New Results on Muon Neutrino to Electron Neutrino Oscillations in MINOS

Lisa Whitehead
Brookhaven National Laboratory

On behalf of the MINOS Collaboration

BNL Particle Physics Seminar, August 11, 2011

Outline

- Formalism
- Description of MINOS
- Electron neutrino identification in MINOS
- Background prediction
- FD data distributions
- Results

Neutrino Mixing

if the flavor (ν_e, ν_μ, ν_τ) eigenstates of the neutrinos are not the same as the mass eigenstates ...

→ each flavor state is a mixture of the different mass states

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

α, β = flavor states
1,2 = mass states

The mixture changes as neutrinos propagate

$$|\nu_\alpha(L)\rangle = \cos\theta \exp\frac{-i\,m_1^2 L}{2E}|\nu_1\rangle + \sin\theta \exp\frac{-i\,m_2^2 L}{2E}|\nu_2\rangle$$

t ≈ L, the distance traveled

Natural units
$\hbar = c = 1$

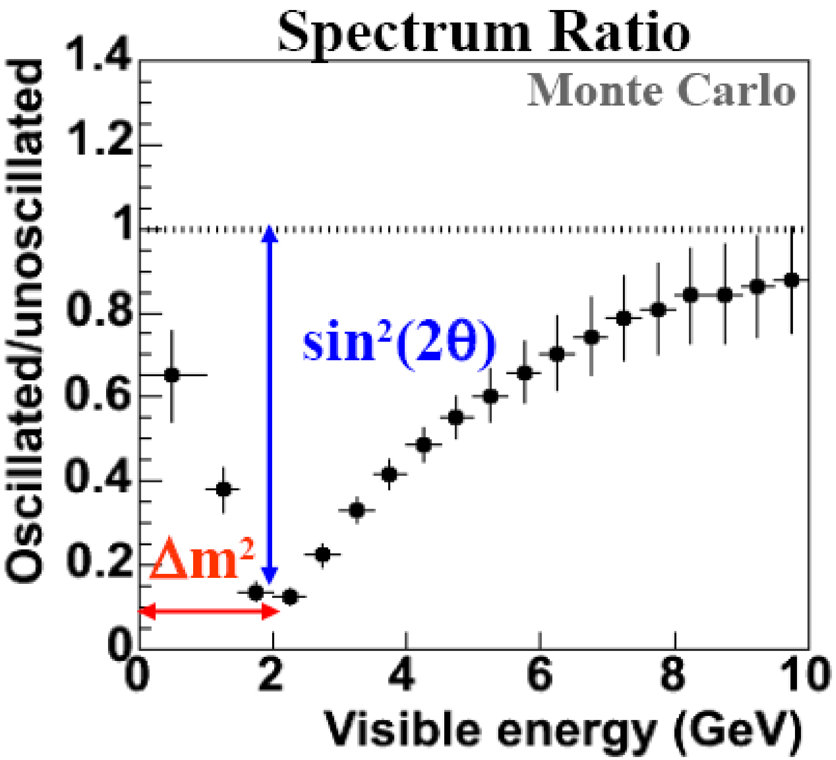
Neutrino Oscillations

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 L/E)$$

1.27 in units of $(GeVc^4)/(eV^2 km)$

θ = mixing angle
L = flight distance
E = neutrino energy

$$\Delta m^2 = m_2^2 - m_1^2$$



Thus a neutrino created in one flavor state can be observed some time later in a different flavor state

The Full Picture

In the standard model of neutrinos, there are 3 light neutrinos

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Mixing can generally be represented by 3 mixing angles (θ_{12}, θ_{23}, θ_{13}) and one phase (δ) *
(same as standard parameterization of the CKM matrix)

3 neutrinos → 2 independent mass squared differences:

$$\Delta m^2_{21}, \Delta m^2_{32} \qquad \Delta m^2_{ij} = m^2_i - m^2_j$$

*If neutrinos are Majorana particles, there are two more phases, but they don't affect neutrino oscillations.

Experimental Status

from solar/reactor ν (Kamland, SNO)

$$\Delta m^2_{sol} = 8\times 10^{-5}\, eV^2$$

$$\theta_{12} \approx 34^o$$

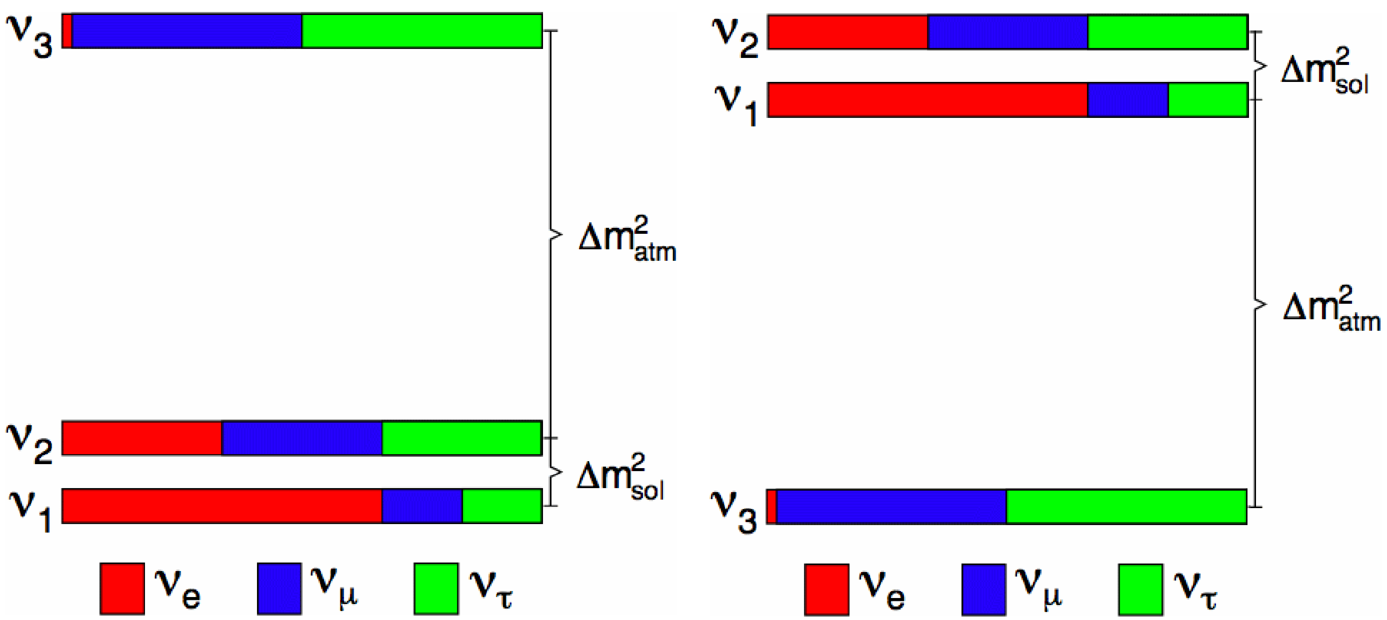
from atmospheric/ accelerator ν (Super-Kamiokande, MINOS)

$$|\Delta m^2_{atm}| = 2.3\times 10^{-3}\, eV^2$$

$$\theta_{23} \approx 45^o$$

Open questions:

Normal Hierarchy or Inverted Hierarchy?

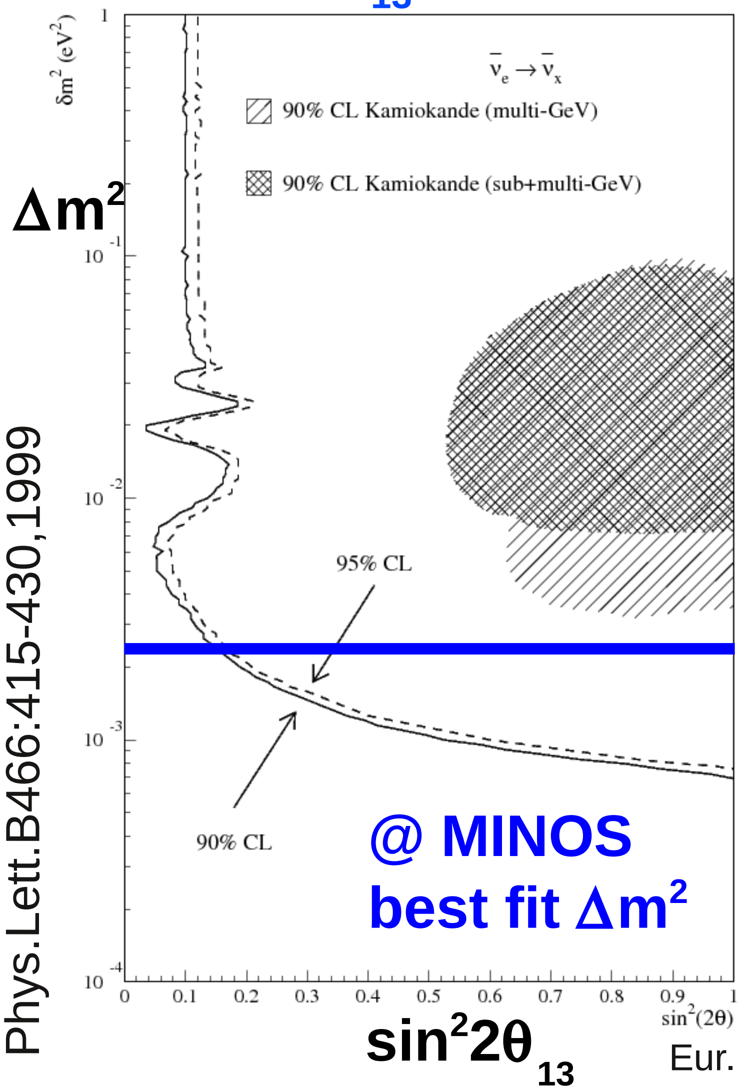


$$\delta = ?$$

$$\theta_{13} = ?$$

Measuring θ_{13} with reactor ν's

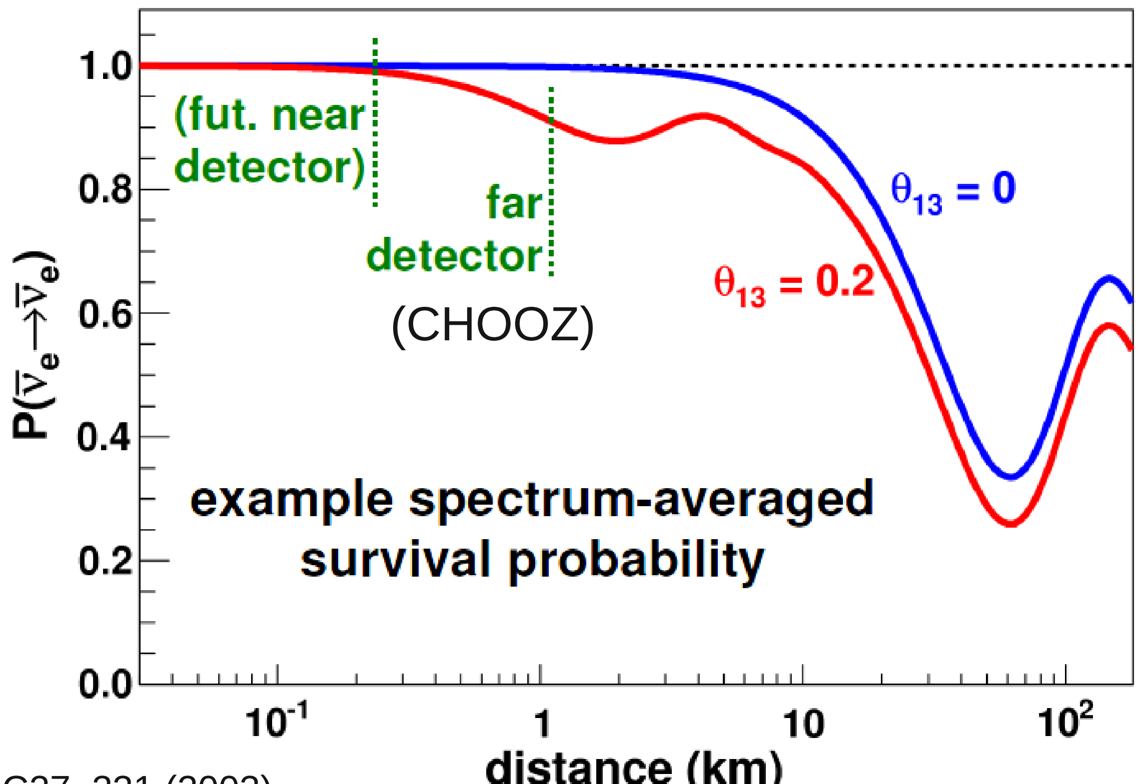
CHOOZ reactor neutrino experiment: $\sin^2 2\theta_{13} < 0.16$



Phys.Lett.B466:415-430,1999

disappearance of $\overline{\nu}_e$ from a reactor

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\,\Delta m^2_{atm} L/E) - C^4_{13} \sin^2 2\theta_{12} \sin^2(1.27\,\Delta m^2_{sol} L/E)$$



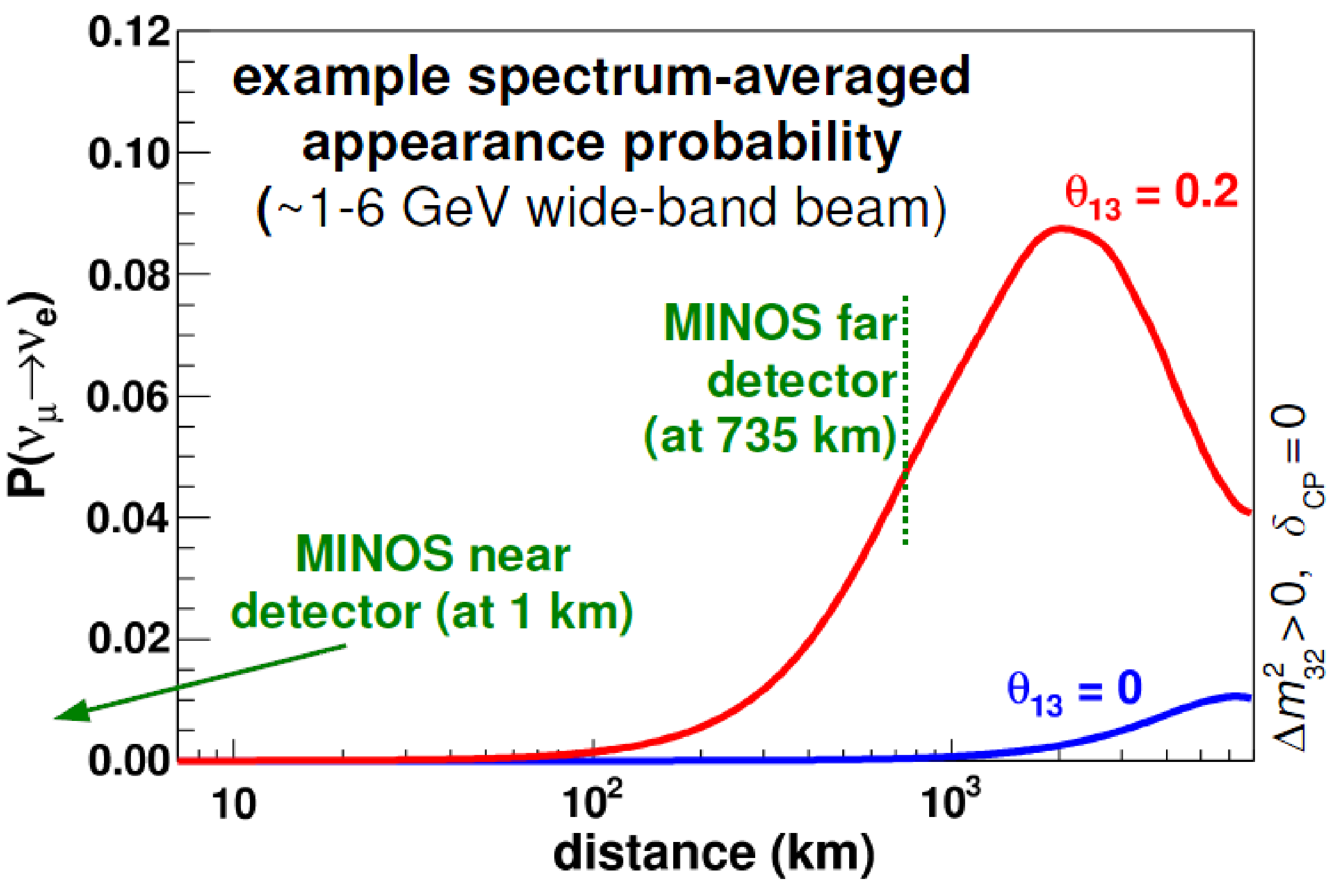
Eur. Phys. J. C27, 331 (2003)

Measuring θ_{13} with accelerator ν's

appearance of ν_e in a ν_μ beam

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

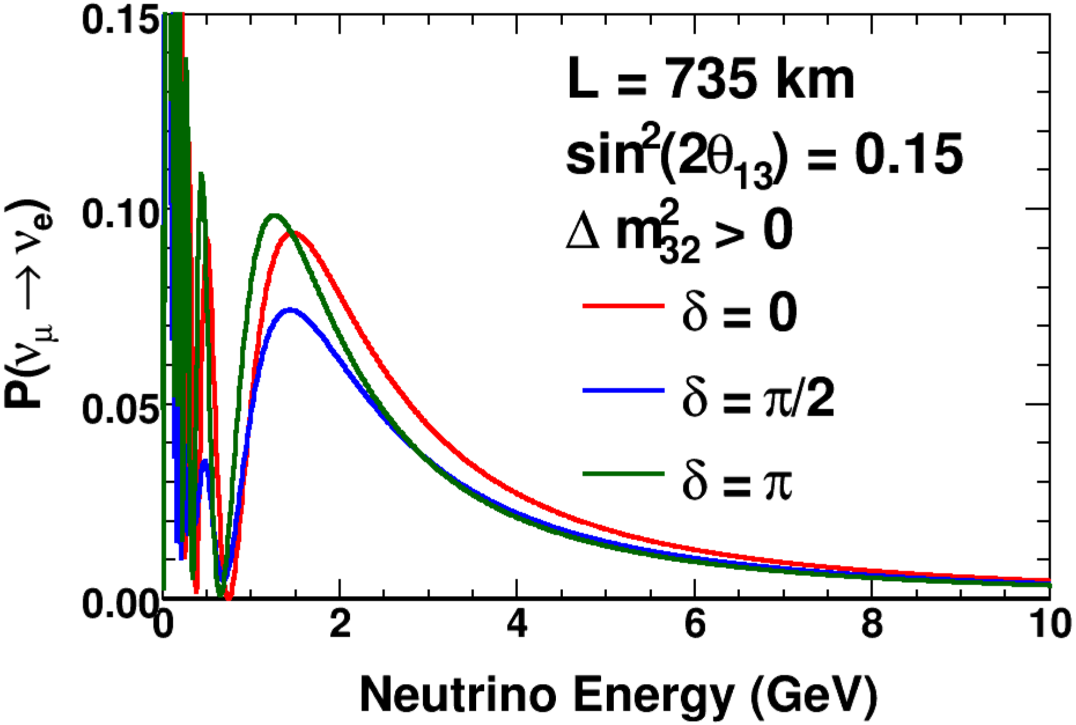
(Dominant term)



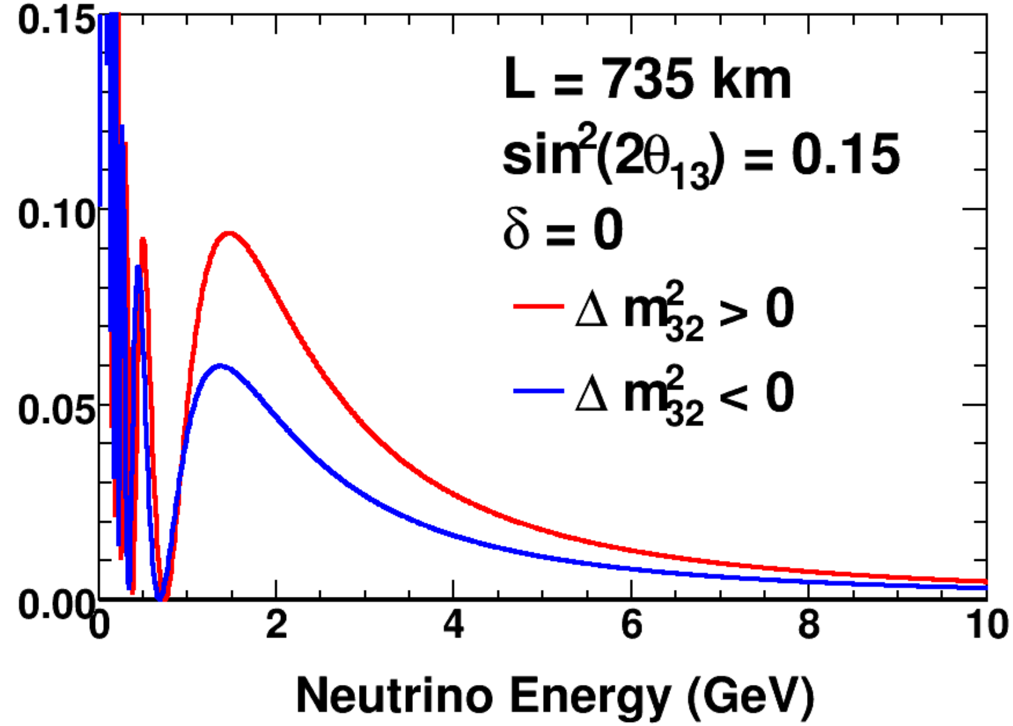
Measuring θ_{13} with accelerator ν's

$P(\nu_\mu \to \nu_e)$ has higher order terms that depend on δ and the mass hierarchy

δ dependence

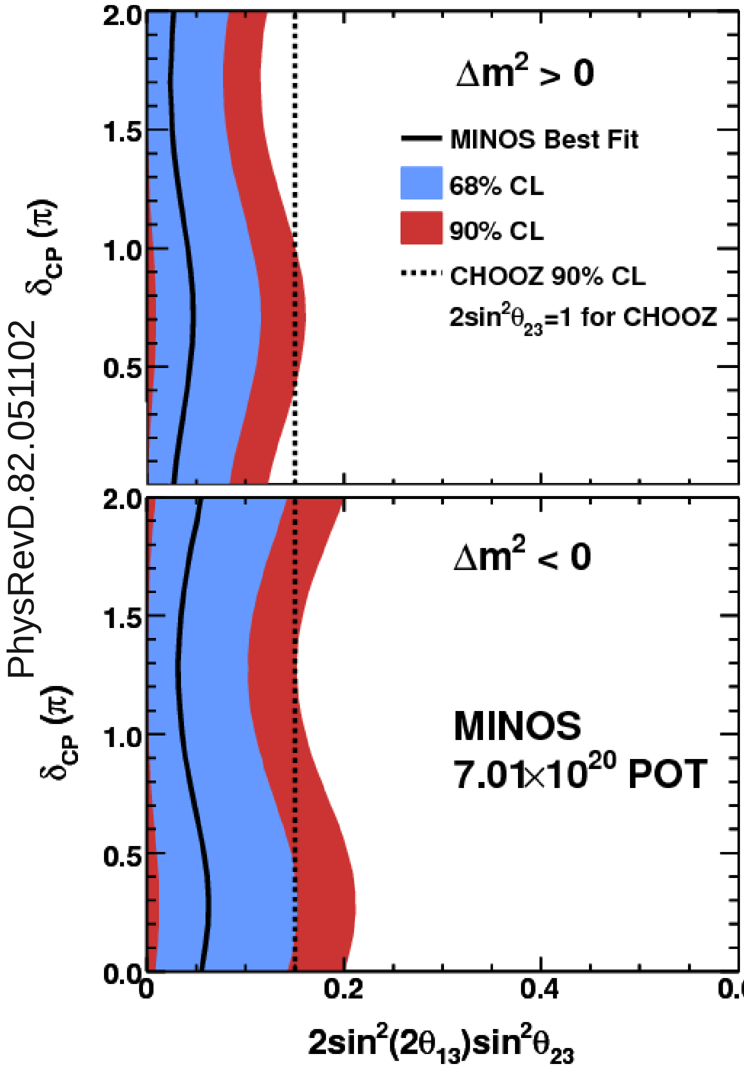


mass hierarchy dependence



Measuring θ_{13} with accelerator ν's

MINOS 2010



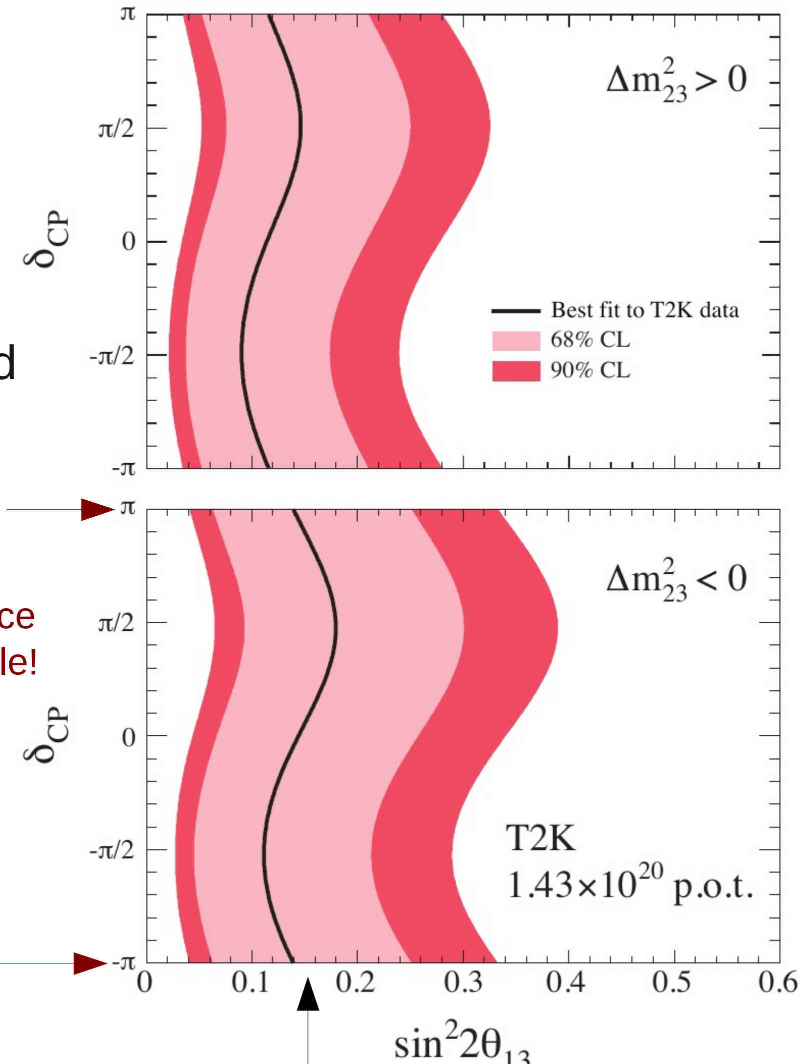
MINOS observed 54 events with 49 expected background events

2π

Note difference in δ scale!

0

T2K 2011



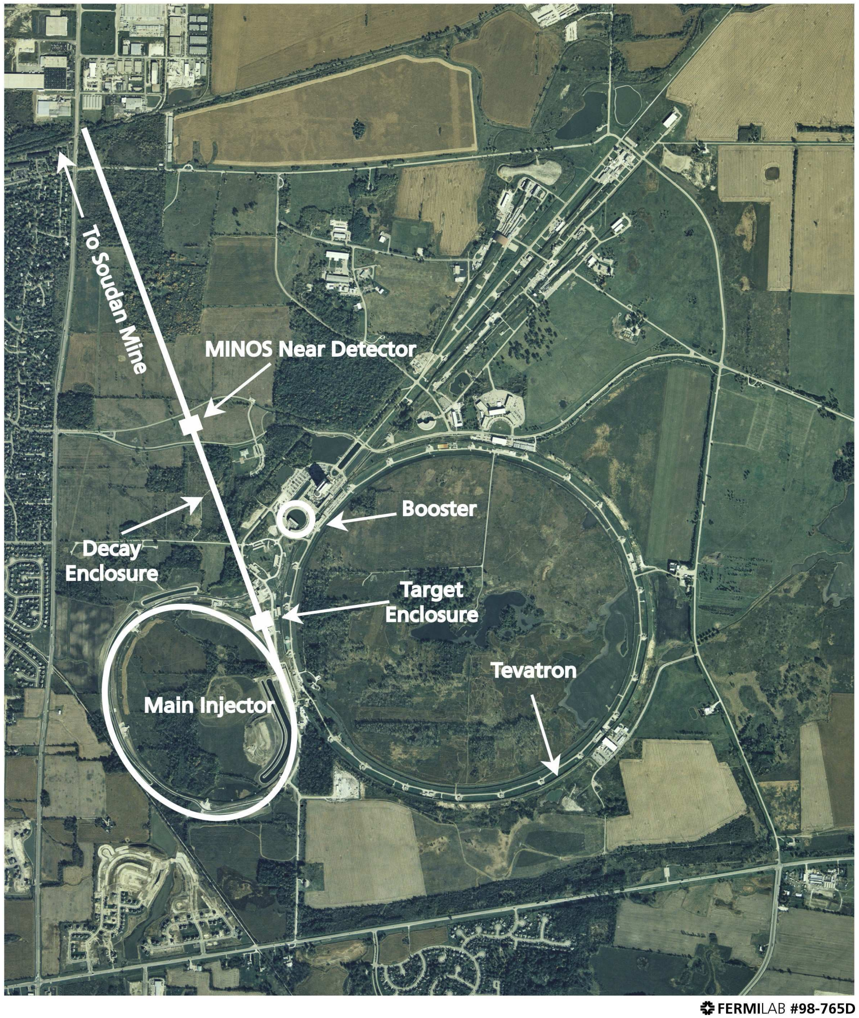
T2K observed 6 events with 1.5 expected background events

arXiv:1106.2822

CHOOZ limit

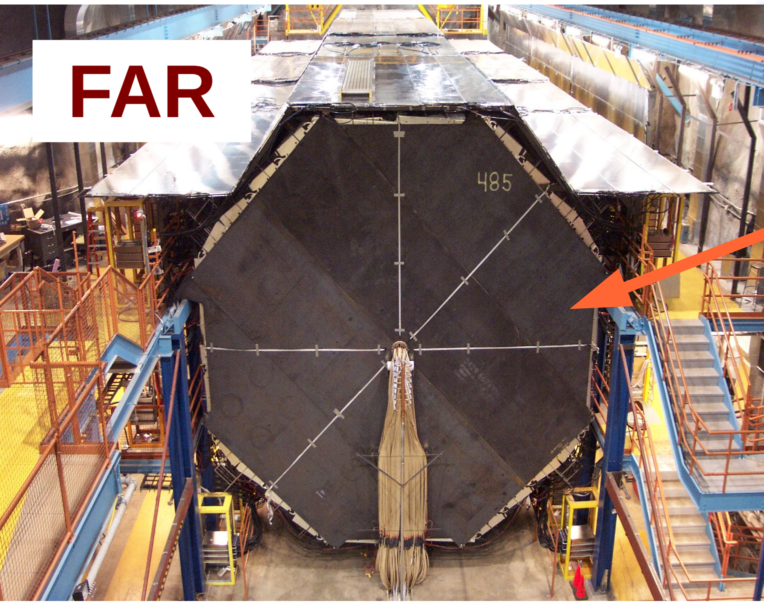
MINOS was the first experiment with sensitivity to θ_{13} beyond the CHOOZ limit!

The MINOS Experiment



MINOS detectors

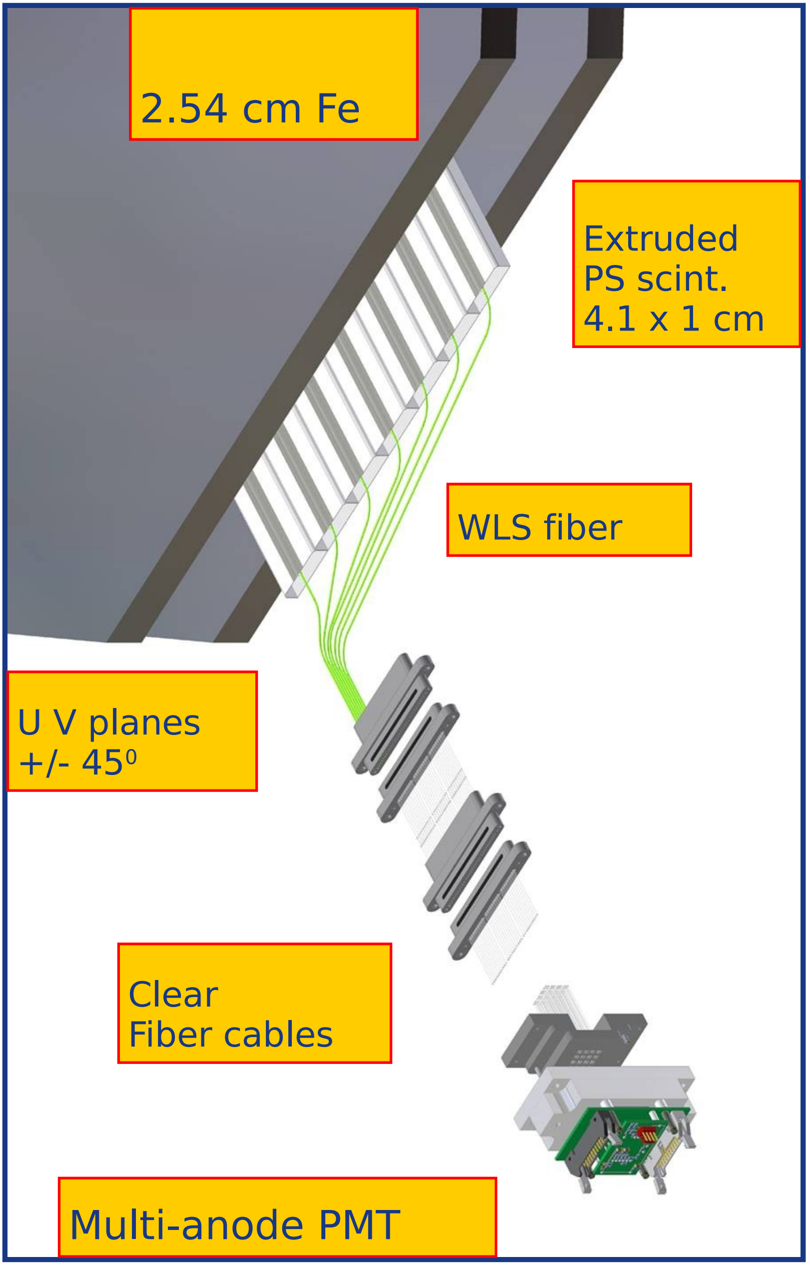
alternating layers of steel plates and scintillator strips in a ~1.3 T toroidal magnetic field



735 km from the target
5.4 kilotons
8 m tall planes
486 planes (30 m)
700 m underground
Few ν interactions/day

1 km from the target
1 kiloton
~4 m tall planes
282 planes (15 m)
100 m underground
Few ν interactions/spill

MINOS detectors



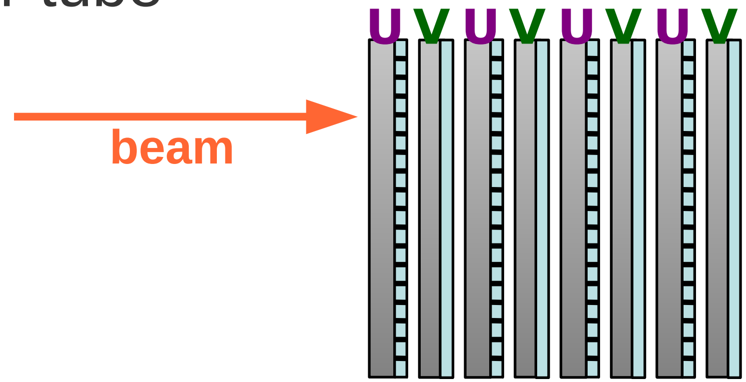
Steel thickness: 2.54 cm (~1.4 radiation lengths)

Strip width: 4.1cm
Moliere radius (radius of 90% containment of EM showers) ~3.7cm

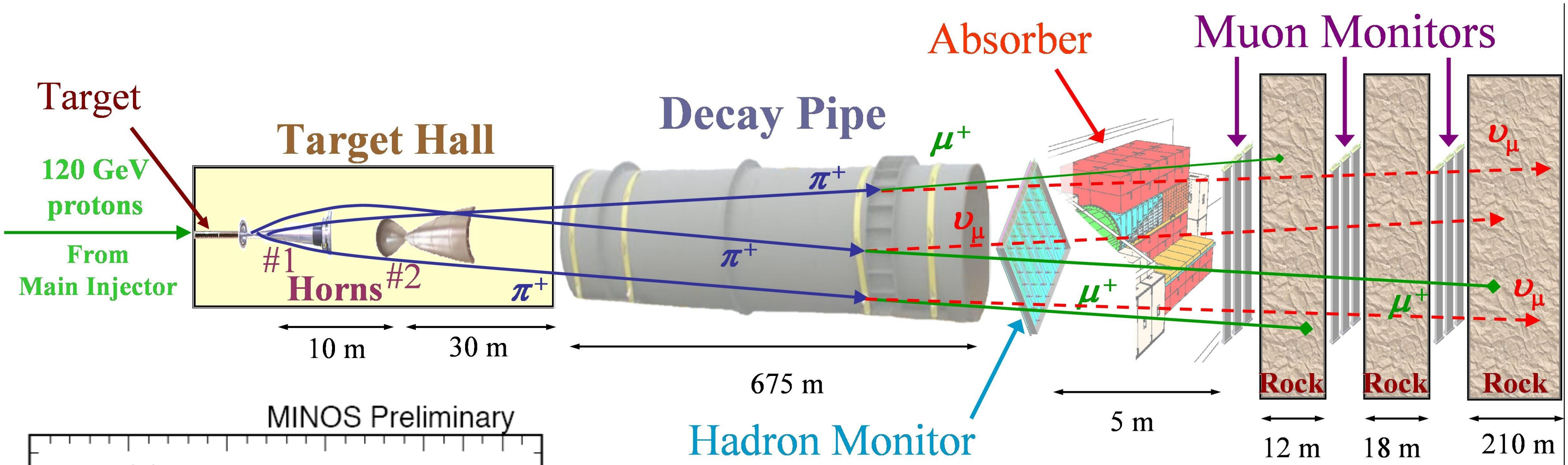
Strips in adjacent planes are oriented orthogonally enabling 3D reconstruction

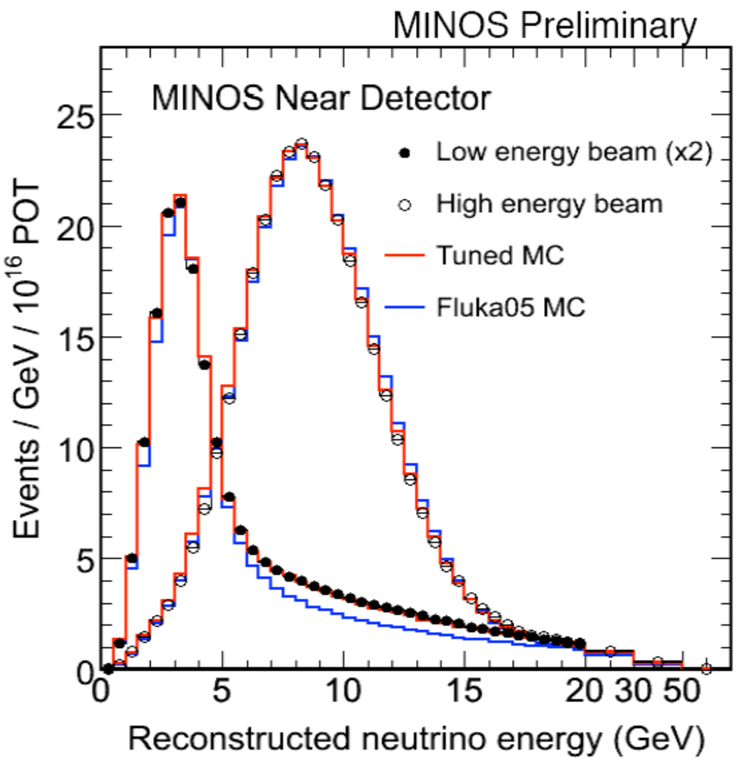
Each strip is read out by a wavelength shifting fiber connected to a multi-anode photomultiplier tube

U/V strips oriented $\pm 45^o$ from vertical



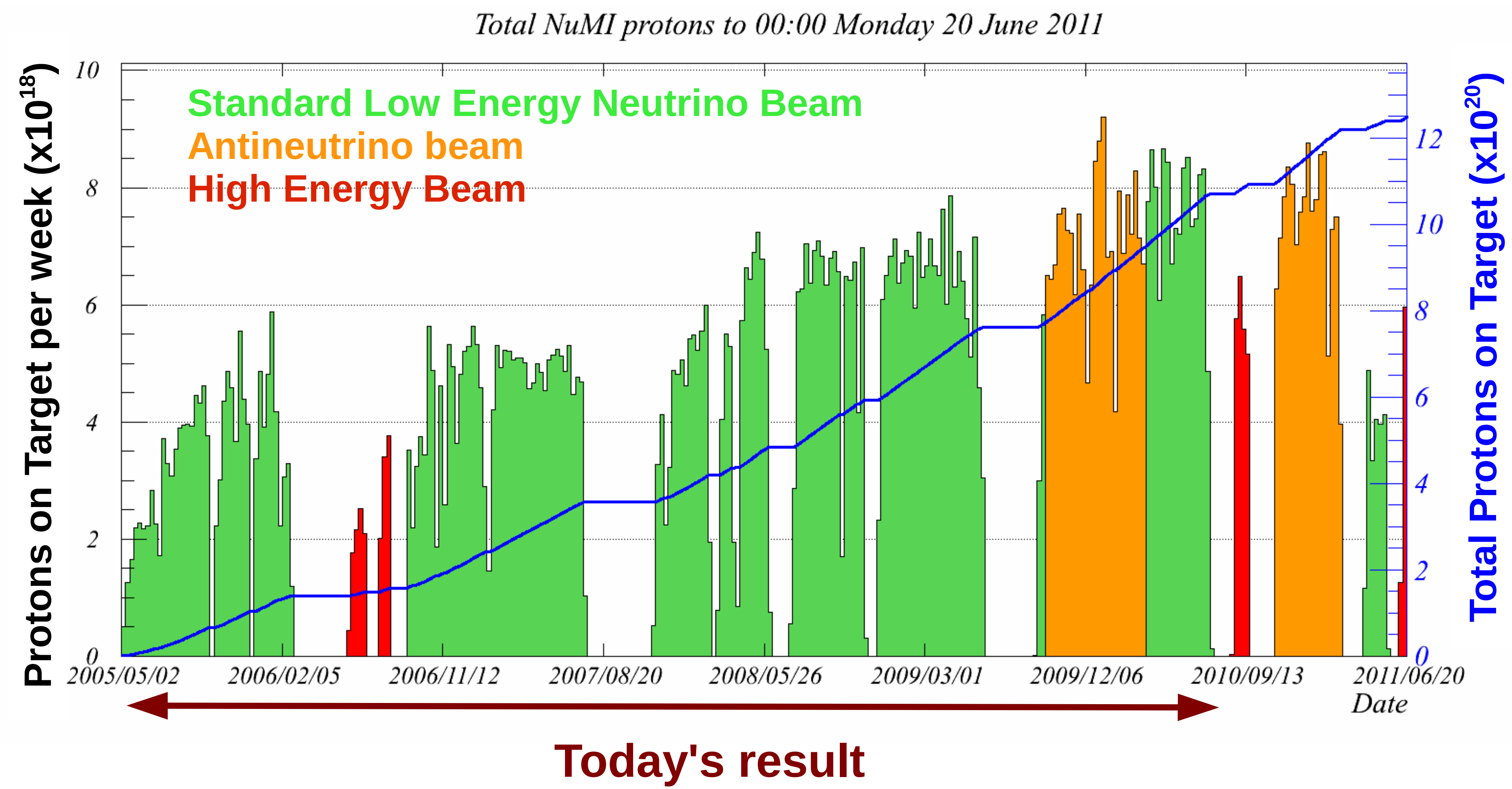
NuMI Beam





- 120 GeV protons hit a carbon target
- magnetic horns focus π^+
- $\pi^+ \rightarrow \mu^+ \nu_\mu$
- ν_e contamination (1.3%) from $\mu^+ \rightarrow e^+ \overline{\nu}_\mu \nu_e$
- Target position can be changed to tune the neutrino energy spectrum

Protons Delivered to Target



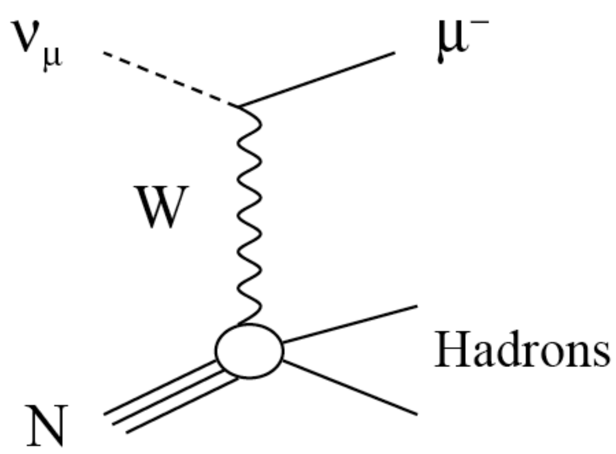
Only data from our standard low energy beam is used for the result. (only the green)

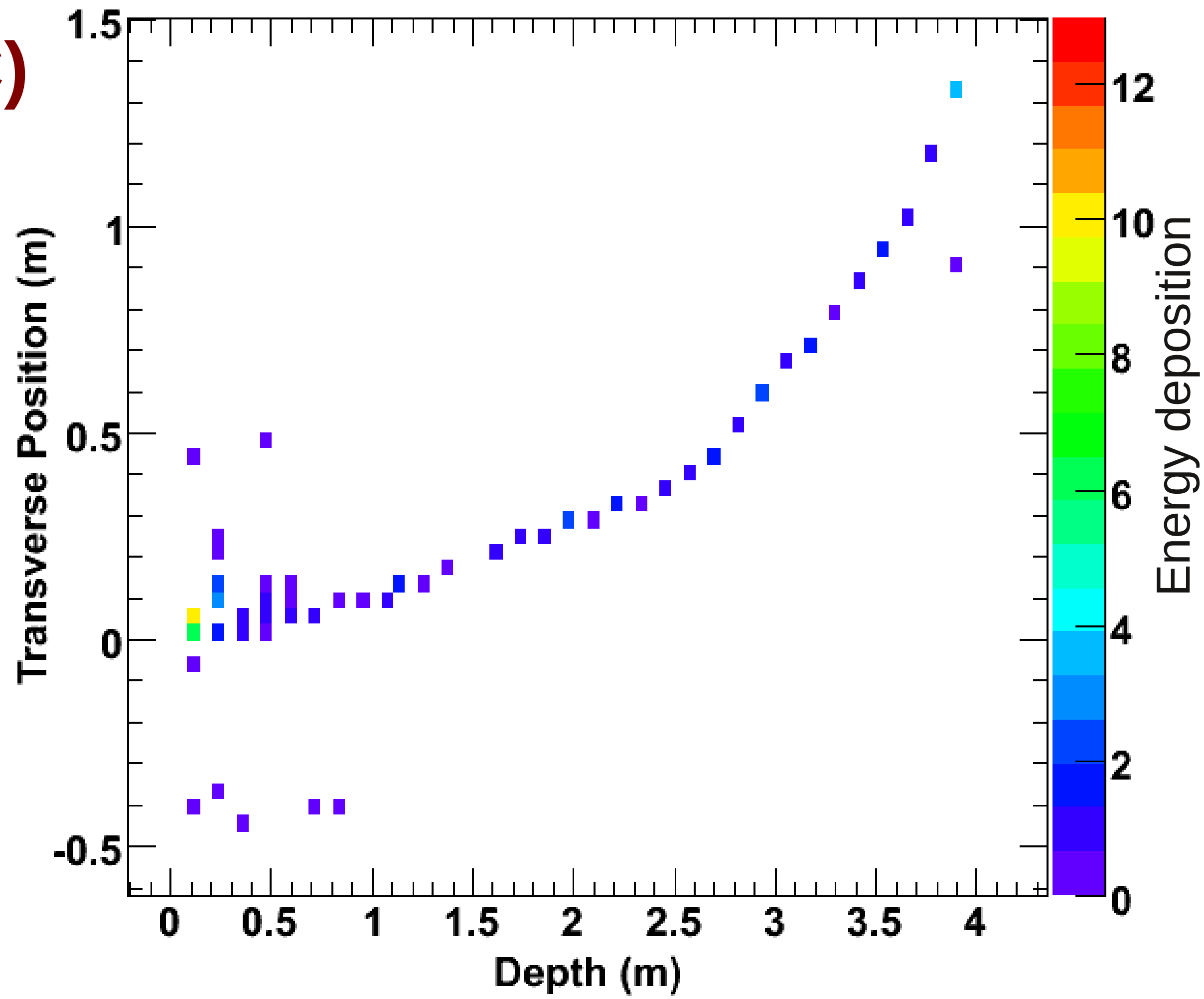
Neutrino Interactions at MINOS

MC event

ν_μ Charged Current (CC)

$$\nu_\mu N \rightarrow \mu^- X$$





The outgoing muon and hadronic shower deposit energy in the detector.

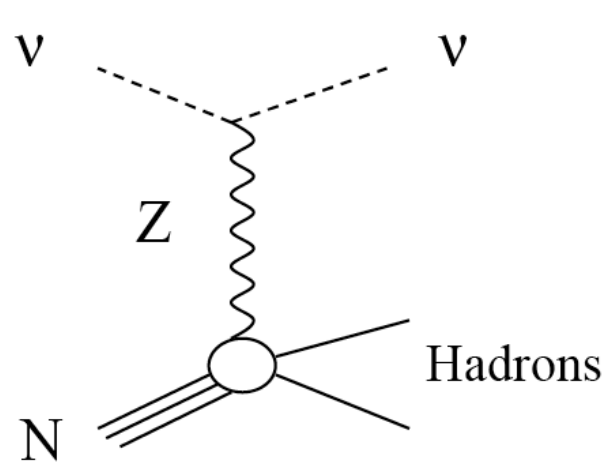
Long μ track with hadronic activity at vertex

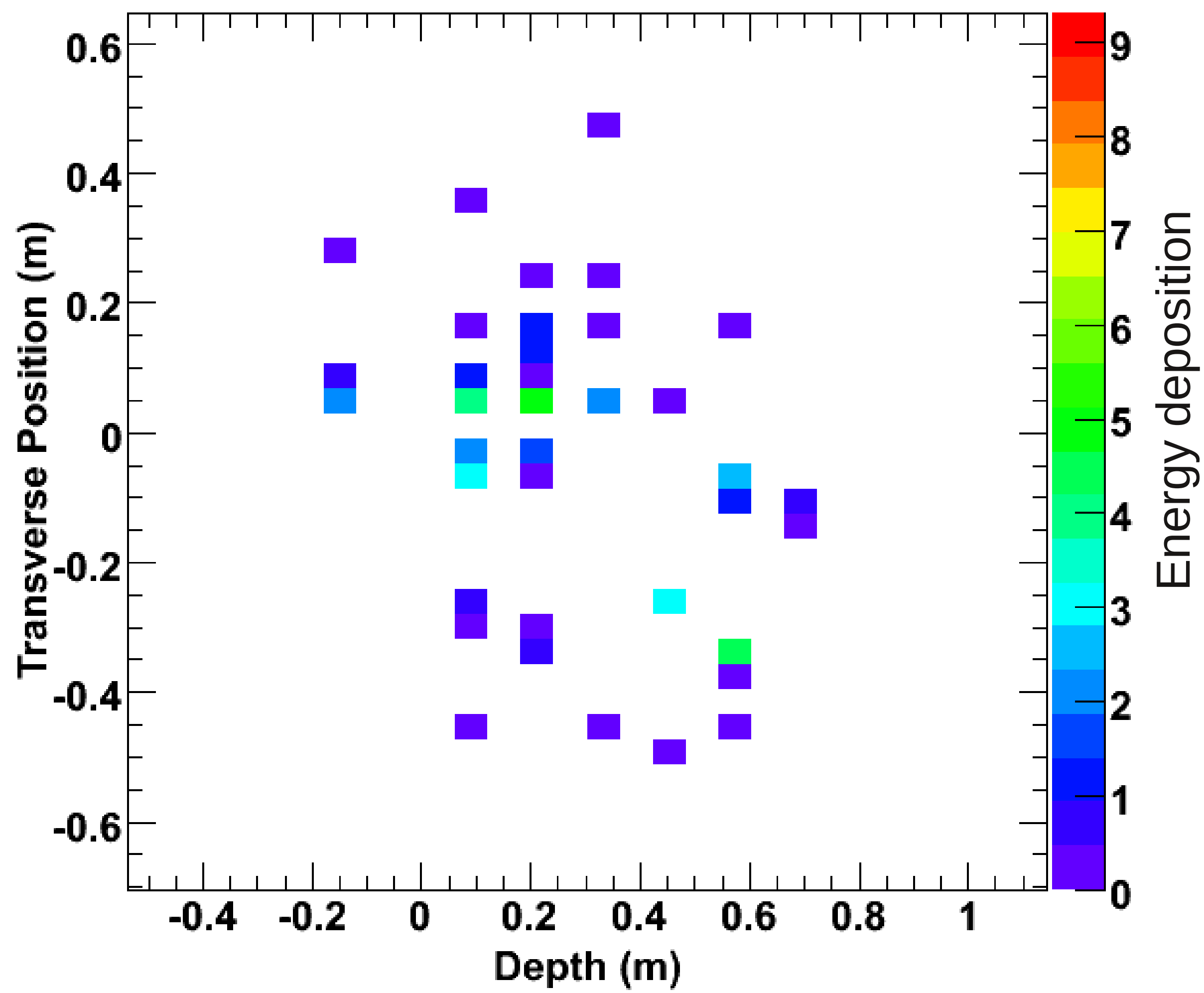
Neutrino Interactions at MINOS

MC event

Neutral Current (NC)

$$\nu N \rightarrow \nu X$$





Only the hadronic shower deposits energy in the detector.

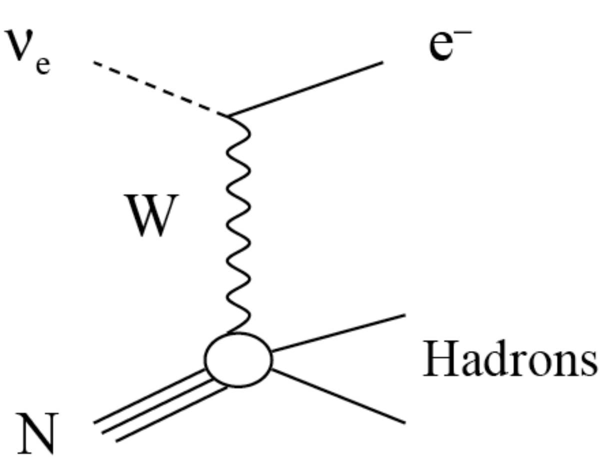
short event, often diffuse shower

Neutrino Interactions at MINOS

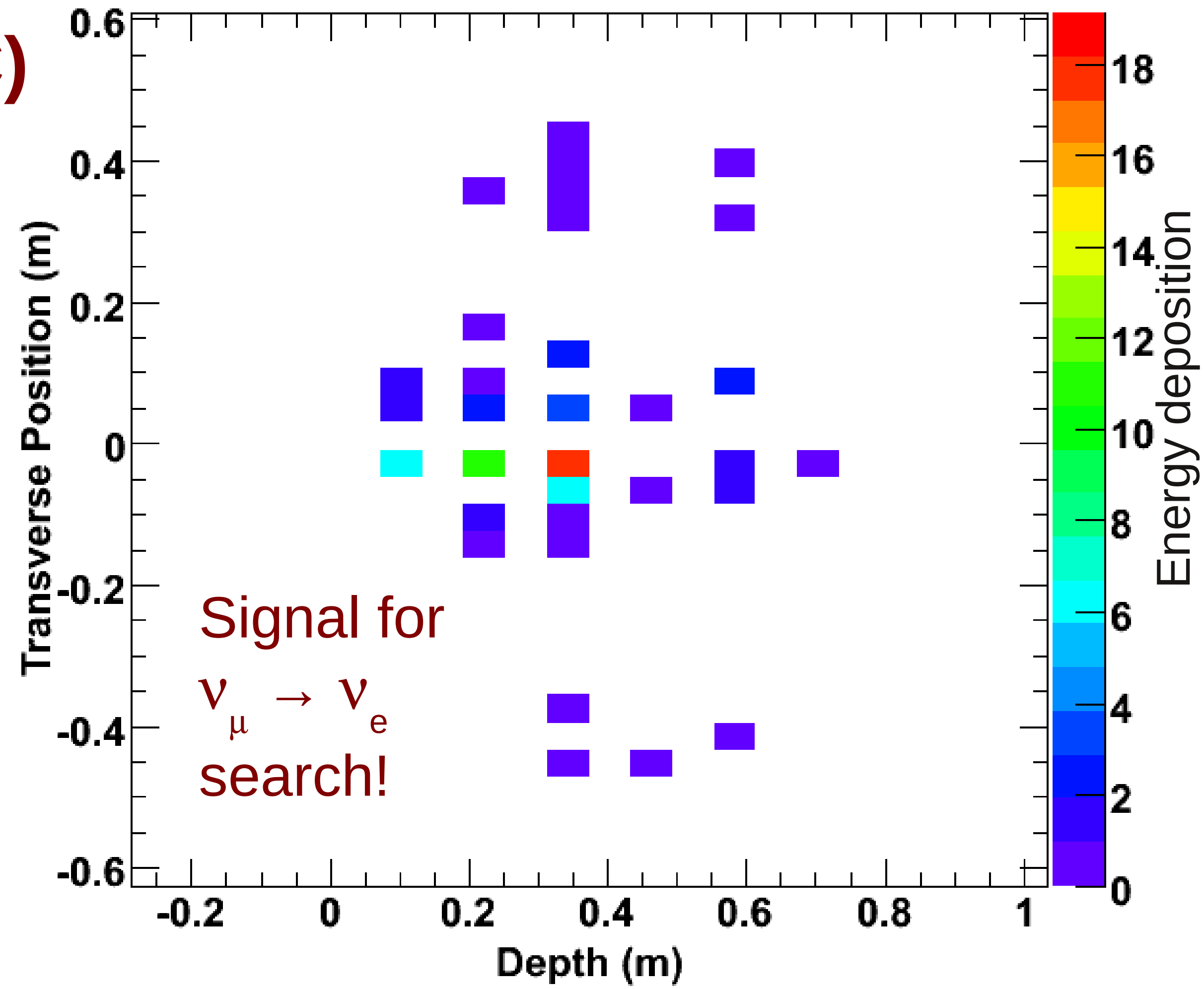
MC event

ν_e Charged Current (CC)

$$\nu_e N \rightarrow e^- X$$



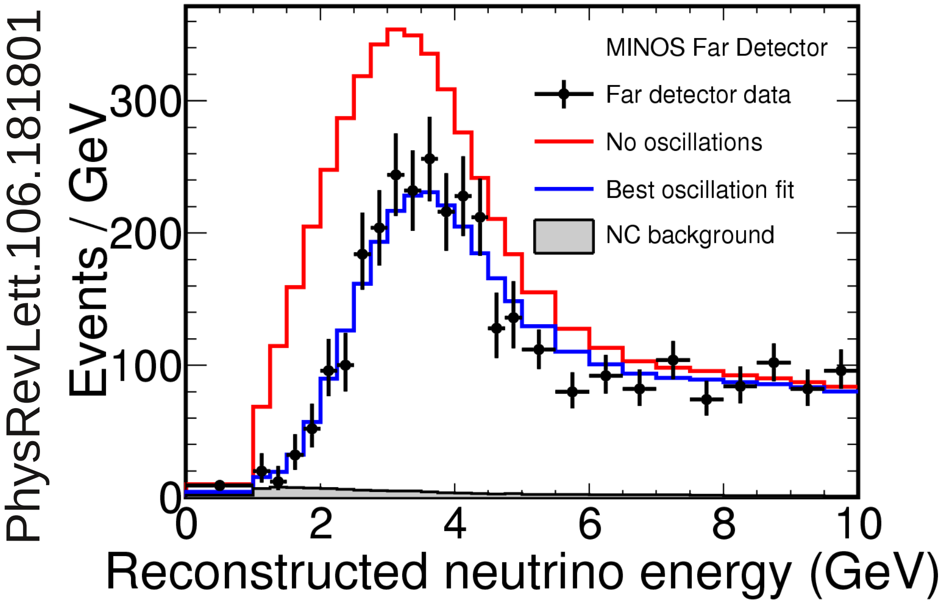
The outgoing electron and hadronic shower deposit energy in the detector.



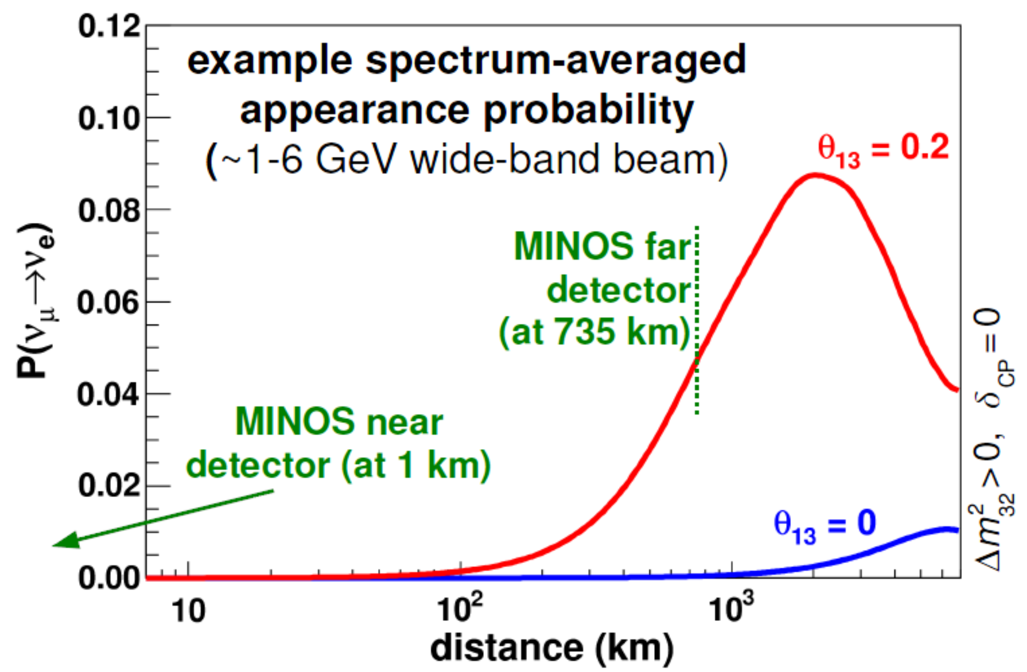
Short event, with compact shower profile

ν_e appearance in MINOS

MINOS measures ν_μ disappearance:



The probability for those missing ν_μ's to become ν_e's is at most a few percent!



Searching for ν_e appearance

1) Determine selection criteria for ν_e candidate events

2) Use ND data to make a background prediction for the FD

3) Is there an excess of ν_e-like events over the predicted background in the FD?

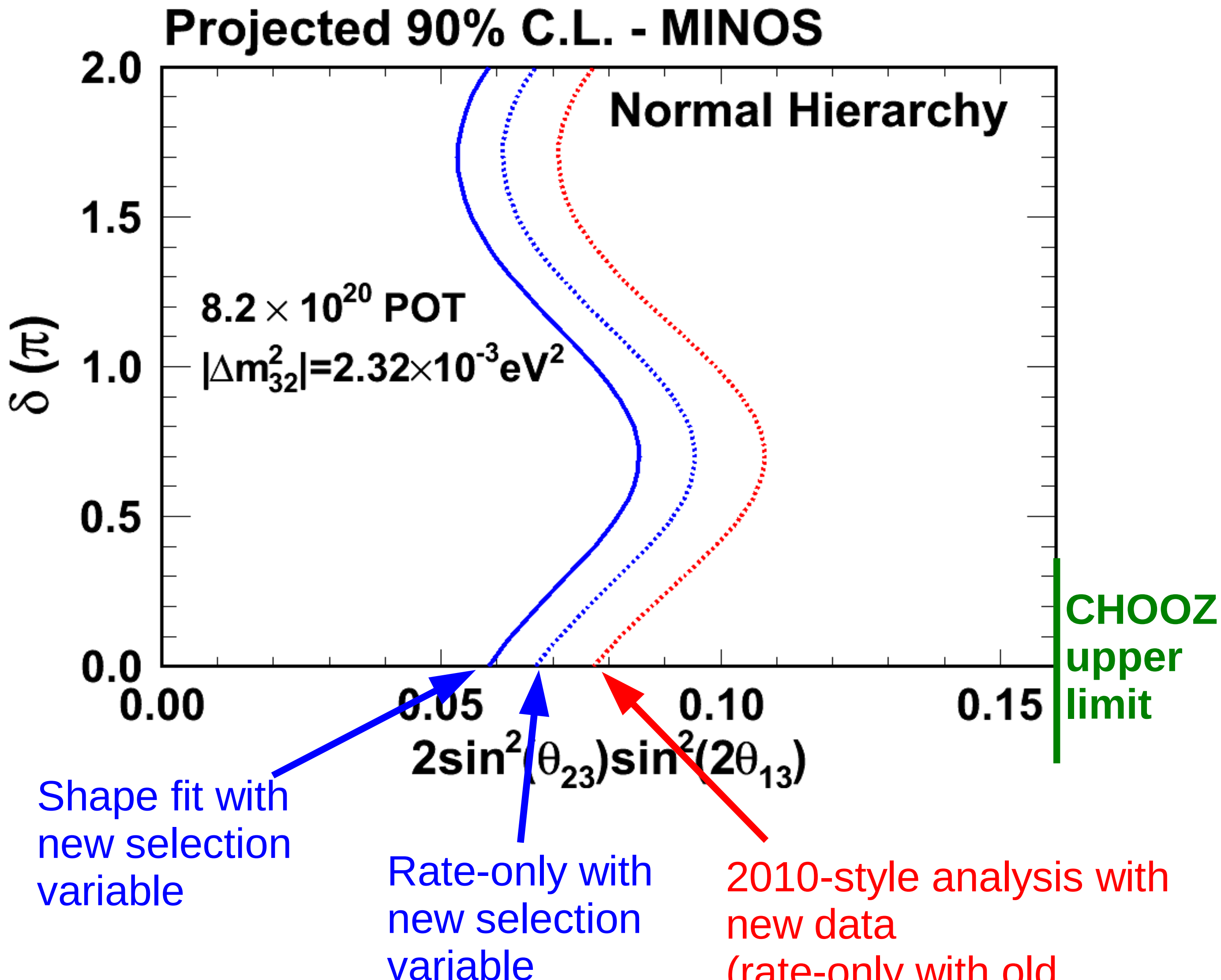
Projected Sensitivity

Sensitivity = 90% CL upper limit we would set if we observed exactly the background prediction.

Since 2010 result:

Phys. Rev. D 82, 051102

- 1.2×10^{20} POT (17%) more data
- Improved event selection variable: 15% sensitivity gain
- Shape fit: 12% sensitivity gain



T2K sensitivity ~0.07 (Neutel11)

1) Determine selection criteria for ν_e candidate events

2) Use ND data to make a background prediction for the FD

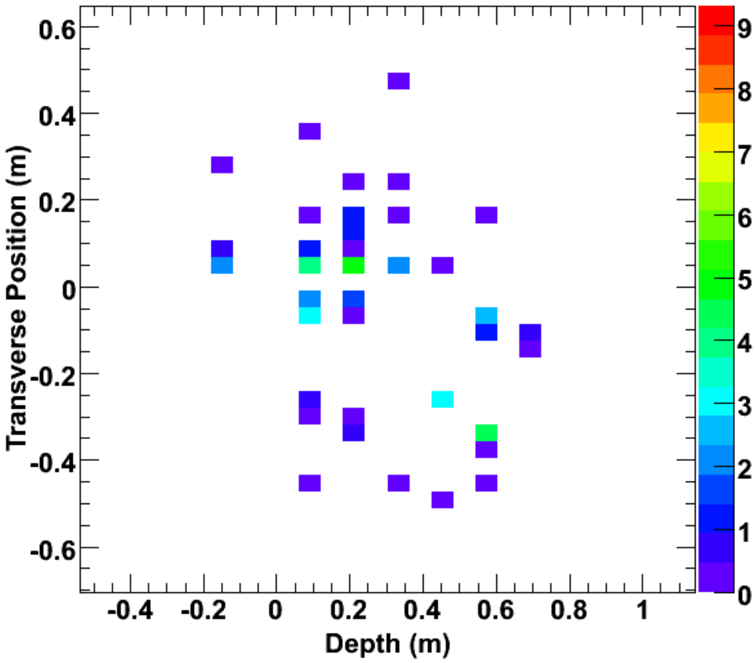
3) Is there an excess of ν_e-like events over the predicted background in the FD?

Selecting ν_e-like events

Preselection cuts to remove events that are obviously not signal:

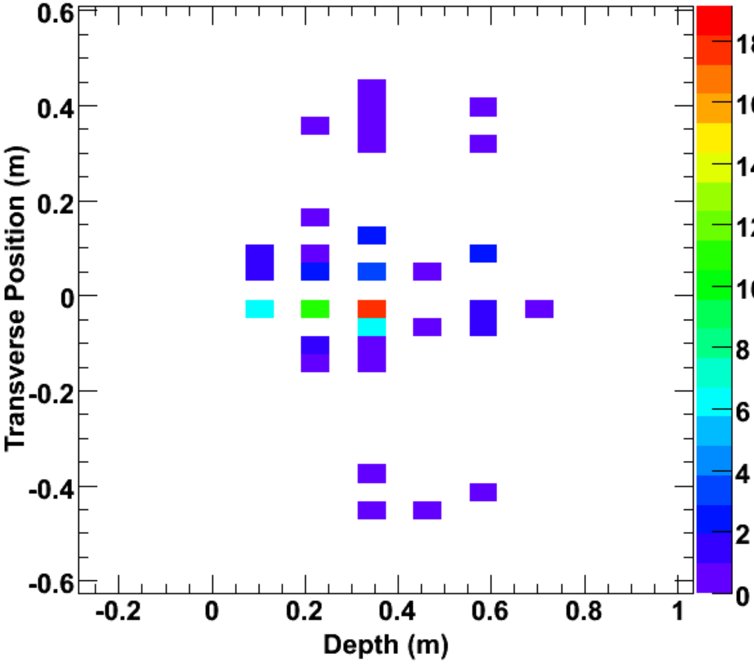
- No long tracks
- At least one well-formed shower
- With visible energy 1-8 GeV

After these cuts, background consists mostly of NC



(NC background)

Need to discriminate



(signal)

Library Event Matching (LEM)

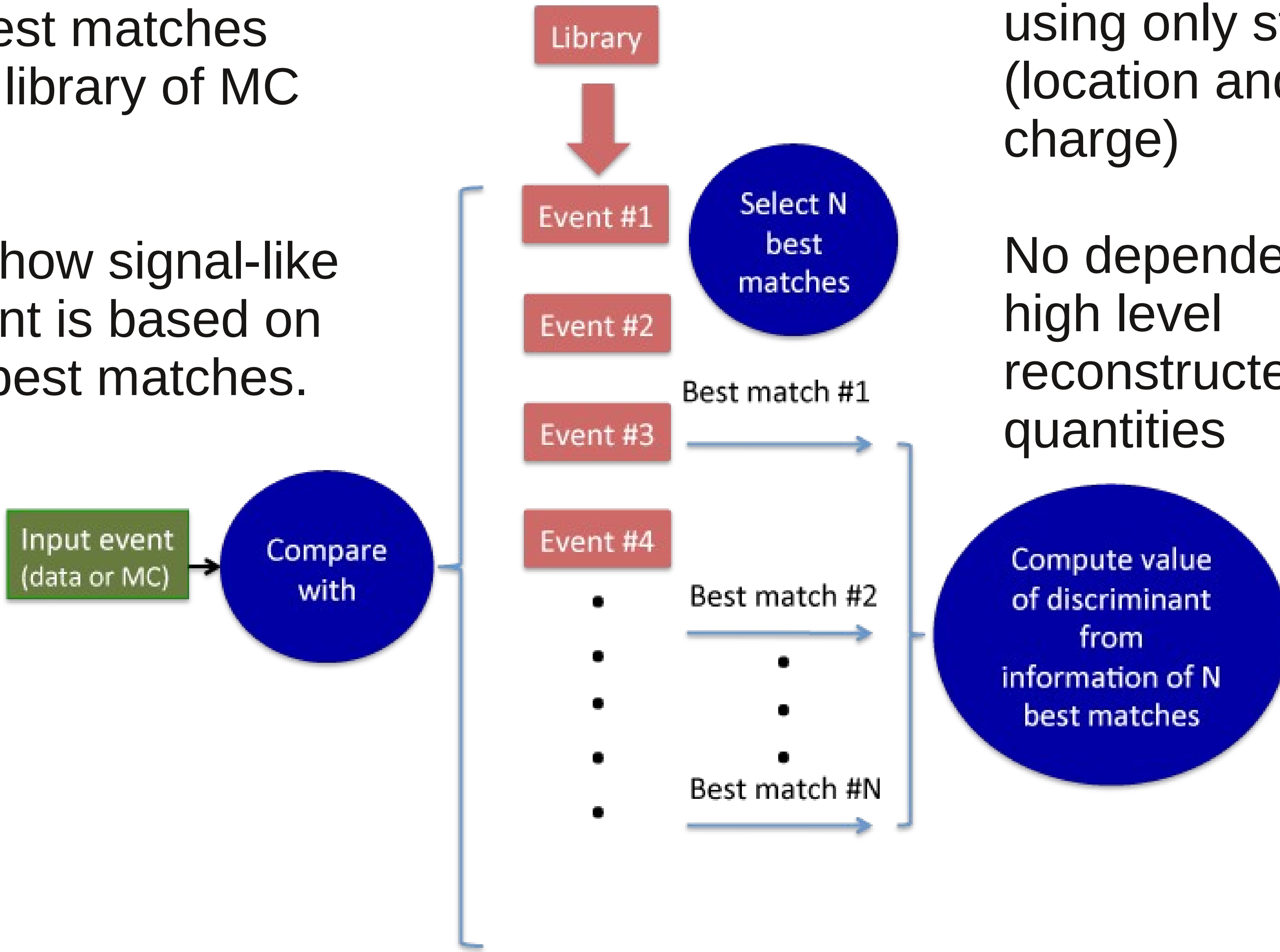
New selection variable!

Find best matches from a library of MC events

Judge how signal-like an event is based on those best matches.

Matching is done using only strip info (location and charge)

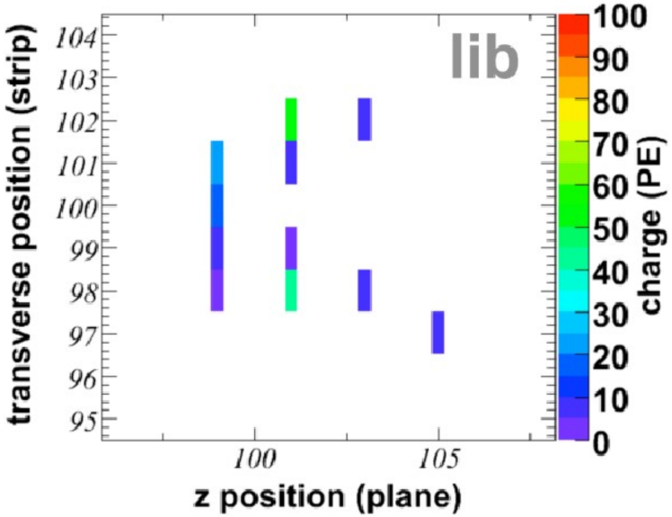
No dependence on high level reconstructed quantities



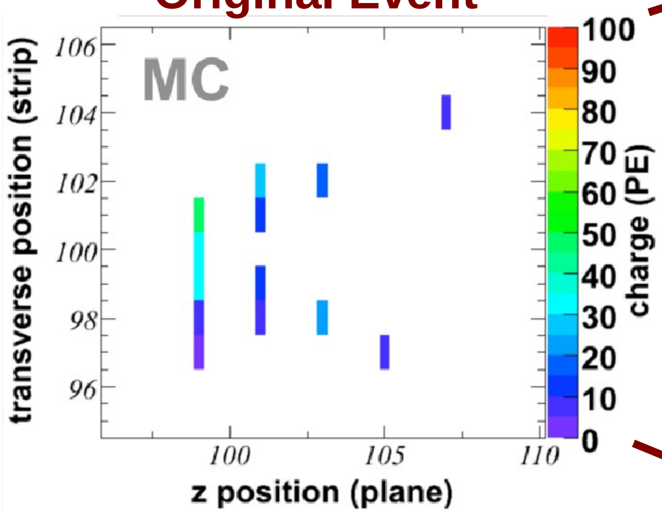
Matching

Each input event is compared to the library events by calculating the likelihood that the photoelectrons in each event came from the same energy deposition.

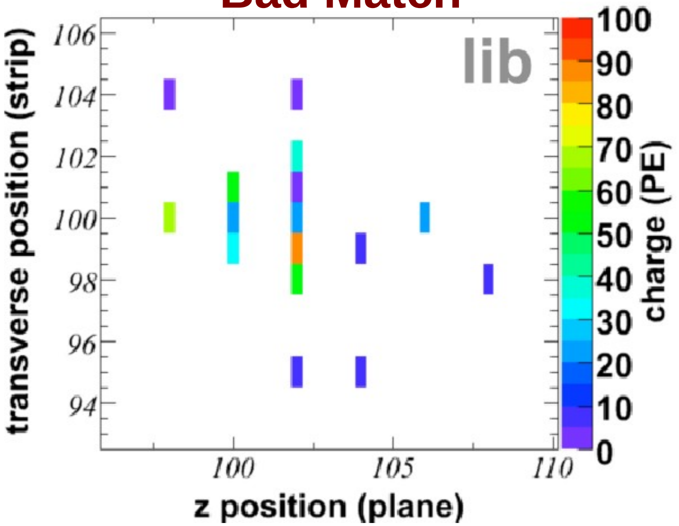
Good Match



Original Event



Bad Match

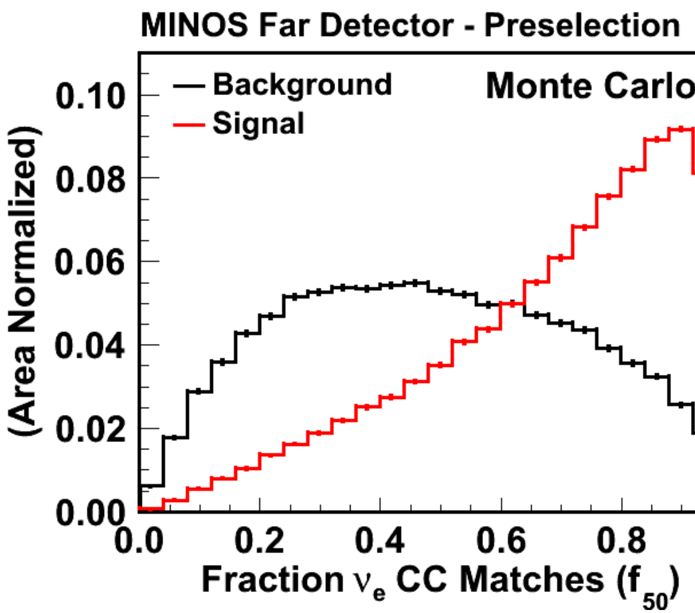


The library consists of:

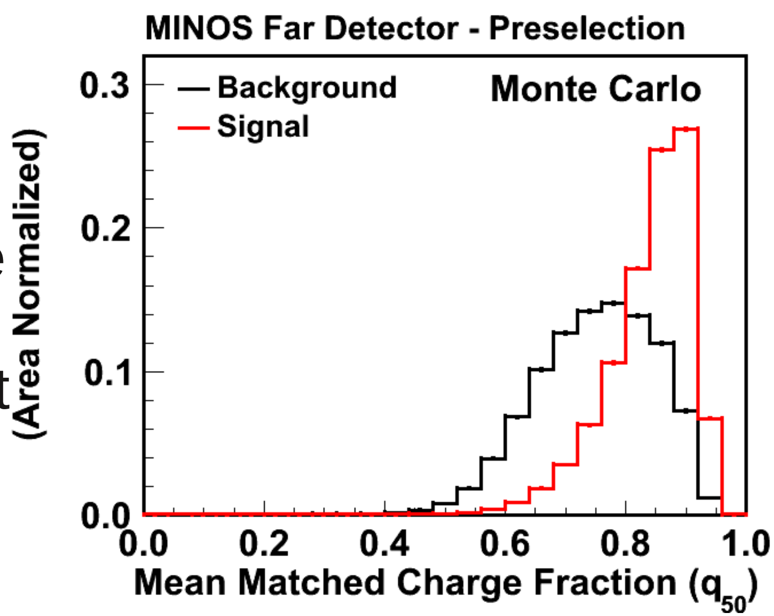
- 20 million signal events
- 30 million background (NC) events

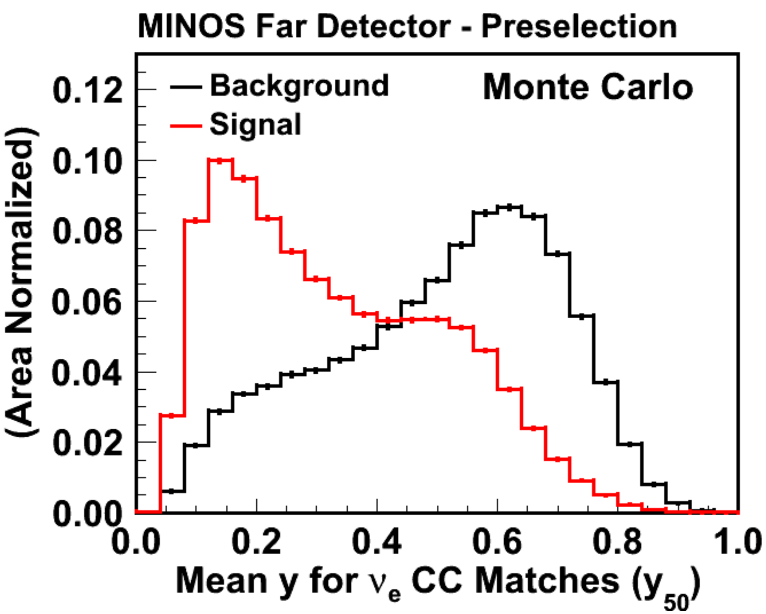
Info from best matches

How many of the best matches are signal?



How well do the charges overlap between the input event and the best matches?





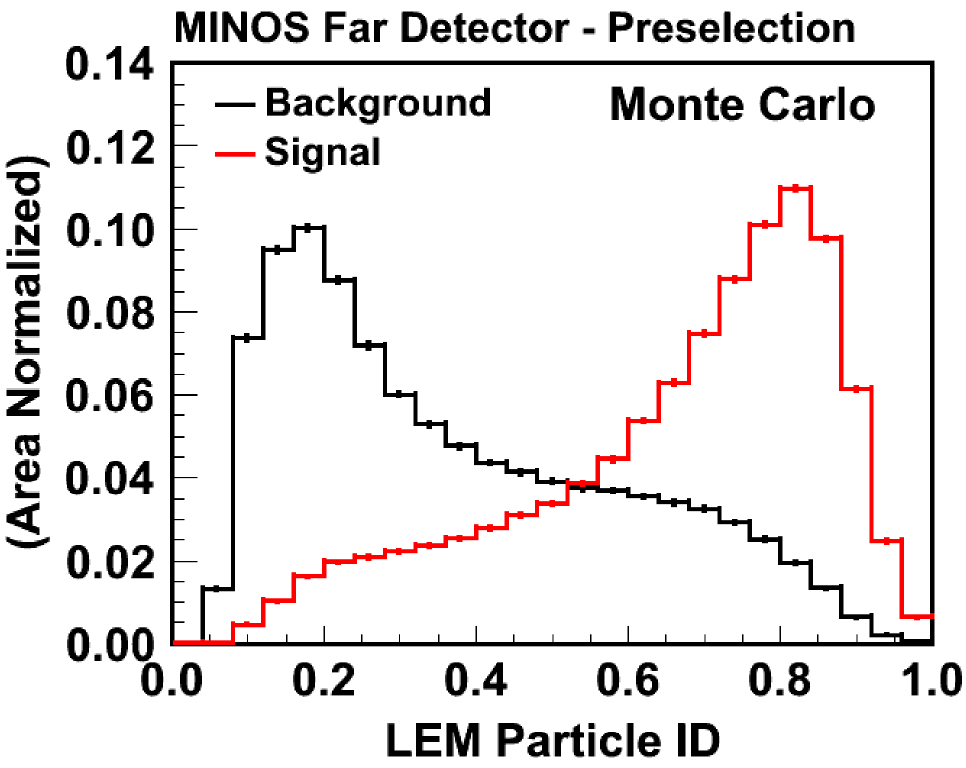
Average y of the ν_e CC matches?

(*y* = fraction of ν energy in the hadronic shower)

Library Event Matching (LEM)

3 variables + reconstructed energy used as inputs to a neural net

Output of neural net is the LEM selection variable



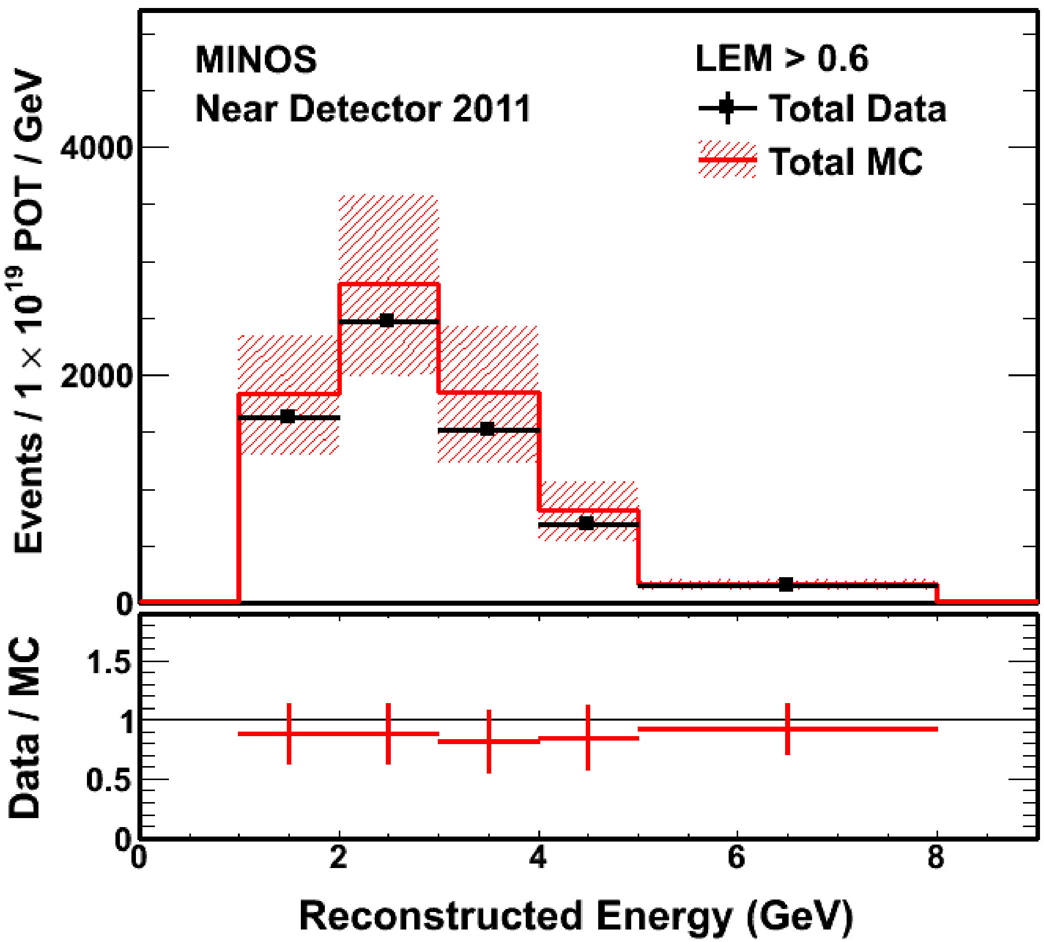
1) Determine selection criteria for ν_e candidate events

2) Use ND data to make a background prediction for the FD

3) Is there an excess of ν_e-like events over the predicted background in the FD?

Selected Near Detector Data

Apply the ν_e selection criteria to the ND data:



- Red shaded area is the systematic uncertainty on the MC simulation – dominated by uncertainties in modeling hadron production in ν interactions

- Having a near detector is essential – no need to rely solely on MC to predict the background in the far detector!

Background Extrapolation

Use ND measurement of NC, ν_μ CC, and beam ν_e CC backgrounds to predict FD background.

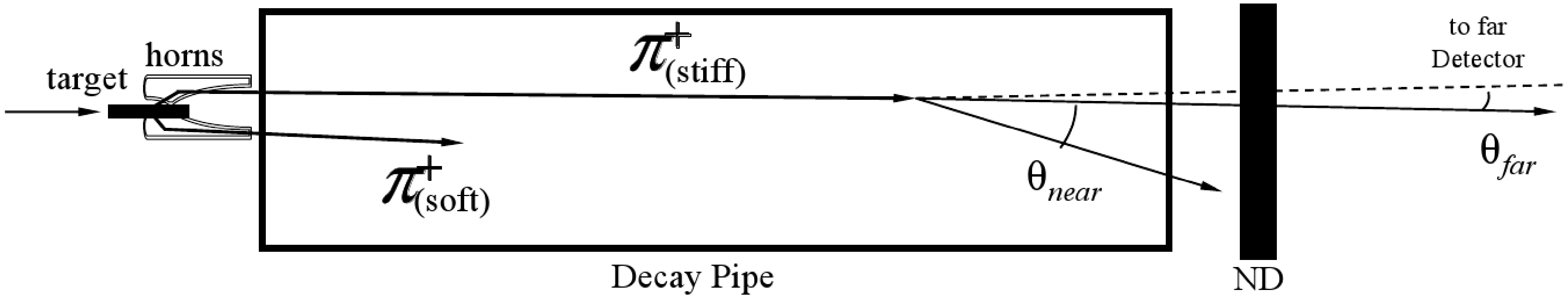
$$F_{\alpha,i} = N_{\alpha,i} \times R_{\alpha,i}^{F/N}$$

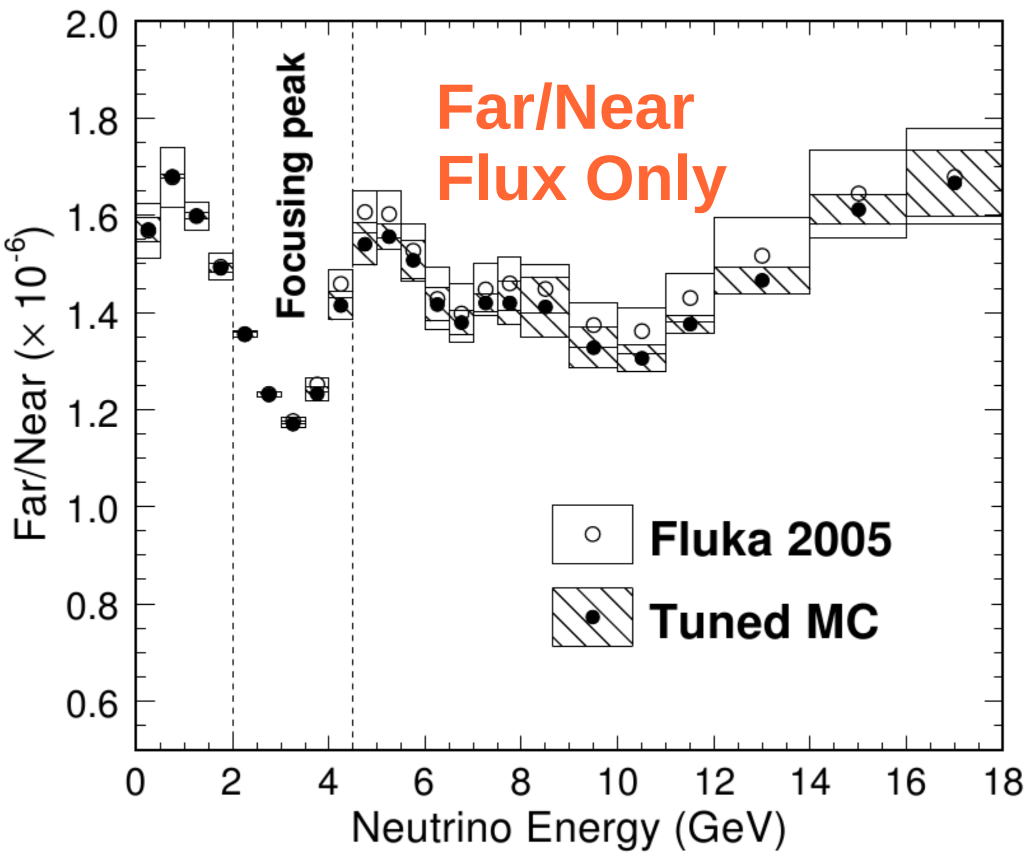
FD prediction for component α in bin i

ND data for component α in bin i

Far/Near ratio: Ratio of selected events for component α in bin i using MC

Far/Near Ratio

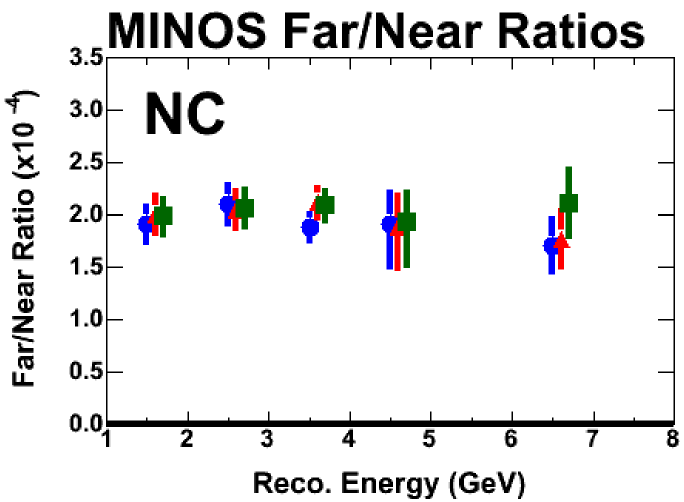


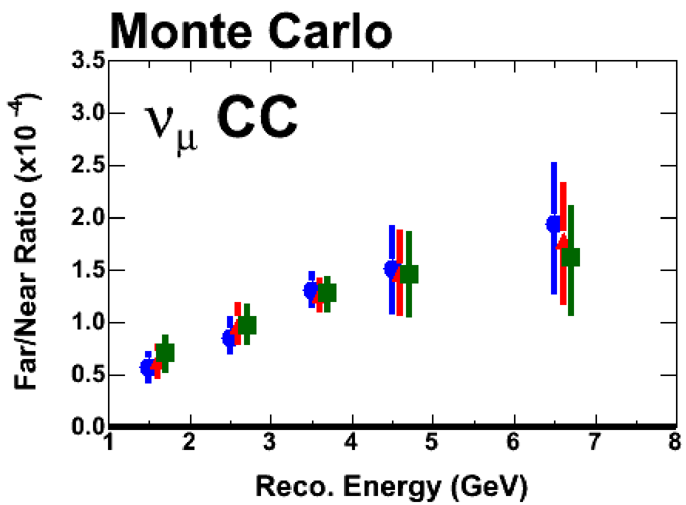


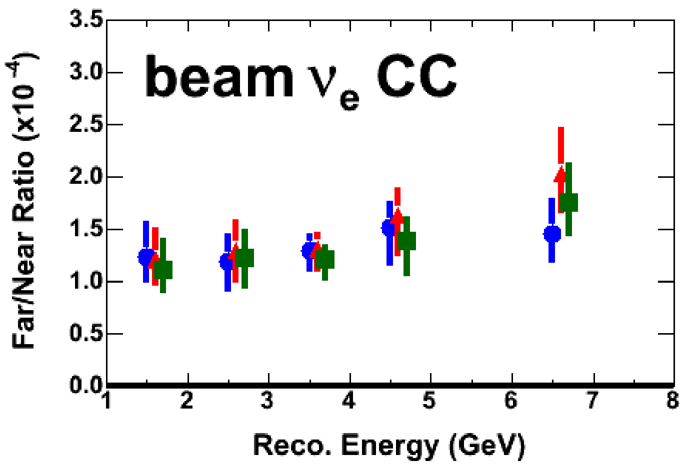
MC Far/Near ratio:

- Flux
  - $1/R^2$ fall-off
  - Point source vs line source (acceptance, decay kinematics, focusing...)

Far/Near Ratio







LEM>0.7

- ● **Run Period 1**
- ▲ **Run Period 2**
- ■ **Run Period 3**

MC Far/Near ratio:
- Flux
- Fiducial volume
- energy smearing
- ν_μ disappearance
- detector effects

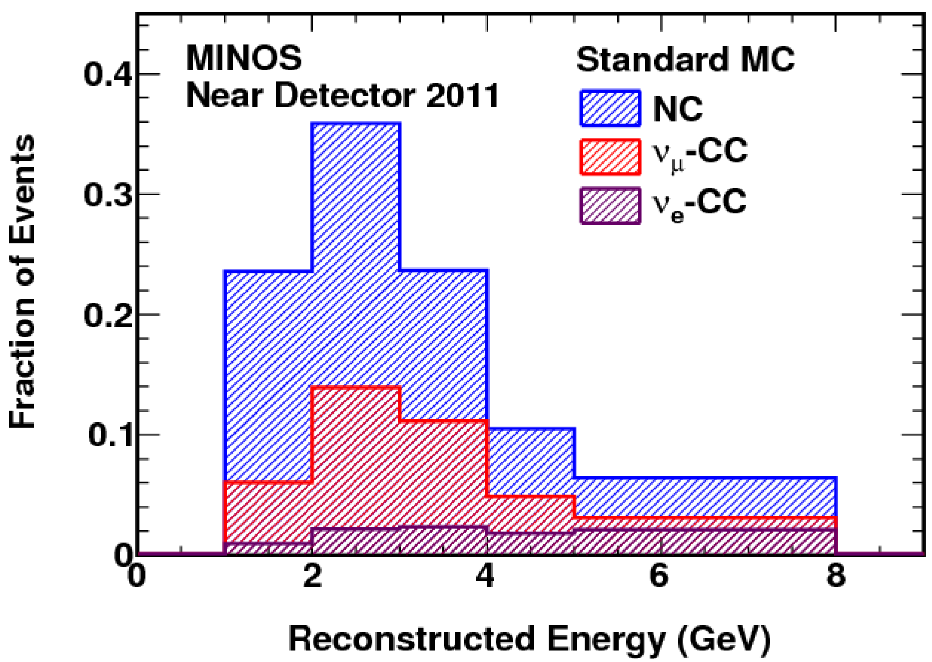
Error bars are systematic.

Near Detector Background

Oscillations affect each background component differently!

Need to know how much of each component in the ND data:

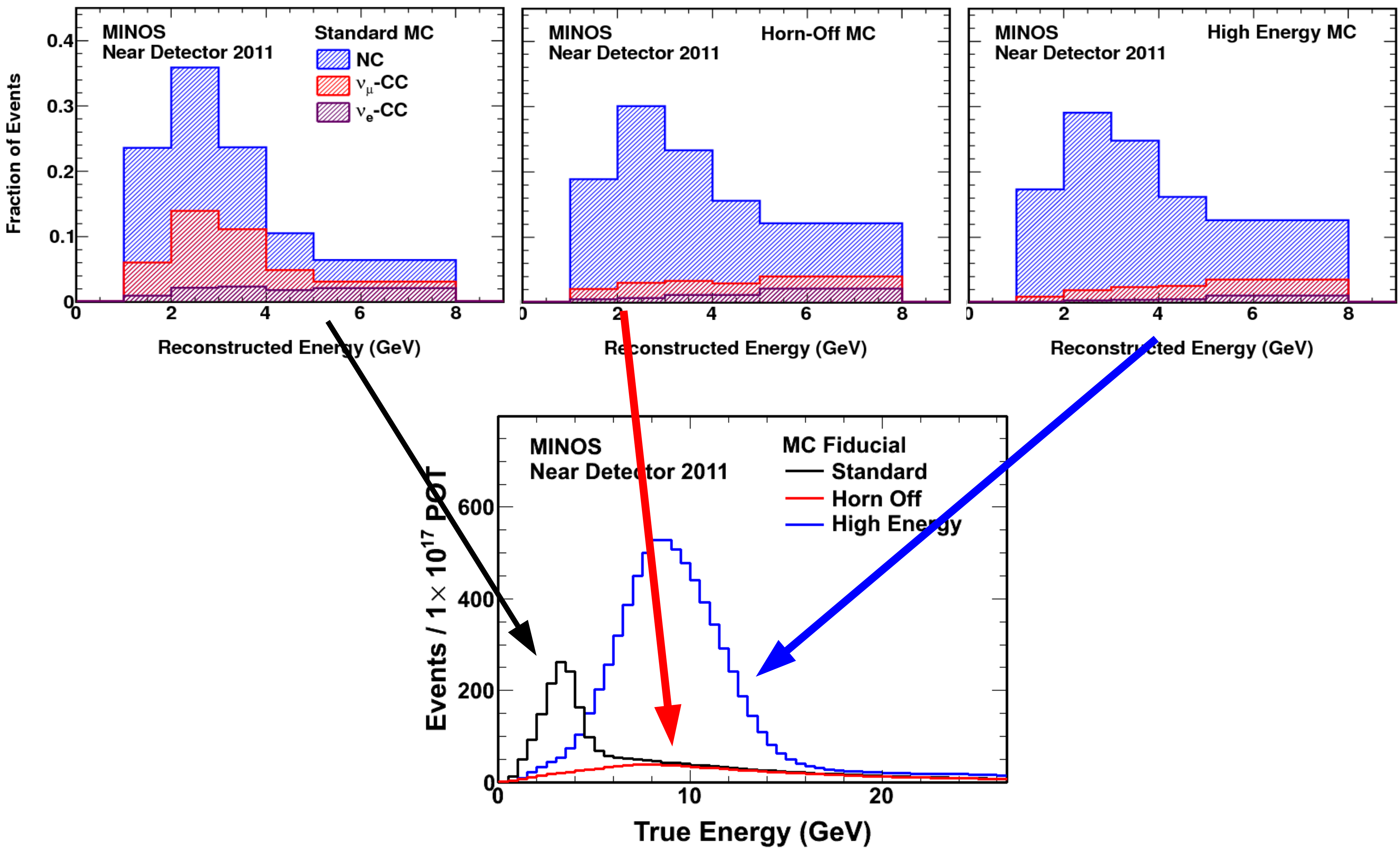
- **neutral current**
- **charged current ν_μ,**
- **charged current ν_e (from beam contamination)**



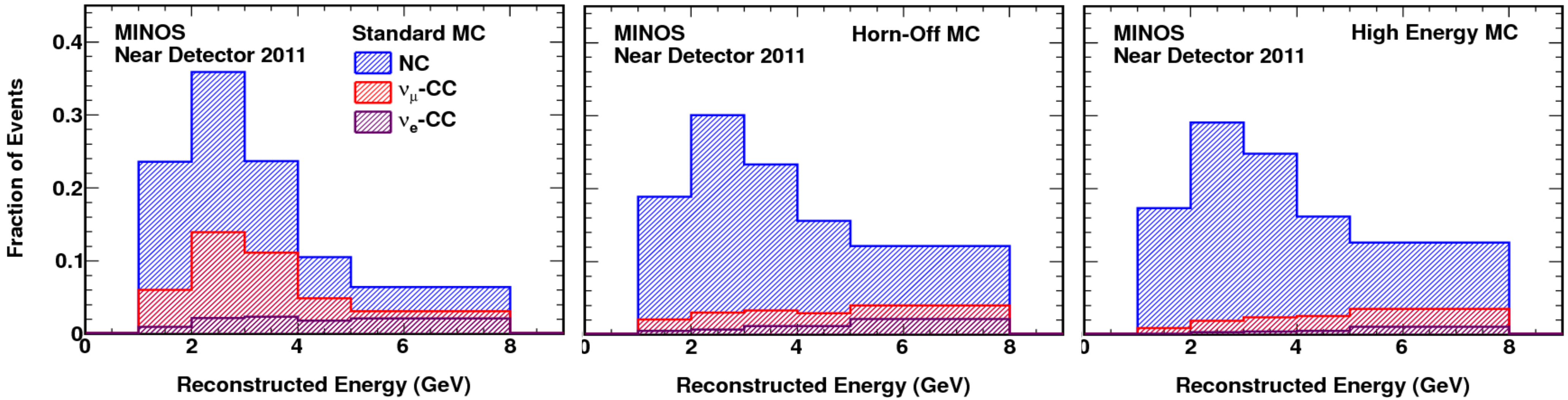
Extract it from the data – don't rely on the simulation

Due to the flexibility of our beam, we can use near detector data taken with different beam configurations to do this...

Different Beam Configurations



Data-Driven Background Separation

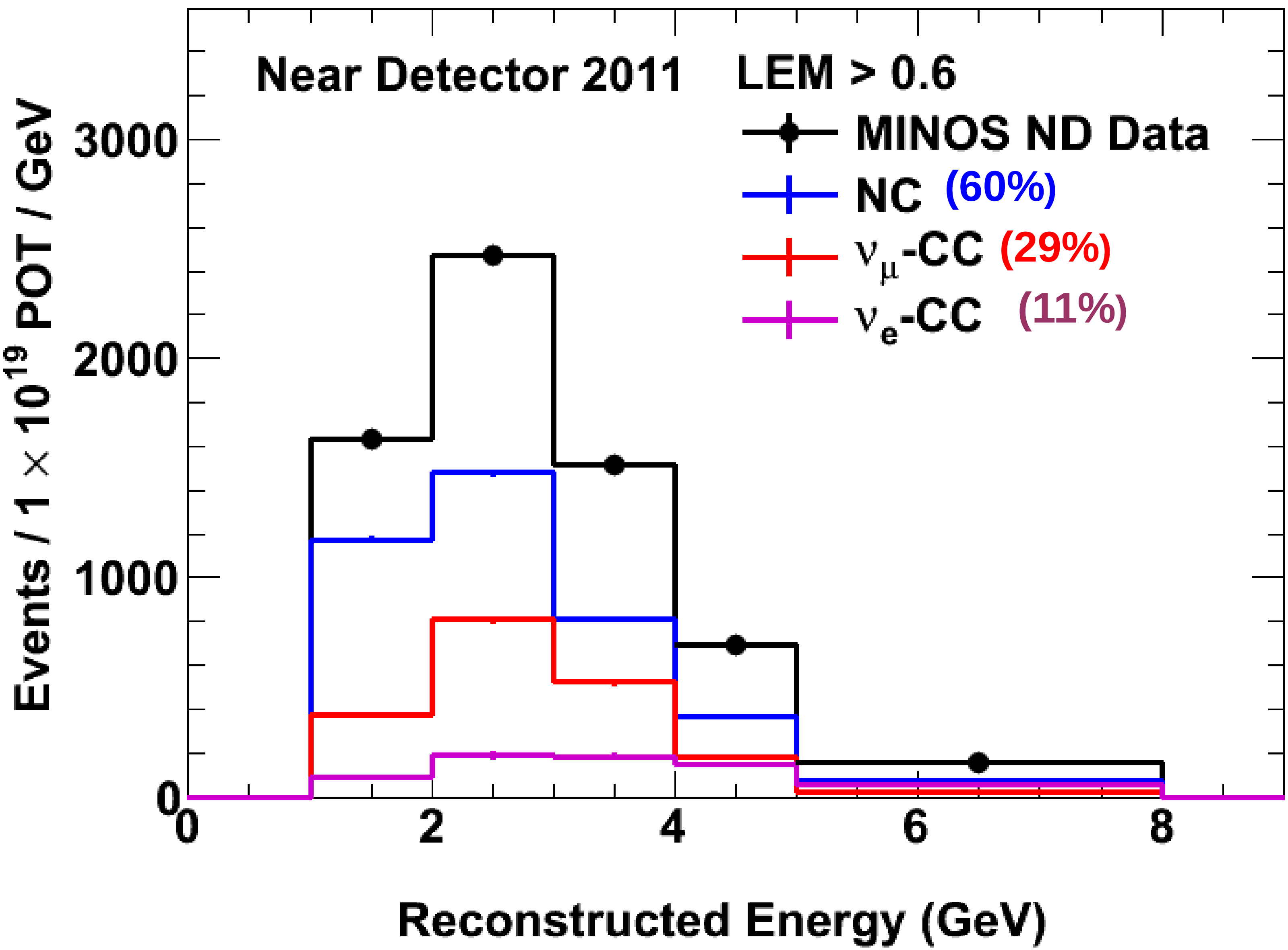


Use these 3 data sets to measure the 3 background components in the standard sample...

Using:
- Total measured rate in each beam configuration
- Relative interaction rates for each background component from the MC simulation

Can fit for the background components in the standard sample

Data-Driven Background Separation



Far Detector Prediction

For 8.2×10^{20} POT

Signal-enhanced region (LEM>0.7)

$\delta=0$

$\Delta m^2 = 2.32 \times 10^{-3}\ \mathrm{eV}^2$

$\theta_{23} = \pi/4$

$\sin^2 2\theta_{13} = 0.16$

Component	# Events
NC	34
ν_μ CC	7
beam ν_e CC	6
ν_τ CC	2
Total Bkgd	**49**
ν_e CC signal	**30**

PRELIMINARY

Predicted background and signal at CHOOZ limit

Note bkgd prediction is dependent on θ_{13}

Background Systematics

1) How well we know the composition of the near detector background (small)

2) How well we know the Far/Near ratio
- Calibration - relative energy calibration, gains, absolute energy calibration, etc
- Relative Far/Near normalization
- Hadronization model - hadrons produced in the neutrino interaction
- etc

Systematic Uncertainty 5.4%

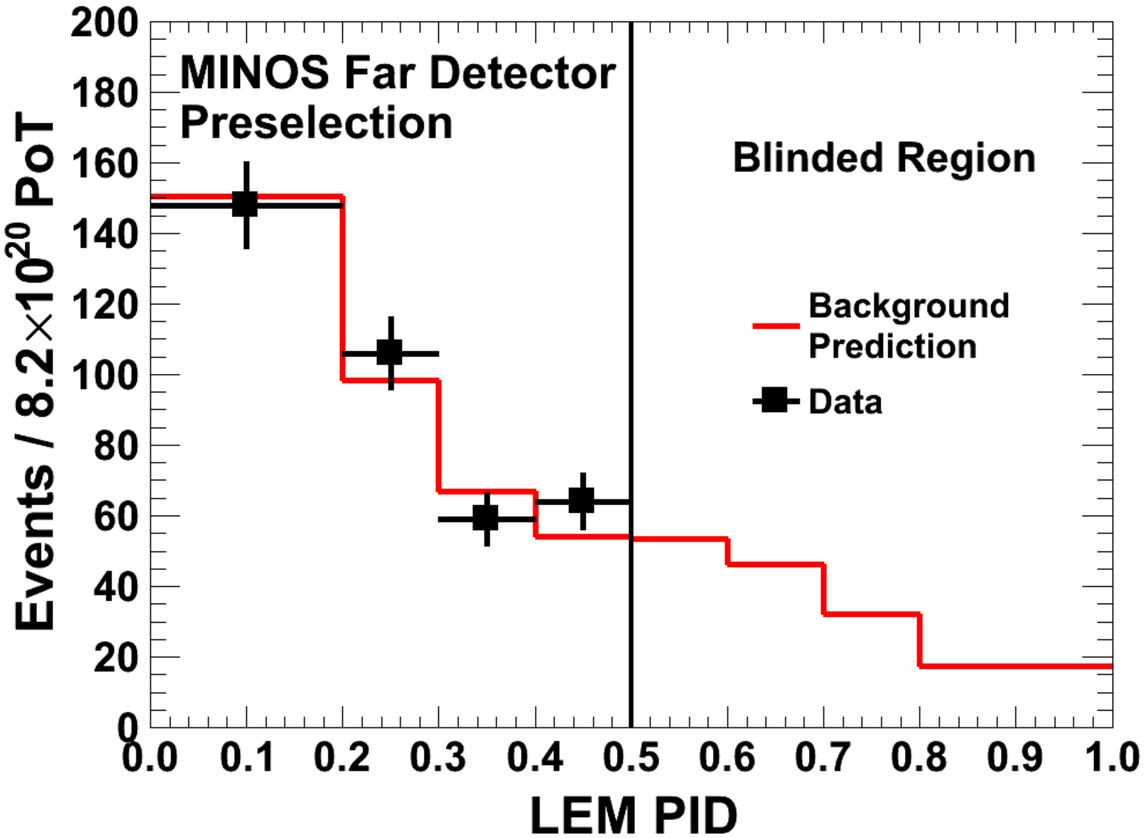
On the background prediction in the signal-enhanced region (LEM>0.7)

1) Determine selection criteria for ν_e candidate events

2) Use ND data to make a background prediction for the FD

3) Is there an excess of ν_e-like events over the predicted background in the FD?

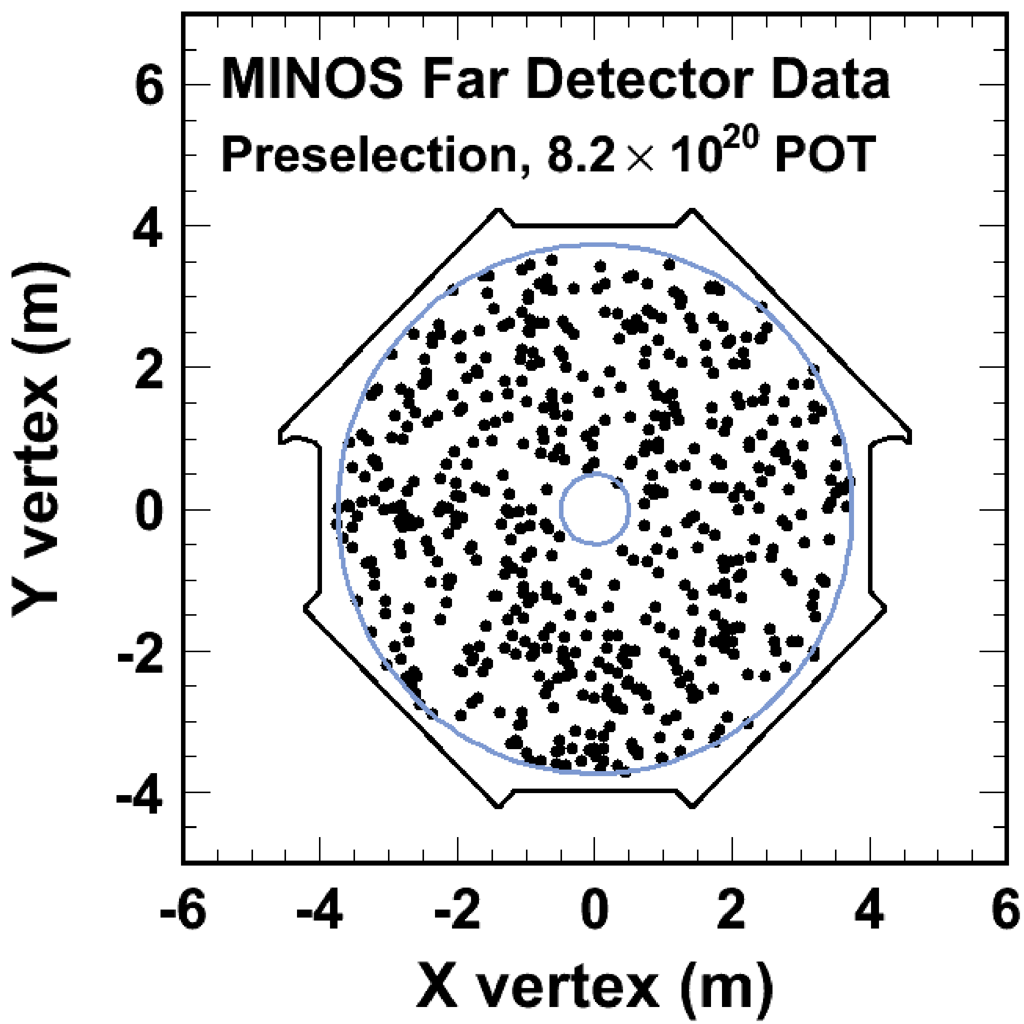
Sideband: Outside the Signal Region



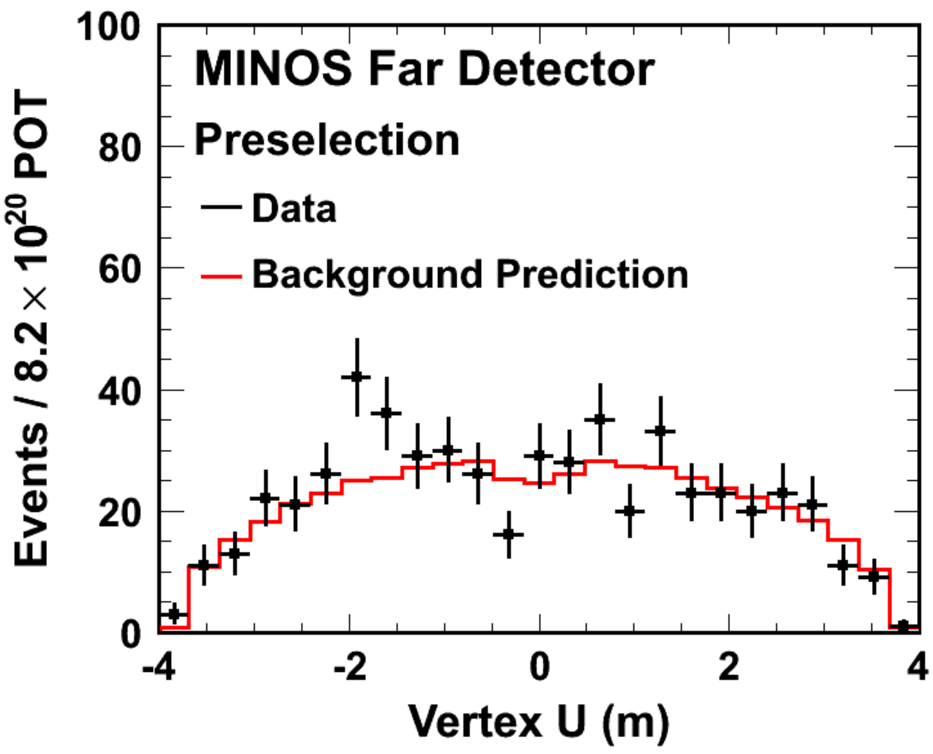
LEM<0.5
observe 377 events
expect 370 +- 19(stat) (@ $\theta_{13} = 0$)

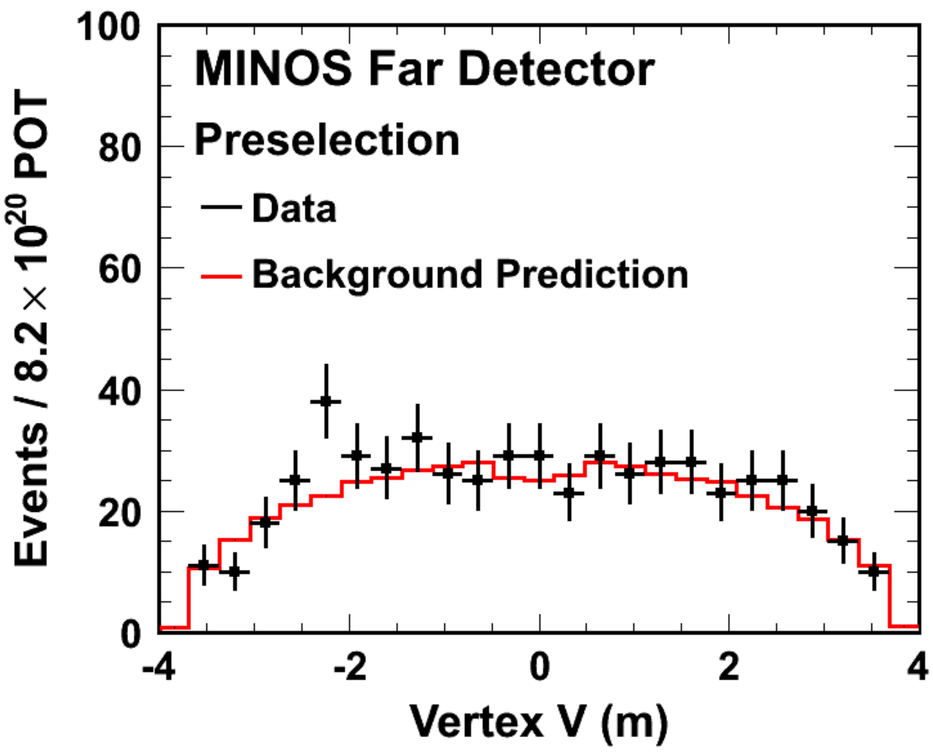
Good test of entire analysis chain - background prediction and extrapolation to far detector.

FD Vertex Distribution

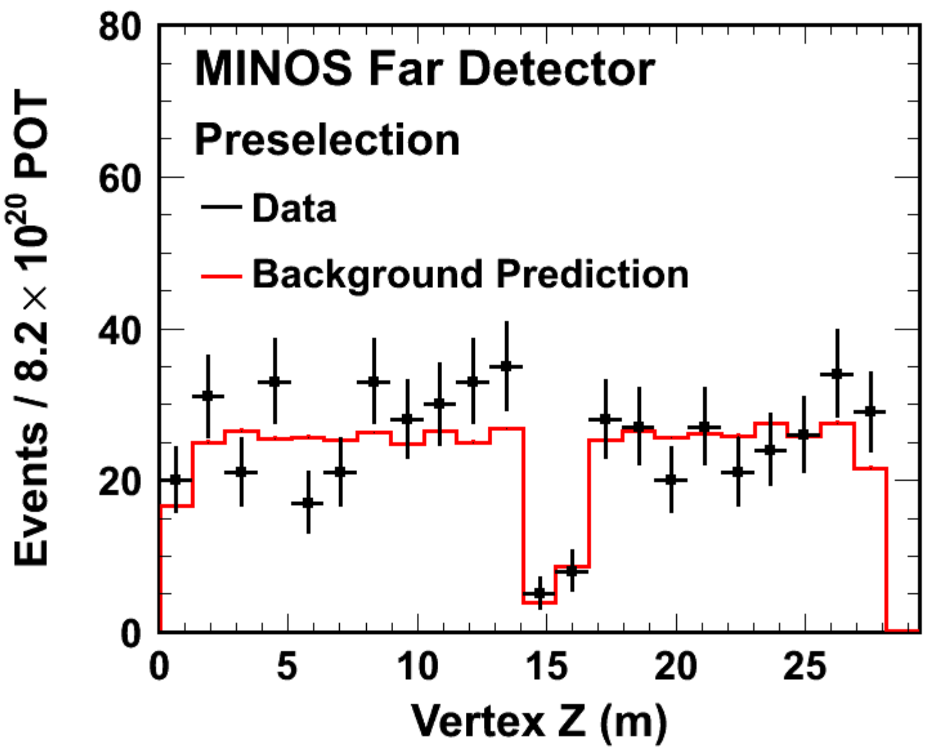


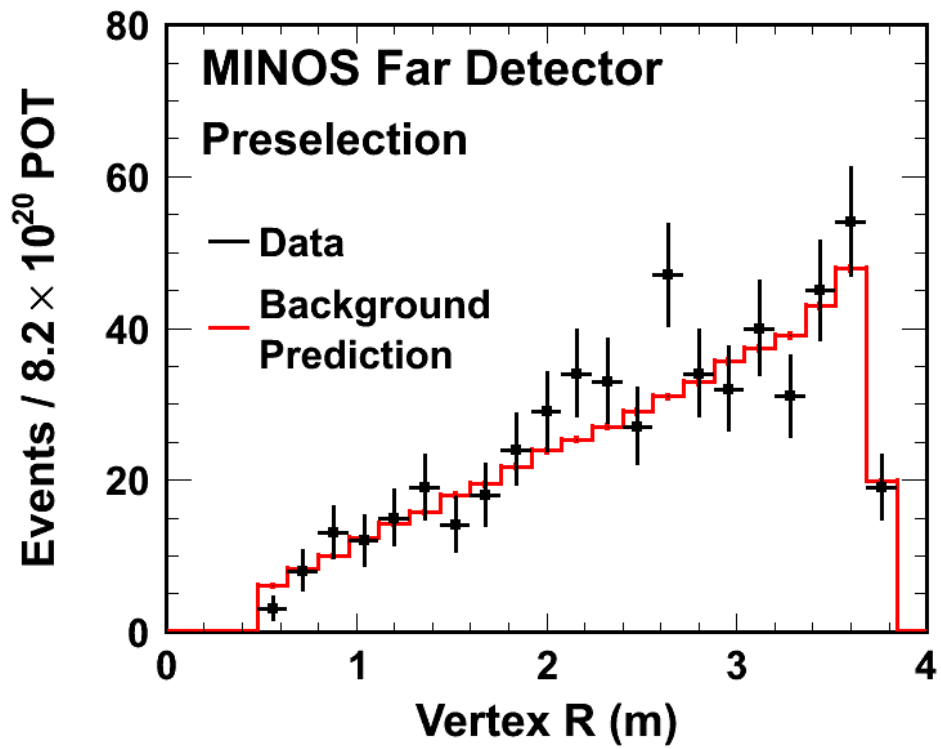
FD Vertex Distributions



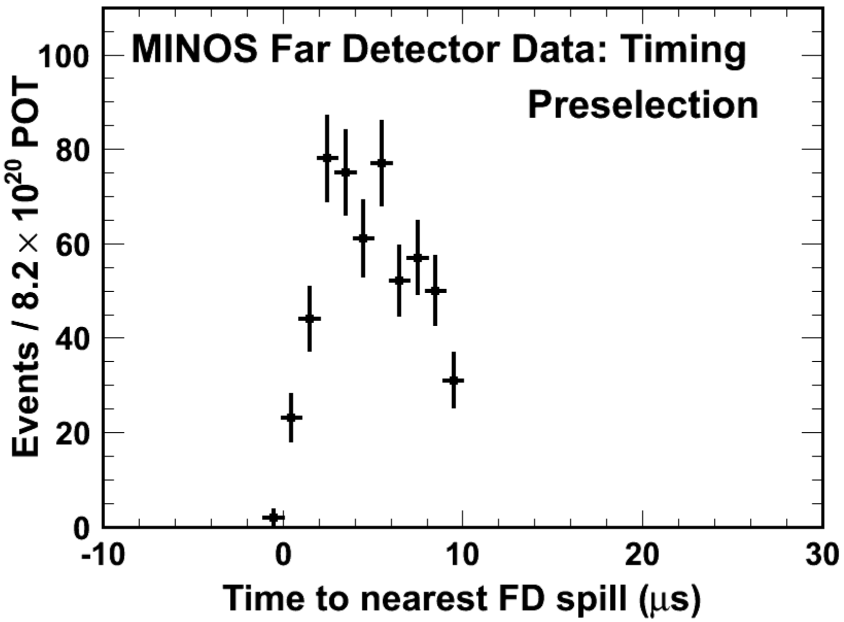


FD Vertex Distributions

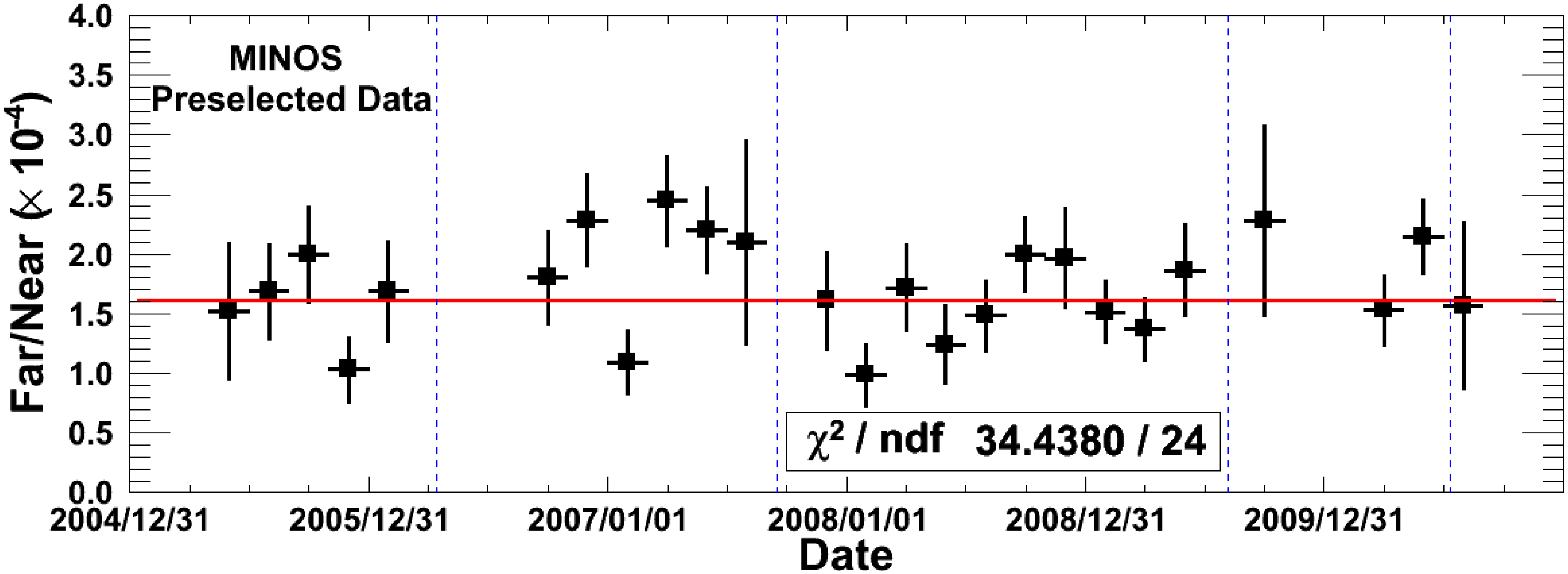




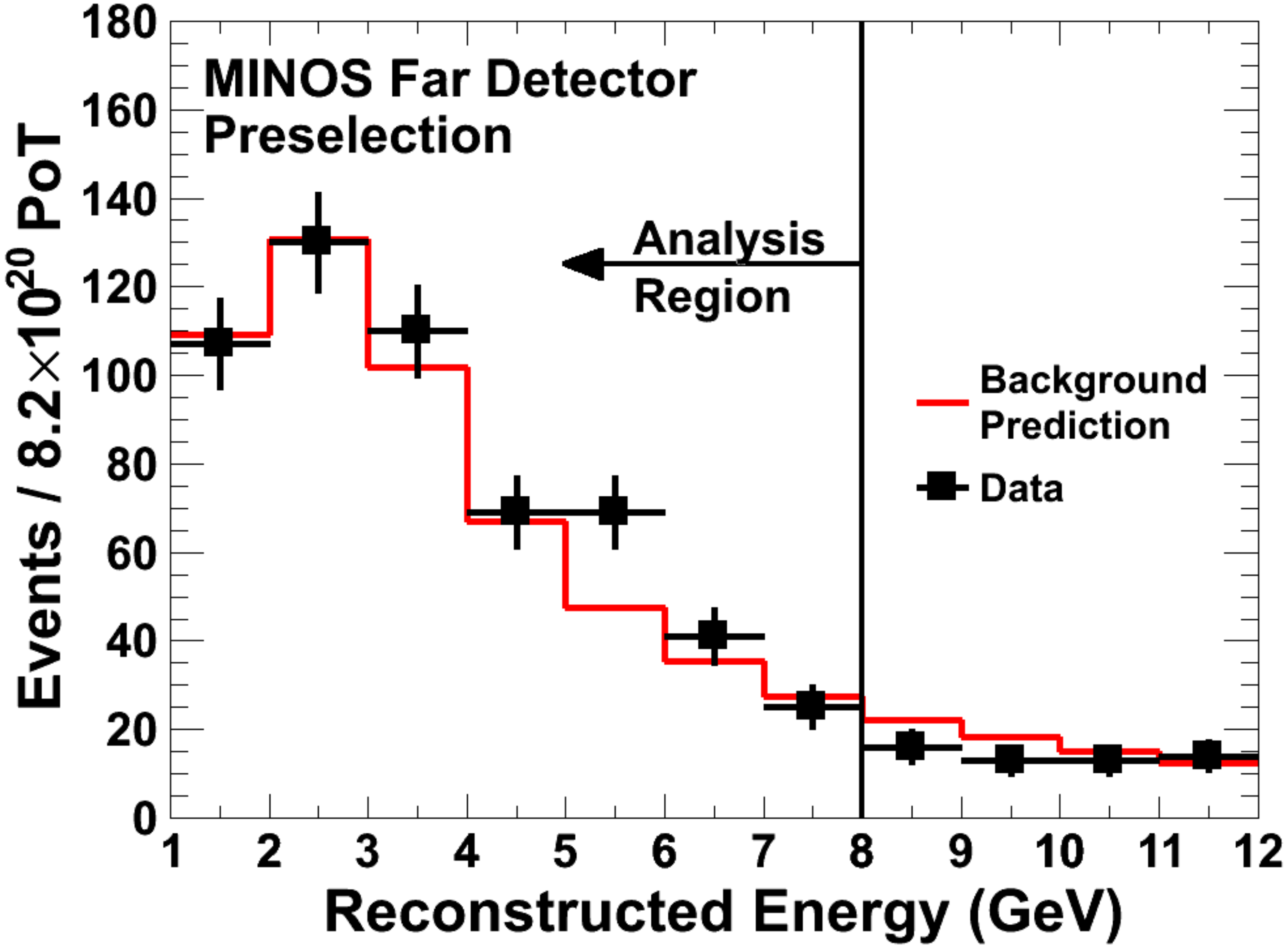
Event Time / Rate Vs Time



Ratio of FD to ND preselected data



FD Energy Spectrum



2.7σ (stat.) excess in the 5-6 GeV region

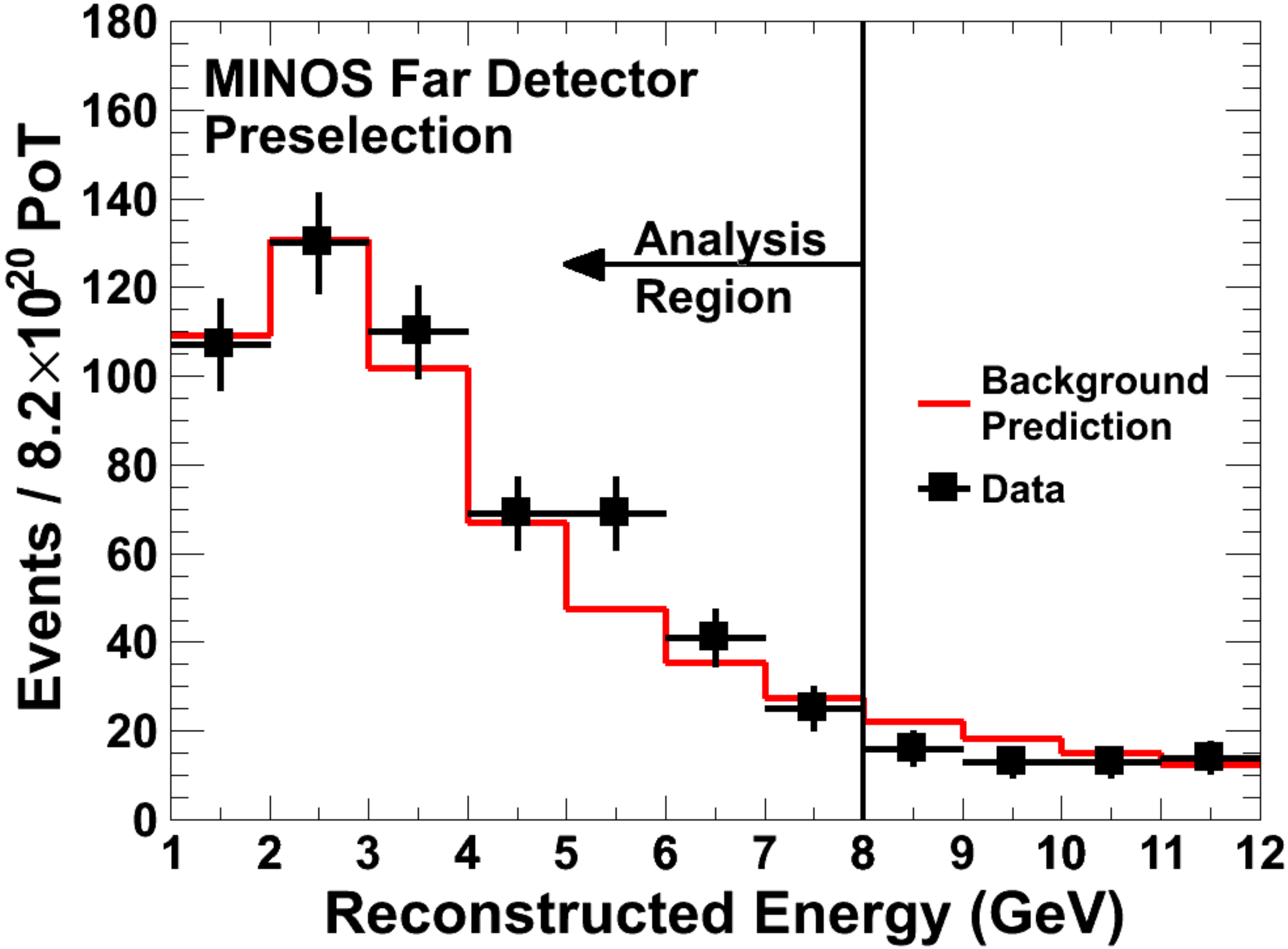
Possible sources?

- statistical fluctuation
- Hot strips, etc
- misclassified events
- actual appearance of shower like events

Investigation:

- Event scanning
- Distributions of basic variables
- Considered cosmics, rock neutrons
- is excess nue-like?

FD Energy Spectrum



Initially planned to fit for θ_{13} to the LEM shape, integrated in energy

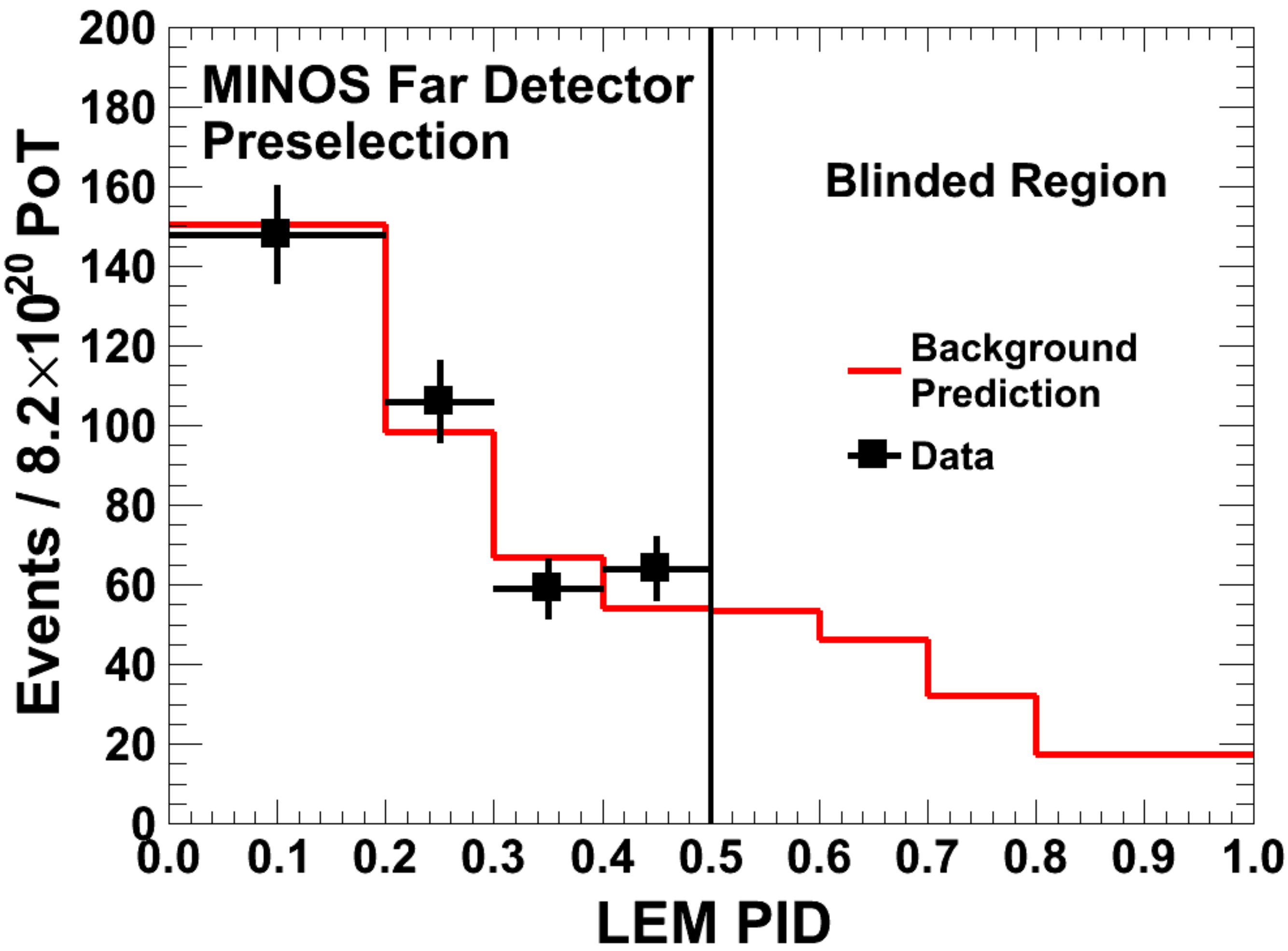
Official result is 2D fit in both energy and LEM shape

- Oscillations are an energy-dependent model: don't want a fluctuation to introduce a false signal
- BUT we don't want to cut data simply because it is statistically unlikely.

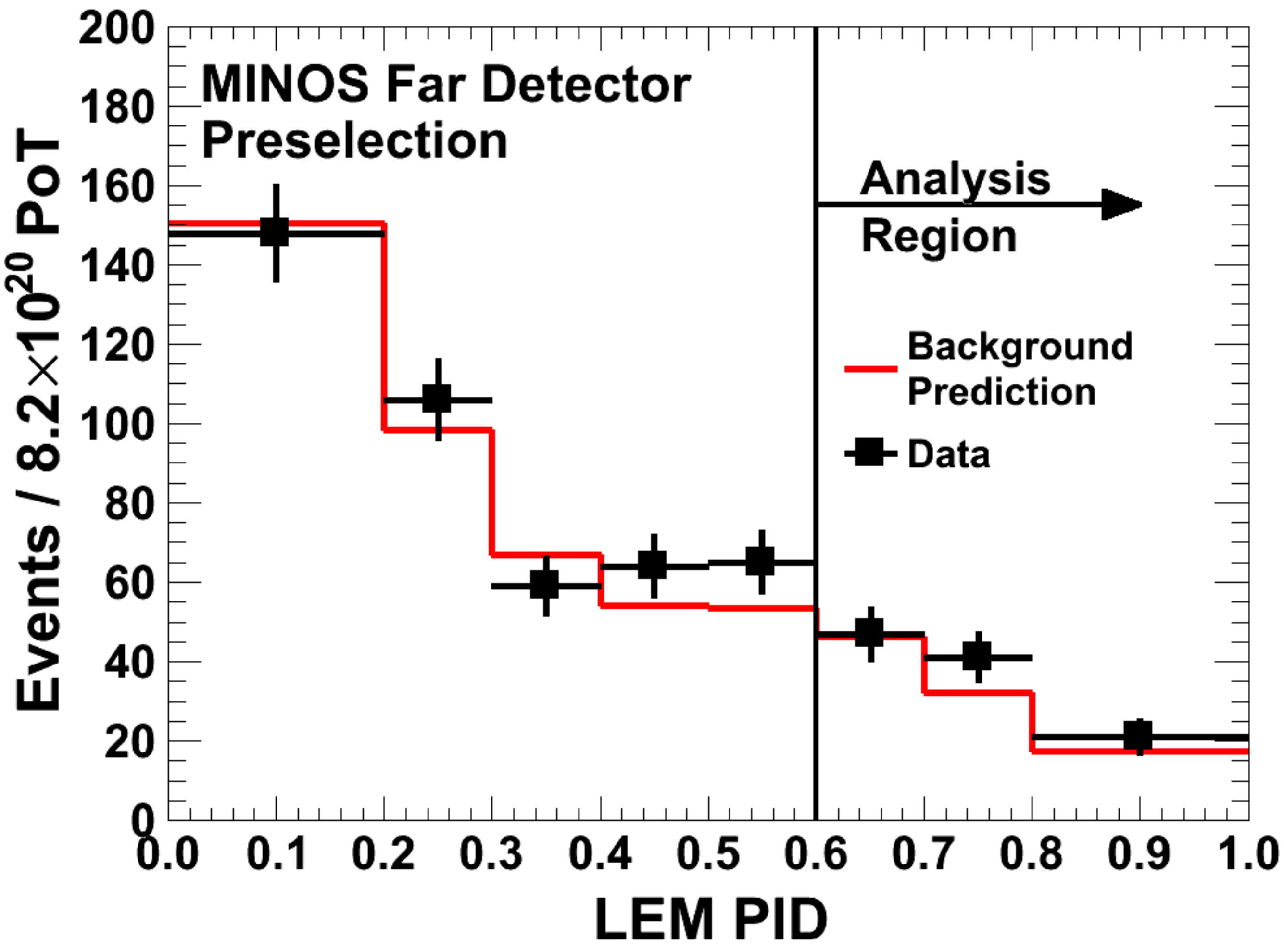
Conclusion: excess is likely a statistical fluctuation.

Data in the signal region....

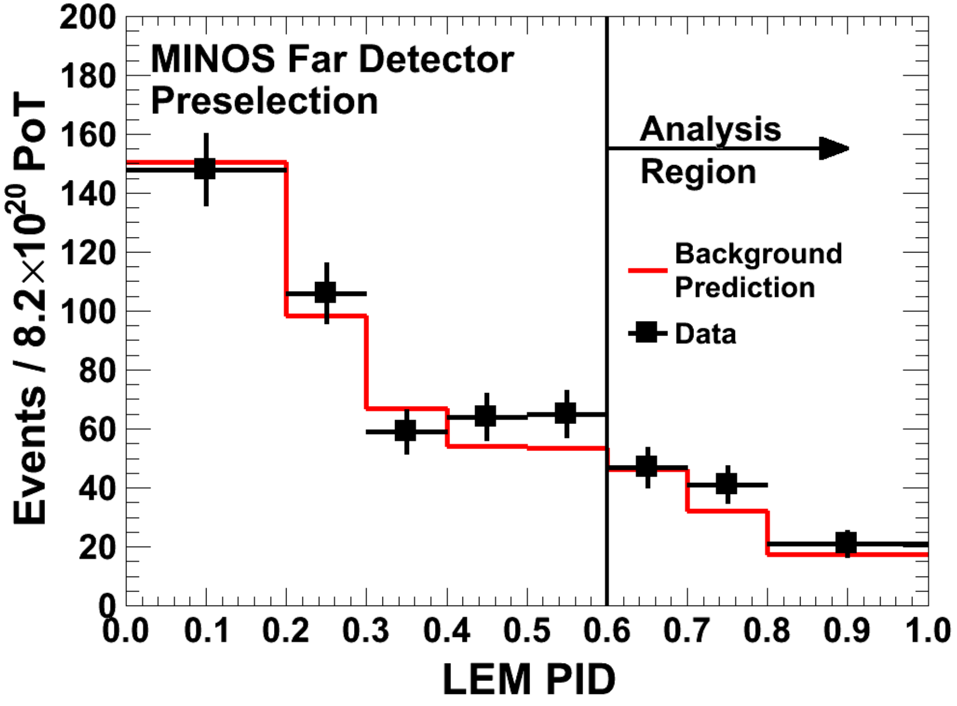
FD Preselected Data



FD Preselected Data



Event Count



In signal-enhanced region (LEM>0.7):

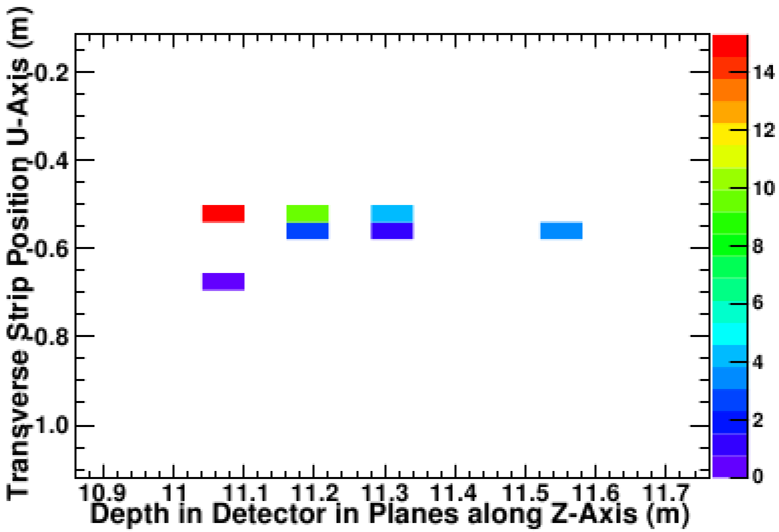
Expected background (θ_{13}=0):

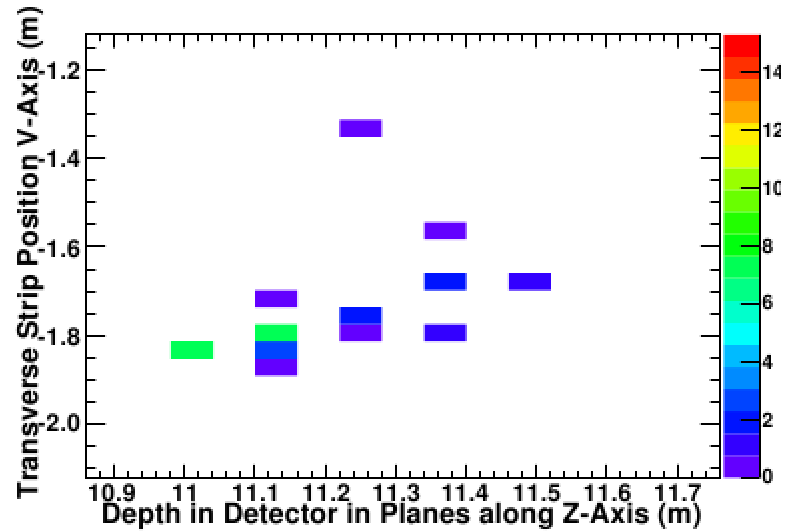
49.6 +- 2.7 (syst) +- 7.0 (stat)

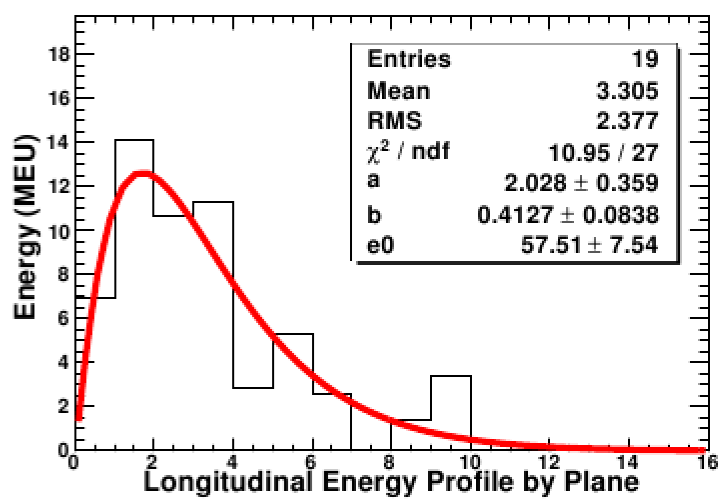
Observed data:

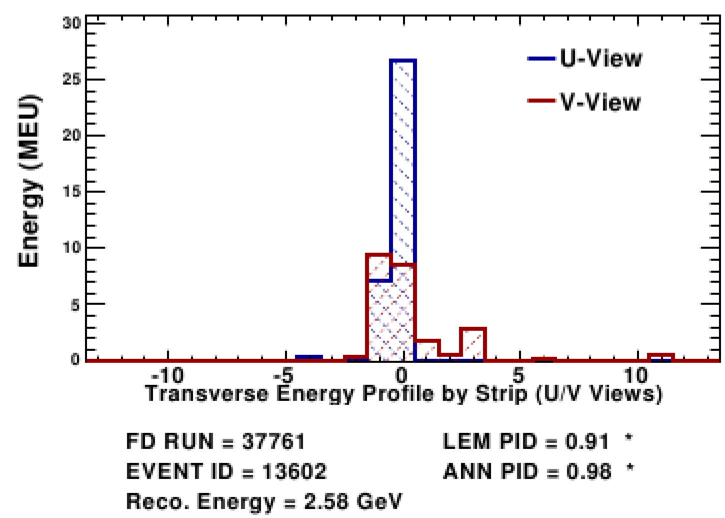
62

Example of a Selected Event

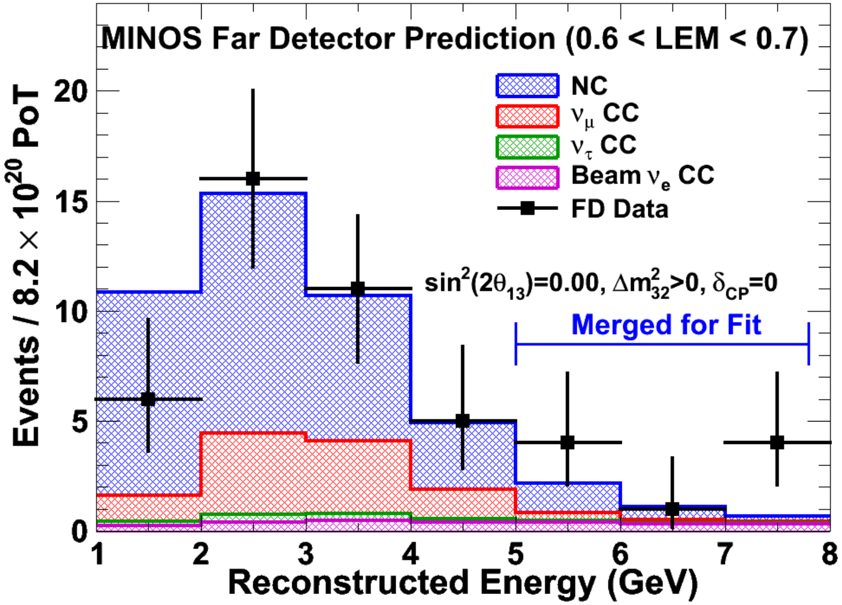


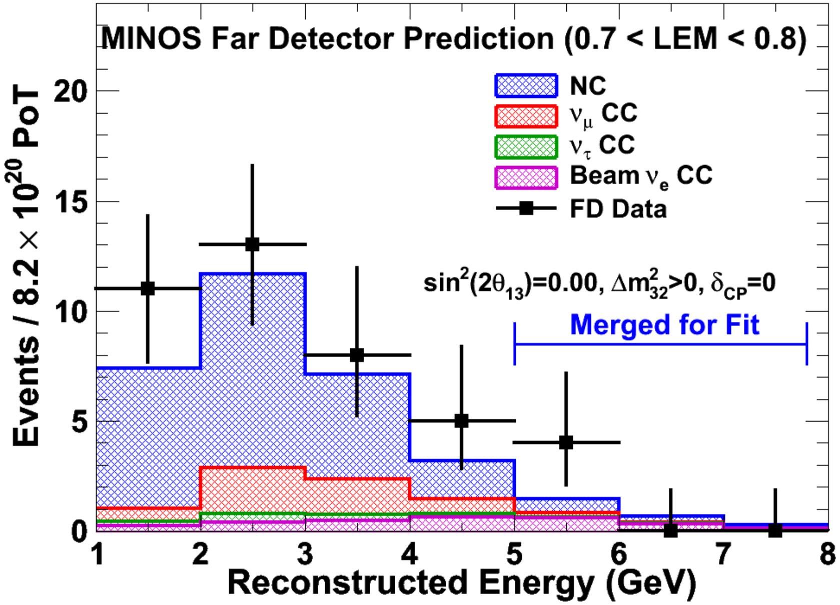


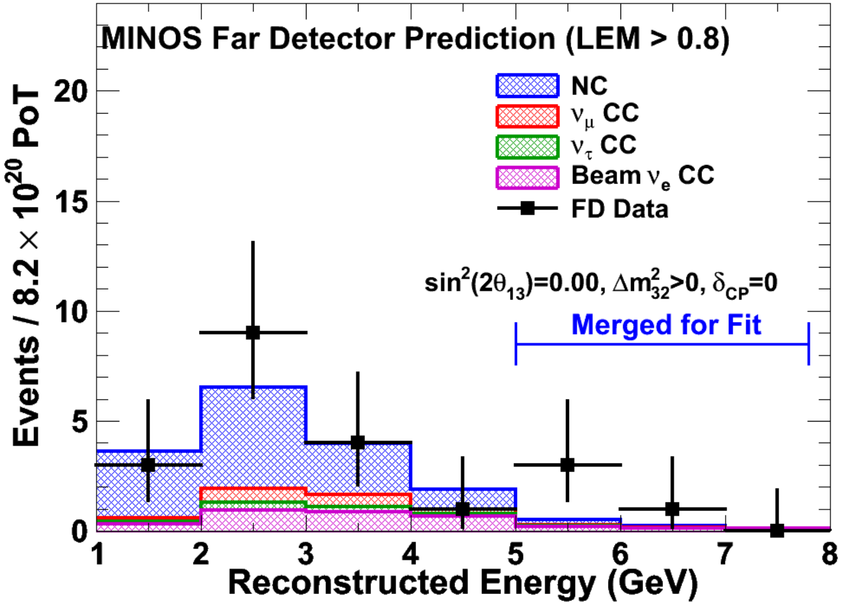




Fitting to Oscillations

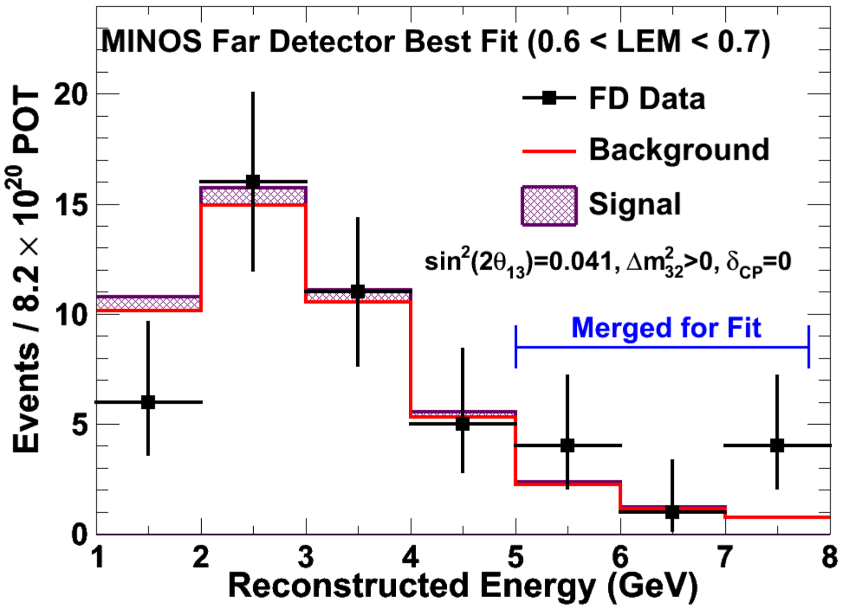


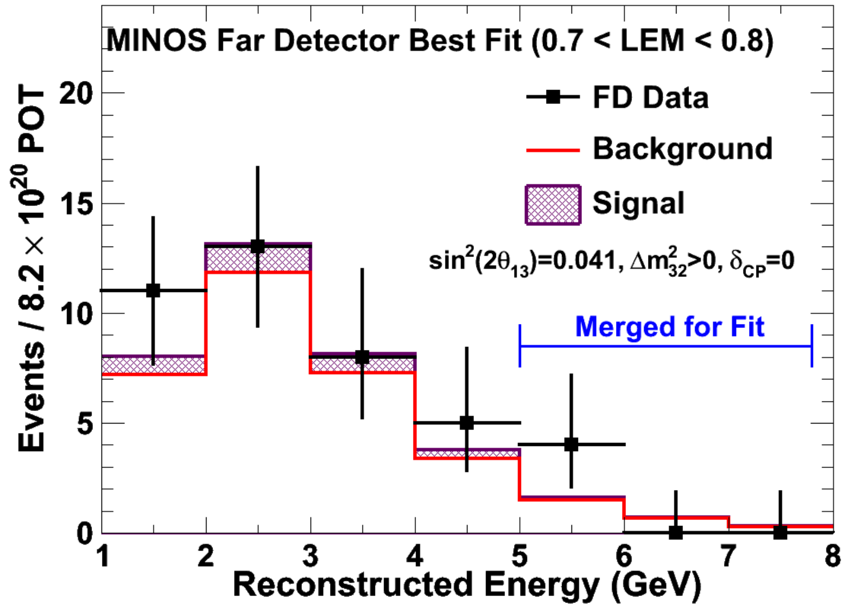


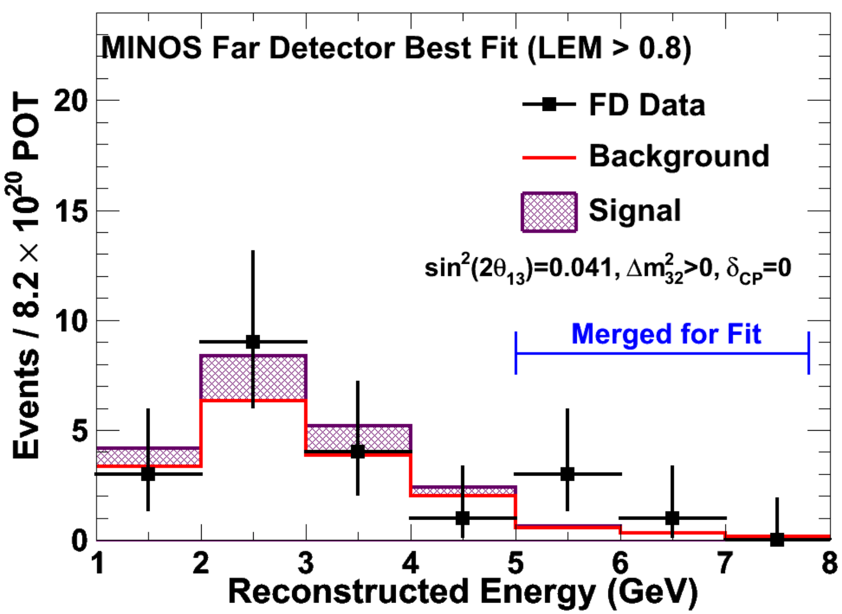


15 bin fit
3 LEM bins x 5 energy bins

Best Fit



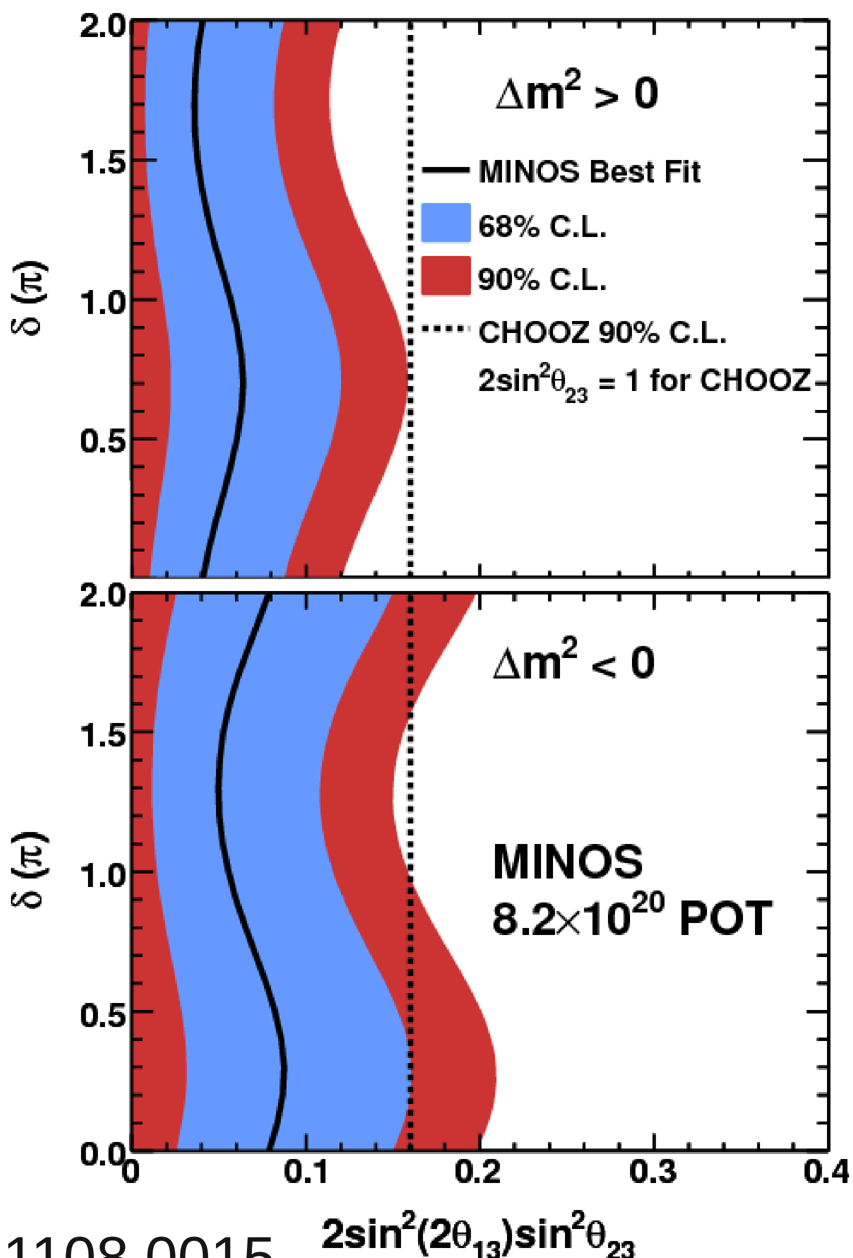




Best fit $\sin^2 2\theta_{13}$ = 0.041

(Assuming δ=0, $\theta_{23}=\pi/4$, normal hierarchy)

Allowed Regions



arxiv:1108.0015

Assuming:
$\delta=0,\ \theta_{23}=\pi/4$
normal (inverted) hierarchy

$$\sin^2(2\theta_{13})<0.12(0.20)$$

90% CL

$$\sin^2(2\theta_{13})=0.04(0.08)$$

Best Fit

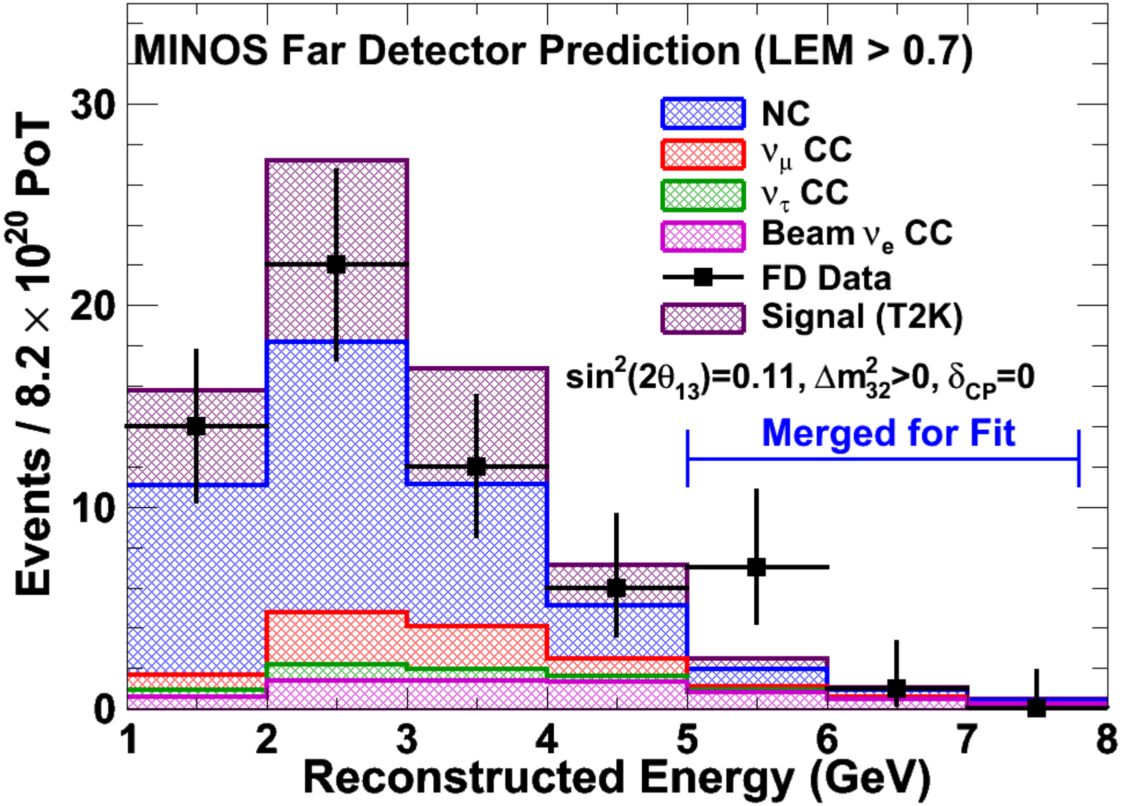
We exclude $\sin^2 2\theta_{13}=0$ at 89% CL

Feldman-Cousins contours

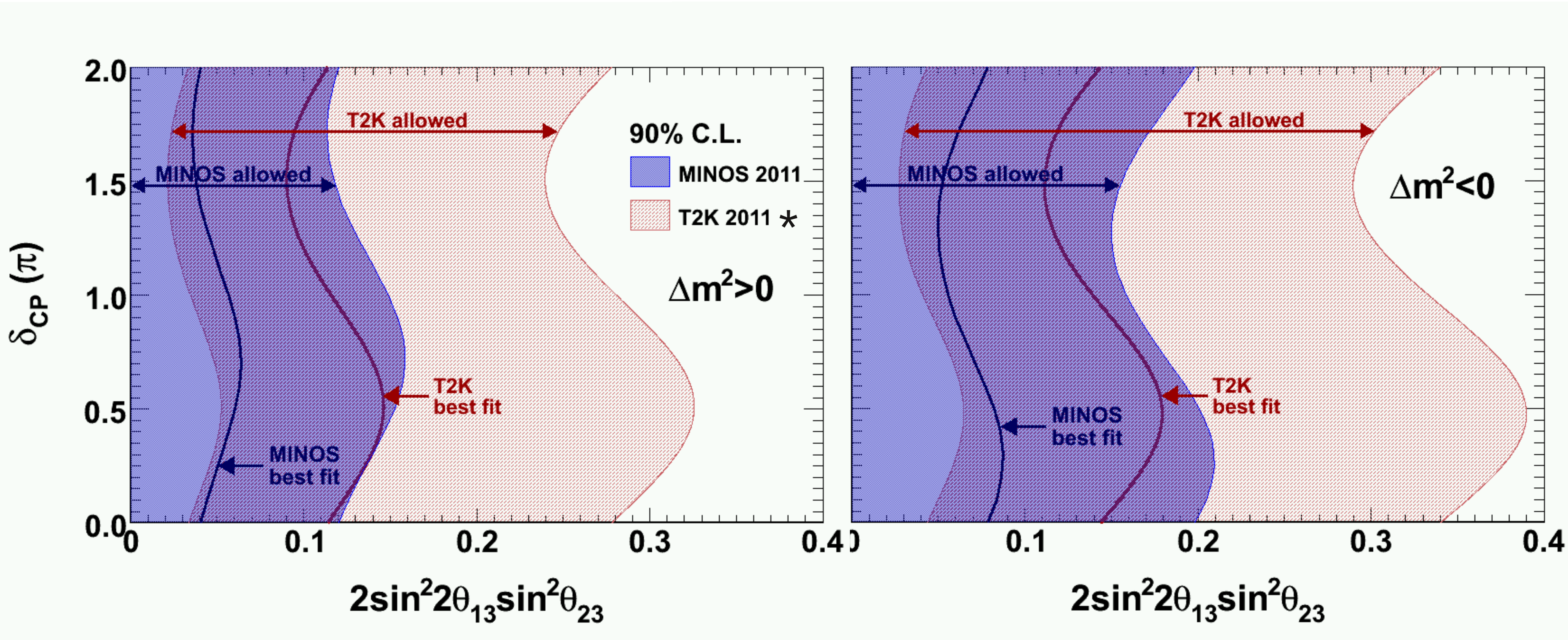
Uncertainties in the other oscillation parameters are included

Comparison to T2K Results

What does our signal prediction look like at T2K's best fit? ($\sin^2 2\theta_{13}$=0.11)

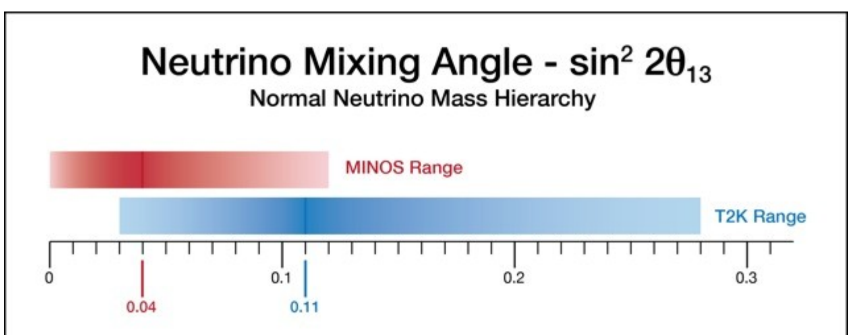


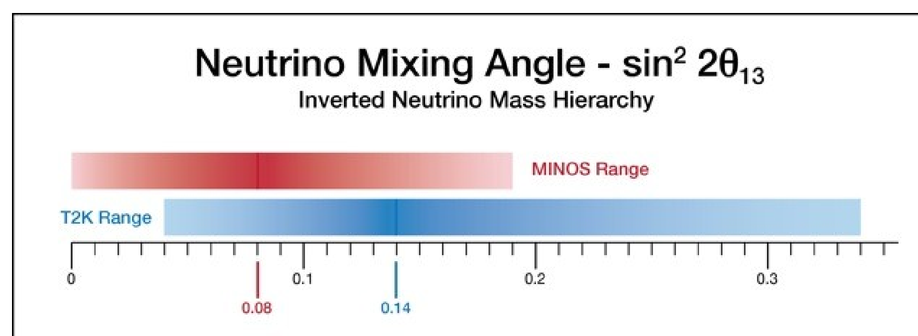
Comparison to T2K Results



* arXiv:1106.2822

Overlay of our allowed region with T2K's
(NOT a combined fit)



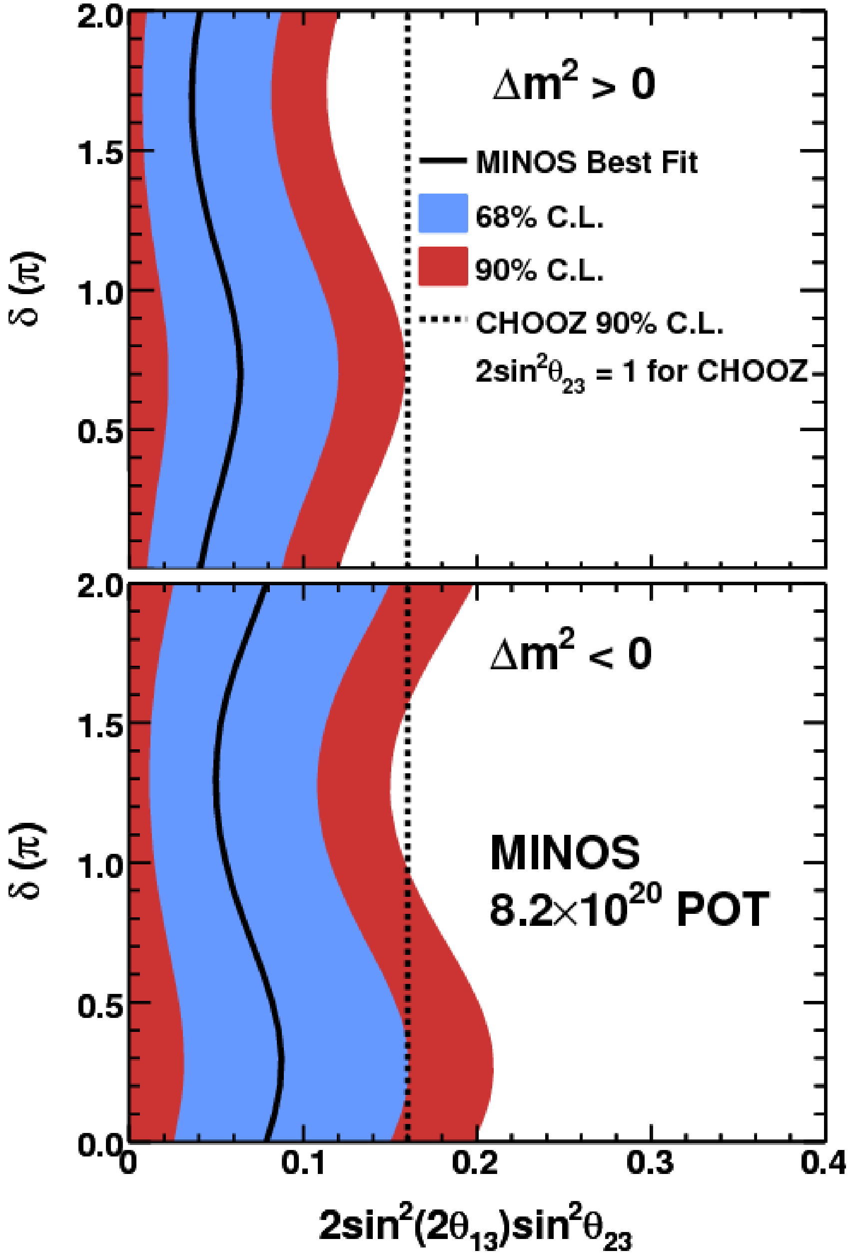


Summary

• MINOS has updated our electron neutrino appearance search with more data and improved analysis techniques: overall 30% gain in sensitivity

• In the signal region, we observe 62 events with an expectation of ~50

• Assuming $\delta=0$, $\theta_{23}=\pi/4$, normal (inverted) hierarchy, we set a 90% CL upper limit of
$\sin^2(2\theta_{13})<0.12$ (0.20)
and a best fit value of
$\sin^2(2\theta_{13})=0.04$ (0.08)
and exclude $\sin^2(2\theta_{13})=0$ @ 89% CL



arxiv:1108.0015