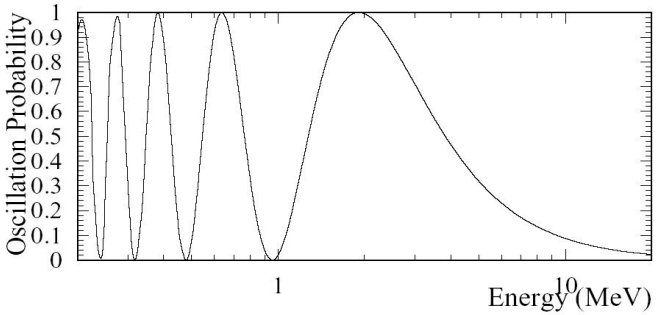
First Accelerator Neutrino Results From The MINOS Experiment

Francisco Yumiceva

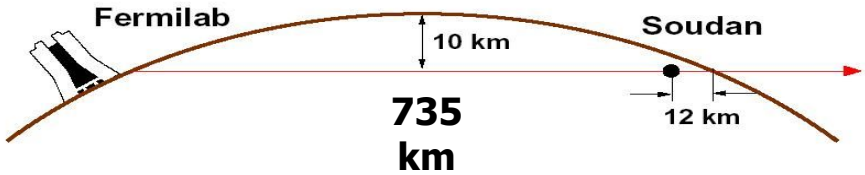
April 26, 2006

Outline

- **Introduction**
  - Neutrino Oscillations



- **The MINOS Experiment**
  - NuMI Beam
  - Detectors



- **Disappearance Analysis**
  - Selection Criteria
  - Systematics Studies
  - Results

$$\Delta m^2_{23},\ \sin^2(2\theta_{23})$$

- **Current Projects**

Neutrino Oscillations

$$|\nu_\alpha\rangle = \Sigma_i U^*_{\alpha i} |\nu_i\rangle$$

flavor state — mass state

Leptonic Mixing Matrix (PMNS)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric $\theta \sim 45°$

Cross-Mixing

Solar $\theta \sim 34°$

Majorana CPV phases

$c_{ij} \rightarrow \cos\theta_{ij}$ $s_{ij} \rightarrow \sin\theta_{ij}$

Probability: $P(\nu_\alpha \rightarrow \nu_\beta) = |\langle\nu_\beta | \nu_\alpha\rangle|^2$

Only two flavors:

Appearance → $$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2[eV^2]\frac{L[km]}{E[GeV]}\right)$$

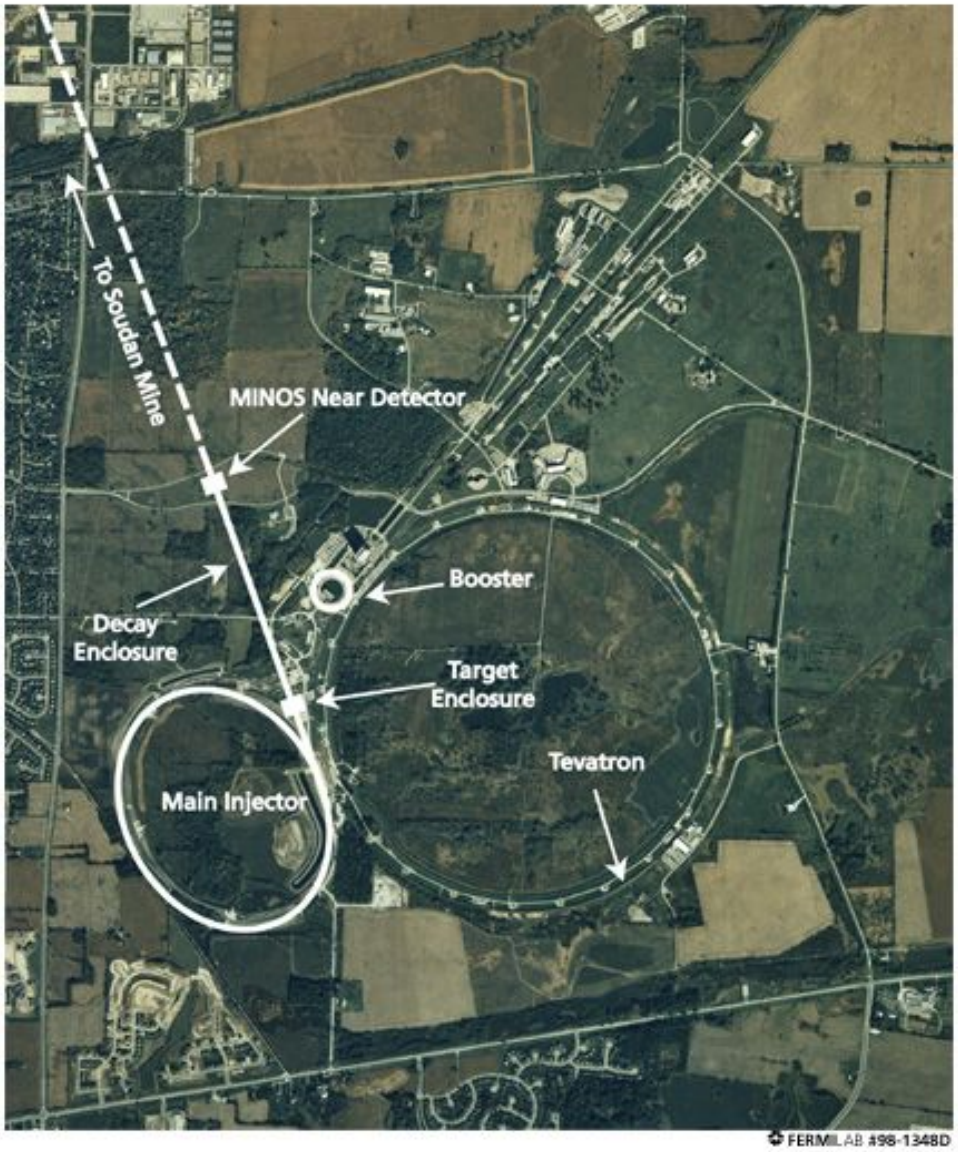
Disappearance → $$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2[eV^2]\frac{L[km]}{E[GeV]}\right)$$

this talk

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

The MINOS Experiment

- **MINOS is a *long-baseline* neutrino oscillation experiment:**



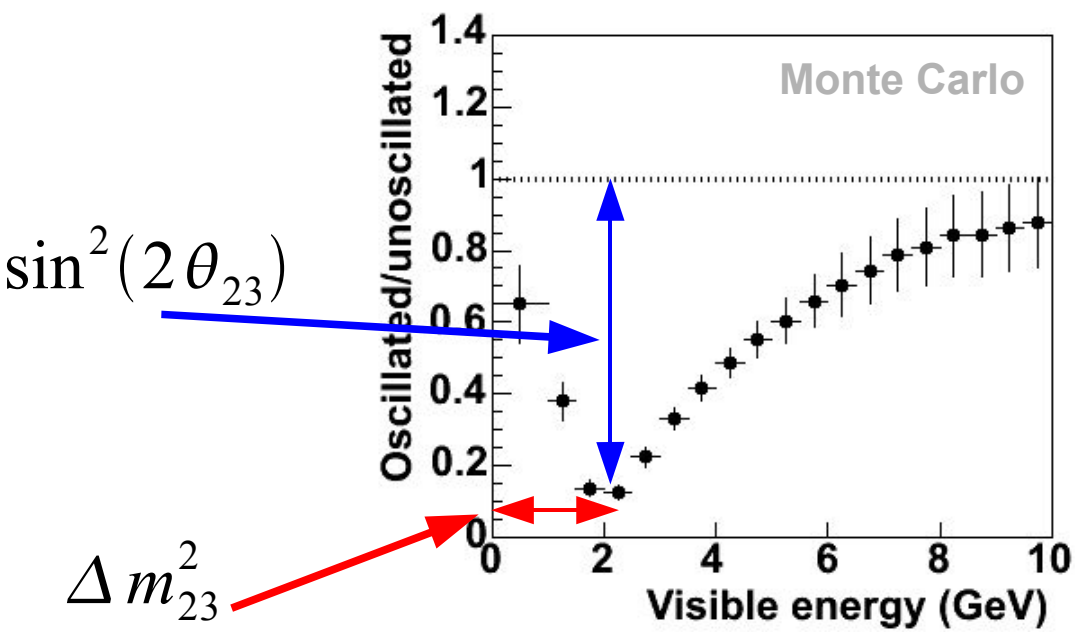
- ν beam generated by 120 GeV protons at Fermilab
  - either 5 or 6 batches for MINOS
- Near detector at Fermilab
  - 1 km from target
  - 100 m below surface
- Deep underground far detector at Soudan, MN
  - 735 km away from Fermilab
  - 710 m below surface

MINOS Physics Goals

- **Atmospheric neutrino oscillations** (hep-ex/0512036)
  - First Observations of Separated Atmospheric ν_μ and $\bar{\nu}_\mu$ Events

- **Precise measurement of** Δm^2_{23} **and** $\sin^2(2\theta_{23})$

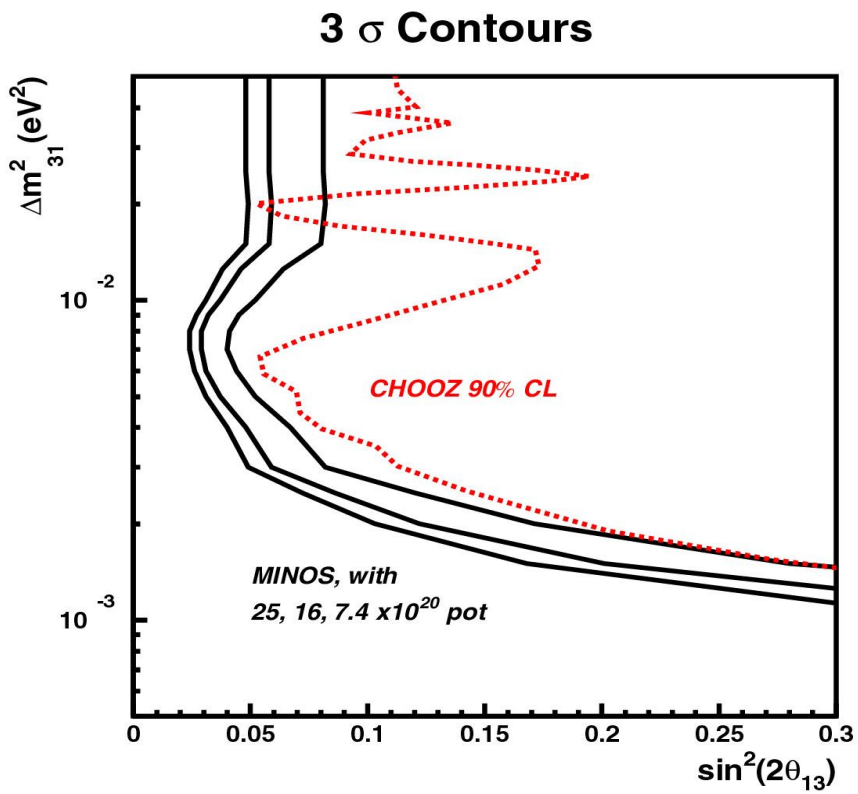
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\,\Delta m^2_{32} \frac{L[km]}{E[GeV]}\right)$$



MINOS Physics Goals

- Search for $\nu_\mu \rightarrow \nu_e$ oscillations

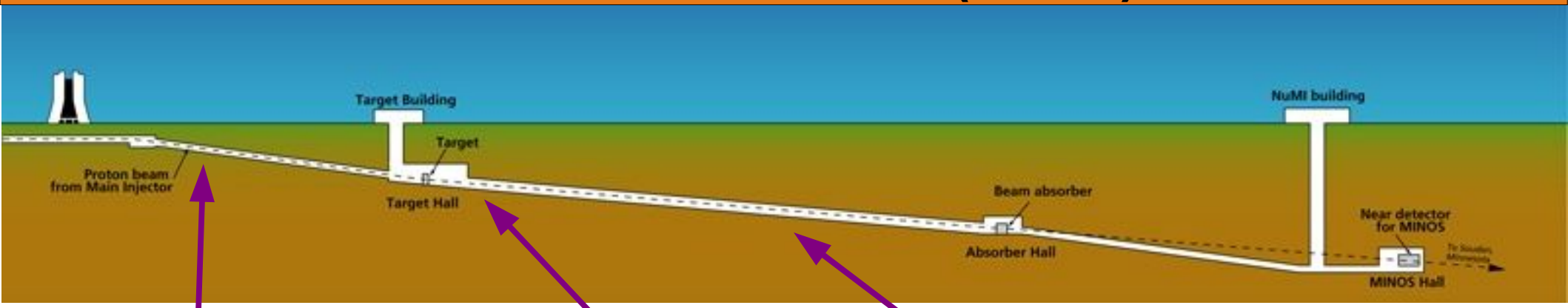
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(1.27\,\Delta m^2_{31} \frac{L[km]}{E[GeV]}\right)$$

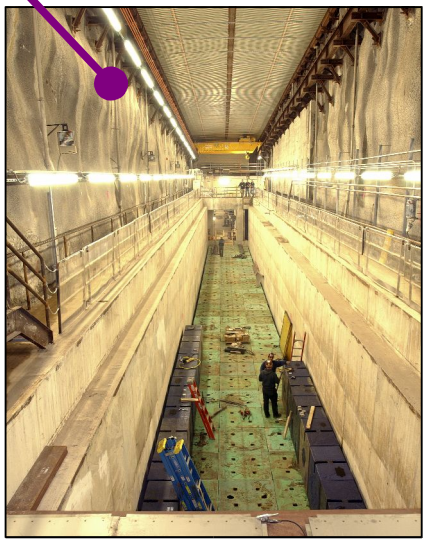


- Test of CPT violation $\nu_\mu \rightarrow \overline{\nu_\mu}$

- Search for **neutrino decay** **and** **sterile neutrino**

Neutrino Beam (NuMI)

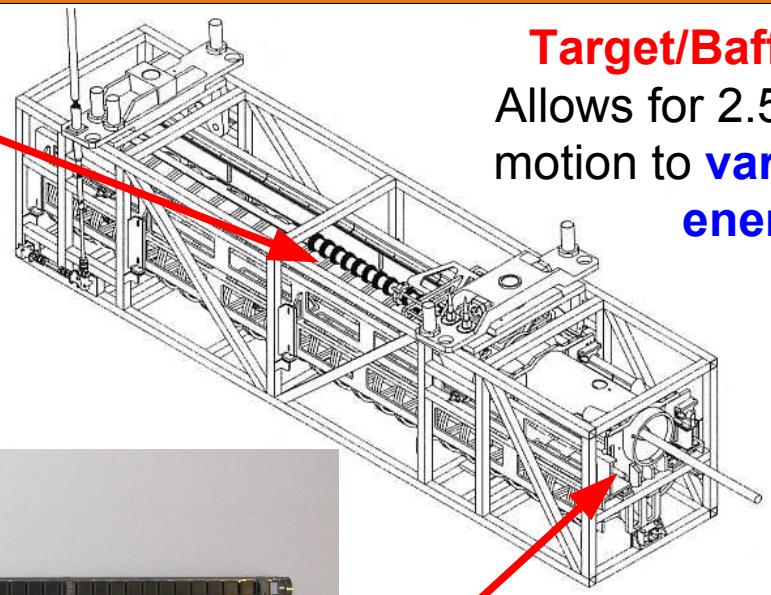




Design Parameters

- **120 GeV protons** from the Main Injector
- Main Injector up to 6 Booster batches/cycle
- Either **5 or 6 batches for NuMI**
- 1.87 second cycle time
- **4×10^{13} protons/pulse**
- 0.4 MW, 10 μs extraction time

NuMI Target and Focusing Horns



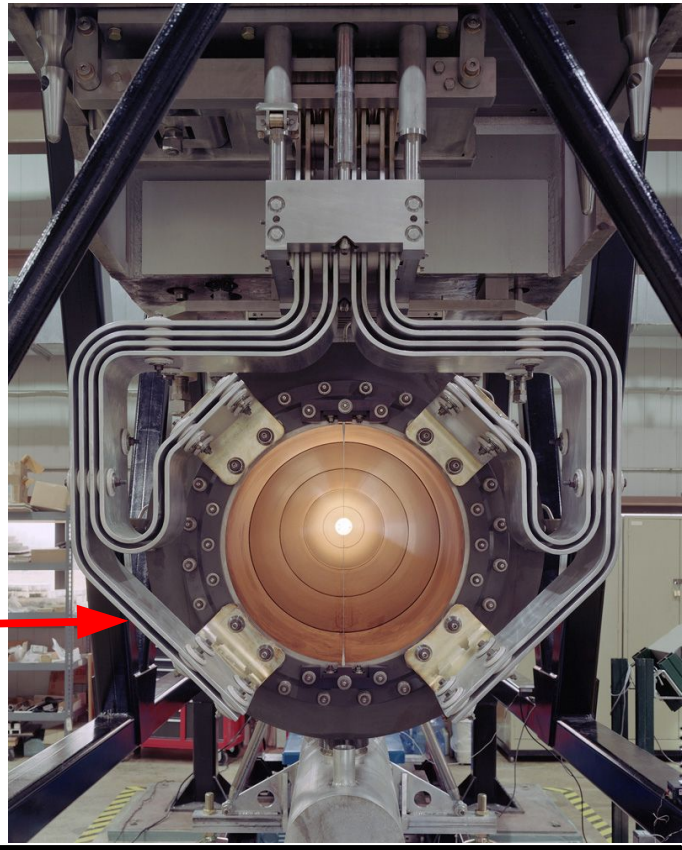
Target/Baffle Carrier
Allows for 2.5 m of target motion to **vary the beam energy**

Baffle

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

Target

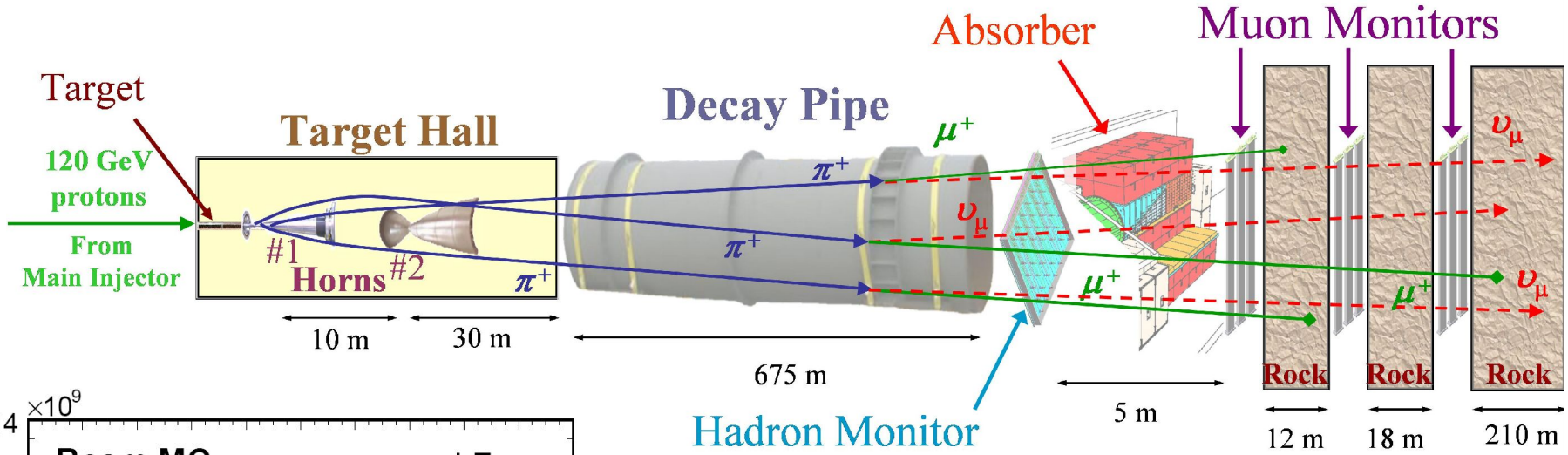
- **47 segments of graphite** of 20 mm length and 6.4x15 mm^2 cross section
- 0.3 mm spacing between segments, for a **total target length of 95.4 cm**

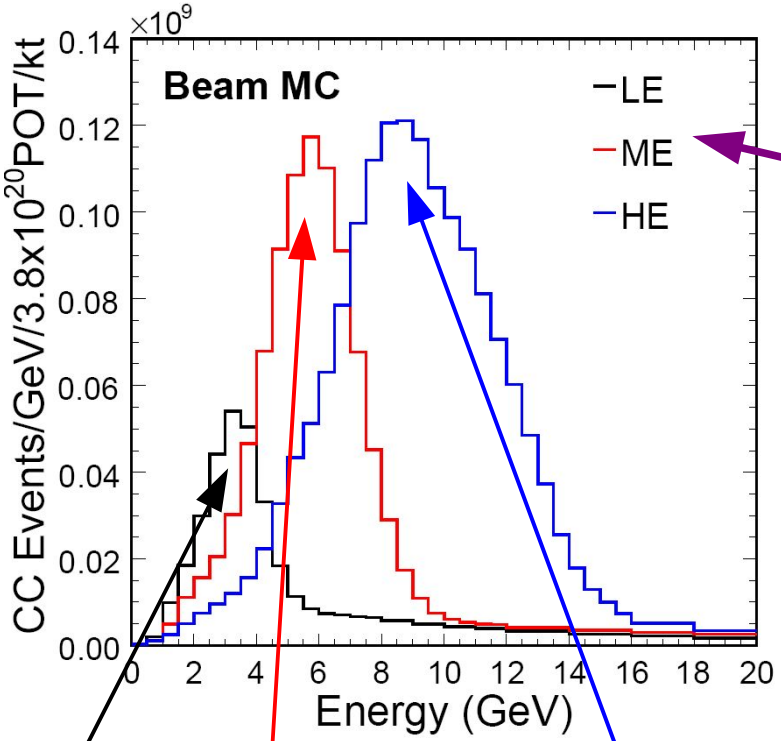


Horns

- **Two parabolic focusing horns**
- Nominal horn current at 200 kA
- Produces 3 Tesla peak field

Neutrino Beam





Low

pseudo Medium

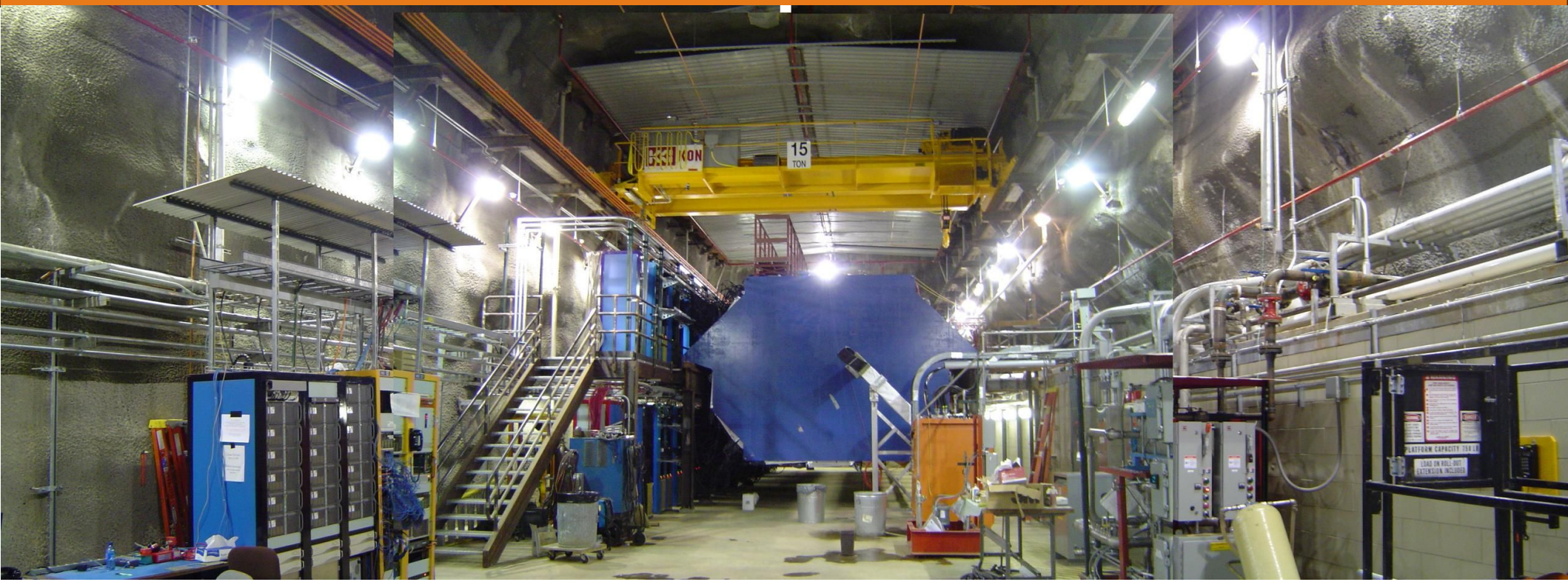
pseudo High

- **Variable neutrino spectrum** by changing target position and horn currents.
- Currently **running at Low Energy** configuration
- Beam composition: **92% ν_μ**, 6.5% $\nu_\mu$bar, 1.5% (ν_e+$\nu_e$bar)

Unoscillated

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

Near Detector



- Fully constructed Aug 2004
- 1 kton mass, 3.8m x 4.8m x 15m
- 282 steel planes, 153 scintillator planes
- Fast QIE electronics
- B ~ 1.2 T
- Multi-pixel PMTs
- GPS time-stamping
- Fully and partial instrumented planes
- Two regions: calorimeter (120 planes), and spectrometer (162 planes)

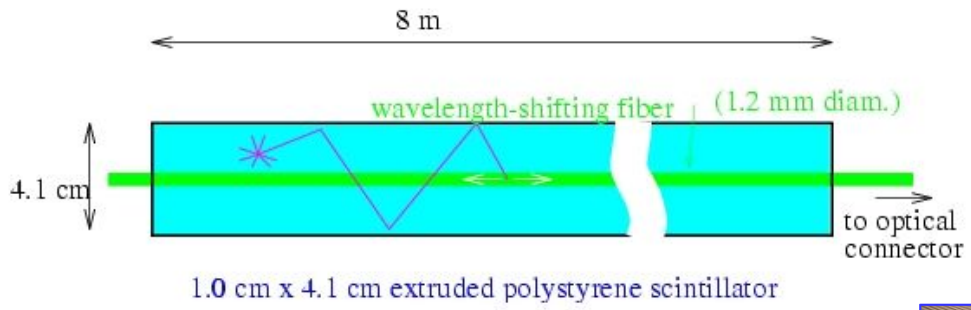
Far Detector

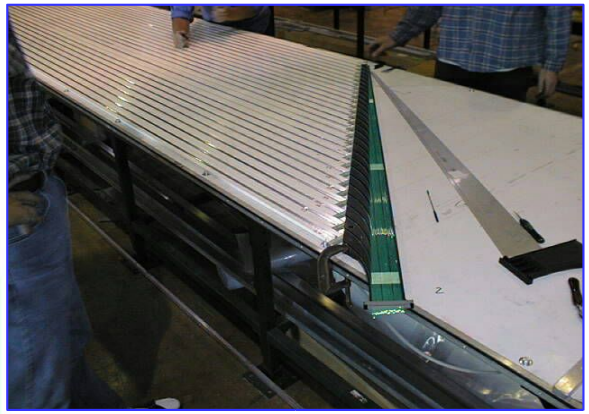
- Fully constructed July 2003
- 5.4 kton, 8m x 8m x 30m
- 484 steel-scintillator planes
- VA electronics
- B ~ 1.2 T
- Multi-pixel PMTs
- GPS time-stamping

Detector Technology

scintillator strips
4.1 x 1 cm

optical fiber readout to multi-anode PMTs

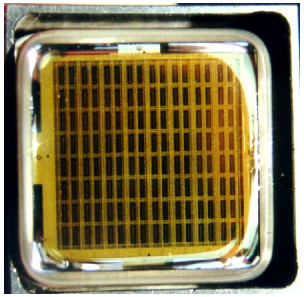




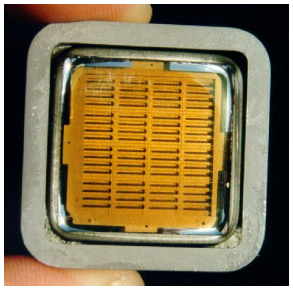
orthogonal orientation on alternate planes – U,V

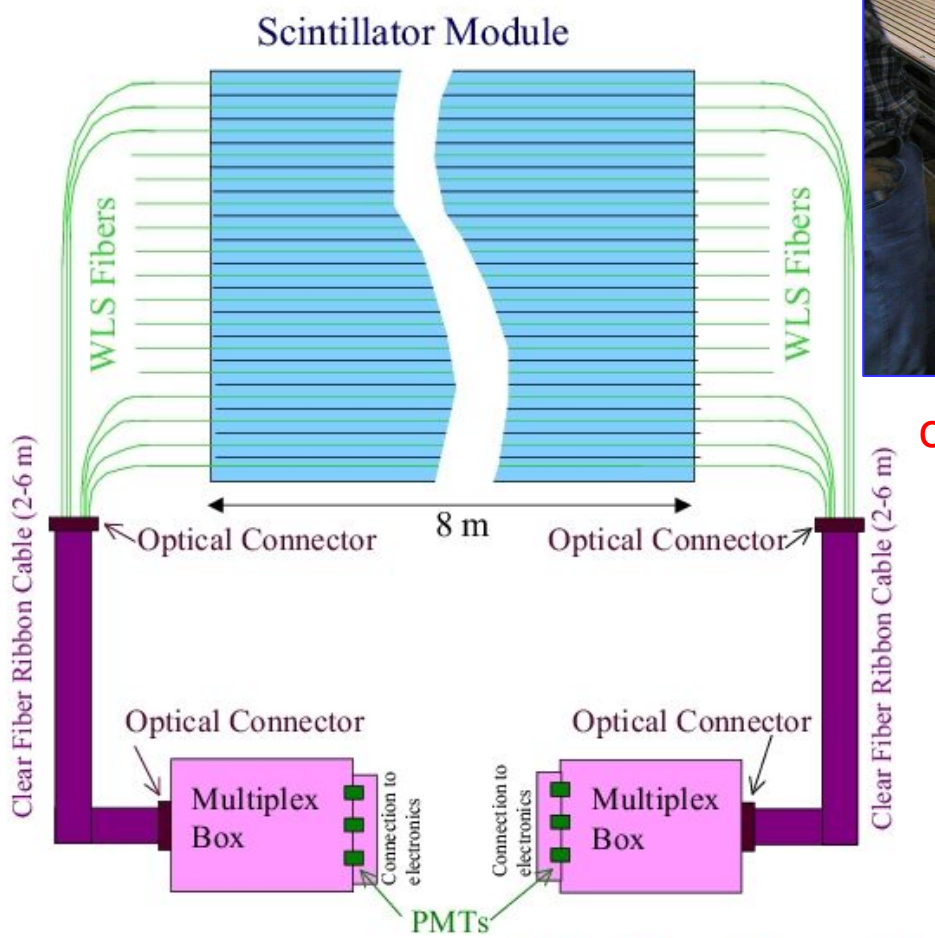
PMTs

M64 (near)



M16 (far)

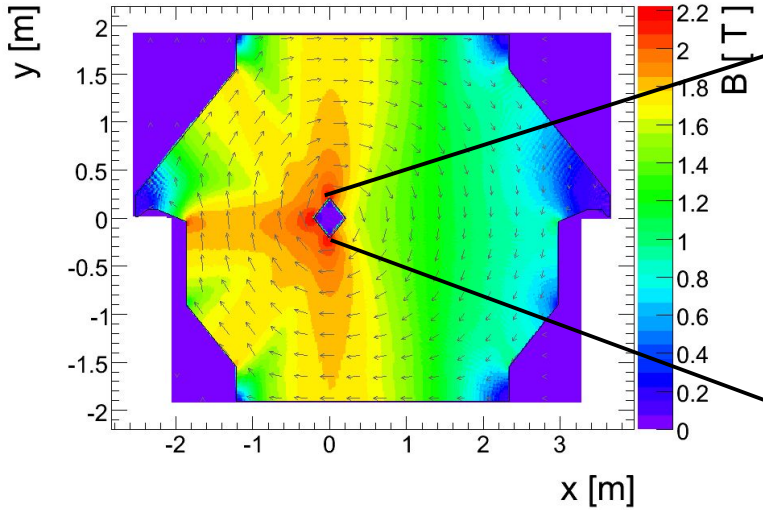


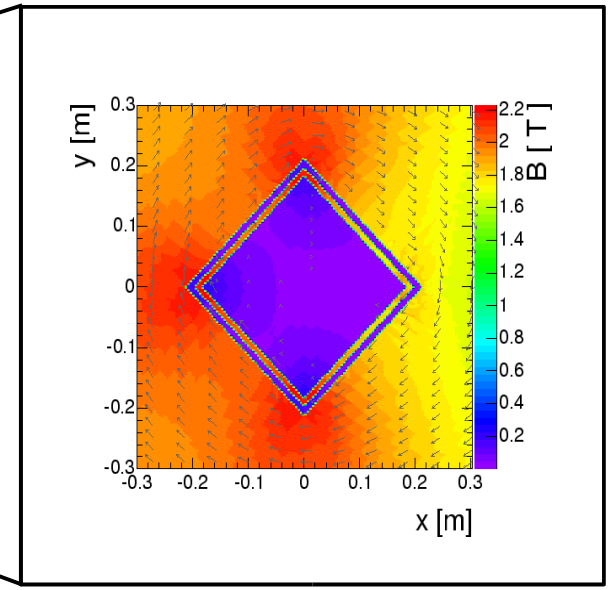


Objects not to scale

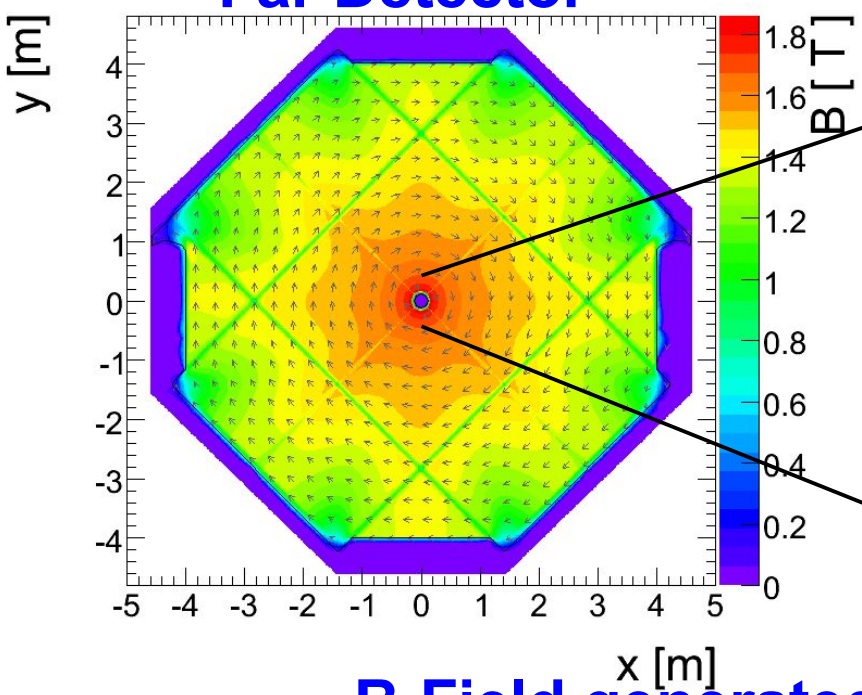
Magnetic Fields

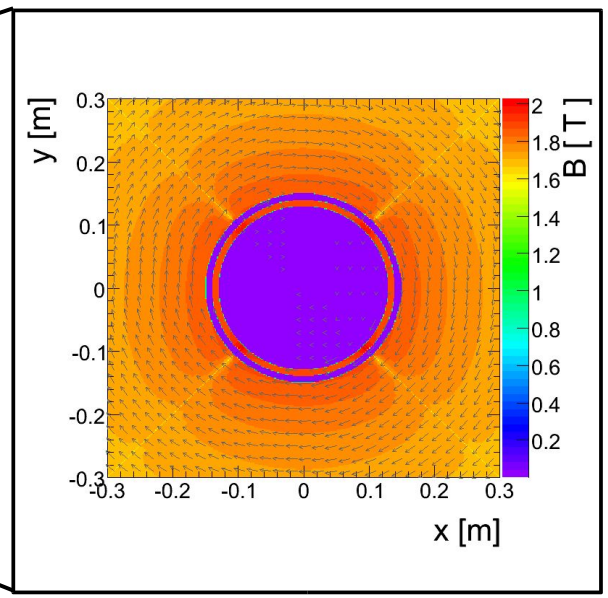
Near Detector





Far Detector

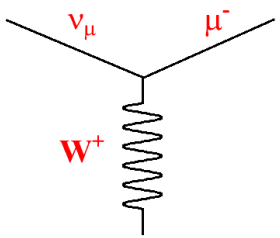


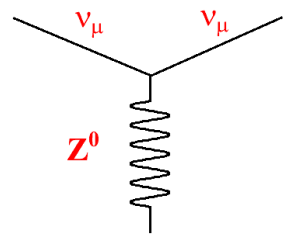


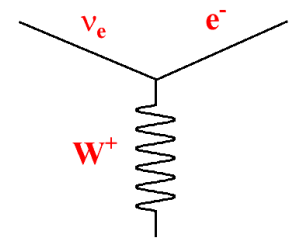
B-Field generated by Finite Element Analysis

Precise knowledge of the field allows an accurate determination of muon momentum

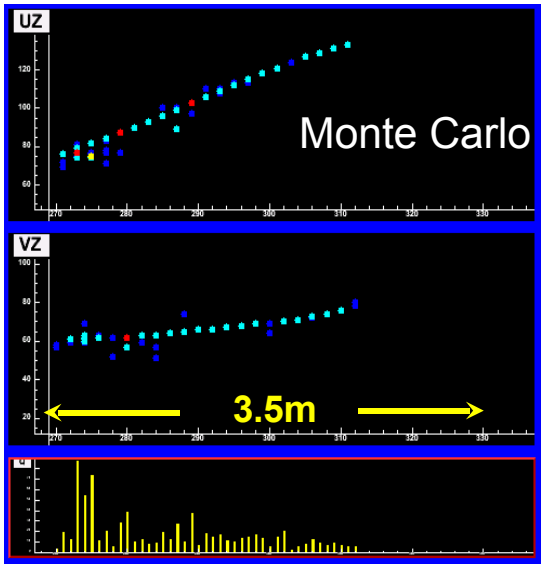
Event Topologies





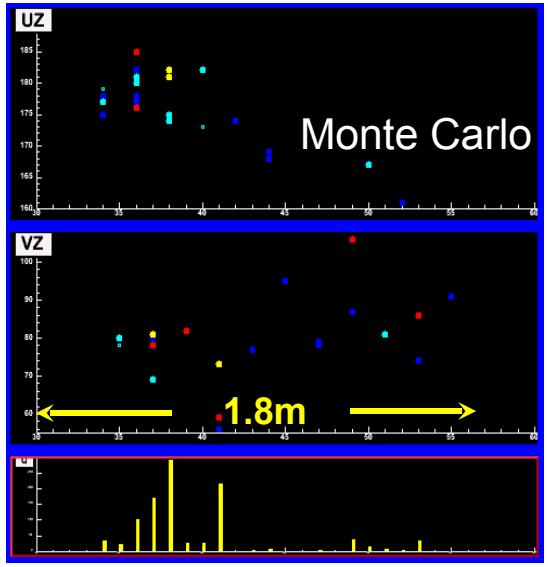


ν_μ CC Event



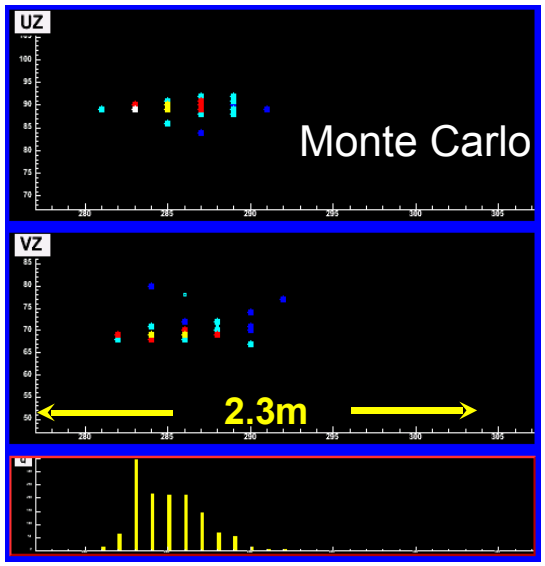
- Long μ track
- Hadronic activity at vertex

NC Event



- Short event
- Often difuse

ν_e CC Event



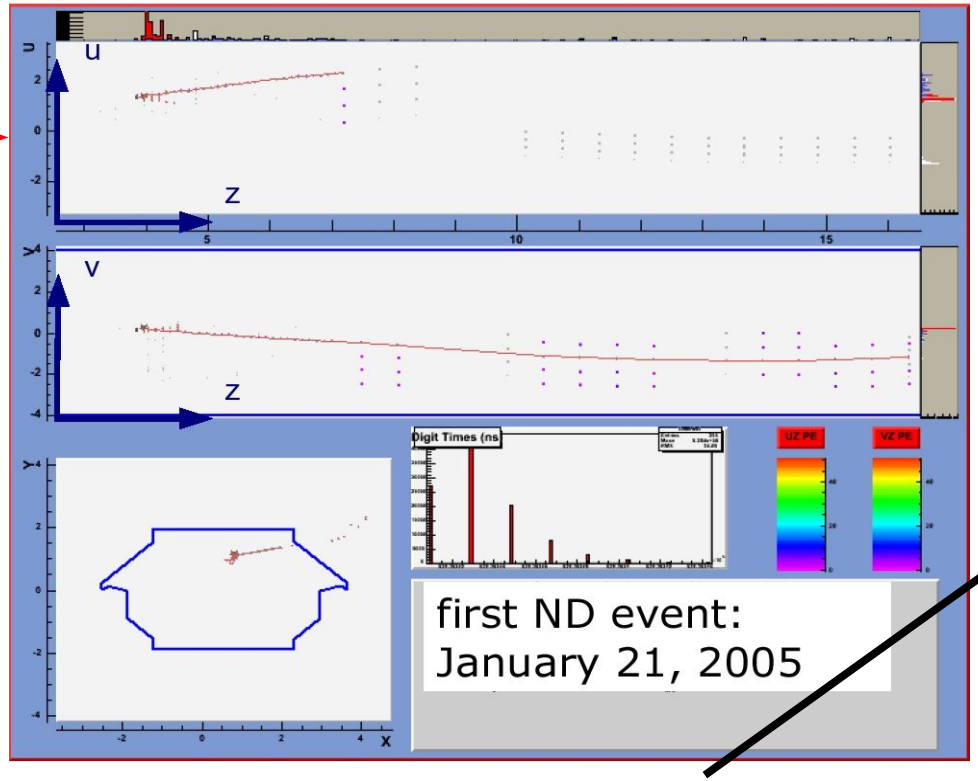
- Short event
- EM shower profile

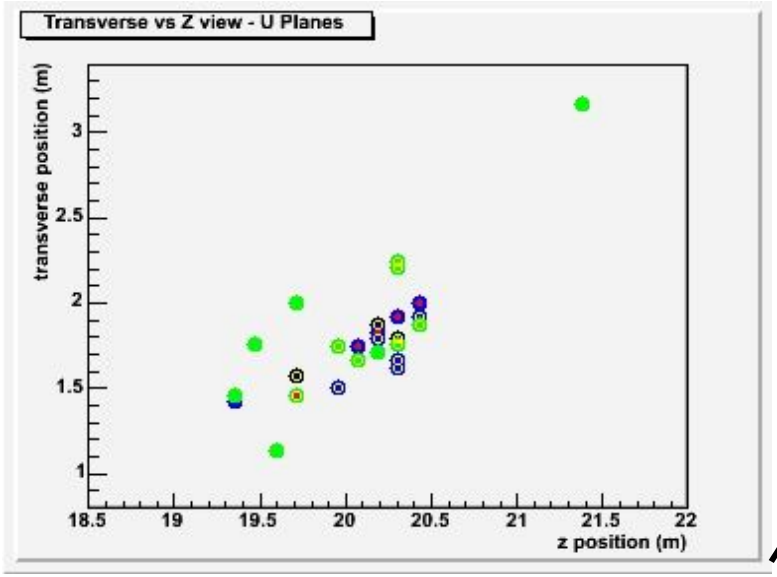
$$E_\nu = E_{had} + E_\mu$$

$55\%/\sqrt{E}$ 6% range, 10% curvature

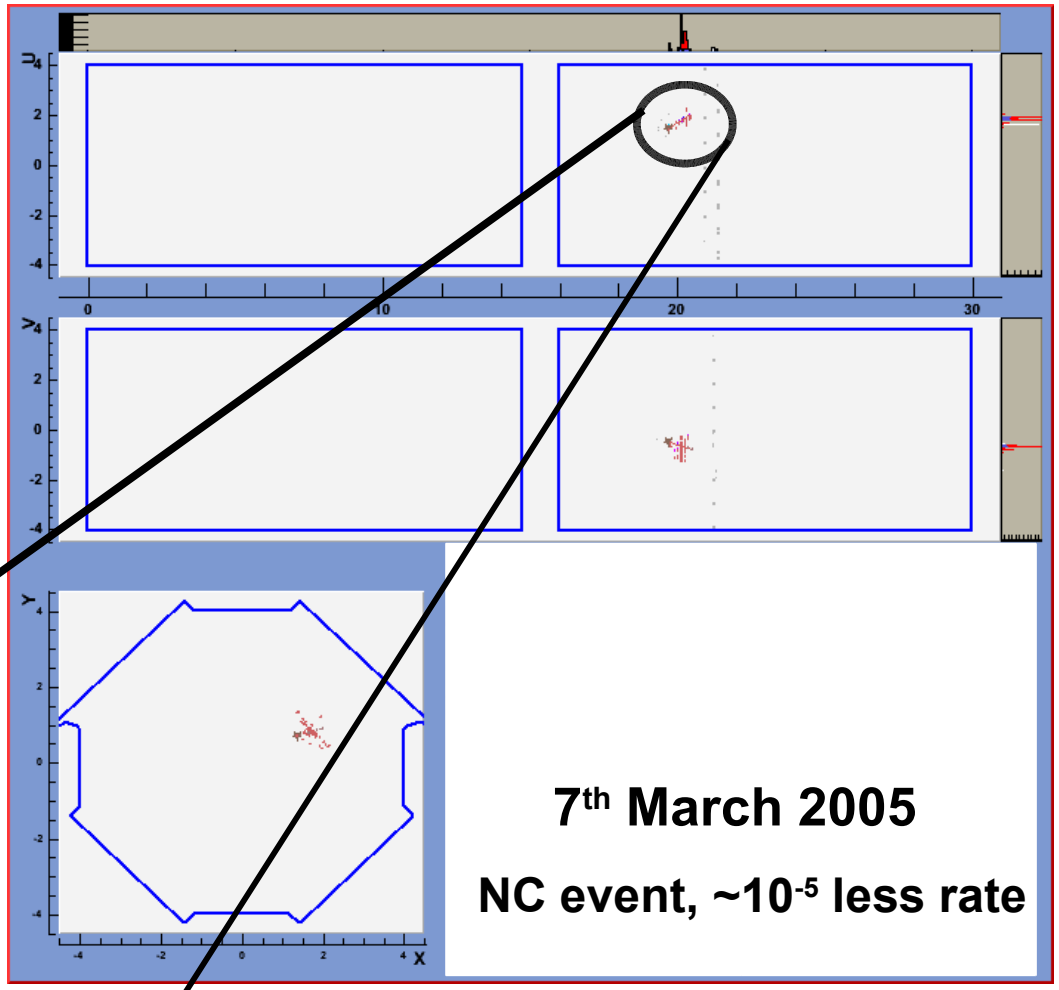
First Beam Neutrino Events

Near Detector

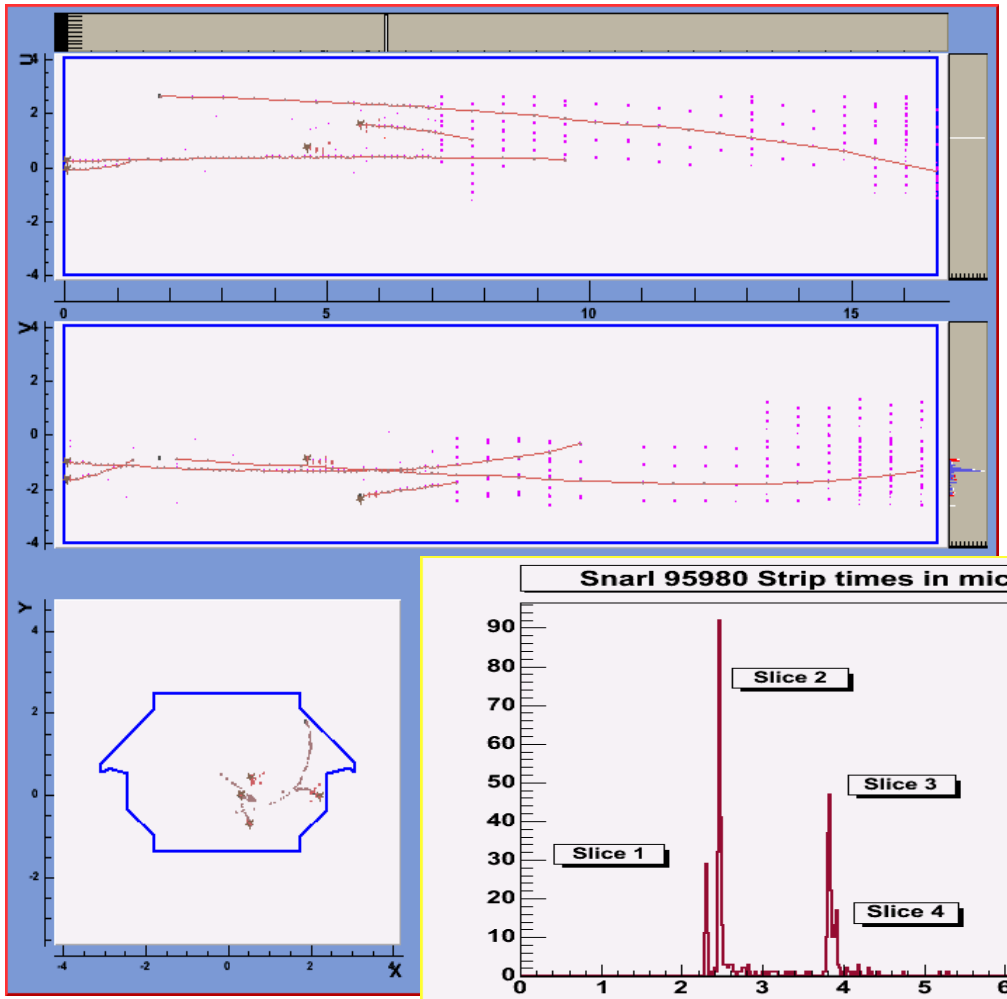


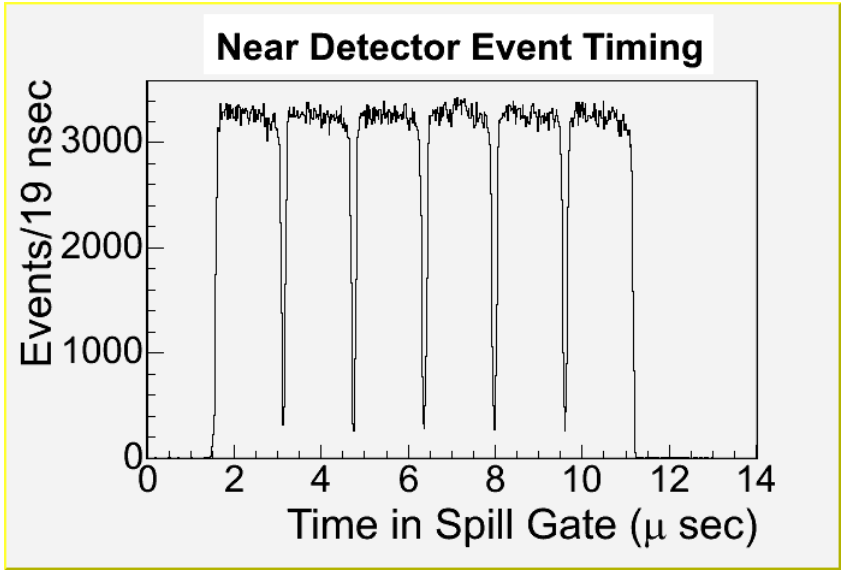


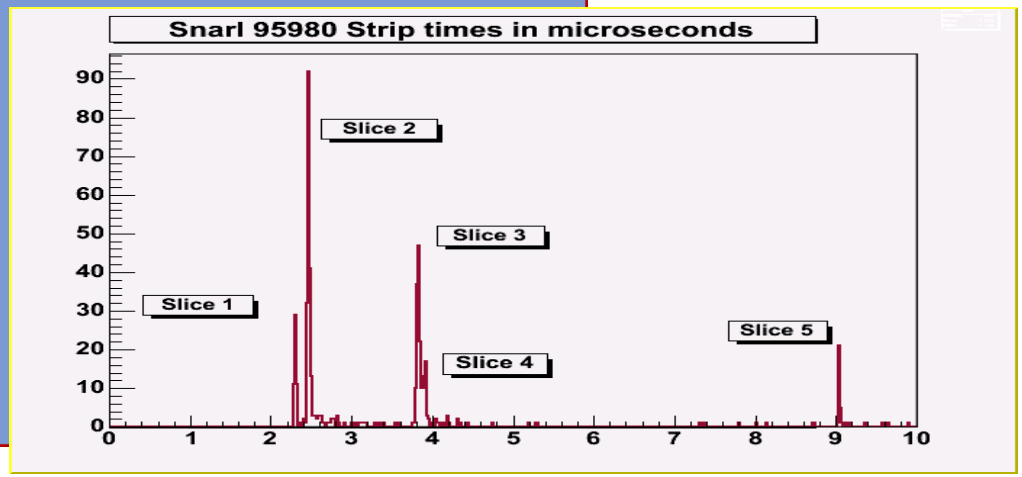
Far Detector



Multiples Events in Near Detector

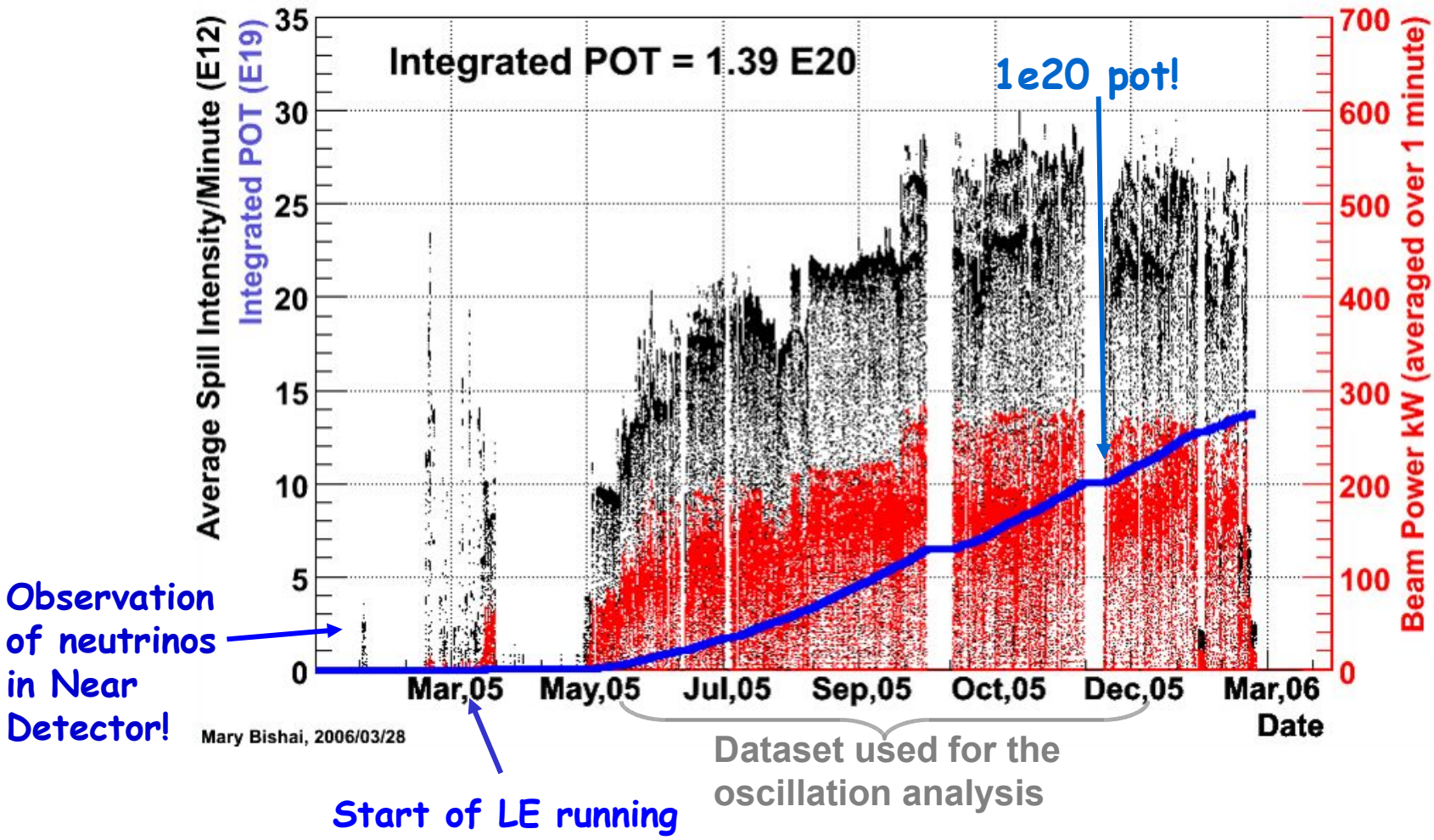






- Multiple interaction per spill in the near detector
- Events are separated by topology and timing

Status of the MINOS Experiment



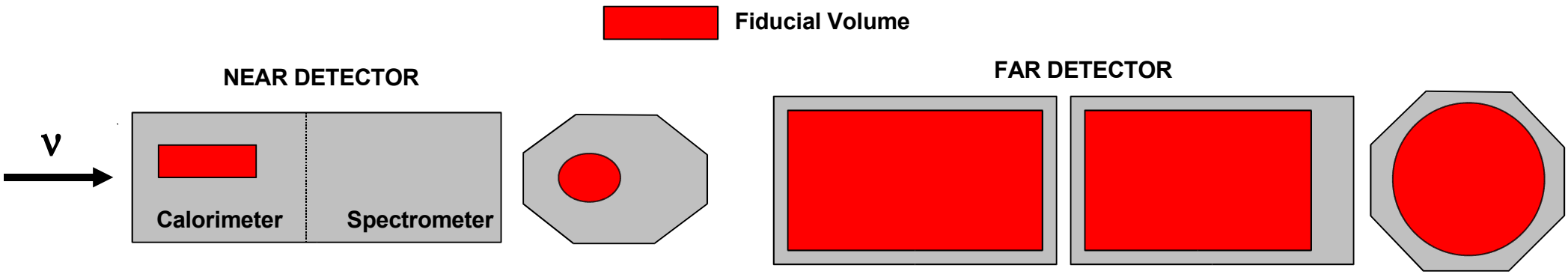
- First neutrino interaction in ND: Jan. 21, 2005
- Physics run: March 05 - Feb. 06: 1.4×10^{20} POT
- Mostly run in **Low Energy position**
- Shorter runs in pseudo-Medium, pseudo-High Energy position, and Horn off
  - Achieved 3×10^{20} POT/spill
  - 270 kW (~30 min)

ν_μ CC Event Selection

1. At least **one good reconstructed track**

2. Reconstructed track vertex within the **fiducial volume** of the detector:

   - **NEAR**: 1m < z < 5m (z measured from the 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.

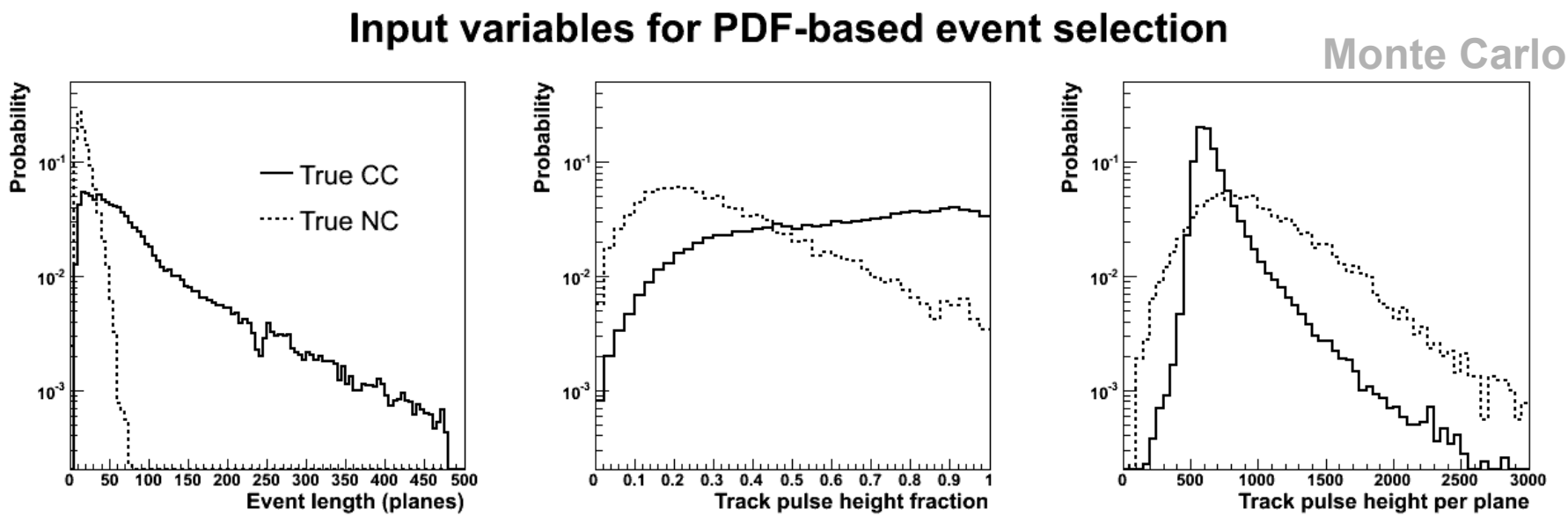


3. Fitted track should have **negative charge** (select ν_μ)

4. **Likelihood-based Particle ID (PID)** parameter to separate CC and NC events.

Likelihood Particle ID

PID constructed with three input Probability Density Functions (PDFs)



Event Length (muon momentum)

Event Pulse Height Fraction (inelasticity)

Track pulse height/plane (track dE/dx)

$$P(\text{CC event}) = \Pi_i \, P_i(\text{CC event})$$

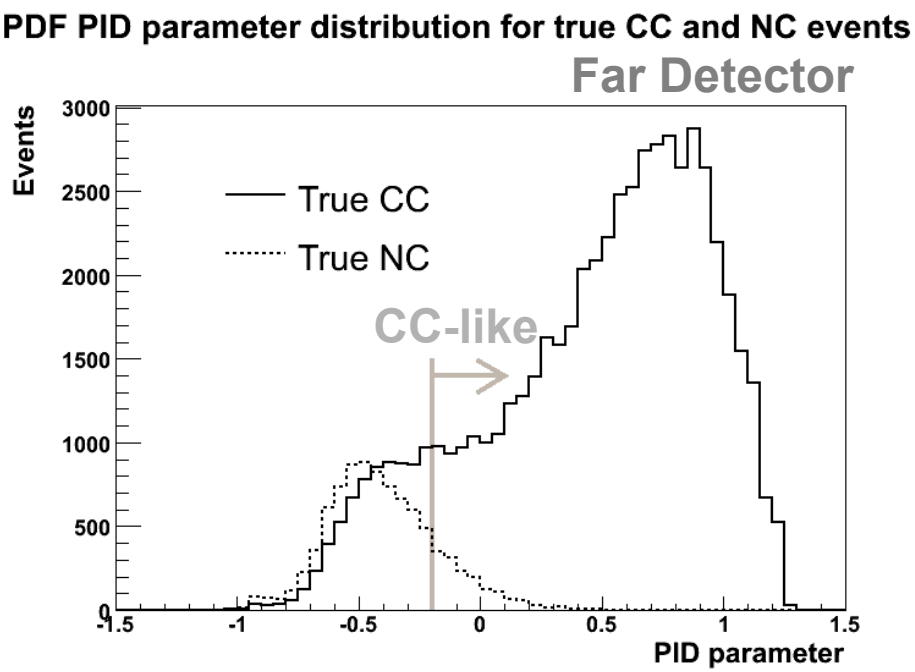
$$P(\text{NC event}) = \Pi_i \, P_i(\text{NC event})$$

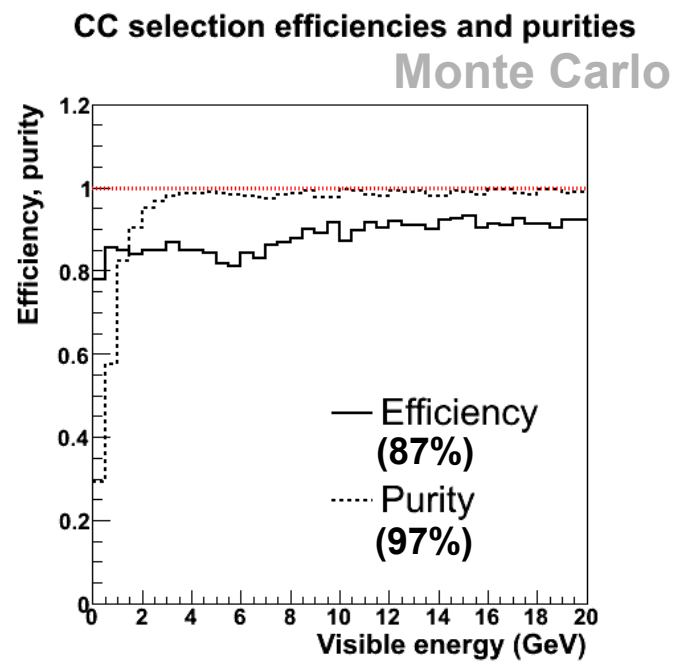
Likelihood PID

- Particle ID (PID) parameter is defined as:

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

- CC Selection criteria: **PID>-0.2 (far)** and **PID >-0.1 (near)**
  - NC contamination limited to the lowest visible energy bins (< 1.5 GeV)
  - Selection efficiency is quite flat as a function of visible energy





Oscillation Measurement

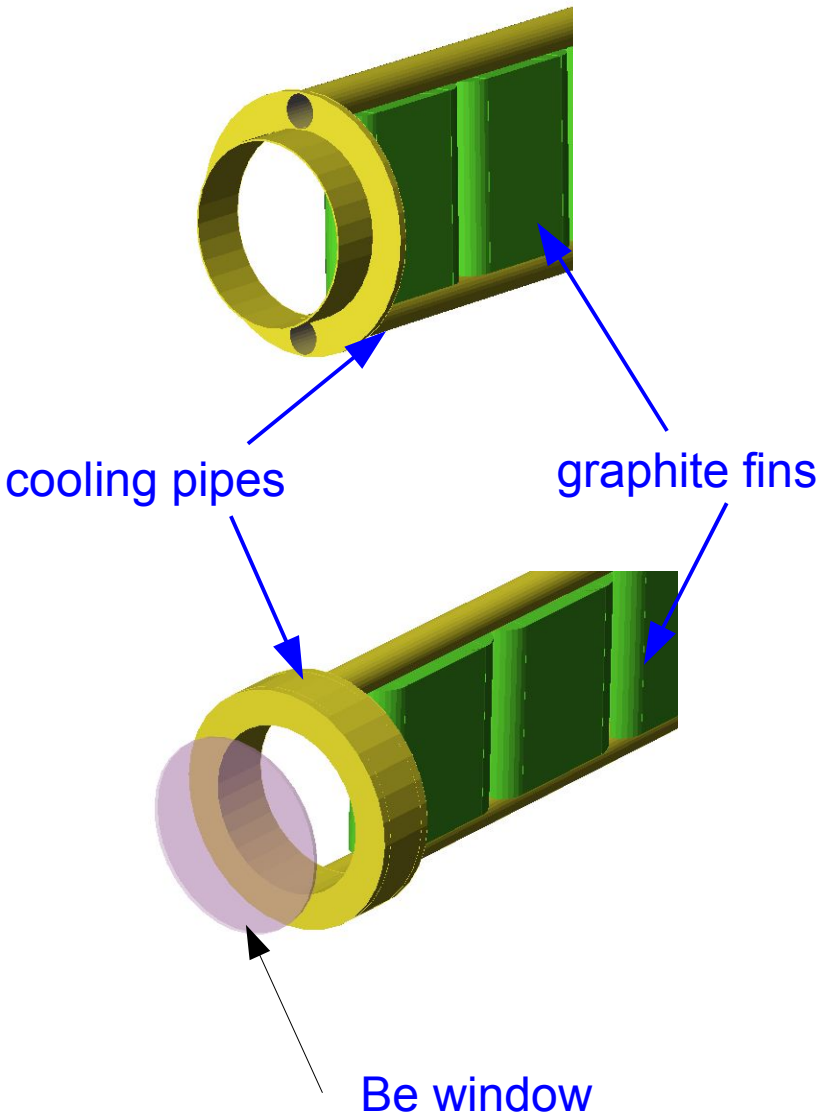
- We need to predict the far unoscillated spectrum

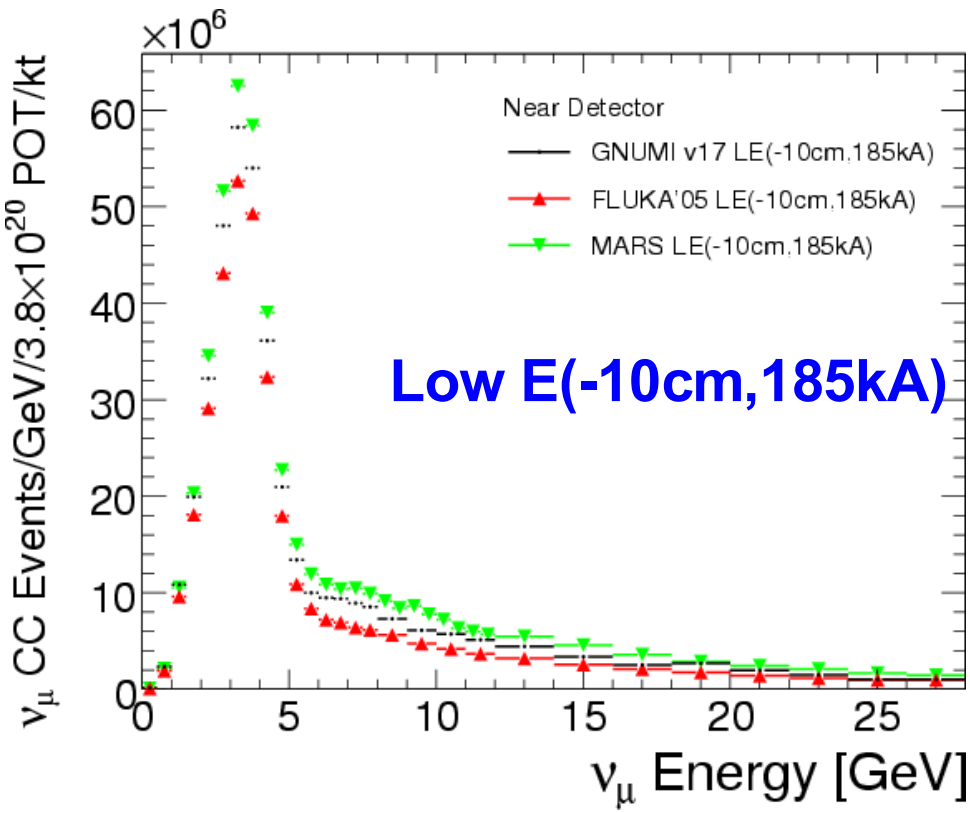
Simulation of the Beam Flux

Hadronic production simulated with a detailed target model in FLUKA'05

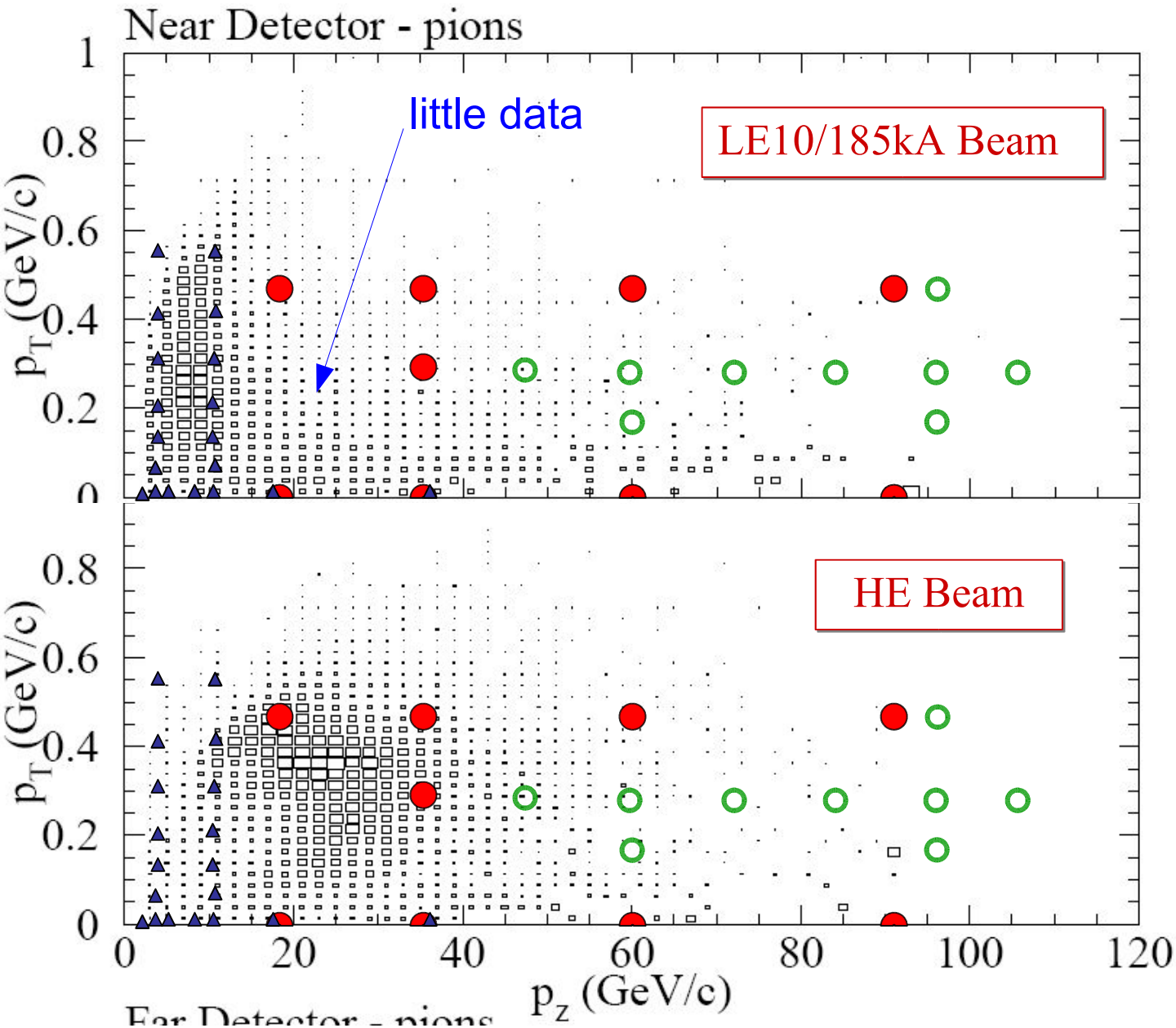
+

Particle Transport and decays with GEANT3





Previous Hadron Production Data



Atherton
400 GeV/*c* p-Be

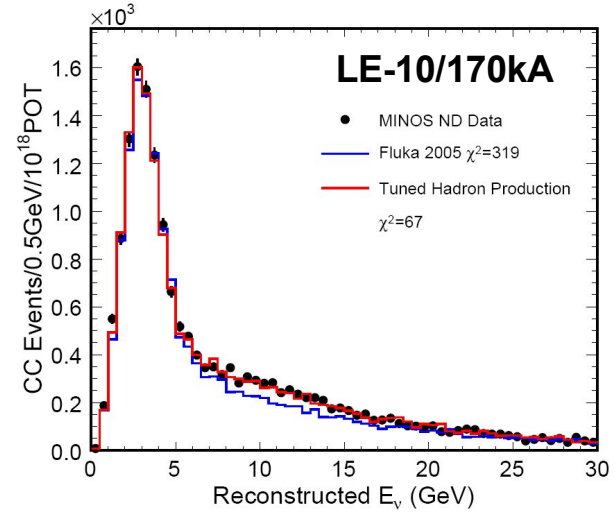
Barton
100 GeV/*c* p-C

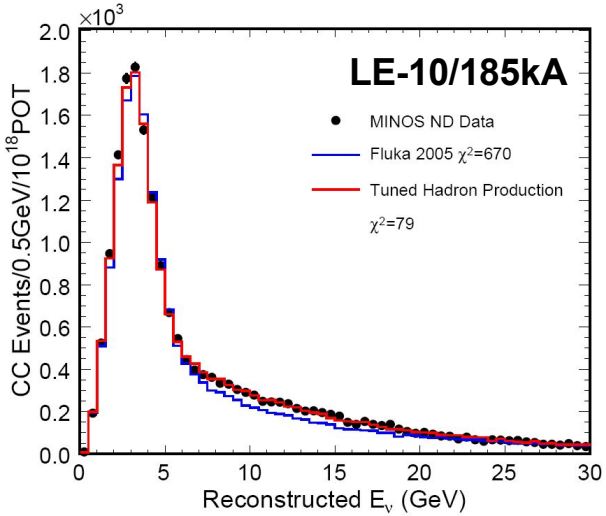
SPY
450 GeV/*c* p-Be

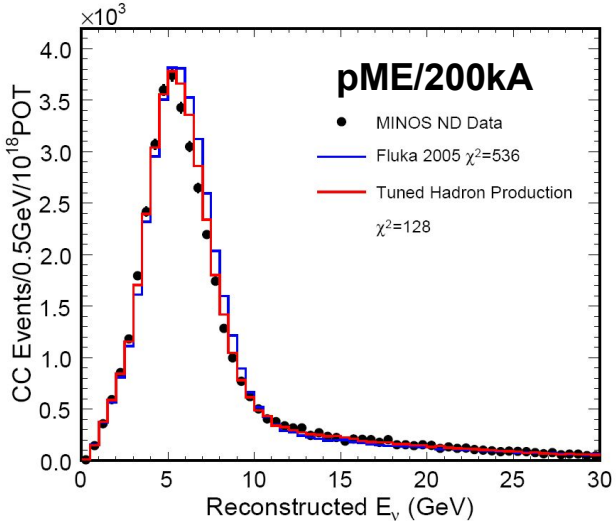
- Never been measured for a thick C-target (MIPP)
- Little data to constraint high energy tail

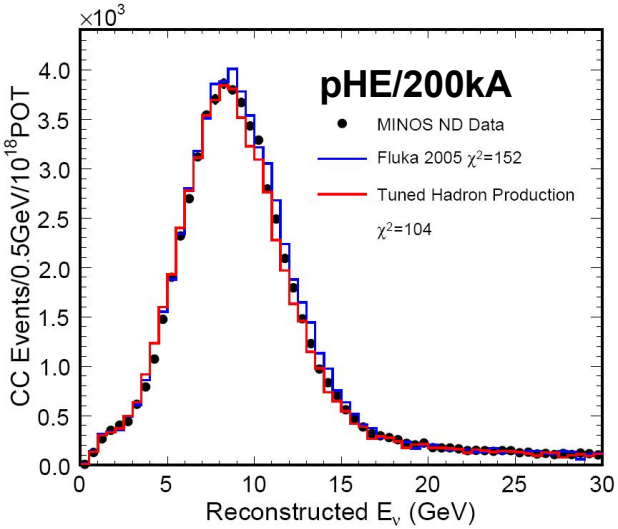
Hadron Production Tuning

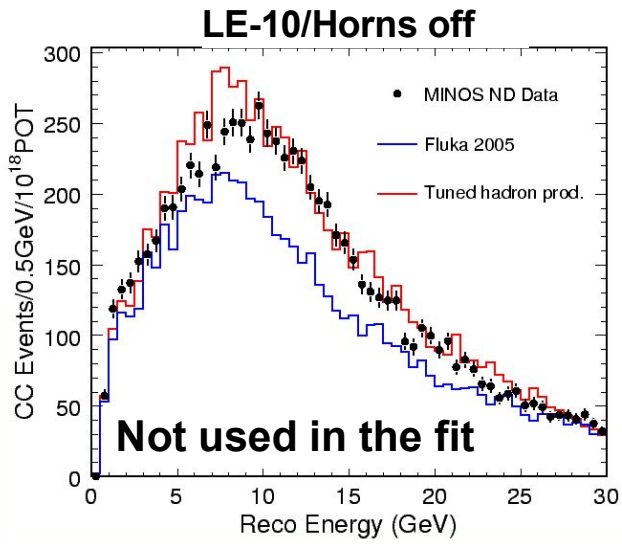
Improvements between data and beam MC were obtained by tuning MC by fitting to hadronic x_F and p_T distributions.

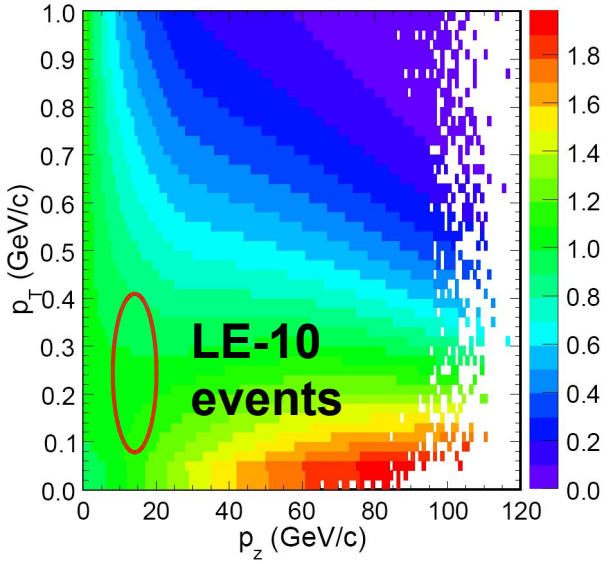








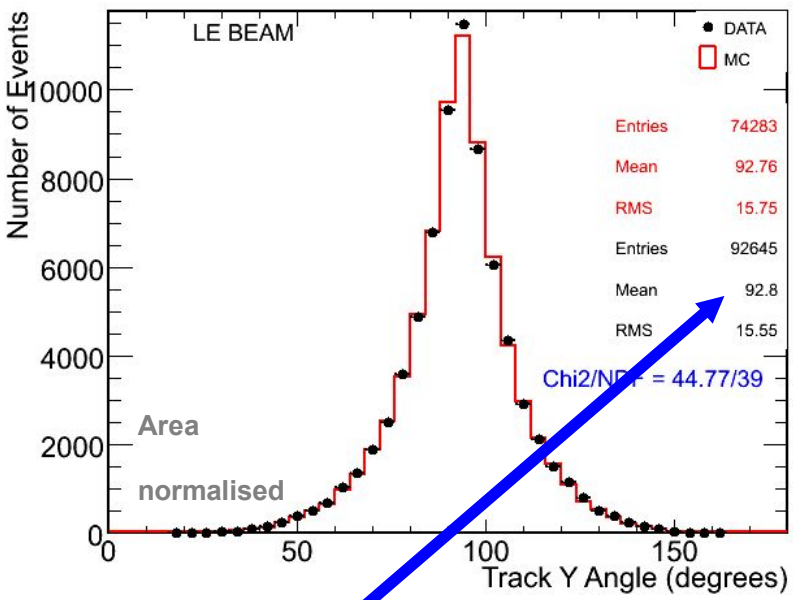




Weights applied as a f(x_F , p_T)

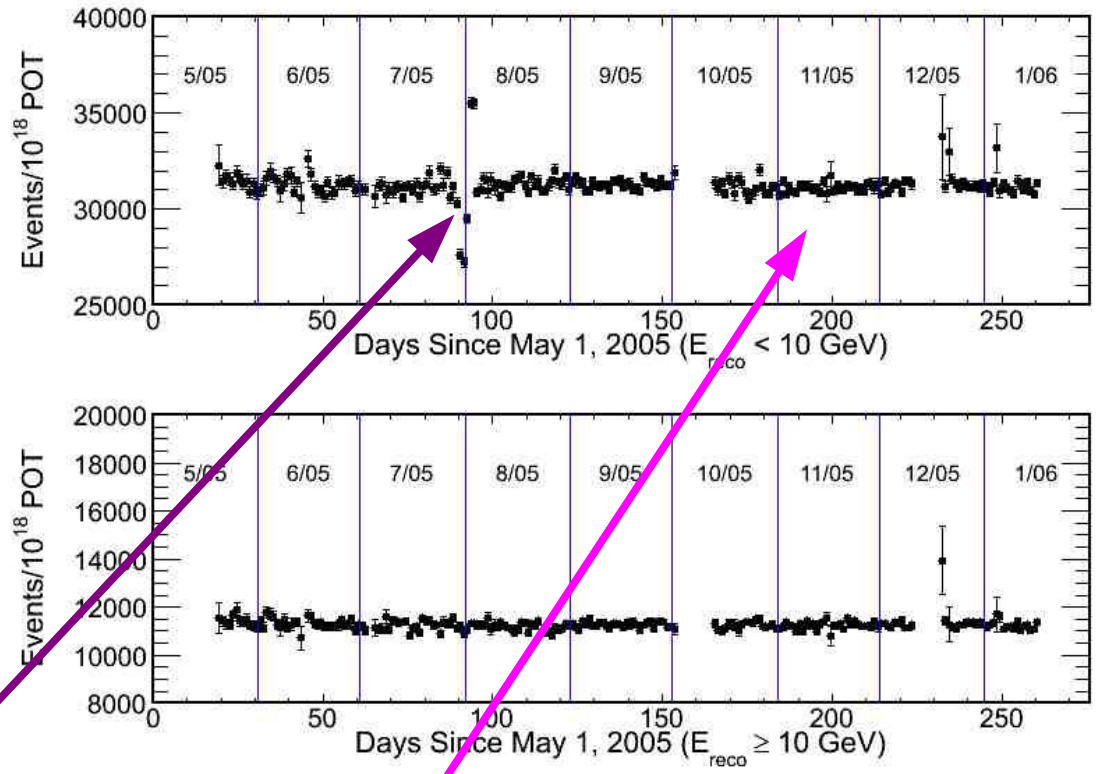
Near Detector Distributions

Reconstructed track angle with respect to vertical



Beam points down 3° to reach Soudan

Near detector event rate

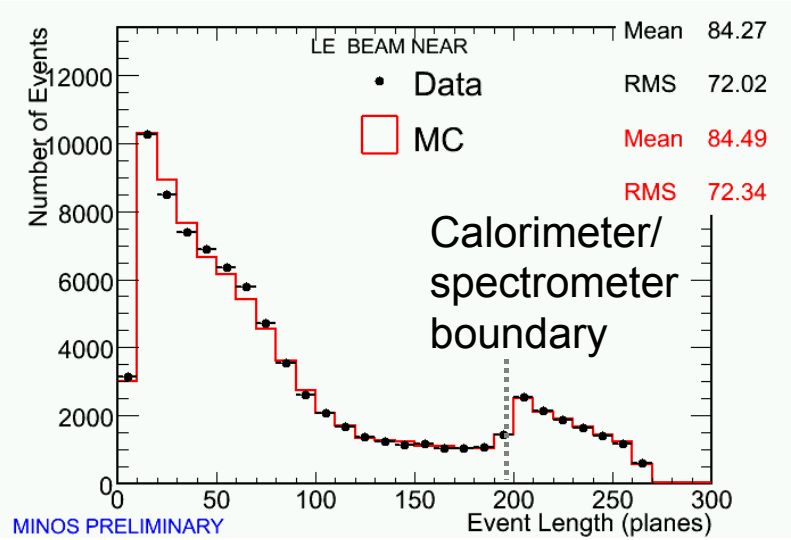


Horn current tests

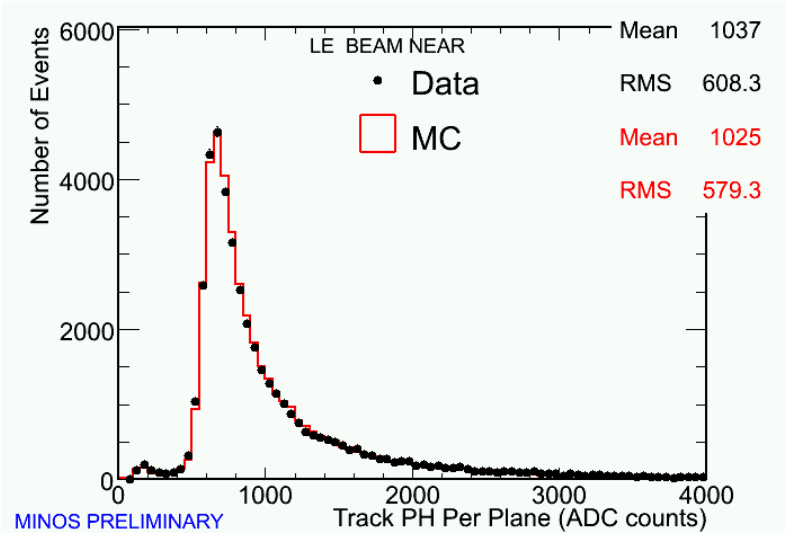
Event rate is flat as a function of time

Likelihood Variables - Low Energy Beam

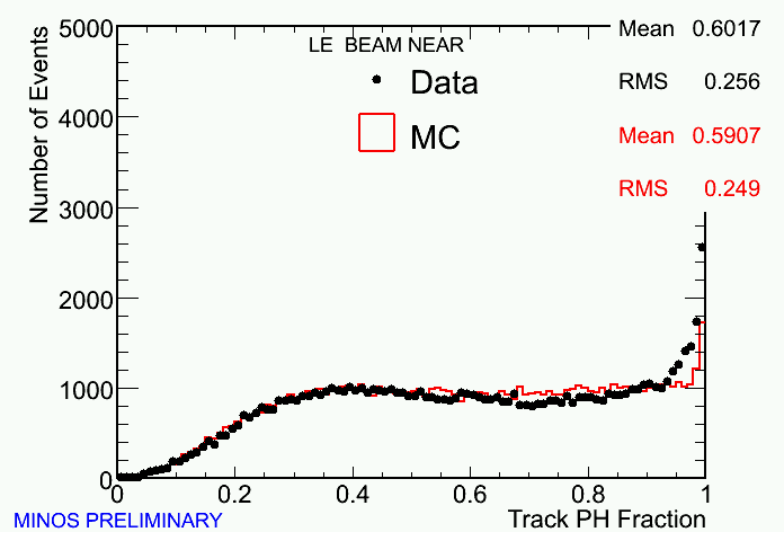
Event length



Track PH per plane

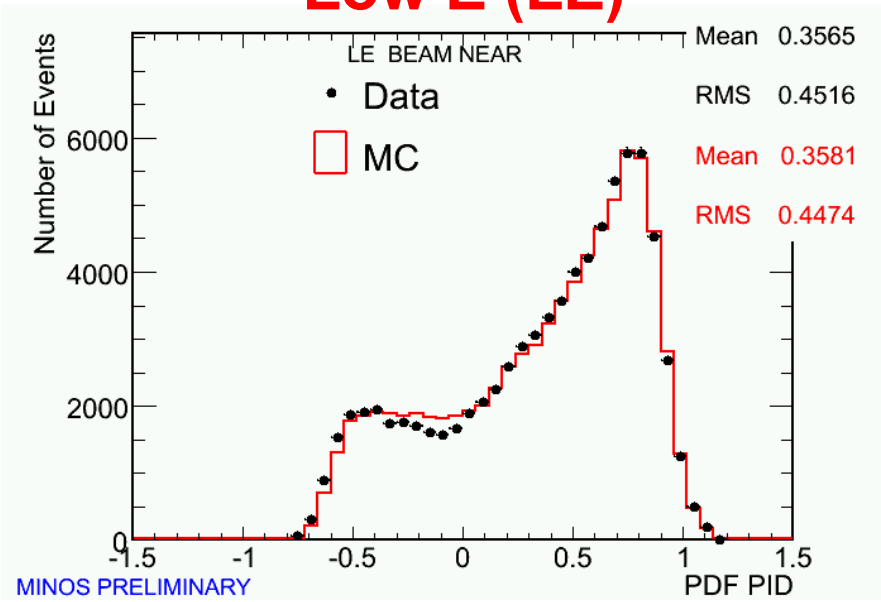


Track PH fraction

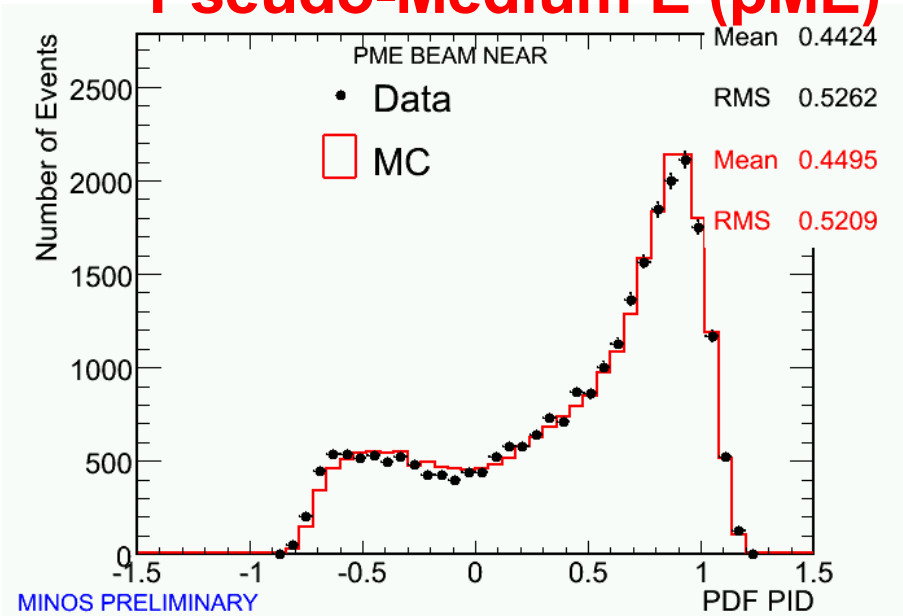


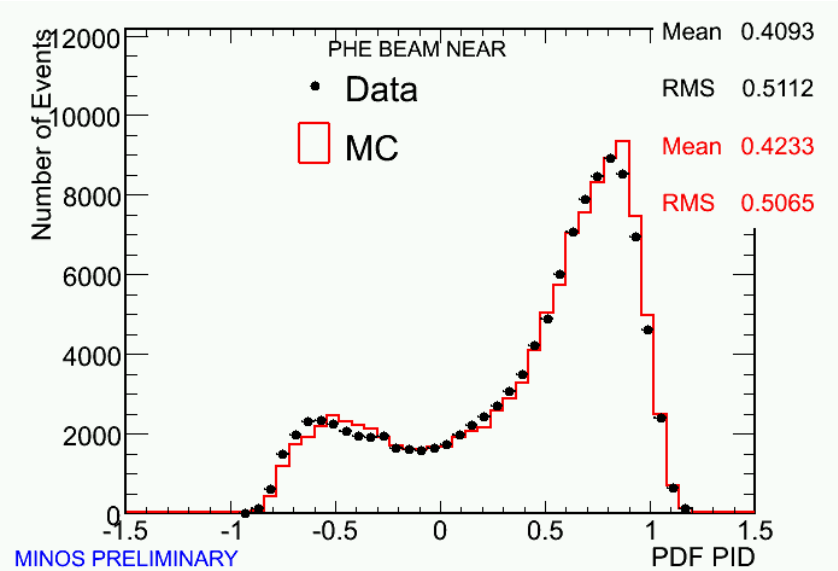
PID Parameter - Various Energy Beams

Low E (LE)



Pseudo-Medium E (pME)



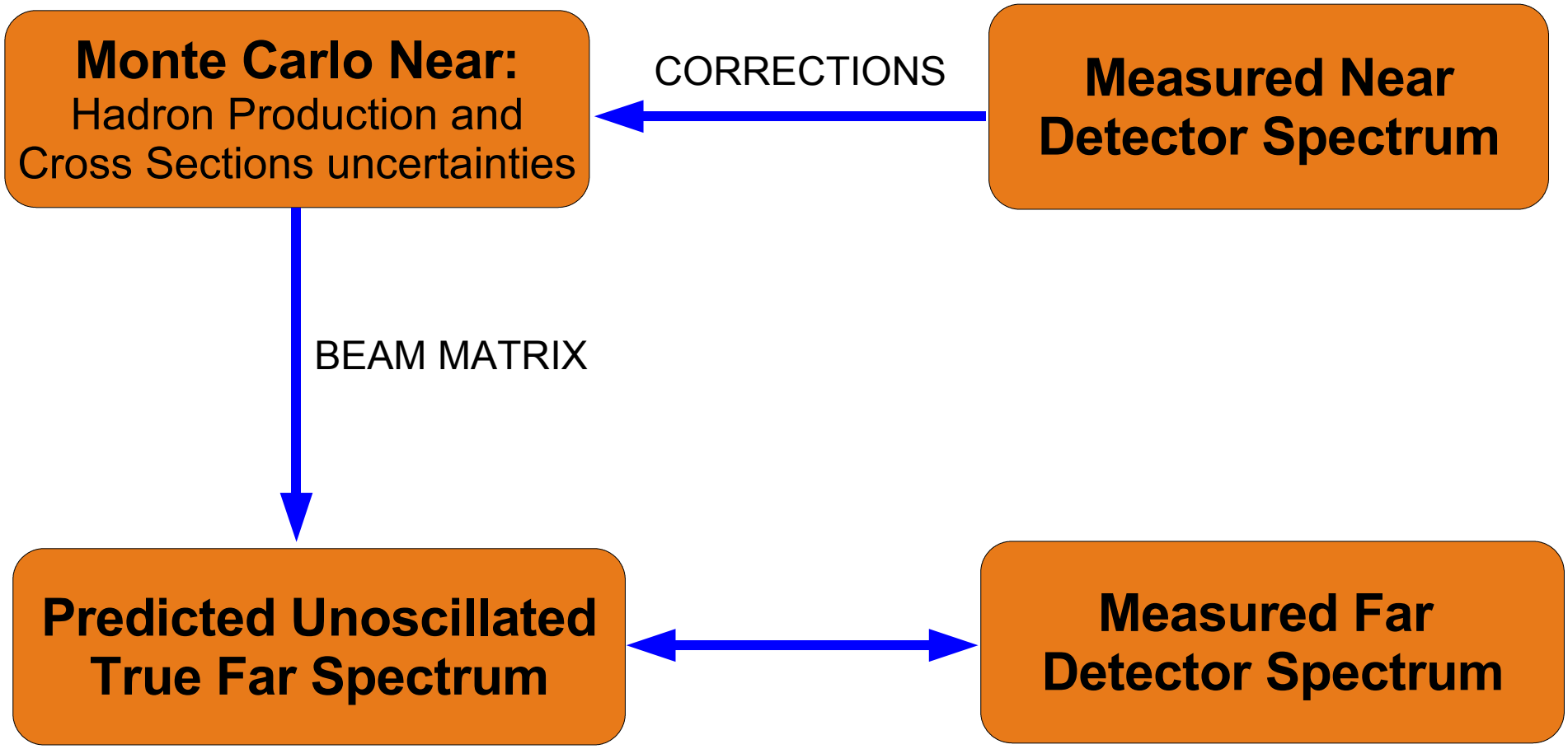


Pseudo-High E (pHE)

Near Detector

ν_μ Disappearance Analysis

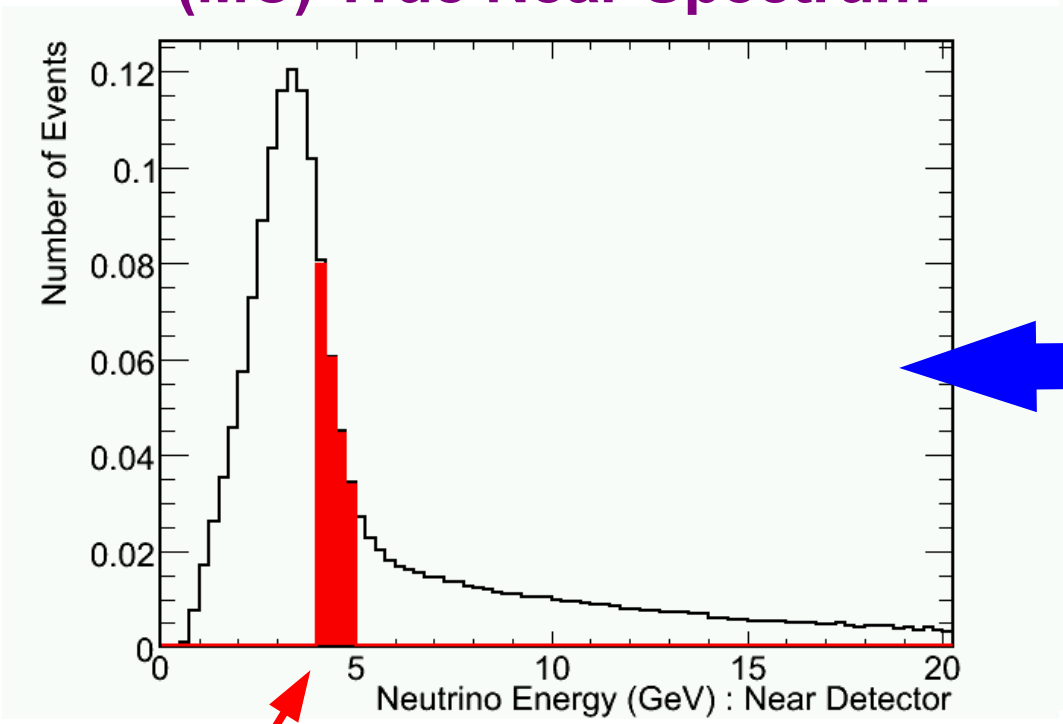
- Oscillation analysis with **0.9×10^{20} POT** (66% of total sample)
- **Blind analysis**:
  - Near detector sample is open.
  - Unknown fraction of far detector sample was open.
  - Remaining fraction was hidden until final analysis.



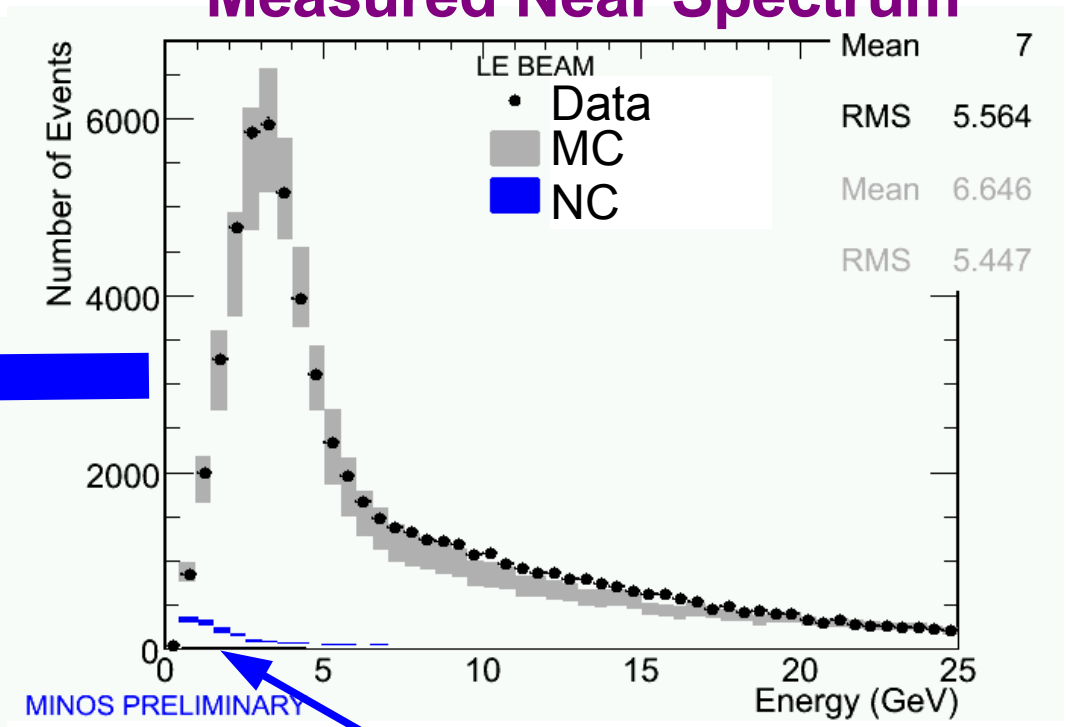
Near True CC Spectrum

- Subtraction of NC background
- Efficiency correction

(MC) True Near Spectrum



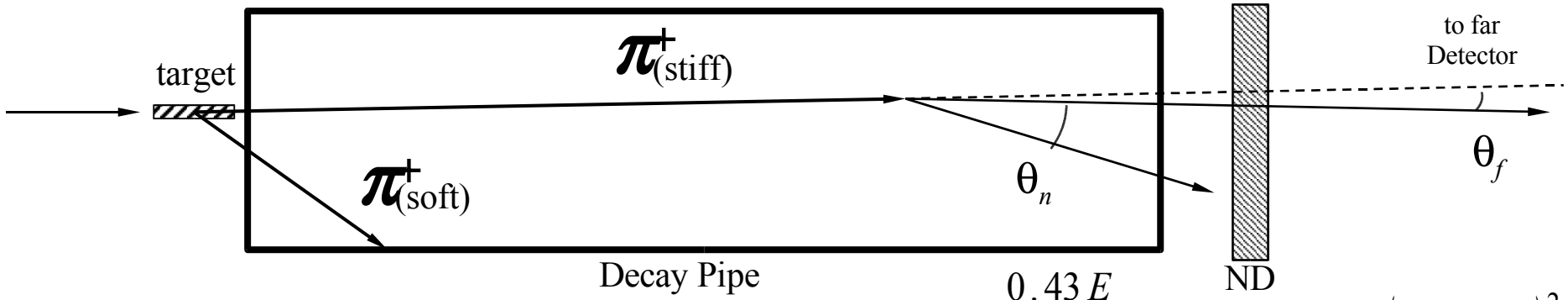
Measured Near Spectrum



sub-section to show procedure

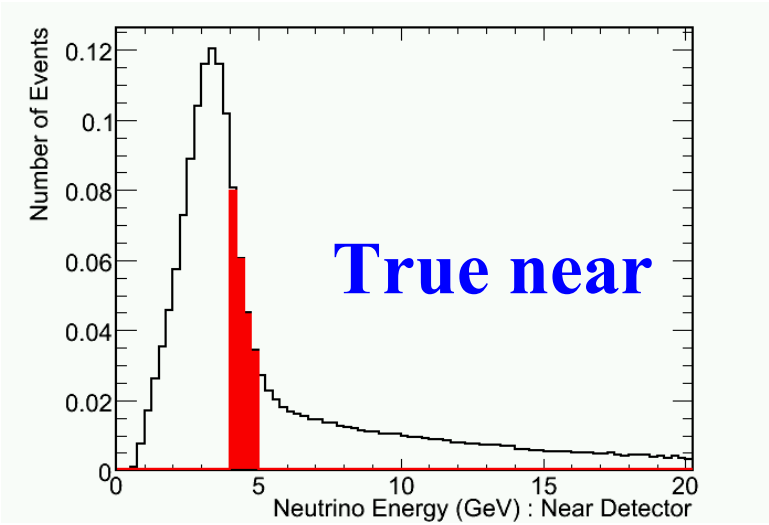
NC background

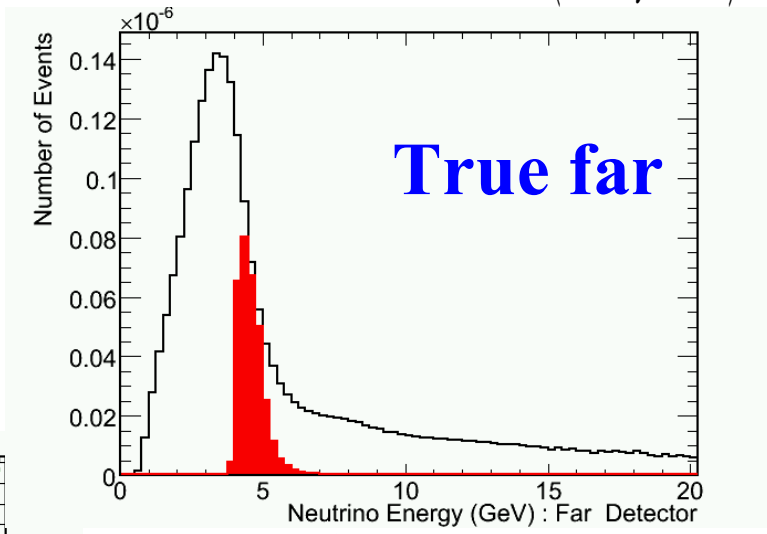
Near/Far Extrapolation



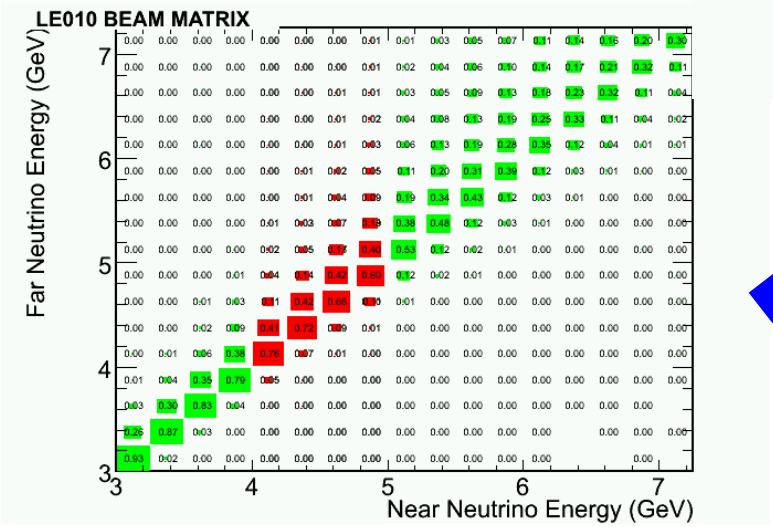
$$E_\nu = \frac{0.43\,E_\pi}{1+\gamma^2\theta^2}$$

$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$





Matrix

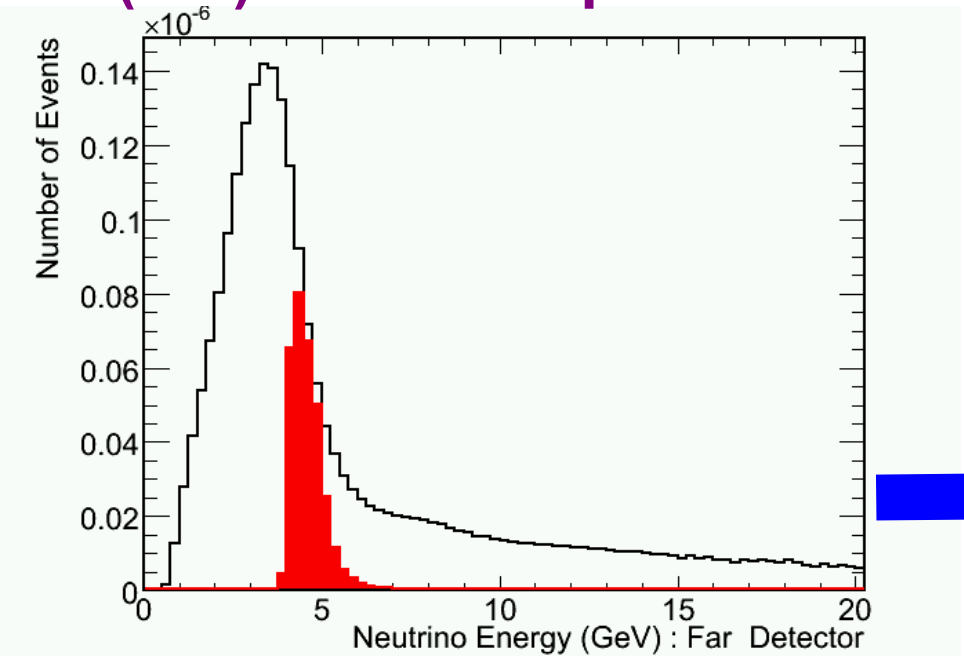


Predicted Far Unoscillated Spectrum

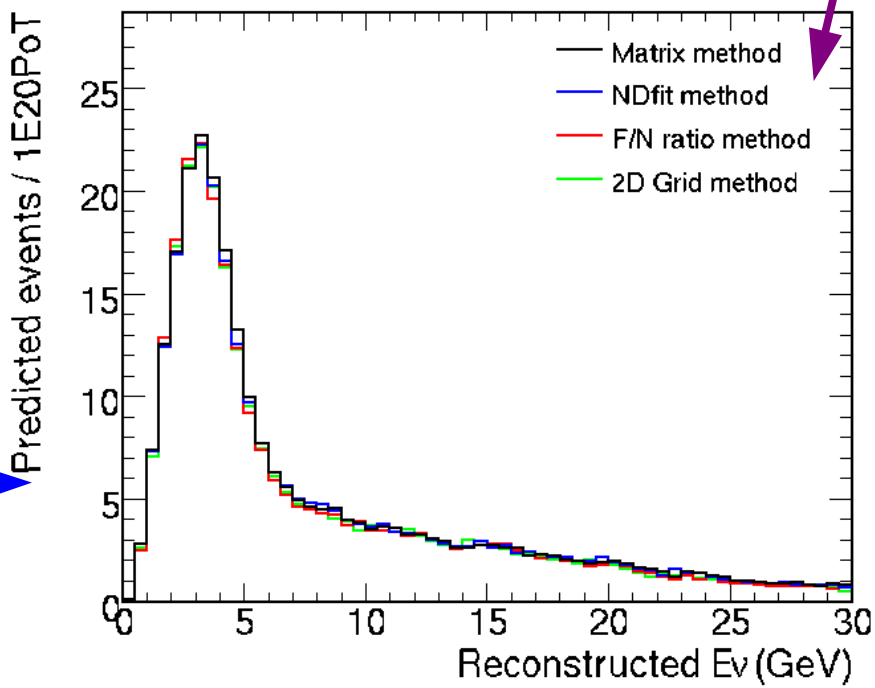
- Include detector response
- Efficiencies
- Backgrounds

Alternative methods give consistent predictions

(MC) True Far Spectrum



(MC) Predicted Far Spectrum



Far Detector Data Selection

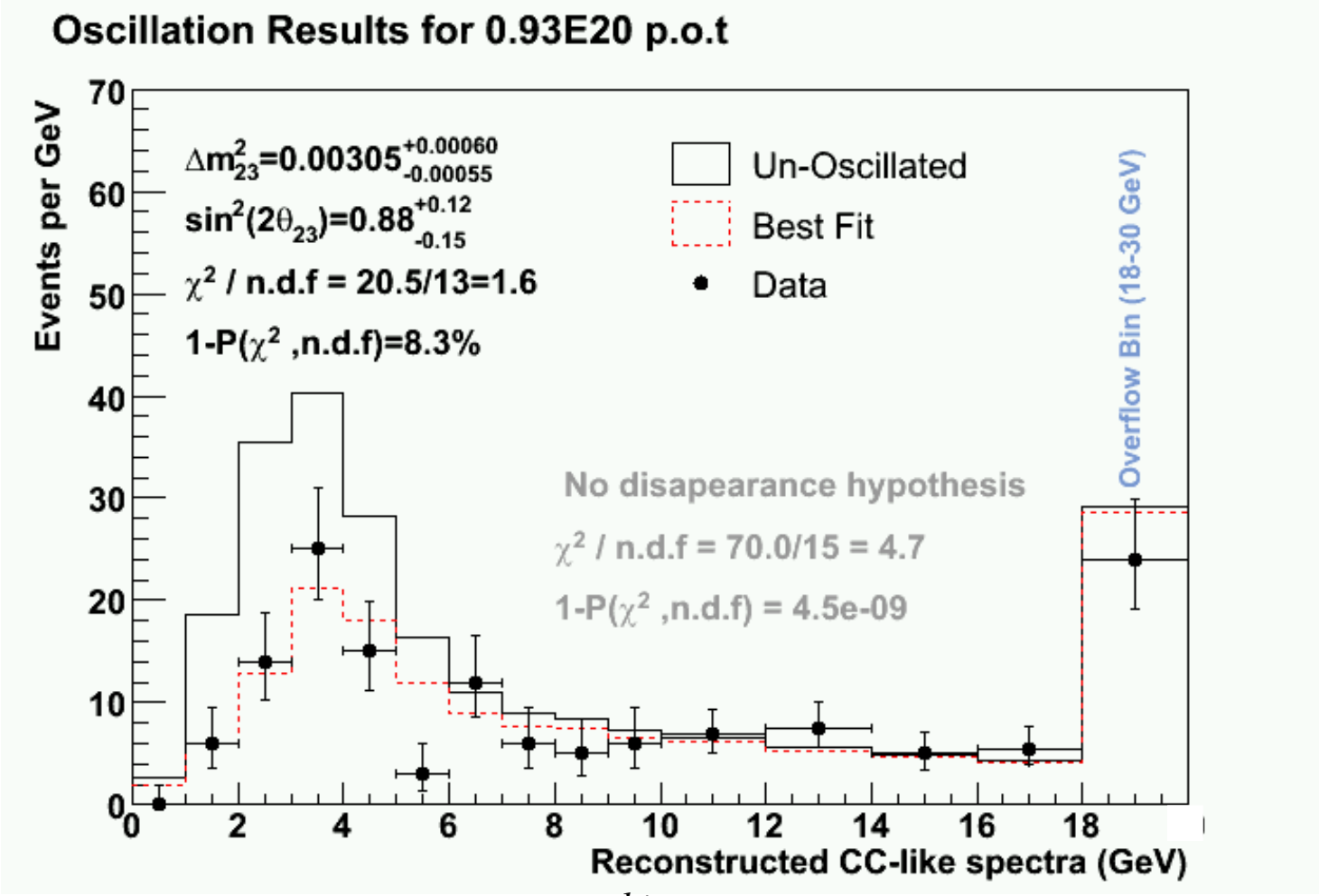
Cut	Events	efficiency
All events in fiducial vol	331	-
Events with a track	296	89.1%
Track quality cuts	281	95.3%
PID cut (CC-like)	204	72.9%
Negative charged tracks	186	91.2%
Reconstructed energy < 30 GeV	166	89.2%

Observed vs Expected Events in Far Detector

Data sample	observed	expected	ratio	significance
All CC-like events ($\nu_\mu+\bar{\nu}_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

- Observation of a **33% deficit of events** between 0 and 30 GeV with respect to no oscillation expectation.
- Statistical significance of this effect is **5 sigma**.

Far Detector Spectrum and Fit

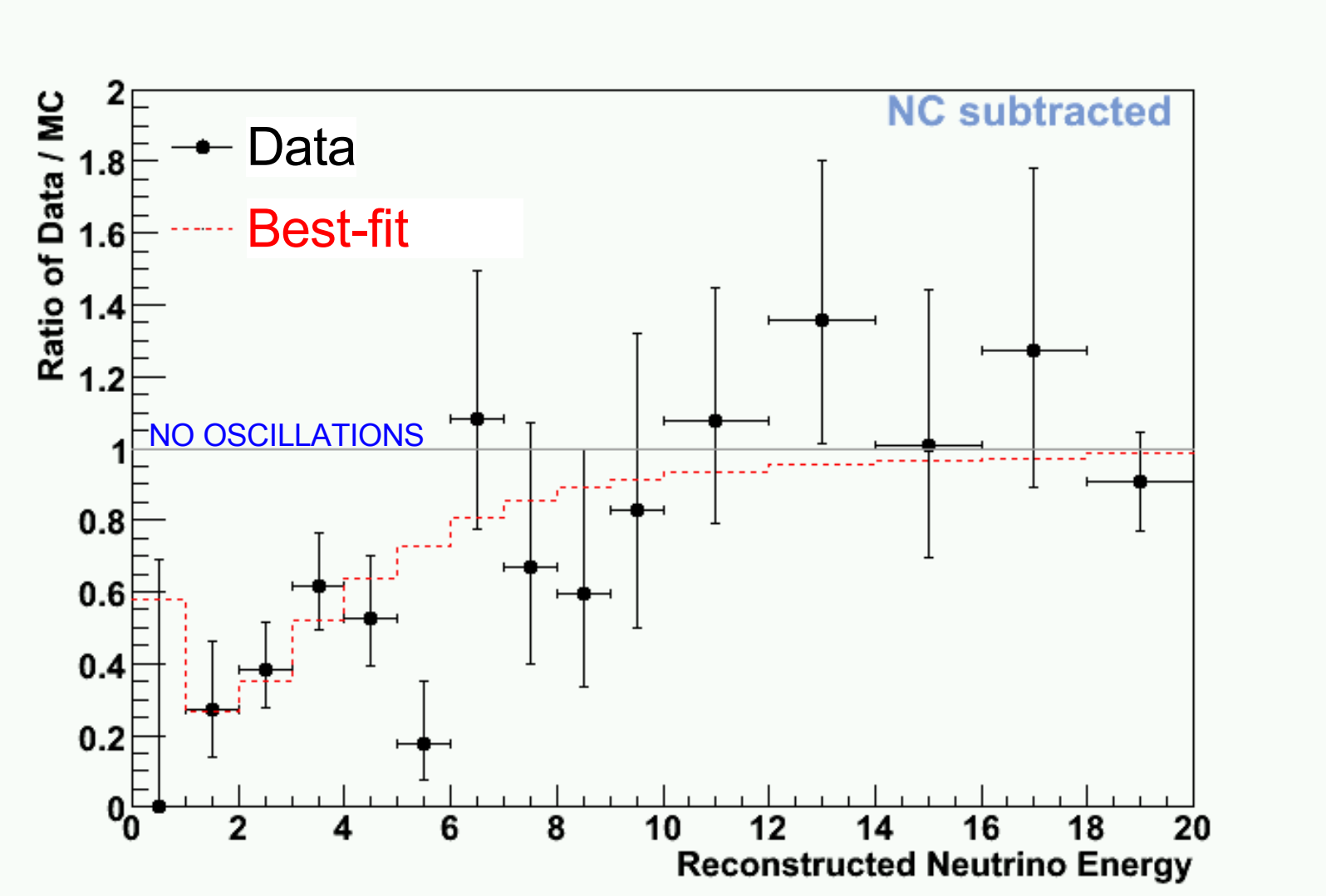


$$\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2 o_i \ln(o_i / e_i)$$

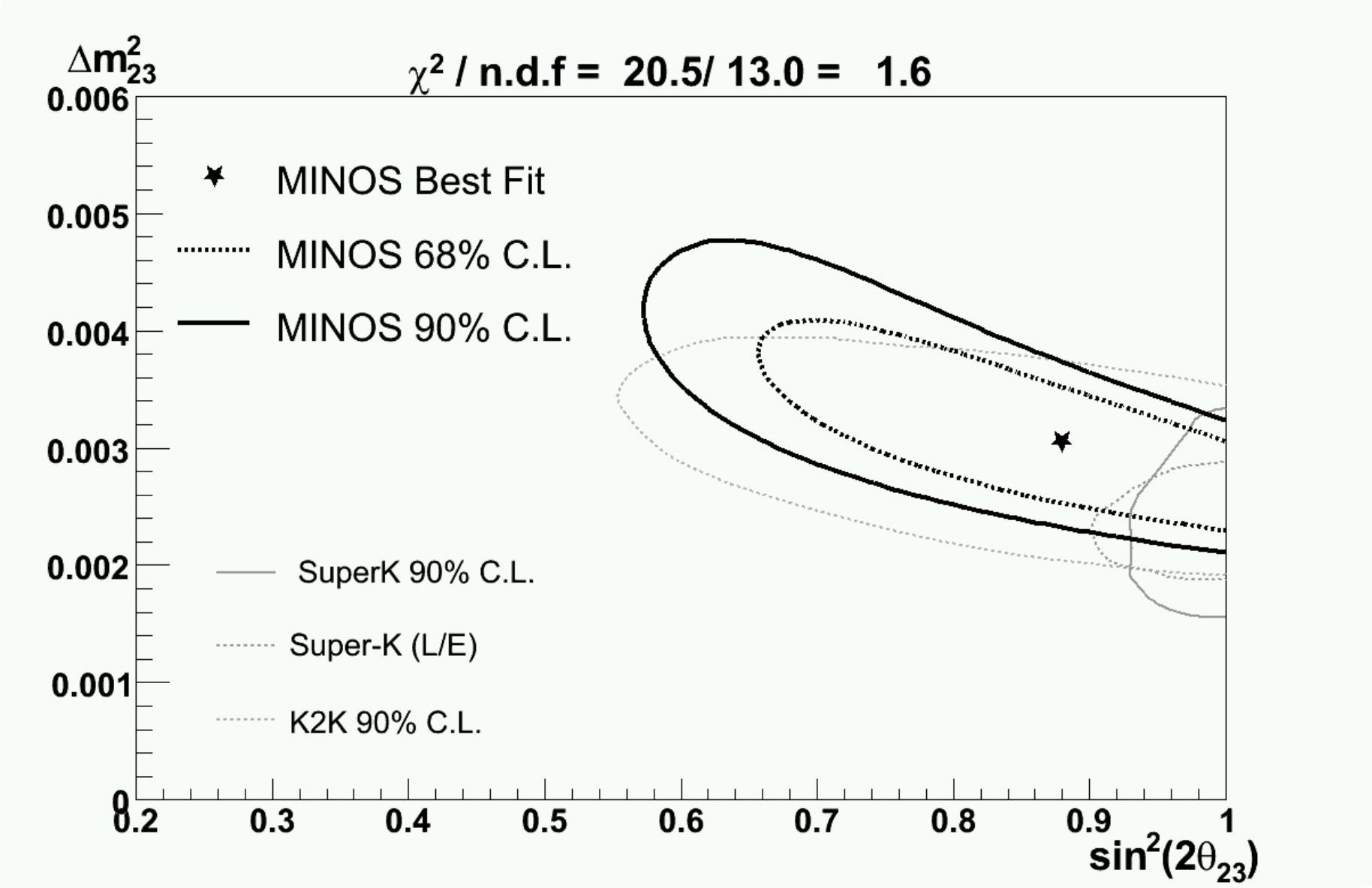
$$\Delta m^2_{23} = 0.00305^{+0.00060}_{-0.00055} \qquad \sin^2(2\theta_{23}) = 0.88^{+0.12}_{-0.15}$$

statistic errors only

Ratio of Data/Monte Carlo

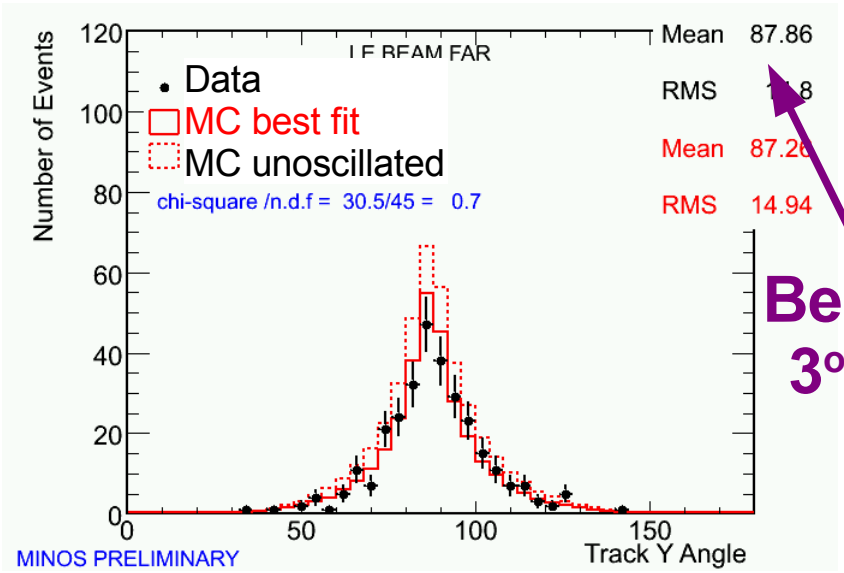


Allowed Regions



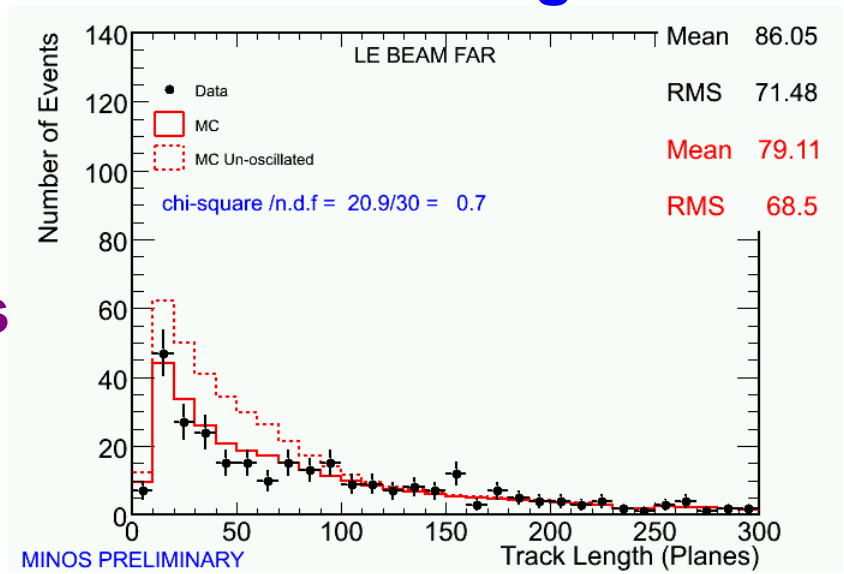
Far Detector Distributions

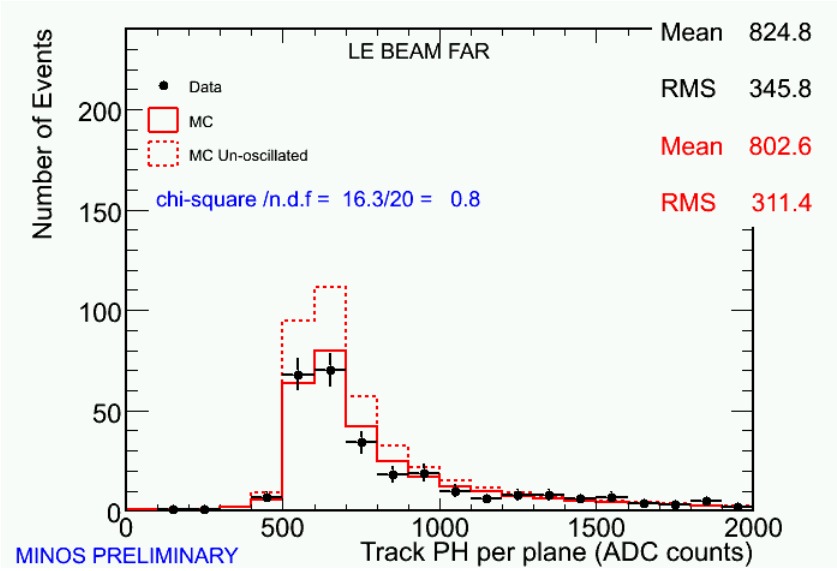
Vertical Track Angle



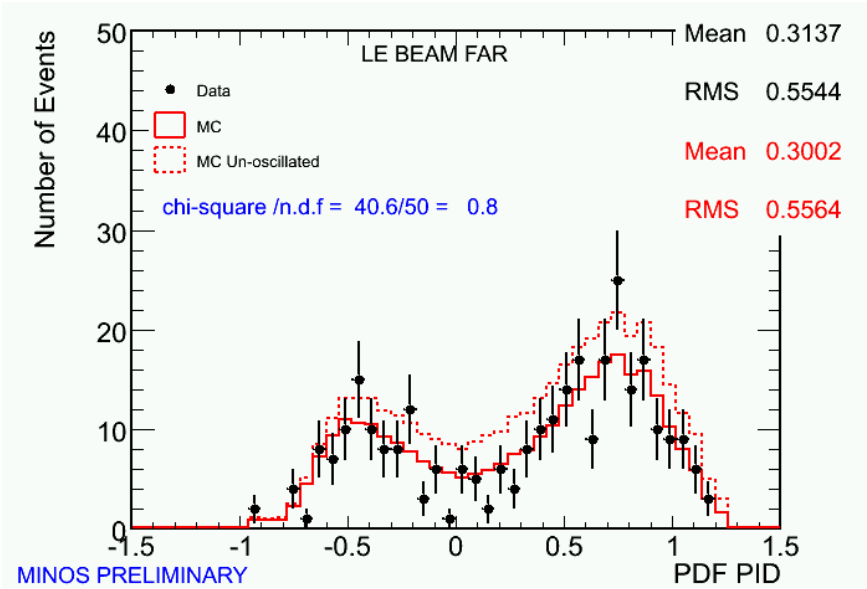
Beam points 3° upwards

Track Length





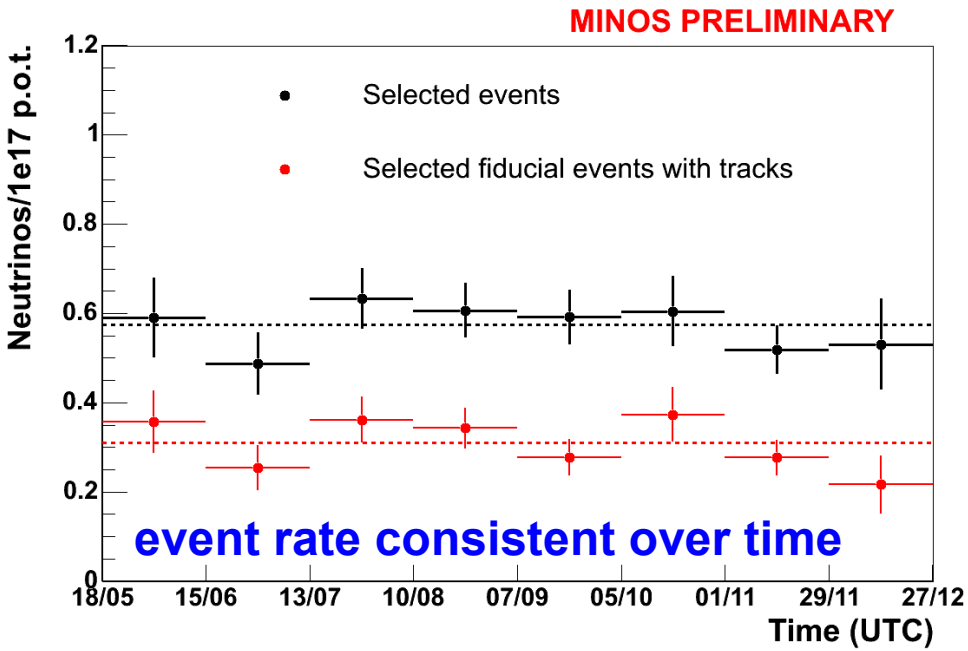
Track Pulse Height per plane

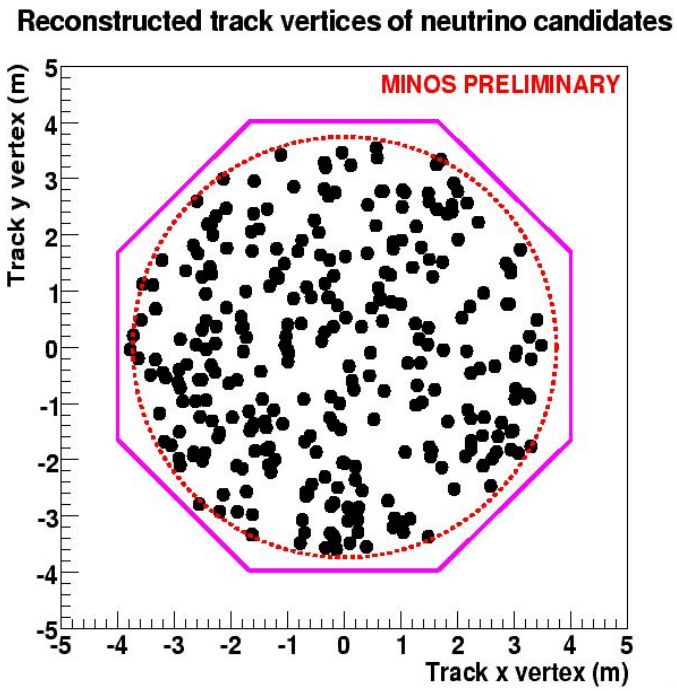


PID Parameter

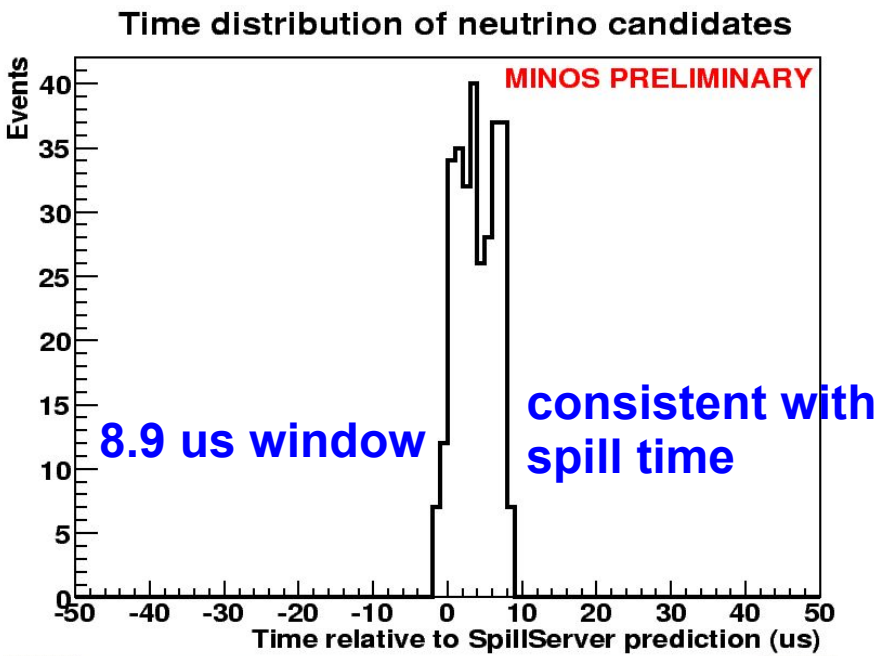
Far Detector Distributions

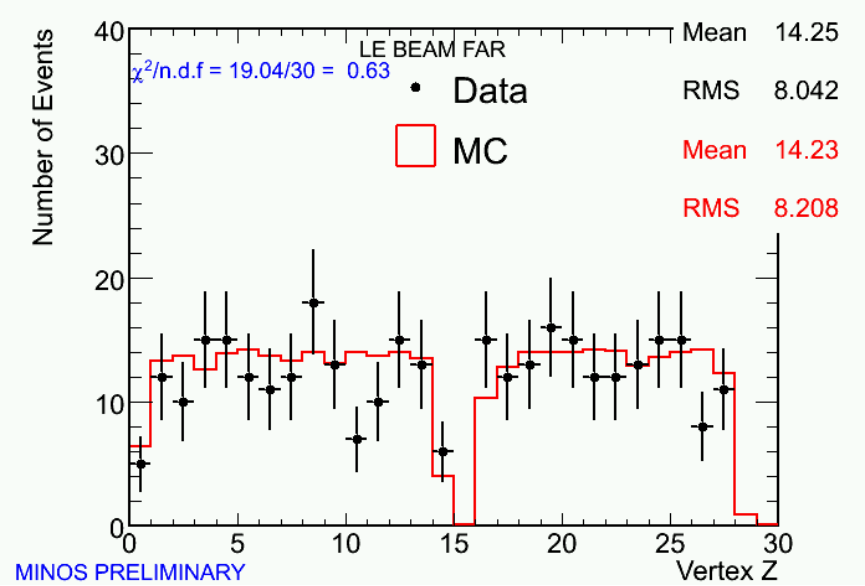
FULL DATASET





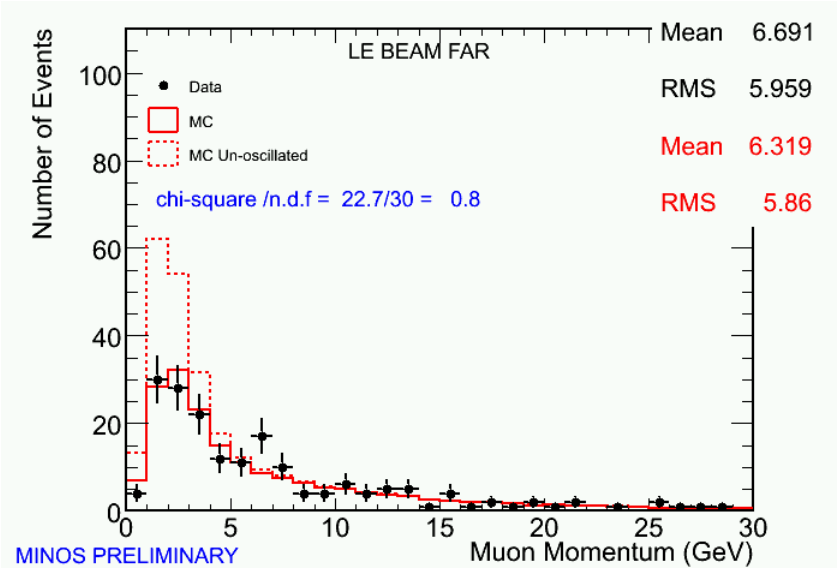
296 selected events with a track uniformly distributed over detector



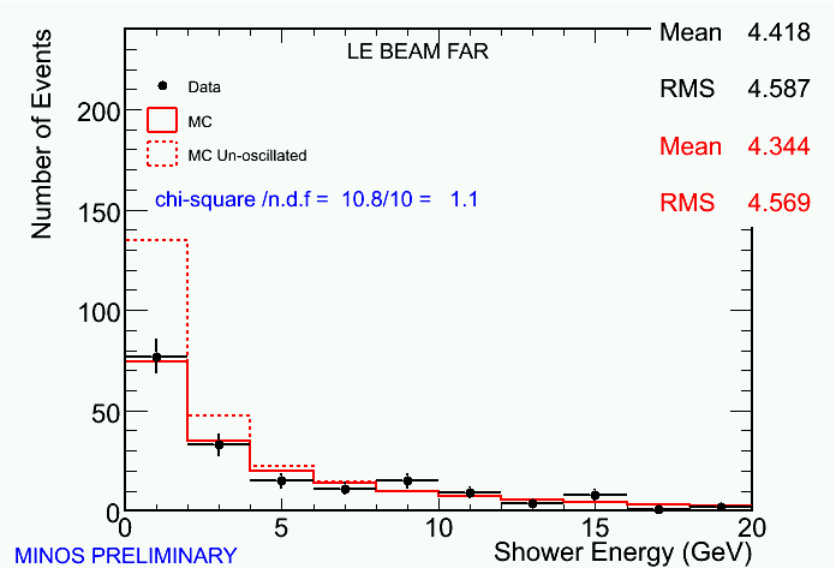


Far Detector Distributions

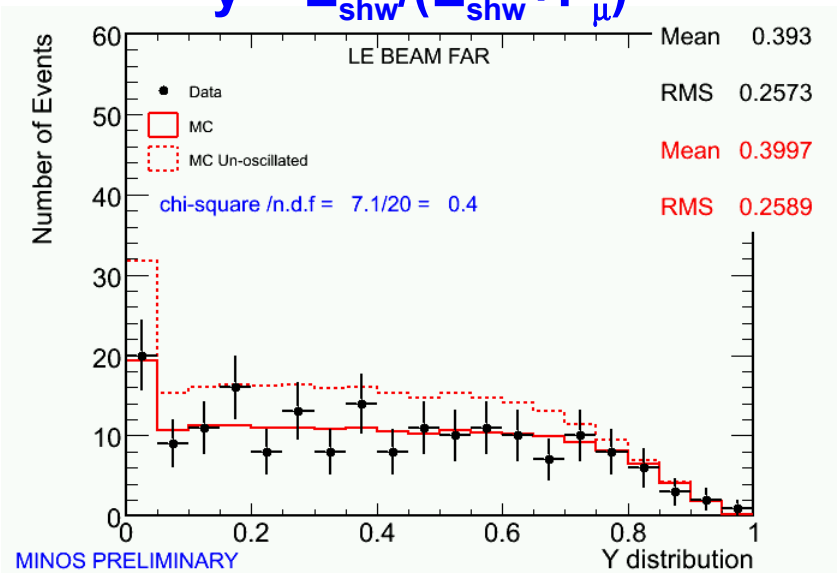
Muon Momentum (GeV/c)



Shower Energy (GeV)



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

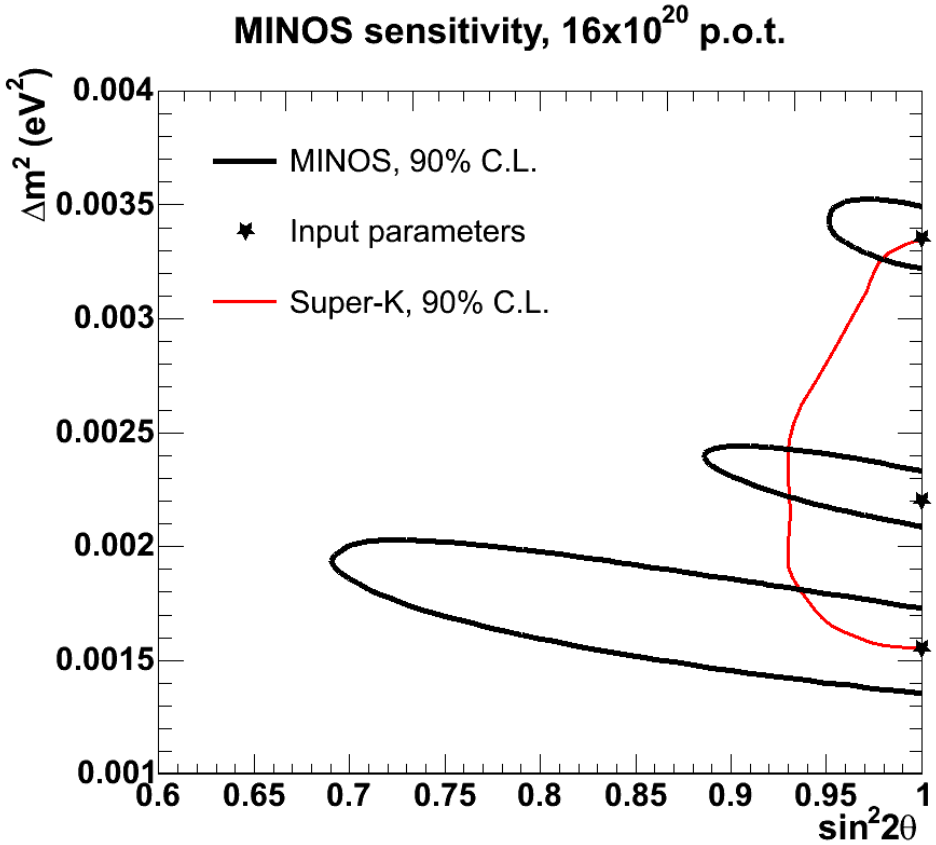


Systematic Errors

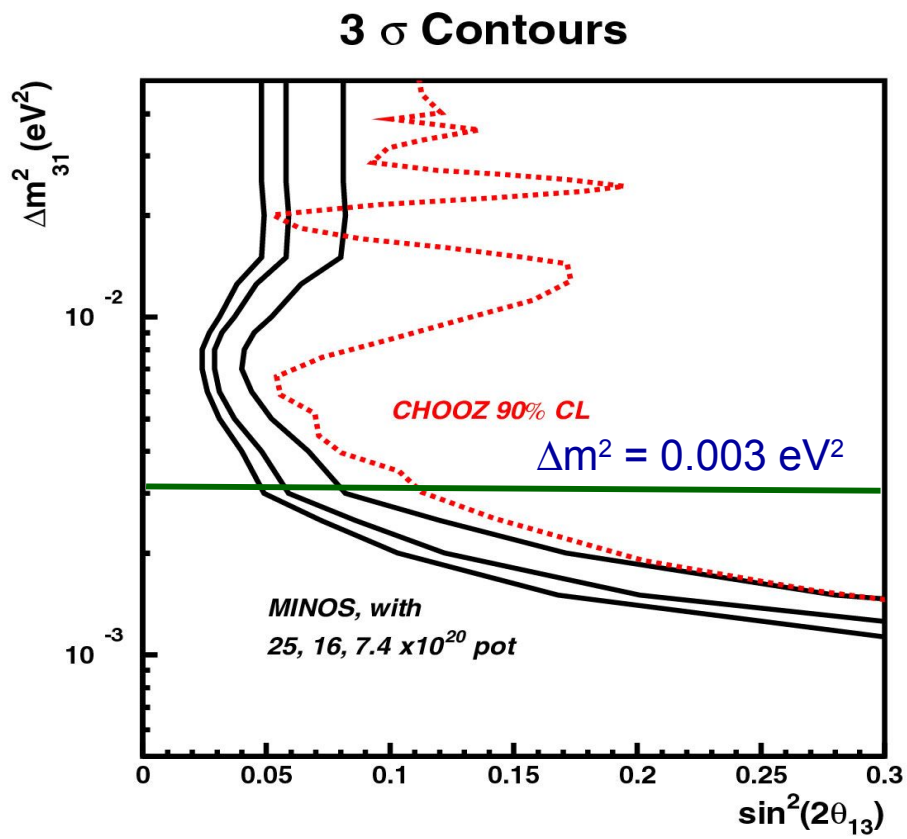
Uncertainty	Δm^2 shift (eV^2)	$Sin^2 2\theta$ shift
Normalisation +/- 4%	0.63e-4	0.025
Muon energy scale +/- 2%	0.14e-4	0.020
Relative Shower energy scale +/- 3%	0.27e-4	0.020
NC contamination +/- 30%	0.77e-4	0.035
CC cross-section uncertainties	0.50e-4	0.016
Beam uncertainty	0.13e-4	0.012
Intranuclear re-scattering	0.27e-4	0.030
Total Systematic (sum in quadrature)	**1.19e-4**	**0.063**
Statistical error (data)	**6.4e-4**	**0.15**

Projected Sensitivity of MINOS

ν_μ disappearance



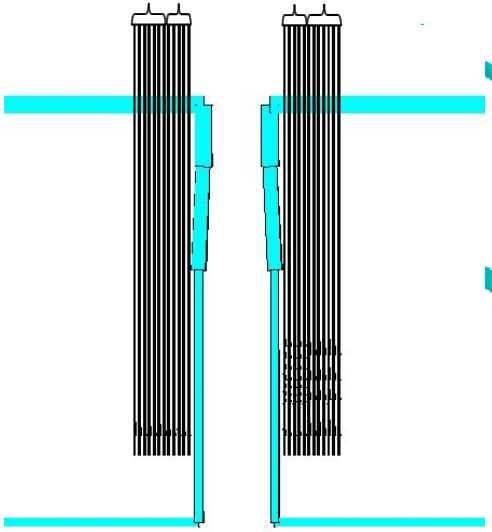
$\nu_\mu \rightarrow \nu_e$

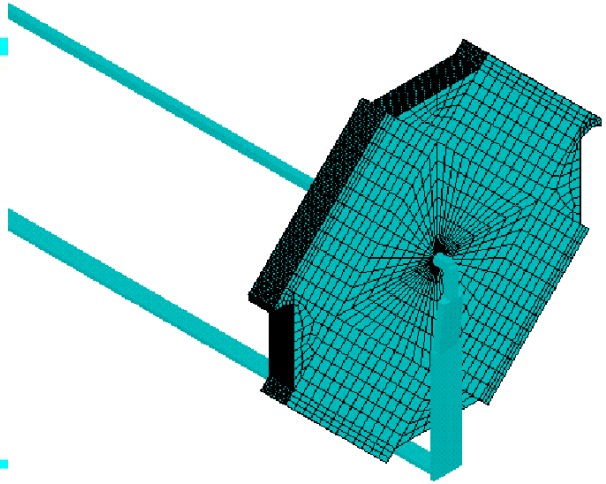


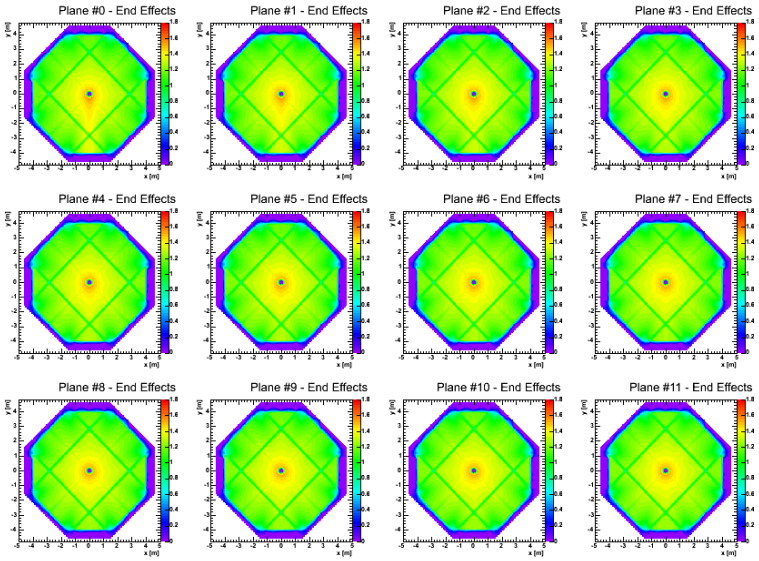
- Precise CC measurements with increased statistics.
- Improve limits in $\nu_\mu \rightarrow \nu_e$ oscillation analysis.
- Rule out alternative models such as neutrino decays

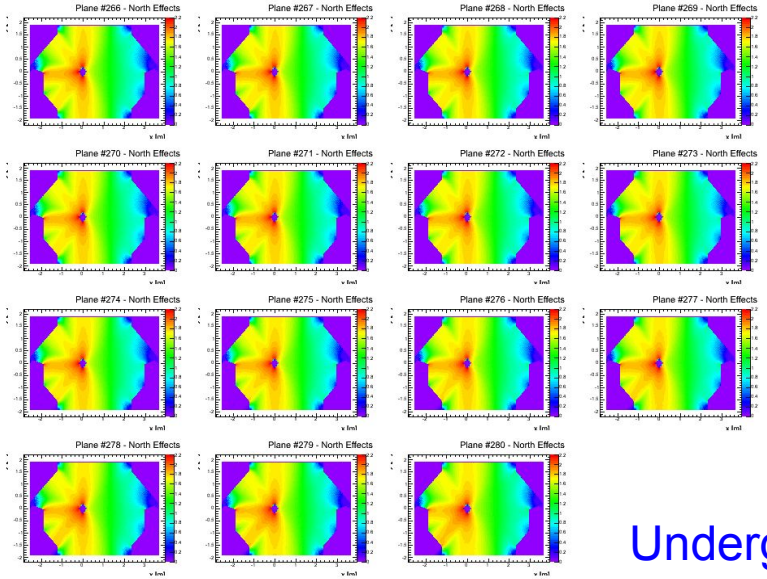
Current Projects – *Modeling of Magnetic Fields*

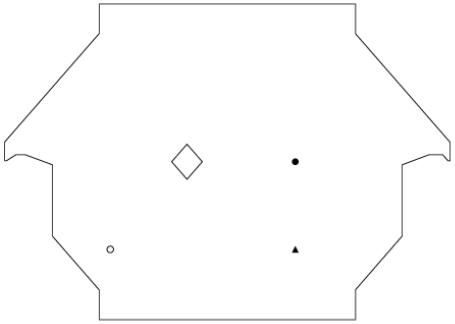
- Modeling of end-of-toroid effects for near and far coils.
- Implementation of maps in the reconstruction code.

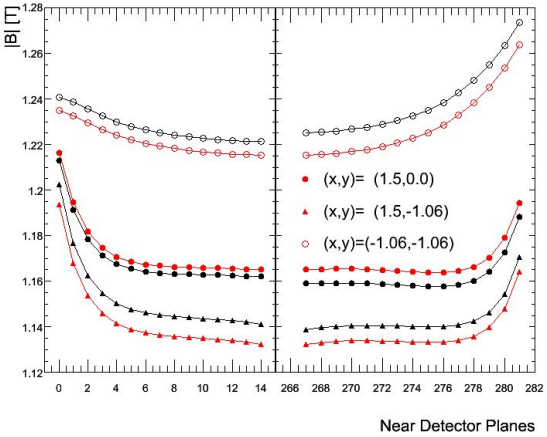








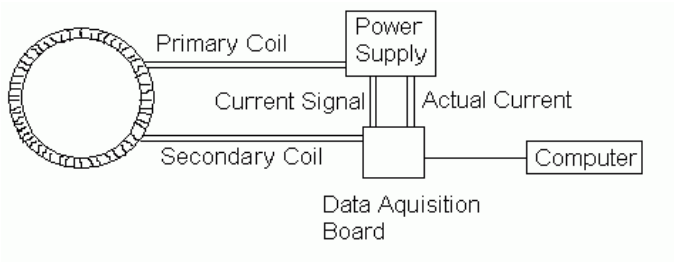


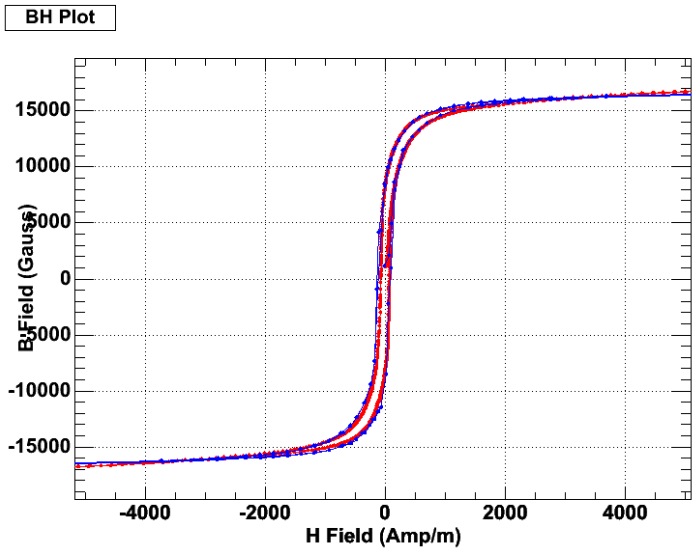


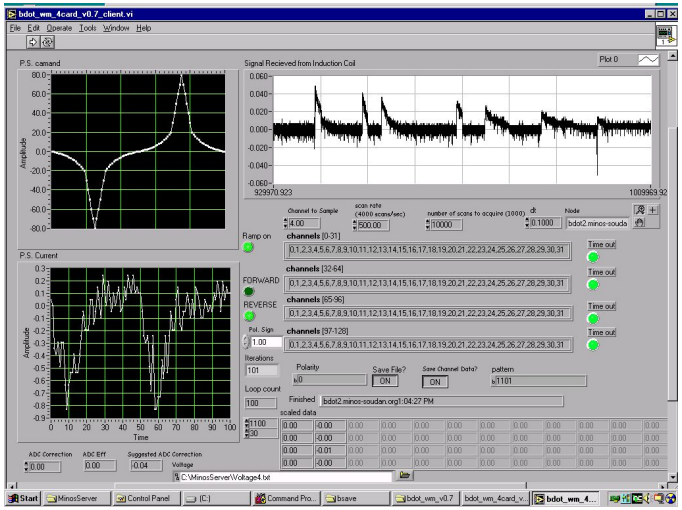
Undergraduate students involved in this work

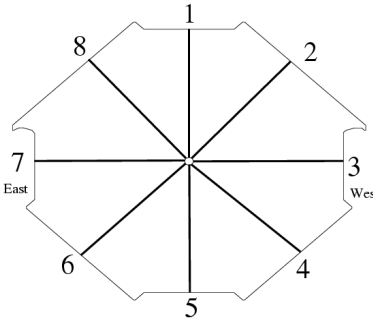
Current Projects – *Magnetic Field Calibration*

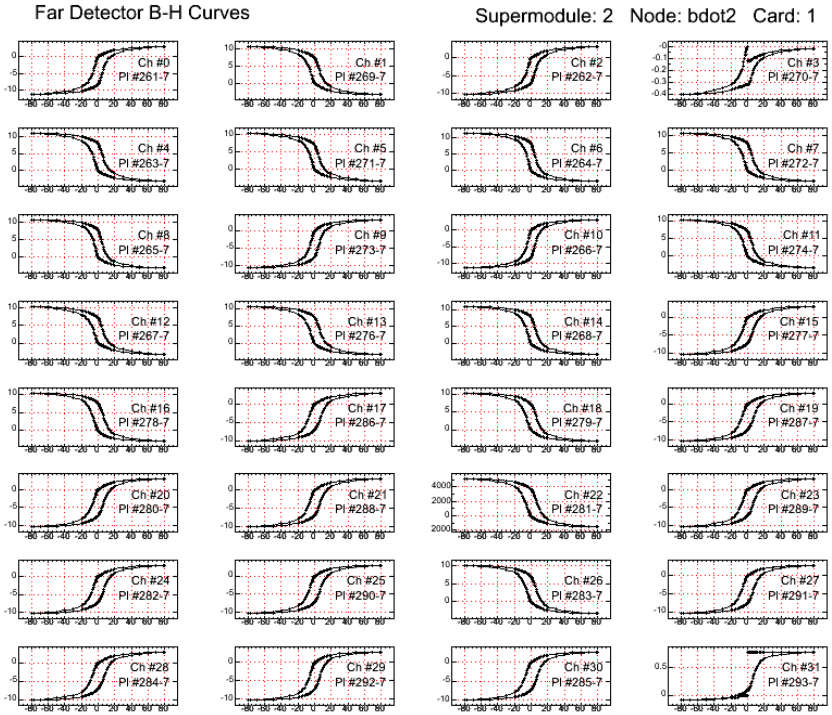
- BH curve of steel samples.
- BH curves from steel planes.







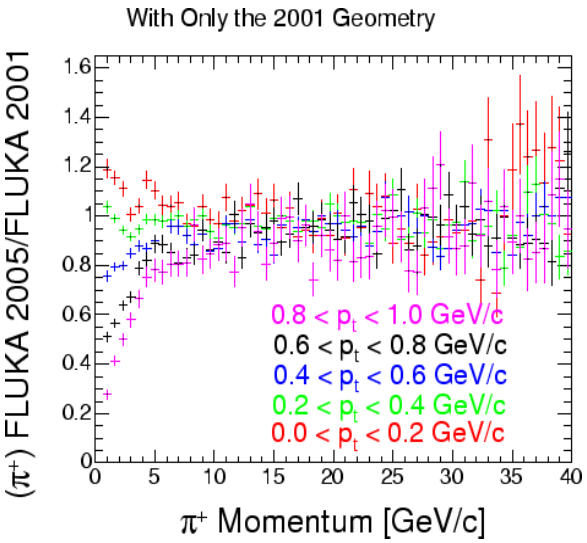


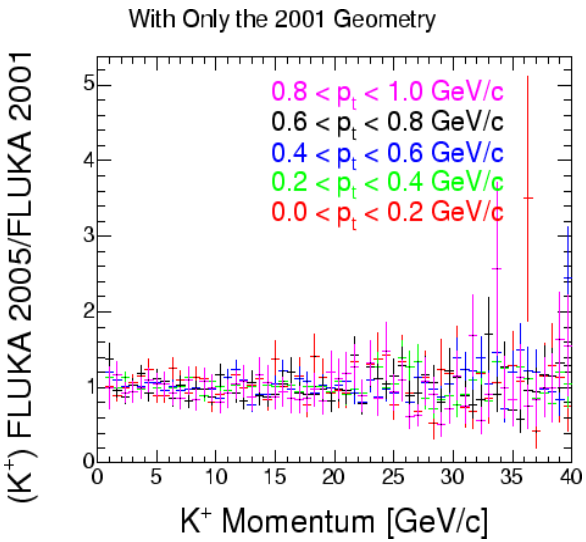


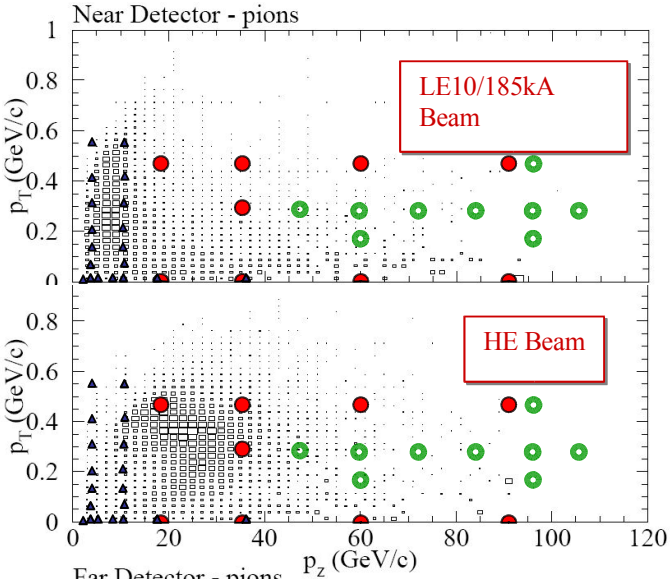
students involved in this work

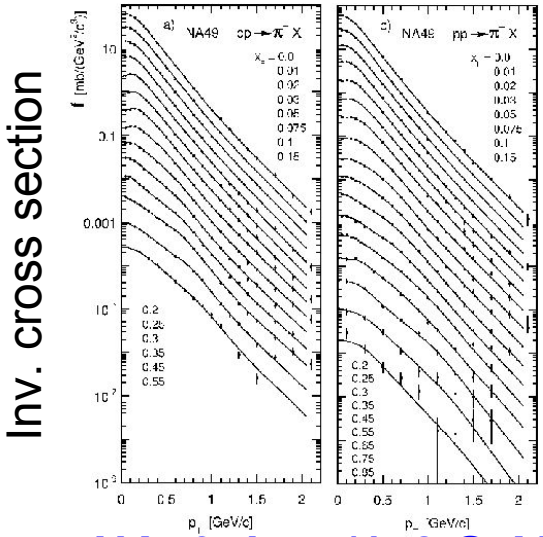
Current Projects – *Hadron Production*

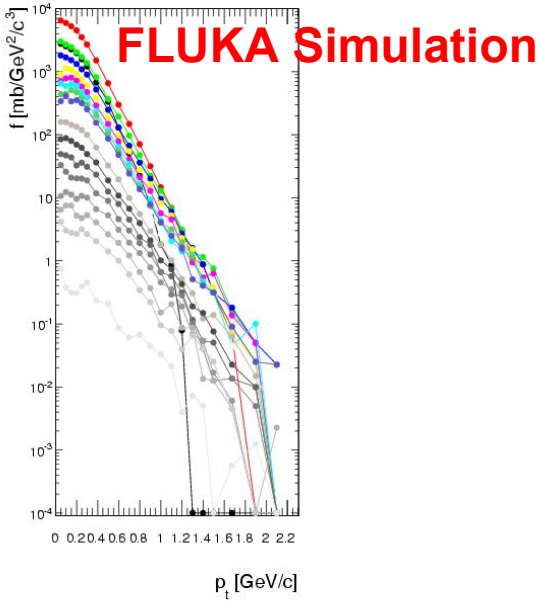
- Improving modeling of hadron production:
  - Accurate target geometry in the simulation
  - Checking models in the simulation





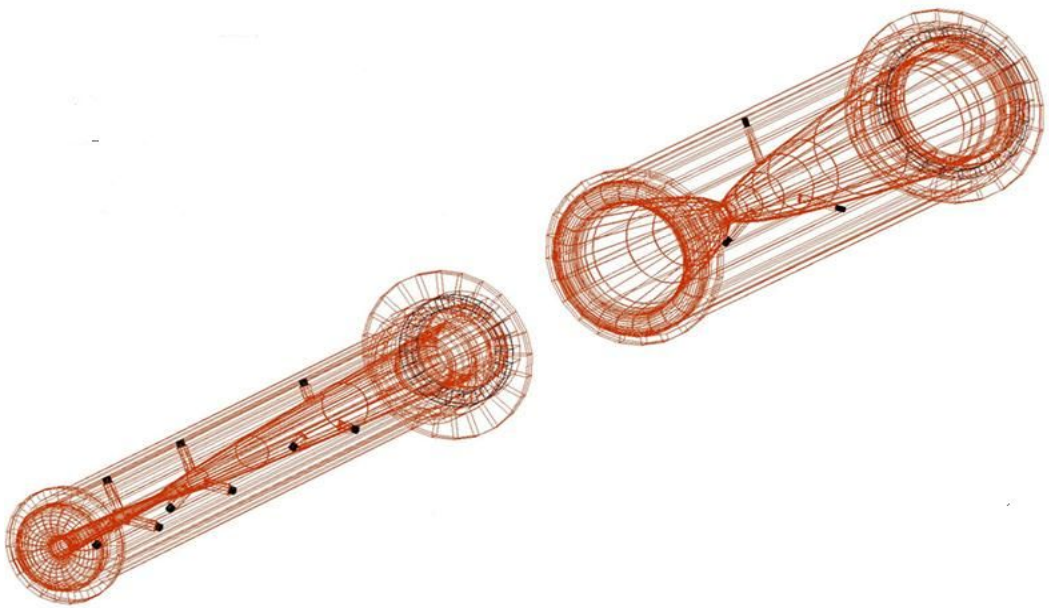






Current Projects – *Beam Simulation*

- Improving the beam simulation:
  - Detailed modeling of the beam line in GEANT4
  - Validation and implementation

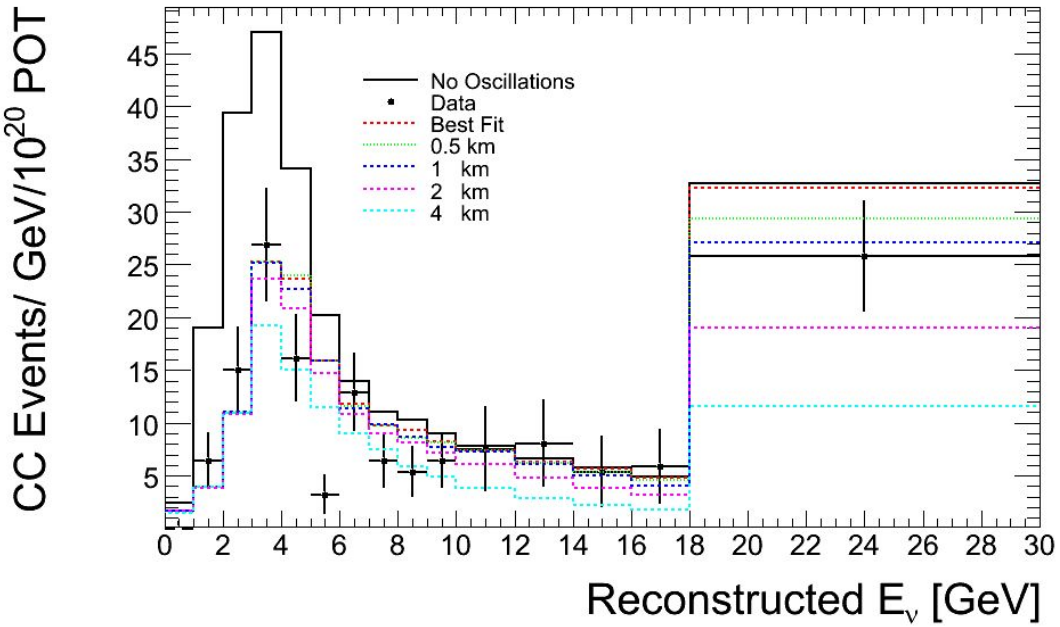


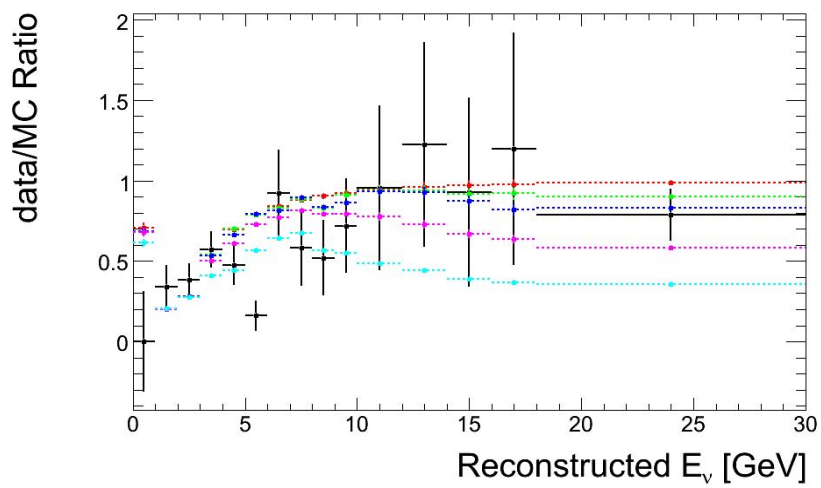
students involved in this work

Current Projects – *Off-Axis Analysis*

VERY PRELIMIRARY

- Cross-check of an off-axis detector analysis





best fit: 1.5 ± 1.3 km

Current Projects – *Monte Carlo Generation*

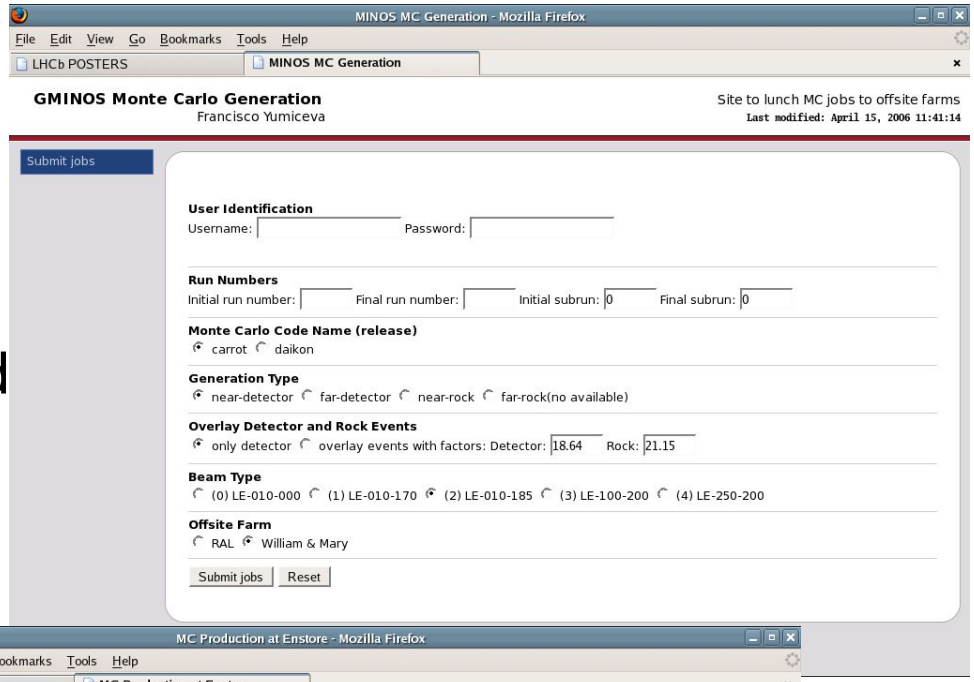
Produced more than 50% of the MINOS MC samples

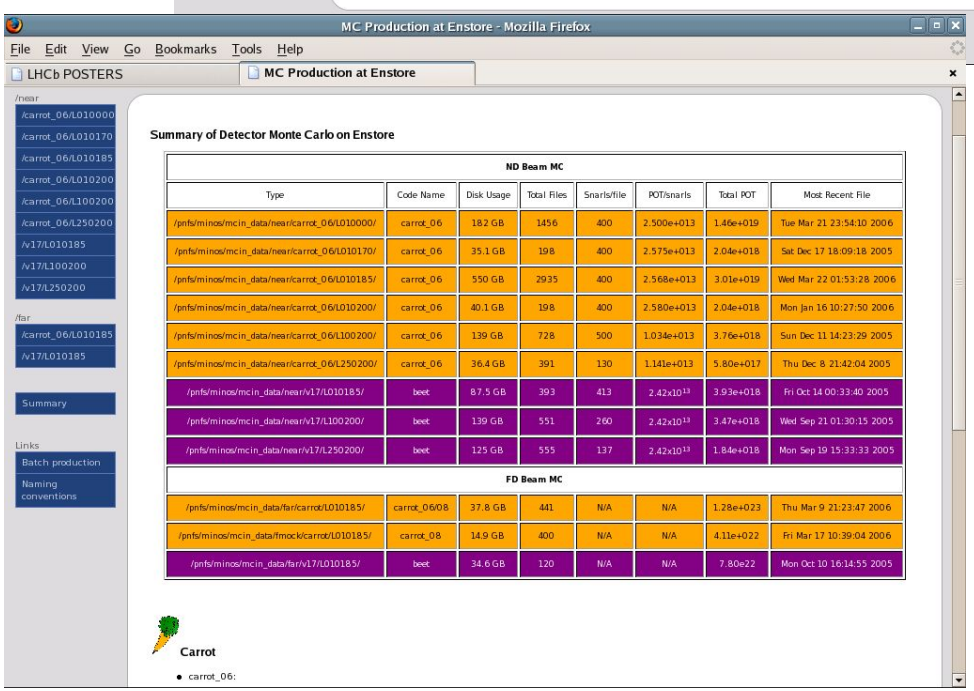
Steps:

- (FLUKA) Hadron production
- (Particle transport) Neutrino flux
- (near detector) Rock events
- Detector events
- (near) Rock and detector event overlaid

Tools:

- Submitting jobs
- Monitoring jobs
- MC samples status





ND Beam MC							
Type	Code Name	Disk Usage	Total Files	Snarls/file	POT/snarls	Total POT	Most Recent File
/pnfs/minos/mcin_data/near/carrot_06/L010000/	carrot_06	182 GB	1456	400	2.500e+013	1.46e+019	Tue Mar 21 23:54:10 2006
/pnfs/minos/mcin_data/near/carrot_06/L010170/	carrot_06	35.1 GB	198	400	2.575e+013	2.04e+018	Sat Dec 17 18:09:18 2005
/pnfs/minos/mcin_data/near/carrot_06/L010185/	carrot_06	550 GB	2935	400	2.568e+013	3.01e+019	Wed Mar 22 01:53:28 2006
/pnfs/minos/mcin_data/near/carrot_06/L010200/	carrot_06	40.1 GB	198	400	2.580e+013	2.04e+018	Mon Jan 16 10:27:50 2006
/pnfs/minos/mcin_data/near/carrot_06/L100200/	carrot_06	139 GB	728	500	1.034e+013	3.76e+018	Sun Dec 11 14:23:29 2005
/pnfs/minos/mcin_data/near/carrot_06/L250200/	carrot_06	36.4 GB	391	130	1.141e+013	5.80e+017	Thu Dec 8 21:42:04 2005
/pnfs/minos/mcin_data/near/v17/L010185/	beet	87.5 GB	393	413	2.42×10^{13}	3.93e+018	Fri Oct 14 00:33:40 2005
/pnfs/minos/mcin_data/near/v17/L100200/	beet	139 GB	551	260	2.42×10^{13}	3.47e+018	Wed Sep 21 01:30:15 2005
/pnfs/minos/mcin_data/near/v17/L250200/	beet	125 GB	555	137	2.42×10^{13}	1.84e+018	Mon Sep 19 15:33:33 2005
FD Beam MC							
/pnfs/minos/mcin_data/far/carrot/L010185/	carrot_06/08	37.8 GB	441	N/A	N/A	1.28e+023	Thu Mar 9 21:23:47 2006
/pnfs/minos/mcin_data/fmock/carrot/L010185/	carrot_08	14.9 GB	400	N/A	N/A	4.11e+022	Fri Mar 17 10:39:04 2006
/pnfs/minos/mcin_data/far/v17/L010185/	beet	34.6 GB	120	N/A	N/A	7.80e22	Mon Oct 10 16:14:55 2005

Summary and Conclusions

- Preliminary CC analysis **using 0.9x10^{20} POT** (66% of the current dataset).
- Result **disfavors no oscillations at 5 sigma**.
- ν_μ disappearance result **consistent with SK and K2K**

$$\Delta m^2_{23} = 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \times 10^{-3} eV^2$$

$$\sin^2(2\theta_{23}) = 0.88^{+0.12}_{-0.15}(stat) \pm 0.06(syst)$$

- Results are **statistics dominated** and we should be able to make significant improvements with a larger dataset.

FIN

Backup slides

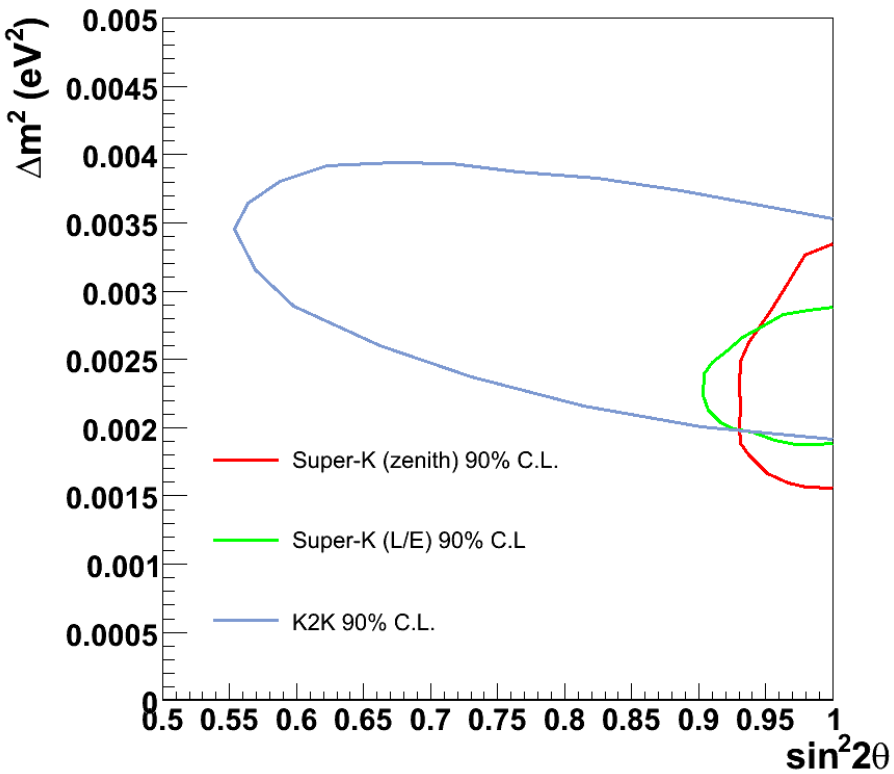
Current knowledge of 2-3 Mixing

- Current best measurements of Δm^2_{23} and $\sin^2 2\theta_{23}$ are provided by Super-Kamiokande (atmospheric neutrino analysis) and K2K (9×10^{19} pot)

- The limits (at 90% C.L.) are:
  - $\sin^2 2\theta > 0.9$
  - $1.9 < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2

- The analysis presented in this talk, which is for 9.3×10^{19} pot, should provide a measurement of the mixing parameters that is competitive with these results

Allowed regions from Super-K and K2K



Calibration

- **Light Injection** system (PMT gain)

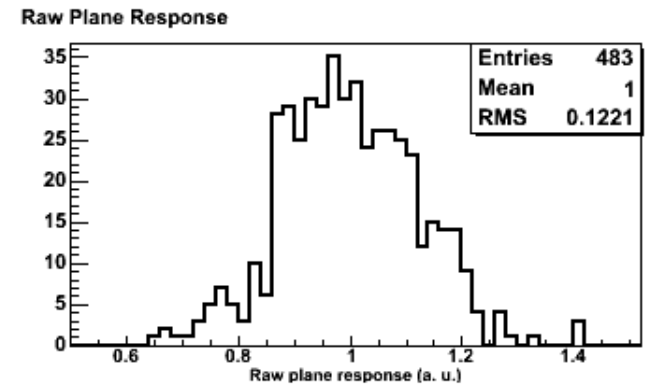
- **Cosmic ray muons** (strip to strip and detector to detector)

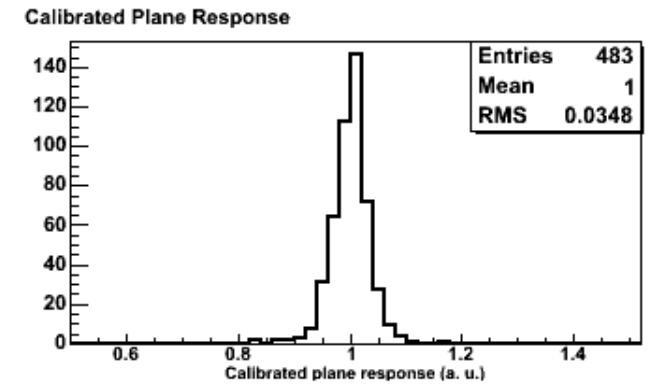
- **Calibration Detector**
  - Mini detector at CERN test beam
  - Operated in both Near and Far configurations
  - **Absolute energy calibration**

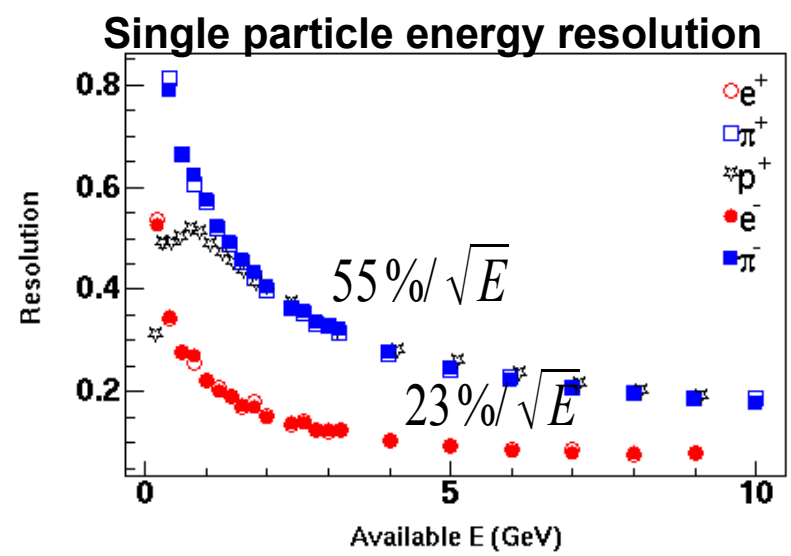
$$E_\nu = E_\mu + E_{had}$$

Energy scale calibration:

- 1.9% absolute error in near
- 3.5% absolute error in far
- 3% relative



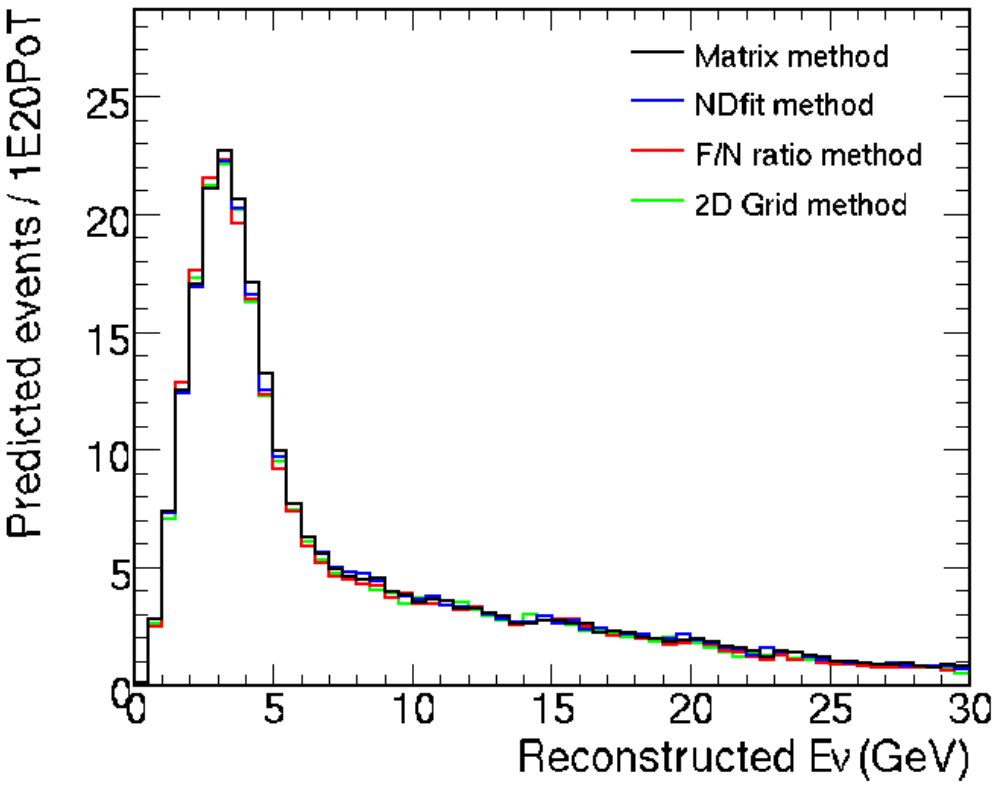




Alternative Methods for Predicting Far Spectrum

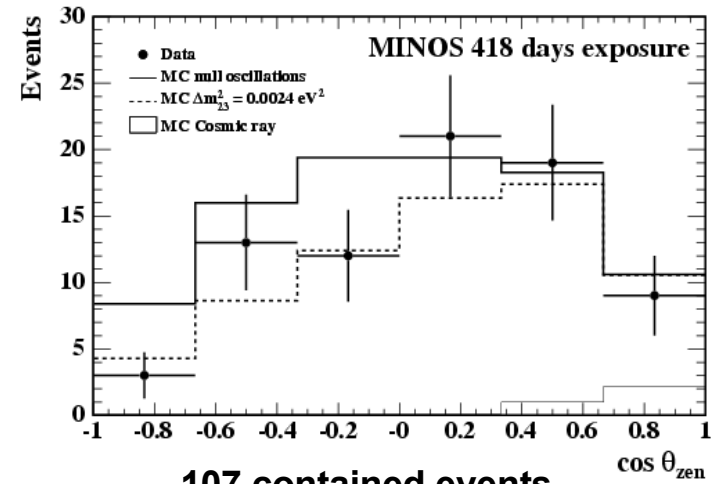
- We have investigated three other methods of deriving the FD spectrum from the ND data:
  - Extrapolation using the Far/Near ratio from the MC
  - Two independent methods of fitting to the ND data in order to derive systematic parameters that are used to reweight the FD Monte Carlo
    - These are termed "NDfit" and "2d Grid Fit" respectively
- These methods have quite different sensitivities to systematic errors, therefore comparing the results obtained with all four is a good check of the robustness of our oscillation measurement

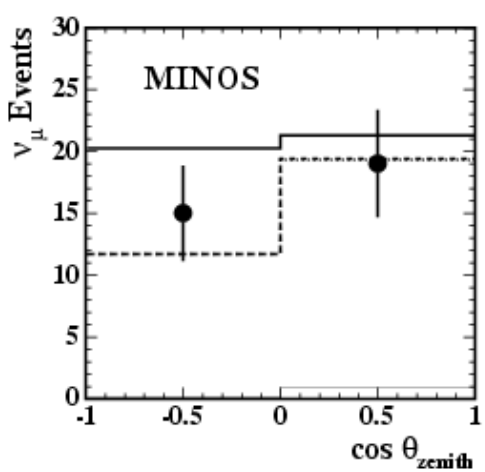
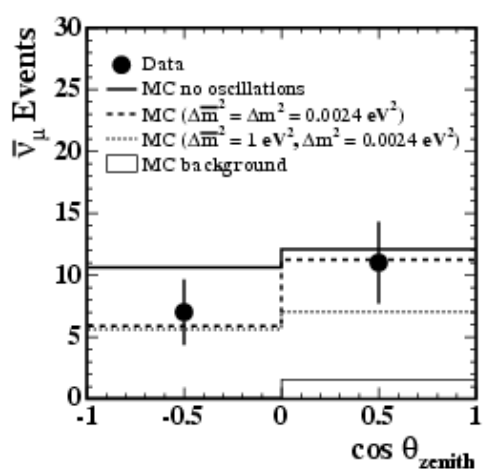
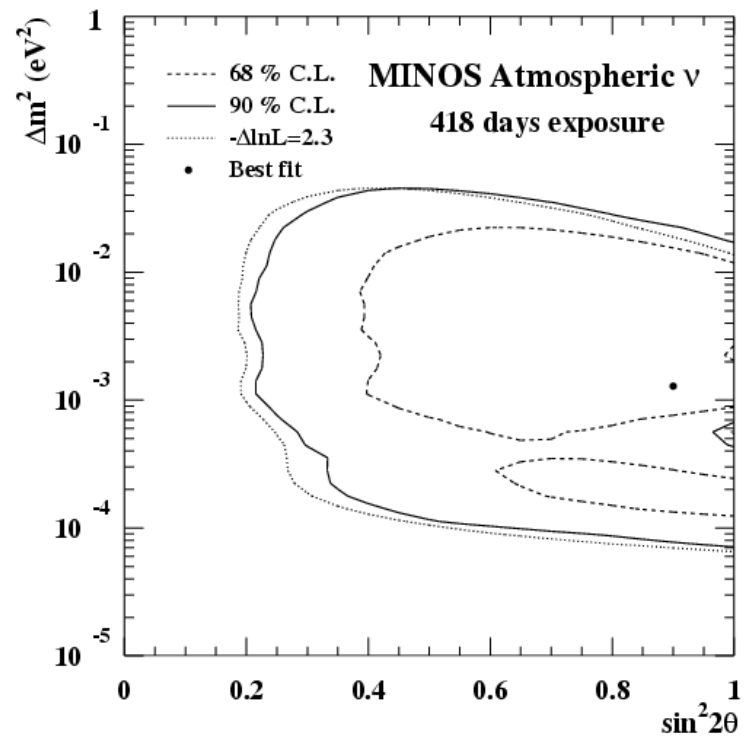
Predicted FD unoscillated spectra



Atmospheric Neutrino Analysis

First direct results on neutrino/anti-neutrino oscillations using atmospheric neutrinos



107 contained events

Selection	Data	Expected no oscillations	Expected $\Delta m^2_{23} = 0.0024\,eV^2$
Low Res.	30	37 ± 4	28 ± 3
Ambig. $\nu_\mu/\overline{\nu}_\mu$	25	26 ± 3	20 ± 2
ν_μ	34	42 ± 4	31 ± 3
$\overline{\nu}_\mu$	18	23 ± 2	17 ± 2