Neutrino Oscillation Results from MINOS

Kregg Arms – University of Minnesota

for the MINOS Collaboration

INFO ’07 Workshop – July 2, 2007

MINOS

Overview

Detector & beam

ν_μ disappearance analysis

Neutrino time-of-flight

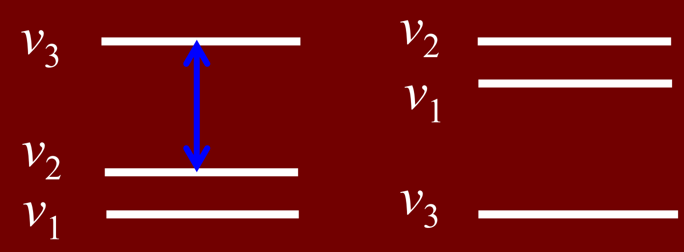
Prospects

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

MINOS physics goals

- **Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis**
  - **Measure precisely $|\Delta m^2_{32}|$ & $\sin^2 2\theta_{23}$**
    - ⇨ **PRL 97, 191801 (2006)**
  - Search for / constrain exotic phenomena
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations
- Compare ν, $\overline{\nu}$ oscillations
  - Test for CPT violation
- Neutrino/nucleon interaction physics
- Atmospheric neutrino oscillations
  - ⇨ PRD 75, 092003 (2007)
  - ⇨ PRD 73, 072002 (2006)
- Cosmic rays
  - ⇨ hep-ex/0705.3815
  - ⇨ 10 papers to ICRC 2007 (Mexico City now!)

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



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

Useful Approximations

ν_μ disappearance (2 flavors):

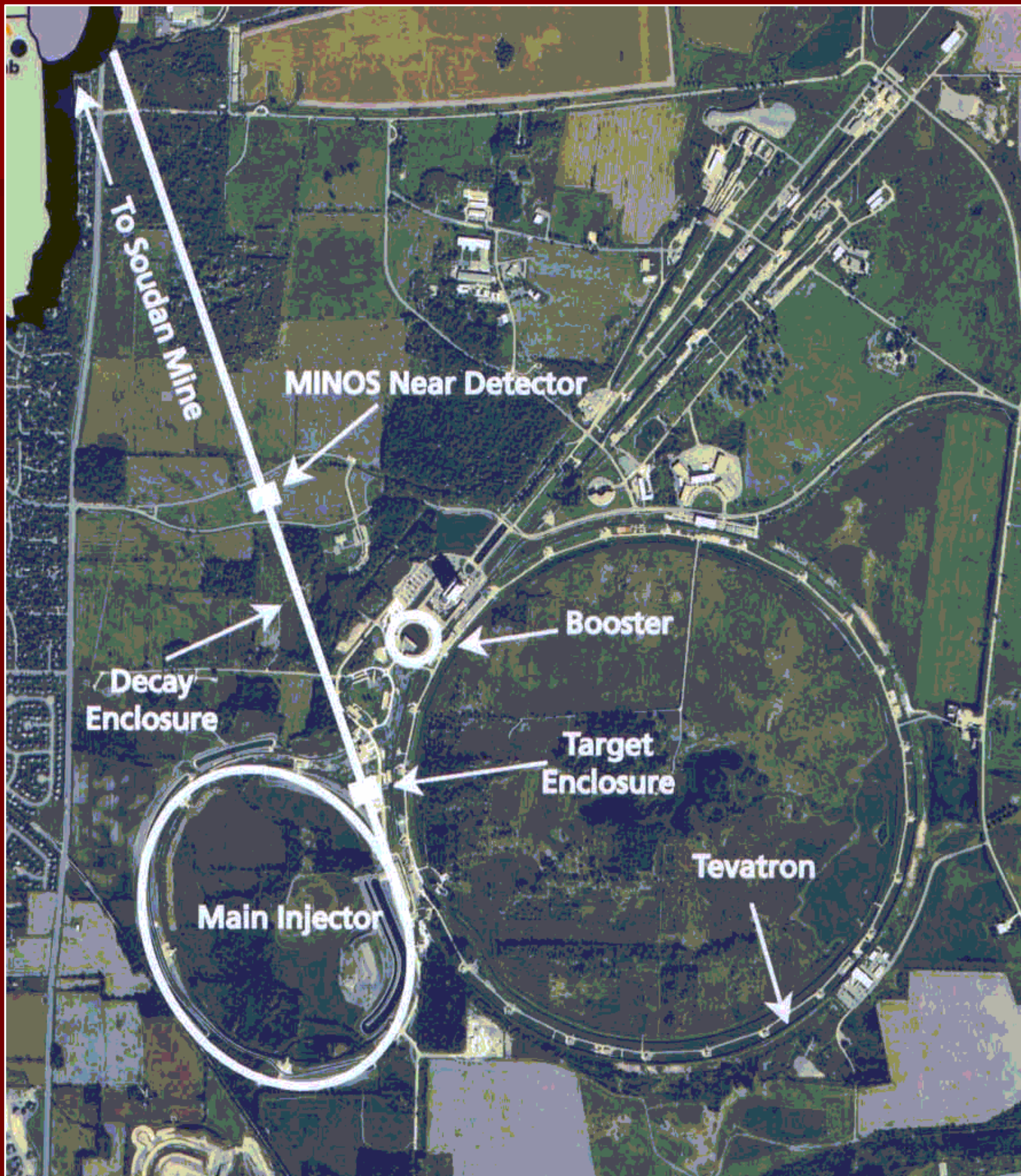
$$P(\nu_\mu \rightarrow \nu_\tau) = 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} \mathbf{L}/\mathbf{E})$$

ν_e appearance:

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

where **L**, **E** are experimental parameters & θ_{23}, θ_{13}, Δm^2_{32} are to be determined

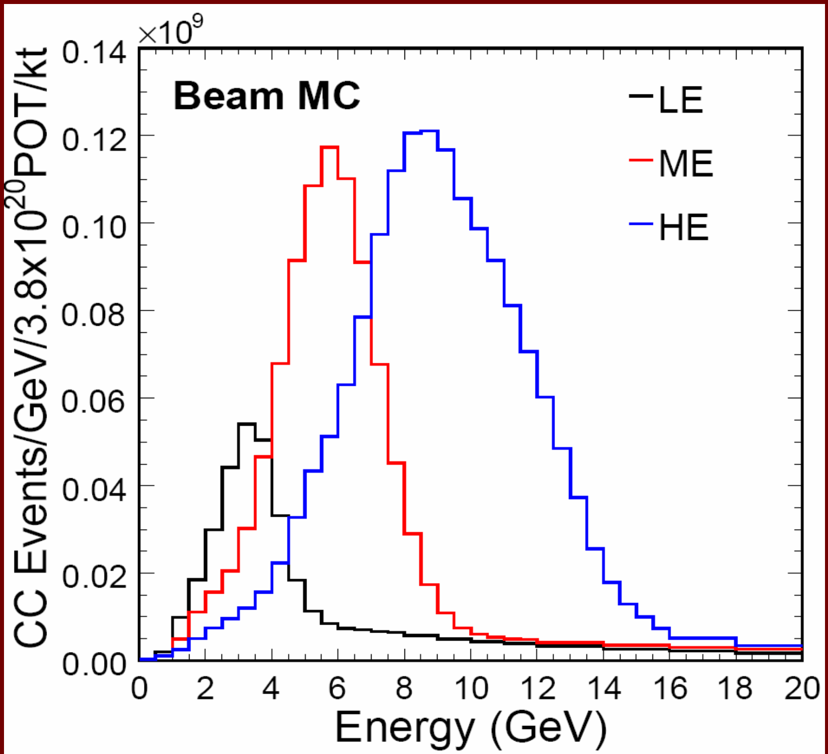
The NuMI facility

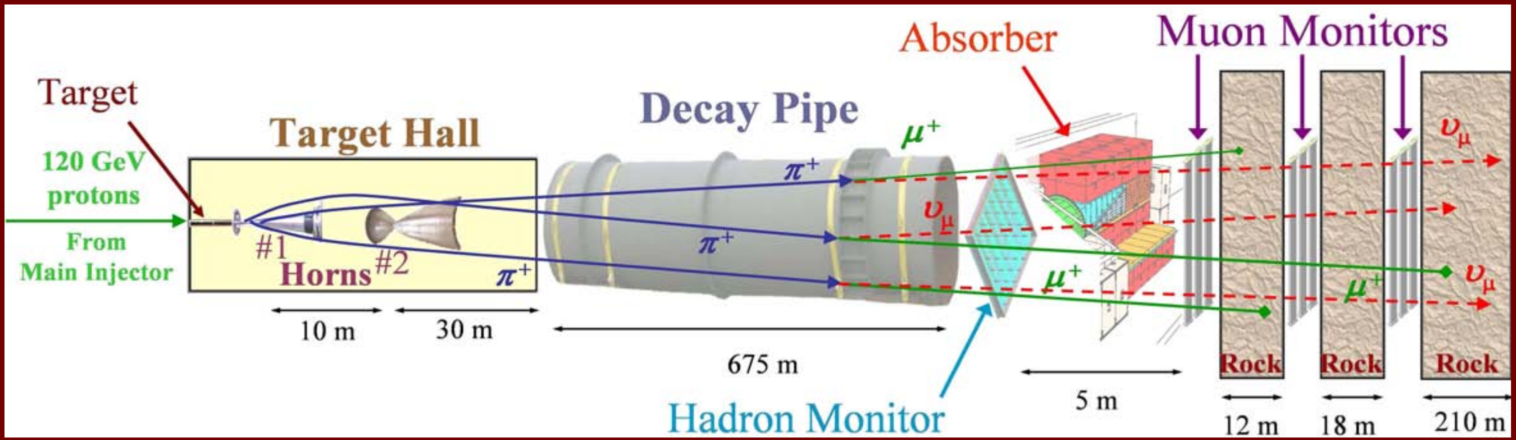


- 120 GeV protons from the Main Injector strike the MINOS target
- Main Injector can accept up to 6 Booster batches/cycle
- 5 – 6 batches for NuMI
- Typical 2.4×10^{13} protons/pulse
- 0.4 MW average power
- Single turn extraction
  - 10μs pulse every ~2.4s

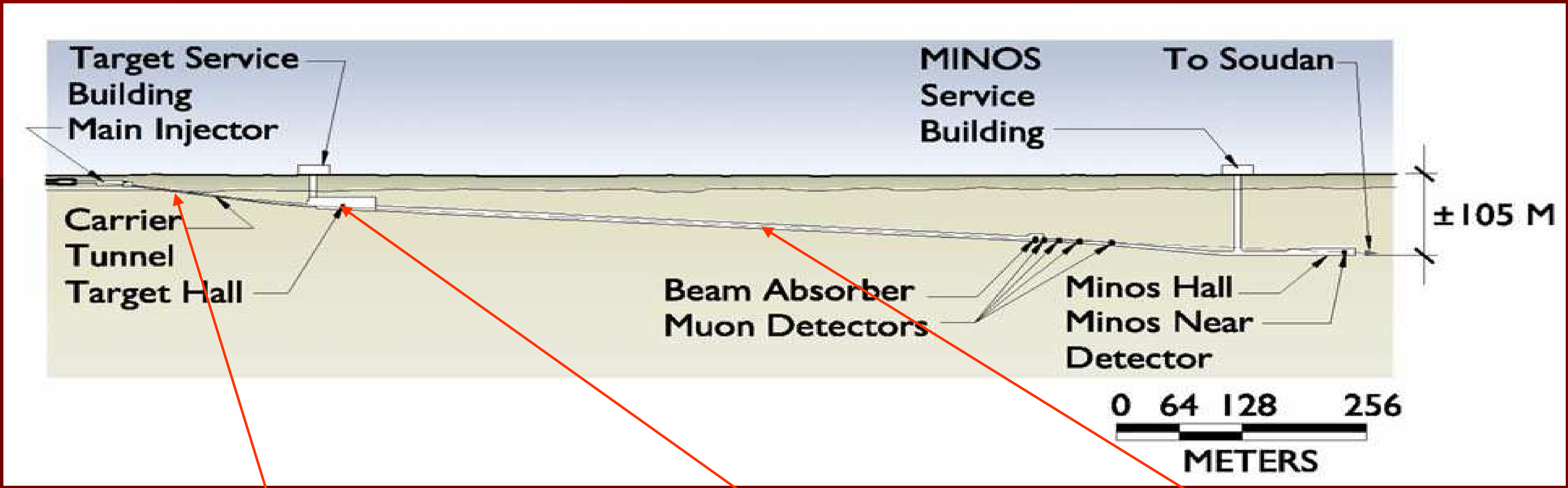
NuMI beam production

- Neutrino beam produced from 120 GeV protons striking a graphite target
  - π and K decays produce a 98.5% pure ν_μ beam
- Continuously adjustable ν energy spectrum by moving the target position relative to first horn:
  - Most data taken in the low energy "LE-10" position, optimum for measuring the oscillation parameters
  - Some running in higher energy positions for beam tuning and systematics studies





NuMI beamline



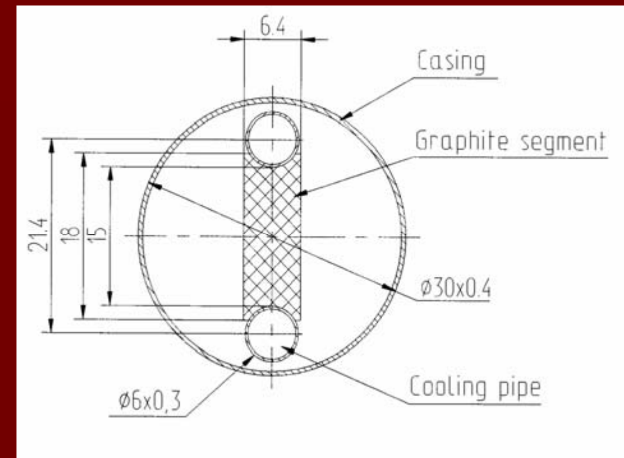
Primary proton line

Target hall

Decay pipe

NuMI target


NuMI target with water cooling lines



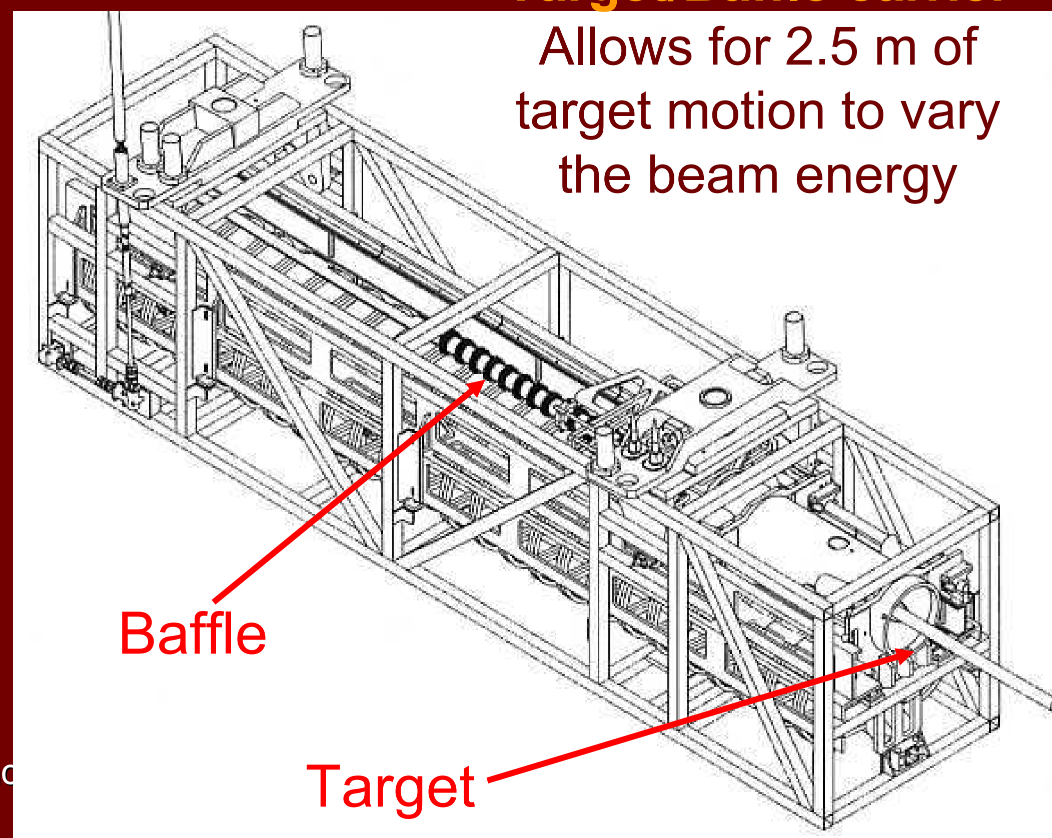
Target:

- 47 segments of graphite of 20 mm length and 6.4×15 mm^2 cross section
- 0.3 mm spacing between segments, for a total target length of 95.4 cm

Baffle:

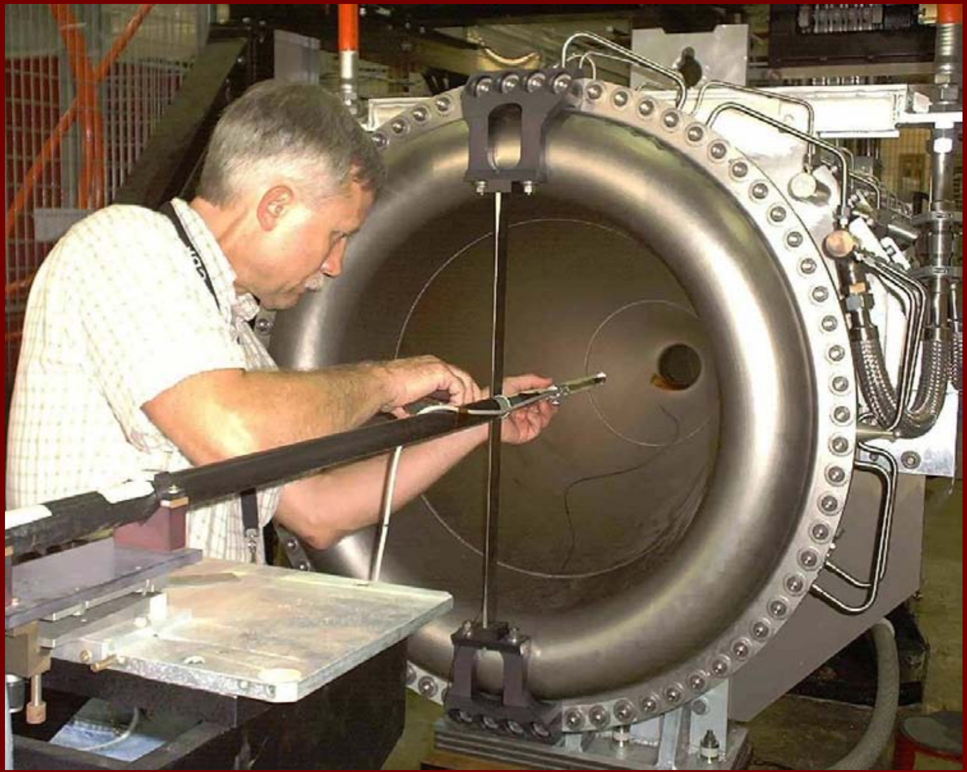
- Protects beam-line components from beam mis-steering
- 150 cm long graphite rod with 11mm diameter hole

Target/Baffle carrier

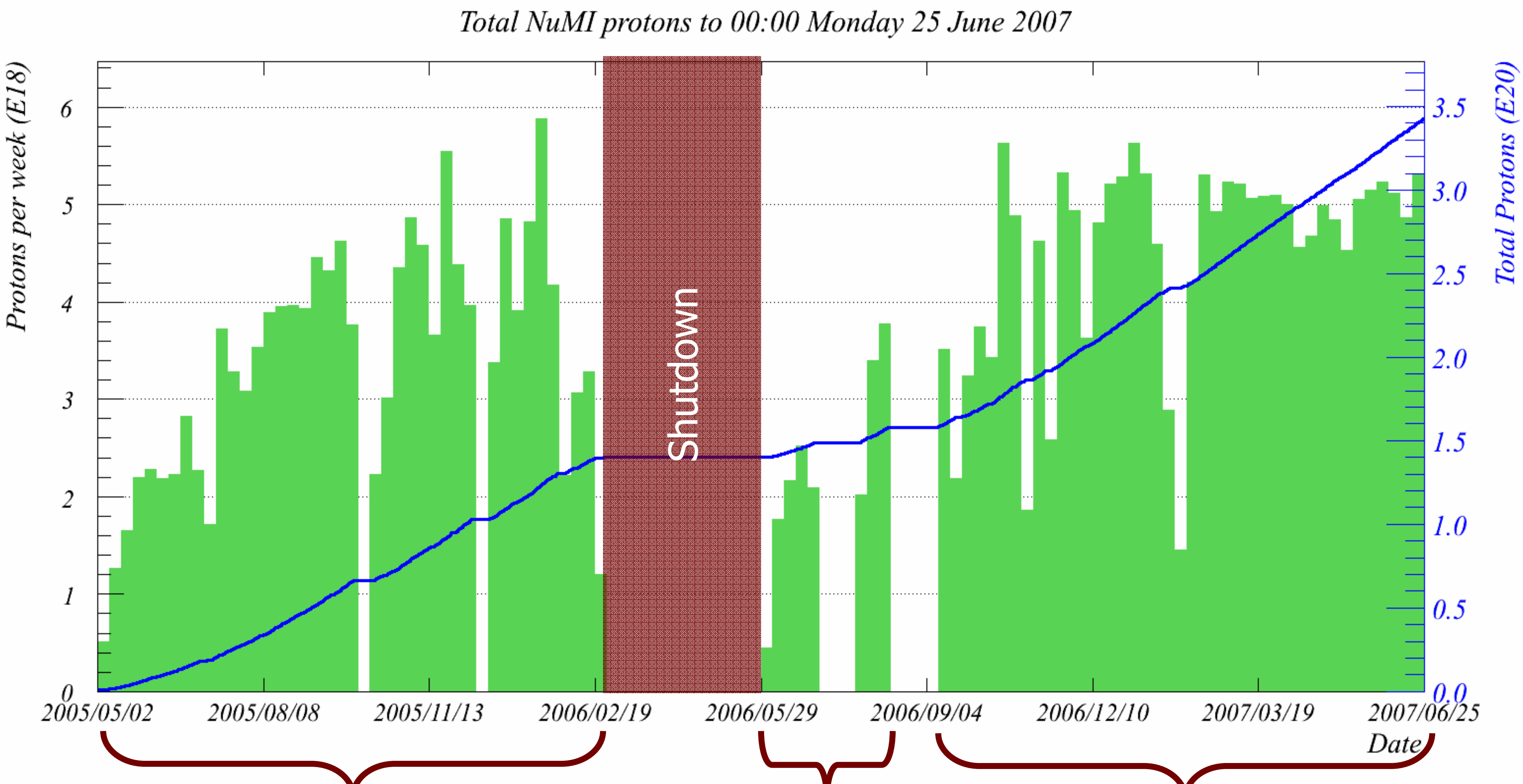


Focusing horns

- Two parabolic focusing horns connected in series.
- Nominal horn current at 200 kA
- Produces 3.0 Tesla peak field



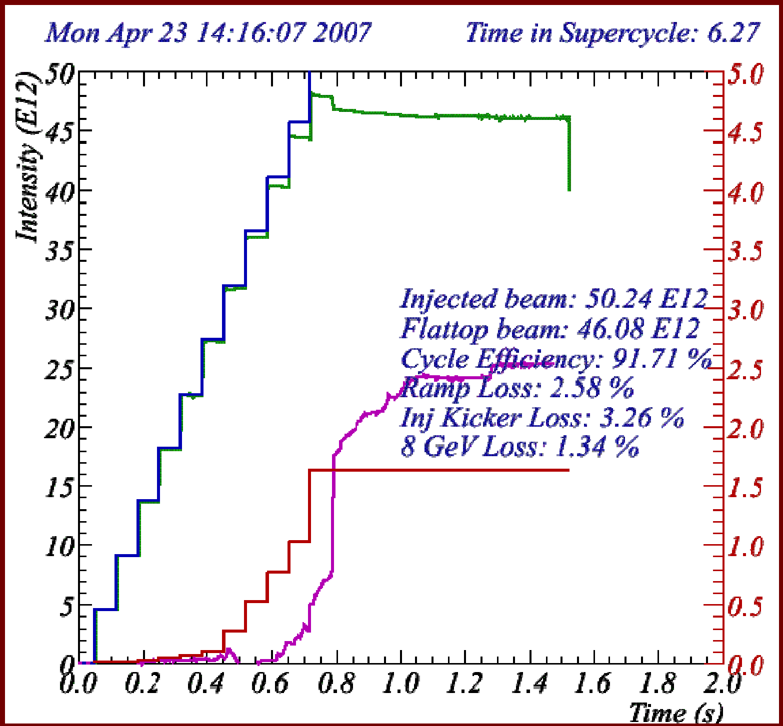
2^{nd} year of MINOS running



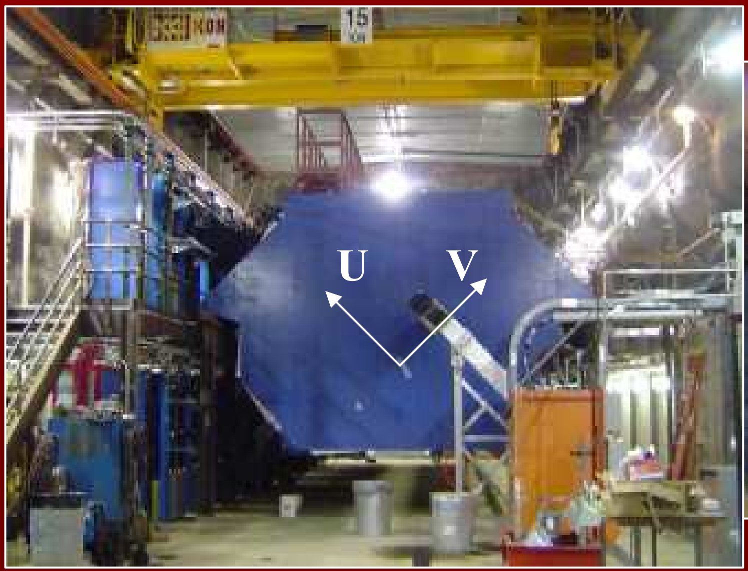
1st year of running (published dataset: 1.27×10^{20} POTs)	Higher energy runs	2nd year of running (99+% FD live time!)

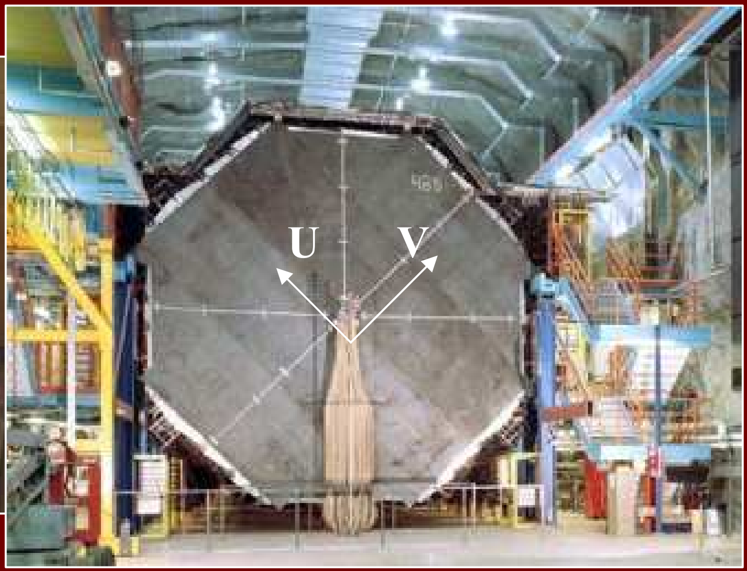
MI intensity improvements: slip stacking

- MI currently running in "2+5" slip stacking
  - 2 MI bunches for pbar
  - 5 MI bunches for NuMI
- AD demonstrated "2+9" slip stacking
  - 2 MI bunches for pbar
  - 9 MI bunches for NuMI
- New record for beam in the MI set in April
  - **4.608×10^{13} POT** with good transport efficiency
  - Beam delivery limited to 4.0×10^{13} POT… brief testing will begin before shutdown with a spare target in-hand – *2.4×10^{13} POT typical up to now*
- AD plans "2+9" as default after the shutdown



MINOS Detectors



Near Detector

0.98 kton

1.04 km from target (FNAL)

100 m underground

$3.8 \times 4.8 \times 15$ m^3

282 steel planes

153 scintillator planes

Iron and Scintillator tracking calorimeters

(functionally identical detectors)

magnetized steel planes B ≈ 1.2T

1×4.1 cm^2 scintillator strips

Multi-anode PMT readout

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

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

Far Detector

5.4 kton

735.3 km from target (Soudan)

705 m underground

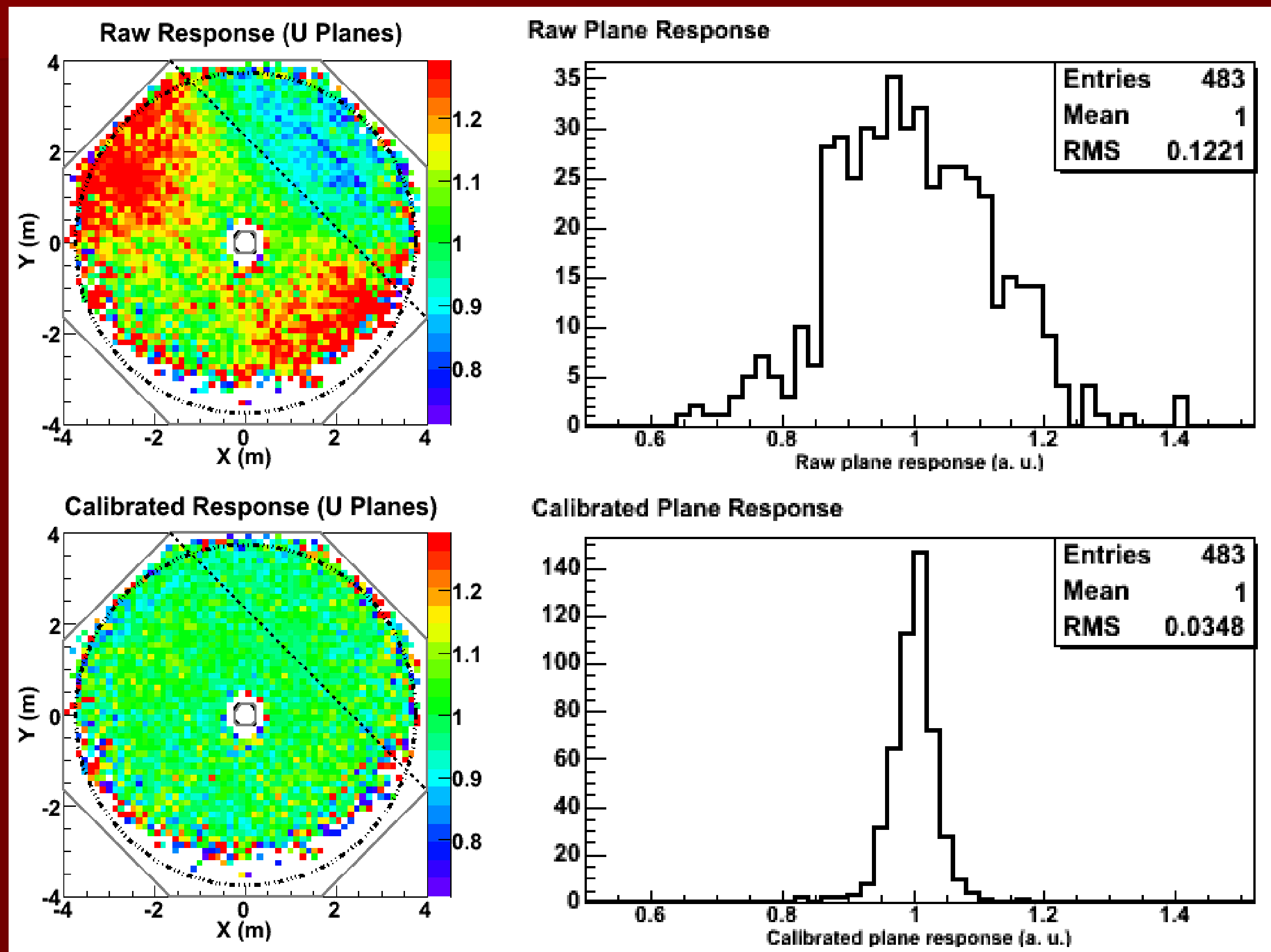
$8 \times 8 \times 30$ m^3

486 steel planes

484 scintillator planes

MINOS Calibration system

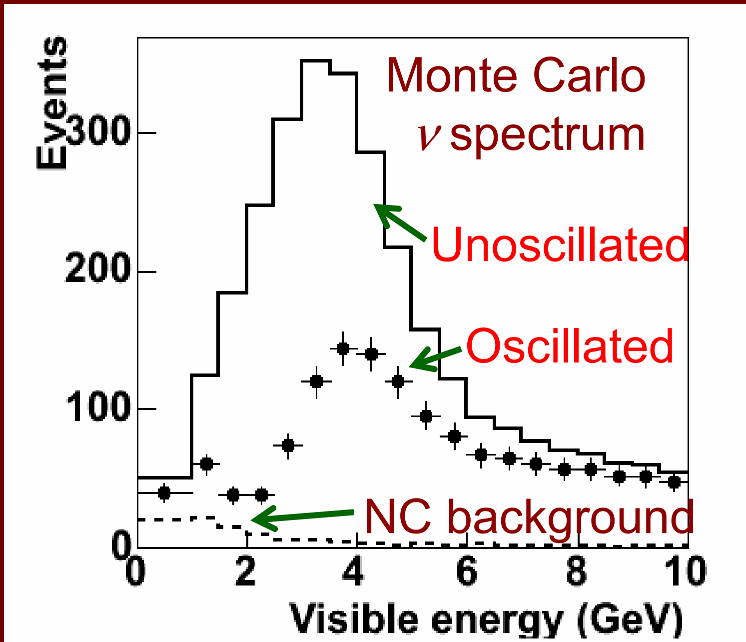
- Calibration of ND and FD response using:
  - Light Injection system (PMT gain)
  - Cosmic ray muons (strip to strip and detector to detector)
  - Calibration detector (overall energy scale)
- Energy scale calibration:
  - 1.9% absolute error in ND
  - 3.5% absolute error in FD
  - 3% relative

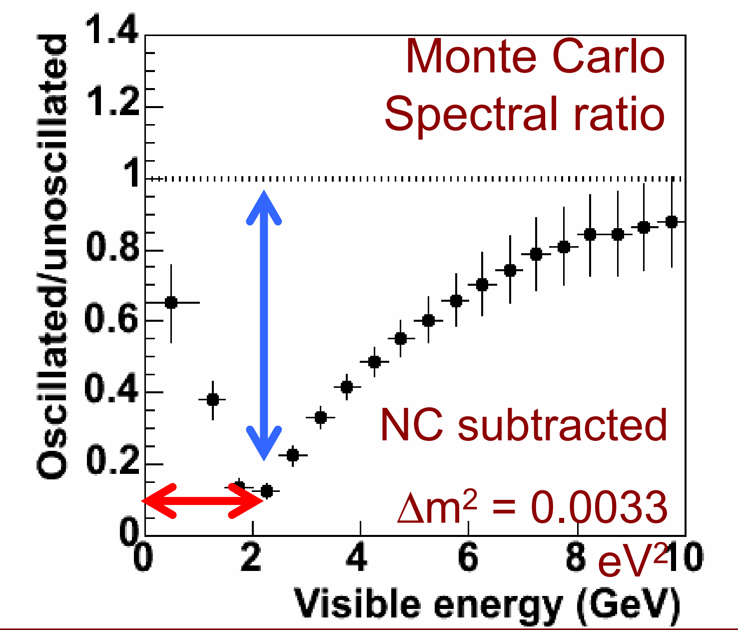


Two-detector ν disappearance

- Produce a high intensity beam of neutrinos at Fermilab
- Measure the energy spectrum at both the near detector & the far detector
- Extrapolate the near spectrum to the far baseline with acceptance corrections (unoscillated)

✓ Common uncertainties in cross-sections and neutrino flux largely cancel

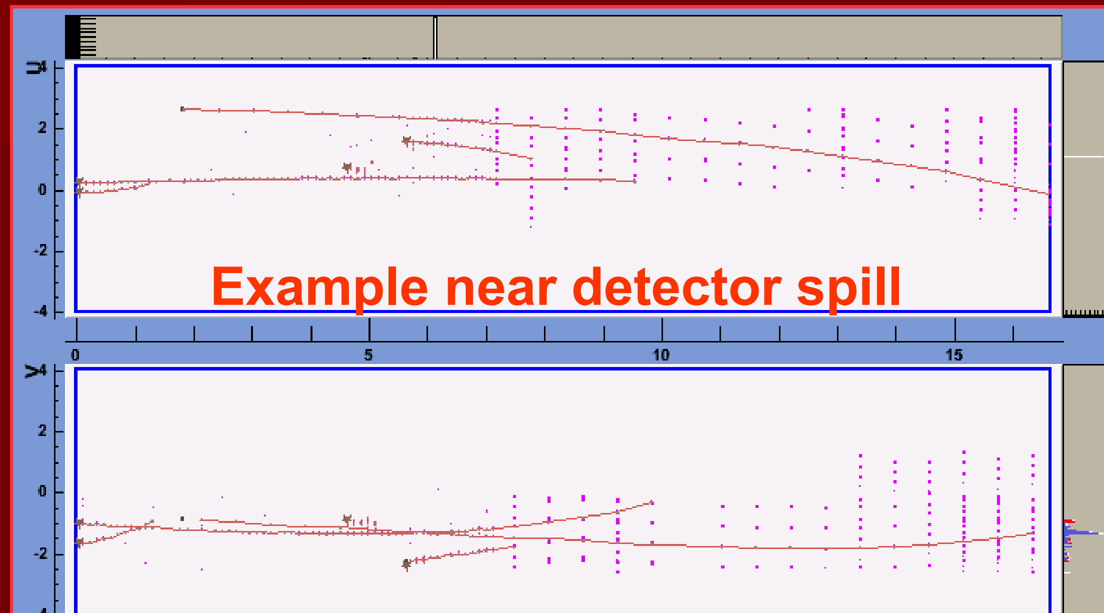


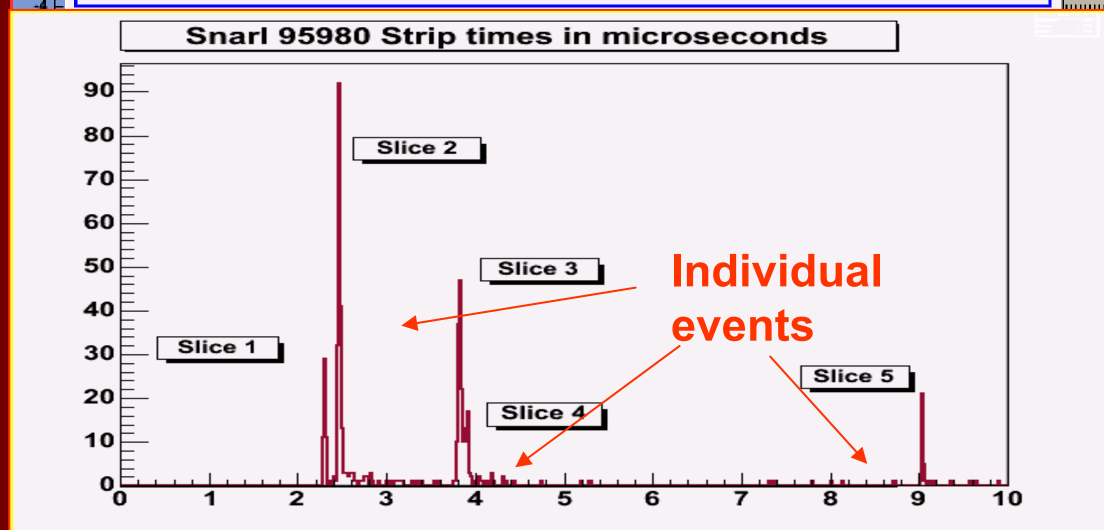


- For the given long-baseline, oscillation parameters Δm_{23}^2 & $\sin^2 2\theta_{23}$ may be extracted from differences in the near-extrapolated & far spectra

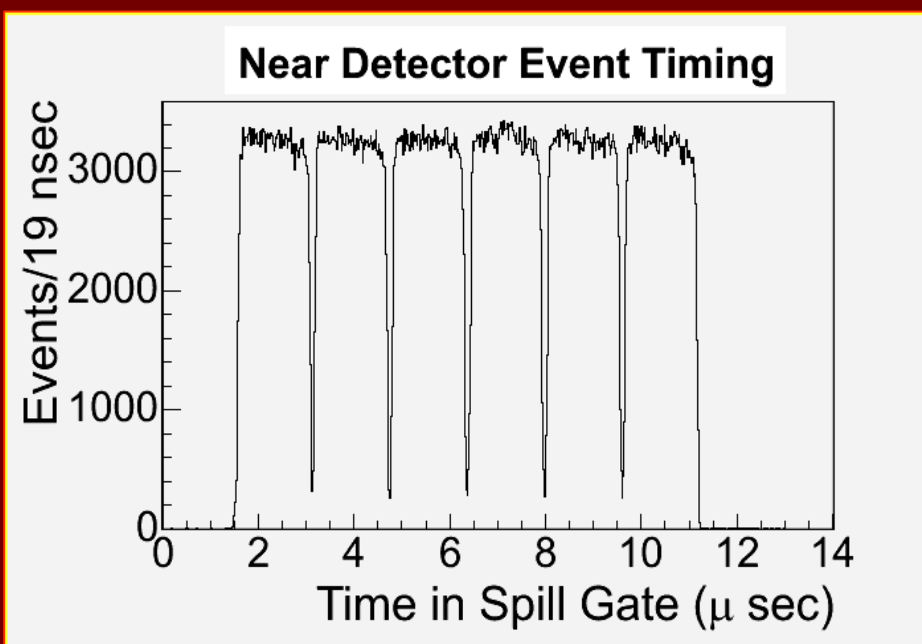
Near detector events

- High flux in near detector results in multiple neutrino interactions per MI spill
- Events are separated by topology and timing (“slices”)





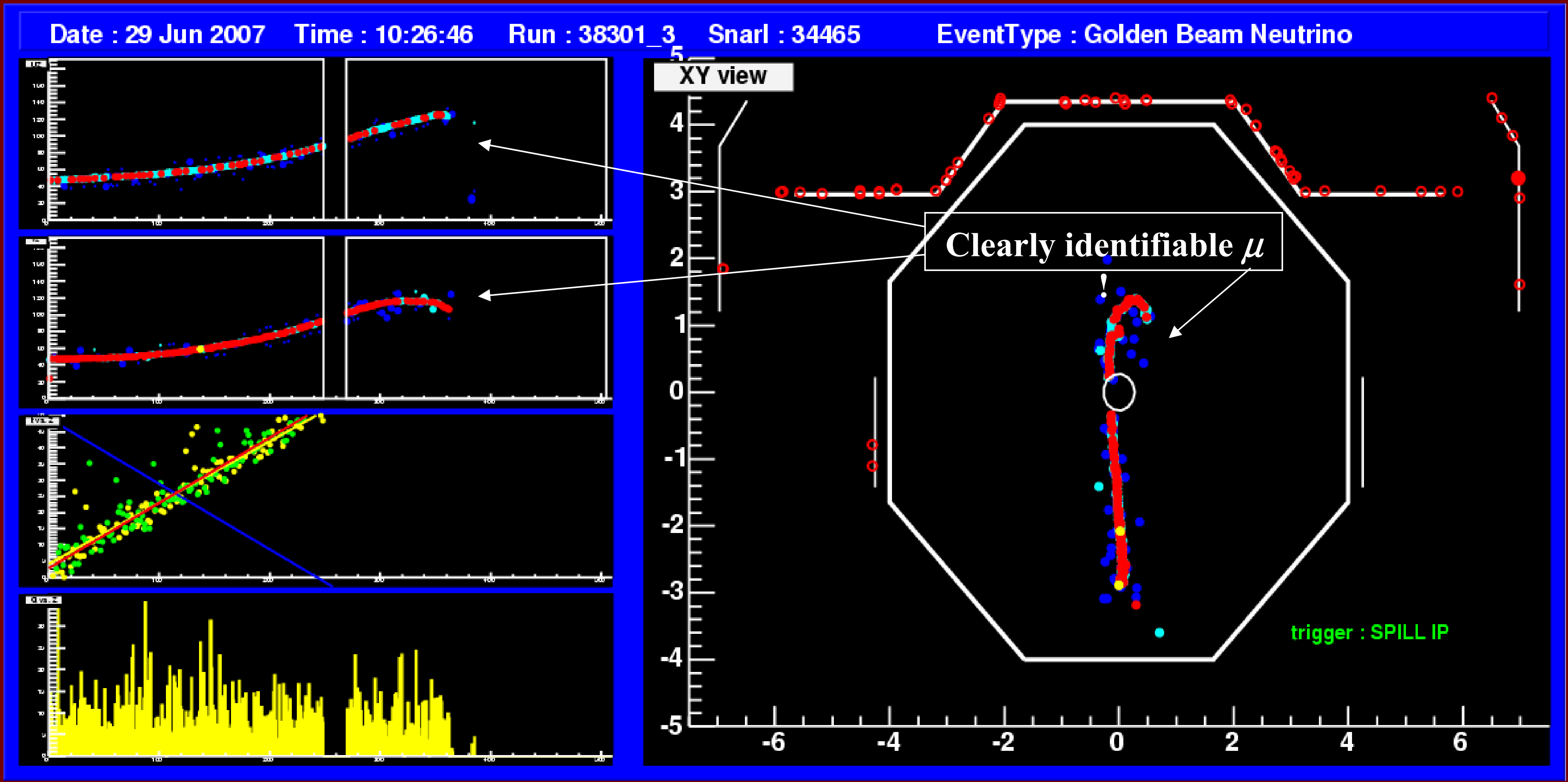
time (μs)



← Batch structure clearly seen!

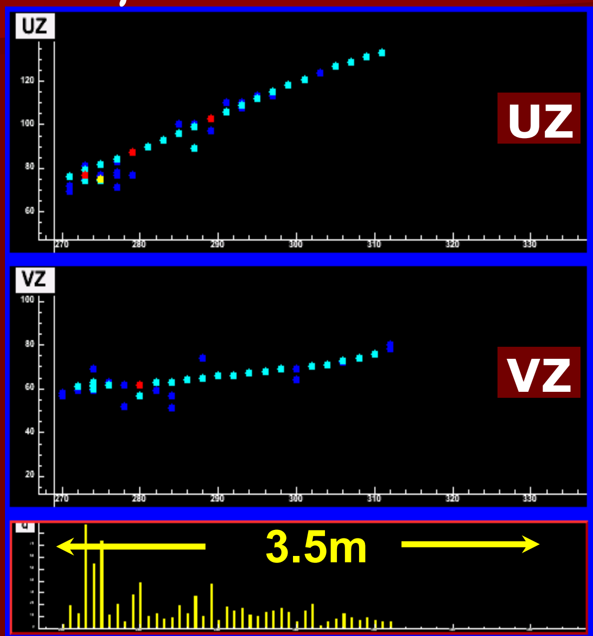
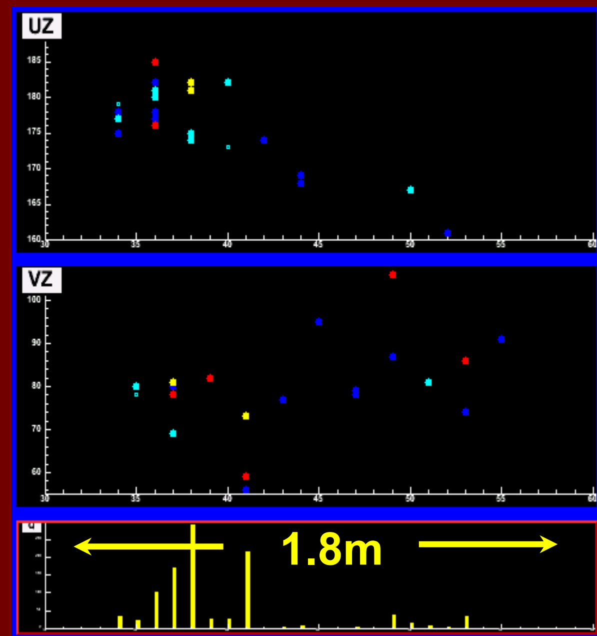
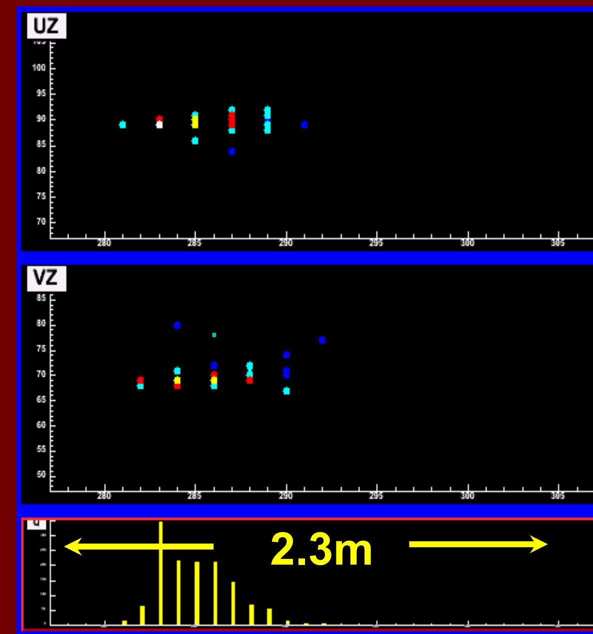
Far detector events

- Beam neutrino interaction rate is ~10^{-6} that of the near detector
- Beam events are identifiable in time with the spill trigger supplied from NuMI



Example event topologies

Monte Carlo

ν_μ CC Event	NC Event	ν_e CC Event
		
long μ track+ hadronic activity at vertex	short event, often diffuse	short, with typical EM shower profile

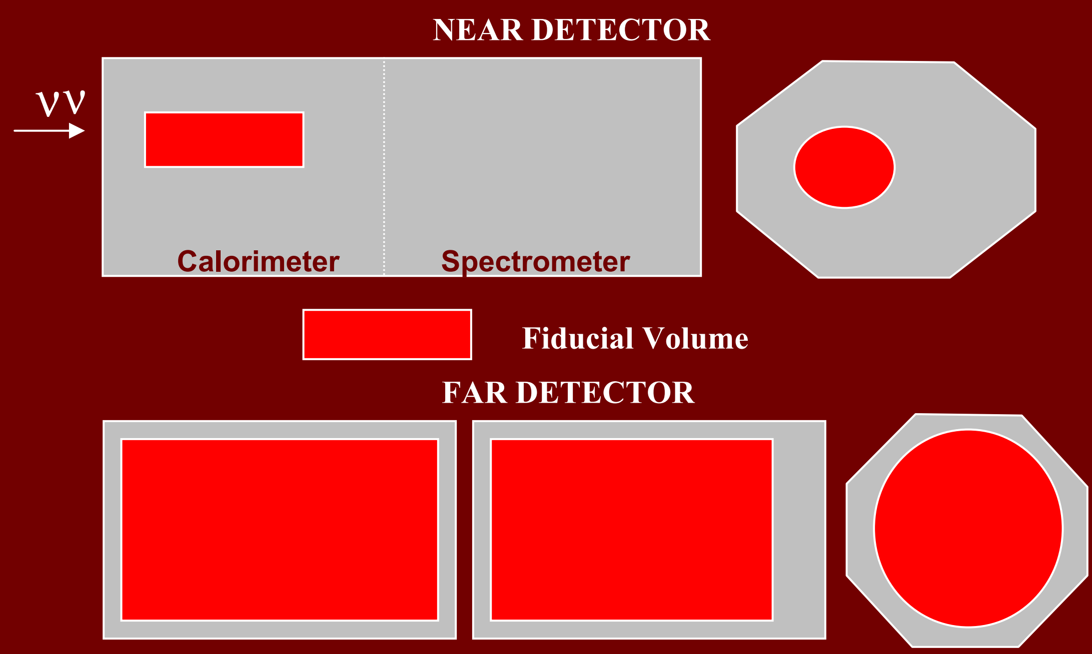
$$E_\nu(CC) = E_{shower} + P_\mu$$

E_{shower}: 55%/√E P_μ: 6% range, 10% curvature

Selection criteria – Near and Far

ν_μ CC-like events must satisfy the following criteria:

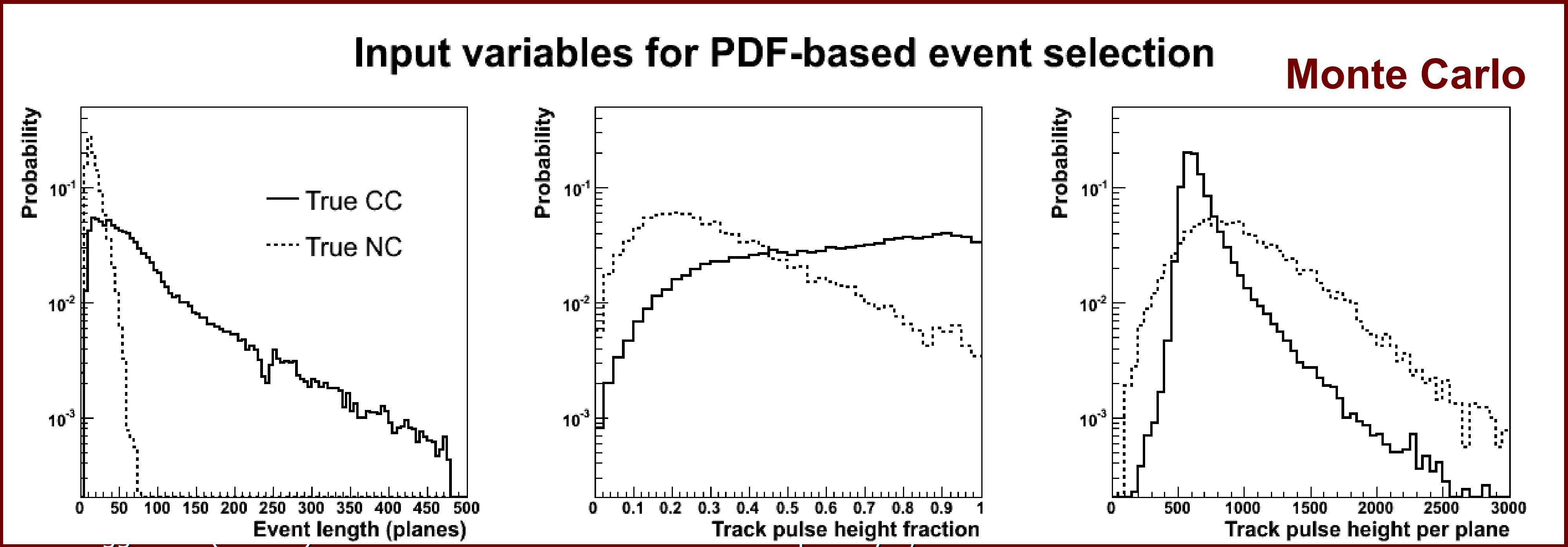
- Event must contain at least one good reconstructed track
- The reconstructed track vertex should be within the fiducial volume of the detector:
  - NEAR:
    - 1m < z < 5m
      (z=0: front face of the detector)
    - R< 1m from beam center.
  - FAR:
    - z>50cm from front face
    - z>2m from rear face
    - R< 3.7m from center of detector



- The fitted track should have negative charge (selects ν_μ)
- Select on likelihood-based CC/NC separation parameter

Selecting CC events

- Events are selected using a likelihood-based procedure, with three input Probability Density Functions (PDFs) that show differences for True CC and NC interactions:
  - **Event length in planes** (*related to muon momentum*)
  - **Fraction of event pulse height in the reconstructed track** (*related to the inelasticity of CC events*)
  - **Average track pulse height per plane** (*related to dE/dX of the reconstructed track*)
- The probability that an event with particular values of these three variables is CC or NC (P_μ and P_{NC} respectively) is then the product of the three CC PDFs and the three NC PDFs at those values

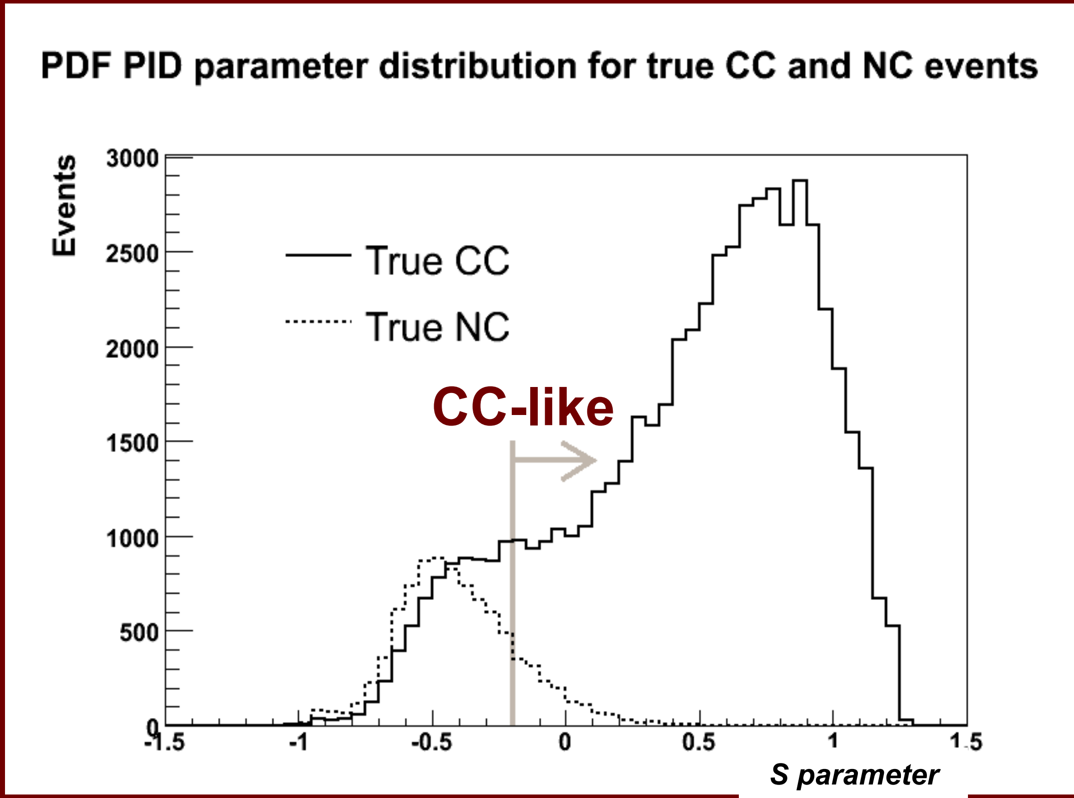


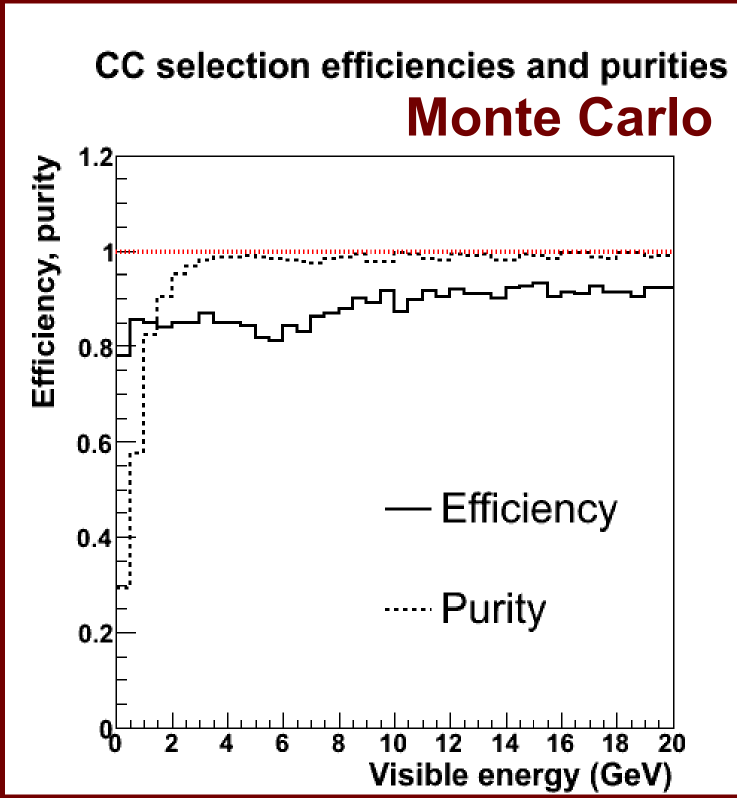
CC selection efficiencies

- The likelihood CC/NC selection (S) parameter is defined as:

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

- CC-like events are defined by the cut S > -0.2 in the FD (>-0.1 in the ND)
  - NC contamination is limited to the lowest visible energy bins (below 1.5 GeV)
  - Selection efficiency is quite flat as a function of visible energy

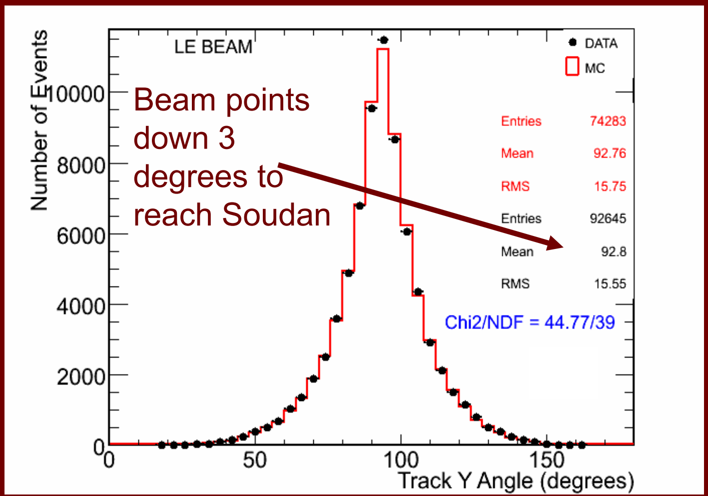




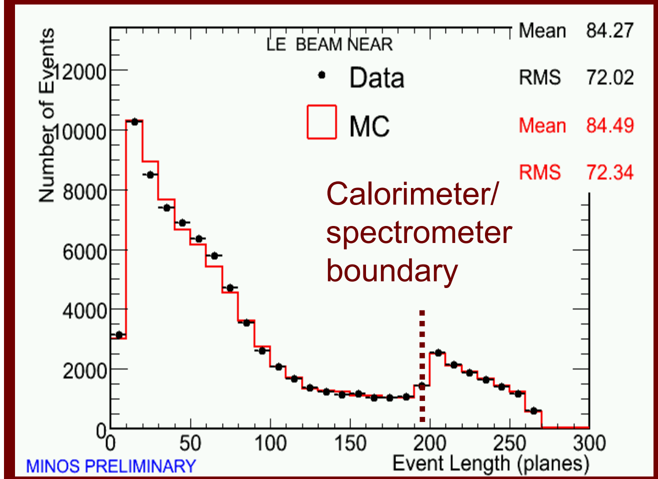
ND data & MC Comparison

- Compare Data and MC distributions for events in the Near detector (high statistics ~10^6 reconstructed events in the fiducial region)
- Good agreement observed in the shapes of both low-level quantities (such as track angles and event lengths), and higher-level quantities, such as the NC/CC separation parameter

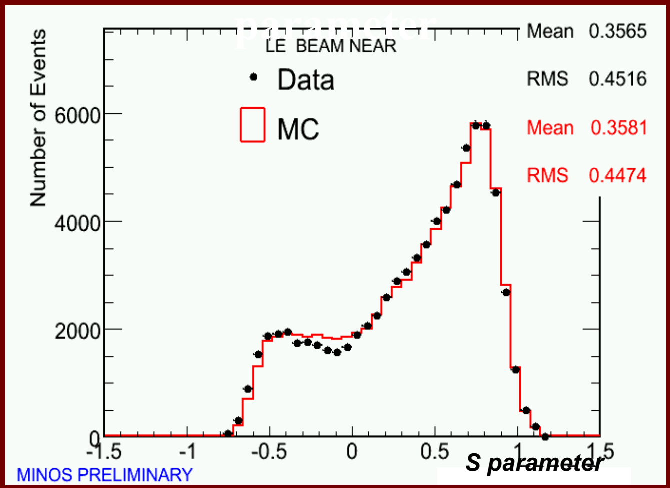
Reconstructed track angle



Event length

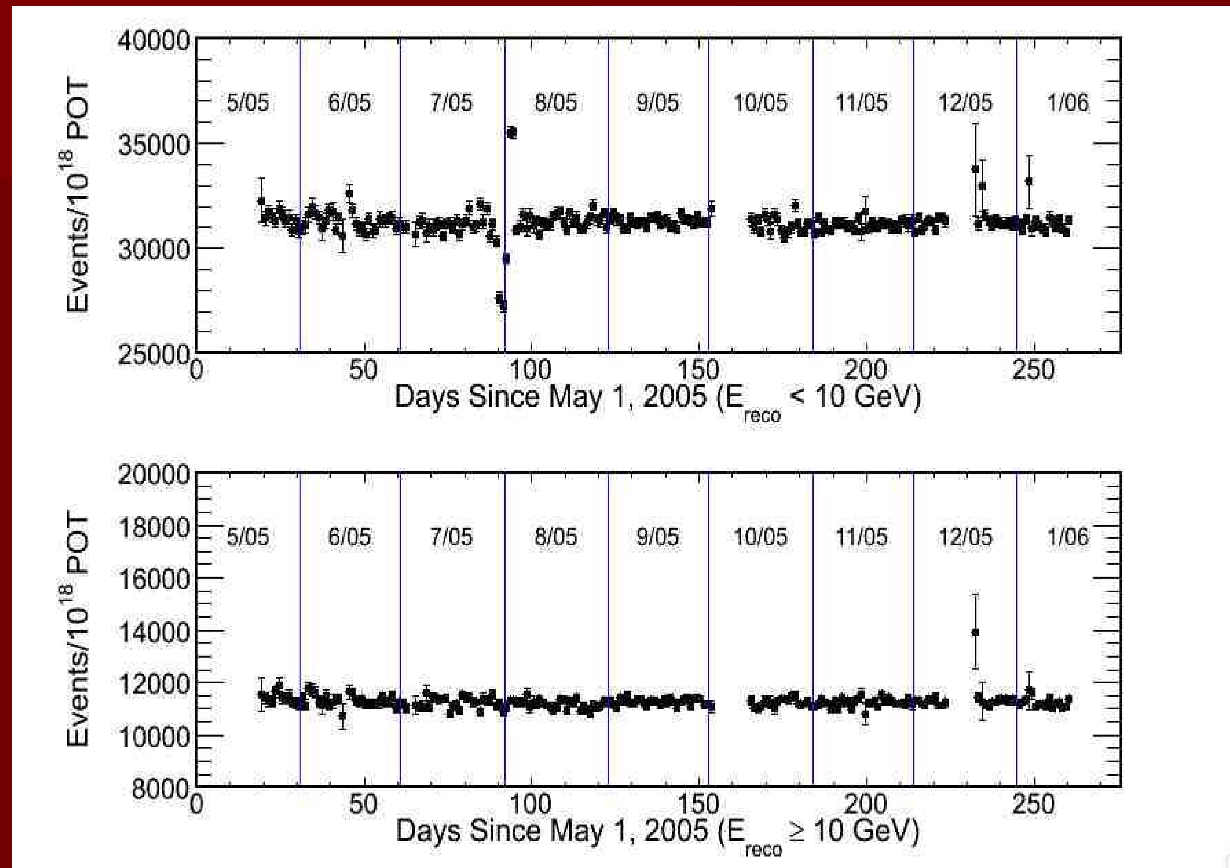


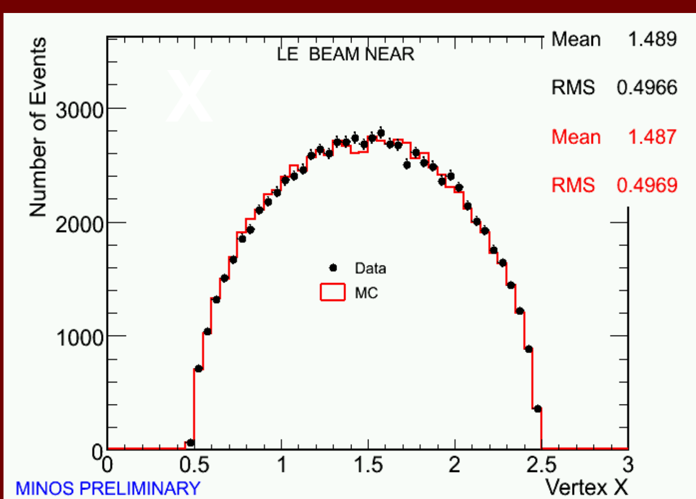
Separation

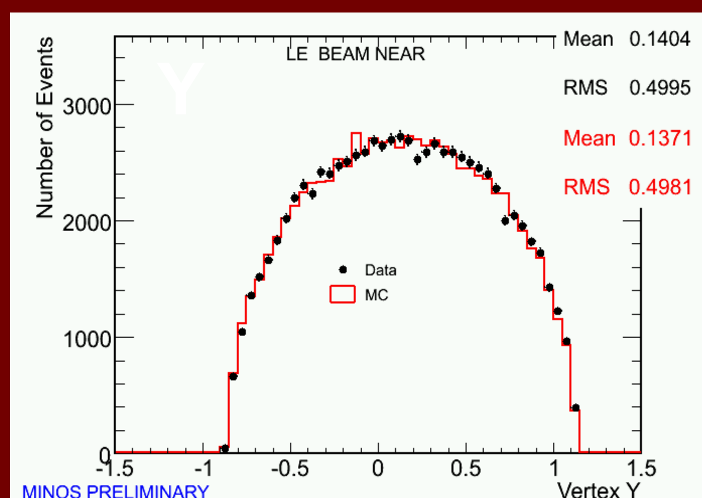


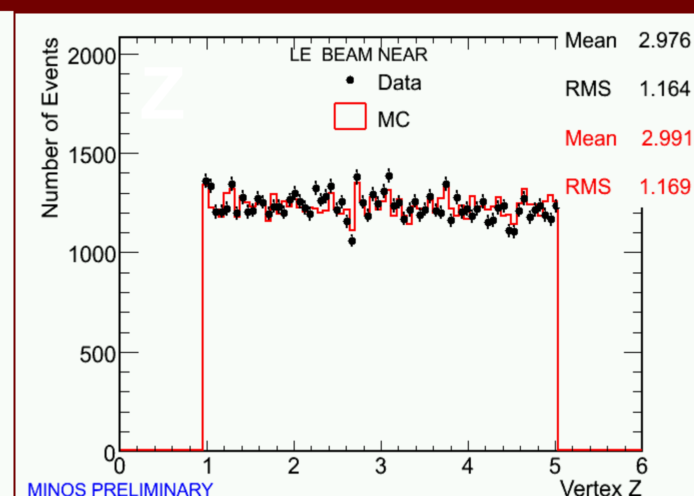
Near detector data quality

- Event rate is flat in time
- Horn current scans: July 29 – Aug 3





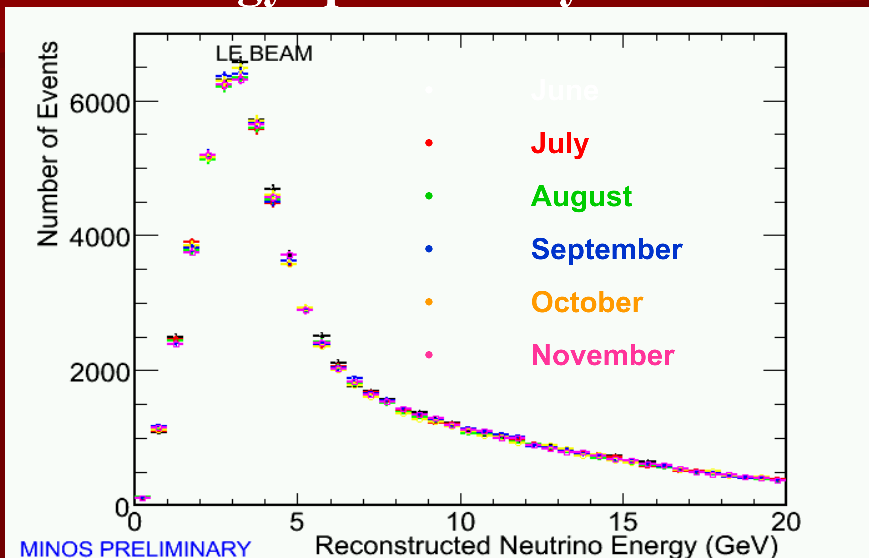




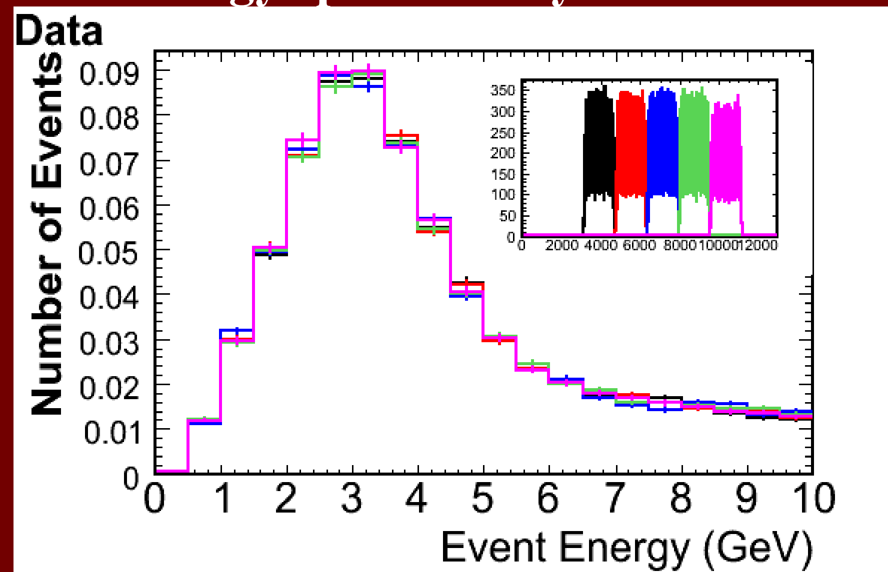
Stability of the energy spectrum & reconstruction with intensity

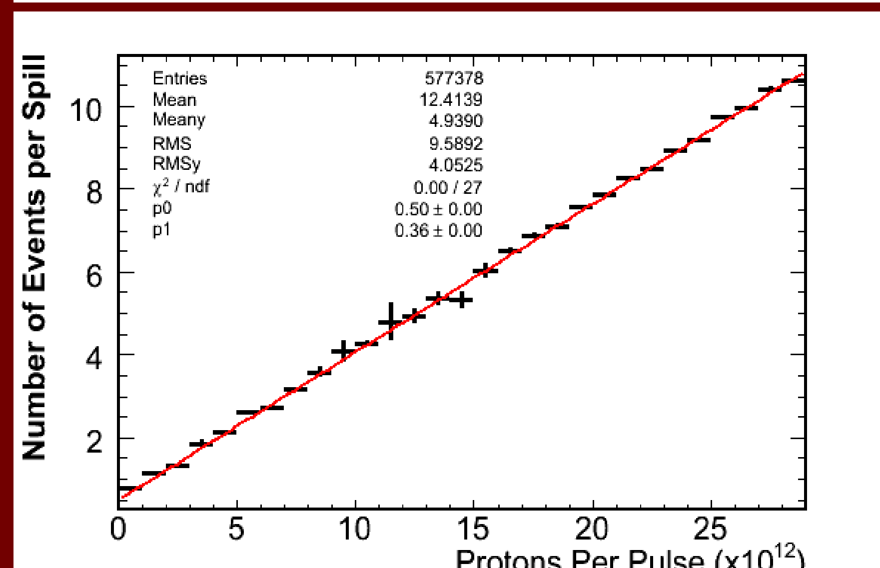
proton intensity ranges from 1e13 ppp - 2.8e13 ppp

Energy spectrum by Month



Energy spectrum by batch





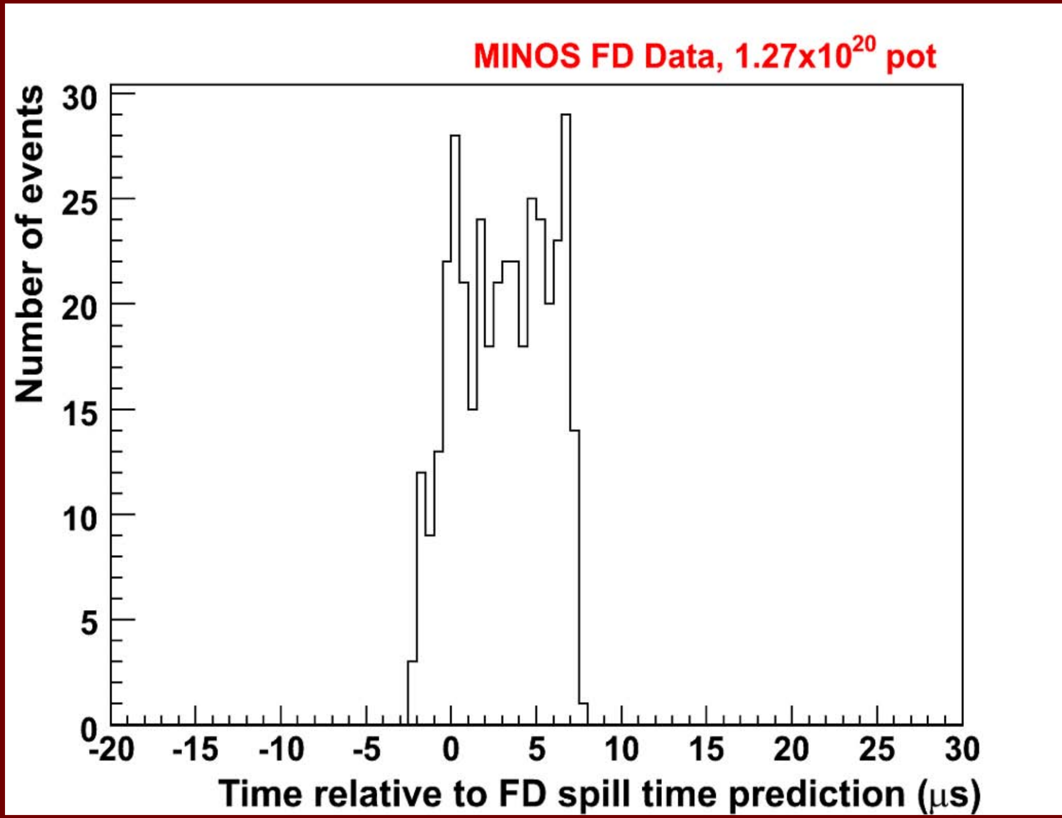
- Reconstructed energy distributions agree to within statistical uncertainties (~1-3%)
- Beam is very stable and there are no significant intensity-dependent biases in event reconstruction

Selecting Far Detector beam events

- Far detector beam events are selected on the basis of timing and topology
  - Events must be in coincidence with the known times of NuMI beam spills (within a 50μs window)
  - Events must point away from FNAL (track angle <50° relative to beam direction)

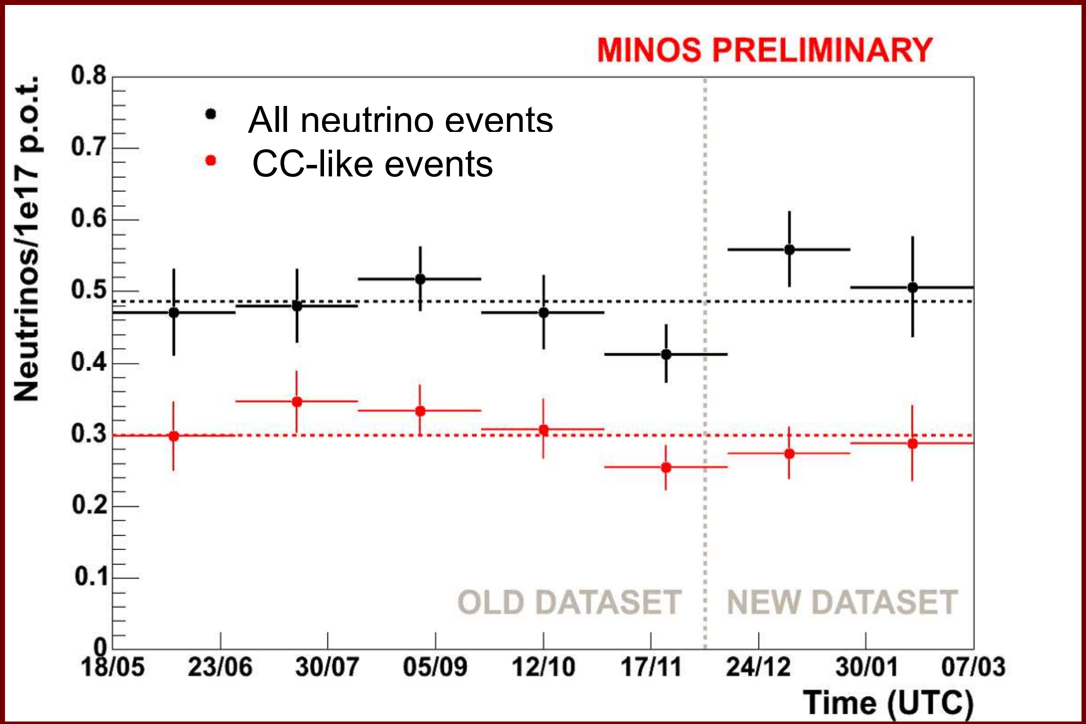
- Reconstructed events must be located within the fiducial volume of the detector

- Results in a very clean sample of neutrino events – expected background from cosmic ray muons < 0.5 events

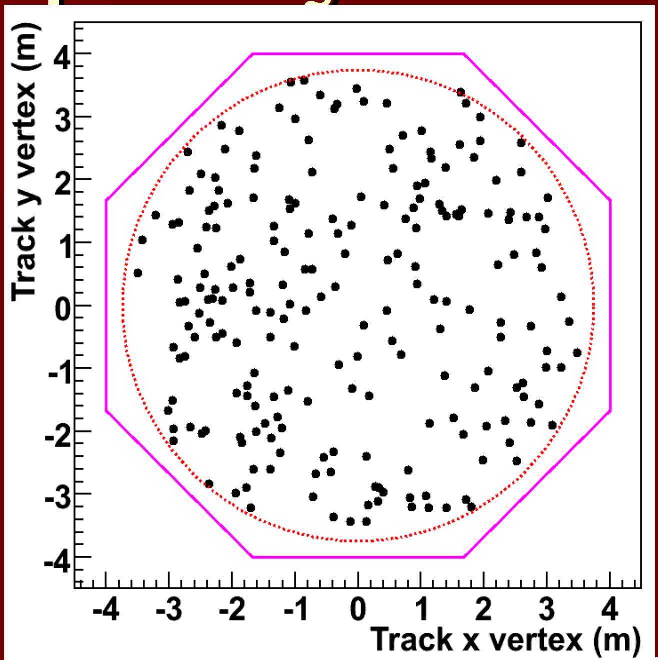


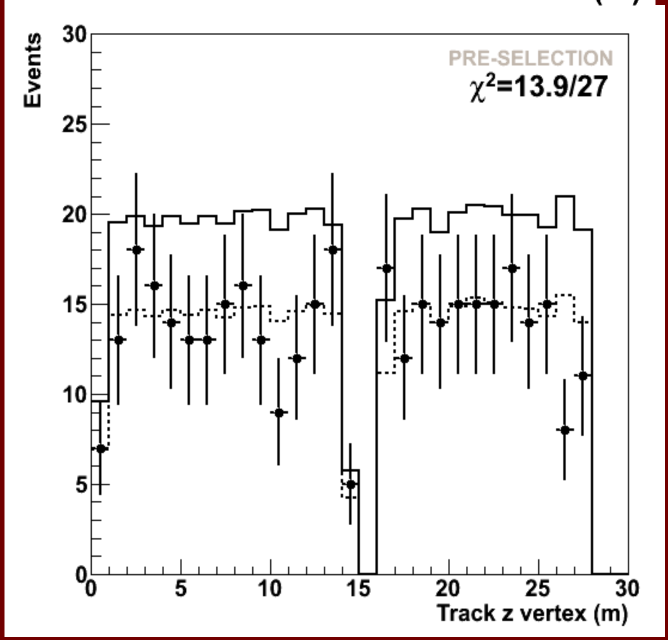
Far detector data quality

- Extensive data quality checks were performed on the FD data prior to performing the oscillation analysis
  - Designed to ensure that there were no event selection or reconstruction biases in the selected data sample



Neutrino rate/pot vs time is flat - no missing events



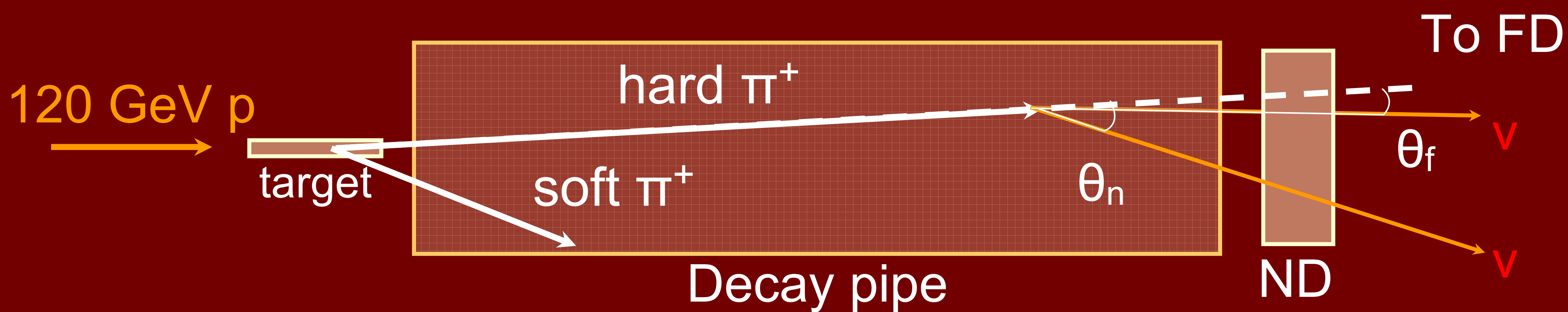


Uniform distribution of event vertices - no evidence of CR background

Extrapolating the flux

- Directly use the Near detector data to extrapolate between Near and Far, **using our Monte Carlo to provide necessary corrections due to energy smearing and acceptance.**

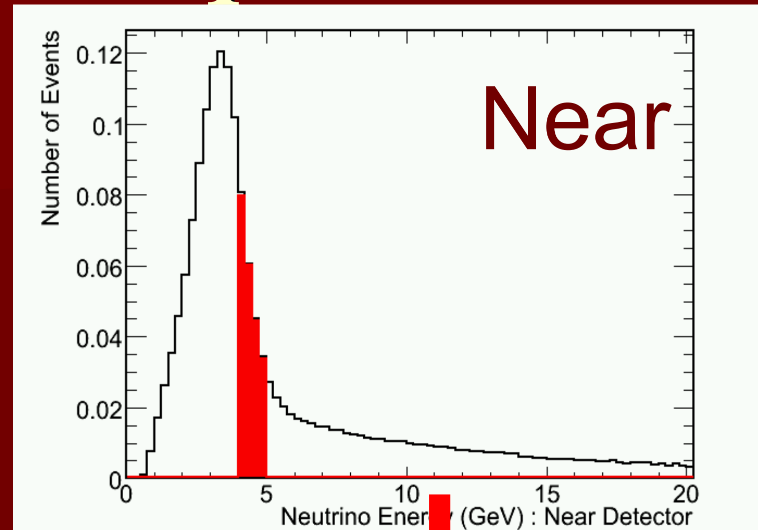
- Use our knowledge of **pion decay kinematics and the geometry of our beamline** (extended neutrino source, seen as point-like from the Far Detector) **to predict the Far detector energy distribution from the measured Near detector distribution**

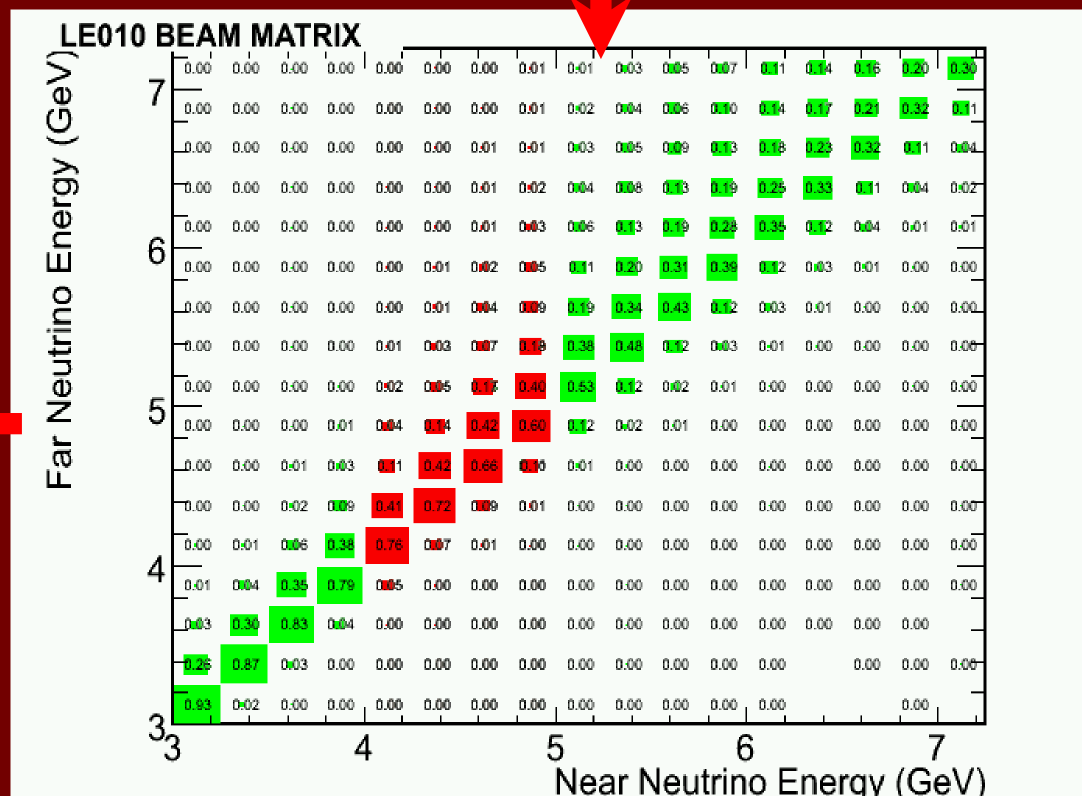


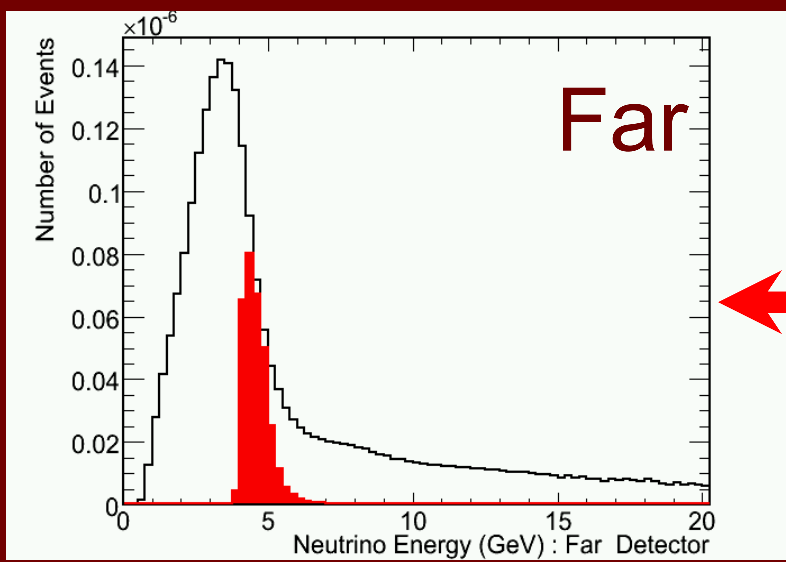
- This strategy is known as the "**Beam Matrix**" method

Beam Matrix Extrapolation

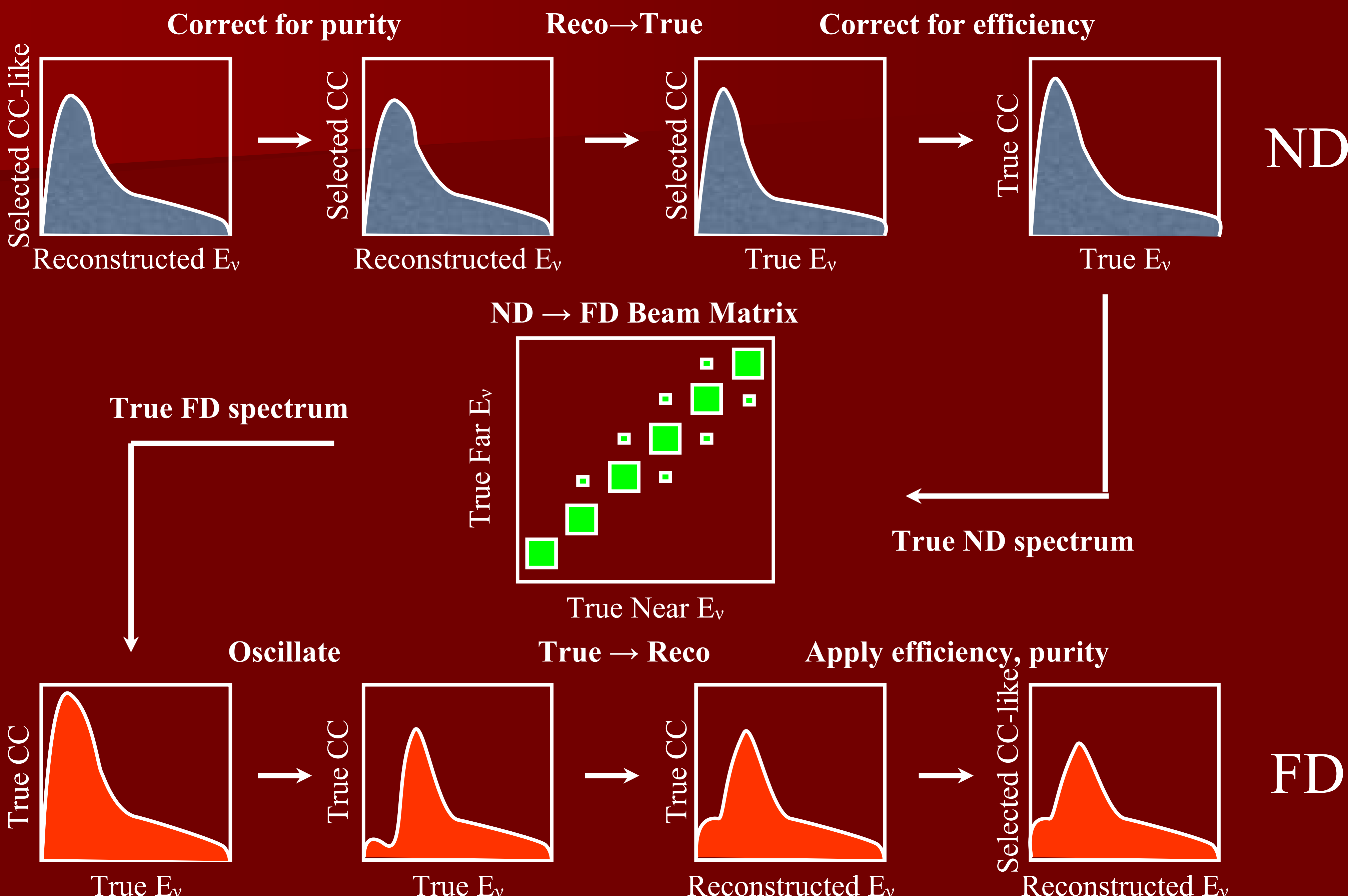
- Beam Matrix encapsulates the knowledge of pion 2-body decay kinematics & geometry
- Provides a very good representation of how the near & far detector spectra are related





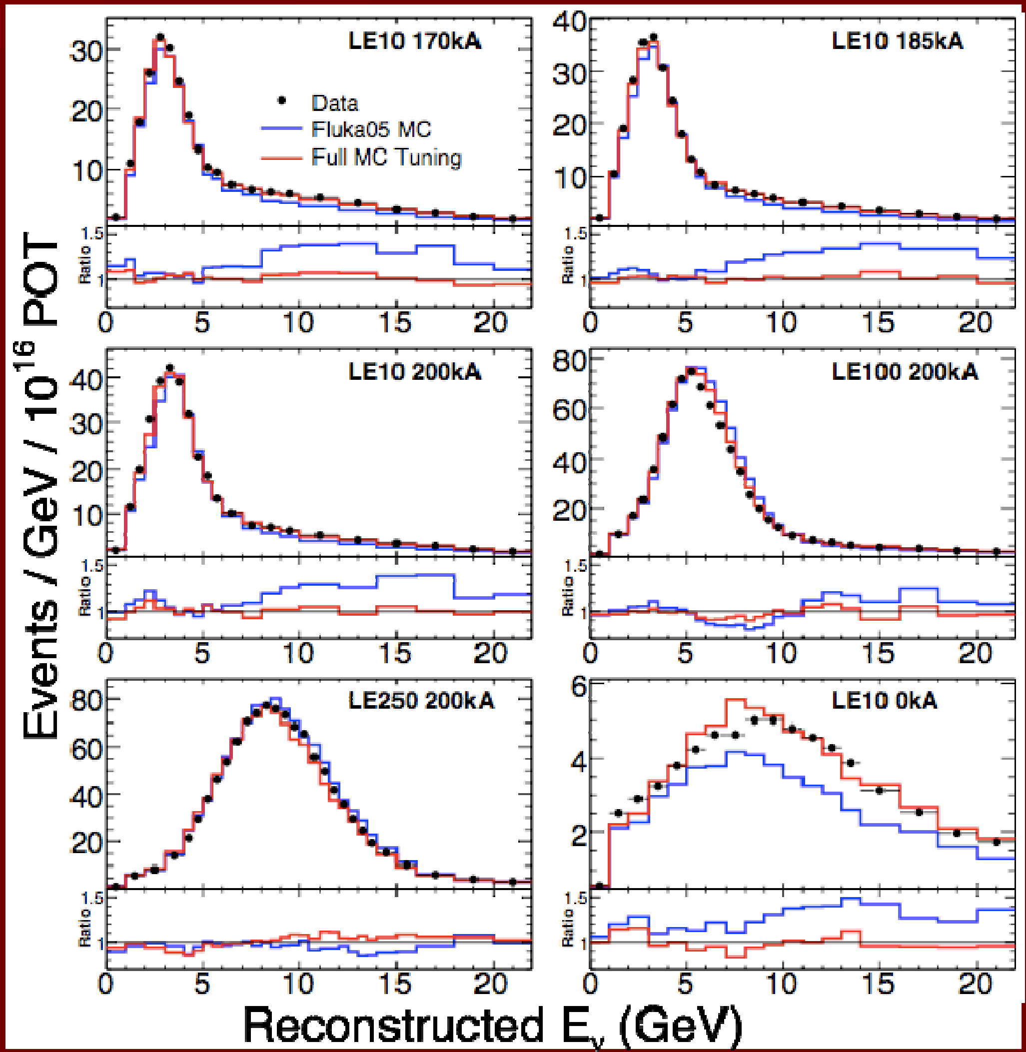


Steps in the Beam Matrix method



Hadron production tuning

- Agreement between Monte Carlo and data is pretty good, but can be better
- A fit is performed to ND data taken in 5 beam configurations using a parameterized form of hadron production which varies smoothly as a function of hadronic x_F and p_T
- Agreement for all beam configurations is improved with this procedure



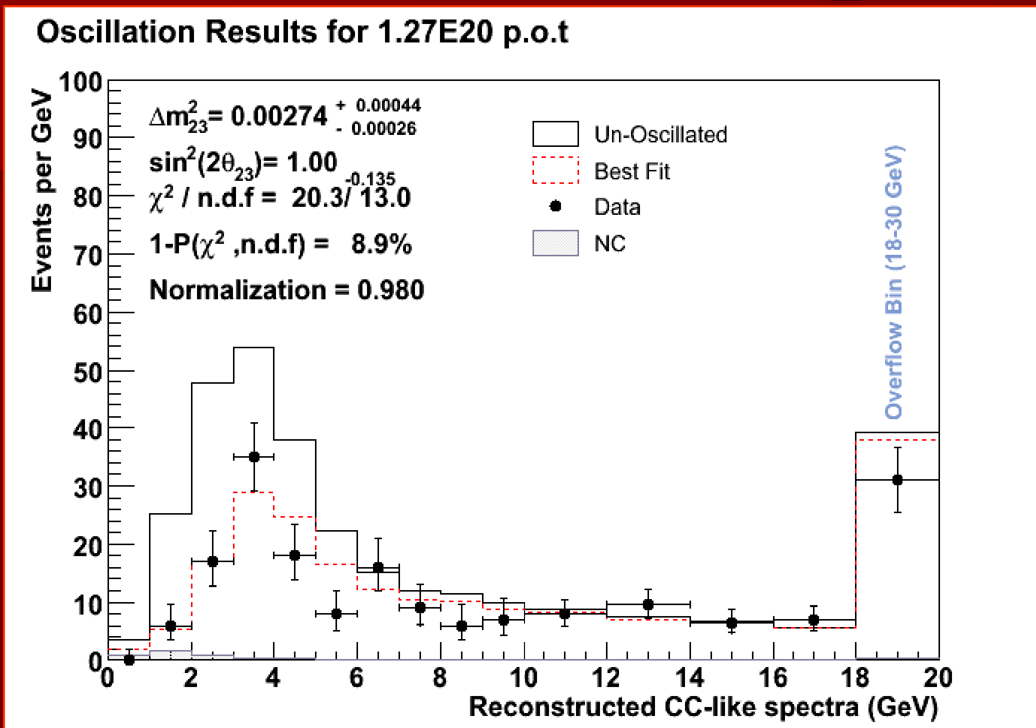
Observation vs. No-Oscillation Prediction

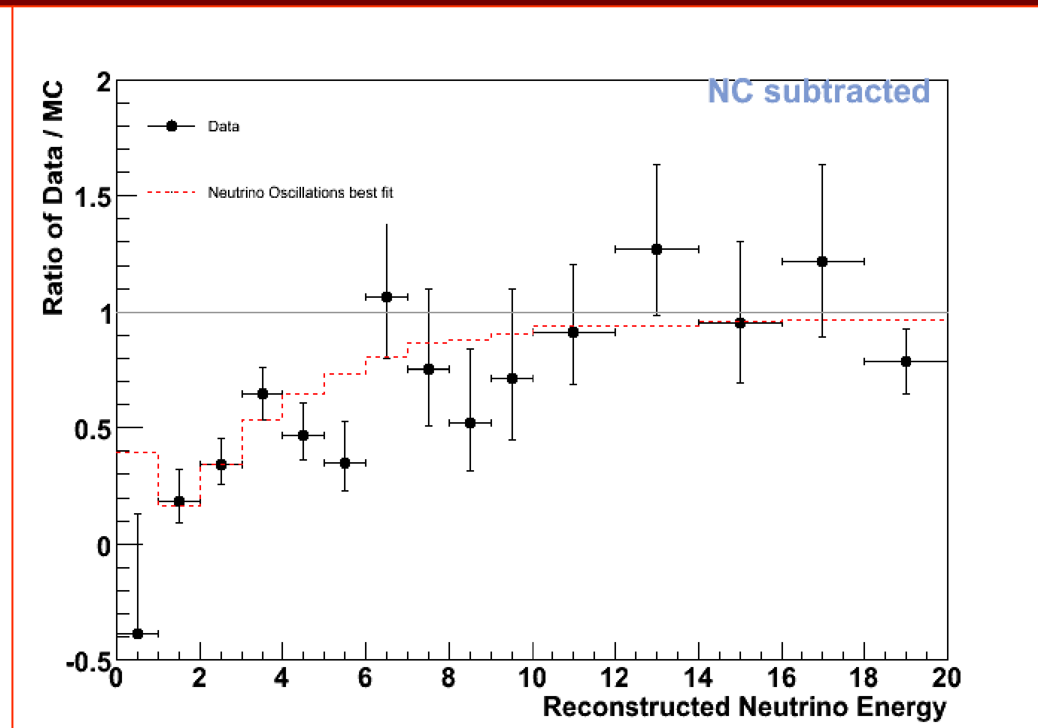
Energy range	Data events	Prediction (no oscillations)	Data/Predictio n	Significance
0-5 GeV	76	168.3±8.8	0.452	5.9σ
0-10 GeV	122	238.9±10.7	0.511	6.2σ
0-20 GeV	193	306.2±13.5	0.630	5.1σ
0-30 GeV	215	335.8±14.4	0.640	5.2σ

We observe a significant energy dependent suppression of events at the Far Detector relative to the no-oscillation prediction in 1.27×10^{20} POTs

⇨ *Largest suppression for energy range less than 10 GeV*

Best-fit spectrum and ratio





Significant energy-dependent suppression of ν_μ events observed (**5.9 standard deviation effect below 5 GeV**)

- ⇨ *Consistent with the neutrino oscillation hypothesis*
- ⇨ *Alternative hypotheses (e.g. neutrino decay) may be tested with more data, esp. at higher energies*

Systematic uncertainties

Systematic Uncertainty	Shift in δm^2 ($x10^{-3}$ 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

- Systematic uncertainties on the oscillation parameters were evaluated using "fake datasets" generated from MC with various systematic shifts applied, and (in the FD) oscillations with $\Delta m^2 = 2.72 \times 10^{-3}$ eV^2, $\sin^2 2\theta = 1$
- The three largest uncertainties identified from this study were included as nuisance parameters in the oscillation analysis

Oscillation fit

- Fit to the visible energy spectrum of the 215 selected Far detector CC events to extract the mixing parameters Δm^2 and $\sin^2 2\theta$:

$$\chi^2(\Delta m^2, \sin^2 2\theta, \alpha_j, \ldots) = \underbrace{\sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i/e_i)}_{\text{Statistical error}} + \underbrace{\sum_{j=1}^{nsyst} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j^2}}}_{\text{Systematic errors}}$$

- Systematic uncertainties:
  - 4% overall normalization
  - 11% absolute shower energy scale
  - 50% NC background rate

  (11% absolute shower energy scale and 50% NC background rate: Common to near and far detectors)

  - Systematic error on mixing parameters estimated to be ~30-40% of statistical error for 1.27e20 POTs

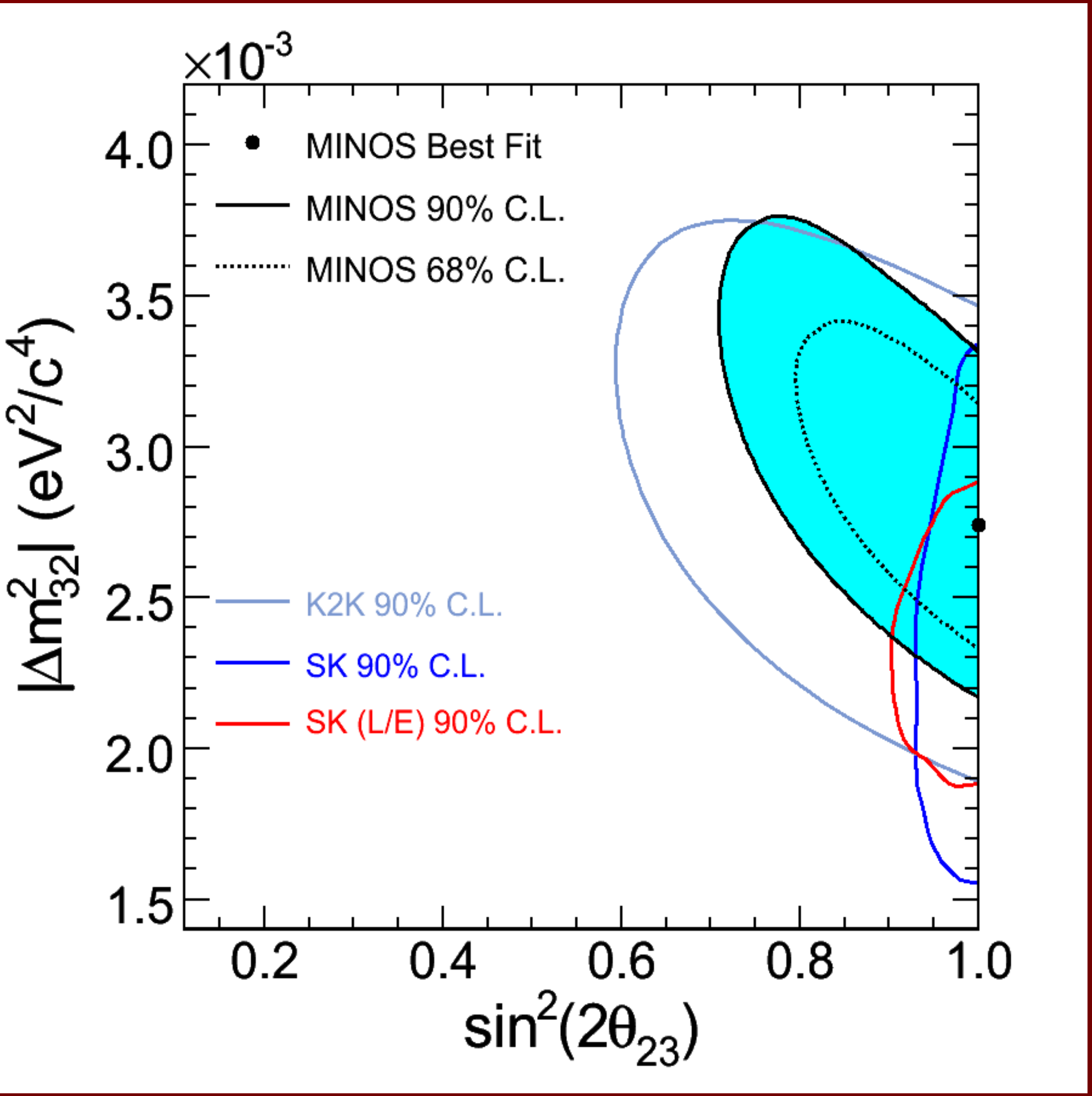
Result of Oscillation Fit

- Our allowed region is in good agreement with previous results from Super-Kamiokande and K2K

- Best-fit oscillation parameters:

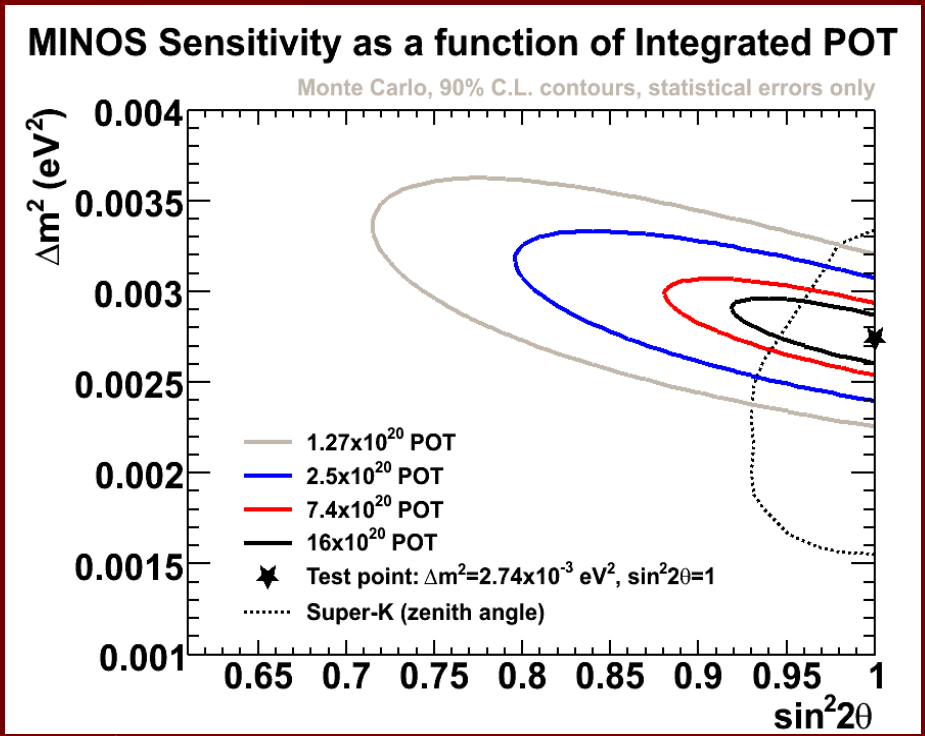
$$\Delta m^2 = 2.74 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2 2\theta = 1.0$$



Upcoming ν_μ analysis improvements

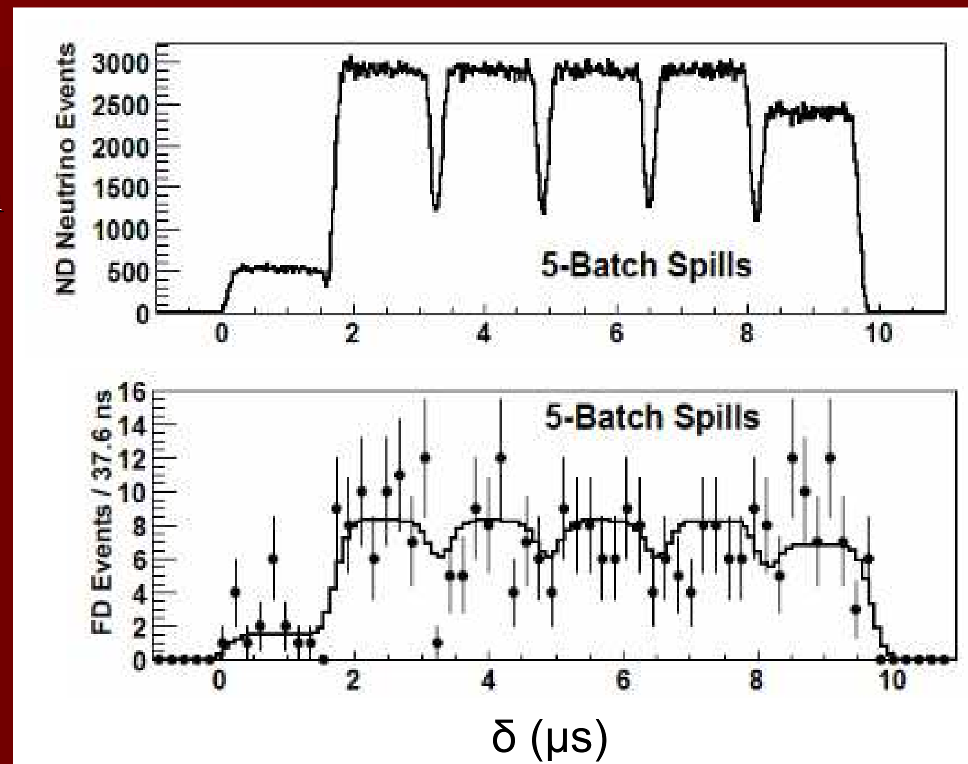
- Modeling & reconstruction
  - Additional data & at higher energies
  - Updated flux model
  - New hadronization & intranuclear scattering models
  - Improved reconstruction & CC/NC separation algorithms
    - ⇨ Potential reduction in NC systematic errors
  - Ongoing improvements in calibration



- Working to extend the oscillation analysis to $\bar{\nu}$ & higher energies
- *New result on the first two years of data expected this summer*

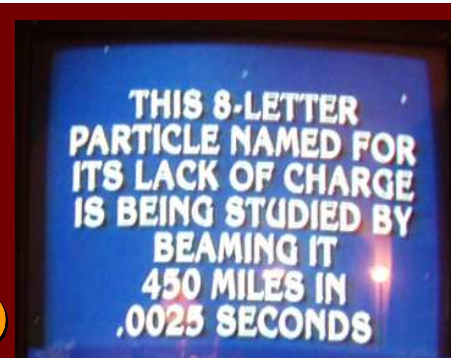
Neutrino Time-of-Flight (TOF)

- PDG limit is
  - $|v-c|/c < 4 \times 10^{-5}$ (95% C.L.)
  - Based on previous experiment with 500m baseline and ~ns precision
- Separation between the detectors
  - L = 734,298.6 ± 0.7 m
- The TOF for a massless particle
  - t = 0.002449356 s
- GPS time-stamping used to synchronize the near & far detectors



δ = -126 ± 32 (stat) ± 64 (syst.) ns

$(v-c)/c = [5.1 \pm 2.9 \text{ (syst. + stat.)}] \times 10^{-5}$ (68% CL)



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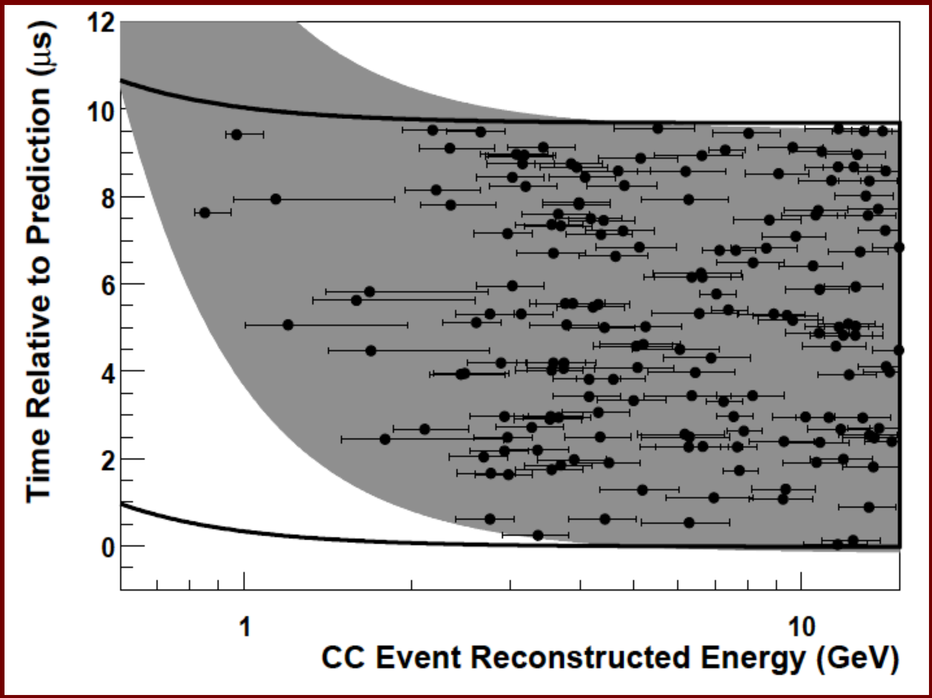
Relativistic mass measurement

- Use time and energy to compute a relativistic mass limit
  - If the neutrino has mass m_ν its time of flight would be

$$T_{m_\nu}(E_\nu) = \frac{\tau}{\sqrt{1-(m_\nu c^2/E_\nu)}}$$

where τ is the TOF for a massless particle



Line = 68% C.L.
Shaded = 99% C.L.

- We find **m_ν < 50 MeV/c^2 (stat.+sys.) @ 99% c.l.**
  - The limit is driven by the few points near edge
  - With full data MINOS dataset ~10 MeV sensitivity @ 99% C.L.

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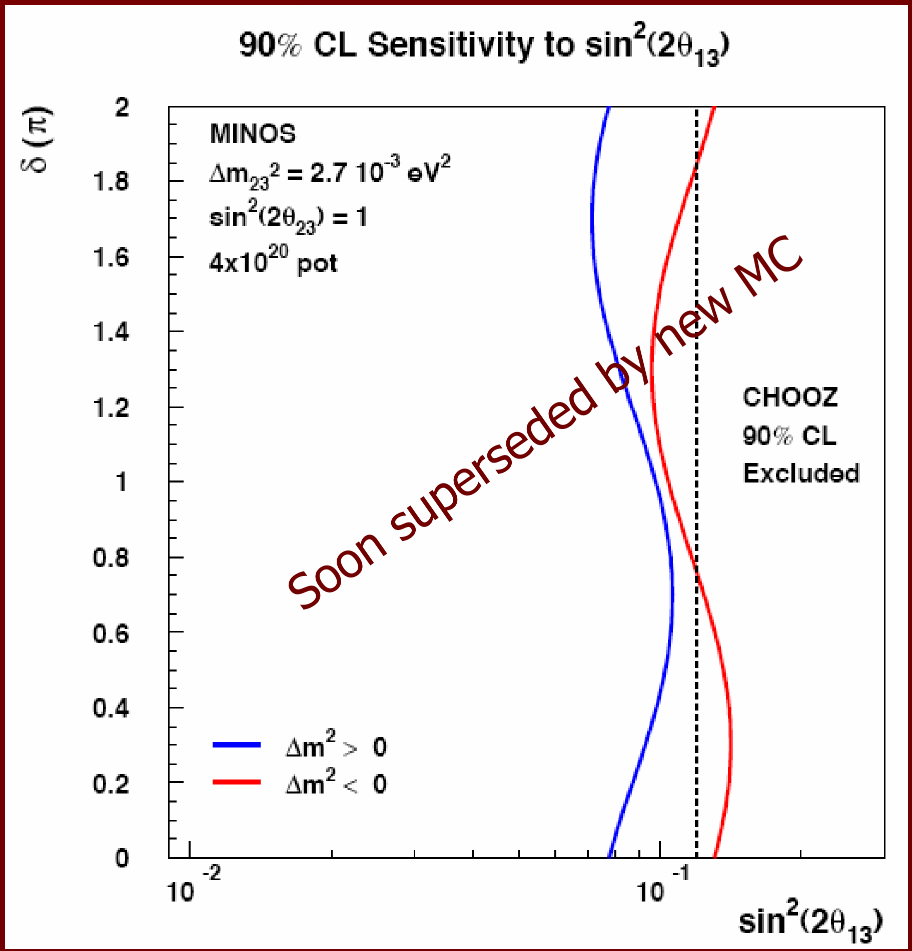
ν_e appearance

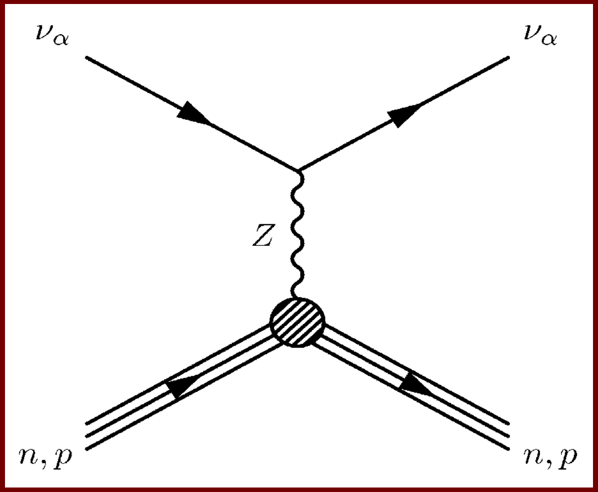
- $\nu_\mu \rightarrow \nu_e$ oscillation yields access to measurement of θ_{13}
- Events are characterized by a compact electron shower with EM profile
- MINOS is a coarse detector for analyzing electromagnetic showers
- Main backgrounds are NC events
- Much more challenging to extract ν_e CC events than NC events

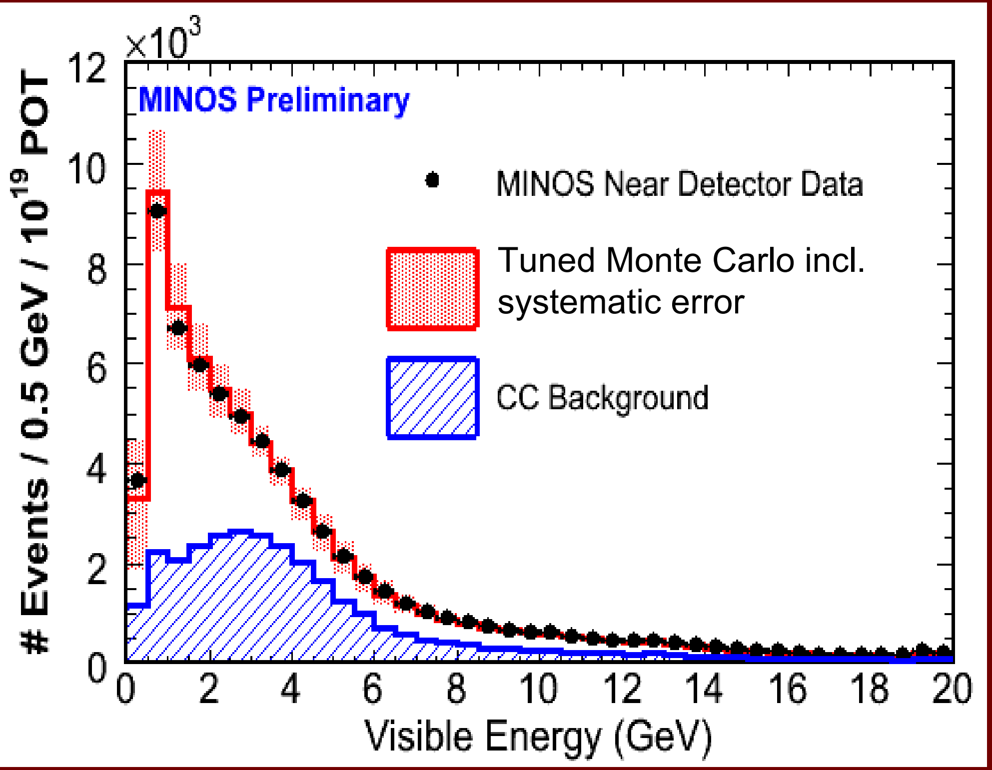


- Analysis is in progress → expect to improve on the CHOOZ limits for some values of CP-violating phase, δ, dependent on the order of the mass hierarchy

Neutral current analysis

- NC unaffected by $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - ⇨ Can test for sterile neutrino contributions
- Near detector NC energy spectrum
  - Far Detector data for this analysis is still blinded
  - Currently working on:
    - Near/Far extrapolation
    - FD systematic error evaluation





Conclusions

- Results from the first year of accelerator neutrino exposure
  - ⇨ Consistent with ν_μ disappearance with the following parameters:

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

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

  - ⇨ Published: *Phys. Rev. Lett. 97 (2006) 191801* (detailed PRD writeup soon)
  - ⇨ Data also used to measure the TOF and relativistic mass of neutrinos (to be submitted to PRD)

$$(v-c)/c = (5.1 \pm 2.9) \times 10^{-5} \text{ (68\% CL, syst. + stat.)}$$

- More than doubled the dataset since shutdown
  - ⇨ Expect new public ν_μ disappearance results this summer
  - ⇨ Significant intensity improvements soon
- New analyses continue on a number of oscillation and non-oscillation measurements