# New Results on Muon Neutrino to Electron Neutrino Oscillations in MINOS

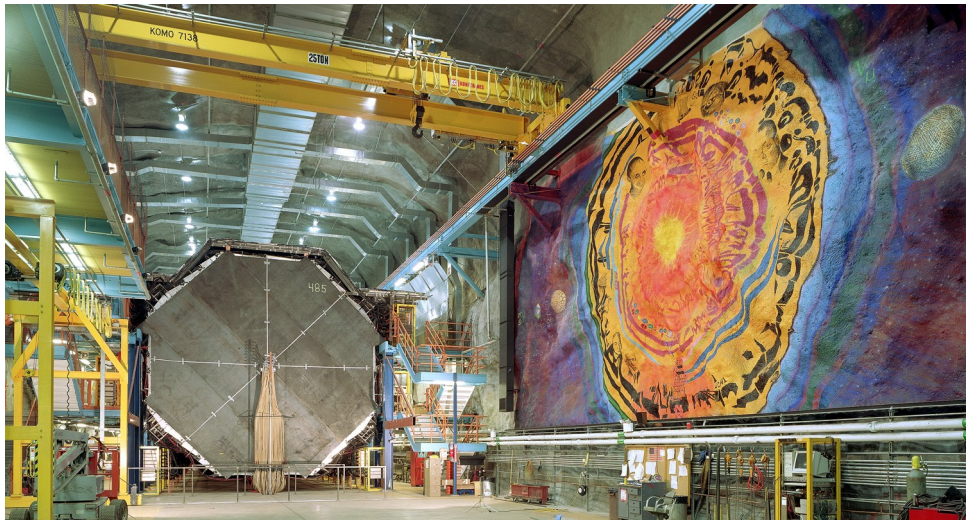
**Lisa Whitehead**
**Brookhaven National Laboratory**

**On behalf of the MINOS Collaboration**

**FNAL Wine and Cheese, June 24, 2011**

# Outline

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



# Neutrino Mixing

if the flavor ($\nu_e$, $\nu_\mu$, $\nu_\tau$) 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
ħ = c = 1

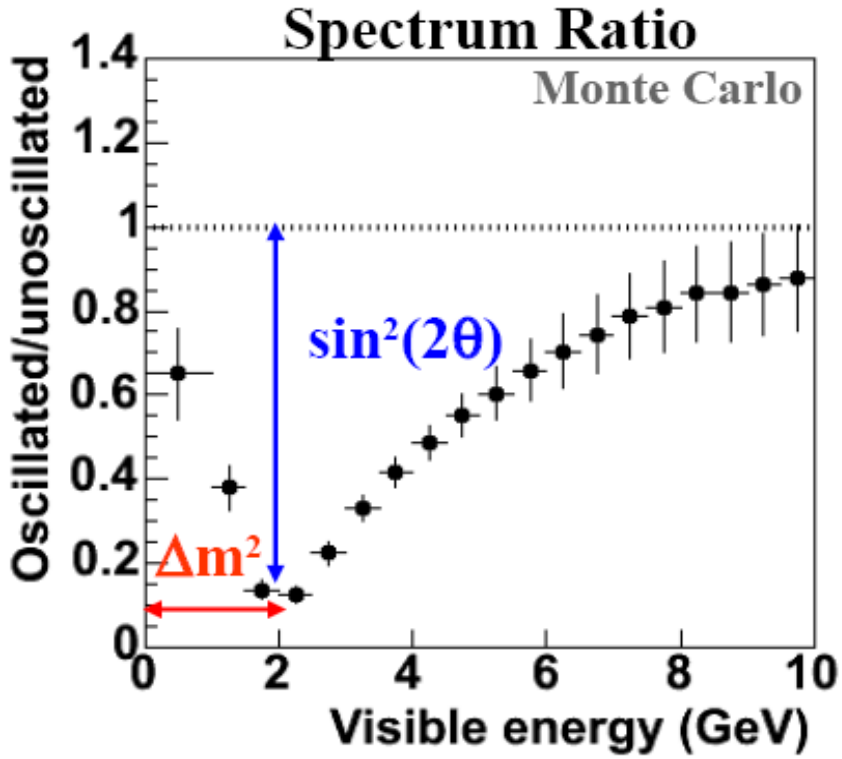
# Neutrino Oscillations

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

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

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 ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and one phase ($\delta$) *

(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)

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

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

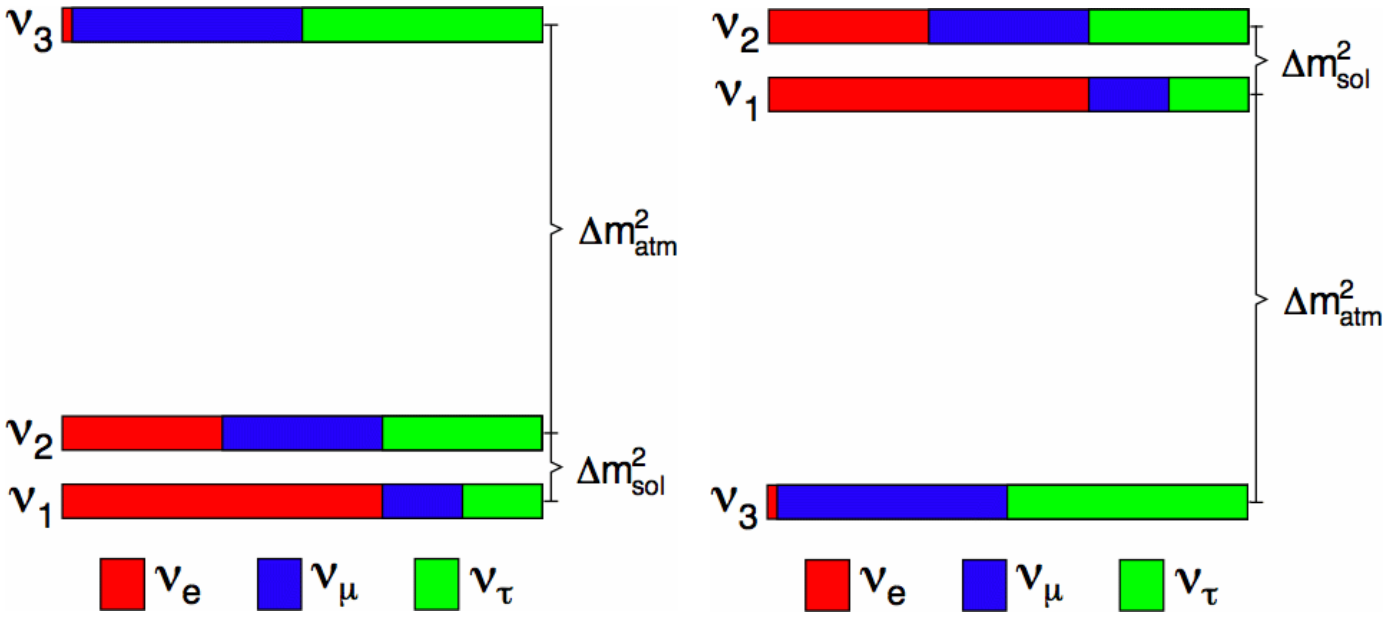
from atmospheric/ accelerator ν (Super-Kamiokande, MINOS)

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

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

## Open questions:

**Normal Hierarchy or Inverted Hierarchy?**




$$\delta = ?$$

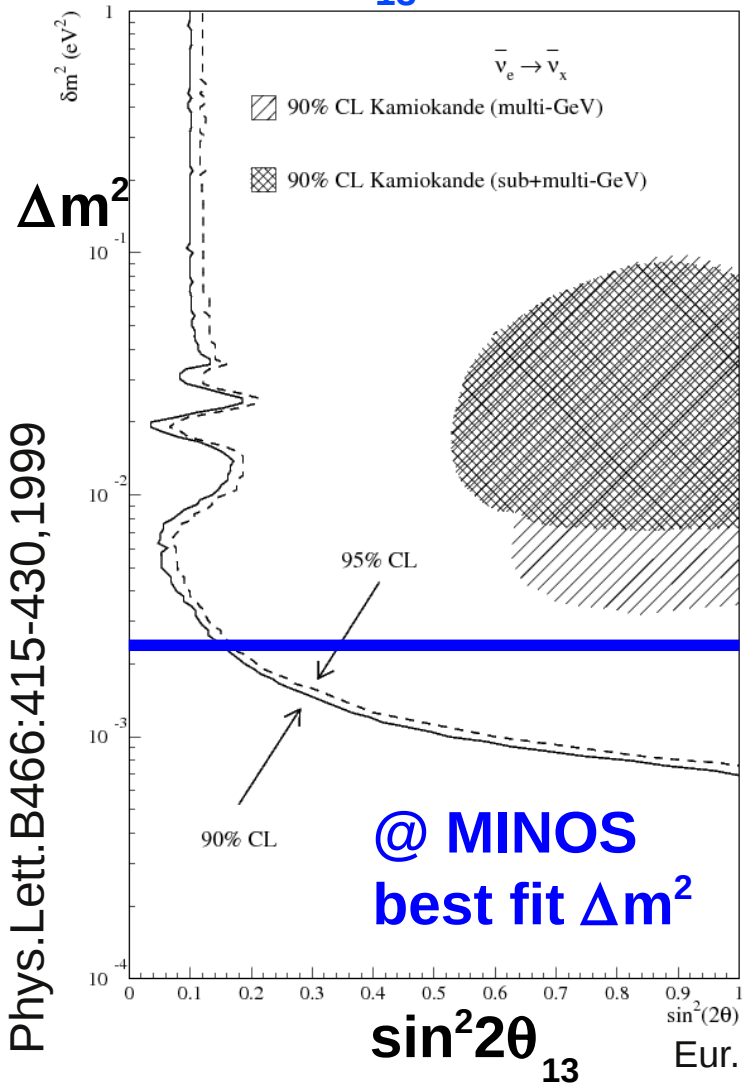
$$\theta_{13} = ?$$

# Measuring $\theta_{13}$ with reactor $\nu$'s

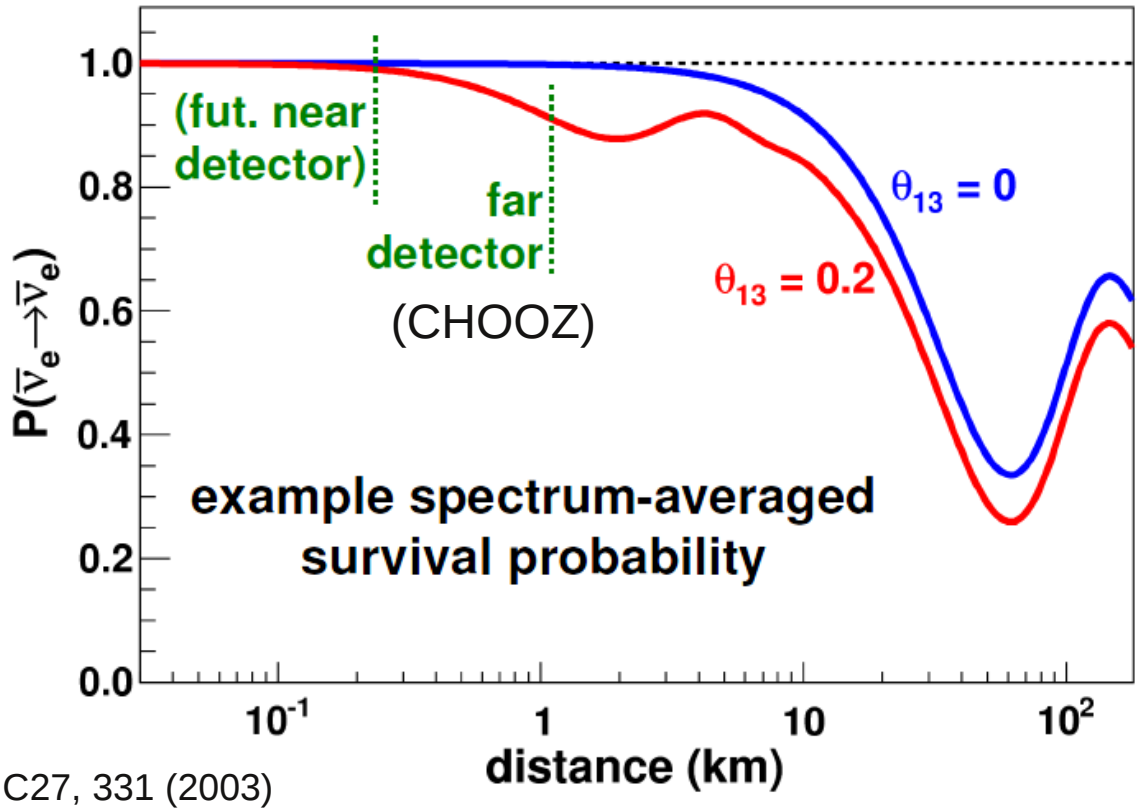
**CHOOZ reactor neutrino experiment: $\sin^2 2\theta_{13} < 0.16$**

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

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




Phys.Lett.B466:415-430,1999



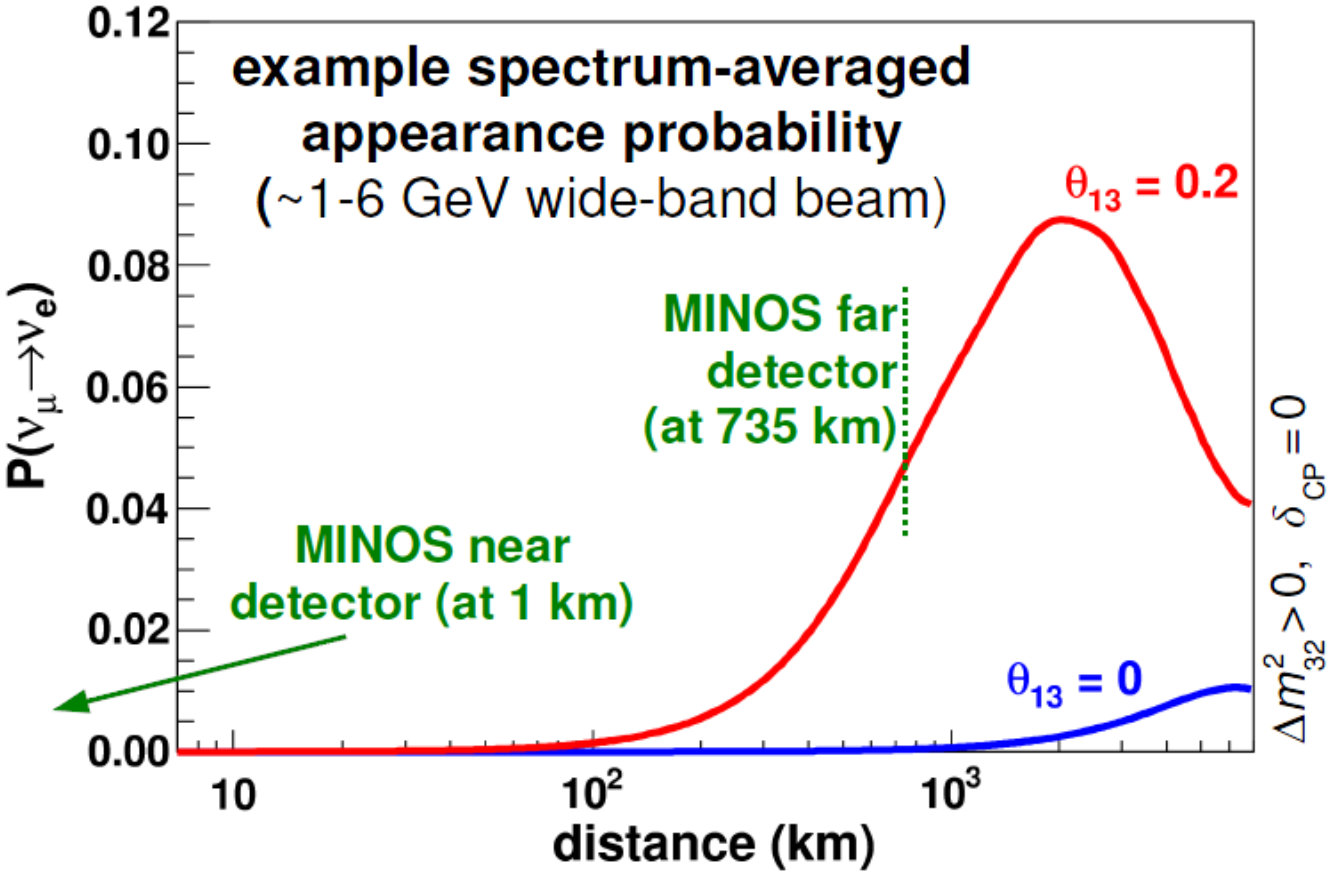

Eur. Phys. J. C27, 331 (2003)

# Measuring $\theta_{13}$ with accelerator $\nu$'s

appearance of $\nu_e$ in a $\nu_\mu$ beam

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

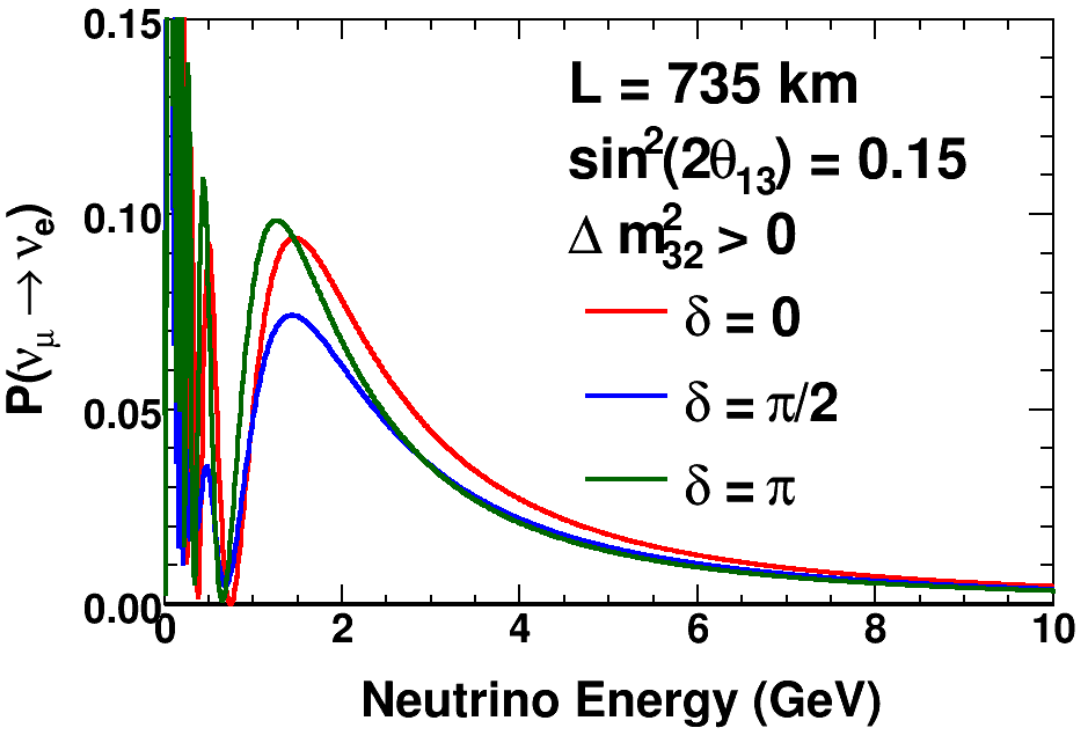
(Dominant term)



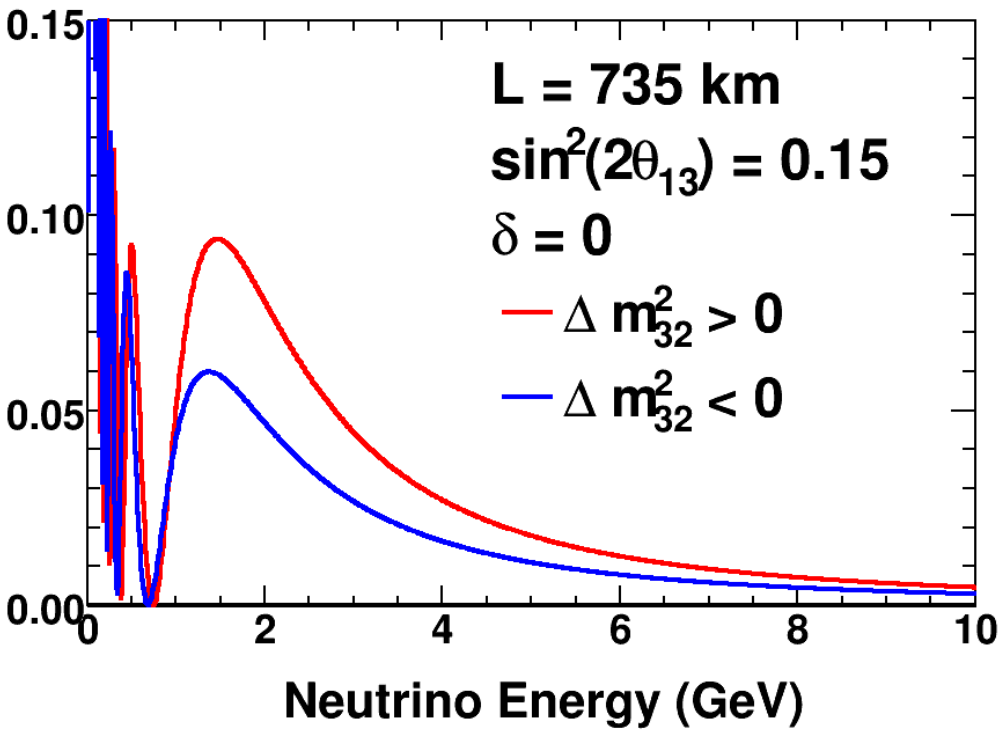
# Measuring $\theta_{13}$ with accelerator $\nu$'s

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

$\delta$ dependence

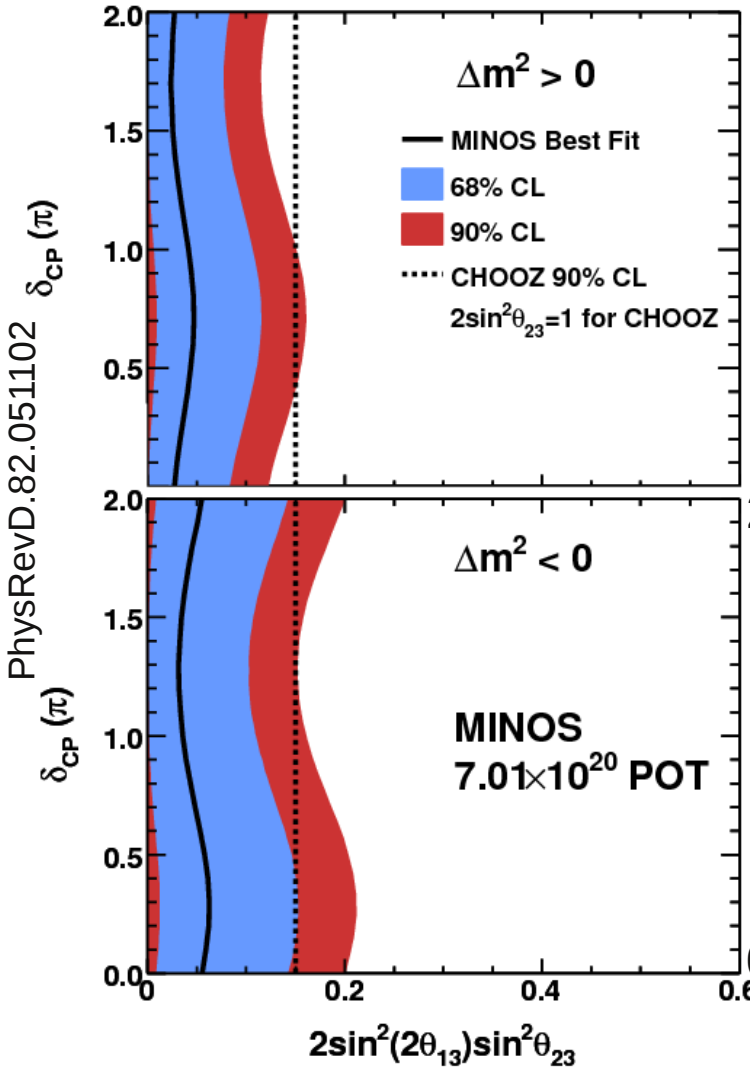



mass hierarchy dependence



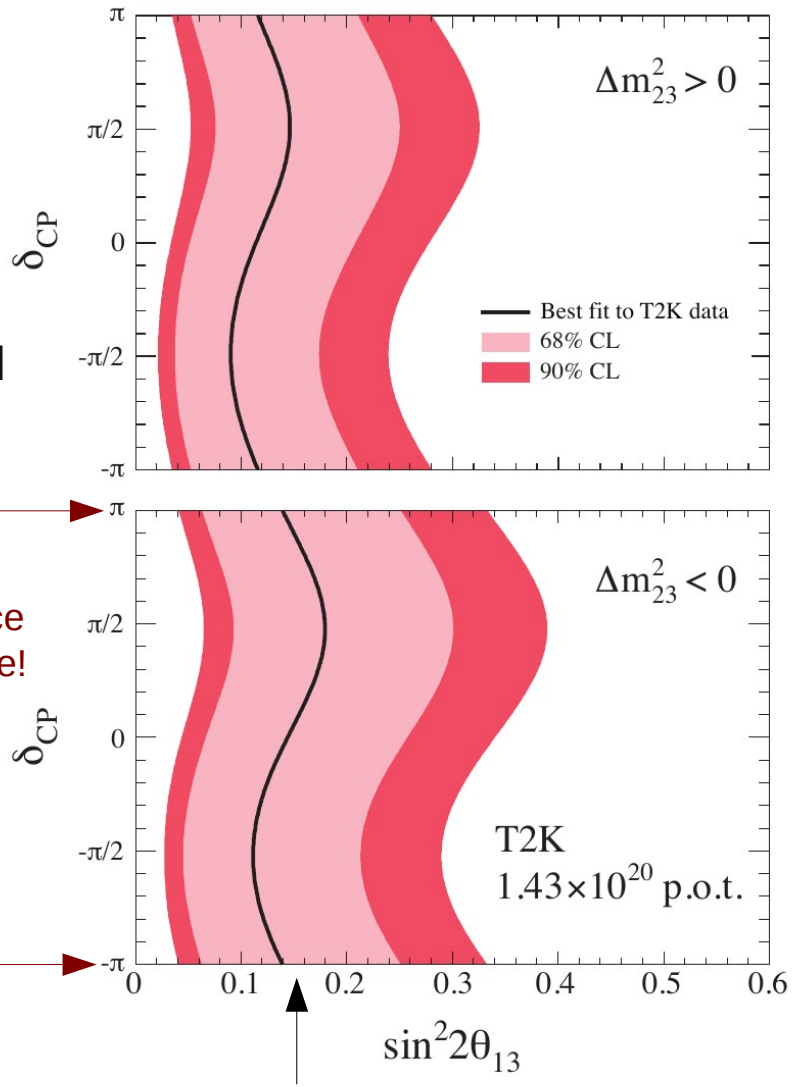
# Measuring $\theta_{13}$ with accelerator $\nu$'s

## MINOS 2010




MINOS observed 54 events with 49 expected background events

## T2K 2011




T2K observed 6 events with 1.5 expected background events

$2\pi$

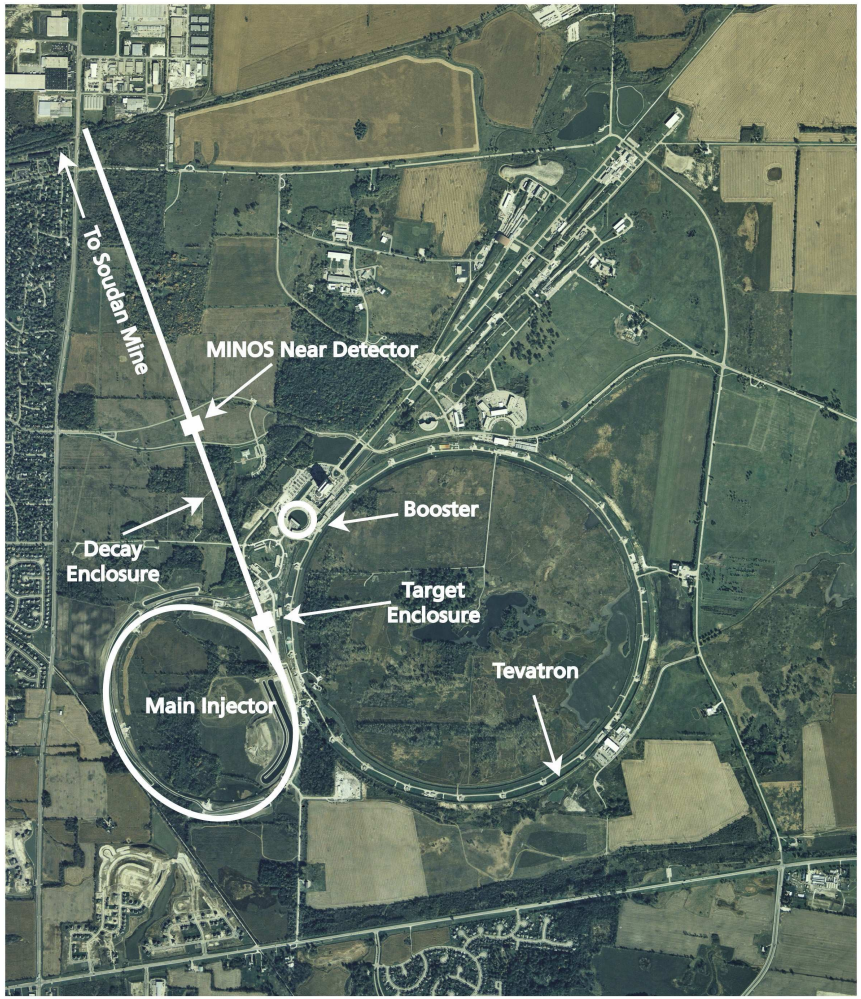
Note difference in $\delta$ scale!

$0$

CHOOZ limit

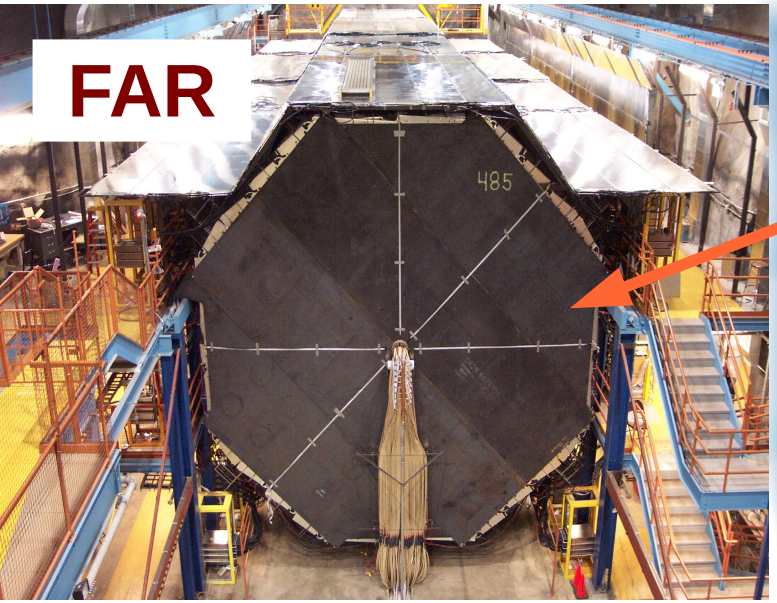
MINOS was the first experiment with sensitivity to $\theta_{13}$ beyond the CHOOZ limit!

# The MINOS Experiment



# MINOS detectors

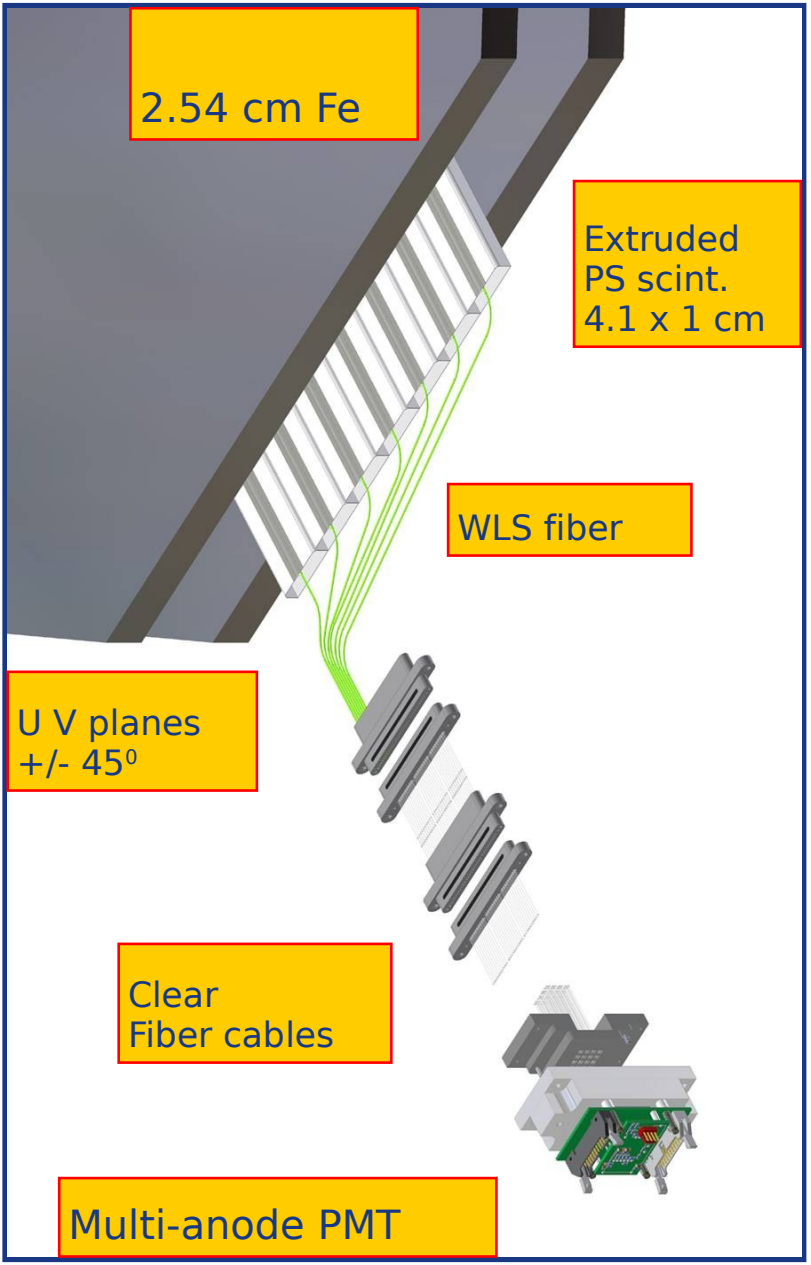
alternating layers of steel plates and scintillator strips in a ~1.3 T toroidal magnetic field



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



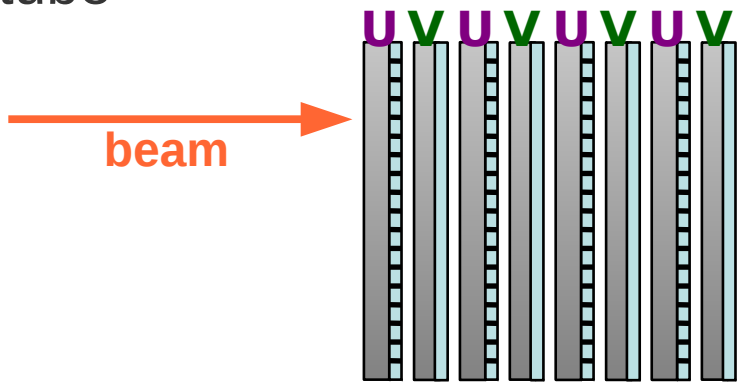

Steel thickness: 2.54 cm (~1.4 radiation lengths)

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 ±45° from vertical

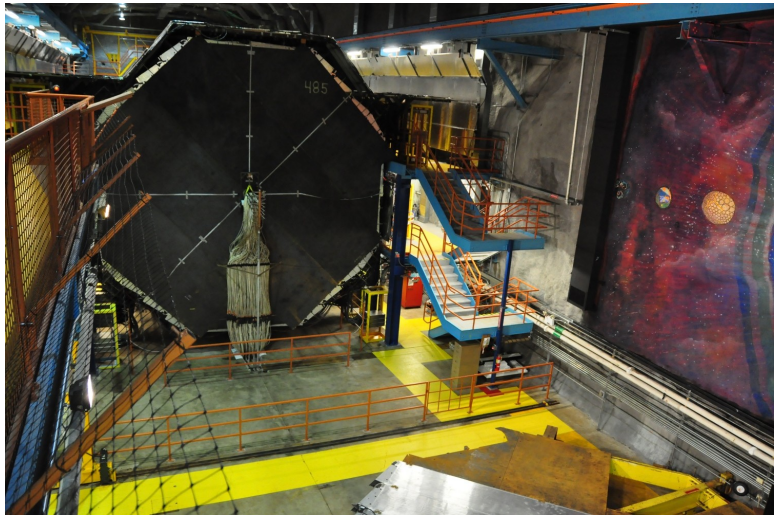


# Soudan Fire and Recovery

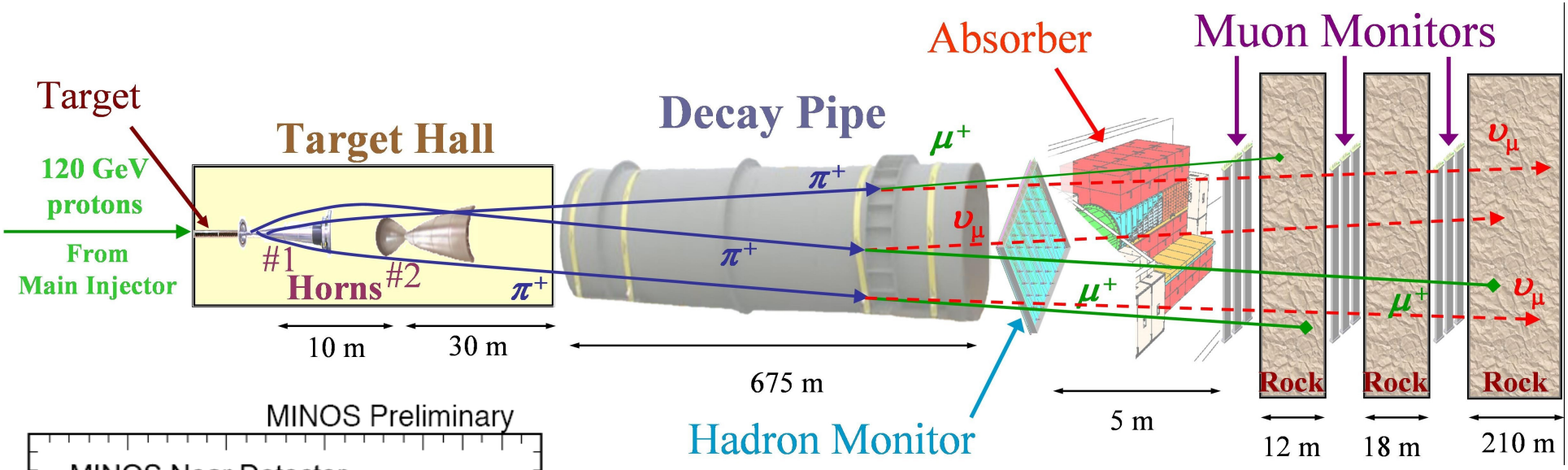
- On March 17 smoke was detected in the MINOS hall at Soudan due to a fire in the shaft
- Power to the lab was shut off automatically
- Foam was pumped in to extinguish the fire
- No damage to the MINOS detector
- Detector returned to full operations May 19

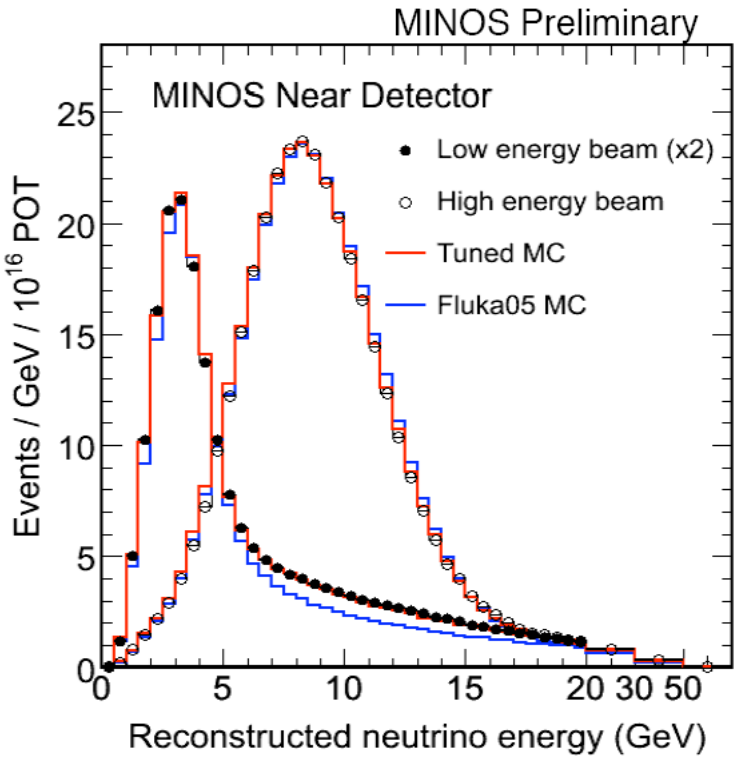
After the fire...

Good as new...



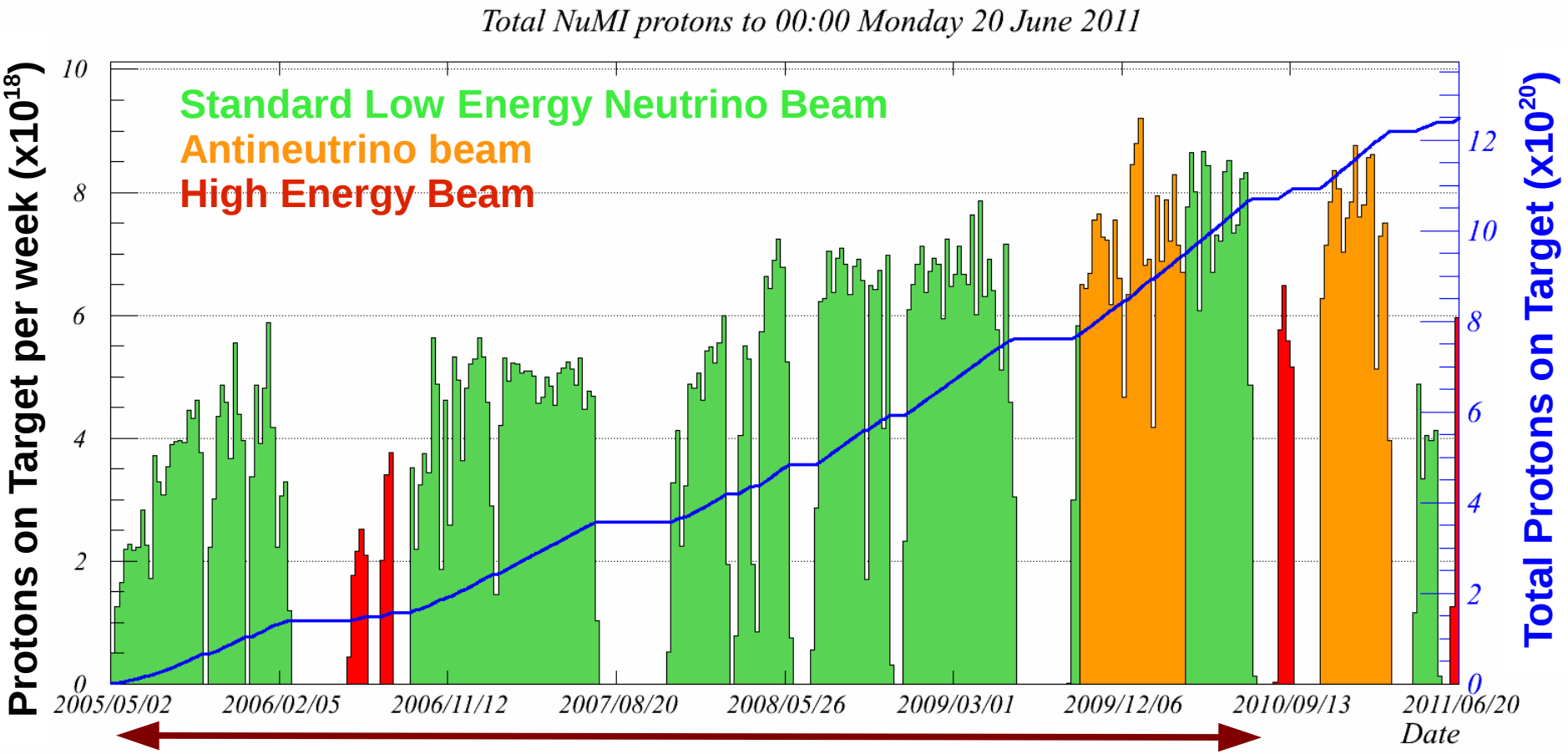
# NuMI Beam




- 120 GeV protons hit a carbon target
- magnetic horns focus $\pi^+$
- $\pi^+ \rightarrow \mu^+ \nu_\mu$
- $\nu_e$ 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



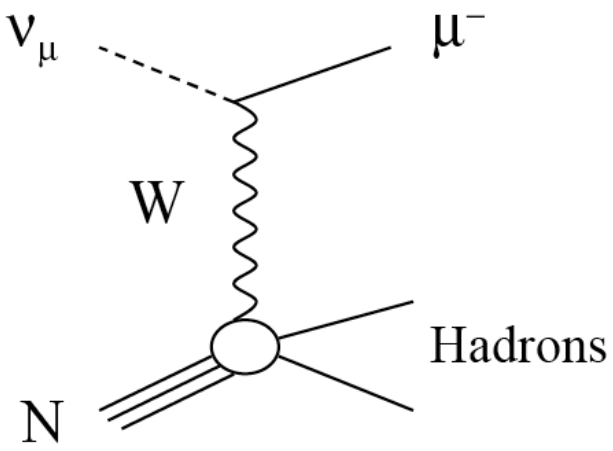

**Today's result**

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

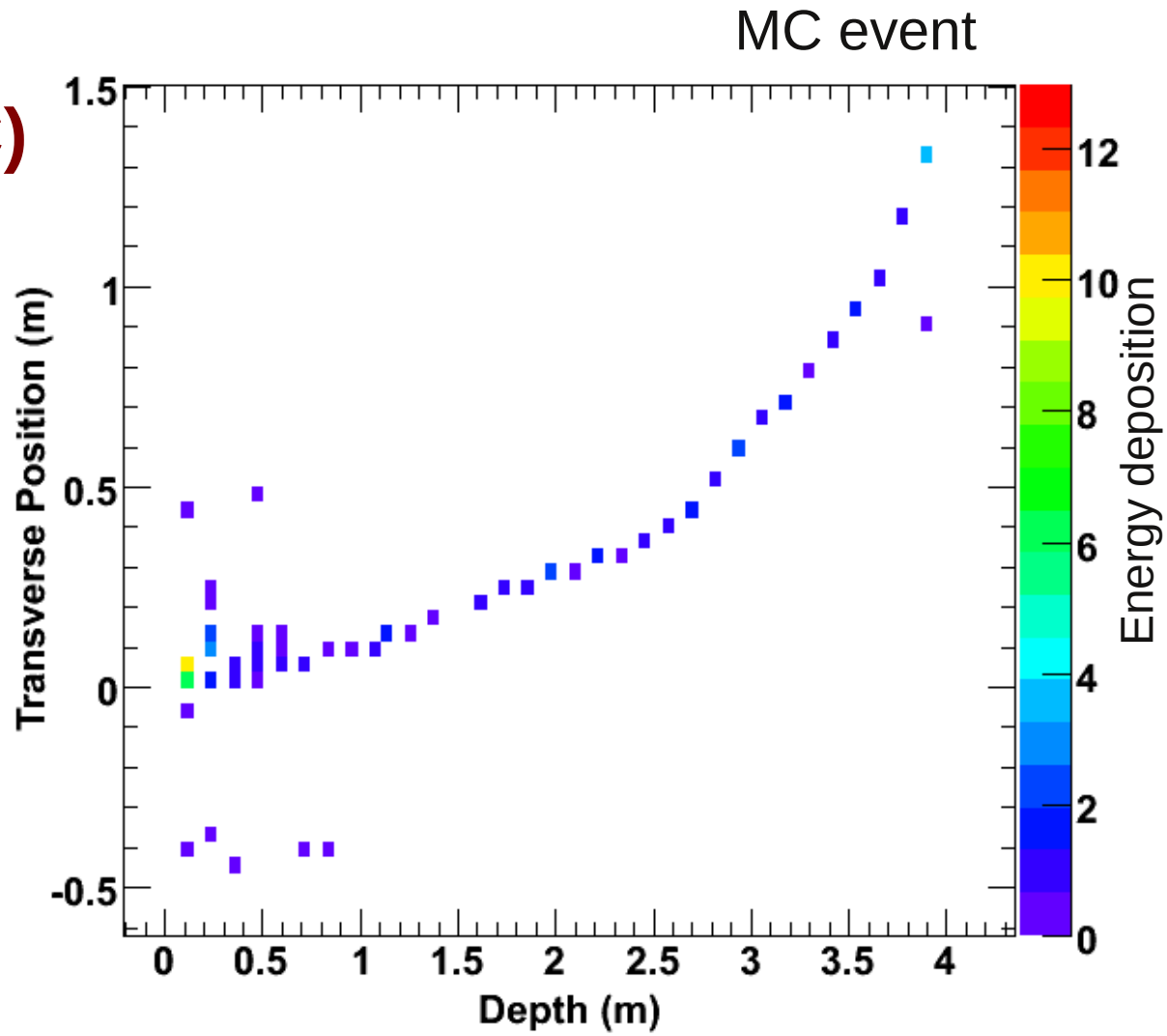
# Neutrino Interactions at MINOS

## $\nu_\mu$ Charged Current (CC)

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




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

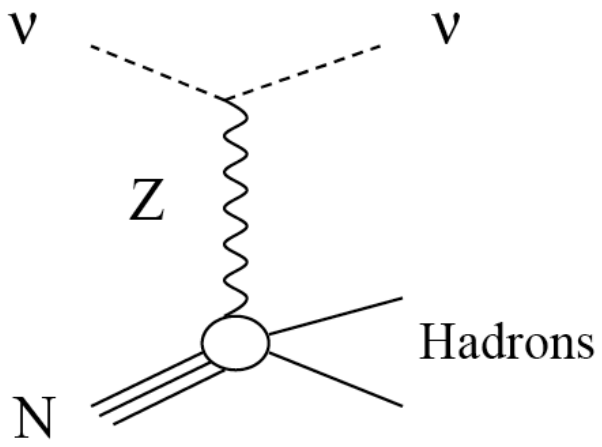



**Long μ track with hadronic activity at vertex**

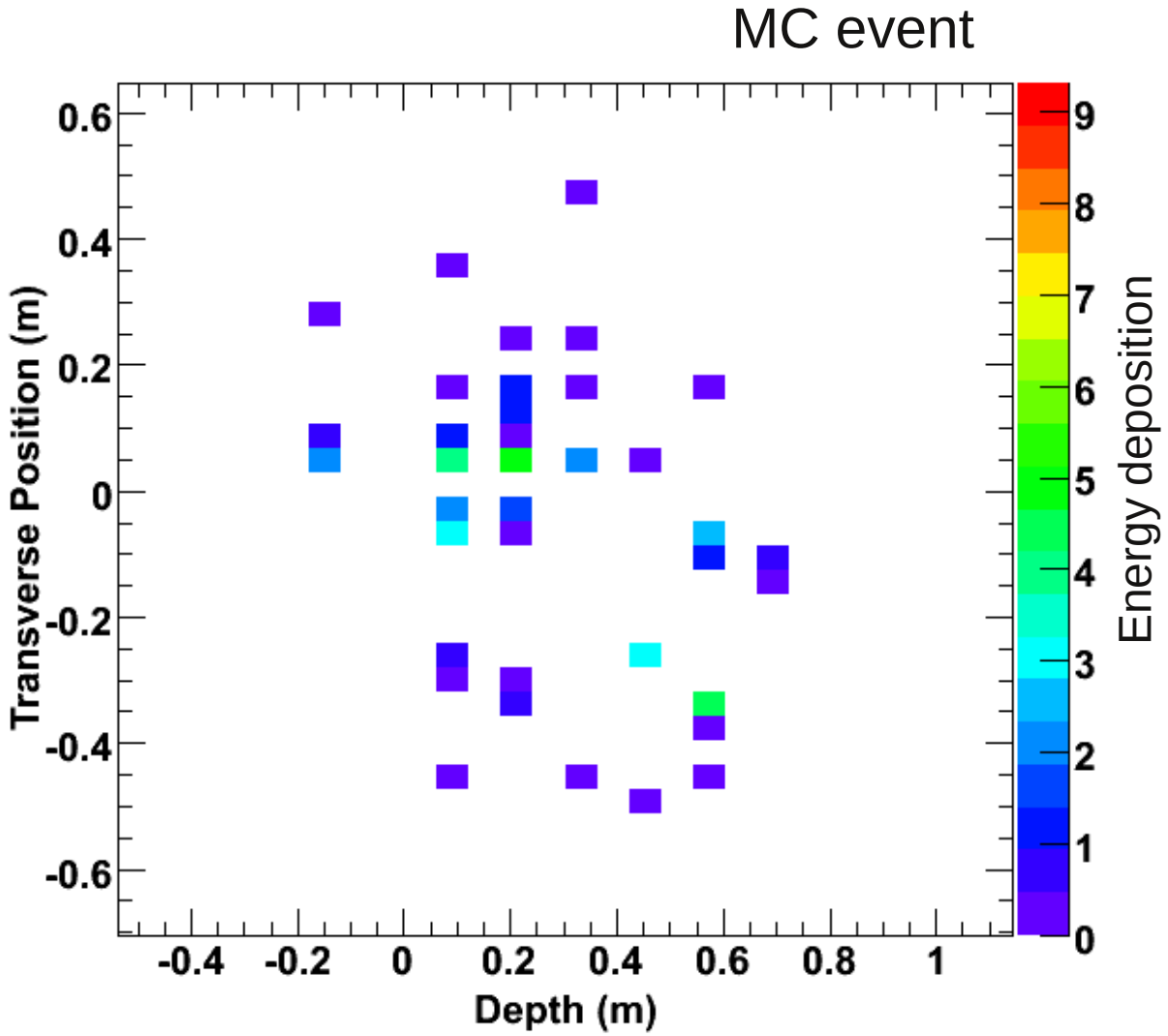
# Neutrino Interactions at MINOS

## Neutral Current (NC)

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




Only the hadronic shower deposits energy in the detector.

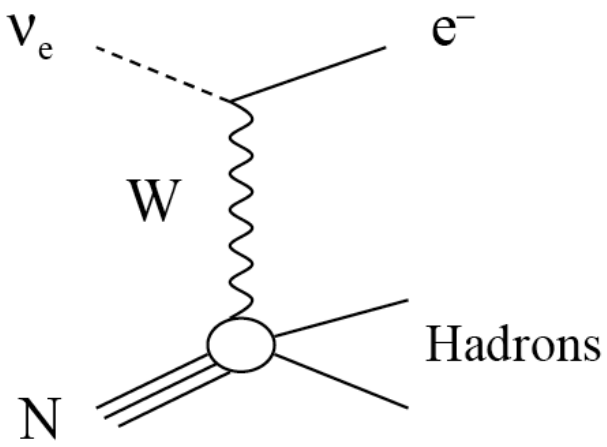



**short event,**
**often diffuse shower**

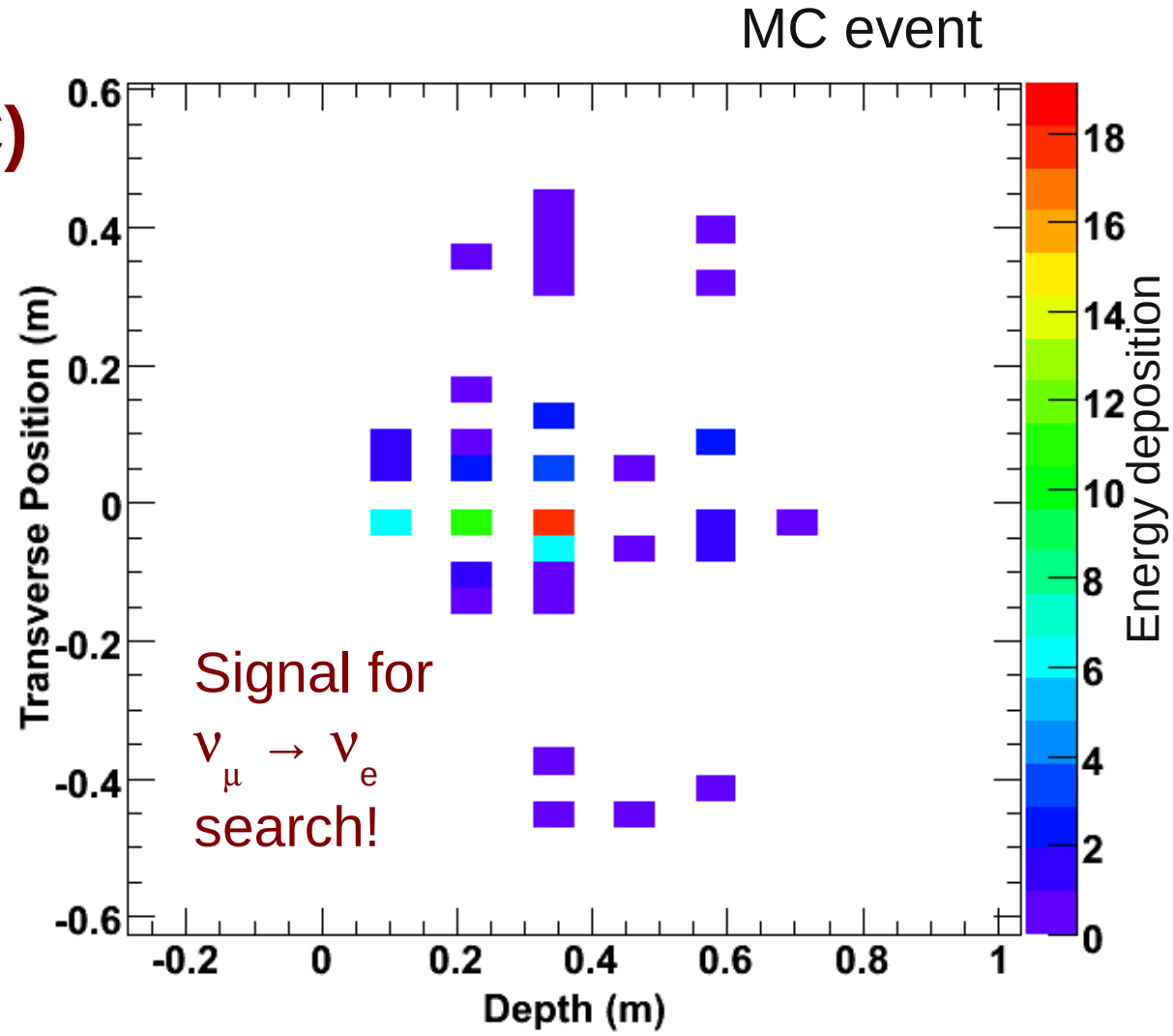
# Neutrino Interactions at MINOS

## $\nu_e$ Charged Current (CC)

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




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

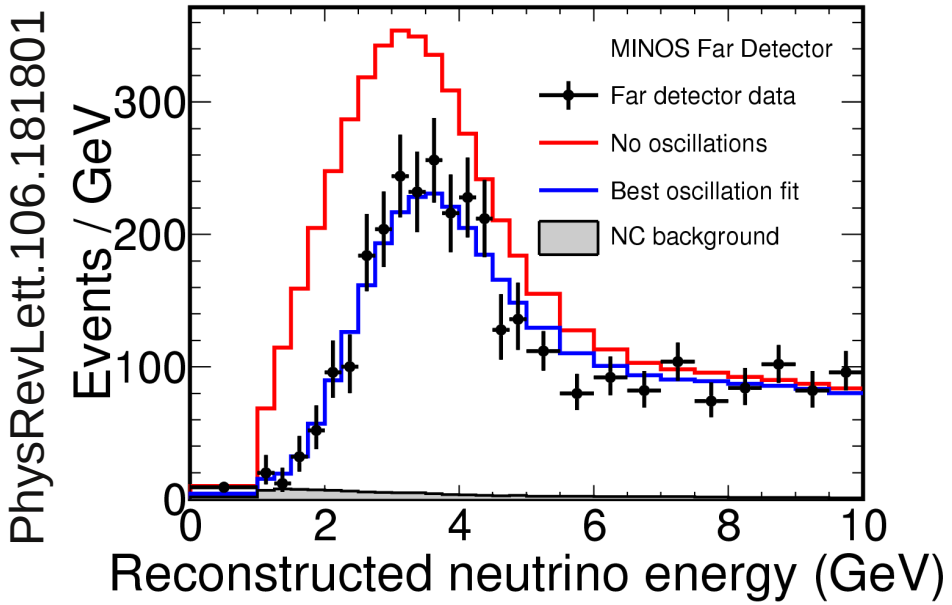


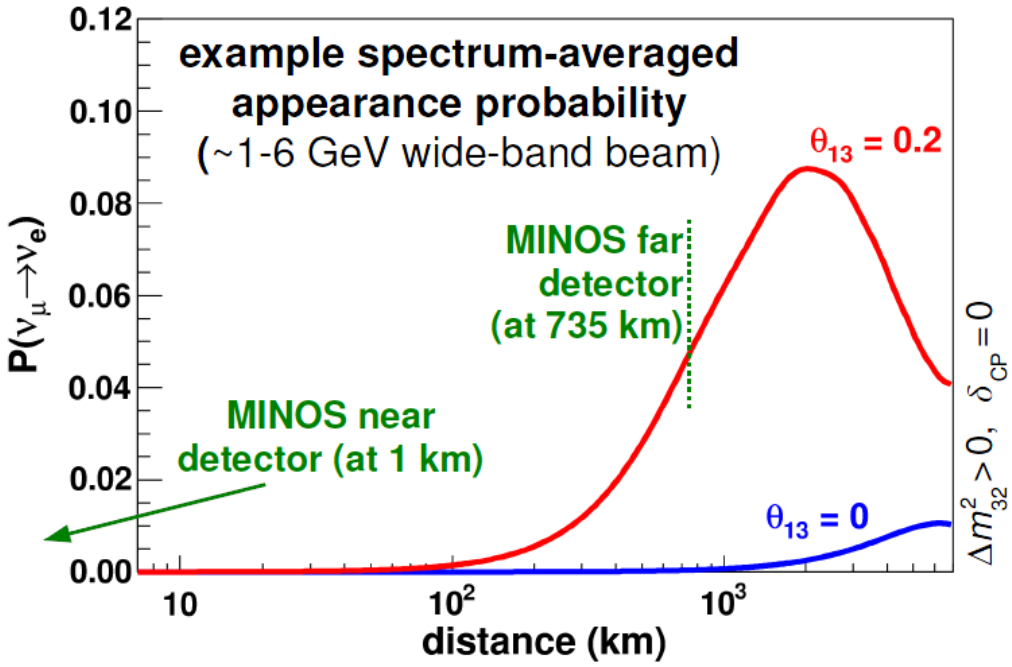

**Short event, with compact shower profile**

# $\nu_e$ appearance in MINOS

MINOS measures $\nu_\mu$ disappearance:

The probability for those missing $\nu_\mu$'s to become $\nu_e$'s is at most a few percent!



# Searching for $\nu_e$ appearance

1) Determine selection criteria for $\nu_e$ candidate events

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

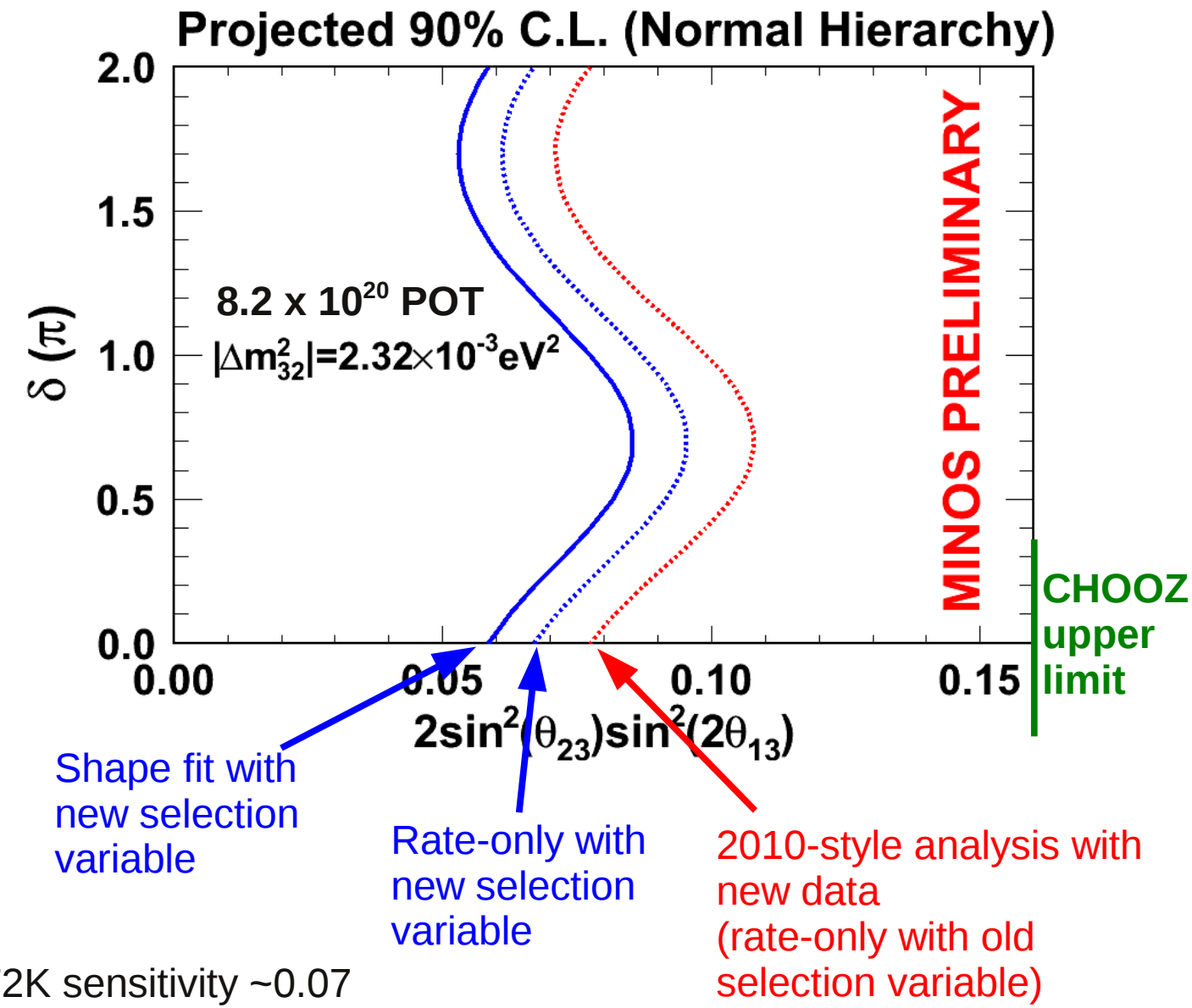
3) Is there an excess of $\nu_e$-like events over the predicted background in the FD?

# Projected Sensitivity

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

Since 2010 result:

- 1.2x10$^{20}$ 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 $\nu_e$ candidate events

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

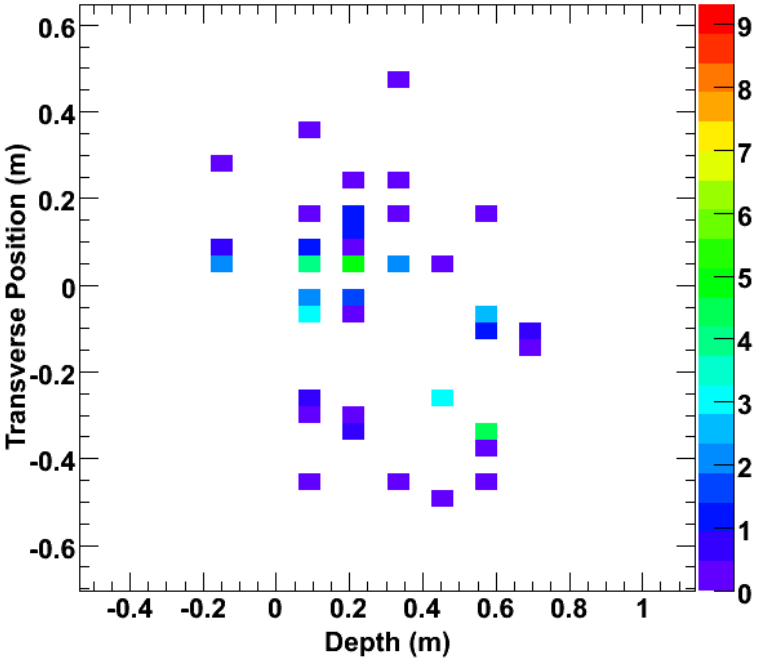
3) Is there an excess of $\nu_e$-like events over the predicted background in the FD?

# Selecting $\nu_e$-like events

Preselection cuts to remove events that are obviously not signal:

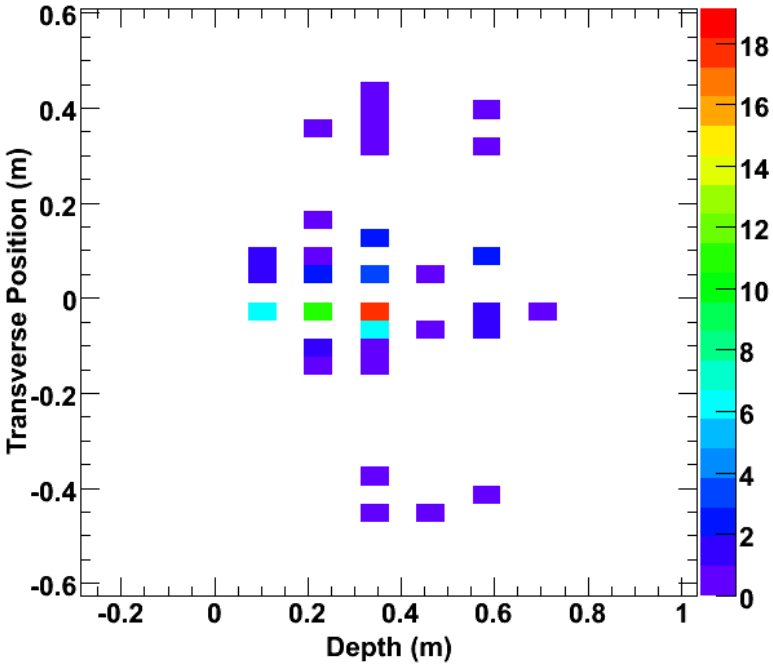
- No long tracks
- At least one well-formed shower
- With visible energy 1-8 GeV

After these cuts, background consists mostly of NC




**(NC background)**

**Need to discriminate**



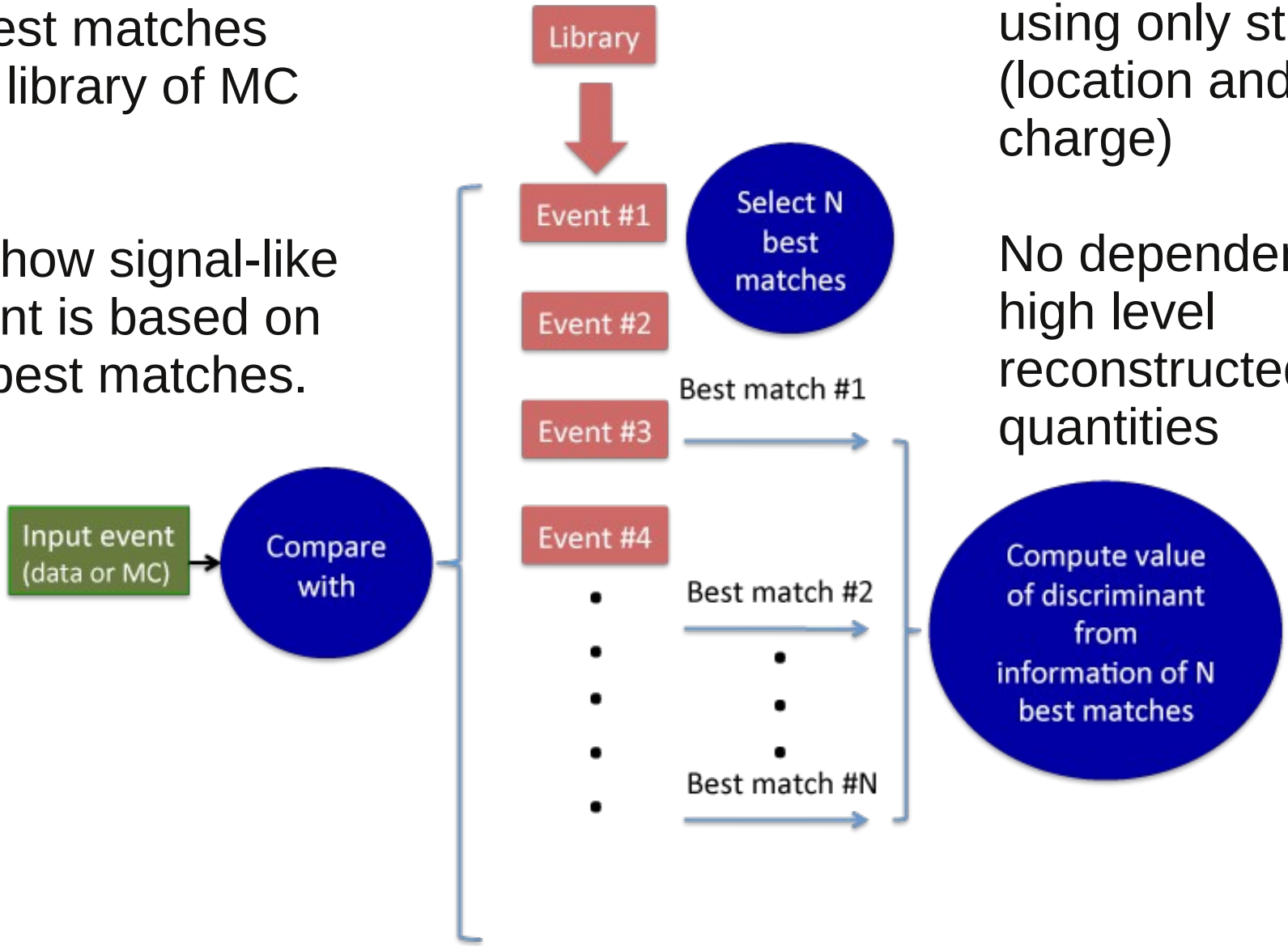

**(signal)**

# 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.



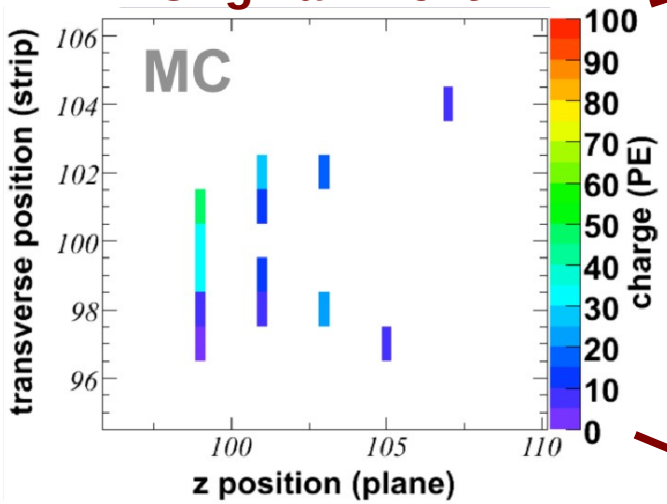

Matching is done using only strip info (location and charge)

No dependence on high level reconstructed quantities

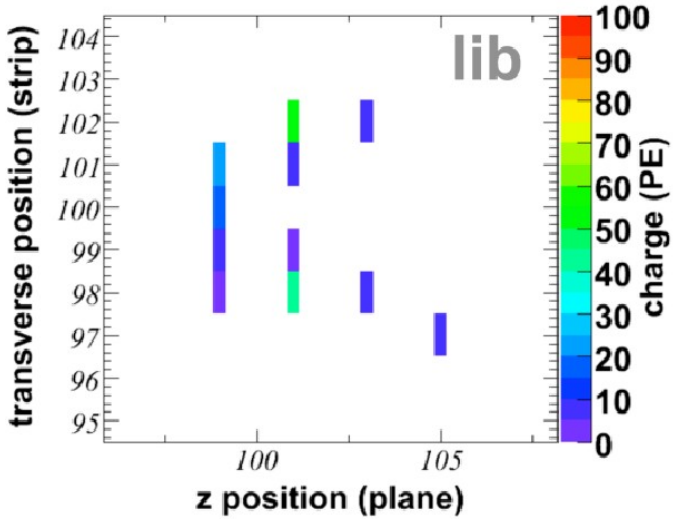
# Matching

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.

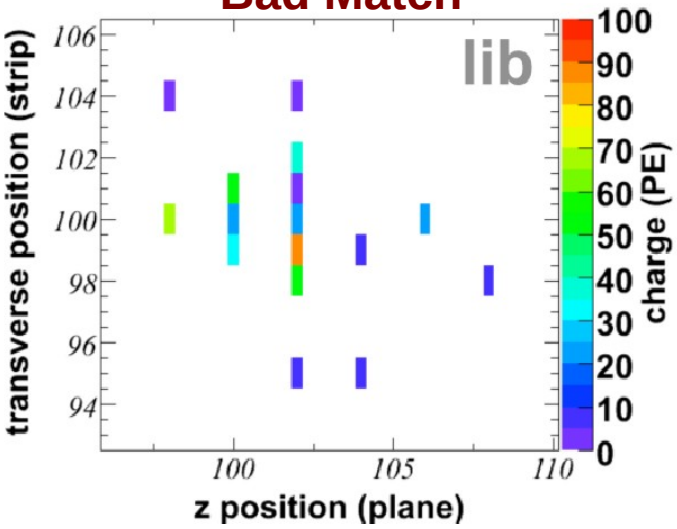
**Original Event**




**Good Match**




**Bad Match**

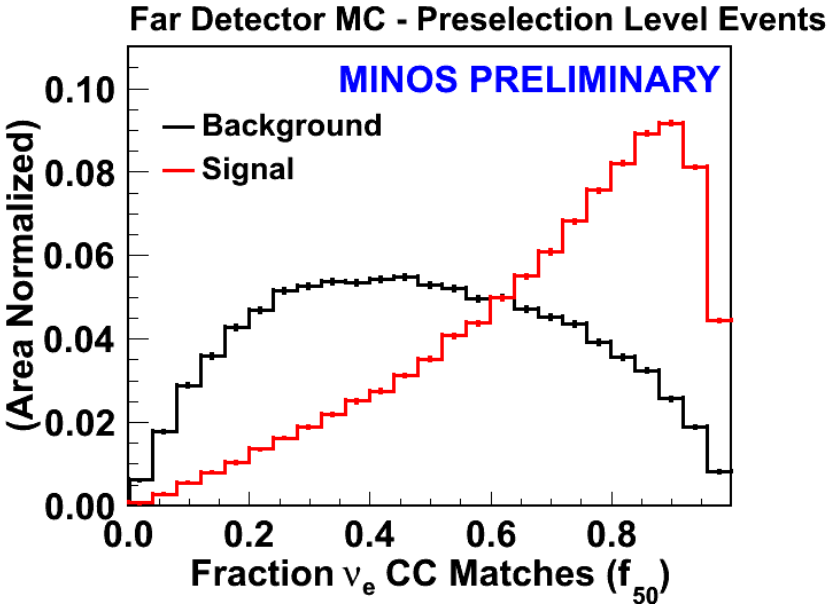



The library consists of:

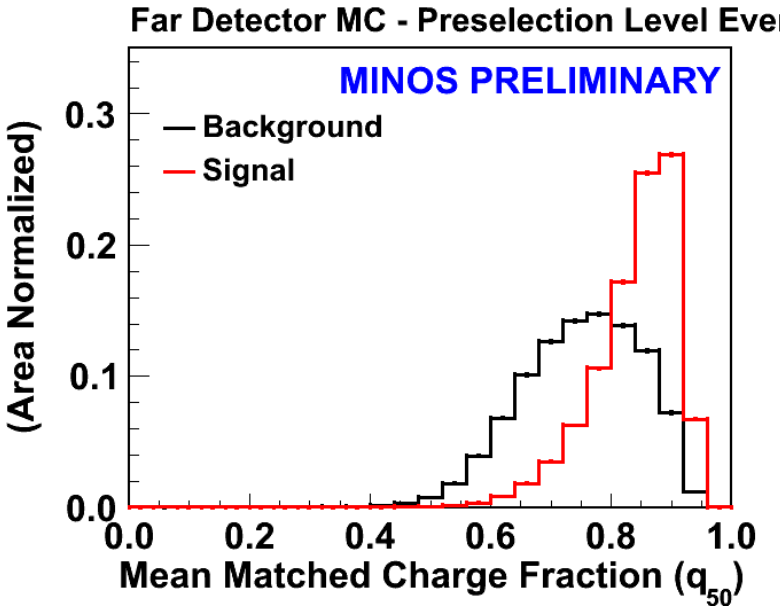
- 20 million signal events
- 30 million background (NC) events

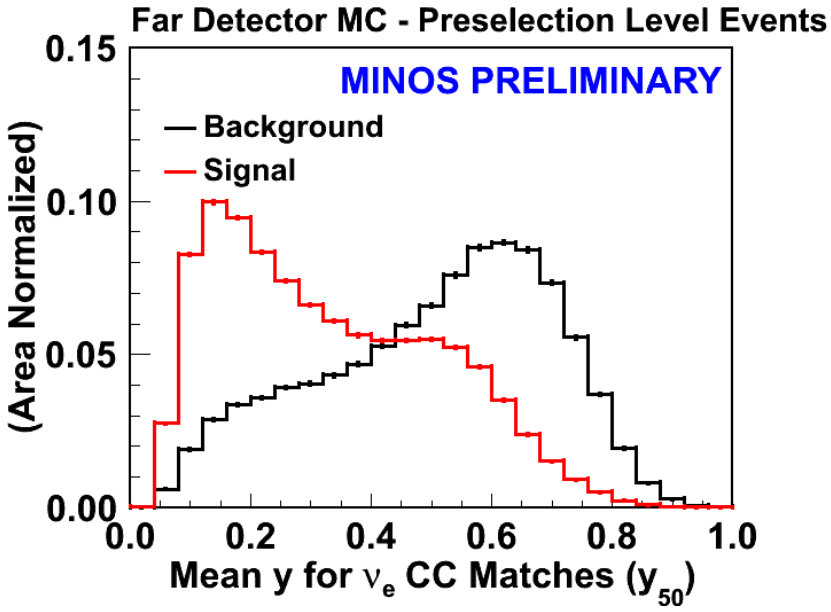
# Info from best matches

How many of the best matches are signal?




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



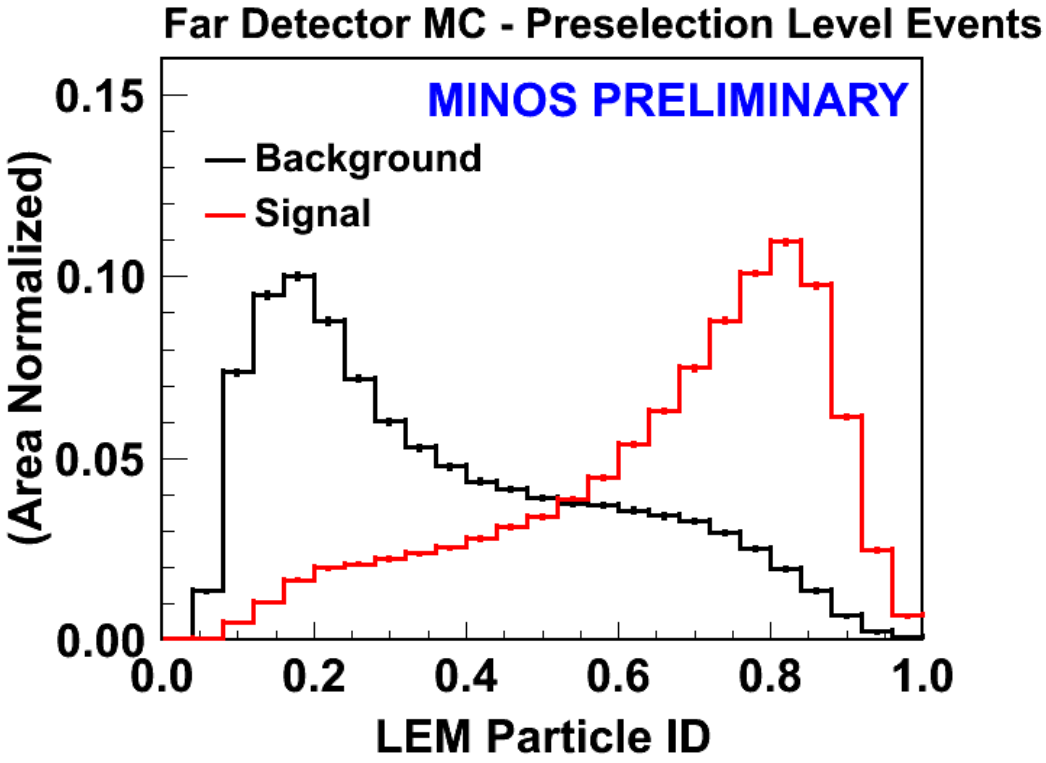

How EM-like is the shower in the best matches?

(*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



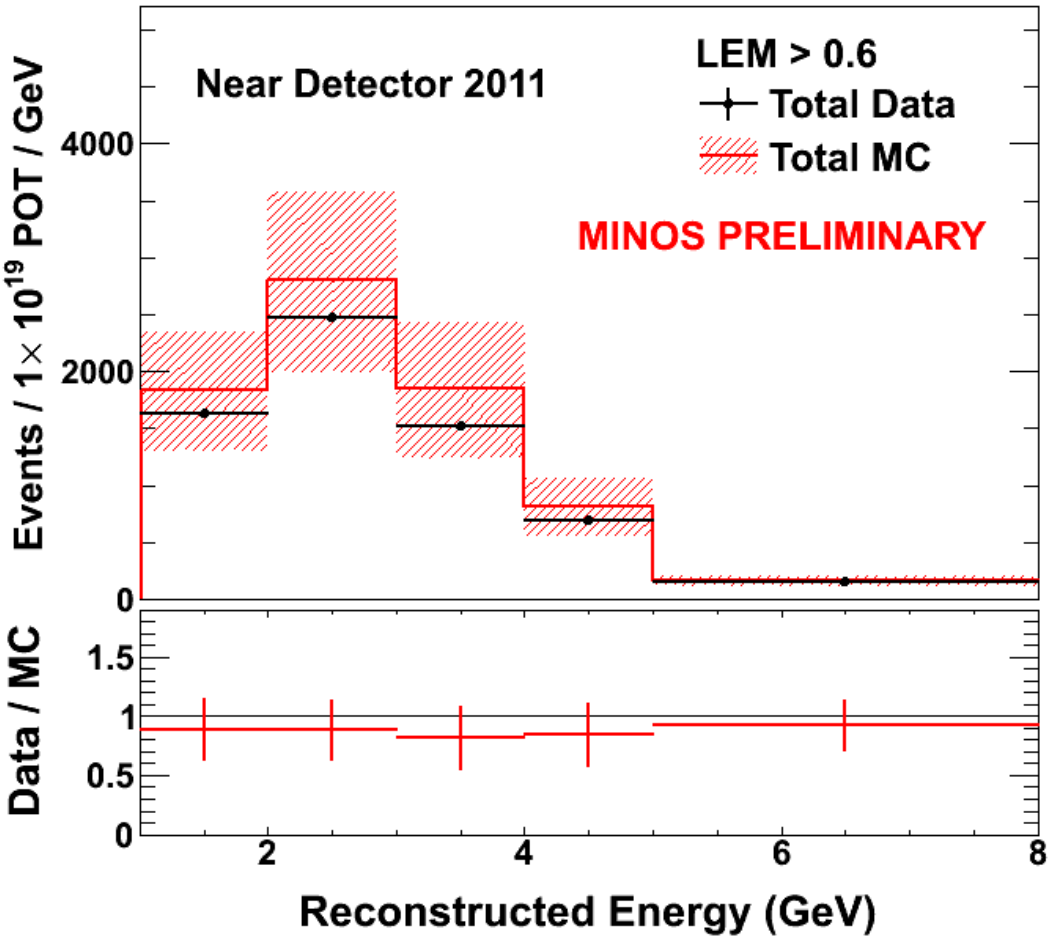
1) Determine selection criteria for $\nu_e$ candidate events

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

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

# Selected Near Detector Data

## Apply the $\nu_e$ 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 $\nu$ 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, $\nu_\mu$ CC, and beam $\nu_e$ CC backgrounds to predict FD background.**

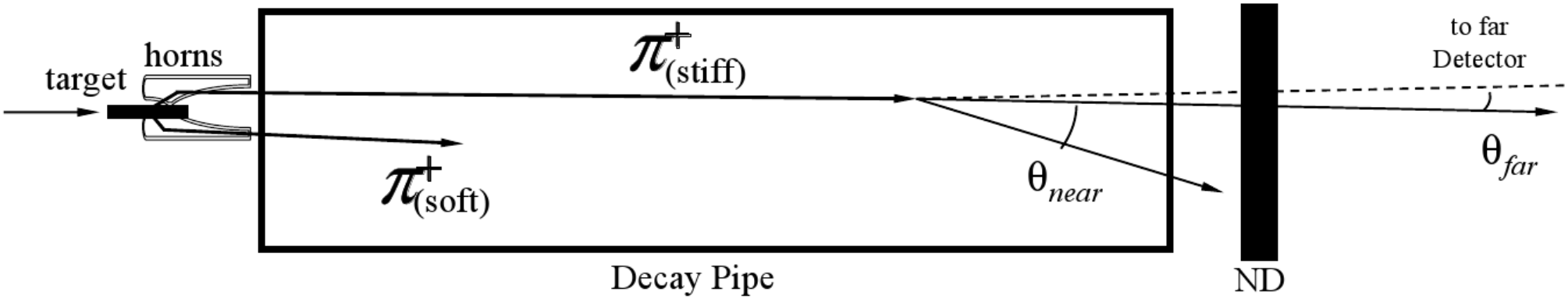
$$F_{\alpha,i} = N_{\alpha,i} \times R^{F/N}_{\alpha,i}$$

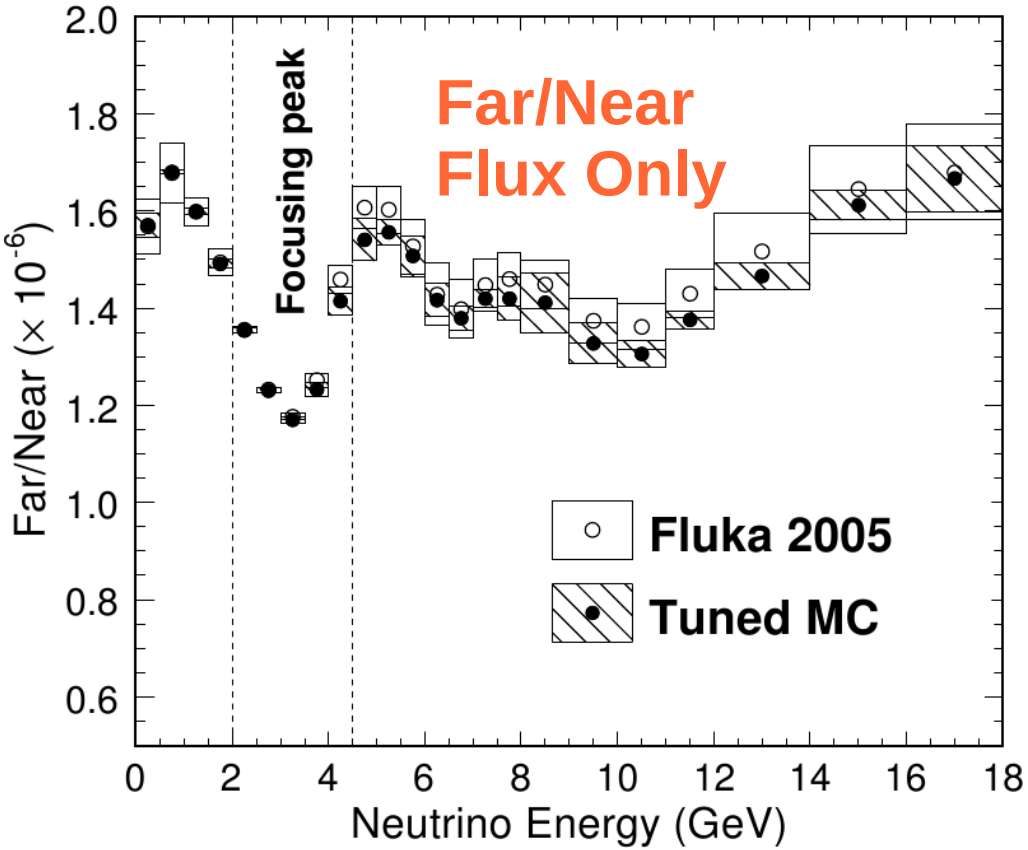
**FD prediction for component $\alpha$ in bin $i$**

**ND data for component $\alpha$ in bin $i$**

**Far/Near ratio: Ratio of selected events for component $\alpha$ in bin $i$ using MC**

# Far/Near Ratio

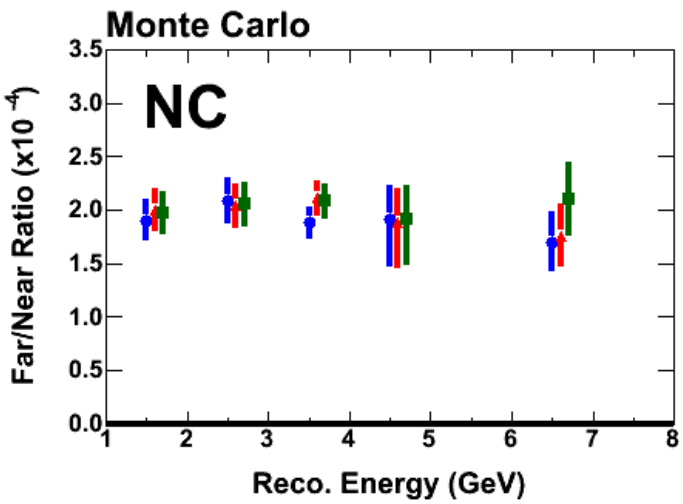


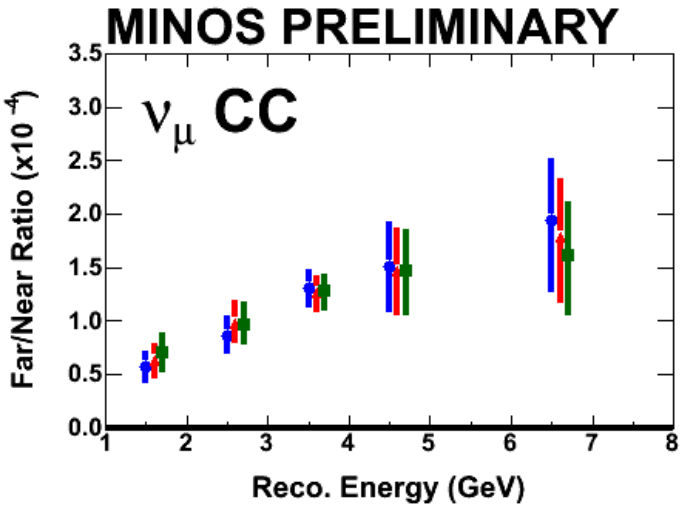



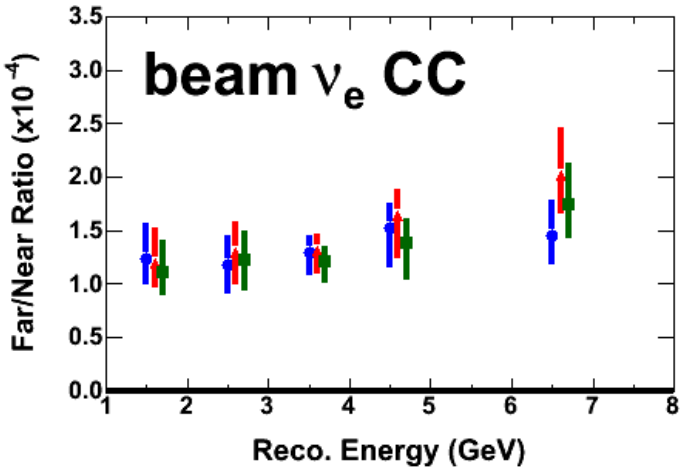

**MC Far/Near ratio**:

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

# Far/Near Ratio




**LEM**

- Run Period 1
- Run Period 2
- Run Period 3

**MC Far/Near ratio**:

- Flux
- Fiducial volume
- energy smearing
- $\nu_\mu$ disappearance
- detector effects

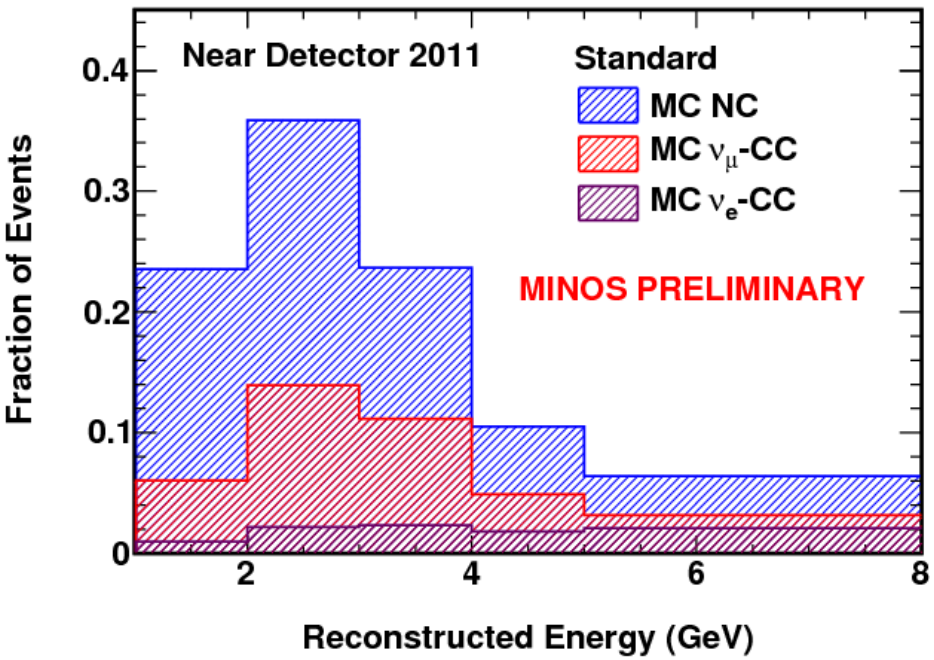
Error bars are systematic.

# Near Detector Background

Oscillations affect each background component differently!

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

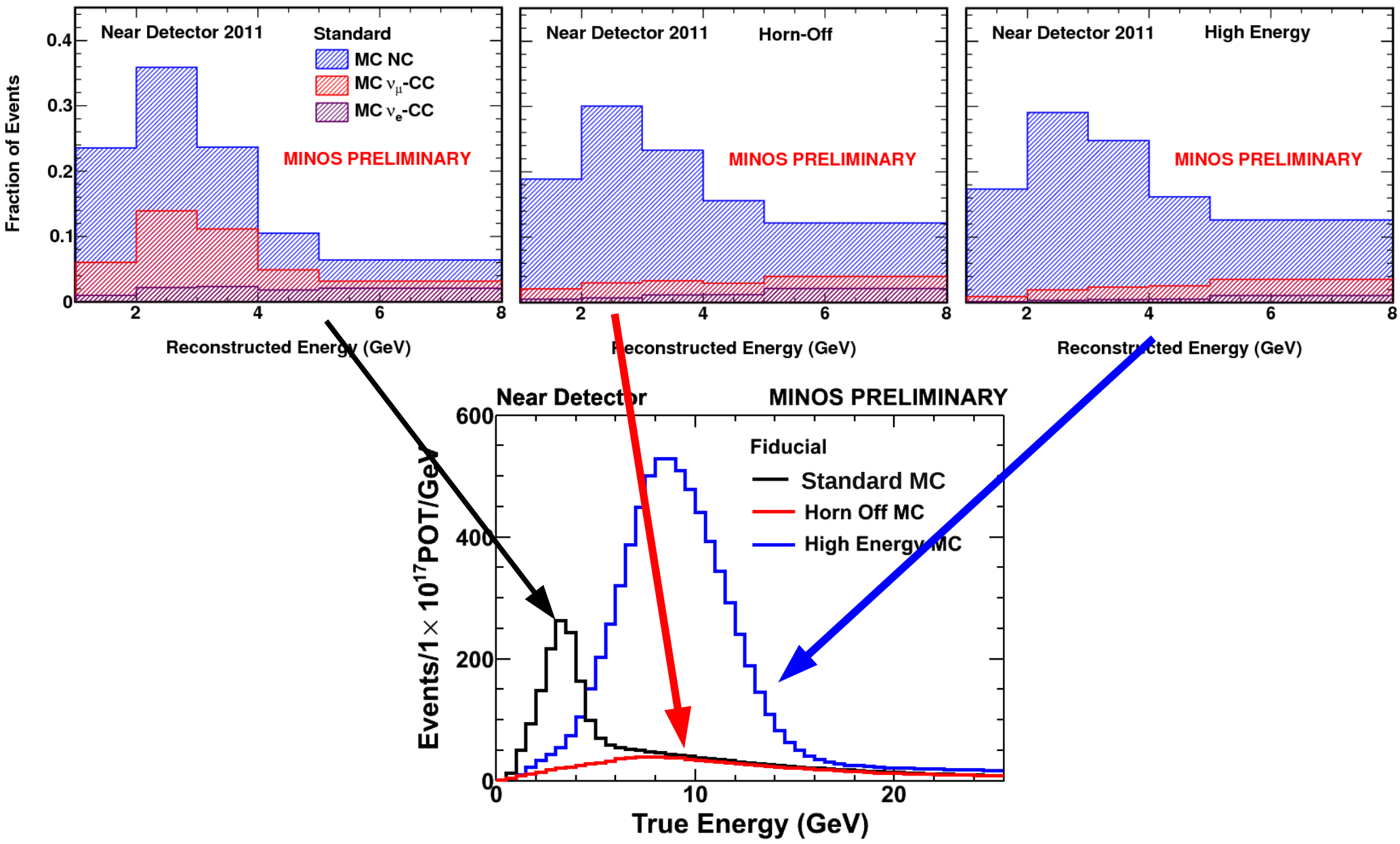
- **neutral current**
- **charged current $\nu_\mu$,**
- **charged current $\nu_e$ (from beam contamination)**



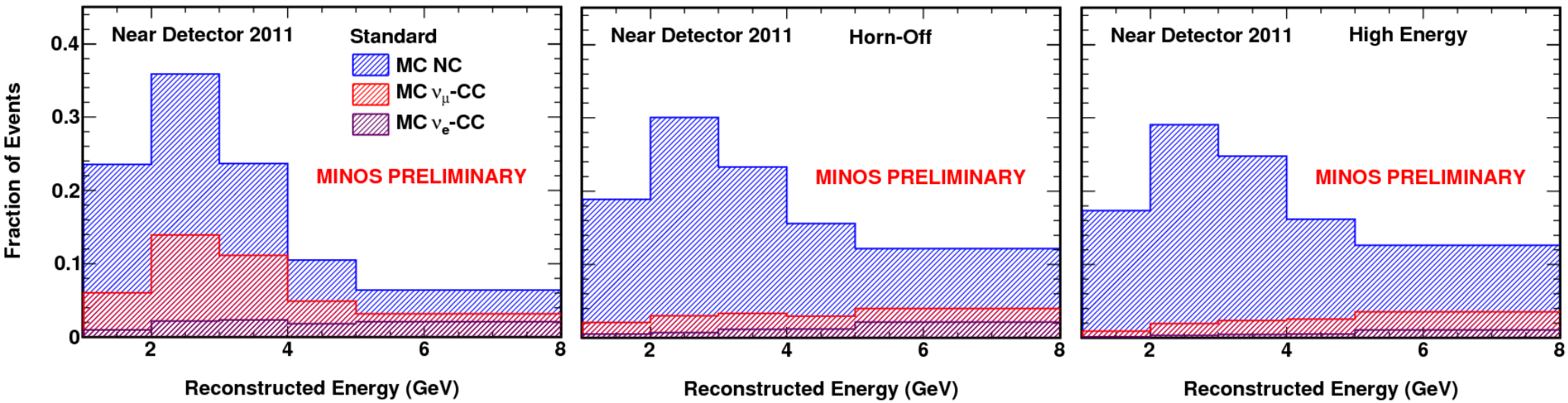

Extract it from the data – don't rely on the simulation

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

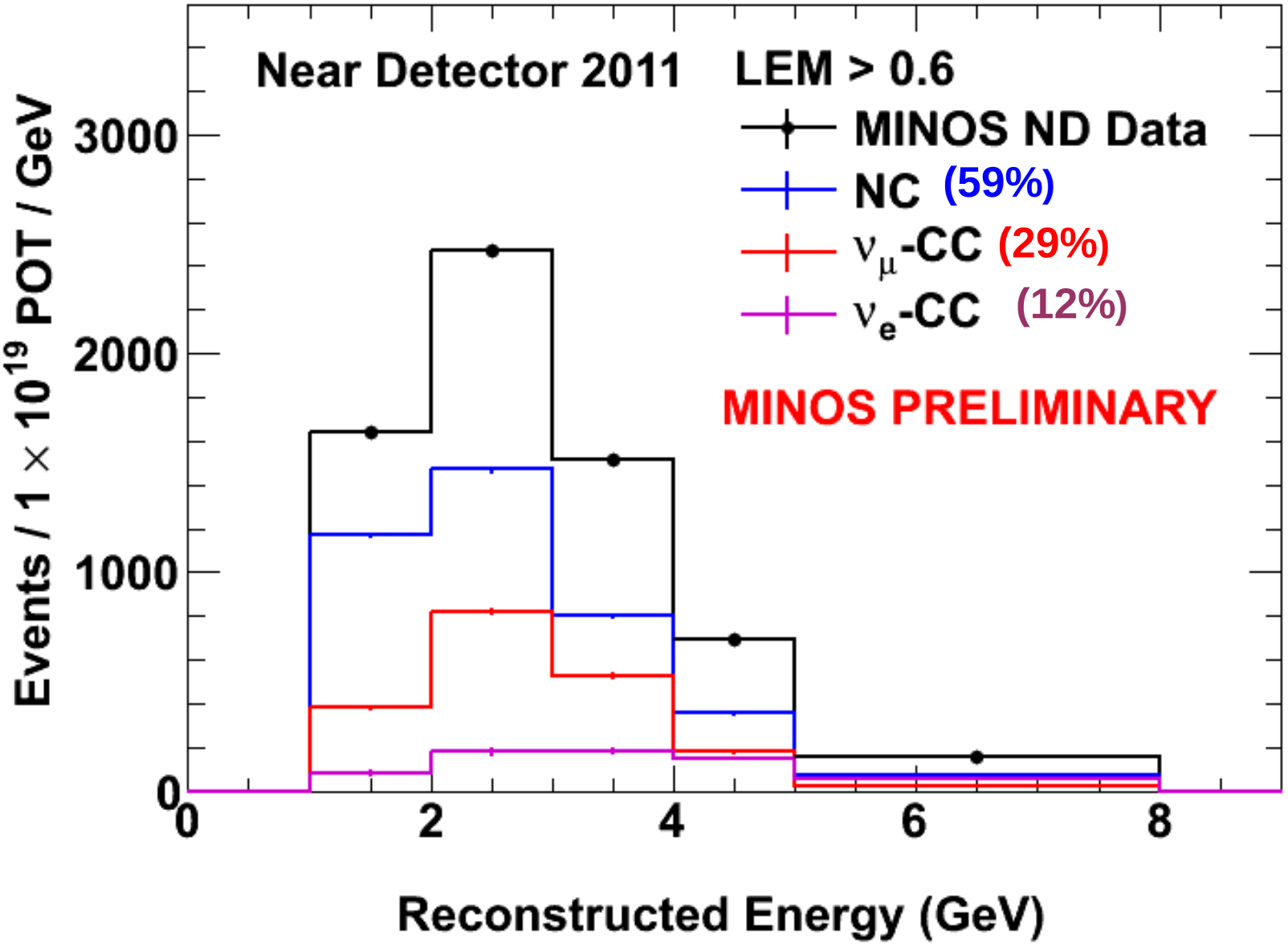



Use these 3 data sets to measure the 3 background components in the standard sample...

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 $8.2 \times 10^{20}$ POT

Signal-enhanced region (LEM>0.7)

$\delta = 0$

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

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

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

| Component | # Events |
|---|---|
| NC | 34 |
| $\nu_\mu$ CC | 7 |
| beam $\nu_e$ CC | 6 |
| $\nu_\tau$ CC | 2 |
| **Total Bkgd** | **49** |
| **$\nu_e$ CC signal** | **30** |

PRELIMINARY

Predicted background and signal at CHOOZ limit

# 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

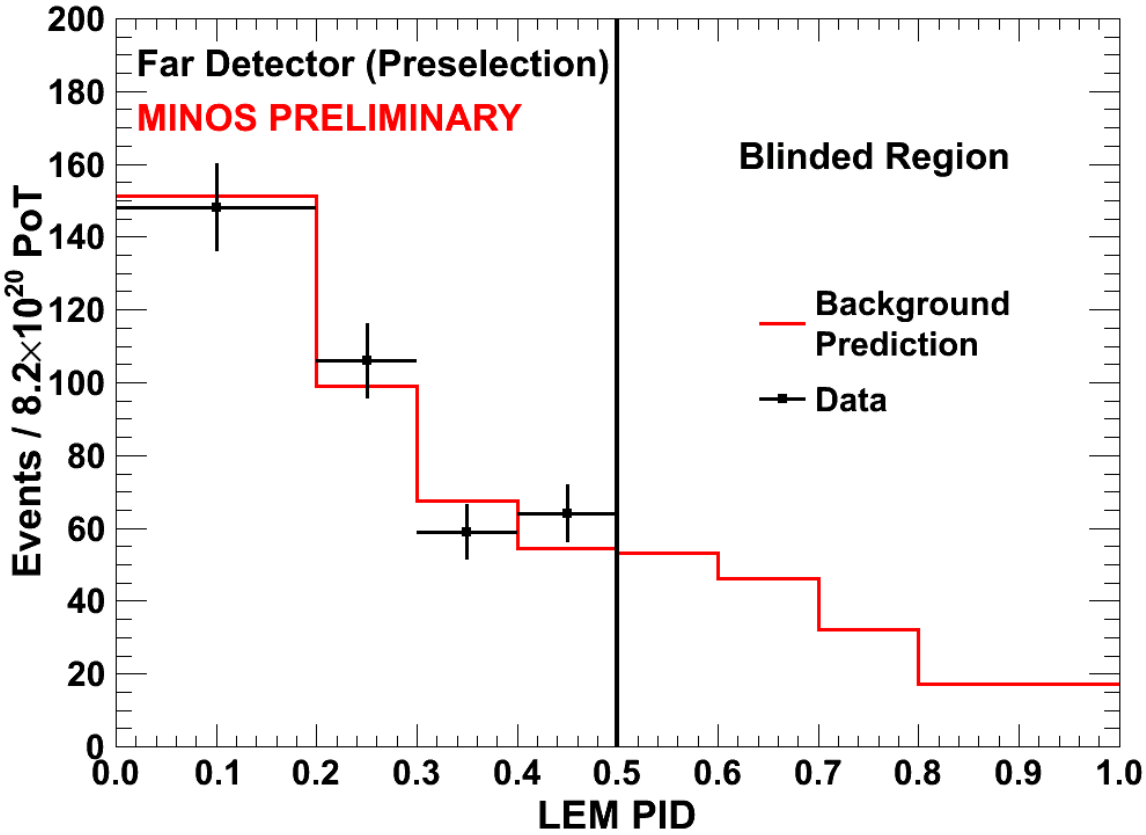
**Systematic Uncertainty 5.7%**
On the background prediction in the signal-enhanced region (LEM>0.7)

1) Determine selection criteria for $\nu_e$ candidate events

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

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

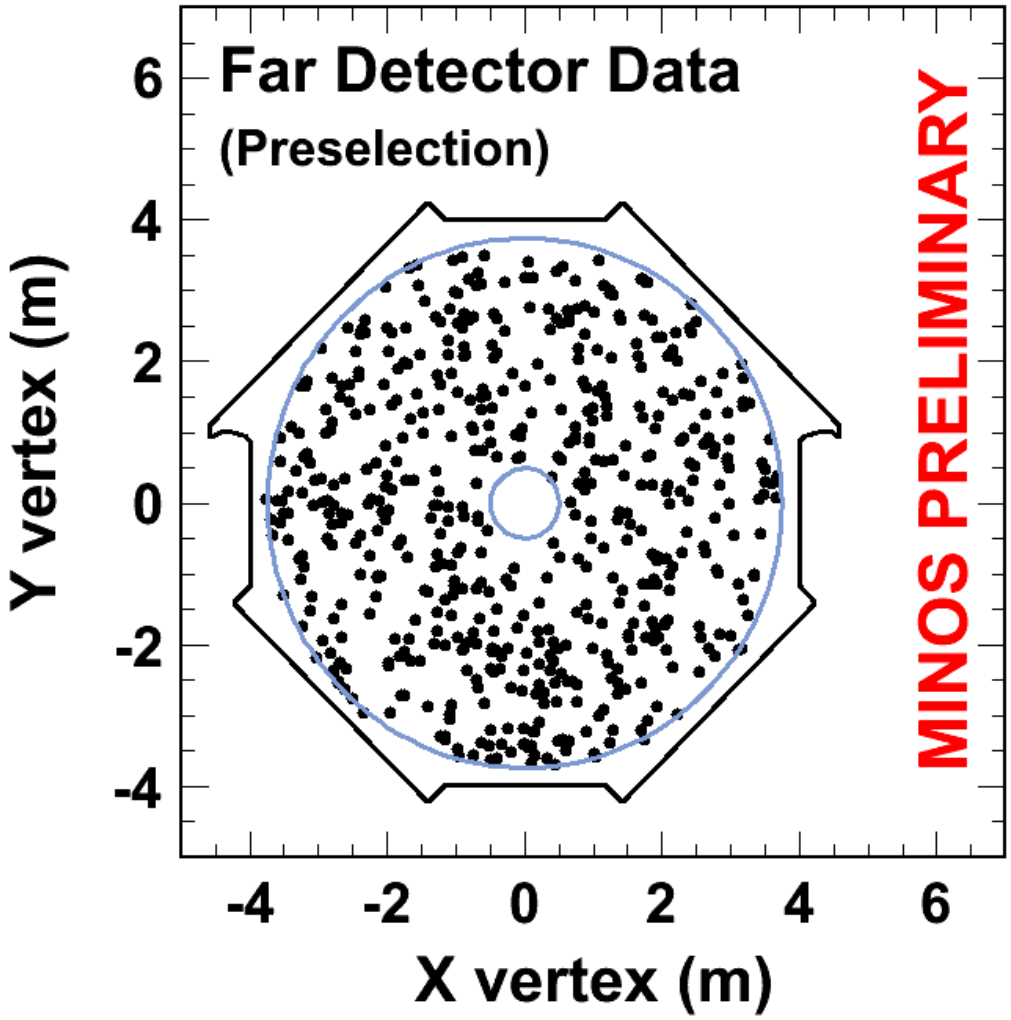
# Sideband: Outside the Signal Region



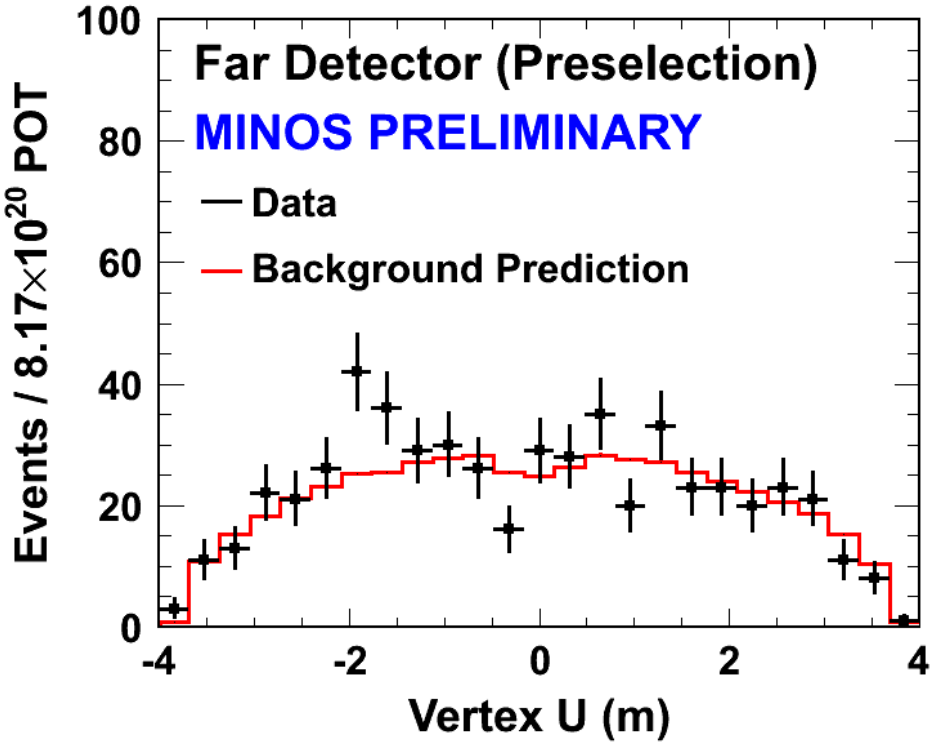

**LEM<0.5**
**observe 377 events**
**expect 372 +- 19(stat)** (@ $\theta_{13} = 0$)

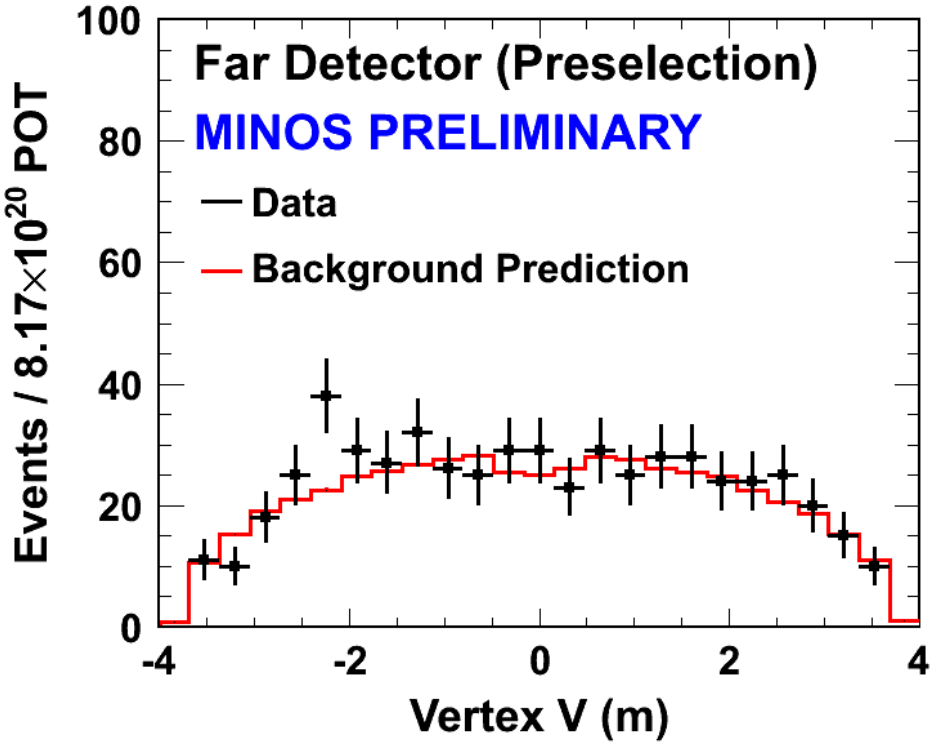
Good test of entire analysis chain - background prediction and extrapolation to far detector.

# FD Vertex Distribution

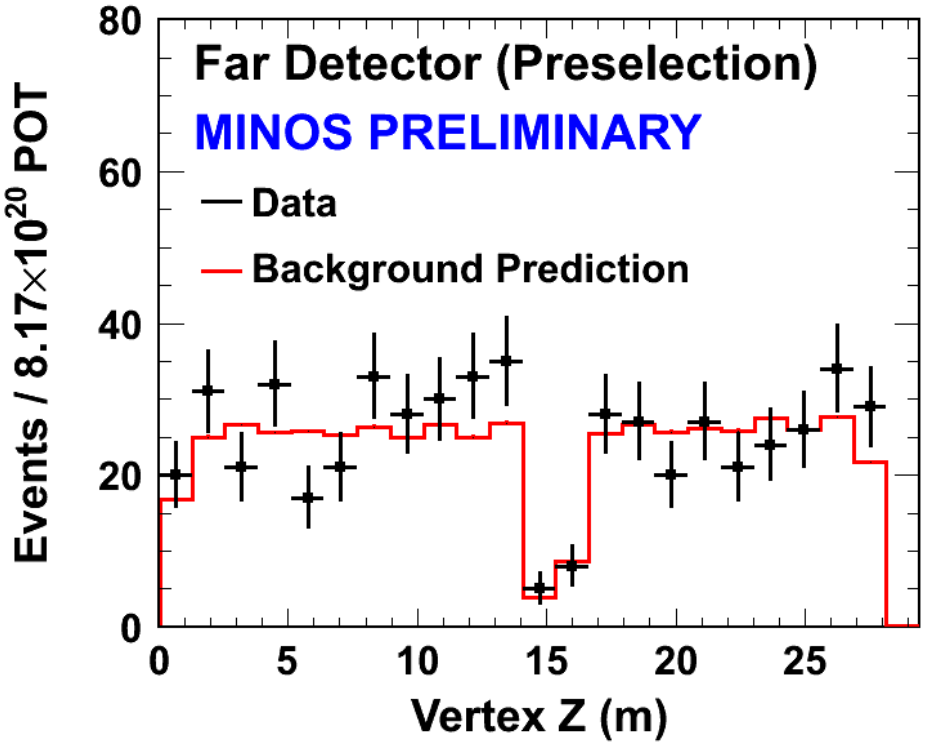


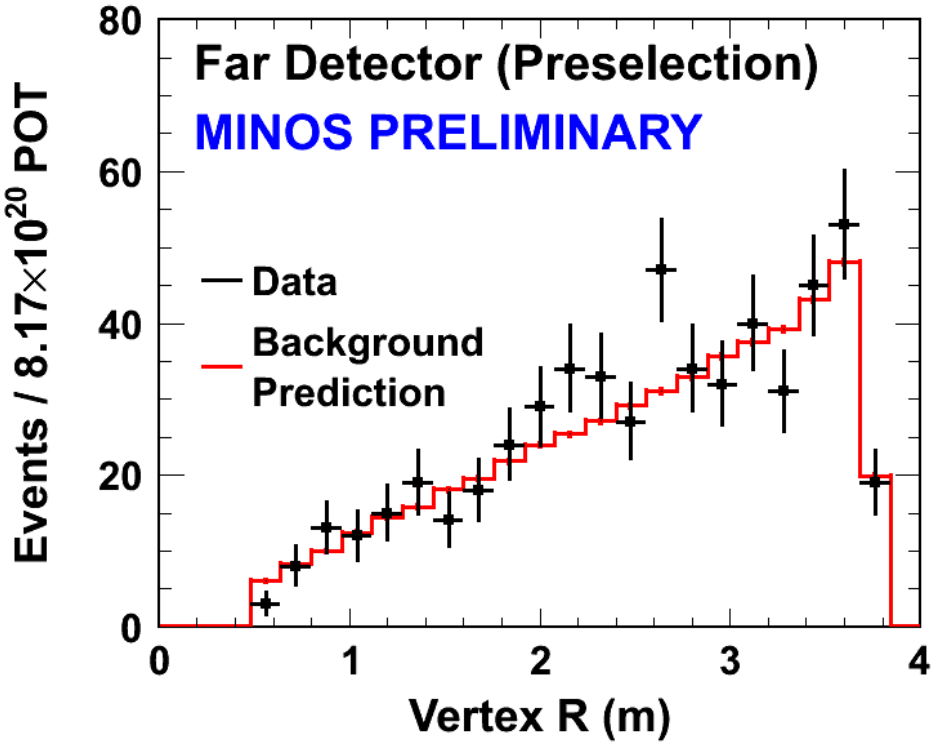
# FD Vertex Distributions



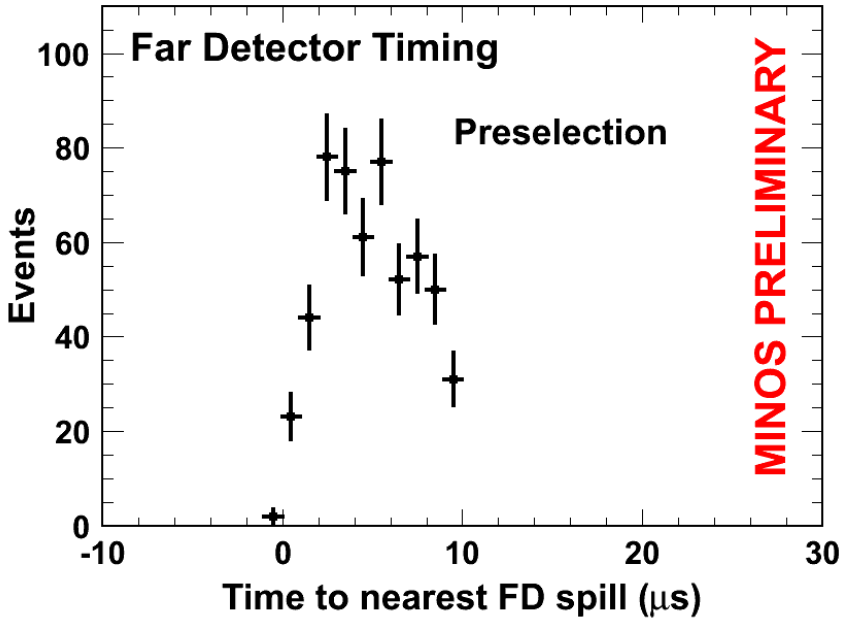



# FD Vertex Distributions

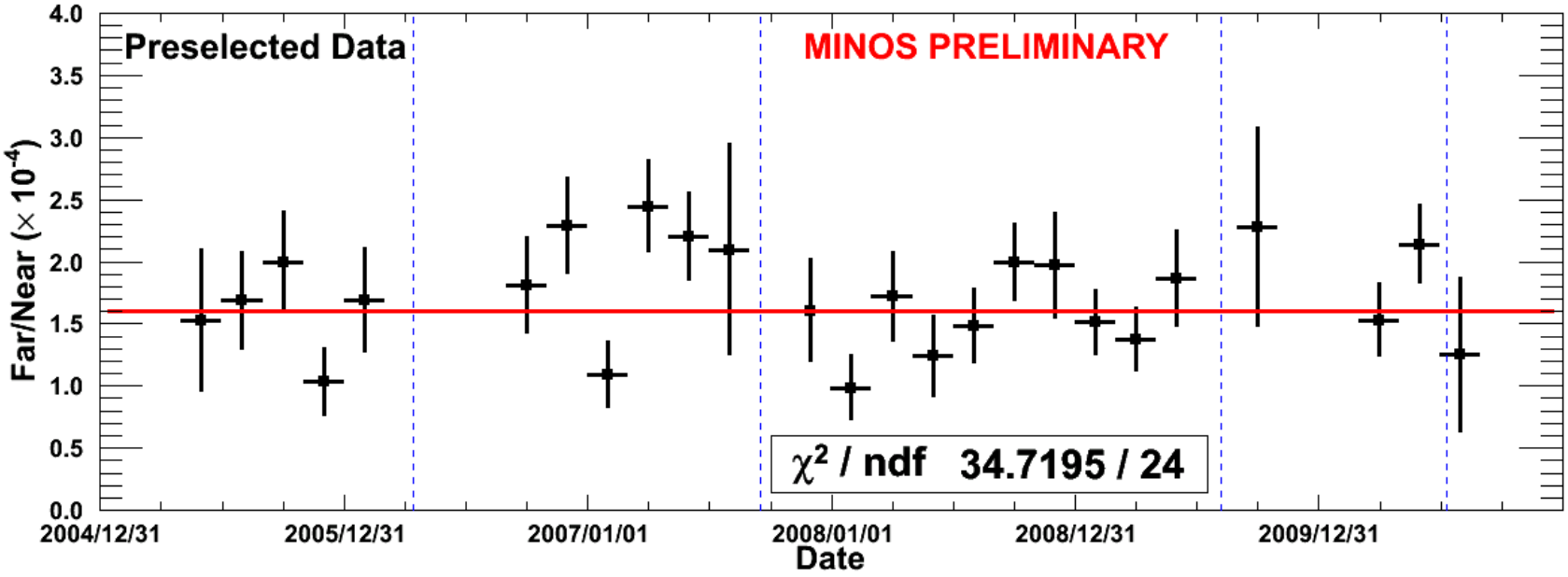


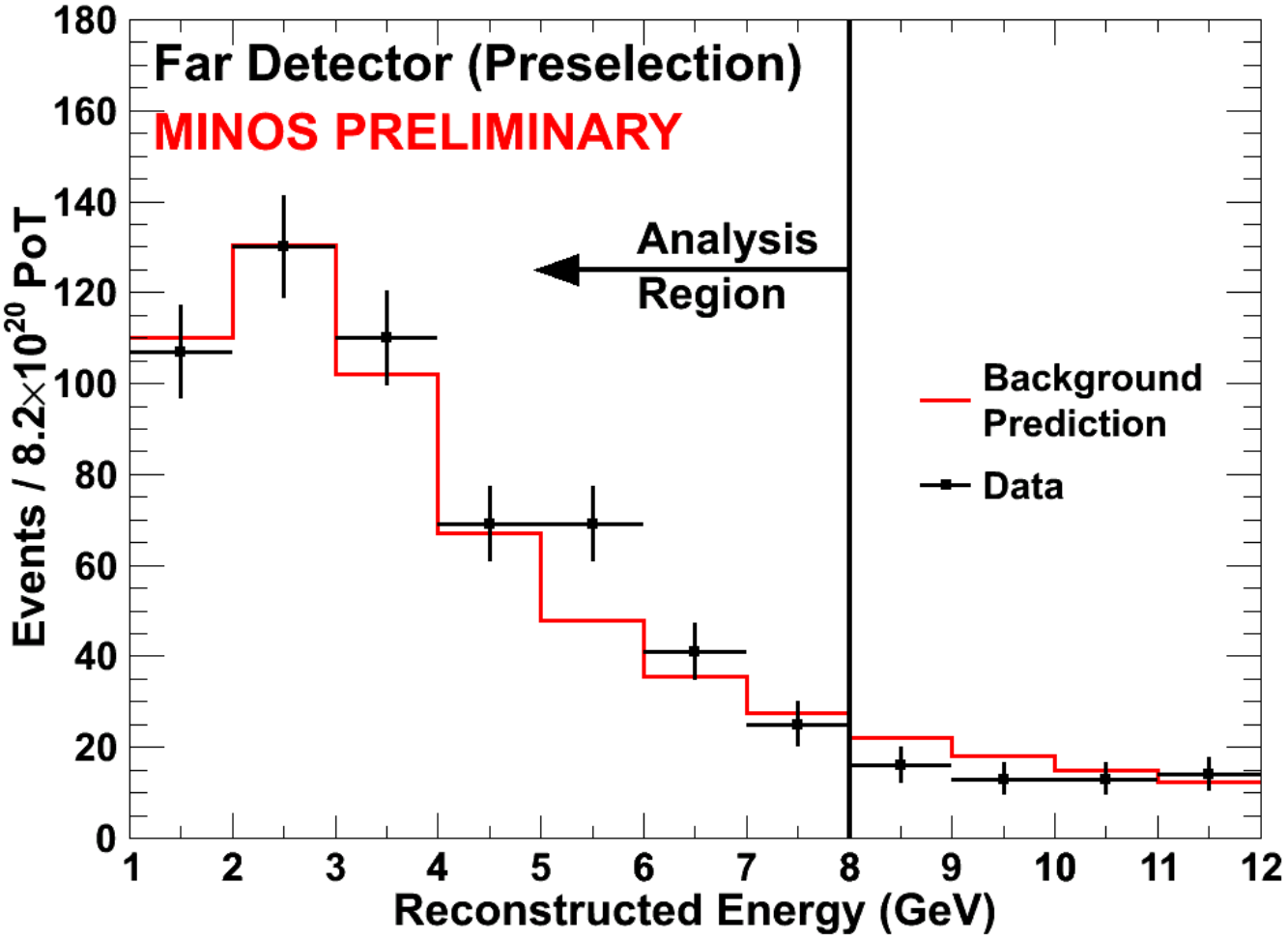
# Event Time / Rate Vs Time




Ratio of FD to ND preselected data



# FD Energy Spectrum

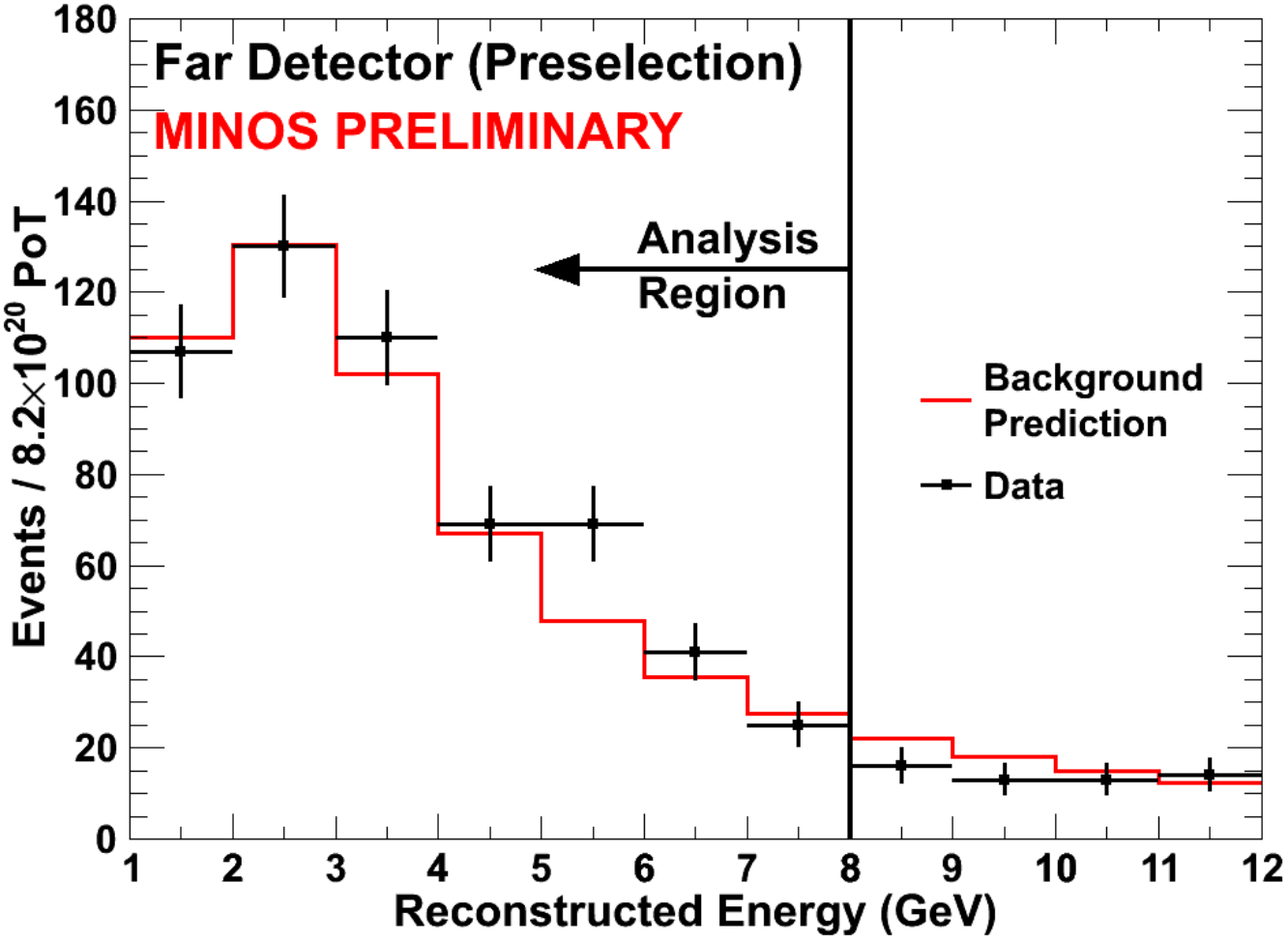



2.7σ (stat.) excess in the 5-6 GeV region

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




Conclusion: excess is likely a statistical fluctuation.

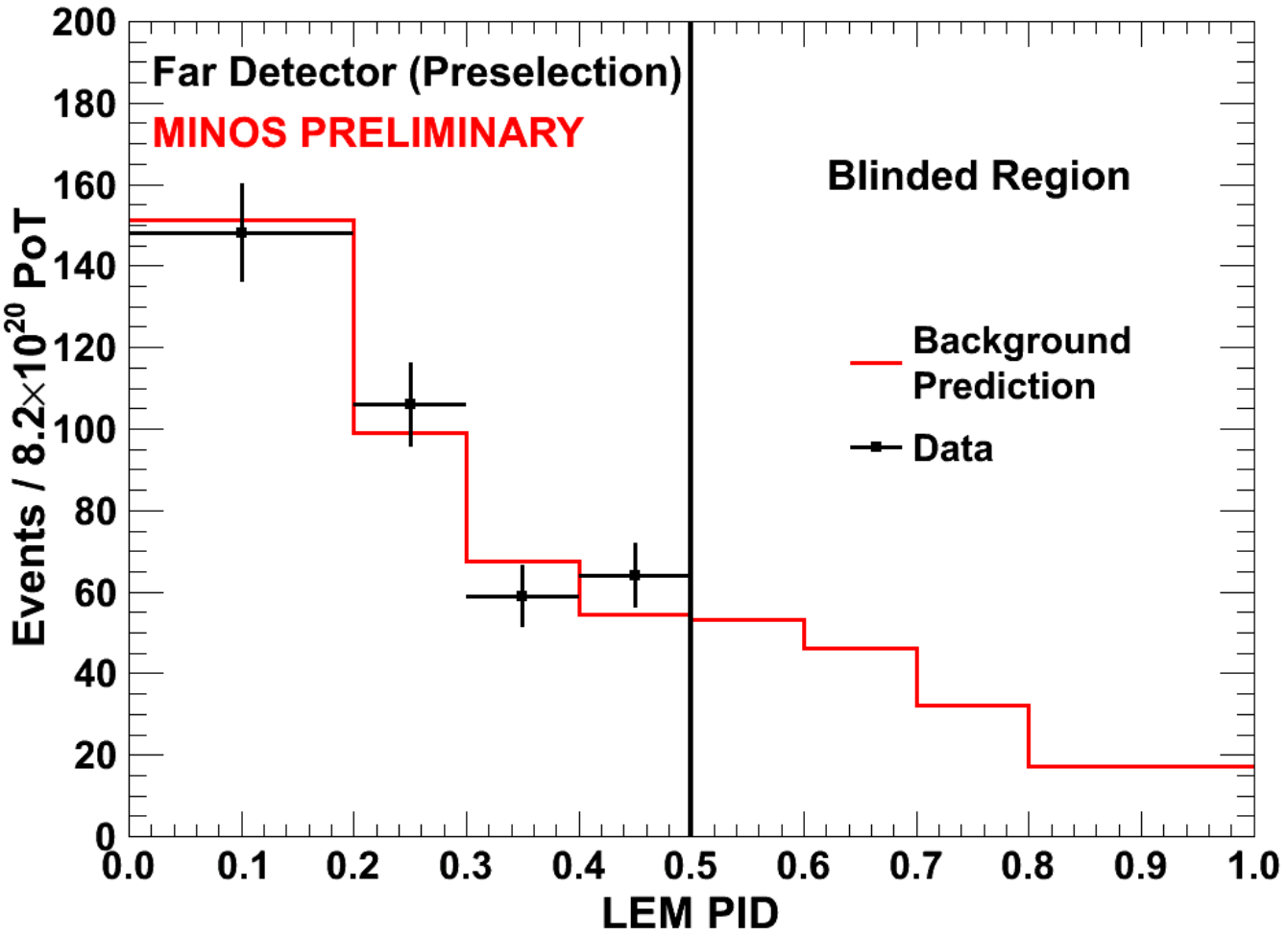
Initially planned to fit for $\theta_{13}$ to the LEM shape, integrated in energy

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

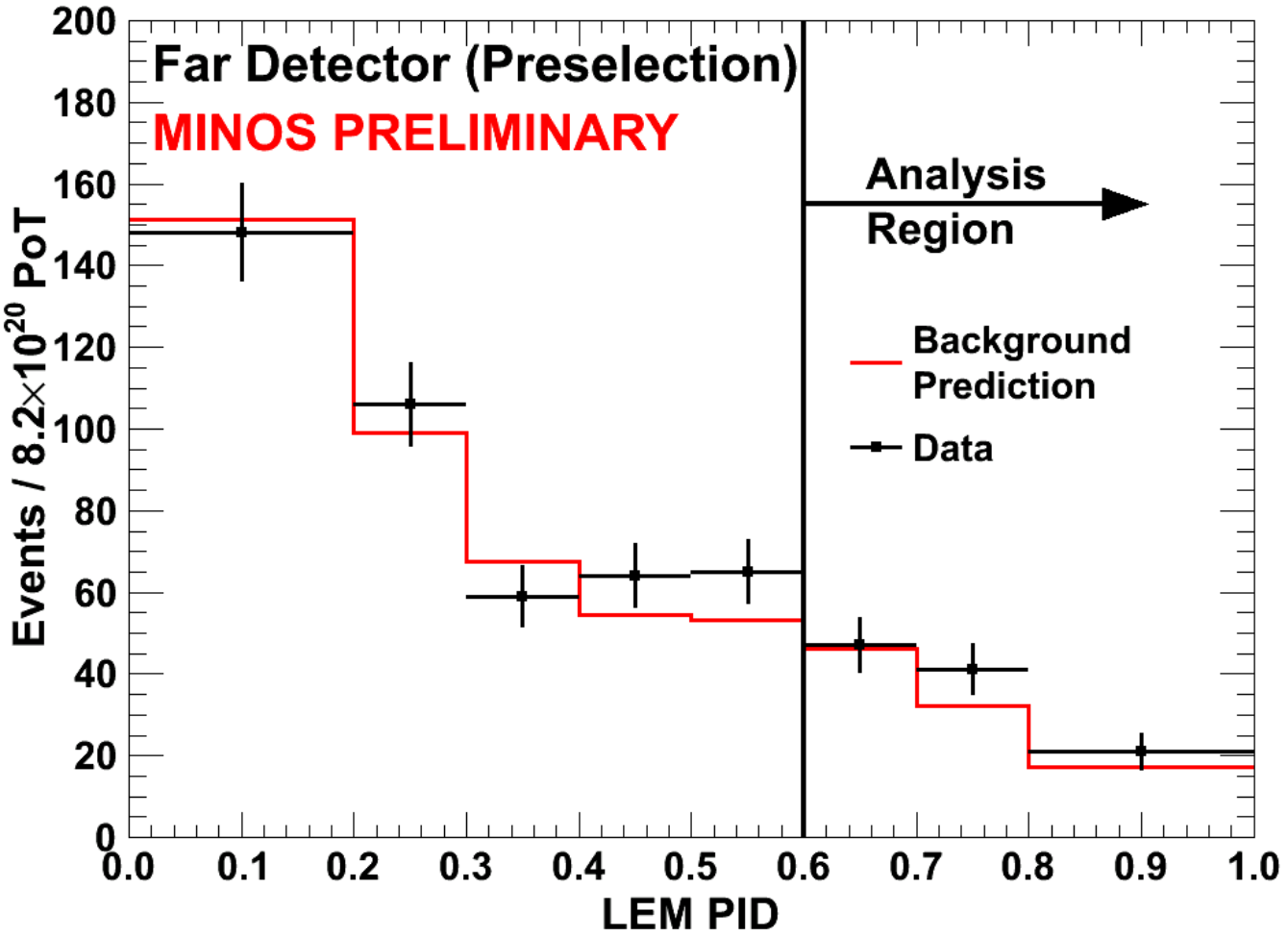
- Oscillations are an energy-dependent model: don't want a fluctuation to introduce a false signal
- BUT we don't want to cut data simply because it is statistically unlikely.

# Data in the signal region....

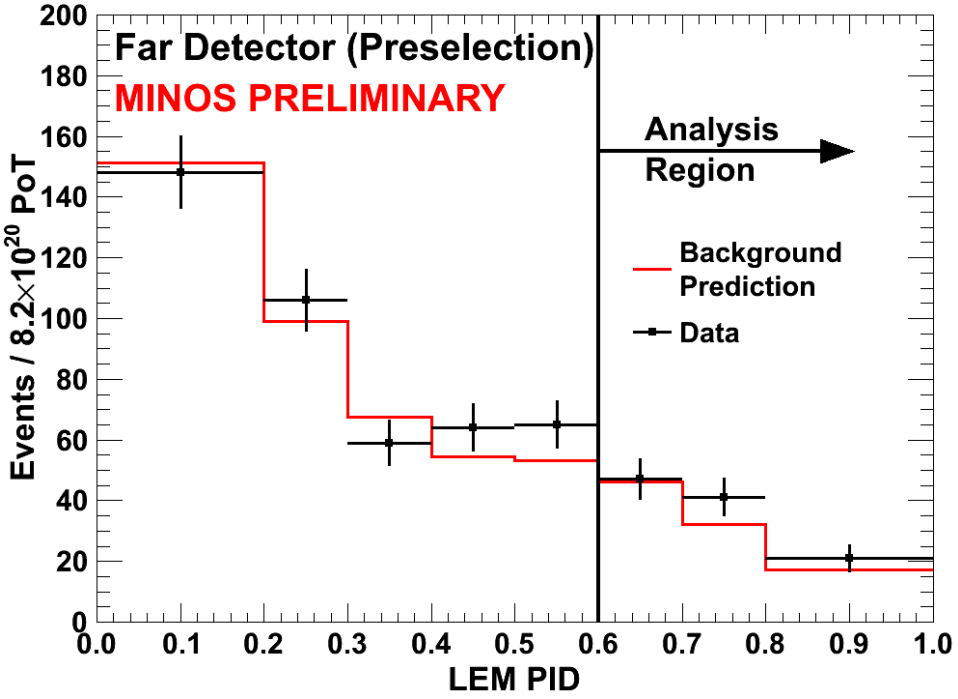
# FD Preselected Data



# FD Preselected Data



# Event Count




In signal-enhanced region (LEM>0.7):

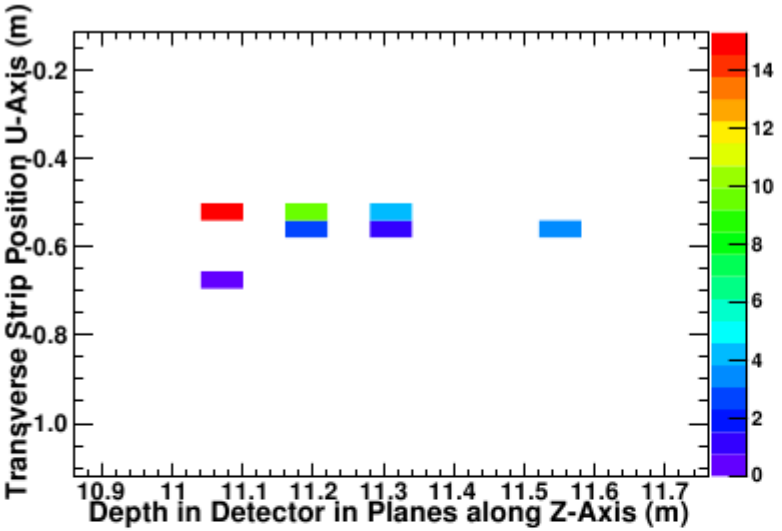
Expected background ($\theta_{13}$=0):

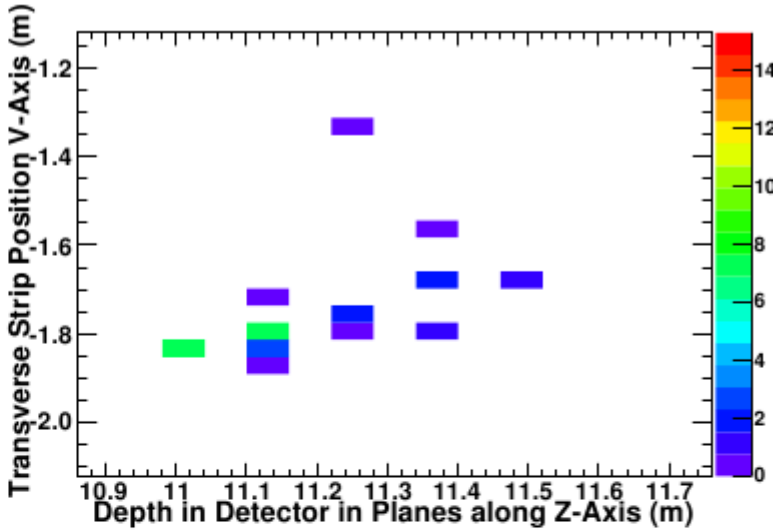
**49.5 +- 2.8 (syst) +- 7.0 (stat)**

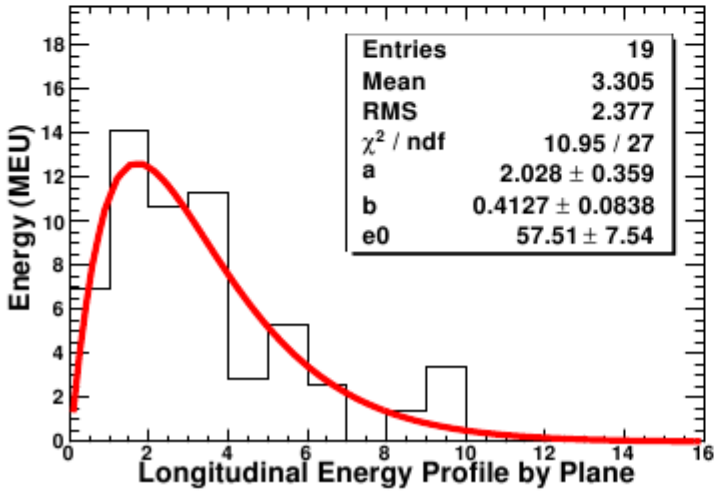
Observed data:

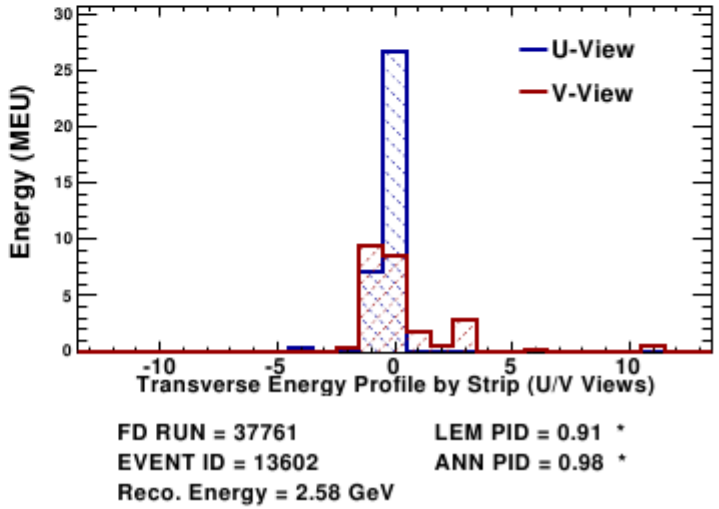
**62**

# Example of a Selected Event

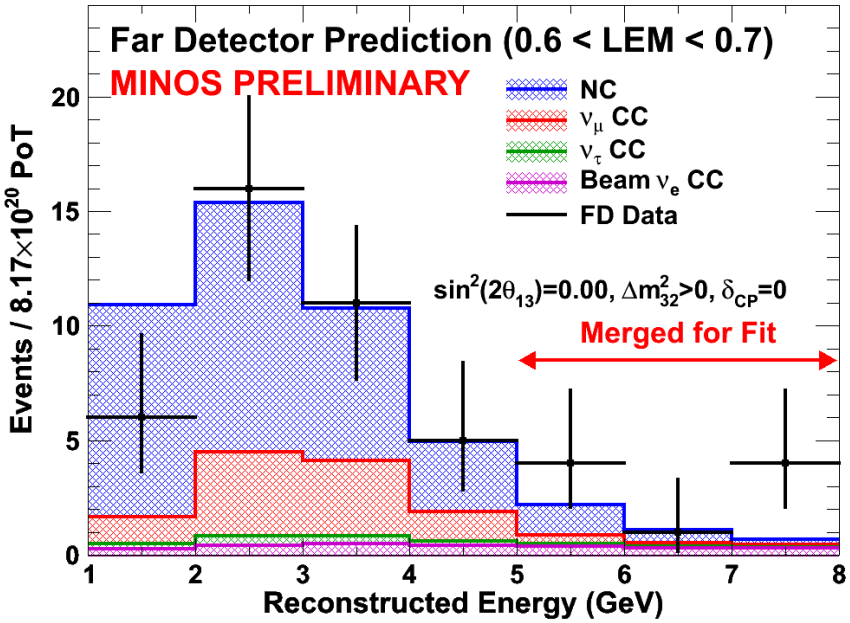


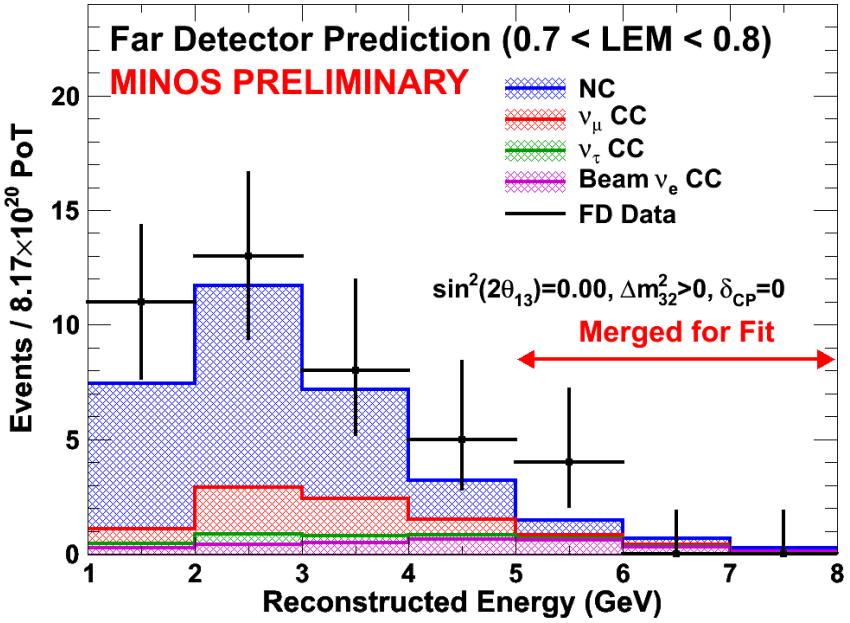



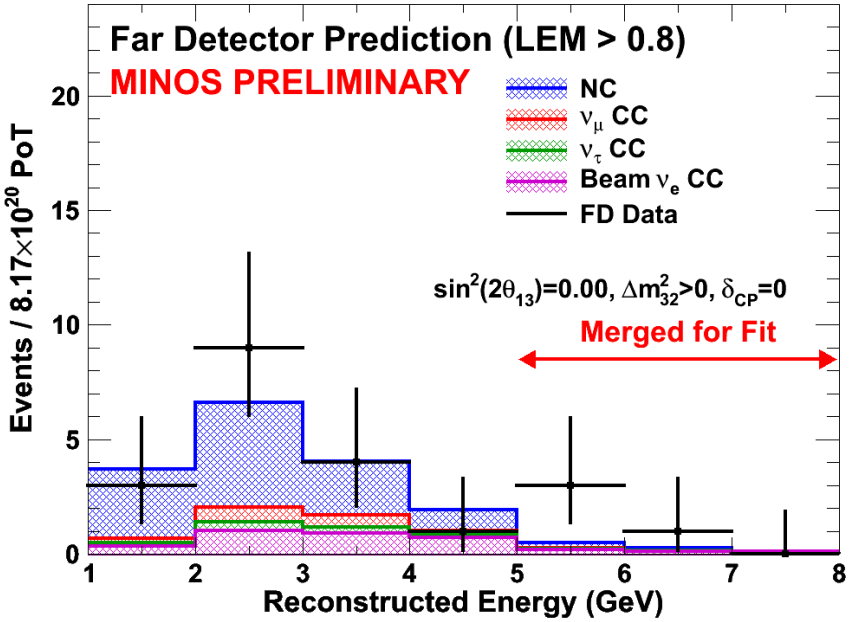



# Fitting to Oscillations

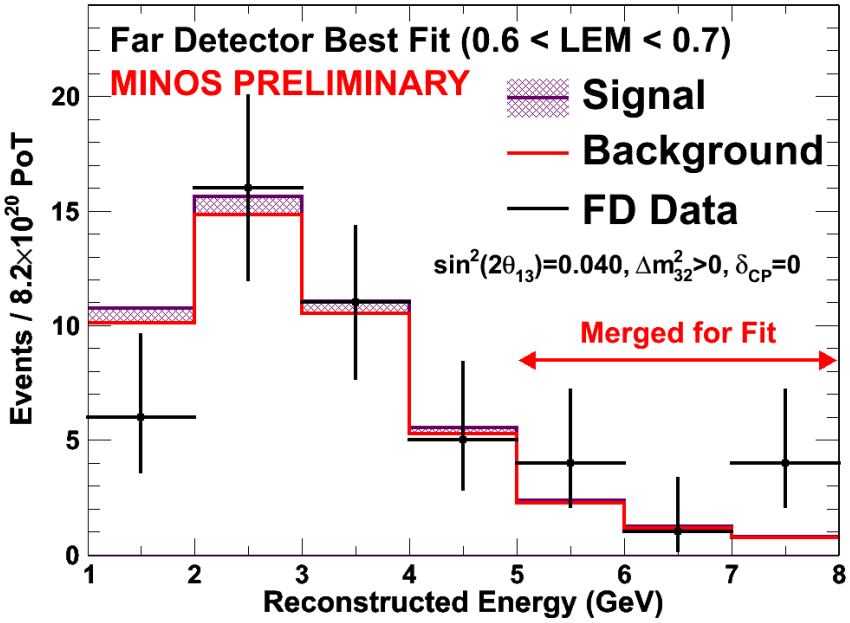


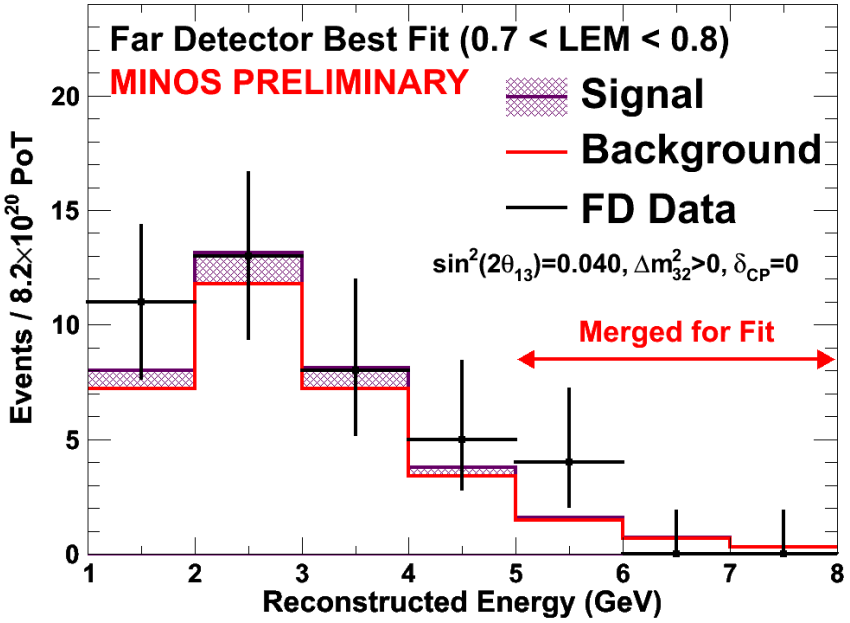



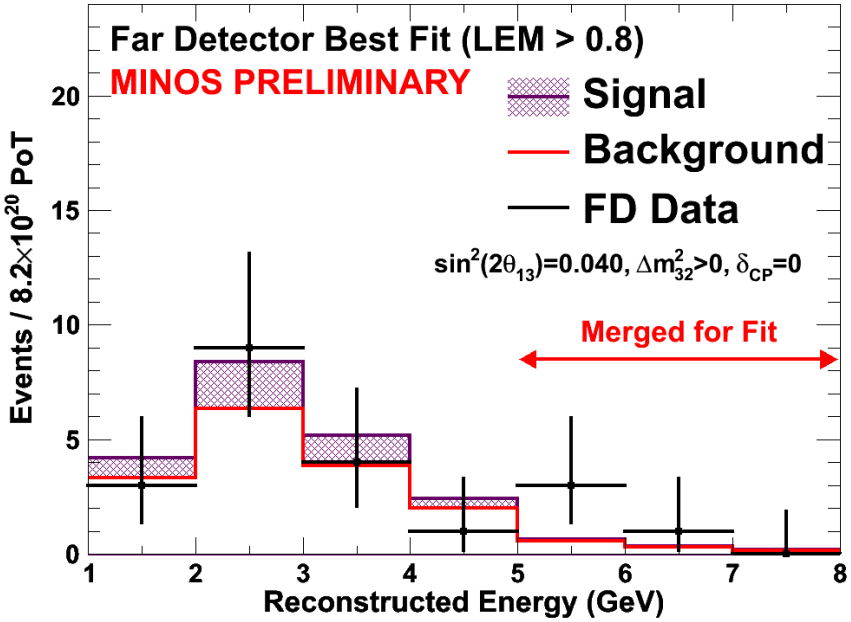




15 bin fit
3 LEM bins x 5 energy bins

# Best Fit



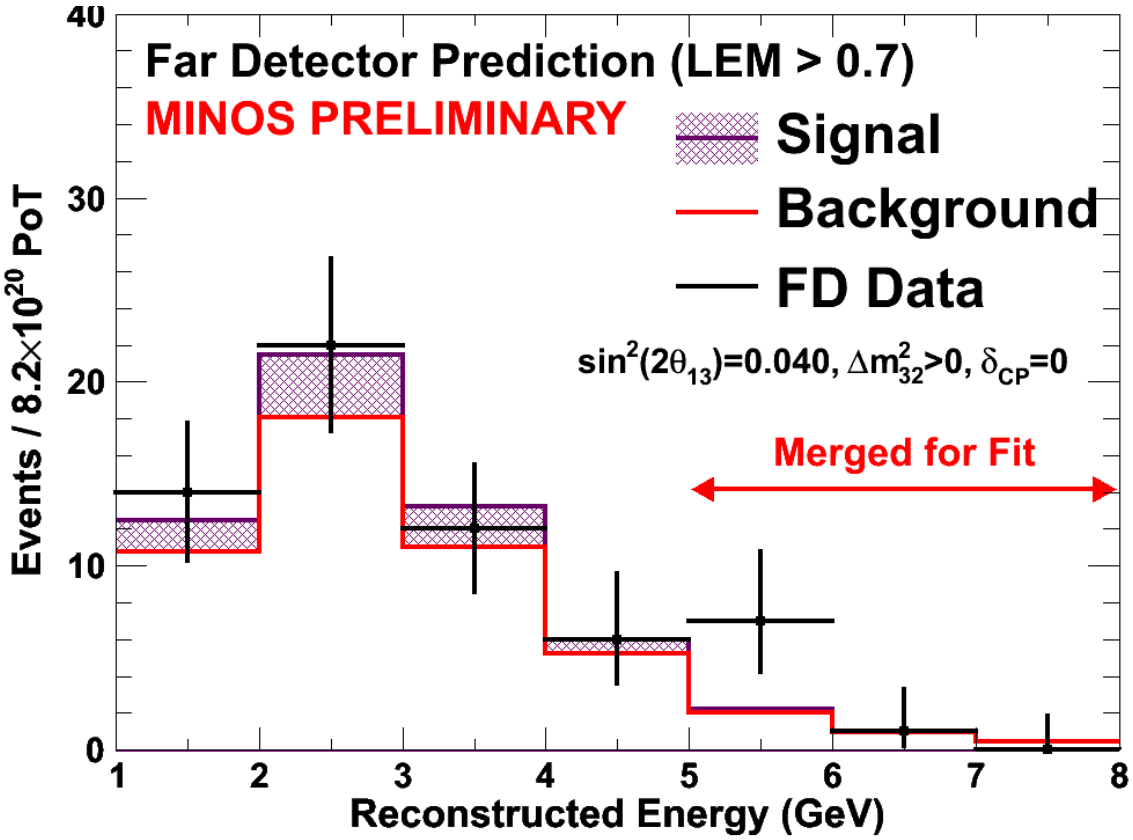




**Best fit $\sin^2 2\theta_{13} = 0.040$**

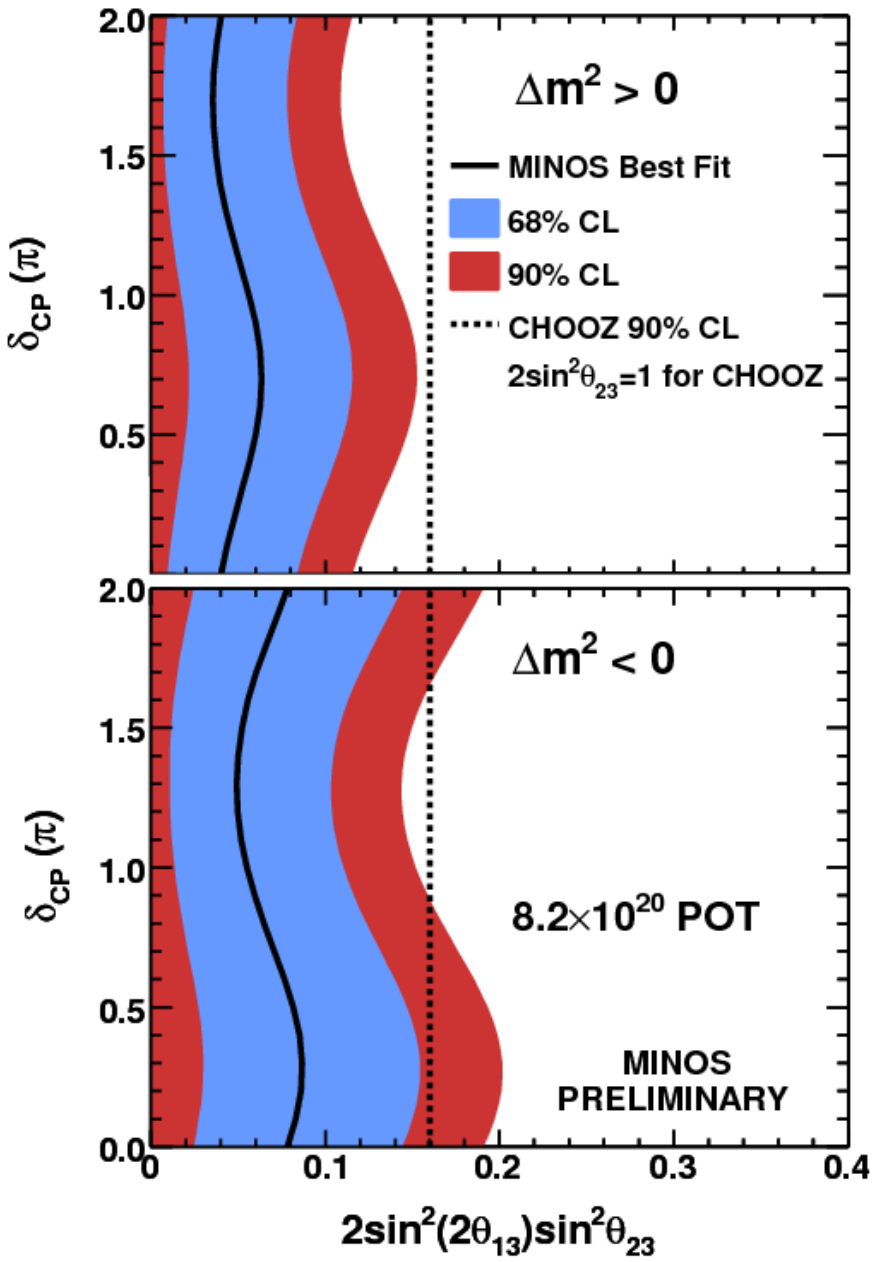
(Assuming $\delta=0$, $\theta_{23}=\pi/4$, normal hierarchy)

# Best Fit

Spectrum for the signal-enhanced region (LEM>0.7) at best fit



# Allowed Regions




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

$$\sin^2(2\theta_{13}) < 0.12\,(0.19)$$

90% CL

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

Best Fit

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

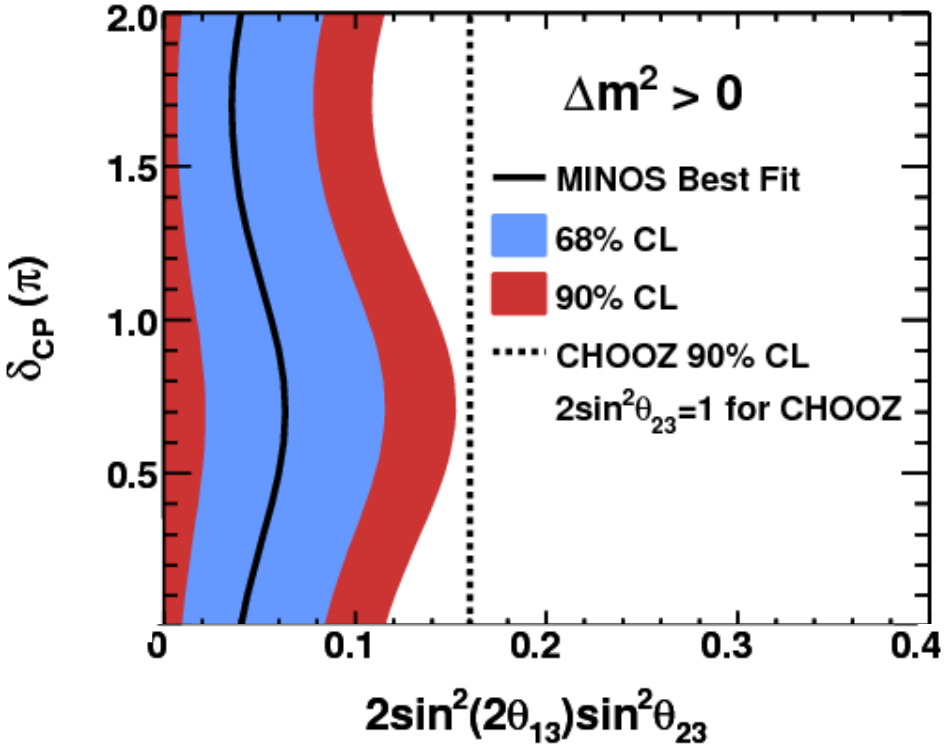
Feldman-Cousins contours

Uncertainties in the other oscillation parameters are included

# Consistency Check of Results

| | Best Fit | 90%Upper Limit |
|---|---|---|
| 2010-style analysis (ANN rate-only) | 0.041 | 0.131 |
| LEM rate-only | 0.064 | 0.147 |
| LEM shape fit | 0.046 | 0.121 |
| **OFFICIAL FIT – LEM x energy shape fit** | **0.040** | **0.115** |

Preliminary

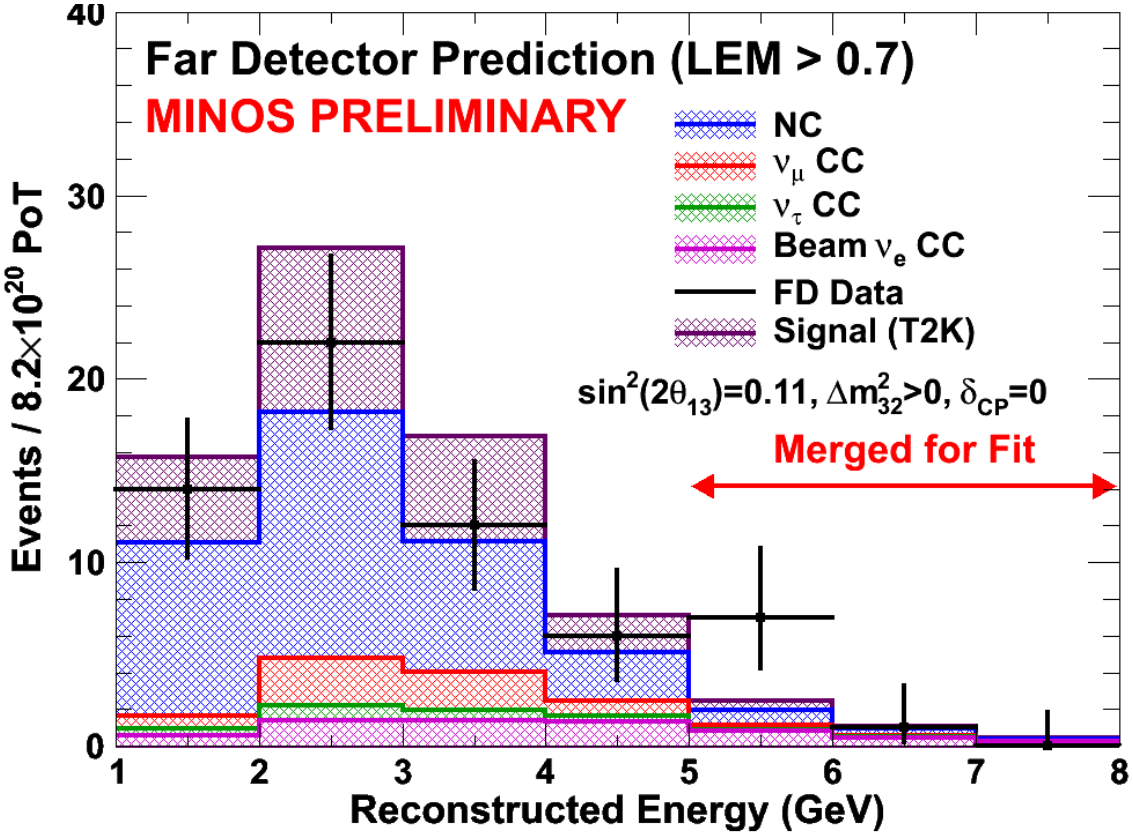



90% CL upper limits in table are NOT Feldman-Cousins limits

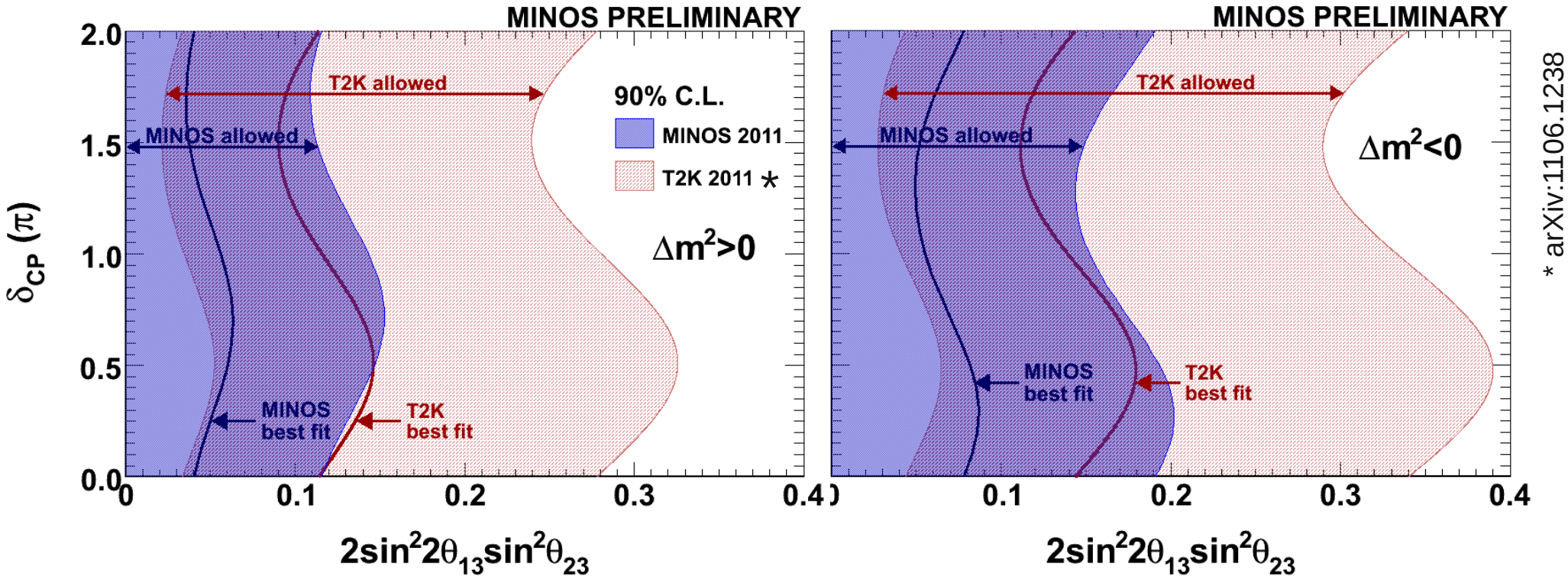
Numbers assume $\delta$=0, normal hierarchy, $\theta_{23} = \pi/4$

# Comparison to T2K Results

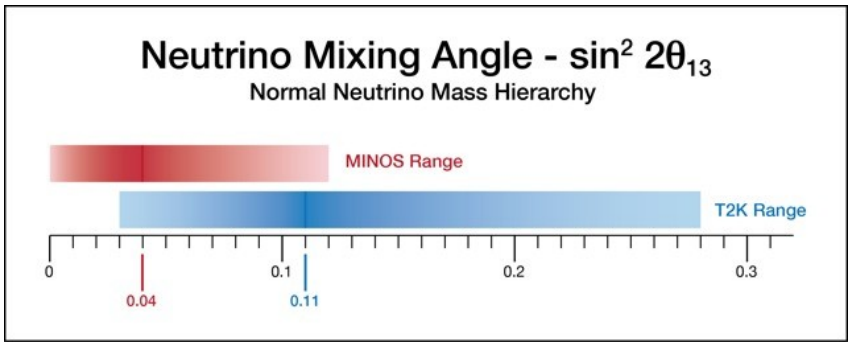
What does our signal prediction look like at T2K's best fit? ($\sin^2 2\theta_{13}$=0.11)

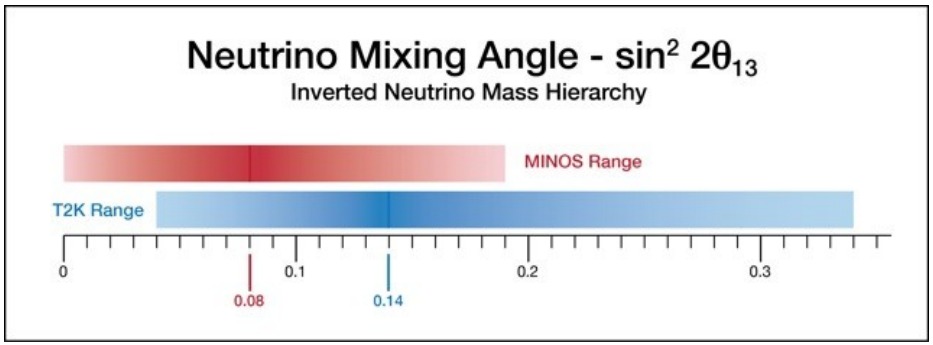


# Comparison to T2K Results




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



# Summary

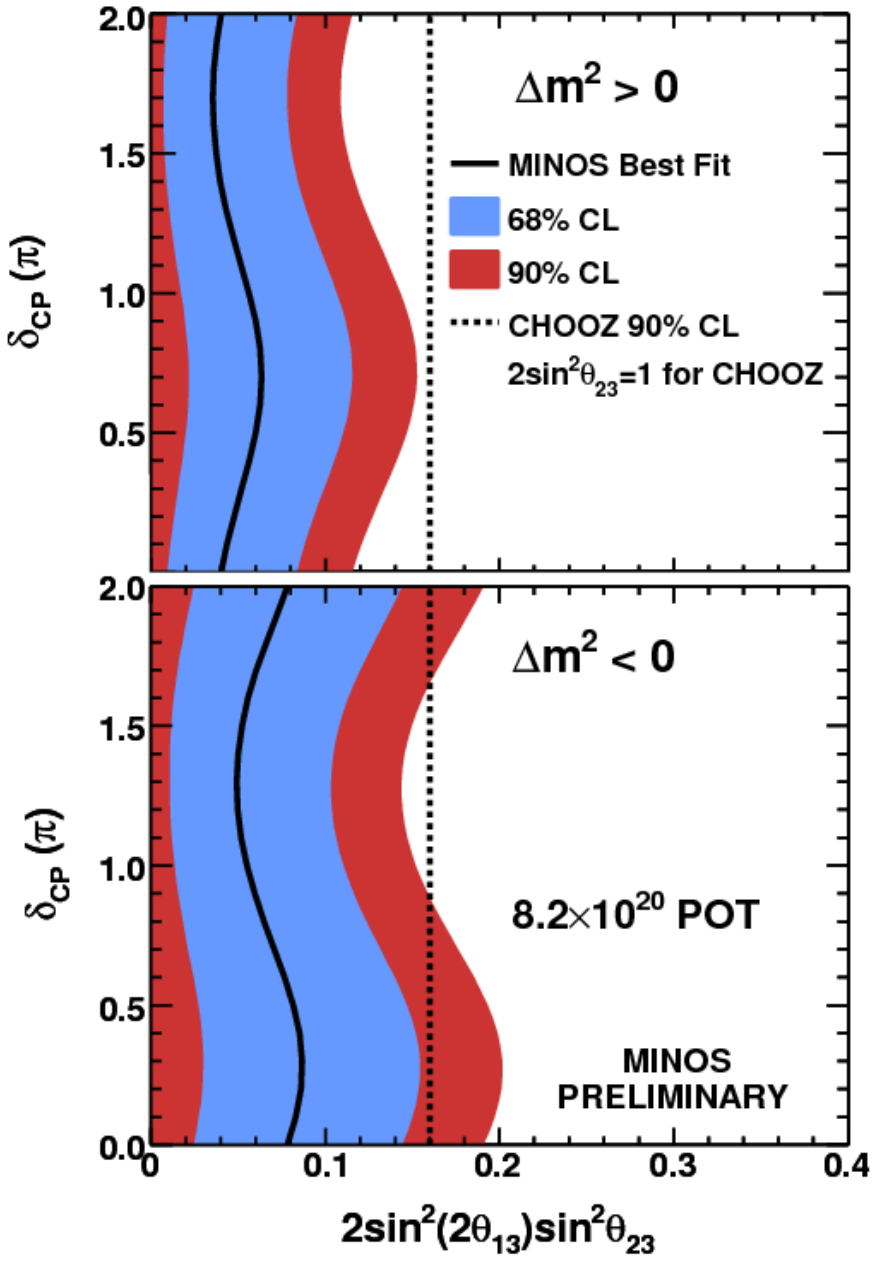
- MINOS has updated our electron neutrino appearance search with more data and improved analysis techniques: overall 30% gain in sensitivity

- 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

**$\sin^2(2\theta_{13})<0.12$ (0.19)**

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