Recent Results from MINOS

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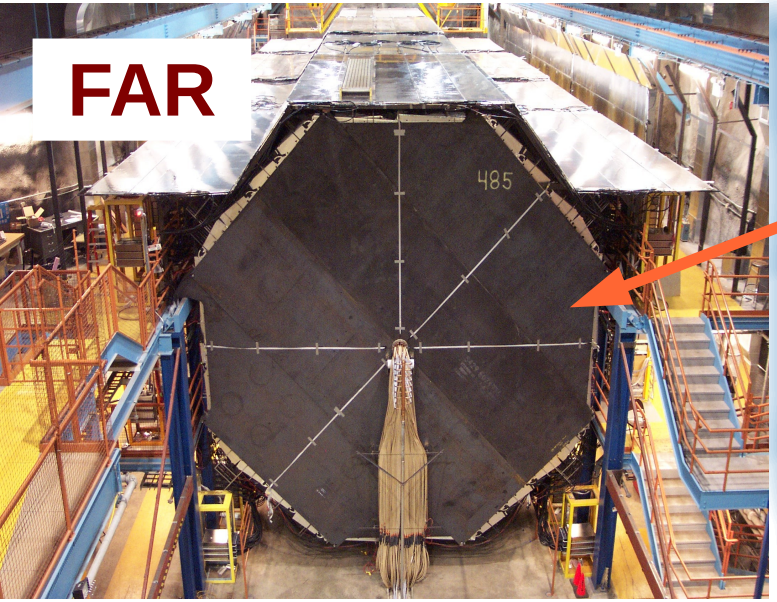
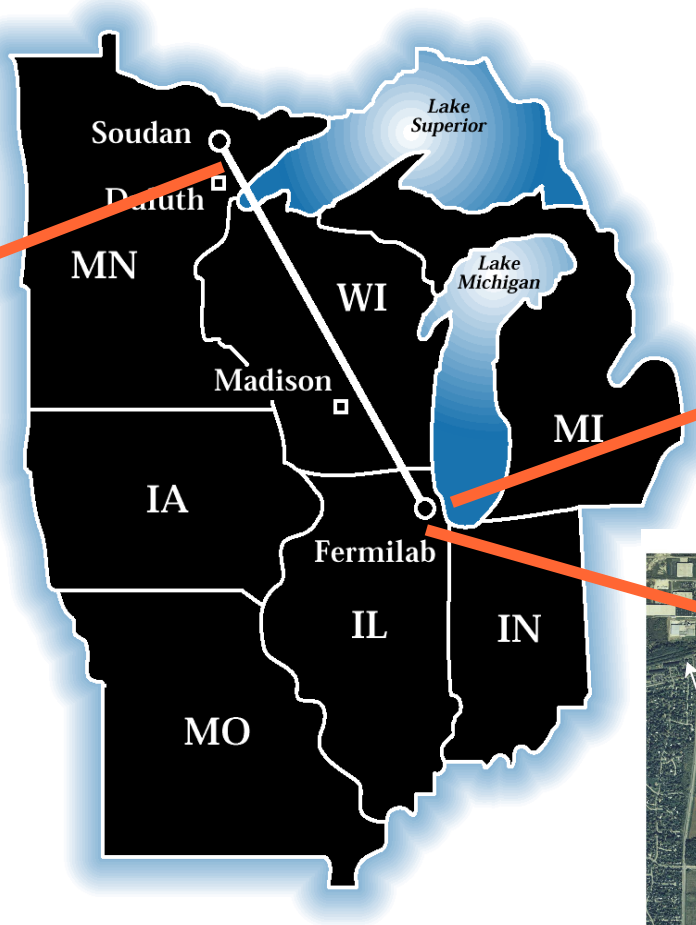
On behalf of the MINOS Collaboration

PANIC, July 28, 2011

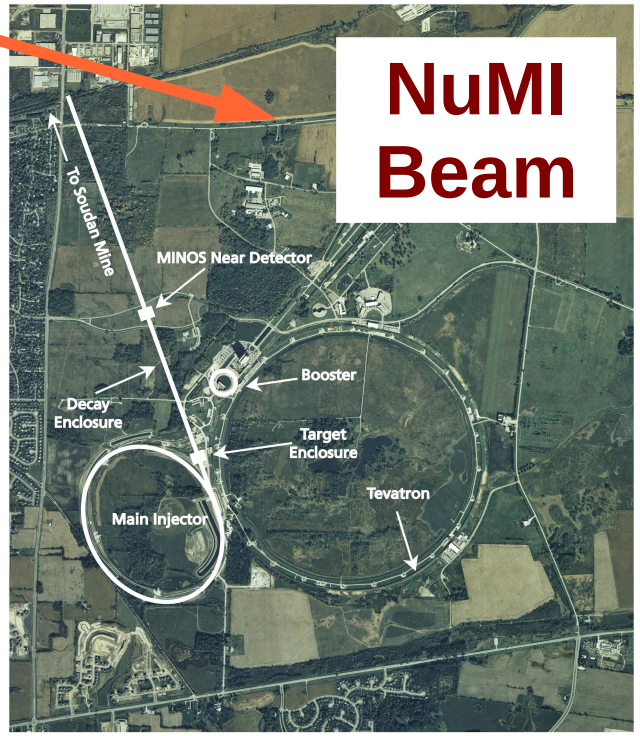
The MINOS Experiment



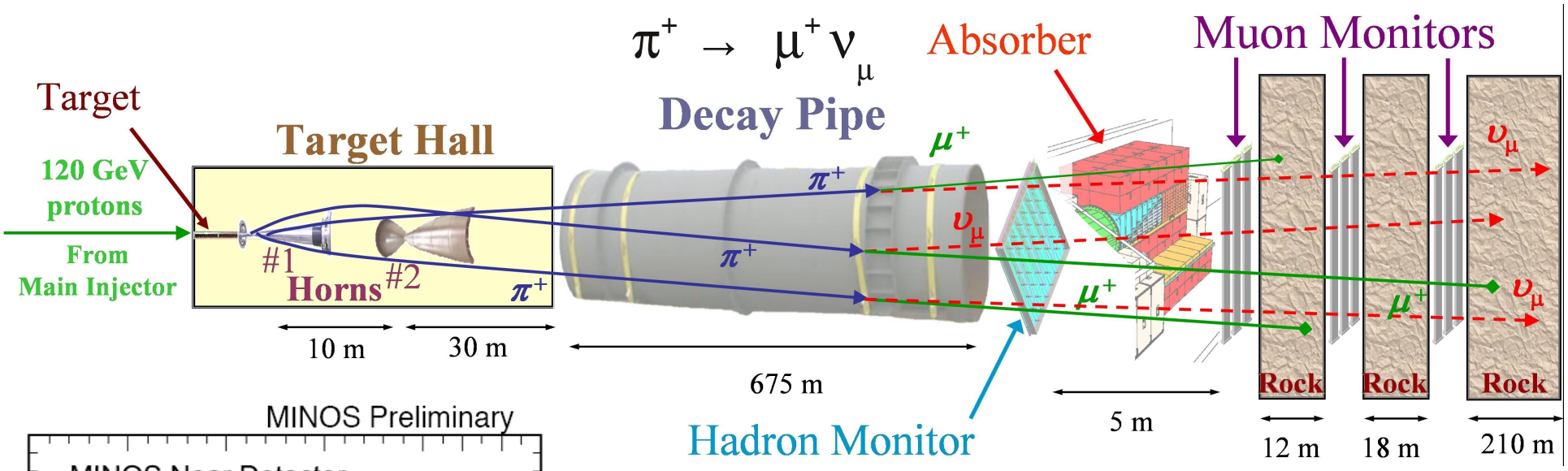


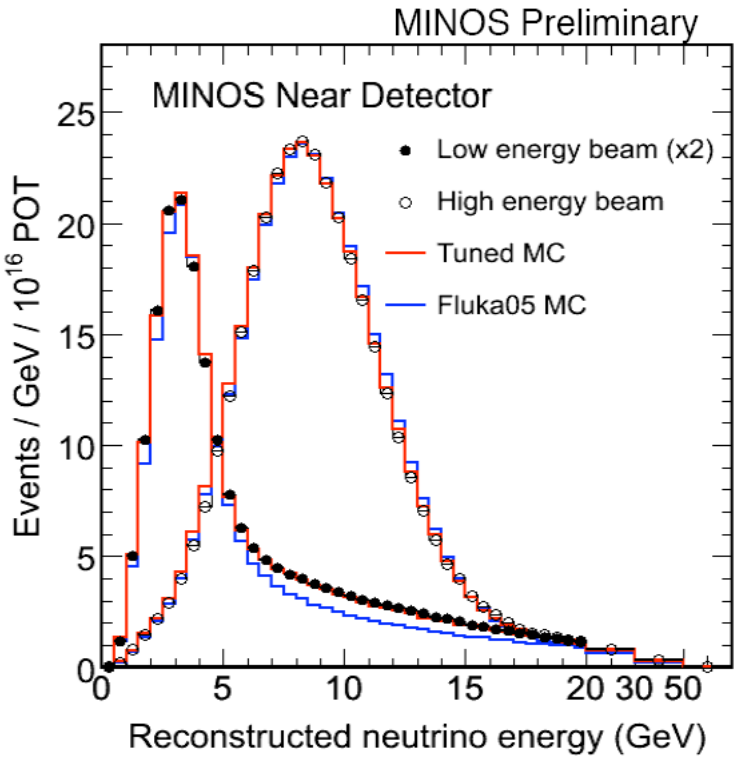
Detectors consist of alternating layers of steel plates and scintillator strips in a ~1.3 T toroidal magnetic field

735 km baseline



NuMI Beam

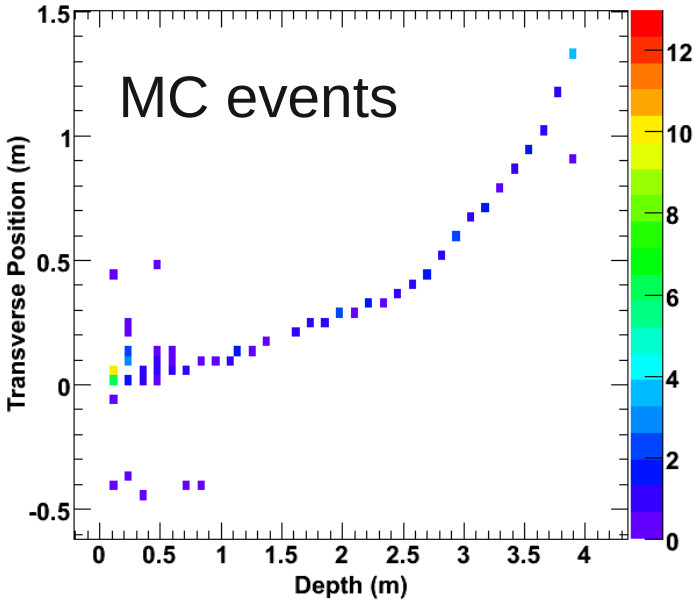




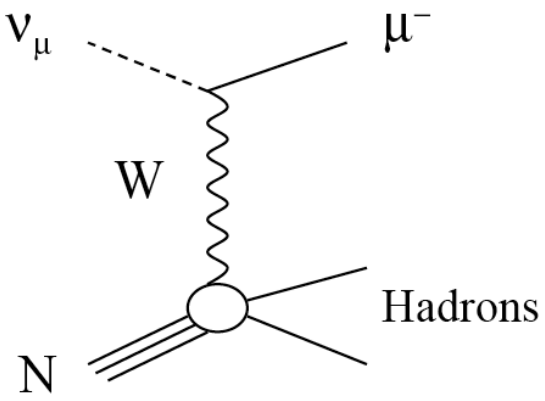
- Target position can be changed to tune the neutrino energy spectrum
- Horn current can be reversed to produce an antineutrino enhanced beam

Neutrino Interactions at MINOS

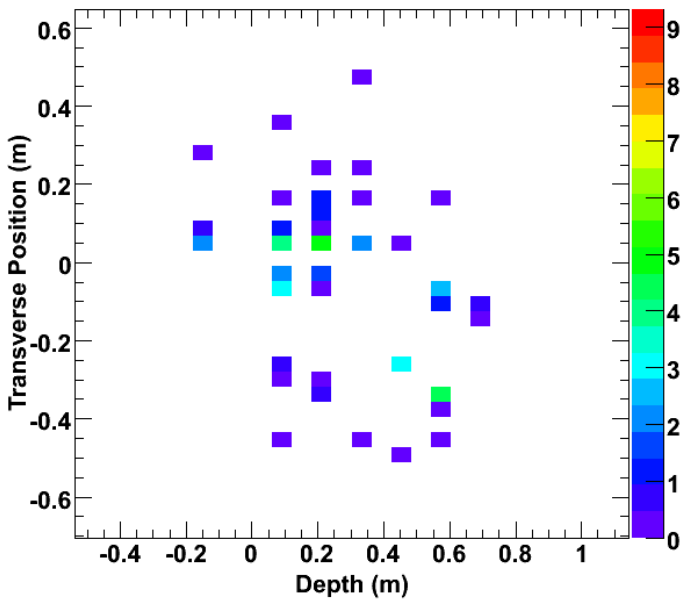
ν_μ Charged Current (CC)



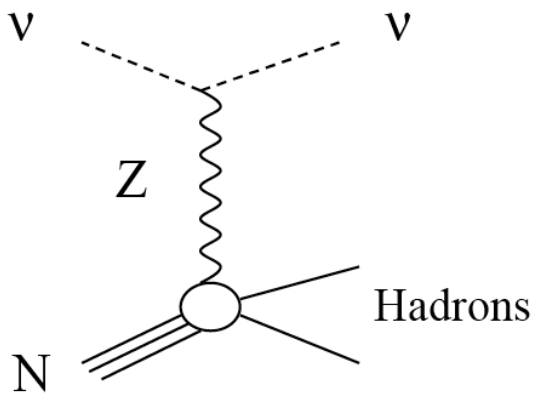
$$\nu_\mu N \rightarrow \mu^- X$$



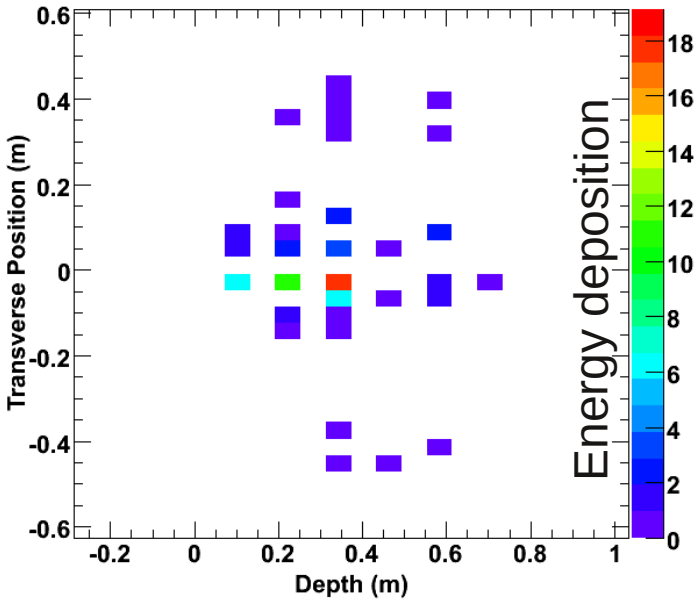
Neutral Current (NC)



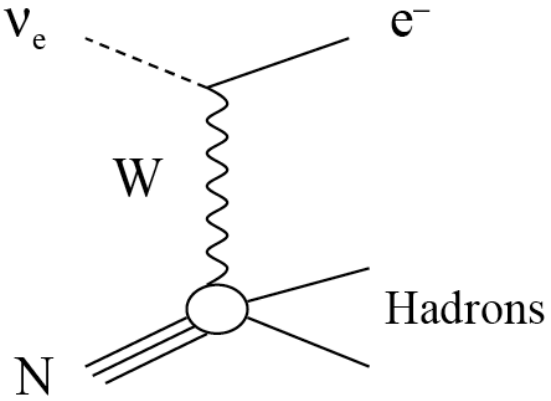
$$\nu N \rightarrow \nu X$$



ν_e Charged Current (CC)



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



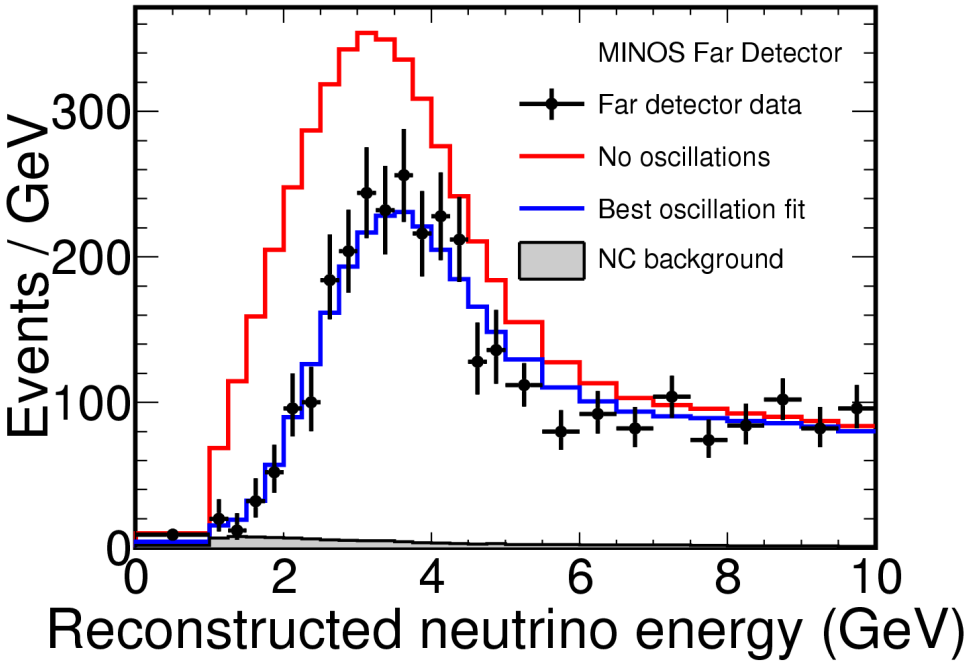
Muon Neutrino Disappearance

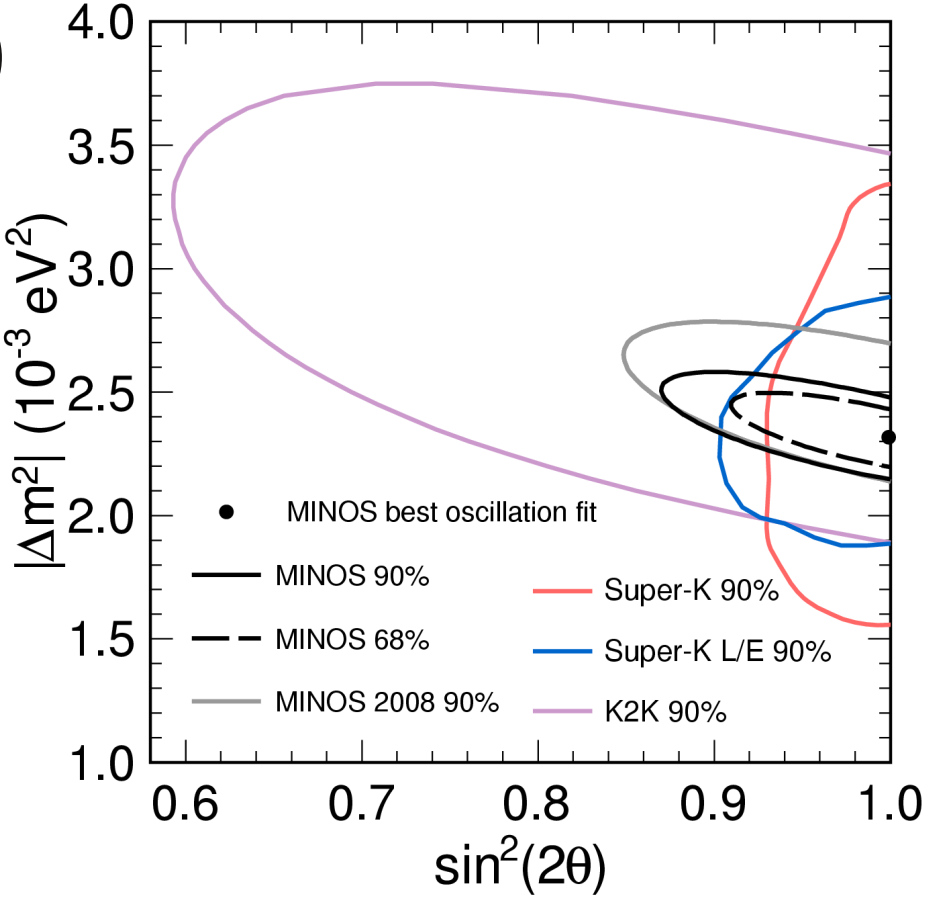
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 L/E)$$

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

$$|\Delta m^2| = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\,eV^2$$

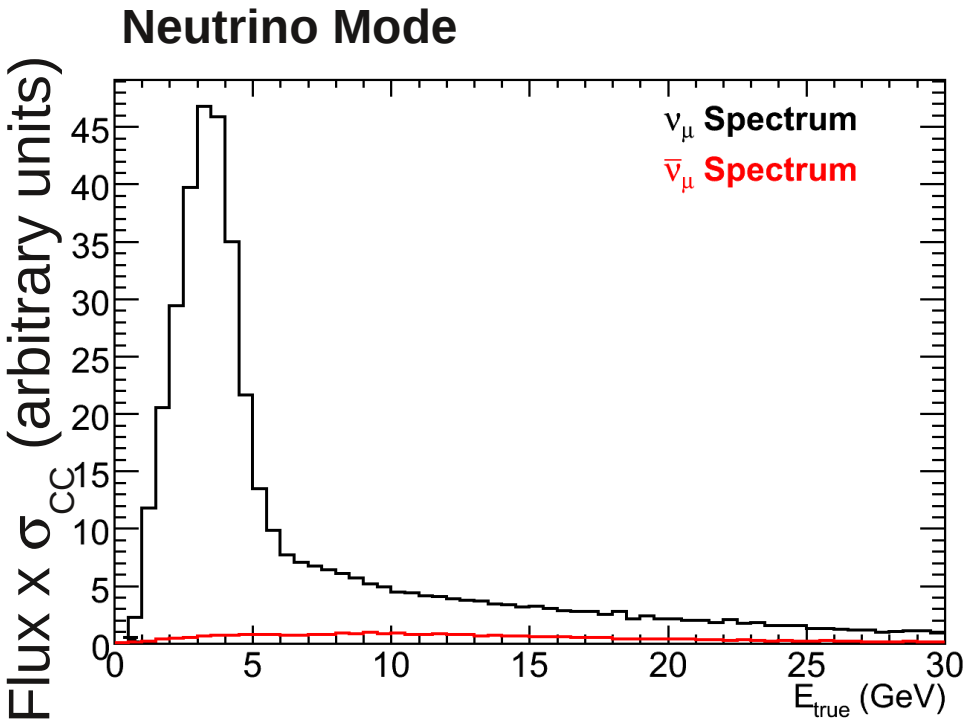
$$\sin^2(2\theta_{23}) > 0.9\,(90\%\ \text{C.L.})$$



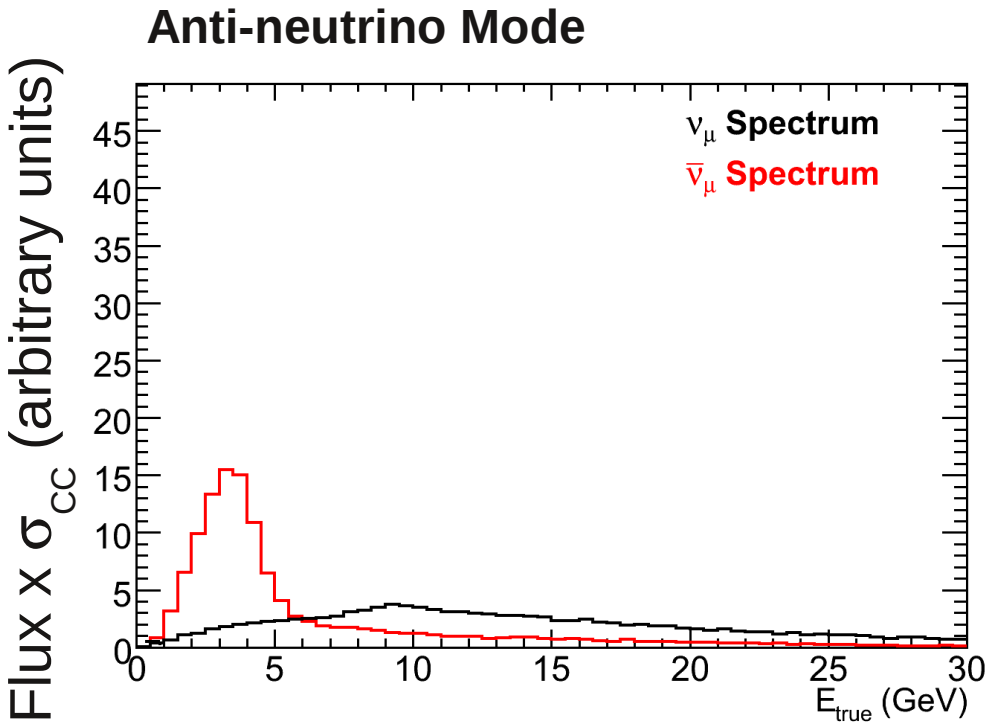


Phys. Rev. Lett. 106, 181801 (2011)

Neutrinos or Antineutrinos



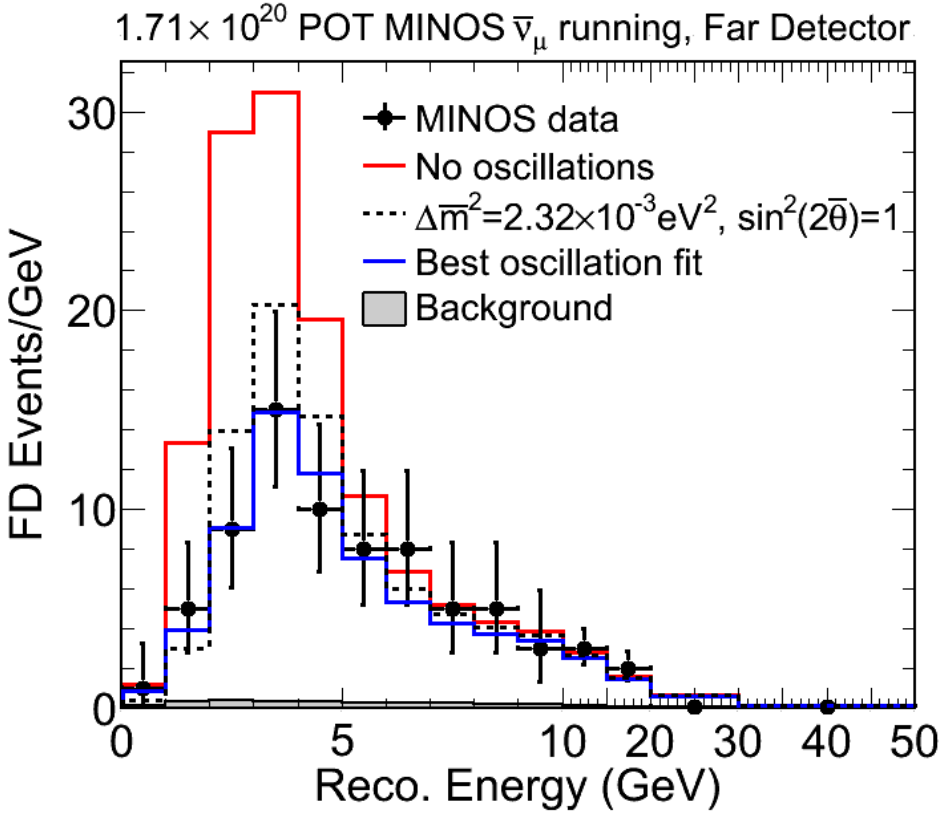
$$\nu_\mu = 91.7\,\%$$
$$\bar{\nu}_\mu = 7.0\,\%$$
$$\nu_e + \bar{\nu}_e = 1.3\,\%$$



$$\bar{\nu}_\mu = 39.9\,\%$$
$$\nu_\mu = 58.1\,\%$$
$$\nu_e + \bar{\nu}_e = 2.0\,\%$$

Antineutrino Disappearance

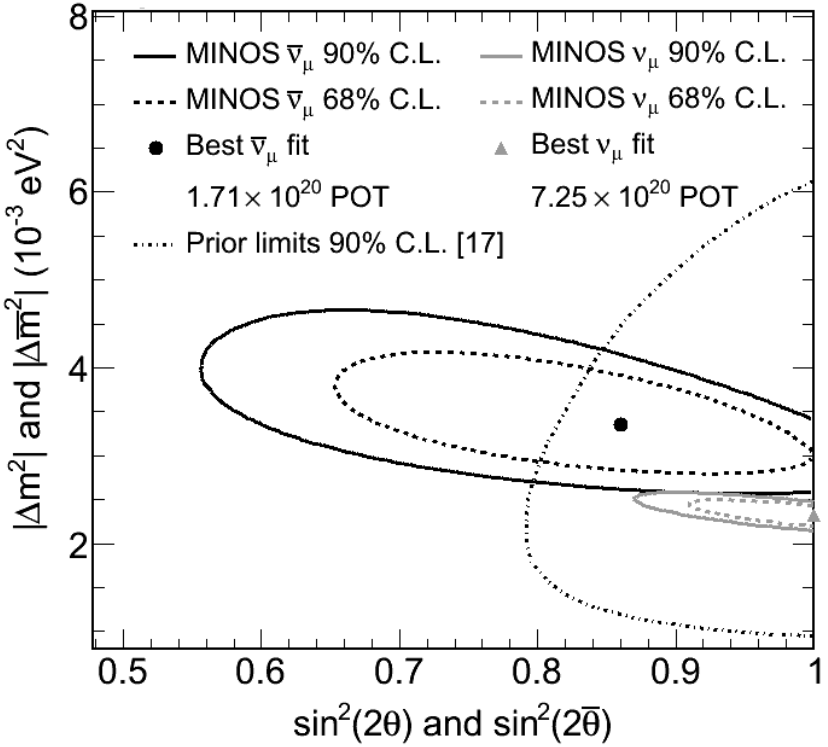
Use the antineutrino-enhanced beam to measure the disappearance parameters with antineutrinos



Excludes the no-oscillation hypothesis at 6.3σ

Phys. Rev. Lett. 107, 021801 (2011)

$$\left|\Delta \overline{m}^2\right| = \left(3.36^{+0.46}_{-0.40}\right) \times 10^{-3}\ \mathrm{eV}^2$$

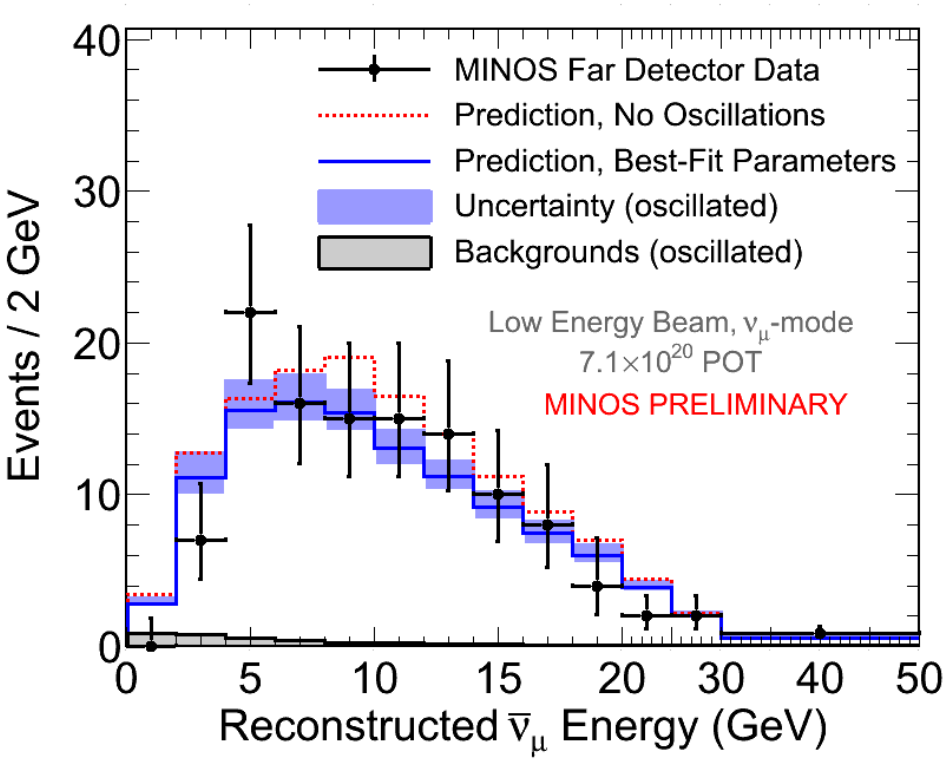


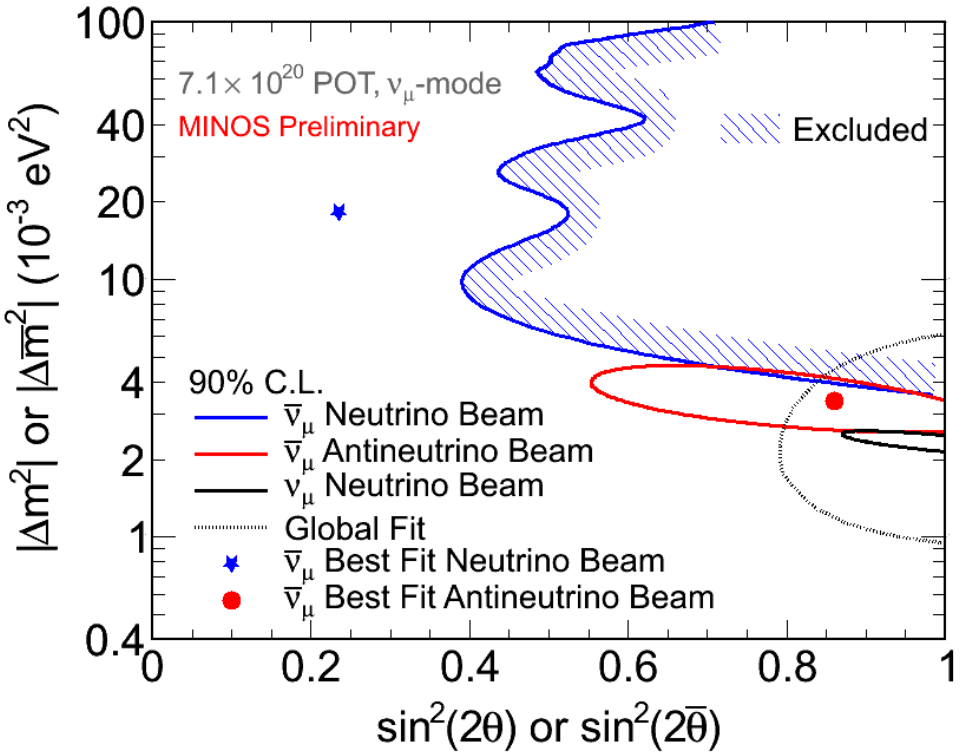
New results with more data this summer!

1.71x10^{20} POT → 2.95x10^{20} POT

Antinus in the Nu Beam

Do an antineutrino disappearance search with the 7% antineutrino component of the neutrino beam...





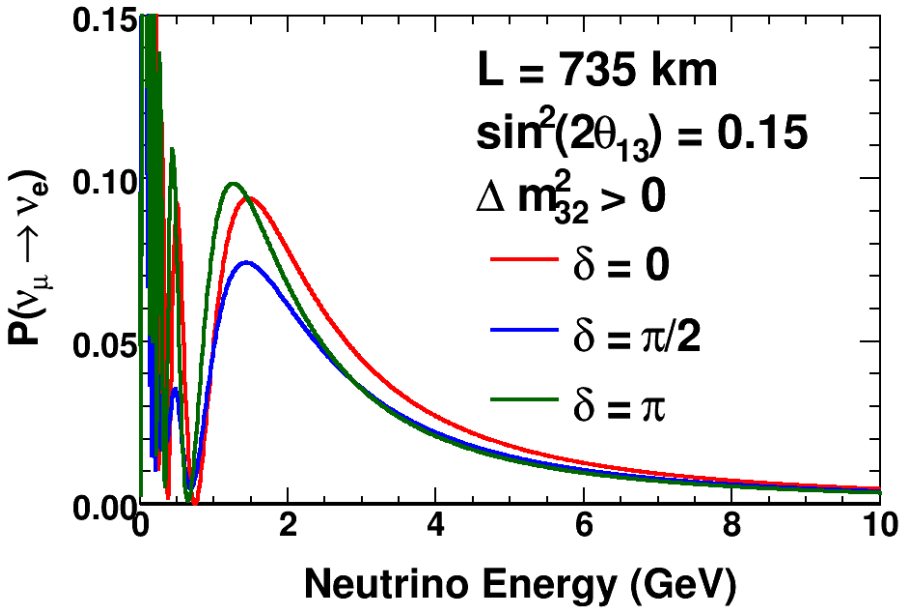
Electron Neutrino Appearance

appearance of ν_e in a ν_μ beam

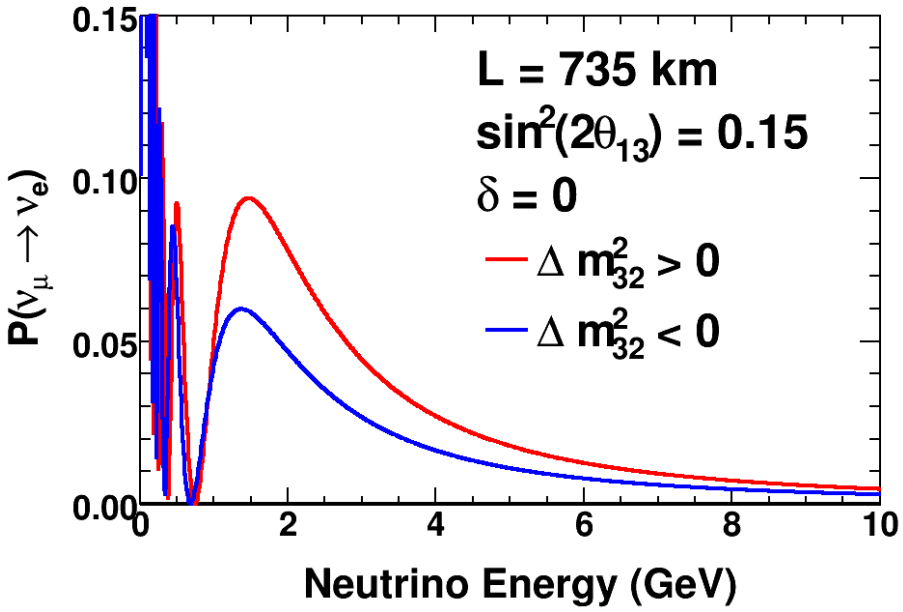
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$ (Dominant term)

Higher order terms that depend on δ and the mass hierarchy

δ dependence



mass hierarchy dependence

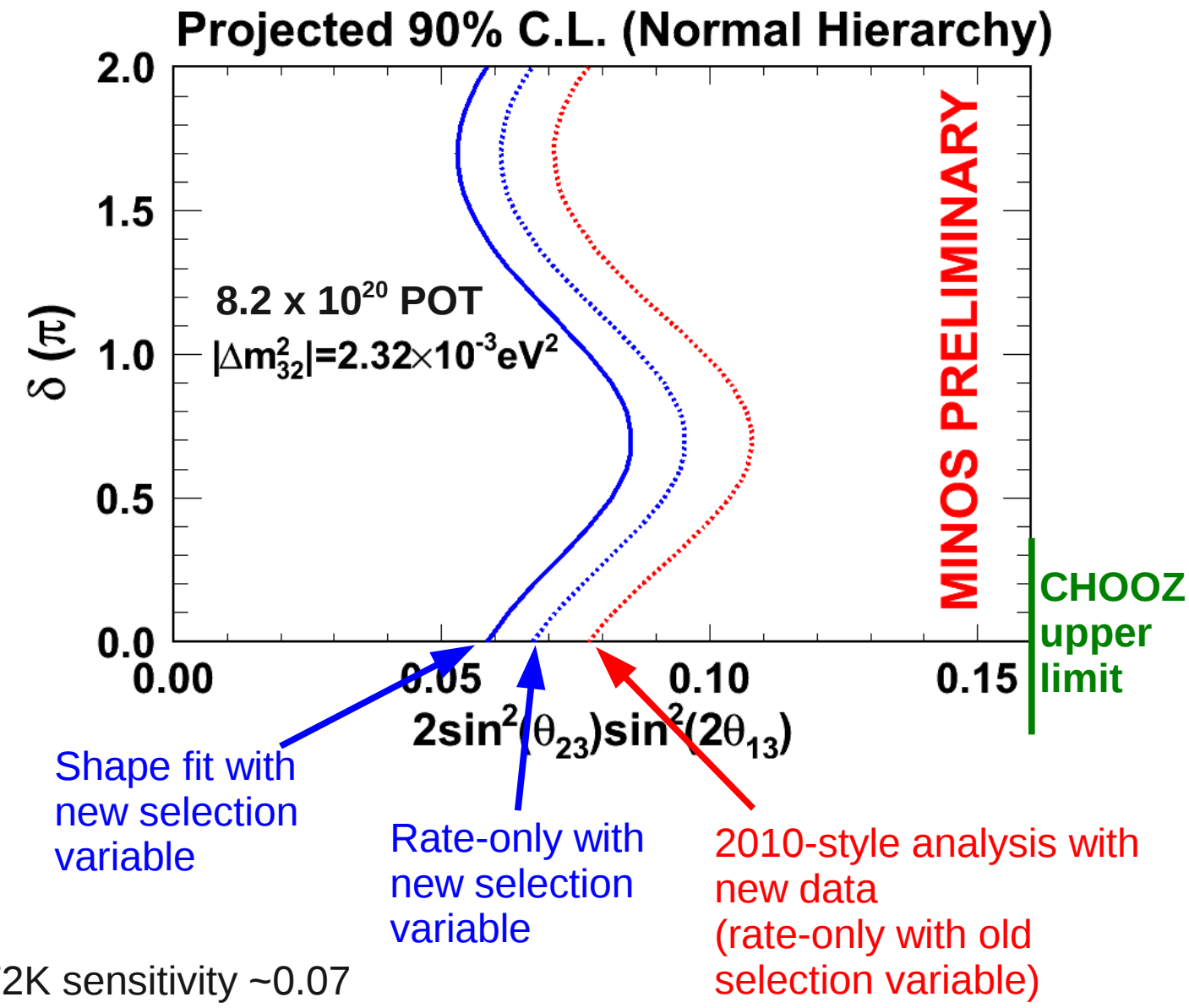


Projected Sensitivity

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

Since 2010 result:
Phys. Rev. D 82, 051102

- 1.2x10^{20} POT (17%) more data
- Improved event selection variable: 15% sensitivity gain
- Shape fit: 12% sensitivity gain



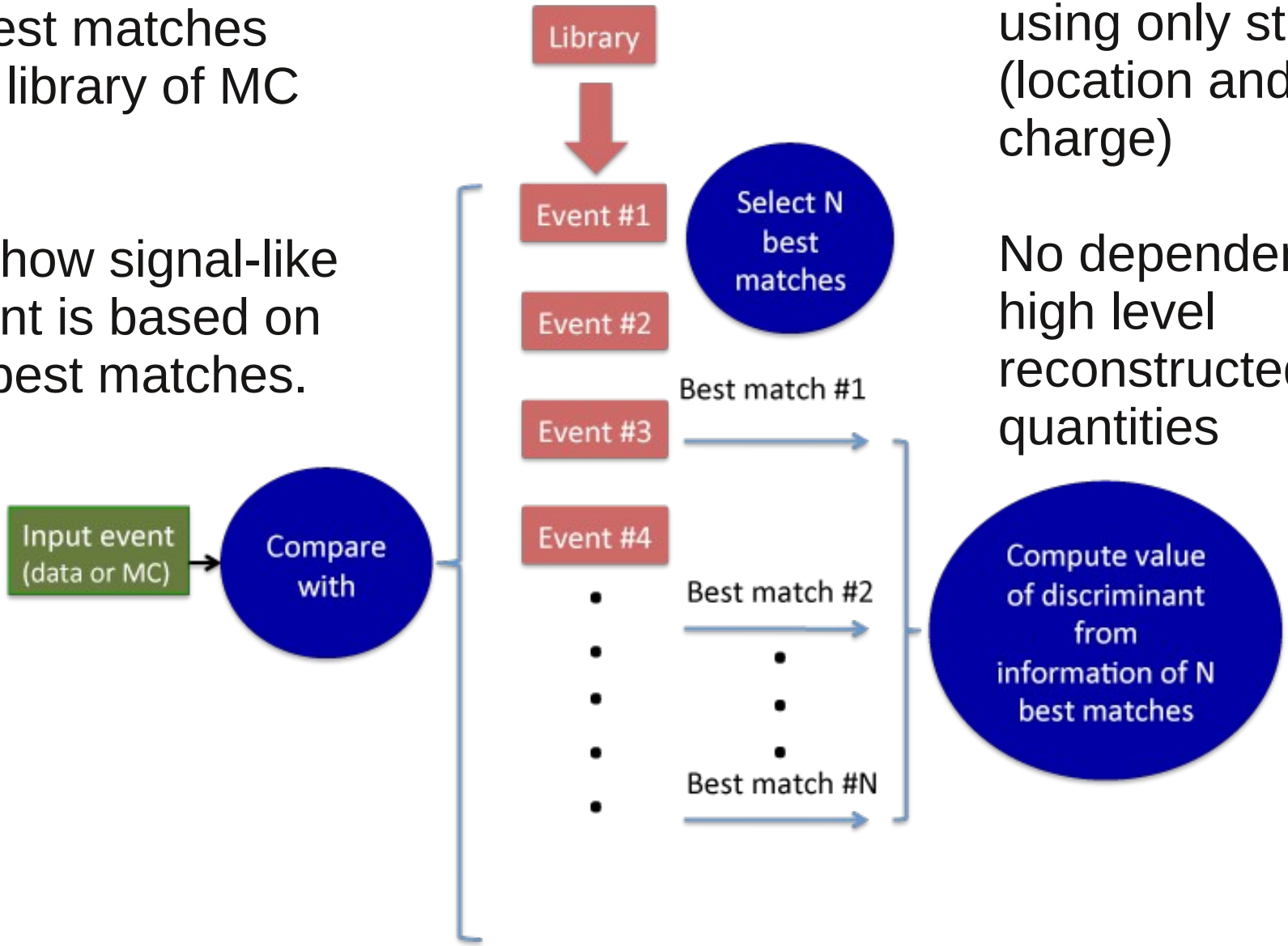
T2K sensitivity ~0.07 (Neutel11)

Library Event Matching (LEM)

New ν_e selection variable!

Find best matches from a library of MC events

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



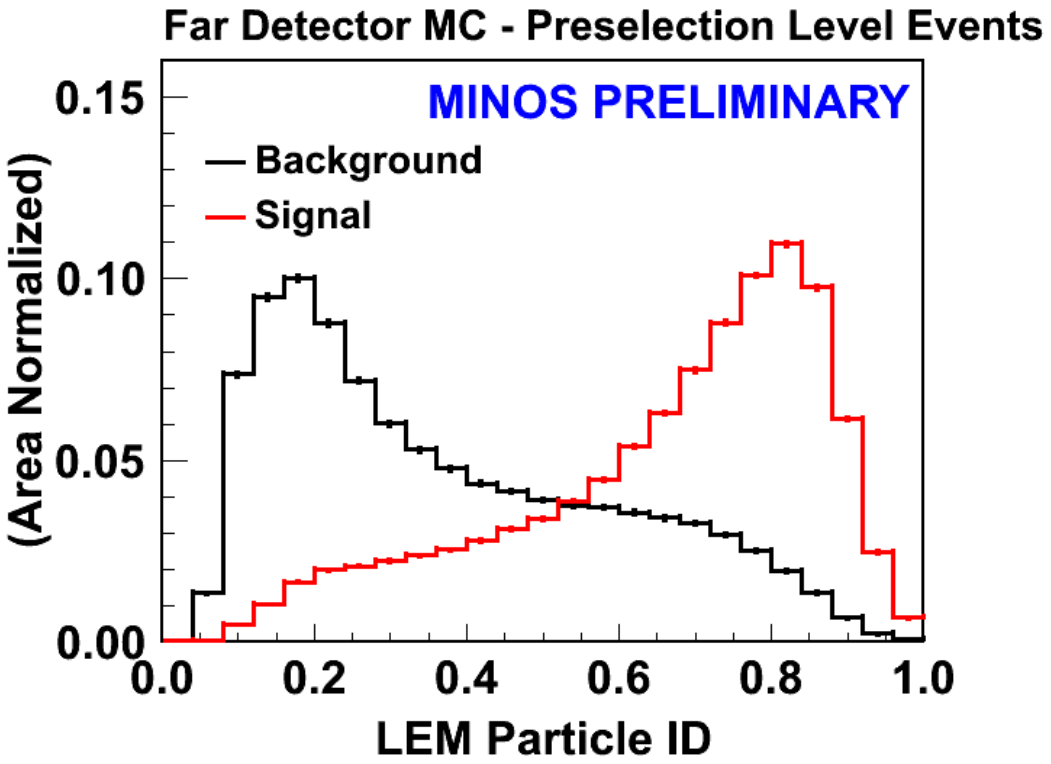
Matching is done using only strip info (location and charge)

No dependence on high level reconstructed quantities

Library Event Matching (LEM)

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

Output of neural net is the LEM selection variable



Prior to using LEM, a set of Preselection cuts is applied to remove events that are obviously not signal:

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

FD Background Prediction

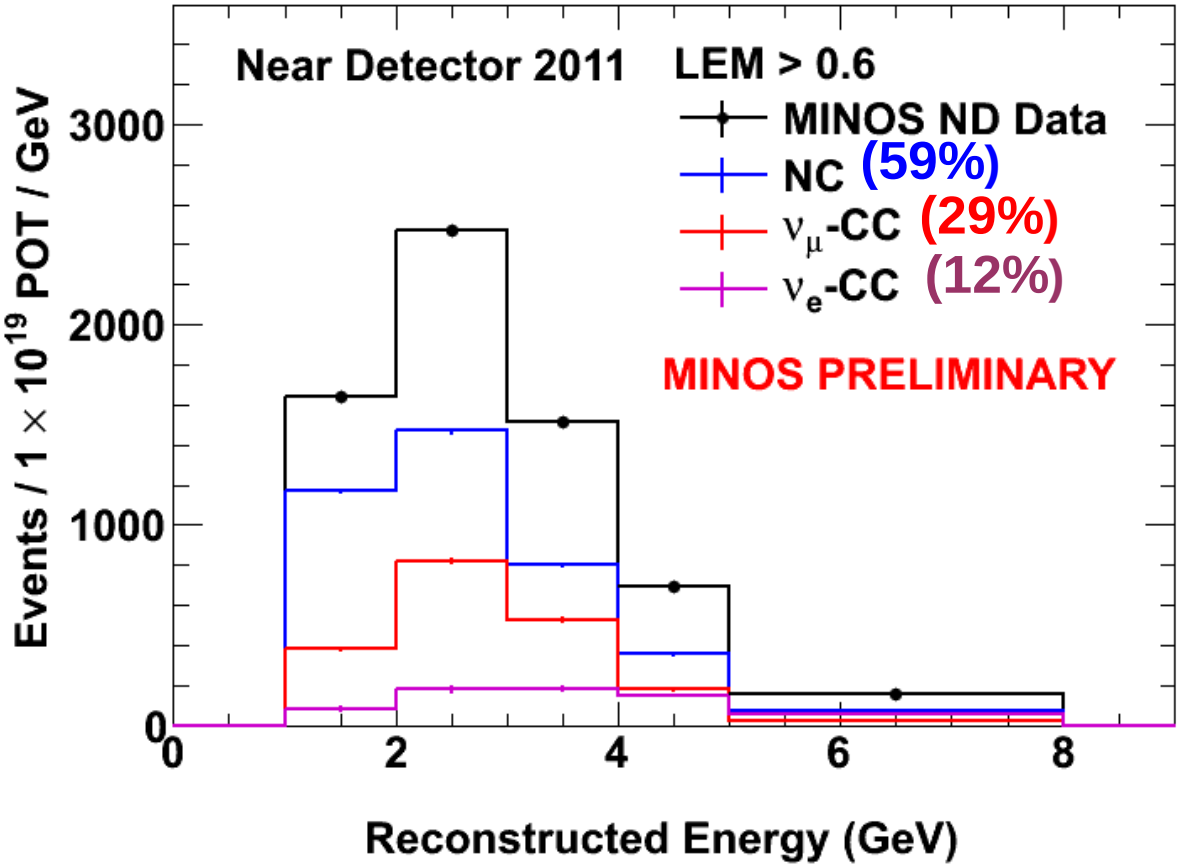
Separately for each event type - Oscillations affect each differently

- **neutral current**
- **charged current ν_μ**
- **charged current ν_e (beam)**

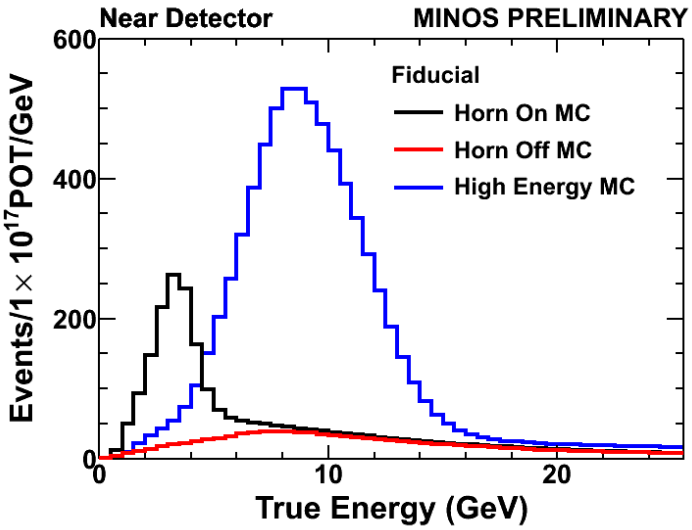
$$F = N \times R^{F/N}$$

ND data

MC Far-to-Near ratio



Separate ND data into the 3 event types by fitting data from 3 different beam configurations:



Far Detector Prediction

For 8.2×10^{20} POT

Signal-enhanced region (LEM>0.7)

$\delta = 0$

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

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

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

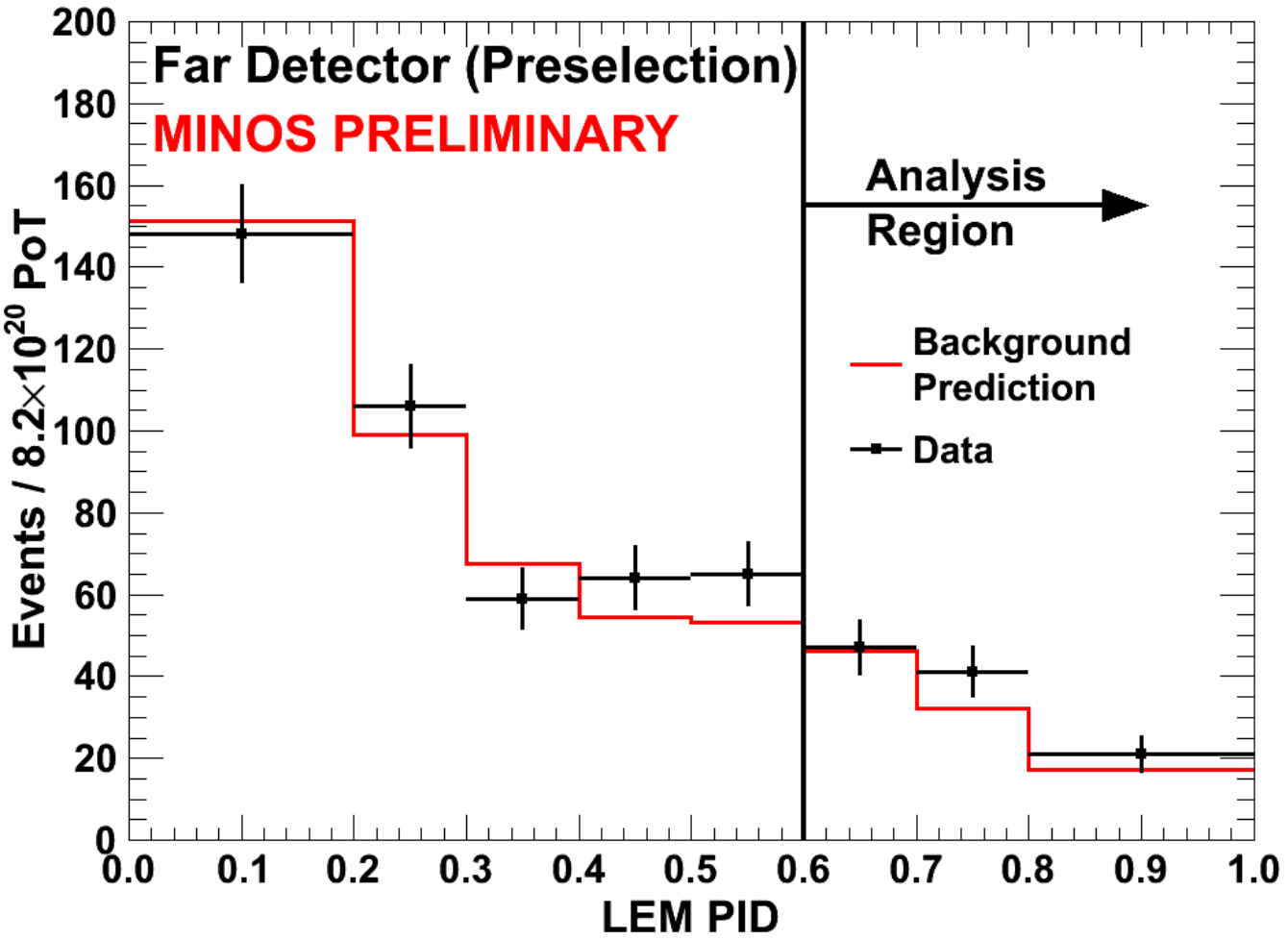
Component	# Events
NC	34
ν_μ CC	7
beam ν_e CC	6
ν_τ CC	2
Total Bkgd	**49**
ν_e CC signal	**30**

PRELIMINARY

Predicted background and signal at CHOOZ limit

Note bkgd prediction is dependent on θ_{13}

Far Detector Data



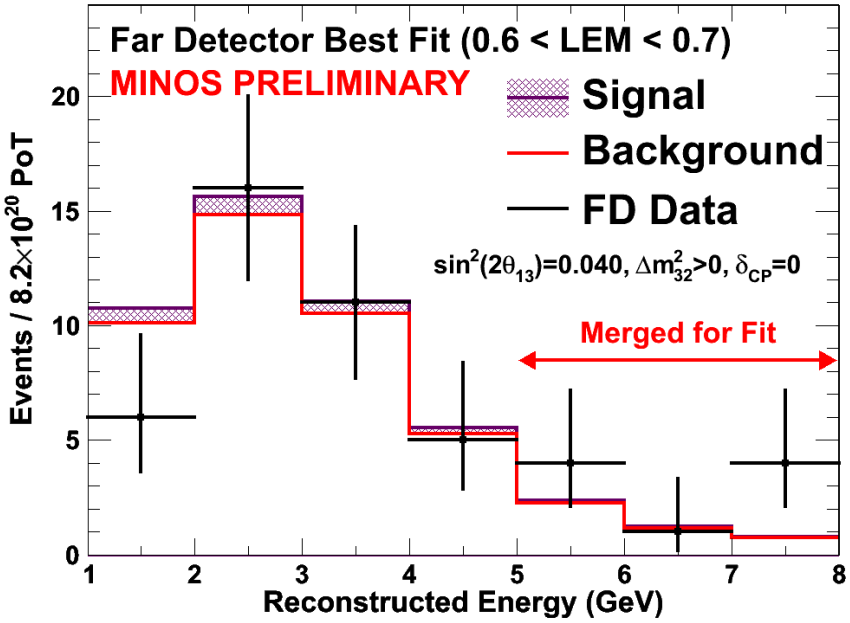
In signal-enhanced region (LEM>0.7):

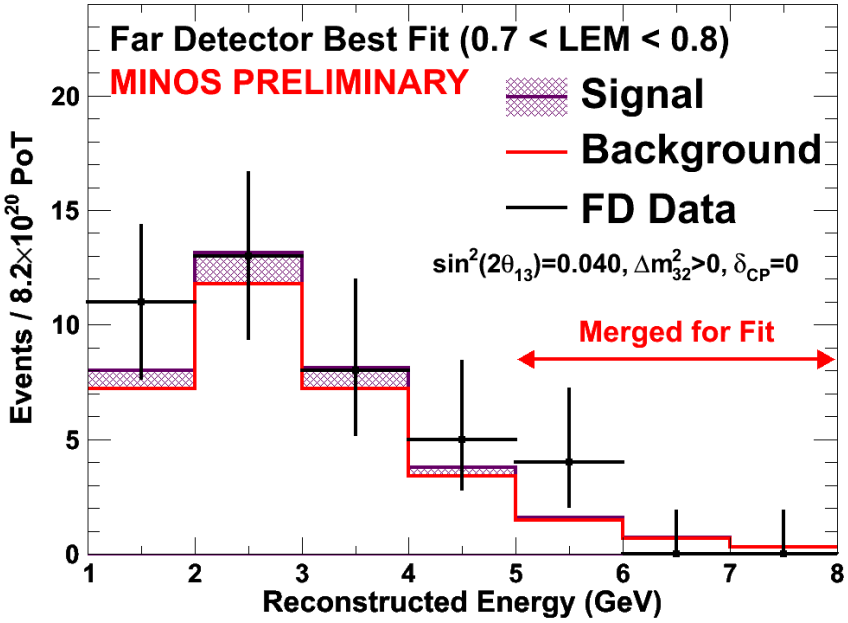
Expected background (θ_{13}=0):

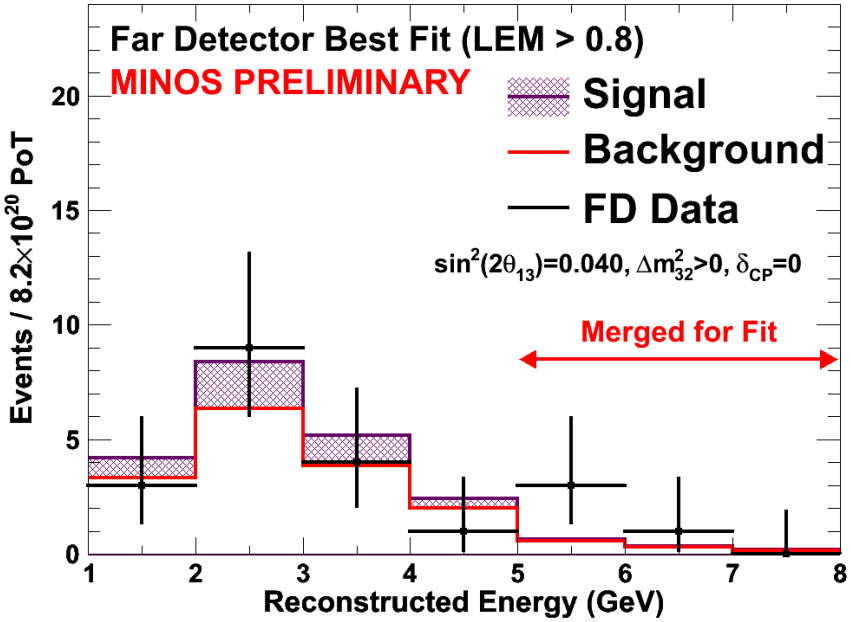
49.5 +- 2.8 (syst) +- 7.0 (stat)

Observed data: **62**

Best Fit





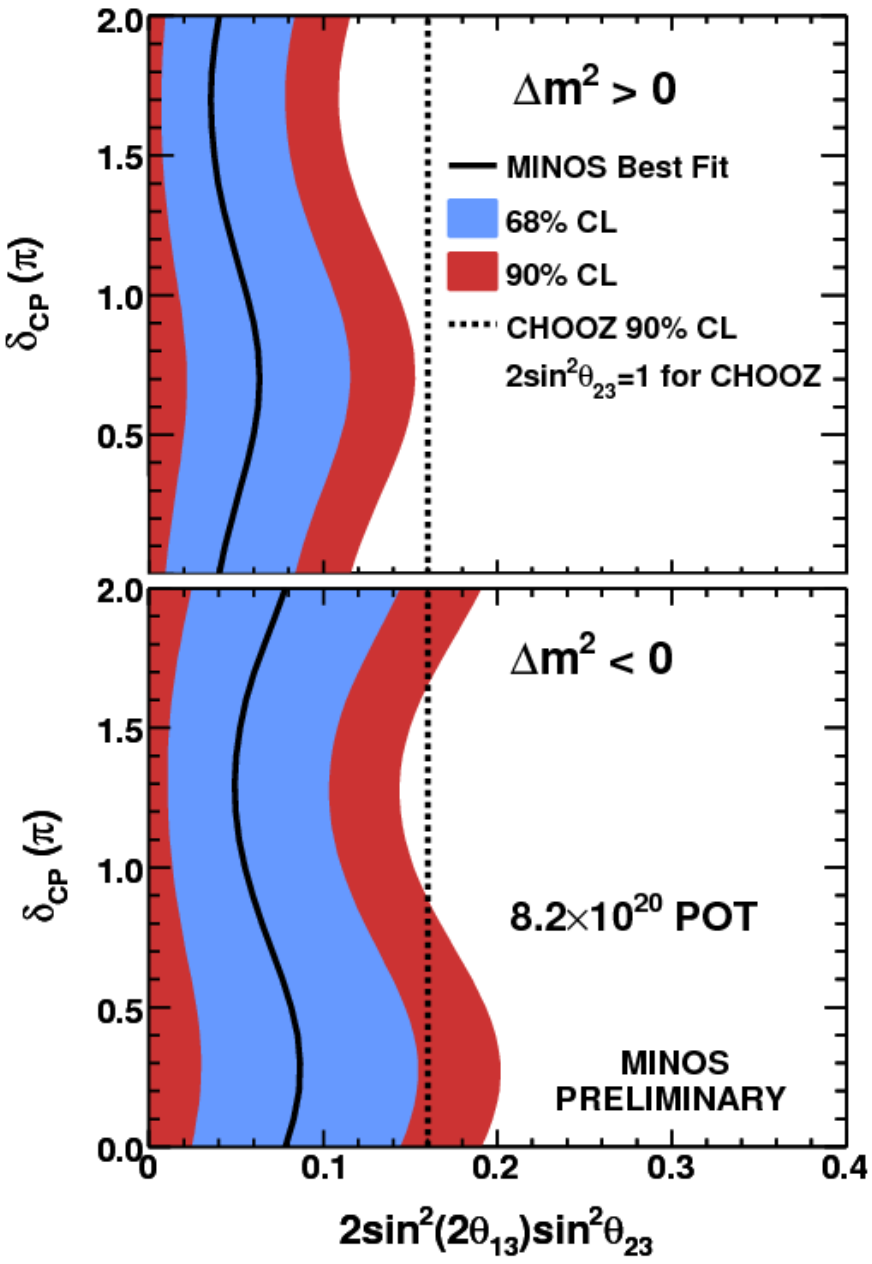


Best fit $\sin^2 2\theta_{13} = 0.040$

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

15 bin shape fit:
3 LEM bins x 5 energy bins

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

Summary

- MINOS has made the most precise measurement of $|\Delta m^2_{32}|$
- MINOS is the 1st experiment to directly observe muon antineutrino disappearance - new results soon!
- MINOS has updated our electron neutrino appearance search with more data and improved analysis techniques: overall 30% gain in sensitivity

Assuming $\delta=0$, $\theta_{23}=\pi/4$, normal (inverted) hierarchy, we set a 90% C.L. upper limit of **$\sin^2(2\theta_{13})<0.12$ (0.19)**

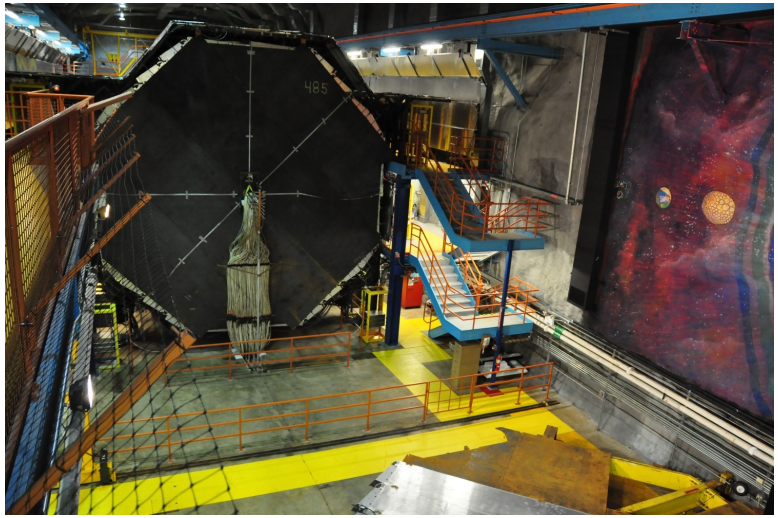
and exclude $\sin^2(2\theta_{13})=0$ @ 89% CL

Soudan Fire and Recovery

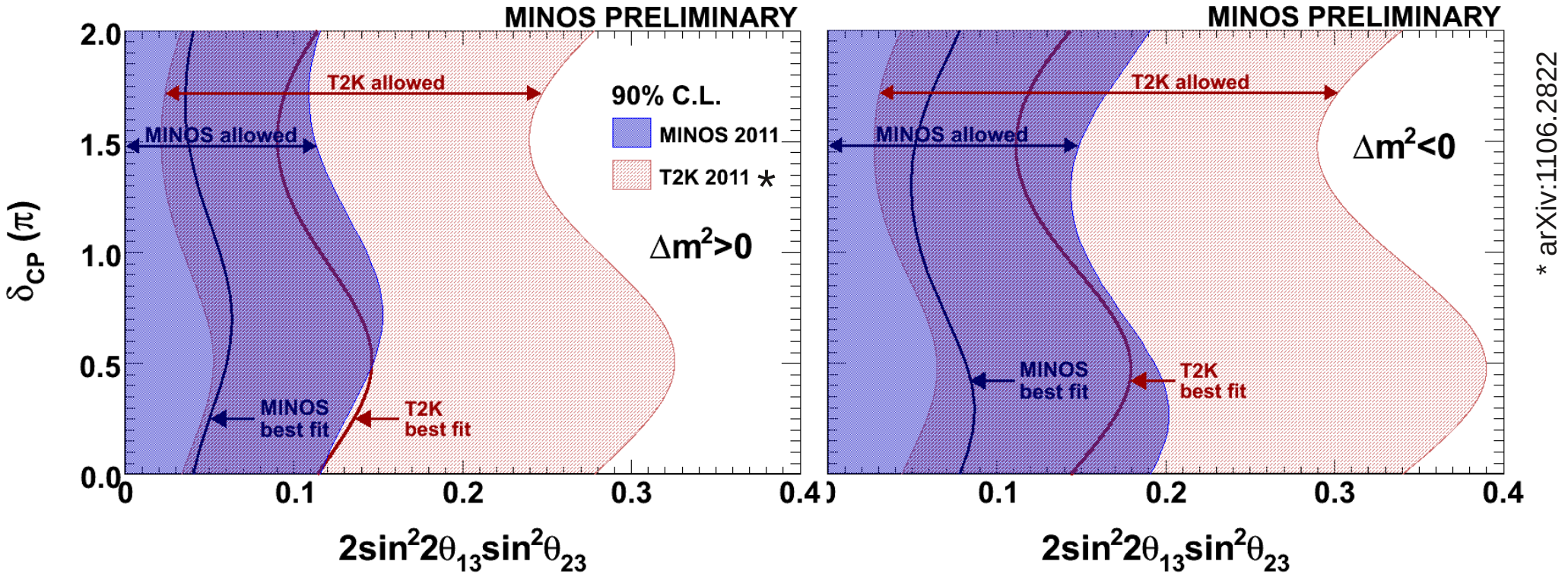
- On March 17 smoke was detected in the MINOS hall at Soudan due to a fire in the shaft
- Power to the lab was shut off automatically
- Foam was pumped in to extinguish the fire
- No damage to the MINOS detector
- Detector returned to full operations May 19

After the fire...

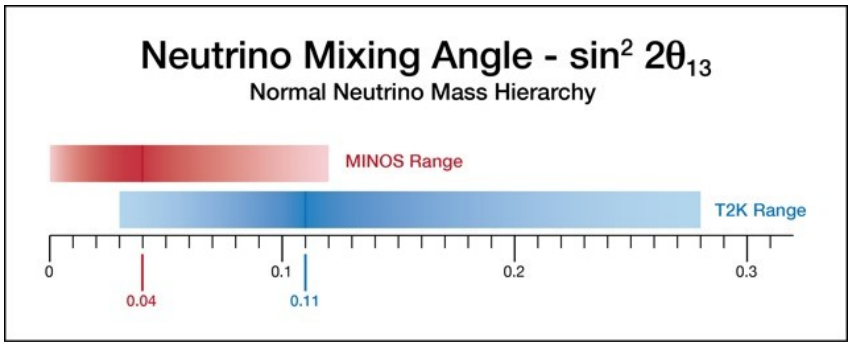
Good as new...

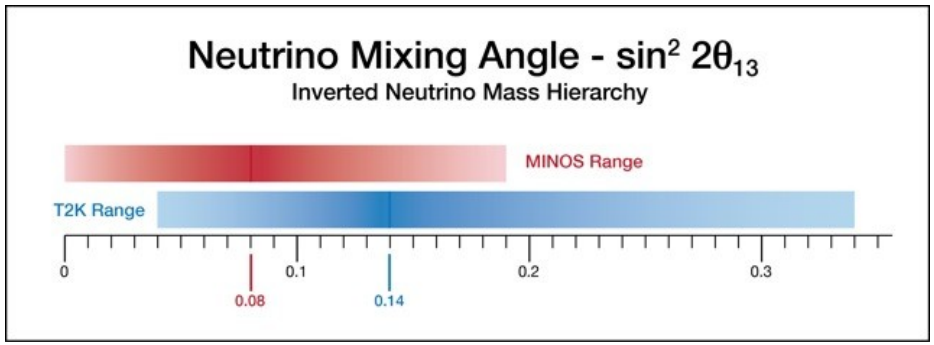


Comparison to T2K Results



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

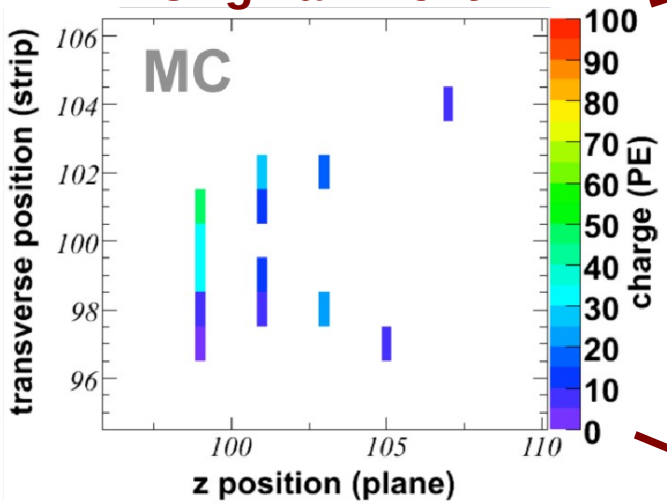




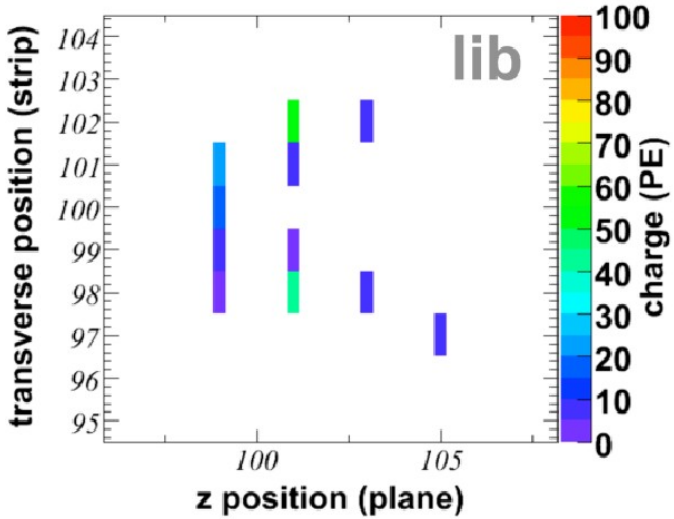
Matching (LEM)

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.

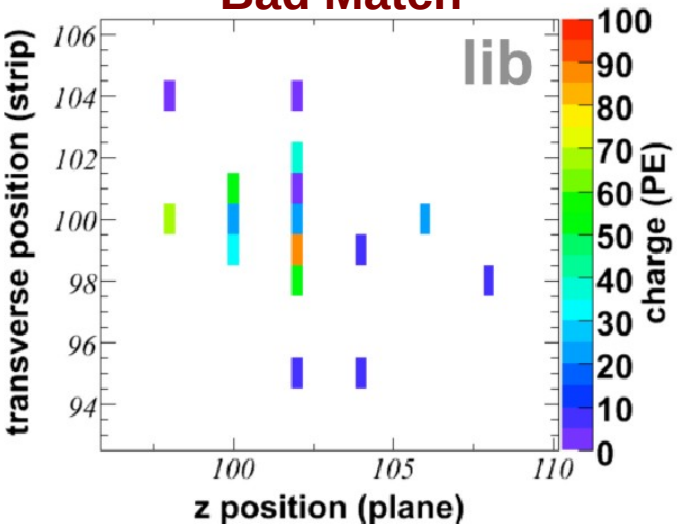
Original Event



Good Match



Bad Match

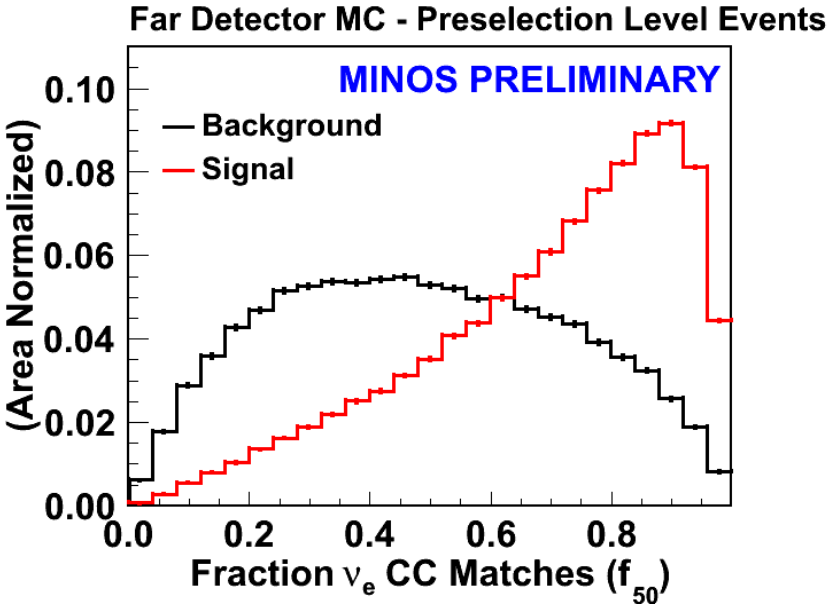


The library consists of:

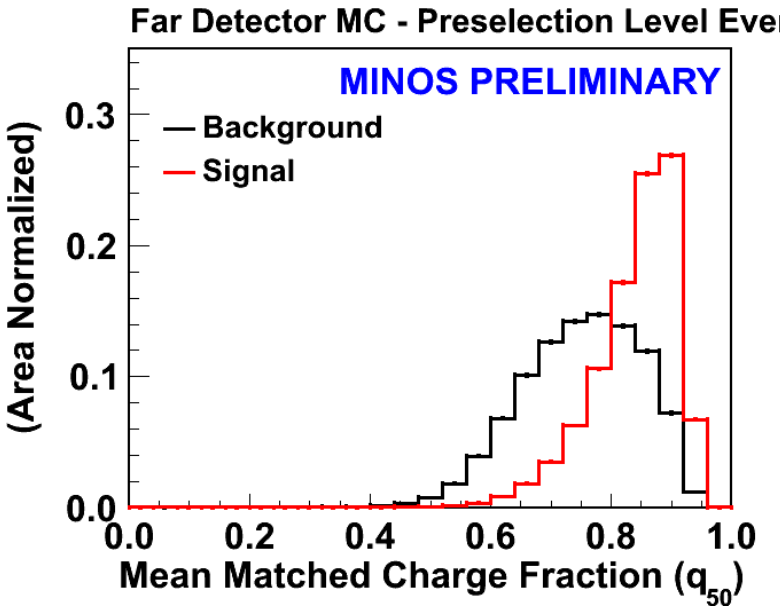
- 20 million signal events
- 30 million background (NC) events

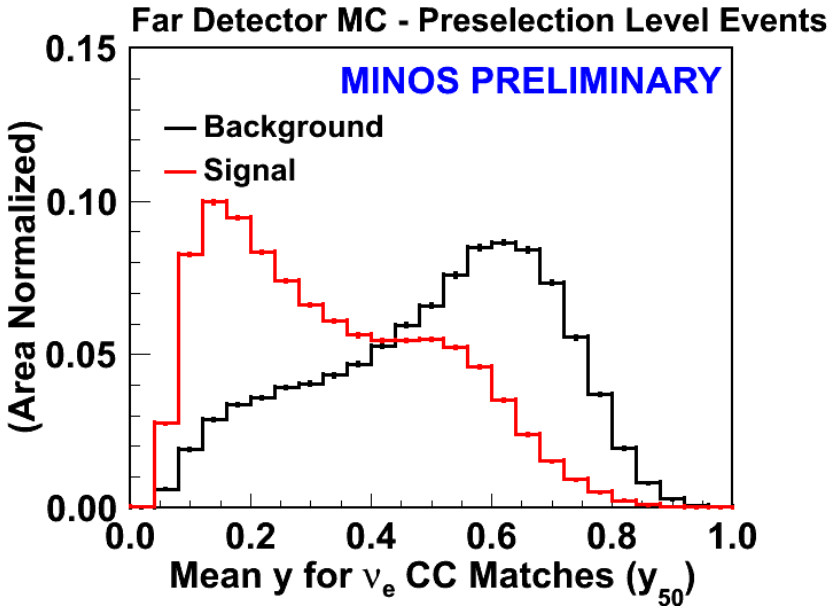
Info from best matches (LEM)

How many of the best matches are signal?



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

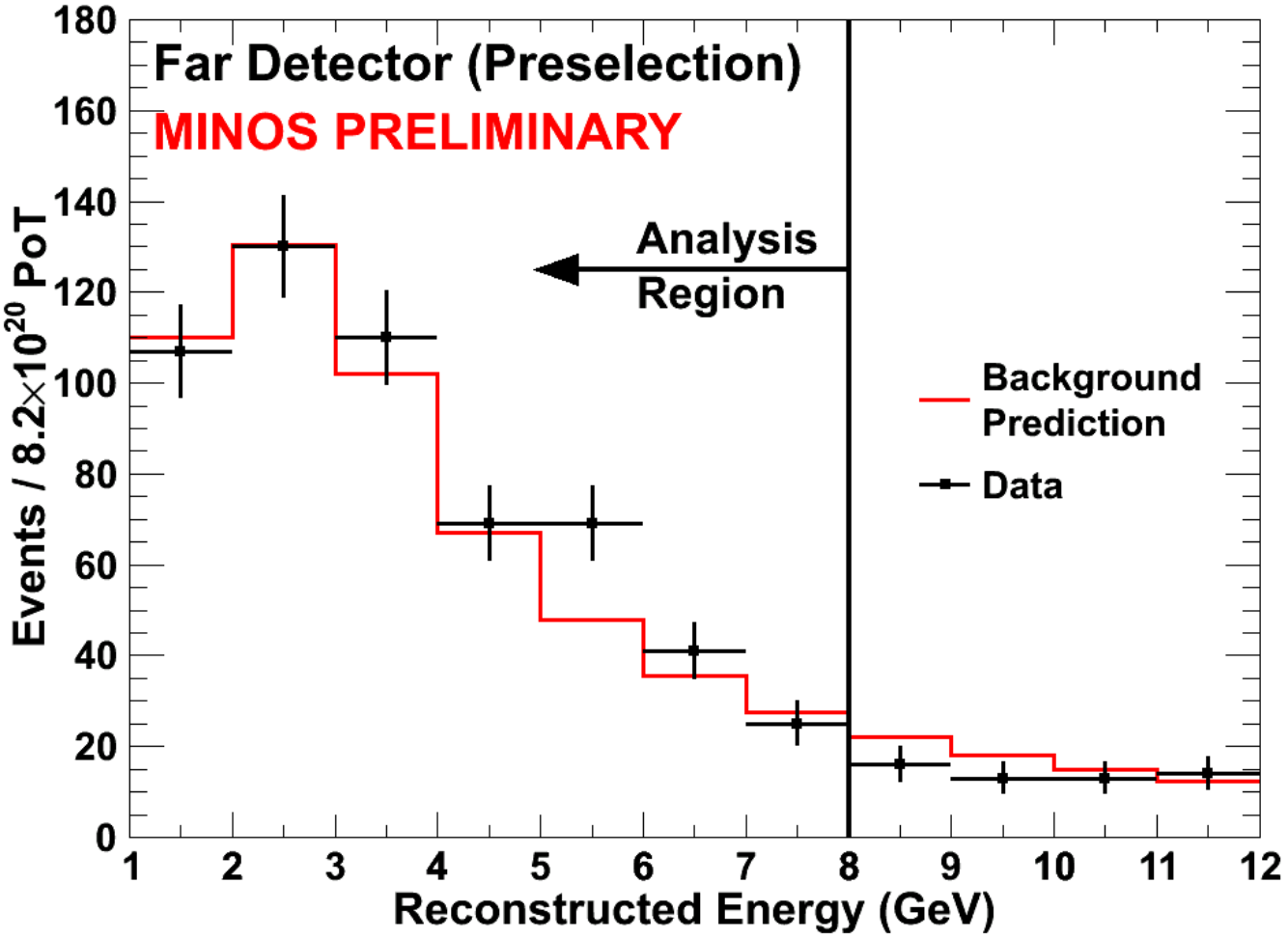




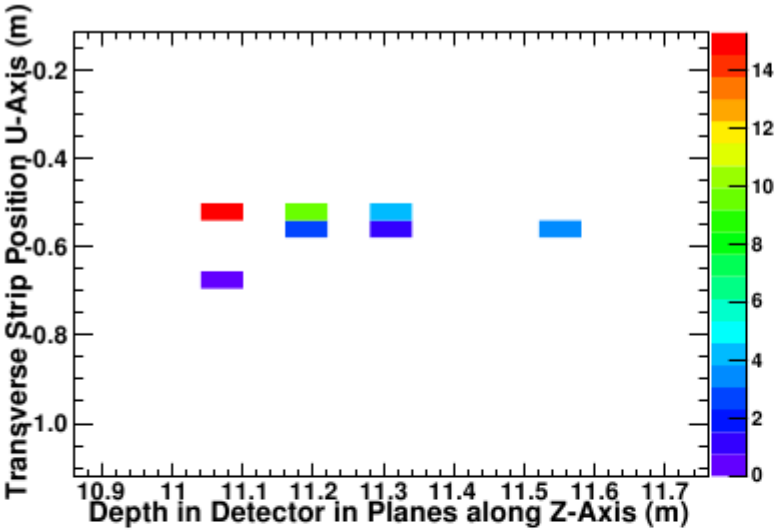
How EM-like is the shower in the best matches?

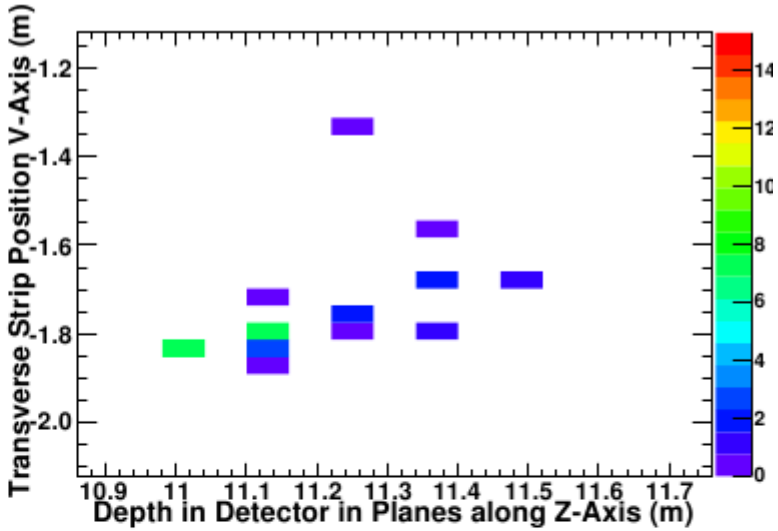
(*y* = fraction of ν energy in the hadronic shower)

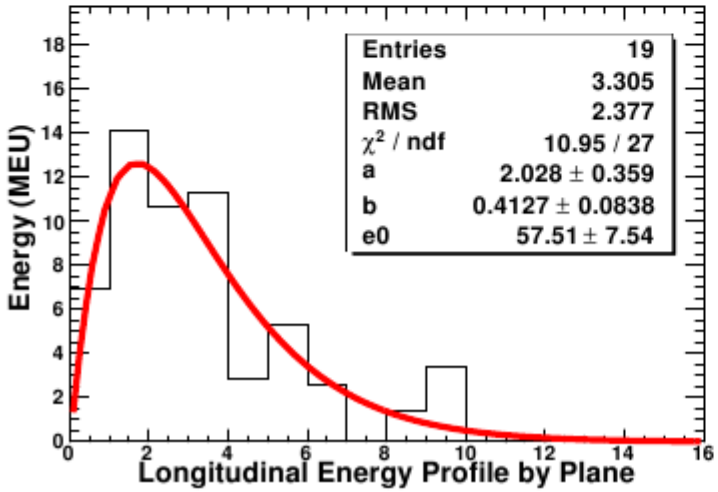
FD ν_e-selected energy spectrum

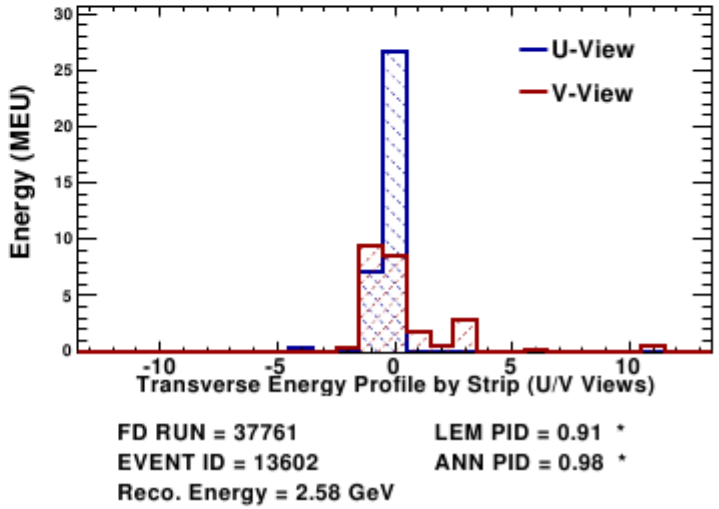


Example of a ν_e-Selected Event

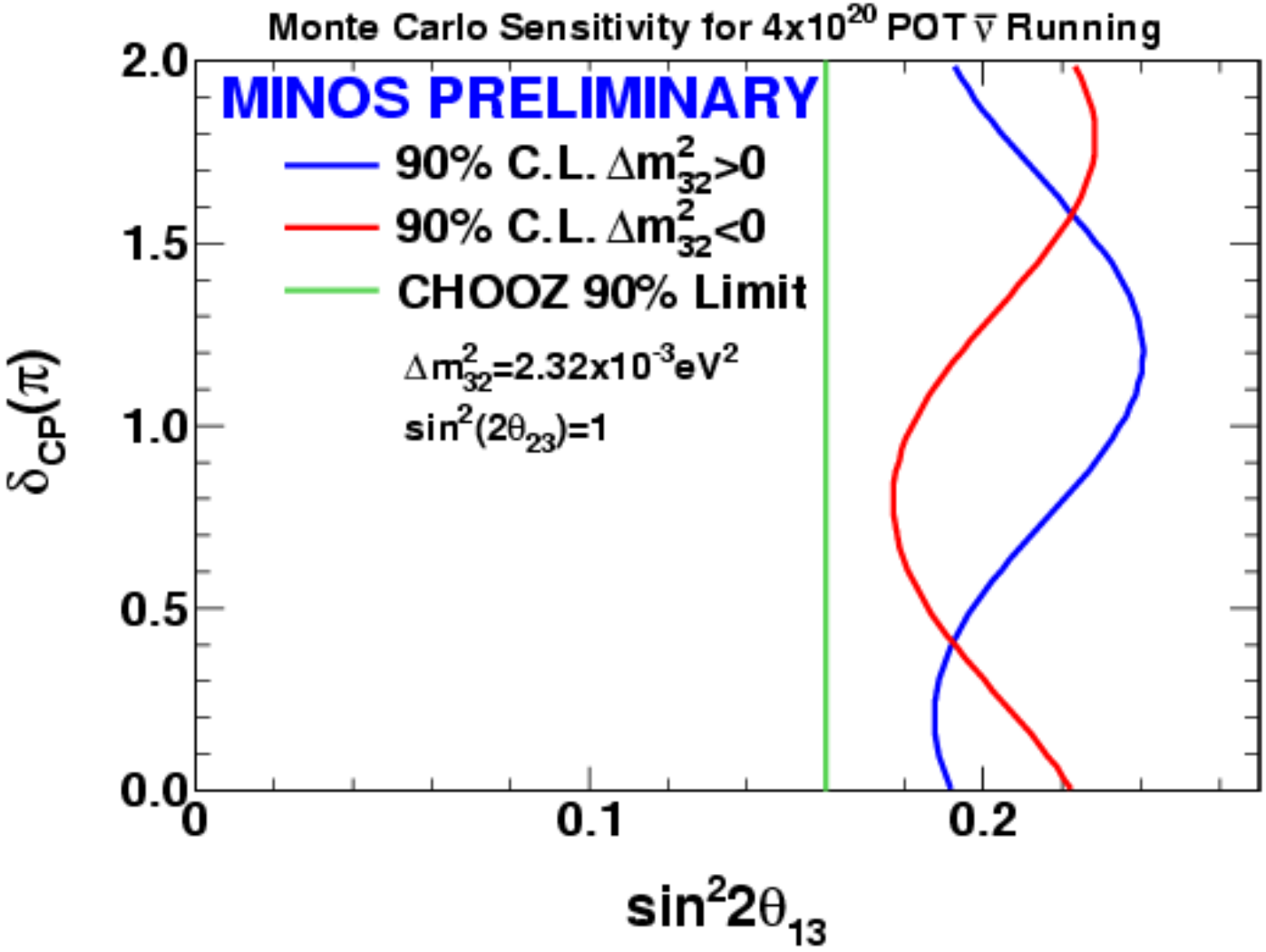




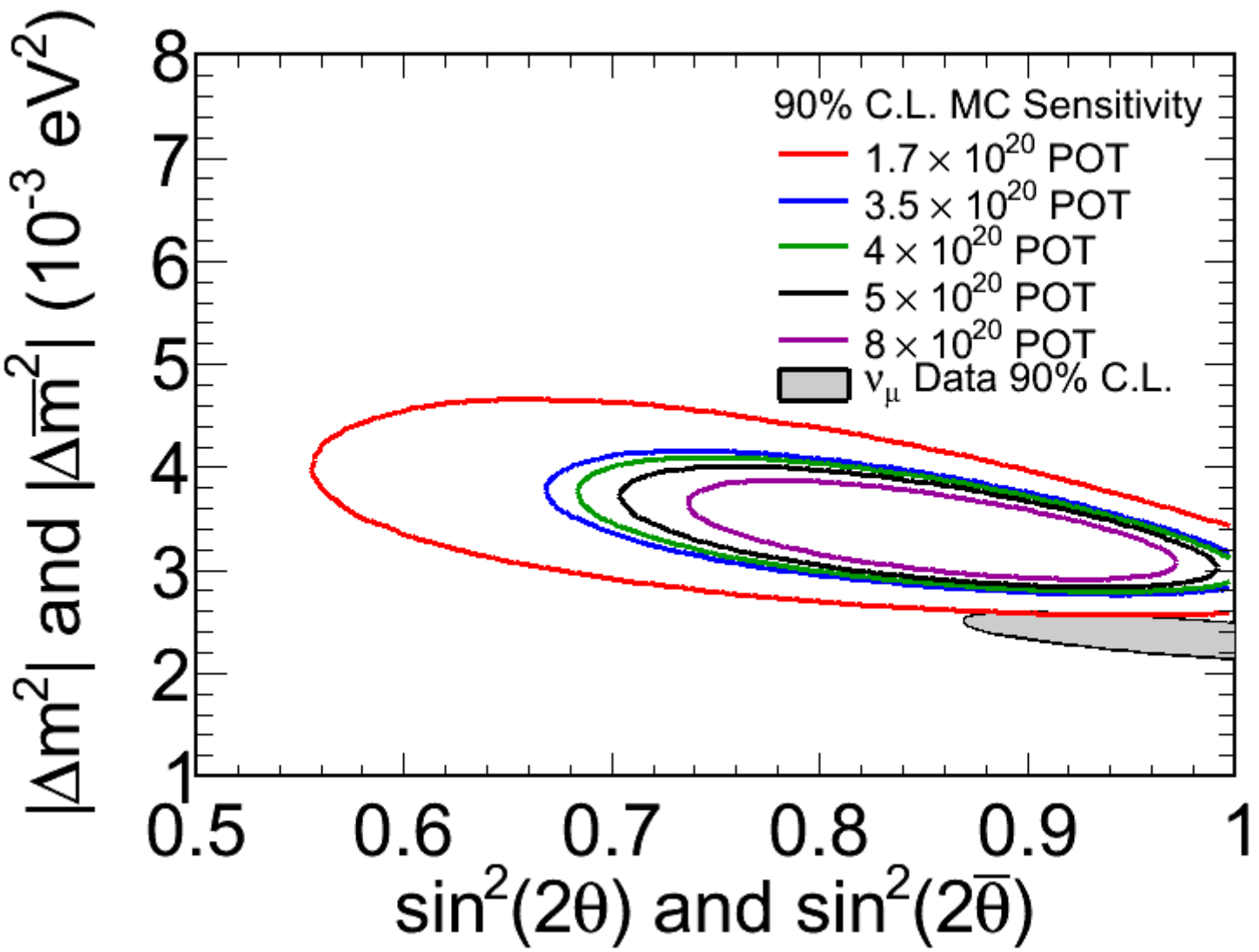


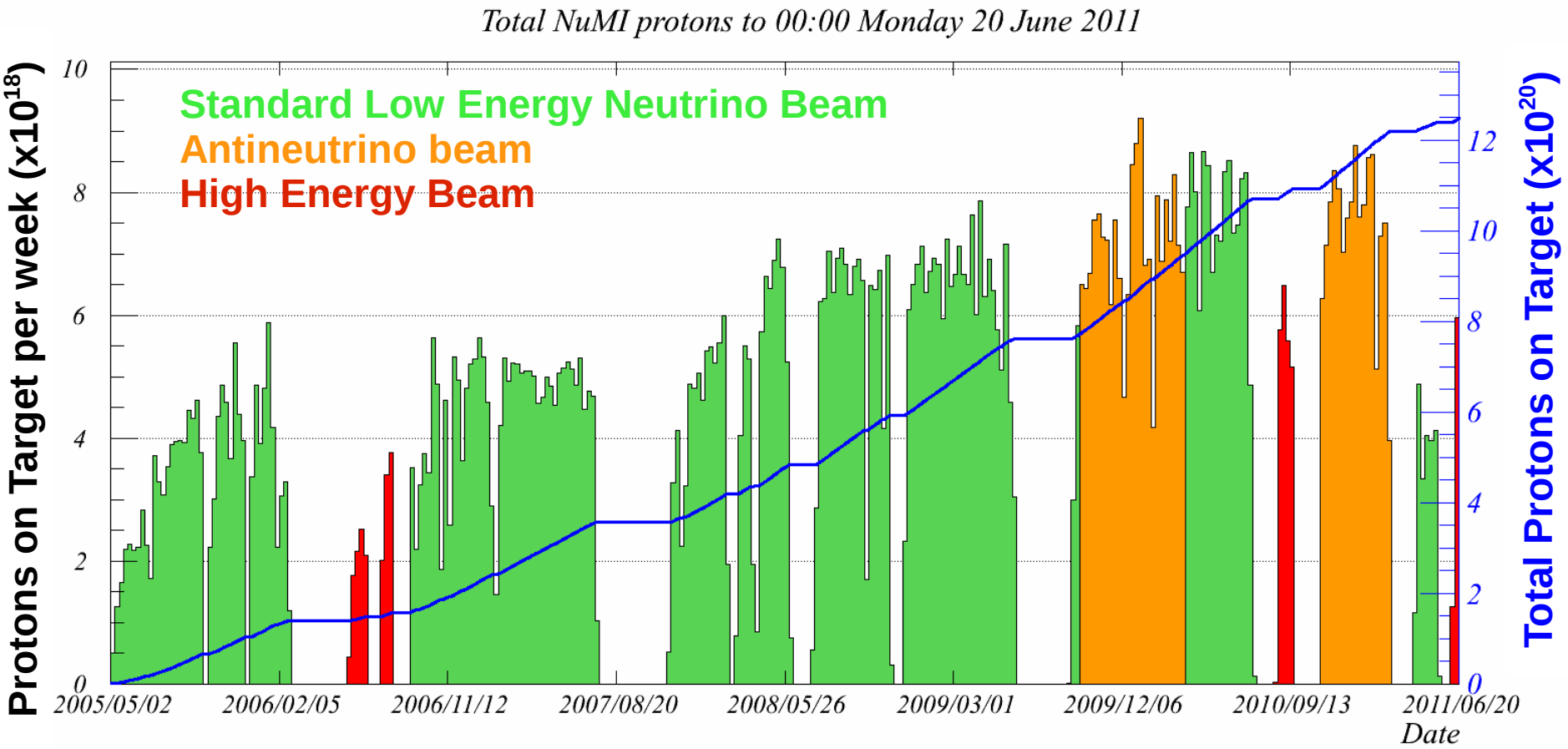


θ_{13} sensitivity with antineurinos



Antinu Sensitivity with more data



Sensitivity assuming true parameters as measured by the 1.71×10^{20} POT antineutrino analysis

Protons Delivered to Target