Recent results from the MINOS experiment

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for the MINOS Collaboration

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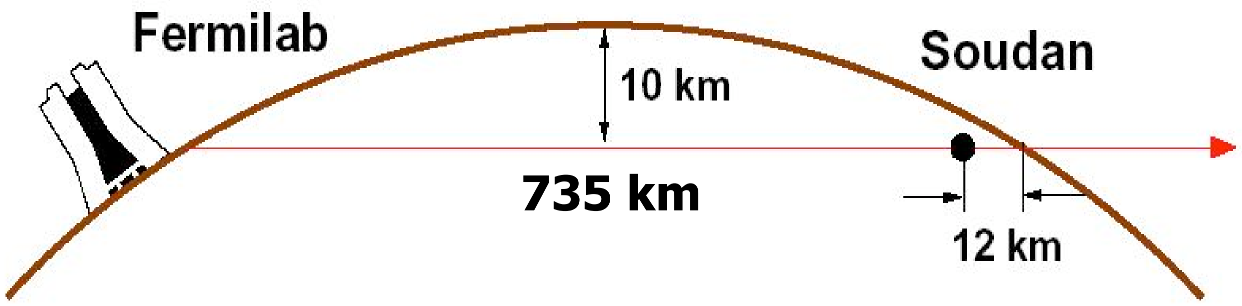
Talk structure

- Outline of the talk:
  - The MINOS experiment
  - Physics goals of MINOS
  - The NuMI beam and the MINOS detectors
  - Overview of the oscillation analysis
  - Analysis improvements for the Summer 2007 result
  - Oscillation analysis of the 2.5×10^{20} POT dataset
  - Future prospects and summary

The MINOS experiment

- **MINOS (Main Injector Neutrino Oscillation Search)** - a long-baseline neutrino oscillation experiment:
  - Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector
  - A Near detector at Fermilab to measure the beam composition and energy spectrum
  - A Far detector deep underground in the Soudan Mine Minnesota, to search for evidence of oscillations



MINOS Physics Goals

- **Verify $\nu_\mu \rightarrow \nu_\tau$ mixing hypothesis and make a precision (<10%) measurement of the oscillation parameters Δm^2 and $\sin^2 2\theta$**
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations (not yet seen at this mass-scale)
- Search for/rule out exotic phenomena
  - Sterile neutrinos
  - Neutrino decay
- Atmospheric neutrino and cosmic ray muon physics

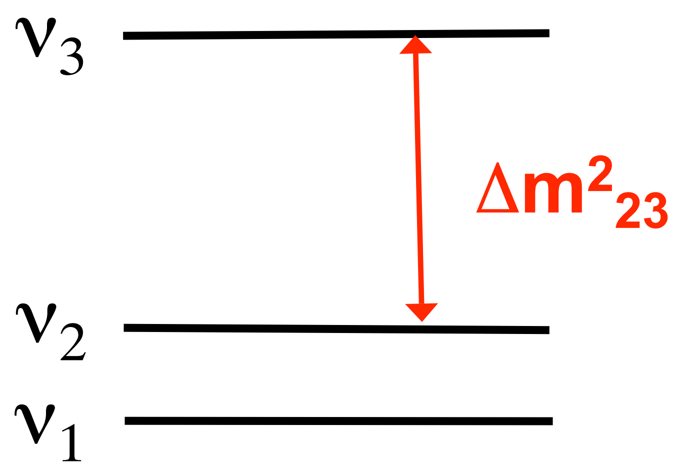
Neutrino mixing

ν_e appearance

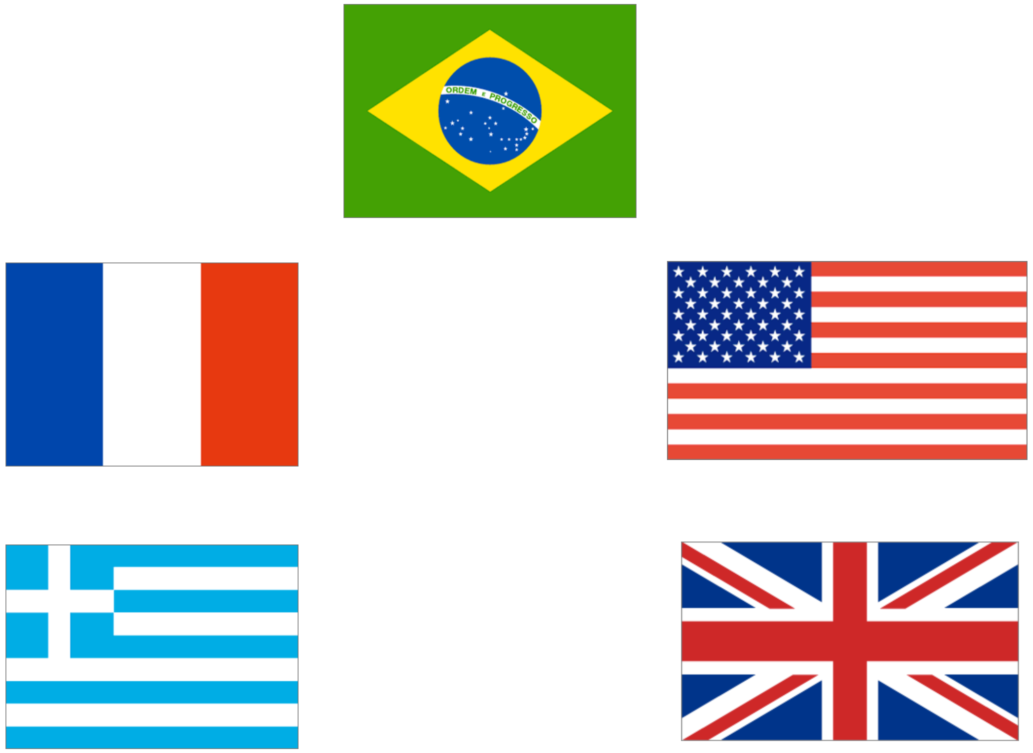
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \begin{matrix} U_{e1} \\ U_{\mu1} \\ U_{\tau1} \end{matrix} & \begin{matrix} U_{e2} & \boxed{U_{e3}} \\ \multicolumn{2}{c}{\boxed{\begin{matrix} U_{\mu2} & U_{\mu3} \\ U_{\tau2} & U_{\tau3} \end{matrix}}} \end{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν_μ disappearance

Neutrino masses



The MINOS Collaboration



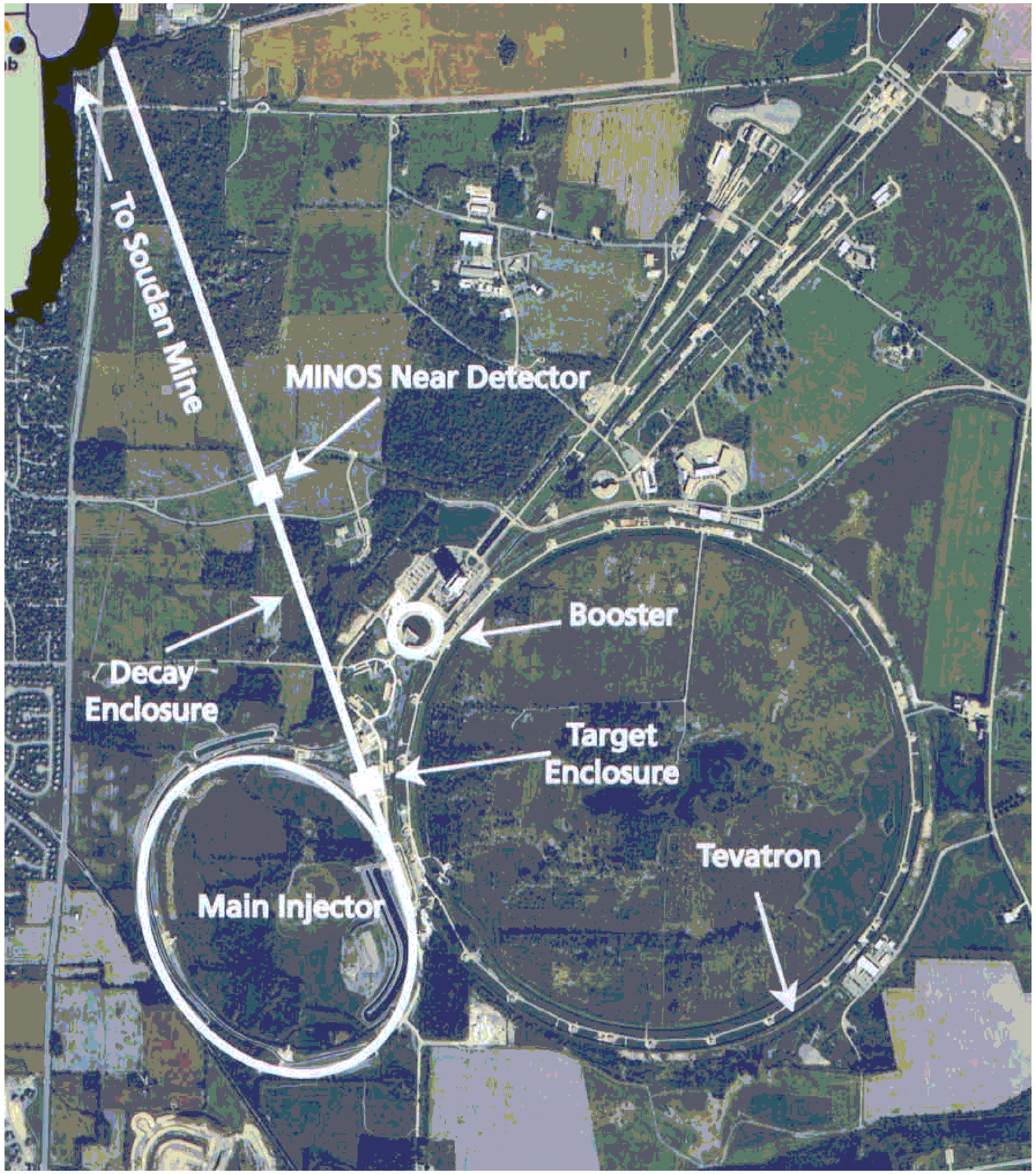
27 institutions

175 scientists

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

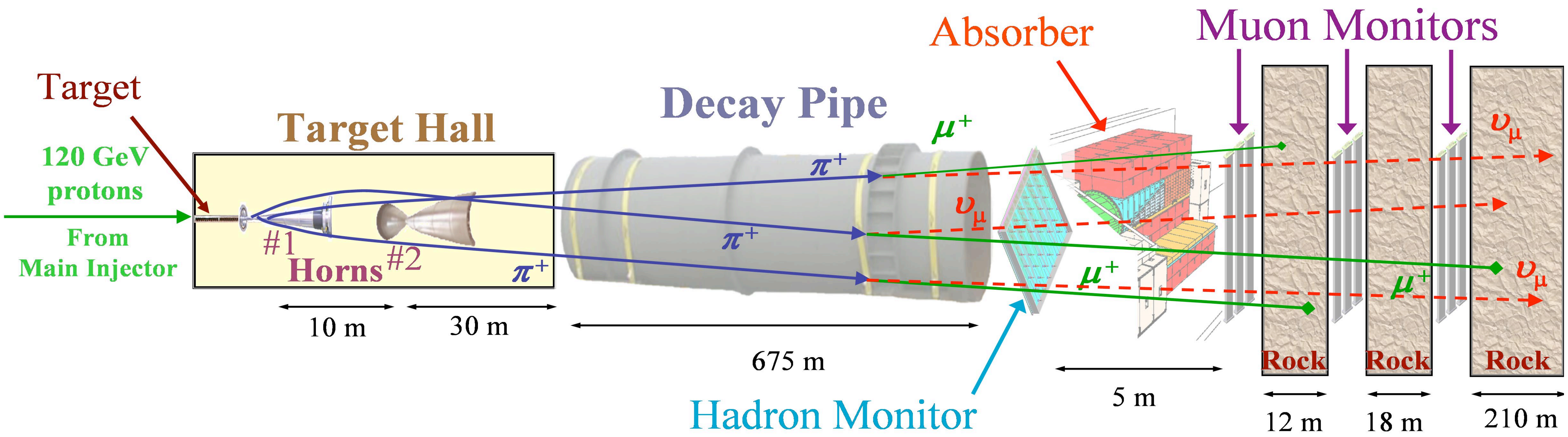
The NuMI beam and the MINOS detectors

The NuMI facility

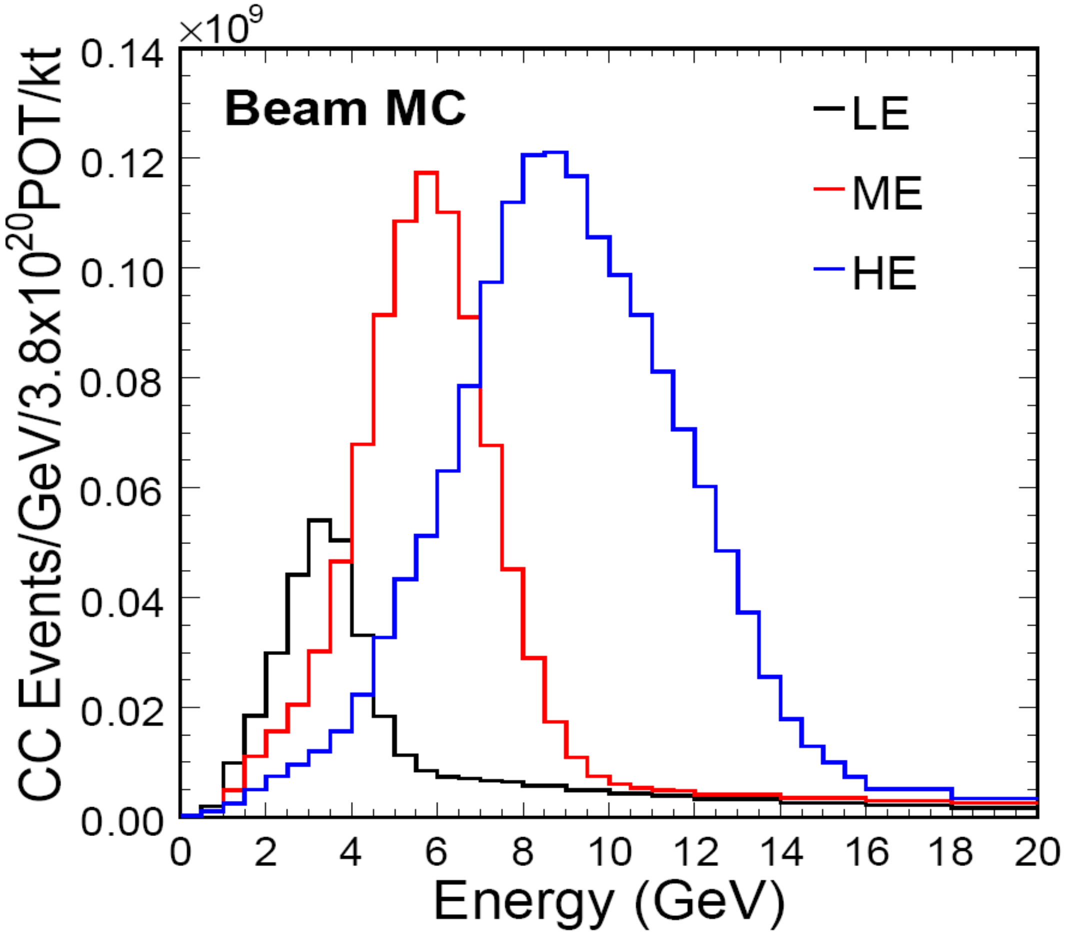


- **Design parameters:**
  - 120 GeV protons from the Main Injector
  - Main Injector can accept up to 6 Booster batches/cycle,
  - Either 5 or 6 batches for NuMI
  - Single turn extraction (10μs)
- **Beam performance (2007)**
  - **Typical intensity**: 2.4x10^{13}ppp every 2.4 seconds (~200kW)
  - **Peak intensity**: 4.05x10^{13}ppp every 2.2s
- **Currently in shutdown - goal for 2008-9 running:**
  - Improve beam power by 30-40% by
    - multi-batch “slip-stacking”
    - 2.2 second cycle time in stacking mode

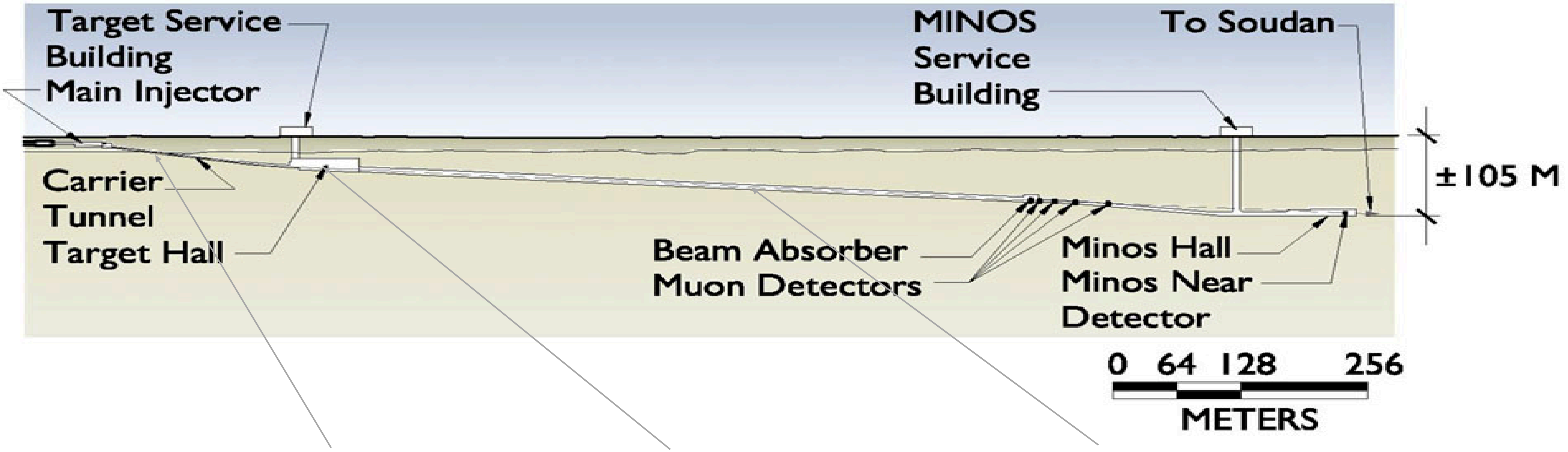
Producing the NuMI beam



- Neutrino beam produced by 120 GeV protons striking a graphite target:
  - π and K decays produce a 98.5% pure ν_μ beam
- Neutrino energy spectrum can be changed by moving target position relative to first horn:
  - Most of our running has been in the low energy **"LE-10"** position, which is optimum for measuring the oscillation parameters
  - Some running in higher energy positions for beam tuning and systematics studies



The NuMI beamline

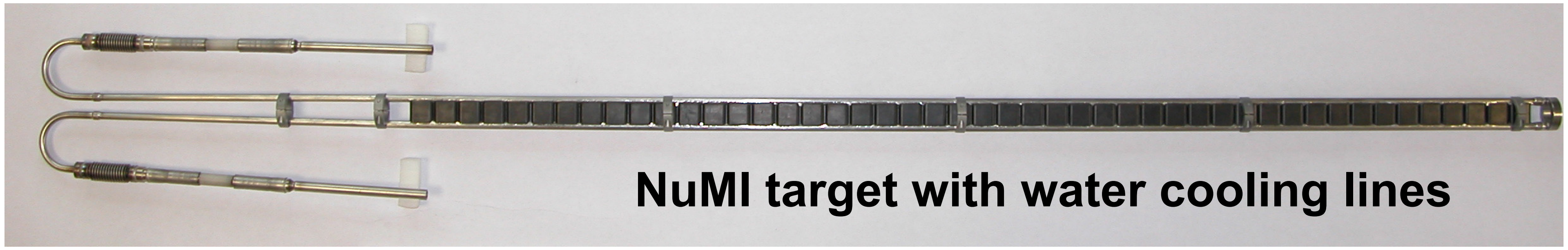


Primary proton line

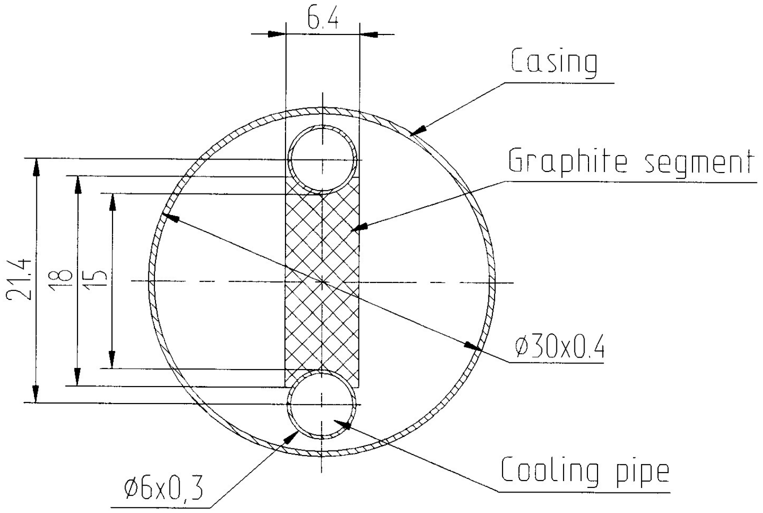
Target hall

Decay pipe

The NuMI target



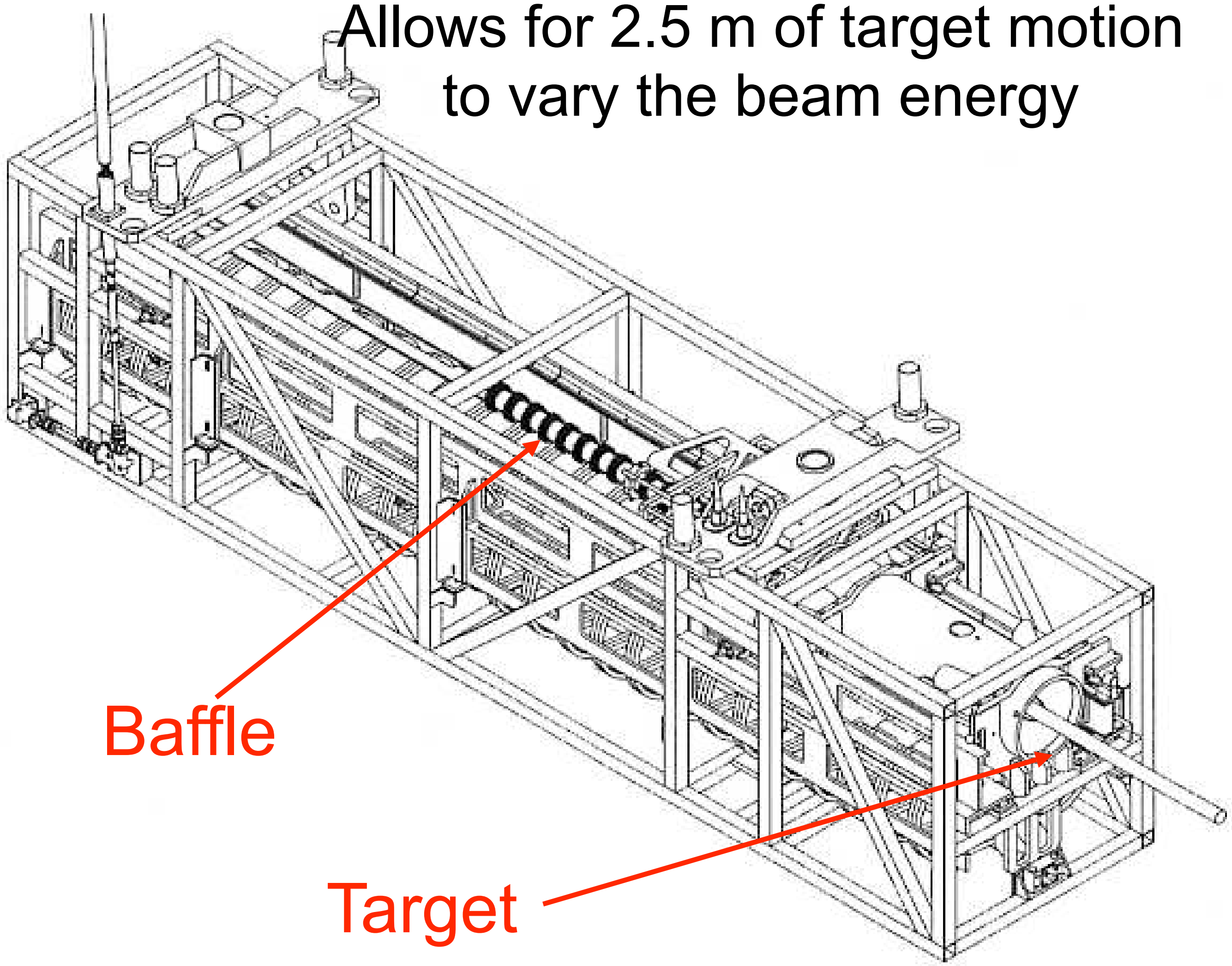
NuMI target with water cooling lines



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

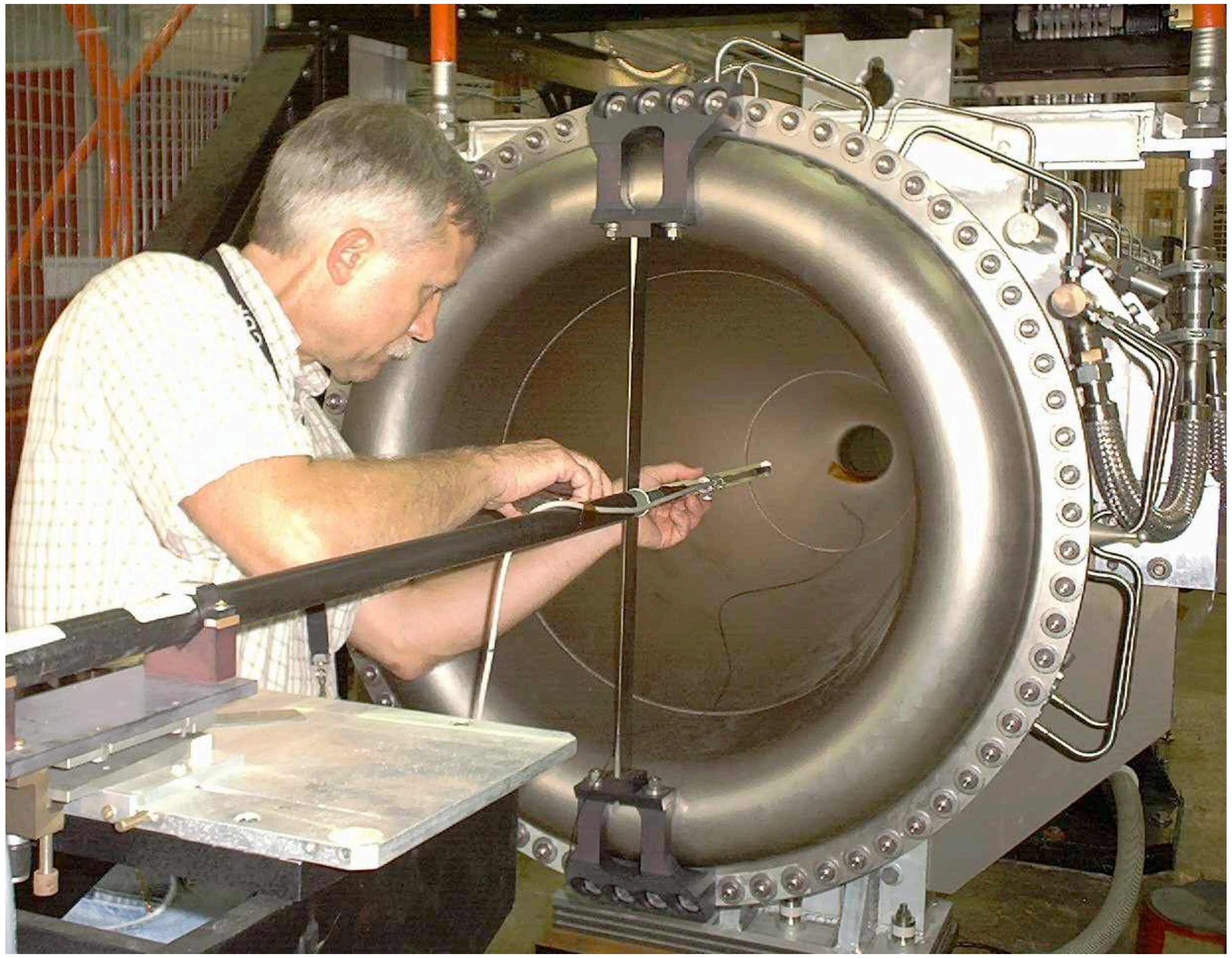
Target/Baffle carrier

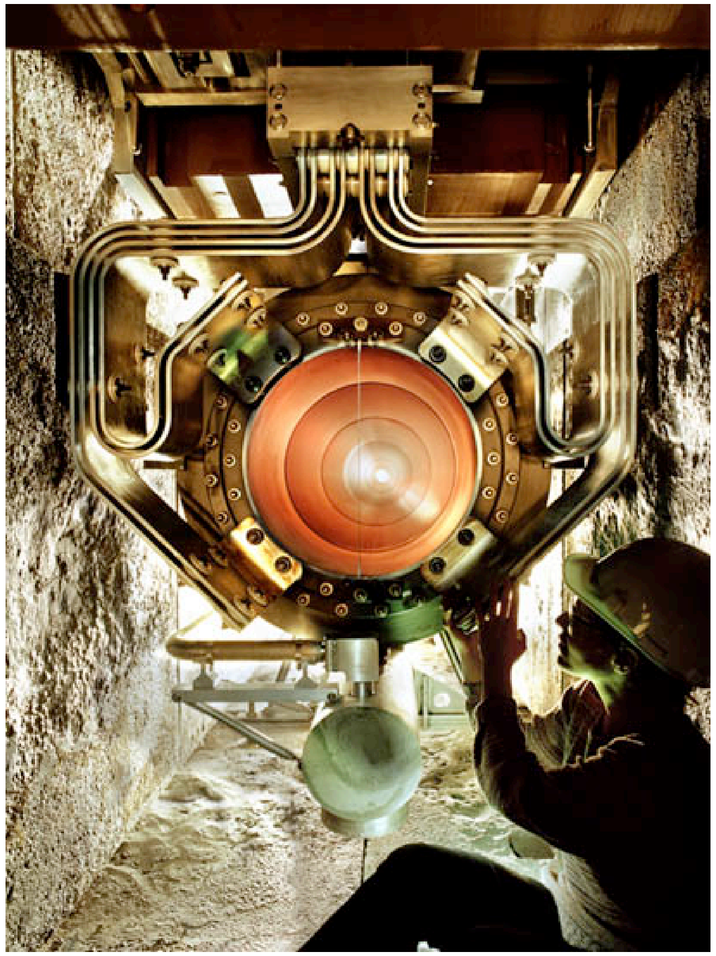
Allows for 2.5 m of target motion to vary the beam energy



Focussing horns

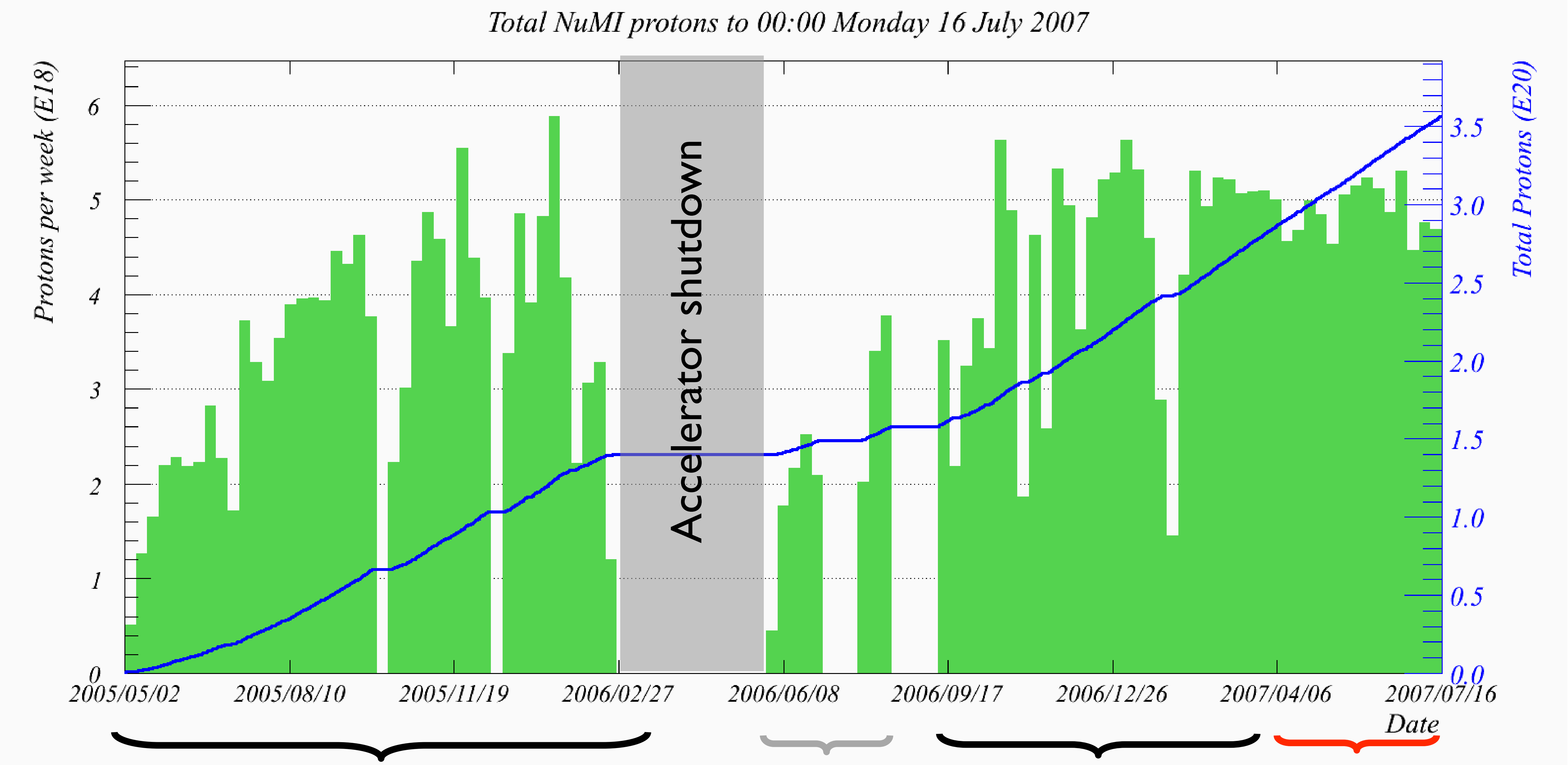
- Two parabolic focussing horns connected in series.
- Nominal horn current at 200 kA
- Produces 3.0 Tesla peak field





Accelerator performance and analysis datasets

Many thanks to FNAL Accelerator Division for the high-quality beam during this period!



RUN I -
1.27×10^{20} POT
(published in PRL)

Higher energy beam running

RUN IIa -
1.23×10^{20} POT
(NEW DATASET)

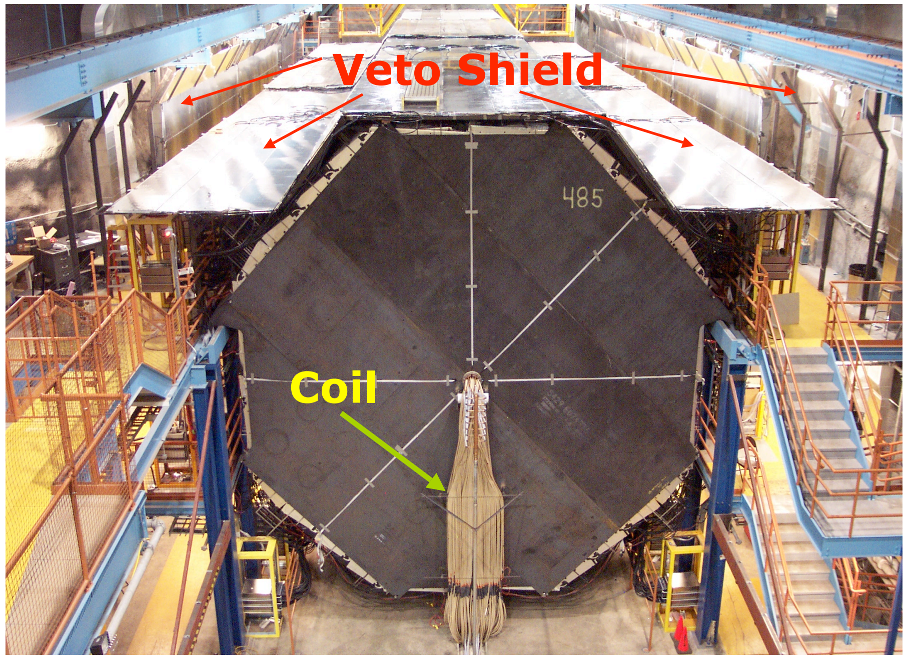
RUN IIb -
$\sim 0.75 \times 10^{20}$ POT
(Not yet analysed)

This analysis: Run I + Run IIa - 2.497×10^{20} POT

The MINOS detectors

“Two functionally identical detectors”

Far Detector at Soudan



Data taking since ~ September 2001. Installation complete in July 2003.

Near Detector at Fermilab

Plane installation fully completed on Aug 11, 2004

5.4 kton mass, 8×8×30m	1 kton mass 3.8×4.8×15m
484 steel/scintillator planes	282 steel and 153 scintillator planes
(x 8 multiplexing)	(x 4 multiplexing after plane 120)
VA electronics	Fast QIE electronics

Magnetised steel - B ~1.2T

Multi-pixel (M16,M64) PMT readout

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

Continuous *untriggered* readout of whole detector (only during spill for the ND)

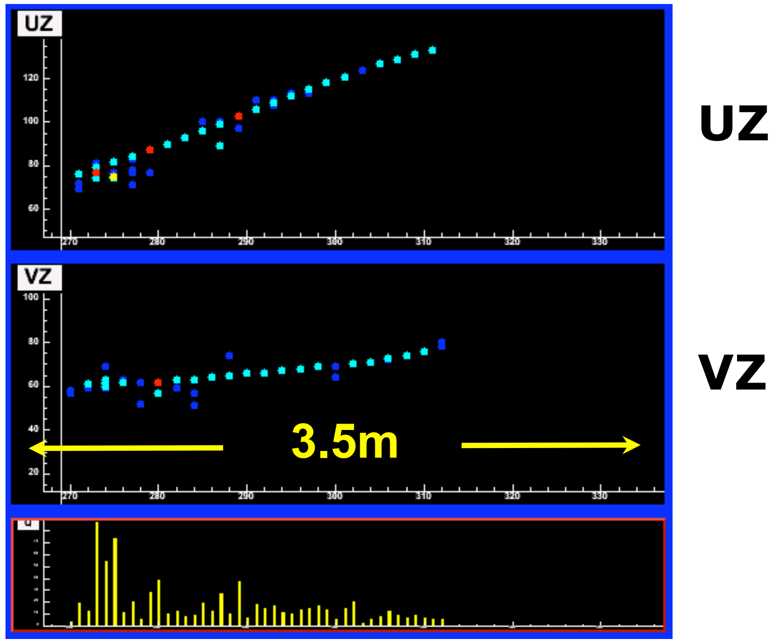
Interspersed light injection (LI) for calibration

Software triggering in DAQ PCs (Highly flexible : plane, energy, LI triggers in use)

Spill times from FNAL to FD trigger farm

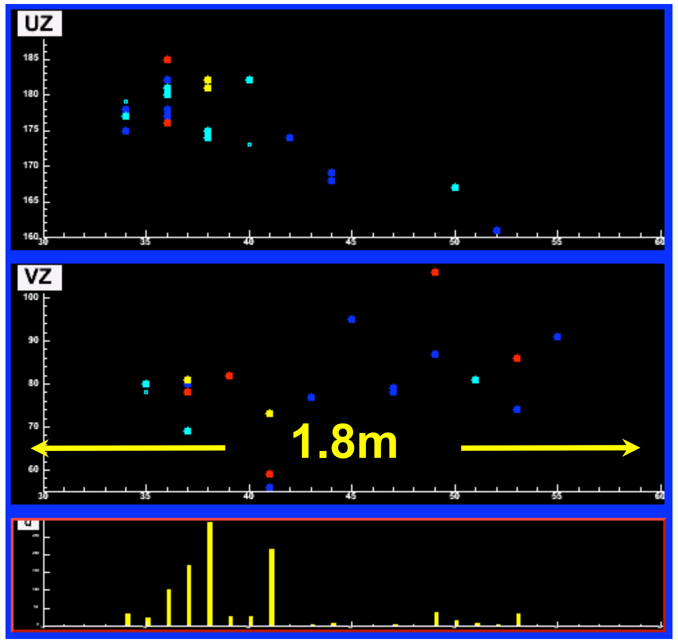
Event Reconstruction

ν_μ CC Event



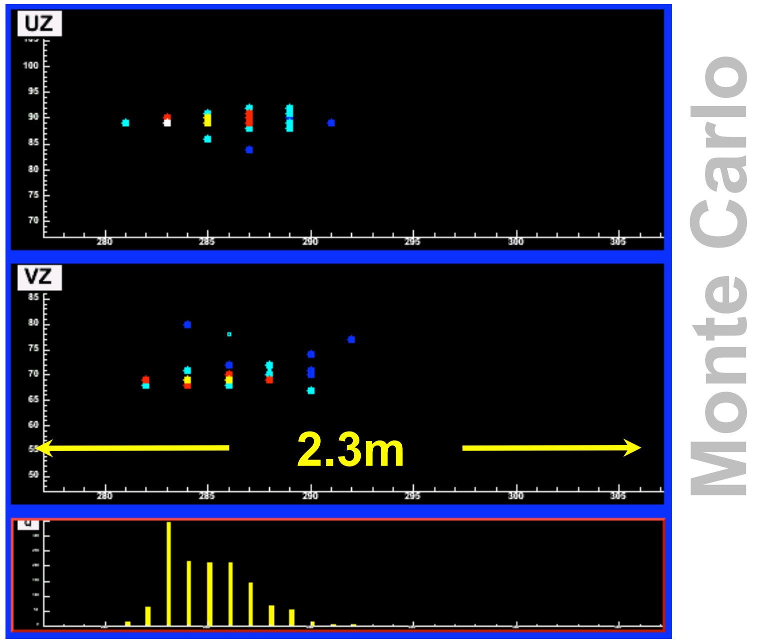
- **long μ track+ hadronic activity at vertex**

NC Event



- **short event, often diffuse**

ν_e CC Event



- **short, with typical EM shower profile**

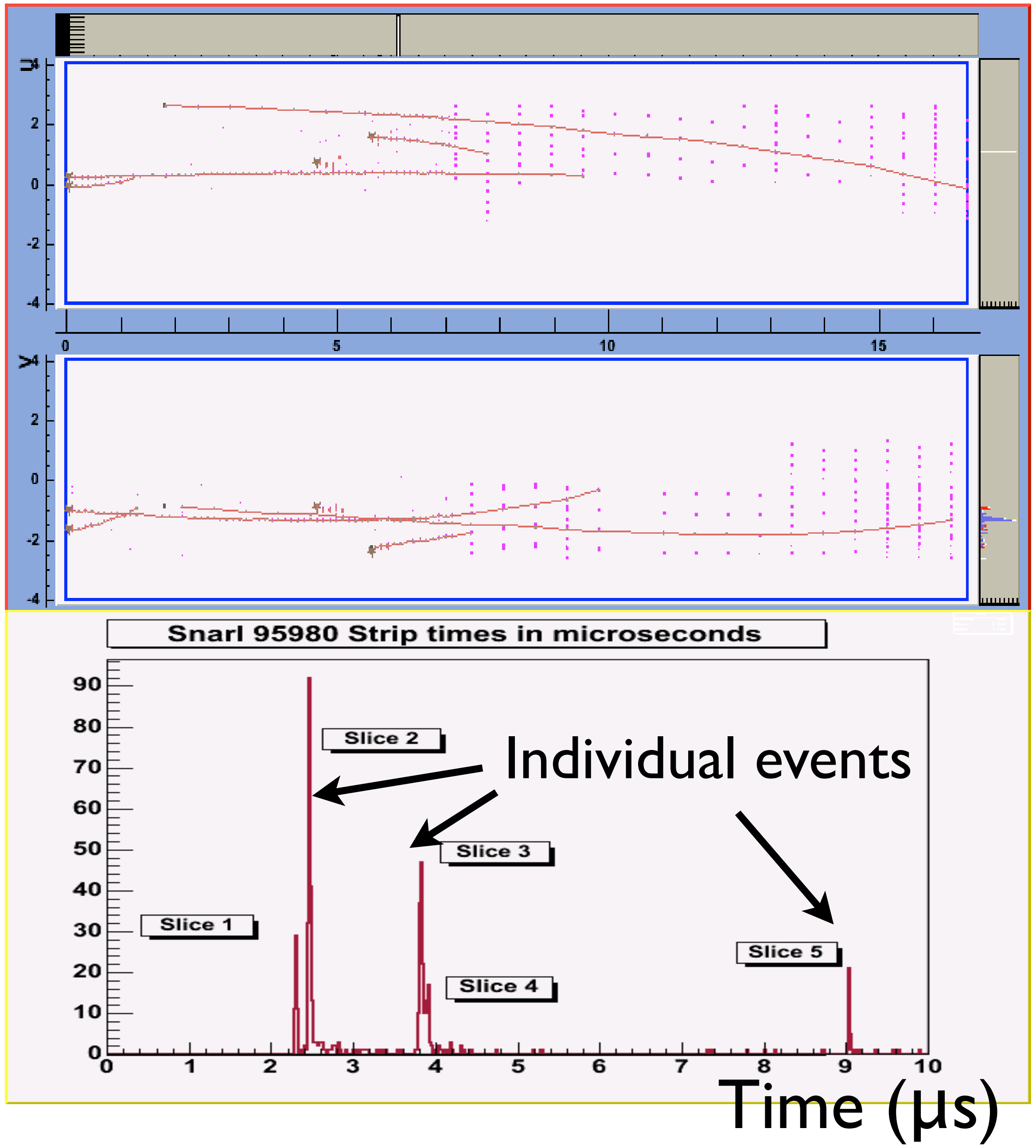
- The signature of ν_μ CC interactions is the presence of a penetrating muon track in the detector
- The reconstructed neutrino energy is the sum of the track momentum (estimated from range if the muon stops in the detector volume, or by curvature if it exits) and the calorimetric energy of the reconstructed hadronic shower

$$E_\nu = \underset{\substack{\uparrow \\ 55\%/\sqrt{E}}}{E_{\text{shower}}} + \underset{\substack{\uparrow \\ 6\%\text{ range, }11\%\text{ curvature}}}{P_\mu}$$

Typical neutrino events

Near Detector

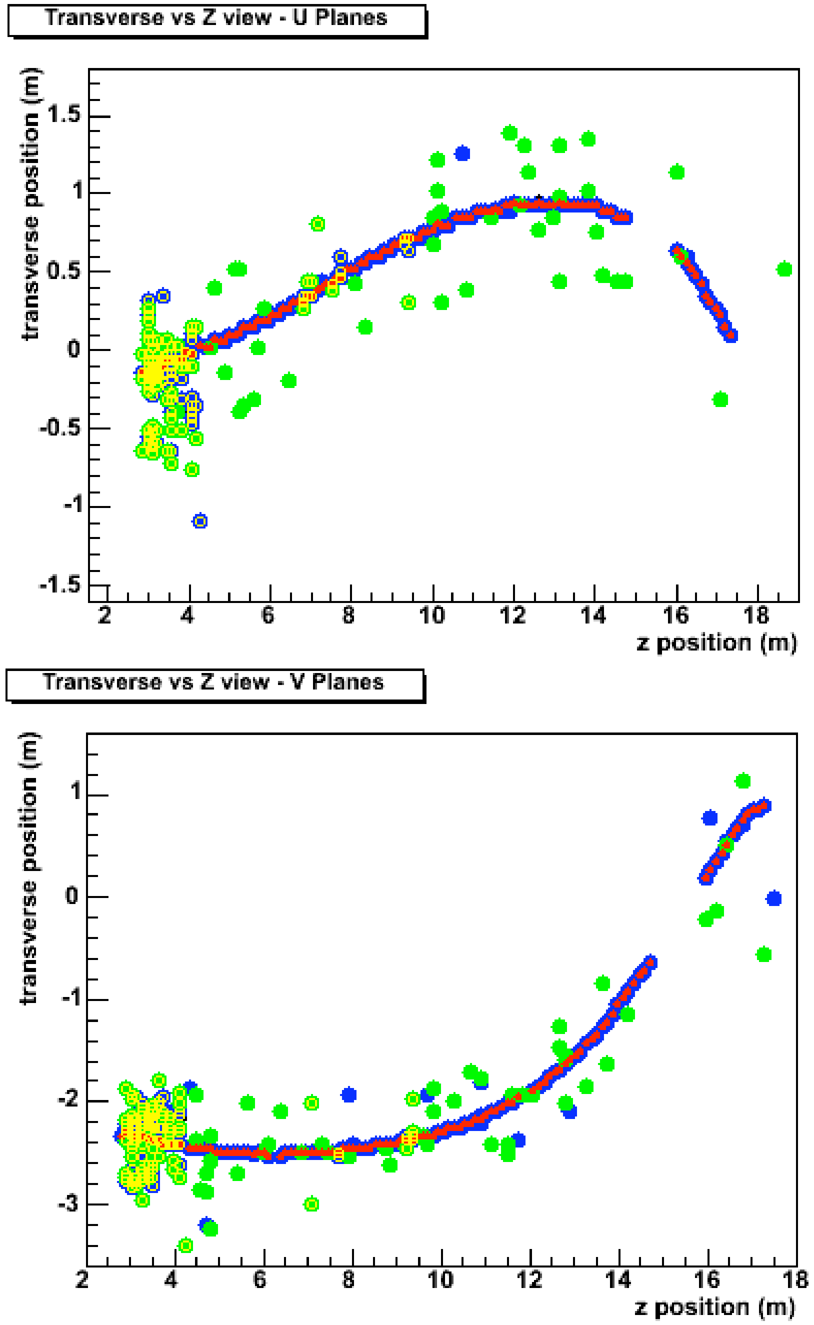
Beam



Individual events

Time (µs)

Far Detector



- Multiple events recorded per beam spill
  - separated by timing and spatial information
- Much lower rate at FD (~10^{-5} x ND rate)

Overview of the analysis method

Brief sketch of the analysis
Analysis improvements relative to the 2006 result
Selecting CC-like events
Comparing Data and MC in the Near Detector
Selecting FD beam-related events

Brief sketch of the analysis

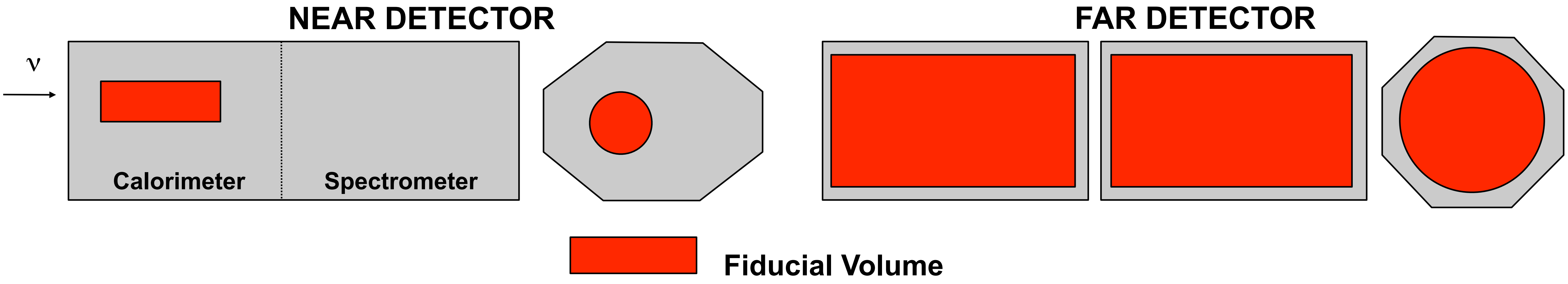
- The strength of the MINOS experiment lies in the "two detector approach"
  - although there are significant uncertainties in the prediction of the absolute NuMI beam flux and cross-sections, these are common to interactions in both Near and Far detectors.
  - By comparing events in the two detectors, we can significantly cancel these uncertainties.
  - We therefore make full use of the Near detector data to predict the neutrino flux in the Far detector, using our Monte Carlo to make small acceptance corrections.
- Our challenge is therefore to select a set of clean and unbiased charged-current events in the two detectors in order to perform the flux extrapolation and oscillation analysis

Improvements over 2006 analysis

- The following improvements were made to the analysis with respect to our 2006 result:
  - **Improved Event reconstruction:**
    - **Re-write of track fitter results in fewer track fit failures in ND and FD**
    - **Improved event builder results in fewer "split" events in ND and FD**
  - **Event selection improvements:**
    - **New CC/NC event separation algorithm results in higher CC selection efficiency and much lower NC background contamination**
    - **Expanded fiducial volume in FD, retains~3% more events**
    - **Relaxed 30 GeV neutrino energy cut**
  - **Interaction model improvements:**
    - **New hadronization and intranuclear rescattering models, provide much better agreement with worlds data. See C. Andreopoulos and T. Yang presentations at NuInt07**
      - **results in +10% change in the overall hadronic energy scale. Comparable to our previously assumed systematic error**
    - **Updated cross-section model based on comparisons with experimental data**

Event selection cuts – Near and Far

- ν_μ CC-like events are selected in the following way:
  1. Event must contain at least one good reconstructed track
  2. The reconstructed track vertex should be within the fiducial volume of the detector:
     - NEAR: 1m < z < 5m (z measured from the front face of the detector), R< 1m from beam centre.
     - FAR: z>20cm from front face, z>1m from rear face, R< 3.7m from centre of detector.
       - **This volume has been expanded relative to our previous analysis - results in 3% more FD events**



  3. The fitted track should have negative charge (selects ν_μ)
  4. Cut on likelihood-based Particle ID parameter which is used to separate CC and NC events.

Selecting charged-current events

- We separate charged-current events from neutral current background on the basis of topological characteristics:
  - A likelihood-based method is used to separate the two samples using, as input variables, quantites related to the prominence of the reconstructed (muon) track in the event.
    - **This method has been improved over the previous analysis by using more discriminating variables, and by using 2 dimensional PDFs (taking correlations between variables into account)**
- Input PDFs used:
  - **Track Topology Variables**
    - Track Pulse Height Per Plane
    - Number of Track-Like Planes
    - Number of Planes
    - Goodness of Muon Track Fit
    - Reconstructed Track Charge
  - **Event Variables**
    - Reconstructed Kinematics Y distribution (Y = Shower Energy / Neutrino Energy)
    - Relative CC/NC Spectrum & CC/NC Priors

PDFs from MC

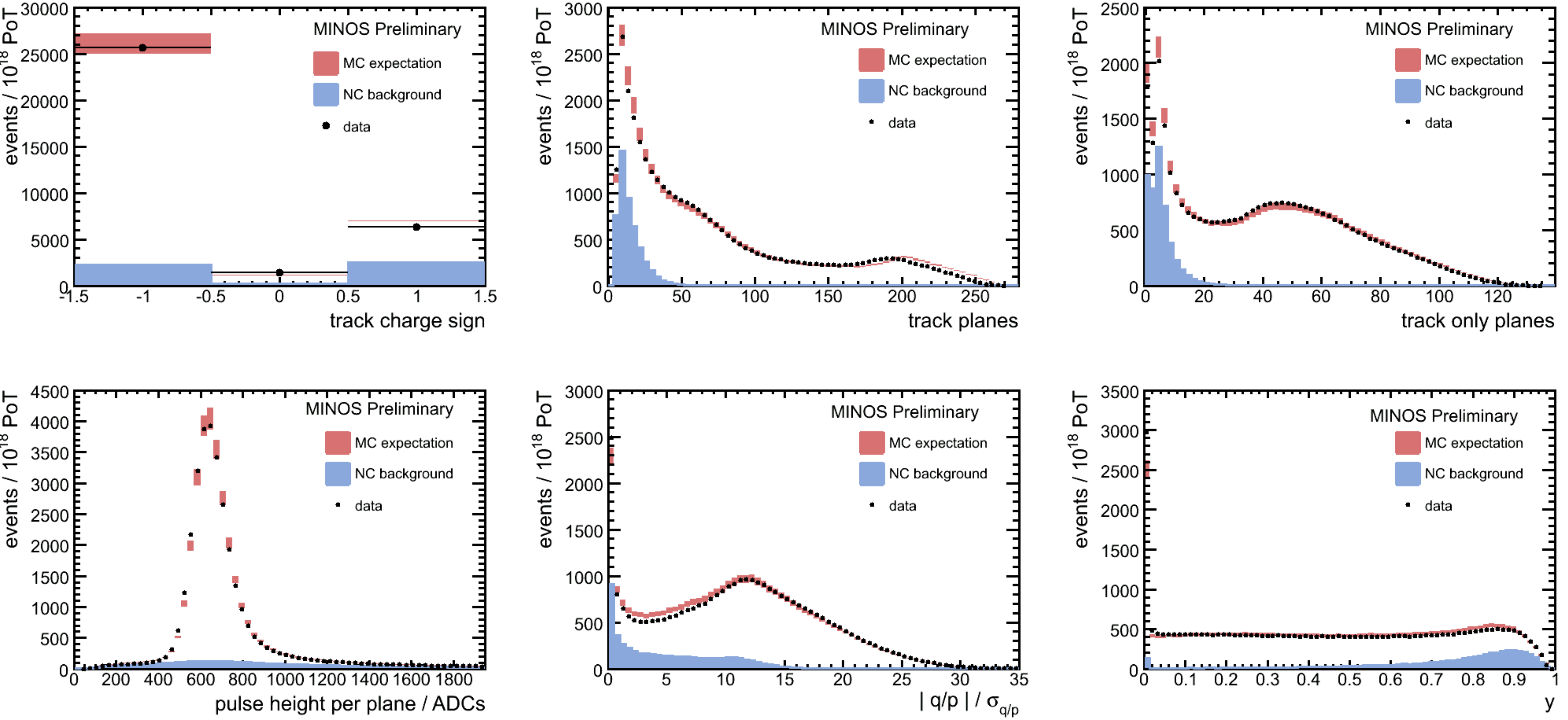
$$P_{CC}(X,Y,Z,\ldots) = P(X|CC)\,P(Y|CC)\,P(Z|CC)\ \ldots\ P(CC)$$

$$P_{NC}(X,Y,Z,\ldots) = P(X|NC)\,P(Y|NC)\,P(Z|NC)\ \ldots\ P(NC)$$

$$\boxed{PID = \frac{P_{CC}}{P_{CC} + P_{NC}}}$$

OUTPUT PID PARAMETER

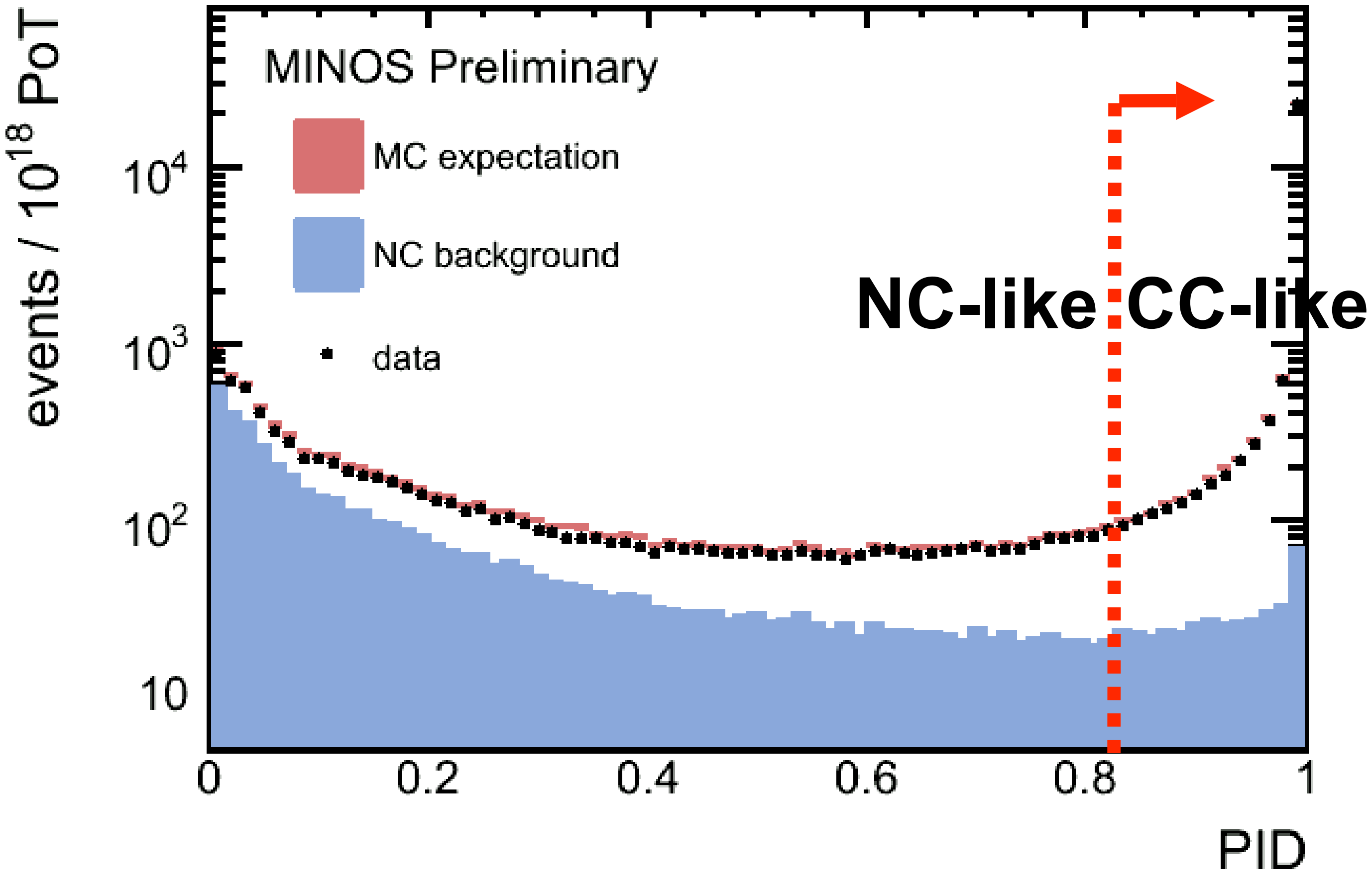
Near detector Data/MC comparisons: PID inputs



- Good agreement between data and MC

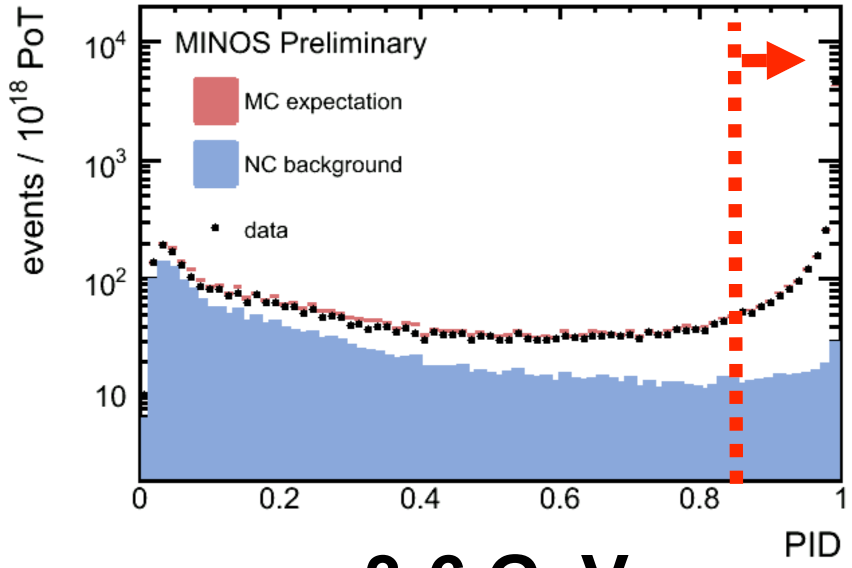
Near Detector: PID distributions

ALL ENERGIES

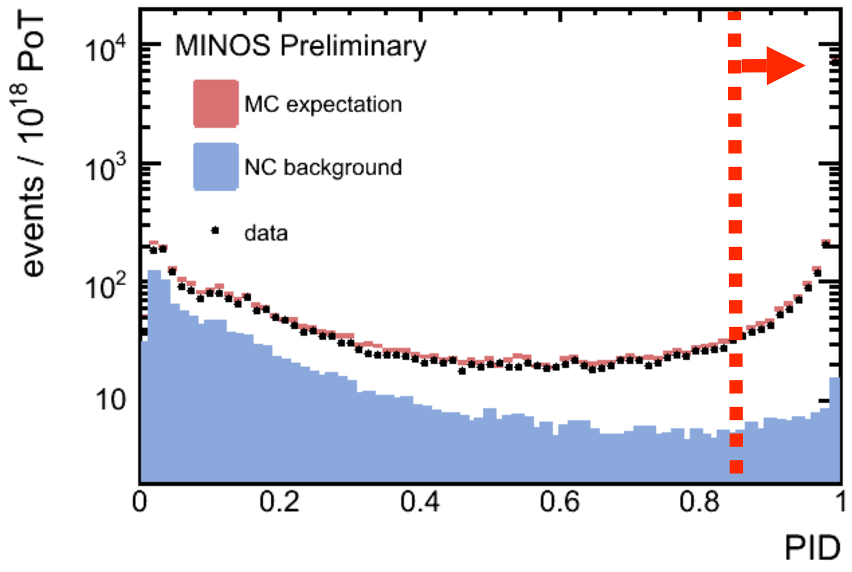


Cut at PID>0.85 to separate CC-like and NC-like events

0-3 GeV



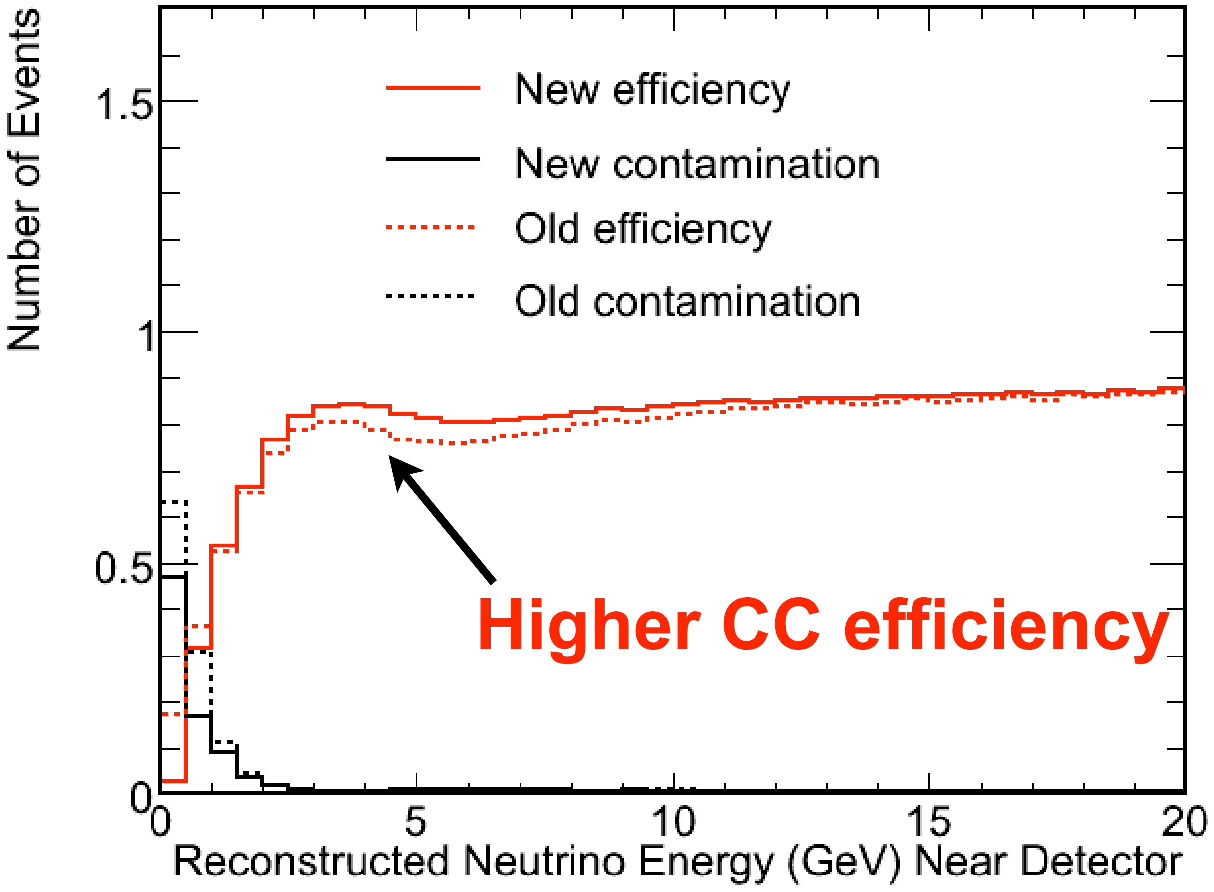
3-6 GeV



- Agreement between data and MC is good for all neutrino energies

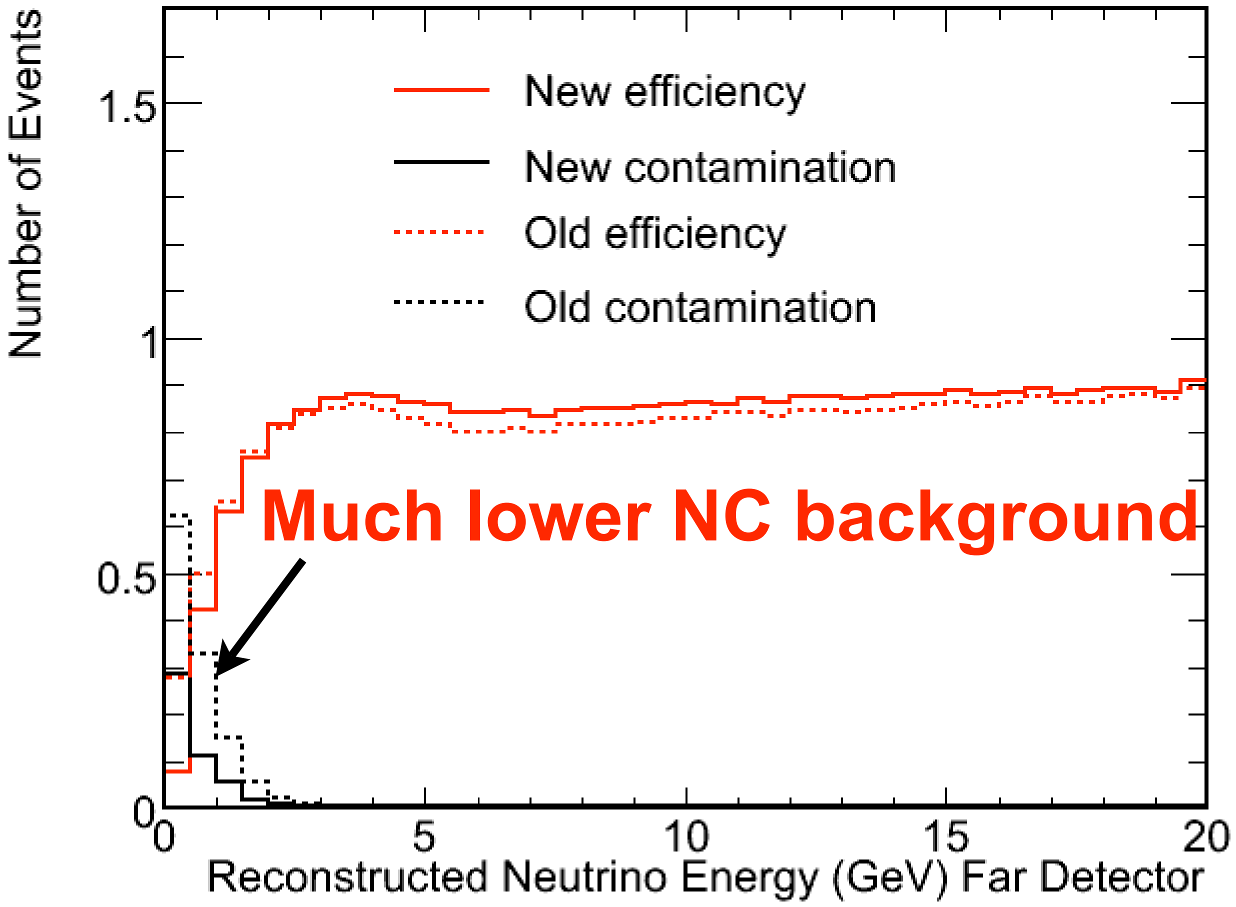
Improvements in selection efficiency

NEAR DETECTOR



Higher CC efficiency

FAR DETECTOR

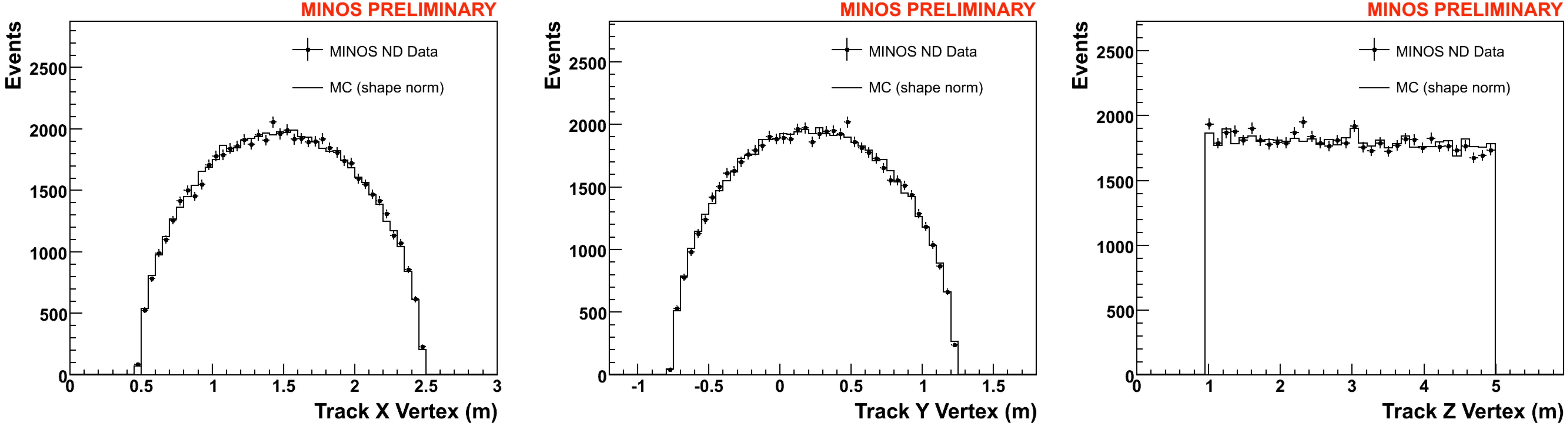


Much lower NC background

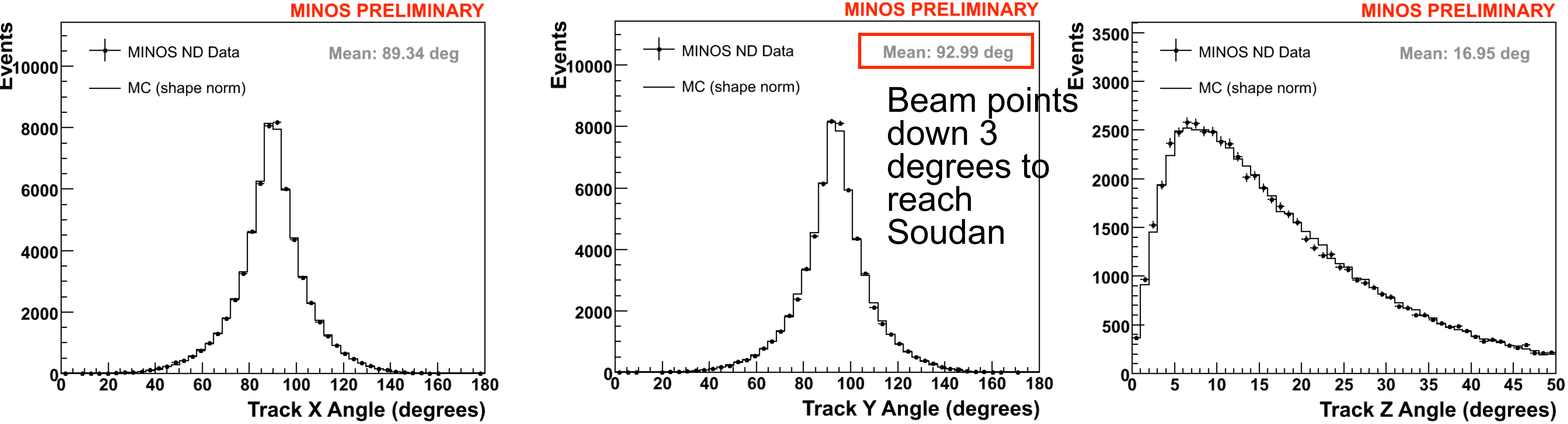
- New PID yields ~2% higher CC selection efficiency and a factor of 2.2 lower NC background contamination than old PID
    - NC background rate important as these events "obscure" the oscillation dip at low reconstructed neutrino energies
- **Adoption of new PID resulted in a significant (~10%) improvement in our sensitivity to Δm^2 and $\sin^2 2\theta$**
- **NC background uncertainty was the leading systematic error in our previous analysis. With the use of the new PID, this error is significantly reduced**

Near Detector: Data/MC comparisons

TRACK VERTICES



TRACK ANGLES



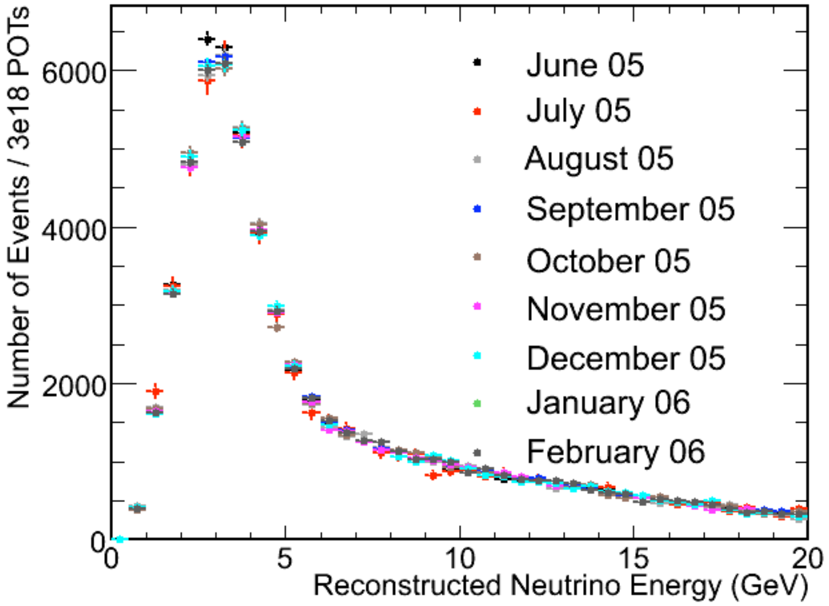
Beam points down 3 degrees to reach Soudan

- Low-level quantities agree well

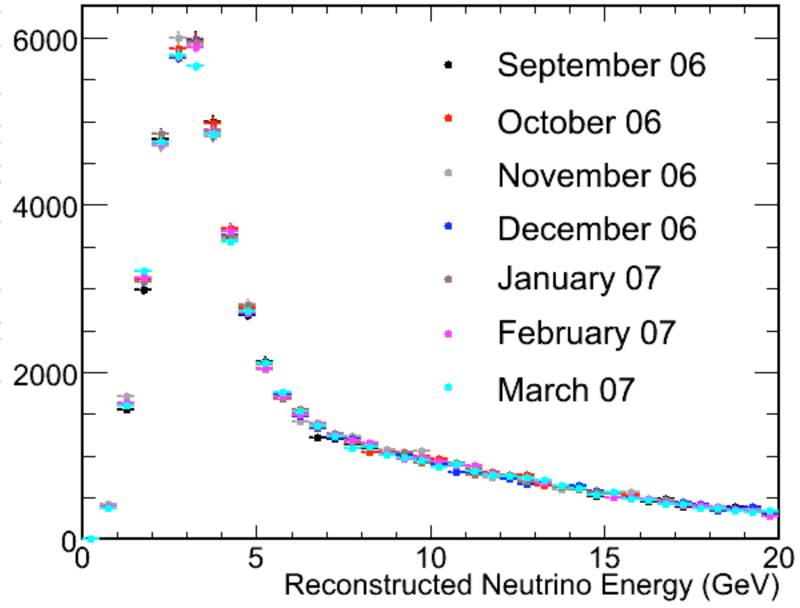
Stability of the reconstructed spectrum

- 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.
- Run I and RunIIa data were taken with slightly different target positions (corresponding to a ~3% change in the overall event rate/POT). They are therefore treated as independent datasets as far as Near-Far extrapolation is concerned. We also apply a correction factor to the MC to account for the target position change

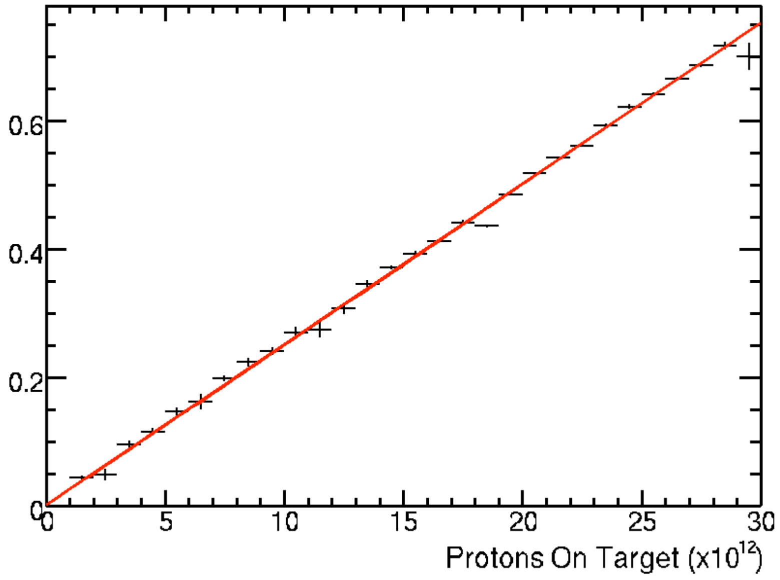
Run I spectra by month



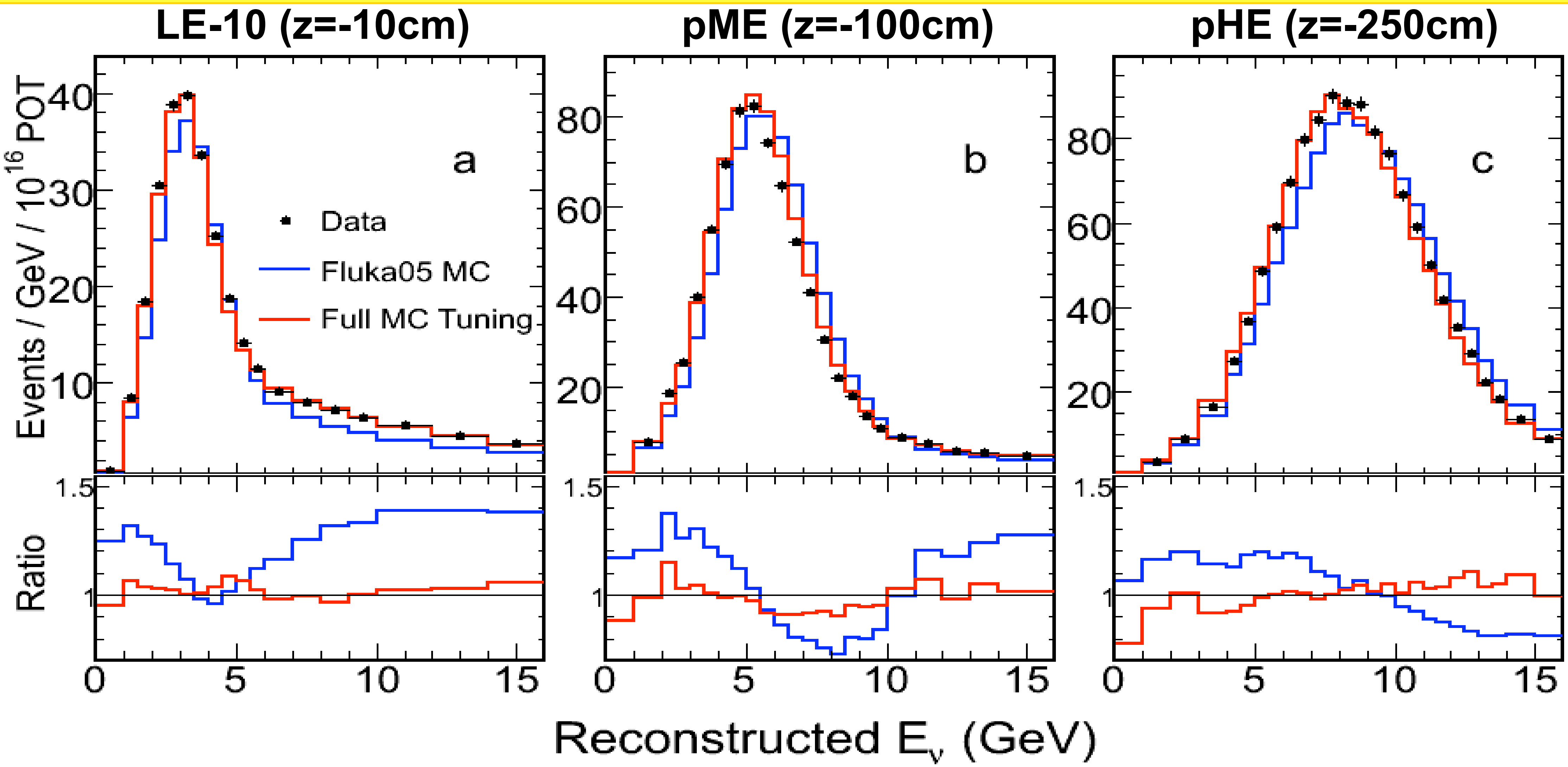
Run IIa spectra by month



Reconstructed events/POT



ND Energy spectra - hadron production tuning



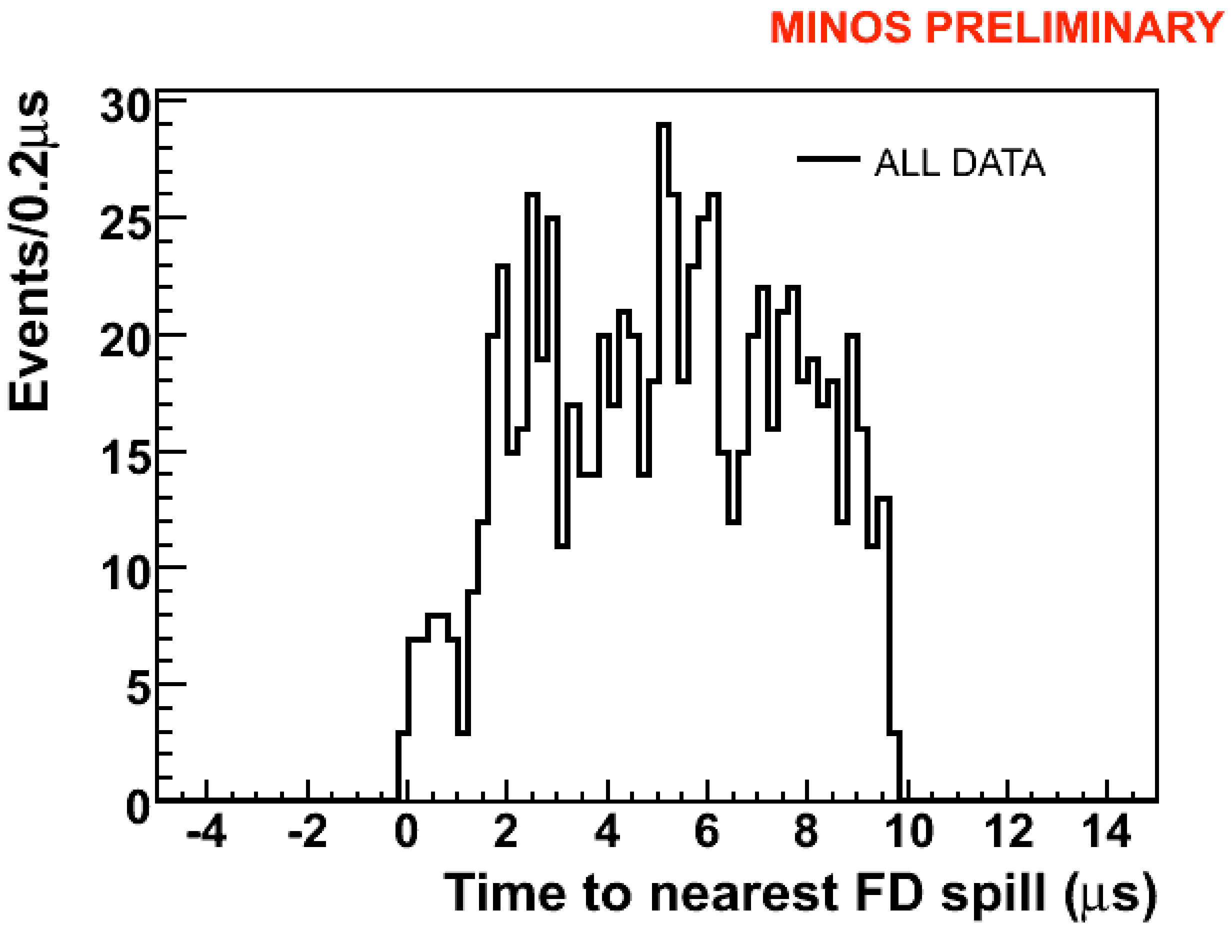
- We have collected data in 7 different beam configurations:
  - different target positions and horn current settings
- We observe a discrepancy between the ND data and our nominal (FLUKA05) MC which changes with beam setting
  - **this suggests that the source of this discrepancy is due to beam modelling uncertainties, rather than cross-section uncertainties.**
- We have used this data to tune our MC using a function that varies smoothly with hadronic x_F and p_T. The tuned MC is in substantially better agreement with data in the various beam configurations

Summary of ND Data/MC agreement

- Large sample (~10^6) of selected events in the ND allows detailed data/MC checks to be carried out.
- Good agreement observed in low-level quantities, PID inputs and the output CC/NC separation parameter. In addition, the reconstructed energy spectrum is stable over the duration of Run I and Run IIa
  - these indicate that our detector modelling is satisfactory and that there are no significant intensity related biases in our reconstruction codes.
- The observed energy spectra show differences between data and MC.
  - this is not surprising given the large *a priori* uncertainties in hadron production and neutrino cross-sections
  - however, by using an extrapolation technique that directly uses the ND data, we can very significantly reduce the effect of these uncertainties on our predicted FD spectrum

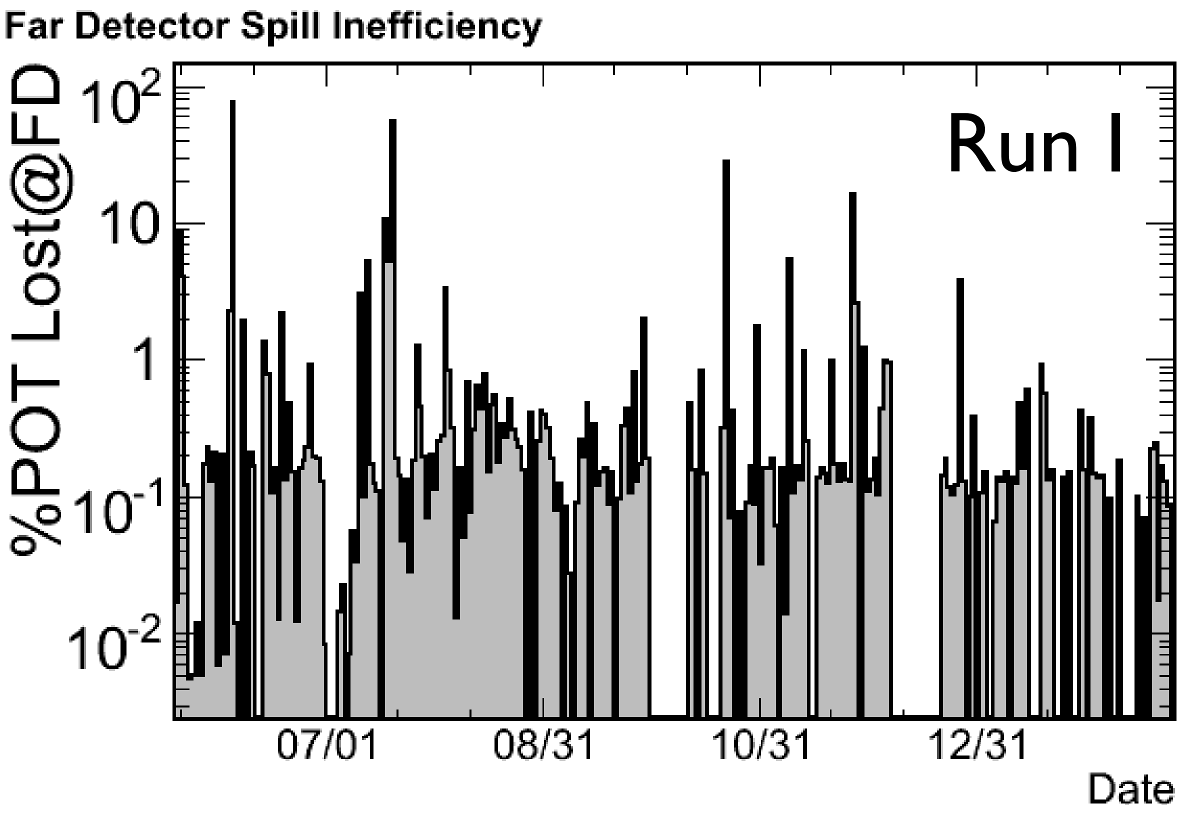
Selecting Far Detector beam events

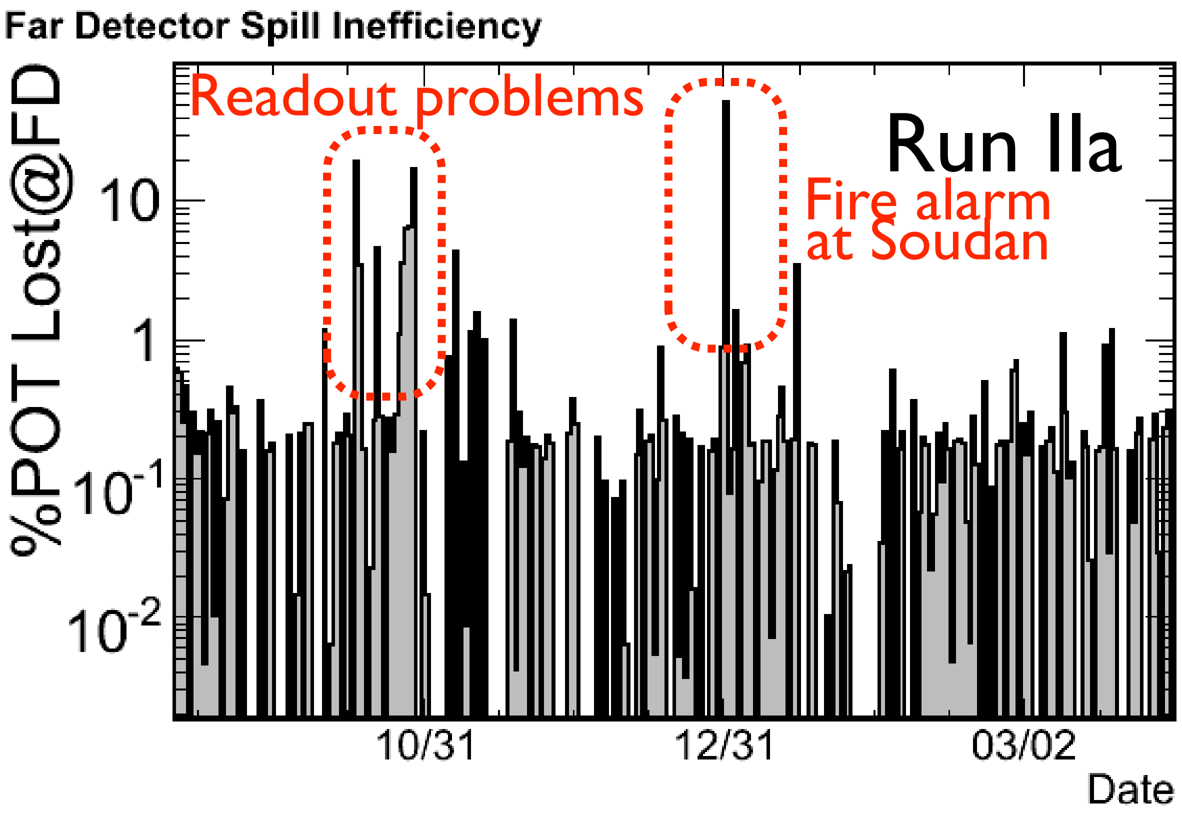
- Far detector beam events are selected on the basis of timing and topology
  - The events must be in coincidence with the known times of NuMI beam spills (within a 50μs window)
  - The events must point away from FNAL (track angle <50° relative to beam direction)
- In addition, the reconstructed events must be located within the fiducial volume of the detector
- These criteria select a very clean sample of neutrino events - expected background from CR muons < 0.5 events



Far Detector Livetime

POT weighted inefficiency - 100-livetime(%)

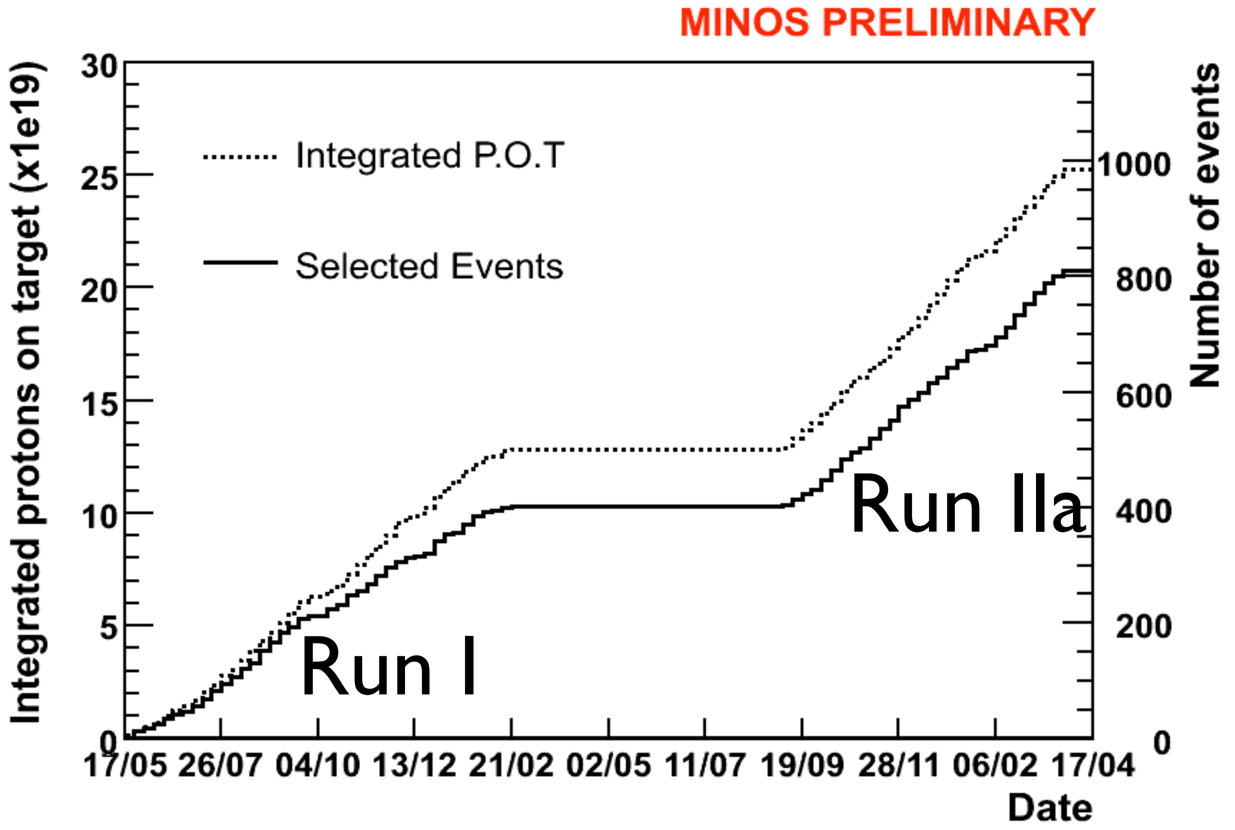


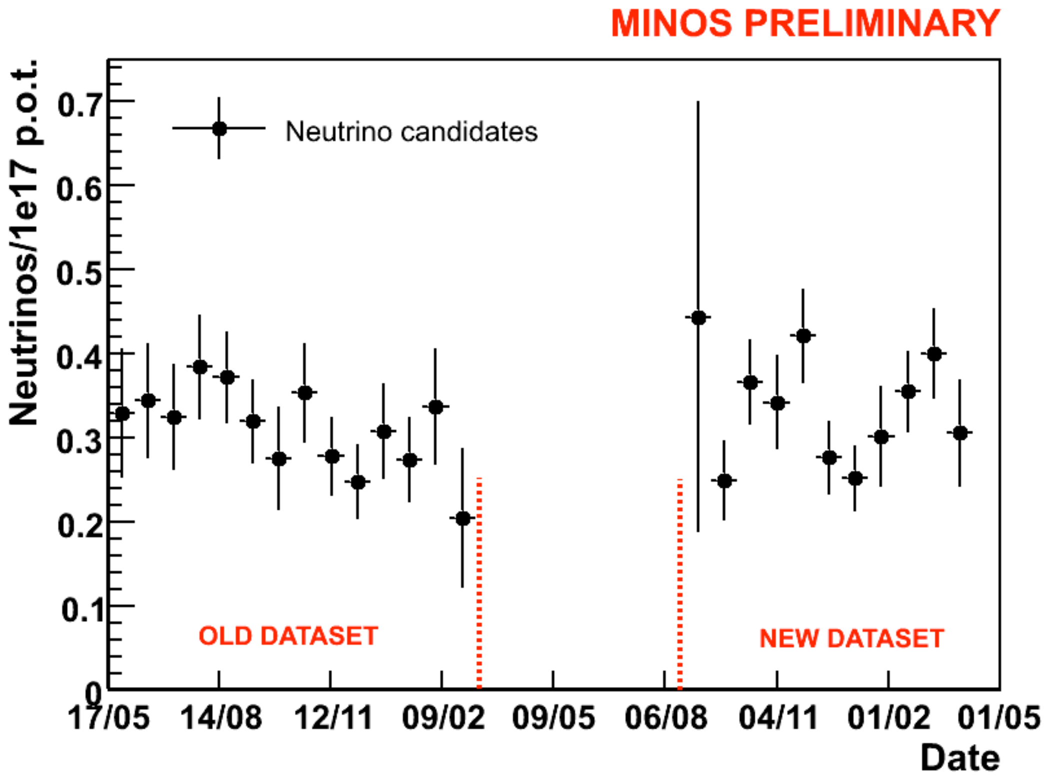


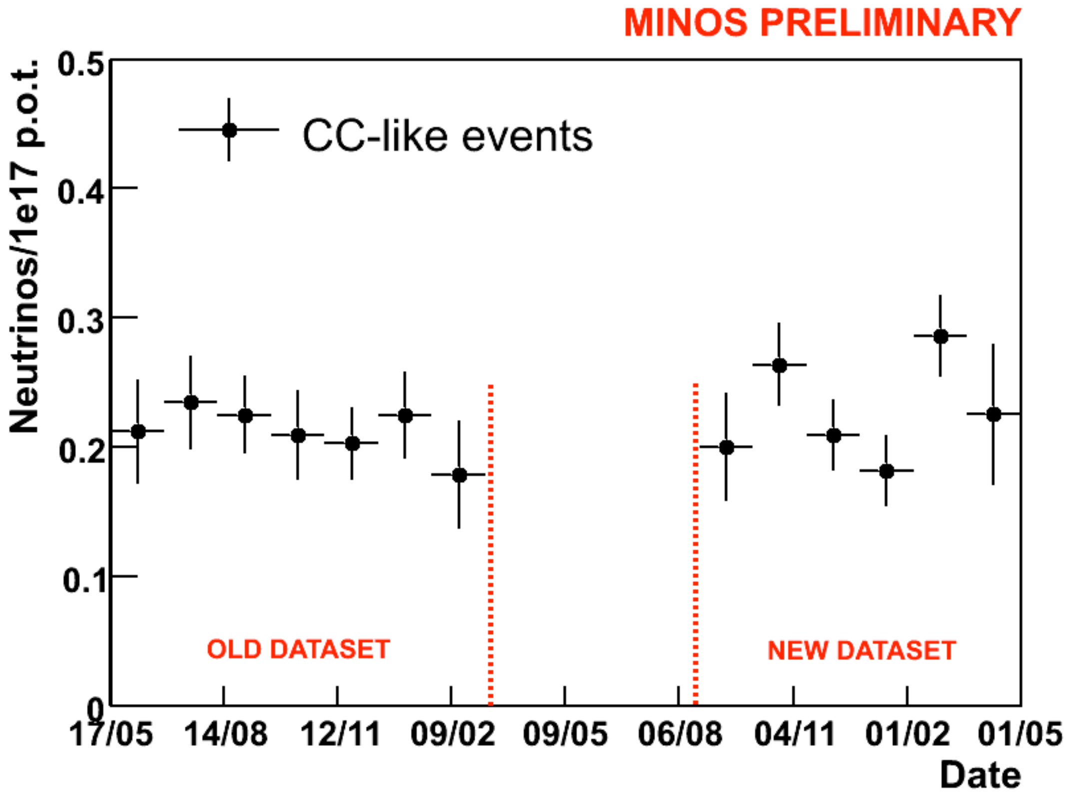
- FD livetime is >99% (RunI: 98.9%, RunIIa: 99.5%)
  - intrinsic ~0.1% inefficiency due to calibration runs
- Many thanks to everyone who helped to maintain such a high livetime!

FD events as a function of time

- Plot shows number of selected FD events taken in the LE-10 beam configuration as a function of time
- Good agreement between number of selected events and protons on target
- Events/POT distributions are flat as a function of time

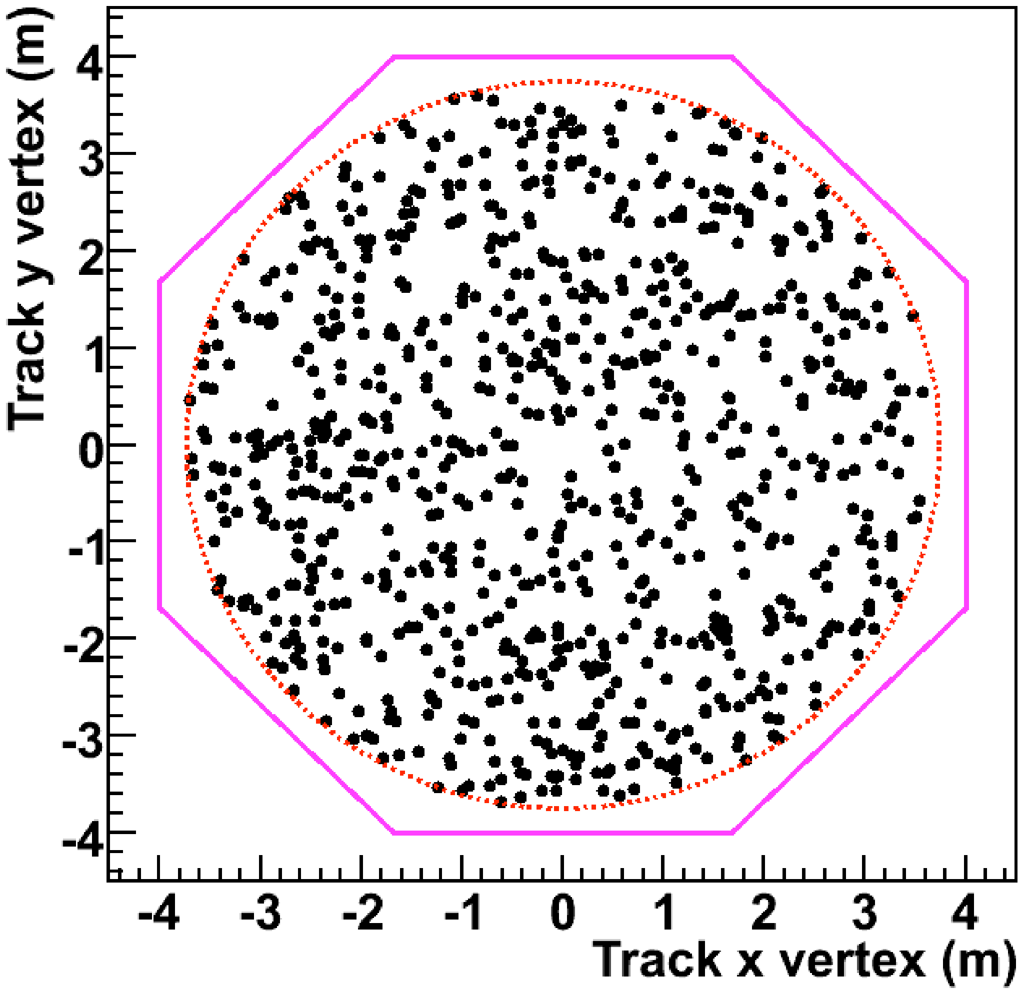




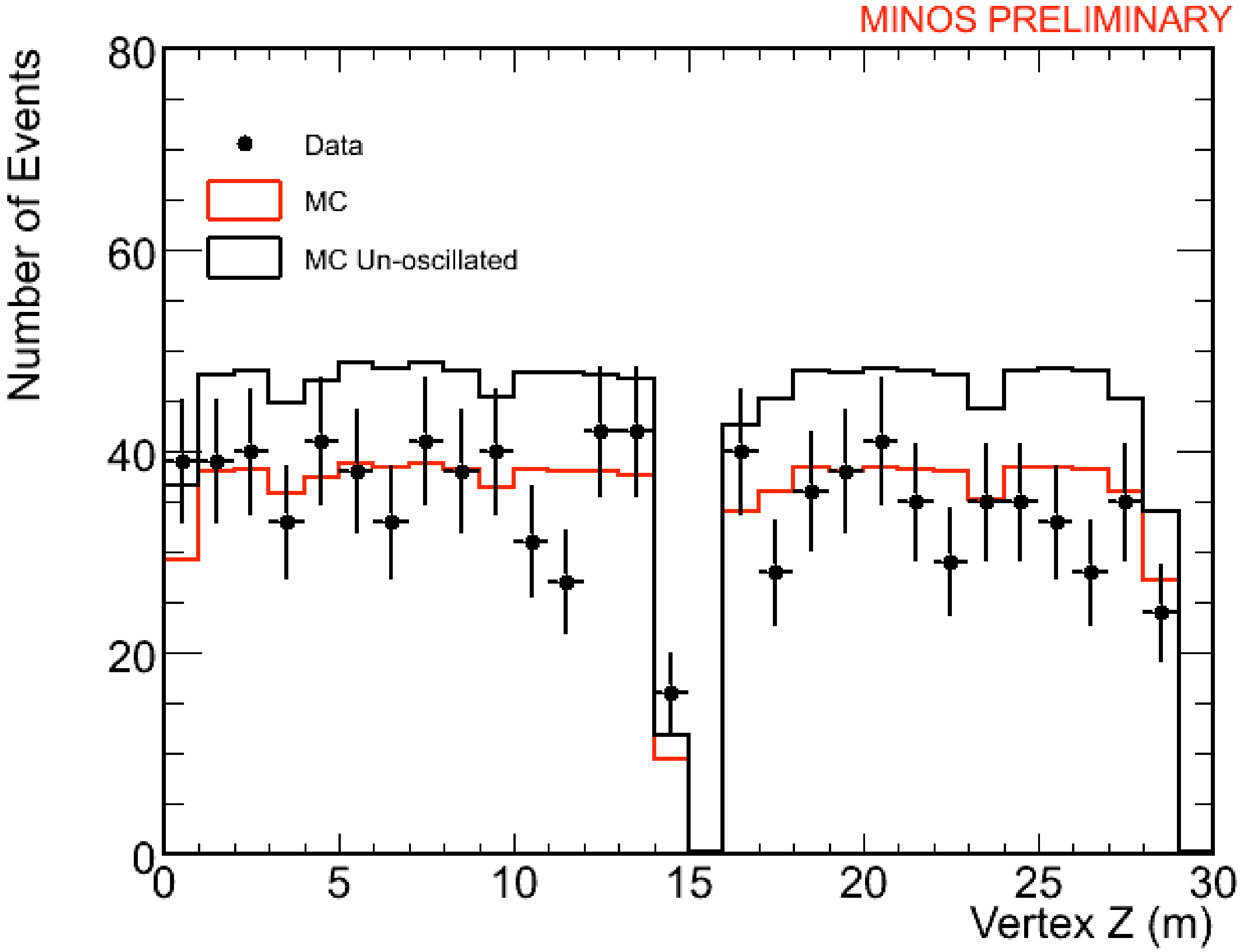


FD track vertices

Track X-Y vertex position



Track Z vertex position



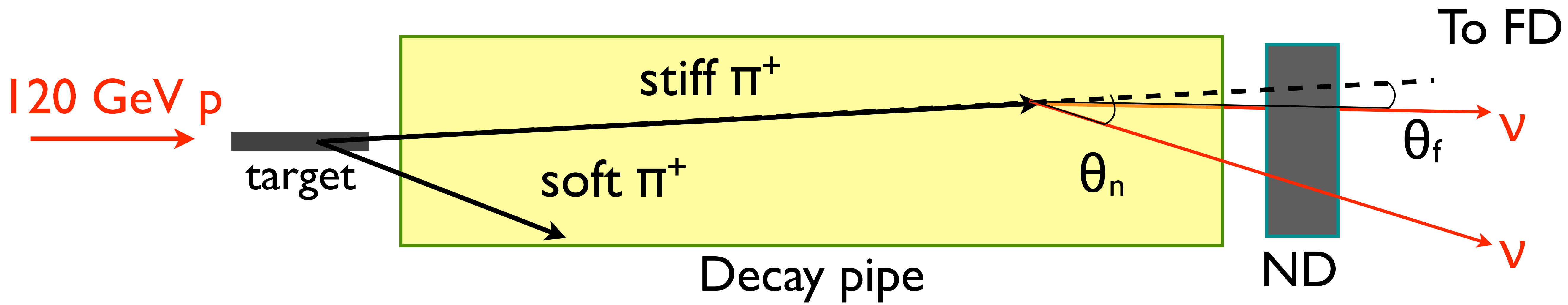
- Uniform distribution of track vertices
  - no evidence of background contamination

Near-Far extrapolation and systematic errors

Extrapolating the flux

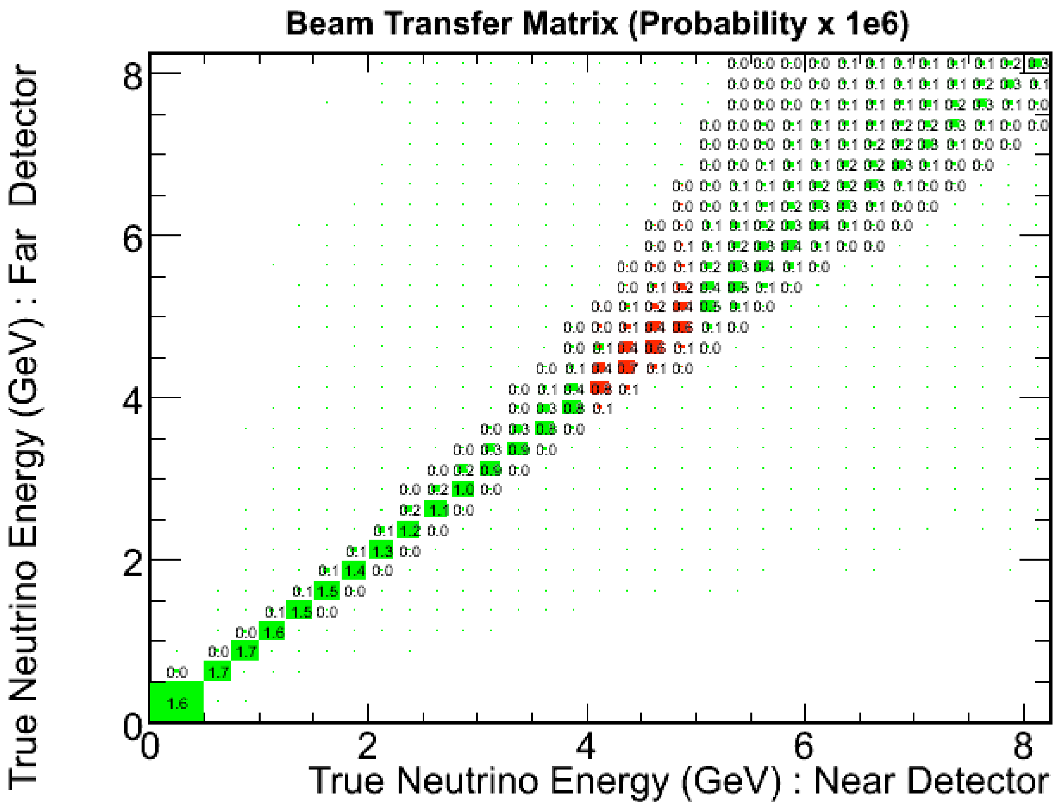
- We directly use the Near detector data to perform the extrapolation between Near and Far, **using our Monte Carlo to provide necessary corrections due to energy smearing and acceptance.**

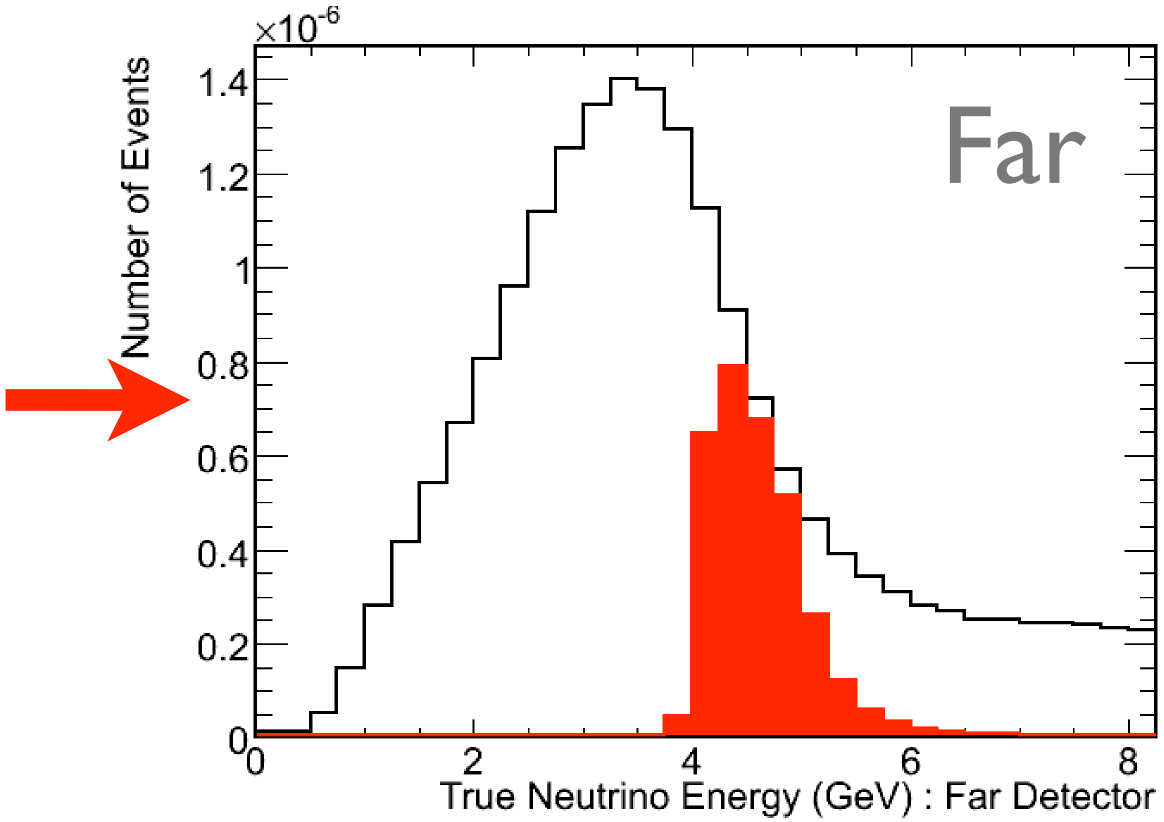
- Use our knowledge of **pion decay kinematics and the geometry of our beamline** (extended neutrino source, seen as point-like from the Far Detector) **to predict the Far detector energy distribution from the measured Near detector distribution**

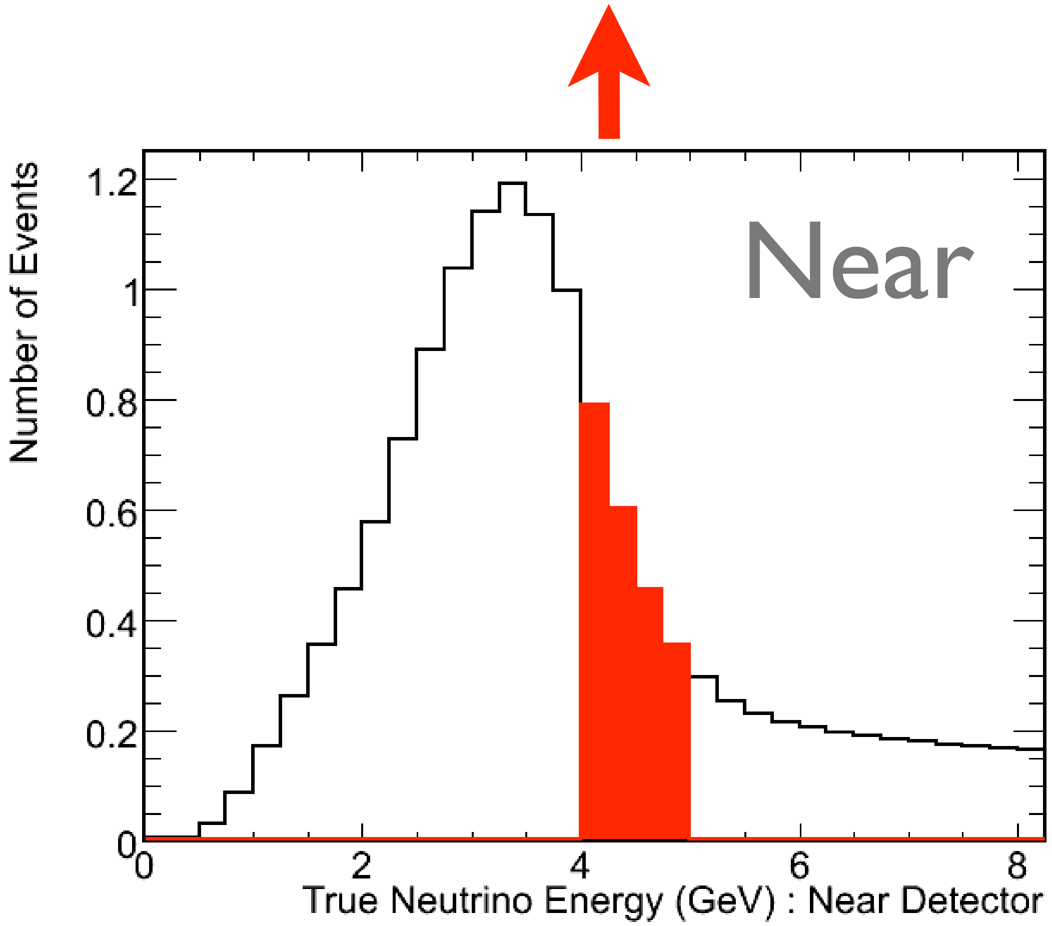


- This method is known as the "**Beam Matrix**" method.
- By making direct use of the ND data, we significantly cancel uncertainties due to **beam modelling and cross-sections**, which are common to both Near and Far detector events

The Beam Matrix

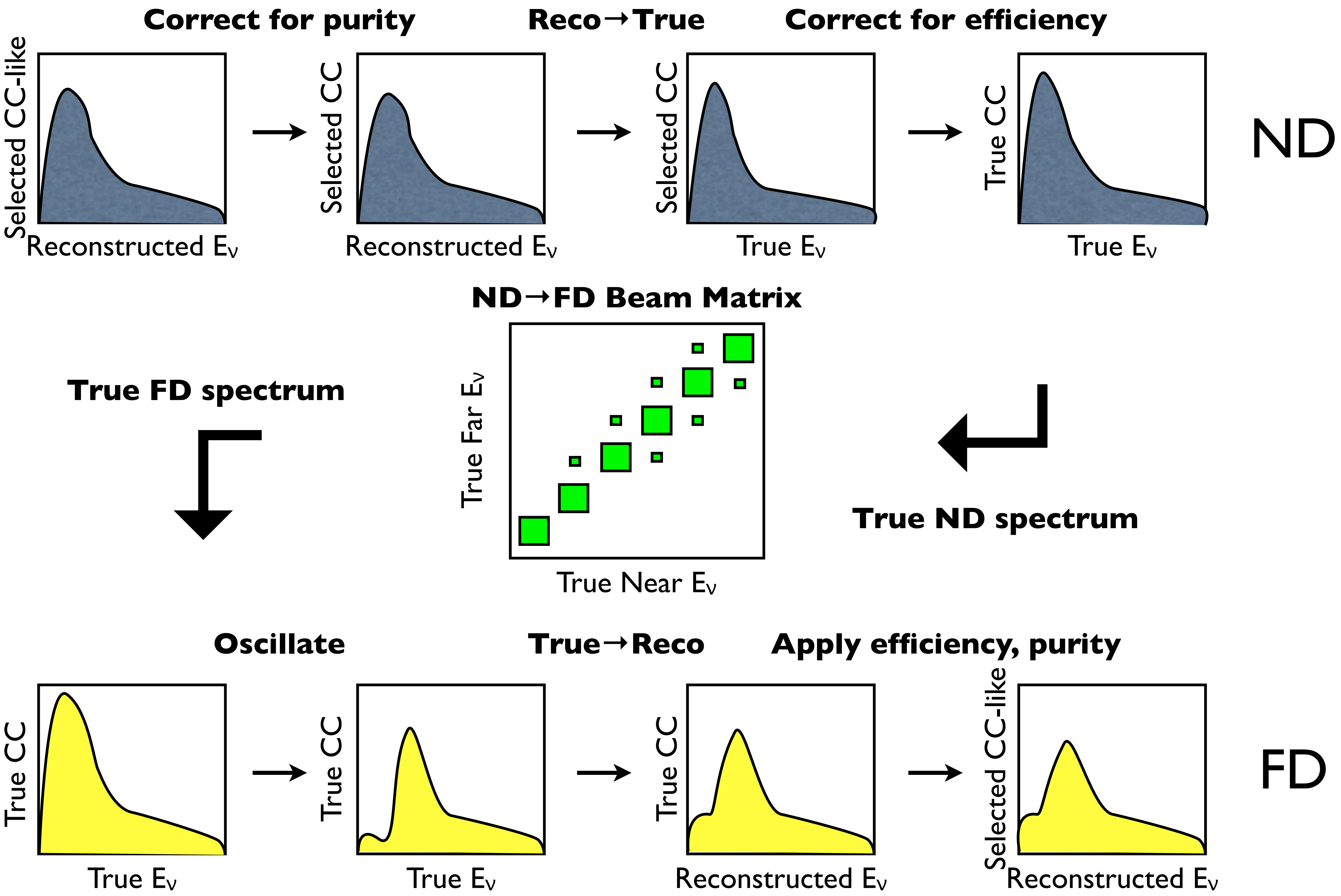






- Beam Matrix encapsulates the knowledge of pion 2-body decay kinematics & geometry.
- Beam Matrix provides a very good representation of how the near and far detector spectra relate to each other.

Steps in the Beam Matrix method



Correct for purity **Reco→True** **Correct for efficiency**

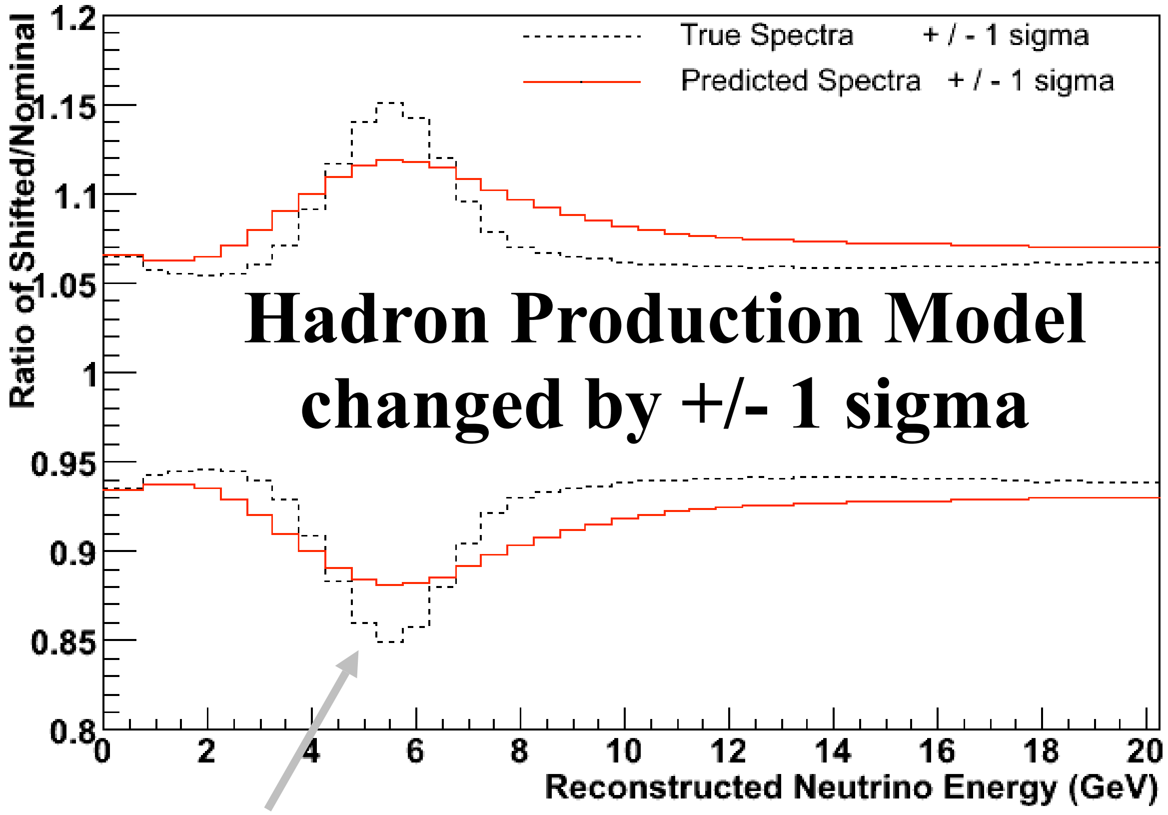
ND→FD Beam Matrix

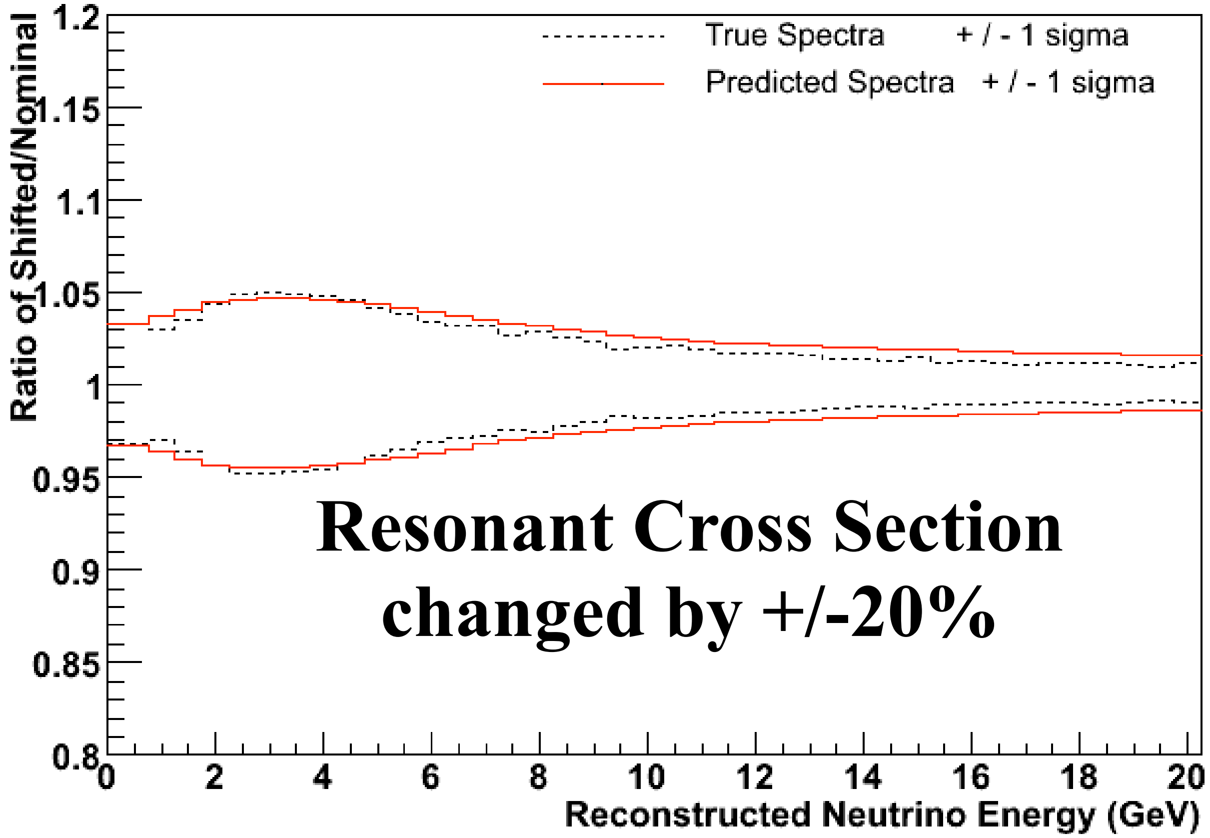
True FD spectrum

True ND spectrum

Oscillate **True→Reco** **Apply efficiency, purity**

Cancelling systematic errors





- We have investigated (using MC) the effect of systematic uncertainties on the predicted FD spectrum. The plots above illustrate uncertainties in beam modelling and neutrino cross-sections
  - the dashed lines show the magnitude of the systematic effect introduced to our reconstructed energy spectrum (relative to nominal MC)
  - the red lines show the predicted spectrum in these two cases, when the Beam Matrix method is used to extrapolate from Near-Far
  - the true and predicted spectra are very close, indicating that the effect of these systematics largely cancel when this method is used.

List of systematic errors studied

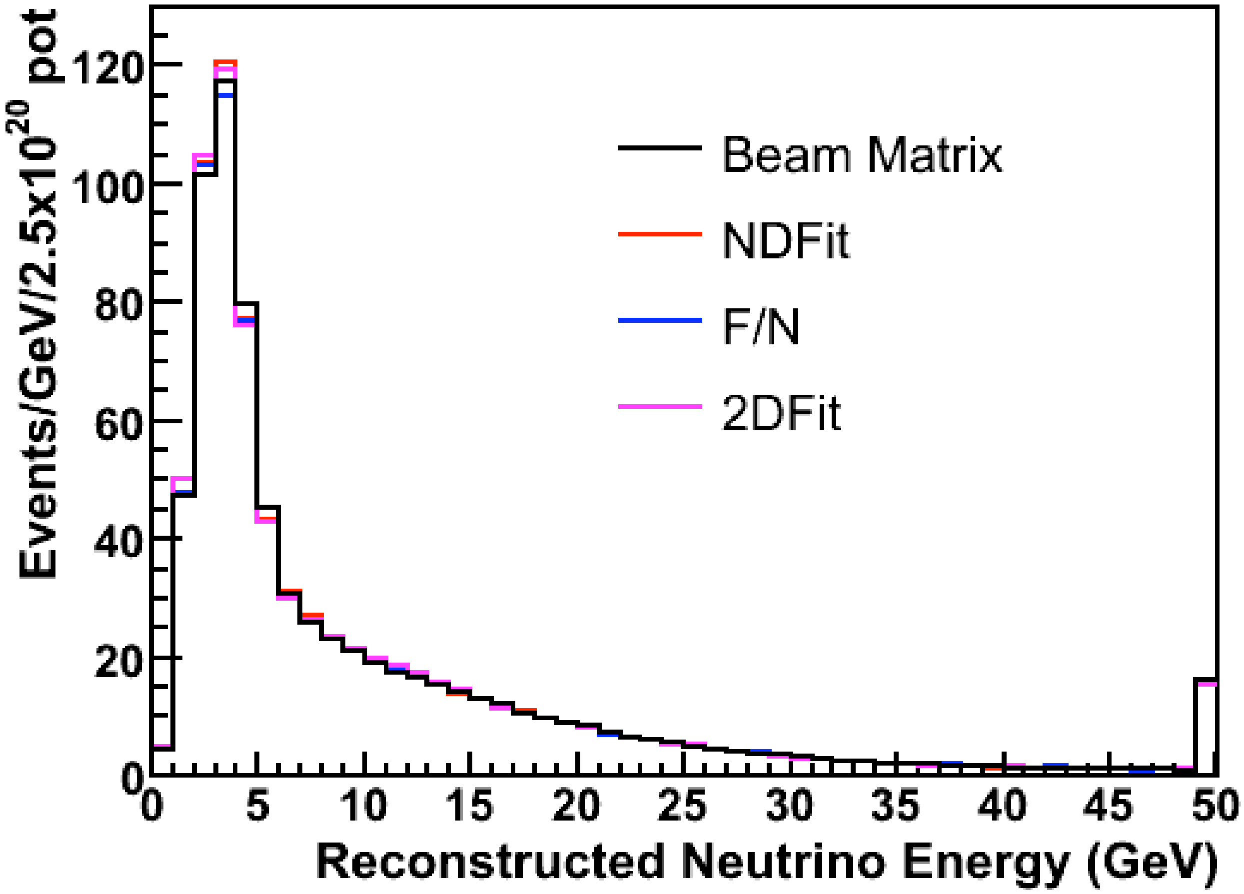
- **Beam:**
  - Uncertainty in the predicted spectrum after beam tuning (see plot on previous page)
- **CC cross-sections:**
  - QEL and RES M_A: 15% error, RES-DIS r_{ijk} scale factors: 20%
- **Normalisation:**
  - 4% relative uncertainty due to fiducial mass, POT counting, reconstruction efficiency uncertainties
- **Energy scales:**
  - 10% absolute shower energy scale: 6% intranuclear rescattering $\oplus$ 6% hadronization $\oplus$ 6% absolute calibration
  - 3% relative shower energy scale
  - 2% uncertainty on muon range, 5% uncertainty on muon curvature
- **NC background**
  - 50% uncertainty on NC background rate (from data/MC comparisons of muon-removed CC events in the Near Detector)

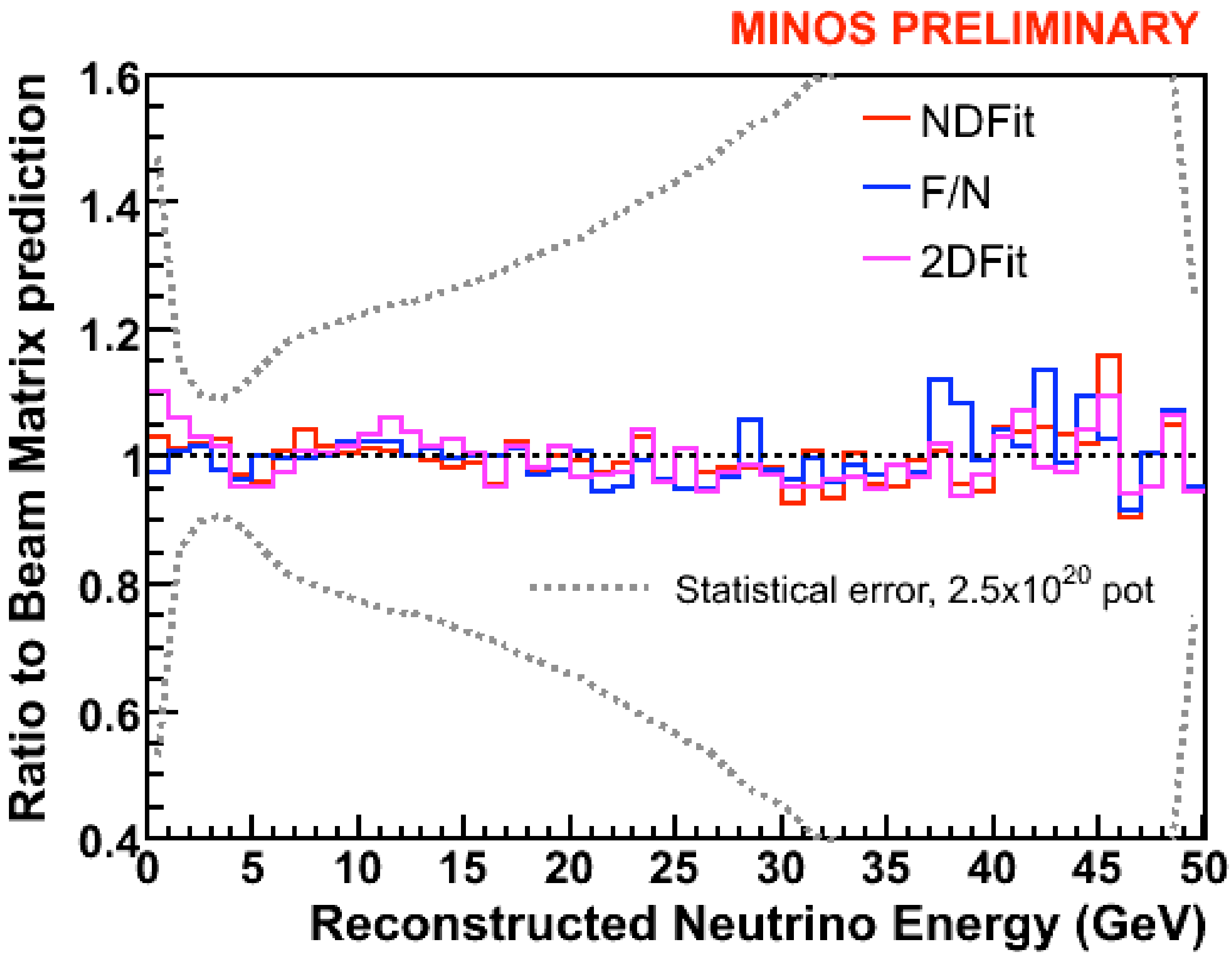
Systematic errors on Δm^2 and $\sin^2 2\theta$

- As explained above, the large *a priori* uncertainties due to beam and cross-section uncertainties largely cancel in the extrapolation
- The main remaining systematic errors are due to the relative normalisation, absolute shower energy scale and NC background contamination

Uncertainty	**Shift in Δm^2 (10^{-3} eV^2)**	**Shift in $\sin^2(2\theta)$**
Near/Far normalization ±4%	0.065	<0.005
Absolute hadronic energy scale ±10%	0.075	<0.005
NC contamination ±50%	0.010	0.008
All other systematic uncertainties	0.007	<0.005
Total systematic (summed in quadrature)	**0.10**	**0.008**
Statistical error (data)	**0.17**	**0.080**

Cross-checks of the extrapolated spectrum





- In addition to the Beam Matrix, we have developed three other extrapolation methods for comparison:
  - **Data driven methods: Far/Near ratio**
  - **Fit based methods: NDFit and 2DFit**
- The predicted spectra for these methods all agree to within +/- 4% - much better than the statistical error on the FD spectrum

Oscillation analysis

Effect of selection cuts on FD data

Cut	Number of Events
Track in fiducial volume	847
Data quality cuts	830
Timing cut	828
Beam quality cuts	812
Track quality cut	811
Track charge<=0	672
PID parameter>0.85	564
Reco Enu<200 GeV	**563 (Final analysis sample)**

Comparison of observed/expected events

Data Sample	**FD Data**	**Expected (Matrix Method; Unoscillated)**	**Data/Prediction (Matrix Method)**
ν_μ CC$_{\text{like}}$ All Energies	563	738±30	0.76 (4.4 σ)
ν_μ CC$_{\text{like}}$ (<10 GeV)	310	496±20	0.62 (6.2 σ)
ν_μ CC$_{\text{like}}$ (<5 GeV)	198	350±14	0.57 (6.5 σ)

- Strong energy-dependent deficit seen
  - below 10 GeV, a deficit of 6.2σ relative to the no oscillation prediction is observed, based purely on the total event rate
- The predicted numbers of events include the 4% normalisation error, which is the dominant contribution to uncertainties on the overall rate.

Oscillation fit

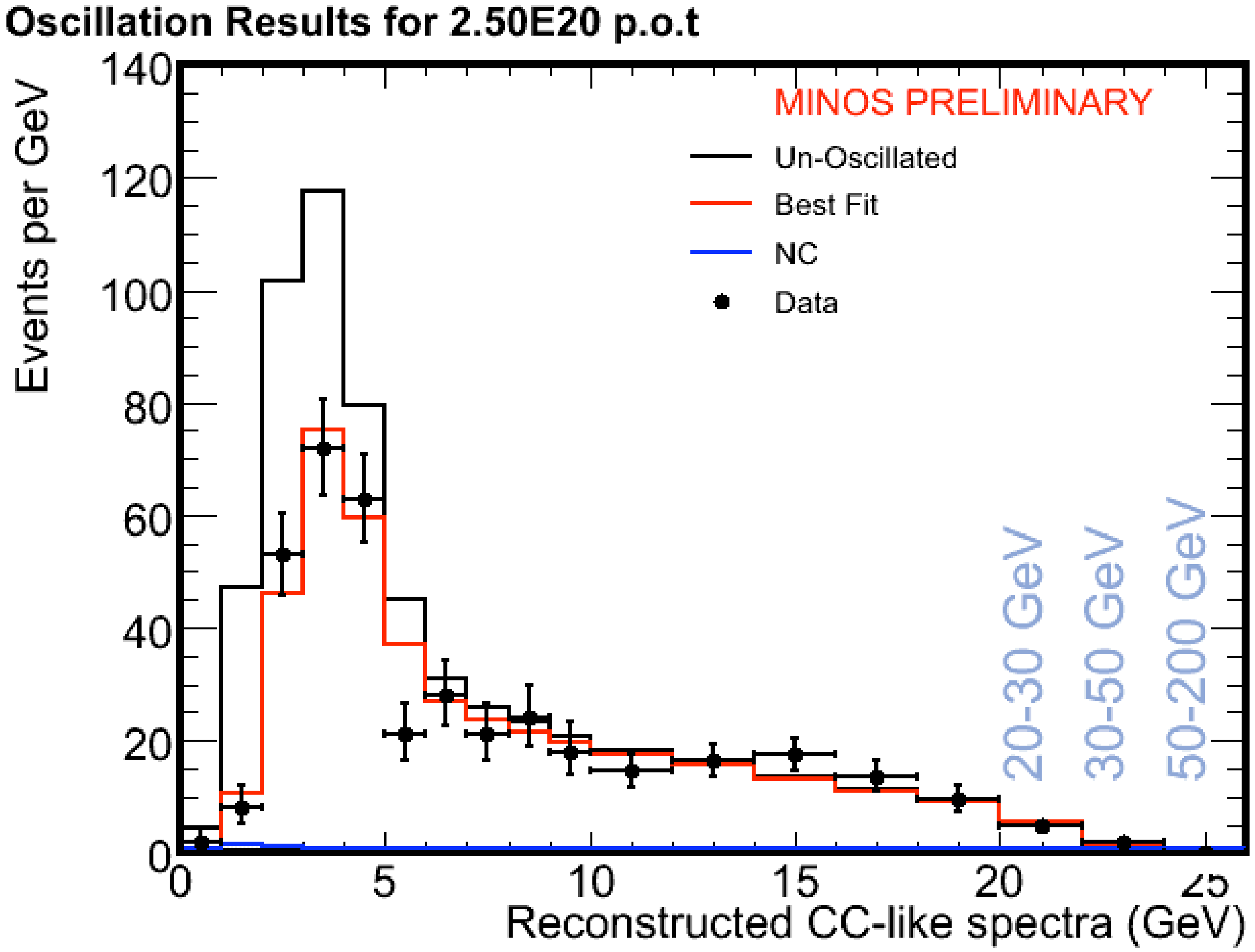
- Fit to the visible energy spectrum of the 563 selected Far detector CC events to extract the mixing parameters Δm^2 and $\sin^2 2\theta$:

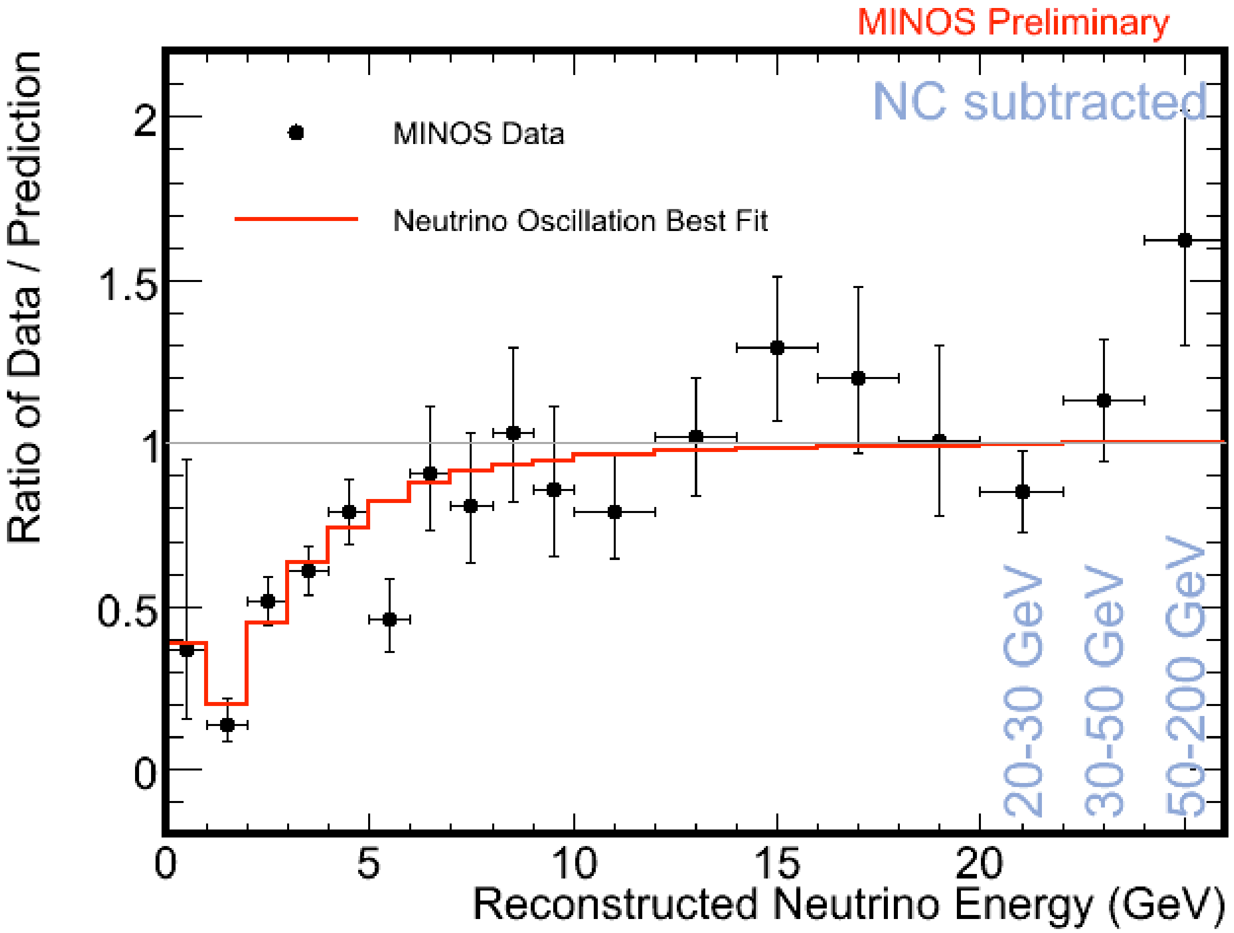
$$\chi^2(\Delta m^2, \sin^2 2\theta, \alpha_j, \ldots) = \underbrace{\sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i/e_i)}_{\text{Statistical error}} + \underbrace{\sum_{j=1}^{nsyst} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j^2}}}_{\text{Systematic errors}}$$

- Systematic uncertainties (leading systematics are included as nuisance parameters in the fit):
  - 4% overall normalisation
  - 10% absolute shower energy scale
  - 50% NC background rate

$$\left.\begin{array}{l}\text{10\% absolute shower energy scale}\\ \text{50\% NC background rate}\end{array}\right\}\ \text{common to near and far detectors}$$

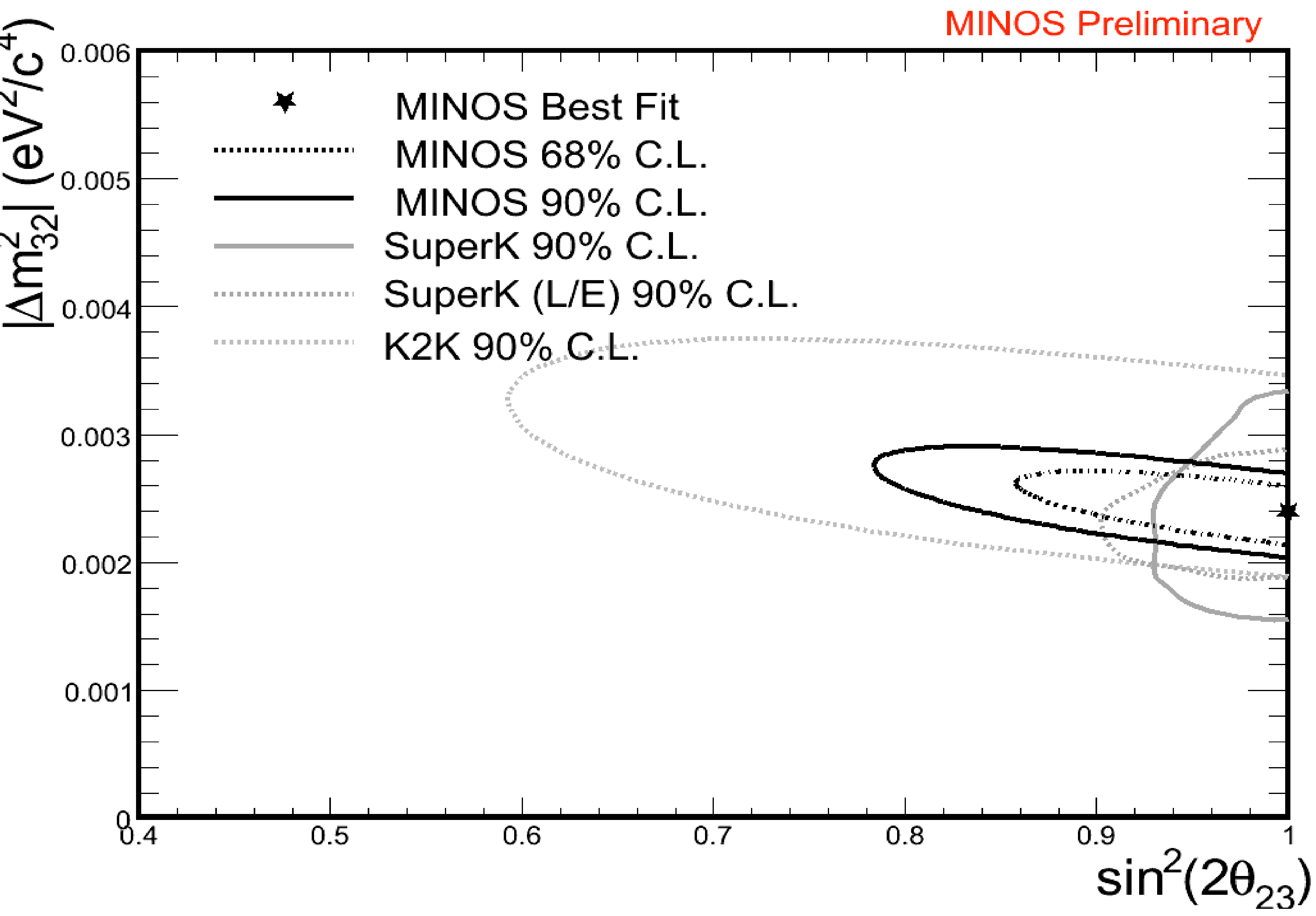
Best-fit energy spectrum

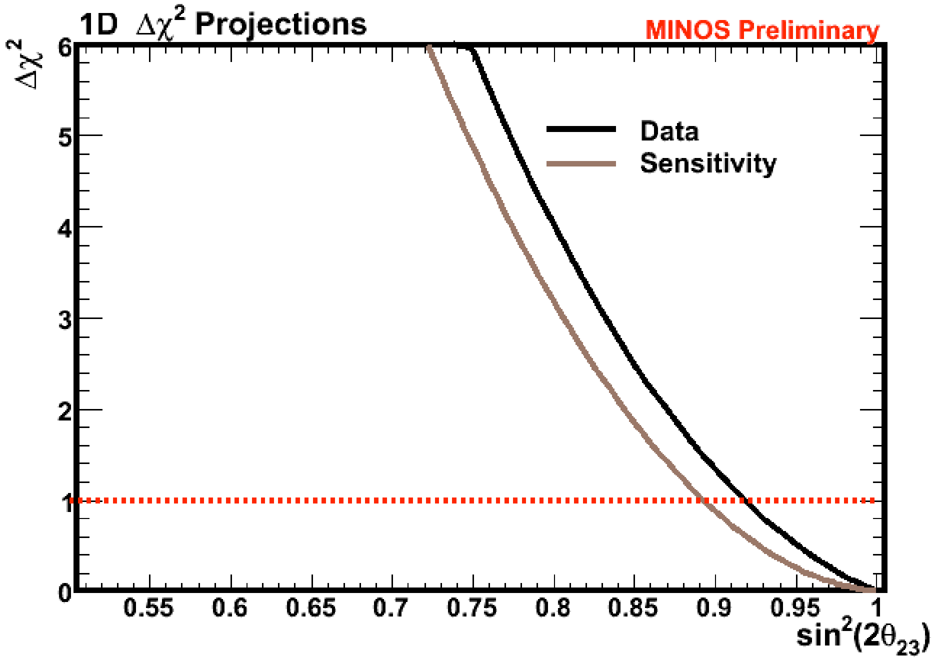


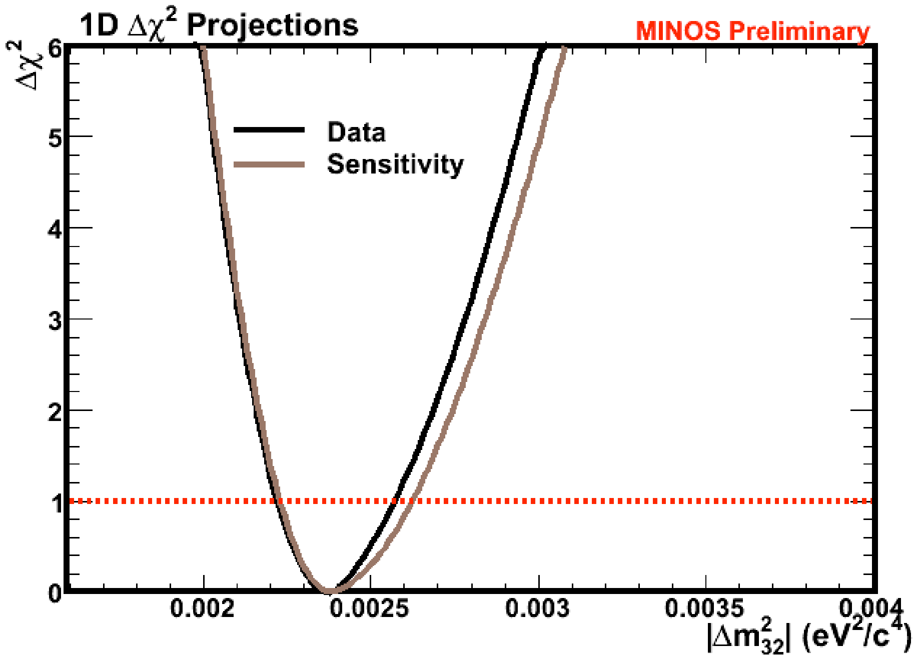


- Best-fit oscillation parameters:
  - **$\Delta m^2 = 2.38 \times 10^{-3}$ eV^2**
  - **$\sin^2 2\theta = 1.0$**
  - **χ^2/ndf=41.2/34** 18 bins x 2 spectra (Run I, Run IIa) - 2
- **No oscillations:** **χ^2/ndf=139.2/36**

Allowed region





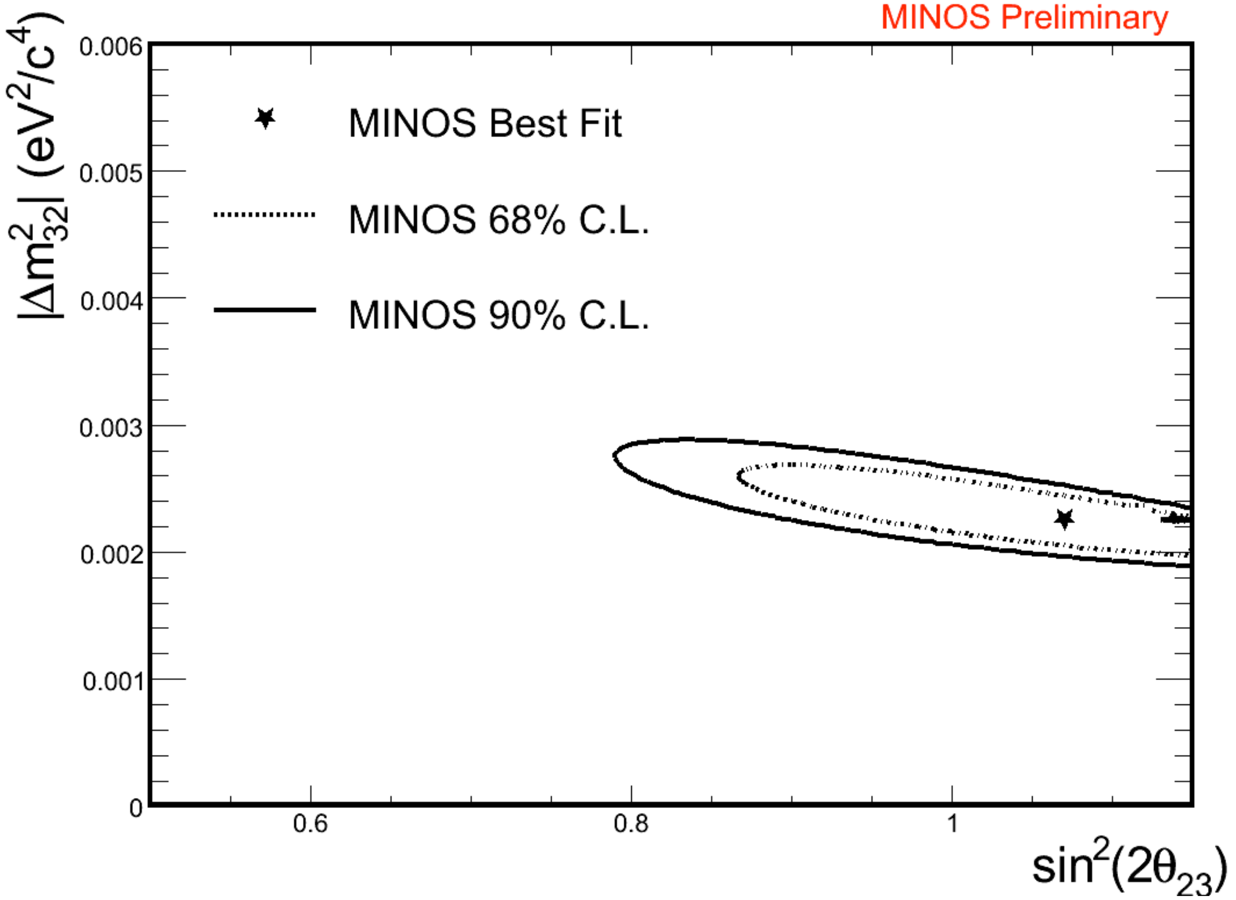


$$\Delta m^2 = 2.38^{+0.0020}_{-0.0016} \times 10^{-3}\mathrm{eV}^2$$

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

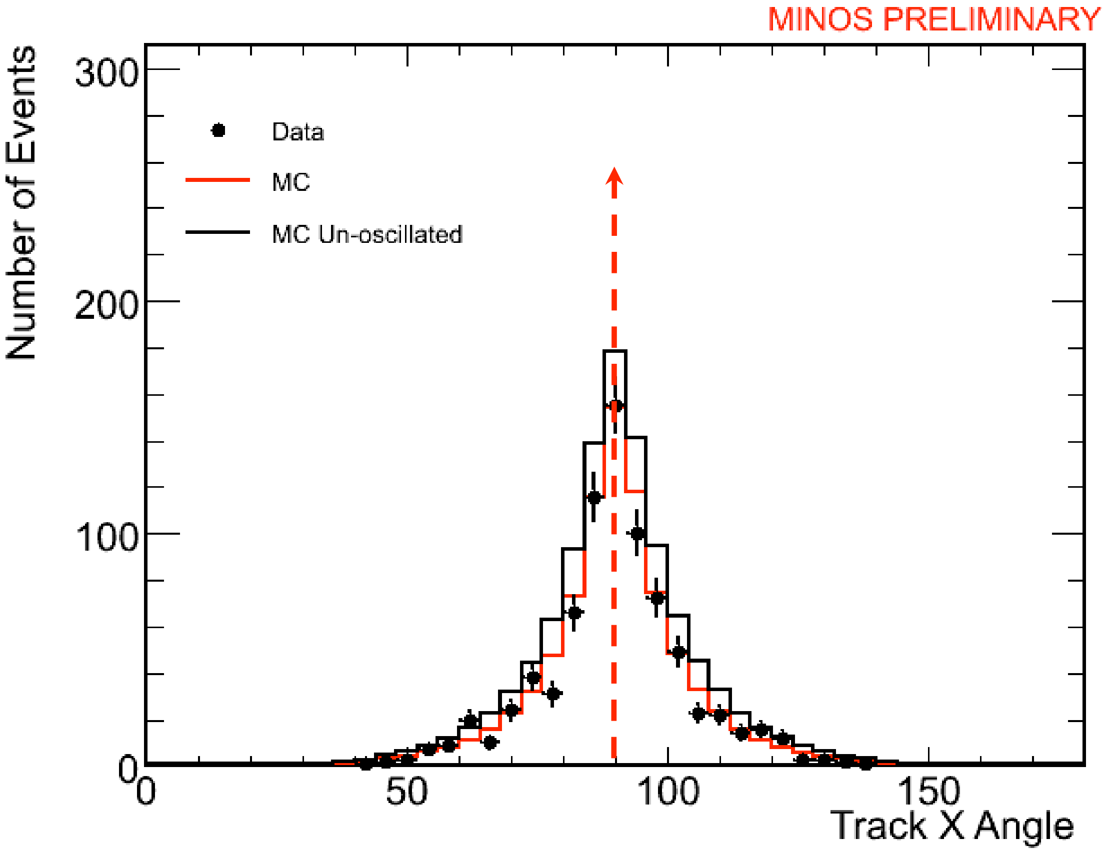
Fit with unconstrained $\sin^2 2\theta$

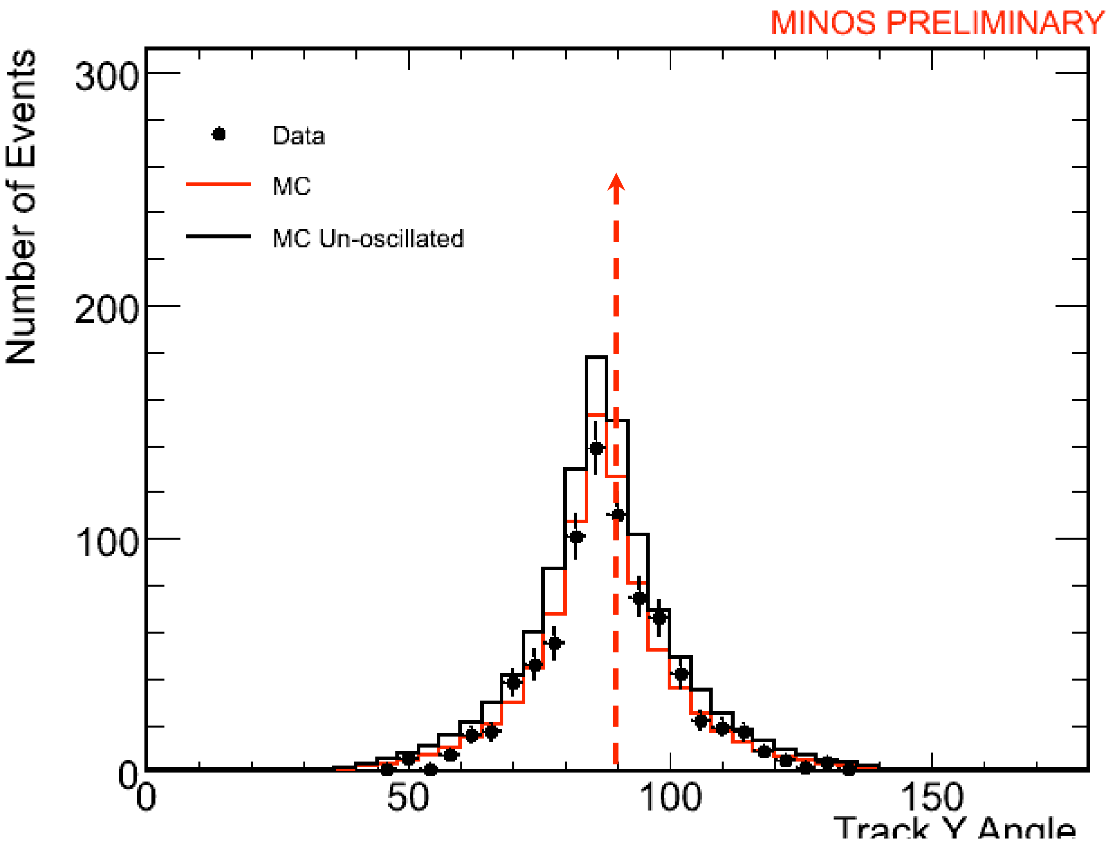
- Best-fit parameters:
  - **$\Delta m^2 = 2.26\times10^{-3}\ \mathrm{eV}^2$**
  - **$\sin^2 2\theta = 1.07$**
  - **$\chi^2/\mathrm{ndf} = 40.9/34$**

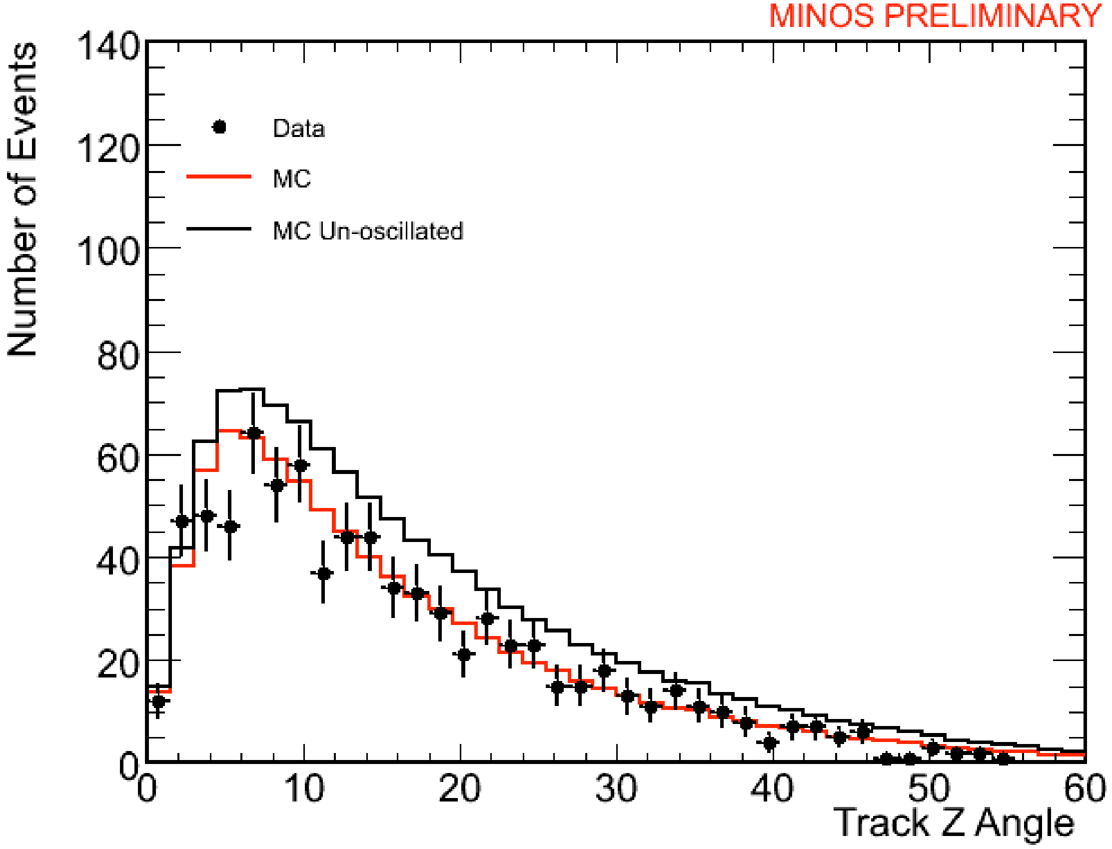


- Our allowed regions are drawn using the approximations:
  - 68% C.L - $\chi^2 = \chi^2_{min} + 2.3$
  - 90% C.L - $\chi^2 = \chi^2_{min} + 4.61$
- We have evaluated the effect of the physical boundary on the allowed region using the unified approach of Feldman and Cousins
  - preliminary (stat errors only) results indicate that our confidence limits are slightly conservative (the above approximations are slightly over-covering)

FD Data/MC comparisons

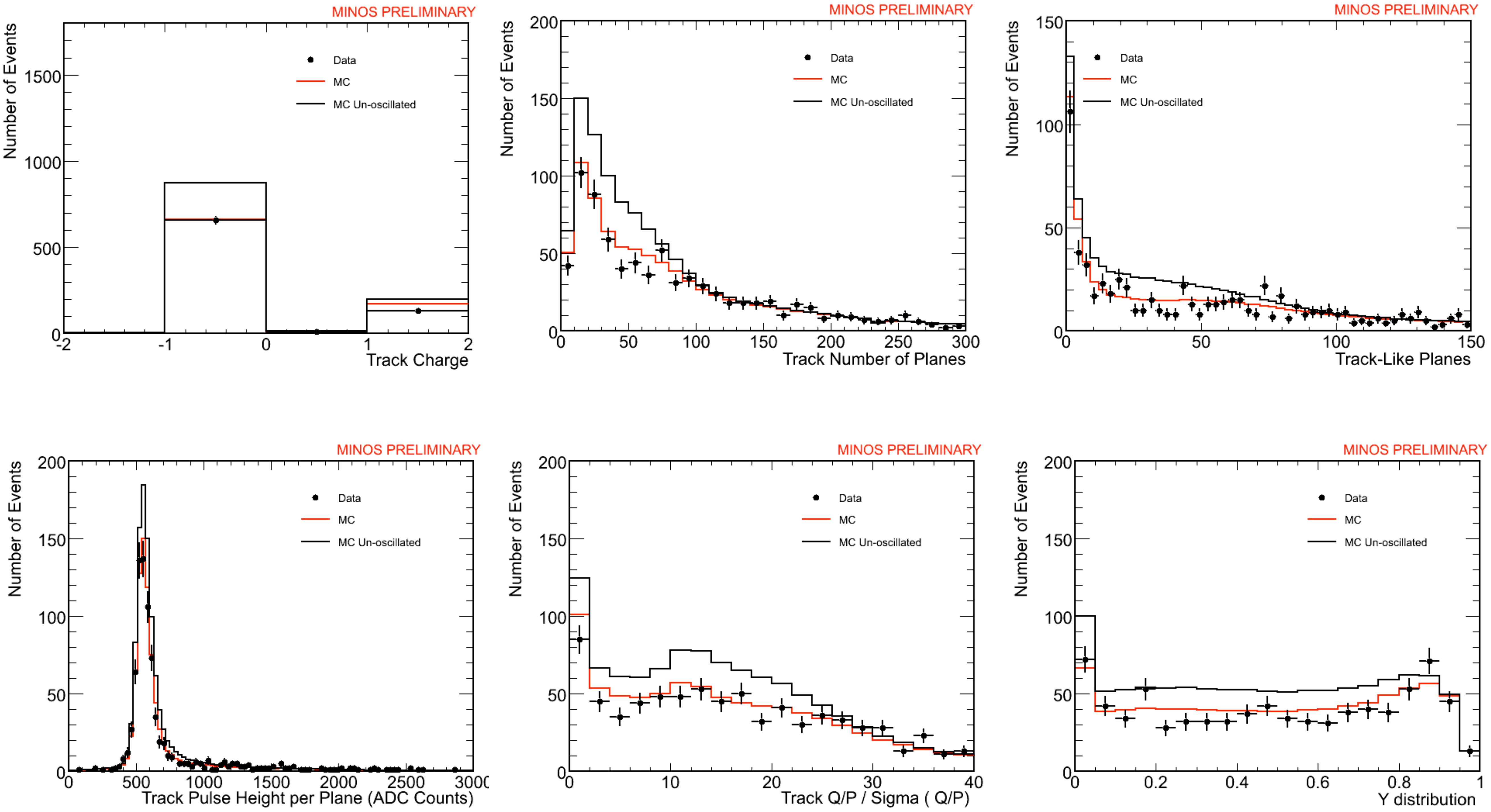






- Neutrinos point 3° up at the FD! (c.f. page 24 for the ND)

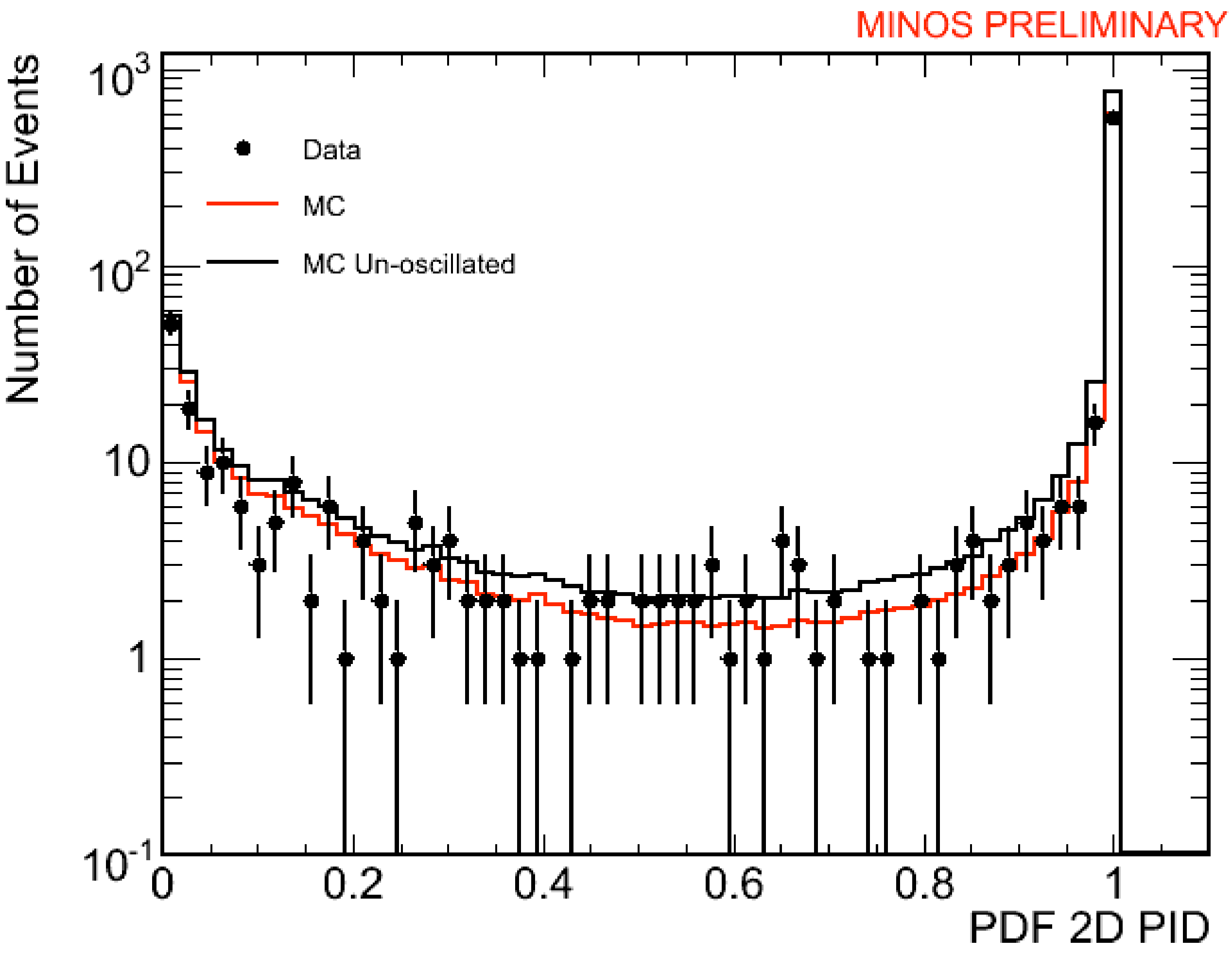
PID input variables



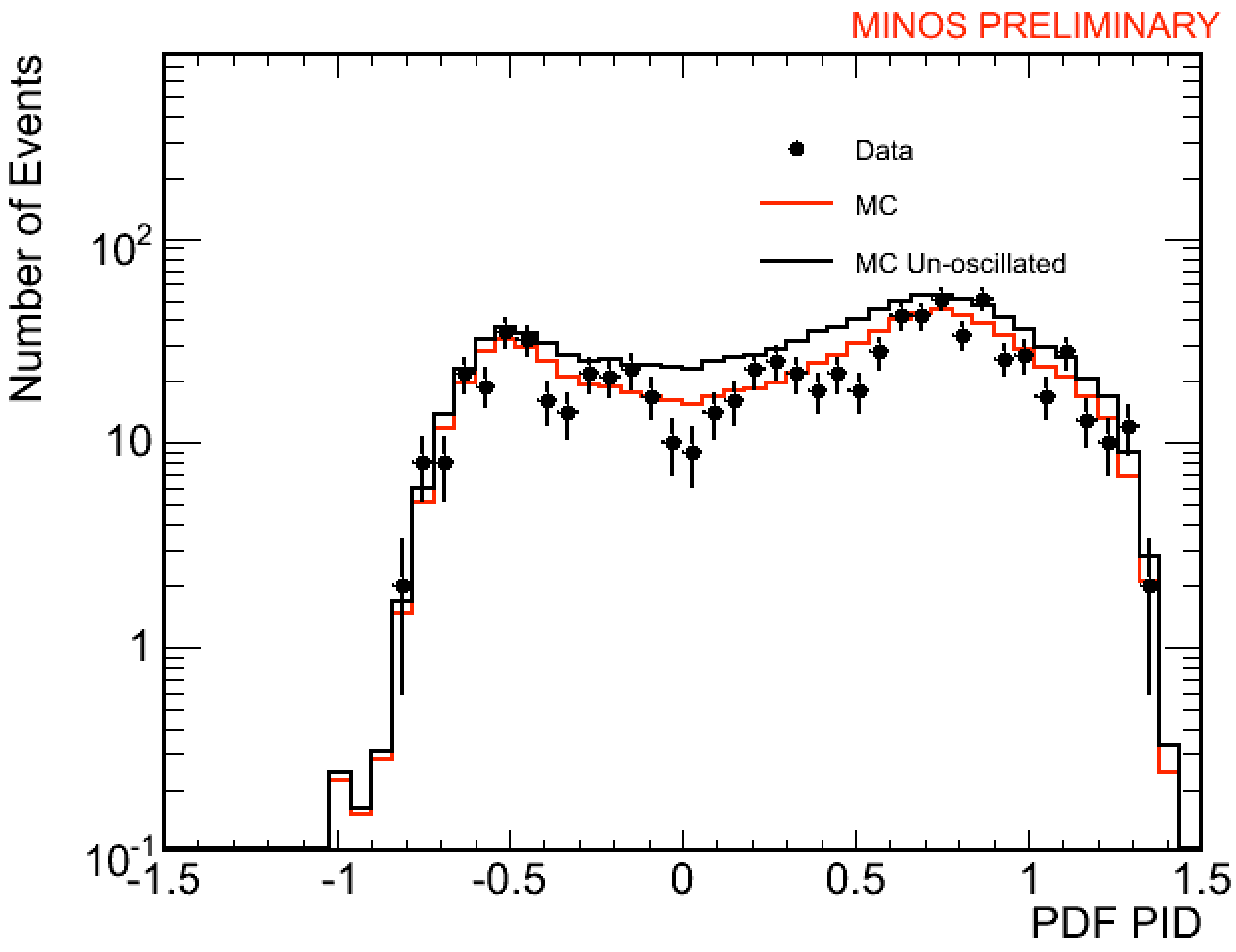
- Agreement between data and oscillated MC very good

PID distributions

NEW PID

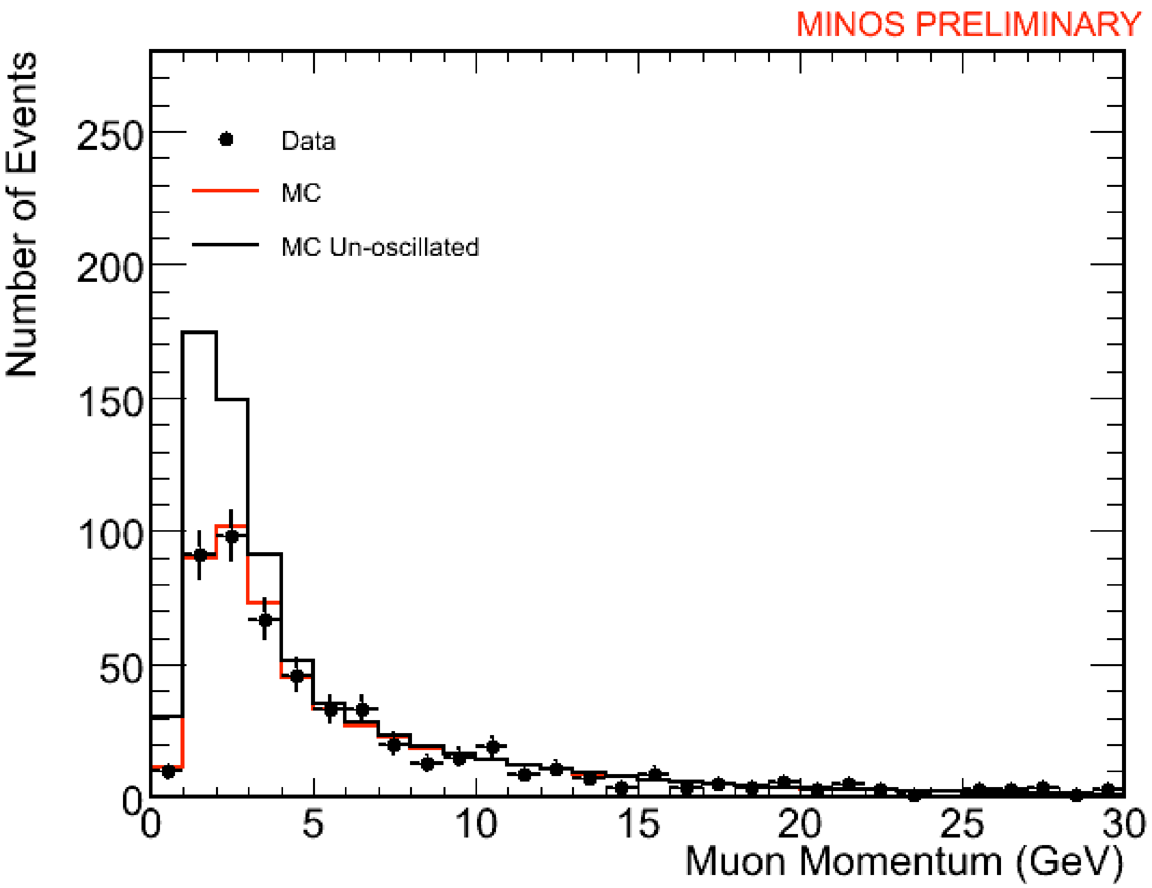


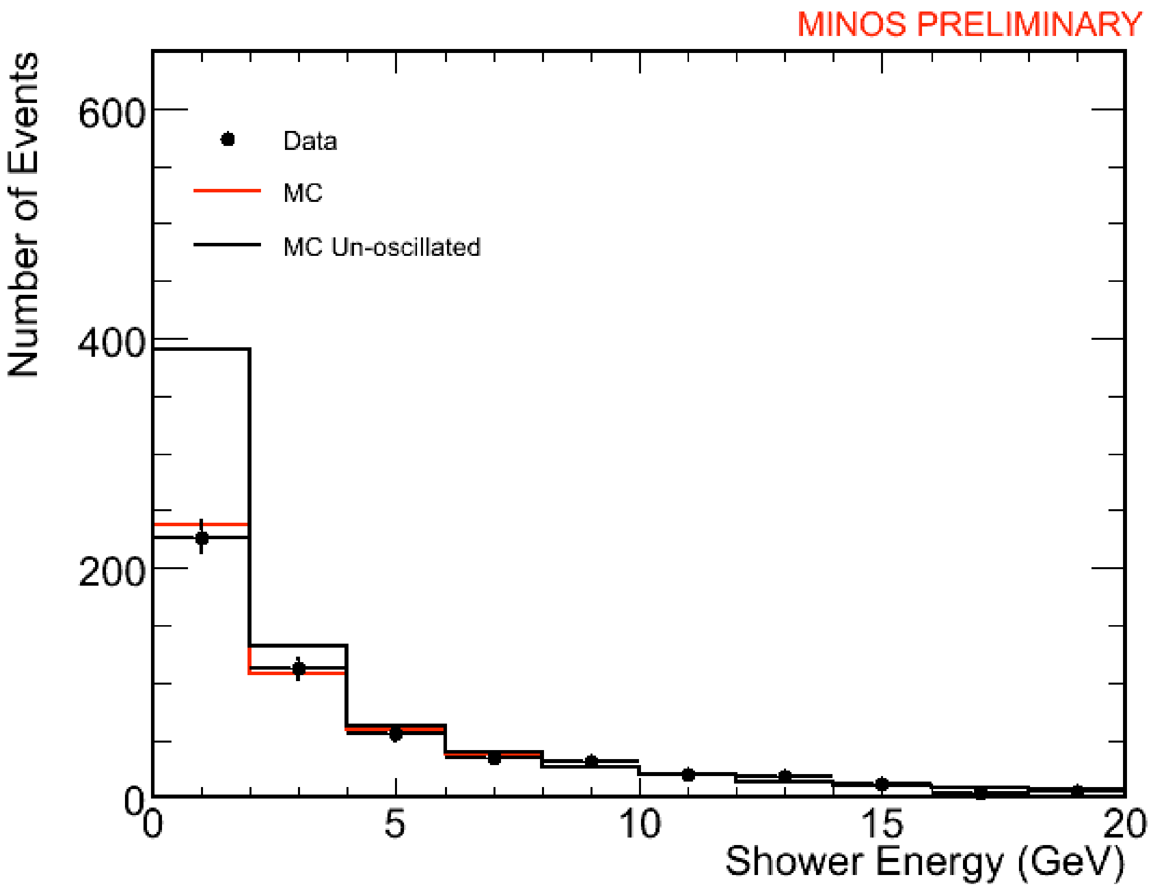
OLD PID



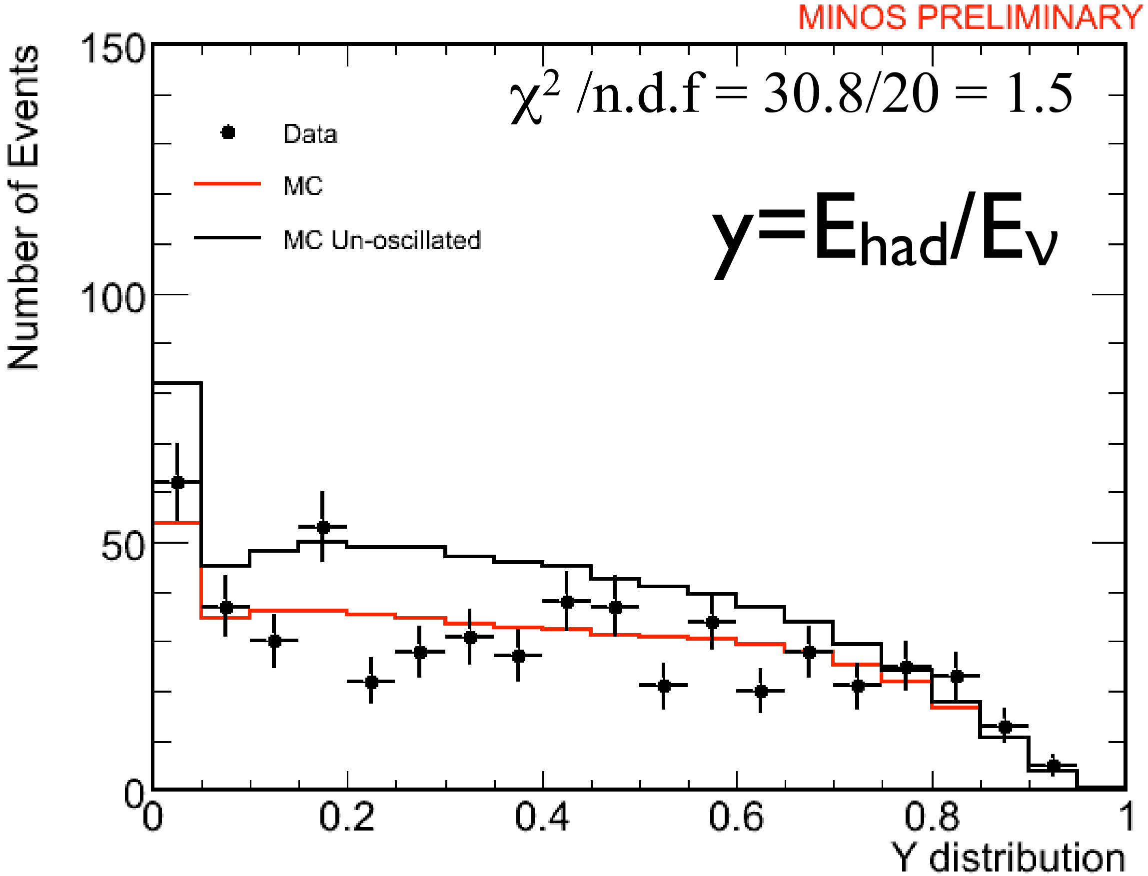
- Agreement between data and oscillated MC very good

FD Energy, y distributions

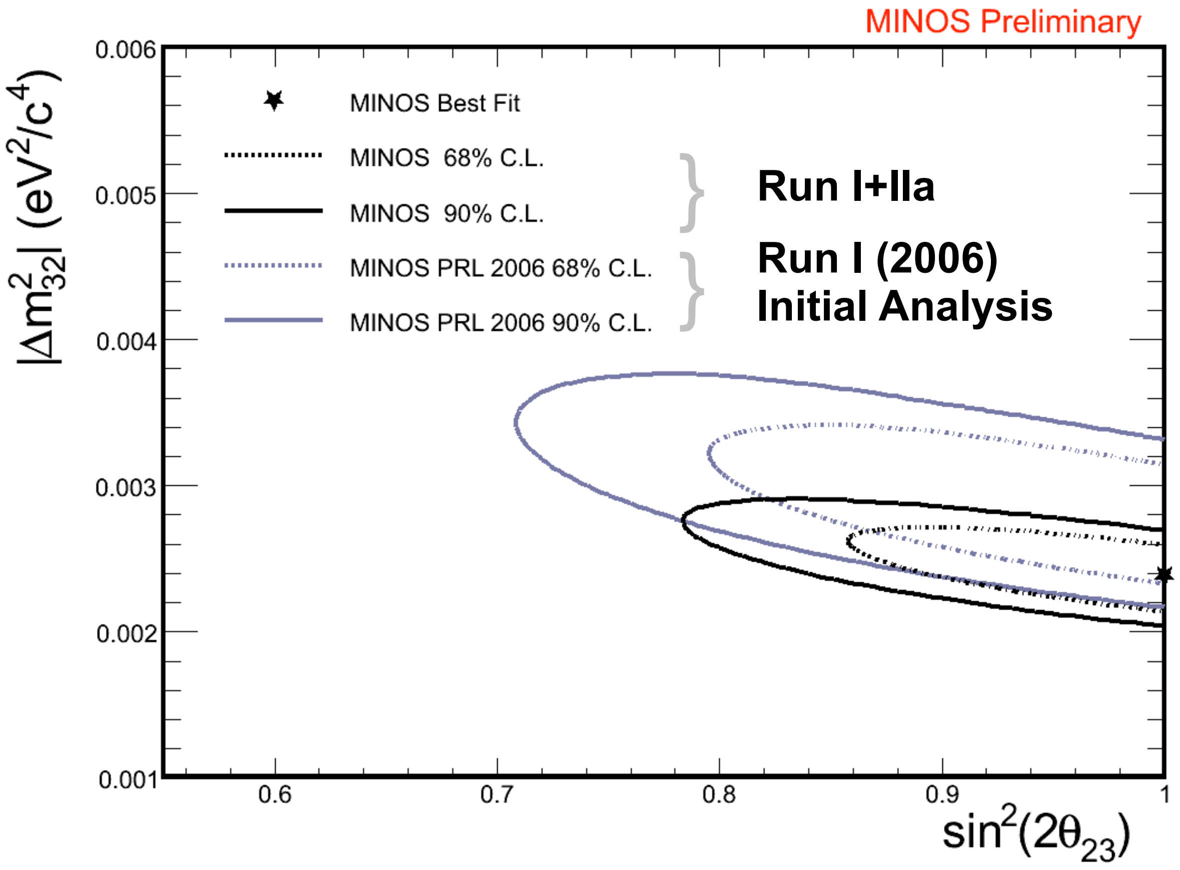


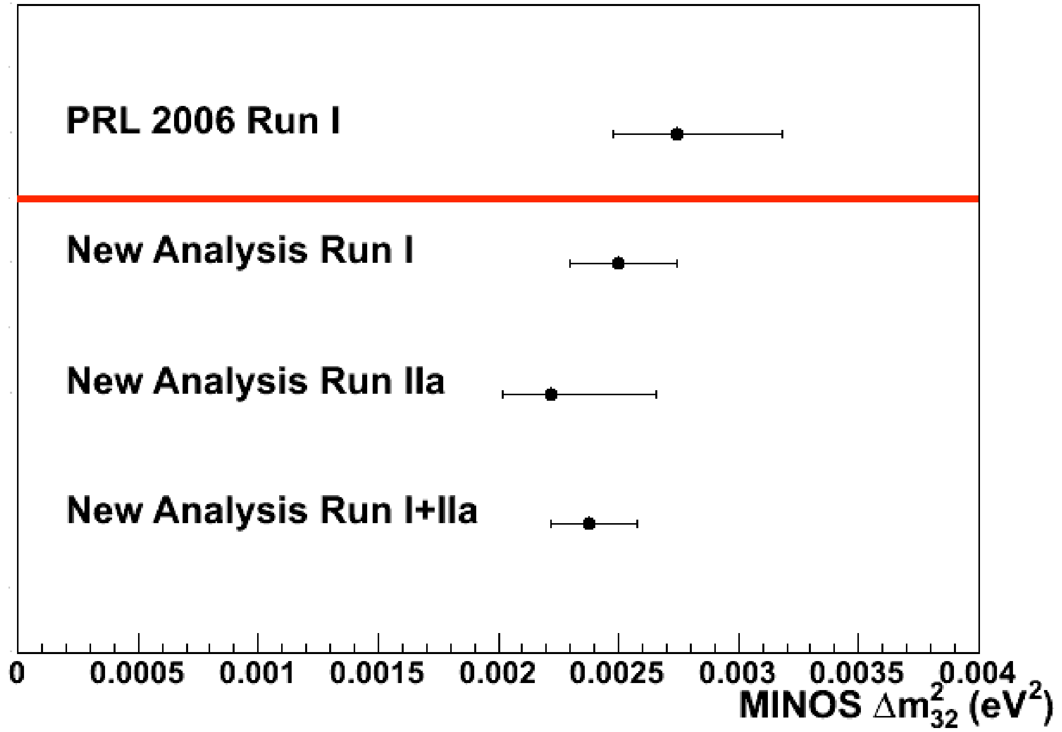


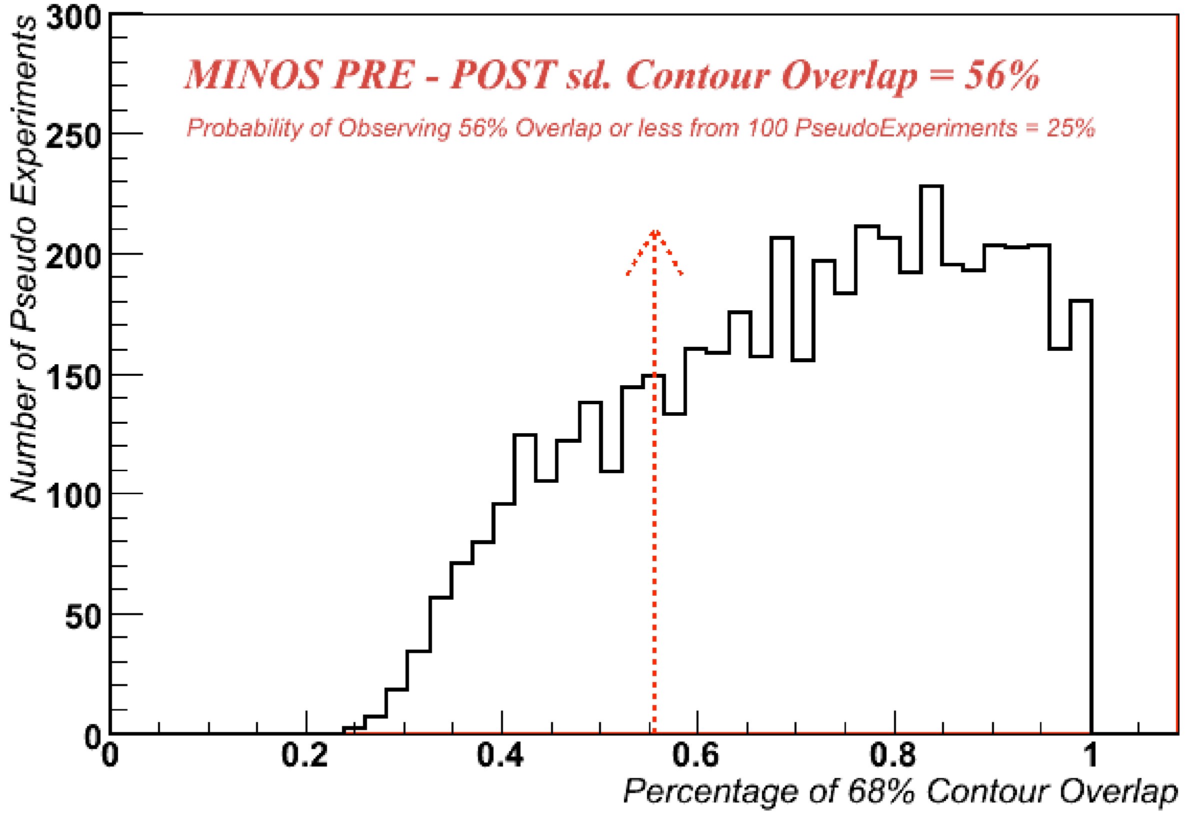
- Good agreement between data and best-fit MC for these kinematic variables



Comparison with 2006 result



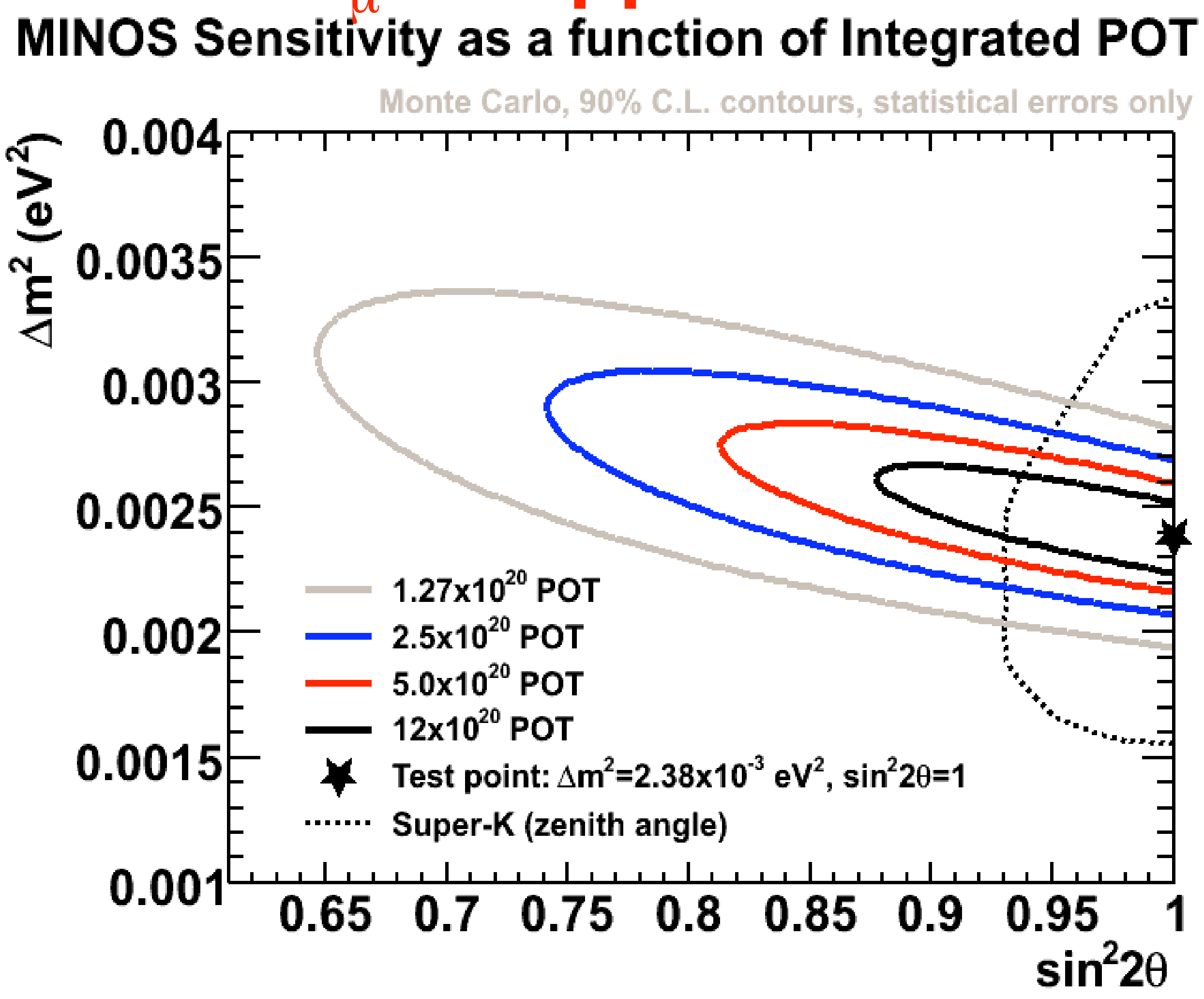




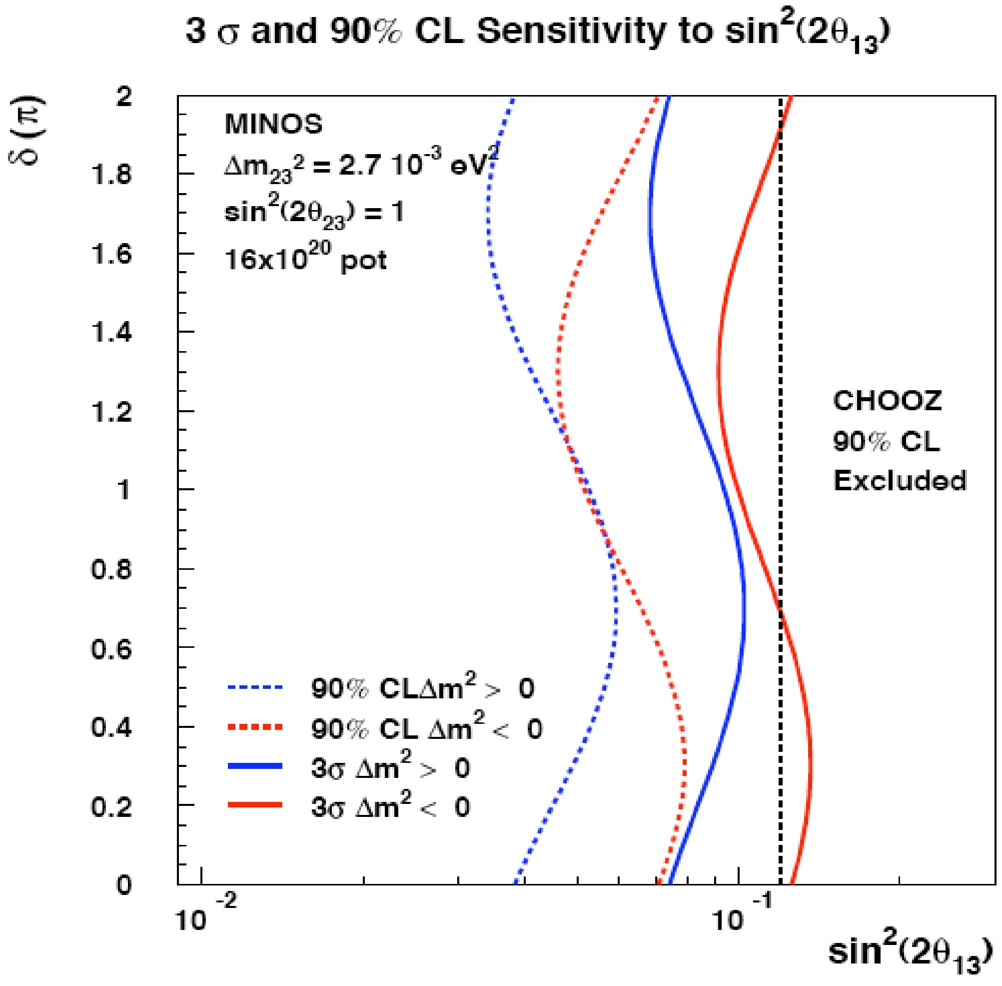
- Best-fit value changed due to:
  - statistics (new events due to improved reco. efficiency different PID, FD fid volume)
  - systematic shift in shower energy (10%) due to new intranuclear rescattering and hadronization models

Future prospects

ν_μ disappearance



$\nu_\mu \rightarrow \nu_e$

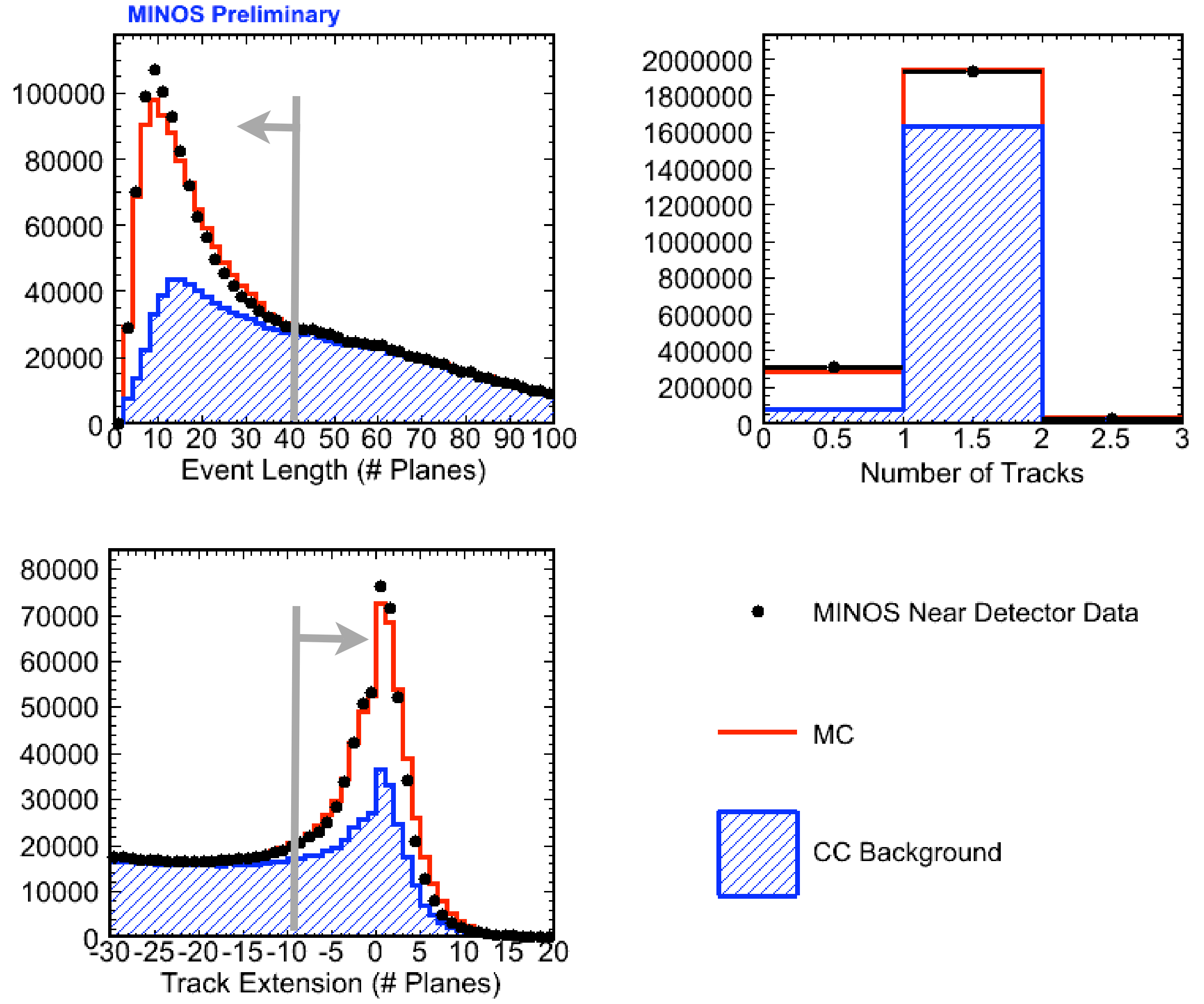


- Significant improvements possible in the measurement of ν_μ disappearance parameters with increased exposure.
- Potential to observe sub-dominant $\nu_\mu \rightarrow \nu_e$ transitions, or improve the current limit on the mixing angle θ_{13} by a factor of 2-3.
- Neutral current measurements ($\nu_\mu \rightarrow \nu_s$, τ appearance) will also be possible with a larger dataset

Selecting NC events in the ND

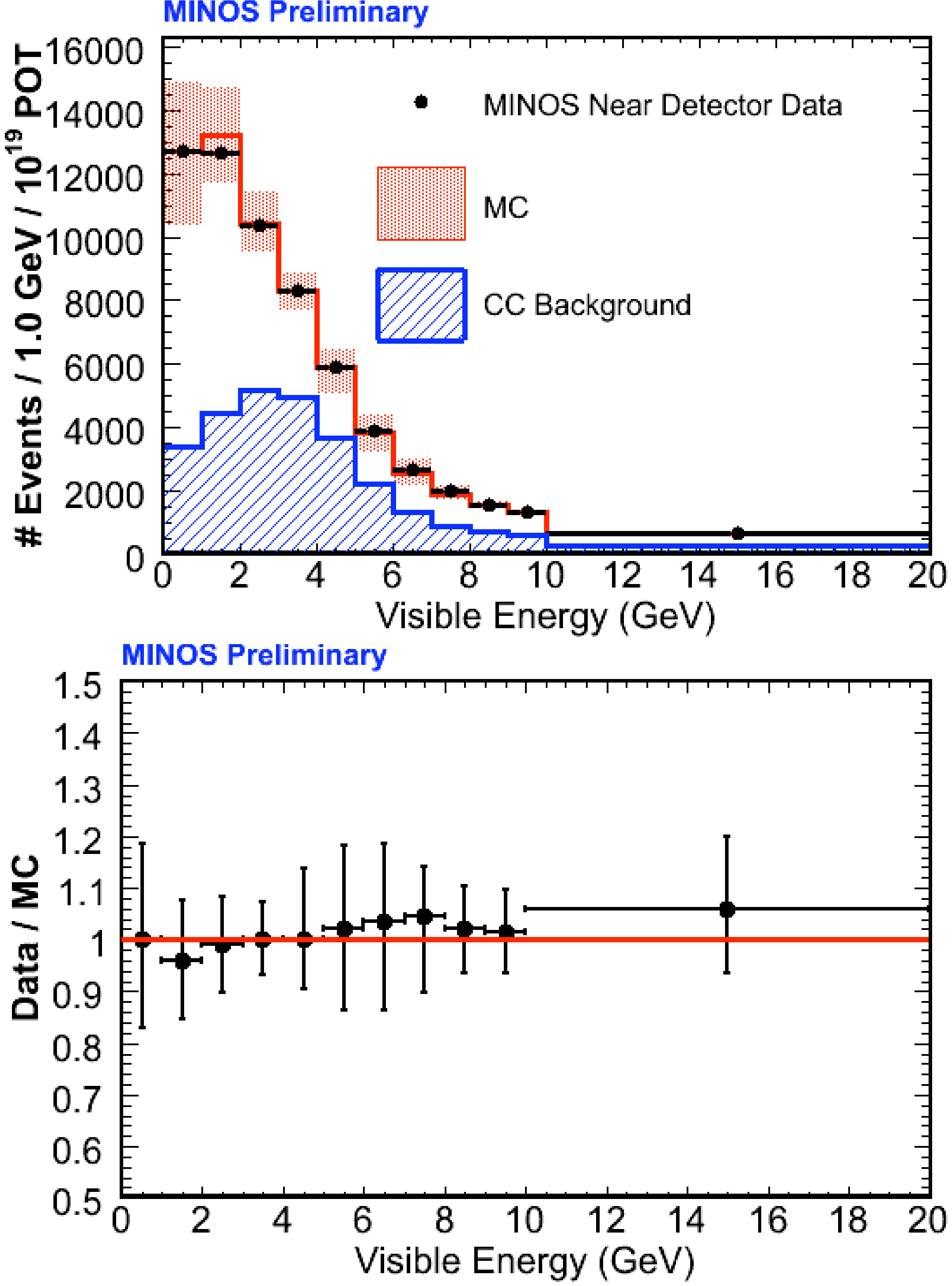
- ***Goal is a NC spectrum measurement in the FD***
  - Sensitive to $\nu_\mu \rightarrow \nu_{sterile}$, ν decay signatures
- First step of this analysis is a measurement of the NC spectrum in the ND
  - Use similar techniques to the CC analysis to extrapolate measured flux to FD
- Use simple cuts to select NC events with high (93%) efficiency (CC contamination ~50%)
- We have developed two methods to obtain clean samples of events for data/MC comparisons
  - these are designed to reject events that overlap in time and space and/or are not well-reconstructed
- ***High multiplicity selection:***
  - Uses timing & topological cuts (selects 860K ND data events for 1.23e20 pot)
- ***Low multiplicity selection:***
  - Use only spills with 1 or 2 reconstructed events (selects 10472 events for 1.23e20 pot)

NC selection variables

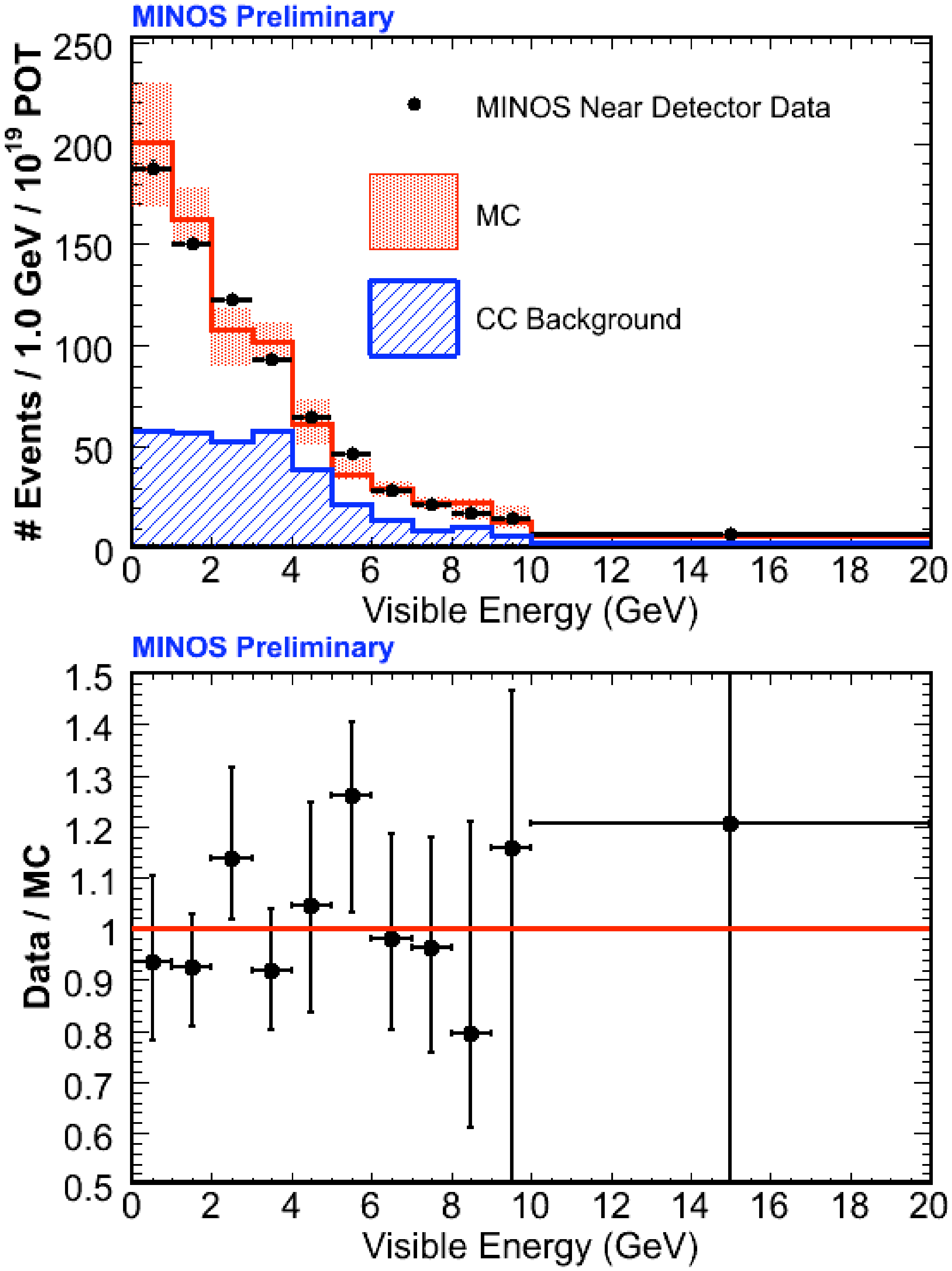


ND Data/MC comparisons

High multiplicity



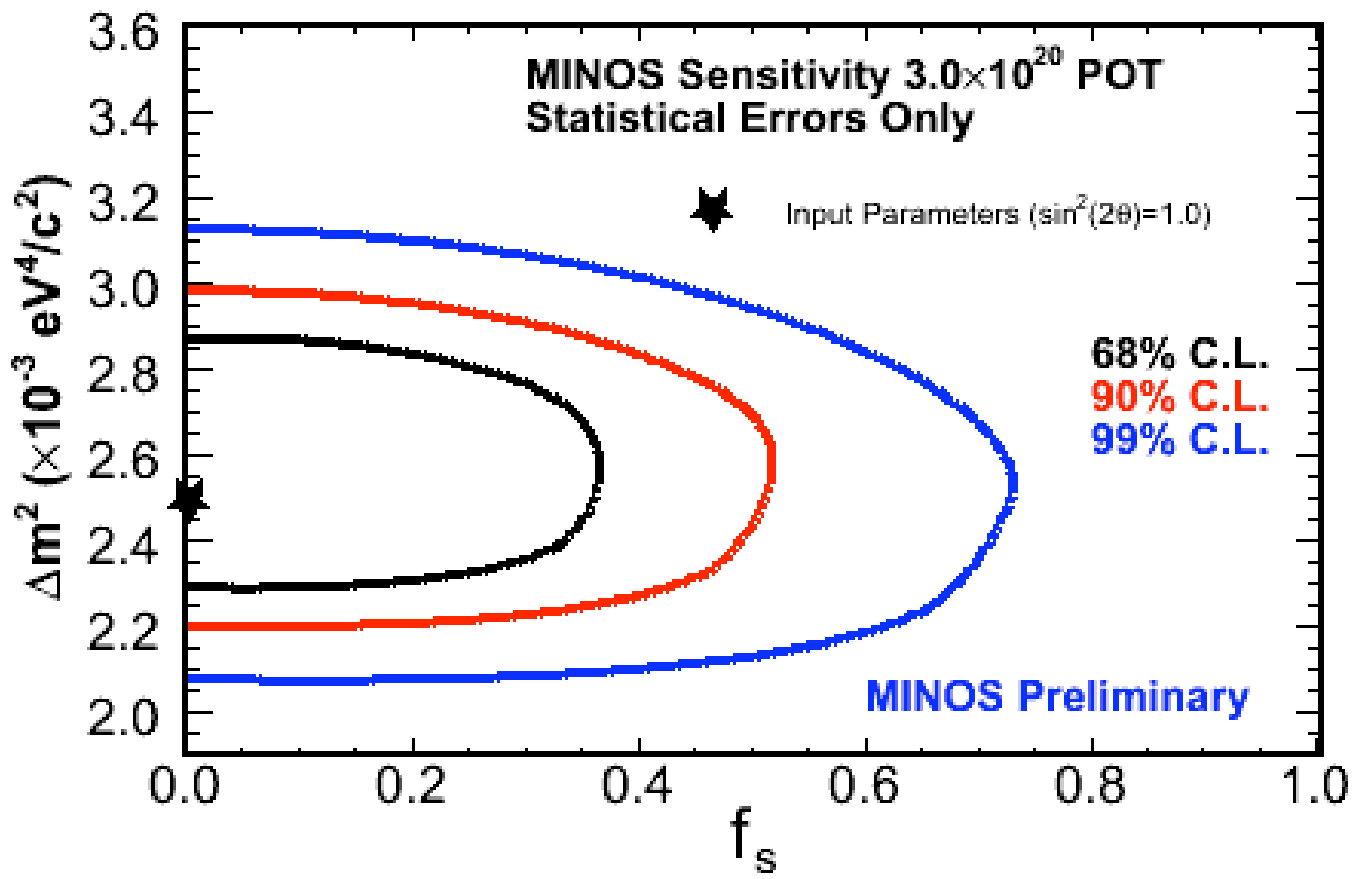
Low multiplicity



- MC error band includes contributions from beam, cross-section and energy scale uncertainties

Projected sensitivity to $\nu_\mu \rightarrow \nu_s$

- The plot at right shows the sensitivity of MINOS to the fraction of ν_μ oscillating to ν_s at the atmospheric neutrino scale



$$P(\nu_\mu \rightarrow \nu_s) = f_s \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E) \qquad P(\nu_\mu \rightarrow \nu_\tau) = (1 - f_s) \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

- At the time of writing, we are in the process of finalising the analysis, and expect to produce a result based on the Run I + Run IIa dataset within the next few months

Summary and conclusions

- In this talk I have presented the updated accelerator neutrino oscillation results from a 2.5×10^{20} pot exposure of the MINOS far detector.
- **Our result strongly disfavours no oscillations and is consistent with ν_μ disappearance with the following parameters (1σ errors shown):**

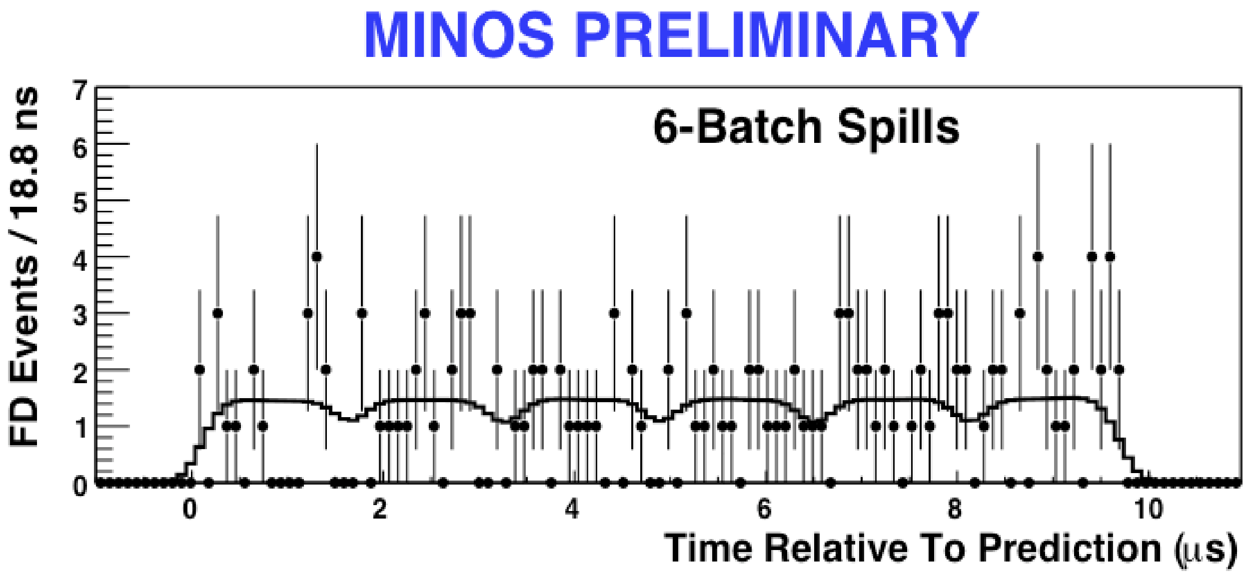
$$\Delta m^2 = 2.38^{+0.0020}_{-0.0016}\times 10^{-3}\mathrm{eV}^2 \qquad \sin^2 2\theta = 1.00_{-0.08}$$

- The systematic uncertainties on this measurement are well under control
  - An updated analysis will be presented next Summer on the full Run I + Run II dataset (3.25×10^{20} pot) and will include tests of non-standard ν_μ disappearance mechanisms such as neutrino decay and decoherence
  - Analyses of Neutral Current and electron neutrino data are underway.
    - A result on possible $\nu_\mu\rightarrow\nu_s$ oscillations is expected in the next few months
- Analysis references:
    - **Phys. Rev. Lett. 97 (2006) 191801 (Run I)** (long paper shortly to be submitted to PRD)
    - **arXiv:0708.1495: (preliminary Run I + Run IIa result)**

Back-up slides

Neutrino Time of Flight

- GPS synchronises two detectors
- Know distance between detectors precisely:
  - 734,298.6 +/- 0.7 m (~2.5 ms at c)
- Measure distribution of event times in two detectors
- Log likelihood fit to time distribution allowing δt to vary



Far detector events - points
Near detector prediction - solid line

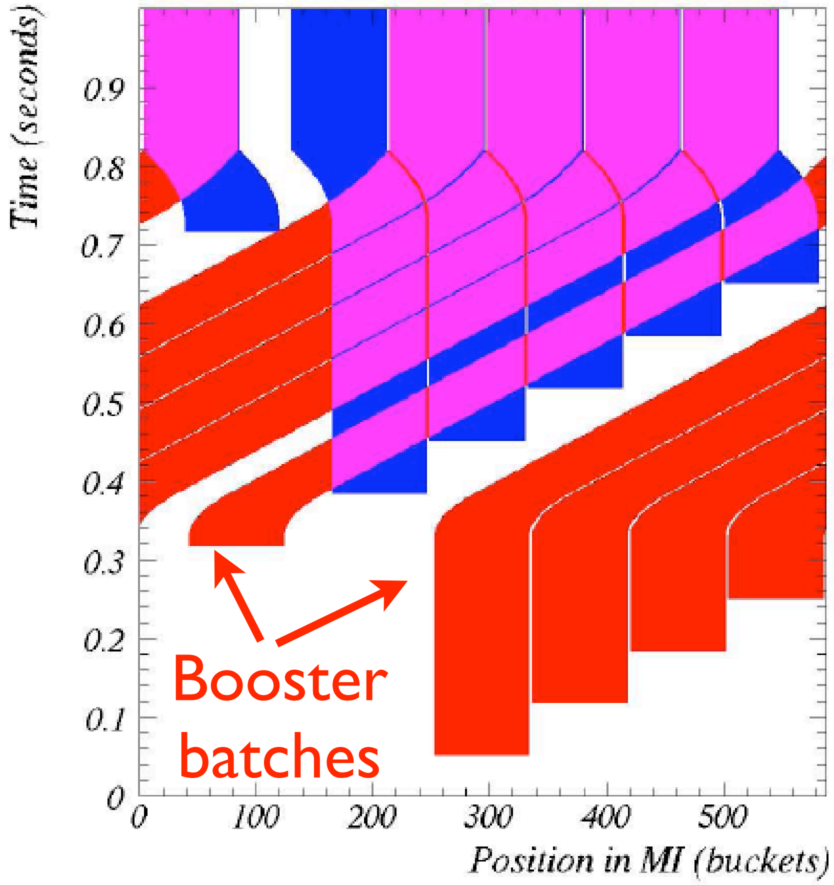
- MINOS Time of Flight:
  - **2449223 +/- 84 (stat.) +/- 164 (syst.) ns (99% C.L.)**
- Nominal Time of Flight:
  - 2449356 ns (for neutrinos travelling at c)

- In terms of velocity:
  - **(v-c)/c = 5.4 +/- 7.5 x 10-5 (99% C.L.)**
  - Previous experiment had baseline of ~500 m with timing precision of ~ns, gave result of:
    - |v-c|/c < 4 x 10-5 (95% C.L.)

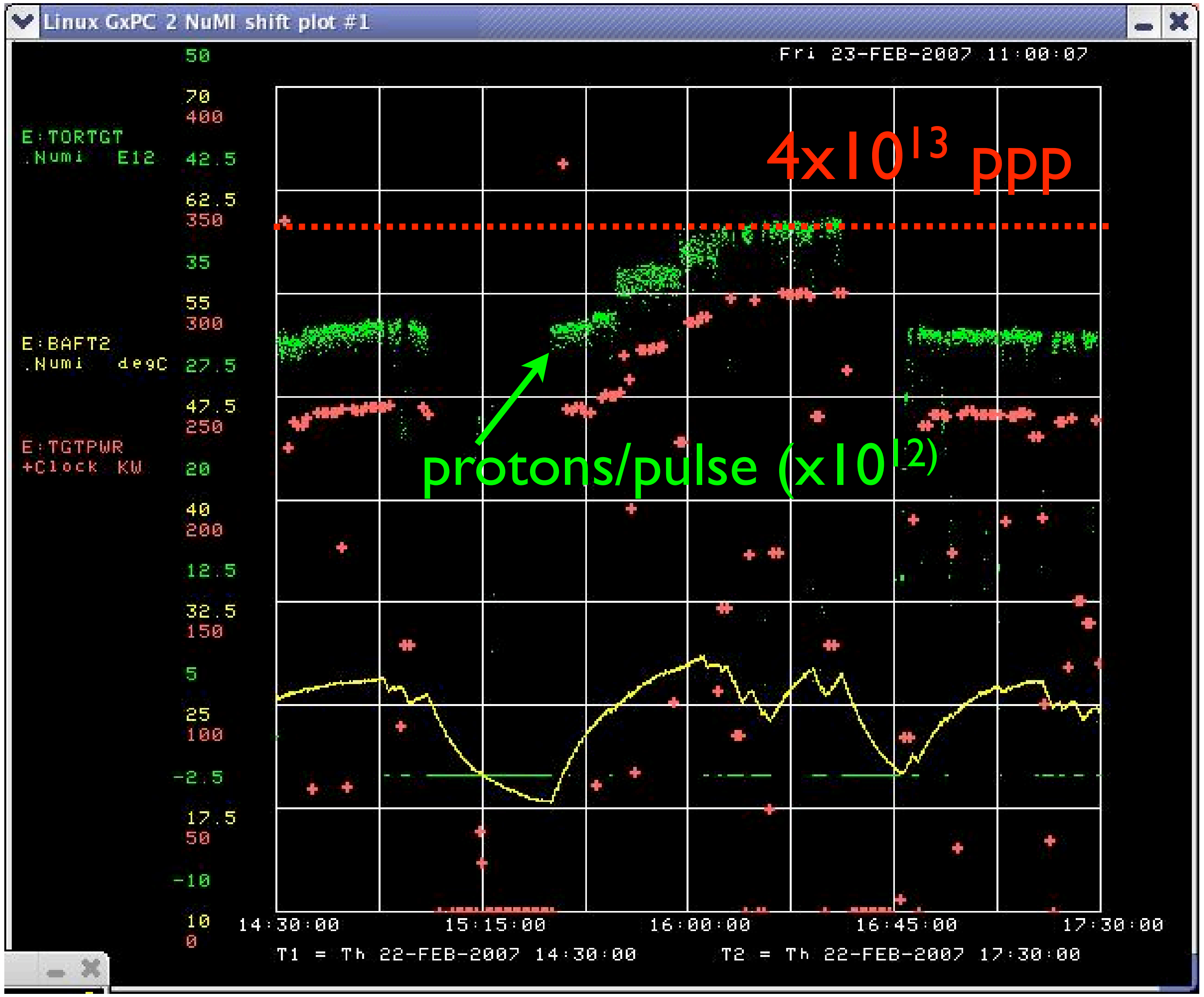
Prospects for higher beam intensity

- Recent progress on increasing beam intensity for NuMI from “slip-stacking” studies
  - slip stacking allows us to inject up to 11 booster batches in Main Injector

Slip-stacking schematic

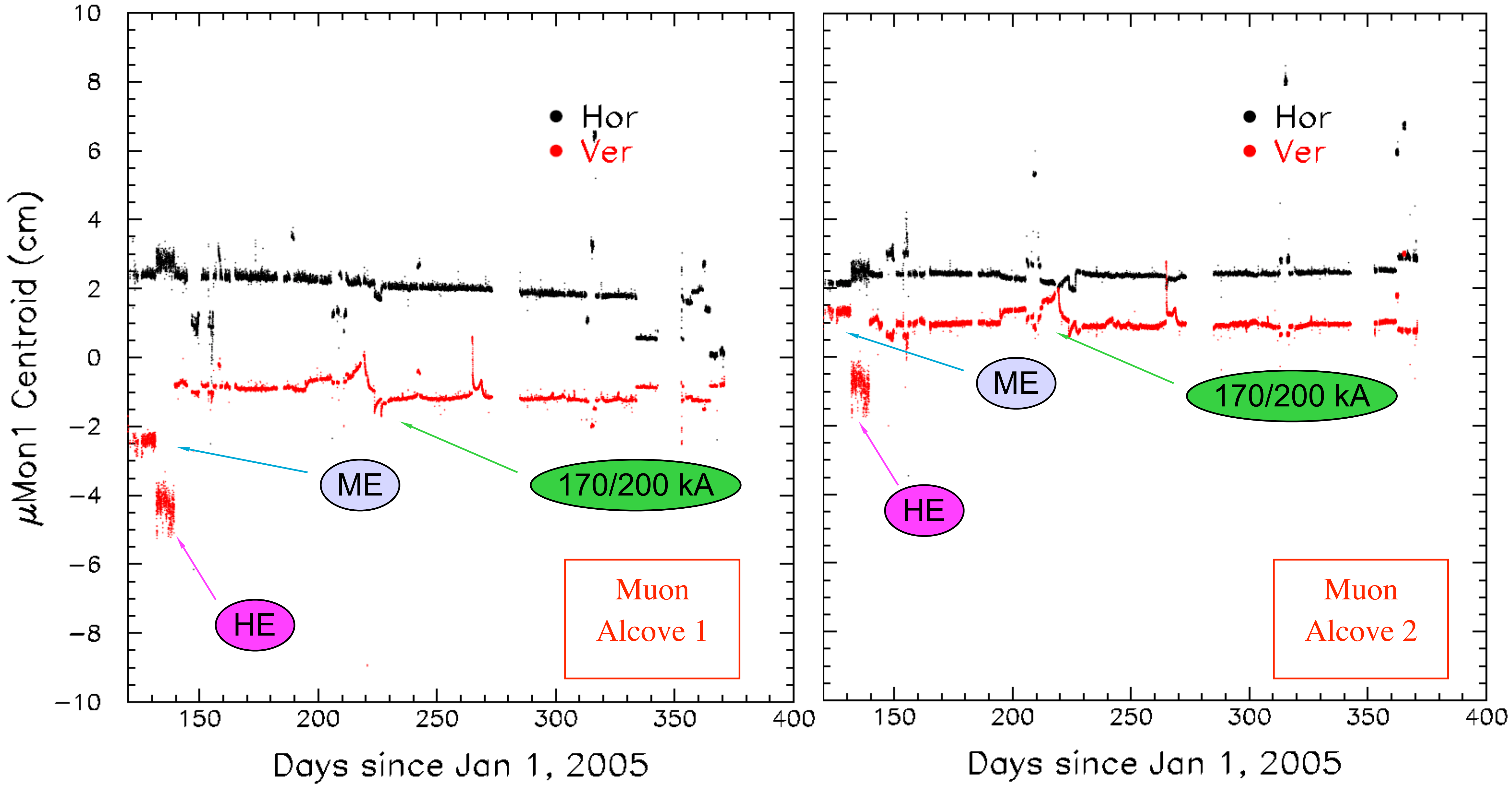


NuMI beam monitoring display - Feb 22nd 2007



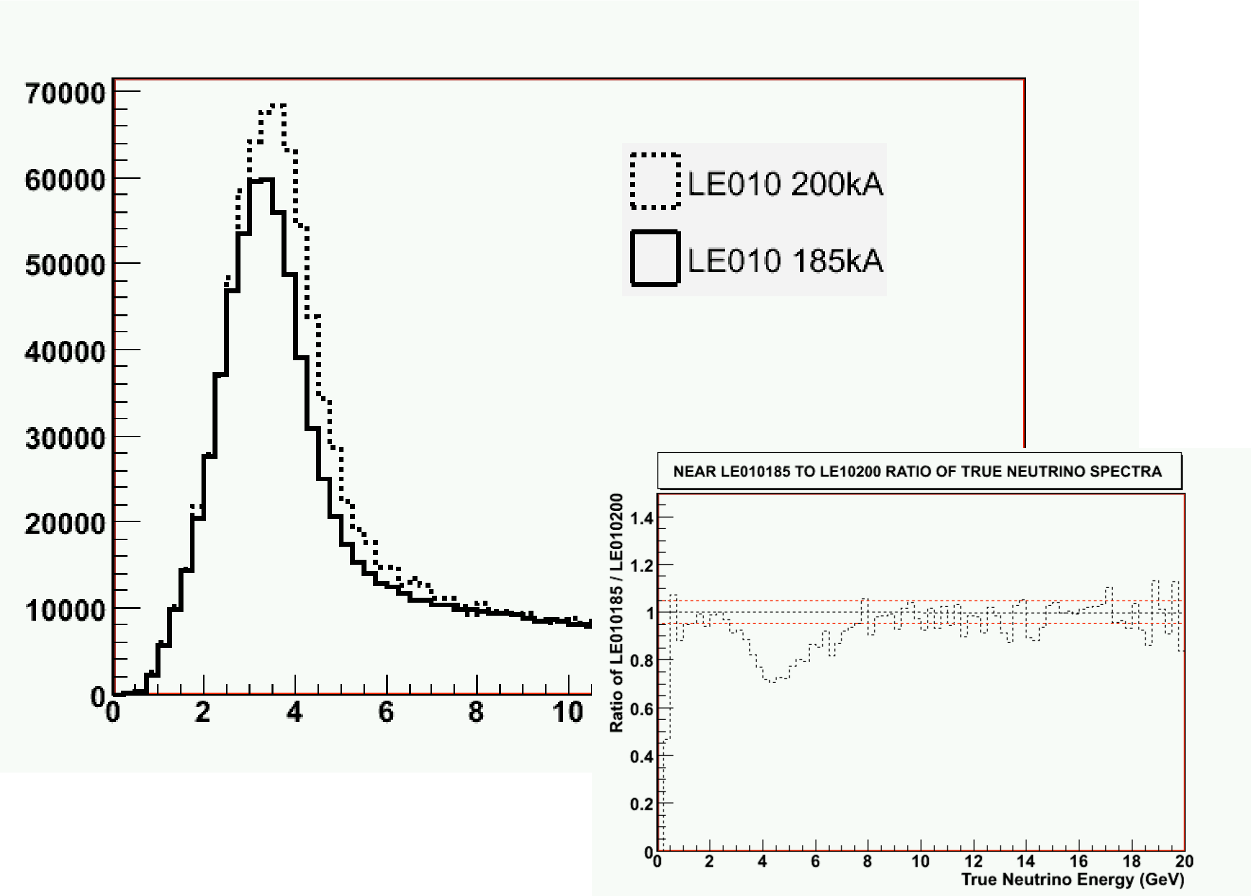
- **On Feb 22nd delivered 4.05x10^{13} protons to the NuMI target in a single pulse**
  - Regular running in this mode will require more study (+ hardware upgrades) but current study is very promising for increasing beam intensity

Beam pointing with μ monitors



- To keep distortions in the FD spectrum <1%, we require <100μrad mis-steering of the ν beam from FNAL
- At the muon monitors, a 10 cm shift in the muon beam centroid corresponds to a 130μrad angular deviation.

Cancellation of beam uncertainties



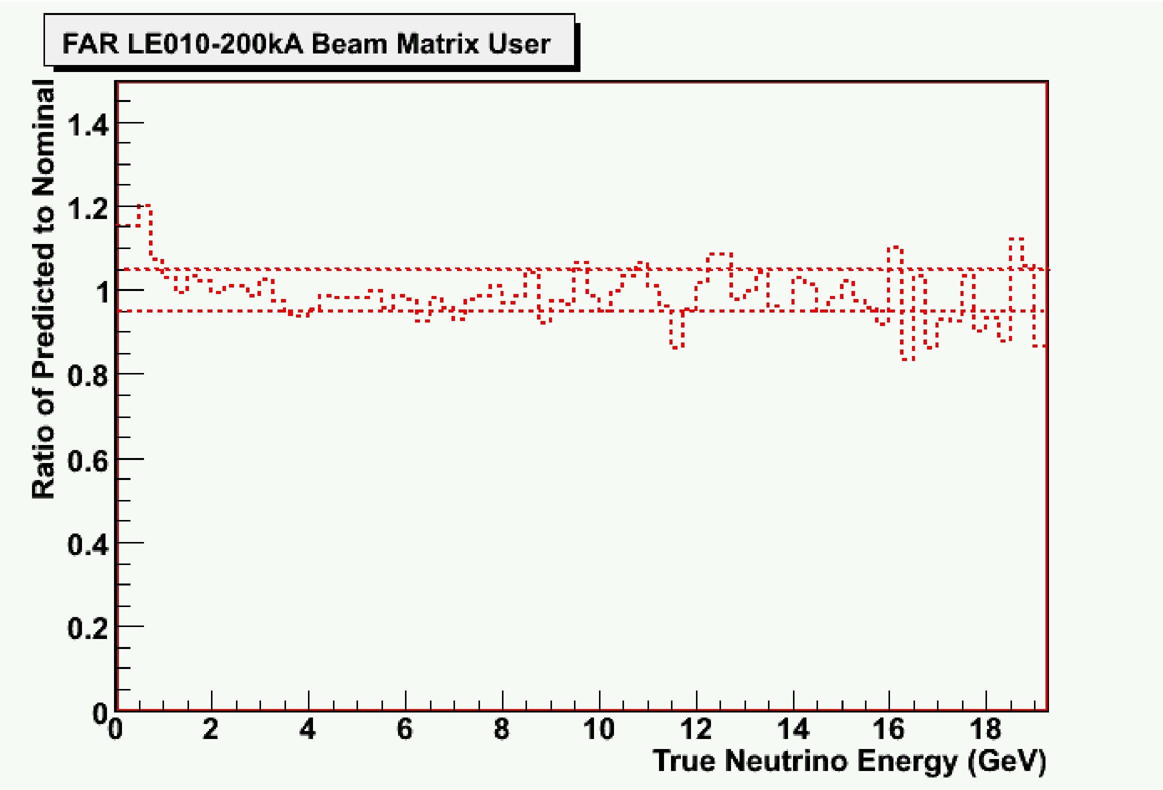
Beam Matrices that correspond to quite different near detector spectra are very similar (spread in each column determined primarily by the geometry of the beamline)

NOTE :Red dotted bands are ± 5%.

Method: Use instead of LE010 185 kA Beam transfer Matrix the LE010 200kA Beam transfer Matrix

These different matrices correspond to quite different “beams” as evident from the Near Detector Spectra.

However, Far Detector Prediction is quite accurate to within < 5%



Cancellation of cross-section uncertainties

ND Spectrum **Beam Matrix** **FD Spectrum**

$$\begin{pmatrix}E_1\\E_2\\E_3\end{pmatrix} \times \underbrace{\begin{pmatrix}\sigma_a&0&0\\0&\sigma_b&0\\0&0&\sigma_c\end{pmatrix}^{-1} \times \begin{pmatrix}b_1&0&0\\0&b_2&0\\0&0&b_3\end{pmatrix}}_{\textbf{ND Flux}\ \longrightarrow\ \textbf{FD Flux}} \times \begin{pmatrix}\sigma_a&0&0\\0&\sigma_b&0\\0&0&\sigma_c\end{pmatrix} = \begin{pmatrix}e_1\\e_2\\e_3\end{pmatrix} \Rightarrow$$

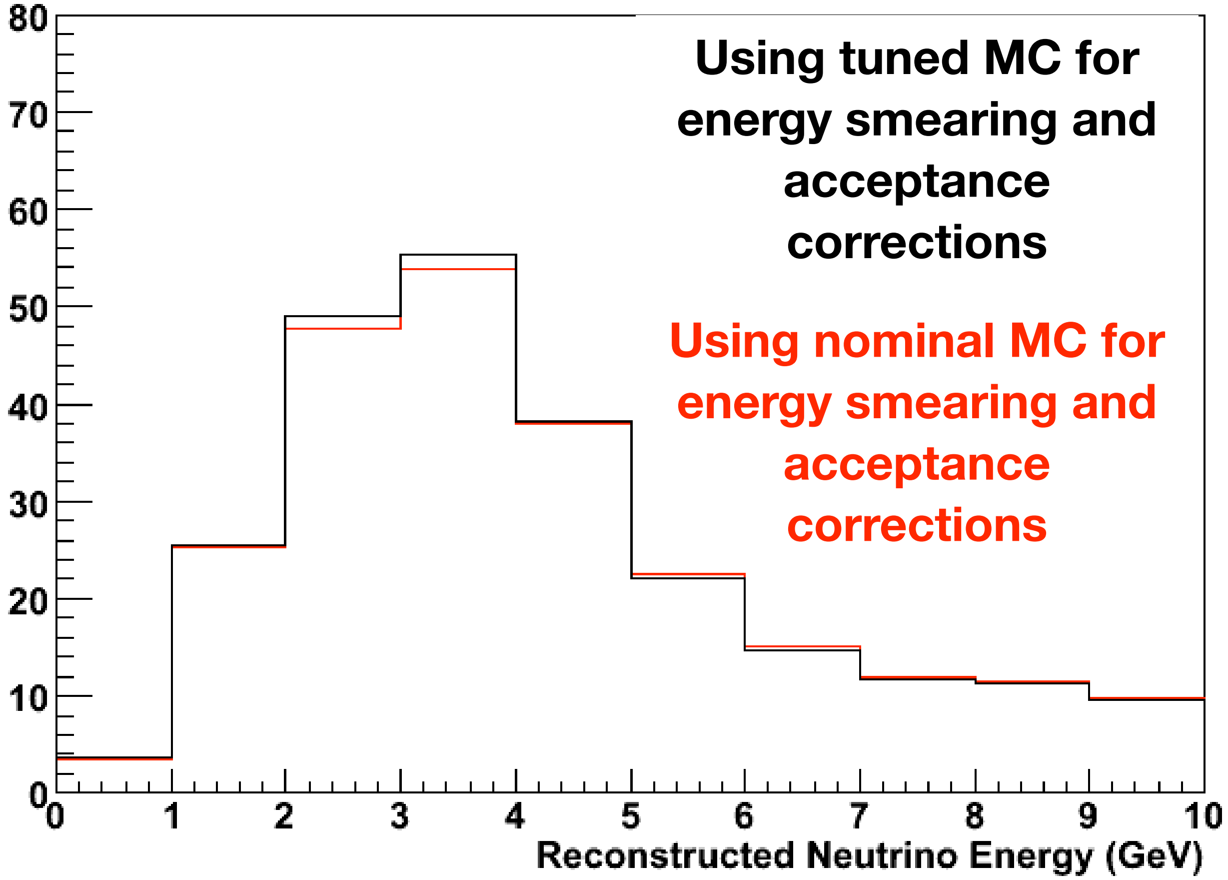
Cross Section matrices & Beam Matrix almost diagonal=>They Commute!

$$\Rightarrow \begin{pmatrix}E_1\\E_2\\E_3\end{pmatrix} \times \underbrace{\begin{pmatrix}\sigma_a&0&0\\0&\sigma_b&0\\0&0&\sigma_c\end{pmatrix}^{-1} \begin{pmatrix}\sigma_a&0&0\\0&\sigma_b&0\\0&0&\sigma_c\end{pmatrix}} \begin{pmatrix}b_1&0&0\\0&b_2&0\\0&0&b_3\end{pmatrix} = \begin{pmatrix}e_1\\e_2\\e_3\end{pmatrix}$$

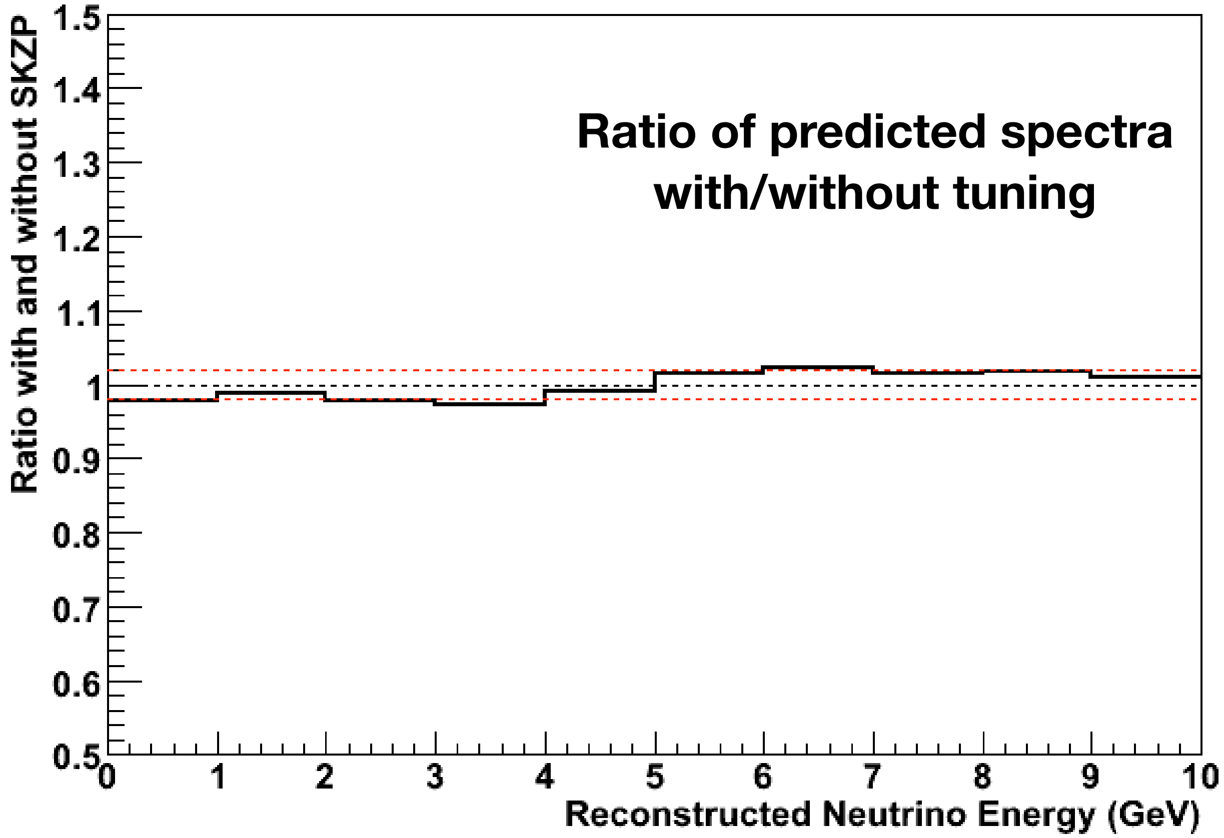
Their Product is I regardless of their values! (In the limit where the Beam Matrix is diagonal)

Effect of MC tuning on the FD prediction

Far Predicted Spectra using the Beam Matrix and with/without hadron production tuning



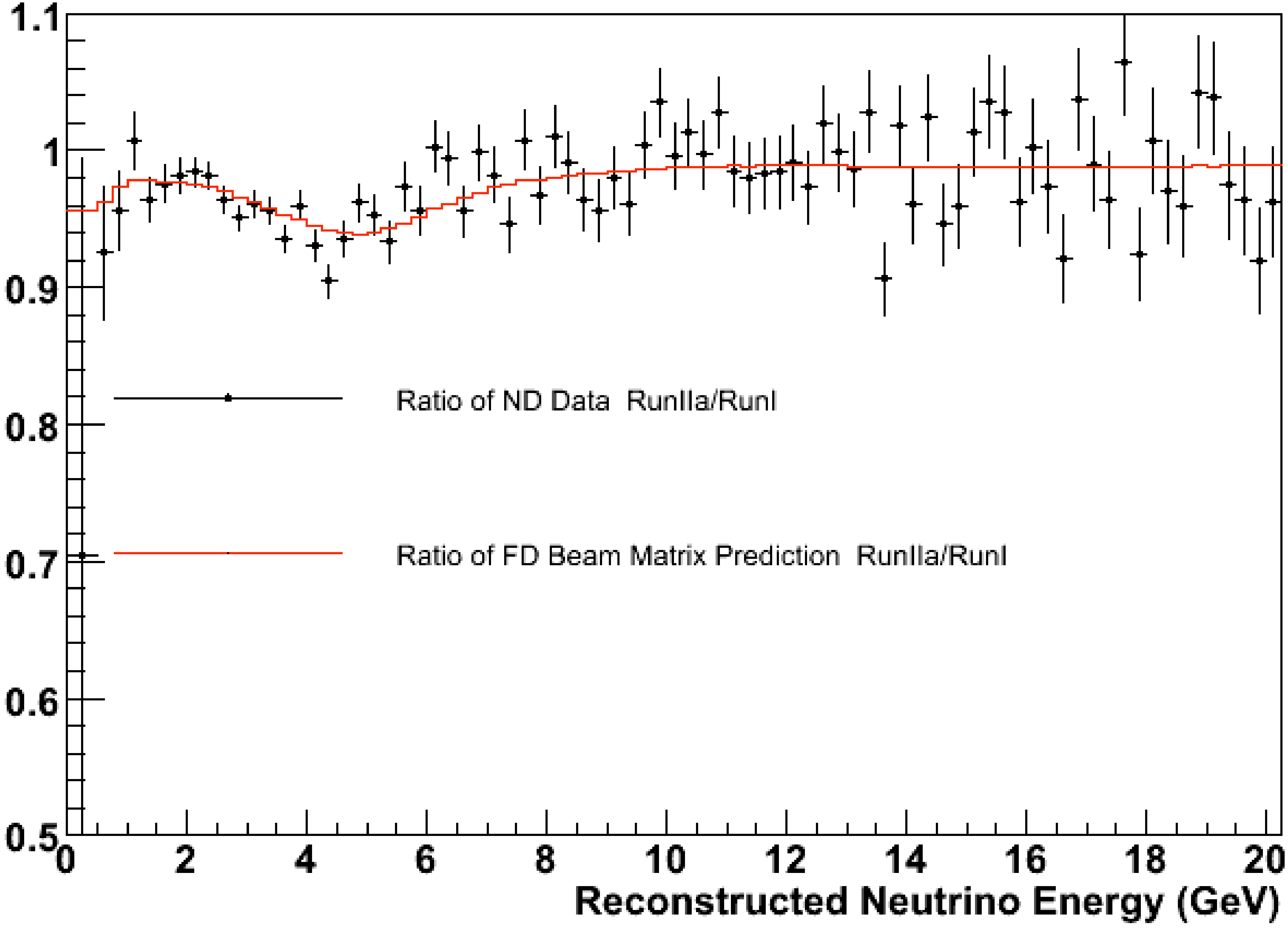
Ratio of Far Prediction using the Beam Matrix and with/without hadron production tuning



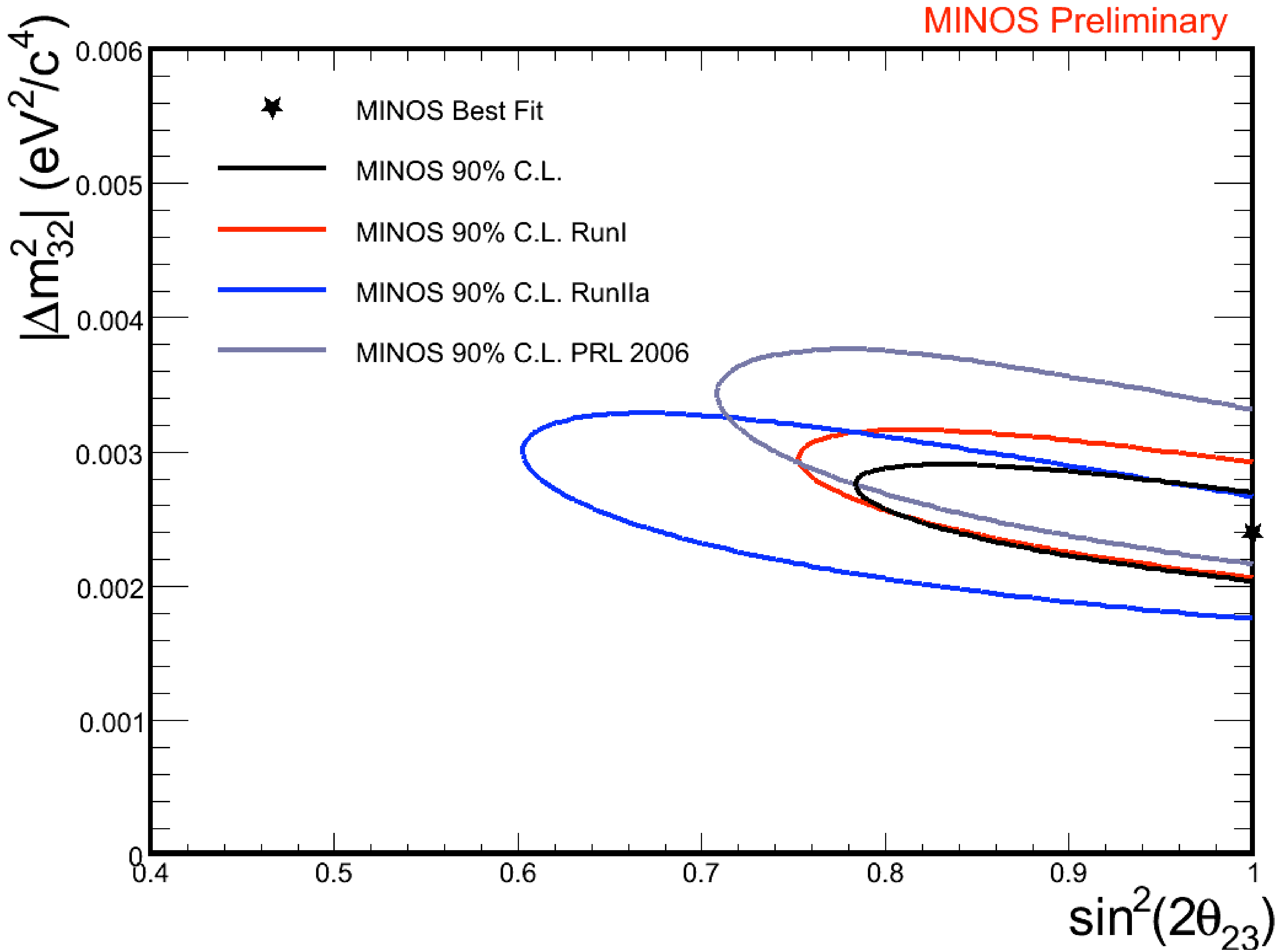
Using the Beam Matrix Method, hadron production tuning does not affect the Unoscillated prediction (obtained from the ND data) by more than 1-2%.

However, its use improves the MC (make it more similar to the data) and therefore uncertainties due to energy smearing-unsmearing and acceptance become smaller.

Run I/Run IIa spectrum differences



Contour evolution



MINOS Detector technology

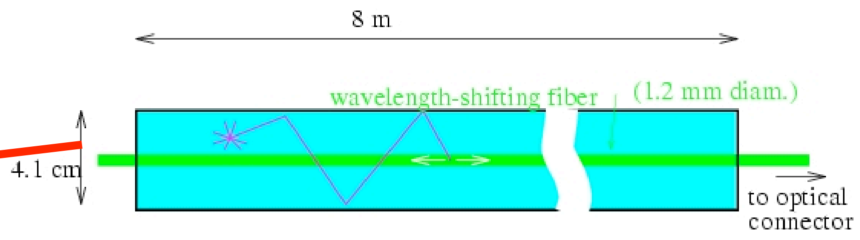
- **MINOS Near and Far detectors are functionally identical:** share same detector technology and granularity:

  2.54 cm thick magnetised steel plates

  4.1x1cm co-extruded scintillator strips (MINOS-developed technology)

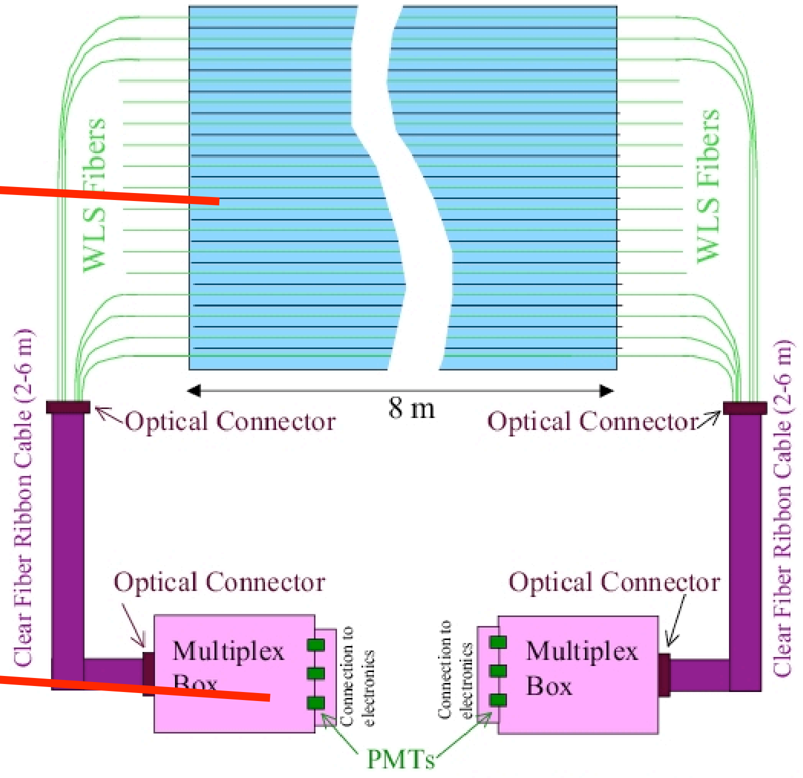
  orthogonal orientation on alternate planes – U,V

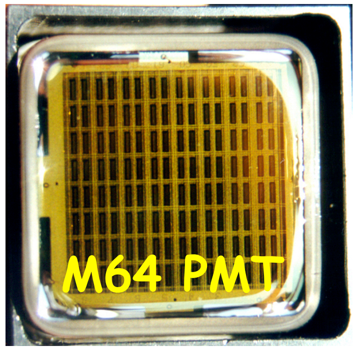
  optical fibre readout to multi-anode PMTs

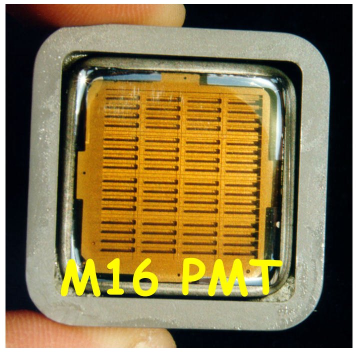


1.0 cm x 4.1 cm extruded polystyrene scintillator

Scintillator Module



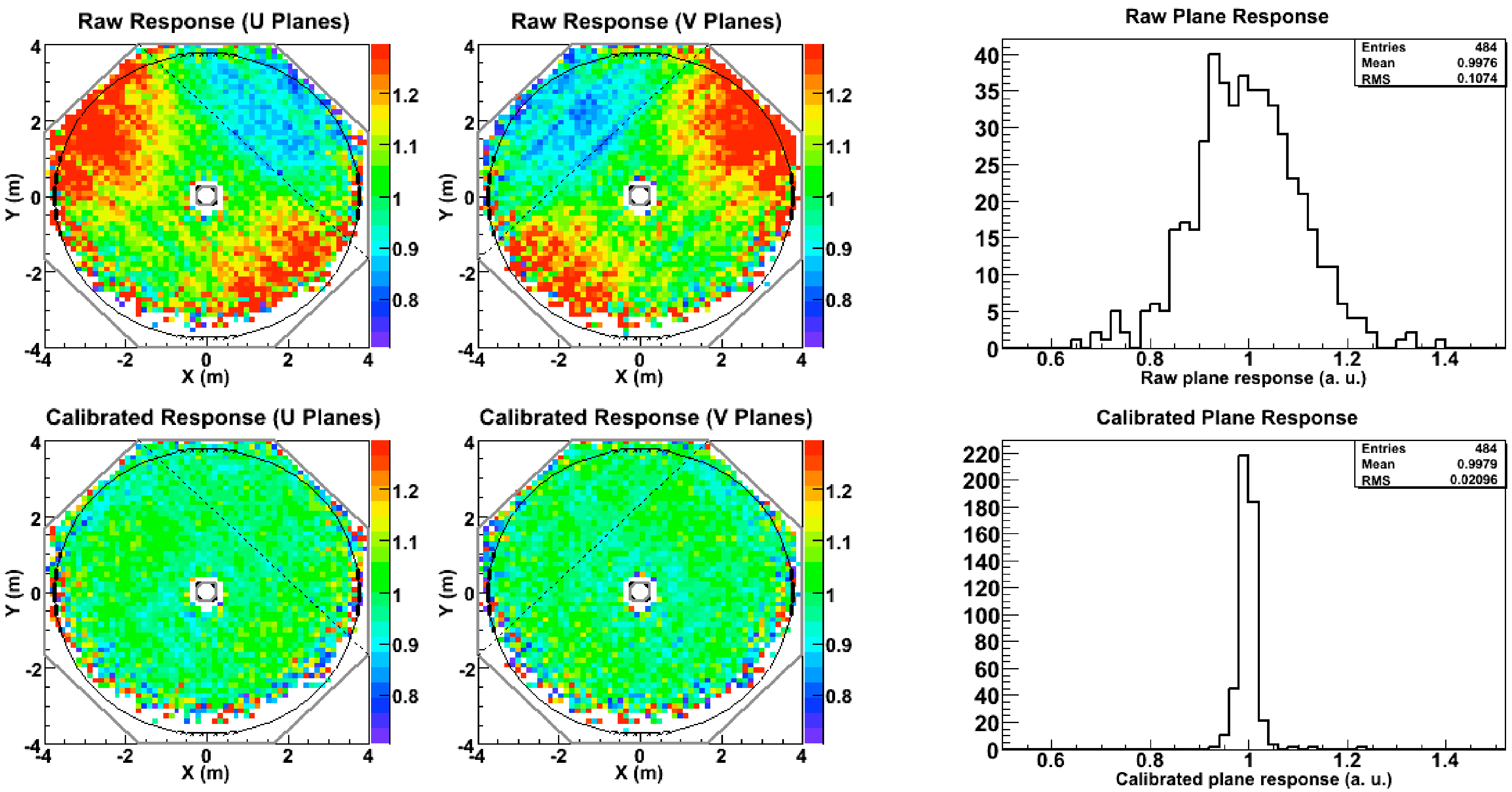




Objects not to scale

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**

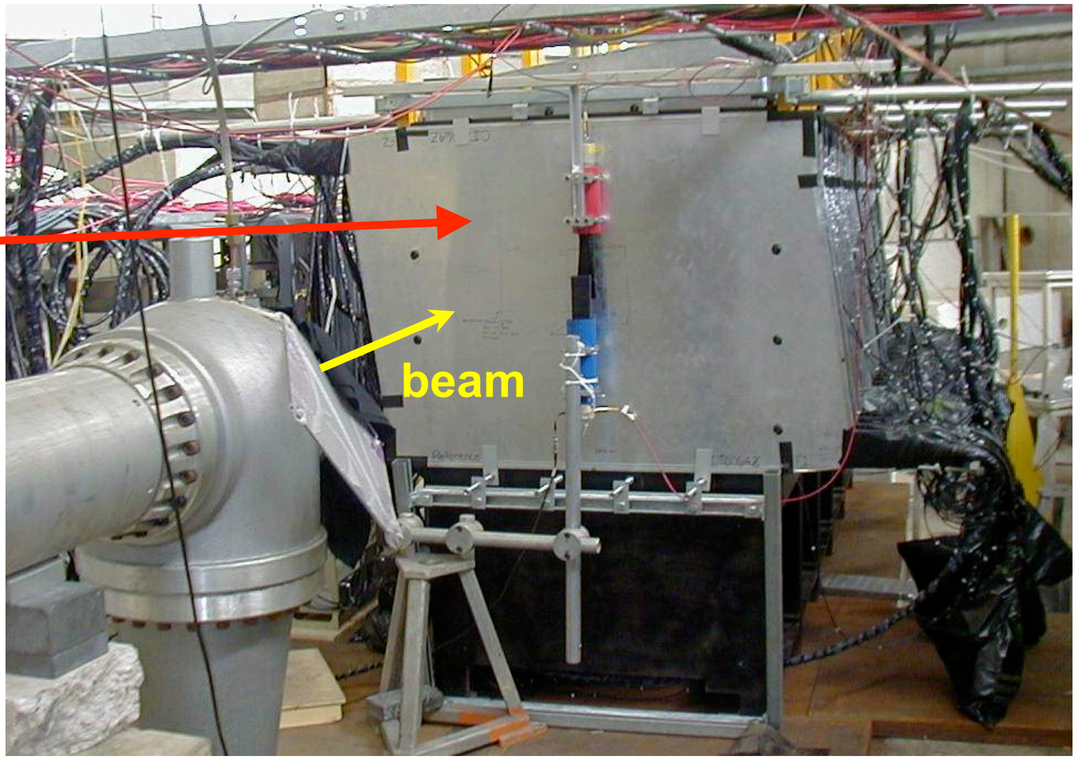


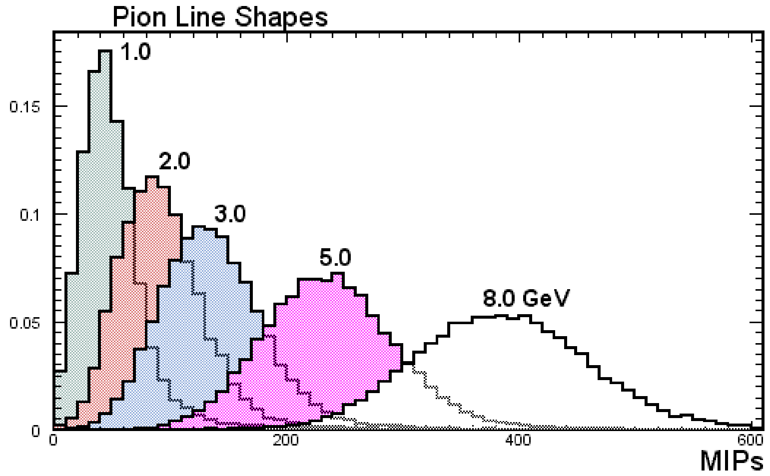
MINOS Calibration Detector

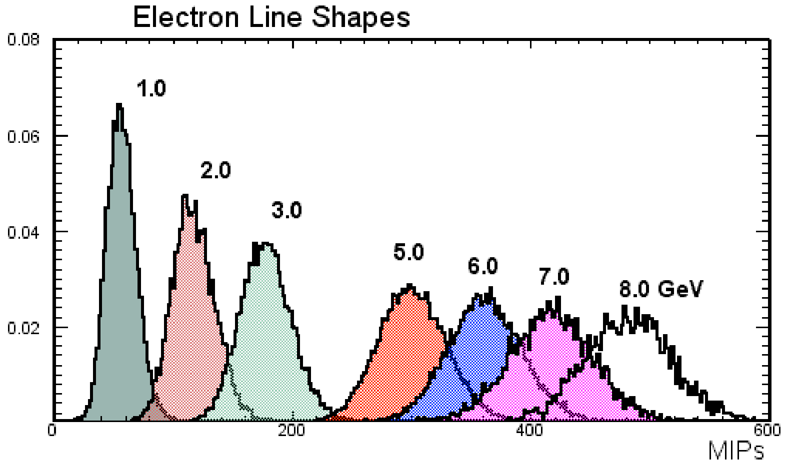
- Help understand energy response to reconstruct E_ν

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

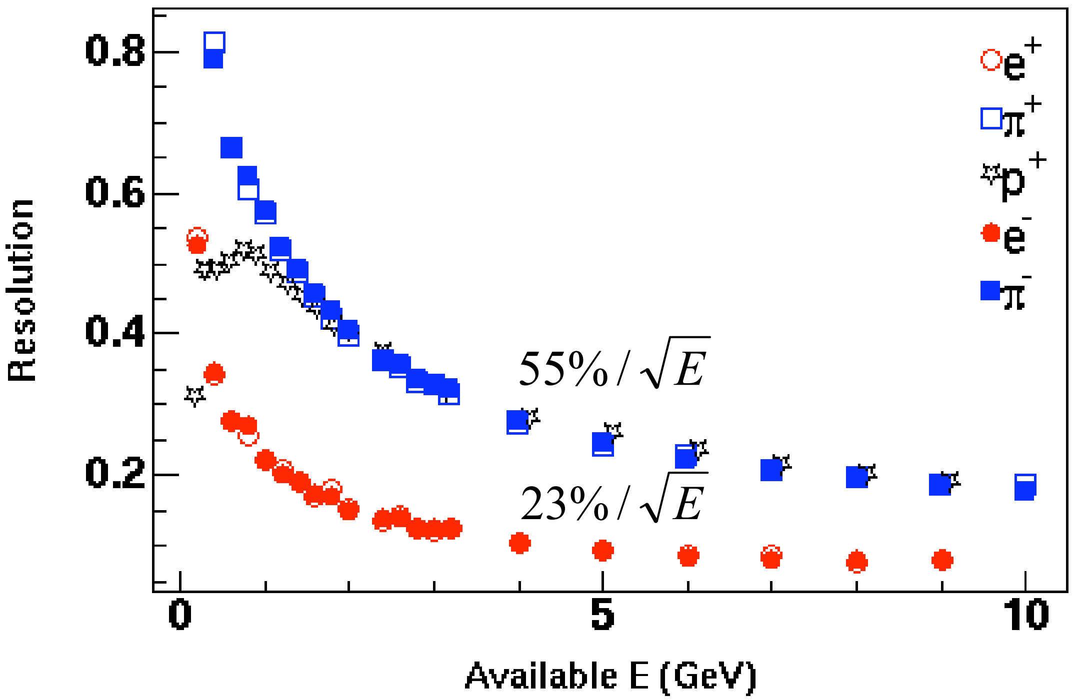
- Measured in a CERN test beam with a "mini-Minos"
  - operated in both Near and Far configurations
  - Study e/μ/hadron response of detector
  - Test MC simulation of low energy interactions
  - **Provides absolute energy scale for calibration**





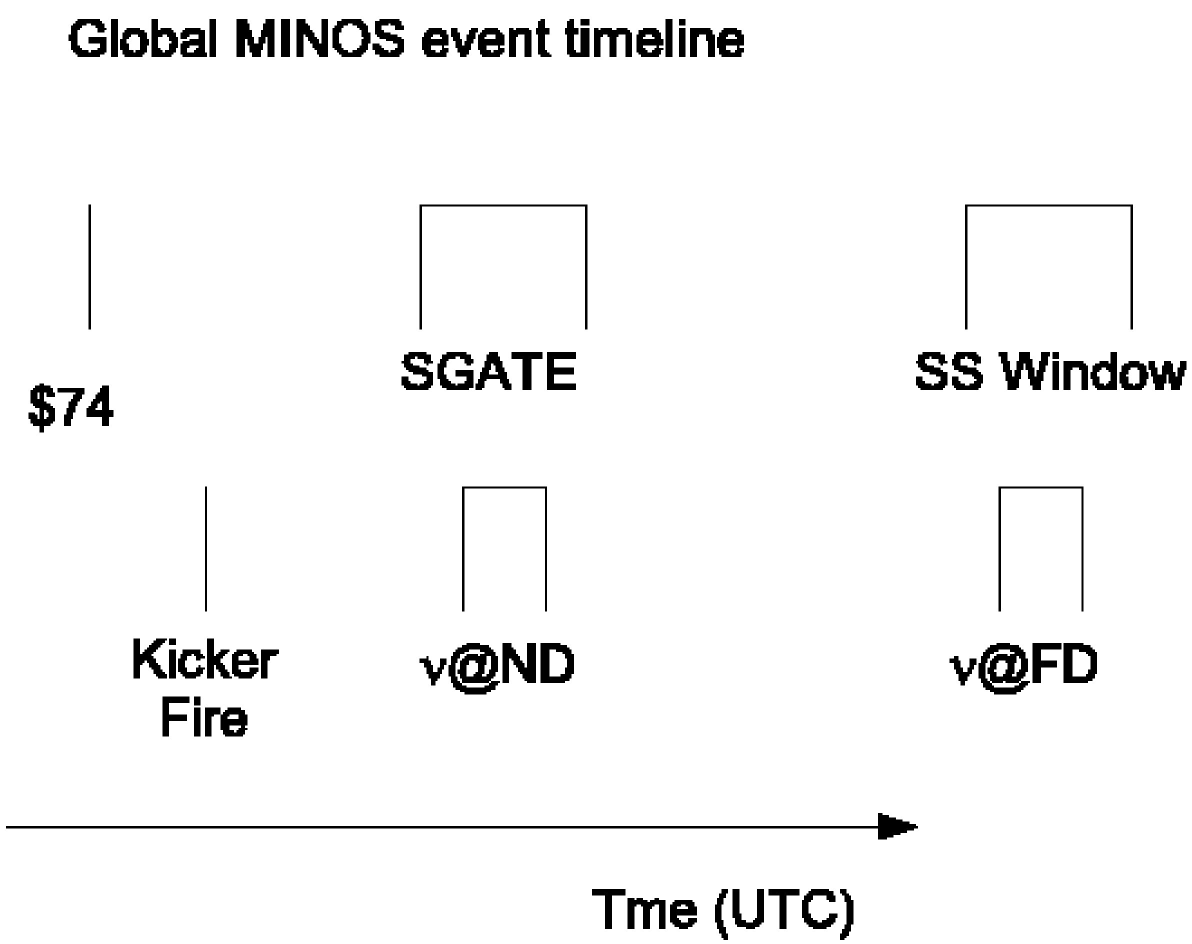


Single particle energy resolution



Event catching - timing and triggering

- The elements of the timing system are as follows:
  - $74 signal from Main Injector – tells kicker magnet (which extracts protons to NuMI) that it is in the queue to fire (which it does ~220 us later).
  - $74 signal sent to clock controller at ND & a spill gate (SGATE) window is opened (in hardware) for 13us around the time neutrinos hit the ND (with an offset of –1.5us)
  - SpillServer process at FD informed when most recent spill occurred.
  - FD trigger farm queries SpillServer process every second. If a spill signal has been received and the Spill Trigger is enabled, the DAQ reads out 100us of previously buffered data around the predicted time that the neutrinos should have hit the FD



NEUGEN cross-section model

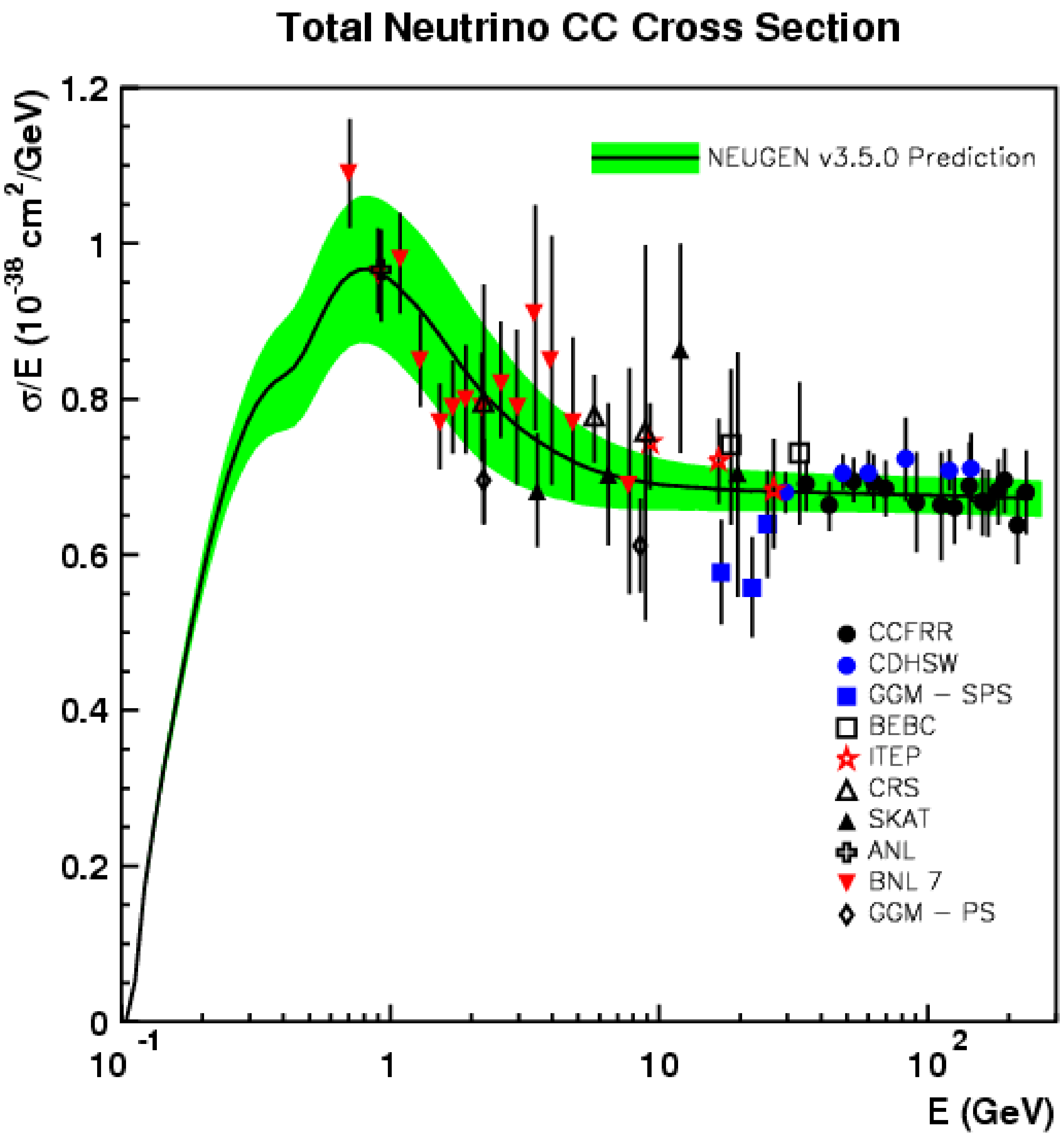
Neutrino-nucleus interactions were generated using the NEUGEN3 neutrino event generator
(H. Gallagher, Nucl.Phys.Proc.Suppl. **112**: 188-194, 2002)

Quasi-Elastic: dipole parametrization
of form factors with ma=0.99 GeV/c^2
(BBBA05 Bradford et al. Nucl.Phys.Proc.Suppl. 159:127-132,2006)

Resonance Production:
Rein-Seghal model for W<1.7 GeV/c^2.
(Annals Phys. **133**: 79, 1981)

DIS: Bodek-Yang modified LO model.
For W<1.7 GeV tuned to electron and neutrino data in the resonance / DIS overlap region.
(Bodek-Yang, Nucl. Phys. Proc. Suppl. **139**: 113-118, 2005 and H. Gallagher, NuINT05 Proceedings)

Coherent Production:
Rein-Seghal (Nucl. Phys. B **223**: 29, 1983*)*

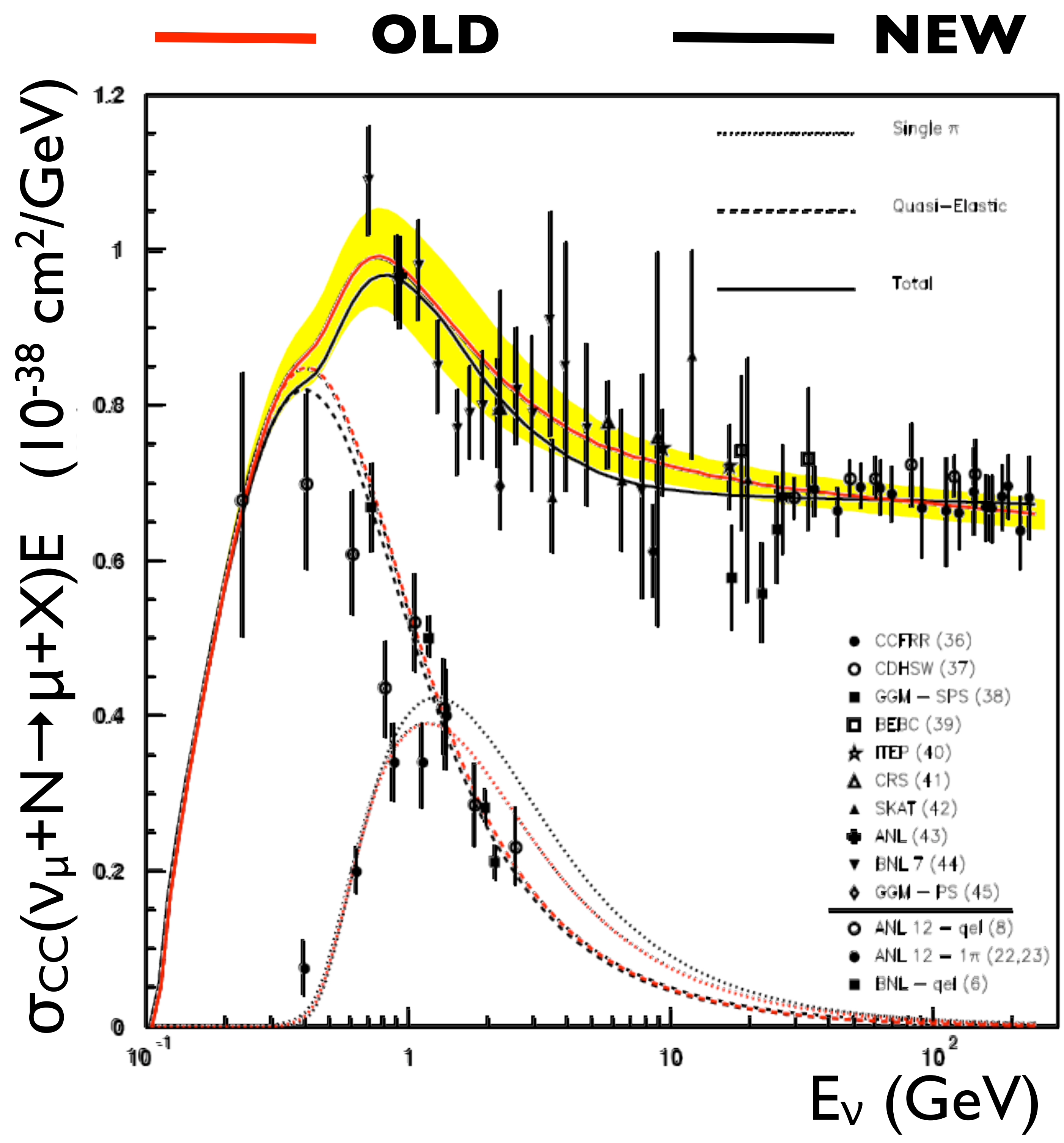


Cross-section changes

- Change in cross-section parameters and total CC cross-section between old (2006) Monte Carlo and the current analysis

	OLD MODBYRS-2	**NEW** MODBYRS-4
QEL-MA	1.032	0.99
RES-MA	1.032	1.12
r_{i12} and r_{i42}	0.20	0.10
r_{i22} and r_{i32}	0.20	0.30
r_{ij3}	1.00	1.00
σ/E (100 GeV)	0.673	0.677

- Corresponds to ~3% drop in rate of CC events, integrated over LE-10 energy spectrum



Exotic models - decay/decoherence

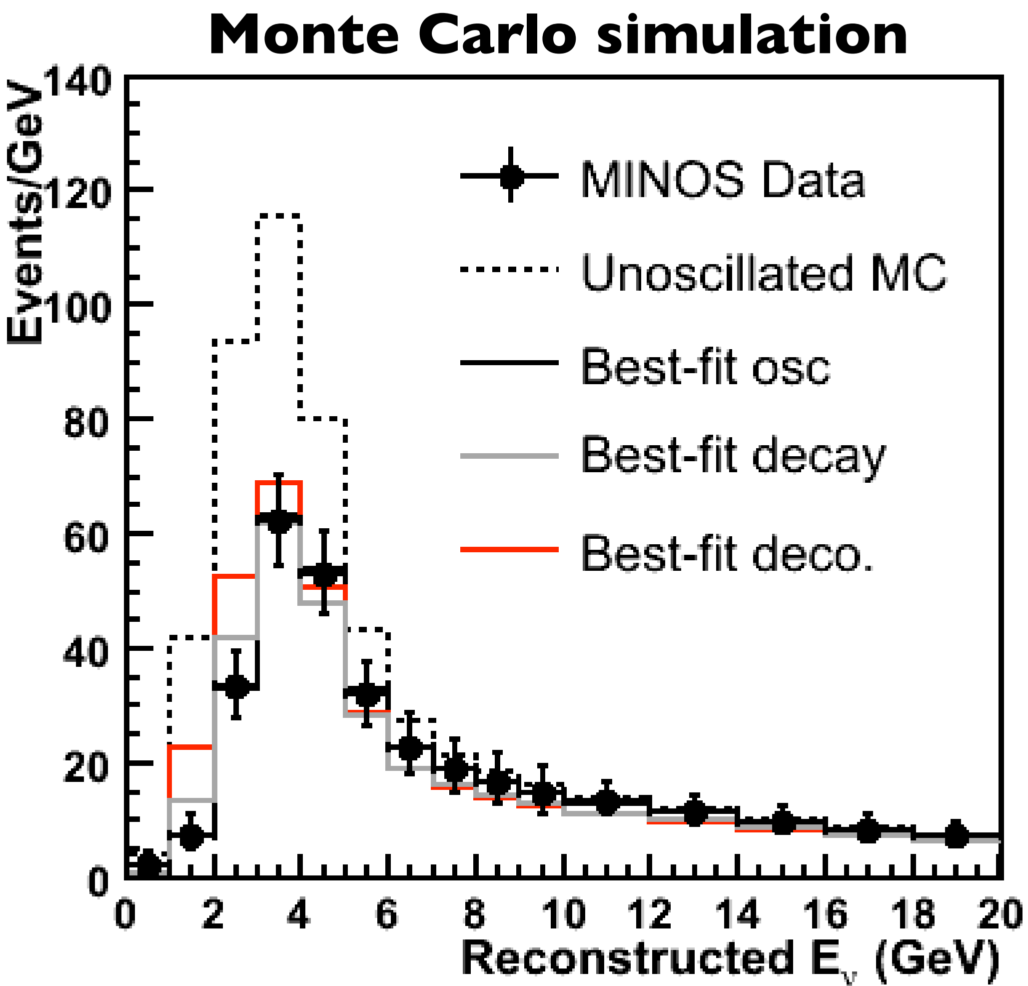
- Decay/Decoherence Disappearance probabilities are exponential functions of energy
  - **no “dips” in spectrum ratio**
- They can mimic oscillation signals, but there are discrepancies at high energy (+low E for decoherence)

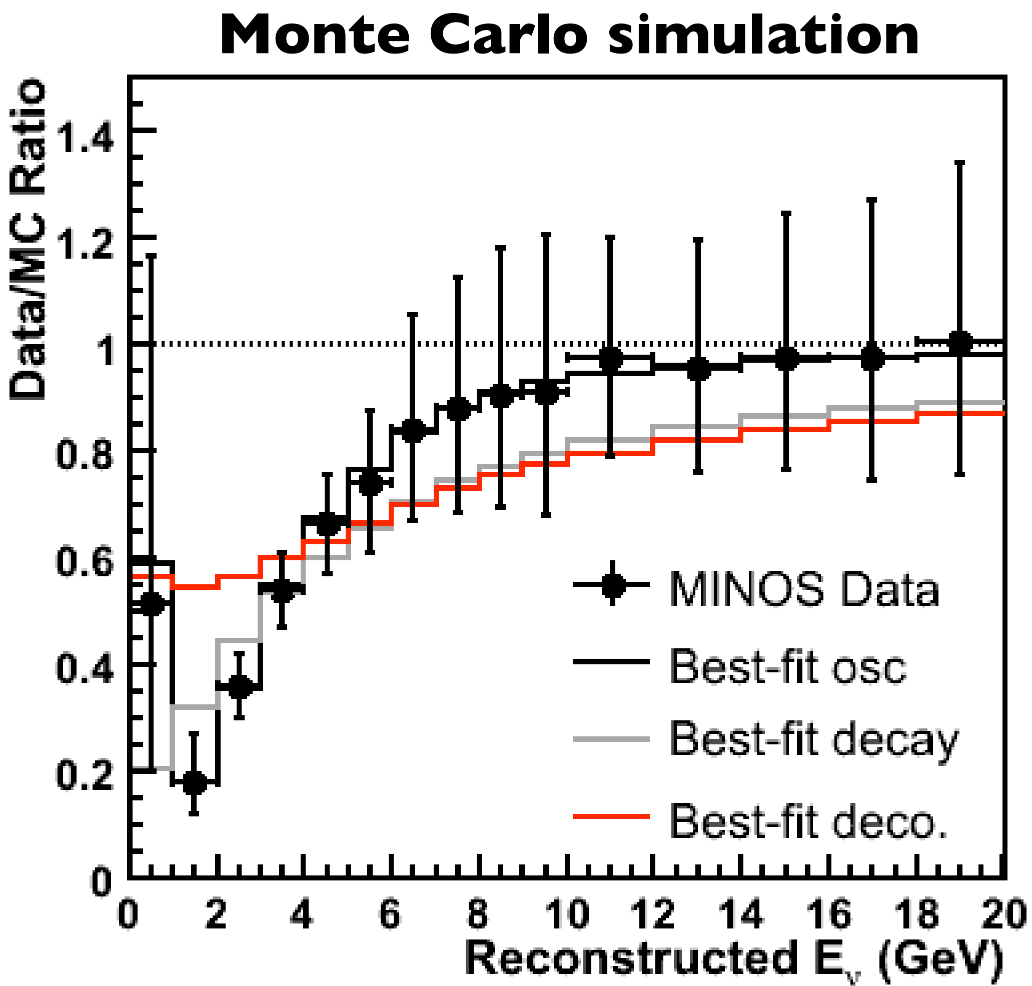
Neutrino Decoherence

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \frac{\sin^2 2\theta}{2}\left(1 - e^{-\frac{\mu^2 L}{2E}}\right)$$

Neutrino Decay

$$P(\nu_\mu \rightarrow \nu_\mu) = (\sin^2\theta + \cos^2\theta e^{-\frac{\alpha L}{2E}})^2$$


Monte Carlo simulation


Monte Carlo simulation

PID correlations

- DP PID: Old CC/NC separation method using 1D PDFs
- AB PID: New CC/NC separation method using 2D PDFs
- Overlap between selected samples is high, however new PID has much lower rate of mis-identified NC events at low energies