URA Thesis Award:

Antineutrino Oscillations in the Atmospheric Sector

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Duke University

for work done at

The California Institute of Technology

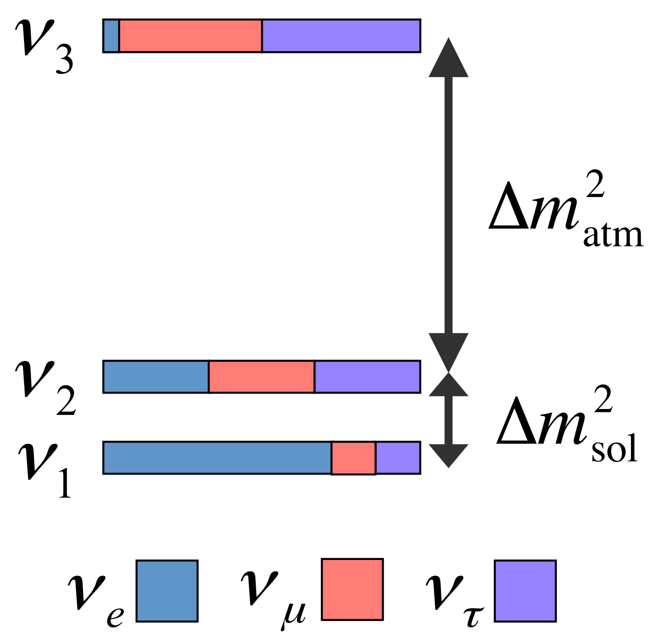
with

The MINOS Collaboration

45th FNAL User's Meeting, June 13th, 2012

The Standard 3-neutrino Picture

- Two mas splittings
  - Large: $\Delta m^2_{atm} \approx \Delta m^2_{23} = 2\times10^{-3}\ \mathrm{eV}^2$
  - Small: $\Delta m^2_{sol} \approx \Delta m^2_{12} = 8\times10^{-5}\ \mathrm{eV}^2$
- Three mixing angles:
  - Atmospheric: $\theta_{23} \approx 45°$ (maximal?)
  - Solar: $\theta_{12} \approx 34°$
  - Reactor: $\theta_{13} \approx 9°$



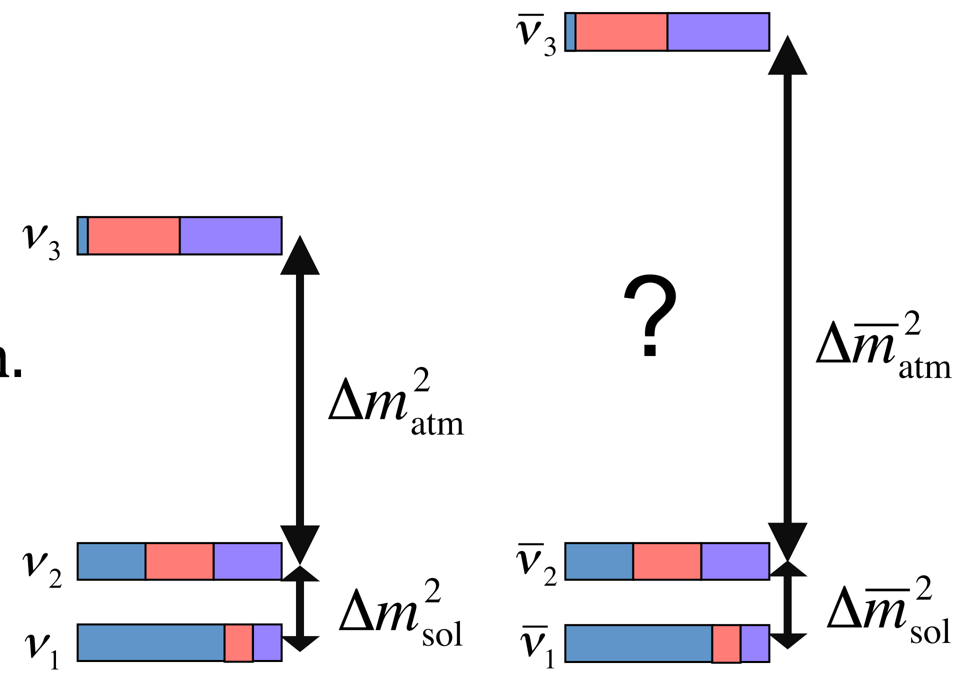
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&&\\ &c_{23}&s_{23}\\ &-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&&s_{13}e^{-i\delta}\\ &1&\\ -s_{13}e^{i\delta}&&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&\\ -s_{12}&c_{12}&\\ &&1\end{pmatrix}\begin{pmatrix}\nu_1\\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

Atmospheric, Accelerator | Reactor, Accelerator | Solar, Reactor

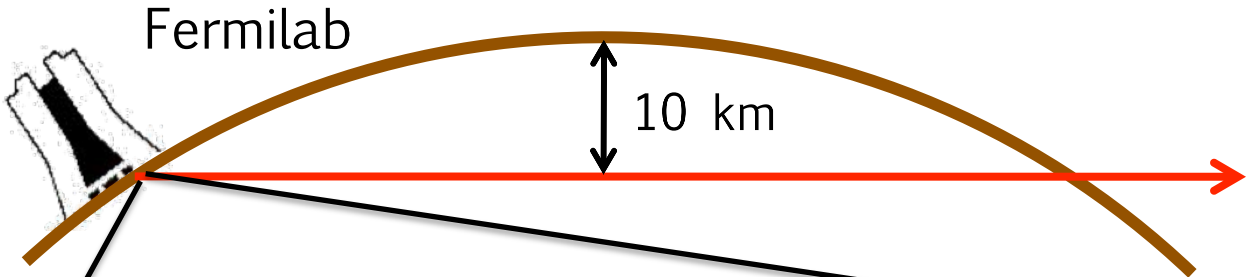
Why study ν_μ and $\bar{\nu}_\mu$?

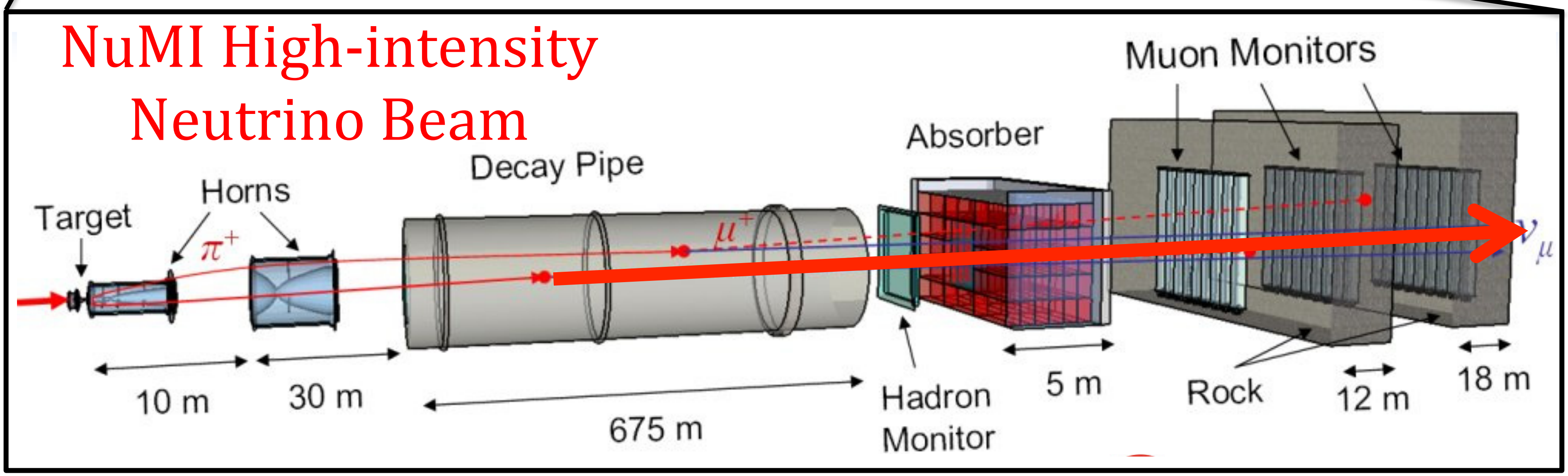
- Standard neutrino model predicts identical oscillations
  - Differences would indicate new physics!
  - Could manifest as different apparent mass-splittings
- Antineutrino parameters are known with much less precision.
  - Only the MINOS experiment that can identify $\bar{\nu}_\mu$ event-by-event
  - Allows a direct measurement of antineutrino oscillations

$$P(\nu_\mu \rightarrow \nu_\mu) \stackrel{?}{=} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

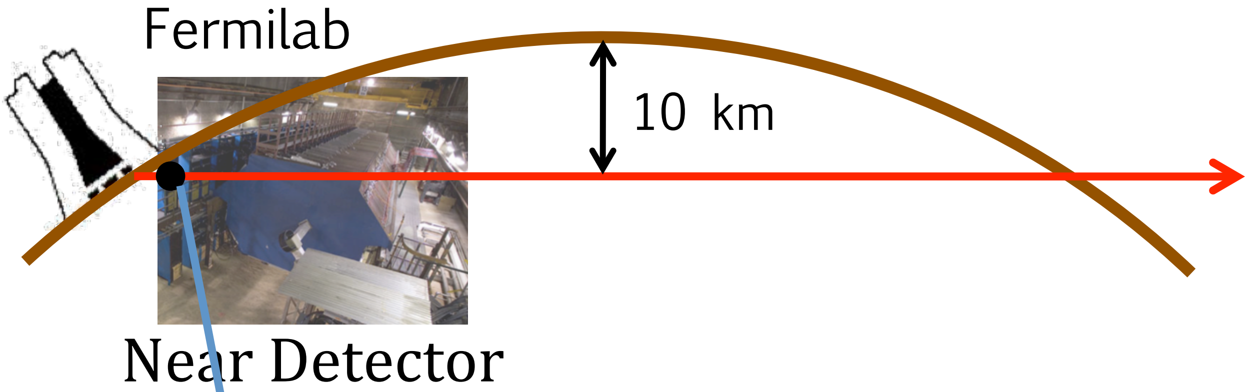


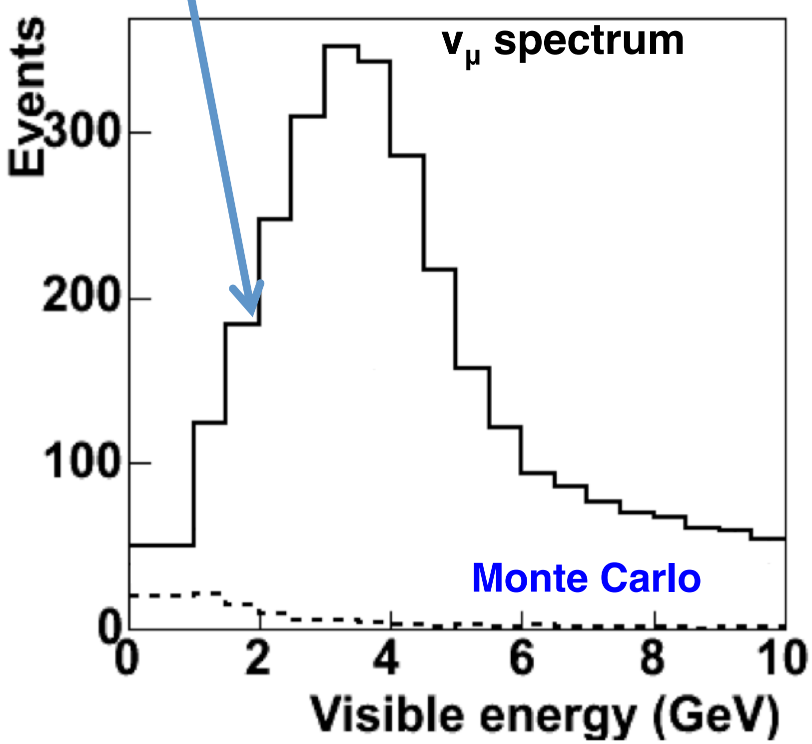
The MINOS Experiment





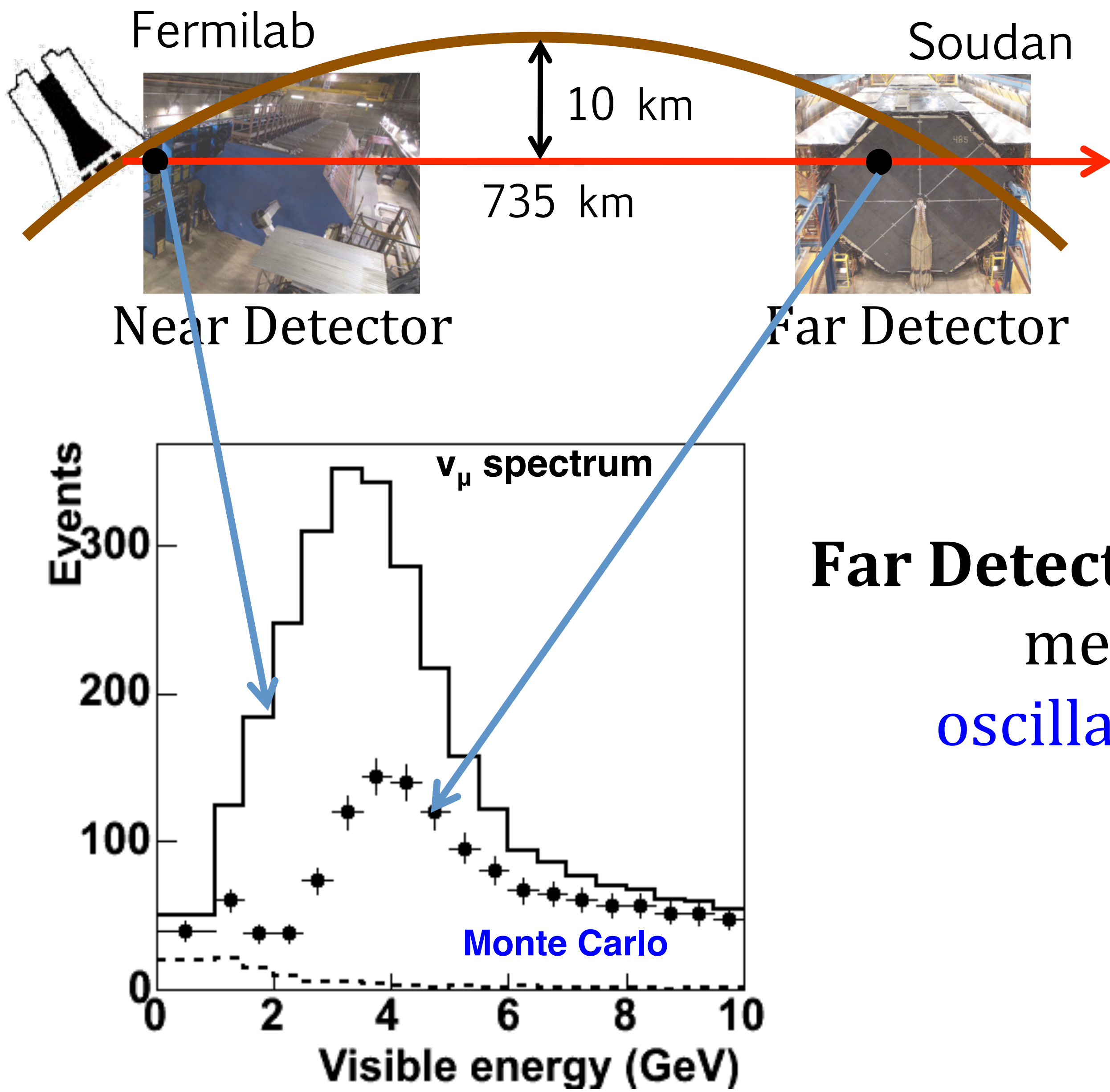
The MINOS Experiment





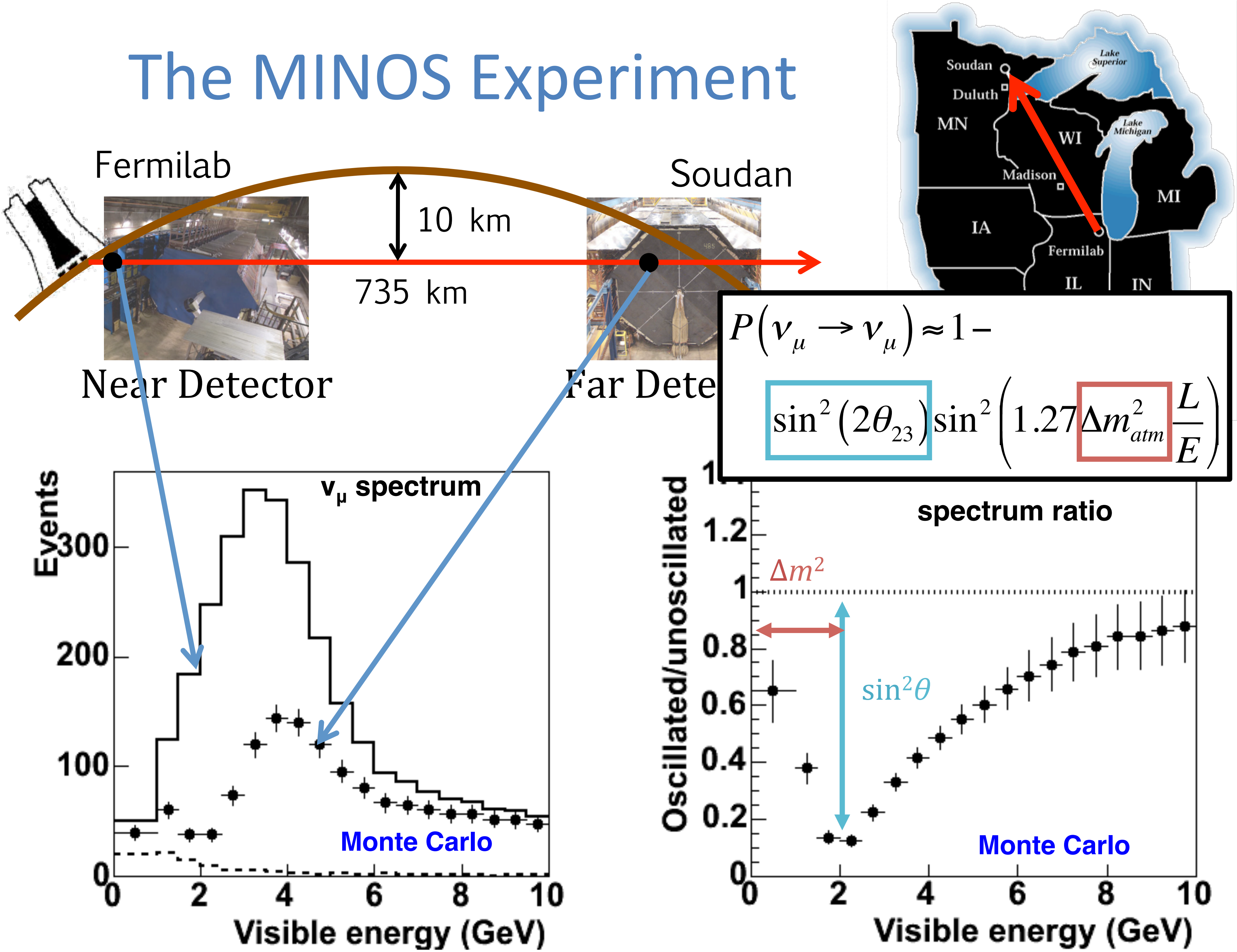
Near Detector at Fermilab measures the initial beam composition and spectrum

The MINOS Experiment



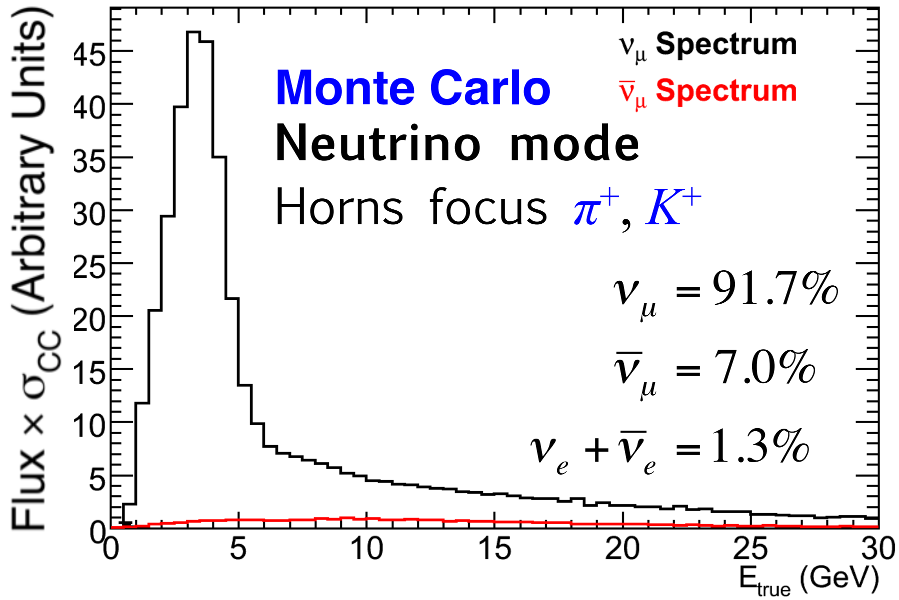
Far Detector in Soudan, MN measures the oscillated spectrum

The MINOS Experiment

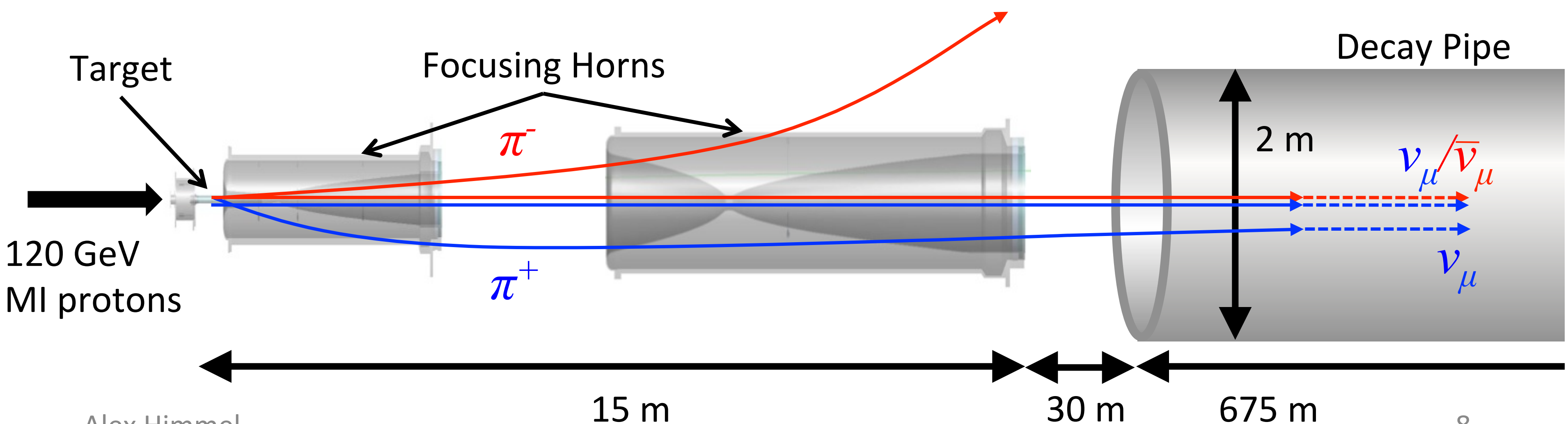


$$P(\nu_\mu \to \nu_\mu) \approx 1 - \boxed{\sin^2(2\theta_{23})} \sin^2\left(1.27 \boxed{\Delta m^2_{atm}} \frac{L}{E}\right)$$

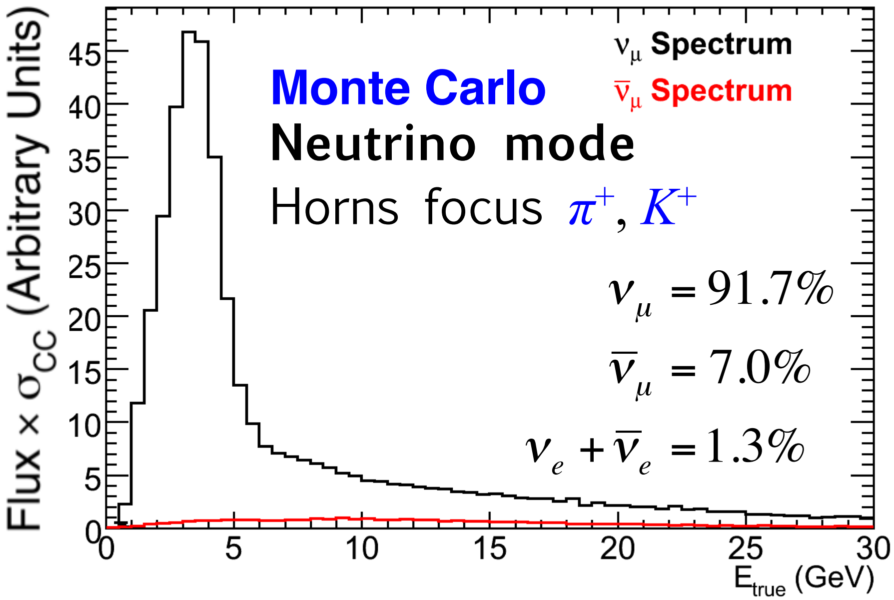
Making a Neutrino Beam

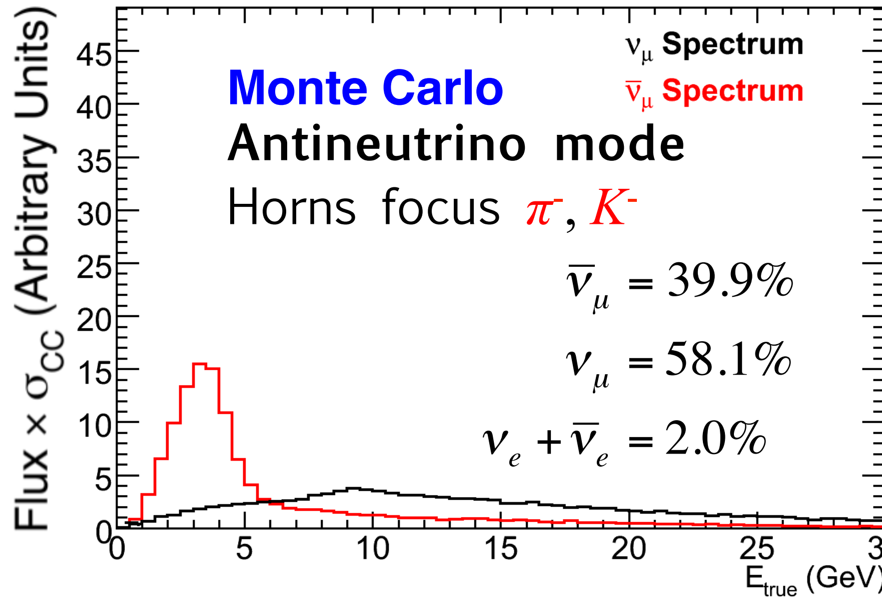


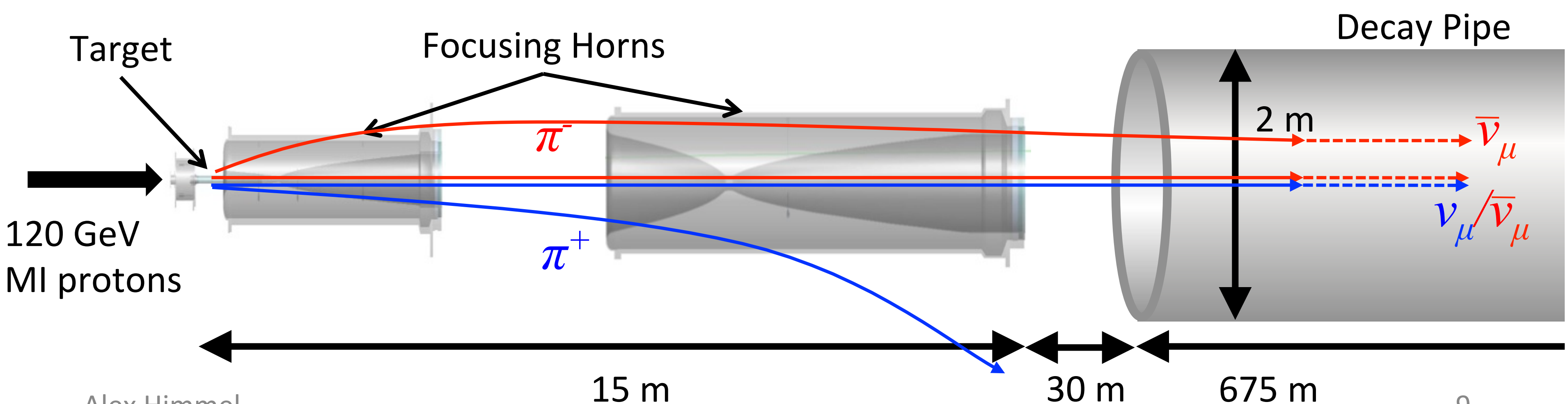
- Horns focus π^+, K^+, which decay into ν_μ
- Higher energy $\bar{\nu}_\mu$ from very forward π^-
- Most of MINOS beam data taken in this configuration



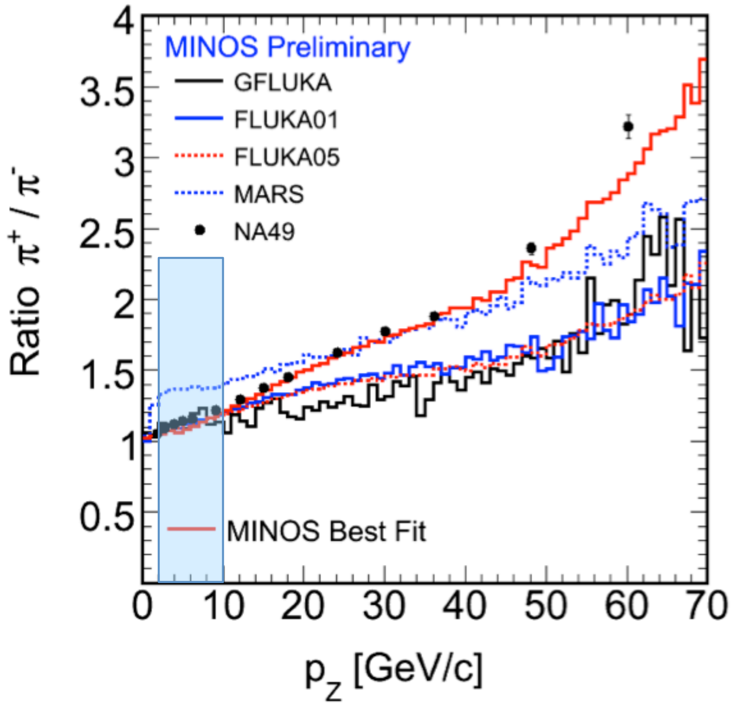
Making an Antineutrino Beam



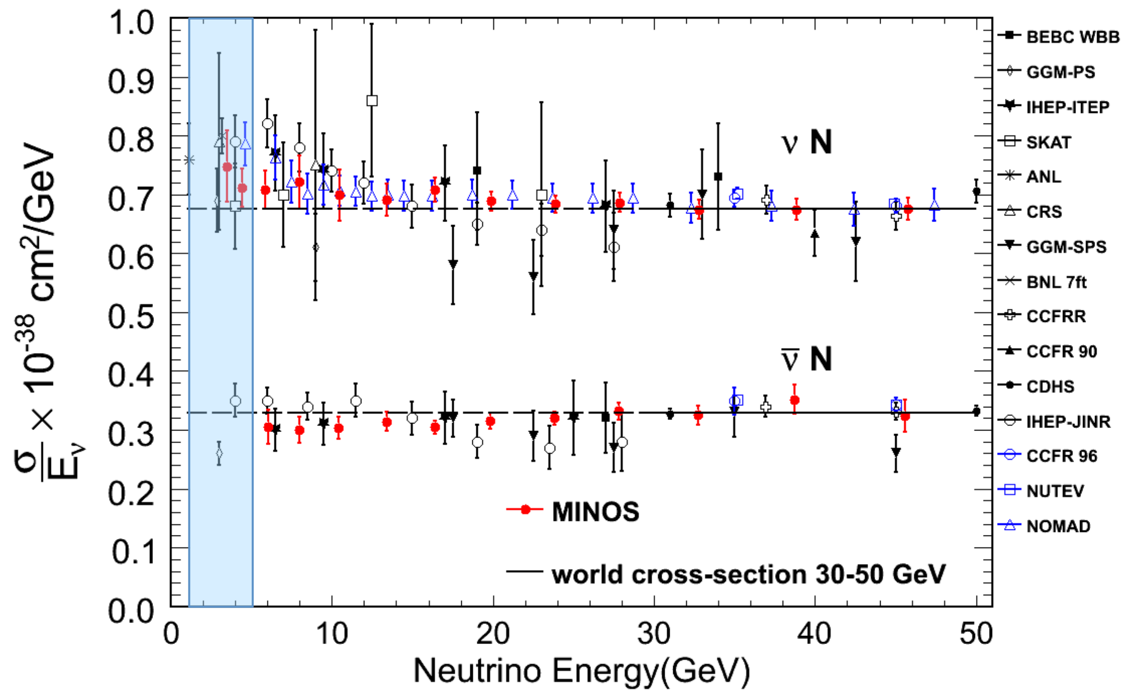




Antineutrino Cross-section



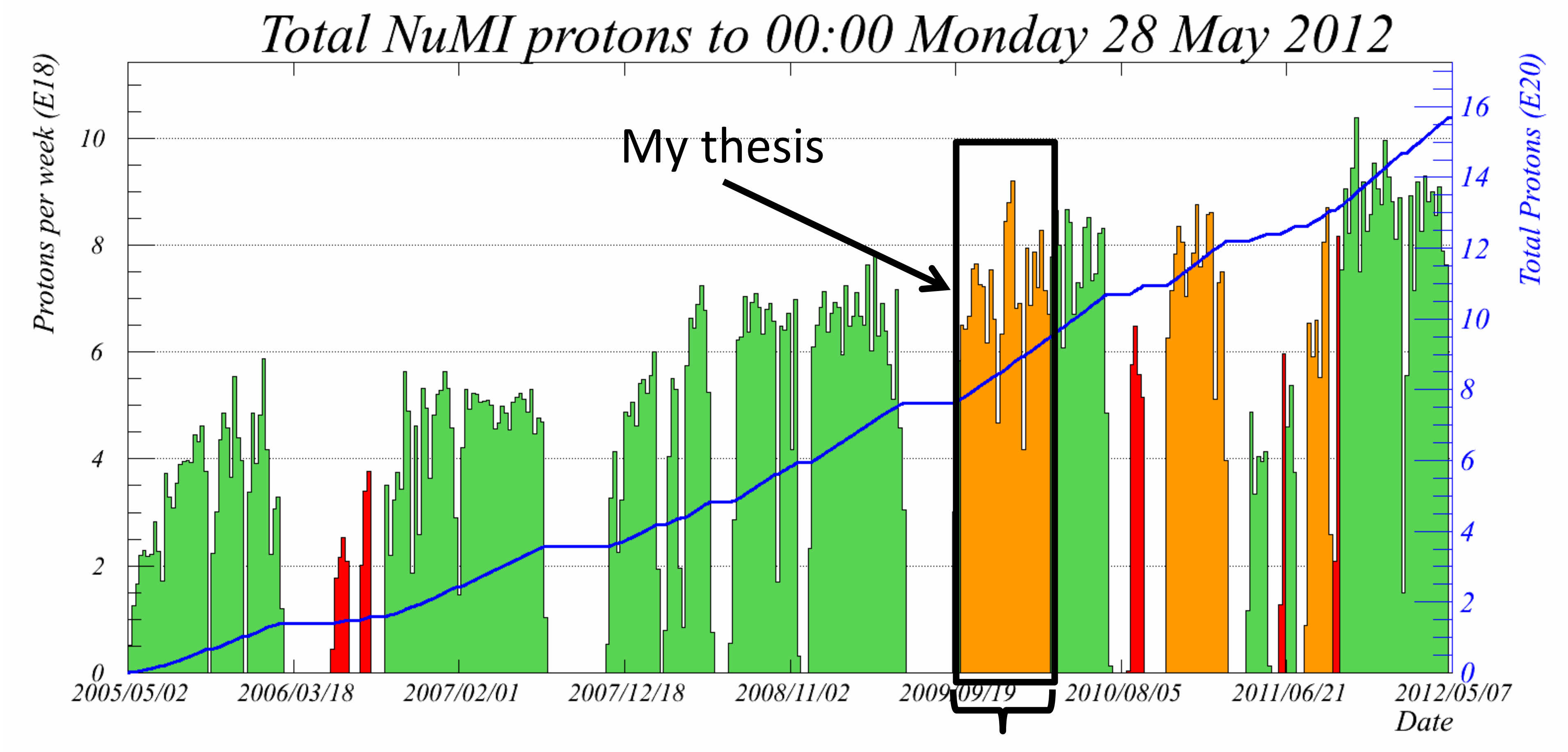
Eur. Phys. J. C 49 897 (2007)



Phys. Rev. D 81 072002 (2010)

- Why is the peak rate ×3 lower?
  - ×1.3 lower π^- production
  - ×2.3 lower interaction cross-section

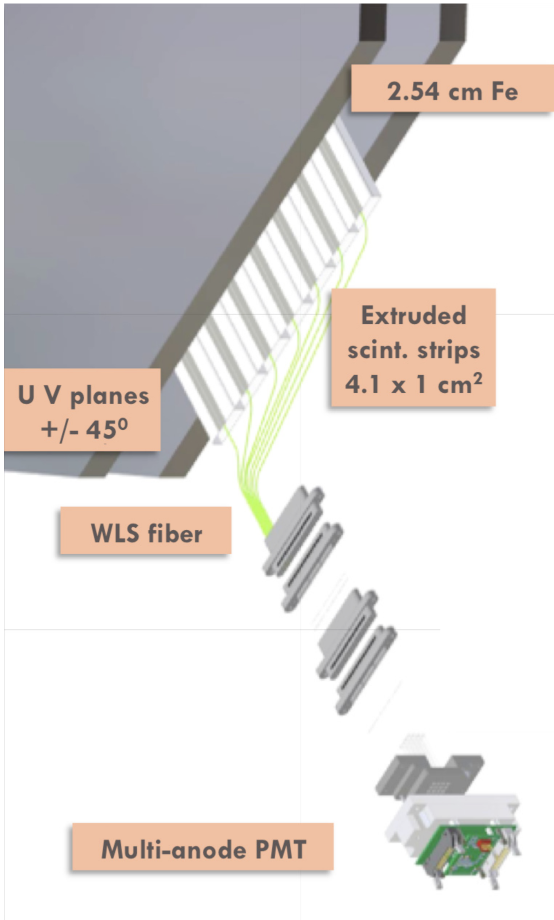
NuMI Beam Performance

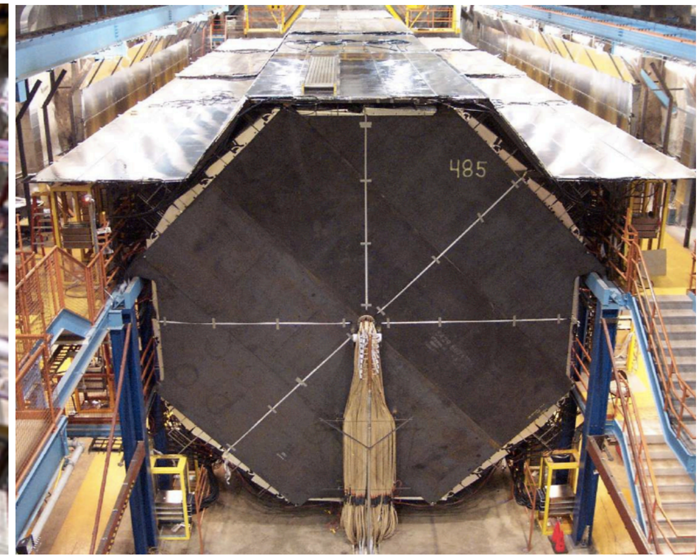


1.71×10^{20} POT

$\bar{\nu}_{\mu}$ mode

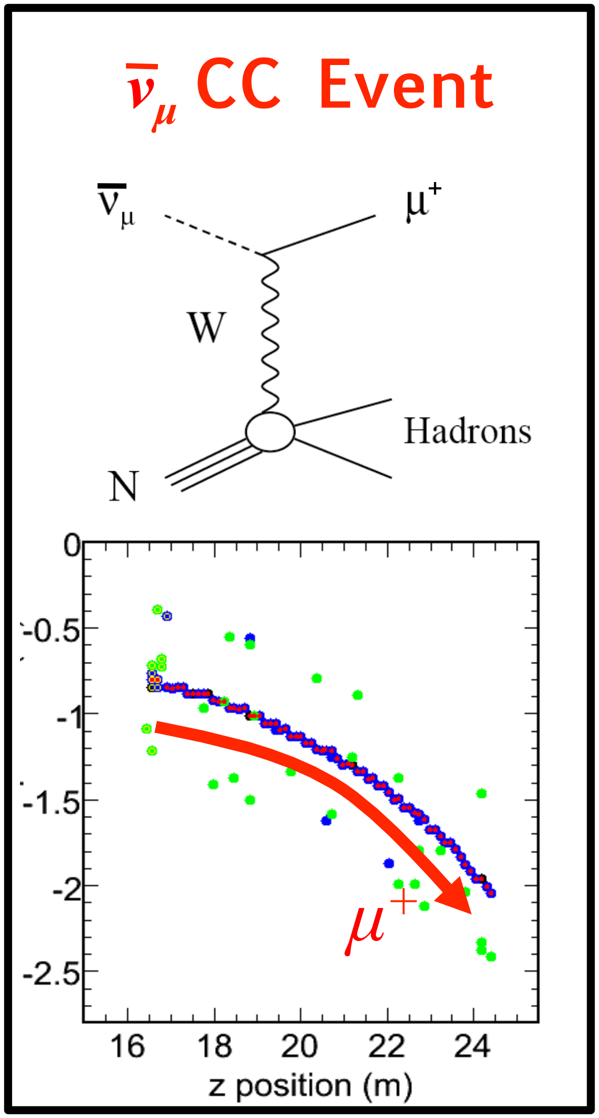
MINOS Detectors



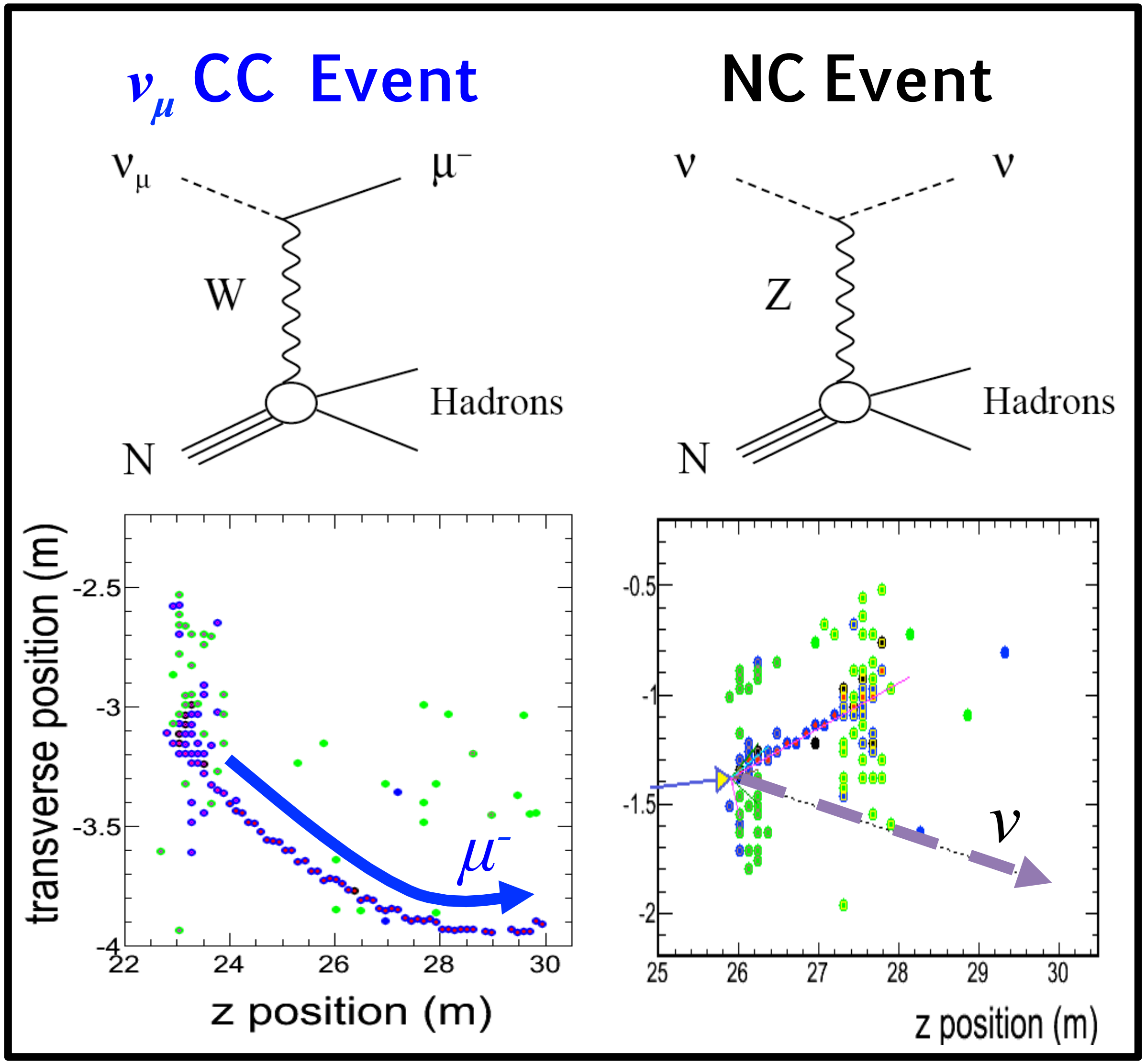


- Alternating layers of steel and plastic scintillator
- Design as similar as possible to minimize systematics
- Event-by-event identification of μ^+/μ^- thanks to 1.3 T magnetic field
- 980 ton Near Detector, 5.4 kiloton Far Detector

Signal



Backgrounds

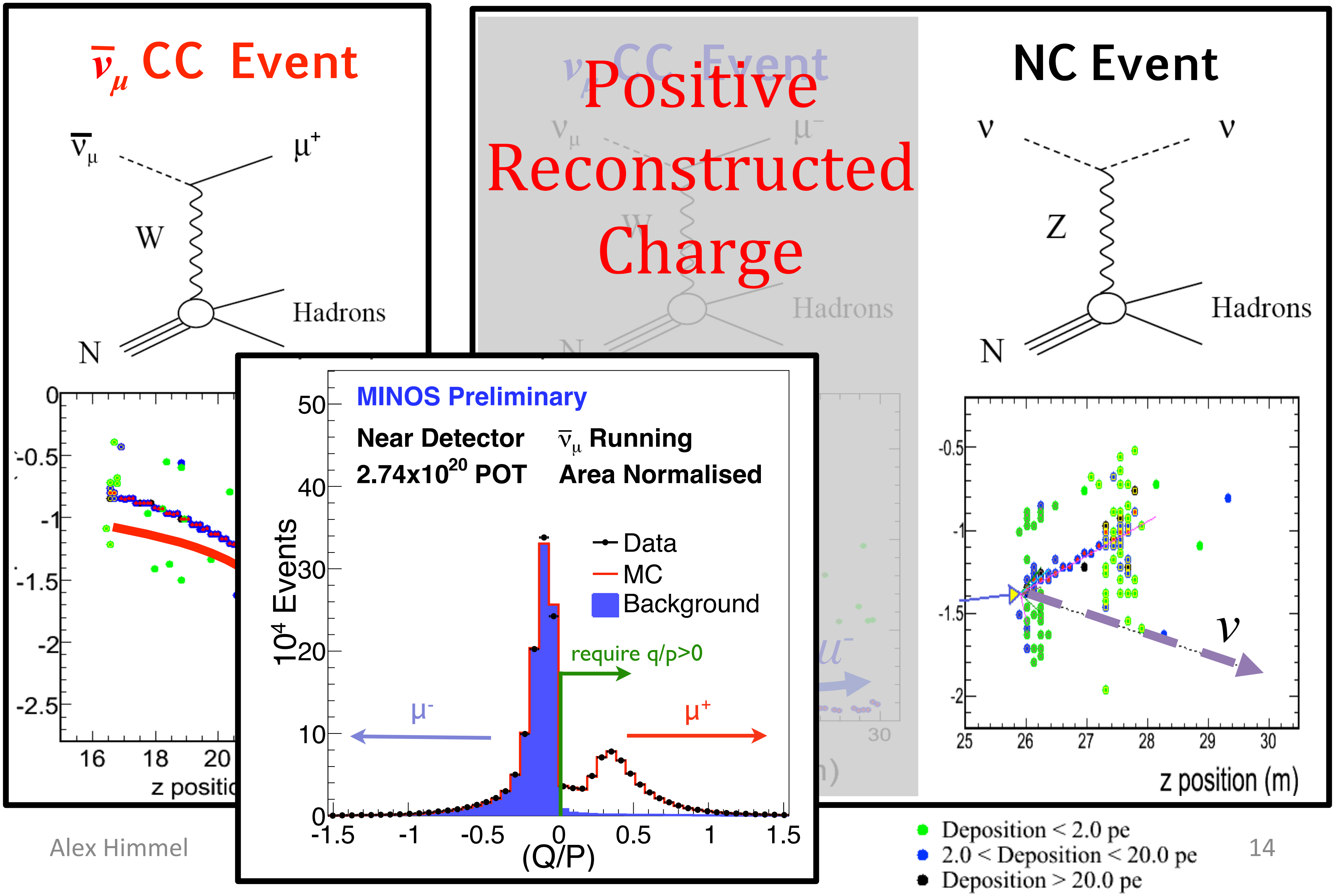


Simulated Events

- Deposition < 2.0 pe
- 2.0 < Deposition < 20.0 pe
- Deposition > 20.0 pe

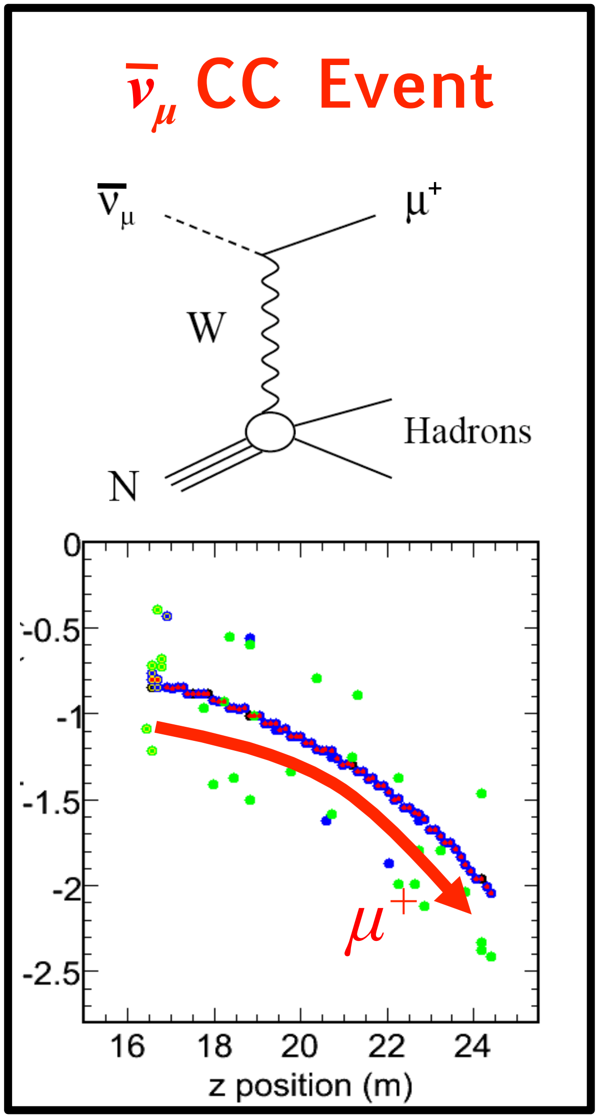
Signal

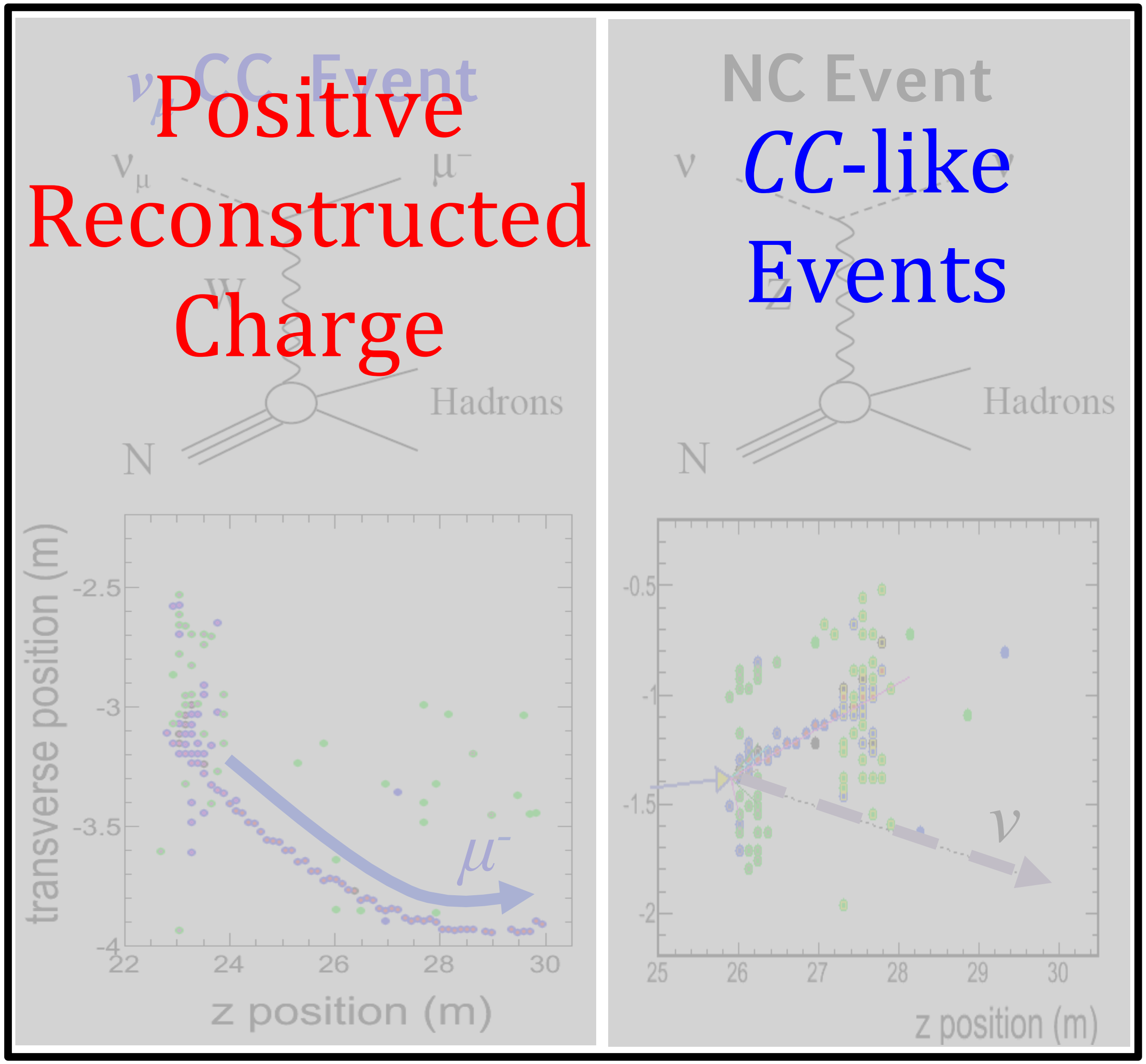
Backgrounds



Signal

Backgrounds





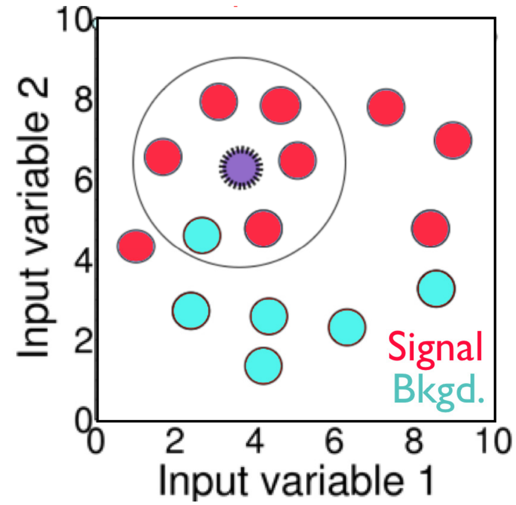
- Deposition < 2.0 pe
- 2.0 < Deposition < 20.0 pe
- Deposition > 20.0 pe

Simulated Events

Selecting Charge Currents

CC/NC Selector

- kNN Algorithm
  - Measure “distance” to MC events
  - Classify on fraction of closest that are signal
- Input Variables
  - Track Length
  - Transverse energy profile
  - 2 dE/dx-like variables



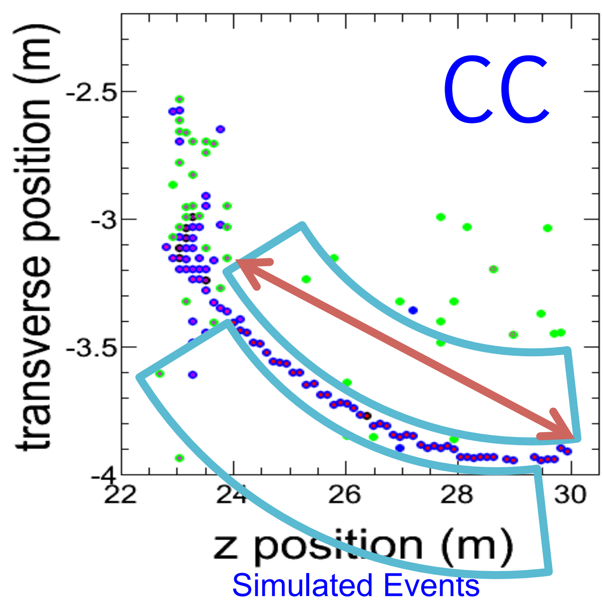
2-Variable Example

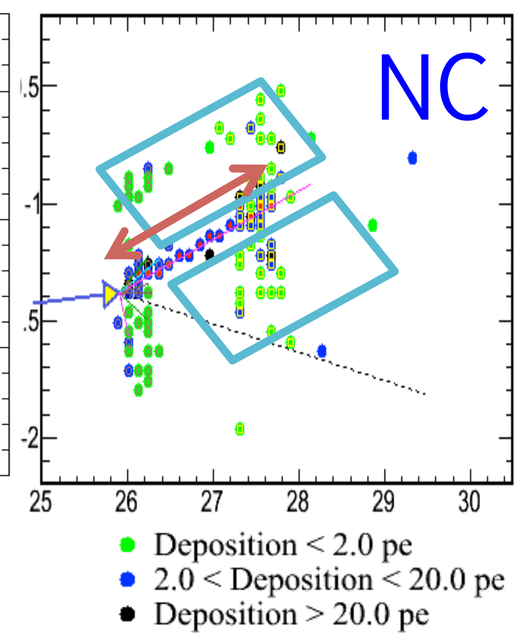
Input Event

5 signal

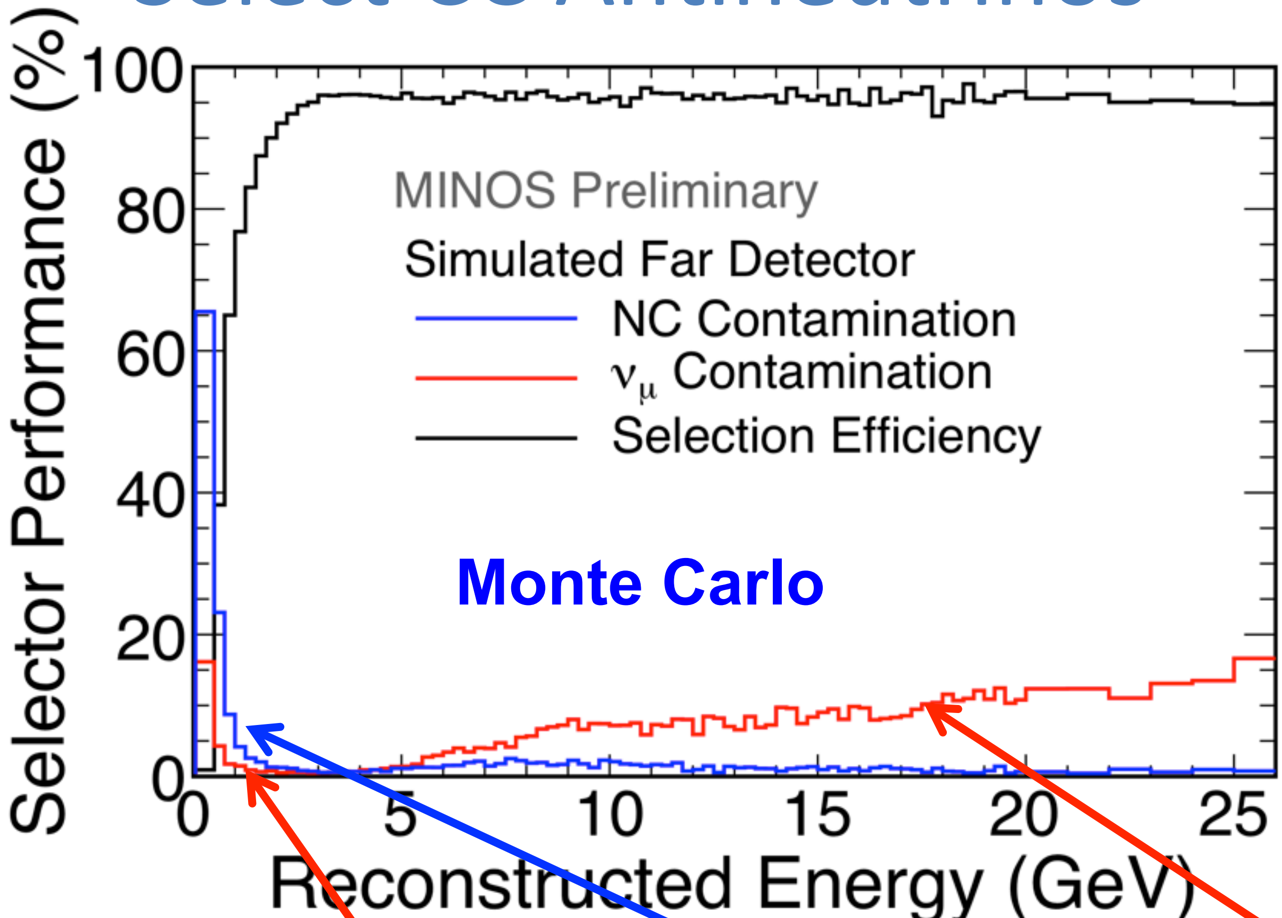
1 background

$\mathrm{kNN_{ID}} = 5/6$





Select CC Antineutrinos



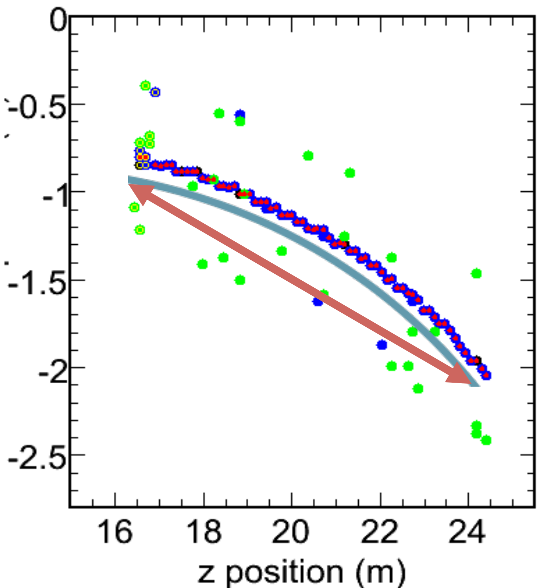
3 remaining Backgrounds:

ν_μCC with a track too short to identify the charge

NC with a fake muon track

ν_μCC with a track too straight to identify the charge

Near Detector Spectrum



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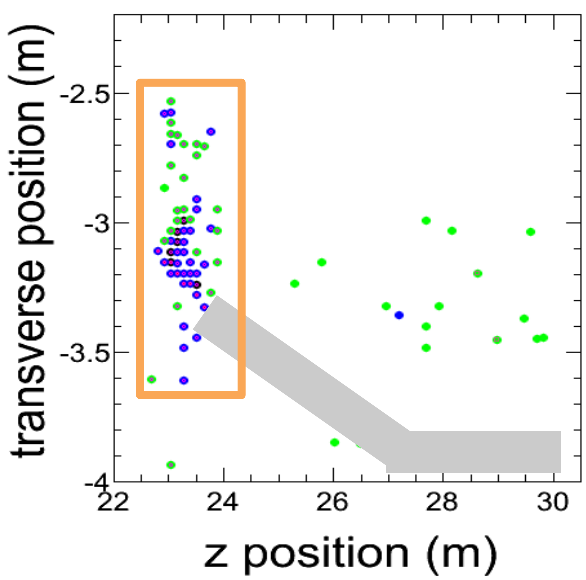

Reconstruct the neutrino energy:

- Muon Track
  - Range (contained)
  - Curvature (exiting)
- Hadronic Shower
  - Calorimetry

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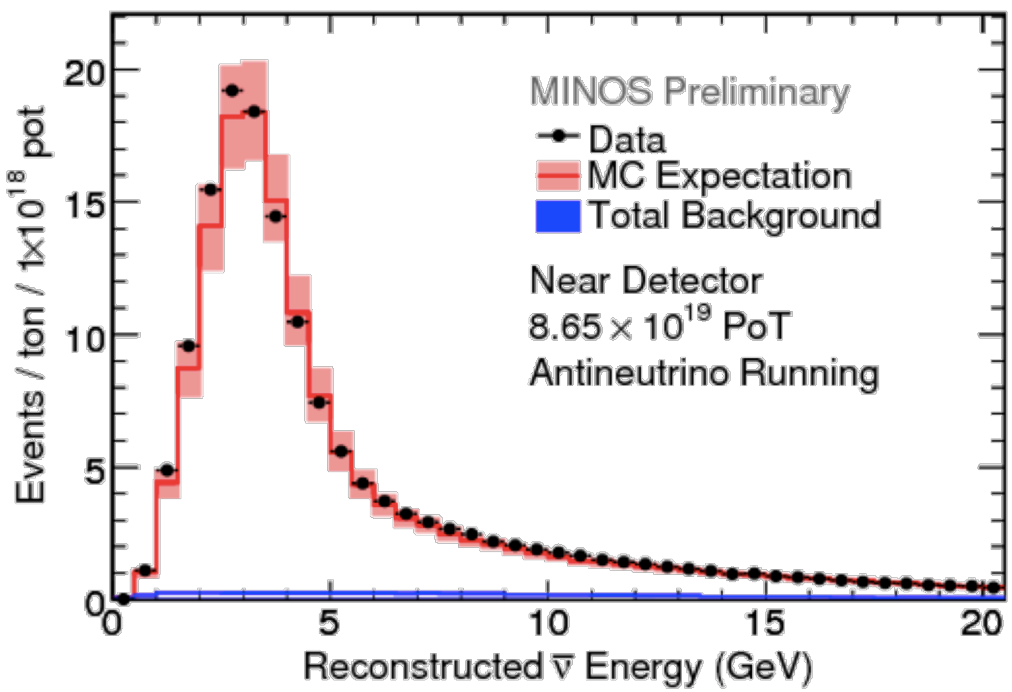
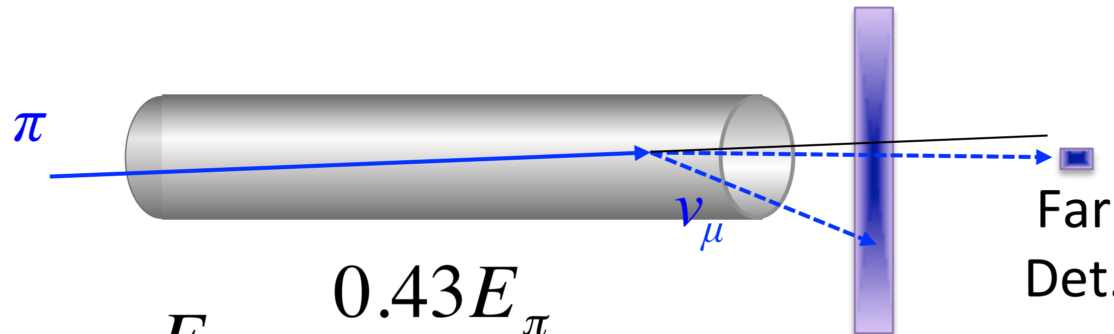
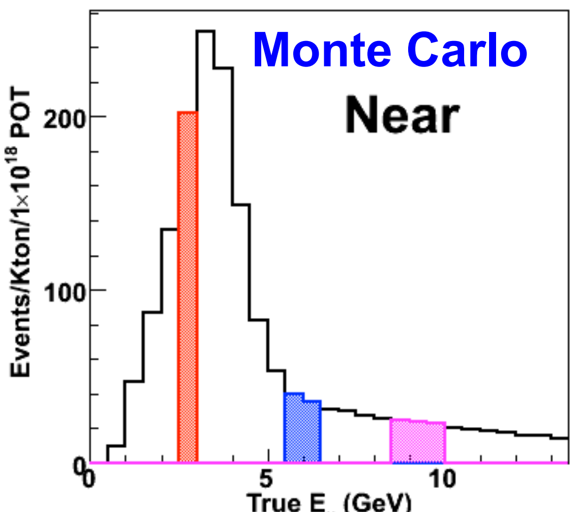


Near-to-Far Extrapolation

- The Near Detector and Far Detector spectra are not identical.
- Use a matrix to encode:
  - beamline geometry
  - decay kinematics



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



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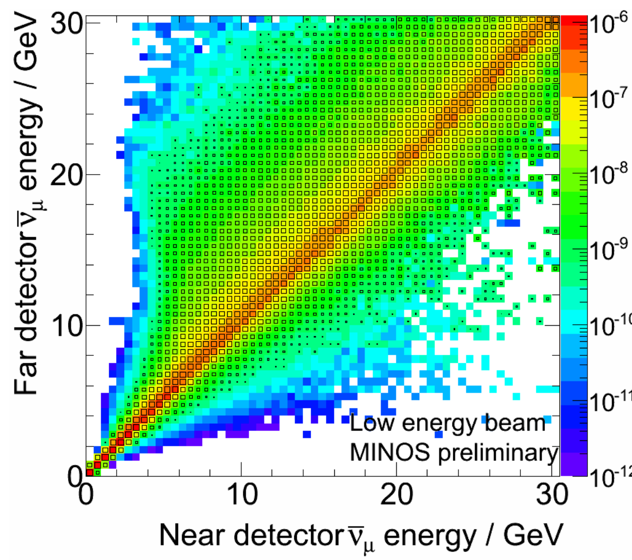

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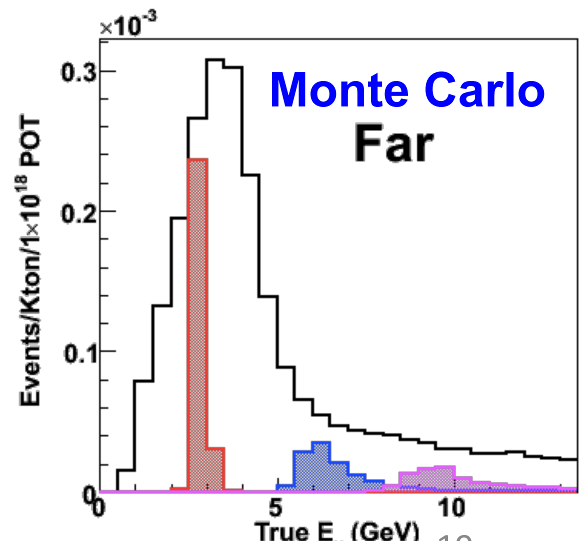
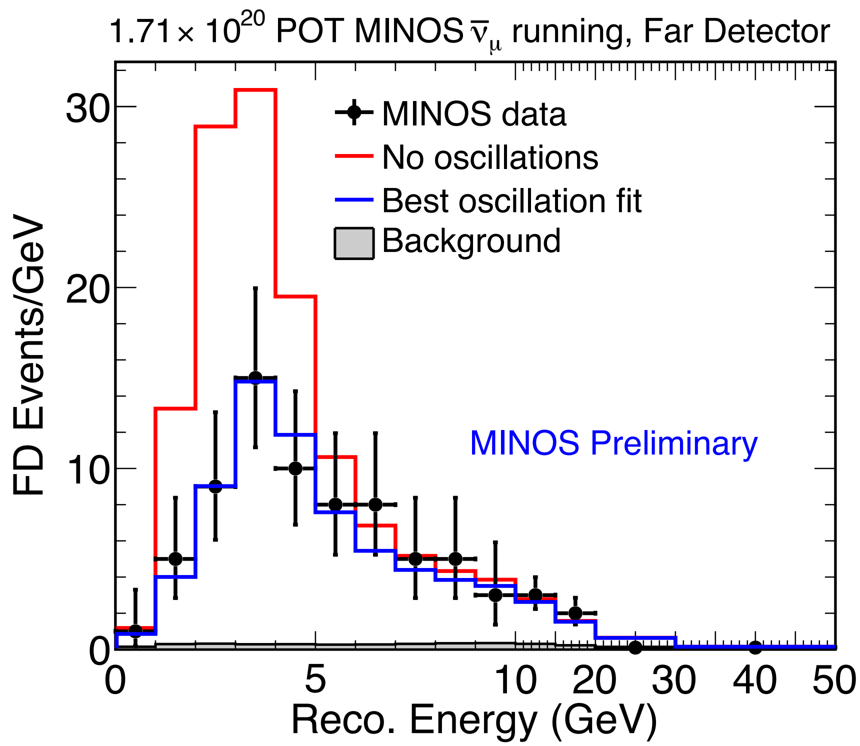
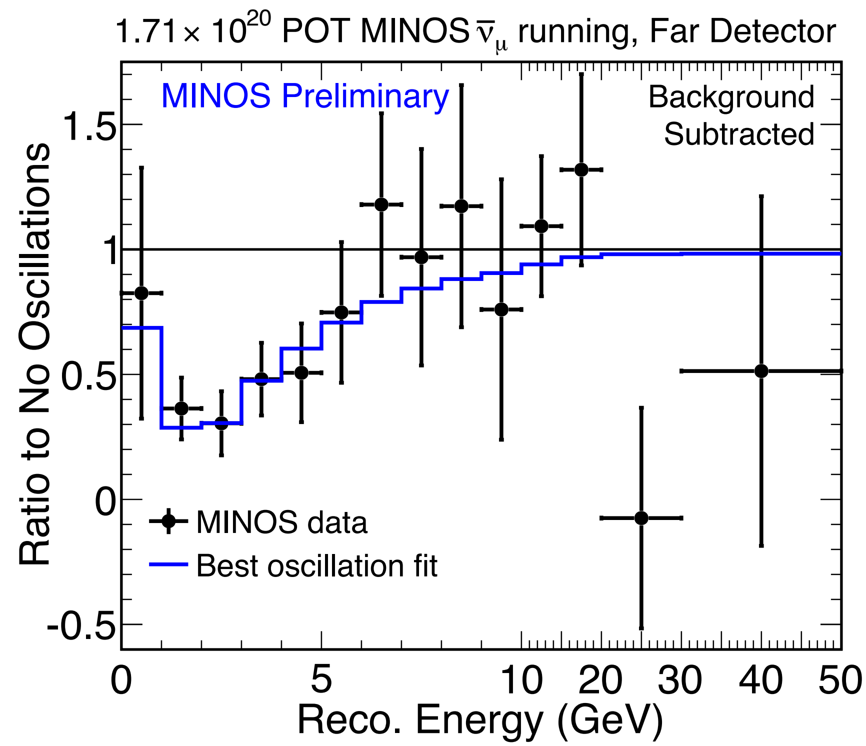


Far Detector Data





➔ **155** expected without oscillations

➔ **97** observed events

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

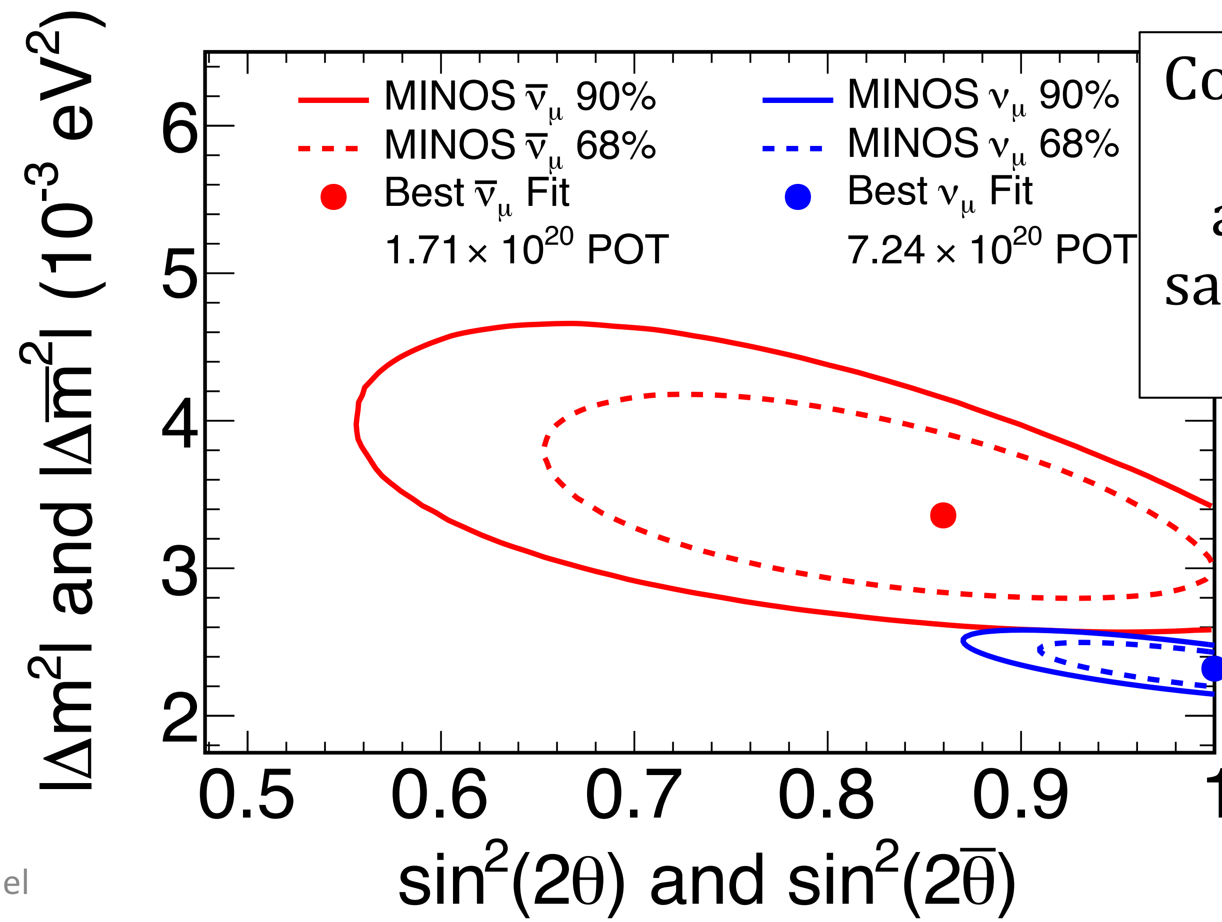
Neutrinos and Antineutrinos

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

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

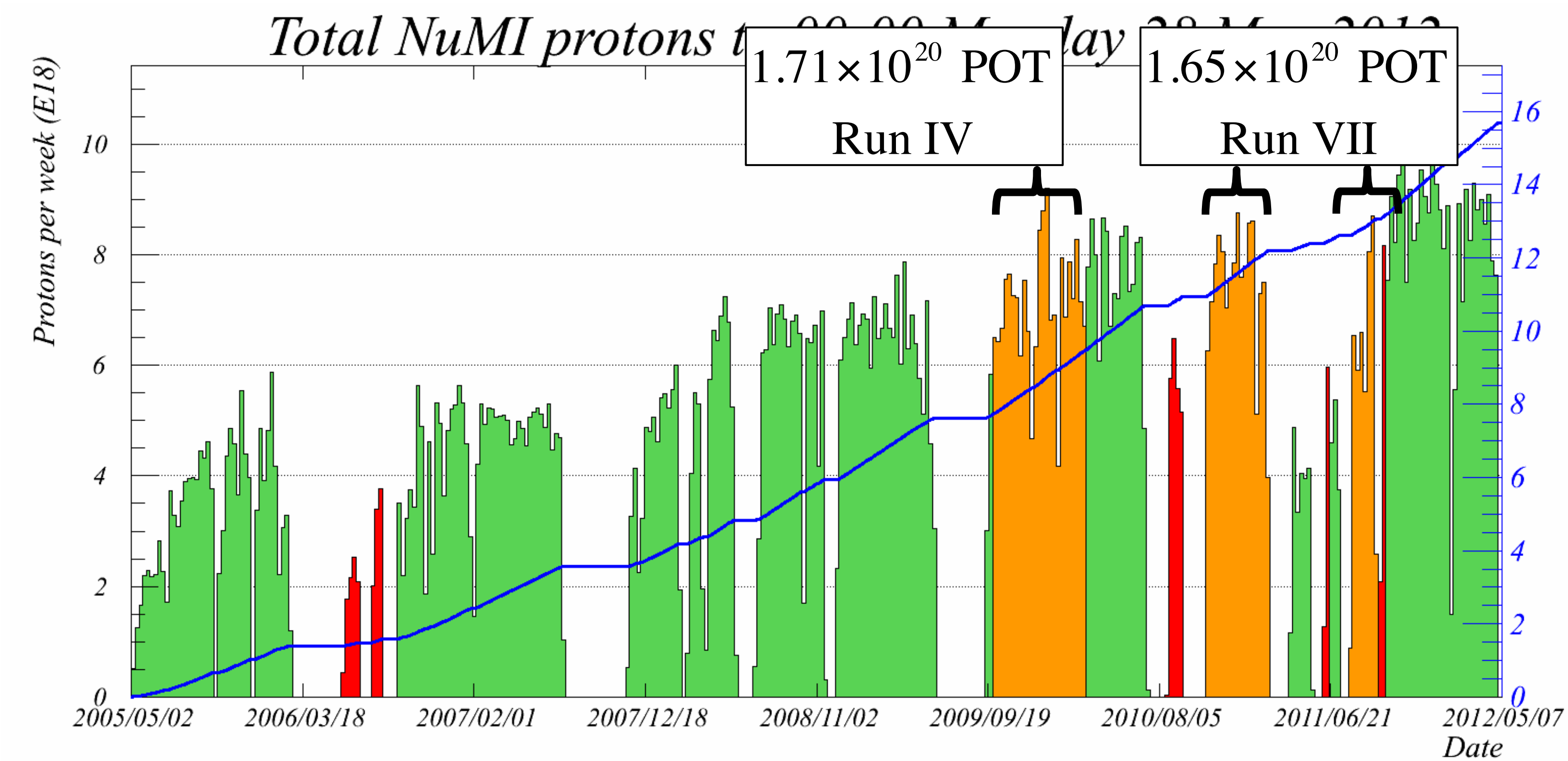
$$\left|\Delta m^2_{atm}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \text{eV}^2$$

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



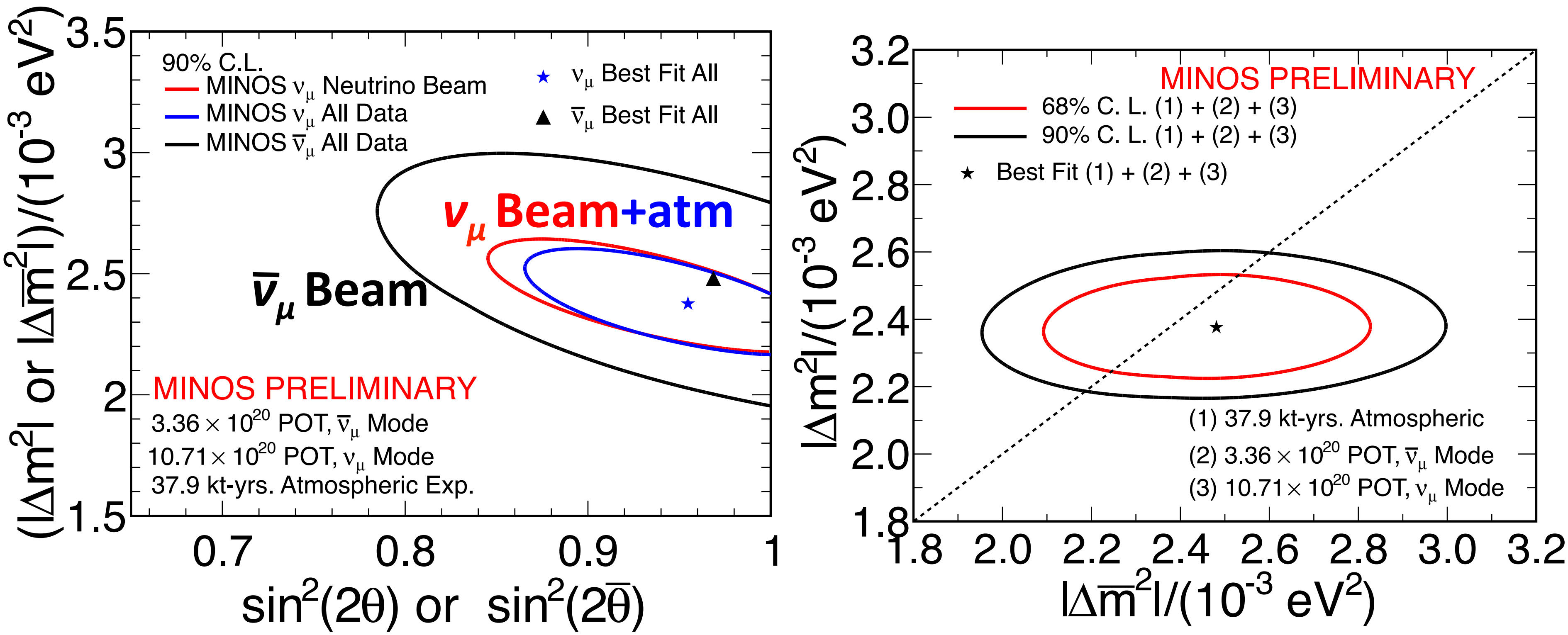
Consistent at the 2% level assuming the same underlying parameters.

New Results



- Since that time, MINOS has accumulated an additional 1.65×10^{20} POT
- New analysis incorporates
  - Remove ND tracks likely to have a failed reconstruction
  - Improved shower resolution
  - Atmospheric neutrino samples included

New Results



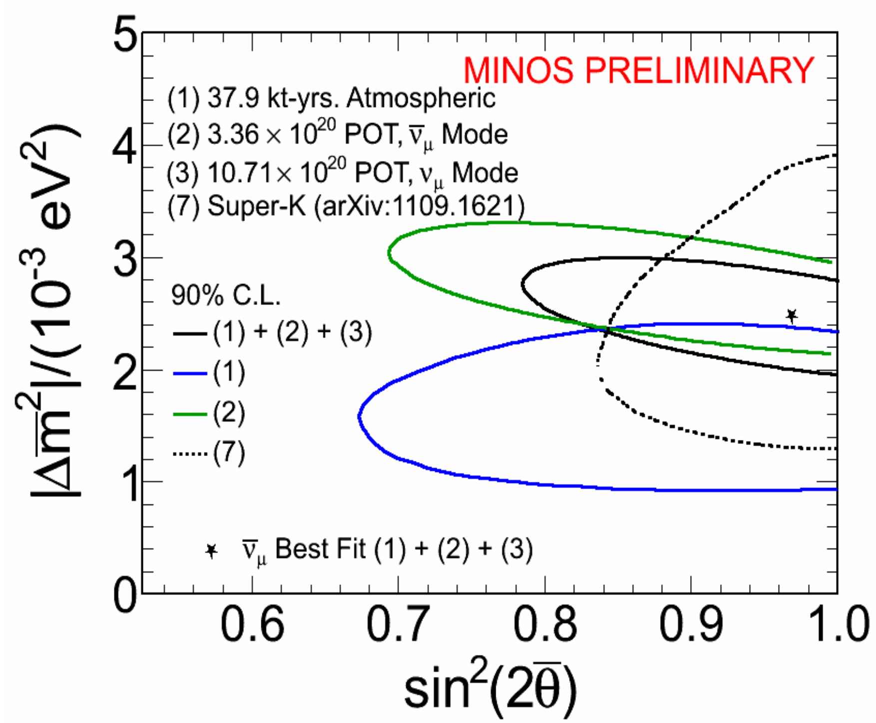
- Final MINOS results presented at Neutrino 2012 show no tension between neutrinos and antineutrinos

Conclusions

- MINOS made the first direct, precision measurement of antineutrino oscillations using a dedicated antineutrino run
- The 1.71×10^{20} POT antineutrino measurement showed some tension with neutrinos (p=2%)
- With an additional 1.65×10^{20} POT and analysis improvements, neutrino and antineutrino parameters are no longer in tension
- Thanks to all my MINOS colleagues, my thesis advisor Harvey Newman, and my many unofficial advisors

MINOS full-exposure results neutrinos vs antineutrinos

Extended fit allows different oscillation parameters for neutrinos and antineutrinos, and confidence limits are placed on the antineutrino oscillation parameters



$$\left|\Delta\bar{m}^2\right| = 2.48^{+0.22}_{-0.27} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.83 \text{ (90\% C.L.)}$$

$$\left|\Delta m^2\right| = 2.39^{+0.09}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

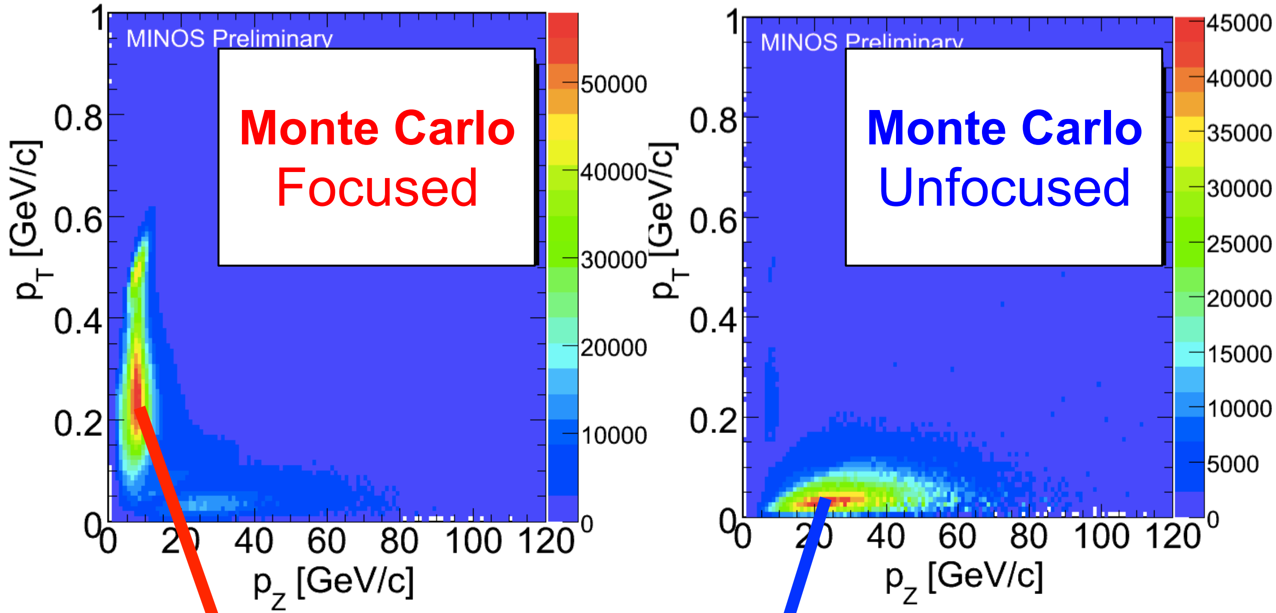
$$\sin^2(2\theta) = 0.957^{+0.035}_{-0.036}$$

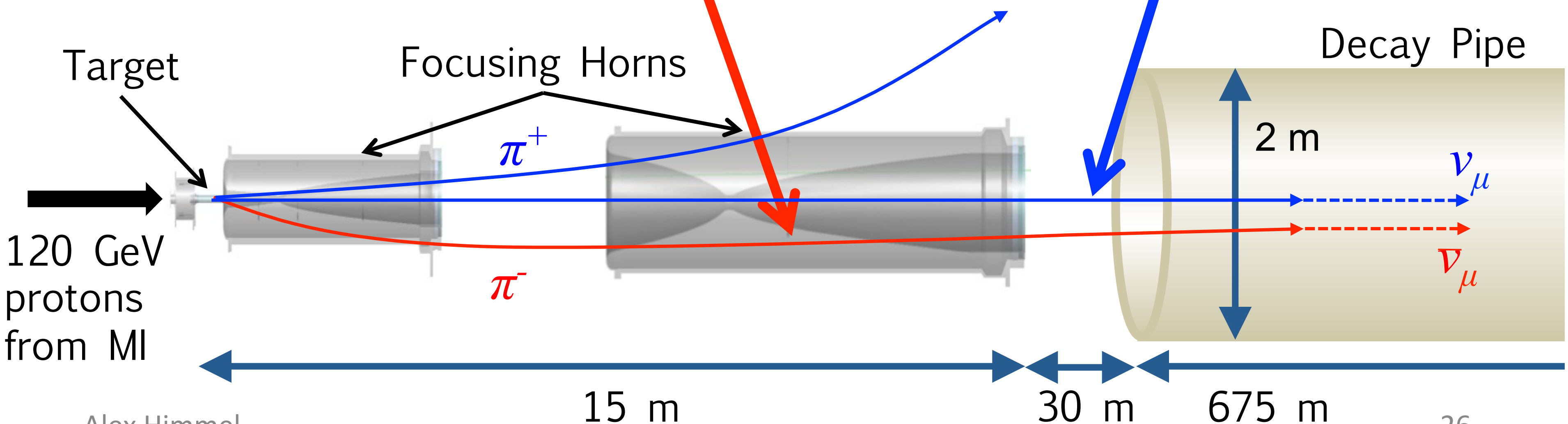
$$\sin^2(2\theta) > 0.90 \text{ (90\% C.L.)}$$

The new data resolves the tension between neutrino & antineutrino parameters

Peak vs. Tail

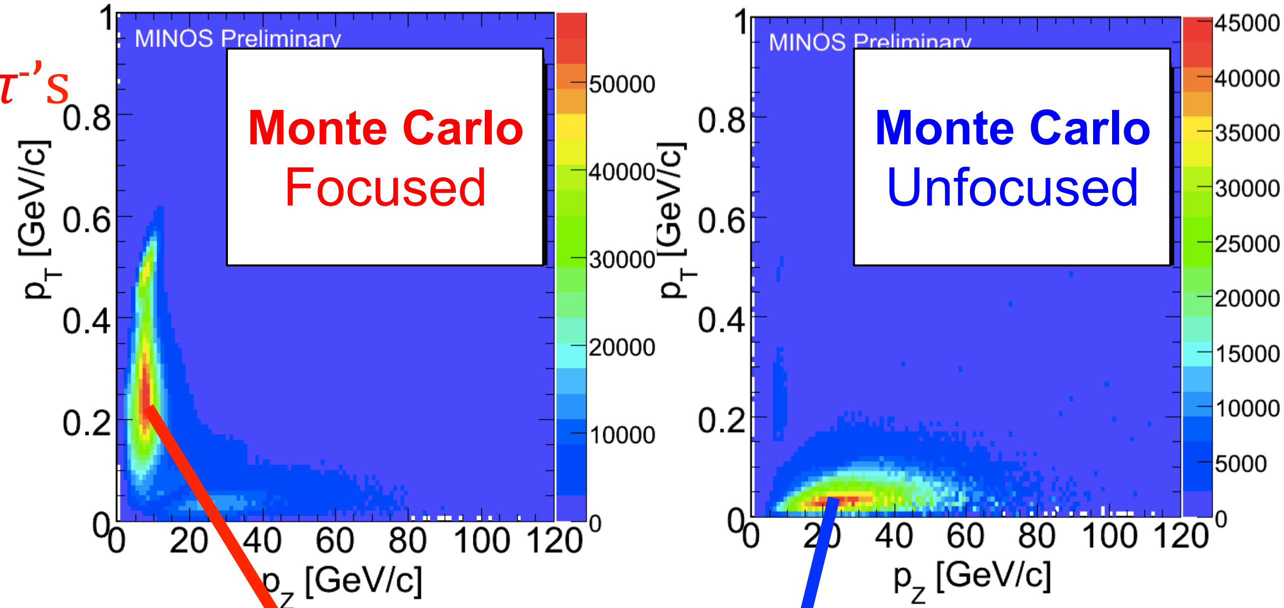
- $\bar{\nu}_\mu$'s from **high-p_t** π's
  - Focused by horns
- ν_μ's from **low-p_t** π^+'s
  - Pass through horn center

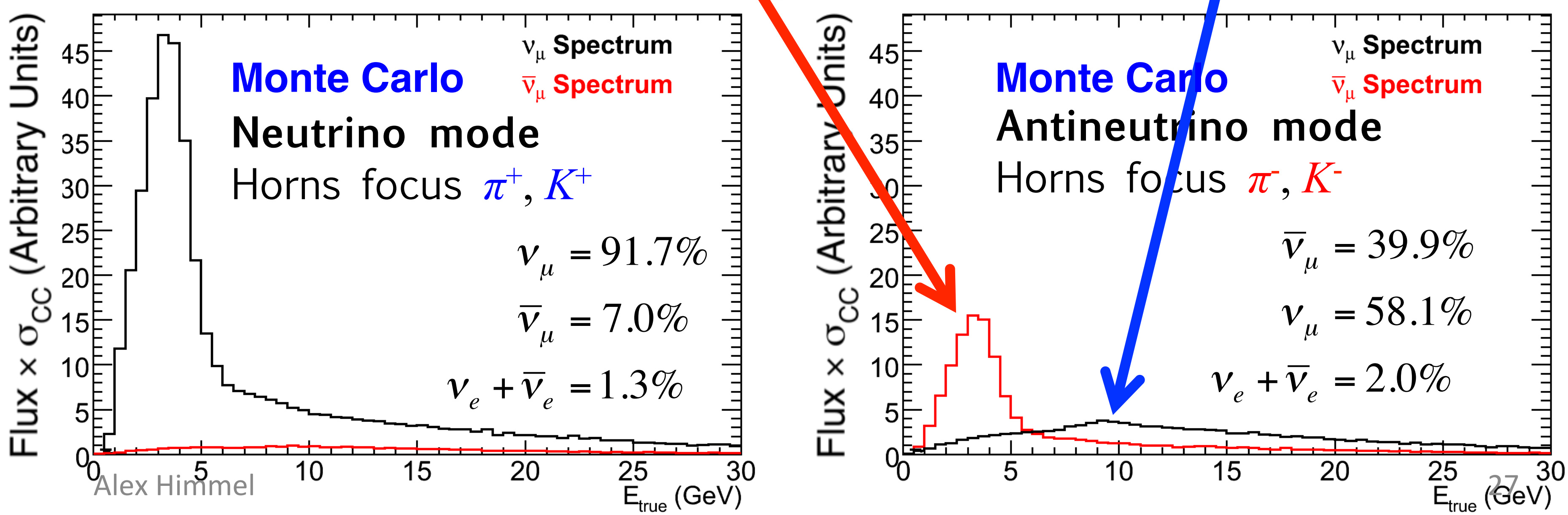




Peak vs. Tail

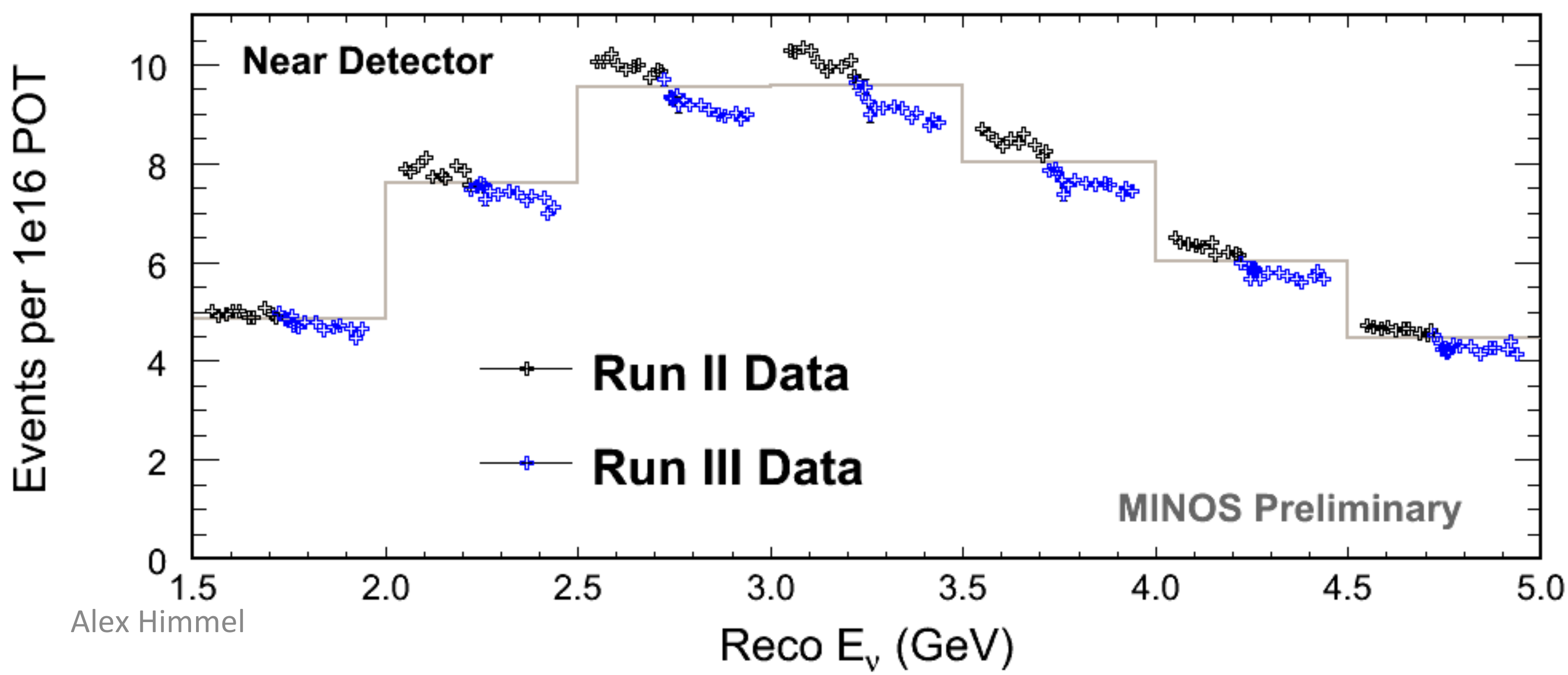
- $\bar{\nu}_\mu$'s from **low-p_t** π^-'s
  - Focused by horns
- ν_μ's from **high-p_t** π^+'s
  - Pass through horn center



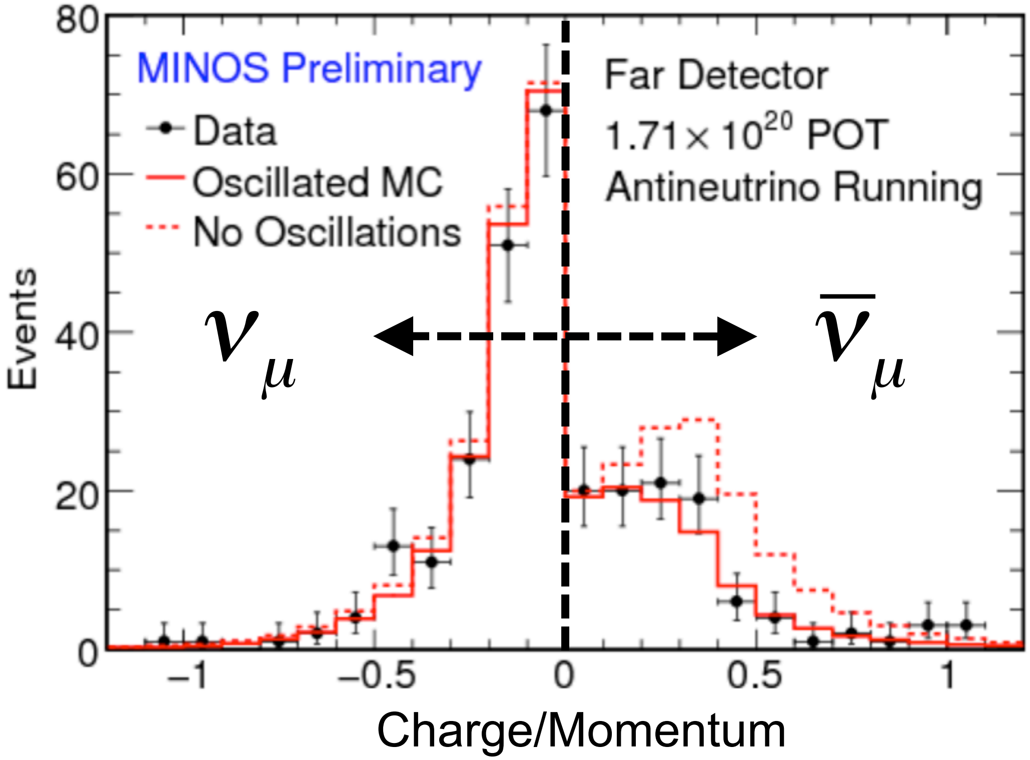


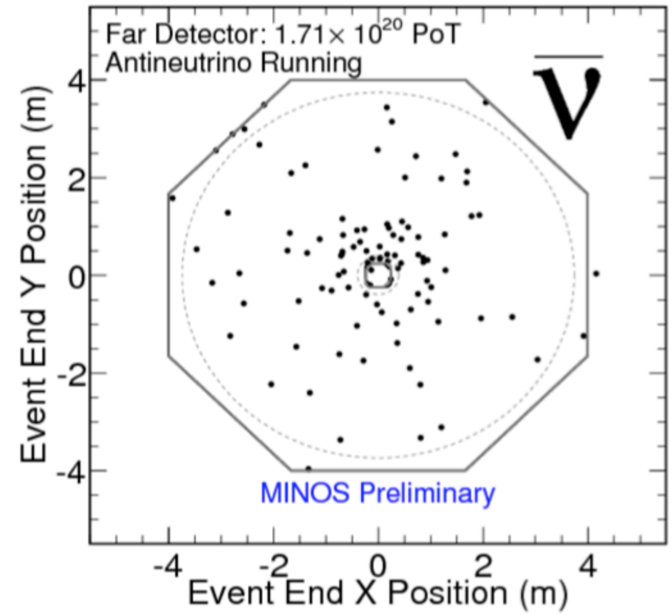
Target Degradation

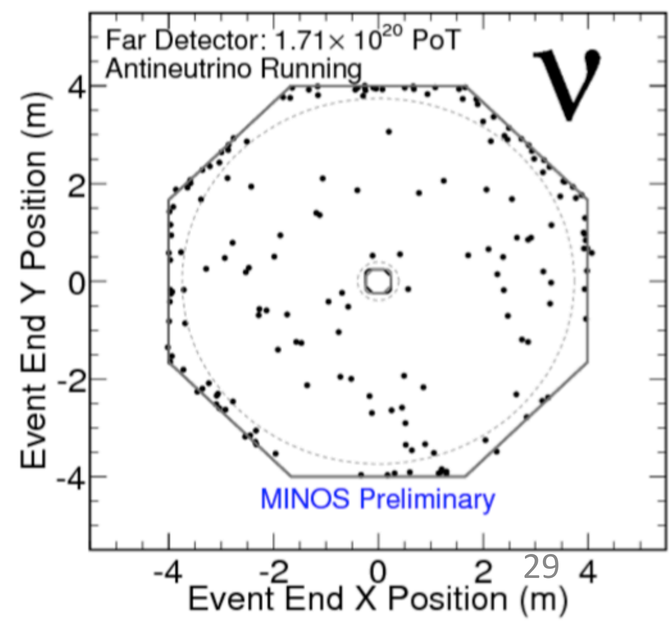
- Began during Run II and continued through Run III
- The exact mechanism of the decay is not known
- Missing fins at the shower max in the target model the energy-dependent effect
- Target to undergo post-mortem later this year
- Cancels between the two detector



Far Detector Data

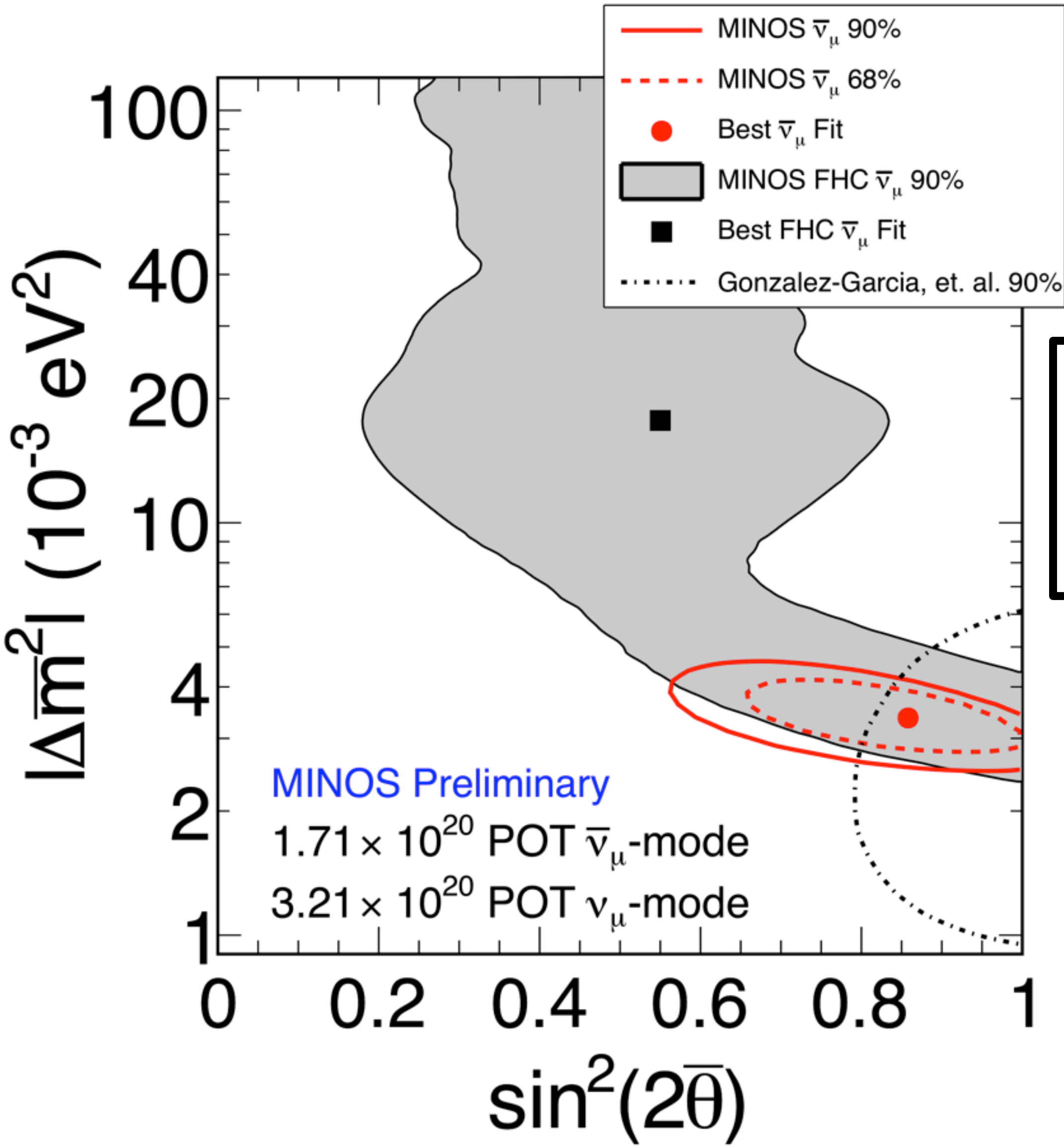






- Good data/mc agreement in charge/momentum
- Antineutrinos focused inwards
- Neutrinos defocused outwards

Antineutrino Contour

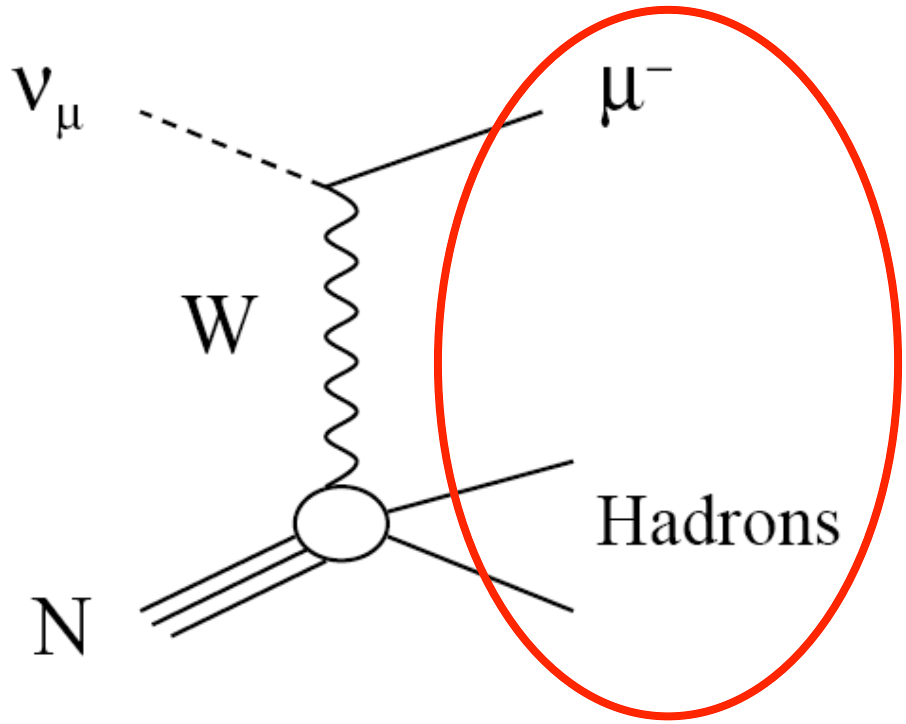


$$\left|\Delta\bar{m}^2_{\rm atm}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ {\rm eV}^2$$

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

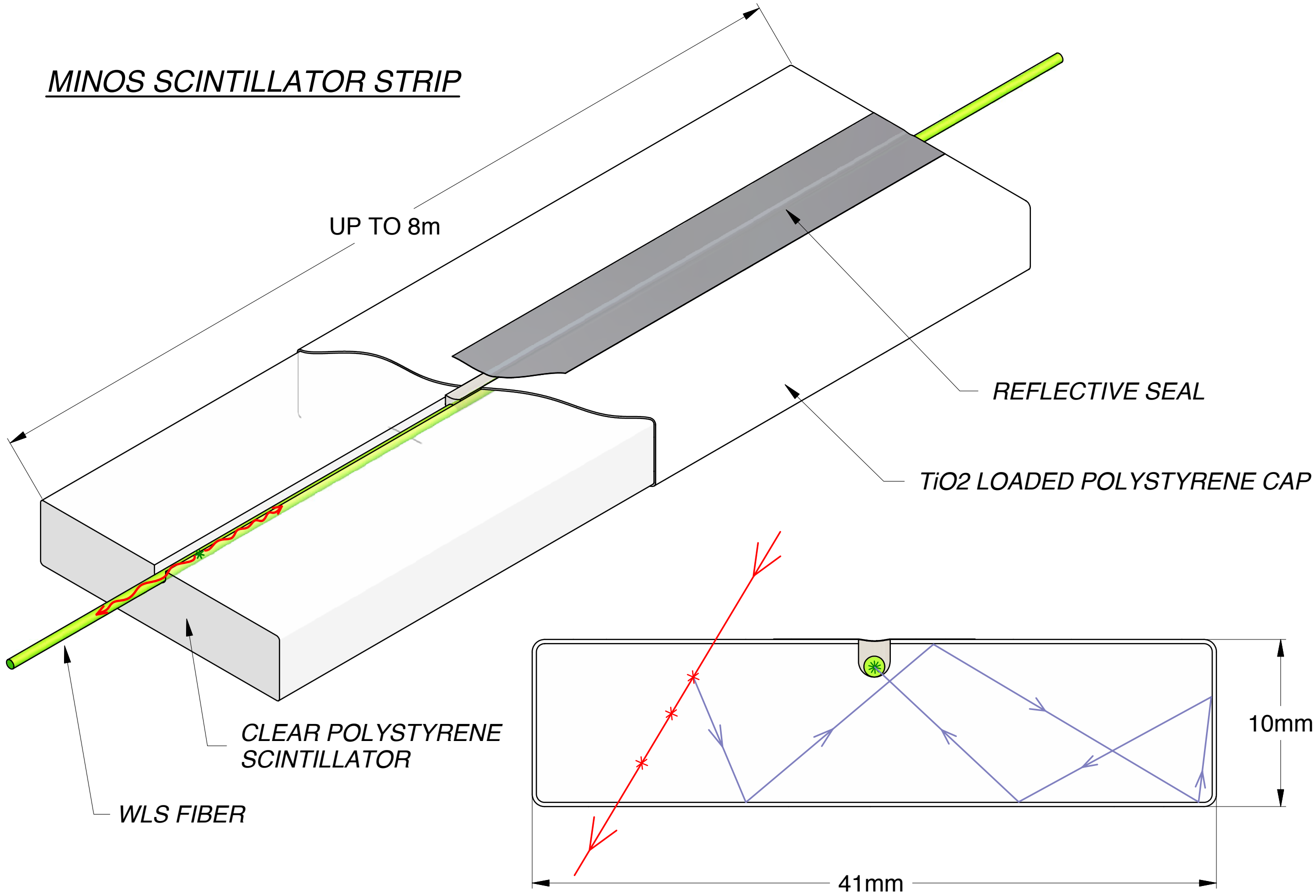
A combined analysis using all antineutrino data is planned.

Detecting Neutrinos



- Cannot directly observe the neutrino
- Instead, observe the charged particles after a neutrino interacts with a nucleus in the detector

Detecting Charged Particles



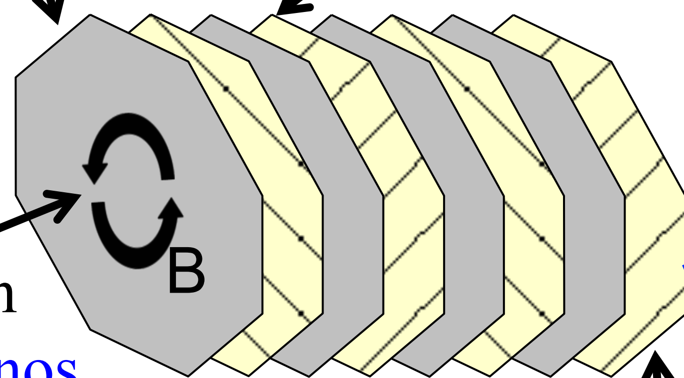
- 4 cm x 1 cm plastic scintillator strips
- Embedded wavelength-shifting fiber
- Scintillation light amplified by multi-anode PMTs

MINOS Detectors

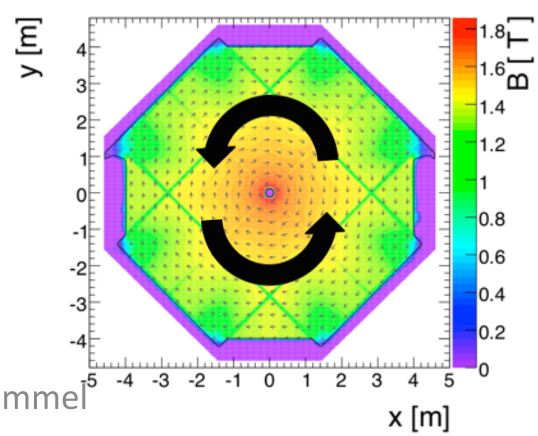
1 in thick Steel

1 cm thick, 4.1 cm wide Plastic Scintillator

Read out on wavelength-shifting fibre to multi-anode PMTs



1.3 T toroidal magnetic field can distinguish neutrinos and antineutrinos

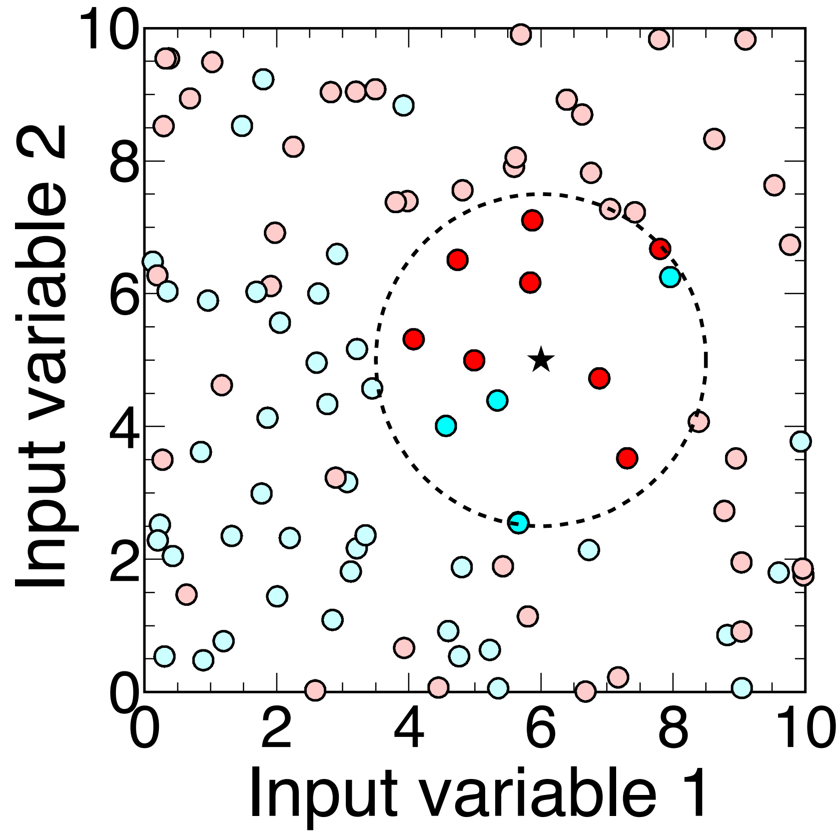


Strips in alternating directions allow 3D event reconstruction

Selecting Charged Currents

- 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
  - Fraction of signal in *k* most similar events is the discriminant

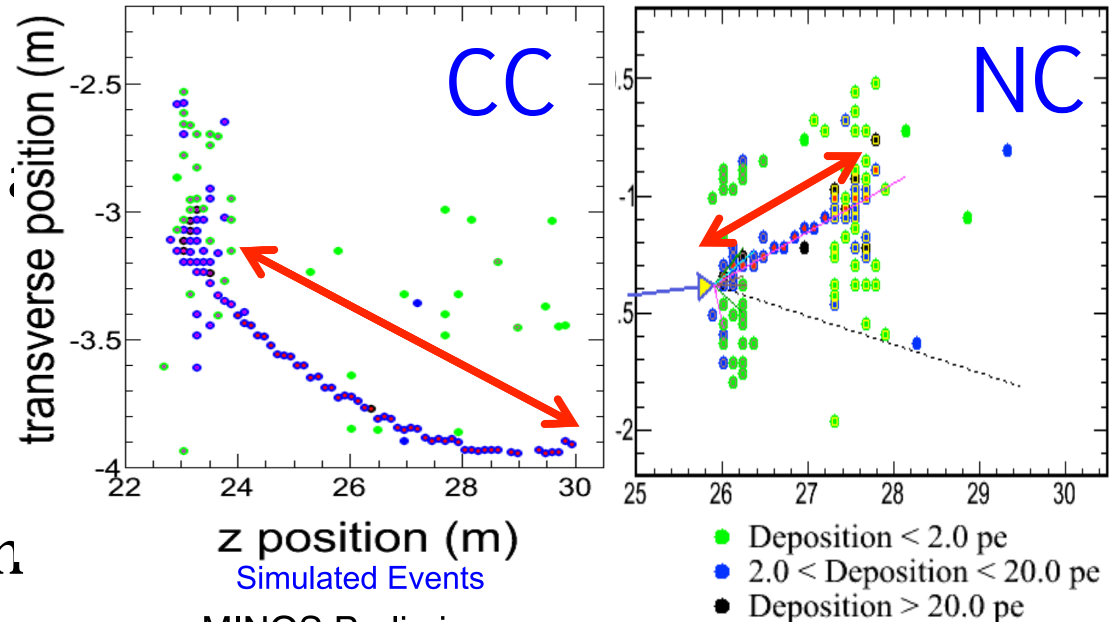


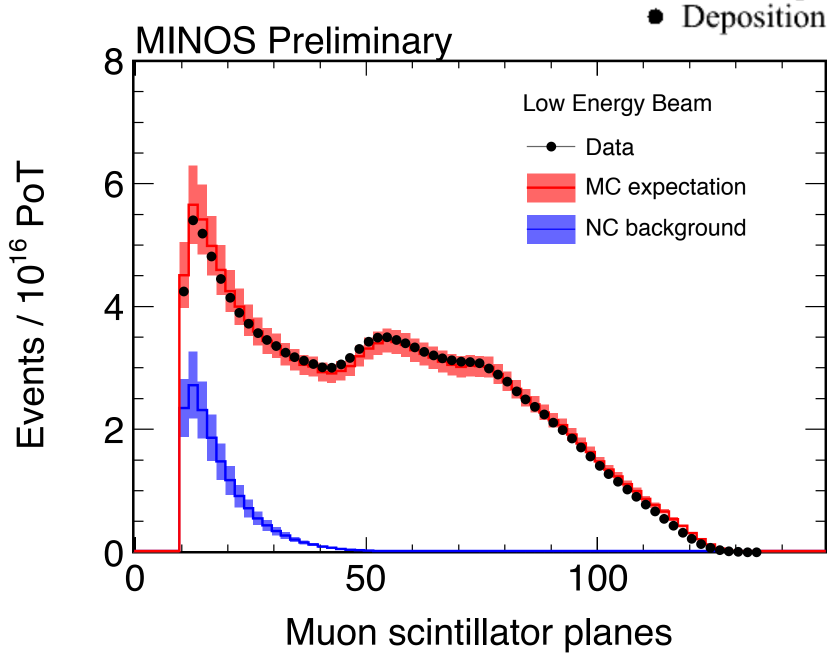
k-Nearest Neighbors

"kNN"

Selecting Charged Currents

- CC/NC separation using a kNN algorithm
- 4-parameter comparison
  - Track length
  - Transverse energy profile
  - Energy deposited per plane
  - Energy fluctuations along the track





Selecting Charged Currents

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  – Transverse energy profile
  – Energy deposited per plane
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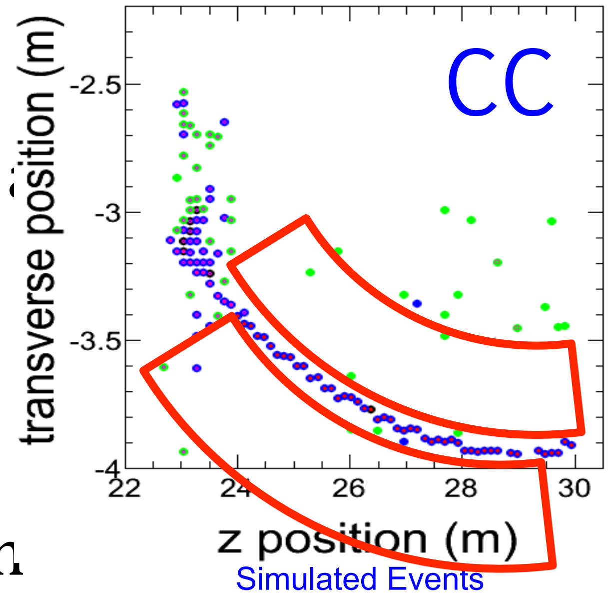

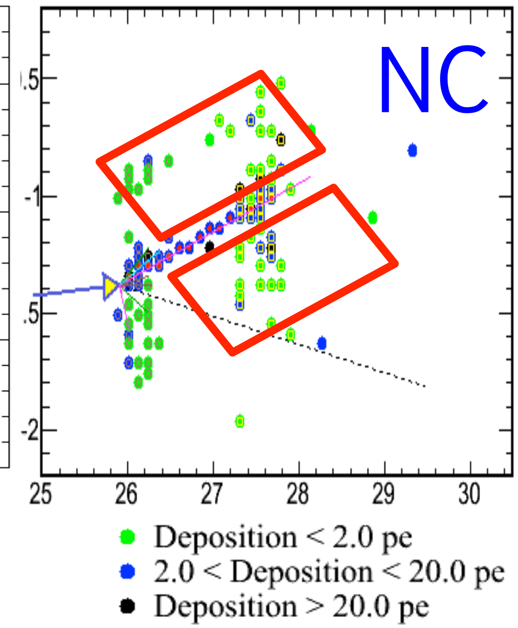

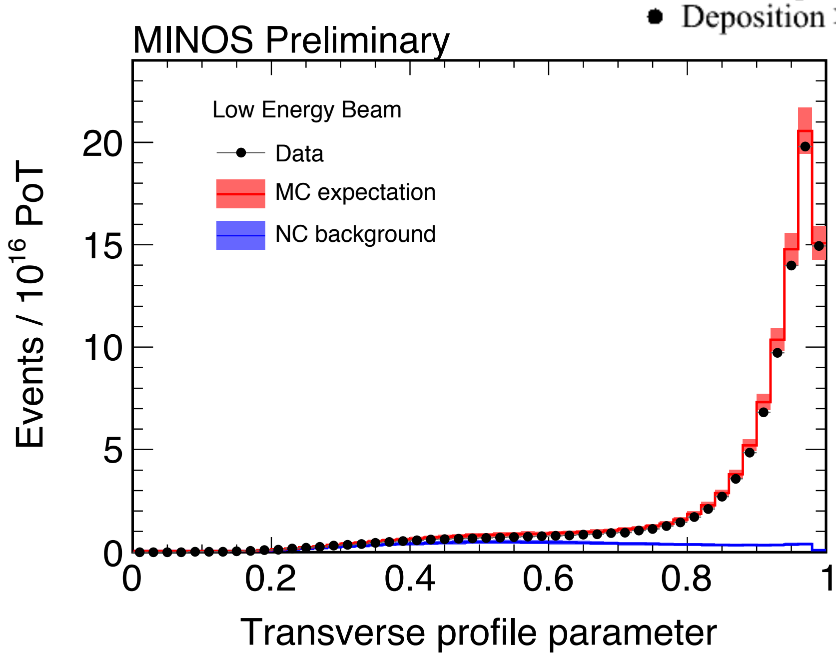

Selecting Charged Currents

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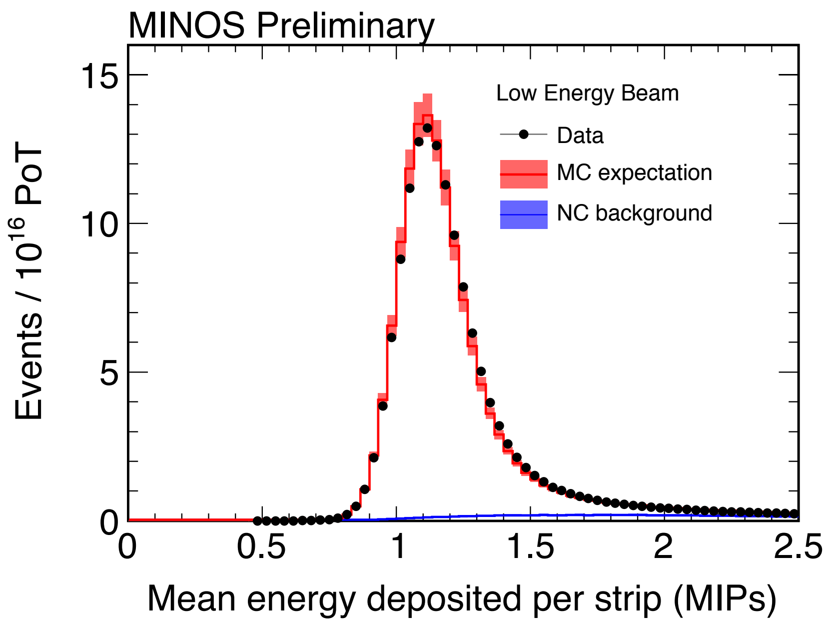
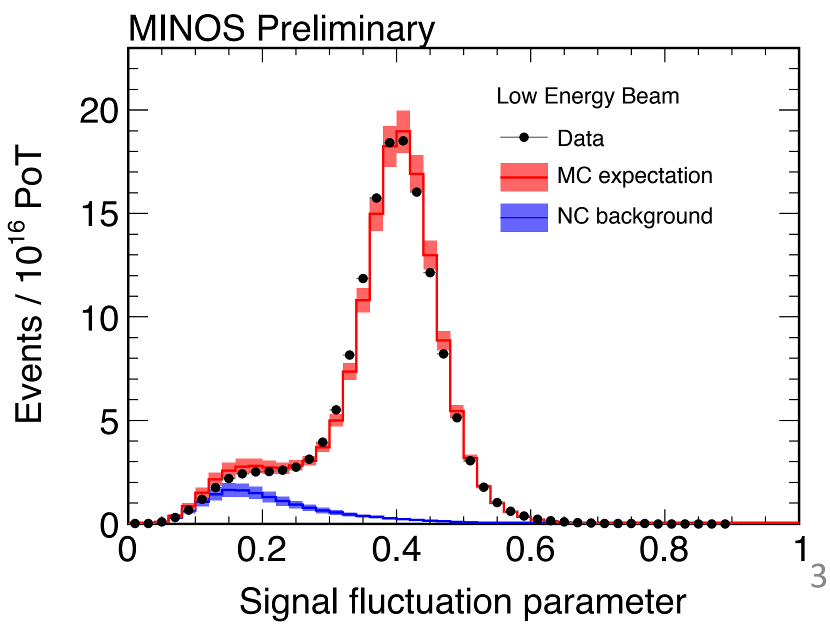
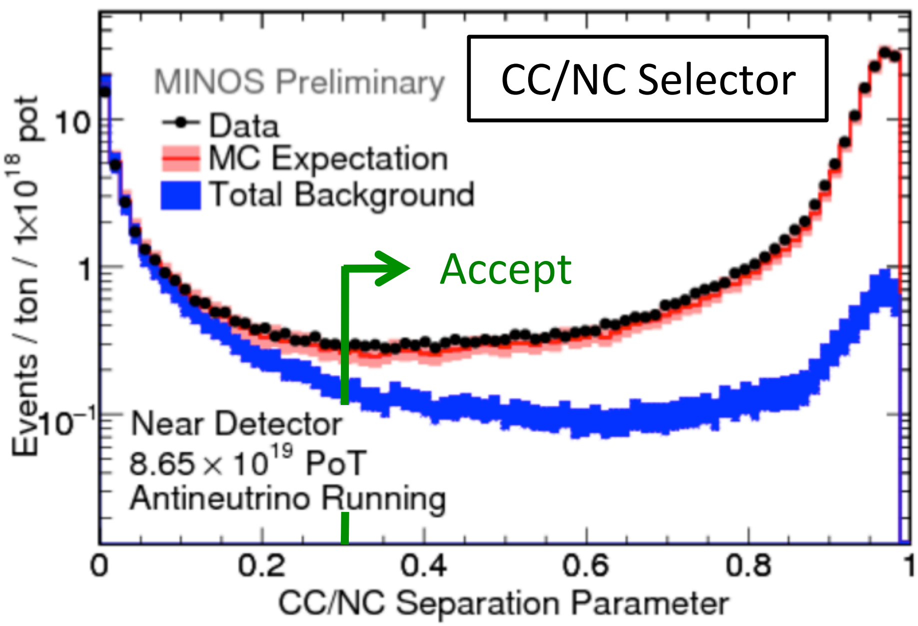
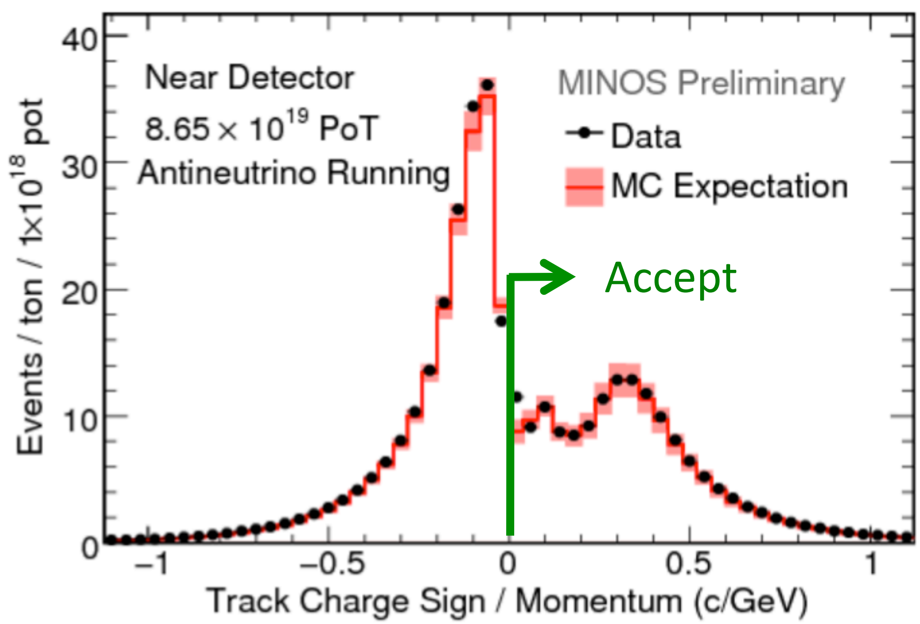




Selecting CC Antineutrinos

- Use the CC/NC Selector
  - Removes NC and high-y CC interactions
- Accept only events with positive reconstructed charge





Fitting for Oscillations

- Fit performed by minimizing a binned -log likelihood

$$-2\ln L(\vec{\alpha}) = 2\sum_i \left[p_i(\vec{\alpha}) - d_i + d_i \ln \frac{d_i}{p_i(\vec{\alpha})} \right]$$

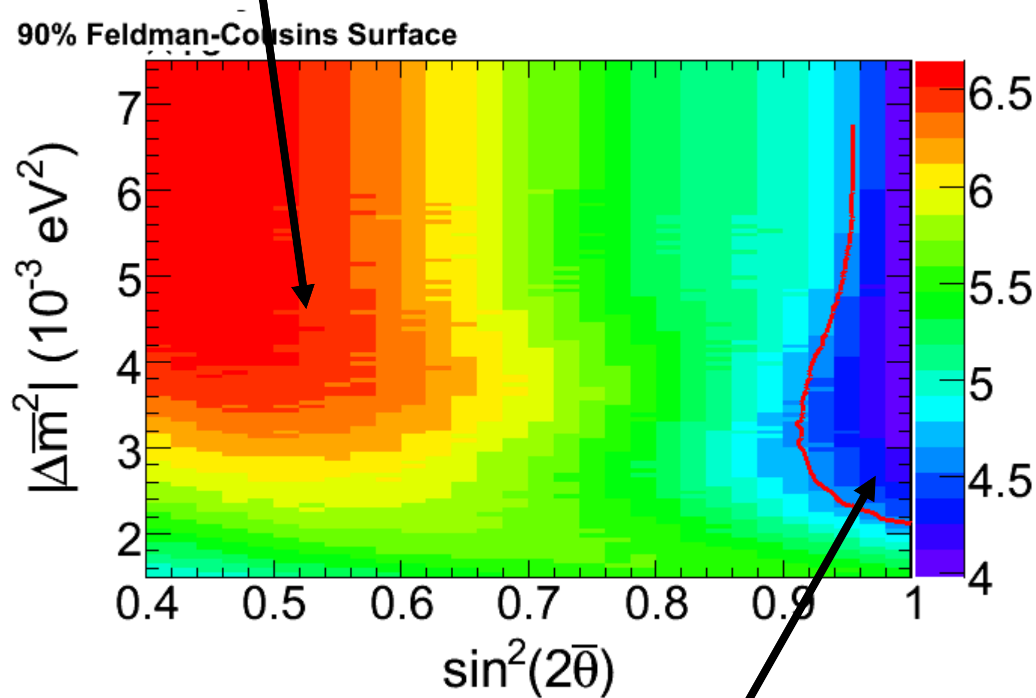
$$\vec{\alpha} = [\Delta\overline{m}^2_{\mathrm{atm}}, \sin^2(2\overline{\theta}_{23})]$$

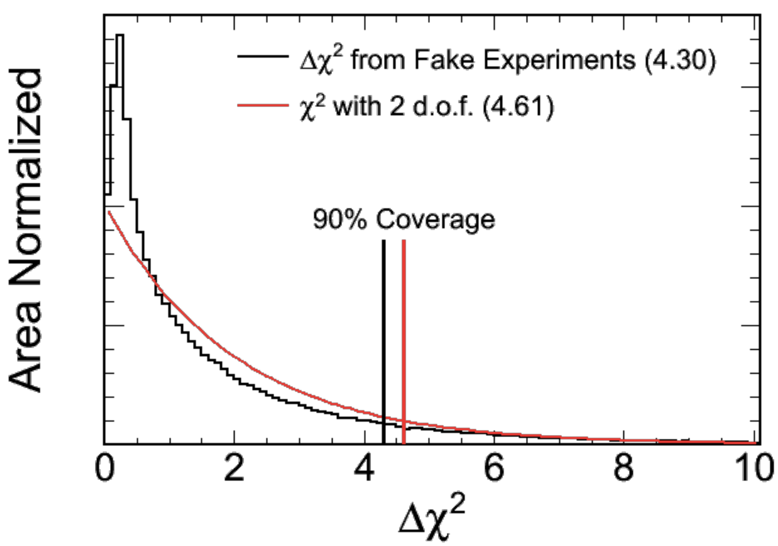
- For antineutrinos, a Feldman-Cousins approach is used
  - Many fake experiments used create empirical χ^2 distributions as a function of the parameters
  - Systematics included in the fake experiments

Feldman-Cousins

- Each point is the $\Delta\chi^2$ that encompasses 90% of fake experiments
  - A perfectly Gaussian surface would be 4.7 everywhere.

Worse than Gaussian
Degeneracy with fast oscillations





Better than Gaussian
Physical boundary gives extra information

Systematics

- Effect of uncertainties estimated by fitting systematically shifted MC
- Systematics are very small relative to the statistical uncertainty