MINOS
Main Injector Neutrino Oscillation Search

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Introduction

- Neutrino physics
  - Oscillations refresher
- MINOS experiment
  - NuMI neutrino beam
  - MINOS detectors
- Neutrino and antineutrino oscillation analyses
- Results
- Other analyses: ν_e, NC, cross sections, atmospherics…

Neutrinos Mix

- Neutrino flavor eigenstates are mixtures of mass eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Flavor eigenstate: Neutrino born with charged lepton of a given flavor.
- Mass eigenstate: Neutrino of definite mass (Tom, Dick, Harry).

Neutrinos Mix

Solar, Reactor — Mixed Sector — Atmospheric, Accelerator

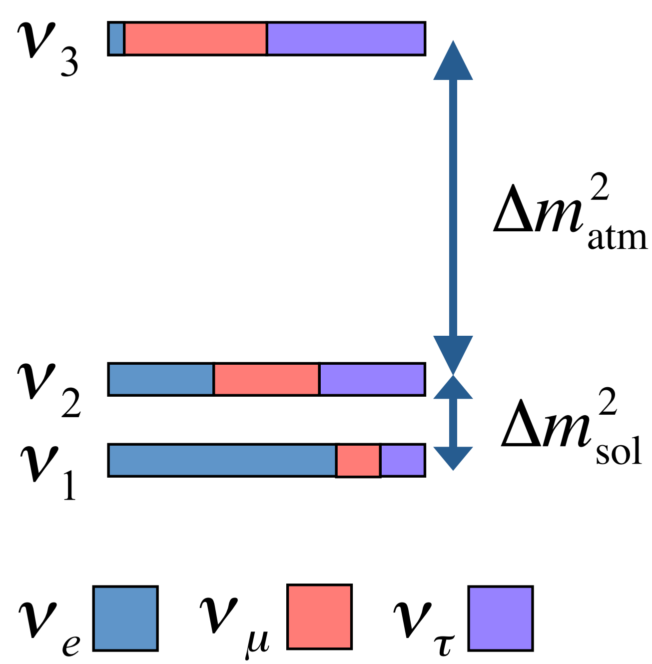
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- With three active neutrinos there are two independent mass splittings

  $\Delta m^2_{\text{sol}} \approx \Delta m^2_{21} \approx 8.0 \times 10^{-5}\text{eV}^2$

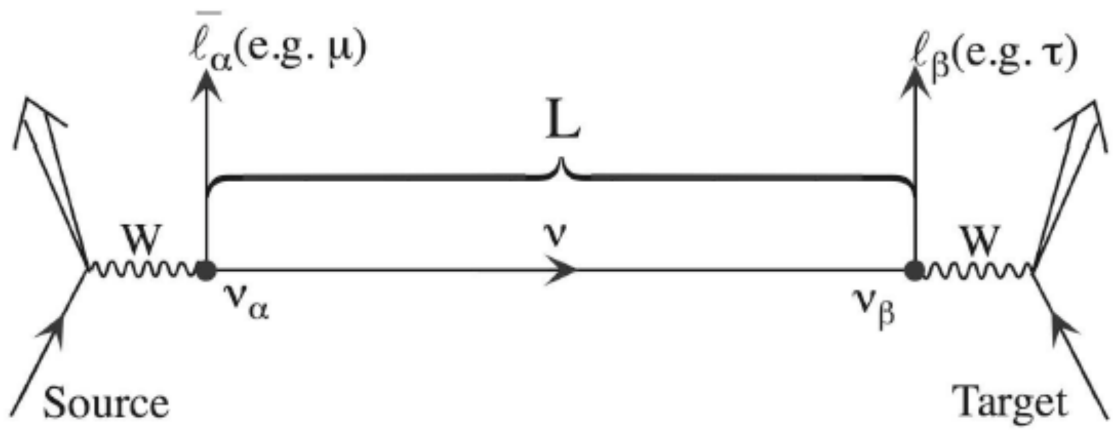
  $\Delta m^2_{\text{atm}} \approx \Delta m^2_{32} \approx 2.4 \times 10^{-3}\text{eV}^2$

- MINOS is sensitive to the larger of the mass splittings and θ_{23}



Two Flavor Oscillations

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$



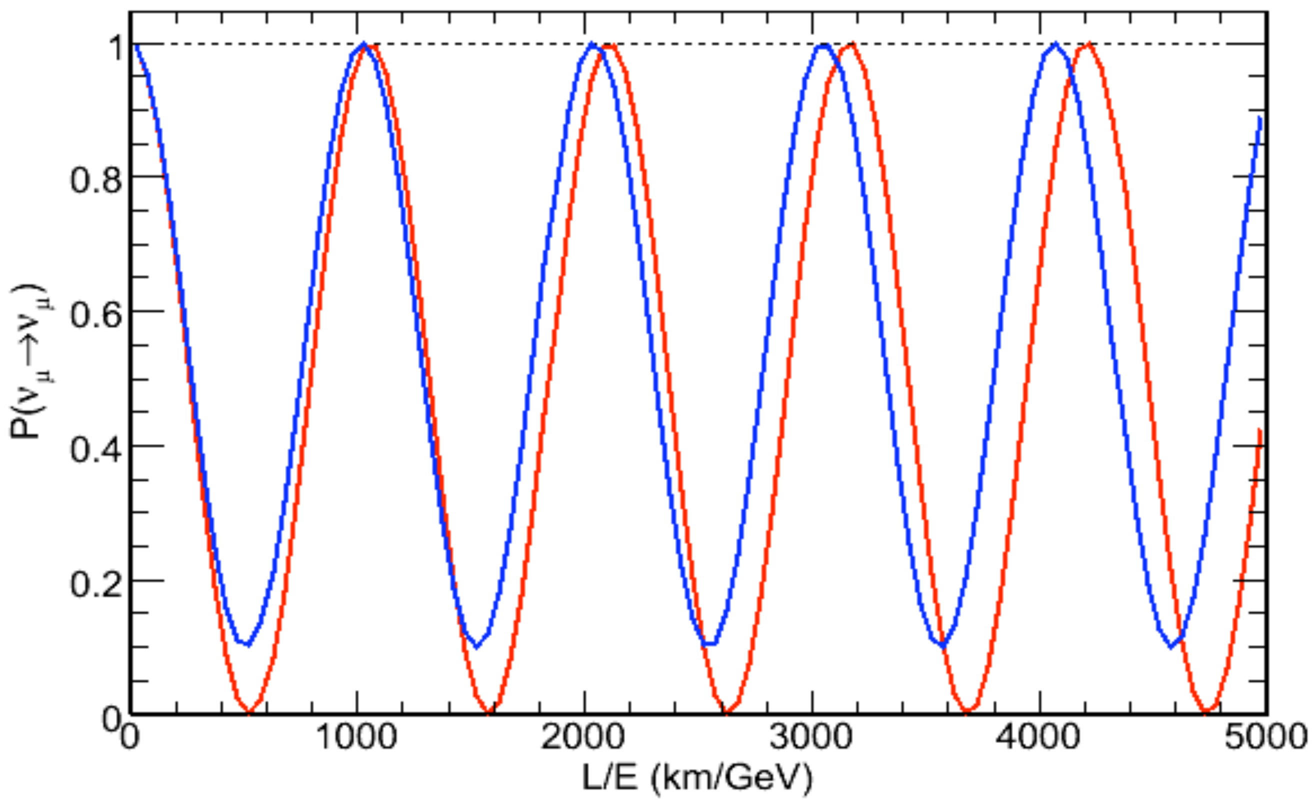
$$|\nu(0)\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_2\rangle + \sin\theta\,|\nu_3\rangle$$

$$P_{\nu_\mu\to\nu_\mu} = |\langle\nu_\mu\,|\nu(L)\,\rangle|^2 = \left|\cos^2\theta\,\mathrm{e}^{-\frac{im_2^2L}{2E}} + \sin^2\theta\,\mathrm{e}^{-\frac{im_3^2L}{2E}}\right|^2$$

$$P_{\nu_\mu\to\nu_\mu} = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m_{23}^2 L}{E}\right)$$

Survival Probability

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27\frac{\Delta m_{23}^2 L}{E}\right)$$

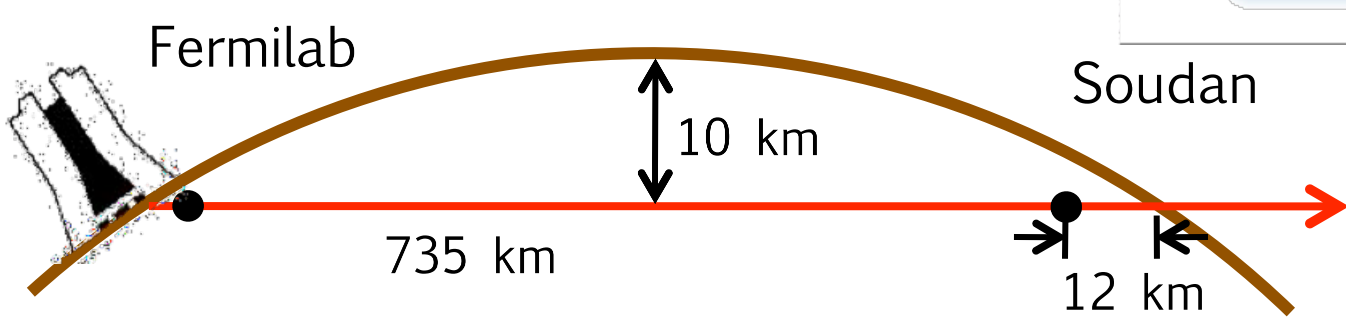


Measuring Neutrino Oscillations

- Make a beam of neutrinos.
  - With a reasonably peaked, well understood energy distribution.
- Build at least one detector, ideally two.
  - One detector at distance = L.
  - One detector at distance = 0.
- Determine L and E.
  - Larger things are easier to measure, maximize disappearance – build detector at dip.
  - Also bear in mind the cost and flux. Build it at the *first* dip.
- Pick your favorite Greek god.

MINOS

- Three components:
  - **NuMI** high-intensity neutrino beam
  - **Near Detector** at Fermilab
  - **Far Detector** in Soudan, MN
- Measure oscillations by looking for disappearance between the detectors
- Detectors are magnetized – unique among oscillation experiments



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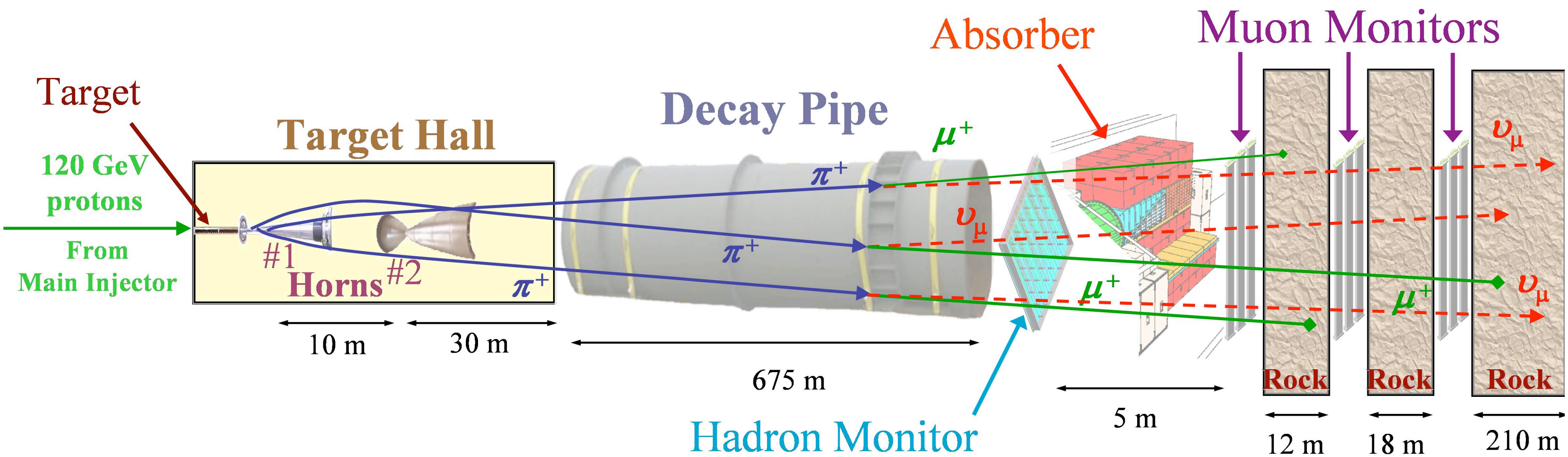
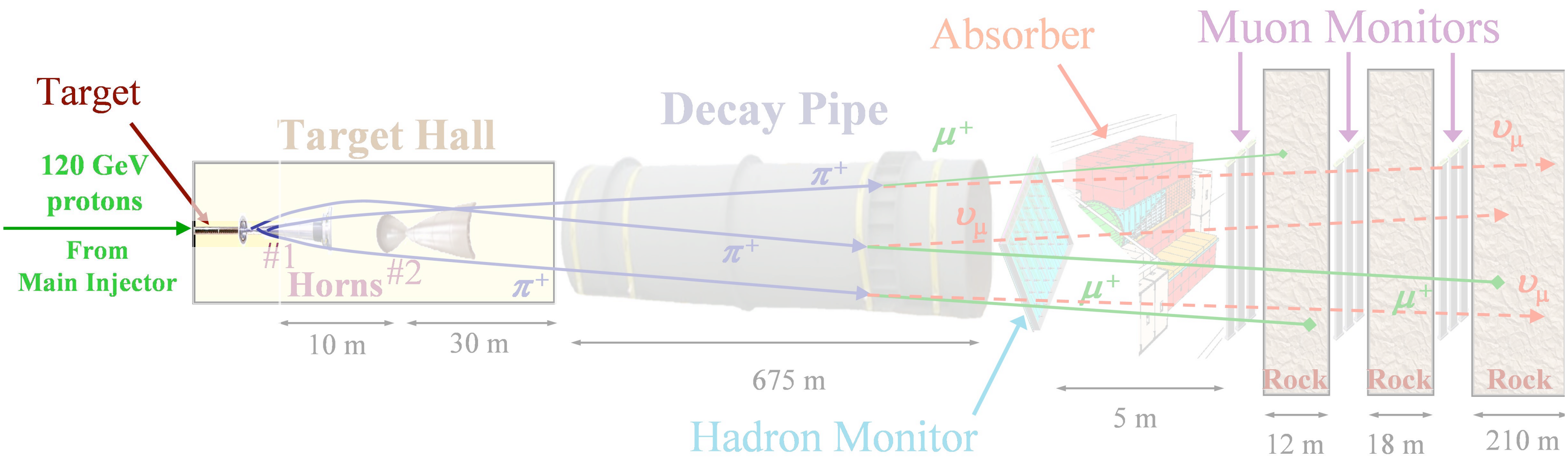
Making a neutrino beam

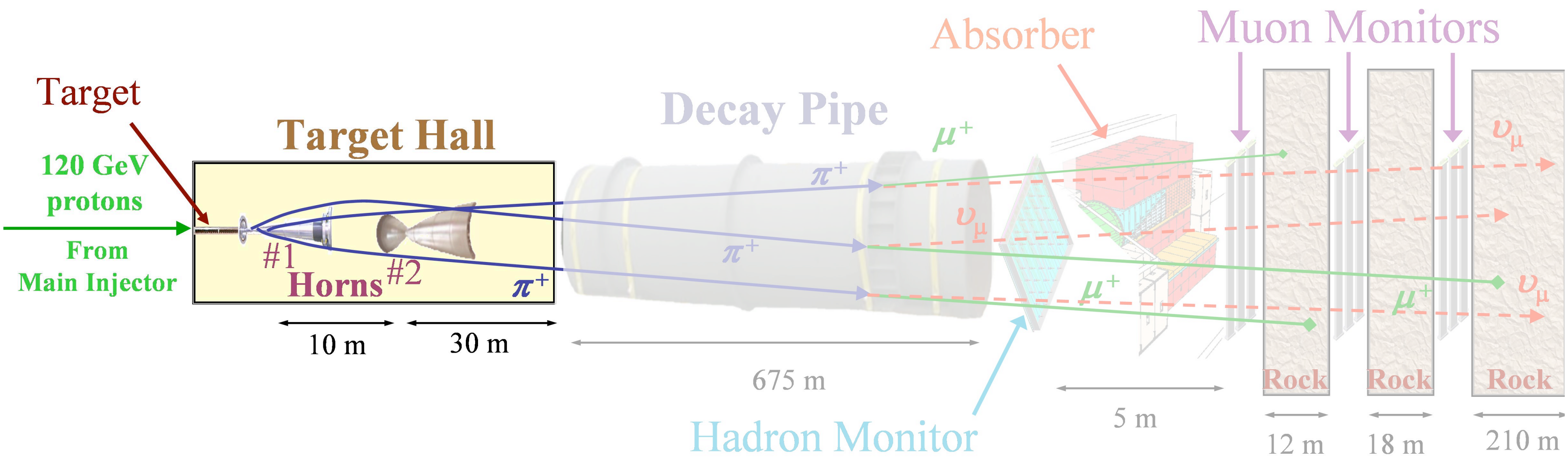


Making a neutrino beam



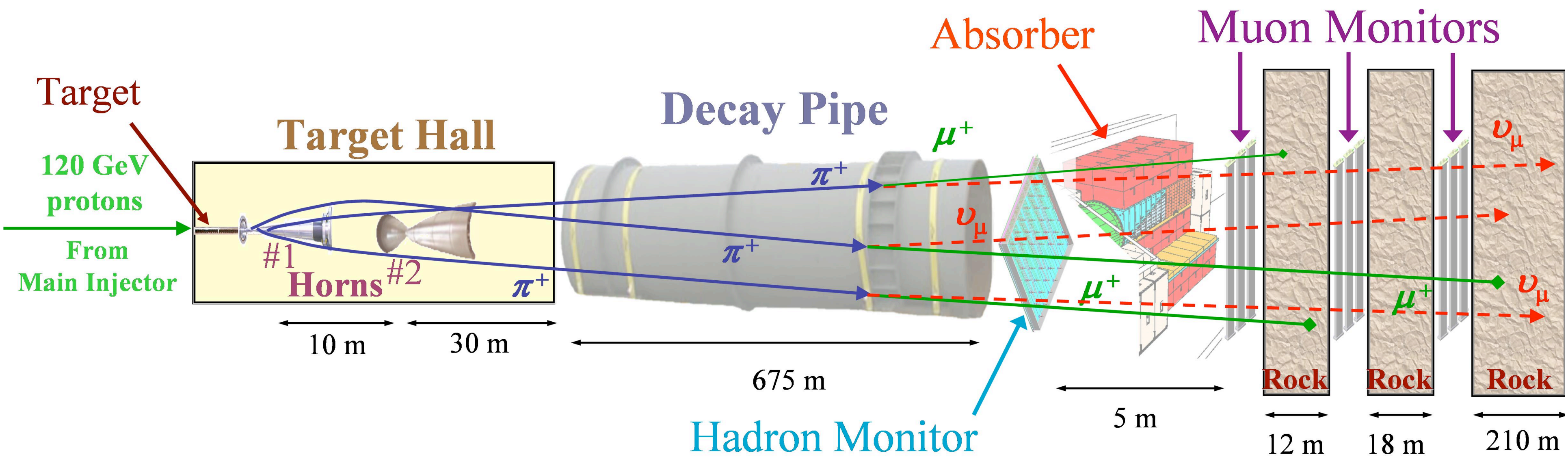
- **Production**
  - bombard graphite target with 120 GeV p^+ from Main Injector
    - 2 interaction lengths
    - 310 kW typical power
  - produce hadrons, mostly π and K

Making a neutrino beam



- **Focusing**
  - hadrons focused by 2 magnetic focusing horns
  - sign selected hadrons
    - forward current, (+) for standard neutrino beam runs
    - reverse current, (–) for anti-neutrino beam

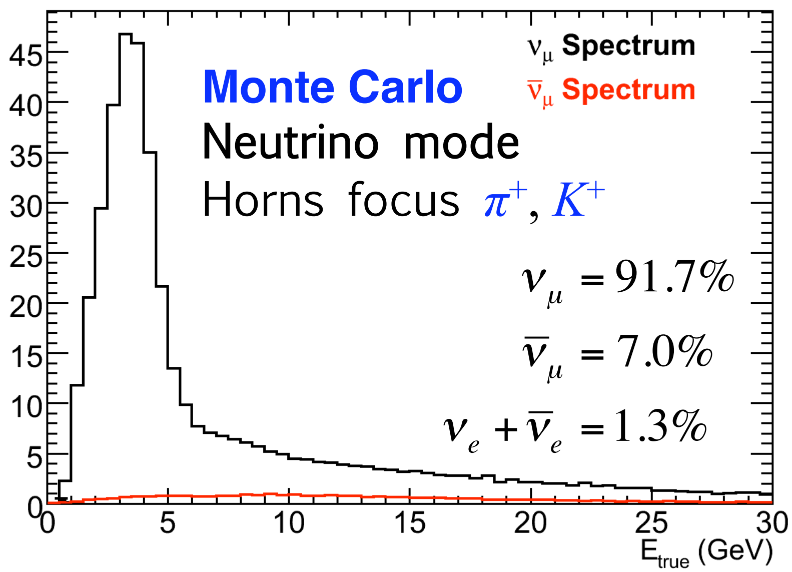
Making a neutrino beam

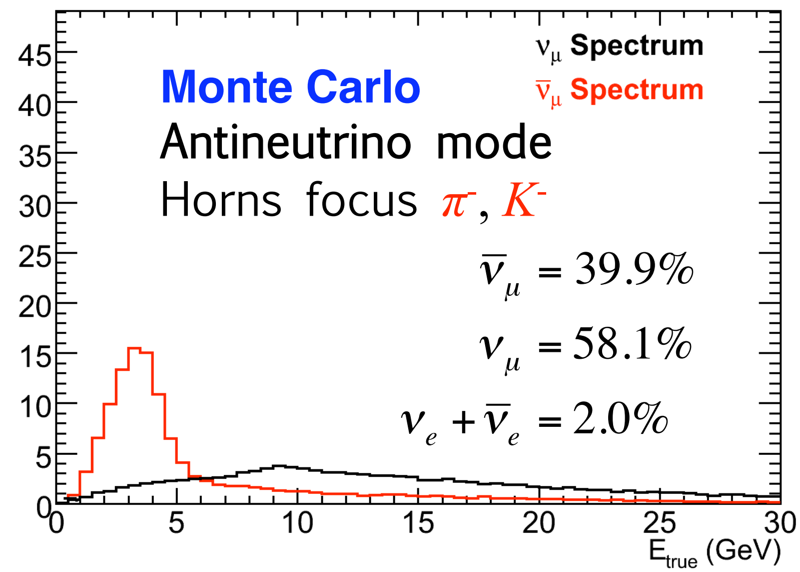


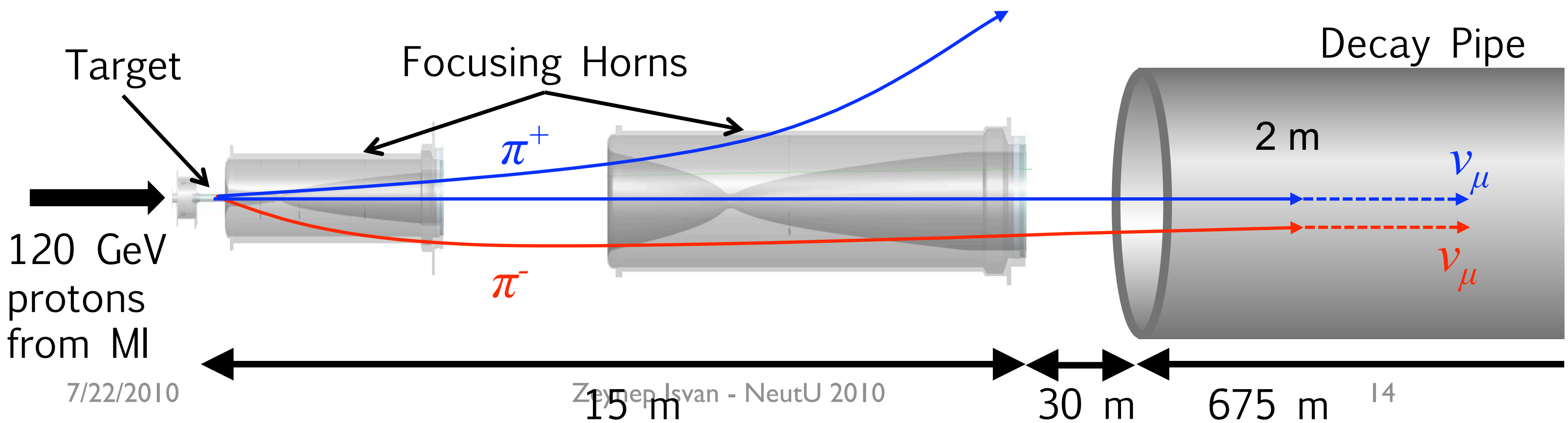
- **Decay**
  - 2 m diameter decay pipe
  - result: wide band beam, peak determined by target/horn separation
  - secondary beam monitored

NuMI is Versatile

- Just as we can make a neutrino beam, we can make an *antineutrino* beam by reversing the horn current.

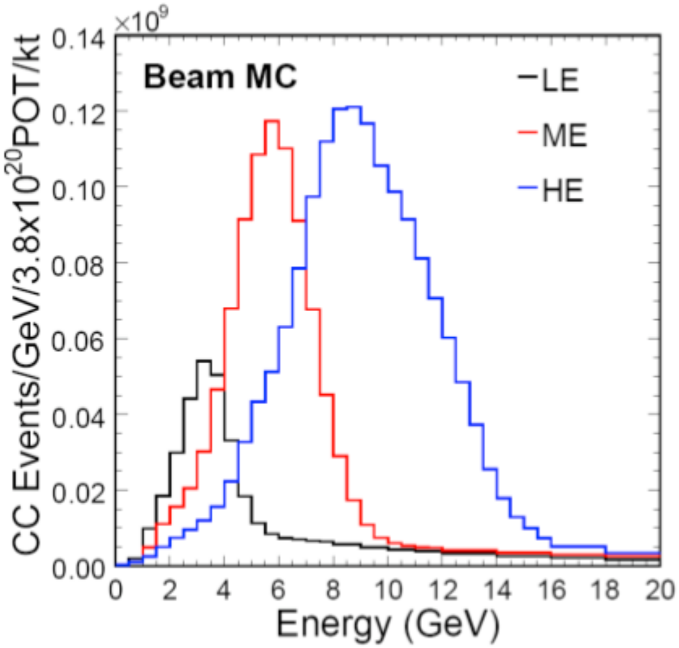




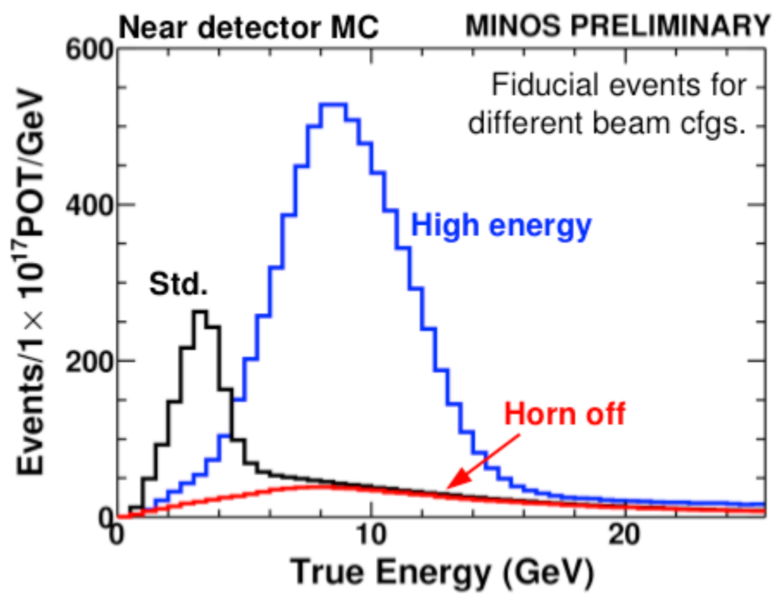


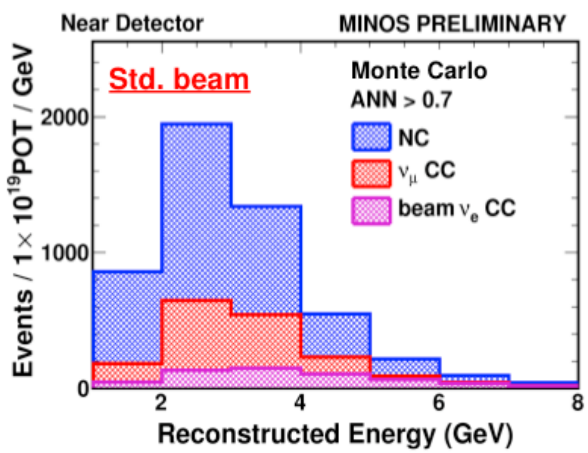
NuMI is Versatile

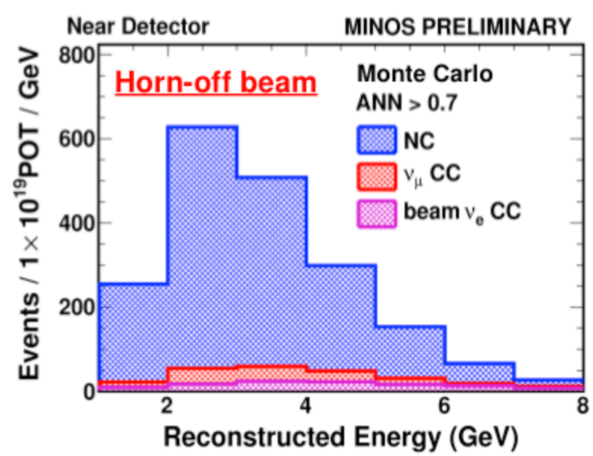
- We can adjust the peak energy by moving the target wrt to the horns



- Or we can turn off the horns altogether…







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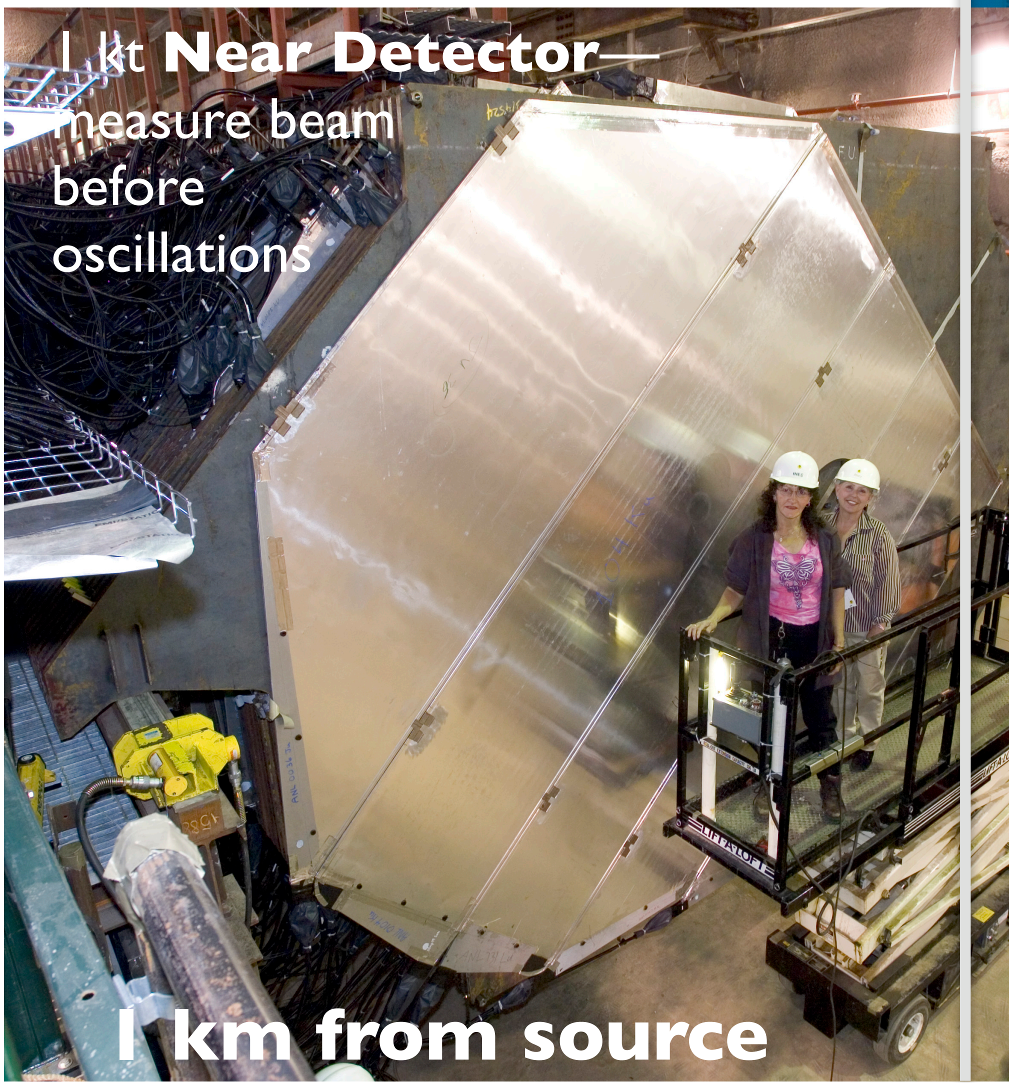
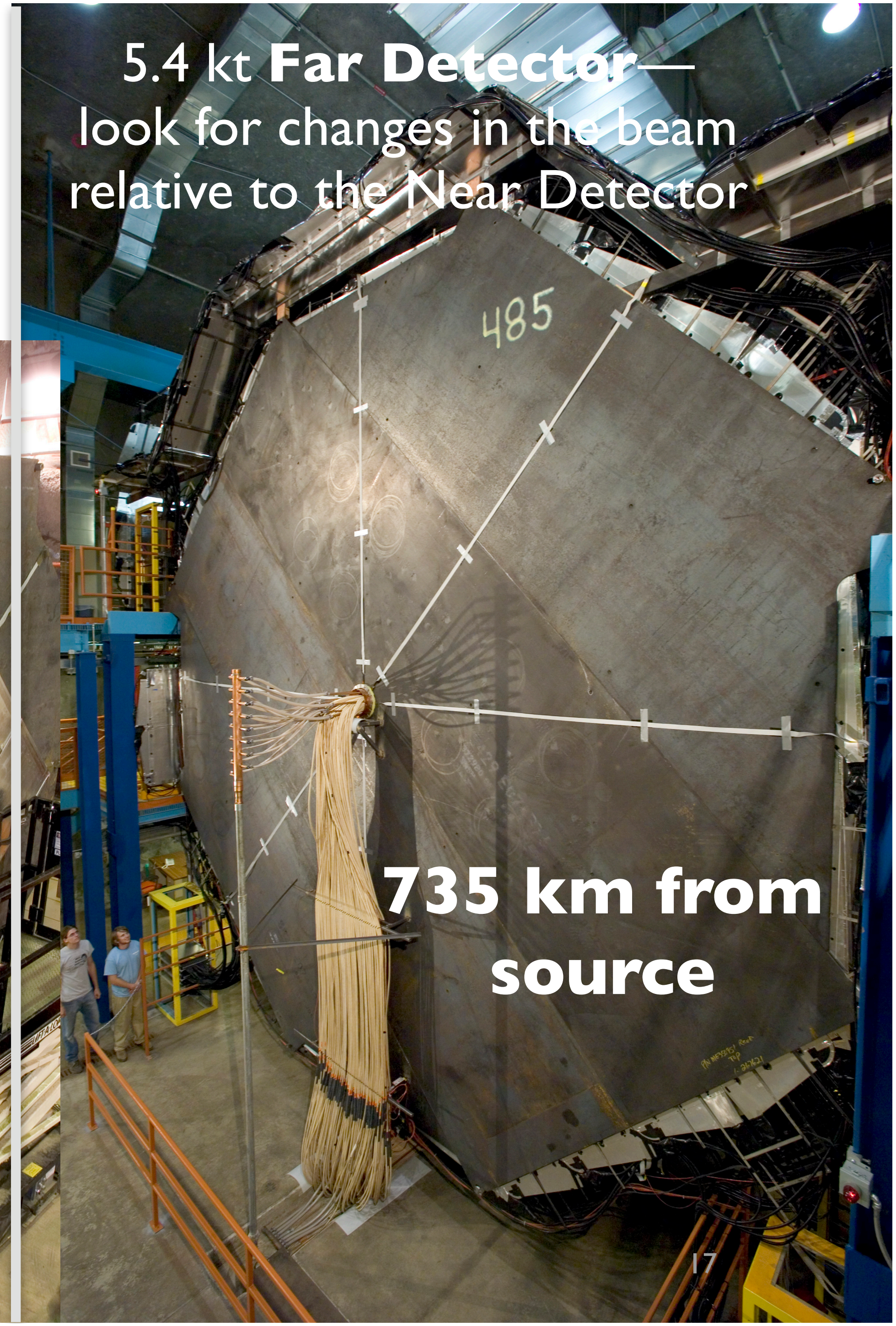
The Detectors

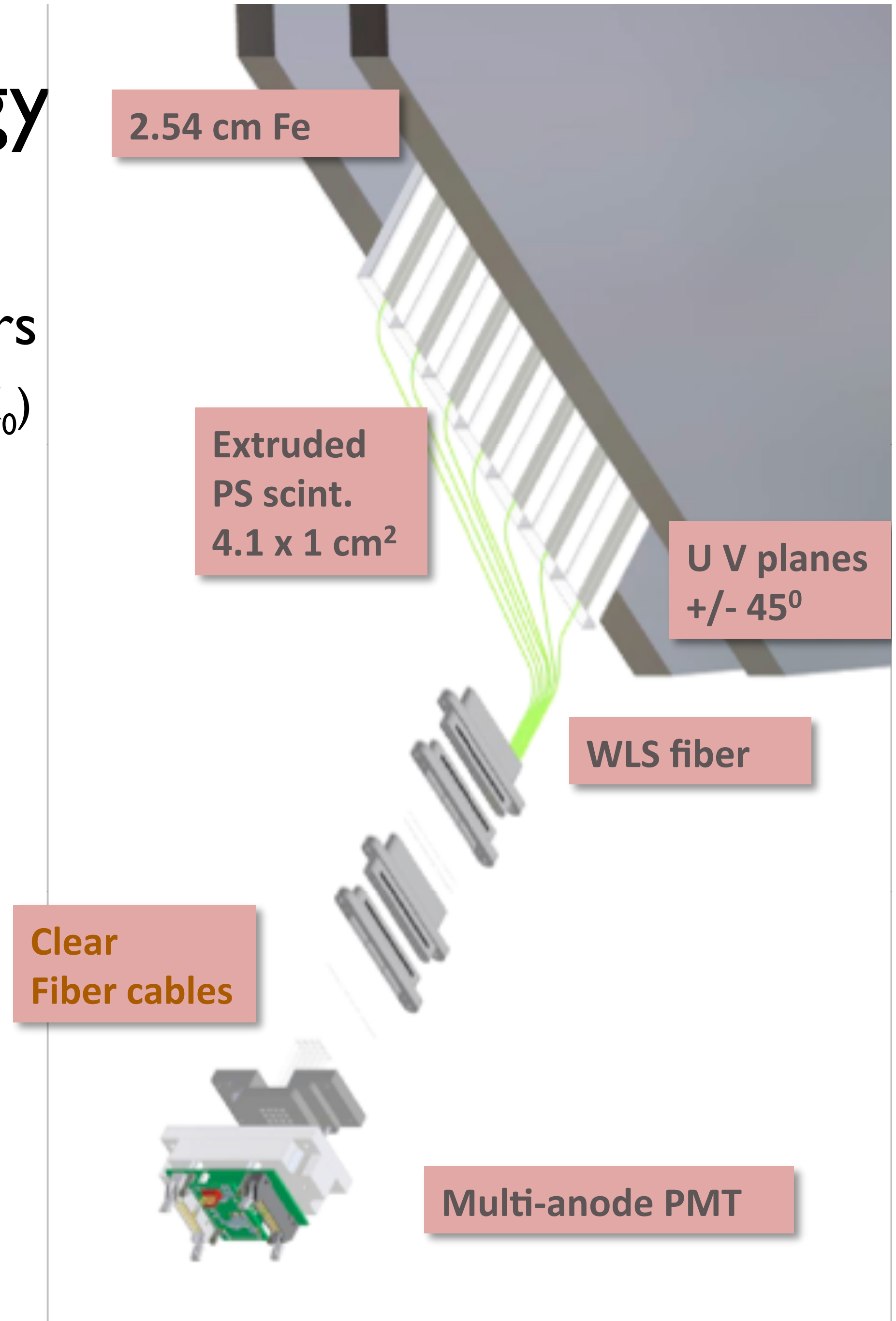
Magnetized, tracking calorimeters



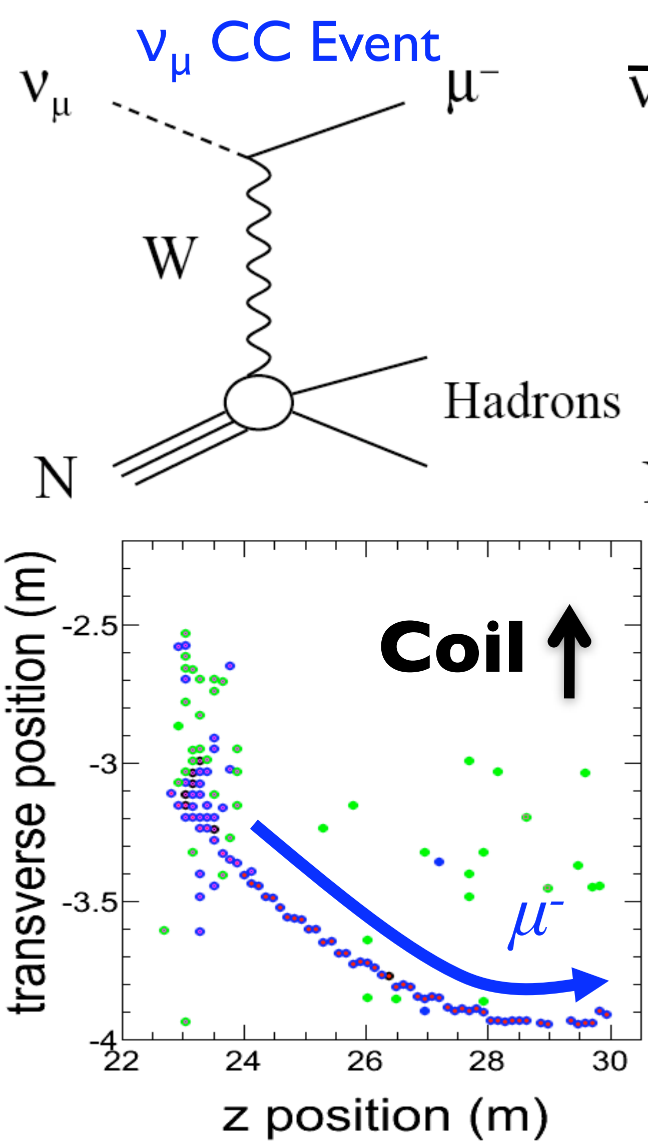


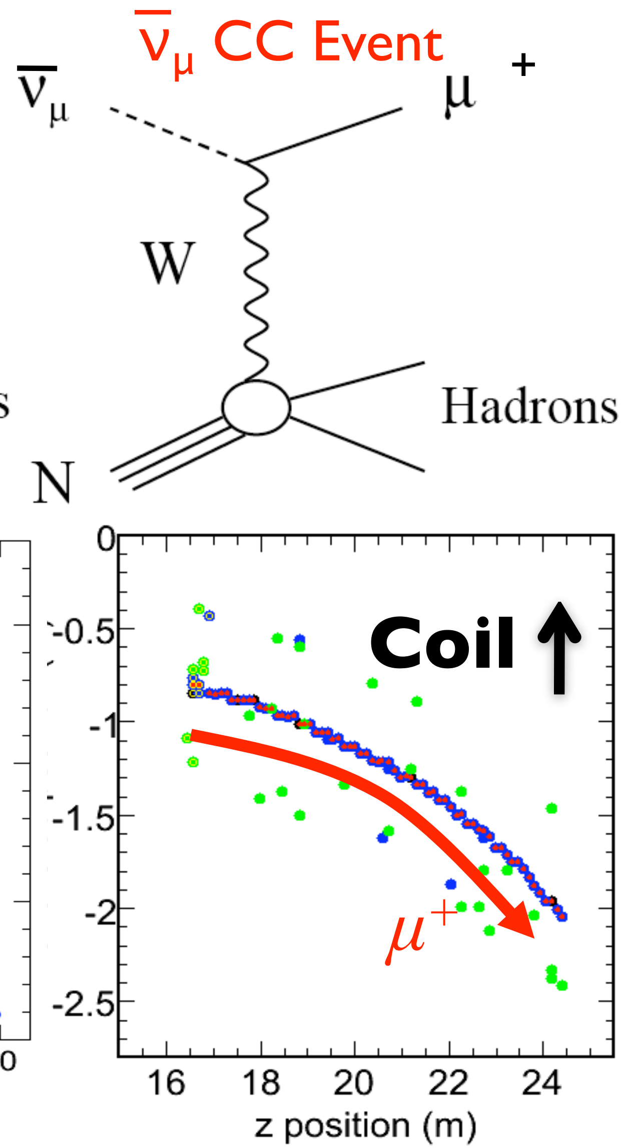
Detector Technology

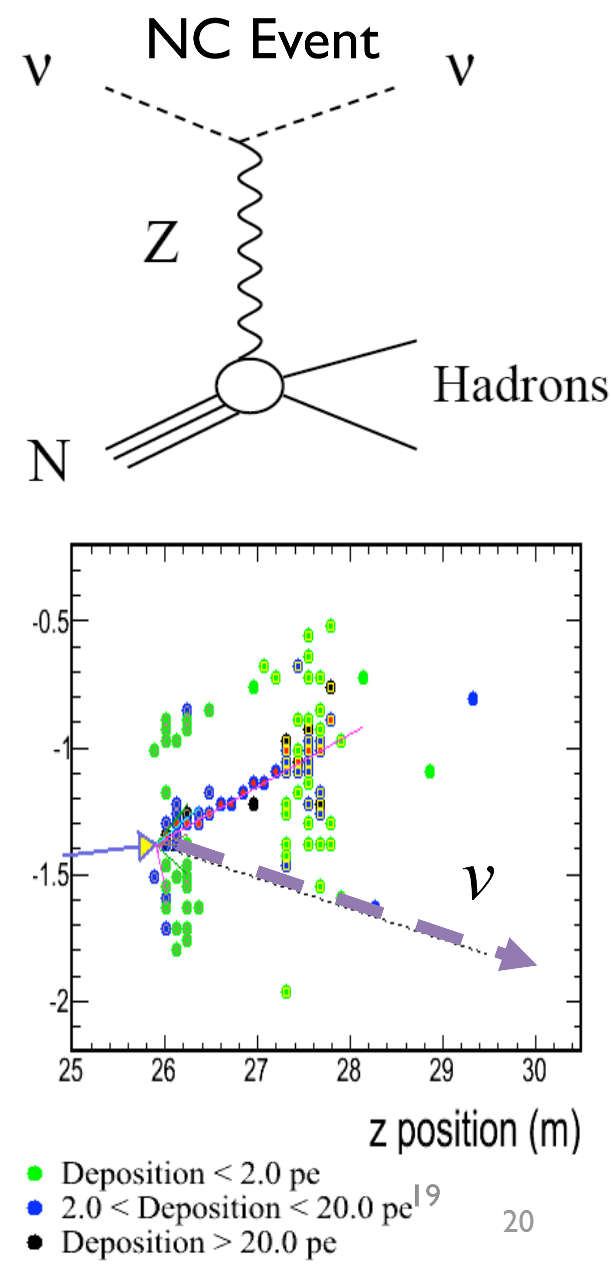
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



Events at the Detectors







Simulated Events

Measuring Neutrino Oscillations

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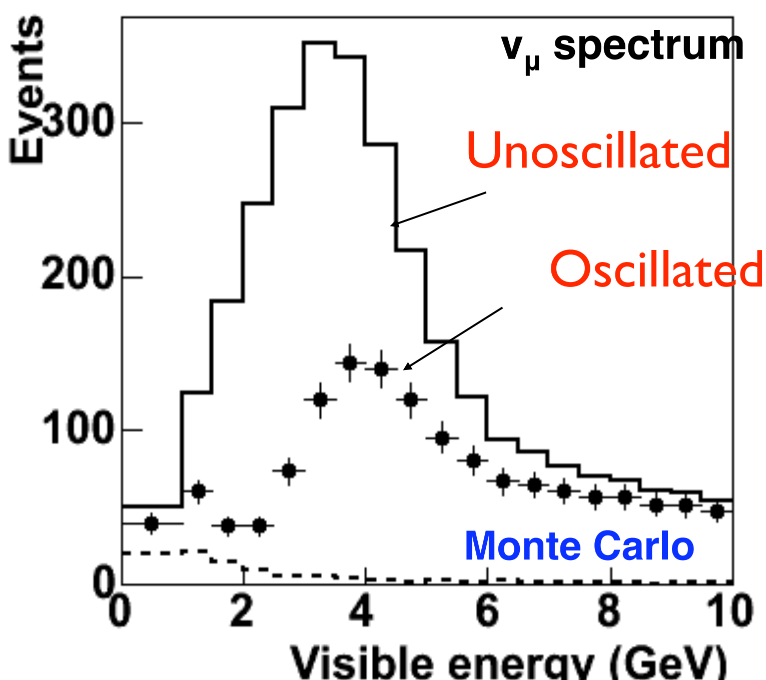
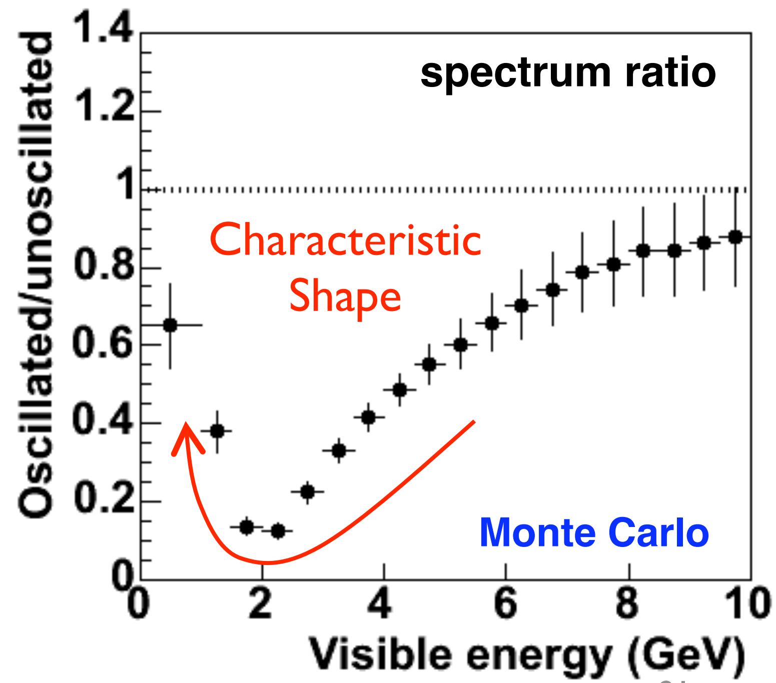
Measuring Oscillations

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right)$$

Monte Carlo

$\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}$ eV^2





Measuring Oscillations

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

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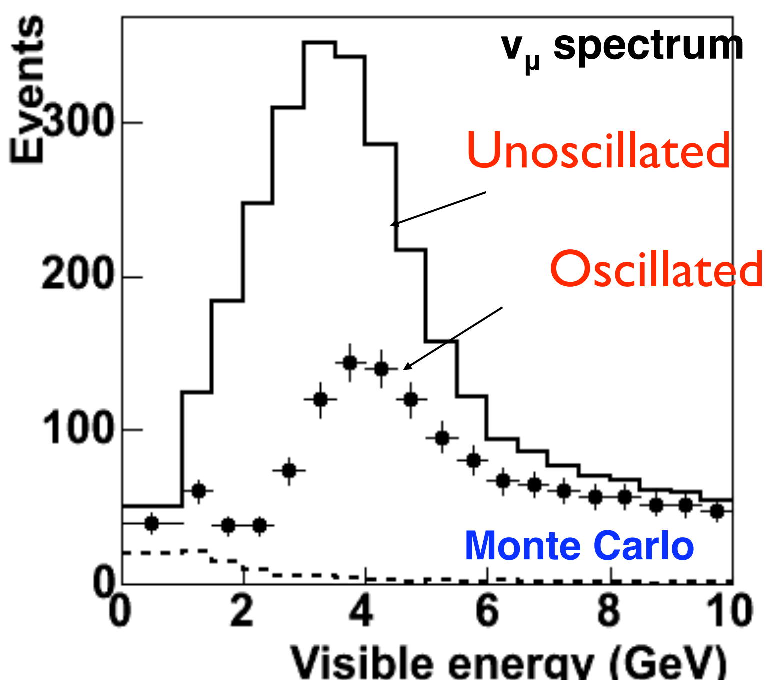
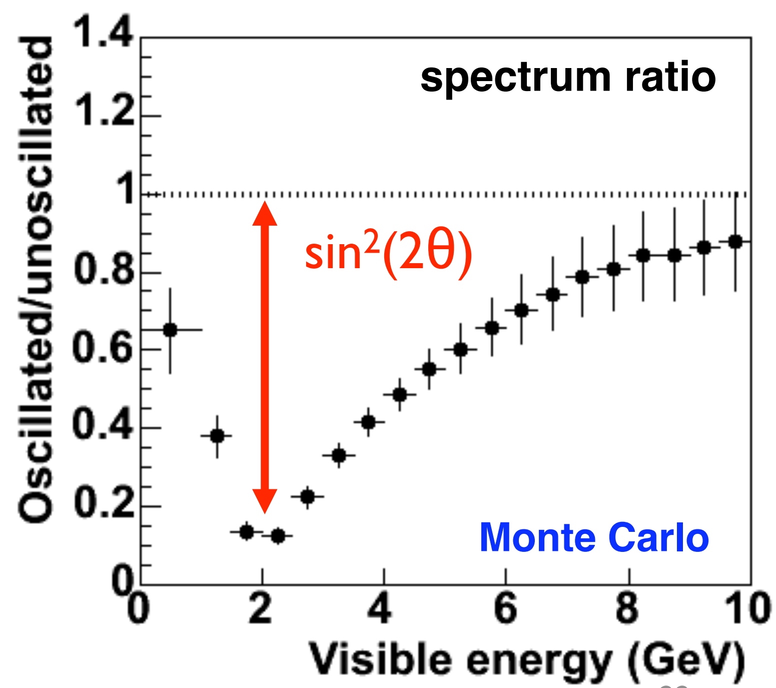
$\sin^2 2\theta = 1.0, \ \Delta m^2 = 3.35\times10^{-3}\ eV^2$





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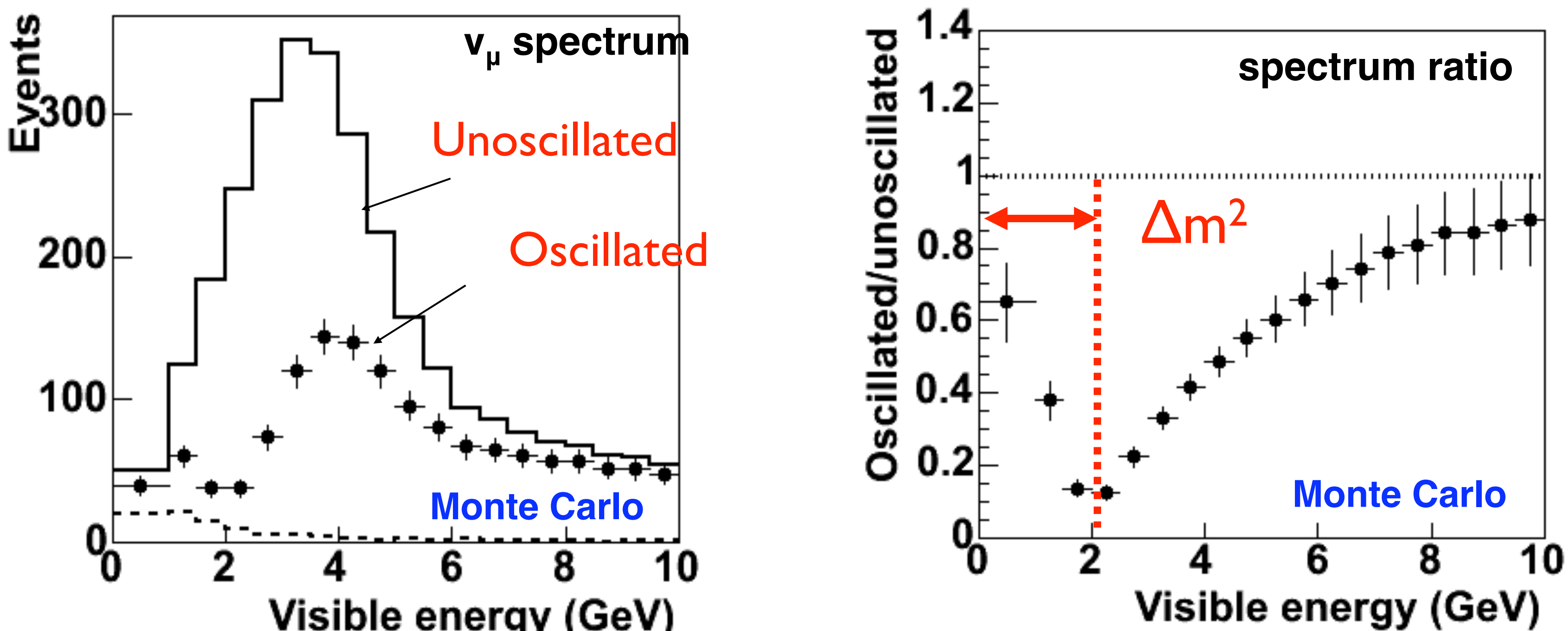


The Analyses

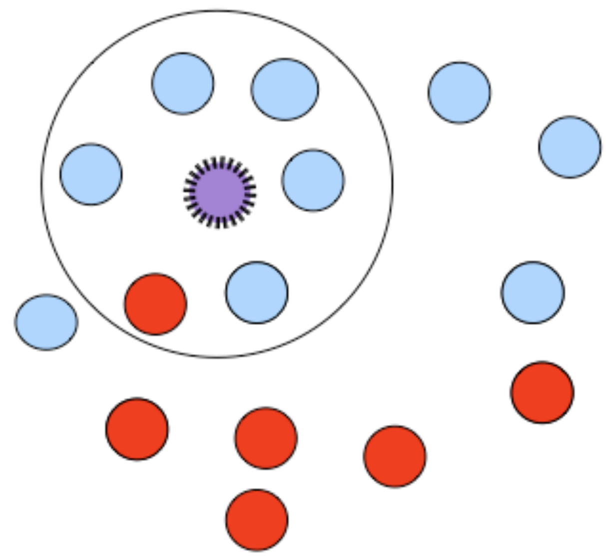
Oscillation Analysis in Brief

- Select (anti)neutrino events in the detectors
- Measure their energies to produce Near and Far detector spectra
- Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
- Fit the Far Detector data to measure oscillations

Selection

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- CC/NC separation using a kNN algorithm
  - Compare to monte carlo events
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile

k-Nearest Neighbors "kNN"



the **k**=6 **n**earest **n**eighbors contain one red and five blue
The point has a kNN of 5/6

Selection

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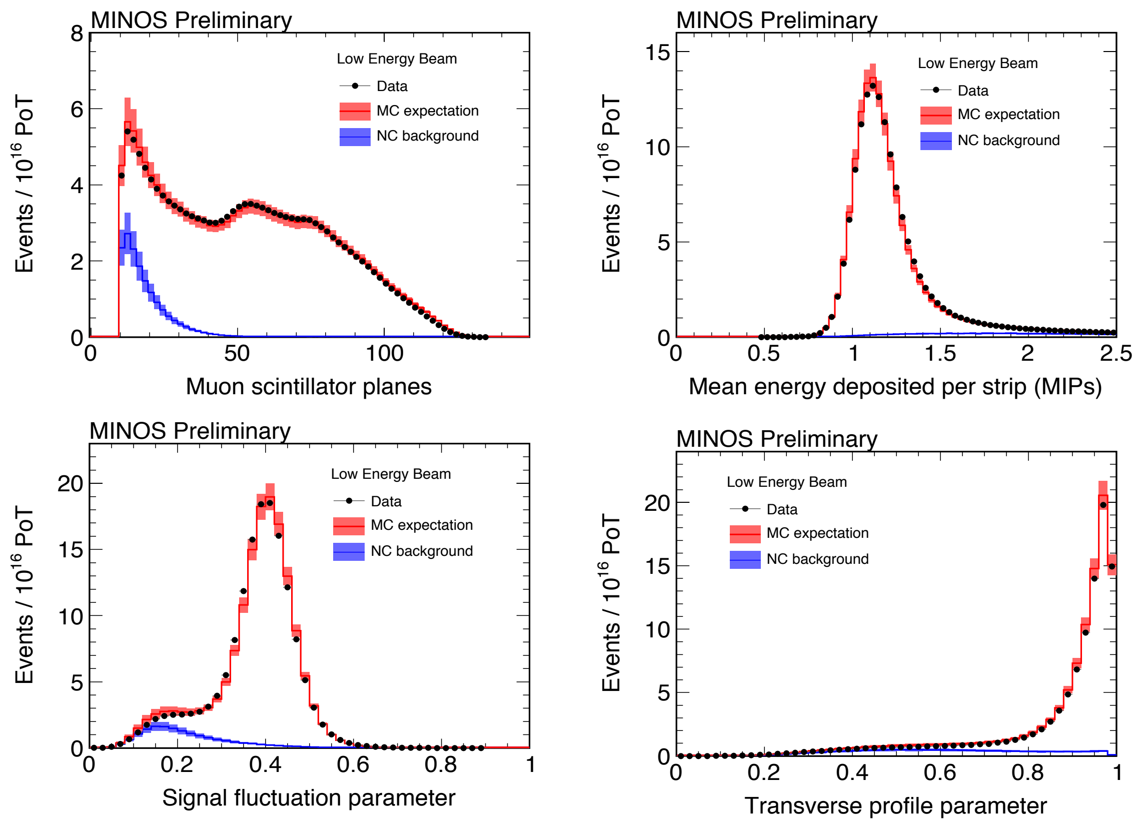

Selection

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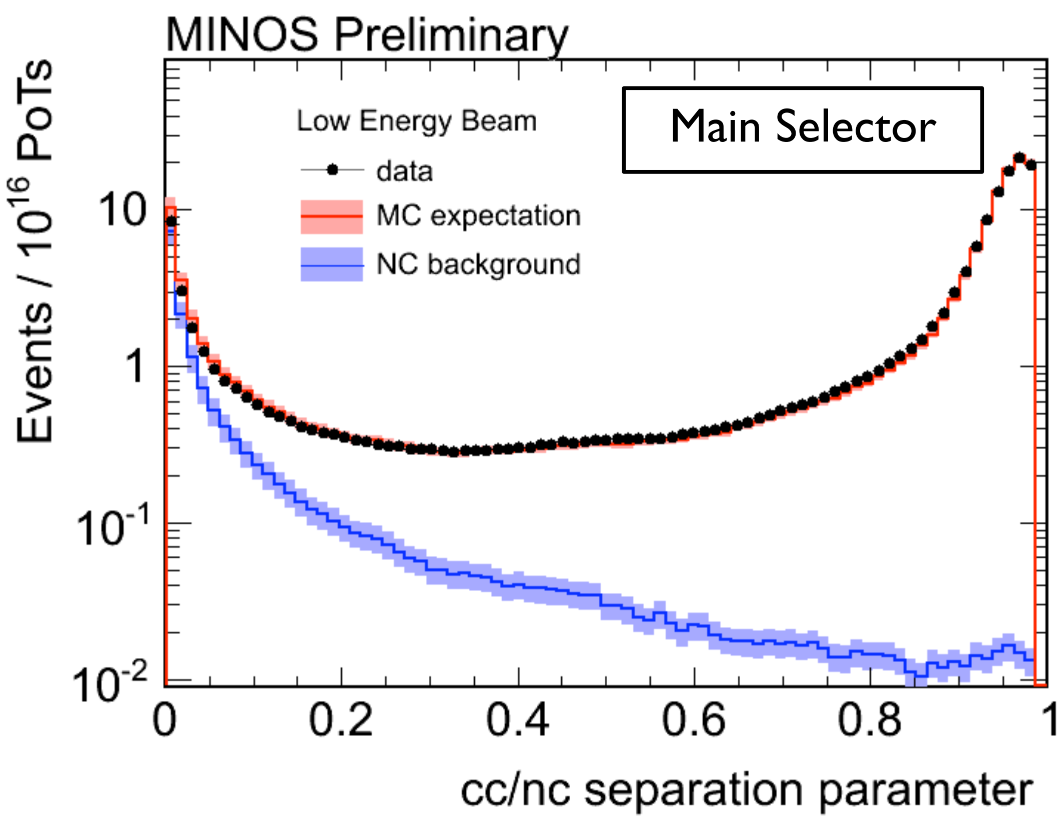
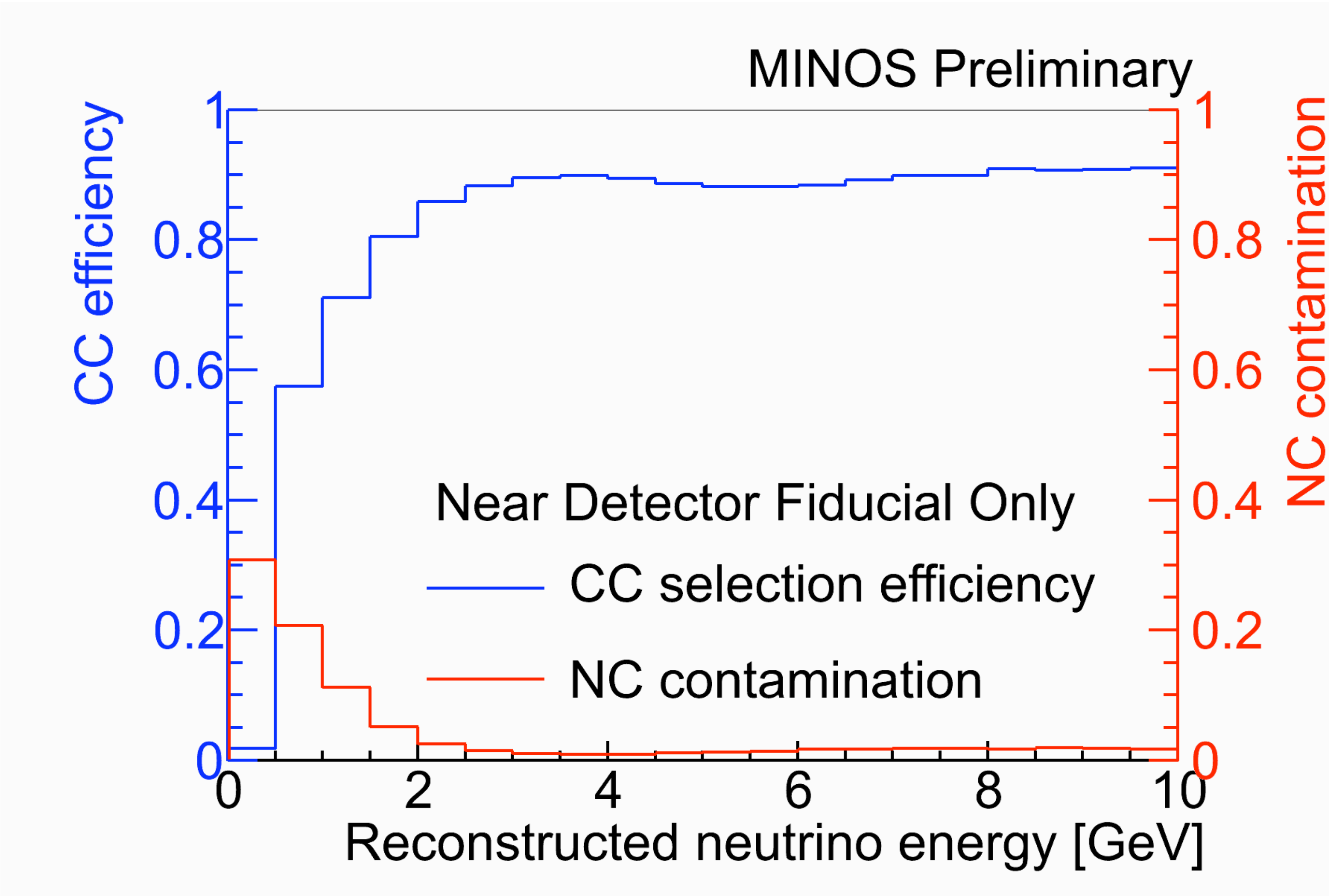
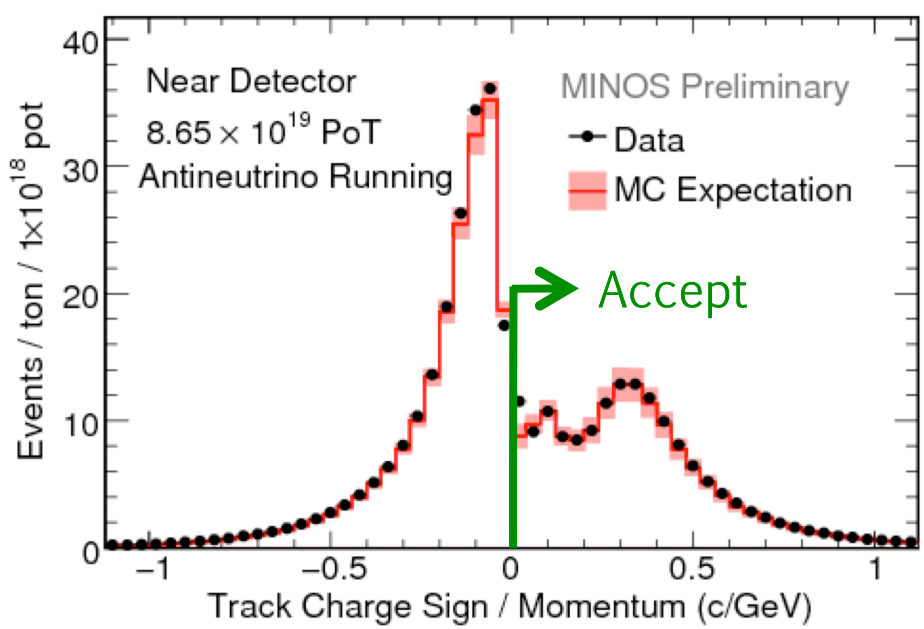


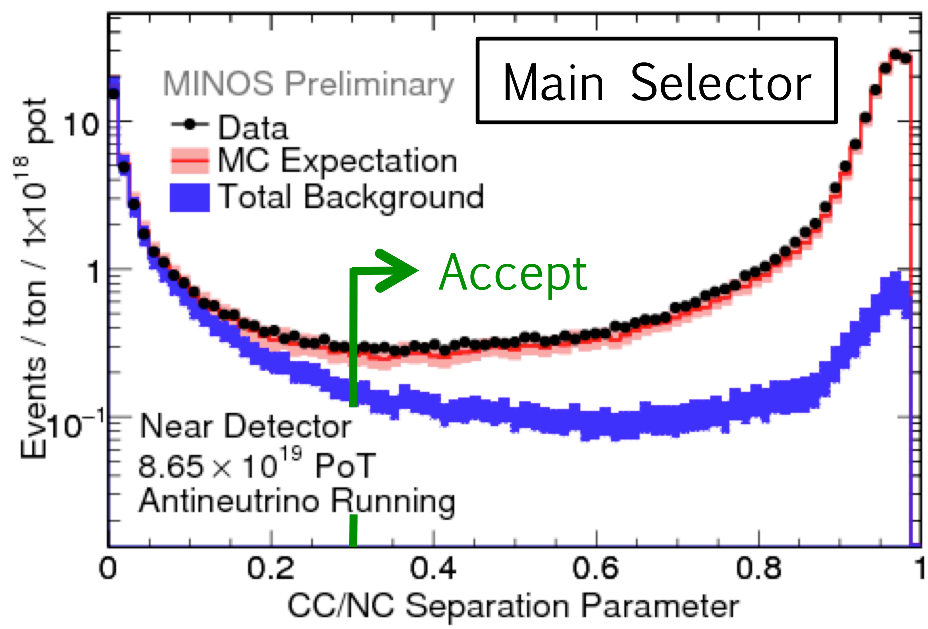
Neutrino Selection Efficiency



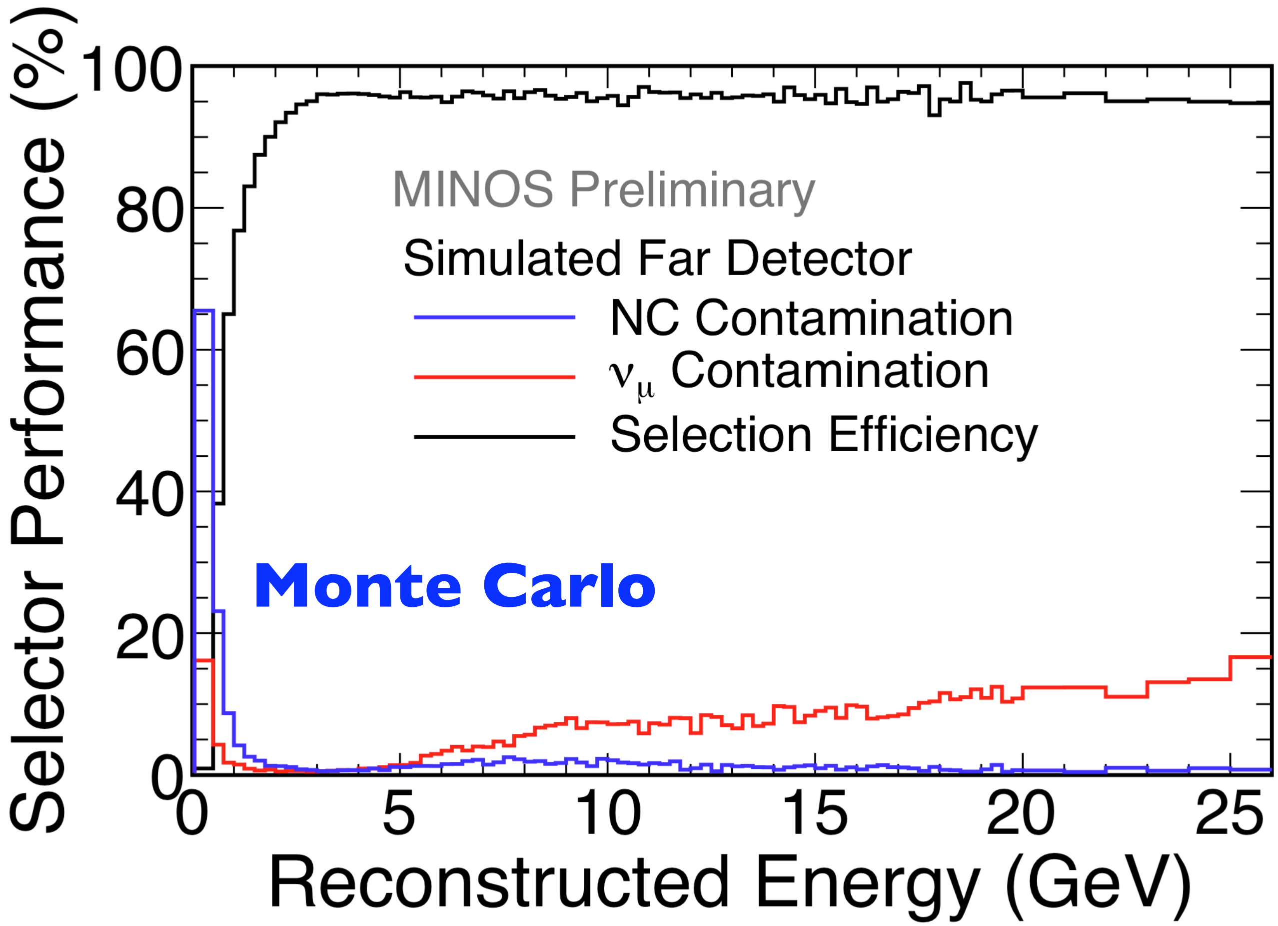
Antineutrino Selection

- Accept only events with positive reconstructed charge
- Use the Main CC/NC Selector from the neutrino analysis
  - Removes NC and high-y CC interactions
- Data/MC agreement comparable to that seen for neutrinos.





Antineutrino Efficiency



High energy ν_μ contamination does not affect the oscillation result

Oscillation Analysis in Brief

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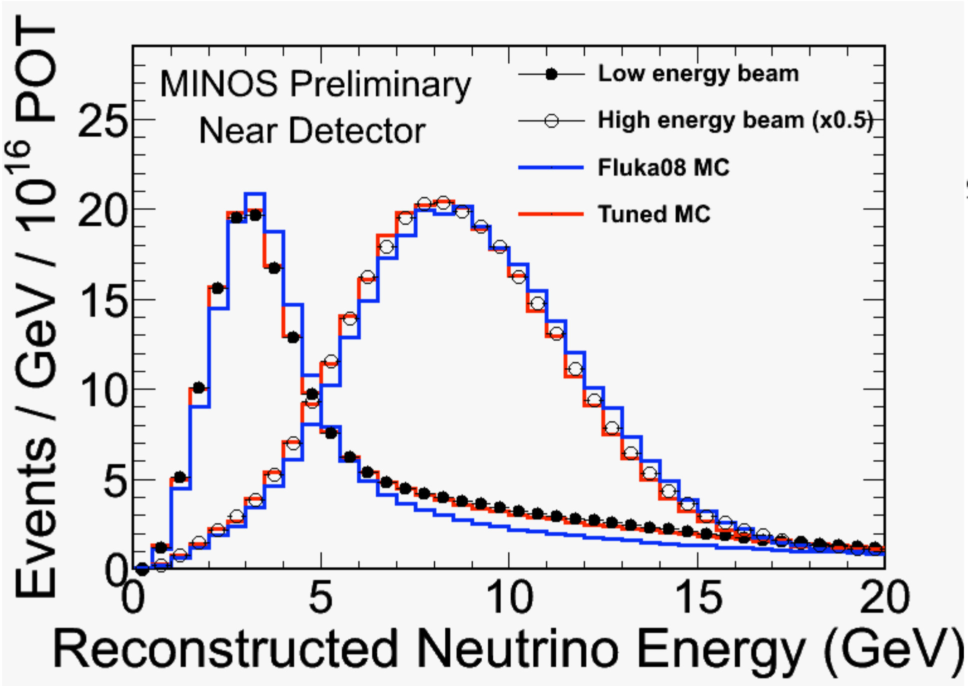
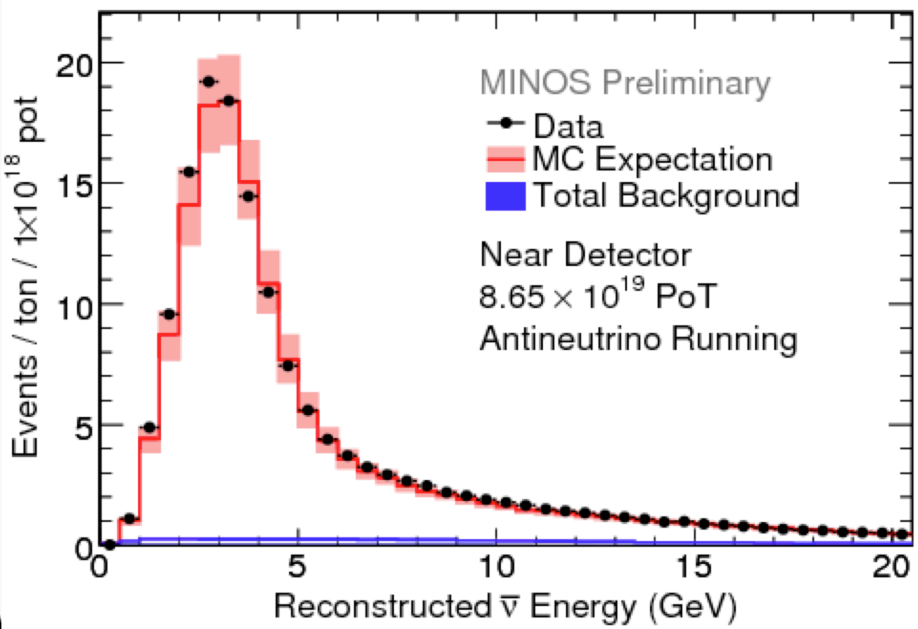
Near Detector Energy Spectra





- Neutrino mode
- Most of our data taken in Low Energy configuration
- High energy beam to give events above oscillation dip

- Antineutrino mode
- Flux and cross section uncertainties cancel when extrapolated from Near to Far detector.

Oscillation Analysis in Brief

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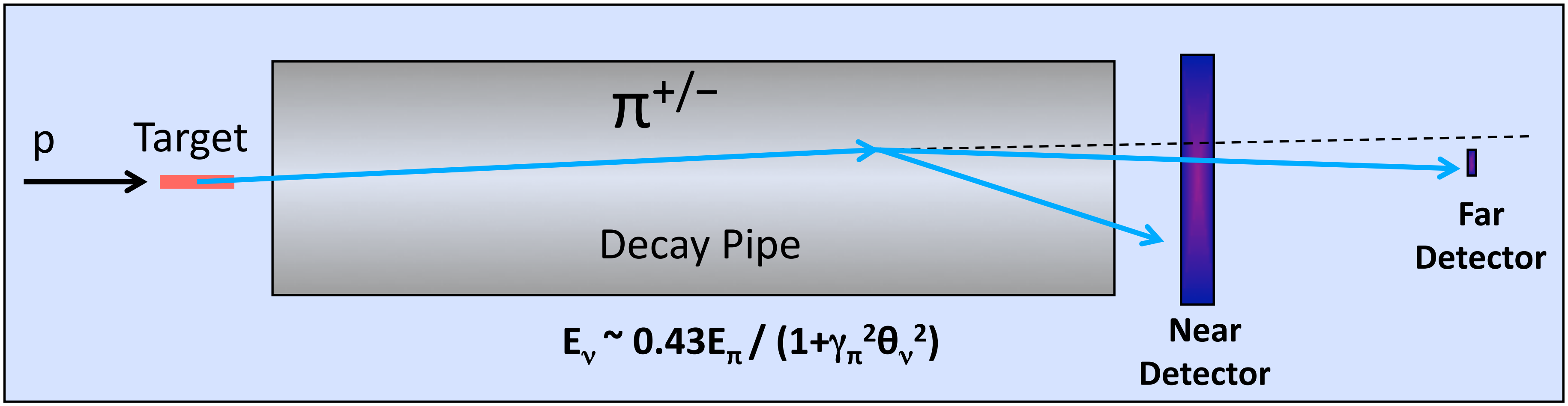
Near to Far Extrapolation

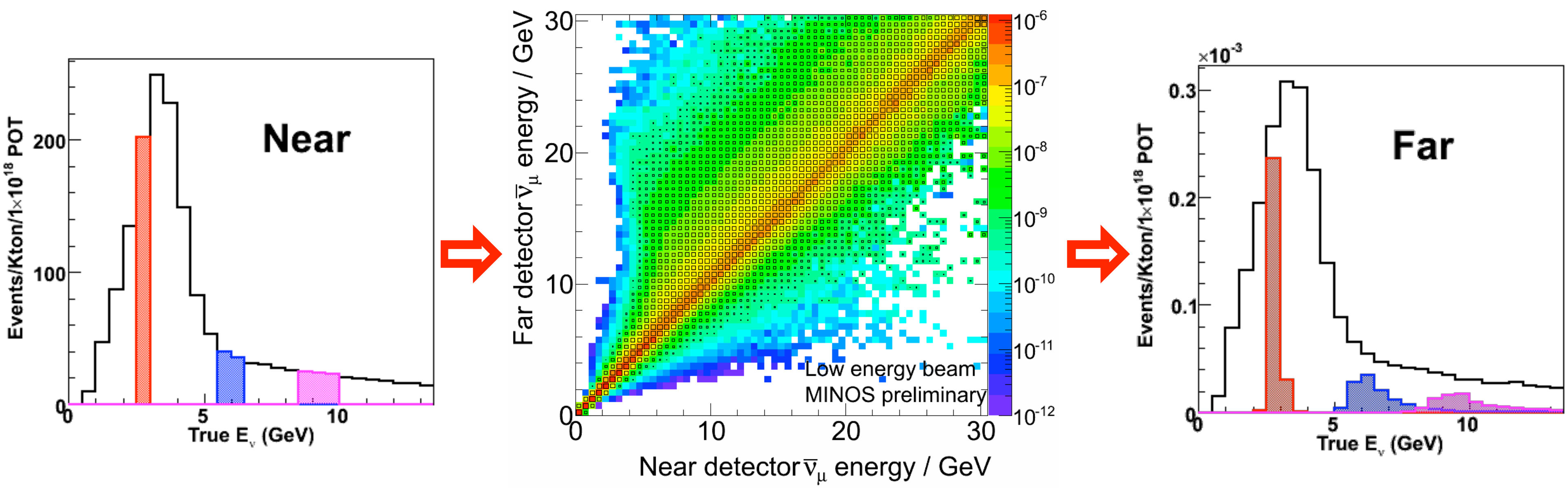
Far spectrum without oscillations is similar, but not identical to the Near spectrum!



- Neutrino energy depends on angle wrt original pion direction and parent energy
  - higher energy pions decay further along decay pipe
  - angular distributions different between Near and Far

Beam Matrix Extrapolation

- A beam matrix extrapolates measured Near spectrum to Far
- Matrix encapsulates knowledge of meson decay kinematics and beamline geometry
  - Matrix element M_{ij} reflects the probability of obtaining a Far event with energy E_j given the observation of a Near event with energy E_i
- MC used to correct for energy smearing and acceptance



Monte Carlo

Oscillation Analysis in Brief

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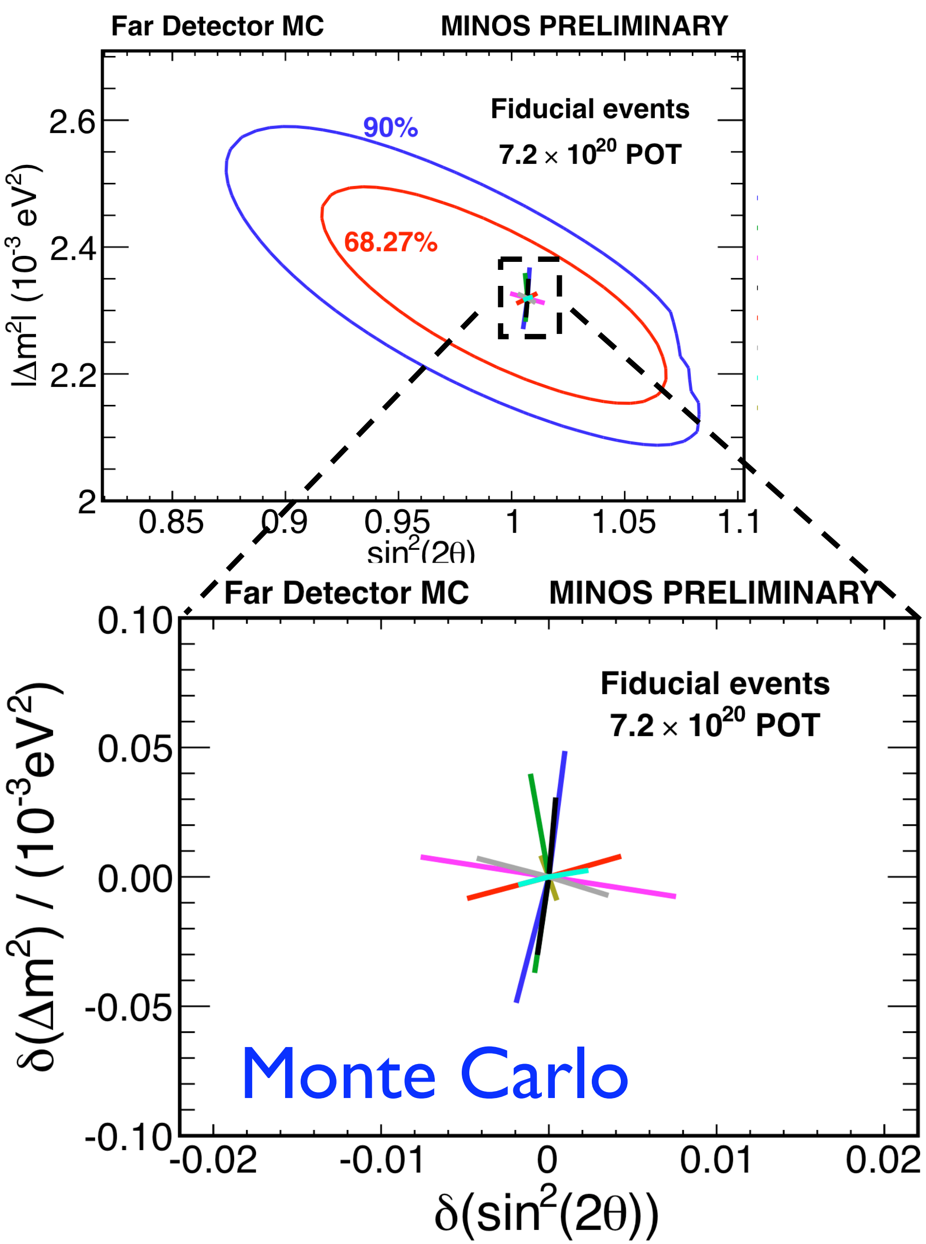
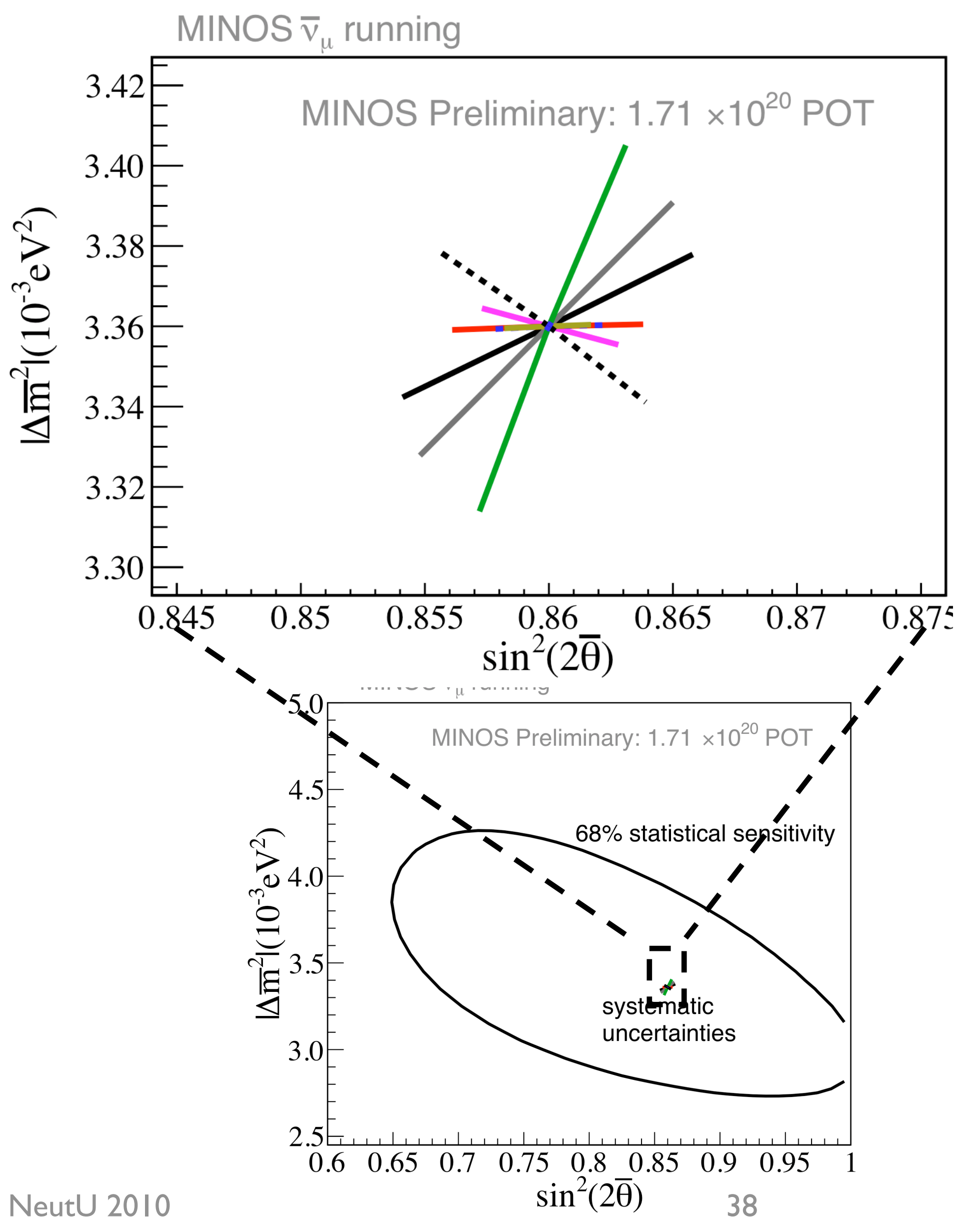
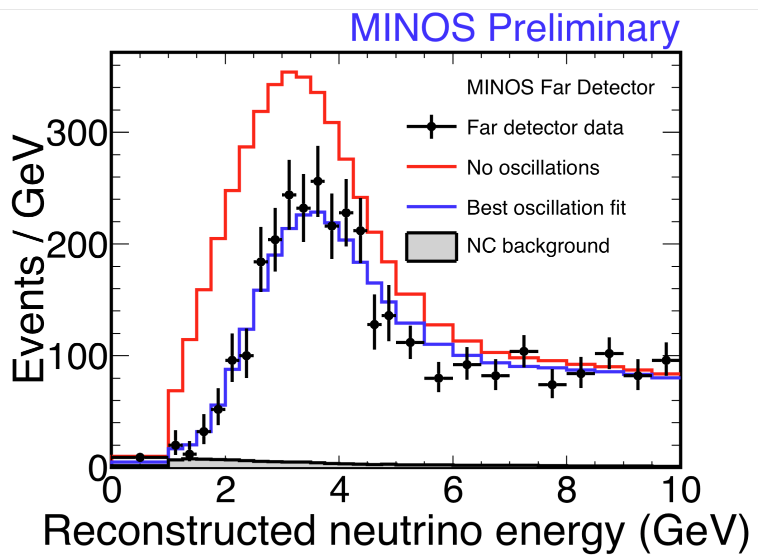
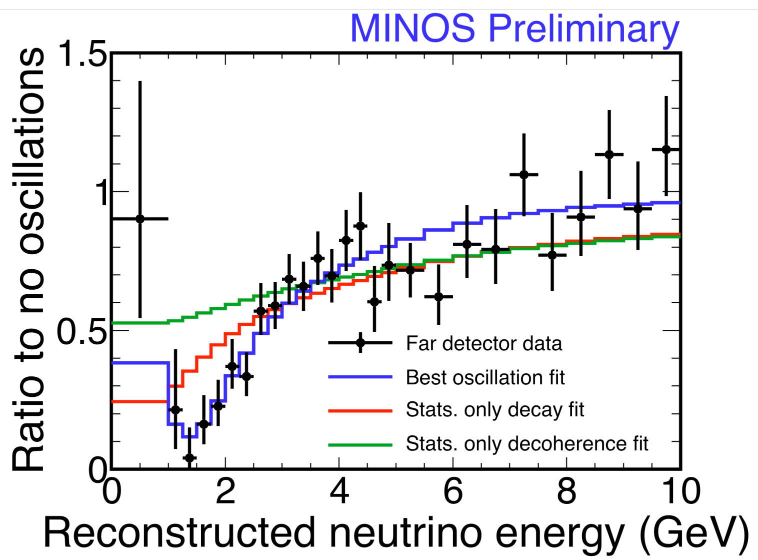
Systematic Uncertainties

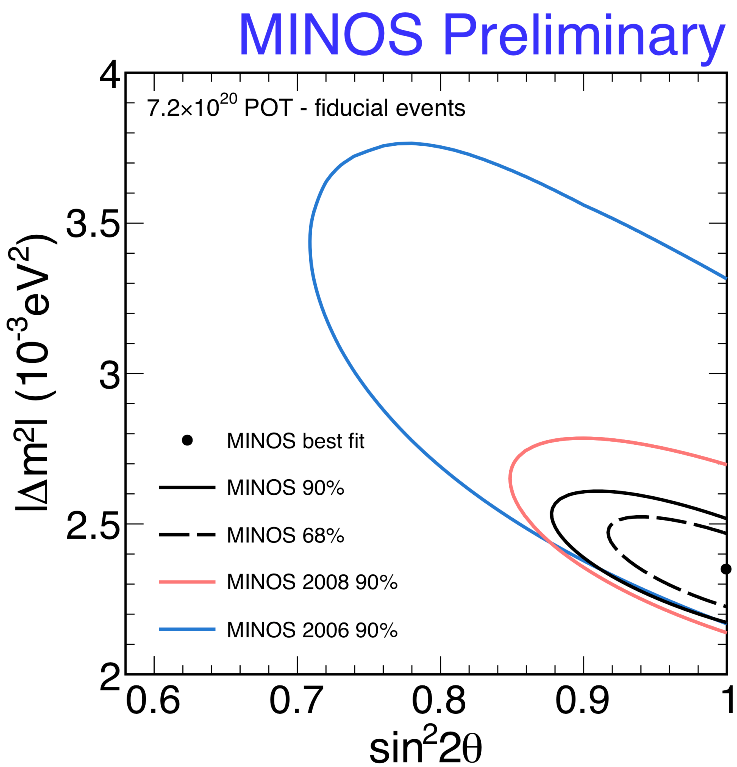




Far Detector Neutrino Data







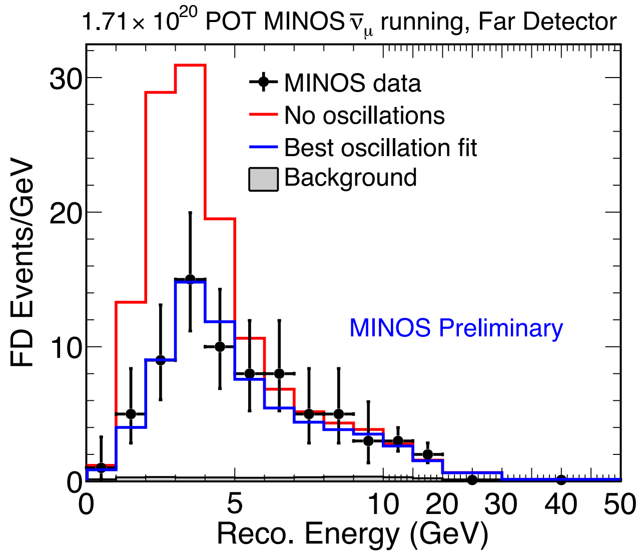
- **2,451** expected without oscillations
- **1,986** observed events

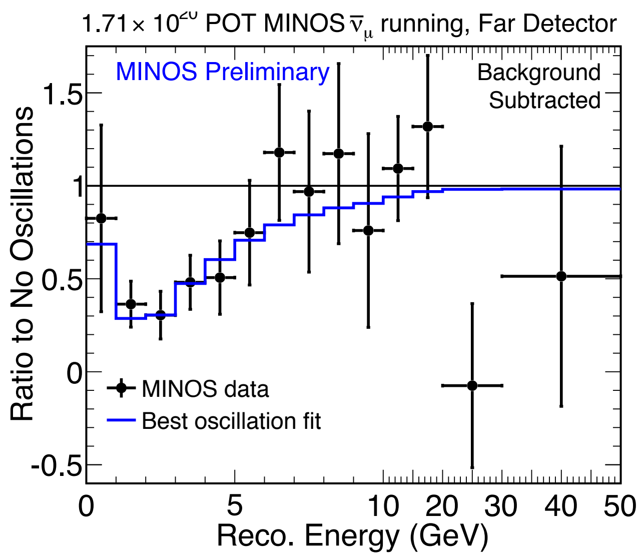
$$\left|\Delta m^2_{\text{atm}}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \text{eV}^2$$

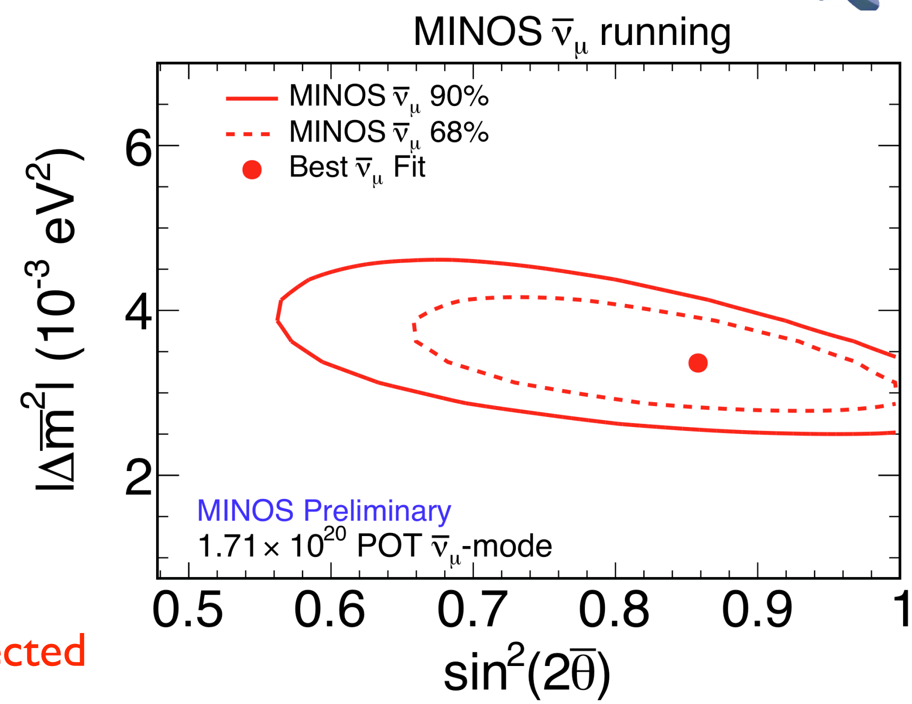
$$\sin^2(2\theta_{23}) = 1$$

$$\sin^2(2\theta_{23}) > 0.91\ (90\%\ \text{C.L.})$$

Far Detector Antineutrino Data







- **155** expected without oscillations
- **97** observed events

No-oscillations hypothesis is disfavored at **6.3σ**

$$\left|\Delta\bar{m}^2_{\mathrm{atm}}\right| = 3.36^{+0.45}_{-0.40}\times10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\left(2\bar{\theta}_{23}\right) = 0.86\pm0.11$$

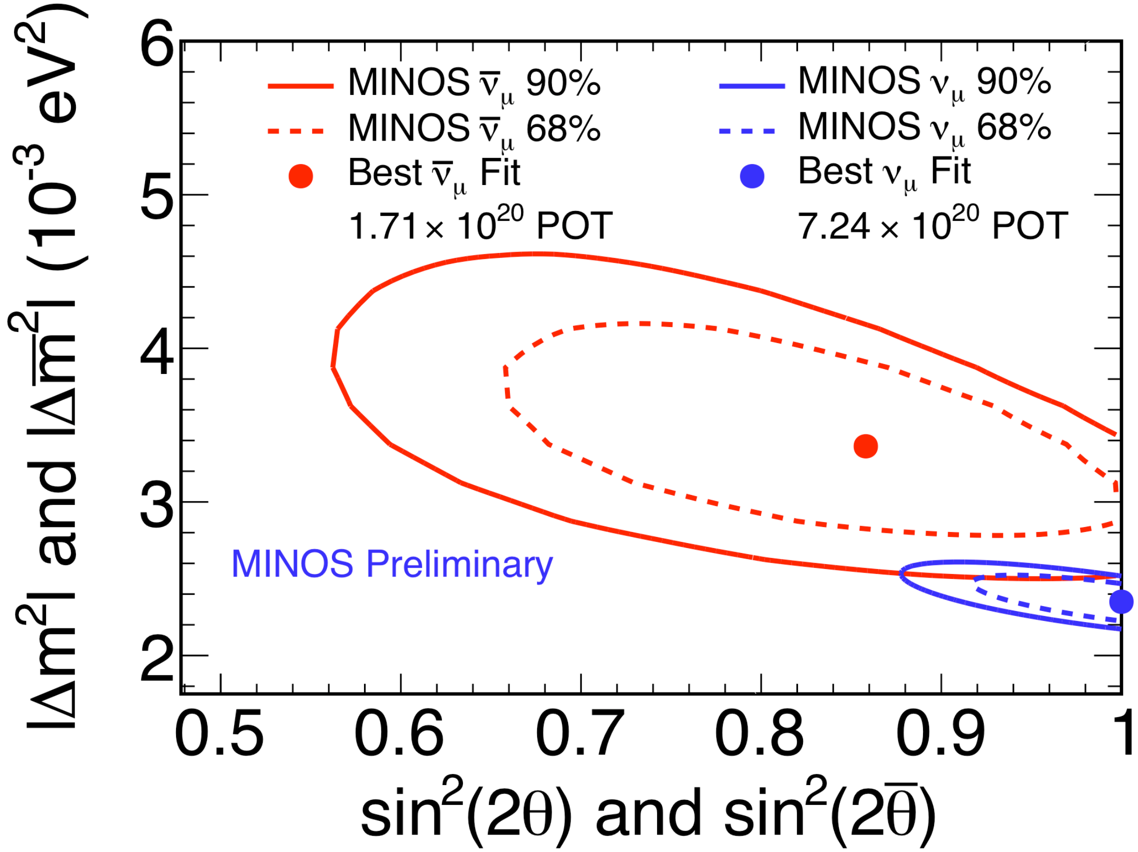
Neutrinos and Antineutrinos

$$\left|\Delta \overline{m}^2_{atm}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ eV^2$$

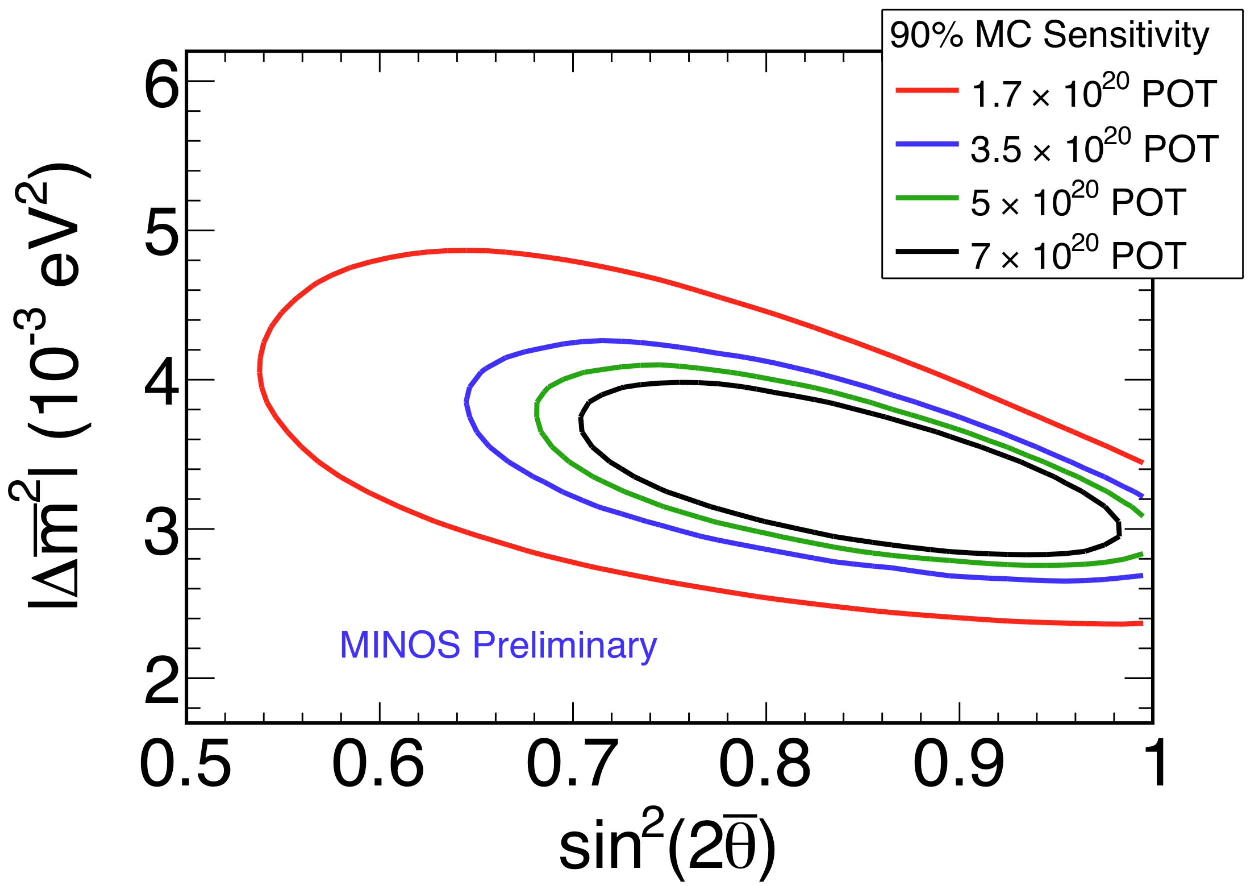
$$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86 \pm 0.11$$

$$\left|\Delta m^2_{atm}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ eV^2$$

$$\sin^2\left(2\theta_{23}\right) > 0.91\ (90\%\ C.L.)$$



With More Antineutrinos…



- Even just another 4.5 months of running (double the current data set) would decrease the error by ~30%.

Conclusions

- MINOS has the most precise measurement of $|\Delta m^2_{atm}|$
- MINOS has the first direct, precision measurement $|\Delta \overline{m}^2_{atm}|$

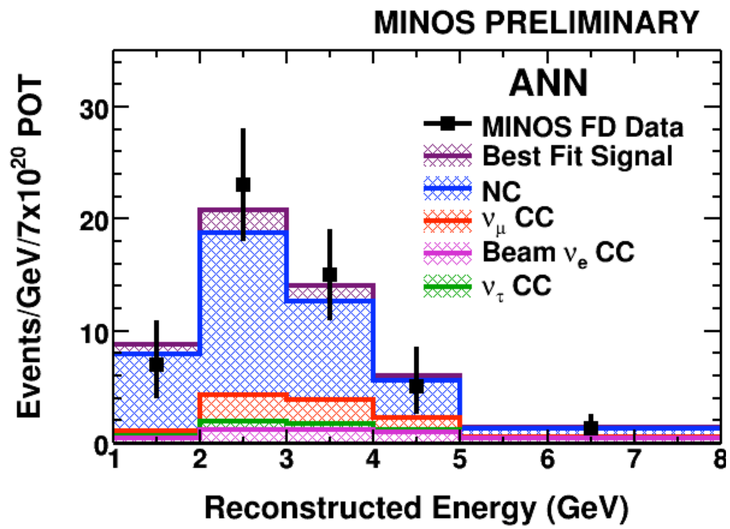
$$\left|\Delta m^2_{\mathrm{atm}}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.91\ (\text{at } 90\%)$$

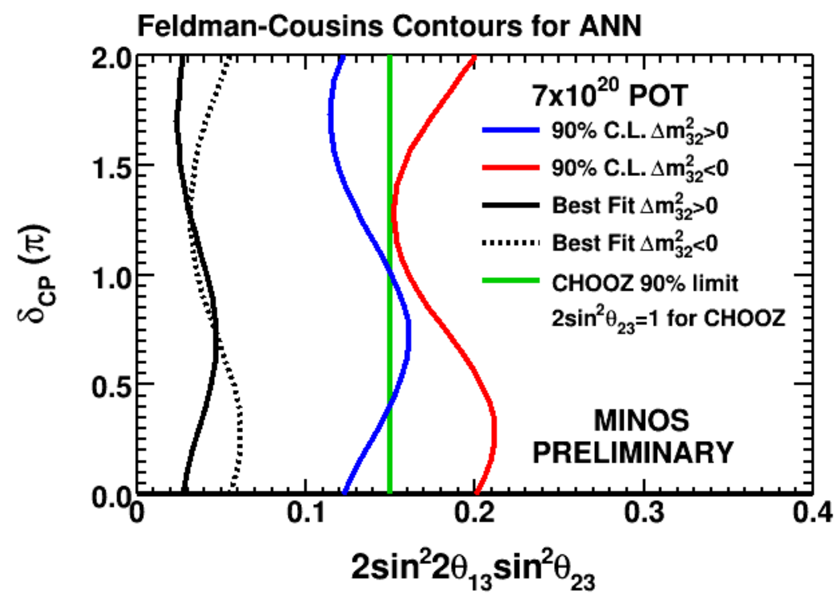
$$\left|\Delta \overline{m}^2_{\mathrm{atm}}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\overline{\theta}_{23}) = 0.86 \pm 0.11$$

- With more antineutrino beam we can rapidly improve the precision on the antineutrino oscillation parameters

MINOS Physics

- Talked about:
  - Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
  - Measurements of $|\Delta \bar{m}^2_{atm}|$ and $\sin^2(2\bar{\theta}_{23})$ via $\bar{\nu}_\mu$ disappearance
- Didn't have time for:
  - Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
  - Search for sterile ν
  - Atmospheric neutrino and cosmic ray physics
  - Study ν interactions and cross sections in Near Detector





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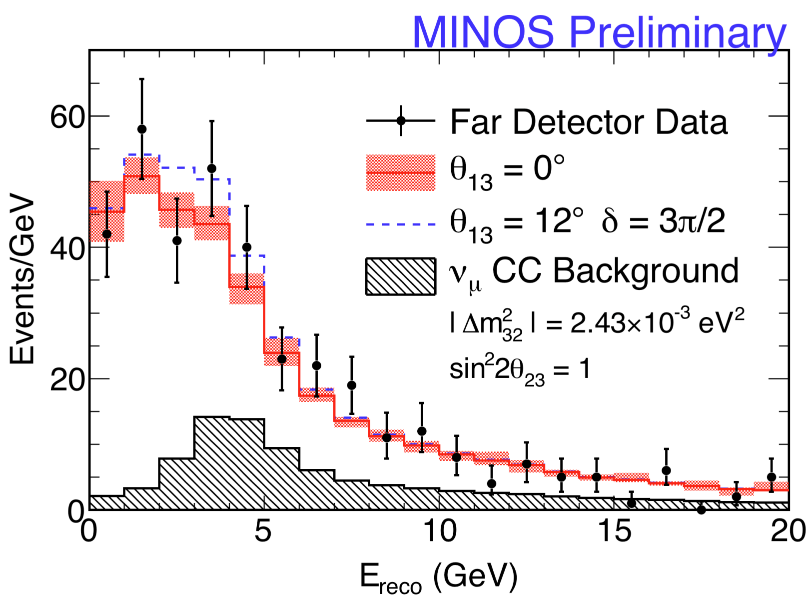

MINOS Physics

- Talked about:
  - Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
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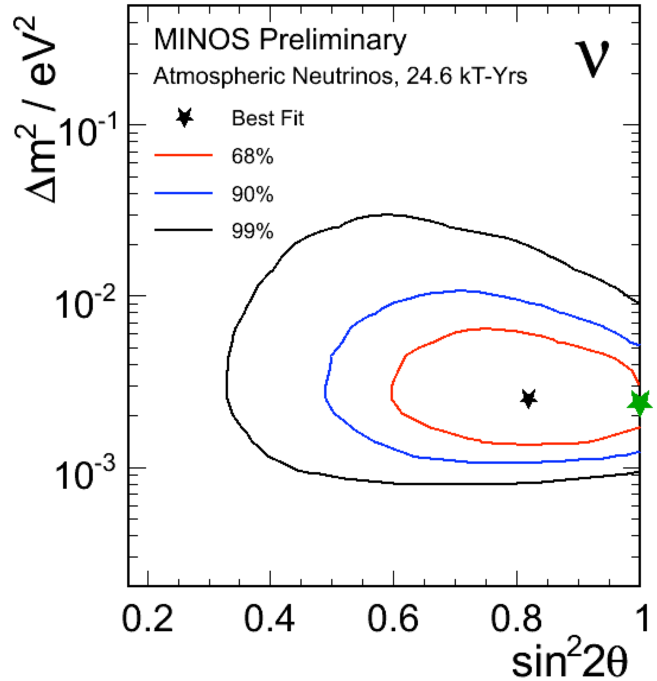

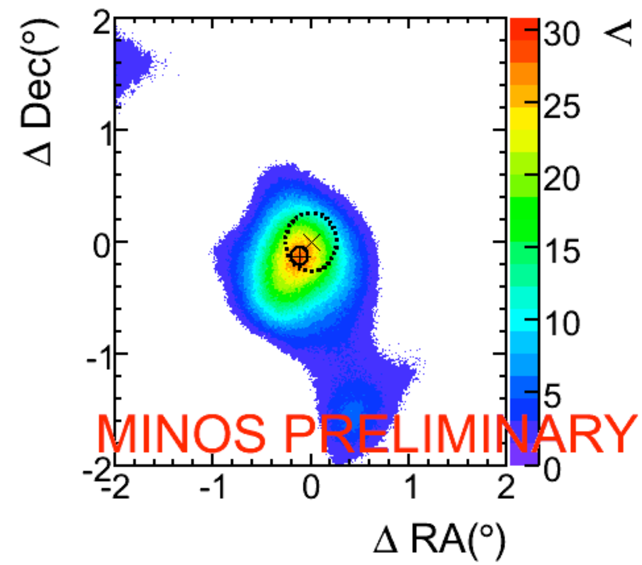

MINOS Physics

- Talked about:
  - Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
  - Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Didn't have time for:
  - Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
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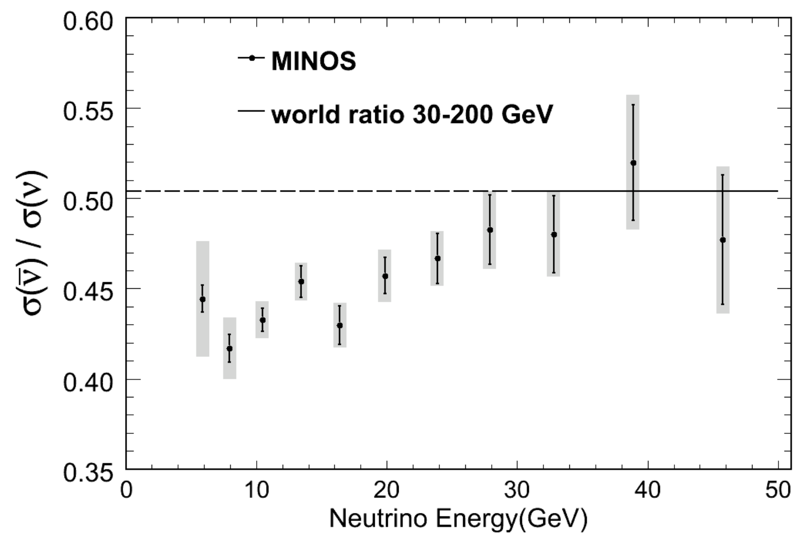


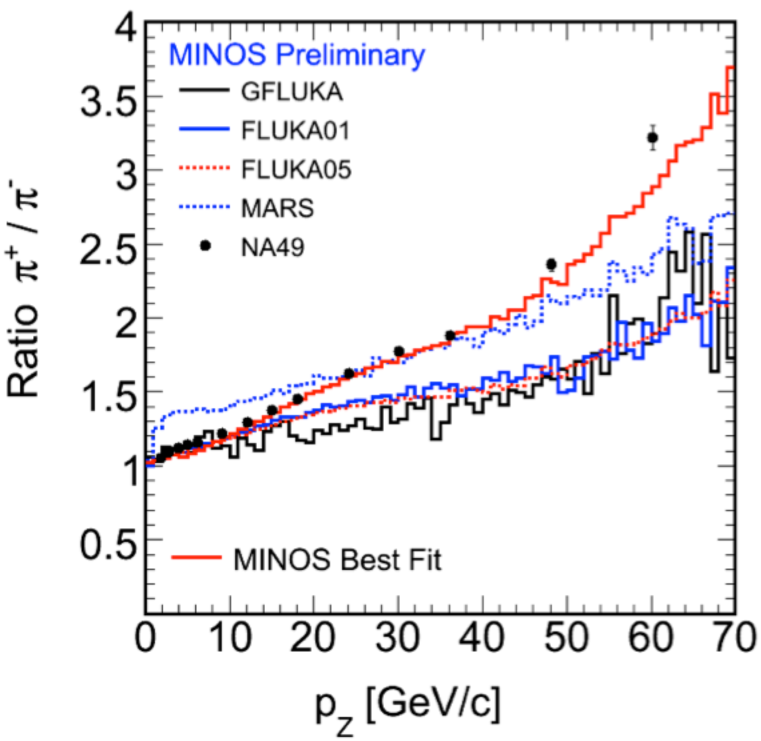
Thank you!

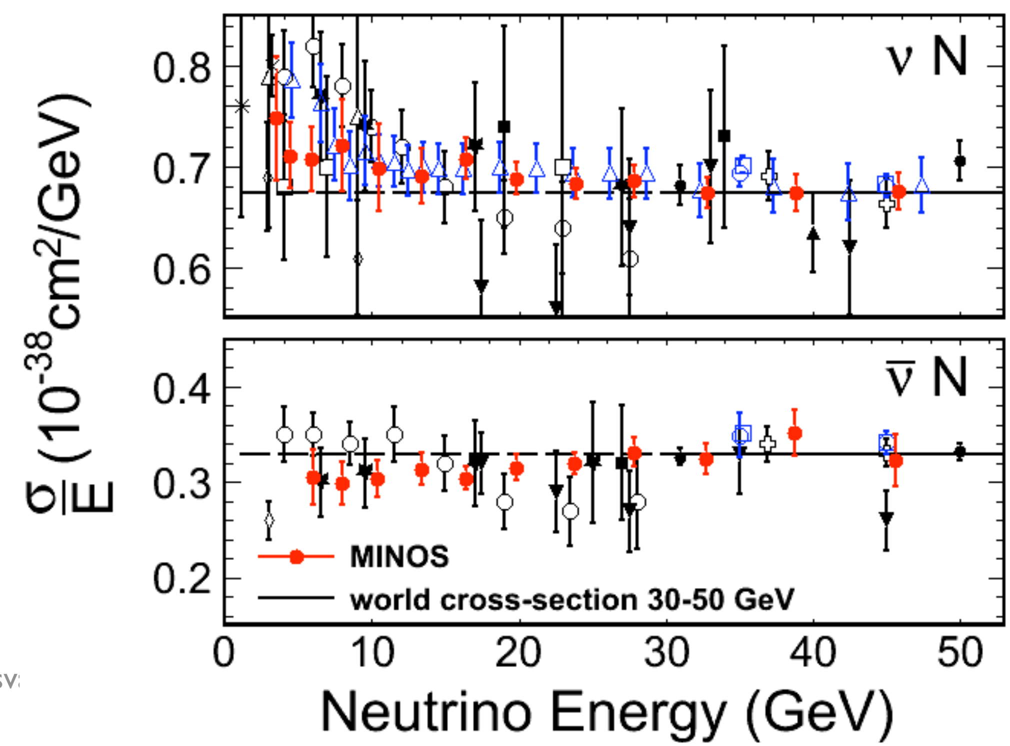
Backup

Making an antineutrino beam

- Hadron production and cross sections conspire to change the shape and normalization of energy spectrum

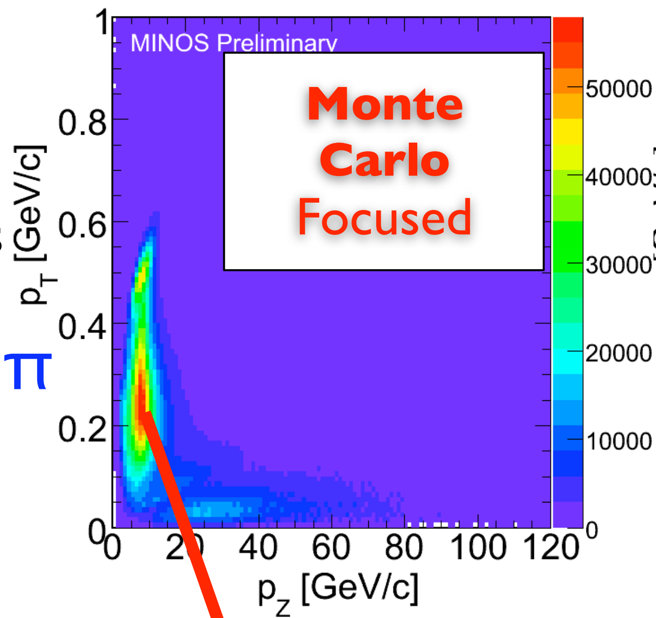
~3x fewer antineutrinos for the same exposure

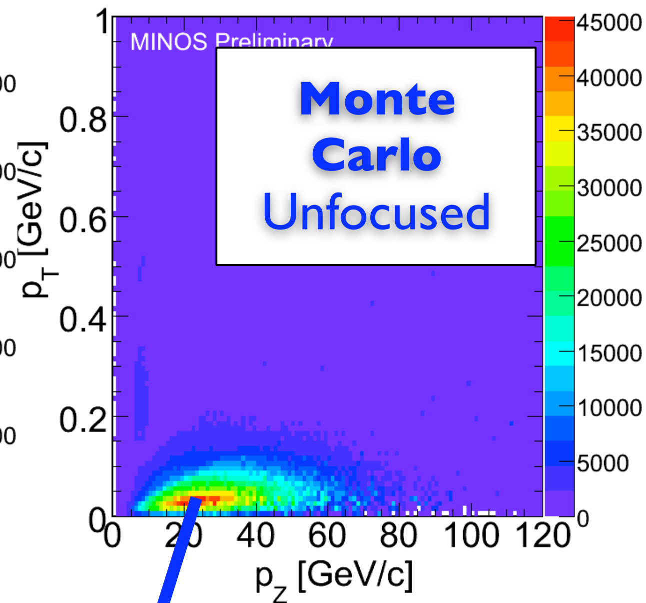


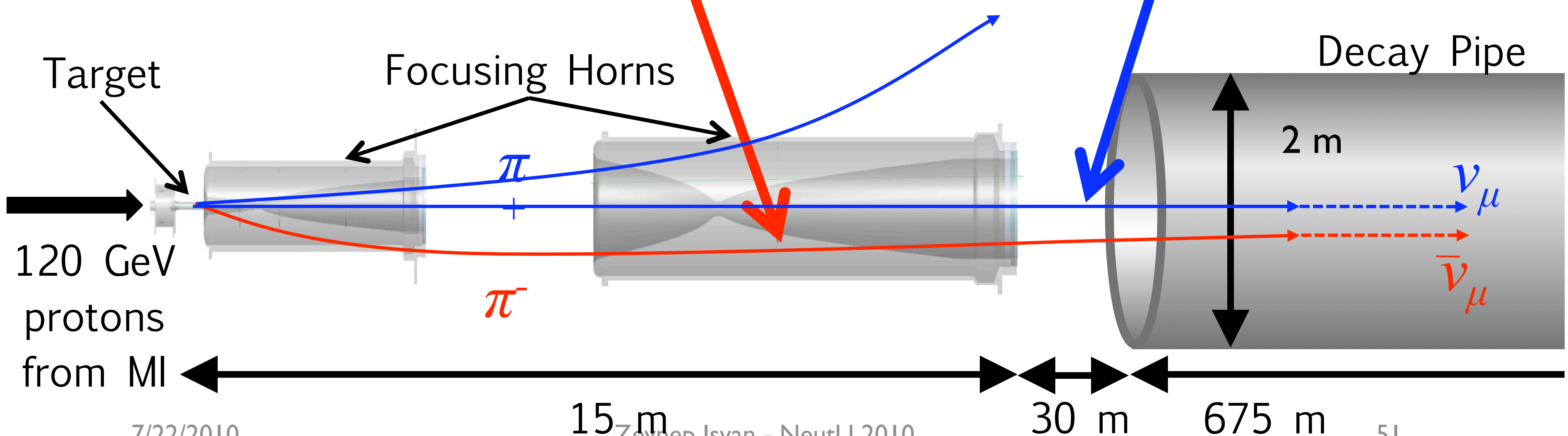


Peak vs. Tail

- $\bar{\nu}_\mu$'s from **high-p_t** π^-'s
  - Focused by horns
- ν_μ's from **low-p_t** π^+'s
  - Pass through horn center

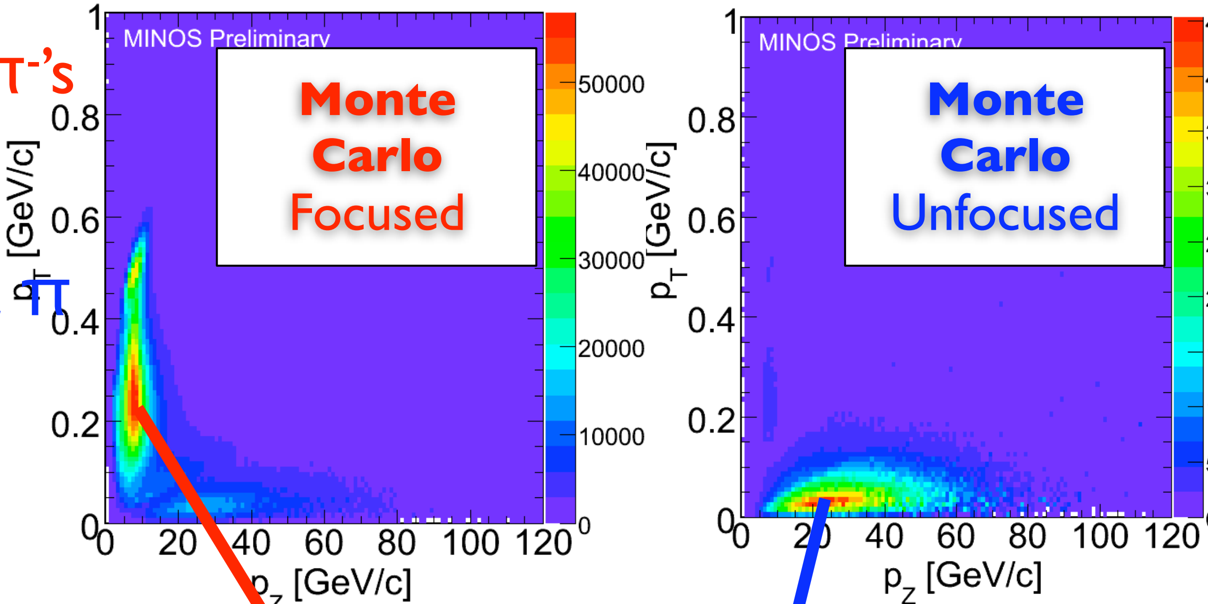


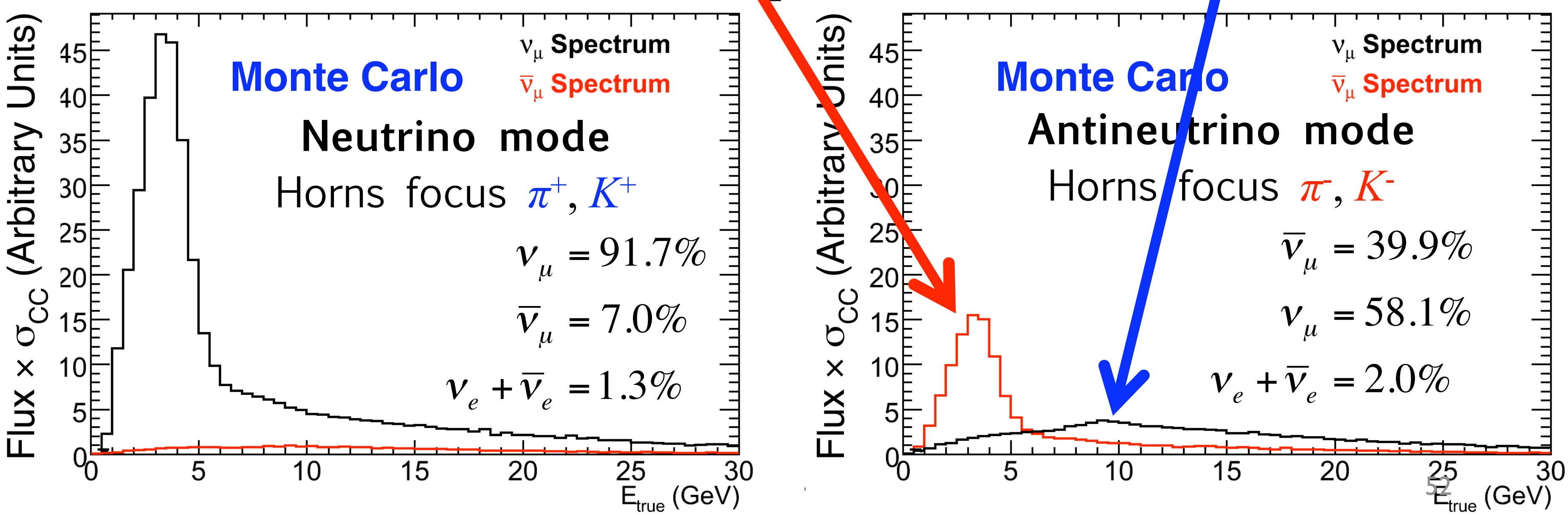




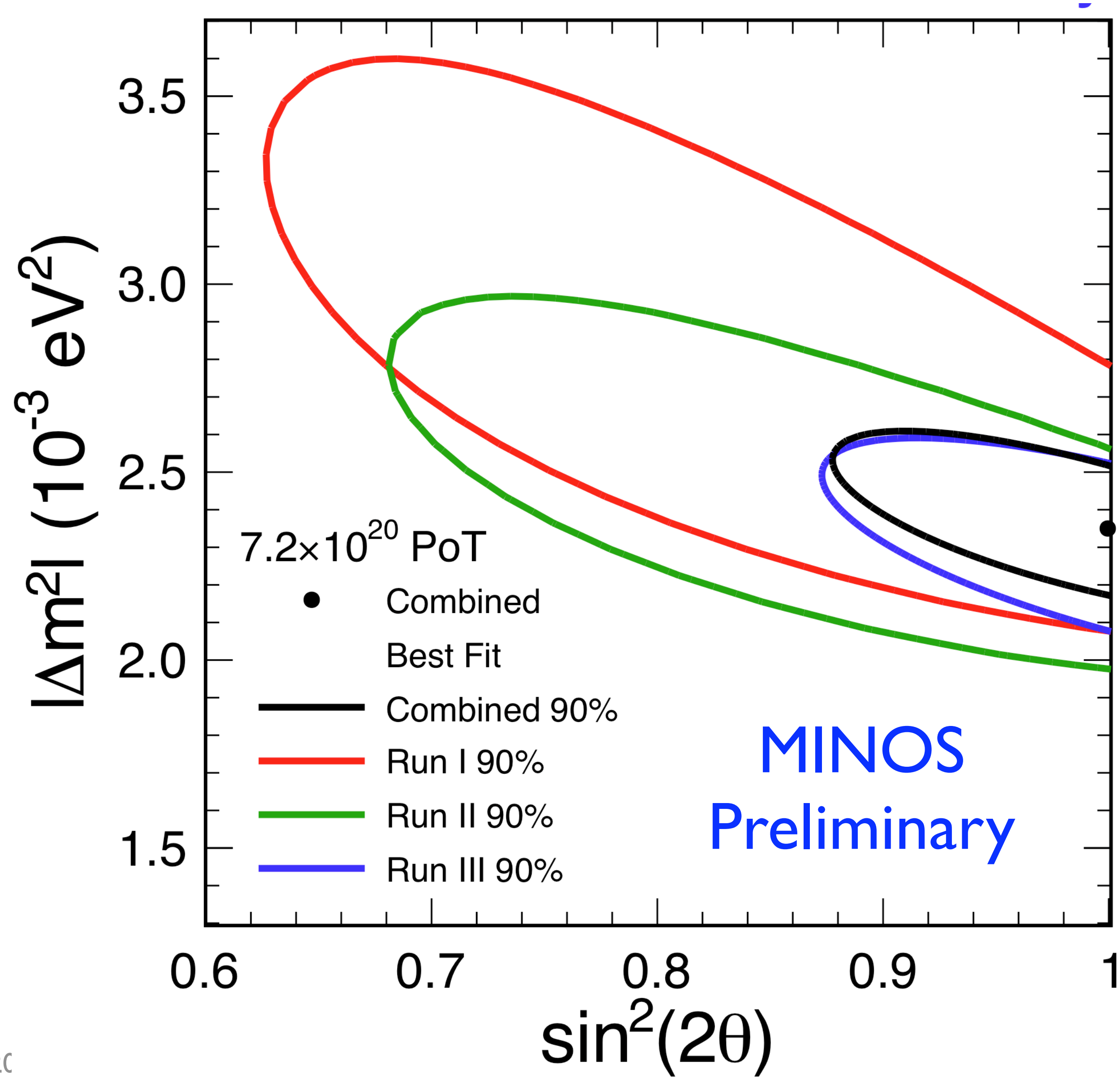
Peak vs. Tail

- $\bar{\nu}_\mu$'s from **low-p_t** π^-'s
  - Focused by horns
- ν_μ's from **high-p_t** π^+'s
  - Pass through horn center

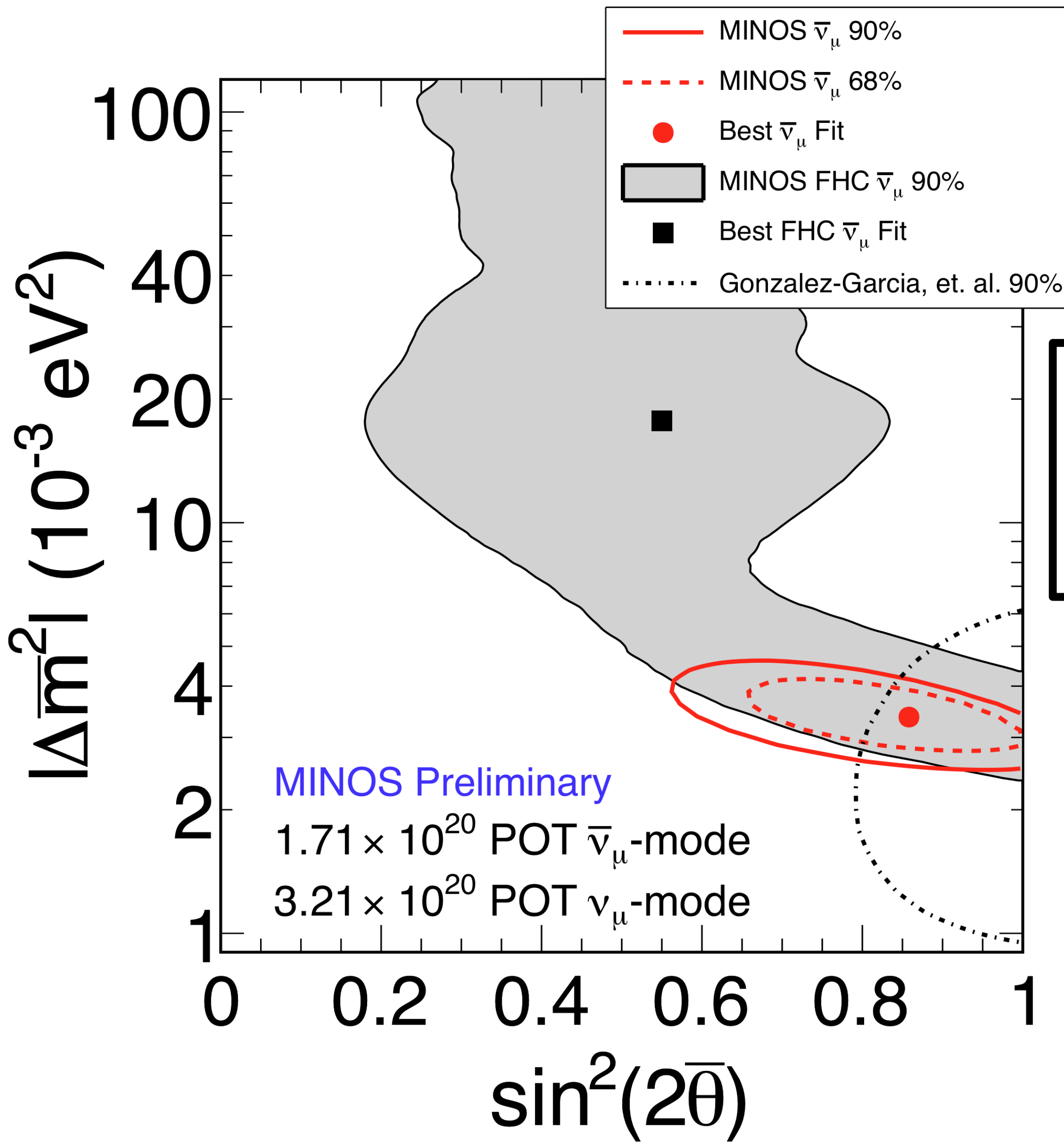




Neutrino Contour by Run



Antineutrino Contour



$$\left|\Delta\overline{m}^2_{atm}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86 \pm 0.11$$

A combined analysis using all antineutrino data is planned.