Latest results from MINOS

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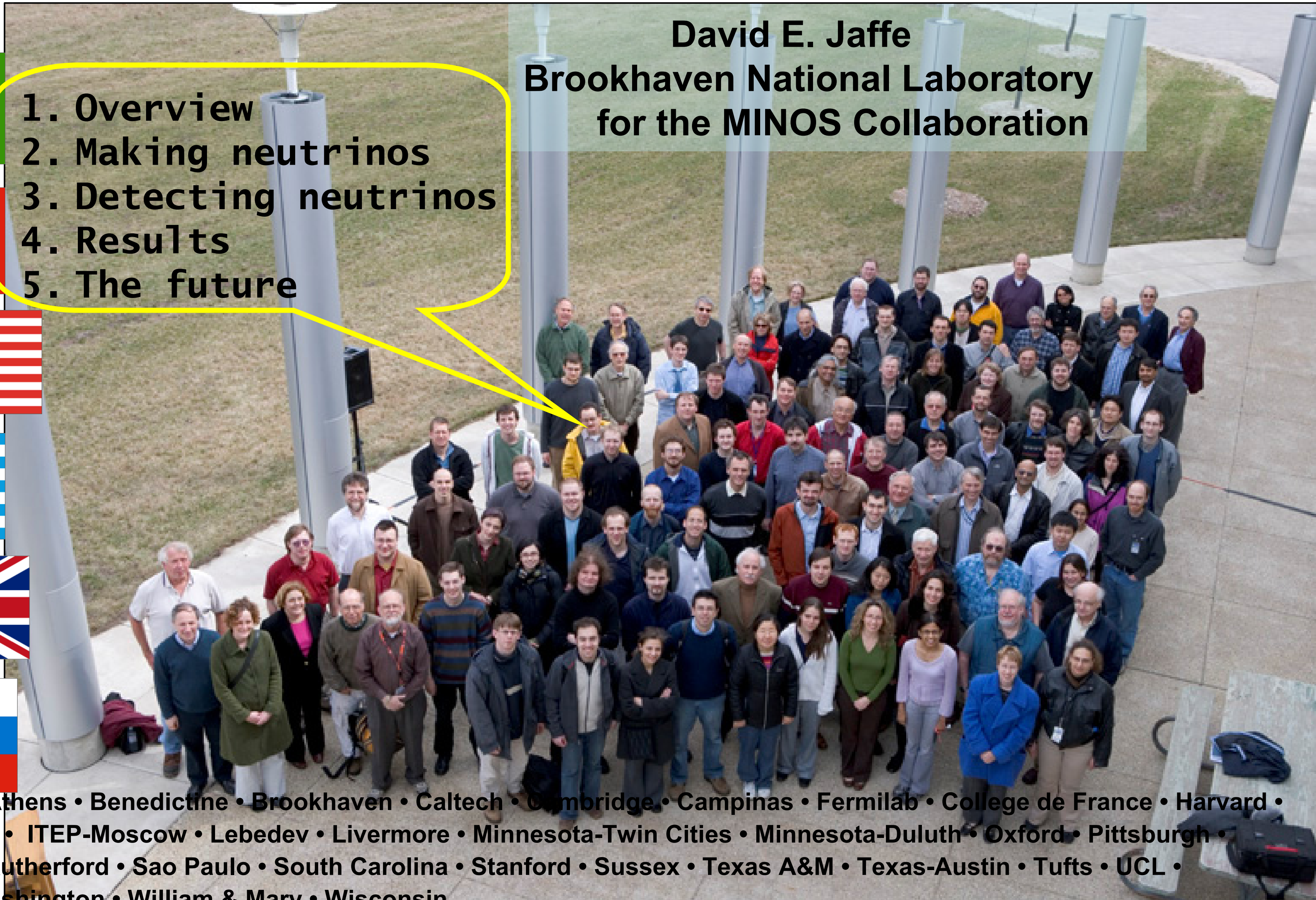
for the MINOS Collaboration

1. Overview
2. Making neutrinos
3. Detecting neutrinos
4. Results
5. The future



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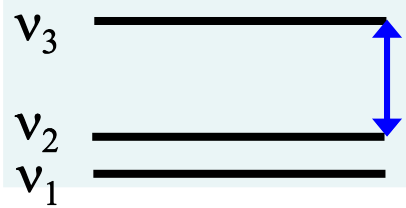
MINOS Physics Goals

- Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - Measure precisely $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
- Search for or constrain exotic phenomena
  - Sterile ν, ν decay
- Compare ν, $\overline{\nu}$ oscillations
  - Test of CPT violation
- Atmospheric neutrino oscillations
  - **Phys. Rev. D73, 072002 (2006)**

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



$\Delta m^2_{32} = m_3^2 - m_2^2$

Units: Δm^2(eV^2)   L(km)   E(GeV)

Useful Approximations:

ν_μ Disappearance (2 flavors):

$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$

ν_e Appearance:

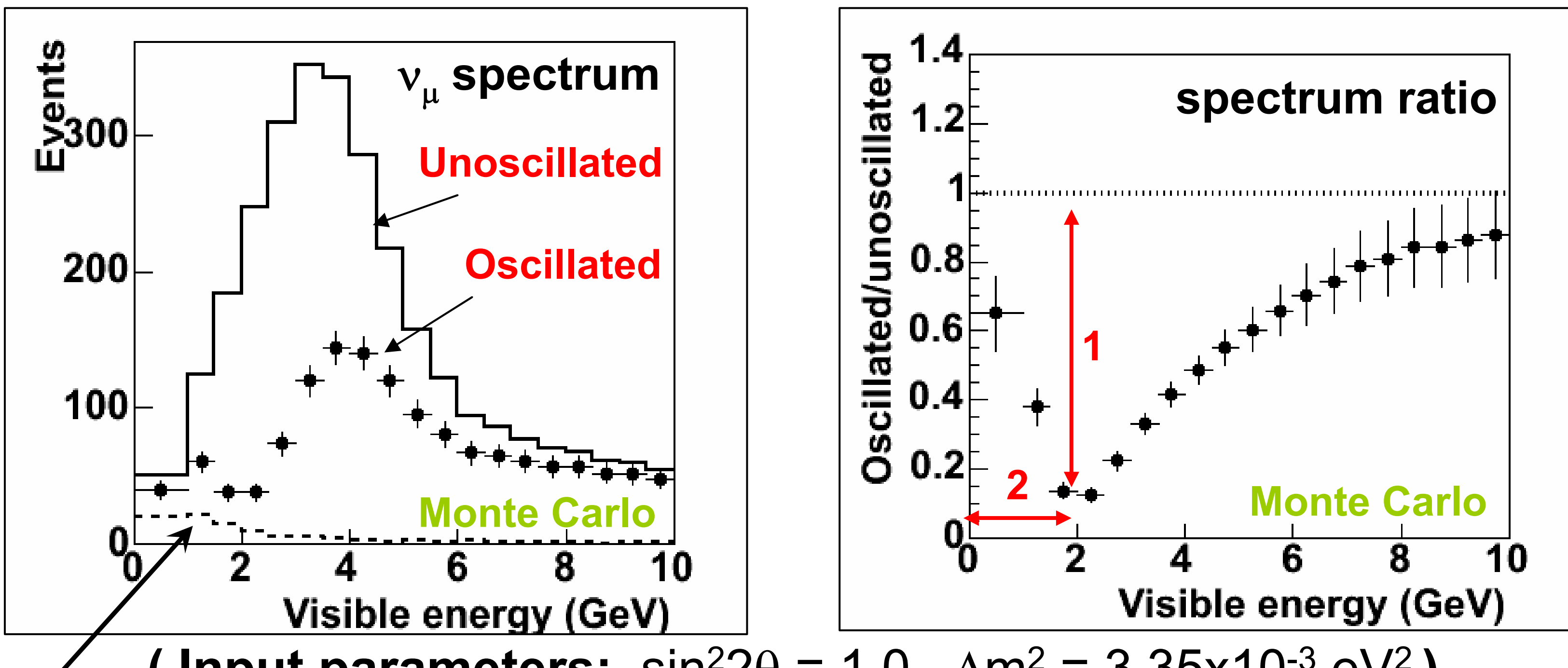
$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{31} L/E)$

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

“Disappearance” measurement

- Generic long baseline ν_μ disappearance experiment
- Predict unoscillated charged current (CC) spectrum at Far Detector (fixed L)
- Compare with measured Energy spectrum to extract oscillation parameters

$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\sin^2 2\theta}_{1} \sin^2(1.267 \underbrace{\Delta m^2}_{2} L/E)$$

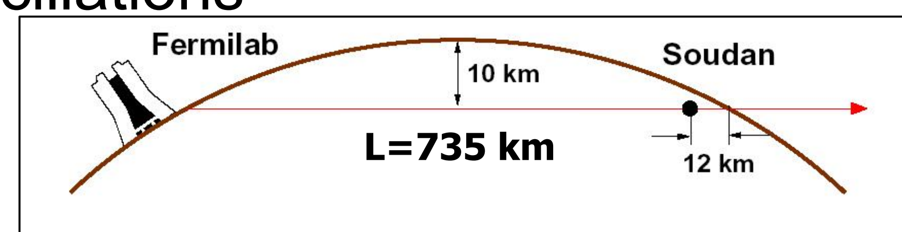


(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2 **)**

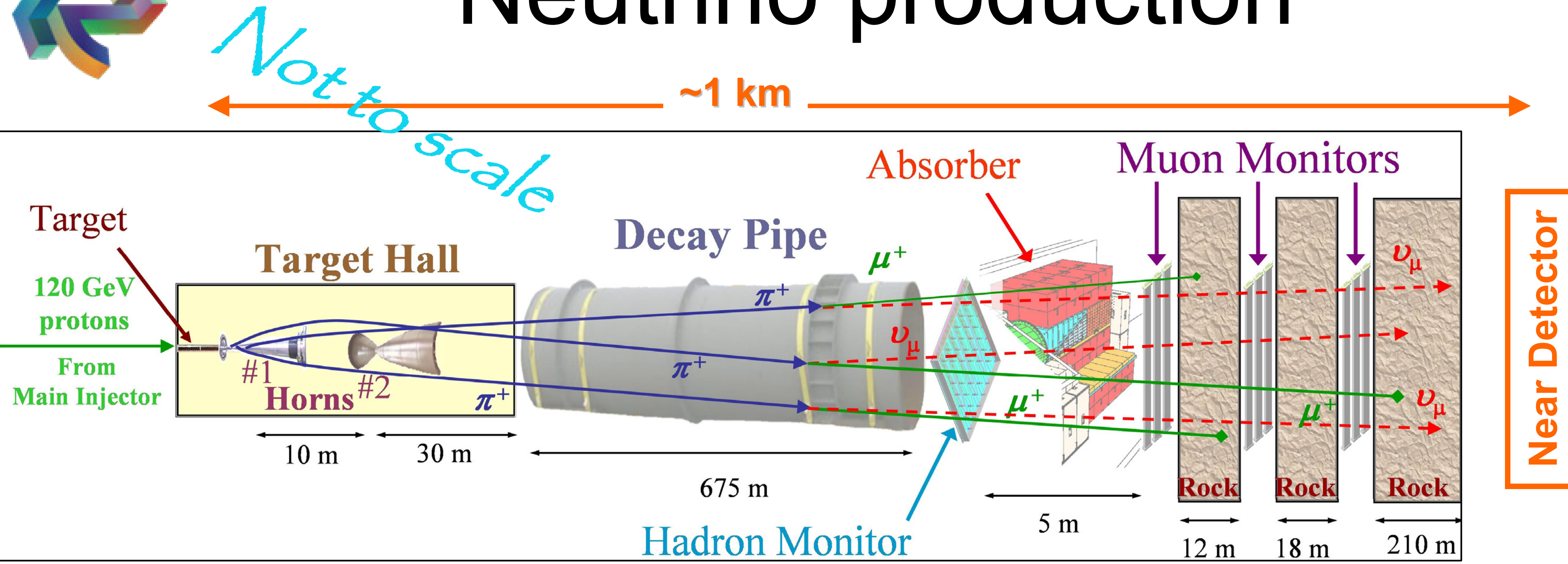
Neutral current (NC) background

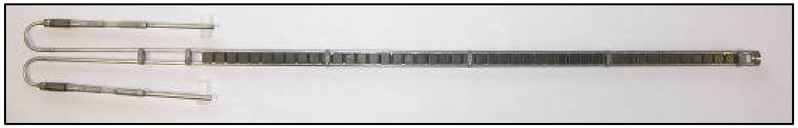
Main Injector Neutrino Oscillation Search

- High power ν_μ beam produced by 120 GeV protons from the Main Injector at FNAL
- Two functionally identical detectors:
  - Near detector (ND) at Fermilab to measure the beam composition and energy spectrum
  - Far Detector (FD), 735km away, in the Soudan Mine, Minnesota to search for evidence of oscillations

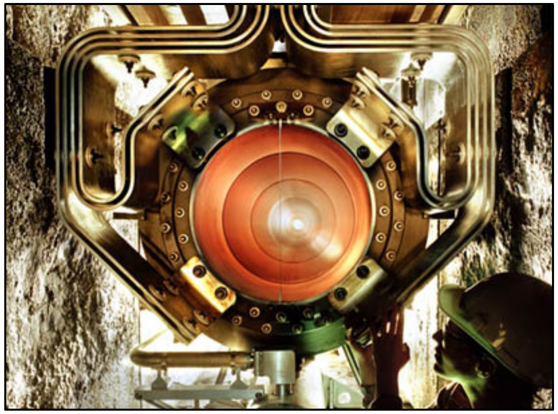


Neutrino production



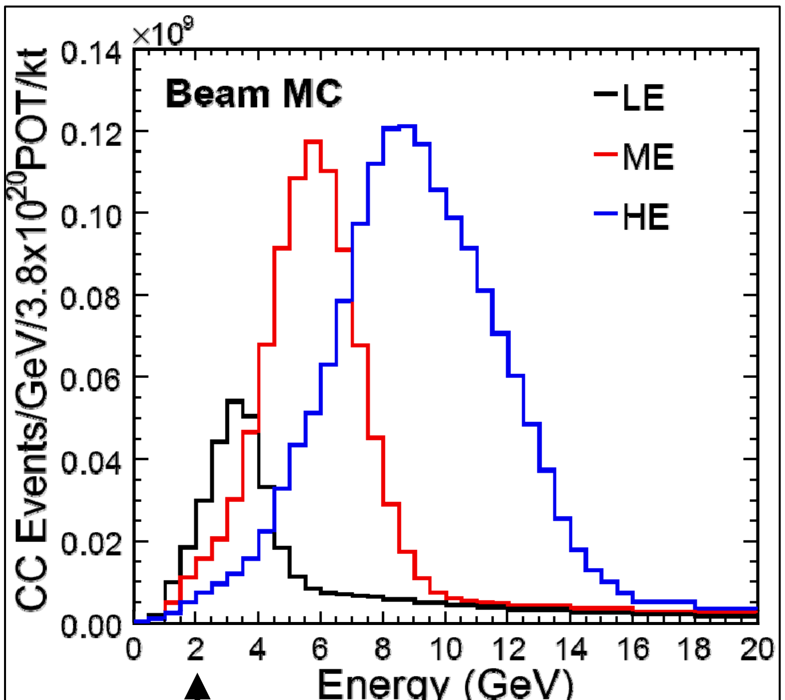


- Moveable segmented graphite target ⇒ variable beam energy
- Two parabolic magnetic focusing horns ⇒ ν or anti-ν beams



NuMI Neutrino Beam

- LE-10 configuration is most favorable for oscillation analysis and constitutes ~95% of total exposure
  - Data taken in 5 other configurations for systematic studies
- LE-10 event composition: 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$, 1.3% ν_e / $\overline{\nu}_e$



Position of oscillation maximum (Δm^2=0.00335eV^2,L=735km)

Expected number of Far Detector events without oscillations

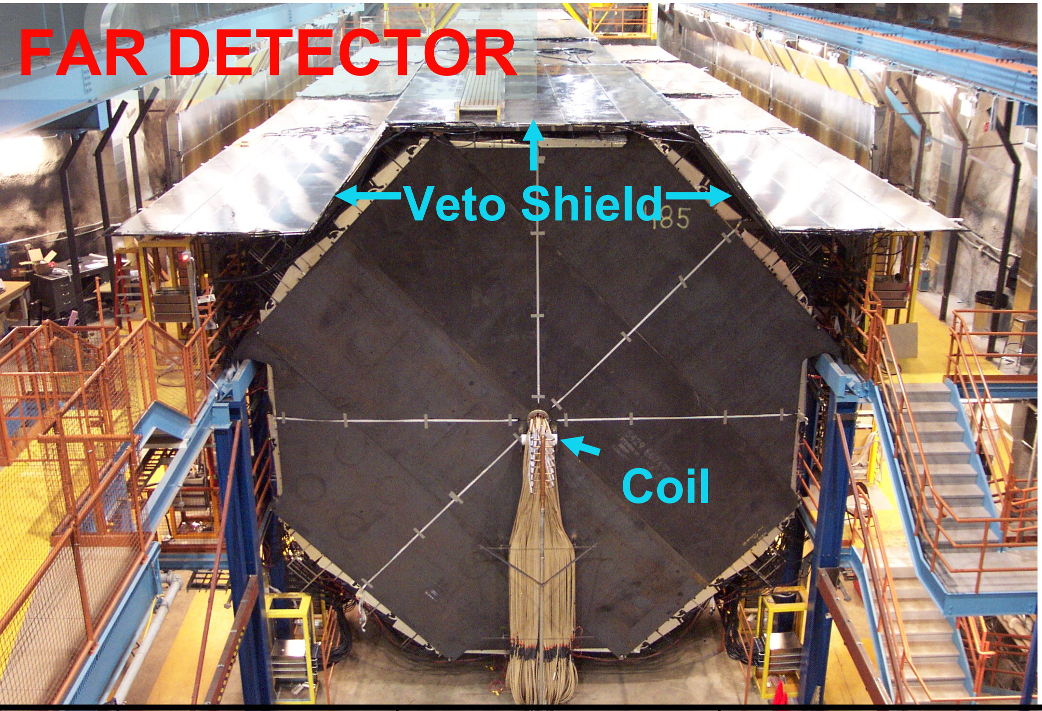
Beam	Target z position (cm)	FD Events* per 1e20 pot**
LE-10	-10	390
pME	-100	970
pHE	-250	1340

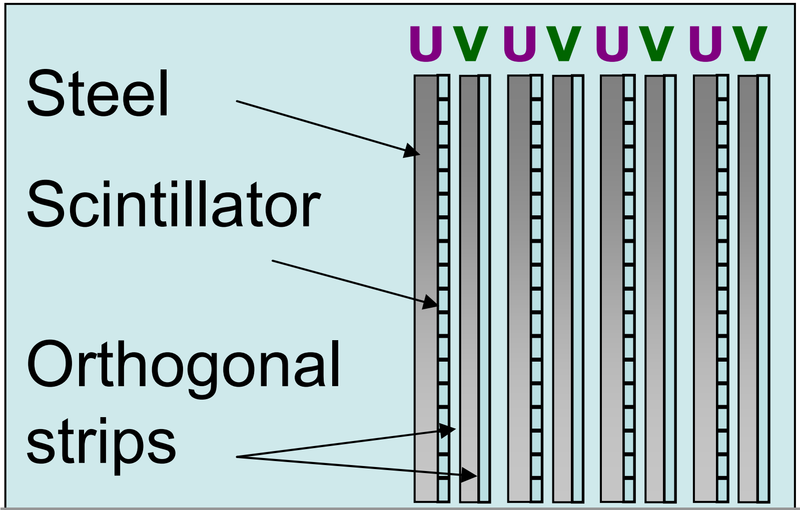
***Events in fiducial volume**
****pot=Protons-on-target**

Neutrino detection

2.54 cm thick magnetized (1.2T) steel plates

4.1x1cm scintillator strips grouped into orthogonal U,V planes

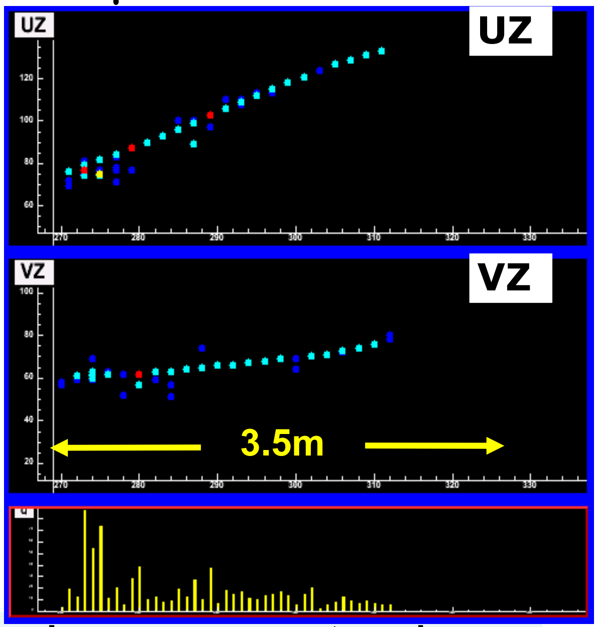




	Far Det	Near Det
Mass(kt)	5.4	1
Size(m^3)	8x8x30	3.8x4.8x1
Steel/Scint. Planes	484/484	282/152

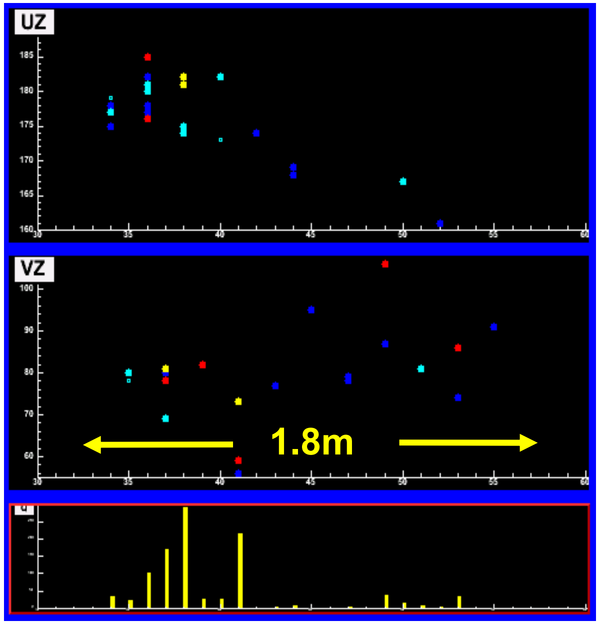
Neutrino interaction identification

ν_μ CC Event



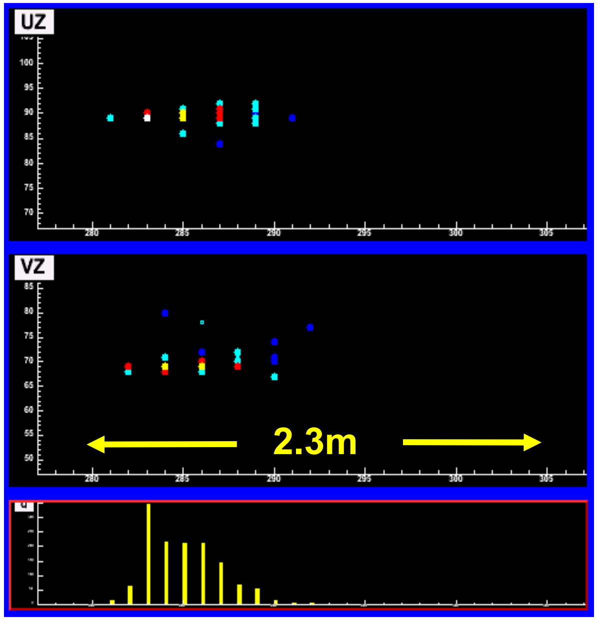
- Long muon track + hadronic activity at vertex

NC Event



- Short showering event, often diffuse

ν_e CC Event



- Short event with typical EM shower profile

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

Shower energy resolution: 55%/√E

Muon momentum resolution: 6% range; 13% curvature

Pre-selecting ν_μ CC Events

Preselection for separating ν_μ CC from NC events

Data quality:

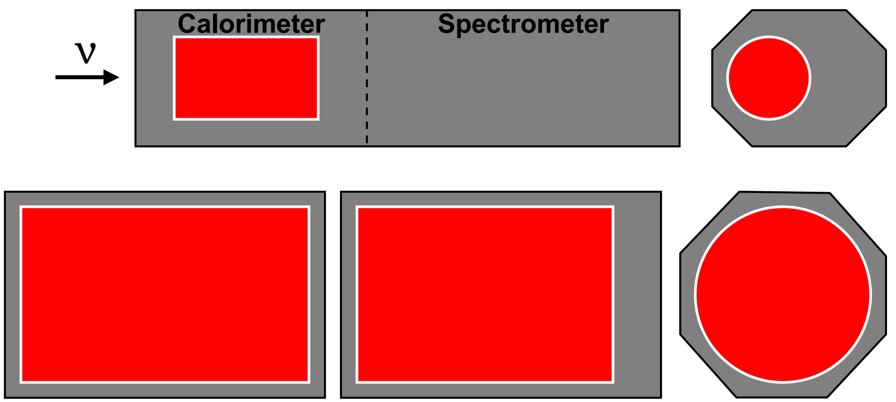
- Beam and detector monitoring cuts

Preselection:

- At least one good reconstructed track
- Track vertex within detector fiducial volume

NEAR: 1m < z < 5m
R<1m from beam center

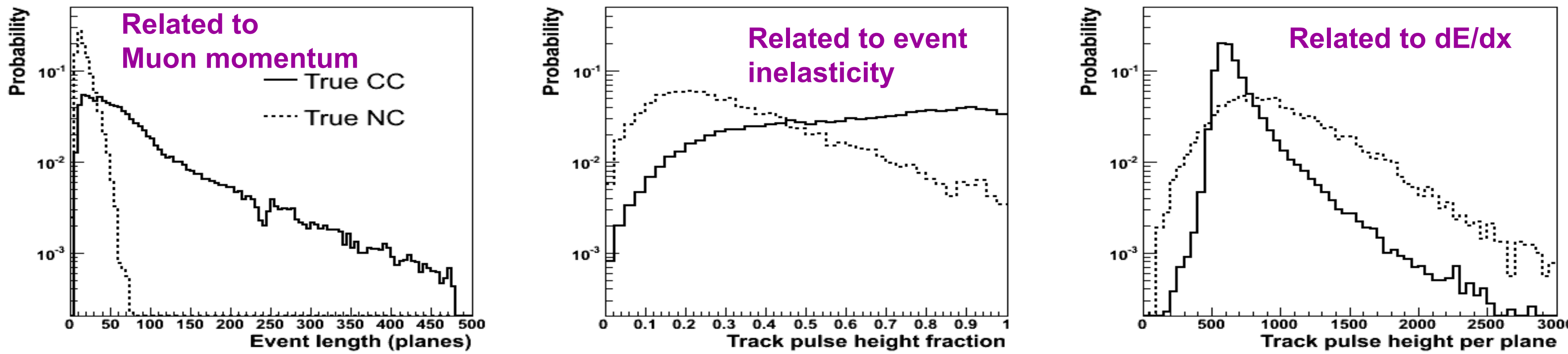
FAR: z>50cm from front face
z>2m from rear face
R<3.7m from center of FD



- Fitted track must have negative charge (to reject $\overline{\nu}_\mu$)

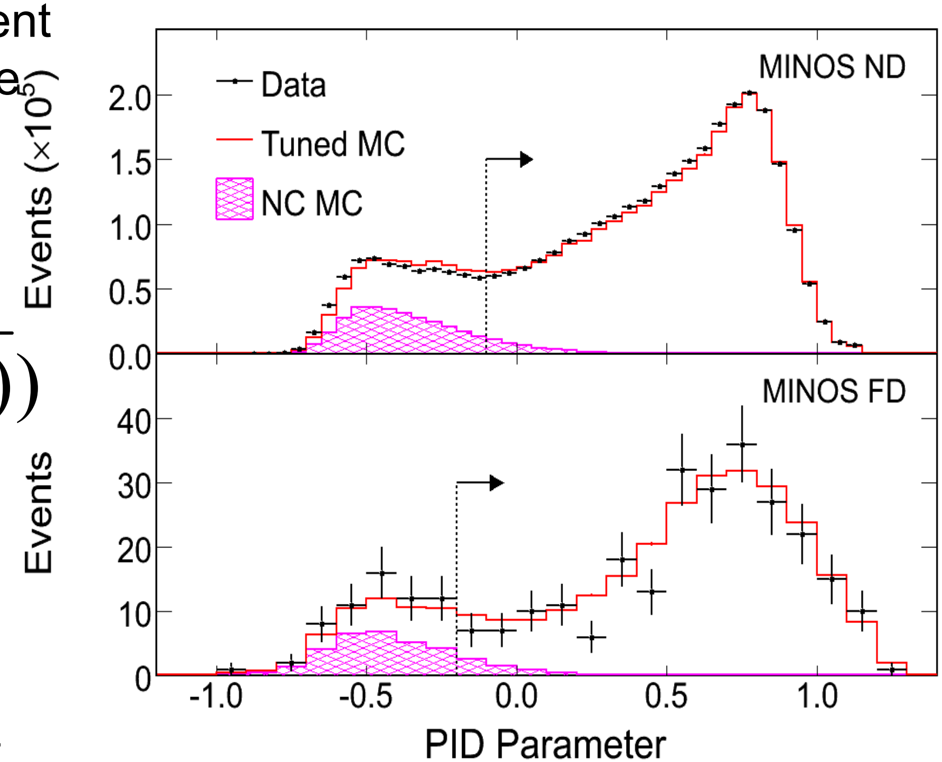
Selecting CC ν_μ interactions

Input variables for PDF-based event selection Monte Carlo

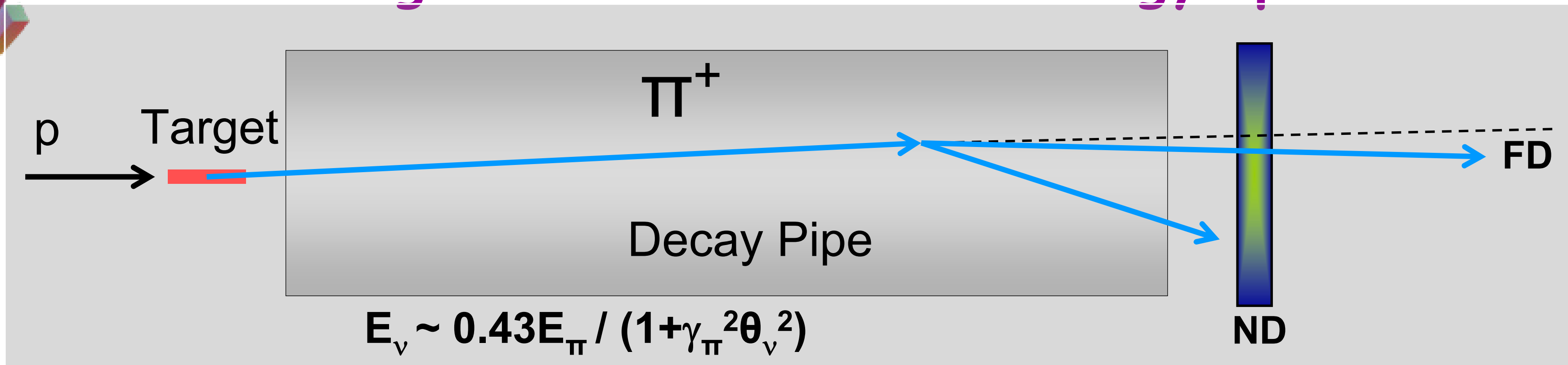


P_{CC}/P_{NC} is the probability that a CC/NC event would be observed with these values where (P_{CC} (P_{NC}), resp.) is the product of the three CC(NC) PDFs at those values

$$PID = -\left(\sqrt{-\log(P_{CC})} - \sqrt{-\log(P_{NC})}\right)$$

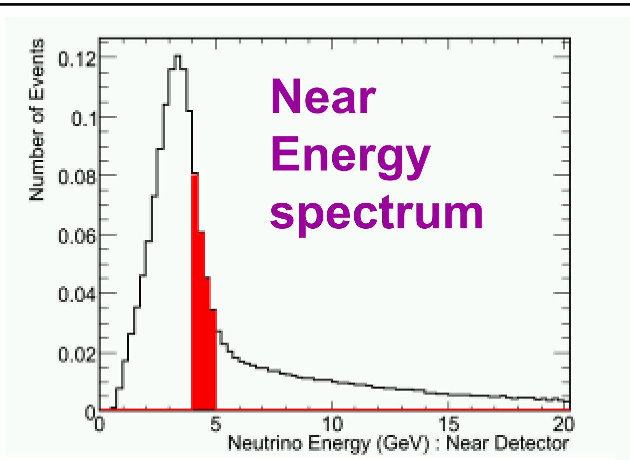


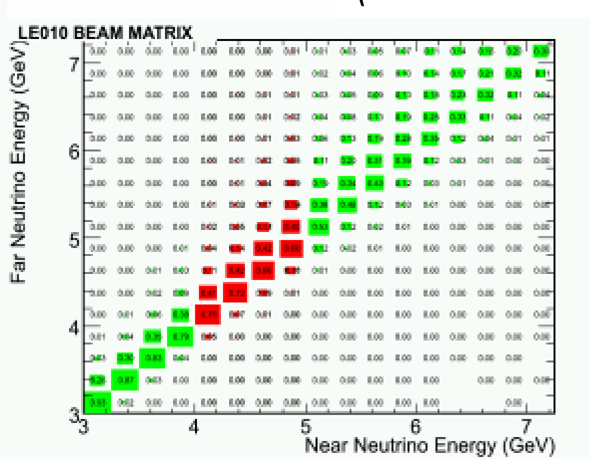
Predicting the unoscillated FD energy spectrum

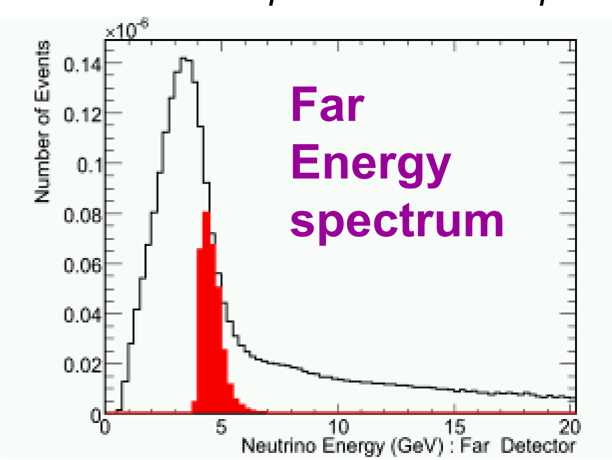


- The unoscillated FD energy spectrum differs from the ND spectrum because the decay angles for neutrinos to reach the detectors differ
- Primary extrapolation method is ‘matrix method’ that contains info of pion 2-body decay kinematics and beamline geometry (MC used to correct for energy resolution and acceptance)

(Several methods were developed for the extrapolation)

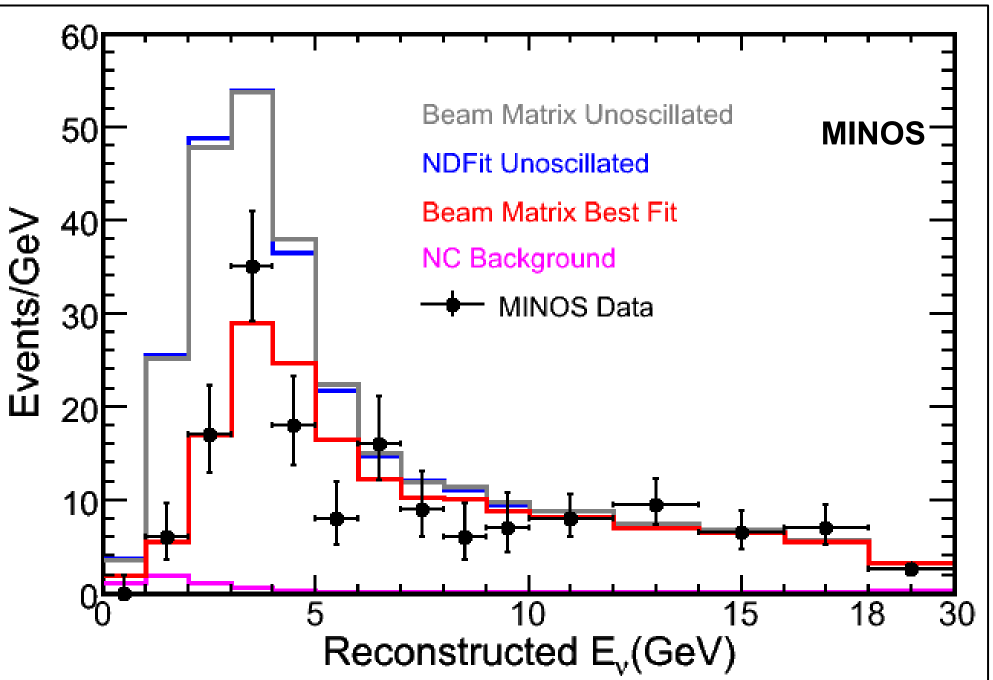


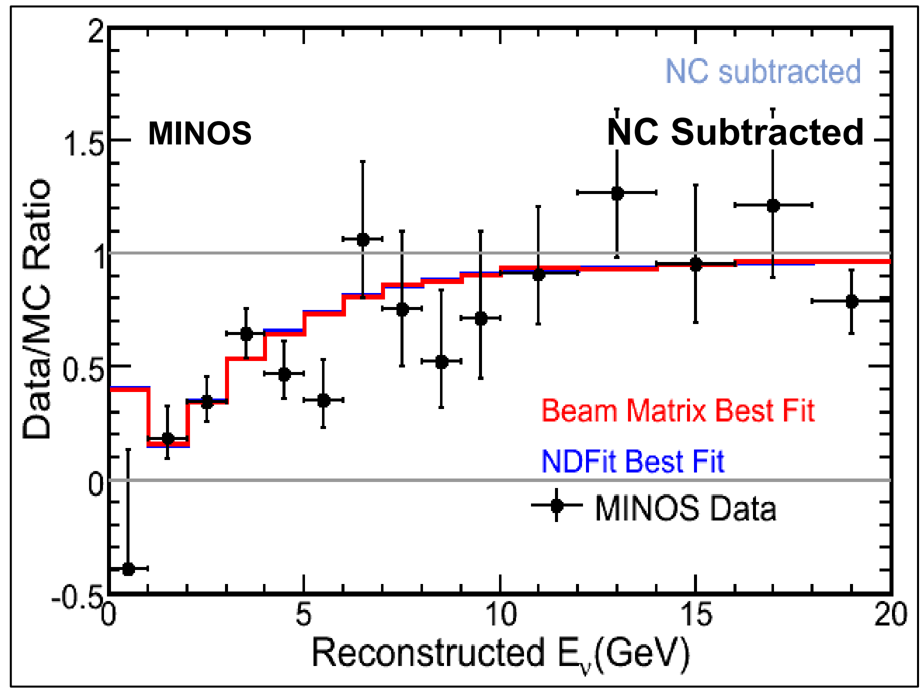




MINOS Best-Fit Spectrum

- Best-fit spectrum for 1.27×10^{20} POT





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

Measurement errors are 1σ, 1 DOF

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

$$\text{Normalization} = 0.98$$

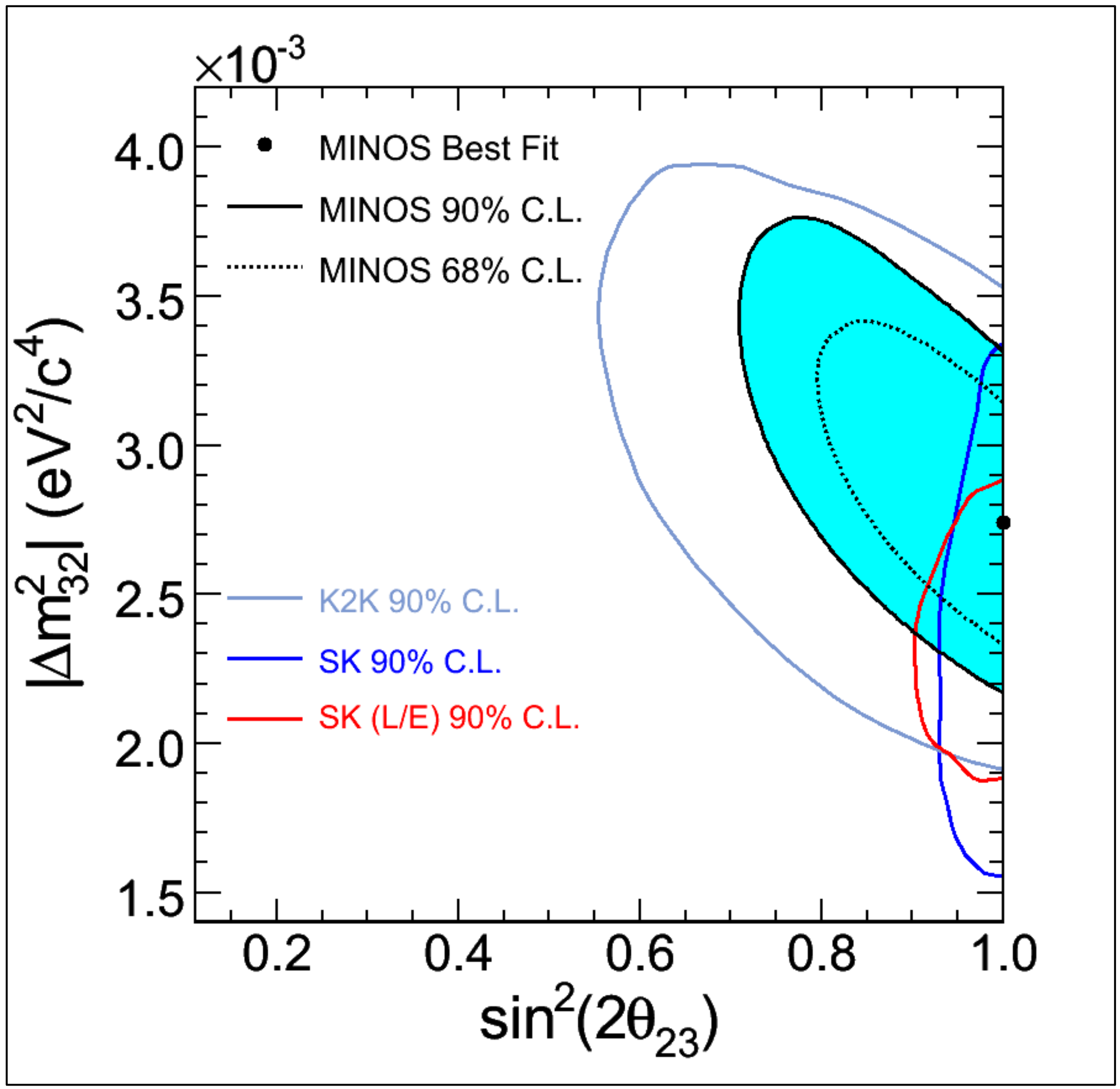
$$\chi^2 = \sum_{i=1}^{\text{nbins}} \left[2(e_i - o_i) + 2o_i \ln(o_i/e_i)\right] + \sum_{j=1}^{\text{nsys}} \Delta s_j^2 / \sigma_{s_j}^2$$

Allowed Region

- Fit includes penalty terms for three main systematic uncertainties
- Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$

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

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$



Systematic Uncertainties

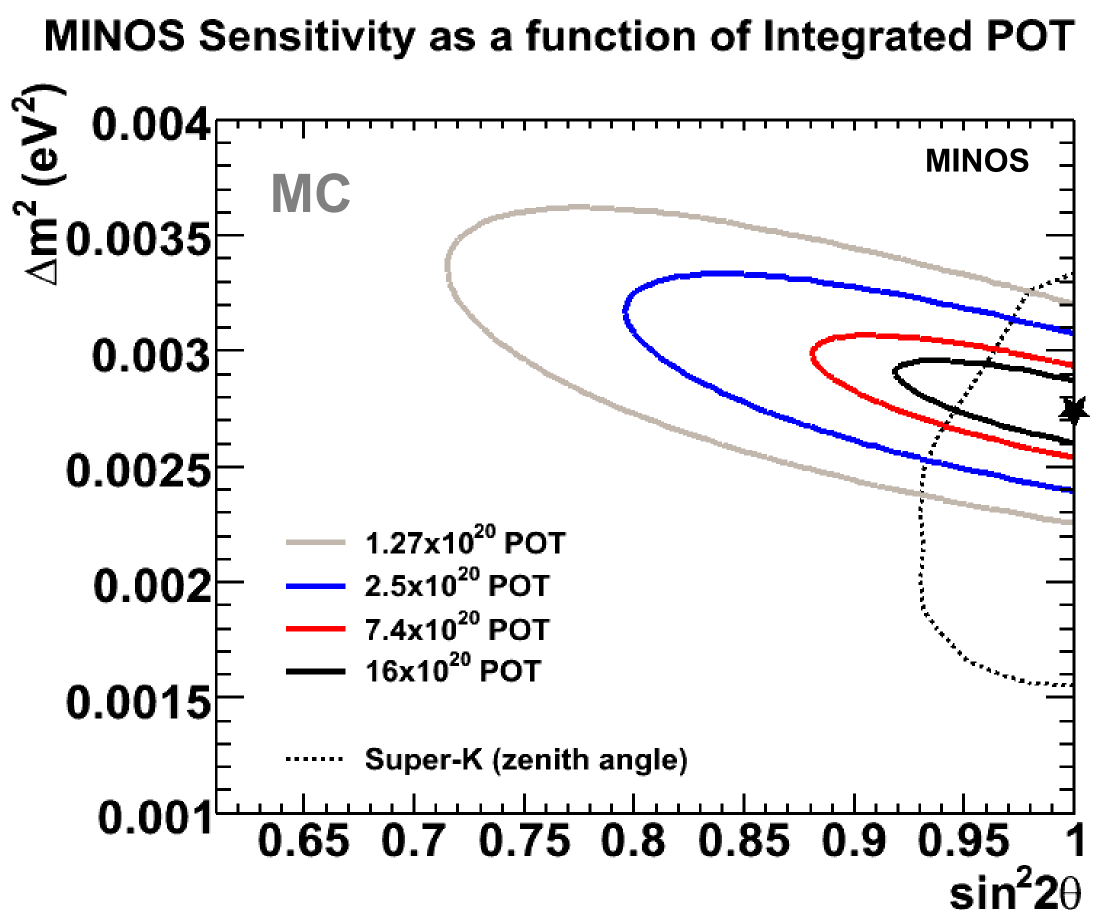
- Systematic shifts in the fitted parameters are computed using MC "fake data" samples for $\Delta m^2 = 2.7\times10^{-3}$ eV^2 and $\sin^2 2\theta = 1.0$
- The uncertainties considered and shifts obtained:

Effect	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 uncertainty (data)	**0.36**	**0.12**

- Magnitude of systematic error is ~40% of statistical error for Δm^2
- Several systematic uncertainties are data driven → improve with more data and study

Projected MINOS Sensitivity

ν_μ Disappearance

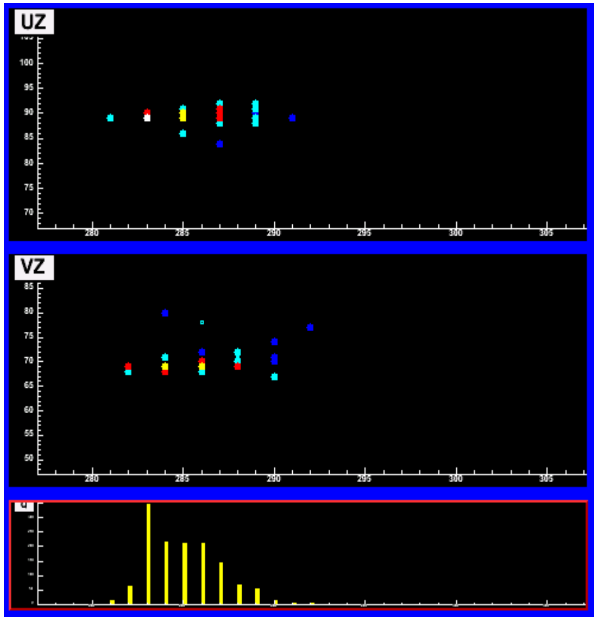


- MINOS sensitivity for different POT
- Current best values used as input:
  - Δm^2_{32}=2.74x10^{-3}eV^2
  - $\sin^2 2\theta_{23}$=1.00
- Contours are 90% C.L. statistical errors only

$\nu_\mu \rightarrow \nu_e$ Oscillation Search

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

ν_e CC Event (MC)



Challenges to ν_e CC signal selection

Steel thickness 2.54cm = $1.44X_0$,

Strip width 4.1cm ~ Molière radius (3.7cm)

typical few GeV ν_e CC shower: 8planes x 4strips

Backgrounds

NC events (primary background) π^0 final states in hadronic system produce EM showers

Intrinsic beam ν_e are identical to signal

High-y ν_μ CC Hadronic shower dominates; muon track is very short or buried

FD: Oscillated ν_τ generally shower-like; τ^- decays to e^- ~20% of the time

ν_e candidate identification

based on compact shower with characteristic EM profile (several methods)

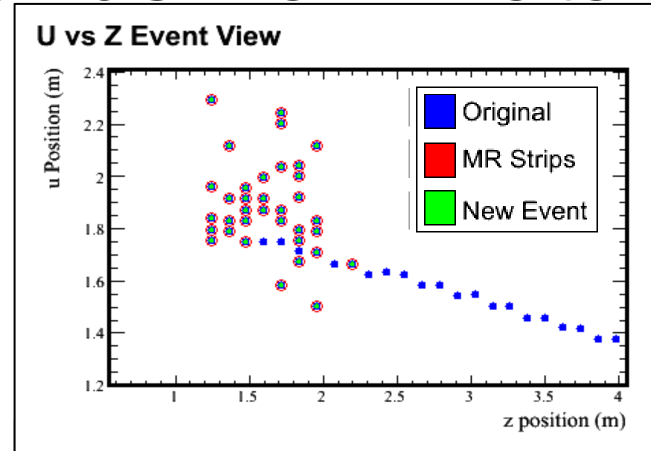
Neural Net selection results

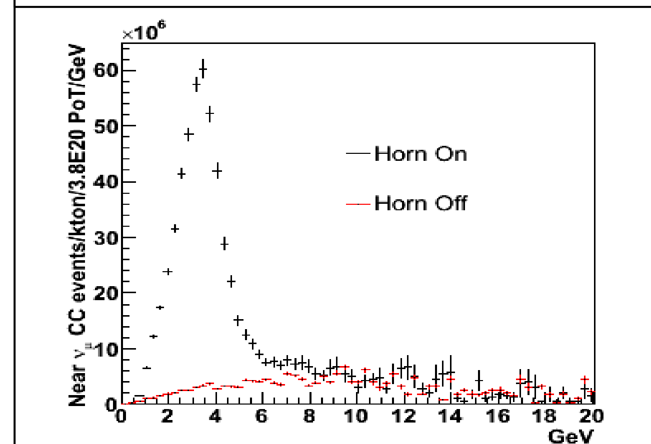
- Oscillation parameters:
  - $\sin^2(2\theta_{13}) = 0.1$
  - $|\Delta m_{32}|^2 = 2.7\times10^{-3}eV^2$
  - $\sin^2(2\theta_{23}) = 1$
- POT = 4×10^{20}

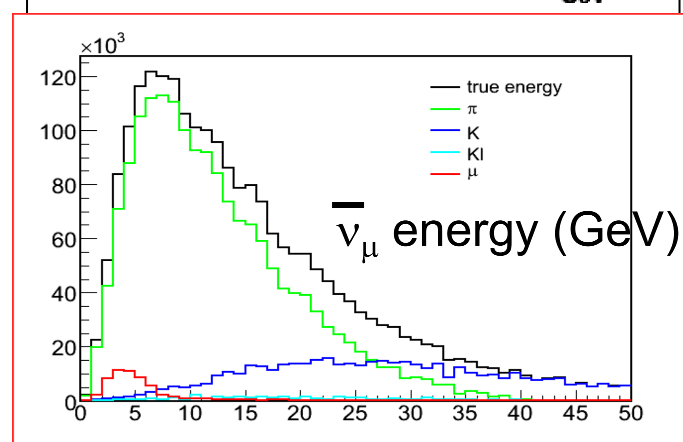
ν_μ CC	NC	ν_e^{beam}	ν_τ CC	Total	ν_e^{osc}
1.4	**9.75**	**2.2**	1.2	14.5	7.3

Estimating ν_e Backgrounds from Data

- Muon removal from CC events to estimate NC contribution
  - Assumes similar hadron multiplicities/shower topologies
  - Requires some corrections from MC
- Use horn-off data to resolve NC, ν_μ CC background components
  - NC component of background is enhanced after event selection
- Estimate $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ component from observed $\bar{\nu}_\mu$ spectrum

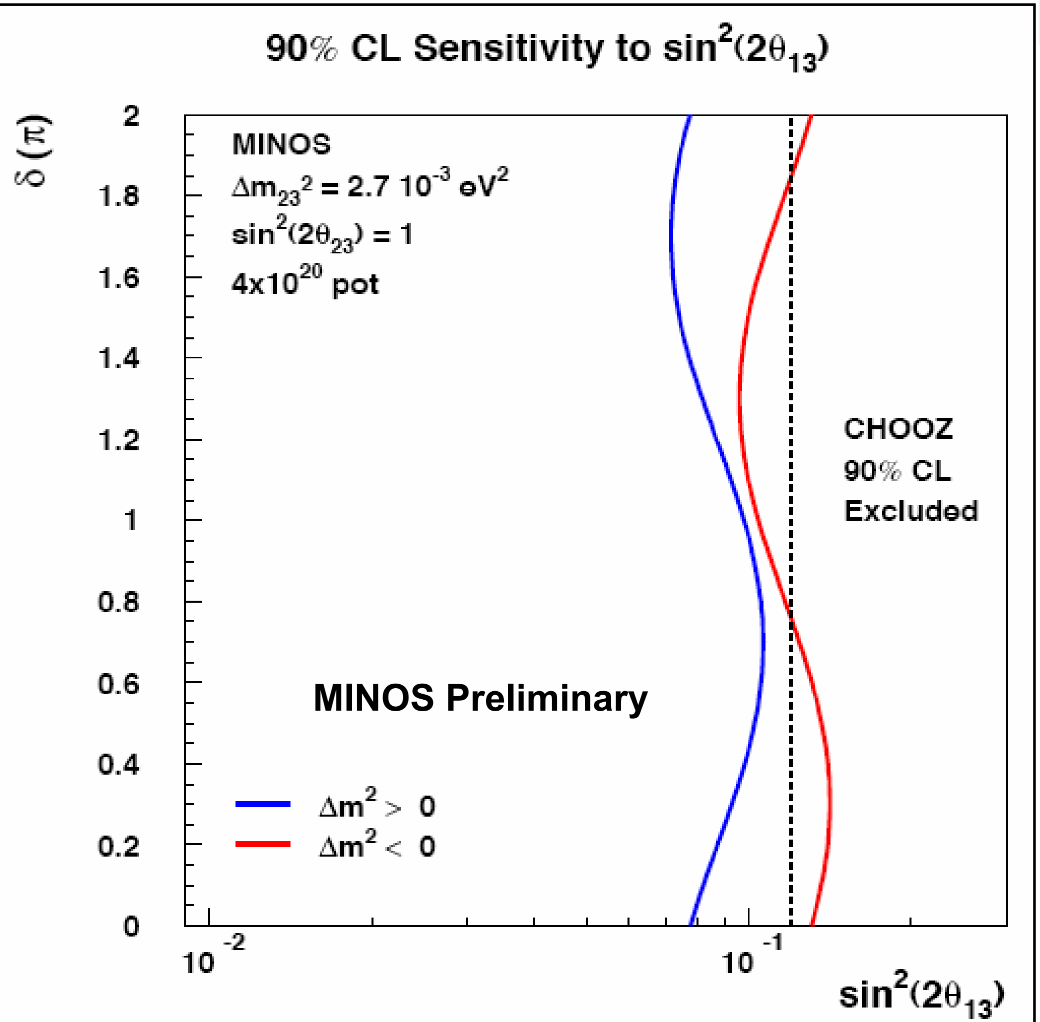






Projected MINOS Sensitivity

ν_e Appearance



- Can improve on current best limit from CHOOZ
- Plot shows δ_{CP} vs $\sin^2 2\theta_{13}$ for both mass hierarchies using MINOS ν_μ CC best fit values and $4\text{x}10^{20}$ POT
  - 10% systematic uncertainty on background included

Summary

- MINOS has completed a ν_μ disappearance analysis of the first year of NuMI beam data
  - Exposure used in analysis: 1.27×10^{20} POT
  - Results are consistent with the oscillation hypothesis with parameters: $$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26} \times 10^{-3}\,\mathrm{eV}^2$$ $$\sin^2 2\theta_{23} = 1.00_{-0.13}$$
  - Constraining the fit to $\sin^2(2\theta_{23}) = 1$ yields: $$\left|\Delta m^2_{32}\right| = 2.74 \pm 0.28 \times 10^{-3}\,\mathrm{eV}^2$$
  - Systematic uncertainties under control and significant improvements expected with data driven studies & more statistics
  - Accepted for publication in PRL (hep-ex 0607088)
- Second year of running is underway. Stay tuned for new results on ν_e appearance, sterile neutrinos,…

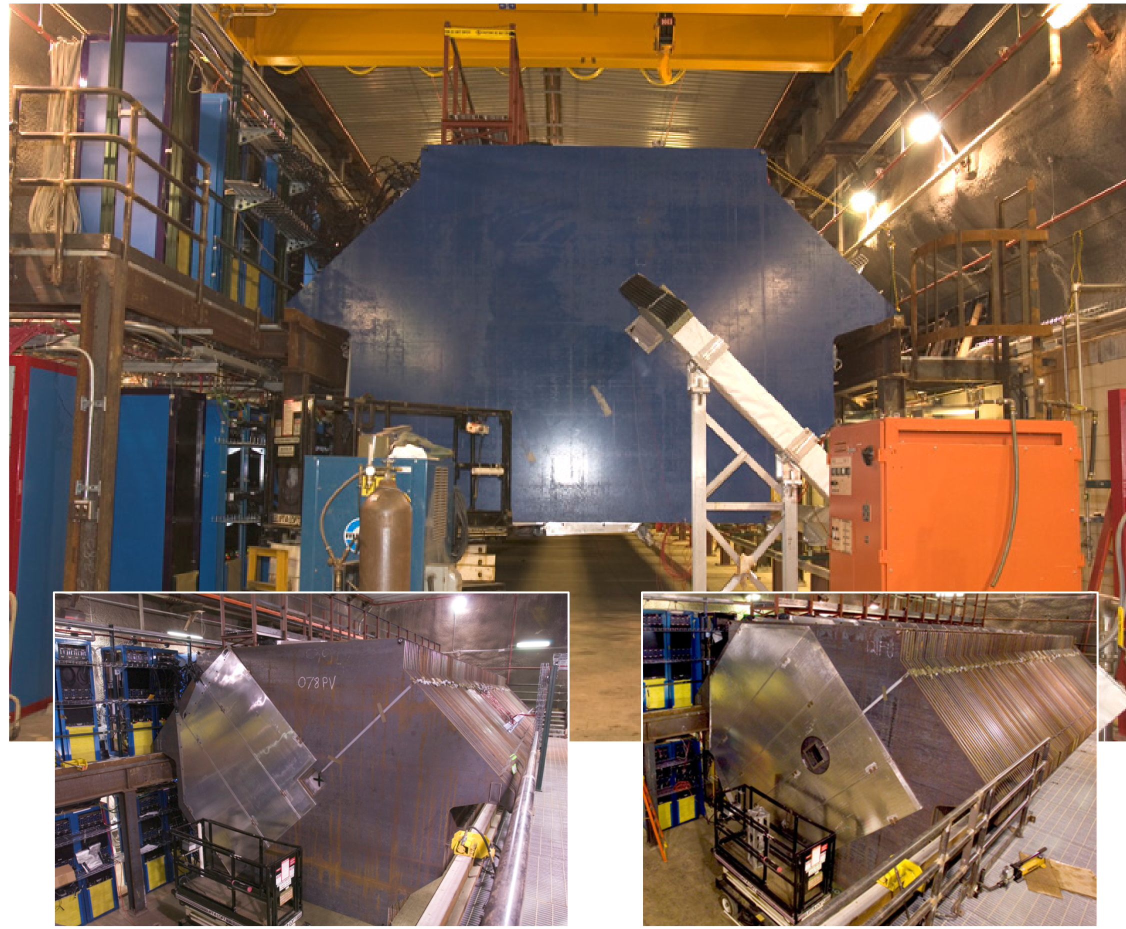
Extras

Near Detector

- Located at FNAL
- 1040m from target
- 103m underground
- 980 ton mass
- 3.8m x 4.8m x 16m
- 282 steel + 153 scintillator planes
- Two distinct sections:

  Front: Calorimeter
  - Every plane instrumented

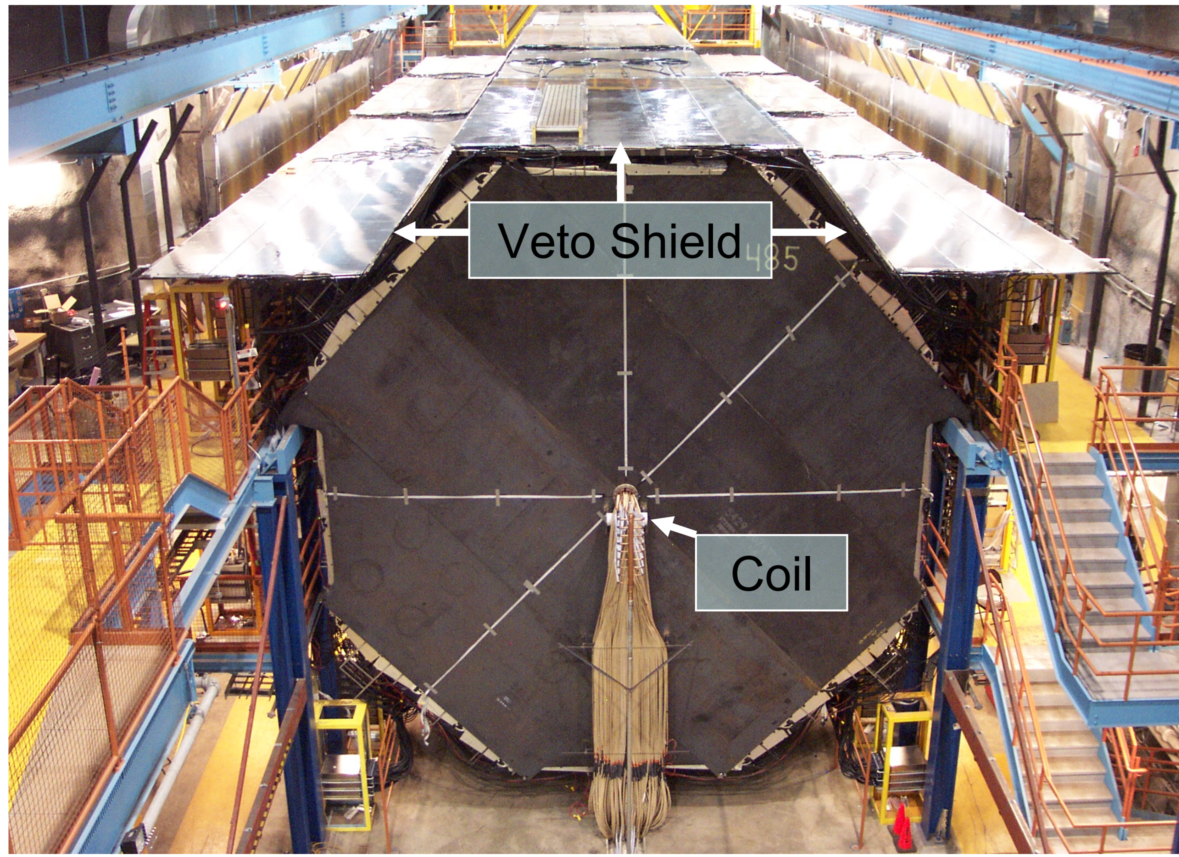
  Back: Spectrometer
  - One in five planes instrumented
- Fast QIE electronics
  - Continuous (19ns) sampling in spill



Plane installation fully completed on Aug 11, 2004

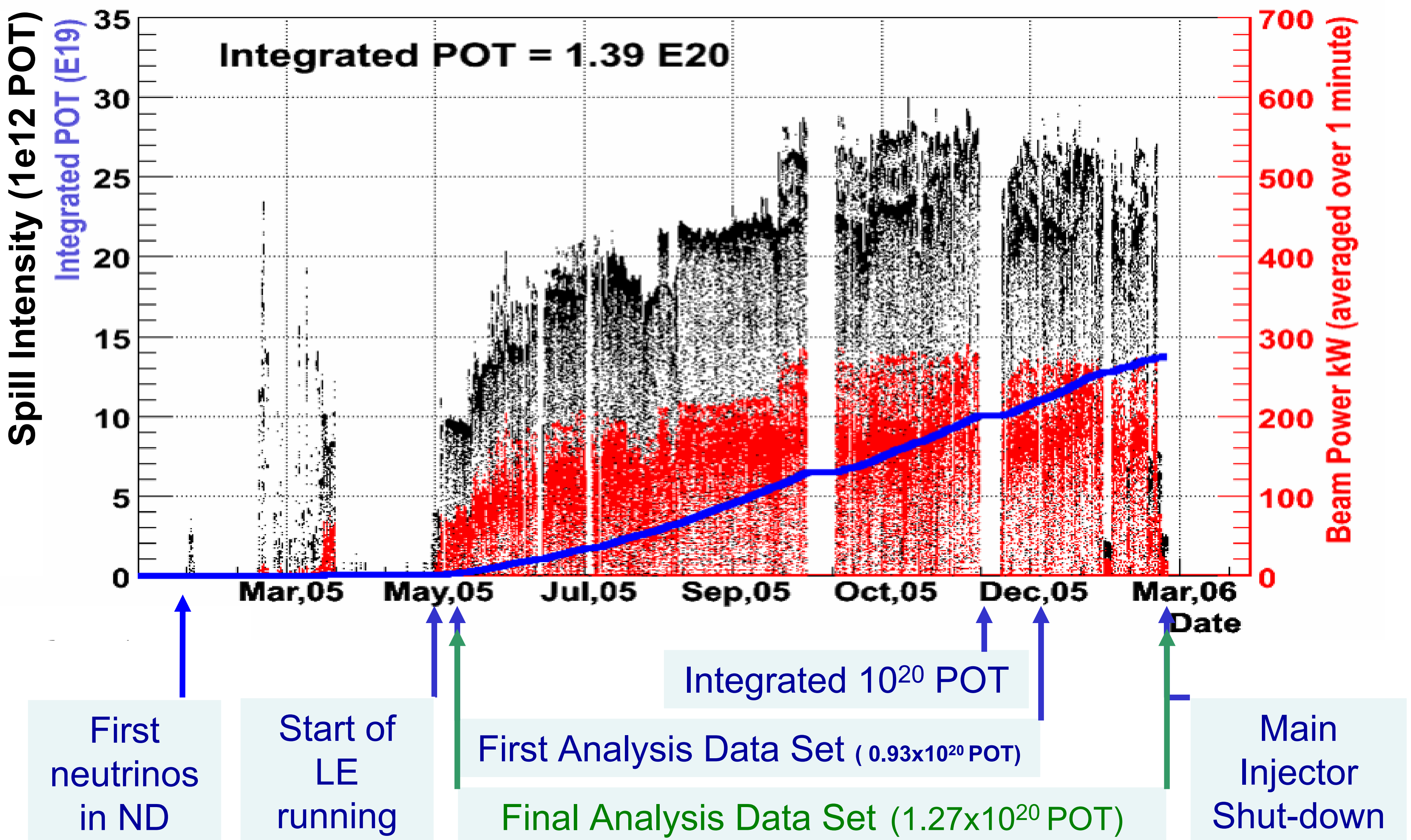
Far Detector

- Located at Soudan mine, MN
- 735 km from target
- 705m underground
- 5.4 kton mass
- 8m x 8m x 30m
- 484 scintillator planes
- 8x optically multiplexed
- VA electronics
- Veto shield for cosmic ray rejection in atmospheric ν analysis
- GPS time stamping to synchronize FD to ND
- Main Injector spill times sent to FD for beam trigger

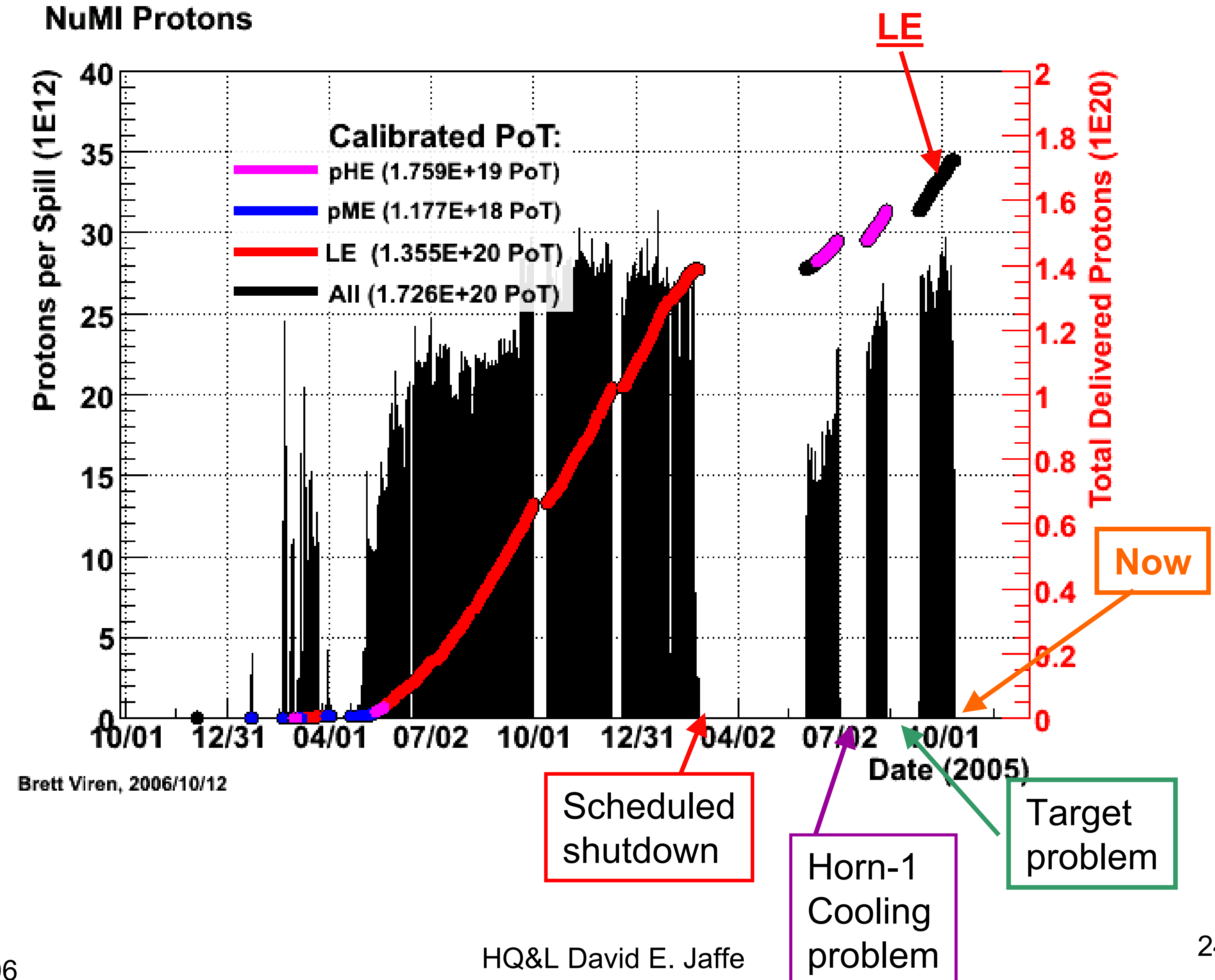


Data taking since ~ September 2001
Installation fully completed in July 2003.

1st Year of NuMI Running

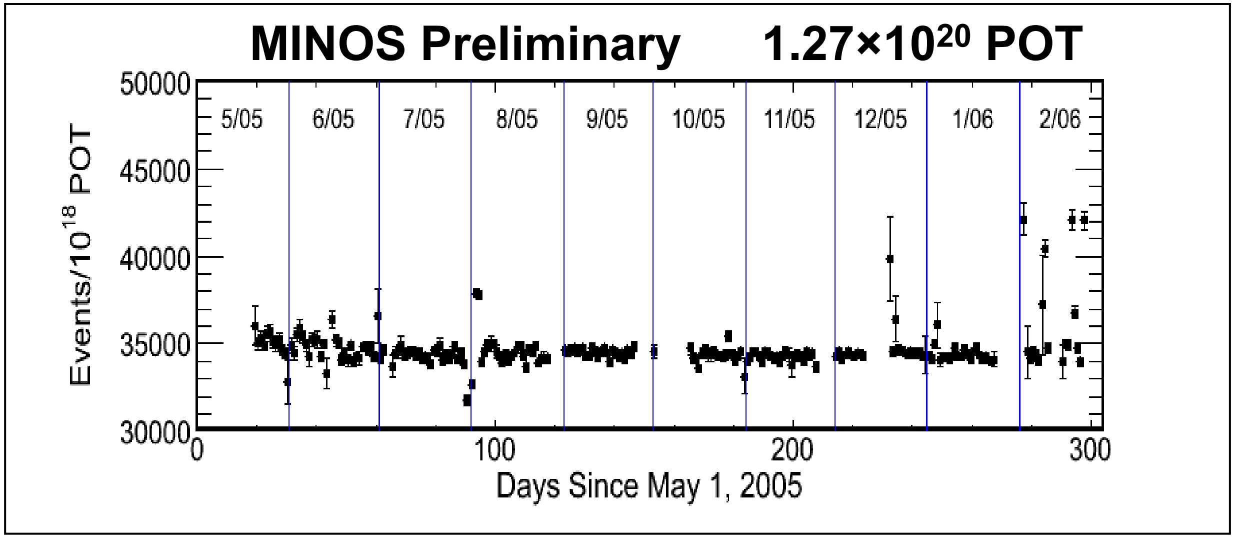


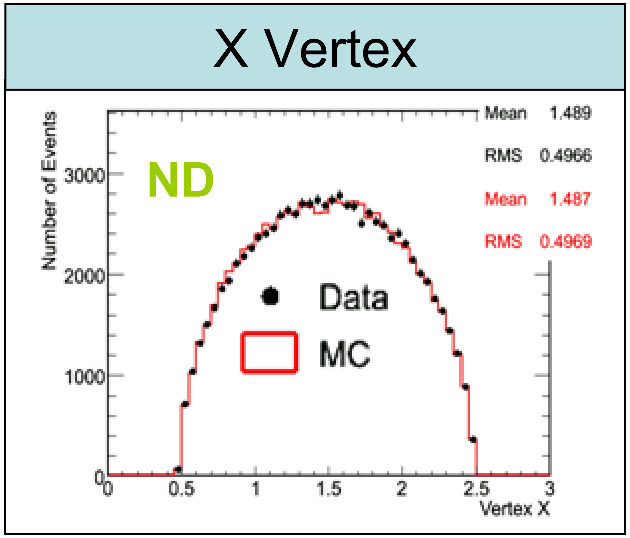
Accumulated protons on NuMI target

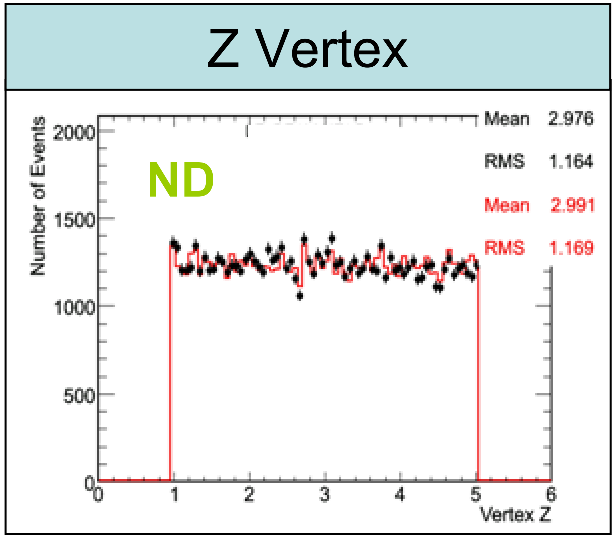


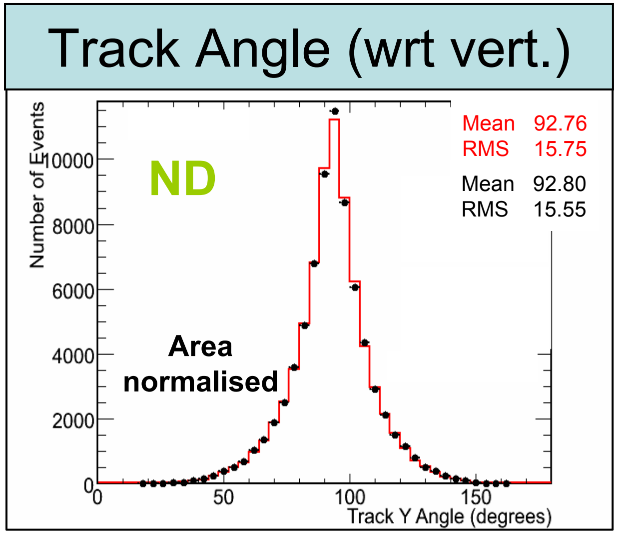
Near Detector Distributions

- Event rate is flat as a function of time
  - Horn current scans on July 29 – Aug 3
  - Different tunes in Feb
- Acceptance well reproduced
- Track angle w.r.t. vertical exhibits characteristic -3° to Soudan

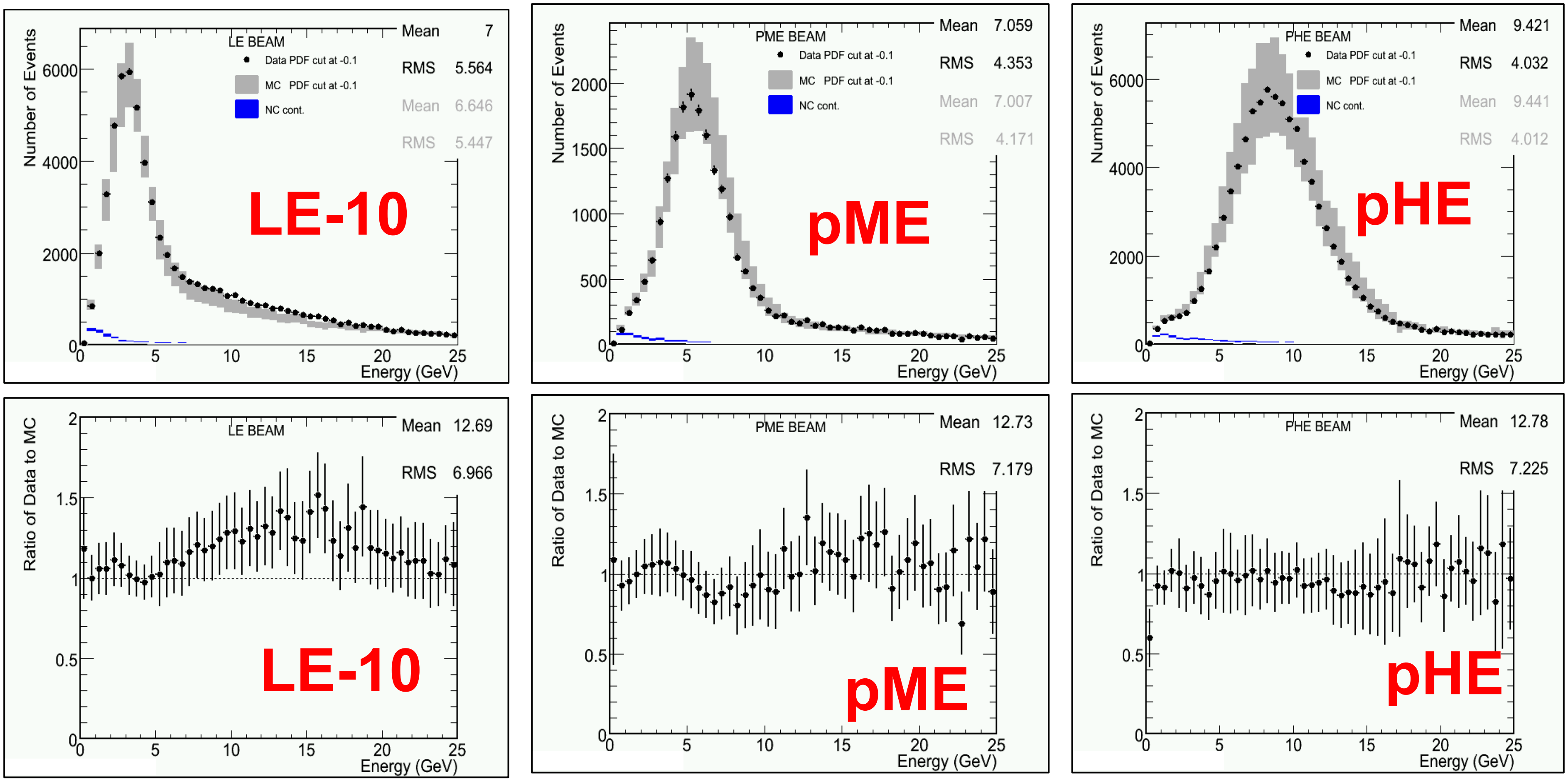








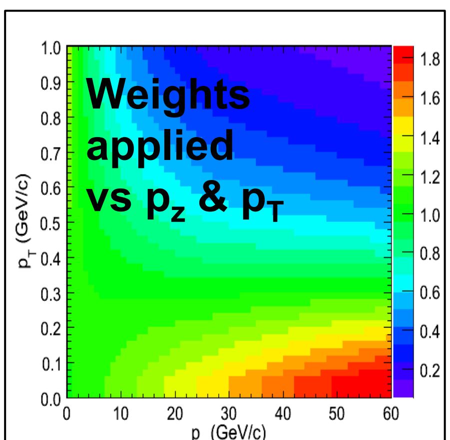
Near Detector Energy Spectra

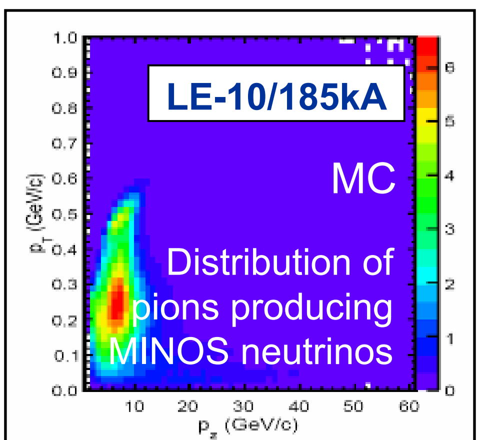


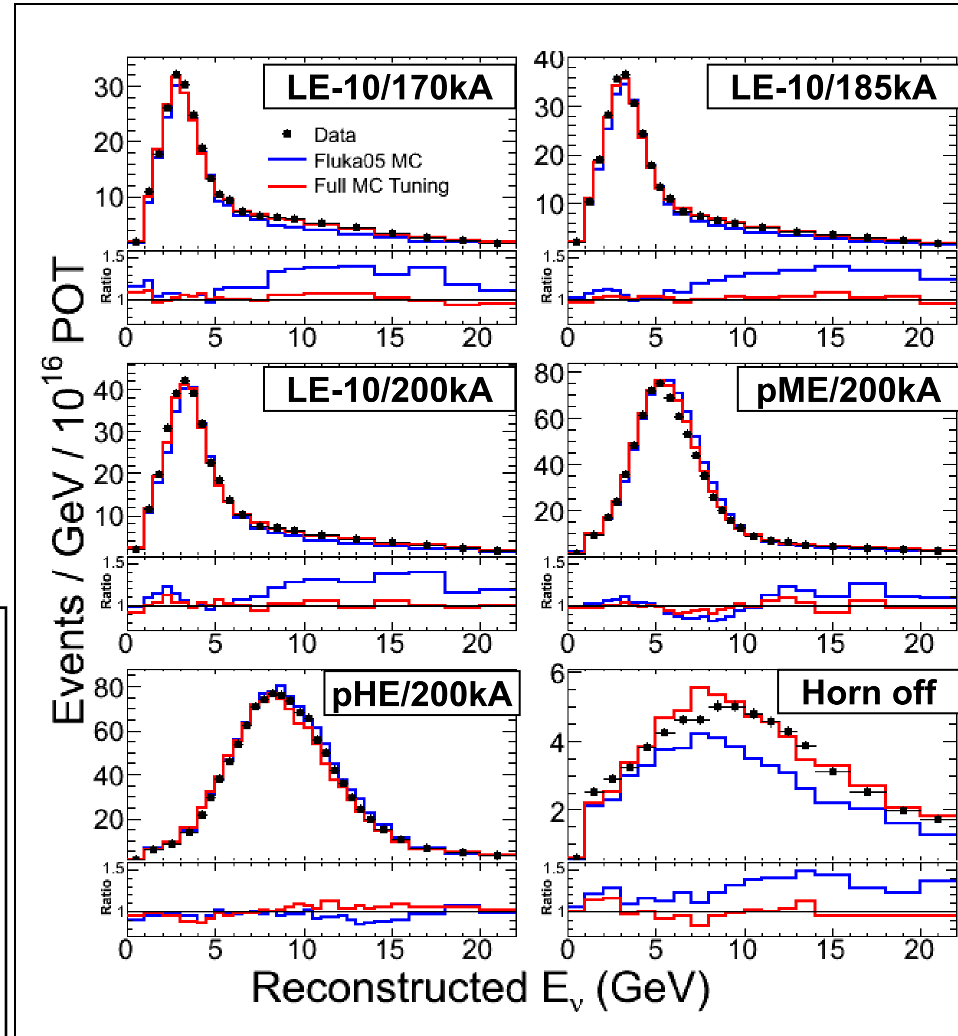
Error envelopes shown on the plots reflect uncertainties due to cross-section modelling, beam modelling and calibration uncertainties

Hadron Production Tuning

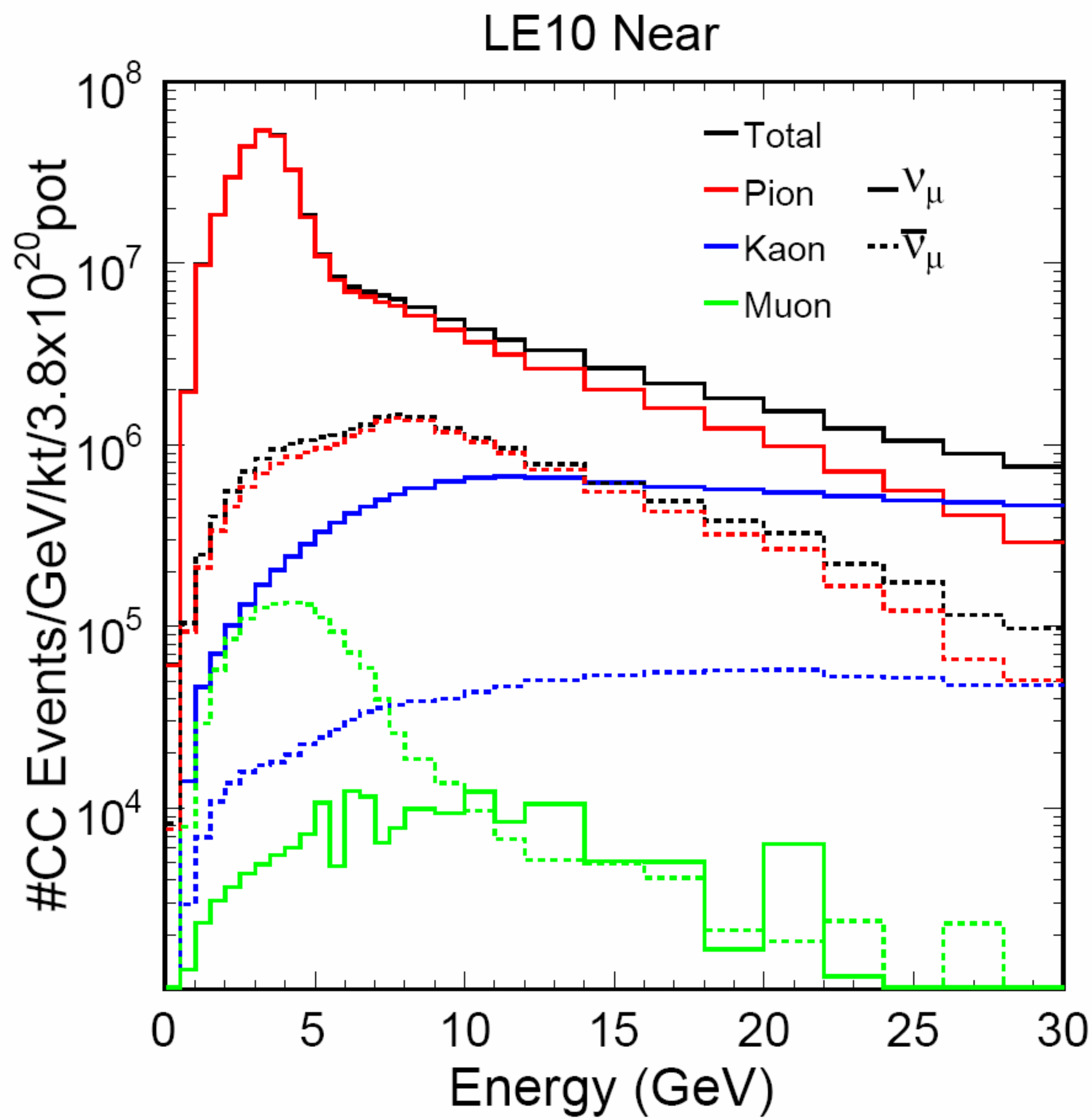
- Parameterize Fluka2005 prediction as a function of neutrino parent x_F and p_T
- Perform fit which reweights parent x_F and p_T to improve data/MC agreement
- Horn focusing, beam misalignments included as nuisance parameters in fits
- Small changes in x-section, neutrino energy scale, NC background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







Beam Composition (MC)

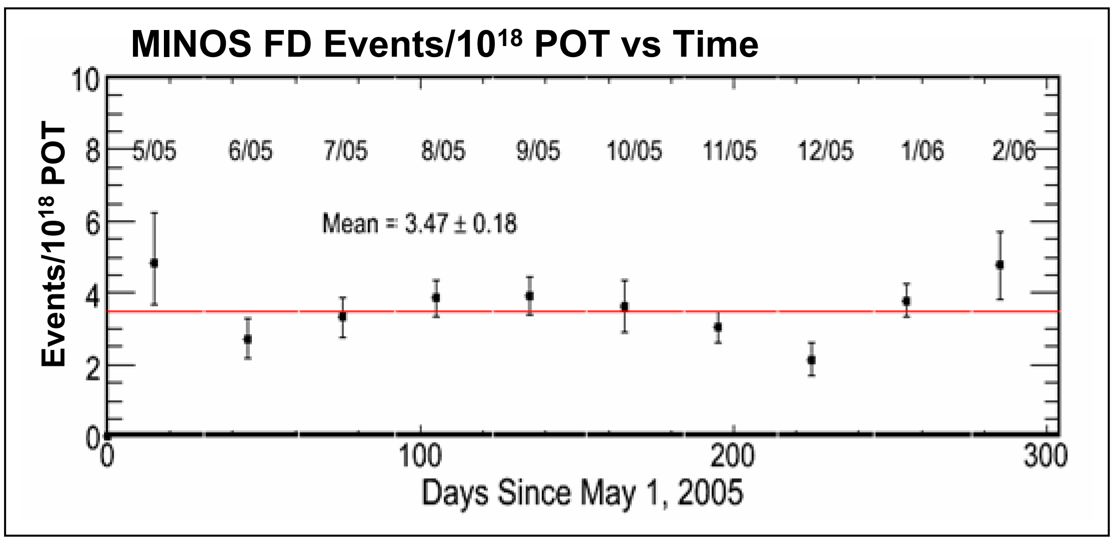


Composition of Charged-Current (CC) Events

- 92.9% ν_μ
- 5.8% $\bar{\nu}_\mu$
- 1.2% ν_e
- 0.1% $\bar{\nu}_e$

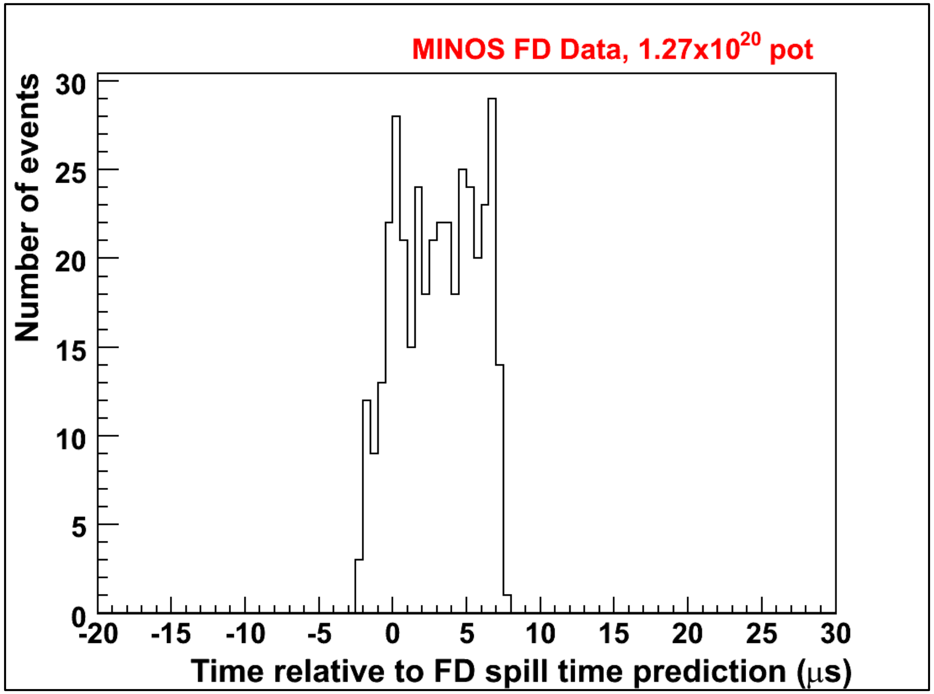
Selecting Far Detector Beam Events

- LE-10 configuration running from May 20th 2005 to March 3rd 2006
  - Total integrated POT: 1.27×10^{20}
  - Far Detector live time: 98.9% (POT weighted)
- Several software triggers in DAQ to read out FD activity:
  - 4/5 plane trigger, minimum energy trigger, beam spill trigger
- Beam spill trigger reads out all activity in 100μs around spill signal (10μs duration)
  - Possible due to GPS time stamping at ND & FD
  - Event rate shows no time dependence



Selecting Far Detector Beam Events

- In addition to applying cut on event selection parameter apply cuts to reject cosmic ray (CR) background
  - 53° cut around beam axis
    - Beam events have distinctive topology - tracks point to FNAL
  - Demand that: -20μs < (event time – spill signal) < 30μs
    - Timing of neutrino candidates consistent with spill signal



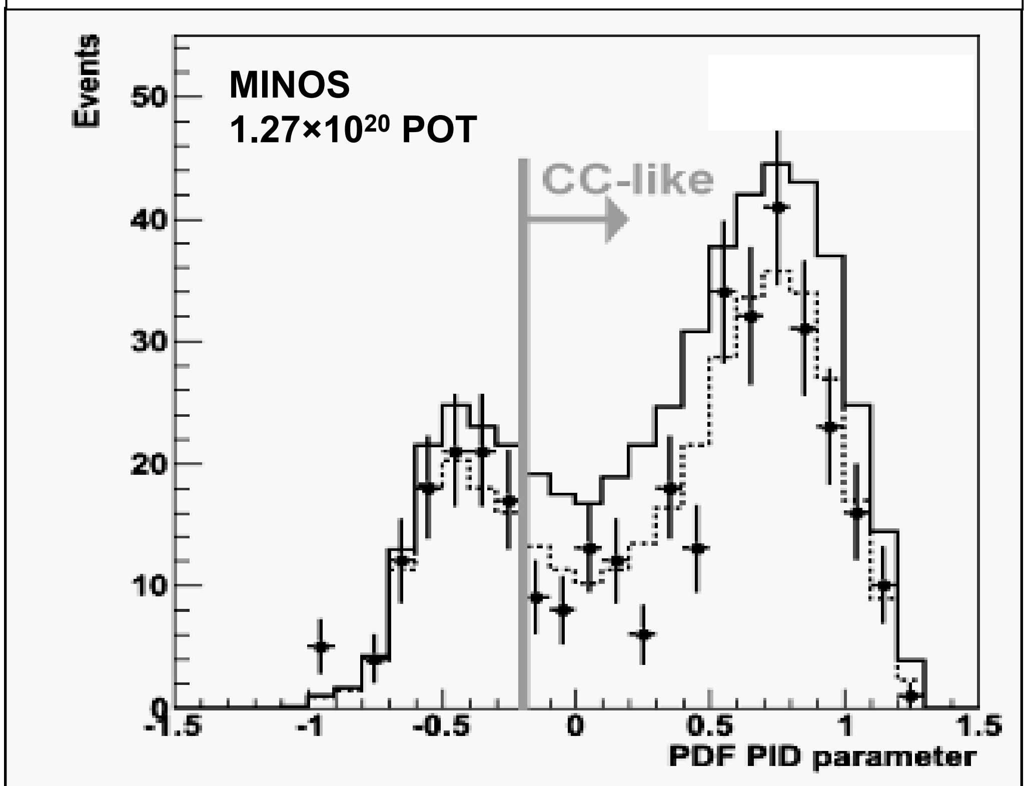
Two CR background estimates:

- Sideband analysis of region outside timing cut using full 1.27×10^{20} POT sample
  → upper limit of 0.5 events
- Using fake triggers in anti-coincidence with spill
  - 2.6M triggers
    → no events selected
    → upper limit of 0.5 events

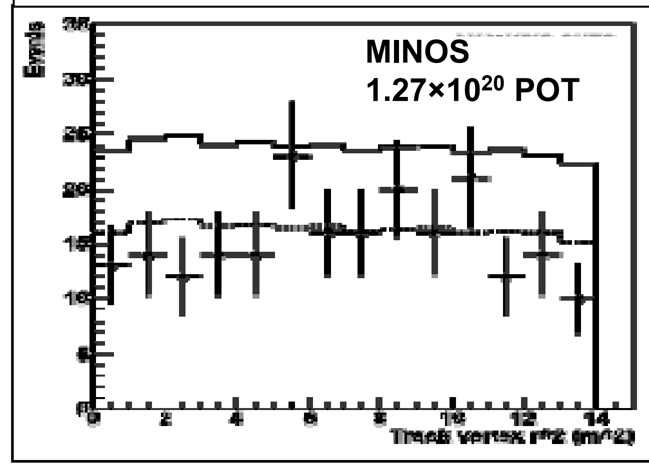
Far Detector Distributions

- Predicted no oscillations (solid)
- Best fit (dashed)

Event Classification Parameter



Track Vertex r^2 (m^2)



$y = E_{shw}/(E_{shw}+P_{\mu})$