MINOS Results from the First Year of NuMI Beam Operation

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Outline

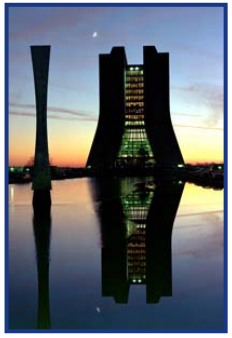
- Introduction to the MINOS experiment
- Data and event selection
- Oscillation analysis
- Results from the First Year of NuMI Beam Running
  - Total exposure of 1.27×10^{20} POT (protons-on-target)
- Summary and Outlook

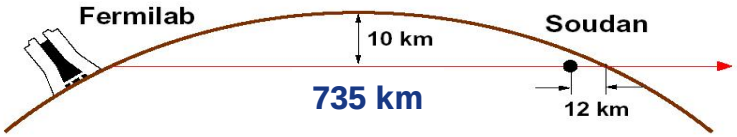
The MINOS Collaboration

175 physicists
32 institutions
in
6 countries

Argonne – Athens – Benedictine – Brookhaven – Caltech – Cambridge – Campinas – Fermilab – College de France – Harvard – IIT – Indiana – ITEP Moscow – Lebedev – Livermore – Minnesota, Twin Cities – Minnesota, Duluth – Oxford – Pittsburgh – Protvino – Rutherford Appleton – Sao Paulo – South Carolina – Stanford – Sussex – Texas A&M – Texas-Austin – Tufts – UCL – Western Washington – William & Mary - Wisconsin

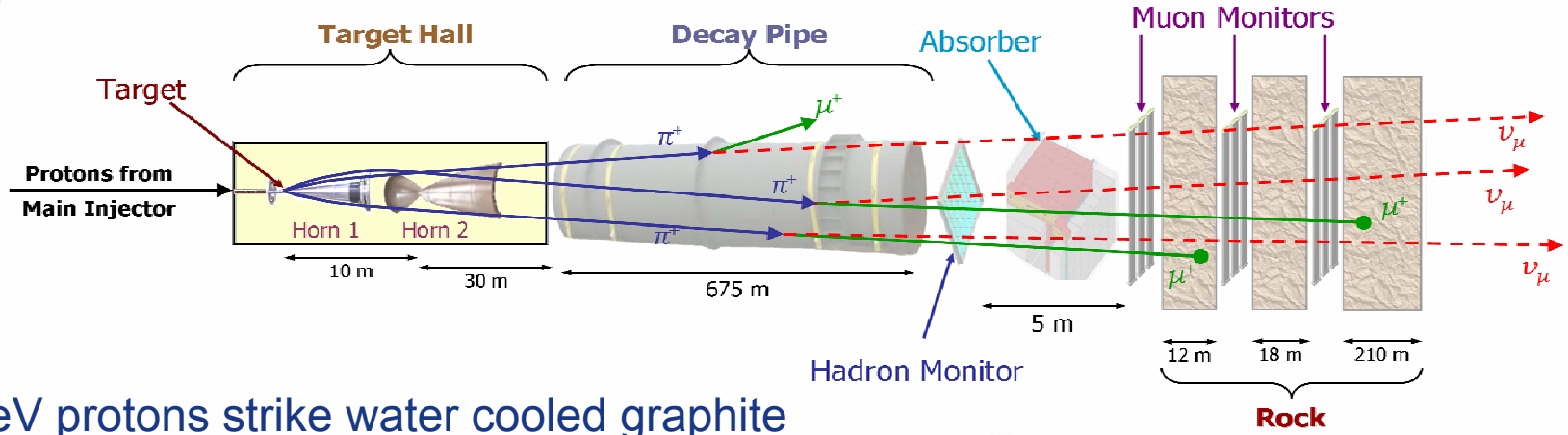
The MINOS Experiment



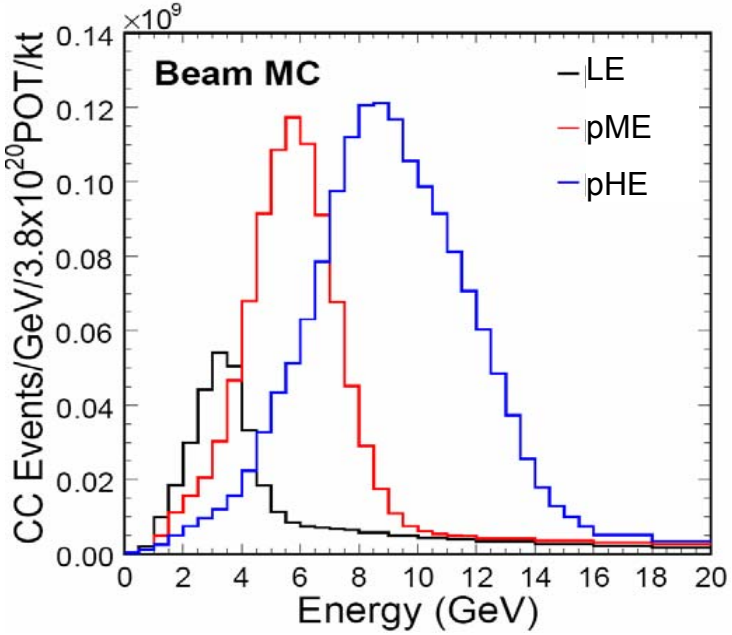


- **MINOS (Main Injector Neutrino Oscillation Search)**
  - Long-baseline neutrino oscillation experiment
  - Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector.
- **Basic concept**
  - Measure the energy spectrum at the Near Detector, at Fermilab
  - Measure the energy spectrum at the Far Detector, 735 km away, deep underground in the Soudan Mine.
  - Compare Near and Far measurements
- **Physics goals**
  - Make a precision measurement of Δm^2_{32} by ν_μ disappearance
  - Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations by ν_e appearance
  - Search for/constrain exotic phenomena (sterile ν's, ν decay)
  - Compare ν, $\bar{\nu}$ oscillations (CPT test)
  - Atmospheric neutrino oscillation studies
    - **Phys.Rev.D73,072002(2006)**

The NuMI Neutrino Beam

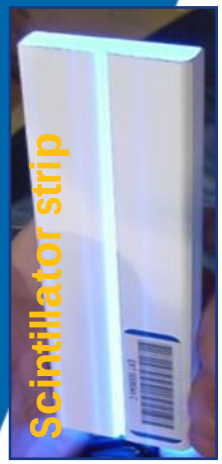


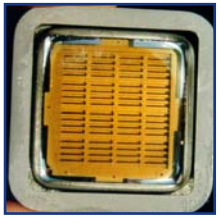
- 120 GeV protons strike water cooled graphite target, producing kaons, pions
- 2 parabolic magnetic horns focus secondaries, which decay into muons, neutrinos
- Beam energy spectrum can be tuned by varying the relative positions of target, horns



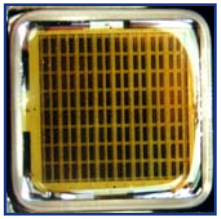
- First year performance
  - 10μs spill of 120 GeV protons every 2s
  - Intensity: 2.3×10^{13} POT/spill
  - 0.2 MW average beam power

MINOS Detector Technology

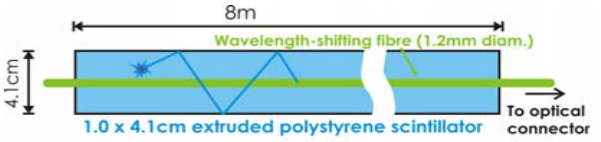


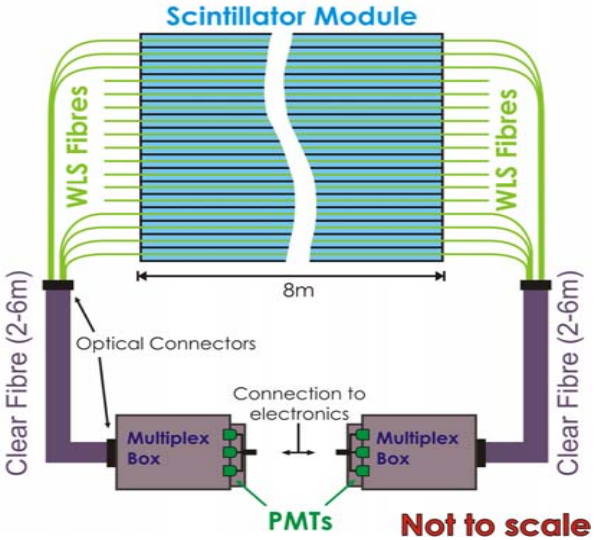


M16

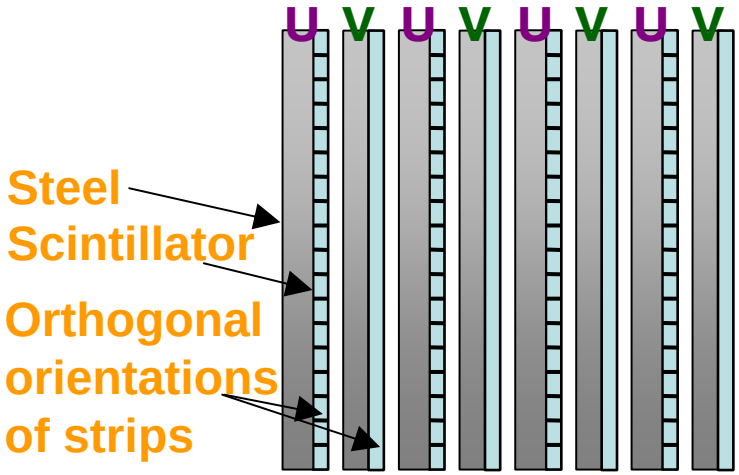


M64





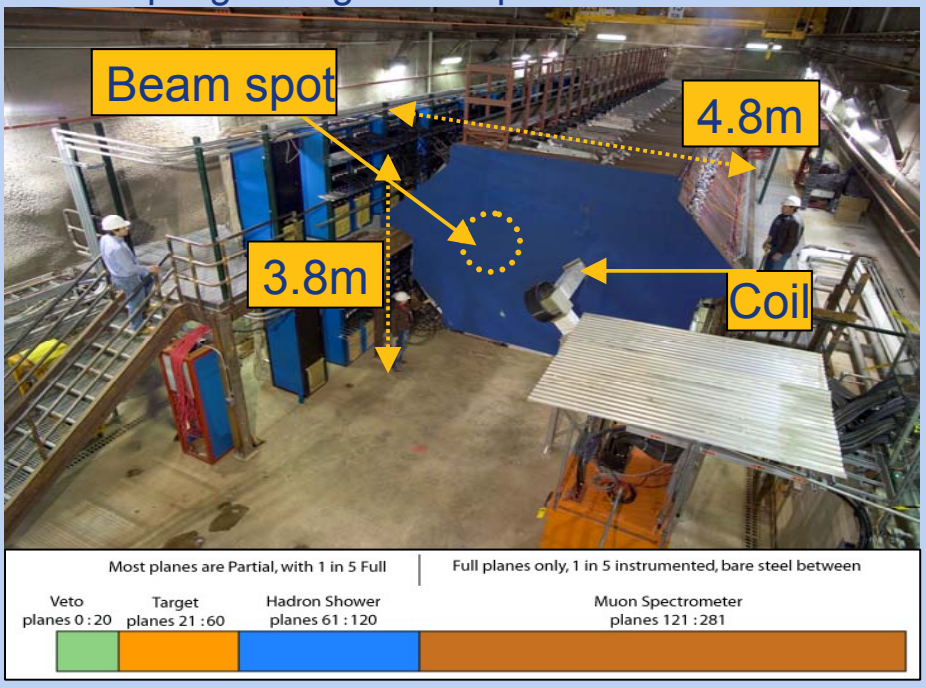
- MINOS Near and Far Detectors are functionally identical
- Iron/Scintillator tracking calorimeter
  - 2.54cm steel planes, <B>=1.2T
  - 1.0 × 4.1cm extruded polystyrene scintillator strips, up to 8m long.
  - Readout via wavelength shifting fibers
  - Hamamatsu multi-anode PMTs (M16 Far and M64 Near)
  - Alternate planes rotated by ±90º (U,V)



MINOS Detectors

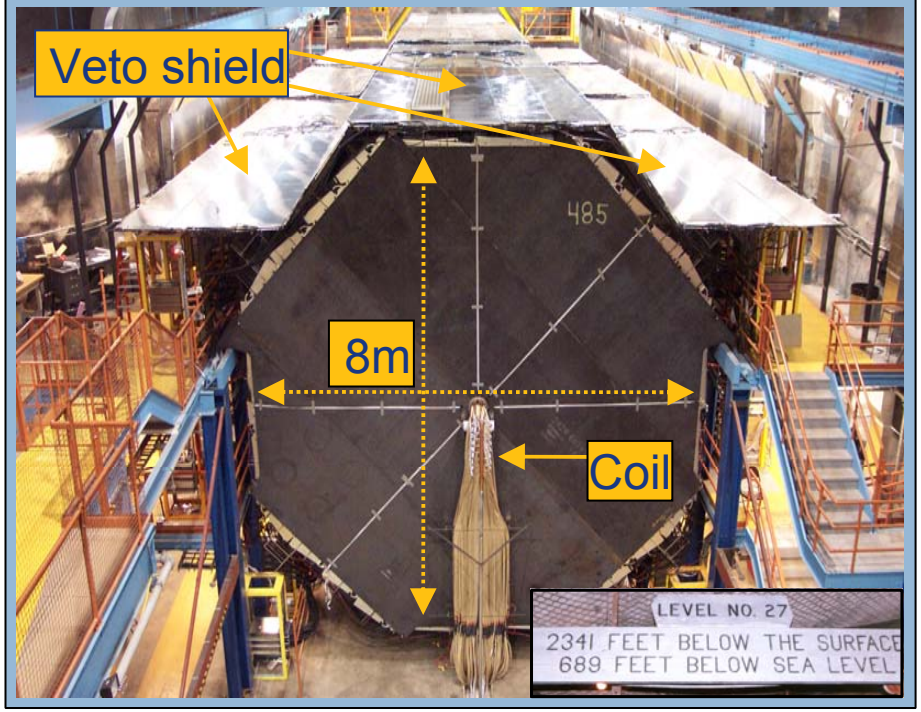
Near Detector

- Located 1km downstream of the target
- ~1kt (980t) total mass
- Shaped as squashed octagon ($4.8\times3.8\times15m^3$)
- Partially instrumented (282 steel, 153 scintillator planes)
- Fast QIE readout electronics, continuous sampling during beam spill



Far Detector

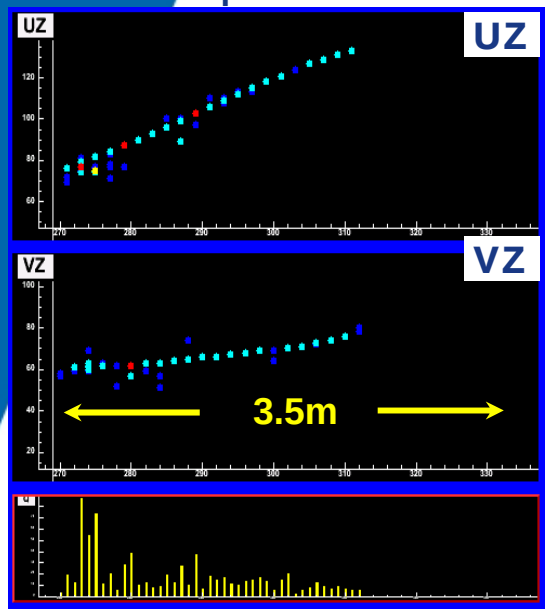
- Located 735km away in Soudan mine, MN
- 5.4kt, 2 supermodules
- Shaped as octagonal prism ($8\times8\times30m^3$)
- 486 steel planes, 484 scintillator planes
- Veto shield (scintillator modules)
- Spill times from Fermilab for beam trigger



Event Topologies

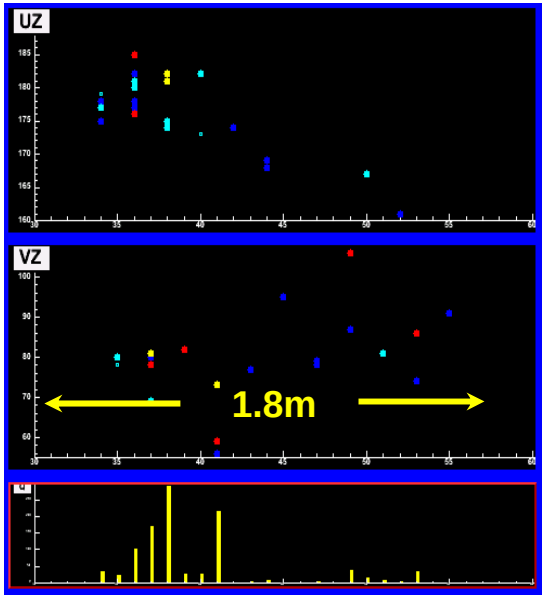
Monte Carlo

ν_μ CC Event



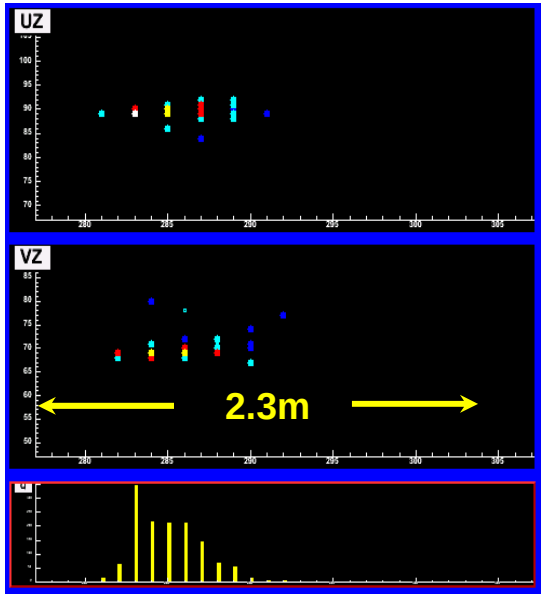
Long μ track + hadronic activity at vertex

NC Event



Short showering event, often diffuse

ν_e CC Event



Short event, with EM shower profile

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

$55\% / \sqrt{E/\mathrm{GeV}}$ 6% range, 13% curvature

Event Pre-Selection Cuts

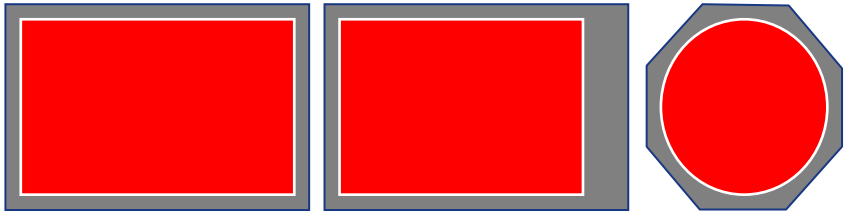
- Beam monitoring and detector quality cuts
- ν_μ CC pre-selection cuts:
  - At least one good reconstructed track
  - The fitted track should have negative charge (selects ν_μ)
  - The reconstructed track vertex should be within the fiducial volume of the detector

NEAR:

1m < z < 5m (from detector front),
R < 1m from beam center.

FAR:

z > 50cm from front face,
z > 2m from rear face,
R < 3.7m from detector center.



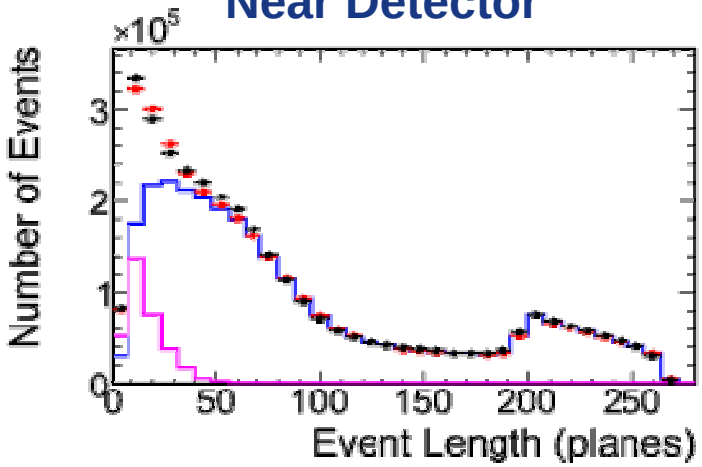
CC Event Selection

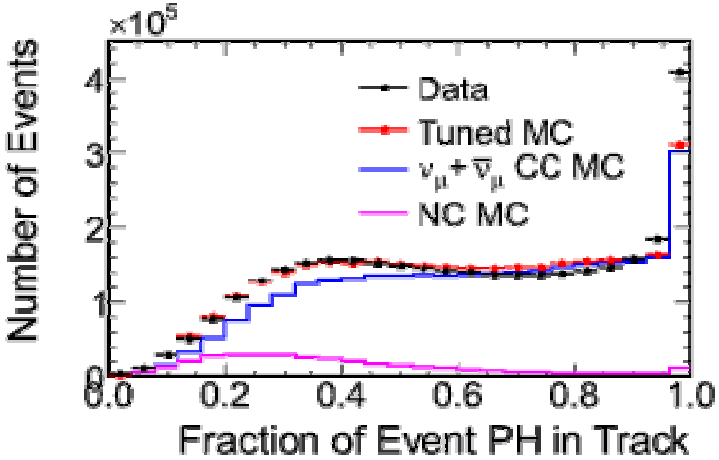
- Final selection employs a likelihood based procedure with probability density functions (PDFs) for three low level variables

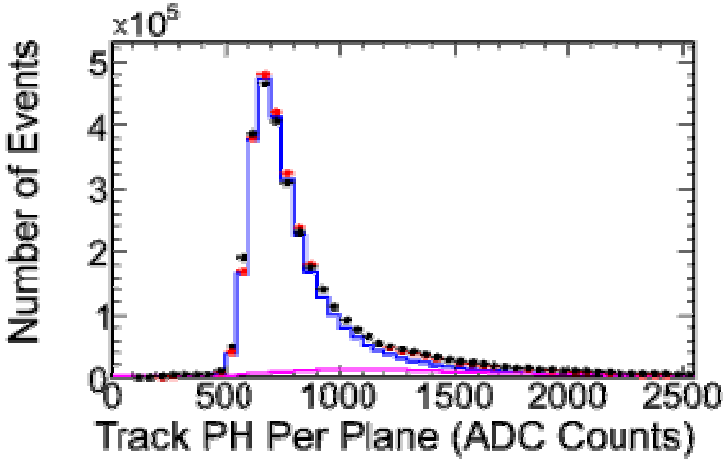
- **Event length**
  - Related to p_μ
- **Fraction of event PH in track**
  - Related to inelasticity of CC events
- **Track pulse height per plane**
  - Related to track dE/dx

- 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





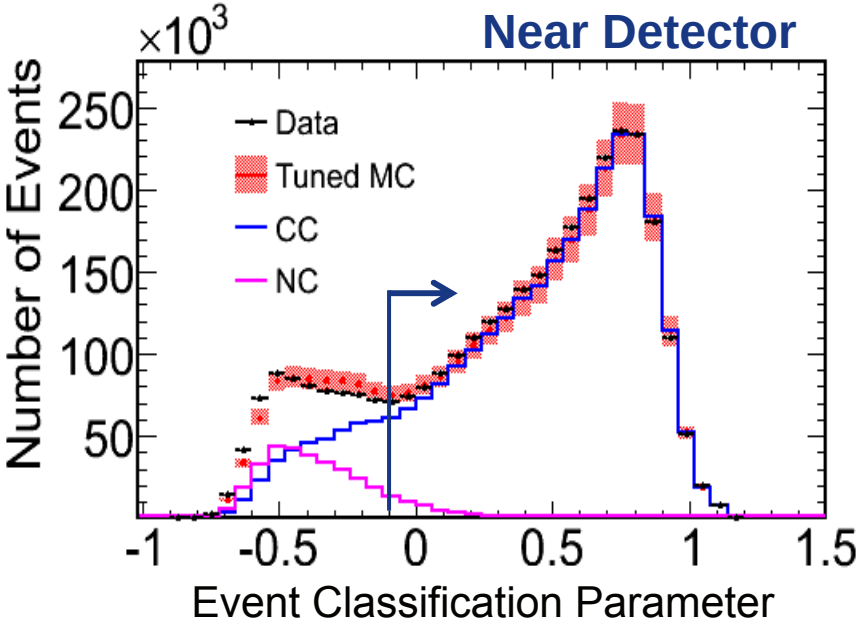


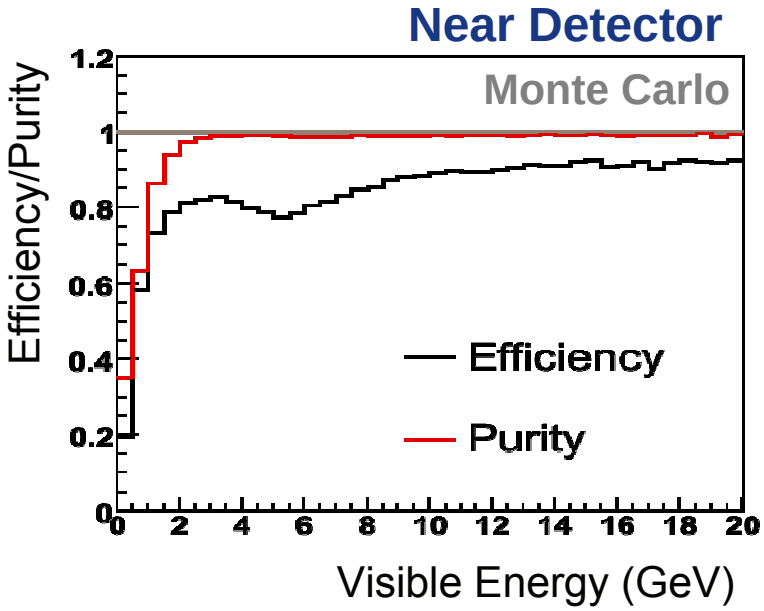
CC Selection Parameter

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

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

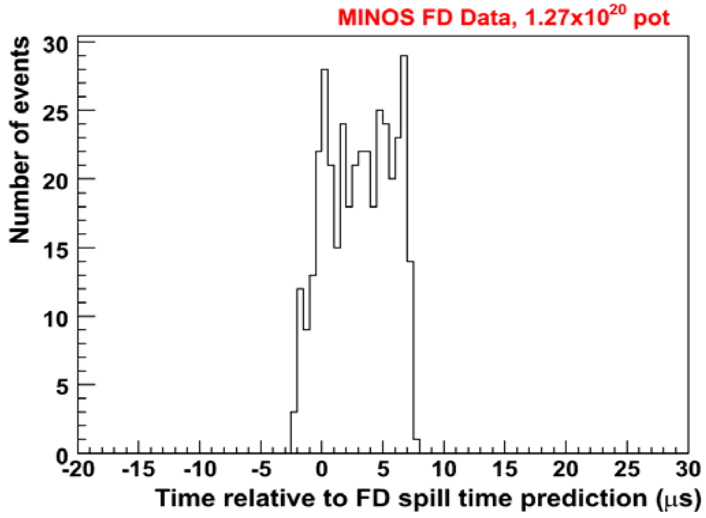
- CC-like events are defined by *PID* > −0.2 in the FD (> −0.1 in the ND)
  - NC contamination limited to low energy bins (below 1.5 GeV)
  - High purity selection. Efficiency mostly flat as a function of visible energy

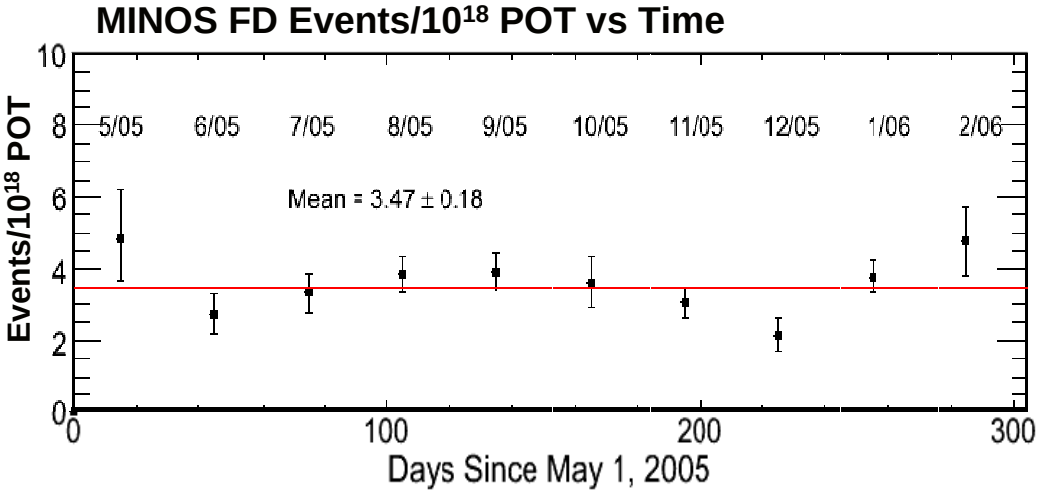




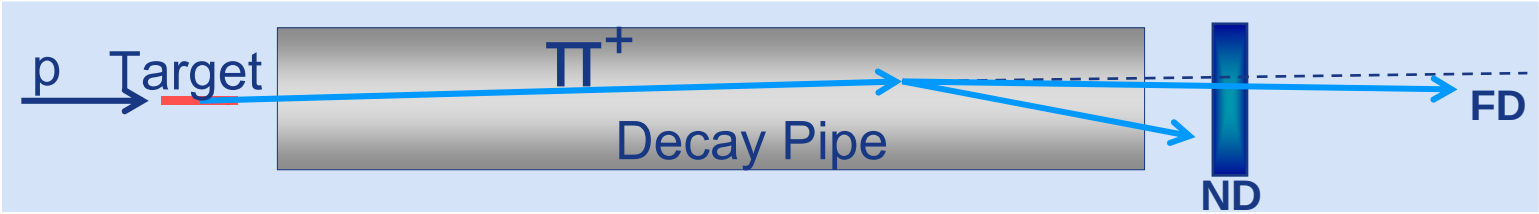
FarDet Beam Event Selection

- Timing
  - Far Detector spill trigger reads out 100μs of activity around beam spill
- Use topology of Far Detector neutrino events
  - Separation from cosmics via 53° cut around beam axis
- Cosmic ray background estimated using
  - Sideband analysis of timing plot: No accepted events outside of expected spill duration
  - Upper limit on BG of 0.5 events
- Event rates show no time dependence
- Blind Analysis Policy: hide fraction of data as a function of event length and energy, "open the box" when the analysis procedures are defined and validated

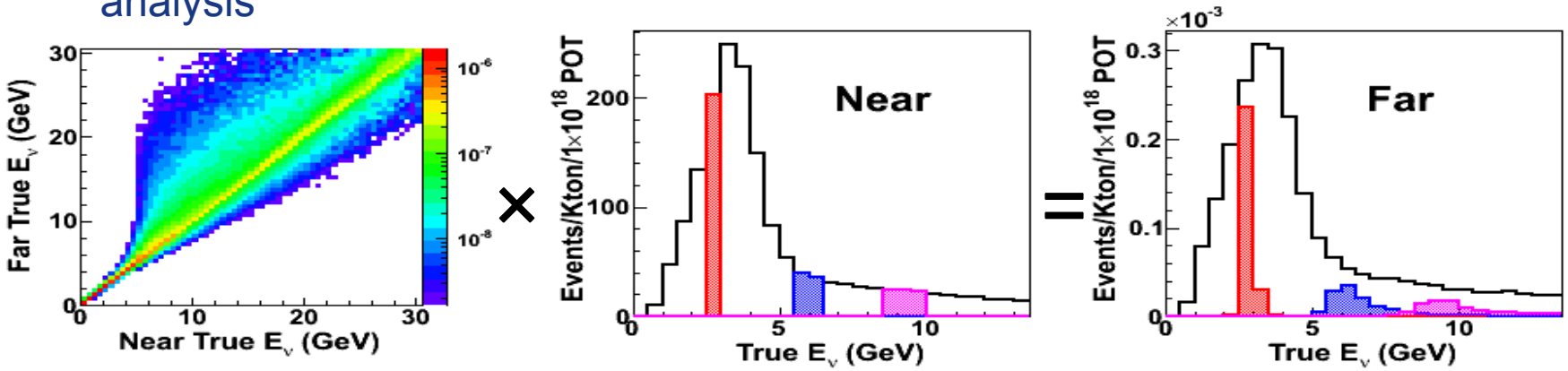




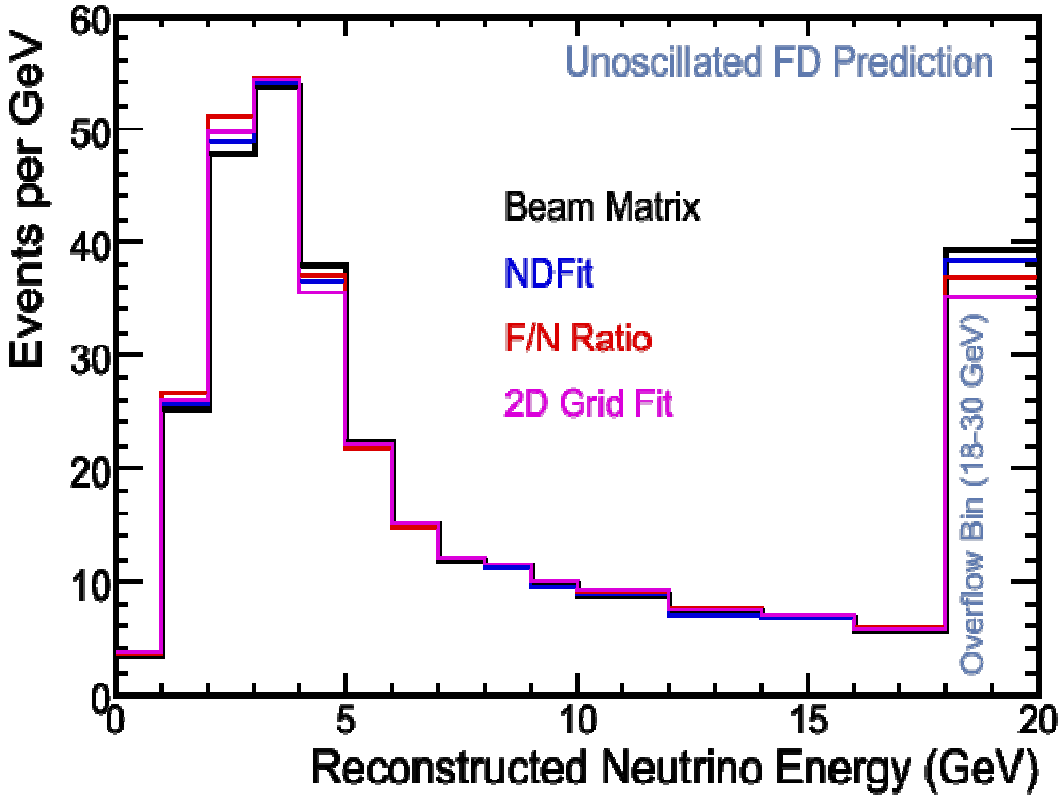
Predicting Unoscillated FD Spectrum



- Start with Near Detector data and perform extrapolation to the Far Detector
  - Use Monte Carlo to provide corrections for energy smearing and acceptance effects and apply them to measured ND spectrum
  - Use knowledge of pion decay kinematics and beamline geometry to construct a **beam transport matrix** and predict FD spectrum from measured ND spectrum
  - Apply detector MC corrections to predict observed FD spectrum
- The "Beam Matrix" method is the primary method used in the MINOS CC analysis



Predicted FD Spectrum



- In parallel to the Beam Matrix method, 3 other extrapolation methods were applied to the data.
- The 4 extrapolation methods investigated give consistent predictions and are robust to different types of systematics.

FD Observed vs. Expected

Data Sample	FD Data	Expected (Matrix Method; Unoscillated)	Data/MC (Matrix Method)
ν_μ (<30 GeV)	215	336.0±14.4	0.64±0.05
ν_μ (<10 GeV)	122	238.7±10.7	0.51±0.05
ν_μ (<5 GeV)	76	168.4±8.8	0.45±0.06

- A 49% deficit with respect to the no disappearance hypothesis is observed for energies between 0-10GeV
- Significance of the effect is 6.2σ (stat+syst)

Systematic Errors

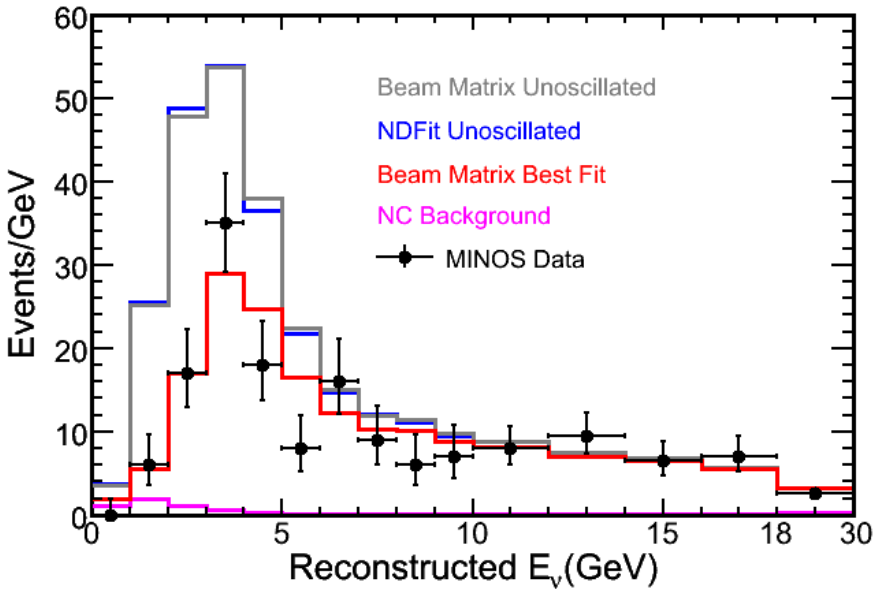
- Magnitude of systematic shifts of the oscillation parameters is computed using MC fake data samples at the best fit values of Δm^2, $\sin^2(2\theta)$, shifted by the values shown in the table

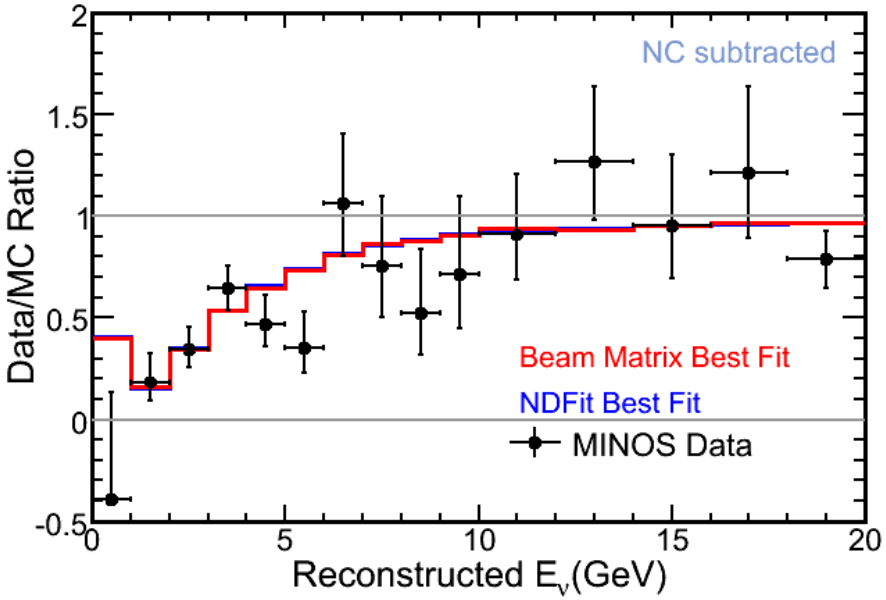
Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2(2\theta)$
Near/Far normalization ±4%	0.050	0.005
Absolute hadronic energy scale ±11%	0.060	0.048
NC contamination ±50%	0.090	0.050
All other systematic uncertainties	0.044	0.011
Total systematic (summed in quadrature)	0.13	0.07
Statistical error (data)	0.36	0.12

- Total systematic error is ~40% of statistical error in Δm^2
- 3 largest systematic uncertainties are included in the oscillation fit as nuisance parameters

MINOS Best Fit Spectrum

- Best fit energy spectrum and Data/MC Ratio for 1.27×10^{20} POT





$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat} + \text{syst})\times10^{-3}\,\text{eV}^2$$

$$\sin^2(2\theta_{23}) = 1.00_{-0.13}\ (\text{stat} + \text{syst})$$

$$\text{Normalization} = 0.98$$

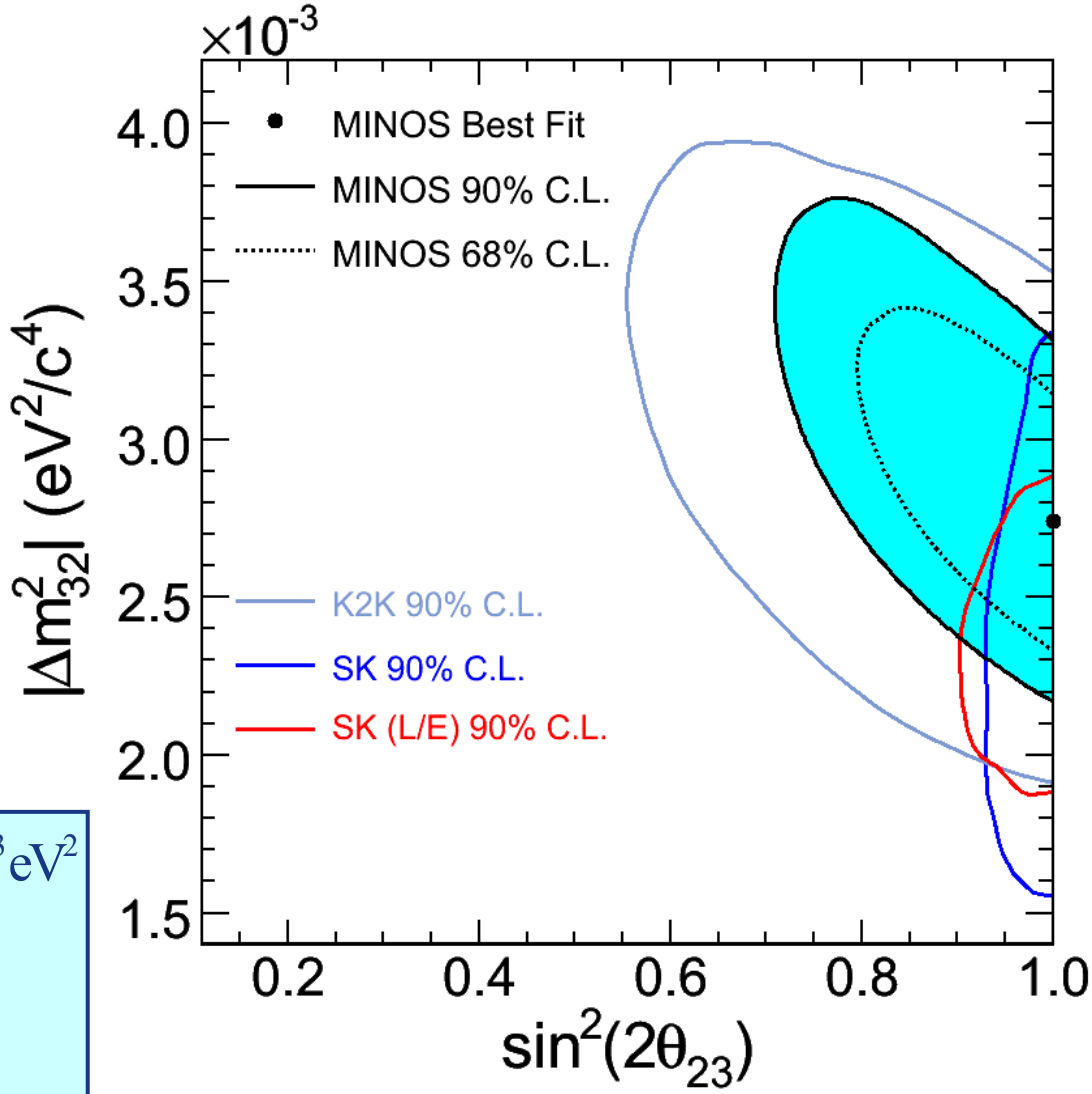
$$\text{Constrained to } \sin^2(2\theta_{23}) \le 1$$

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

Penalty terms for systematic uncertainties

MINOS Allowed Regions

- Contour obtained using the Beam Matrix extrapolation method
- Fit includes nuisance parameters corresponding to largest systematic uncertainties



$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat} + \text{syst}) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2(2\theta_{23}) = 1.00_{-0.13}\ (\text{stat} + \text{syst})$$

$$\text{Constrained to } \sin^2(2\theta_{23}) \le 1$$

Summary

- MINOS has completed an oscillation analysis of the first year of NuMI beam exposure, corresponding to **1.27×10^{20} POT**
  - Excludes no ν_μ disappearance at **6.2σ** (rate only)
  - Consistent with neutrino oscillations with parameters:

$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat} + \text{syst})\times10^{-3}\,\text{eV}^2$$

$$\sin^2\left(2\theta_{23}\right) = 1.00_{-0.13}\ (\text{stat} + \text{syst})$$

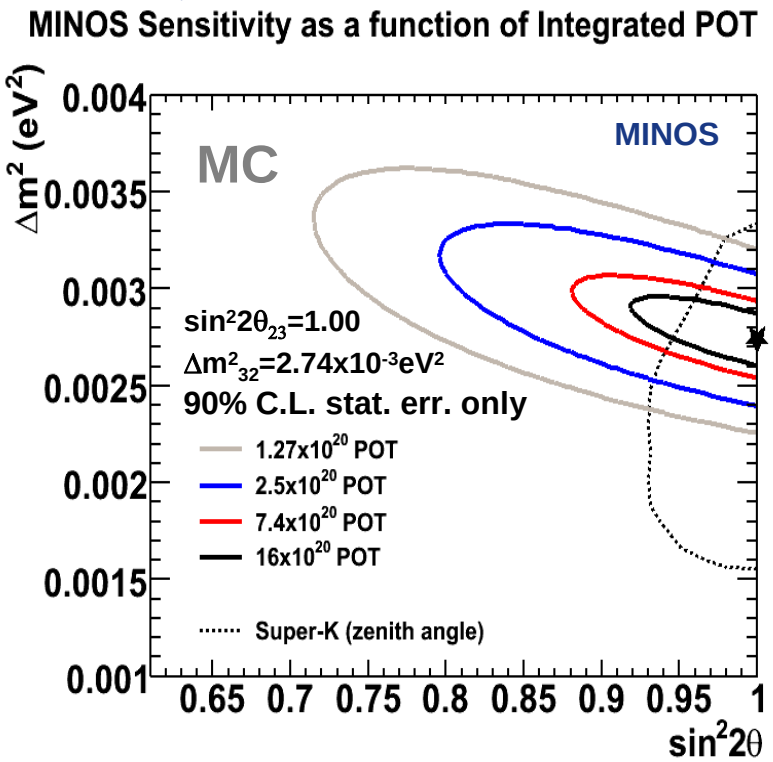
  - Results submitted to PRL (**hep-ex-0607088**)

- The systematic uncertainties are under control and substantial improvements on understanding them should be made as MINOS collects more data

- Second year of data taking is underway, look forward to improved results, other analyses

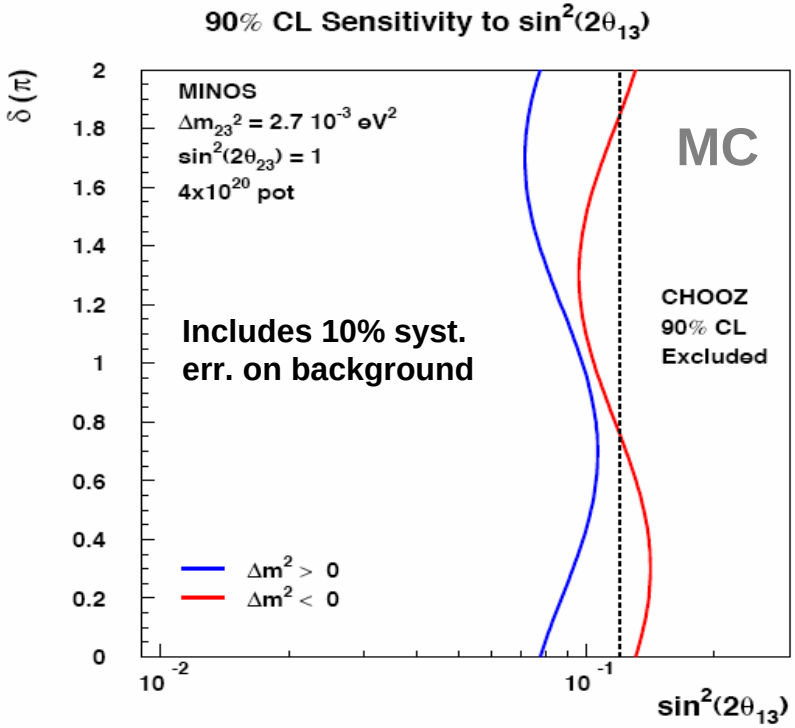
Outlook

ν_μ Disappearance



- MINOS will significantly improve the current result as the number of POT increases

ν_e Appearance

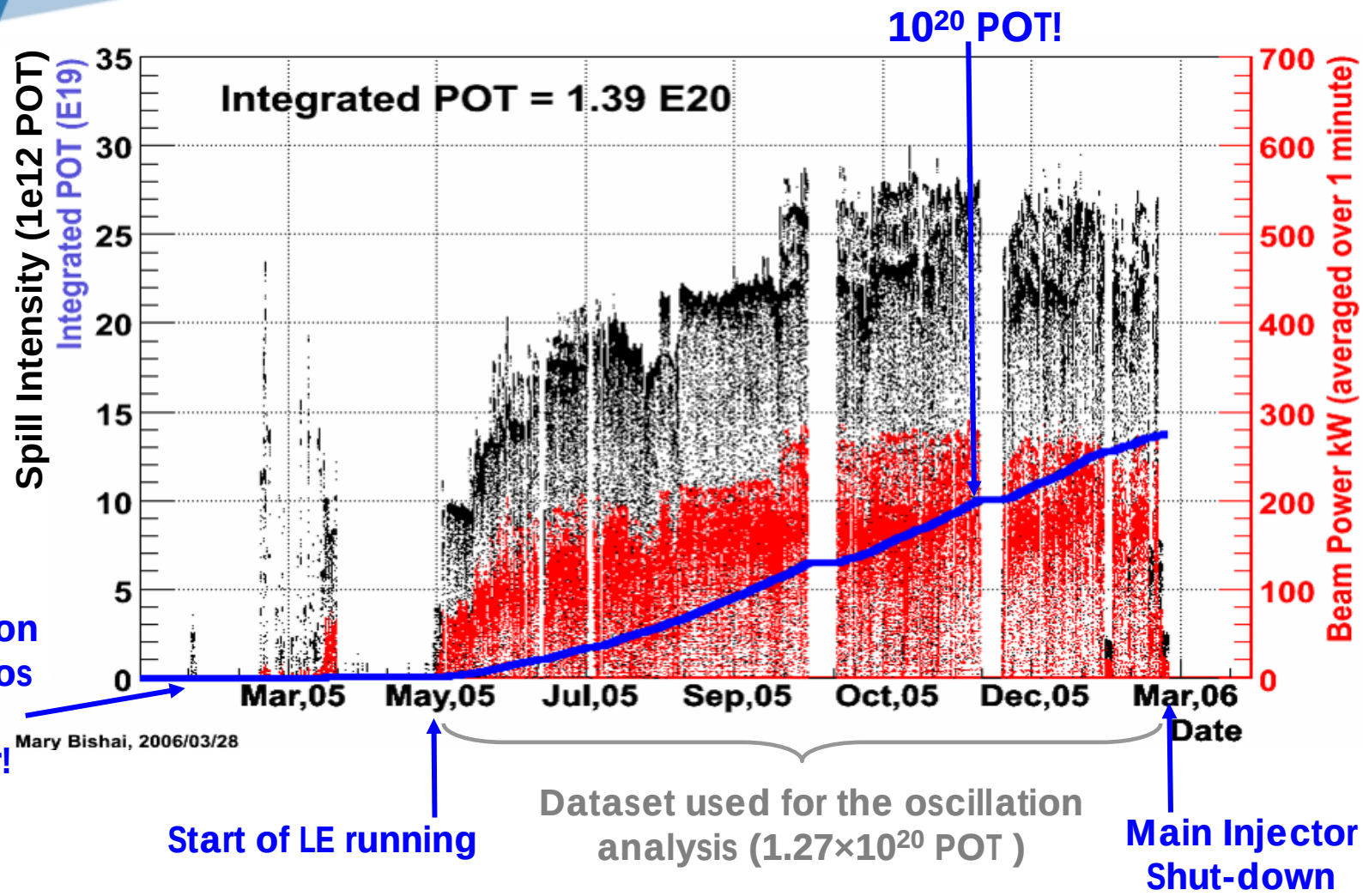


- MINOS could make the first ever measurement of θ_{13}
  - Can improve on current best limit set by CHOOZ

More to come soon!!

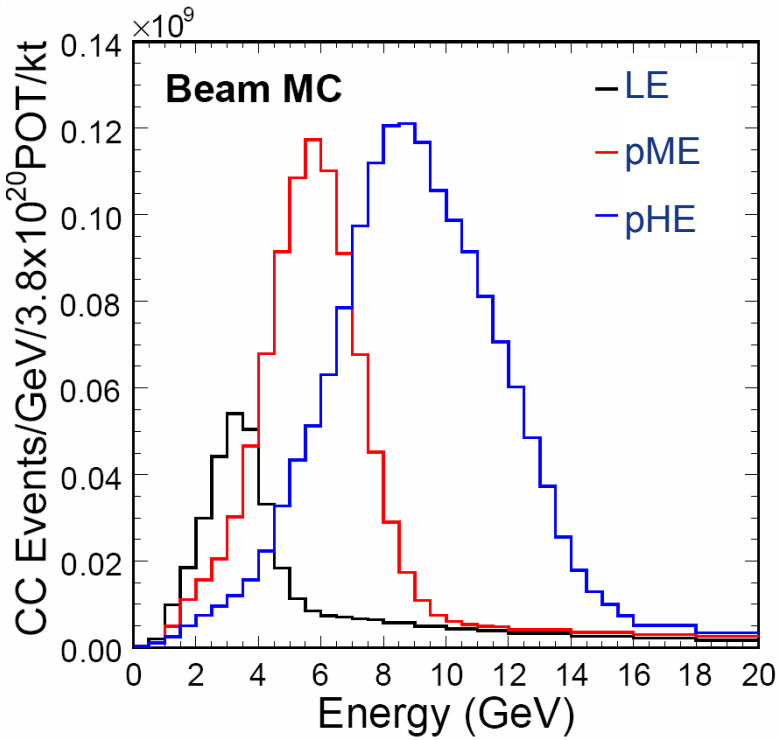
Backup Slides

First year of NuMI Running



NuMI Beam Composition

- Movable target relative to horns allows beam energy tuning
- **Currently running in the LE-10 configuration**
- ~1.5 $\times 10^{19}$ POT in pME and pHE configurations early in the run for commissioning and systematics studies



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

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

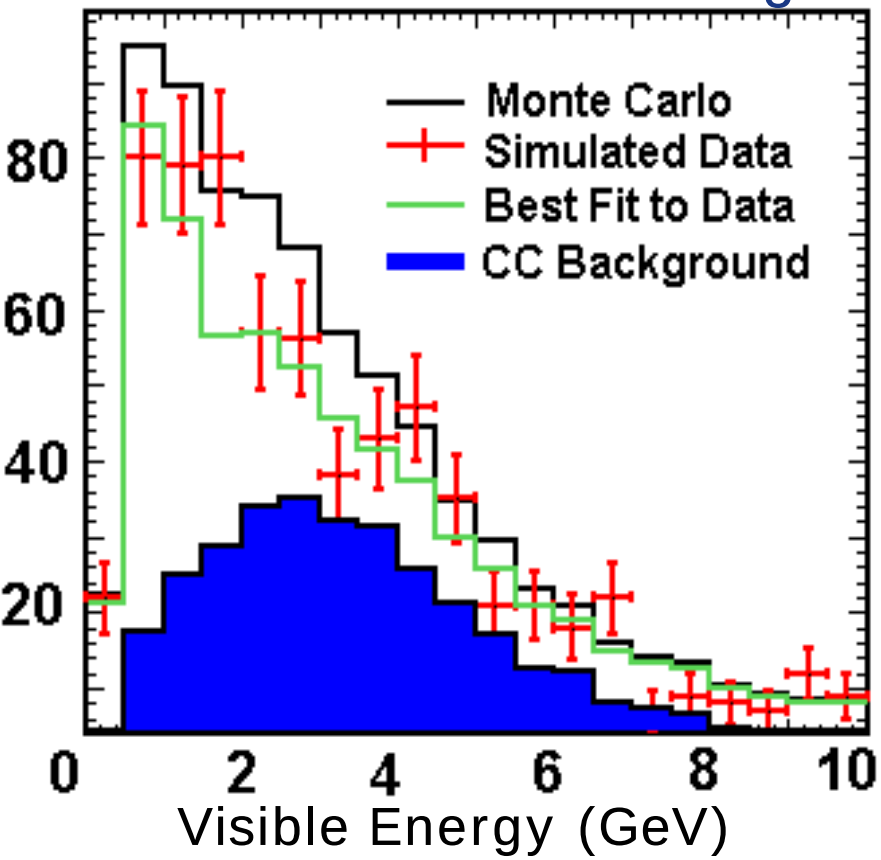
Beam	Target z position (cm)	FD Events per 1 $\times 10^{20}$ POT
LE-10	-10	390
pME	-100	970
pHE	-250	1340

Events expected in fiducial volume

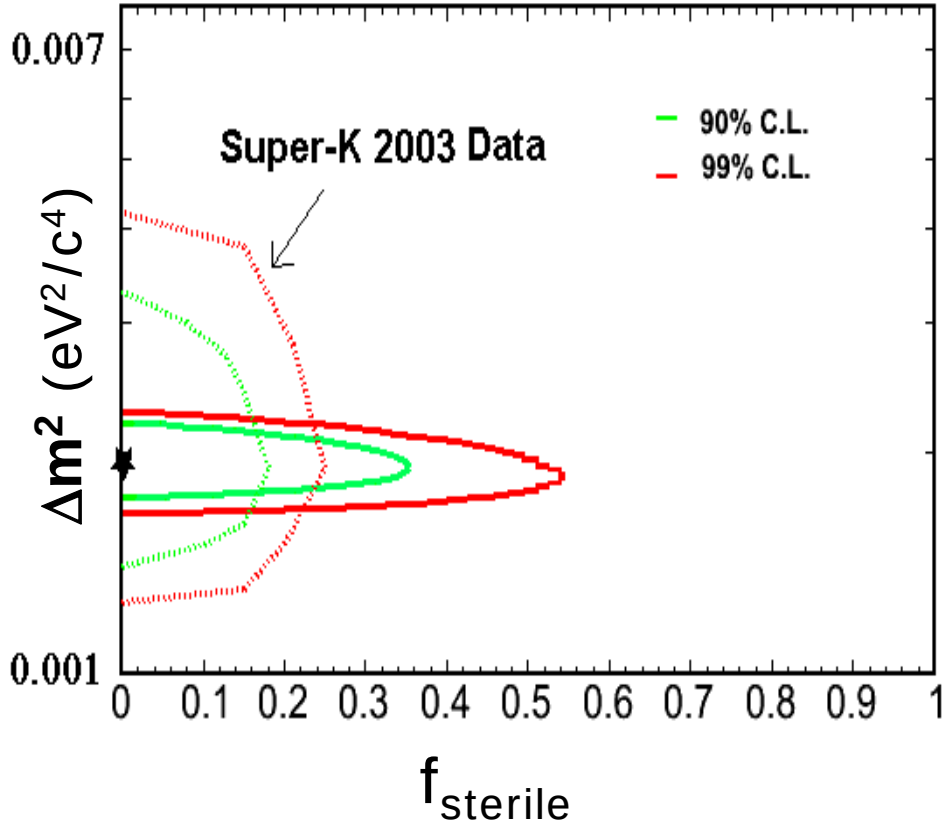
Search for ν_s

- Far Detector Mock Data with Dm2 = 0.00212 eV^2 , $f_{sterile}$ = 0.11
- Performed a Chi-squared Fit between Mock Data and prediction at Far

7.4e20 Protons on Target



Monte Carlo

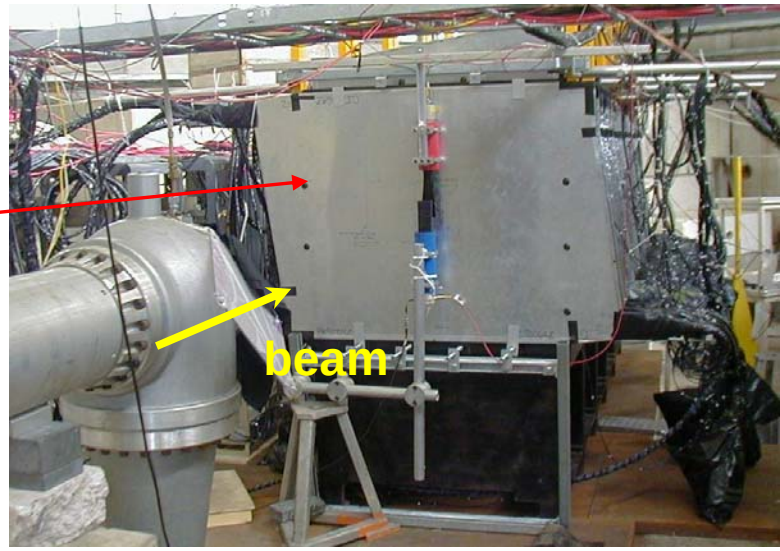


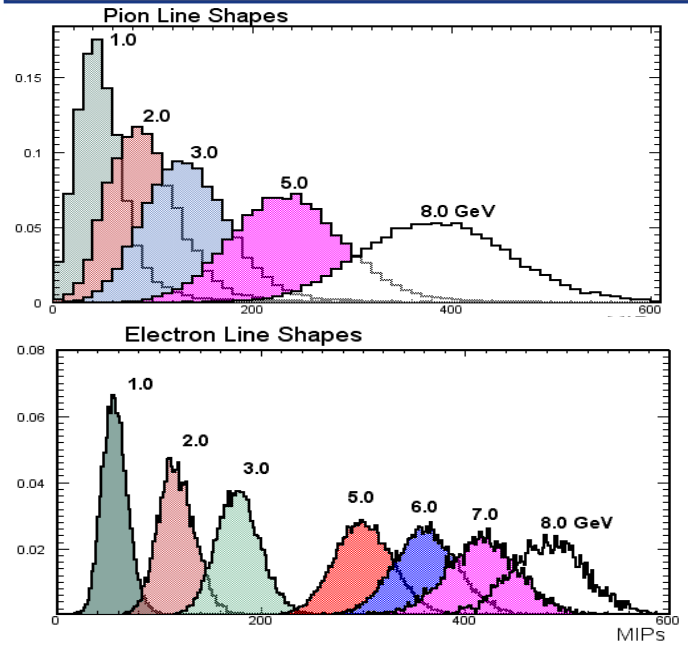
The MINOS Calibration Detector

- Help understand energy response to reconstruct E_ν

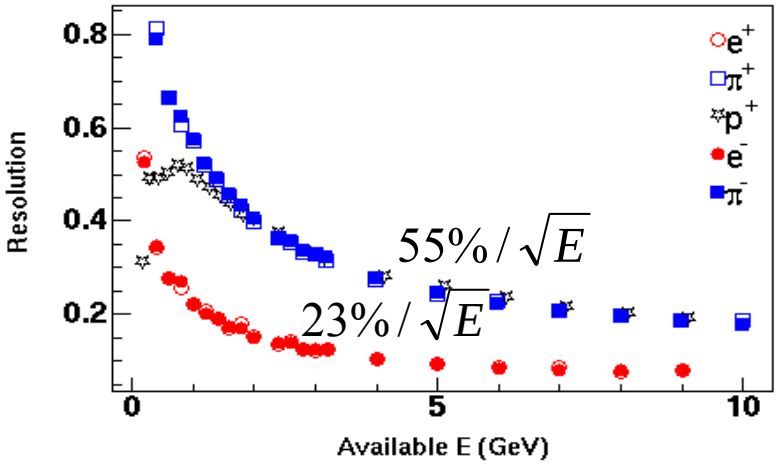
  $$E_\nu = p_\mu + E_{had}$$

- 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**



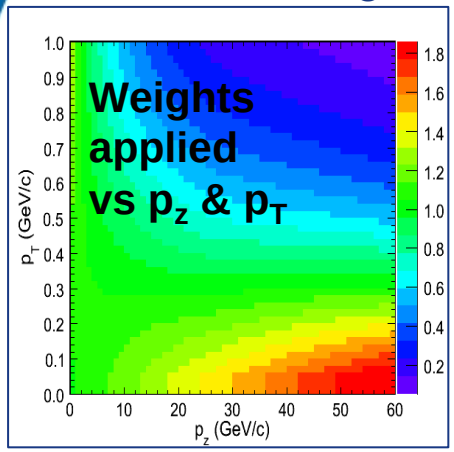


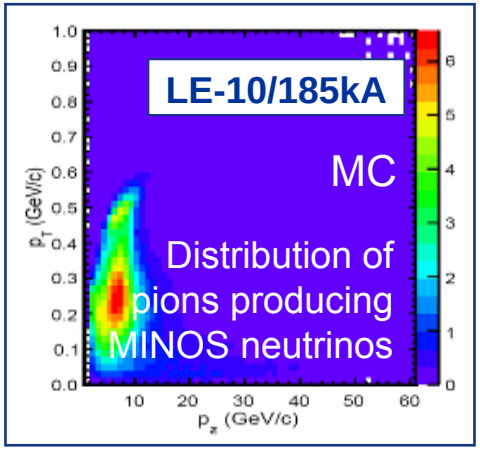
Single particle energy resolution

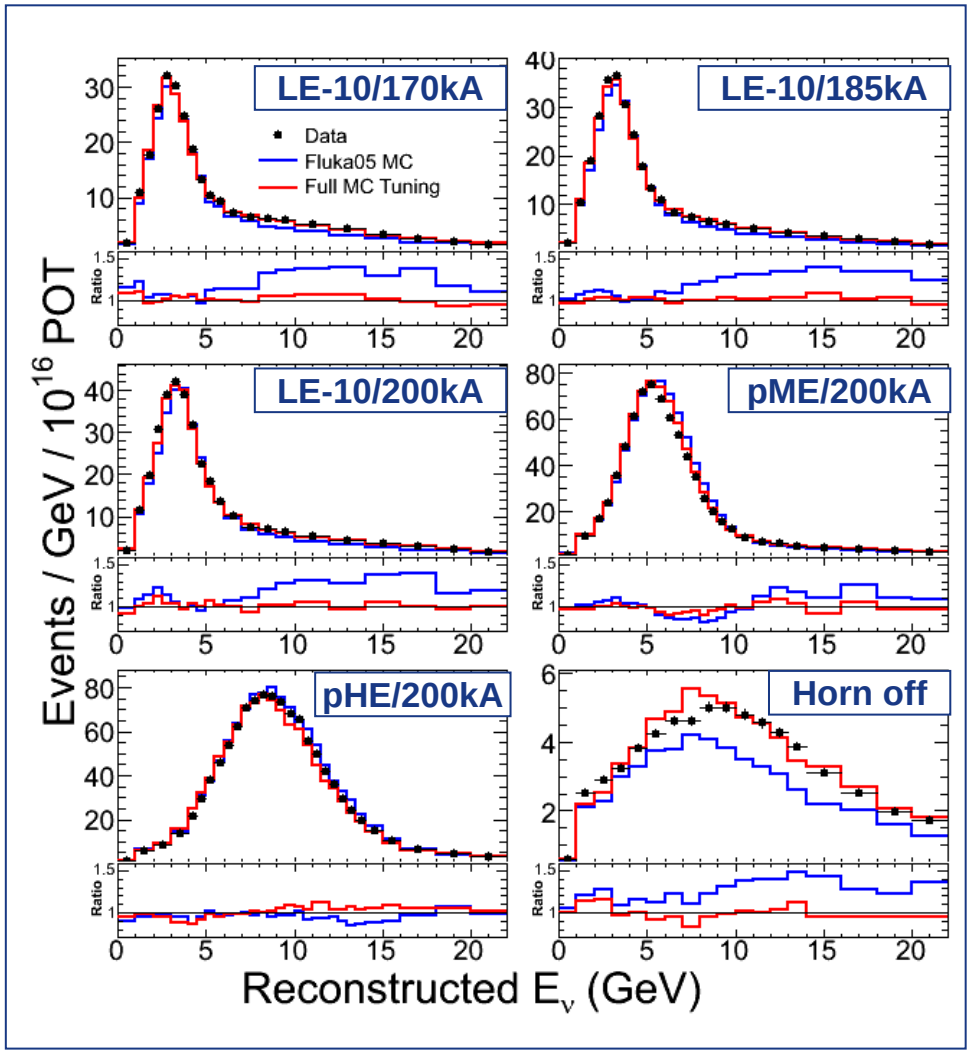


Hadron Production Tuning

- 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

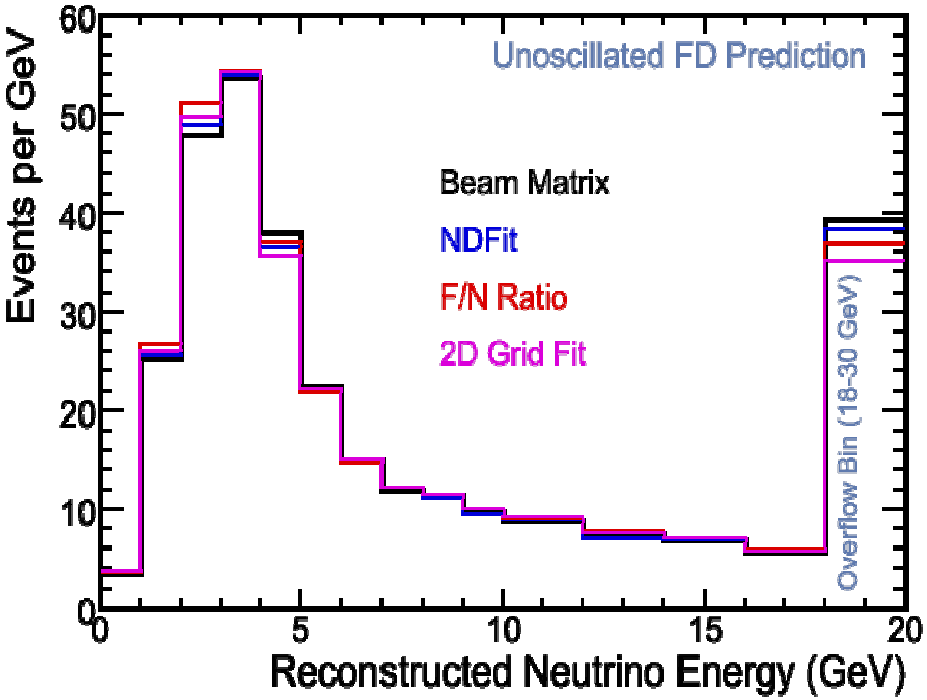






Other Extrapolation Methods

- 3 other extrapolation methods were applied to the data:
- **NDfit**: 1D fit to E_ν distribution in ND data used to determine systematic parameters and reweight FD MC accordingly
- **2D Grid Fit**: 2D fit to (E_ν, y) grid in ND data used to determine systematic parameters and reweight FD MC accordingly
- **F/N Ratio**: Uses Far/Near spectrum ratio from MC to scale the events in each ND energy bin into a number of FD events in that same bin



- The 4 extrapolation methods investigated give consistent predictions and are robust to different types of systematics.

Breakdown of FD Selection

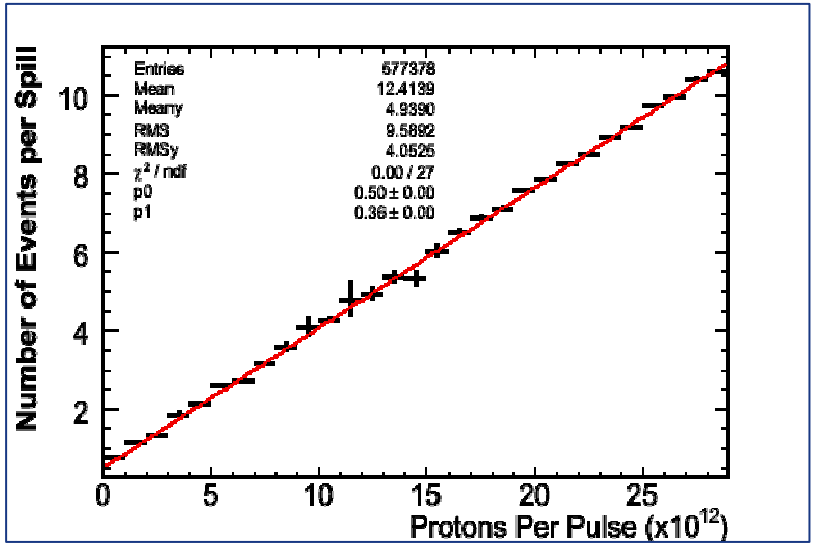
Cut	Events	Efficiency
All Events in fiducial volume	438	-
Events with a track	384	87.7%
Track quality cuts	365	95.1%
PID cut (CC-like)	267	73.2%
Track charge sign cut (negative μ only)	244	91.4%
Reconstructed energy <30 GeV	215	88.1%

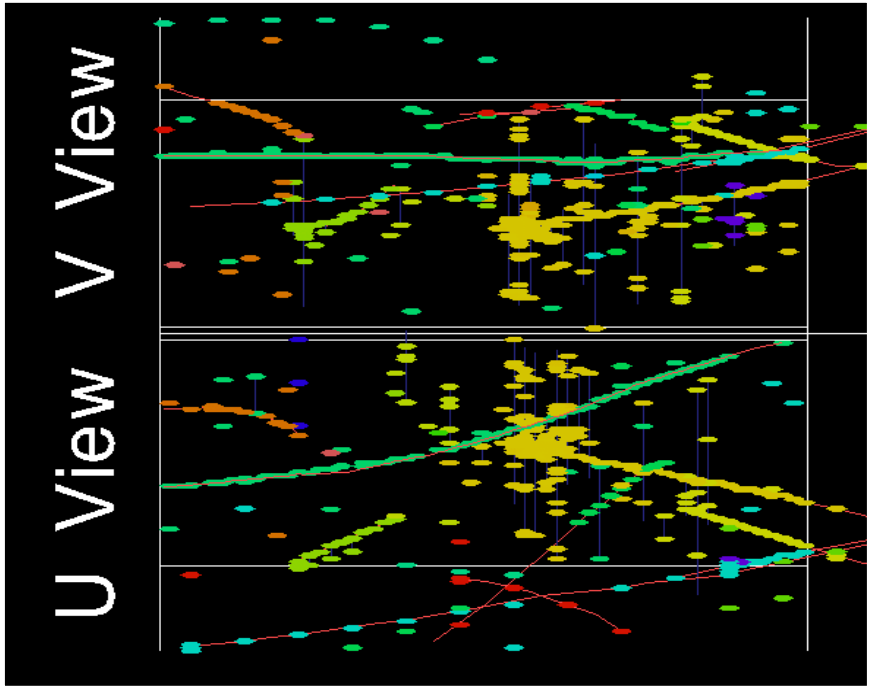
Systematic Shifts

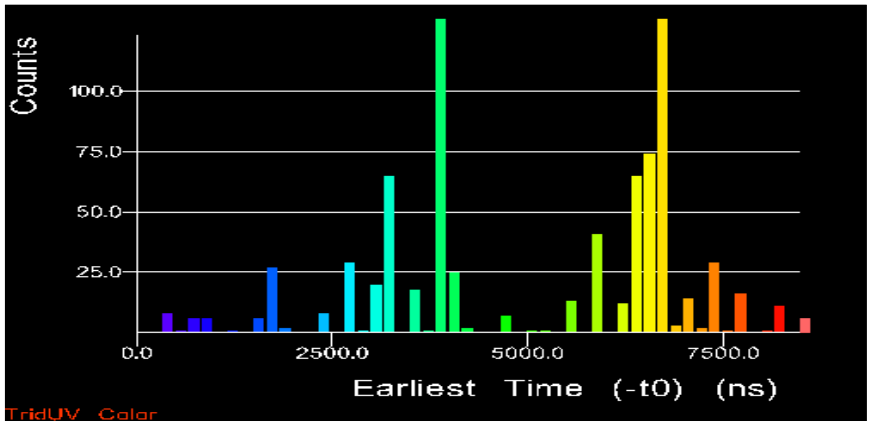
Preliminary Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2 2\theta$
Near/Far normalization ±4%	0.050	0.005
Muon energy scale ±2%	0.033	0.003
Relative shower energy scale ±2%	0.050	0.005
Absolute shower energy scale ±6%	0.033	0.005
Intranuclear re-scattering ±10%	0.050	0.048
NC contamination ±50%	0.090	0.050
Total (sum in quadrature)	0.13	0.07
Statistical error (data)	0.36	0.12

Near Detector Spill

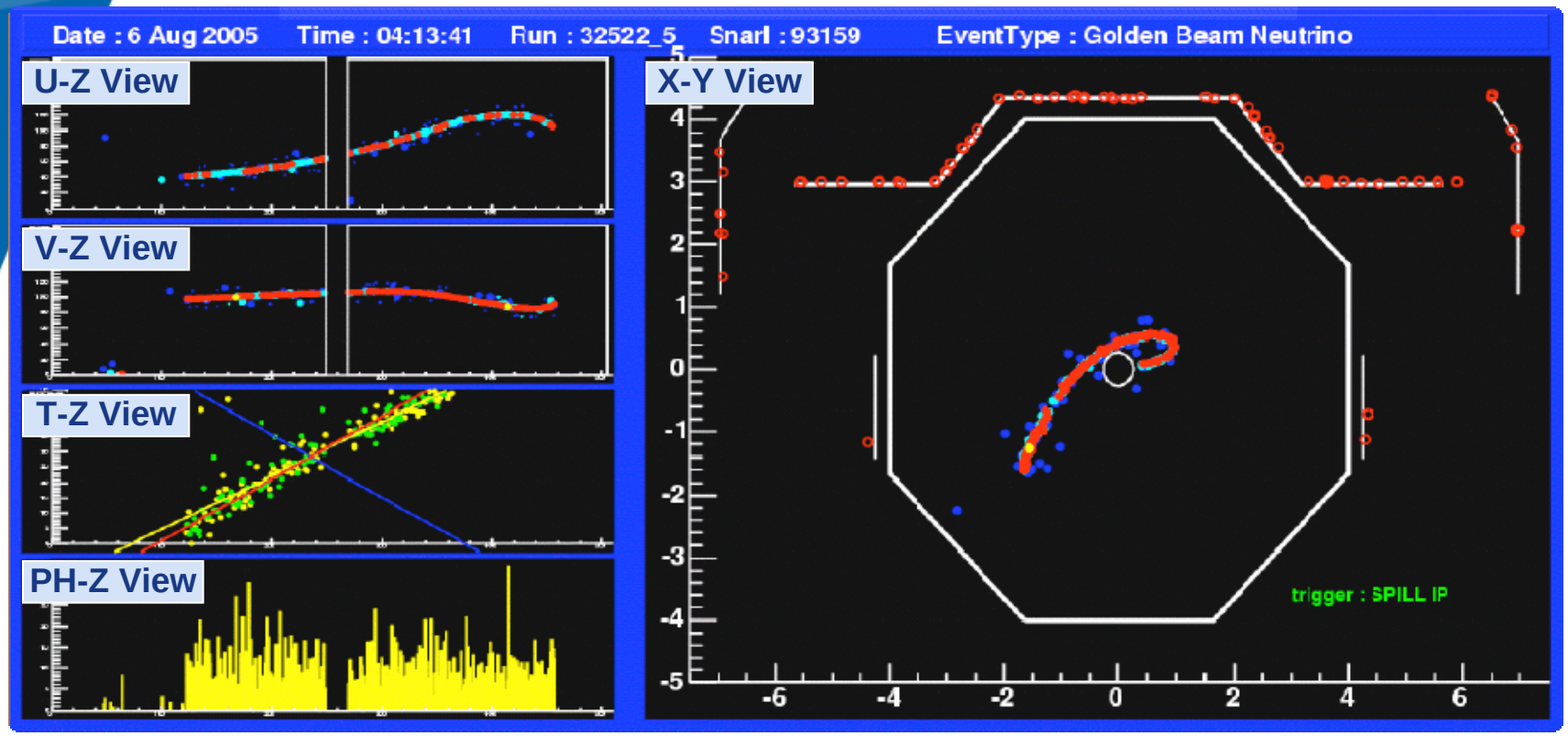
- Multiple events in ND per Main Injector spill
  - Over 1×10^7 fiducial events collected
- Events are separated using topology and timing
  - Color in display indicates time
    - Blue hits are early, red are late
- No rate effects observed
  - Linear increase in event rate with beam intensity







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