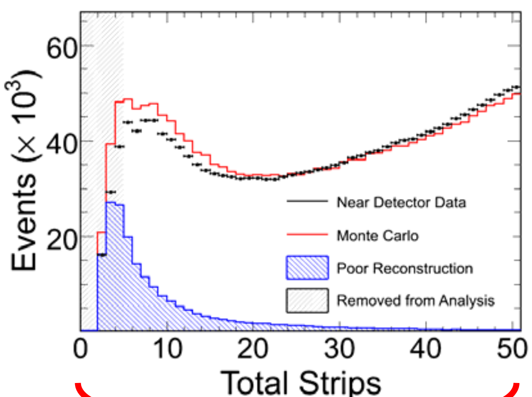


Event Pre-Selection Cuts

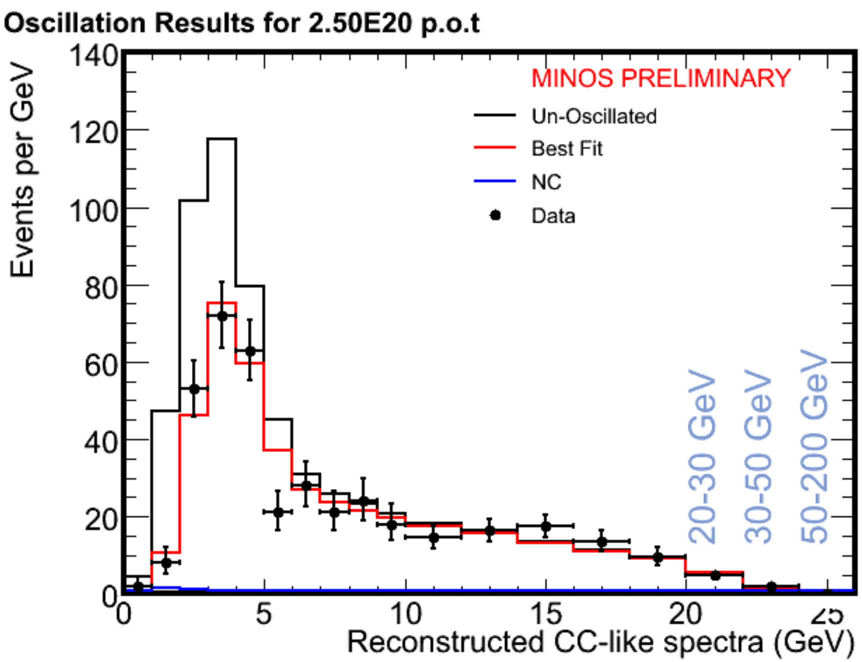


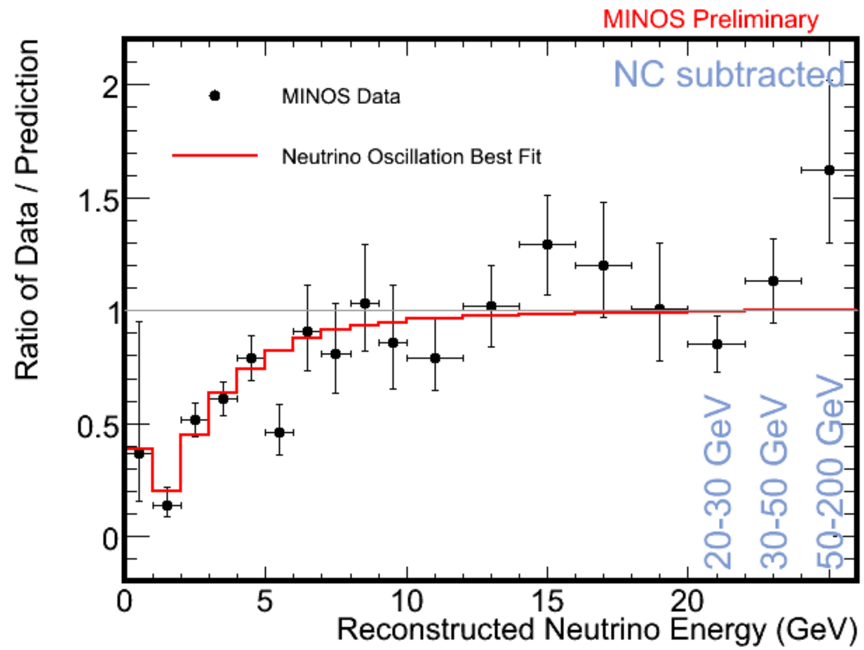
- Time separation between events $\Delta t > 40ns$
- Longitudinal spatial separation $\Delta z > 1m$, if $40ns < \Delta t < 120ns$
- Total number of event strips < 4
- Event steepness cut: (#strips/plane)/ #planes < 1.0
- If event energy < 5 GeV and shower planes > track planes: #strips in partially instrum. region < 4





MINOS CC Measurement





Measurement errors are 1σ, 1 DOF

$|\Delta m^2_{32}| = 2.38 ^{+0.20}_{-0.16}$ (stat + syst) x 10^{-3} eV^2

$\sin^2 2\theta_{23} = 1.00_{-0.08}$ (stat + syst)

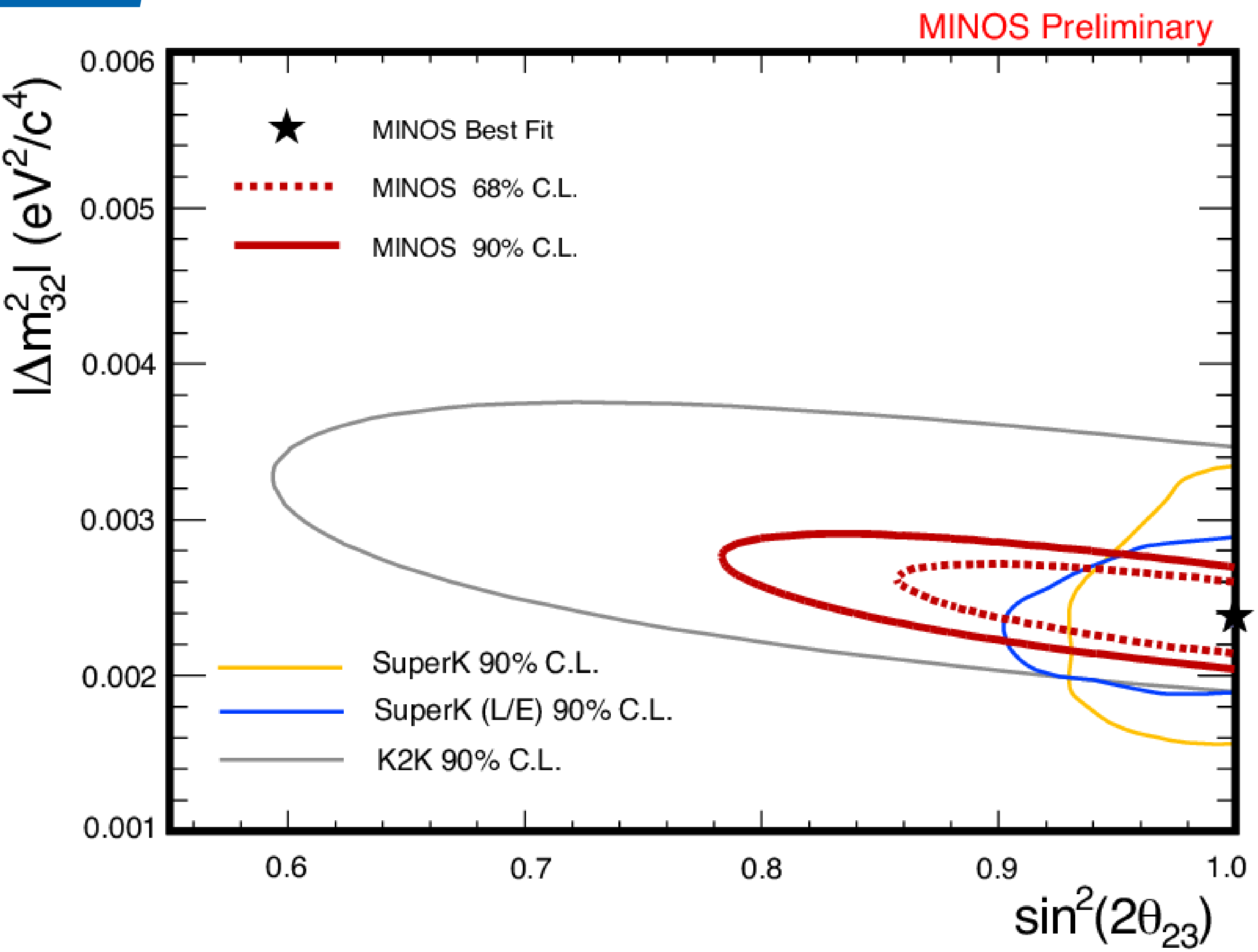
χ^2/ndf=41.2/34 (18 bins x 2 spectra (Run I, Run IIa) – 2)

$o_i = \text{observed}$

$e_i = \text{expected}$

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

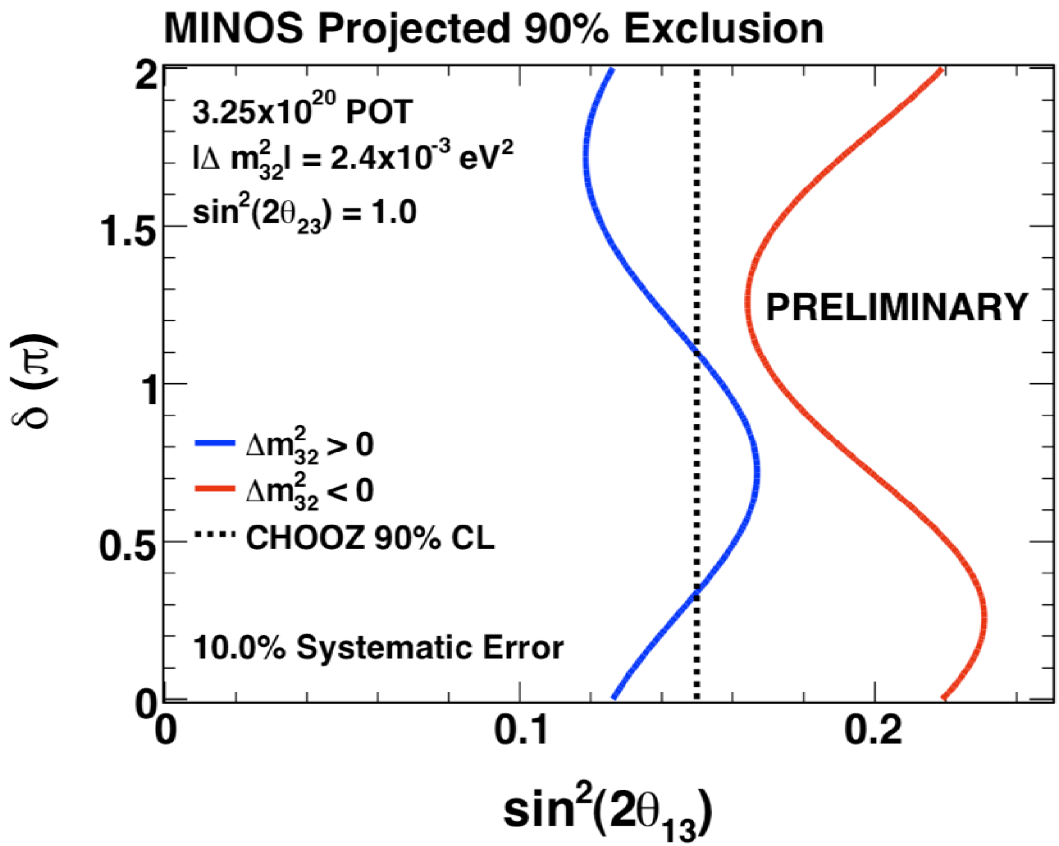
MINOS CC Allowed Regions



- Fit includes systematic penalty terms
- Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$
- Consistent with previous experiments
- Best measurement of $|\Delta m^2_{32}|$

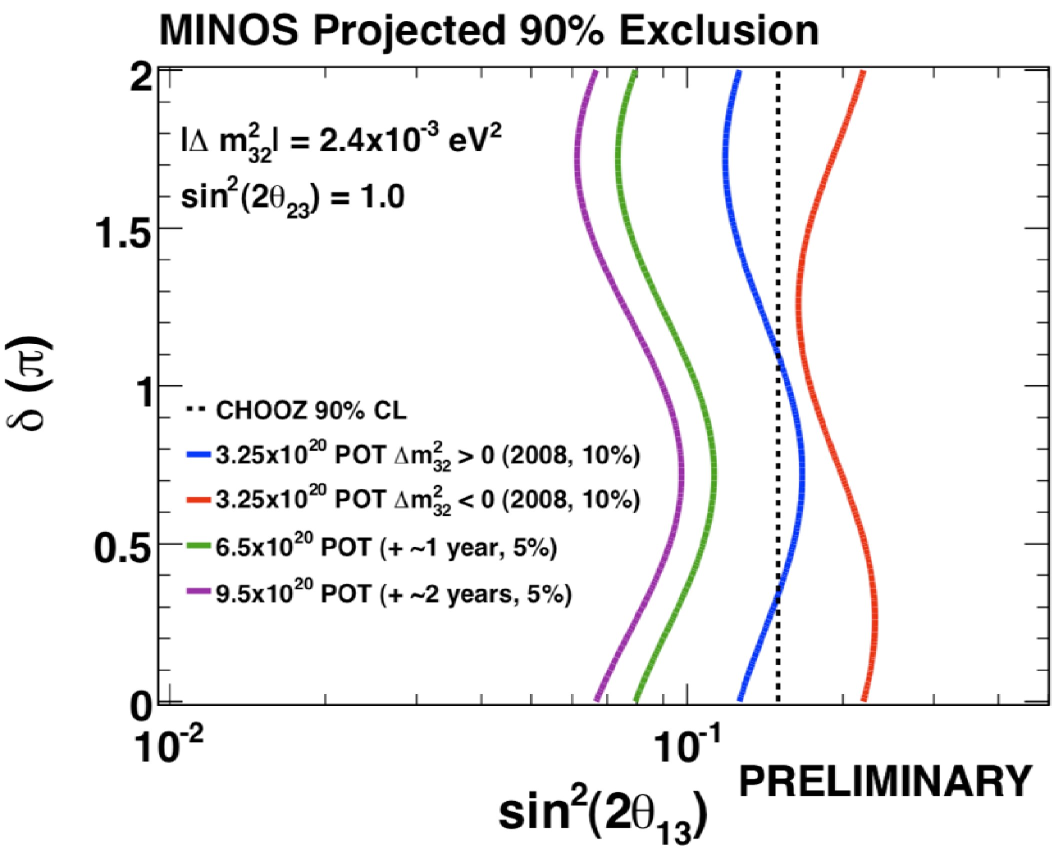
Projected θ_{13} Limits

- ν_e appearance limit projections
- Shown as a function of CP-violating phase δ, since over the MINOS allowed Δm^2 range the limits vary little
- Plot is for 3.25×10^{20} POT exposure, with estimated 10% systematics
- Blind analysis in progress

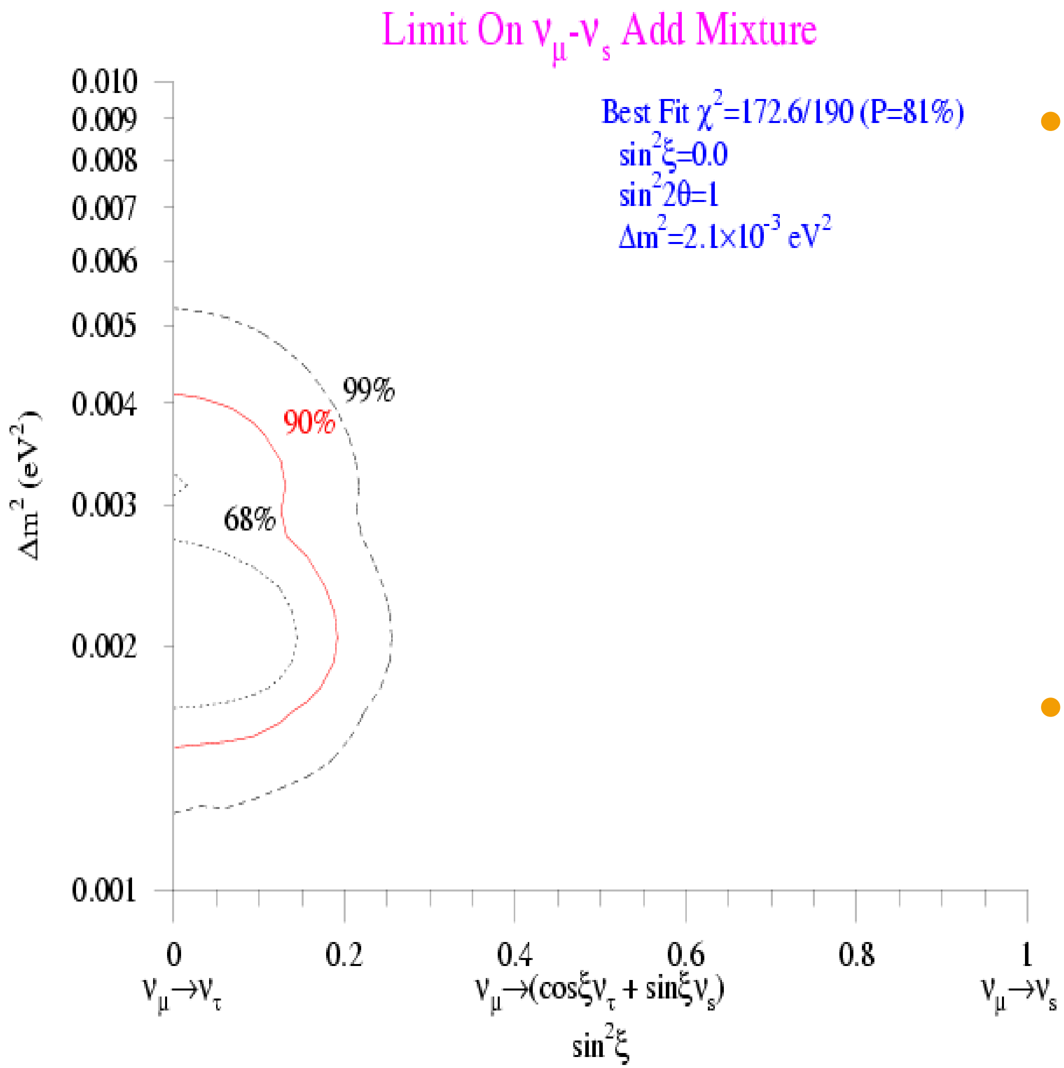


Projected θ_{13} Limits

- Projected limits shown for expected MINOS exposures
- Data-driven systematics are hoped to drop to 5% in the future
- Inverted hierarchy shown only for lowest exposure



ν_μ to $\nu_{sterile}$ in SuperK



- High energy ν experience matter effects which suppress oscillations to sterile ν
  - Matter effects not seen in up-μ or high-energy PC data
  - Reduction in neutral current interactions also not seen
  - constrains ν_s component of ν_μ disappearance oscillations
- Pure ν_μ-ν_s disfavored
  - ν_s fraction < 20% at 90% c.l.

$$\sin^2 \xi \approx 2|U_{s3}|^2$$