MINOS Status in the 2nd year of beam running

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University College, London

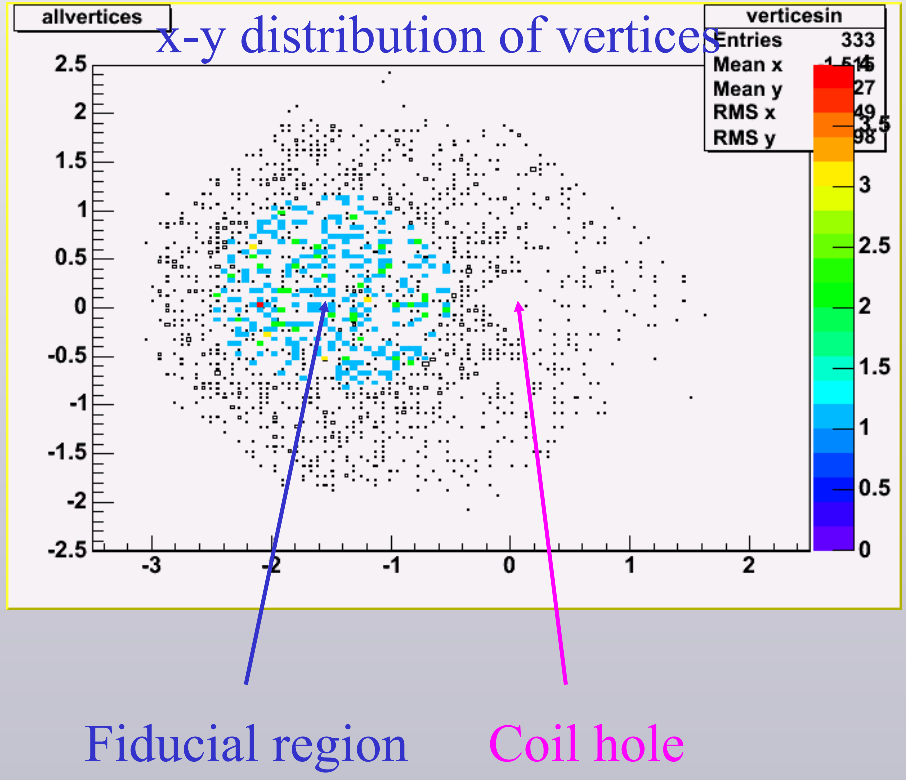
For the MINOS collaboration

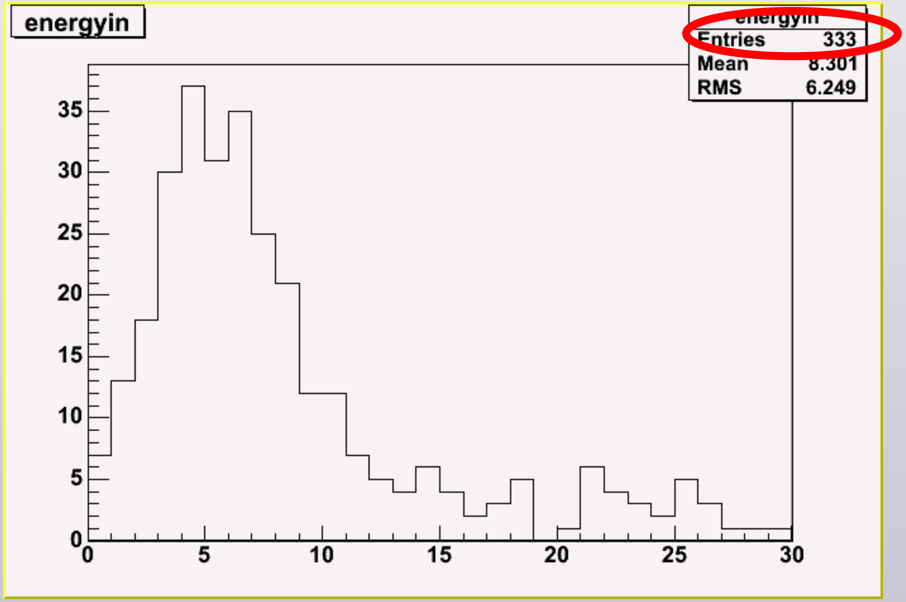
Overview

- **Introduction to NuMI and MINOS**
  - Physics Goals
  - NuMI beam and MINOS detectors
- **Experiment operation**
  - Data collection
  - Event reconstruction and selection
  - Near and far detector distributions
- **Oscillation Analysis**
  - Prediction of the Far Detector spectrum (no oscillations)
  - Oscillation fits, parameter extraction
- **Future**

An Anniversary!

2 years ago, at the XI International Workshop on Neutrino Telescopes, we showed our first distributions of accelerator neutrinos!





neutrino "energy" distribution (for contained events only)

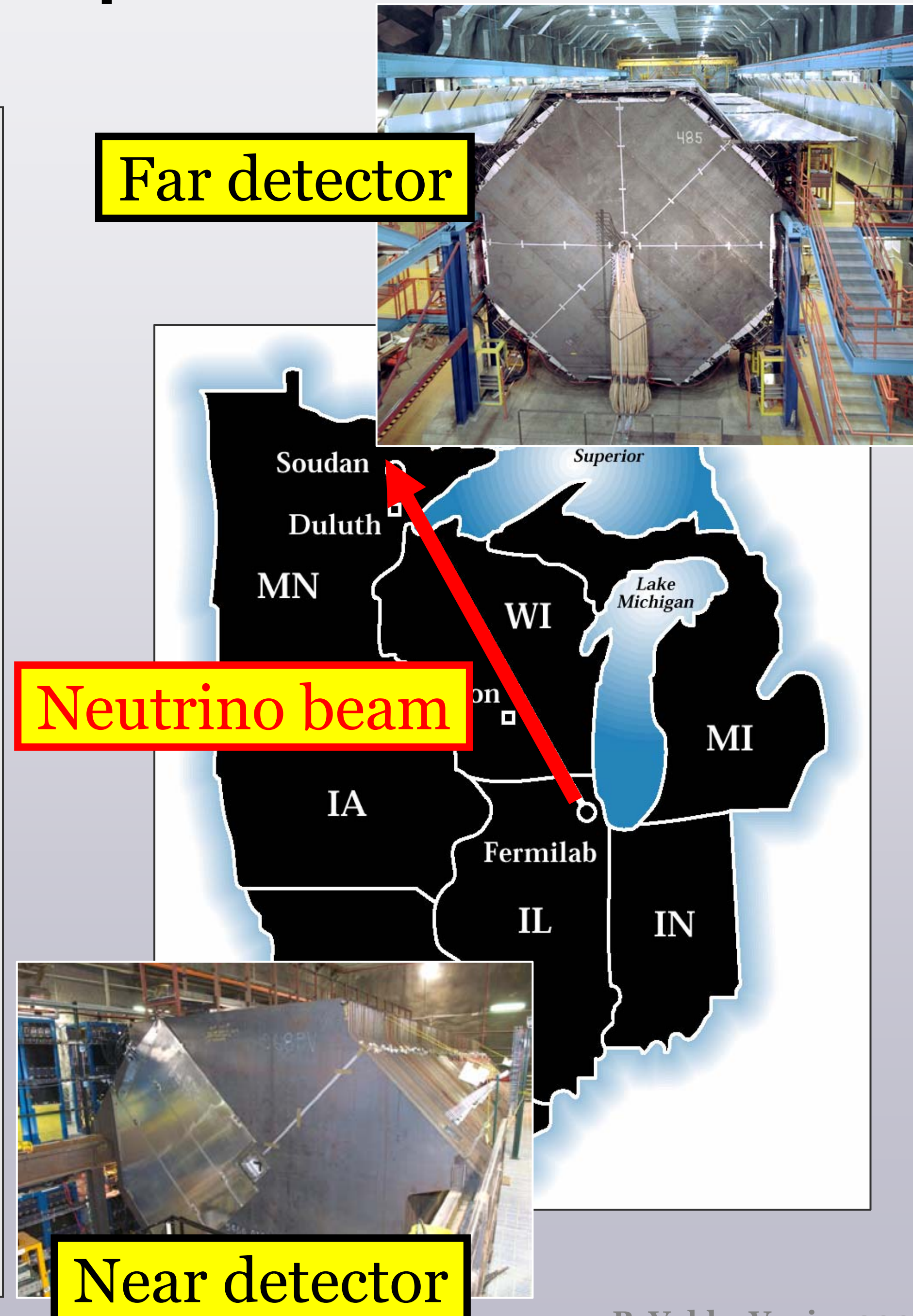
Caveat: No B field, residual field only

Roughly 1 day's data at 1 pulse/minute (rather than 1/2 sec) at ~1.3 x 10^{12} ppp

From S. Wojcicki's talk at Neutrino Telescopes 2005

The MINOS Experiment

- **Main Injector Neutrino Oscillation Search**
- **Muon neutrino beam produced by 120 GeV/c Main Injector at Fermilab**
- **Two functionally identical detectors, separated by 735km**
- **Near Detector (Fermilab) measures beam before oscillations**
- **Far Detector (Soudan, MN) measures distortions w.r.t. the Near Detector**



MINOS Physics Goals

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

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

Weak Eigenstates | PMNS Mixing Matrix | Mass Eigenstates

Useful Approximations:

ν_μ Disappearance (2 flavors):

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

ν_e Appearance:

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

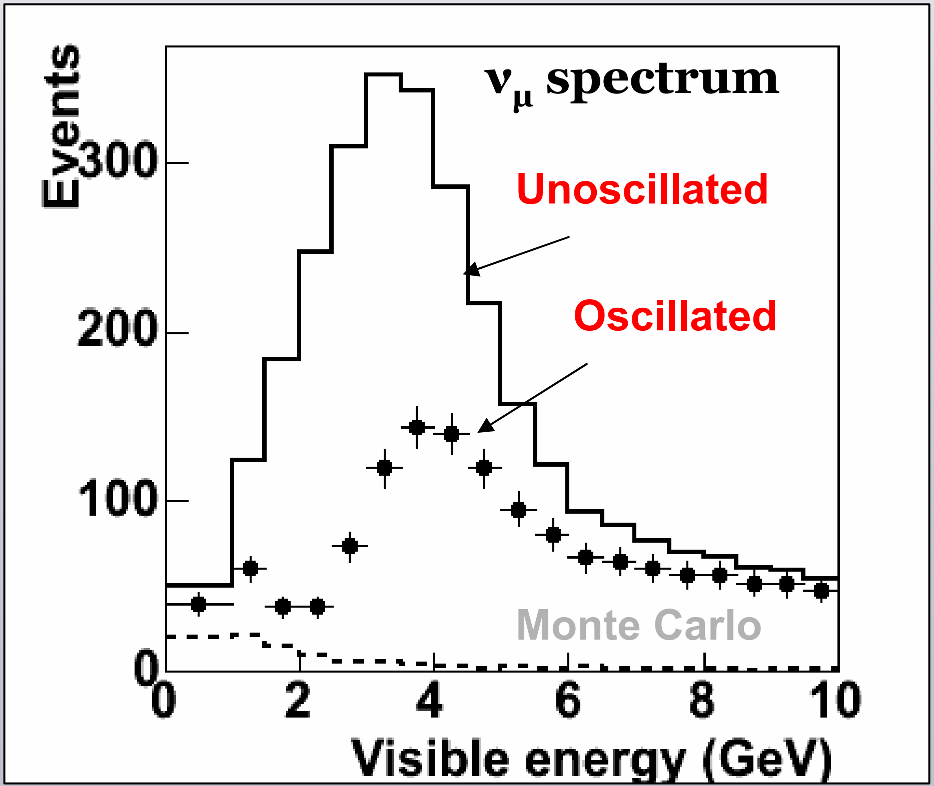
Where L, E are known and θ_{23}, θ_{13},

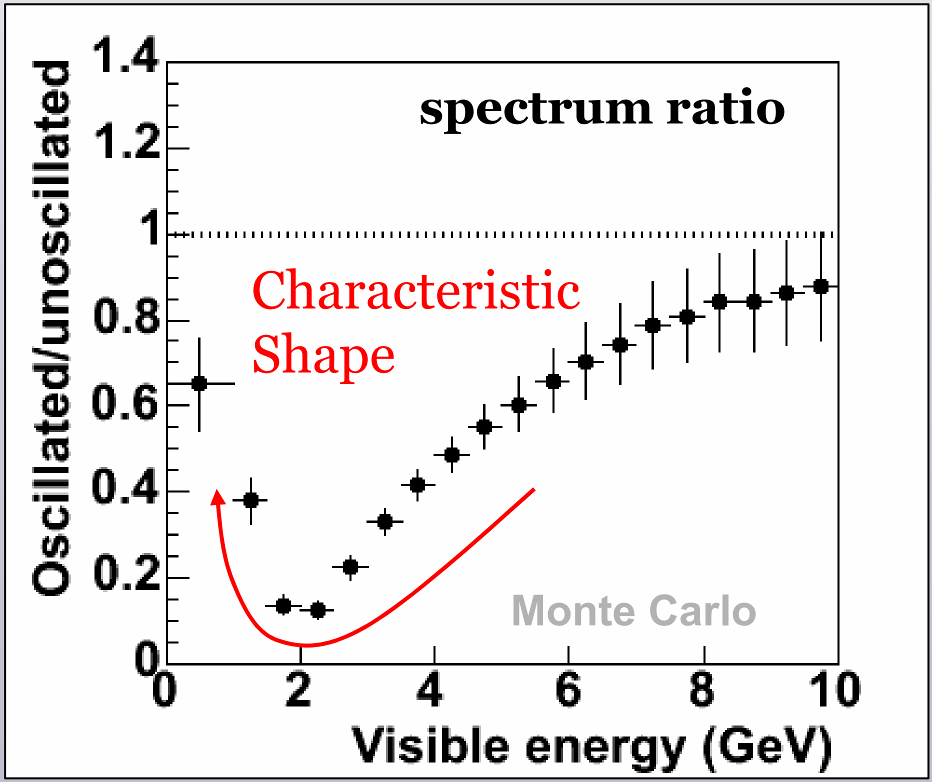
$\Delta m^2_{32} = m^2_3 - m^2_2$ are to be measured

Oscillation Measurement

- Long baseline ν_μ disappearance experiment
- Predict unoscillated CC spectrum at Far Detector
- Compare with measured spectrum to extract oscillation parameters

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267\Delta m^2 L / E)$$





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

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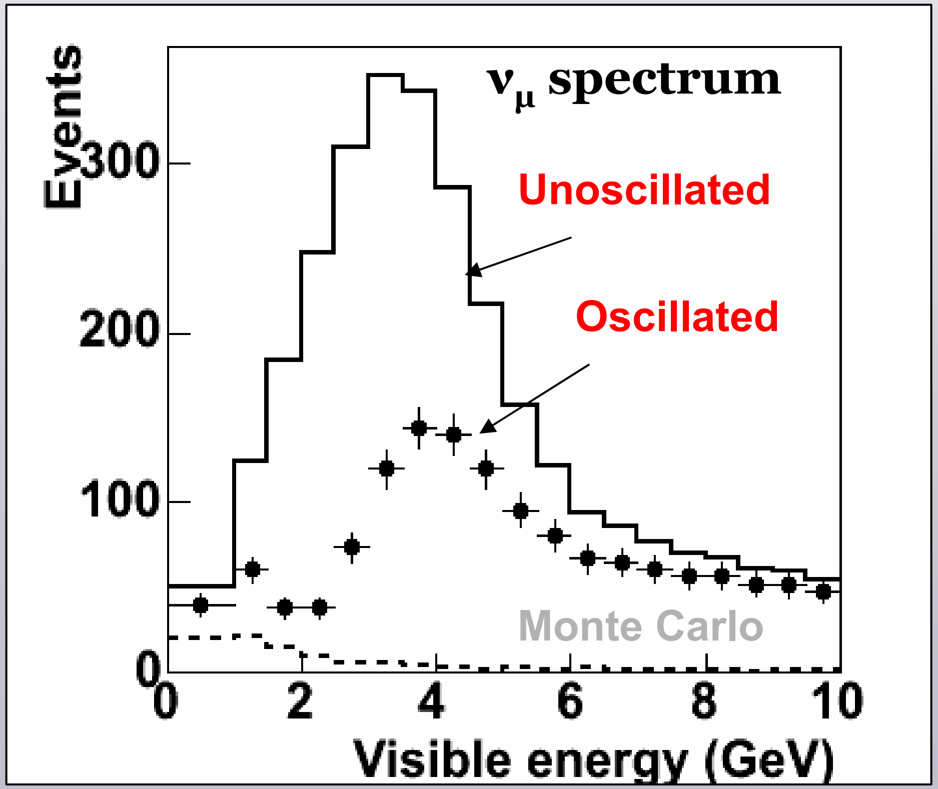

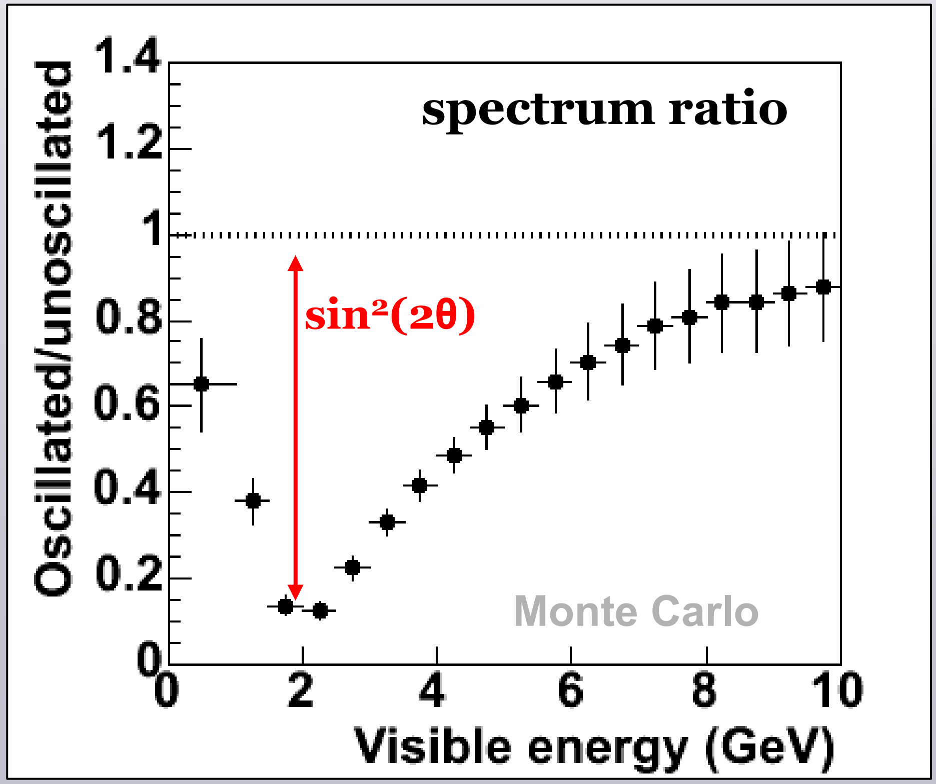

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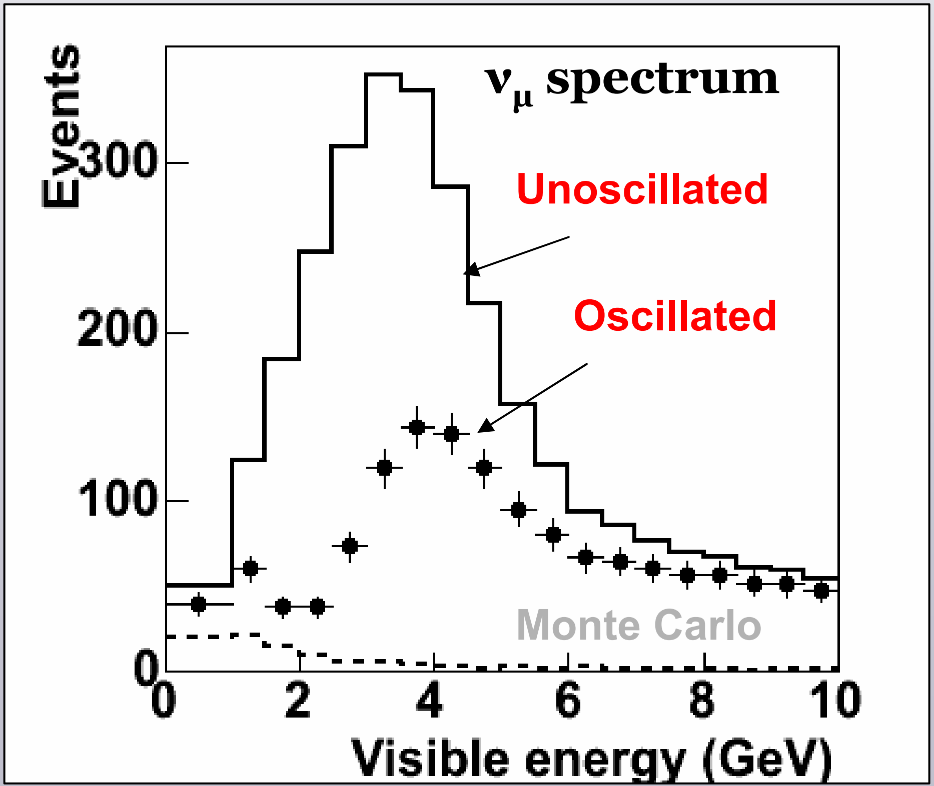

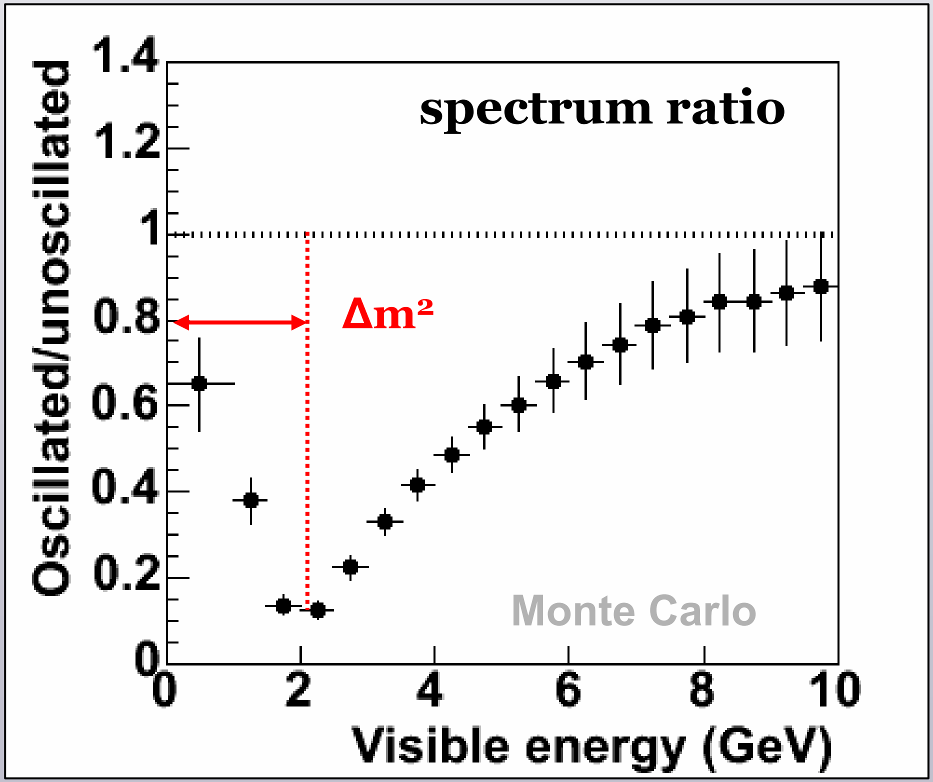

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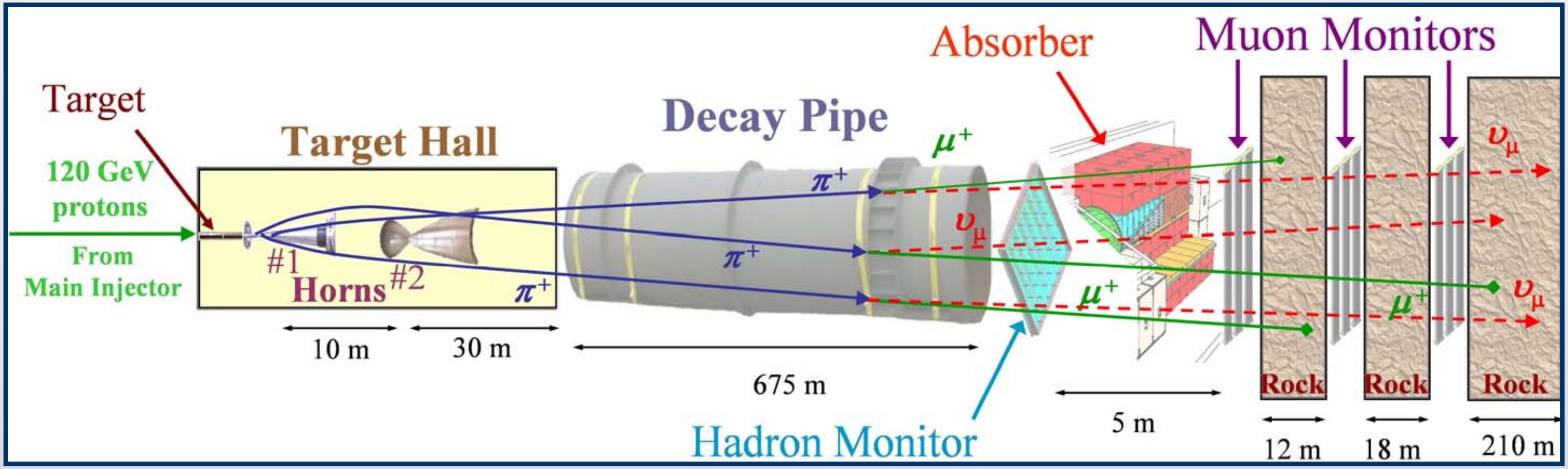
Making A Neutrino Beam



- **Neutrinos at the Main Injector** (NuMI)
  - 120 GeV/c protons from the Main Injector
  - bombard graphite target
  - produce π and K
  - focus charged hadrons
    - distance between target and focusing elements determines beam energy
    - TUNABLE!
  - hadrons decay to ν's
  - ν travel (through rock) to Near and Far Detectors

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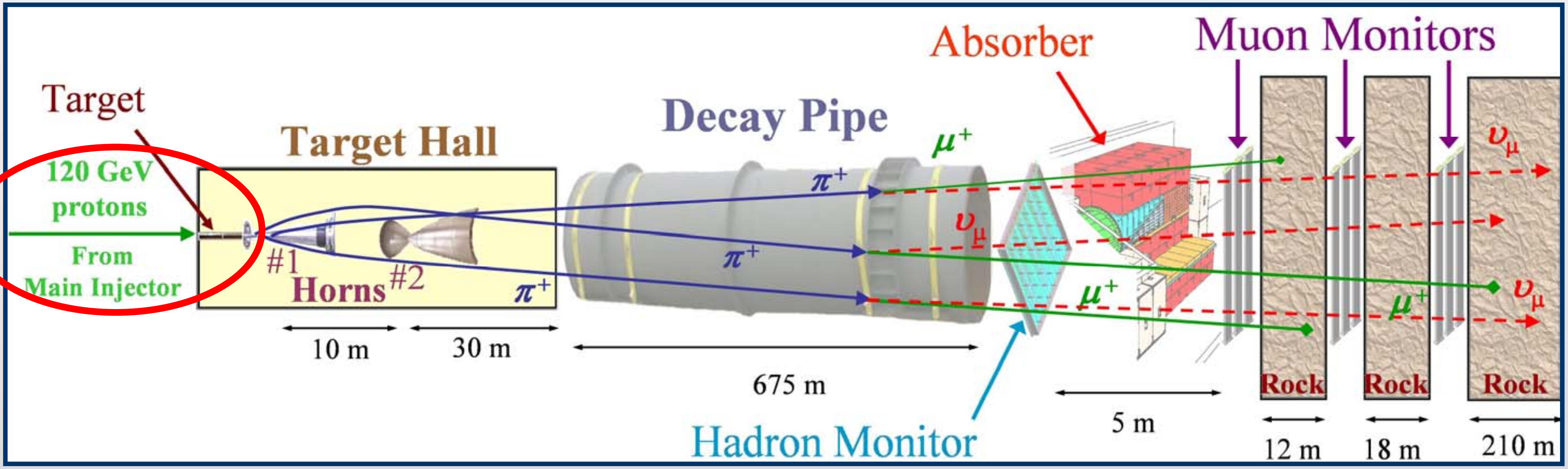

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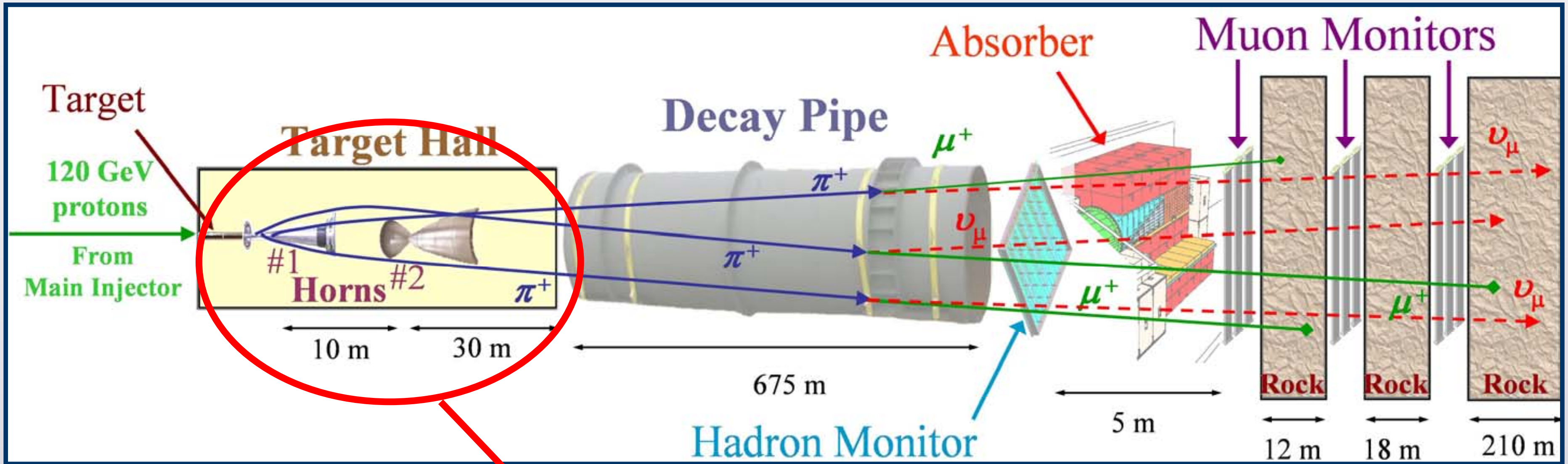

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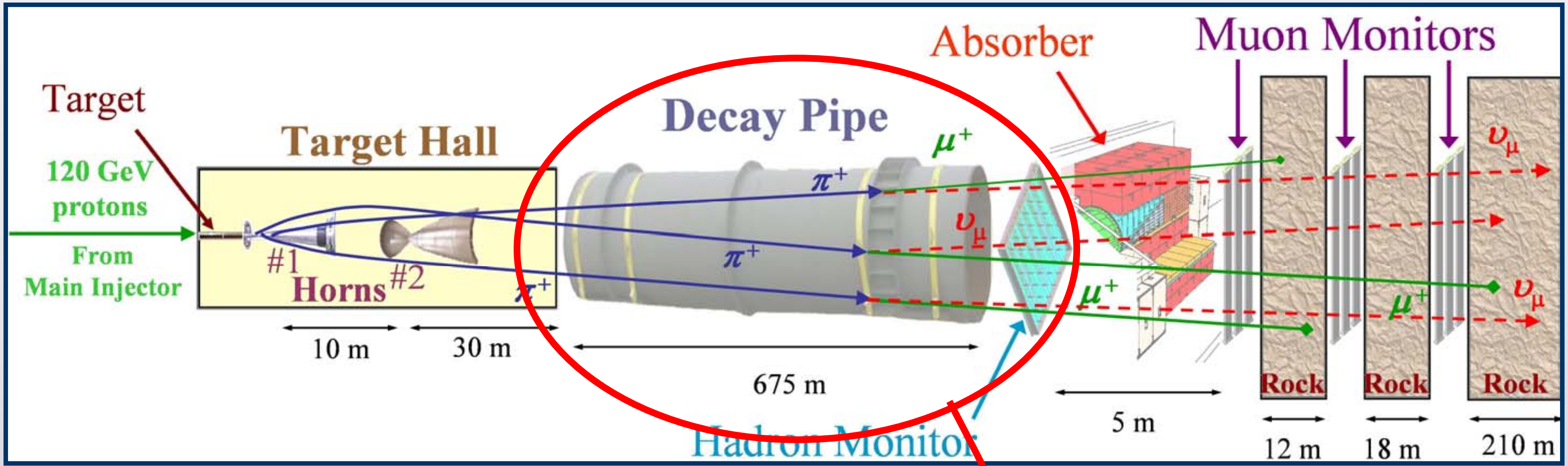

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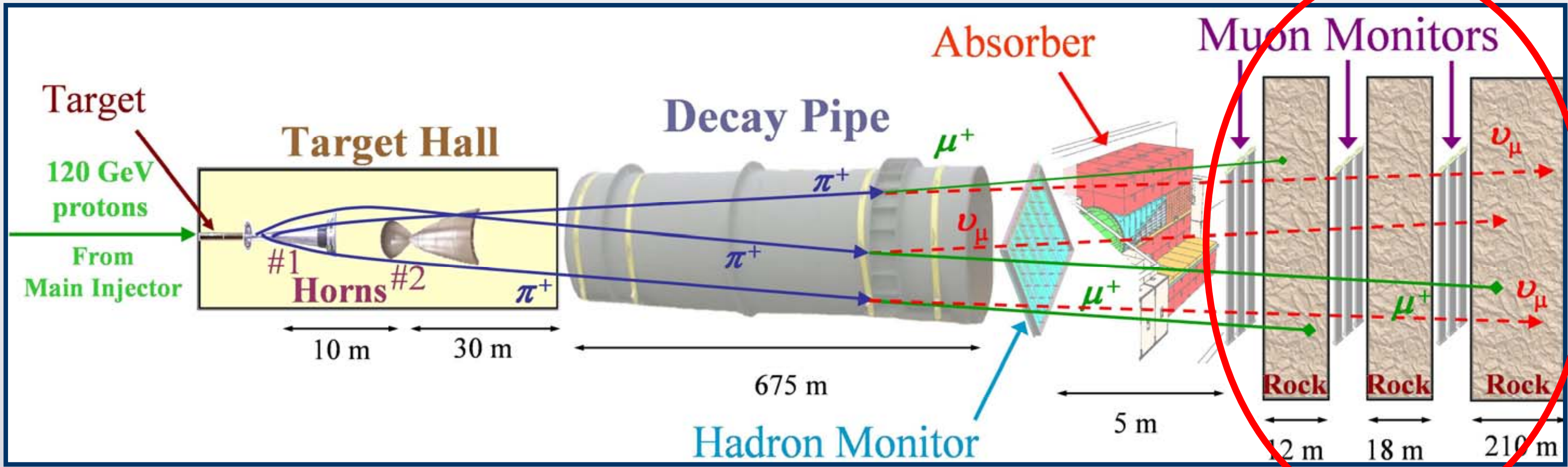

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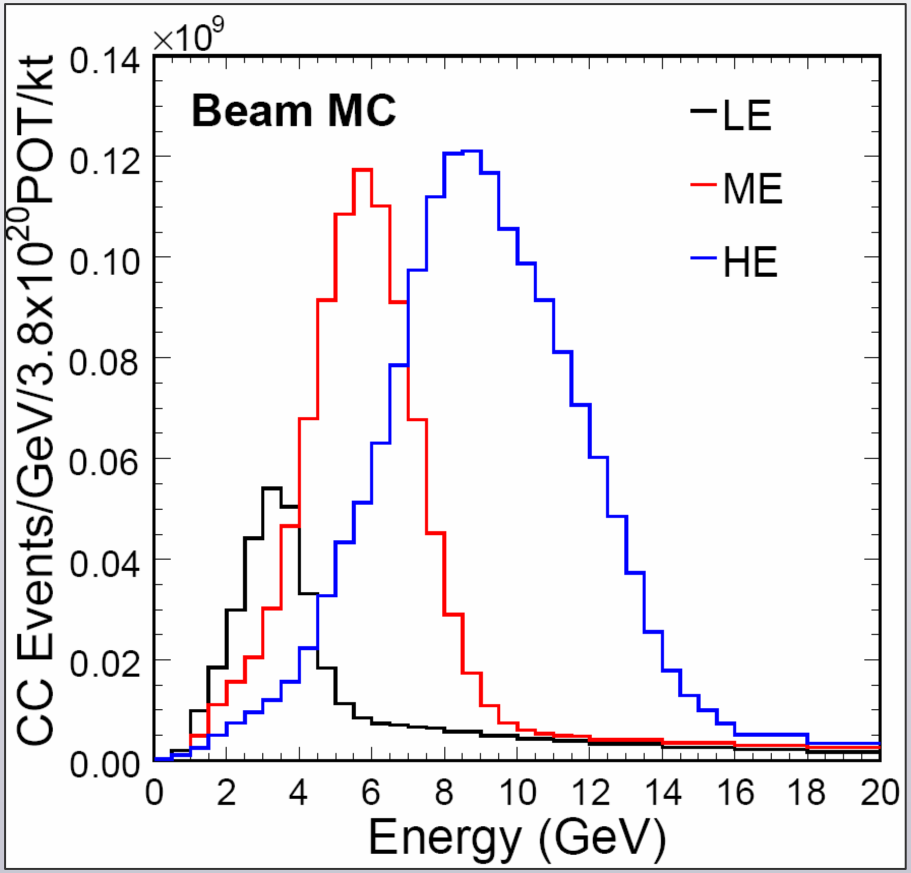
The NuMI neutrino beam



$\nu_\mu = 92.9\%$
$\bar{\nu}_\mu = 5.8\%$
$\nu_e + \bar{\nu}_e = 1.3\%$

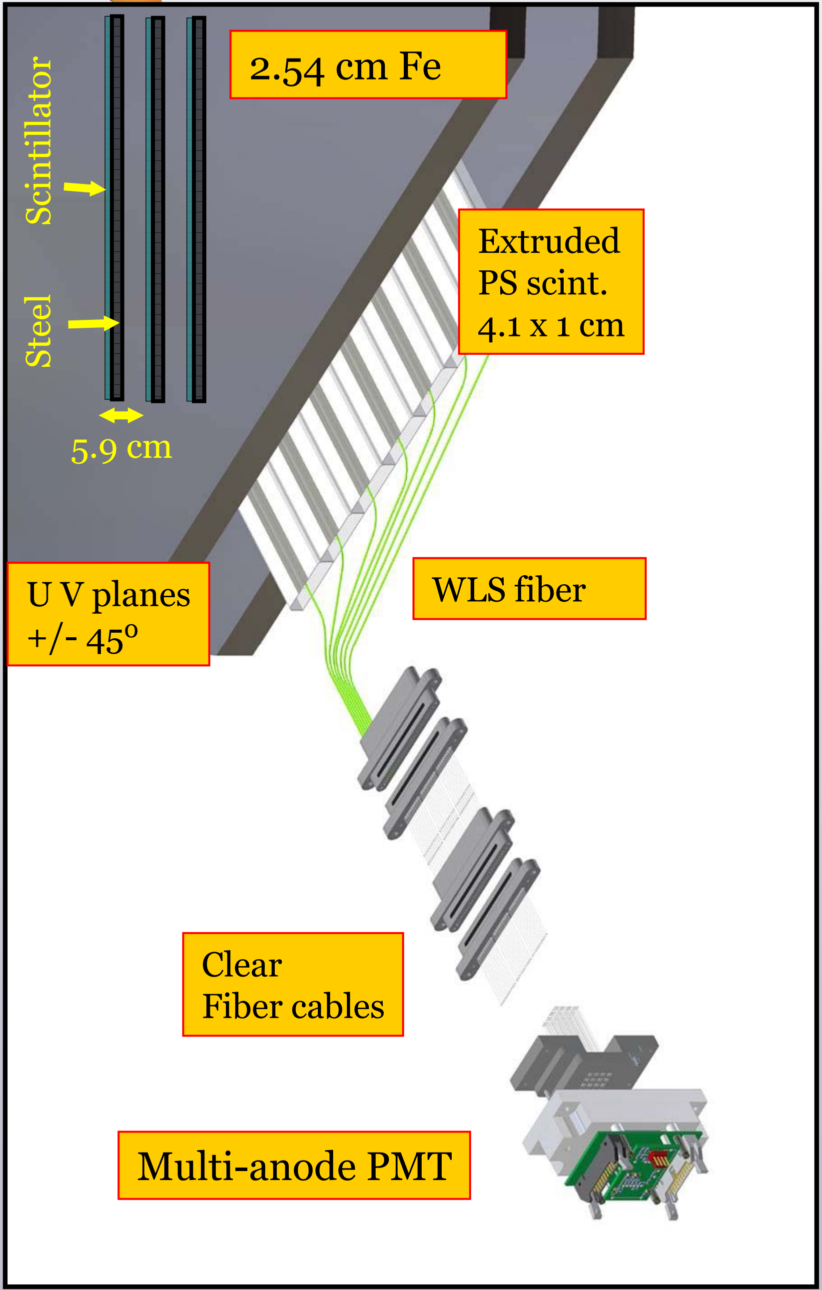
Expected number of events (no osc.) in Far Detector

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

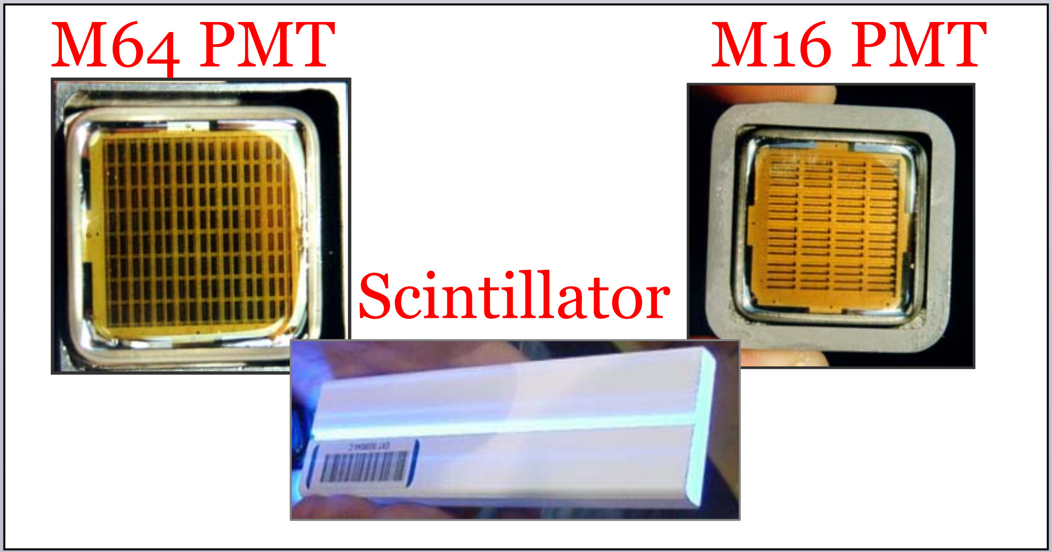
- **Majority of data in the LE-10 configuration**
- **Took ~1% of total exposure in ME and HE for commissioning and systematics studies**

Longer time scale—move horns to optimize event rate at different energies

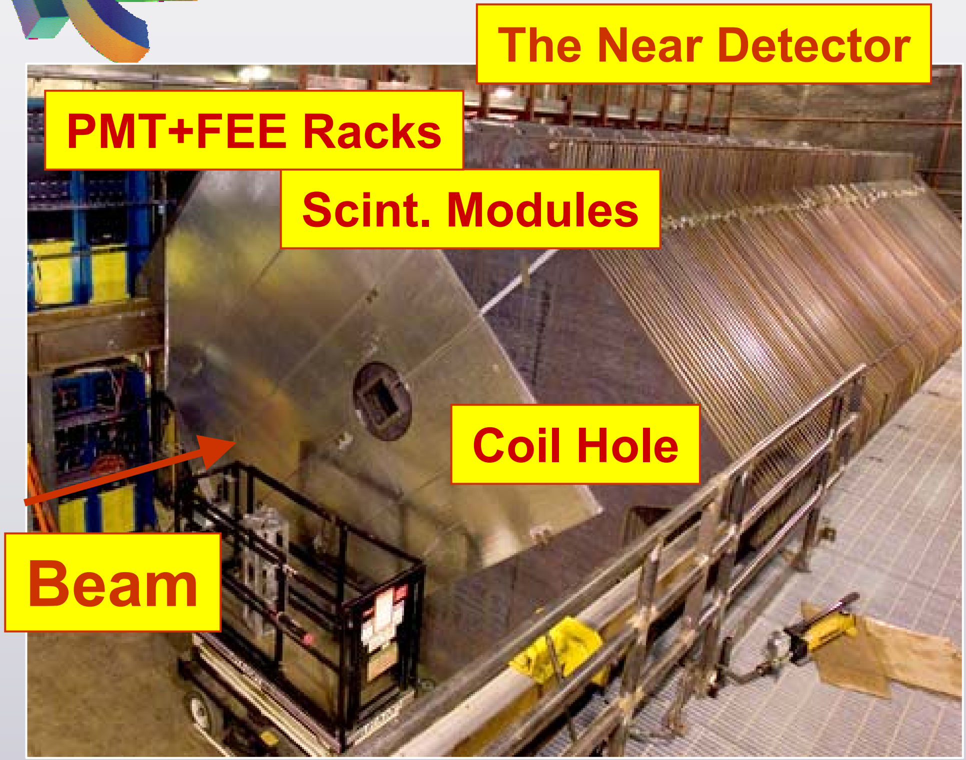
Detector Technology

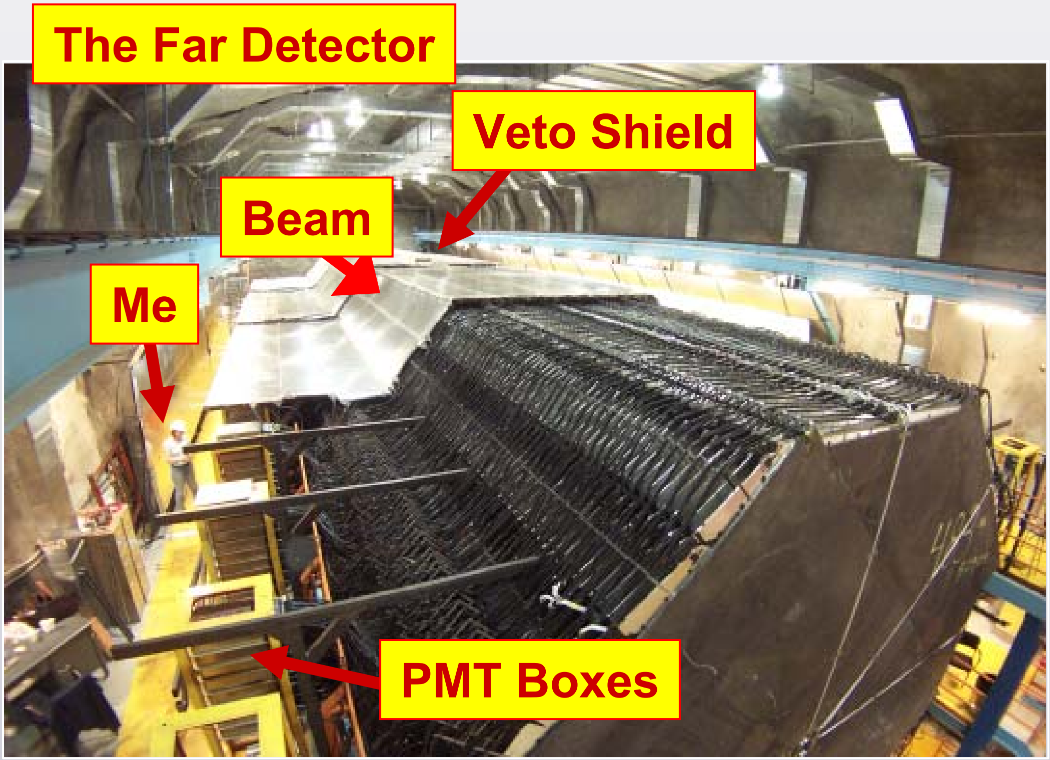


- Functionally equivalent detectors
- Tracking sampling Calorimeters
    - 2.54 cm thick Steel Absorber,
    - 1 cm thick active plastic scintillator
    - 5.94 cm longitudinal segmentation
    - 4.1 cm transverse segmentation
- Alternating planes rotated +/- 90 deg
- WLS collects/routes light to PMTs
- Magnetized detectors <B>=1.3 T



The Detectors





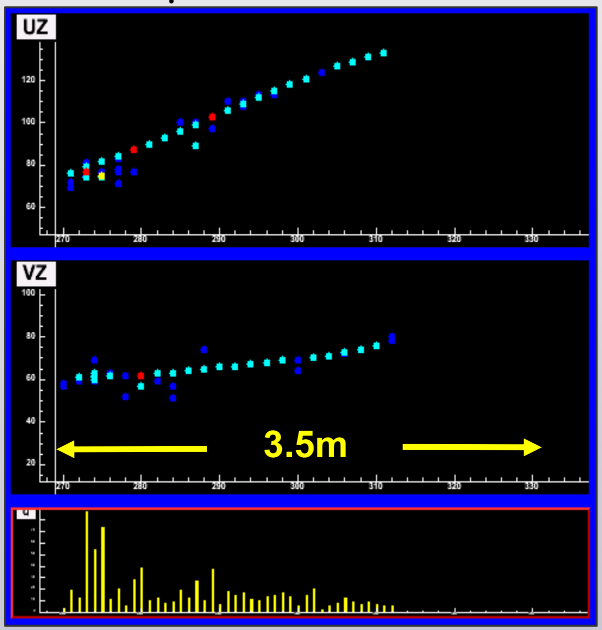
- Measures beam before oscillations
- 1 kton
- 1 km from target
- 103 m underground
- High rates—fast electronics

- Measures beam after oscillations
- 5.4 kton
- 735 km from target
- 705 m underground
- Low rate environment
- Taking data since 2001 (completed in 2003)

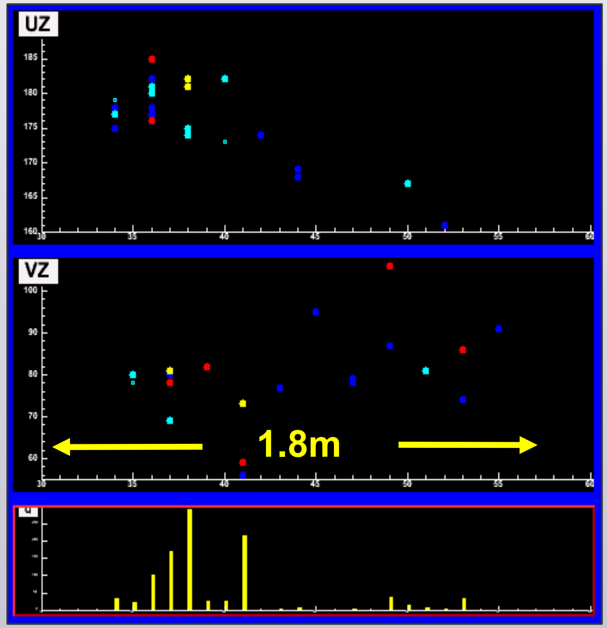
Event Topologies

Identify different neutrino interaction types by topology

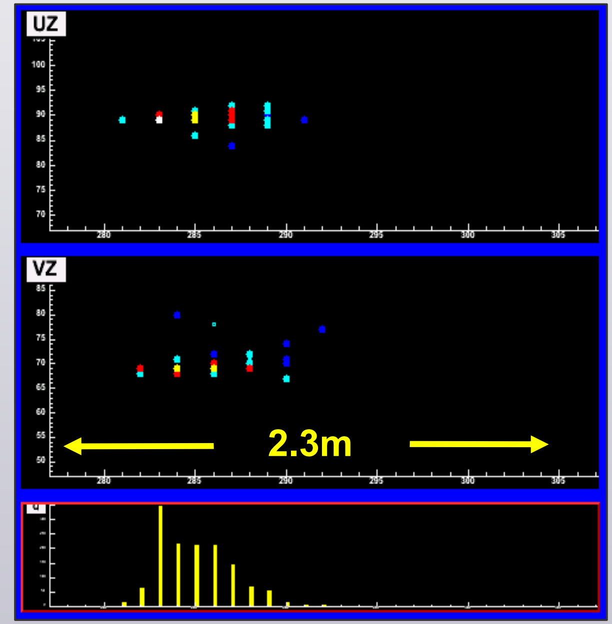
ν_μ CC event	NC event	ν_e CC event
ν_μ+N->μ+X	ν_μ+N->ν_μ+X	ν_e+N->e+X



- long μ track+ hadronic activity at vertex



- short event, often diffuse



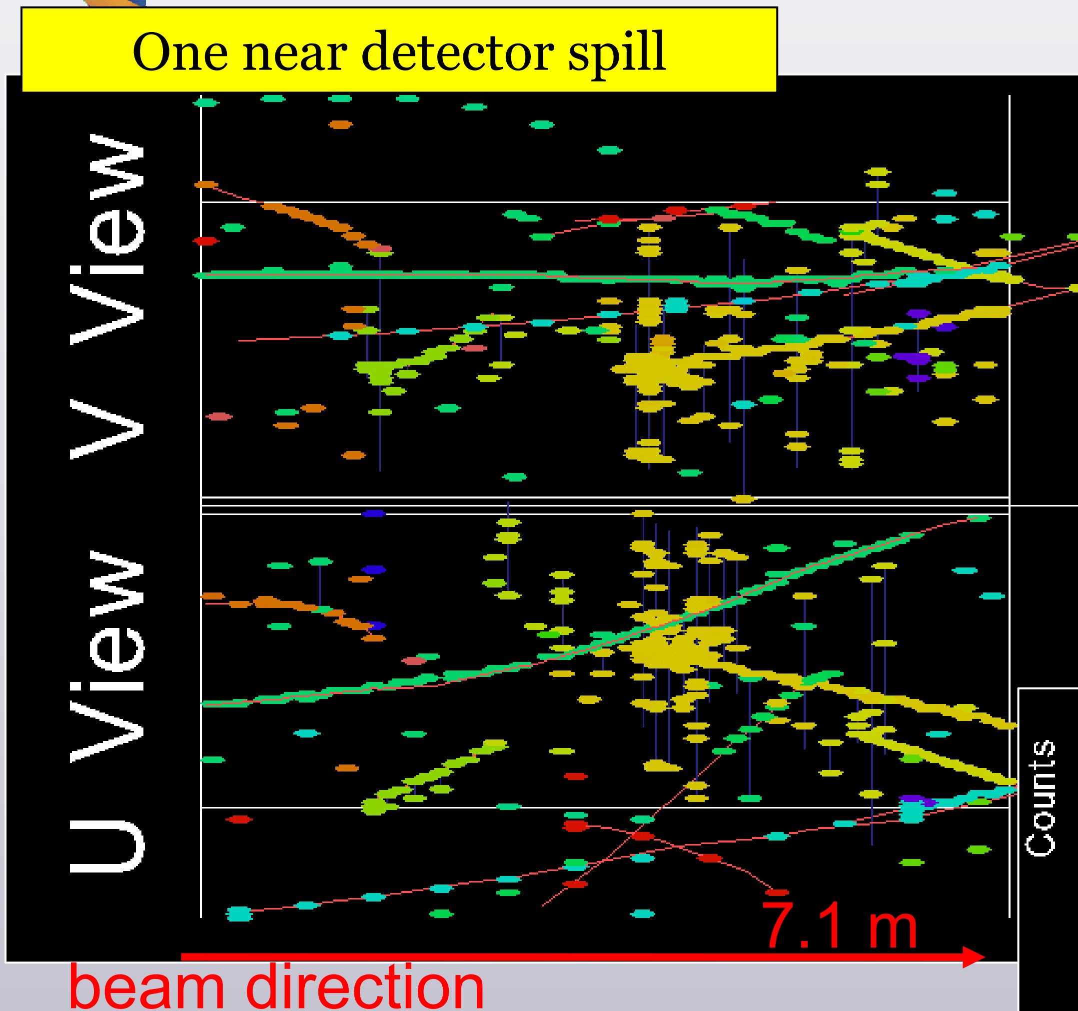
- short, with typical EM shower profile

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

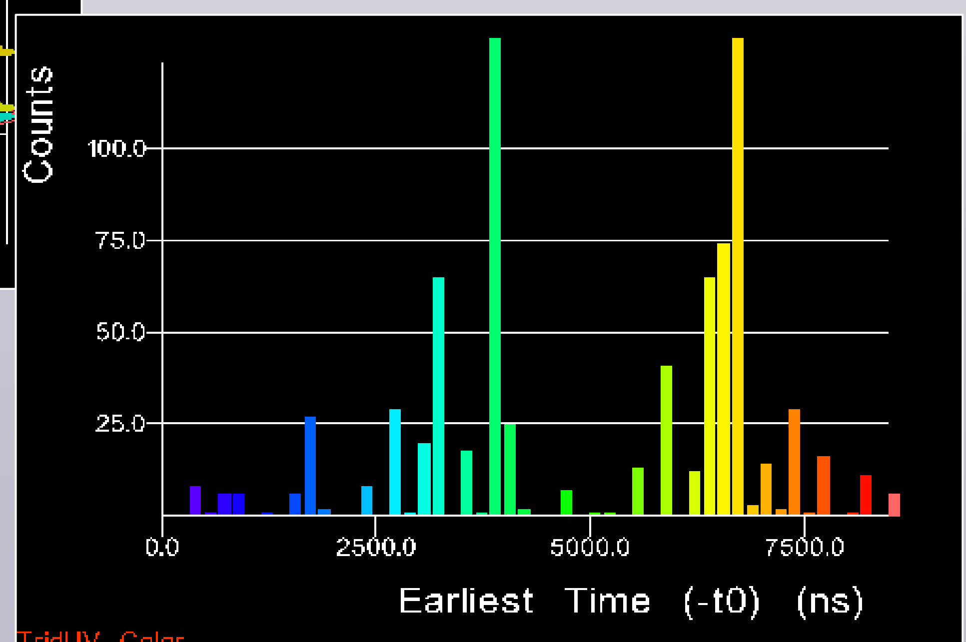
Muon Energy Resolution
6% range, 10% curvature

Shower Energy Resolution: 55%/√E

Near Detector Spill



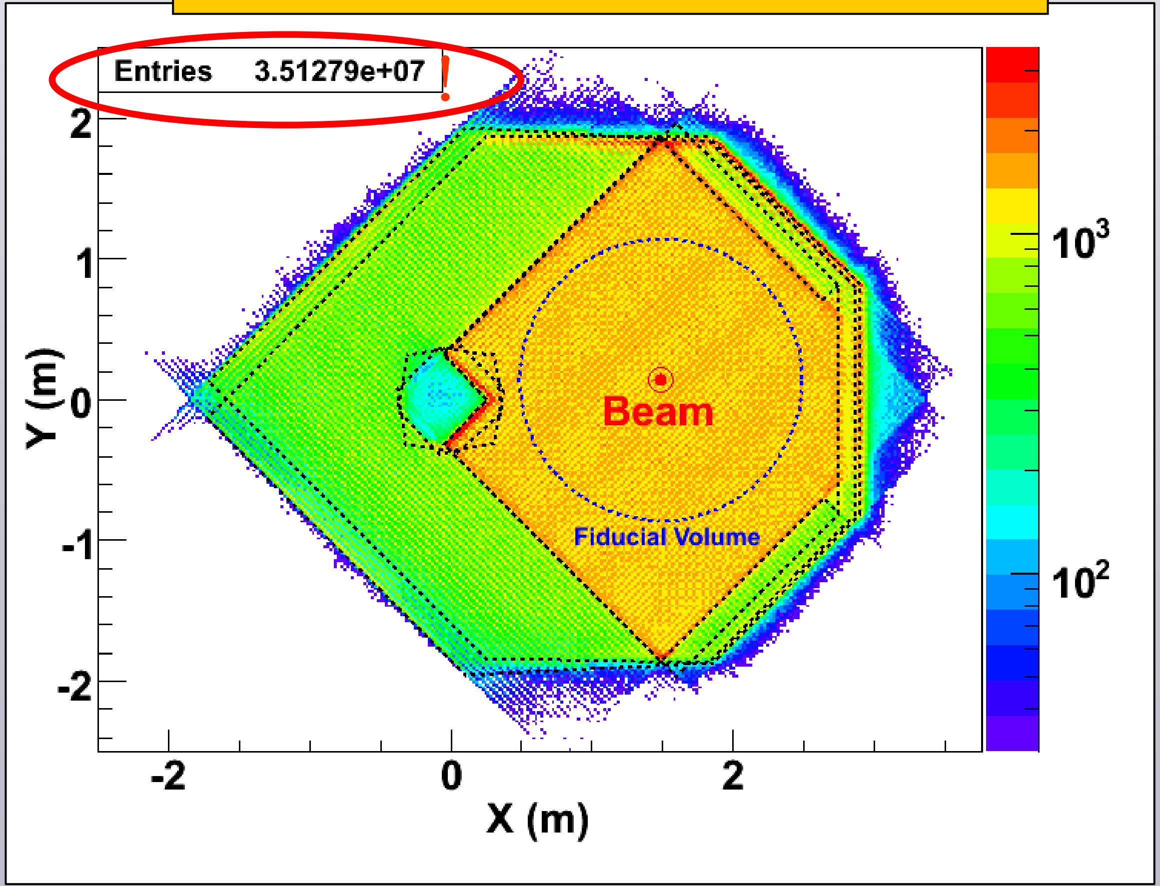
- **High rate in Near detector results in multiple neutrino interactions per MI spill**
- **Events are separated by topology and timing (19ns resolution)**



Near Detector rates

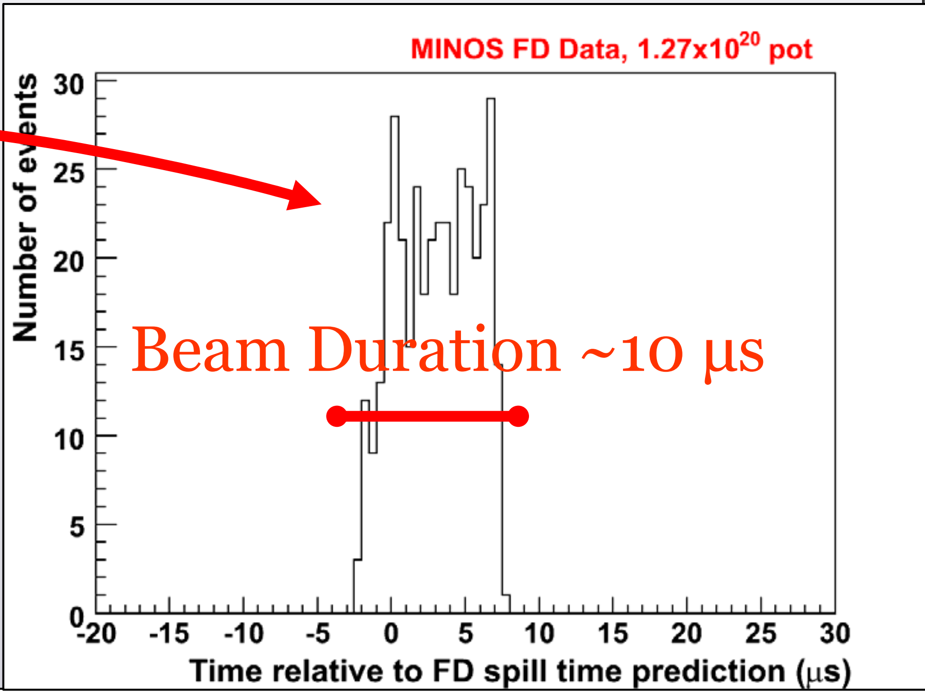
- **High event rates in the Near detector**
  - ~8 events / spill
  - ~35 million events
  (~2.5 million in fiducial volume for 1.27 x 10^{20} pot)
  - Image detector with Neutrinos!

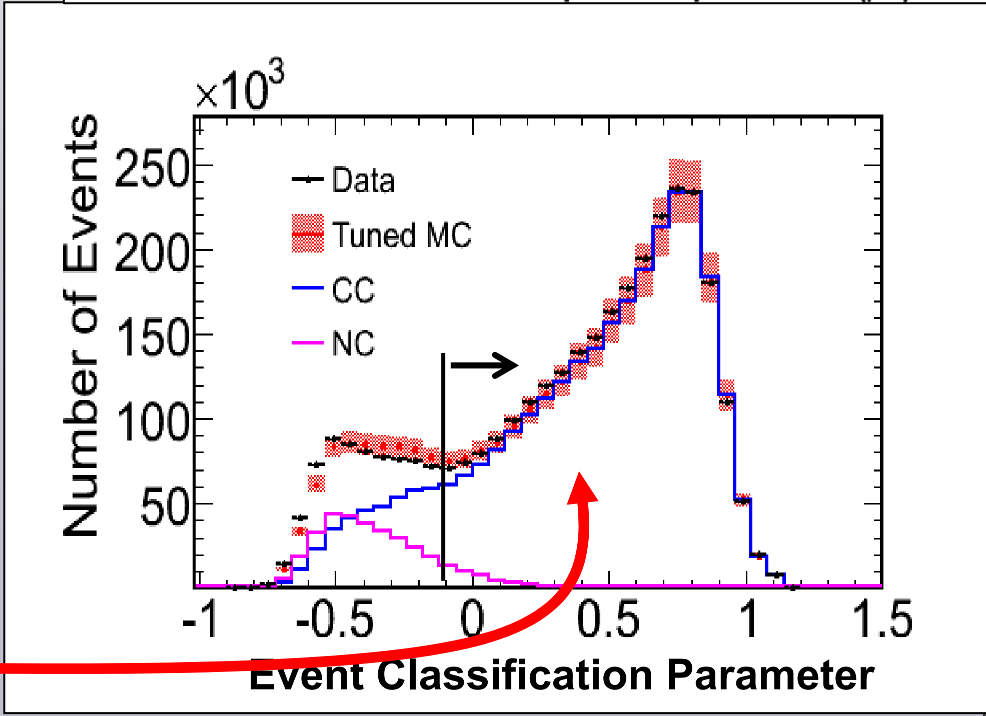
Reconstructed ν event vertices



ν_μ-CC event selection

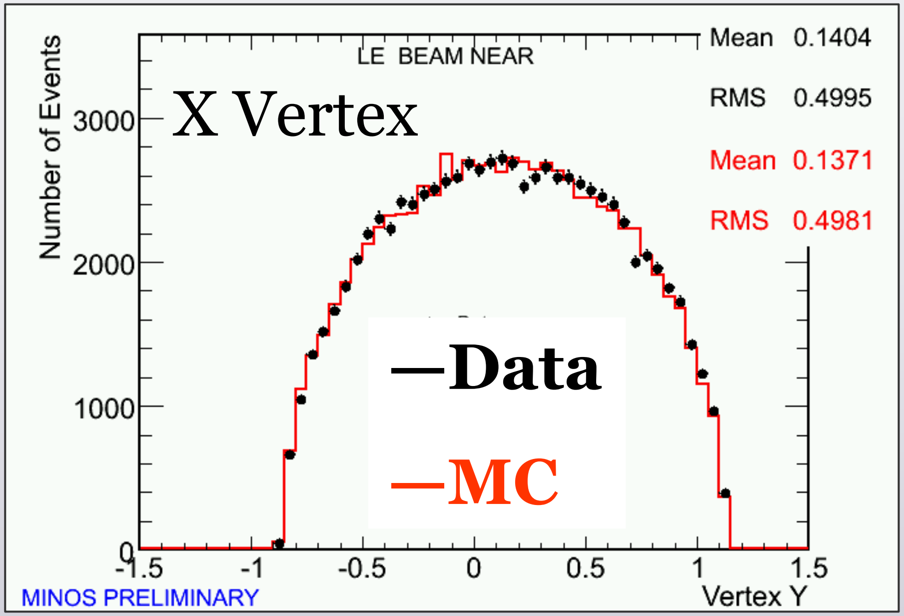
1. Select events in time with the beam
2. Event contains one track
3. Vertex within the fiducial volume:
   - NEAR: 4.5% of total volume
   - FAR: 72.9% of total volume
4. Fitted tracks with negative charge (selects ν_μ)
5. Additional cuts in FD to remove polluted events, steep cosmic tracks
6. Cut on likelihood-based Particle ID parameter based on low level shape variables to separate CC and NC events.

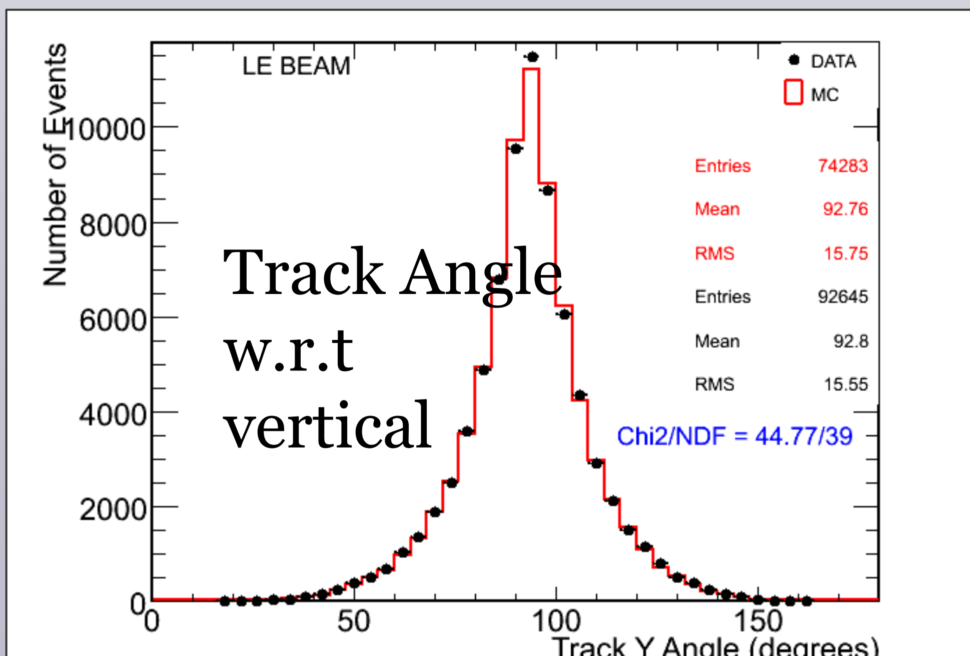




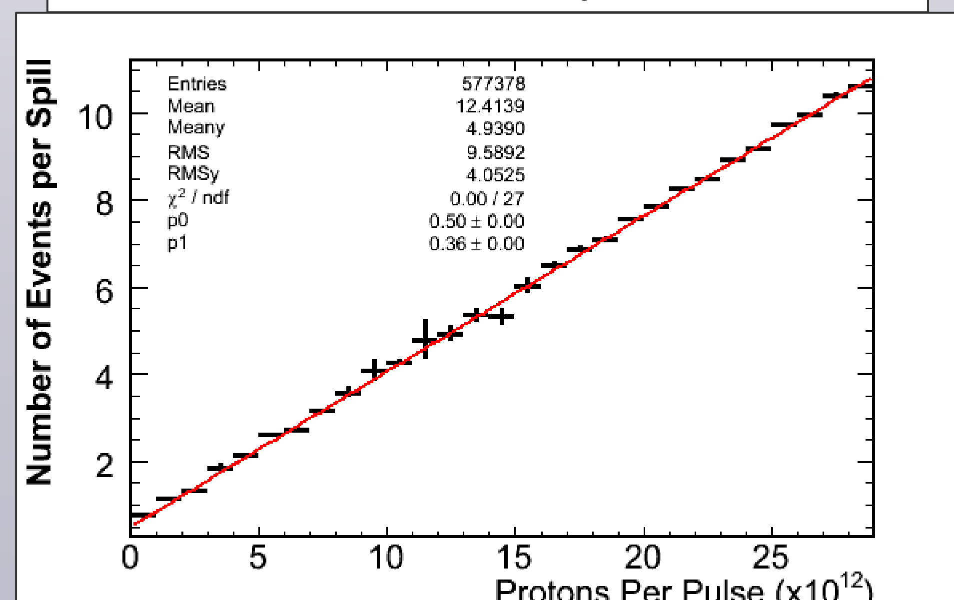
Near detector distributions

- Detector acceptance well modeled in MC
- Beam points down 3°—points to Soudan
- No intensity related biases

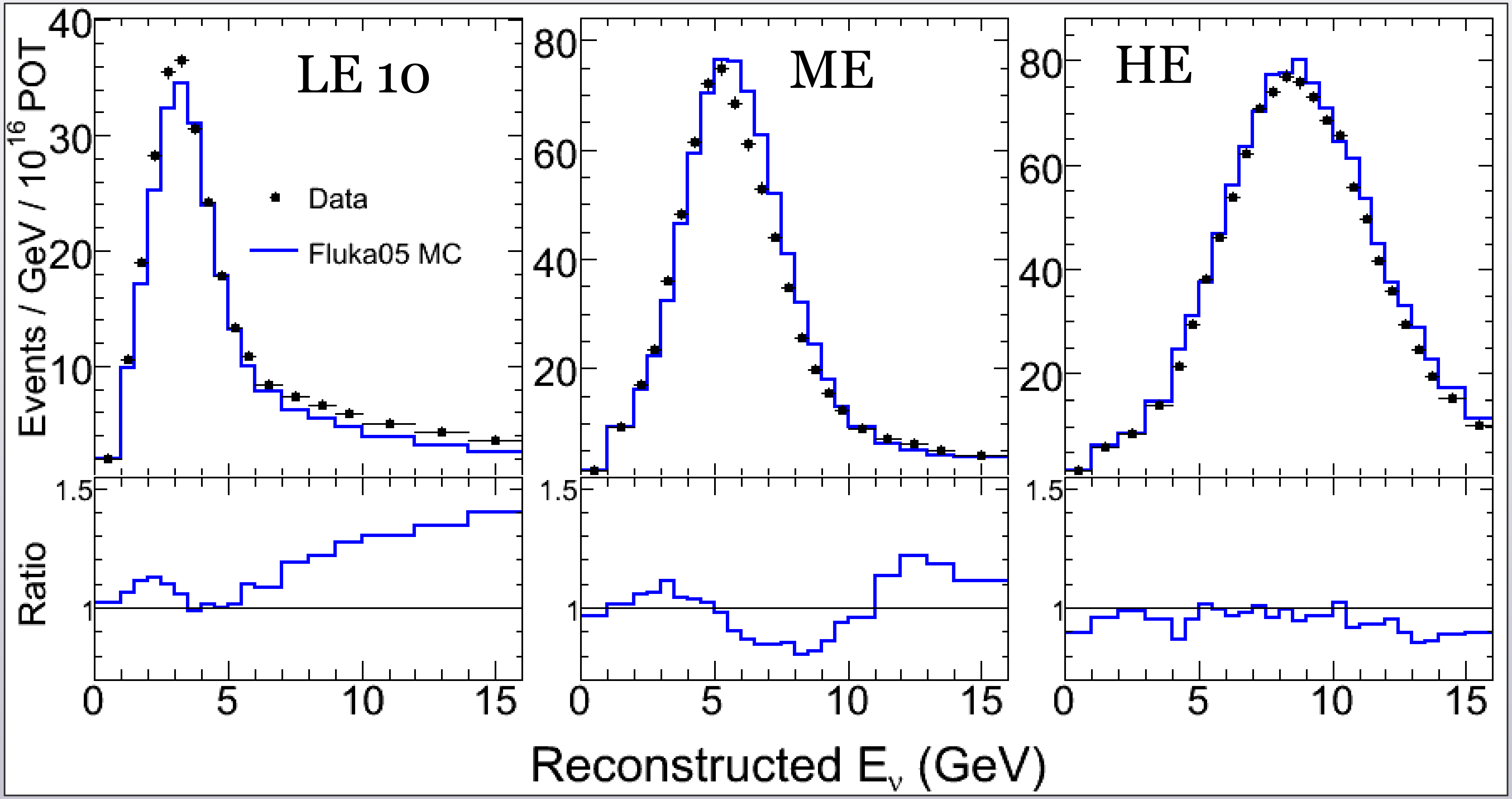




Reconstruction stability w.r.t intensity



Energy Spectra in ND



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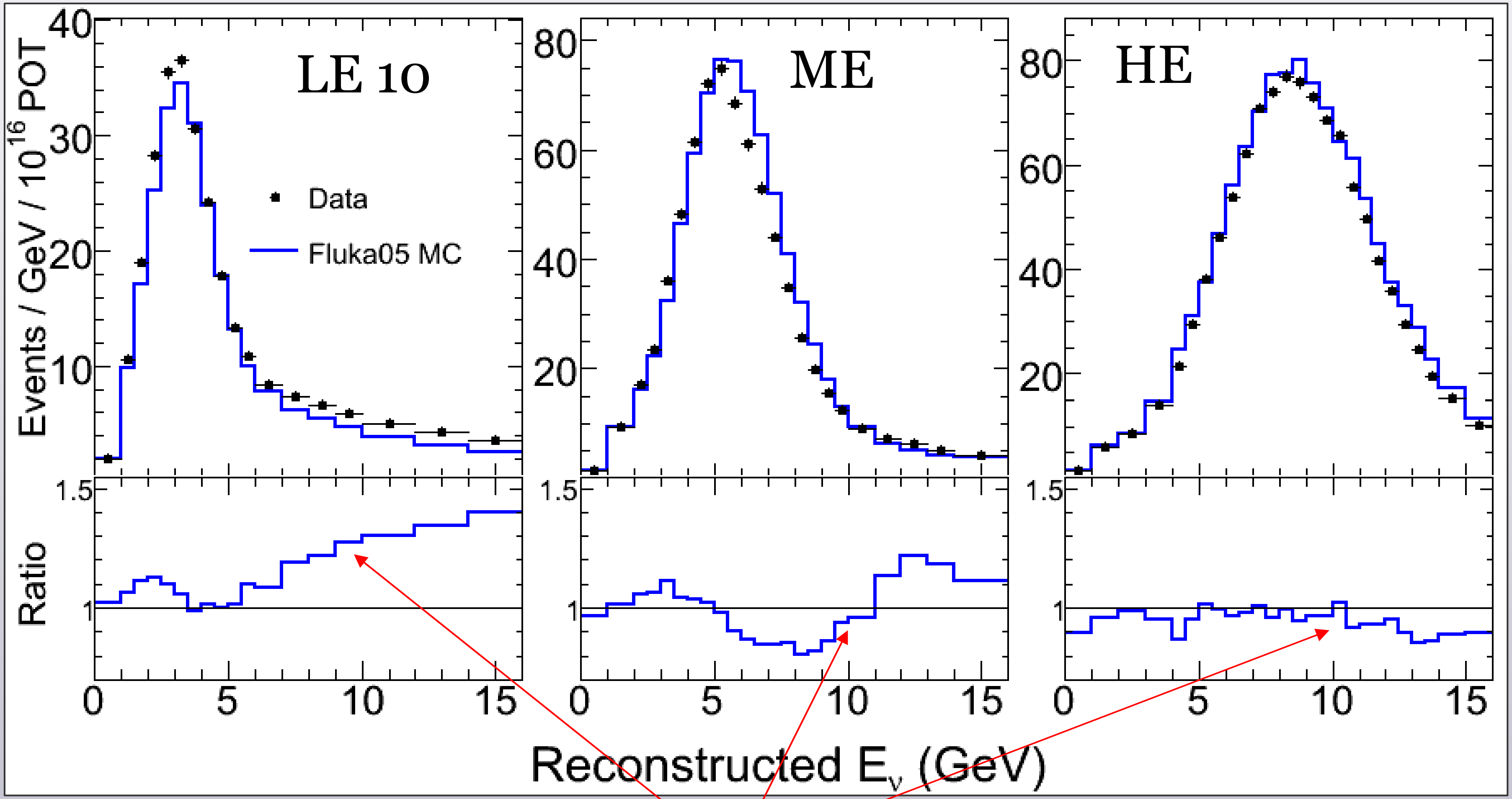
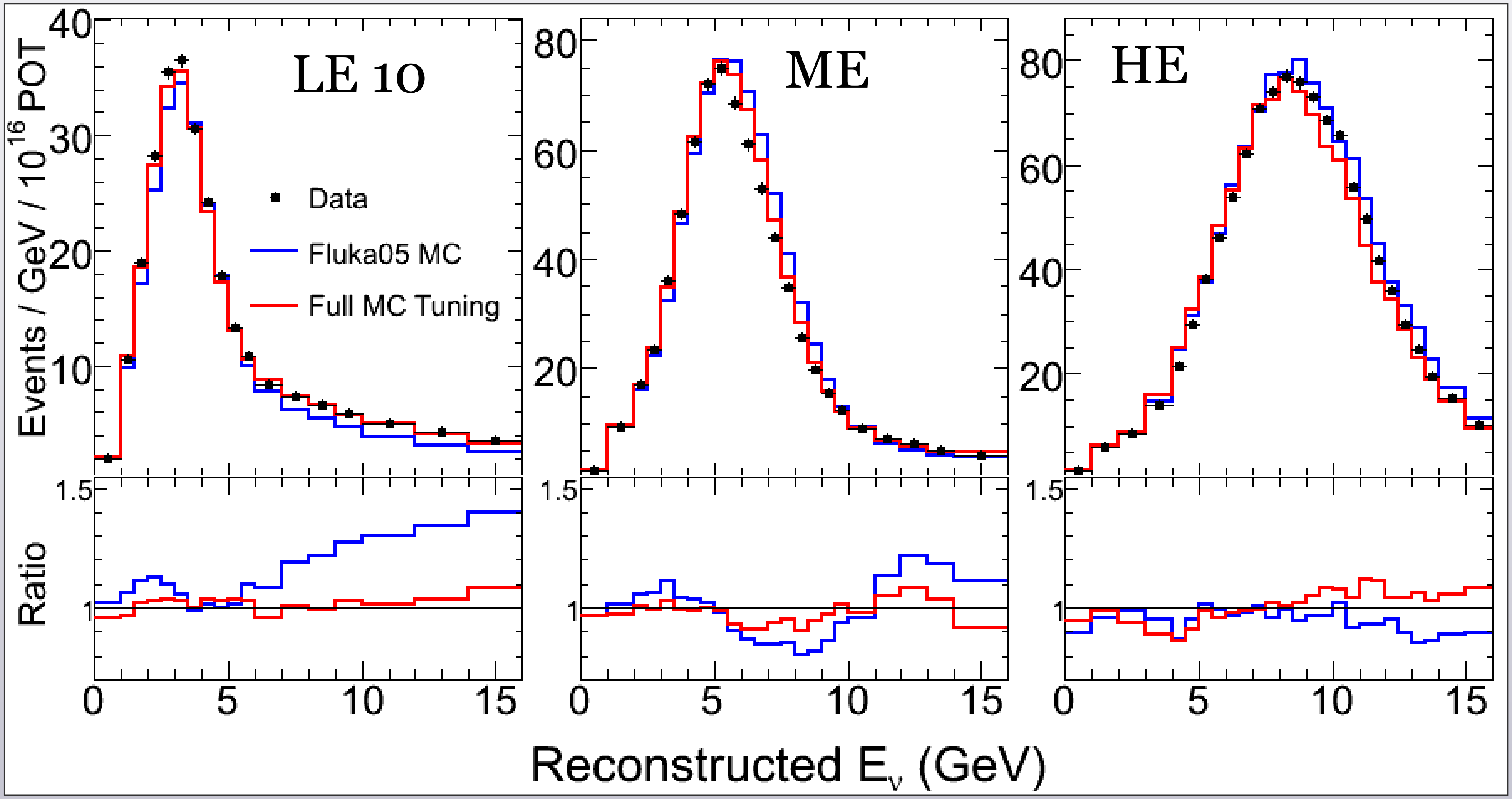


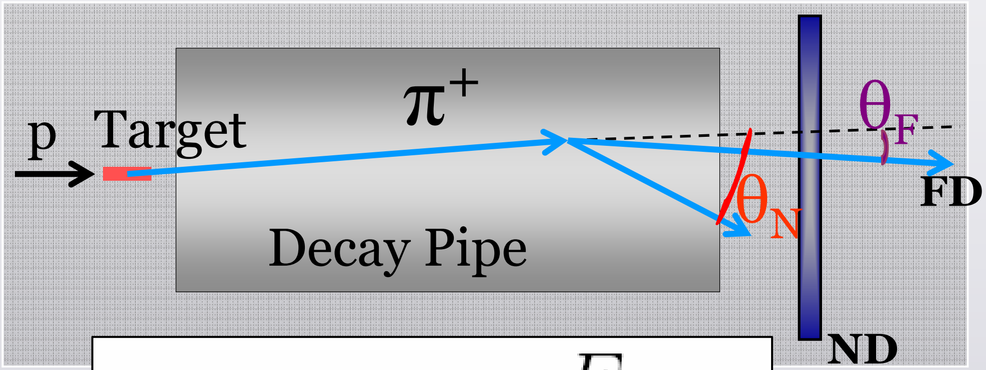
Discrepancy between Data/MC changes energy with different beam tunes suggests production of Hadrons off the target is to blame.

Energy Spectra in ND



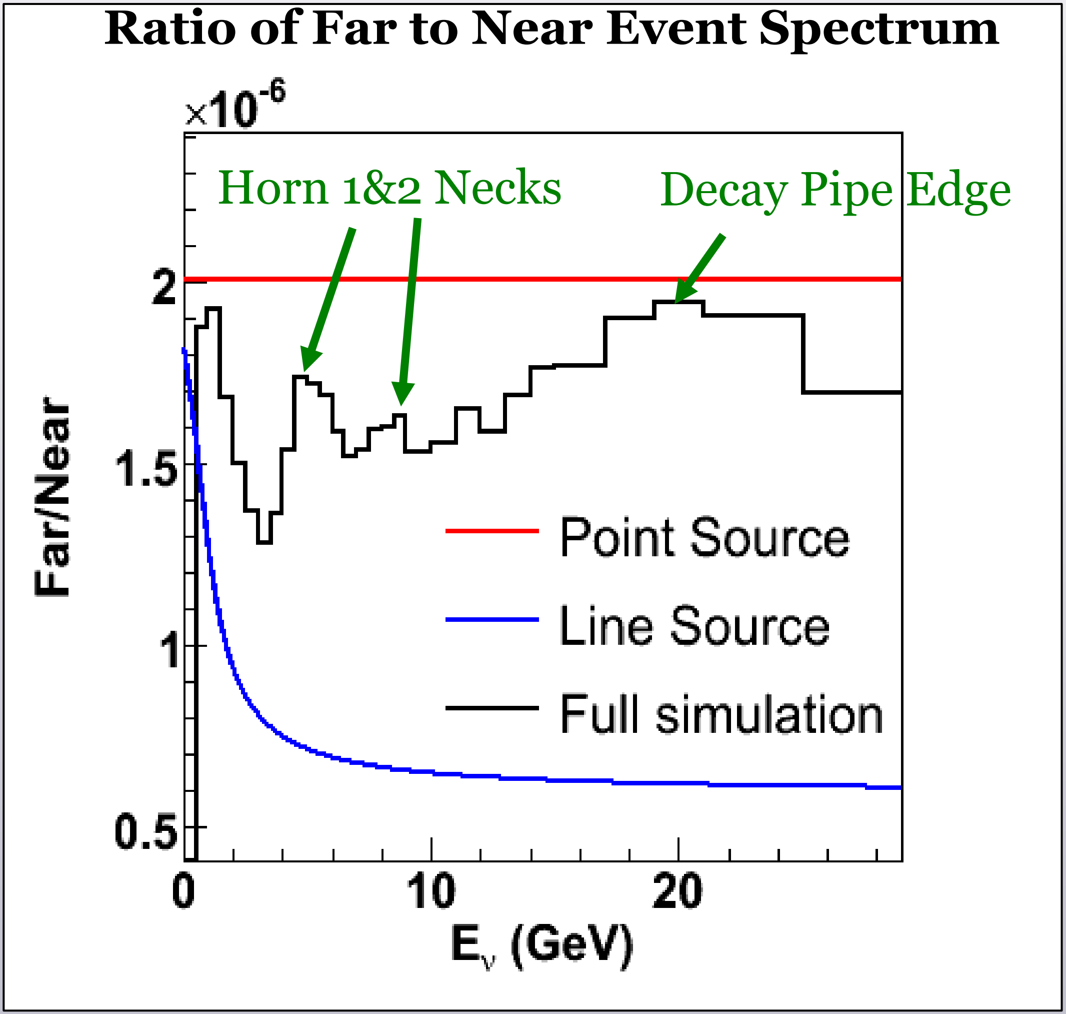
- Remaining data/MC discrepancies ~5-10% level in all 6 beam configurations
- Data/MC agreement builds confidence, but not strictly necessary in 2 detector experiment
- Use ND data to predict neutrino energy spectrum in FD in absences of oscillations

Prediction of FD spectrum



$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- Neutrino Energy depends on angle wrt original pion direction
- Angular distributions differ between Near and Far

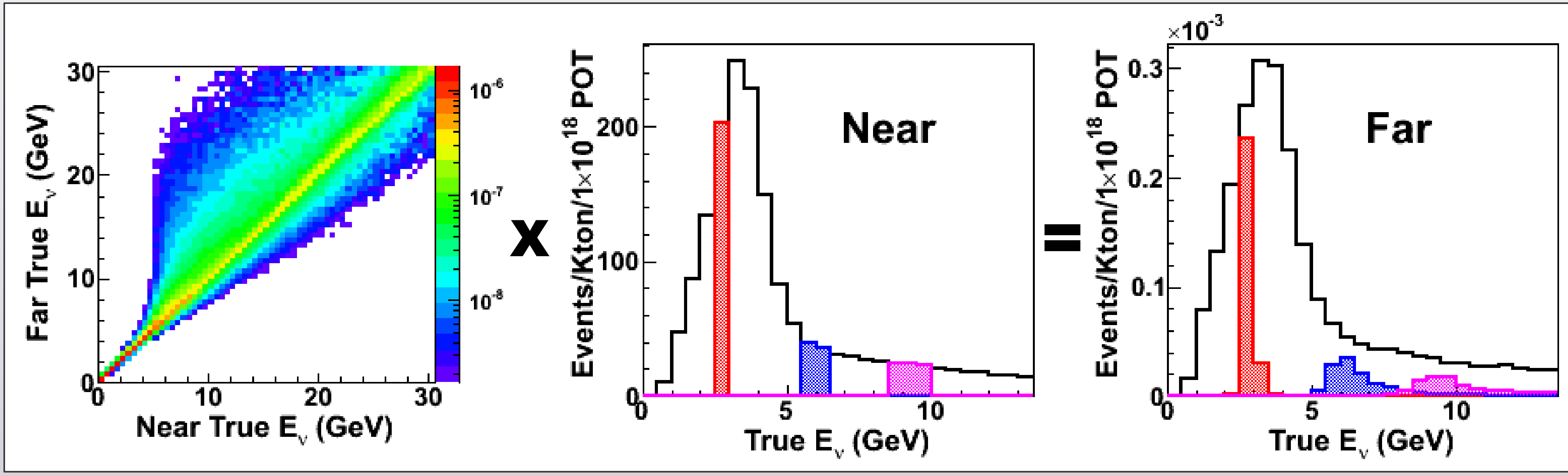


Far Spectrum without oscillations is similar, but not identical, to the Near spectrum!

Predicting the FD Spectrum

- **Several procedures for predicting the FD spectrum:**
  - "Far/Near" & "Beam Matrix"—directly extrapolate ND data spectrum using best knowledge of beam kinematics, use MC to correct for efficiency, purity, resolution.
  - "ND-Fit" & "2D-Grid"—Describe ND distributions by fitting physics quantities, predict FD spectrum from best fit (e.g., by reweighting MC)
- **All yield compatible results, at 1.27 x 10^{20} POT exposure, for all sources of systematic error we have studied**

Beam Matrix: Near→Far

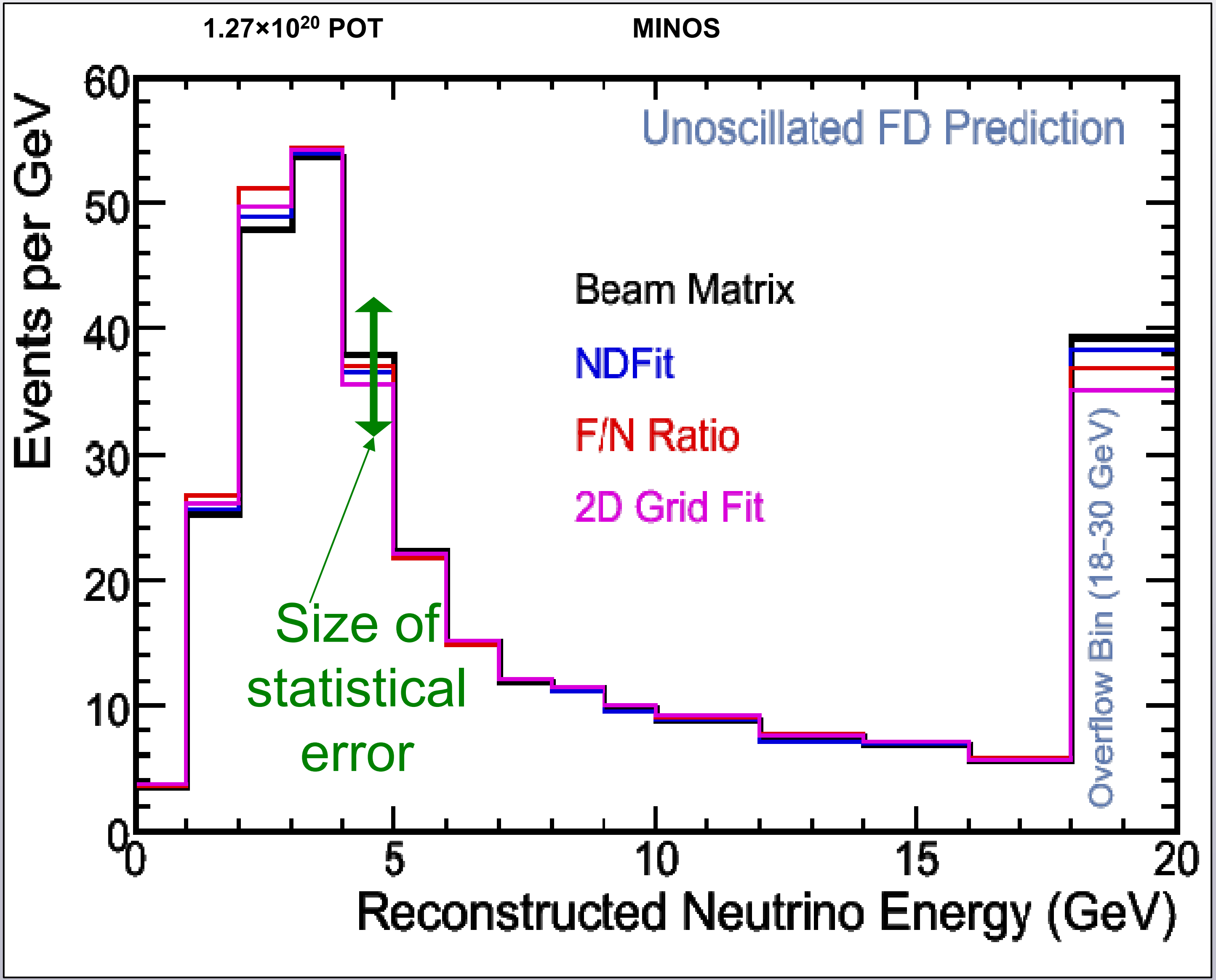


- Simplest method—use ratio of F/N from MC, multiply by Near Data
- Next level of sophistication—2-D Beam Matrix generated using beam MC, relates neutrino energy in Near to energy in Far

FD Prediction From All Methods

All methods agree to within ~ 5% bin-by-bin

Once we measure the ND spectrum, we know the FD unoscillated spectrum.



Observed Number of Events

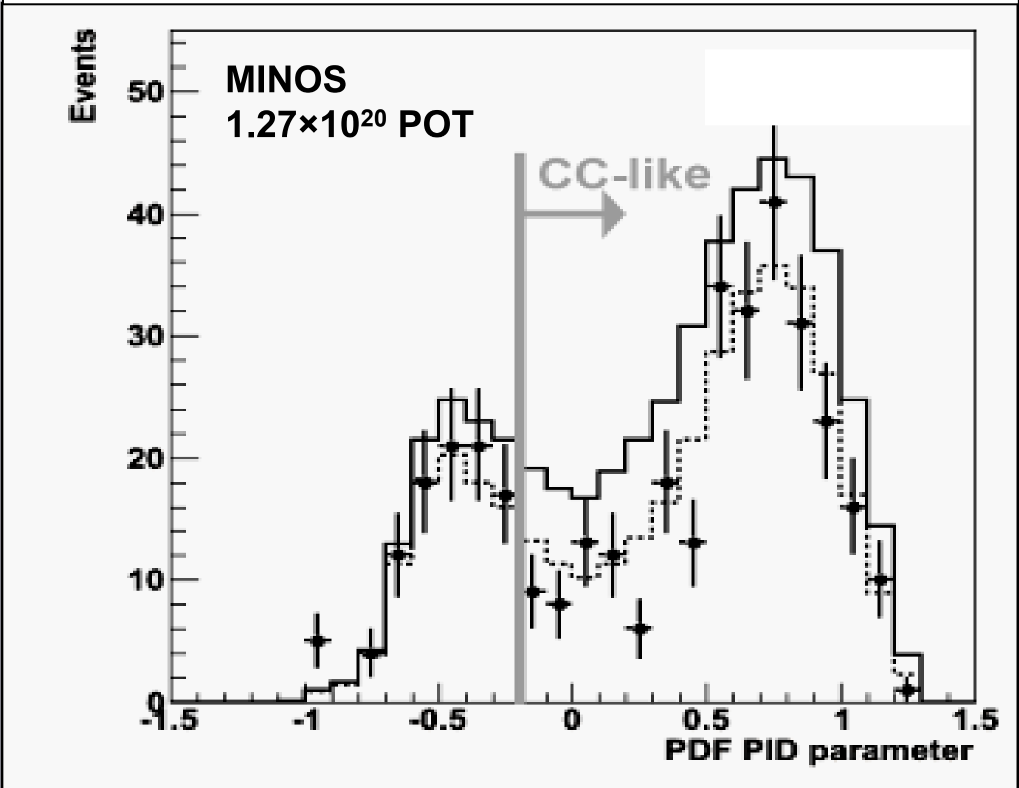
Data Sample	FD Data	Expected (Matrix Method; Unoscillated)	Data/MC (Matrix Method)
ν_μ (<30 GeV)	215	336.0±14.4	0.64±0.05
ν_μ (<10 GeV)	122	238.7±10.7	0.51±0.05
ν_μ (<5 GeV)	76	168.4±8.8	0.45±0.06

- An energy dependent deficit
- Below 10 GeV a 49% deficit is observed
- Significance is 6.2σ (stat+syst)

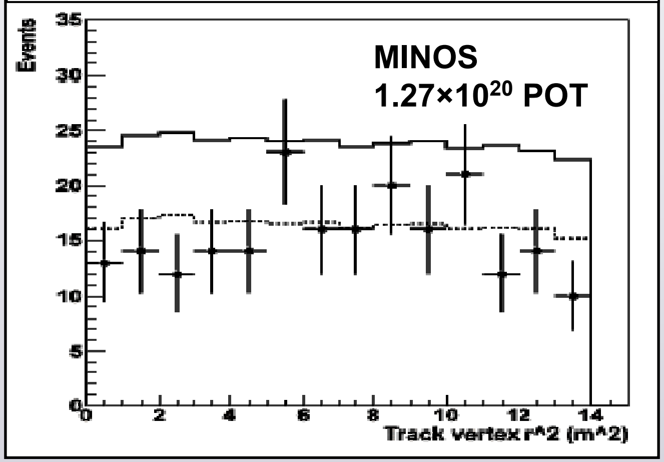
Far Detector Distributions

- Predicted no oscillations (solid)
- Best fit (dashed)
- Clear deficit of CC like events

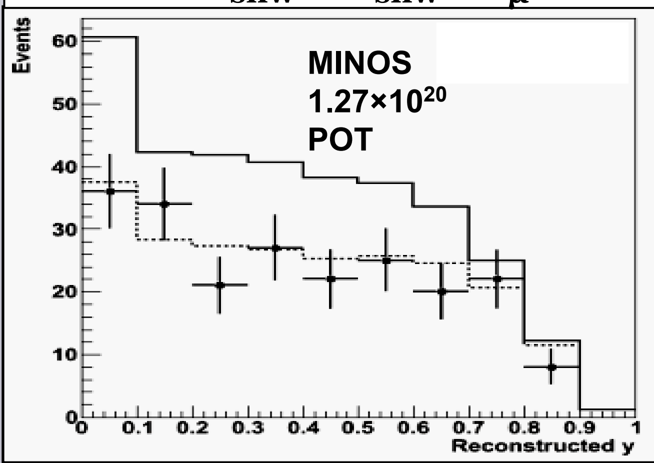
Event Classification Parameter



Track Vertex r² (m²)



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

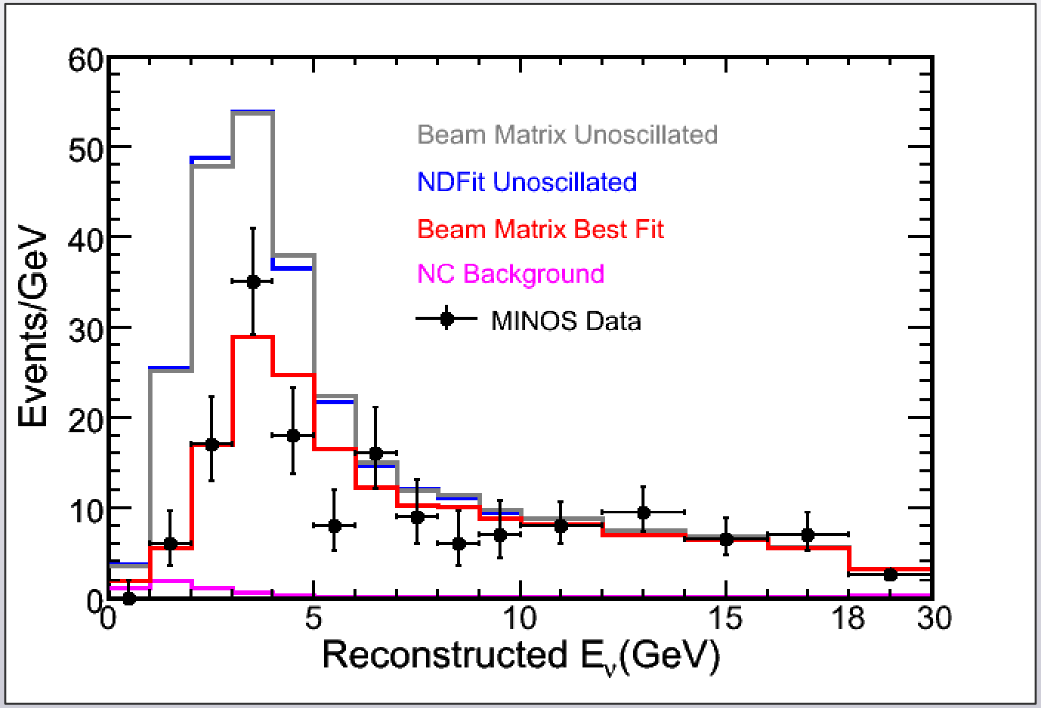


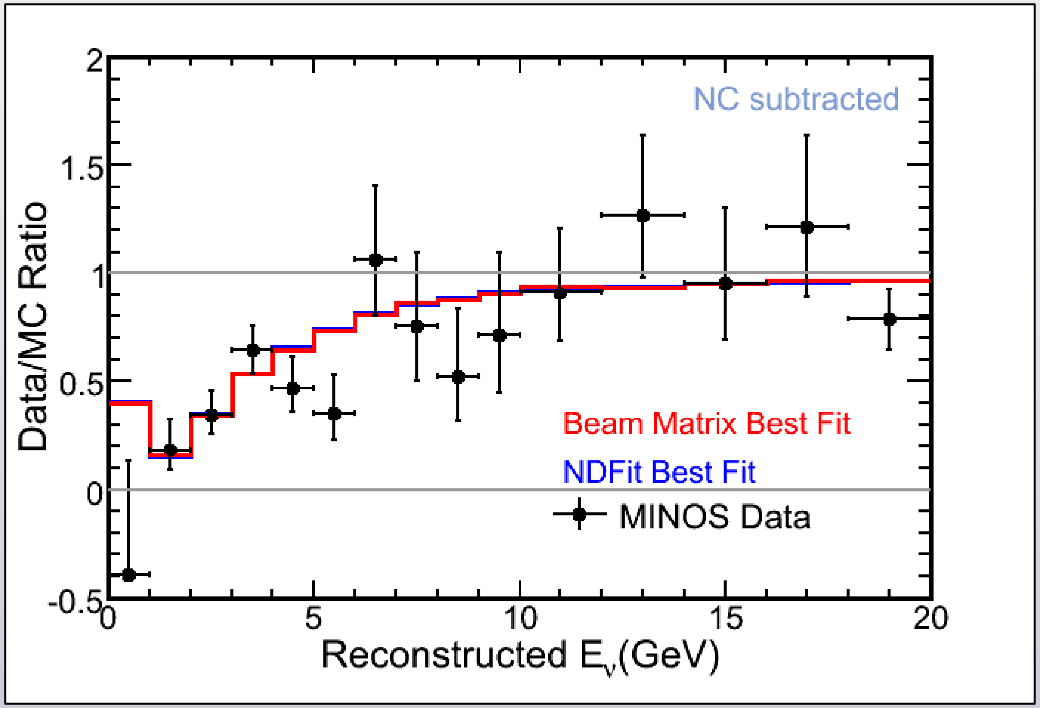
Systematic Errors

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

- Systematic shifts in the fitted parameters are computed using MC "fake data" samples
- Magnitude of systematic error is ~40% of statistical error for Δm^2
- Several systematic uncertainties are data driven, expected to improve with more data and study
- Three largest included in fit as nuisance parameters

Fit to Oscillation Hypothesis





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

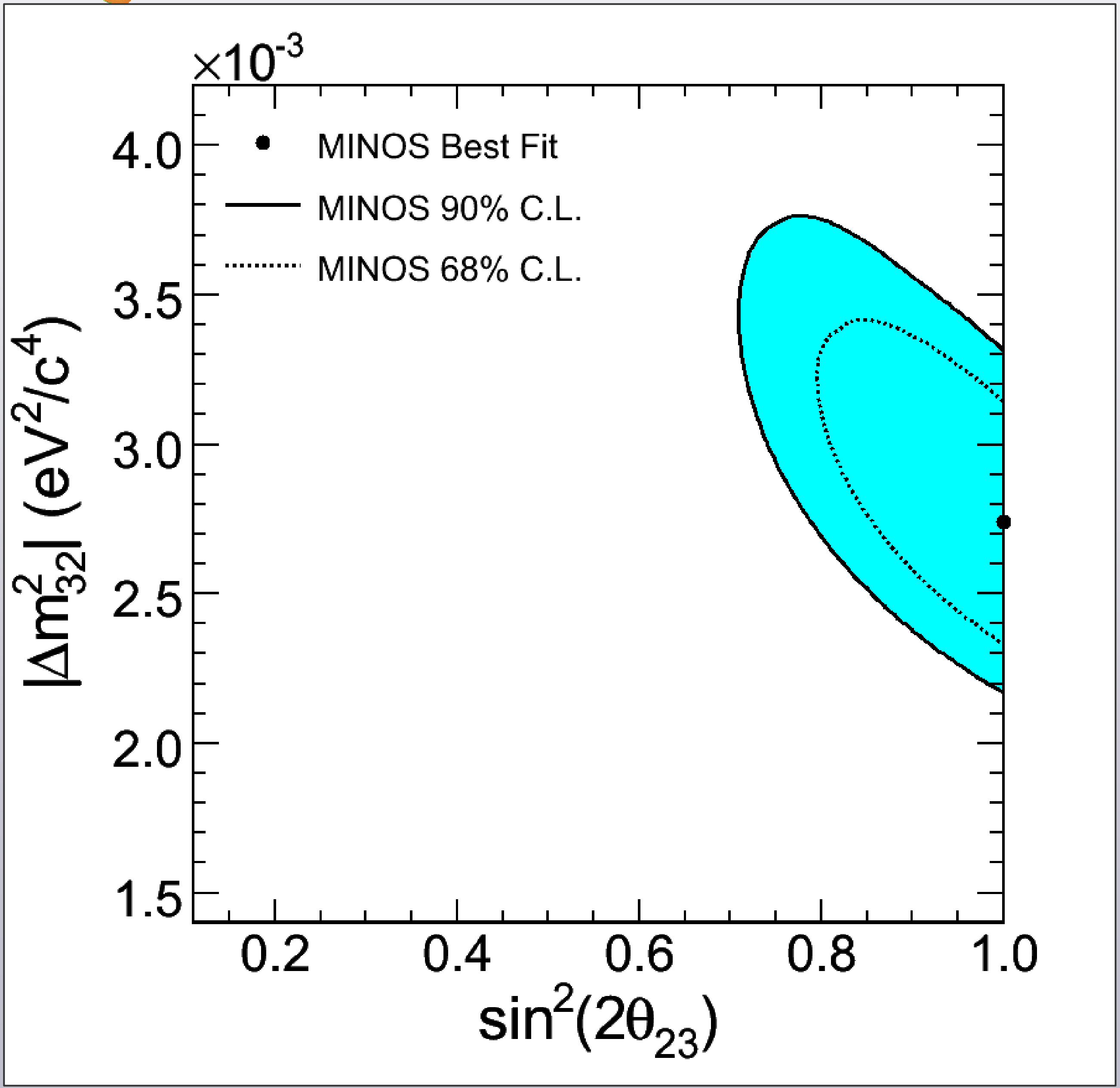
$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\mathrm{stat}+\mathrm{syst})$$

$$\mathrm{Normalization} = 0.98$$

Measurement errors are 1σ, 1 DOF
Fit constrained to $\sin^2(2\theta)\leq 1$

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

Allowed Region

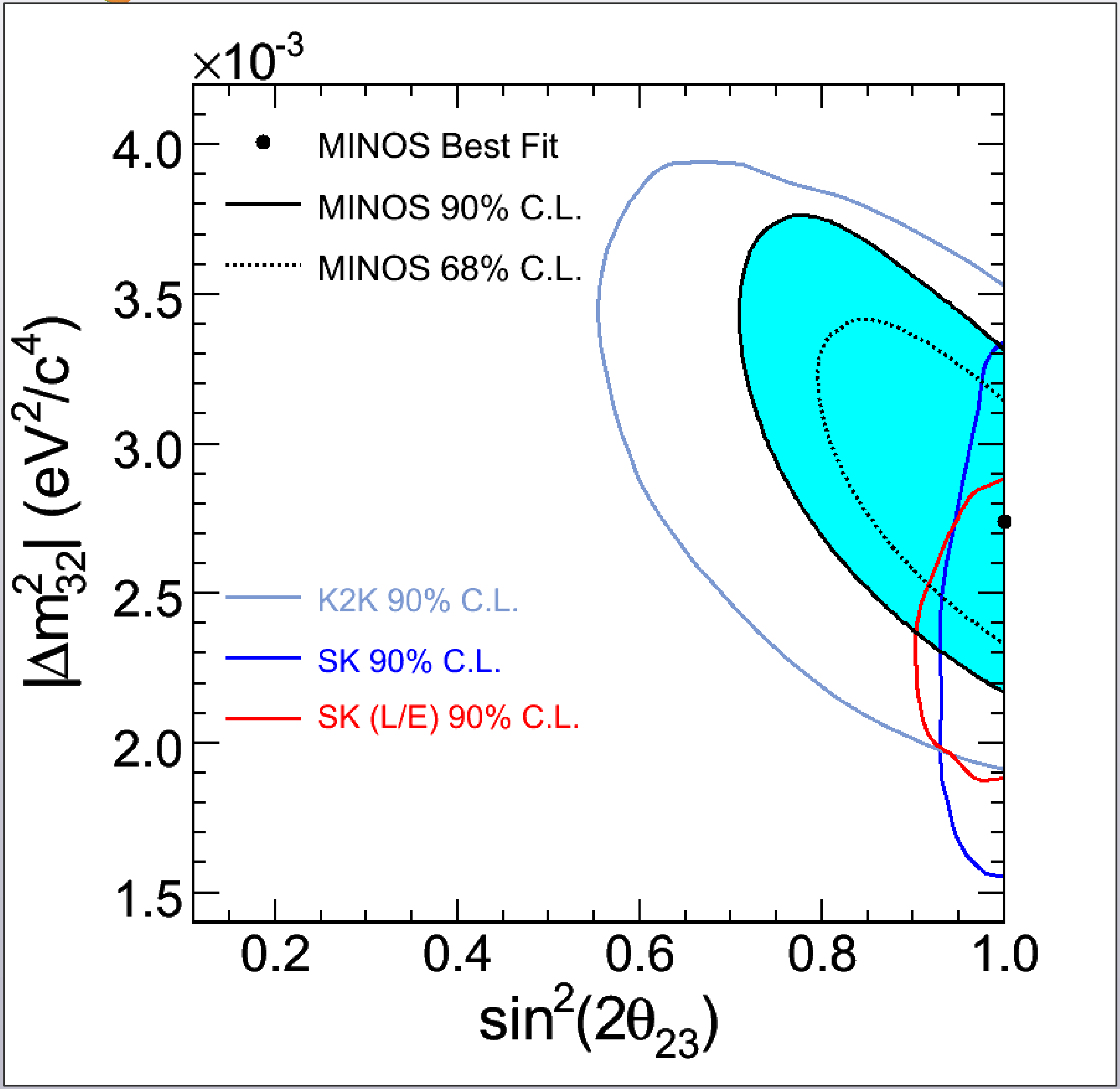


- Fit includes penalty terms for three main systematic uncertainties
- Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$

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

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

Allowed Region



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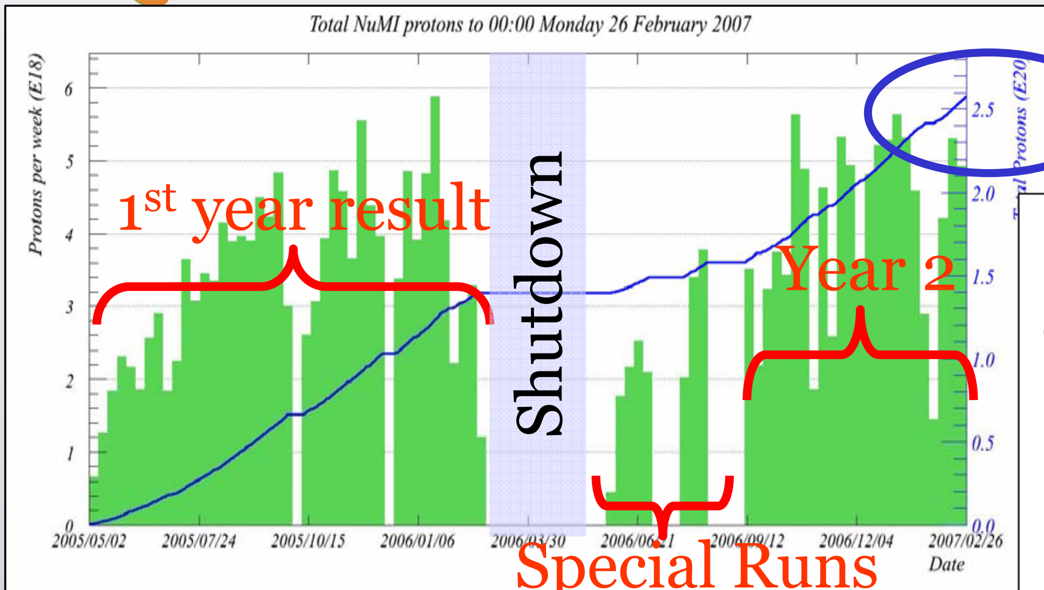
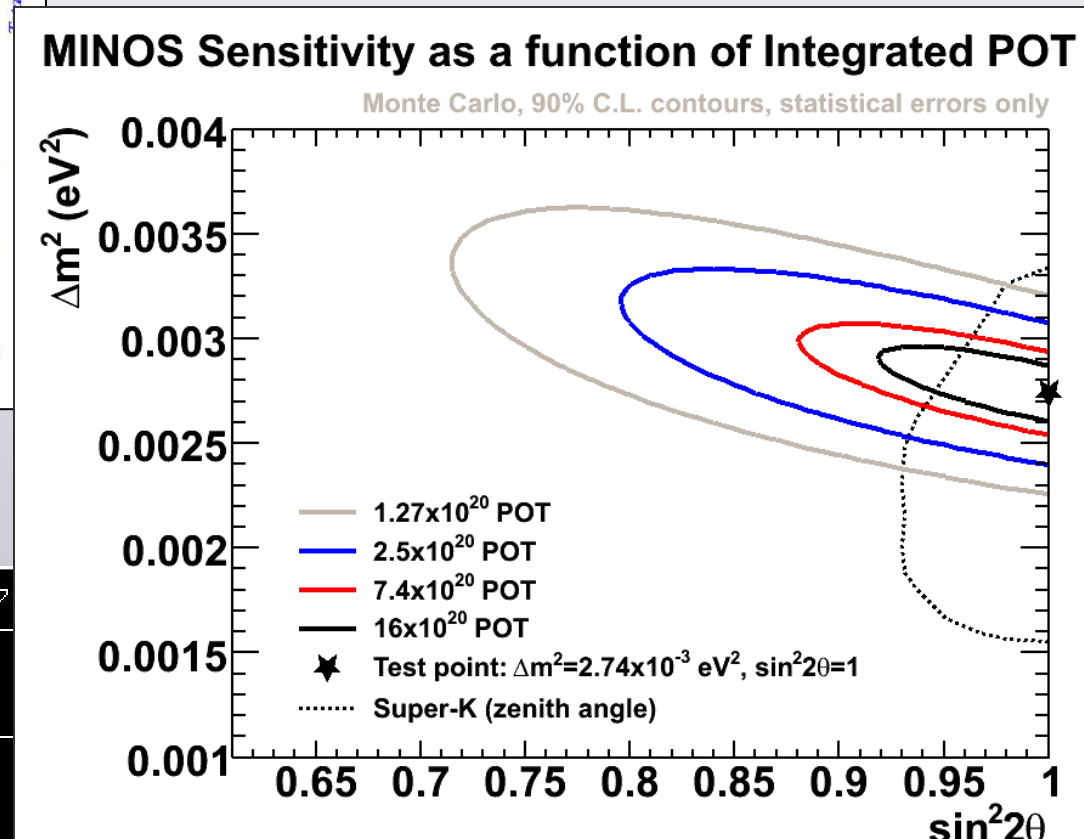
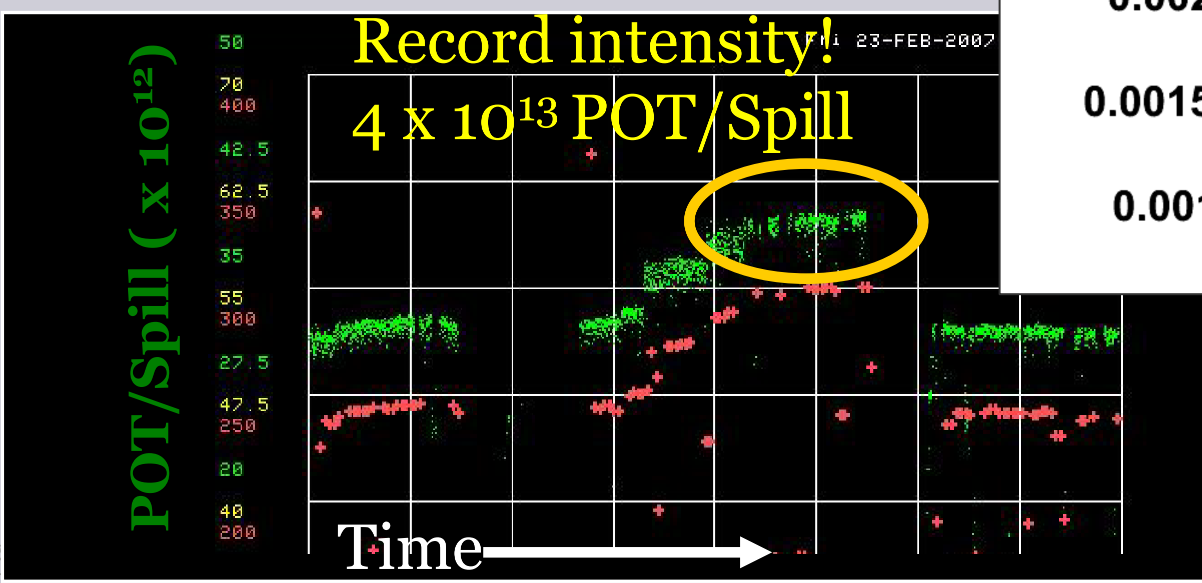
Projected Sensitivity



> 2.5 x 10^{20} total POT

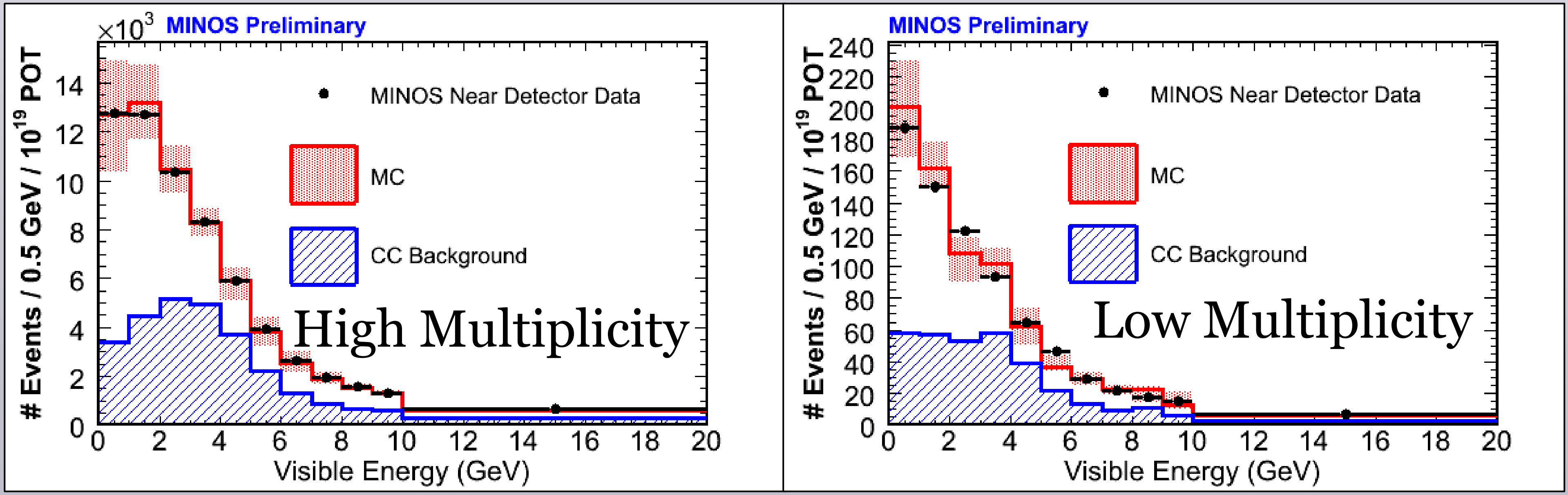




Future Prospects

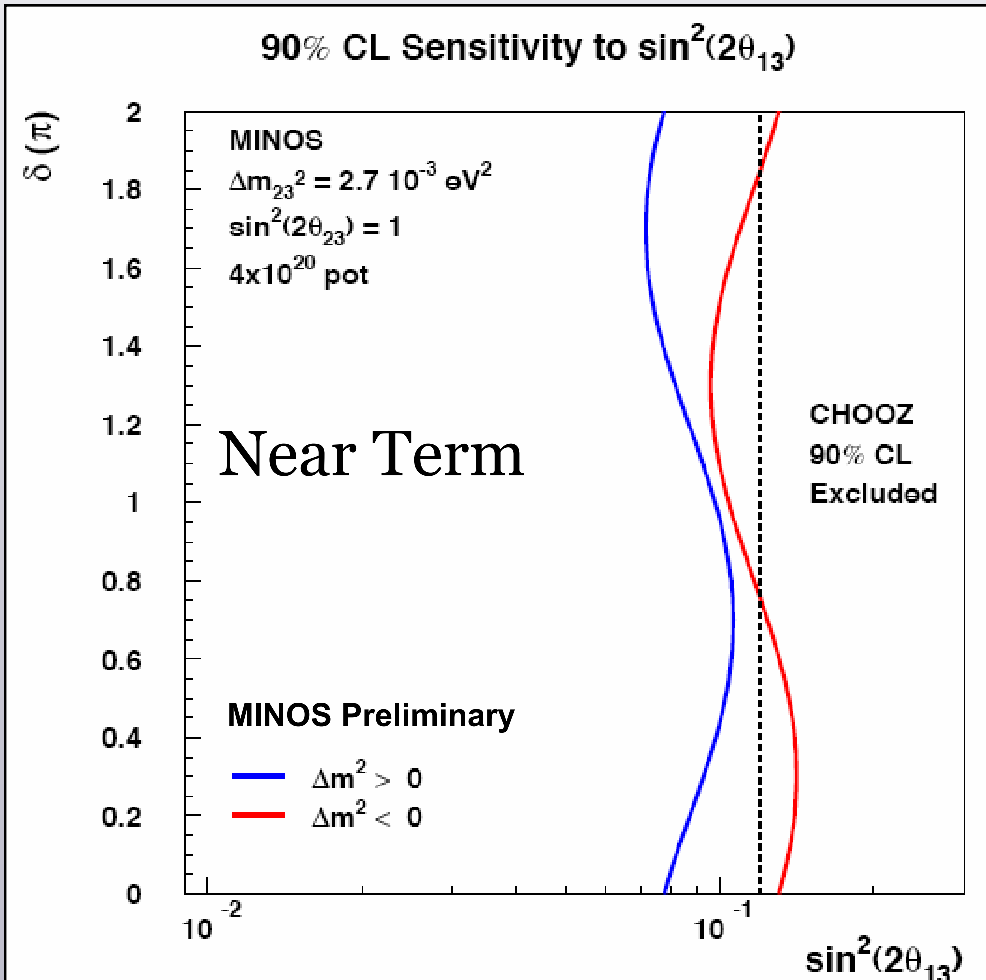
- **Compare Near/Far Neutral Current energy spectrum. Sensitive to $\nu_\mu \rightarrow \nu_{sterile}$, ν decay**
- **First step, understand the NC spectrum in the Near**
  - NC events prone to intensity related reco issues
  - Study spills with a lot of events, and spills with fewer events

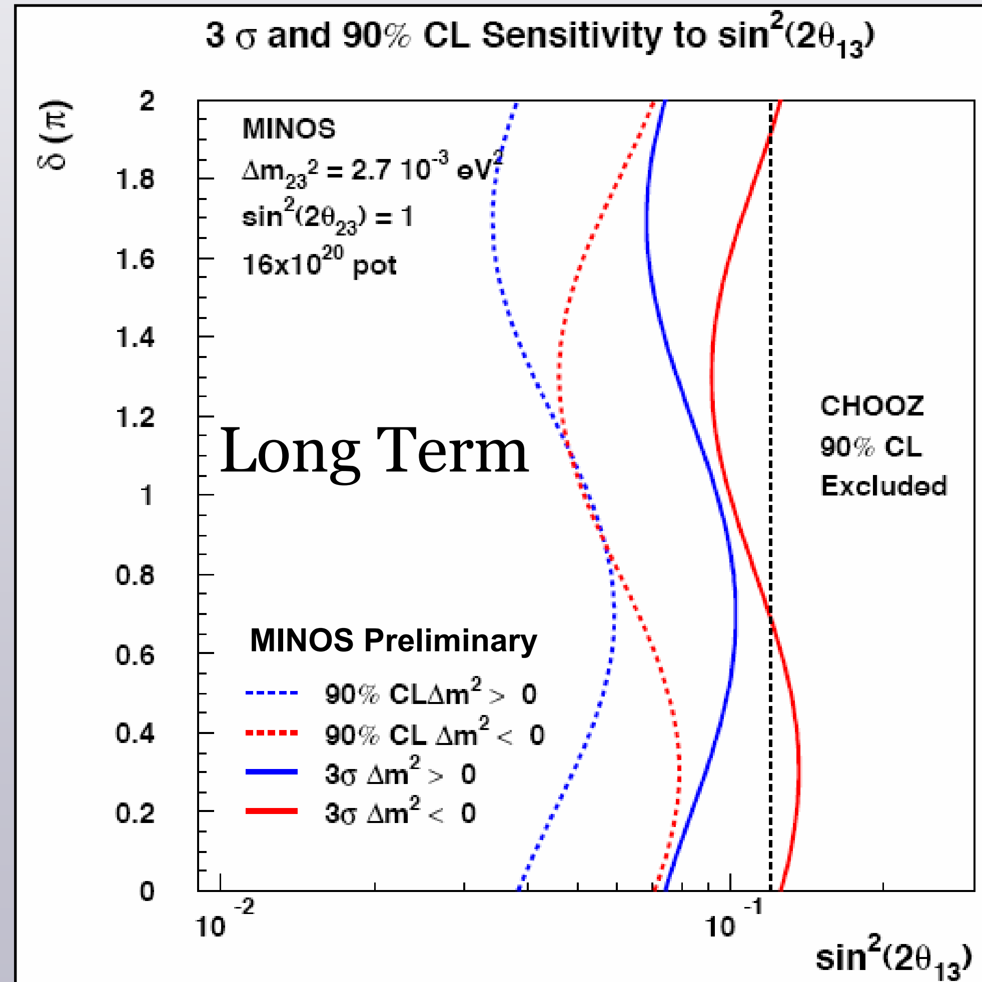
First result on track for Fall!



Future Prospects

MINOS will also look for $\nu_\mu \rightarrow \nu_e$ oscillations





Summary

- **MINOS has completed an analysis of the first year of NuMI beam data**
  - Exposure used in analysis: 1.27 x10^{20} POT
  - Exclude no oscillations at 6.2σ (based only on event rate)
  - Results are consistent with the oscillation hypothesis with parameters:

$$\boxed{\begin{array}{l}\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26} \times 10^{-3}\,\mathrm{eV}^2 \\ \sin^2 2\theta_{23} = 1.00_{-0.13}\end{array}}$$

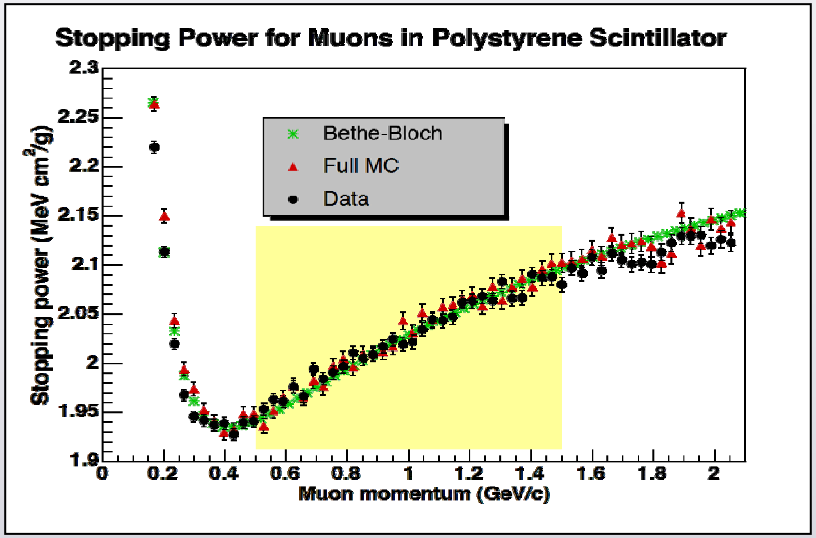
  - Constraining the fit to $\sin^2(2\theta_{23}) = 1$ yields:

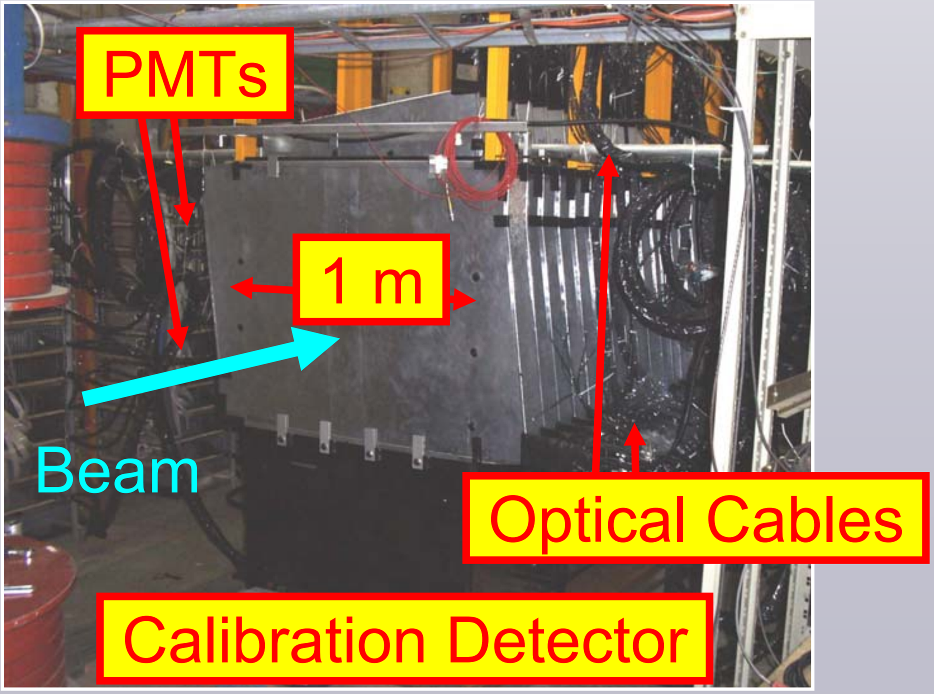
$$\boxed{\left|\Delta m^2_{32}\right| = 2.74 \pm 0.28 \times 10^{-3}\,\mathrm{eV}^2}$$

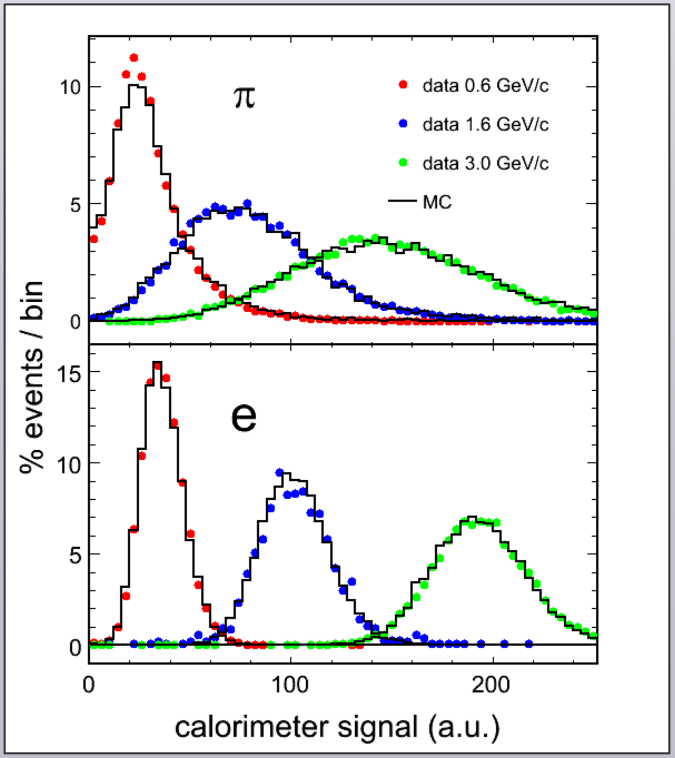
- **Systematic uncertainties under control**
  - Significant improvements expected with data driven studies & more statistics
- **First year results published in PRL 97:191801, 2006**
  - Hep-ex/0607088
- **Second year of running is underway!**

Calibration

- LED based light injection system tracks channel gain over time
- Cosmic rays intercalibrate strips
- Stopping muons intercalibrate detectors
- Dedicated calibration module in CERN test beam for absolute shower energy scale



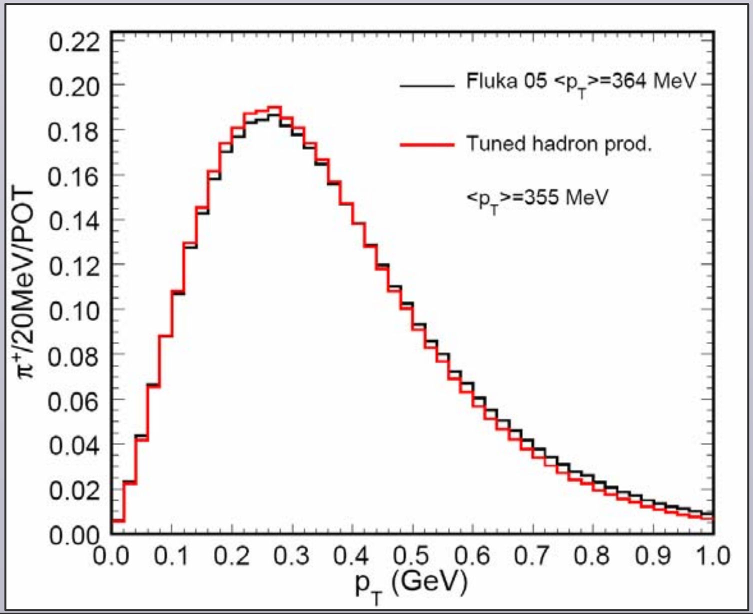


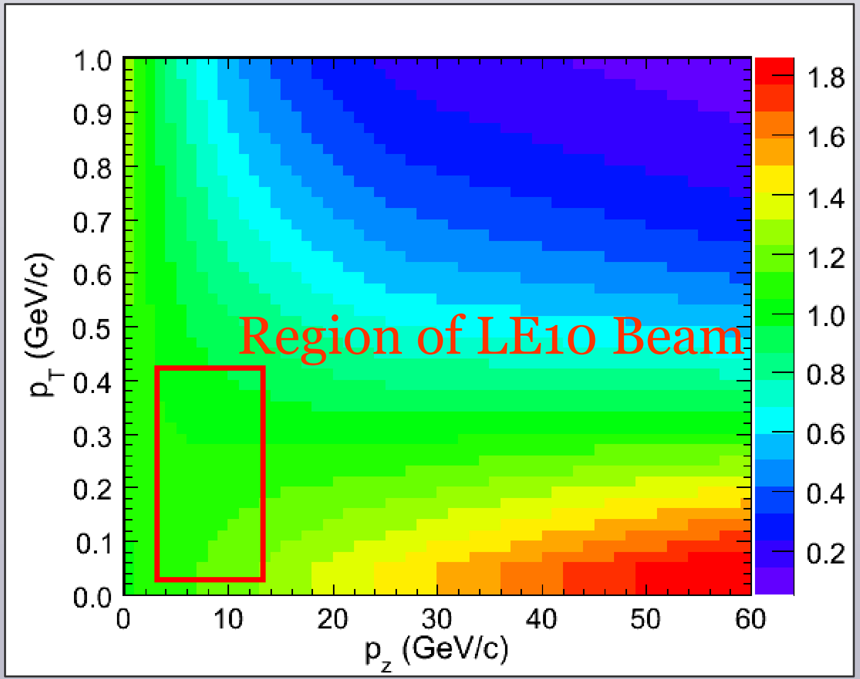


Hadron Production Tuning

Model	$\langle p_T \rangle$ (GeV/c)
GFLUKA	0.37
Sanf.-Wang	0.42
CKP	0.44
Malensek	0.50
MARS – v.14	0.38
MARS – v.15	0.39
Fluka 2001	0.43
Fluka 2005	0.364
Fluka2005 Tuned	0.355

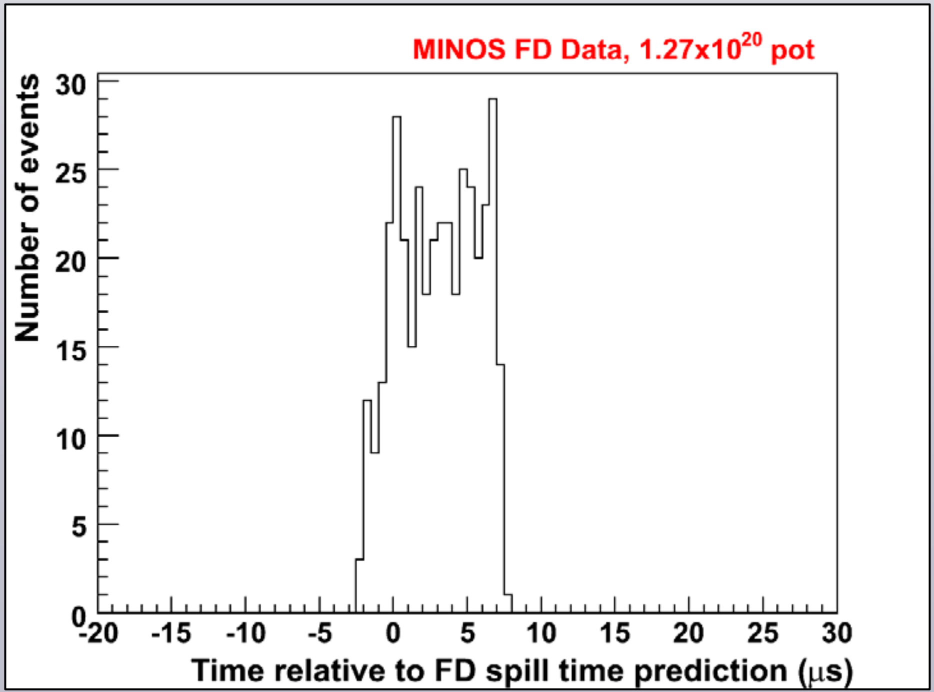
- Weights ~20% in region of p_T vs p_z that produces MINOS neutrinos
- Hadron production tuning changes mean p_T less than model spread





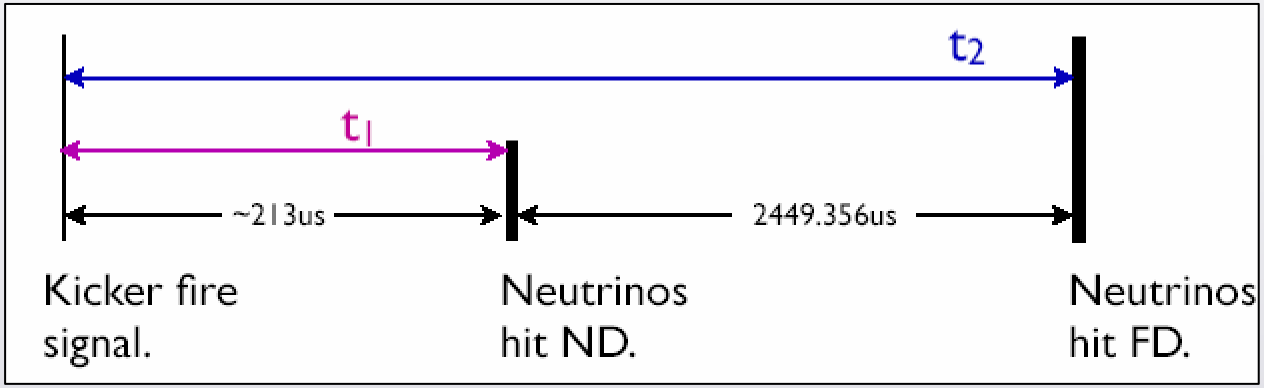
Selecting FD beam events

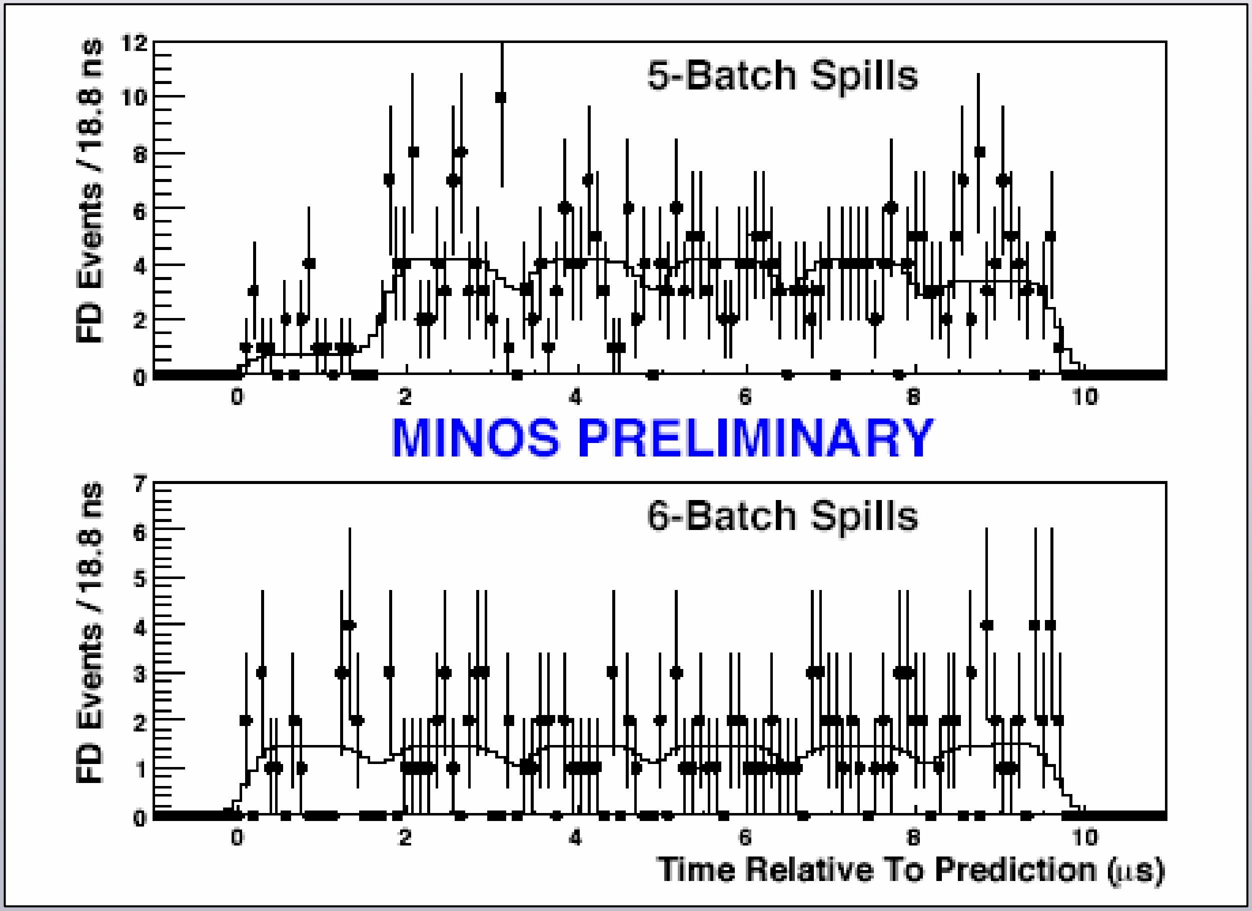
- **Time stamping of the neutrino events is provided by two GPS units (located at Near and Far detector sites).**
  - FD Spill Trigger reads out 100μs of activity around beam spills
- **Far detector neutrino events have very distinctive topology and are easily separated from cosmic muons (0.5 Hz)**



- **In 2.6 million "fake" triggers, 0 events survived the selection cuts**
- **No accepted events outside of expected spill duration**
- **Upper limit on cosmic events, 0.5 events**
- **Upper limit on rock interactions, 0.4 events**

Neutrino Time of Flight





Time of Flight Measurement:

Nominal: (734298.6 ± 0.7 m distance)
2449356 ns

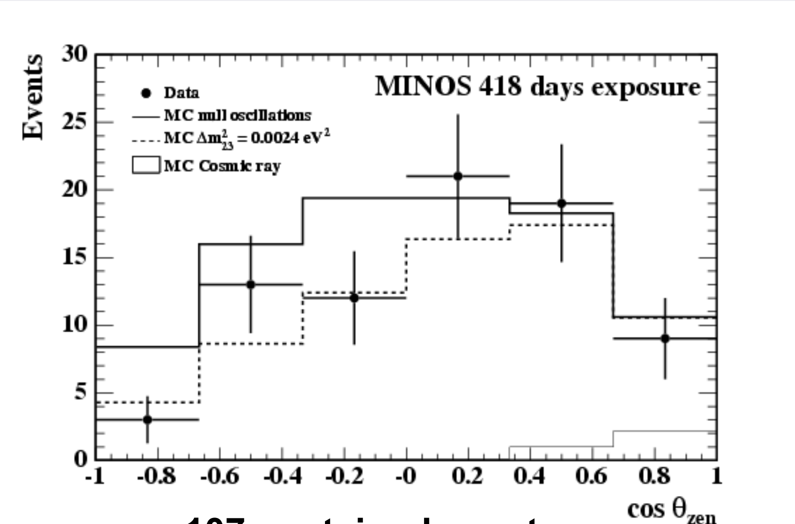
Measured:
2449223 ± 84 (stat) ± 164 (sys) ns
99% C.L.

Neutrino Velocity:
$(v-c)/c = 5.4 \pm 7.5 \times 10^{-5}$
99% C.L.

Atmospheric neutrino analysis

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

Selection	Data	Expected no oscillations	Expected $\Delta m^2_{23} = 0.0024\,\mathrm{eV}^2$
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



107 contained events