Neutrino Oscillations with MINOS

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University of Sussex

Seminar at Queen's University

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Introduction

- Quantum mechanics and neutrino oscillations
- MINOS physics goals
- NuMI beam
- MINOS detectors
- The Analyses
  - muon neutrino disappearance
  - muon anti-neutrino disappearance
  - electron neutrino appearance

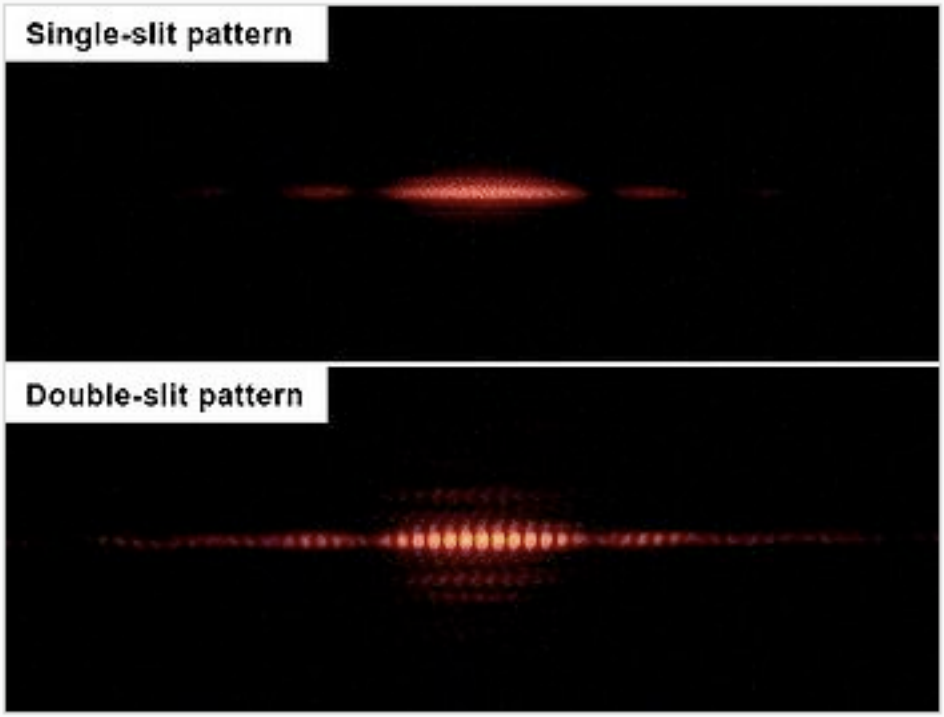
Neutrino Oscillations

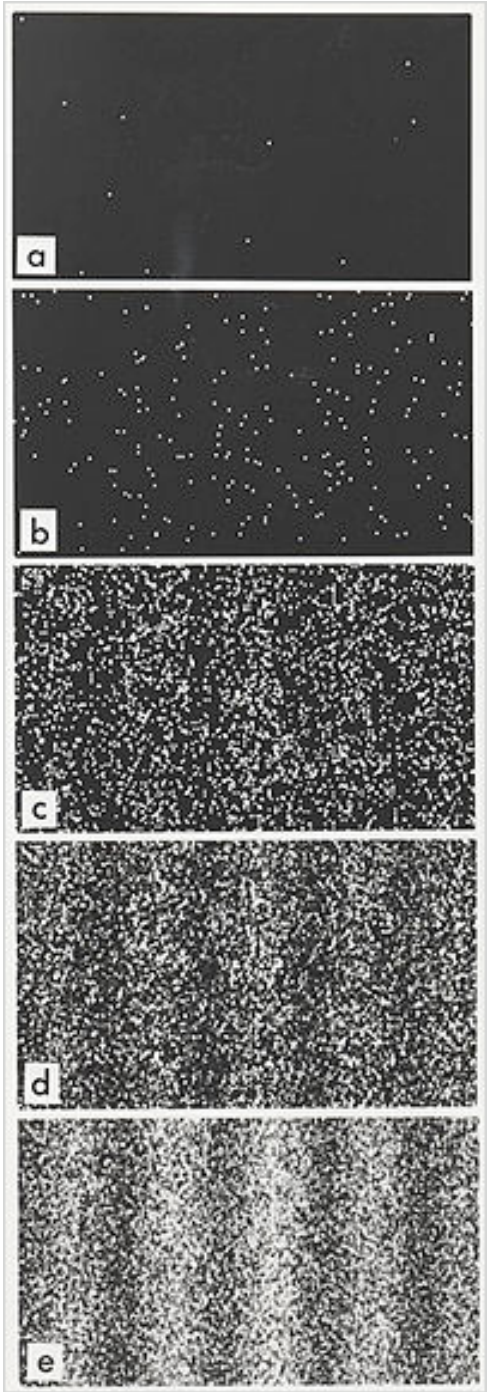
(from the very top)

Starting somewhere completely different…

Young's Double Slits

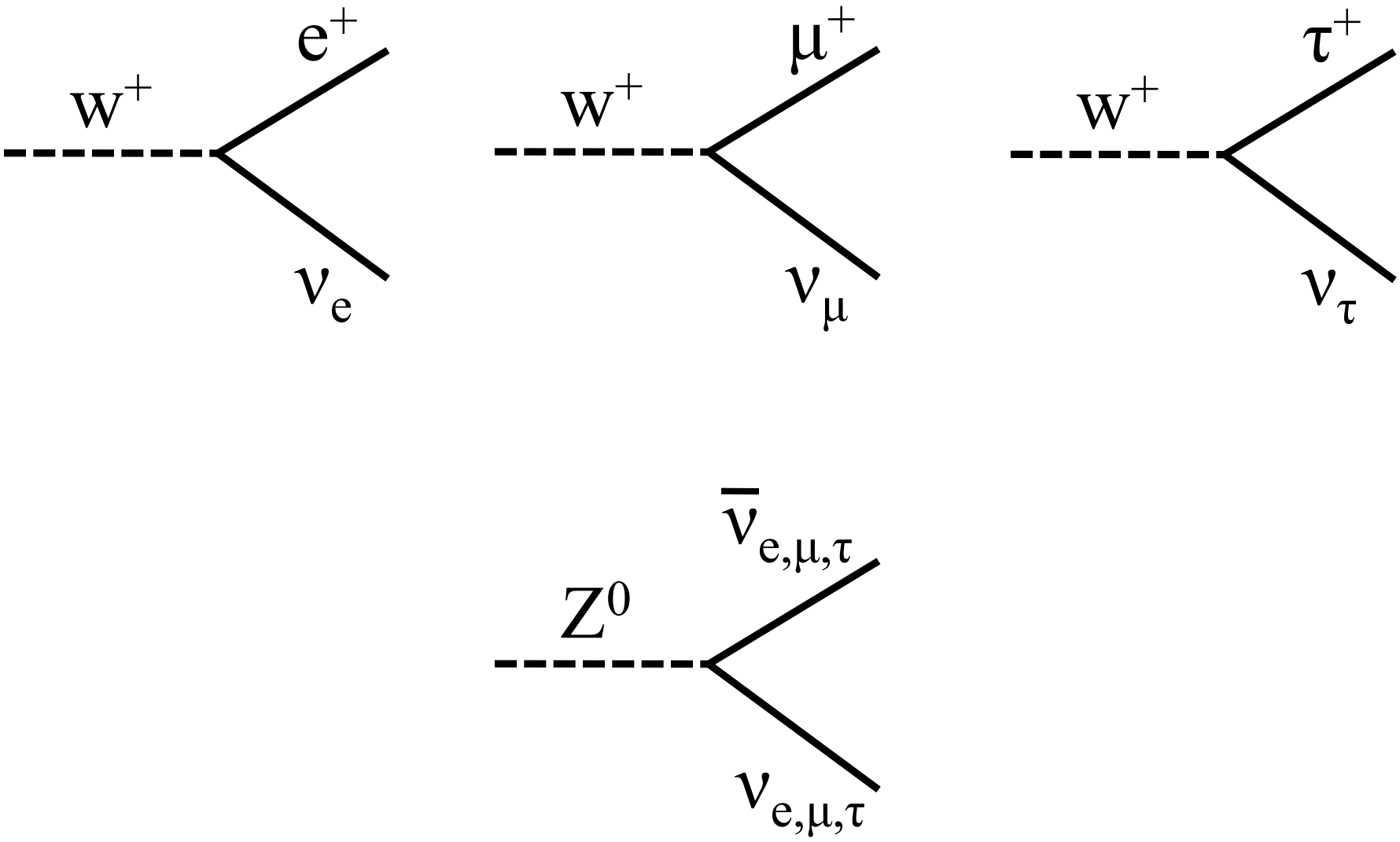
"all of quantum mechanics can be gleaned from carefully thinking through the implications of this single experiment" (R. Feynman)



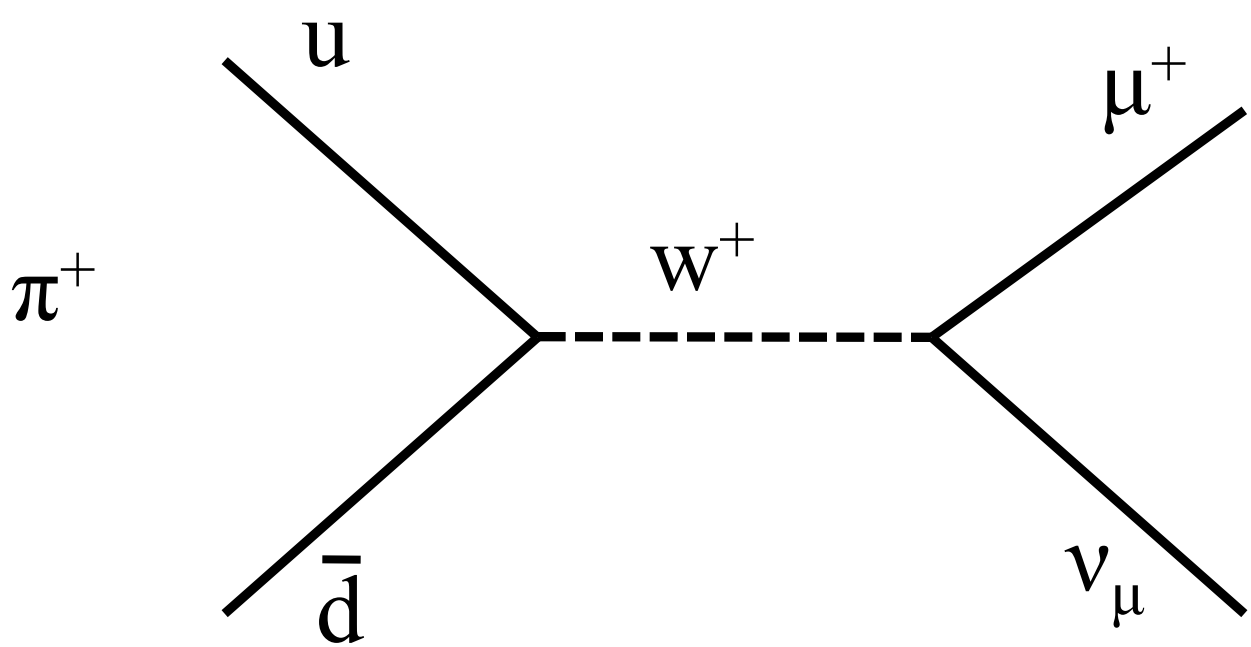


Both patterns valid…

Neutrino Flavours and Interactions

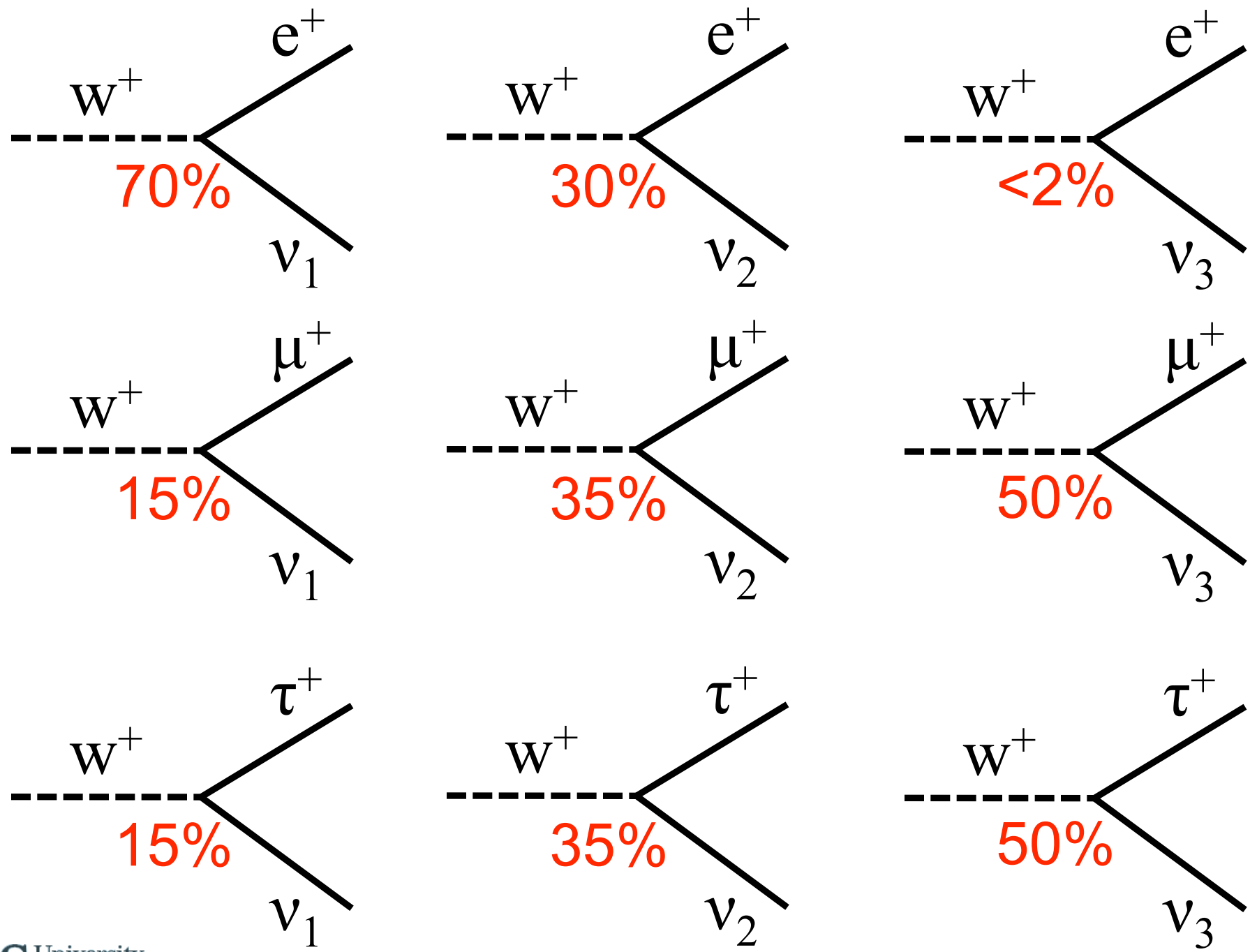


A charged pion decay at rest…

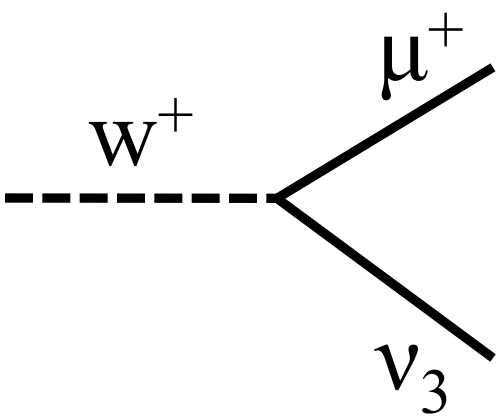


… could be used to determine the neutrino mass (experimentally impossible currently!)

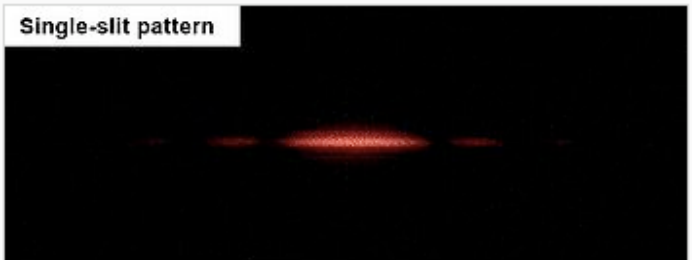
If an extremely precise experiment was done we would actually observe 3 distinct neutrino masses for the ν_μ

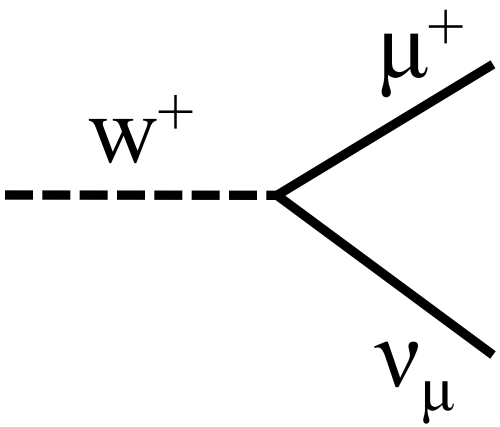

W^+
e^+
70%
ν_1
W^+
e^+
30%
ν_2
W^+
e^+
<2%
ν_3
W^+
μ^+
15%
ν_1
W^+
μ^+
35%
ν_2
W^+
μ^+
50%
ν_3
W^+
τ^+
15%
ν_1
W^+
τ^+
35%
ν_2
W^+
τ^+
50%
ν_3

The Analogy

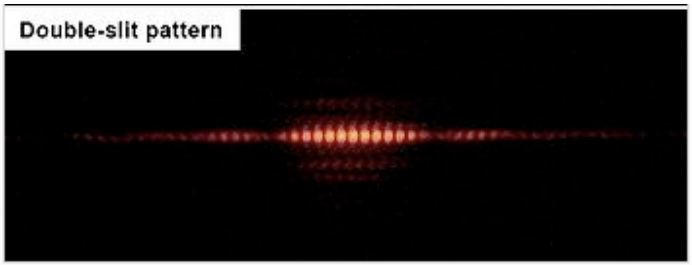


The neutrino behaves as a well defined "classical" state: no interference





The neutrino behaves as a superposition thus we can get an interference pattern



Interference pattern = Neutrino oscillations

Neutrino Oscillations

- Unitary matrix relates the neutrino mass eigenstates ν_1, ν_2, ν_3 to the weak interaction eigenstates ν_e, ν_μ, ν_τ

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

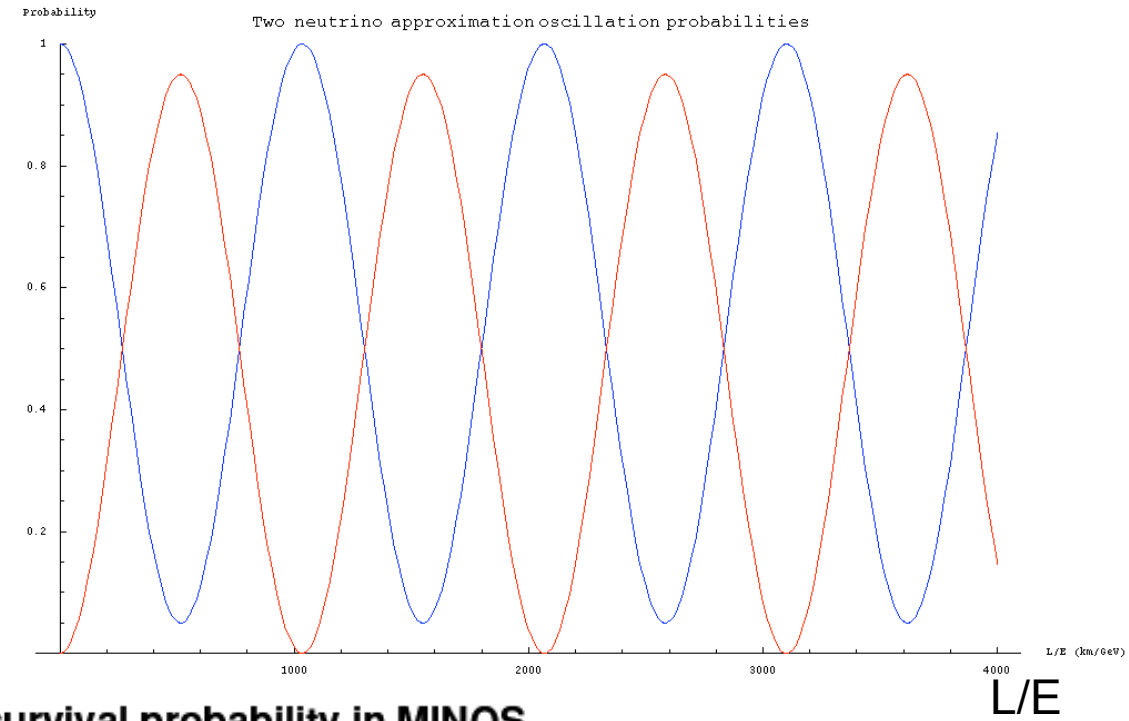
- Neutrinos produced as ν_e, ν_μ (a superposition), but propagate as ν_1, ν_2 (diff. masses get out of phase)

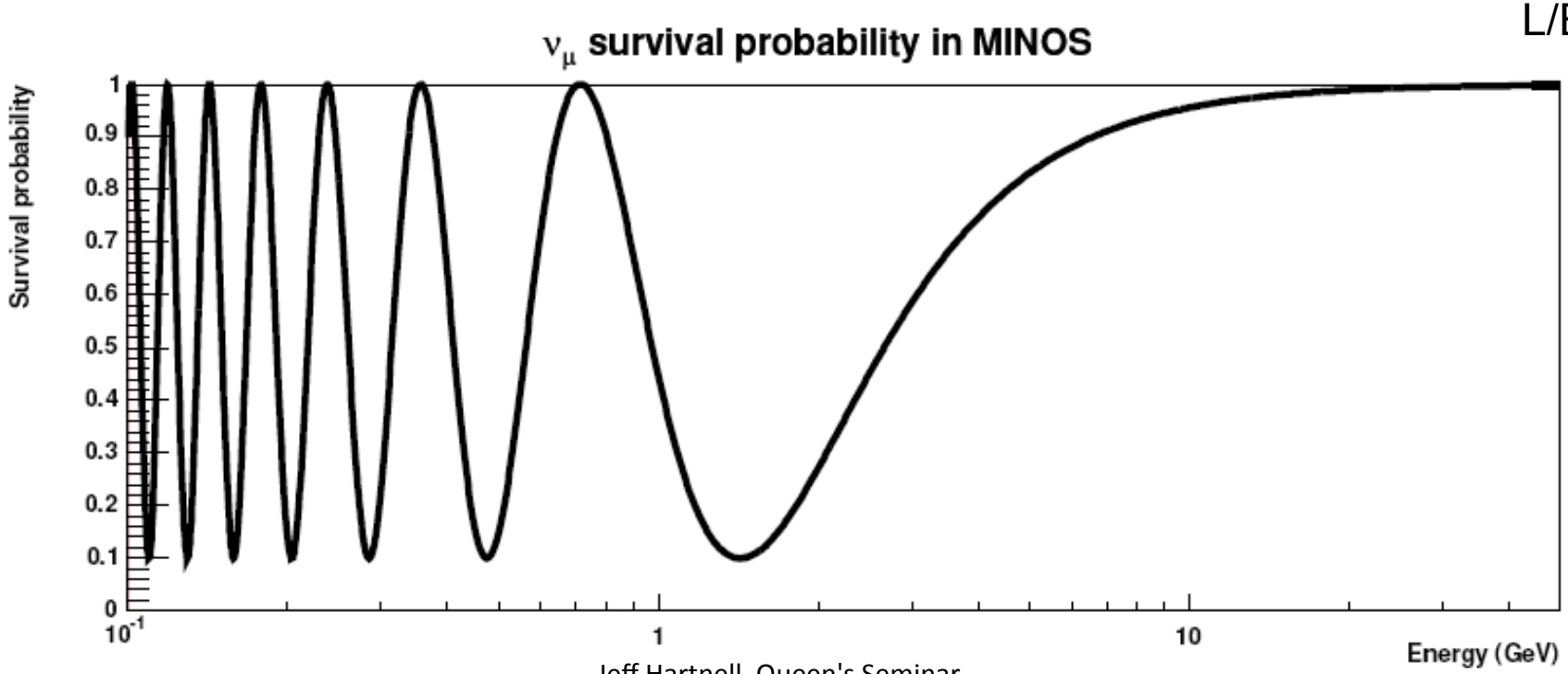
$$\nu_i(t) = \nu_i(0) \cdot e^{-iE_i t}$$

- Leads to oscillation probability:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$

Simple Oscillation Probability



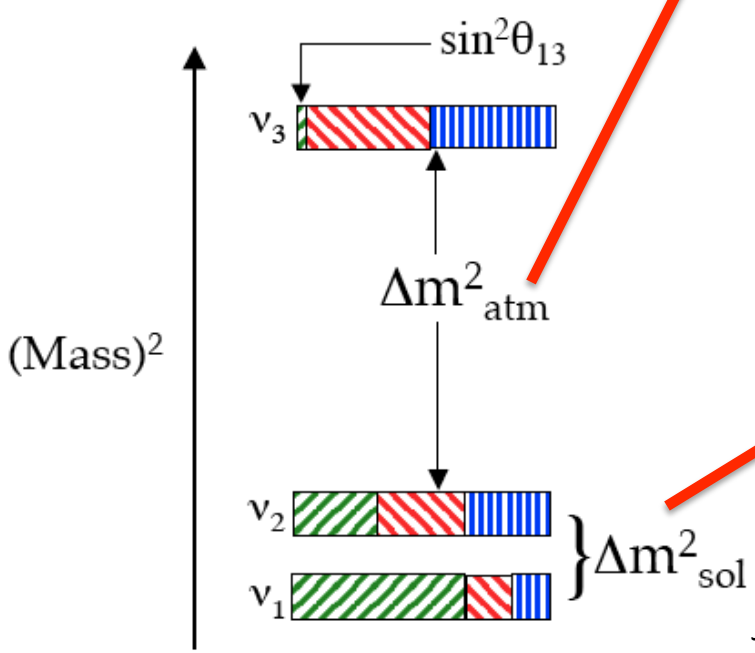


Full 3-Flavour Overview

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Subdominant term



$\Delta m^2_{31} = m_3^2 - m_1^2$, L/E≅500 km/GeV

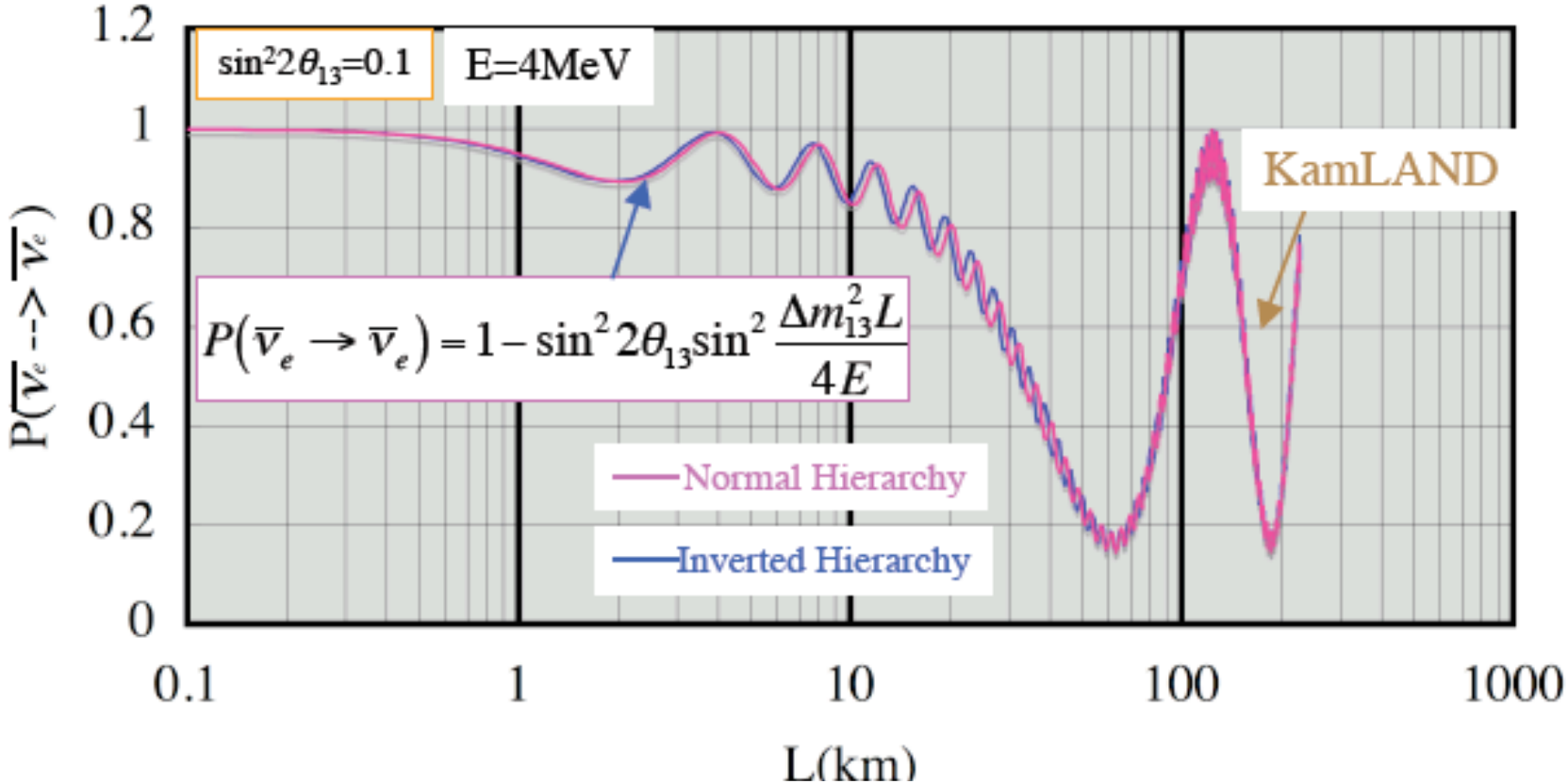
$\Delta m^2_{32} = m_3^2 - m_2^2$, L/E≅500 km/GeV

(≅0.5 km/MeV)

$\Delta m^2_{21} = m_2^2 - m_1^2$, L/E≅15000 km/GeV

Two Examples of Oscillation Probability

1



2

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2\left(1.27 \Delta m^2_{31} \frac{L}{E}\right) +$$

$$\sin^2(2\theta_{12}) \cos^2(\theta_{23}) \sin^2\left(1.27 \Delta m^2_{21} \frac{L}{E}\right) +$$

$$\sin(2\theta_{13}) \sin(2\theta_{23}) \sin(2\theta_{12}) \sin\left(1.27 \Delta m^2_{31} \frac{L}{E}\right) \sin\left(1.27 \Delta m^2_{21} \frac{L}{E}\right) \cos\left(1.27 \Delta m^2_{32} \frac{L}{E} \pm \delta_{CP}\right)$$

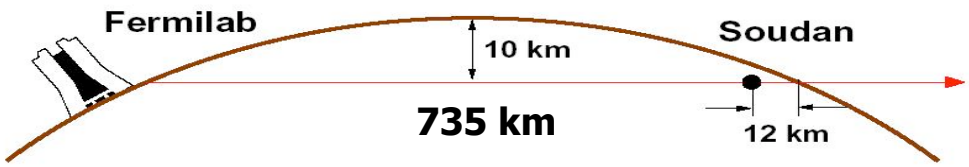
The MINOS Collaboration

120 scientists
30 institutions

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab Goias • Harvard • Holy Cross • IIT • Indiana • Iowa State • Minnesota-Twin Cities Minnesota-Duluth • Otterbein • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary

MINOS Overview

- Main Injector Neutrino Oscillation Search
- Neutrinos at the Main Injector (NuMI) beam at Fermilab
- Two detectors:
- Near detector at Fermilab
  - measure beam composition
  - energy spectrum
- Far detector in Minnesota
  - search for and study oscillations



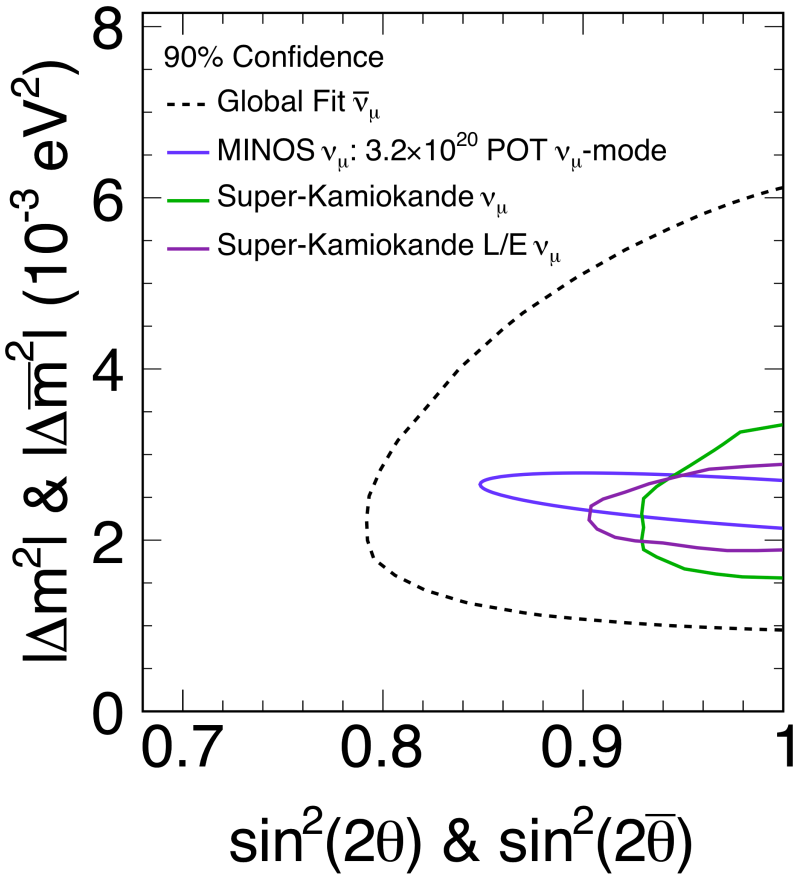
MINOS Physics Goals

- Search for sub-dominant ν_μ -> ν_e oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector
- 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

Why study ν_μ and $\bar{\nu}_\mu$?

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

- Antineutrino parameters are less precisely known.
  - No direct precision measurements
  - MINOS is the only oscillation experiment that can do event-by-event separation



- Differences may imply new physics in the neutrino sector manifested as a difference in the effective mass-splitting.

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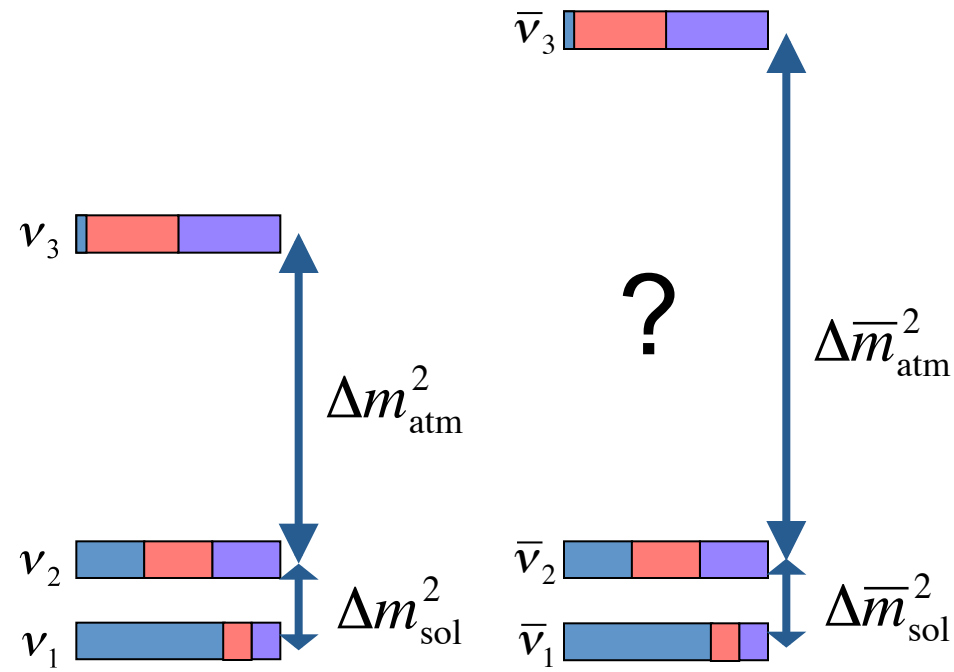

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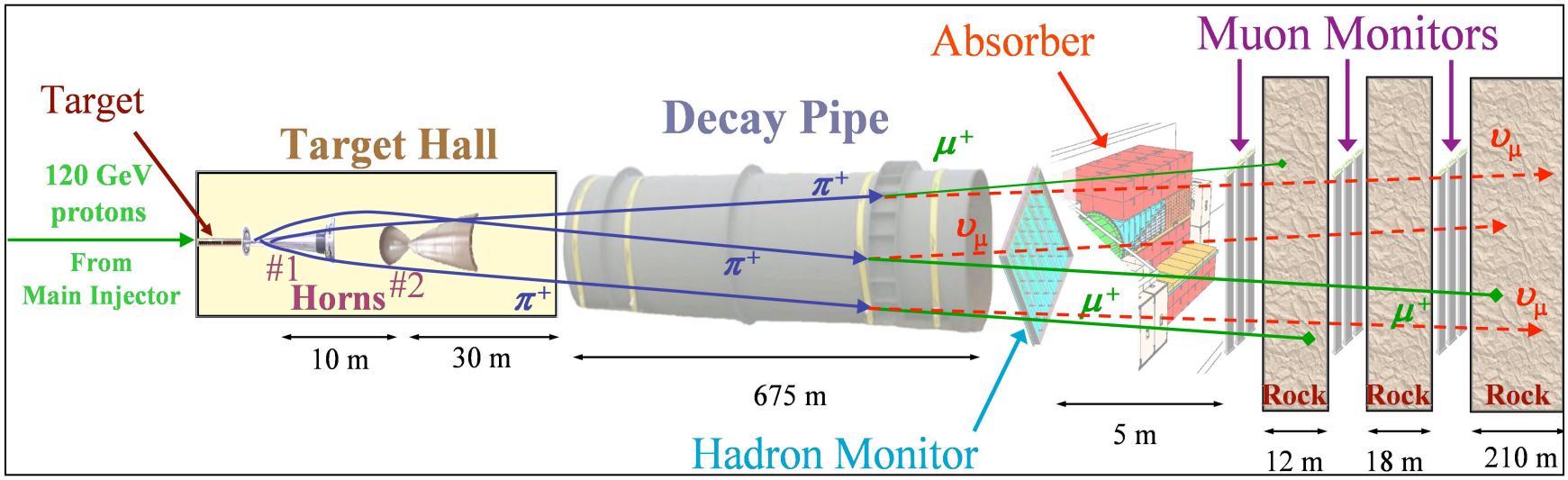
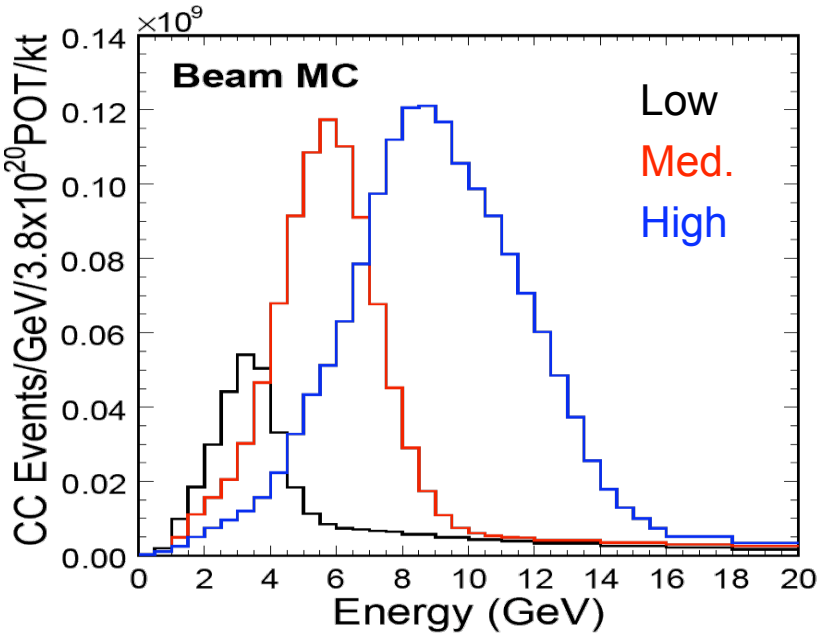
NuMI Neutrino Beam

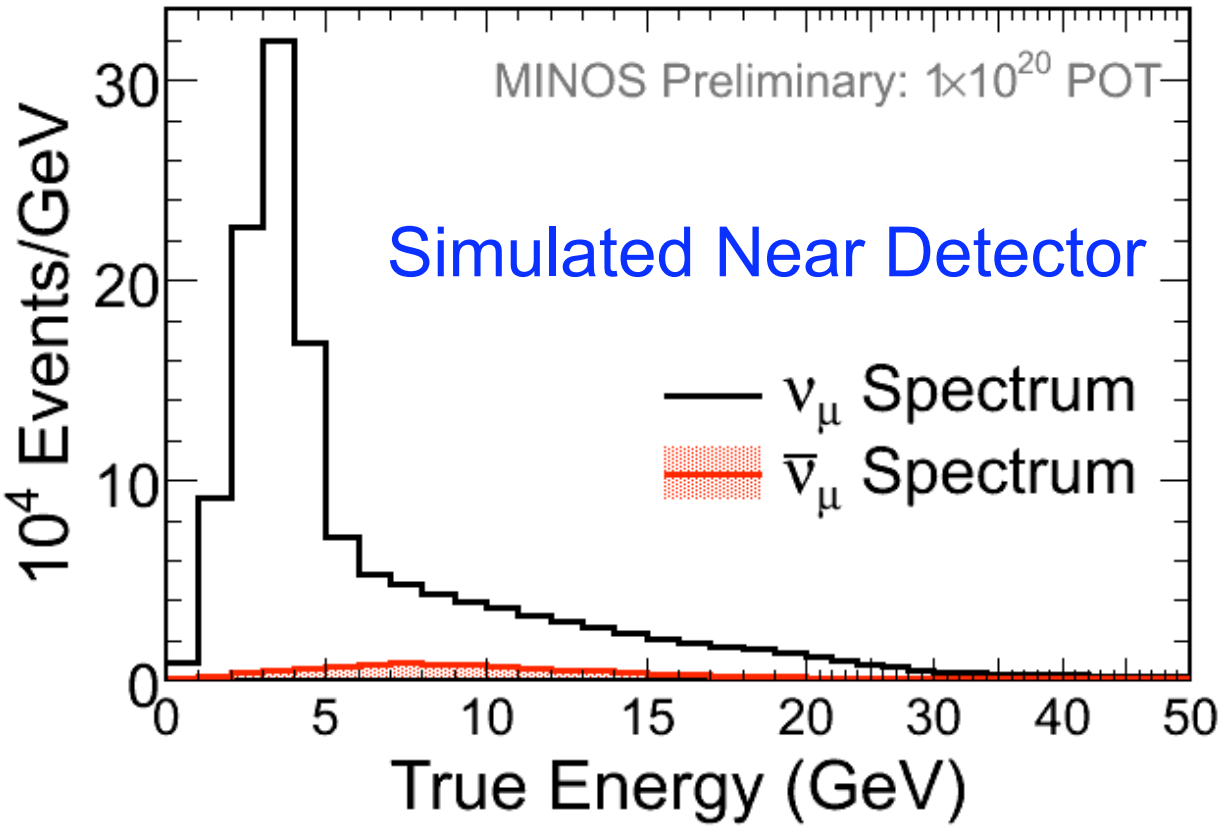


- 120 GeV protons strike target
- 10 μs long pulse of ~3×10^{13} protons every 2.2 seconds (275 kW)
- Two magnetic horns focus secondary π/K
  - decay of π/K produce neutrinos
- Variable neutrino beam energy

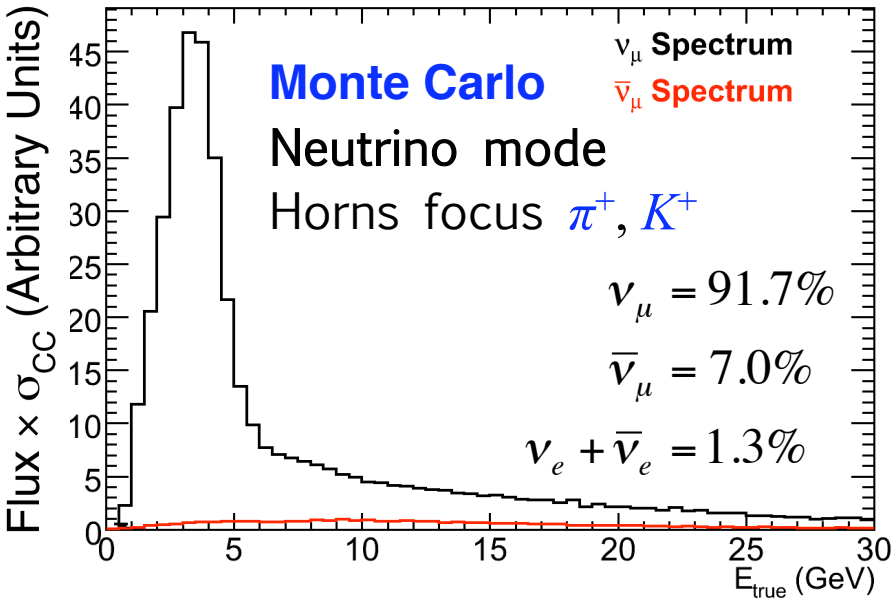


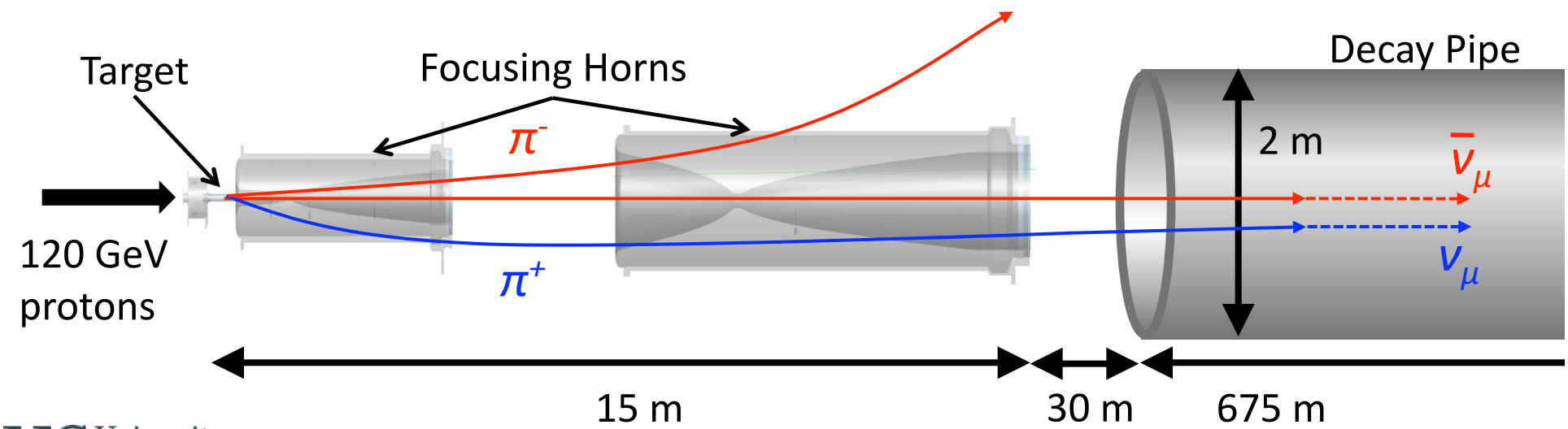
Neutrino Beam Composition

- Low energy neutrino mode
- Near detector CC interactions:
  - 91.7% ν_μ
  - 7.0% $\bar{\nu}_\mu$
  - 1.3% $\nu_e + \bar{\nu}_e$

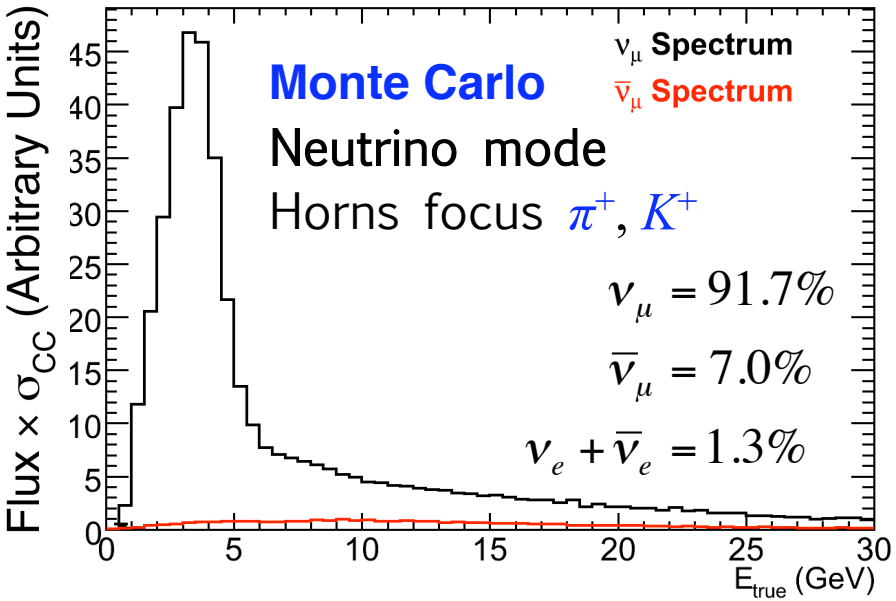


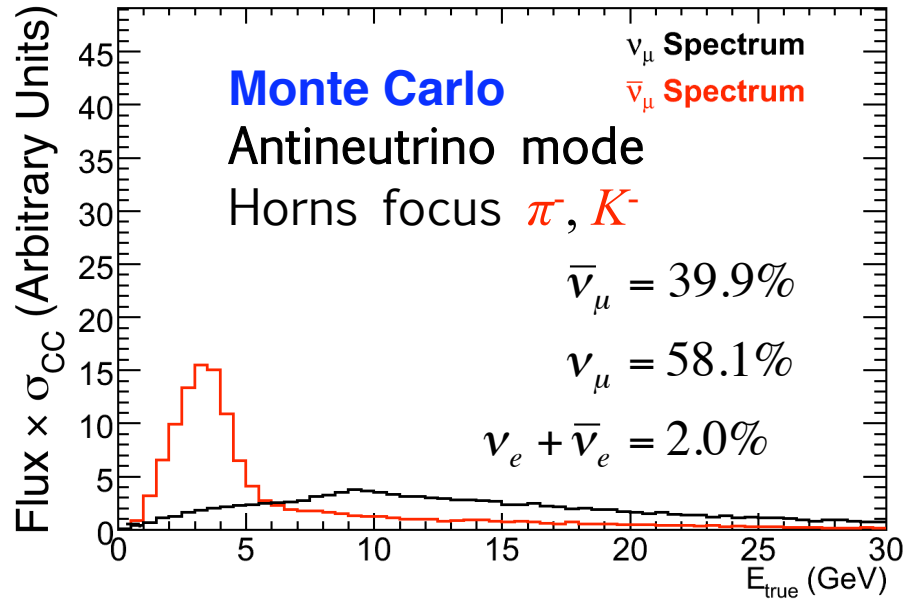
Neutrino Mode

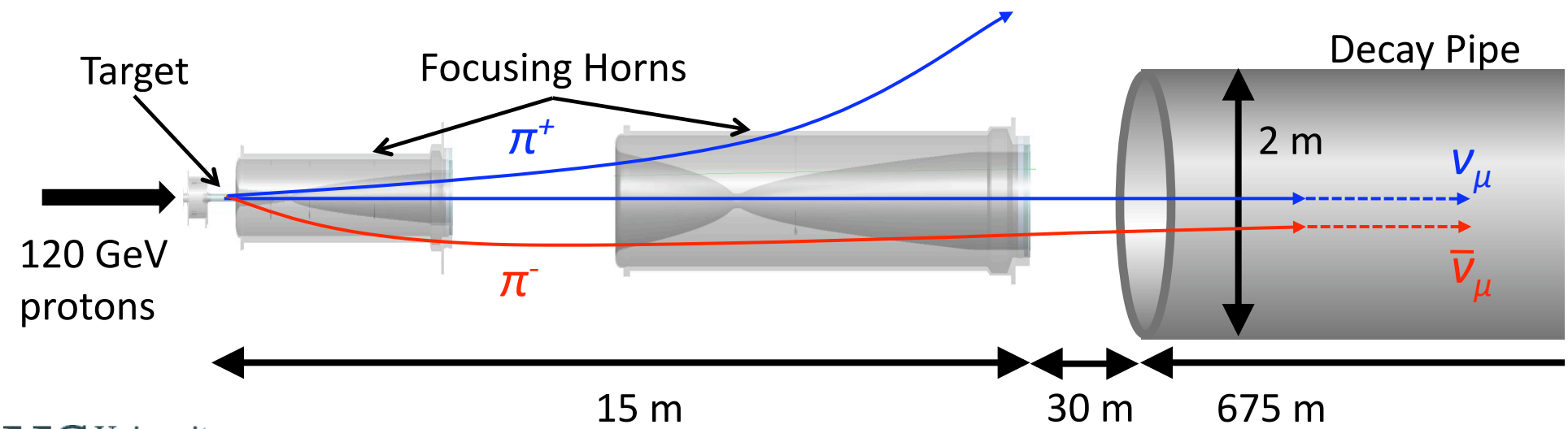




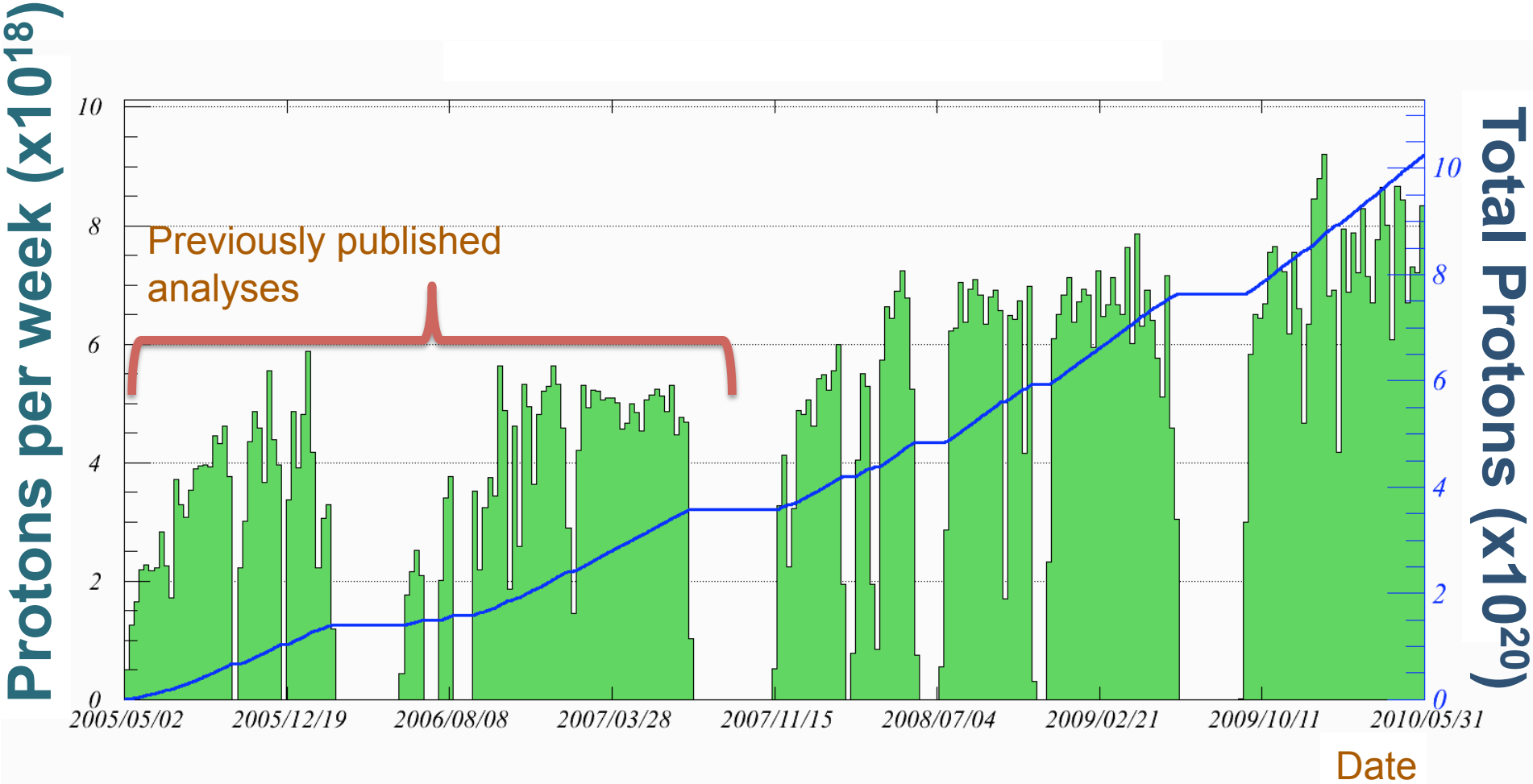
Anti-neutrino Mode





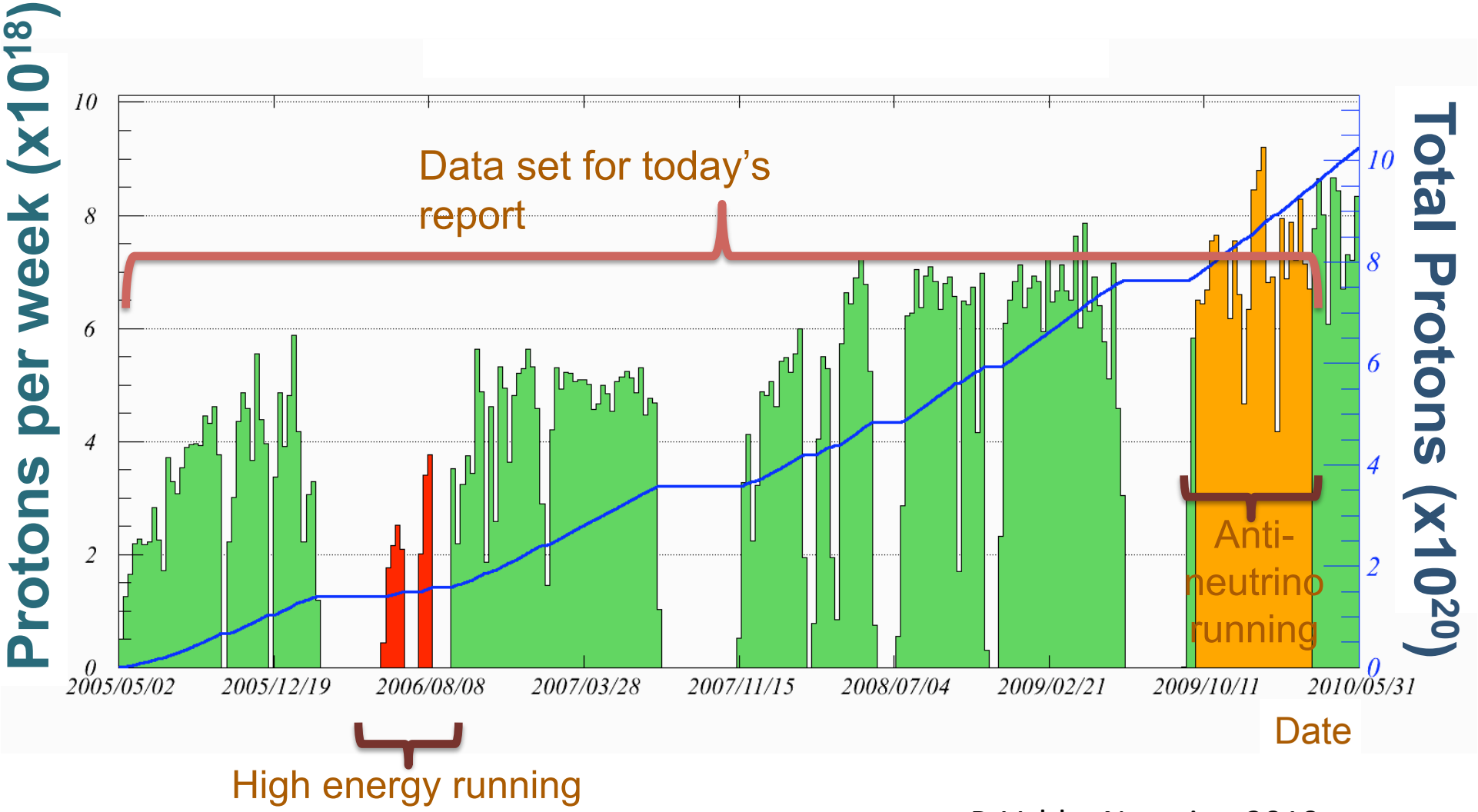


Beam Performance



P. Vahle, Neutrino 2010

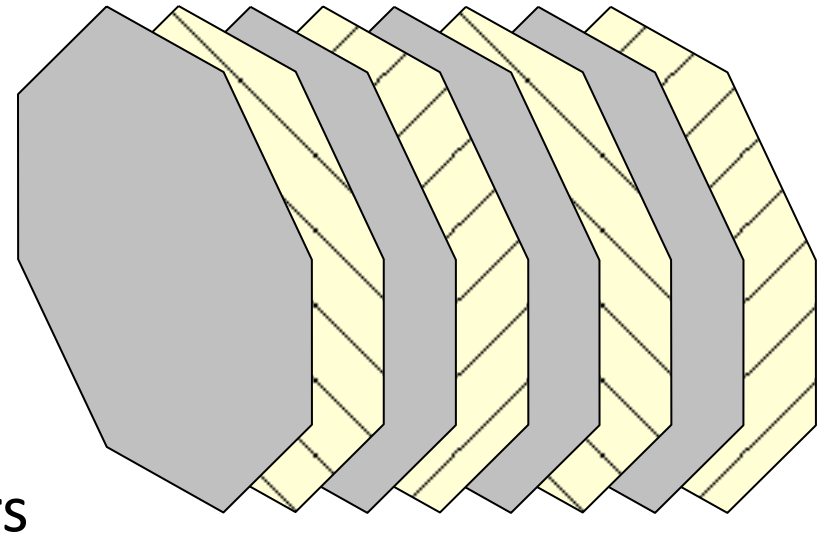
Beam Performance

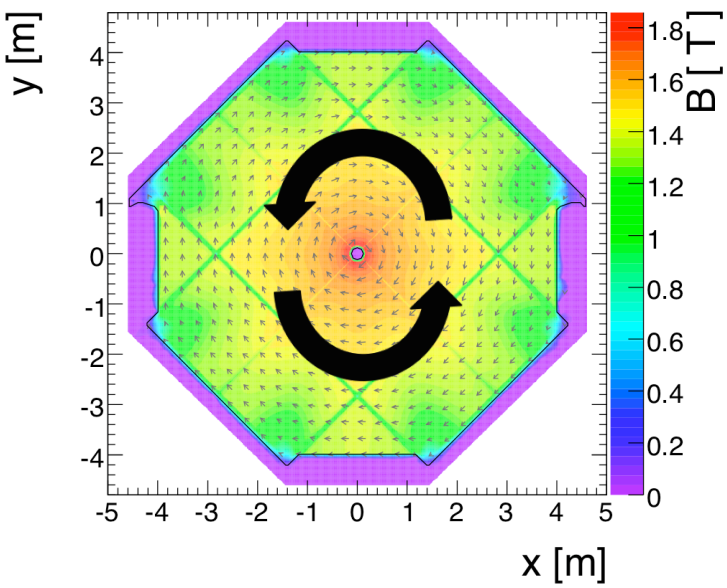


P. Vahle, Neutrino 2010

MINOS Detectors

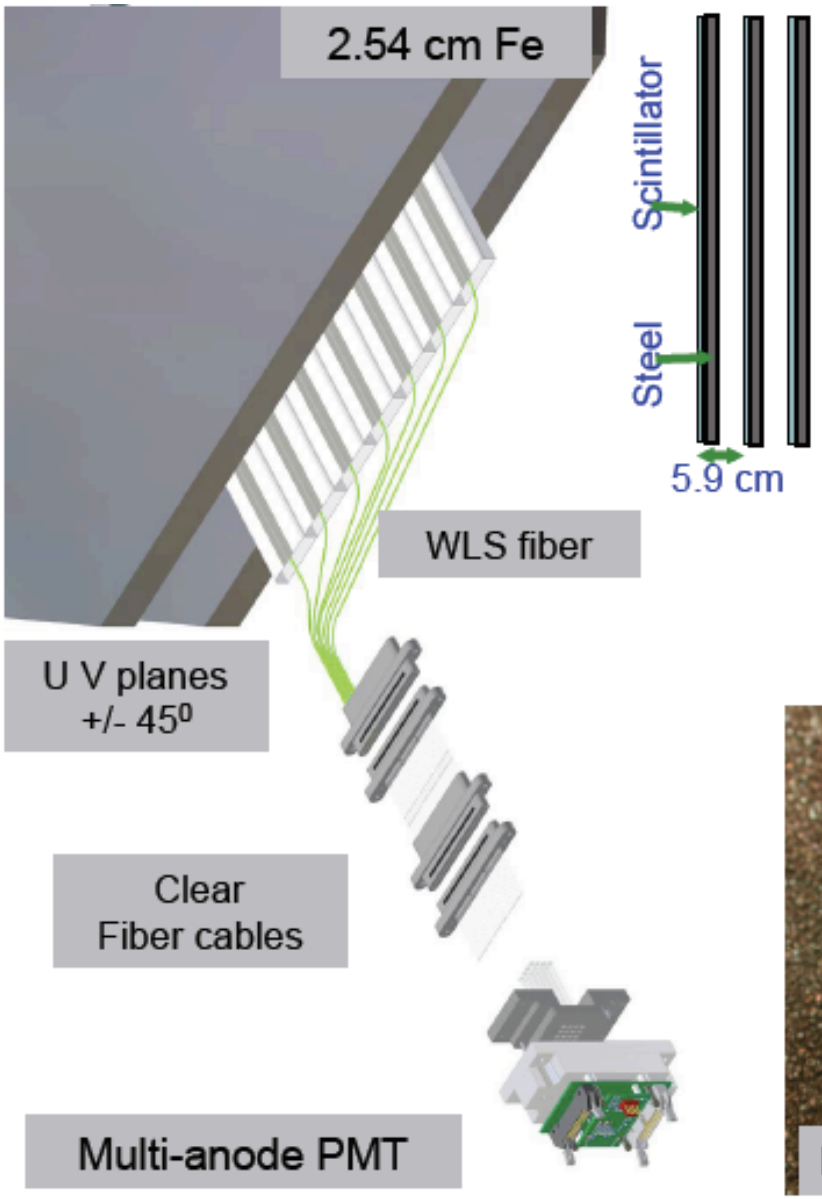
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



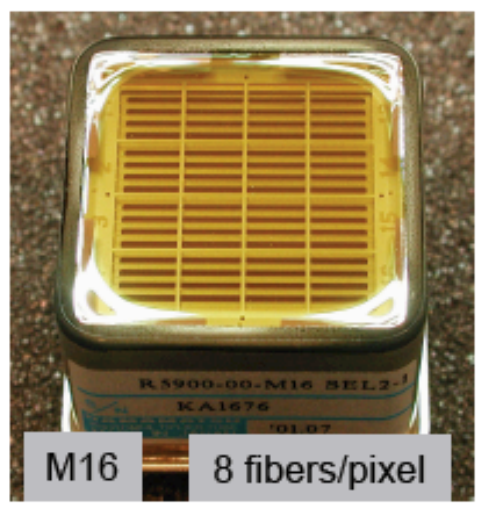


P. Vahle, Neutrino 2010
A. Himmel, FNAL W&C

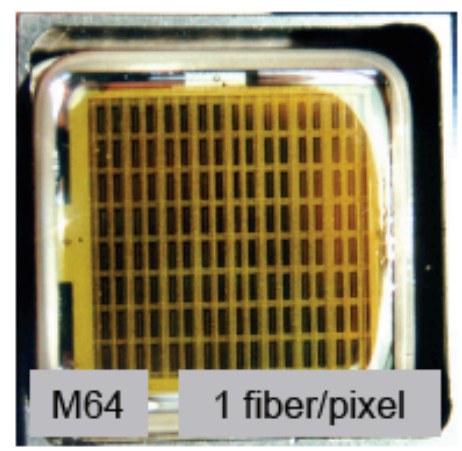
MINOS Detector Technology



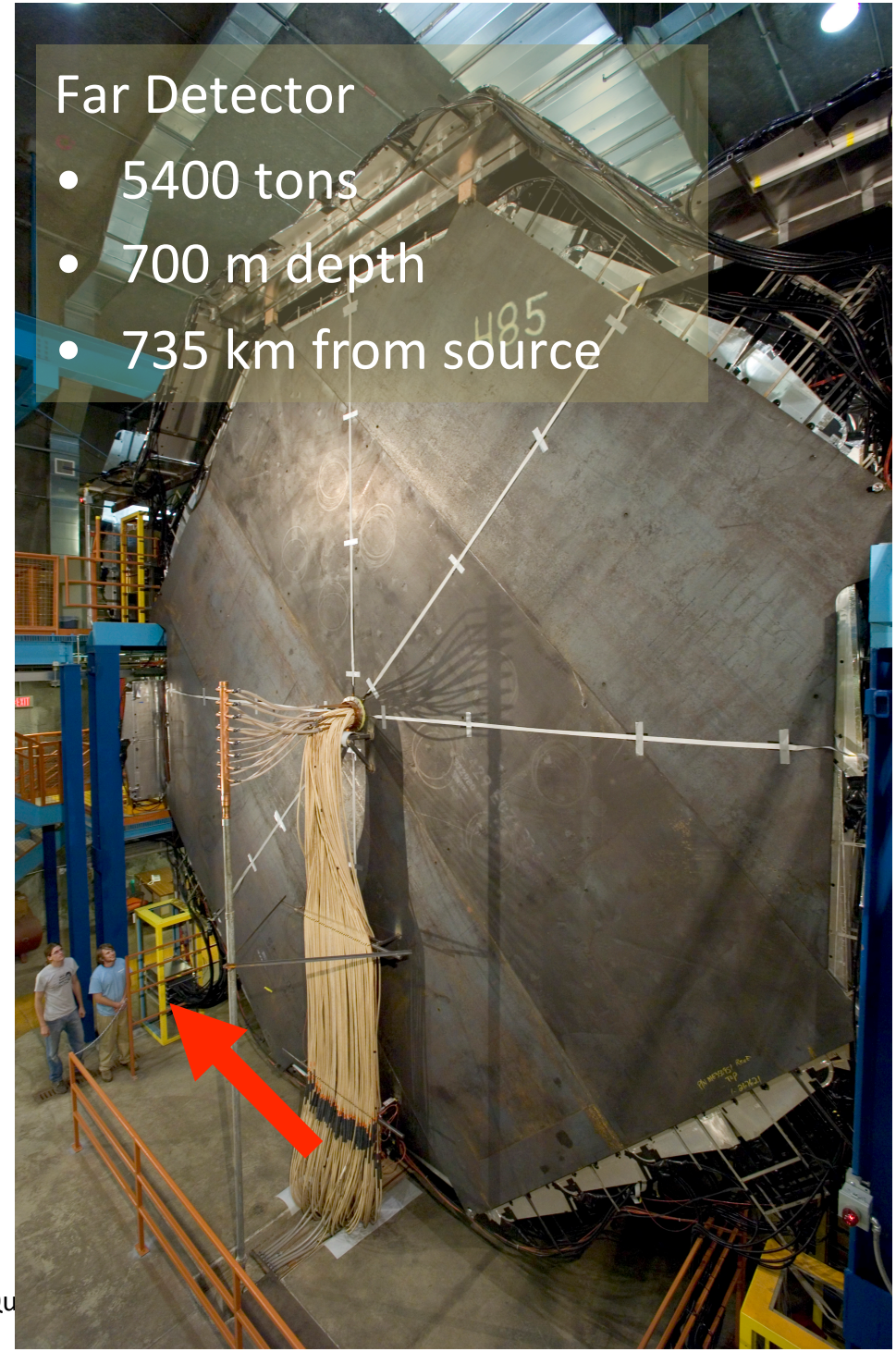
Far Det



Near Det



MINOS Detectors

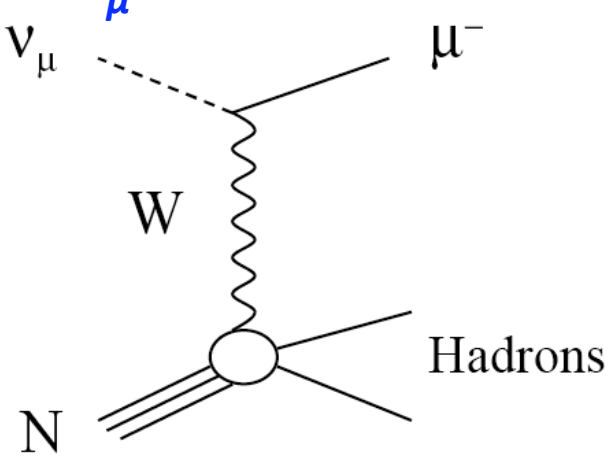


Video

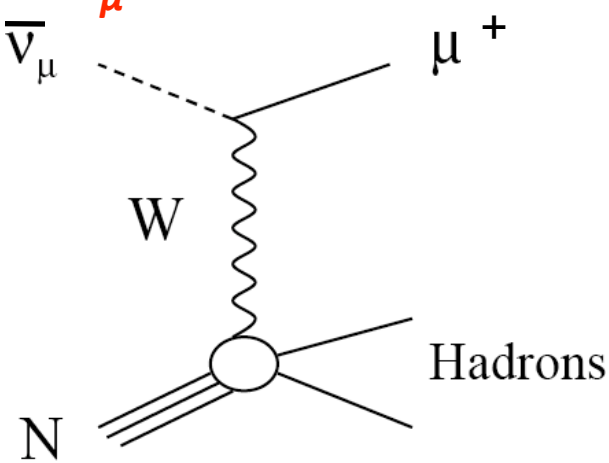
(plane_build_100_seconds.avi)

MINOS Event Topologies

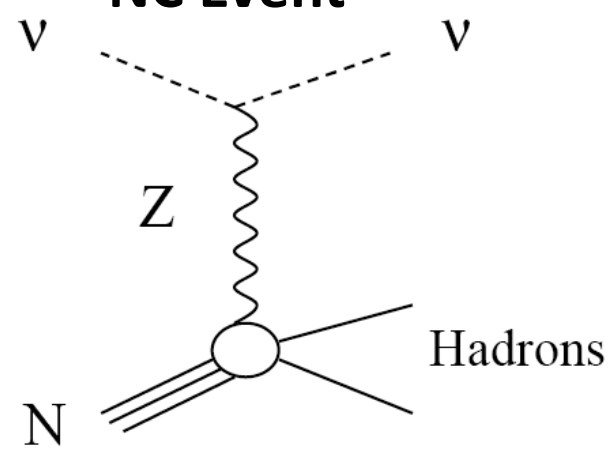
ν_μ CC Event

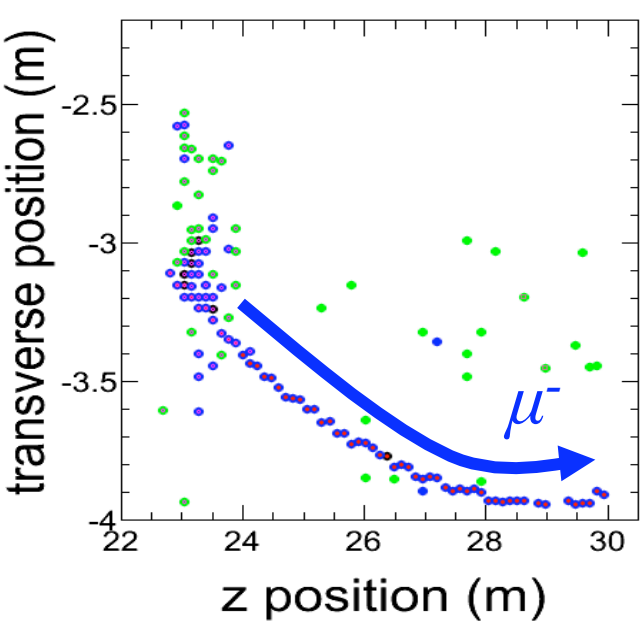


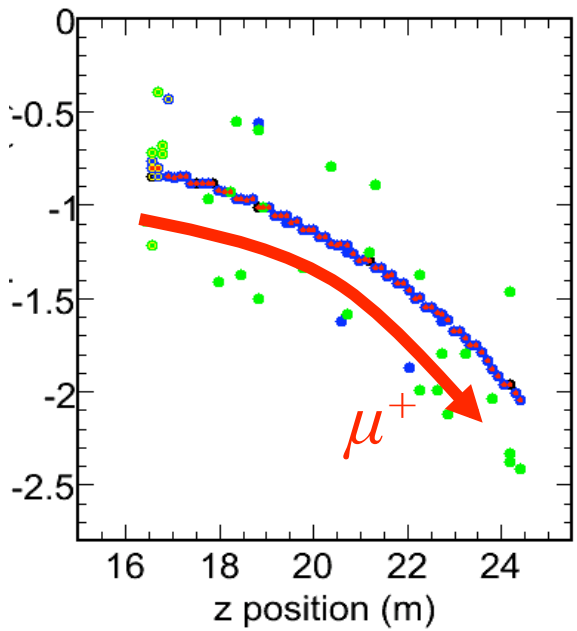
$\bar{\nu}_\mu$ CC Event

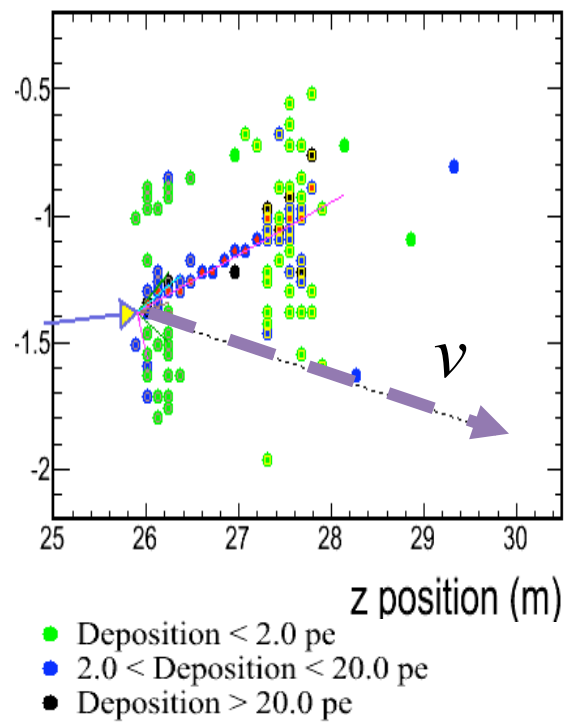


NC Event





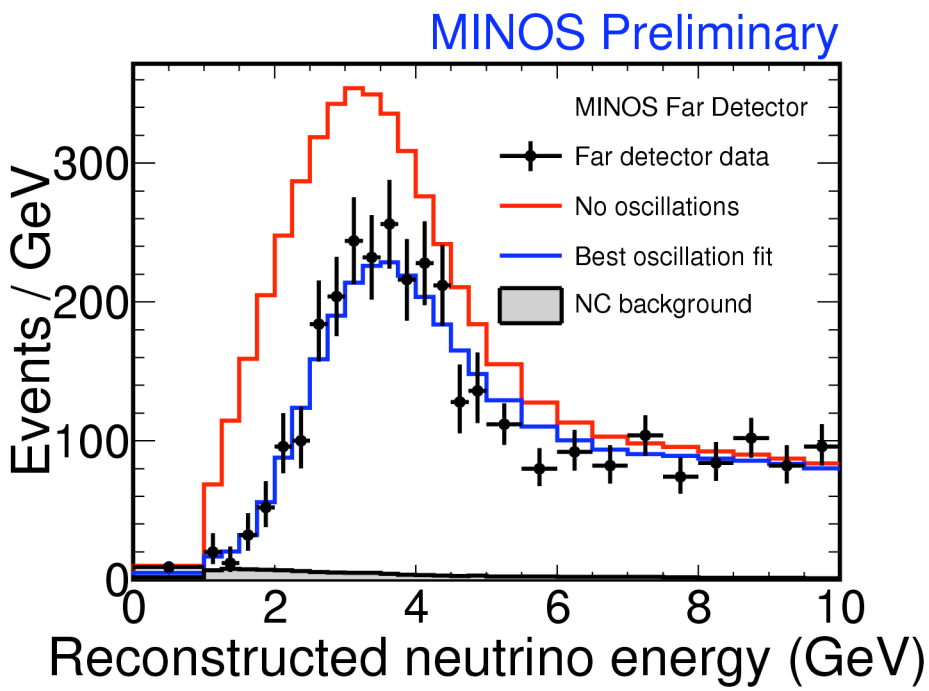


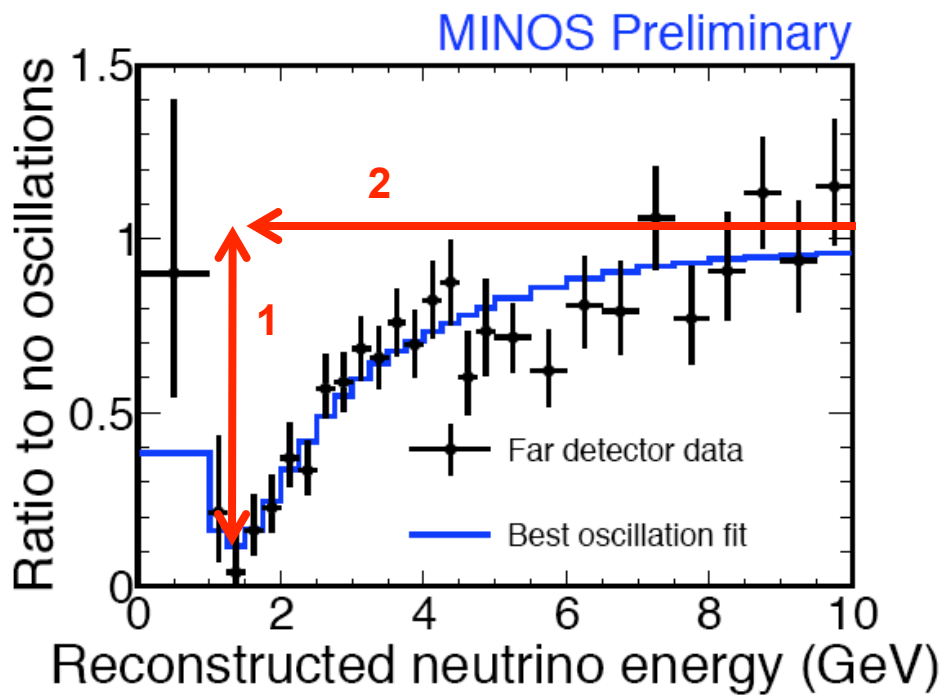


Simulated Events

Experimental Approach

- **Two detector experiment** to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimised
  - Measure unoscillated ν_μ spectrum at Near detector
    - extrapolate using MC
  - Compare to measured spectrum at Far detector





$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \boxed{\sin^2 2\theta}\,\sin^2(1.267\,\boxed{\Delta m^2}\,L/E)$$

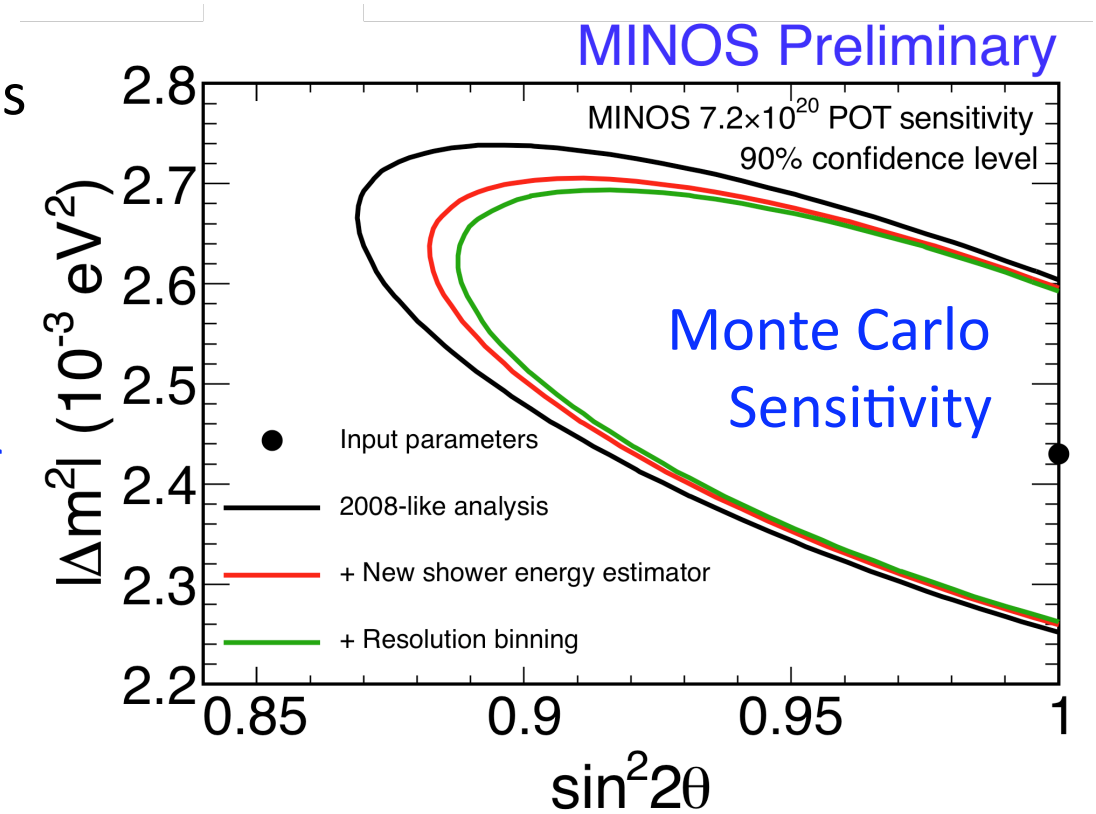
1 2

The Analyses

The Neutrino Analysis

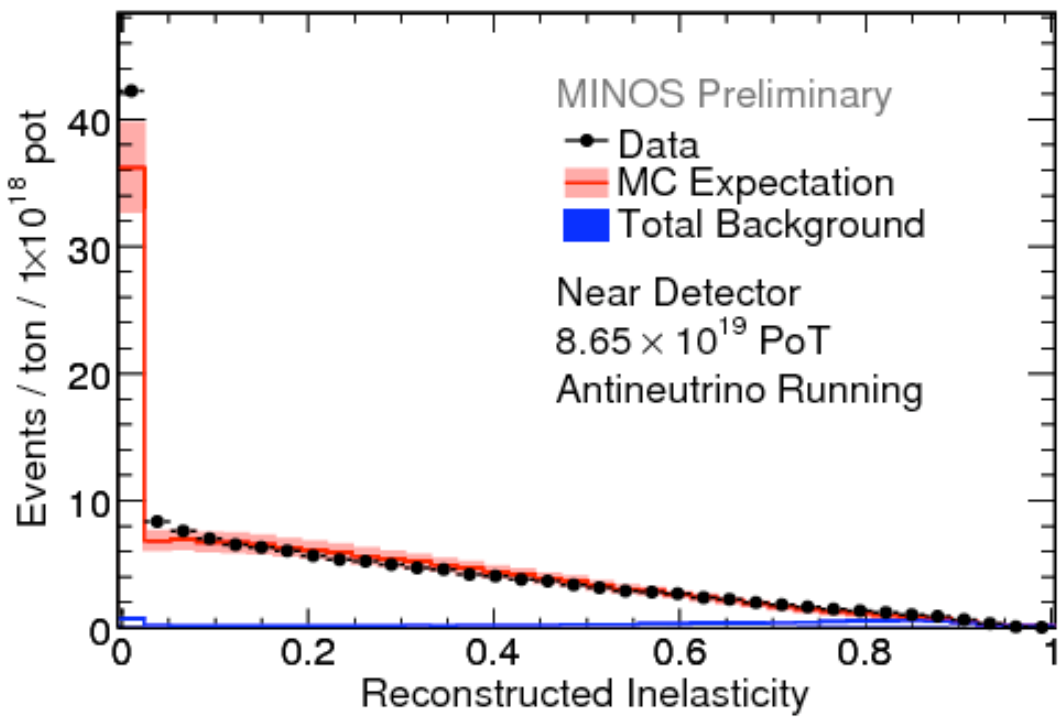
Since our previous 2008 measurement…

- Additional data
  - 3.4×10^{20} to 7.2×10^{20} protons-on-target
- Improvements in the analysis
  - Updated simulation and reconstruction
  - New selection improves low-energy efficiency
  - New shower energy estimator with 30% better low-energy resolution
  - Split the data set into bins of resolution
  - No charge sign cut – reclaim mis-identified neutrino events at low energy



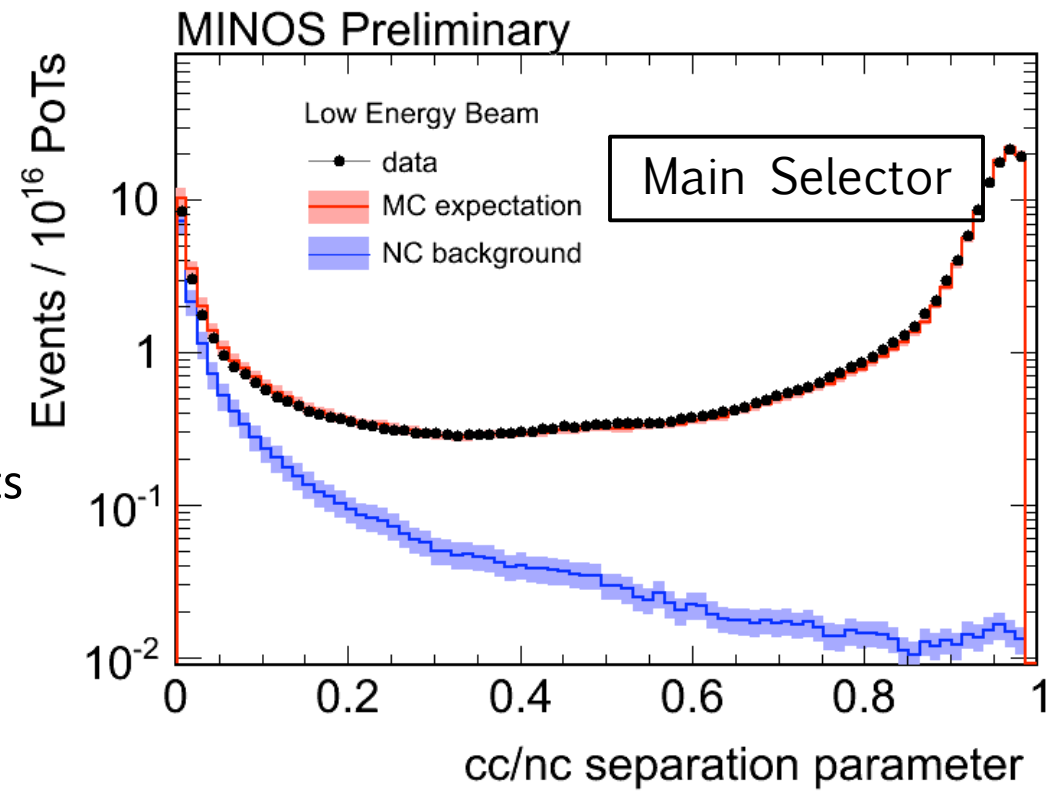
The Anti-neutrino Analysis

- Essentially the neutrino analysis of 2008
  - No resolution binning, shower estimator, new selector
  - Only stopped taking antineutrino data on March 22nd
- What's different with antineutrinos?
  - Lower statistics ~1/12th events
  - Larger wrong-sign component
  - Interactions are less hadronic

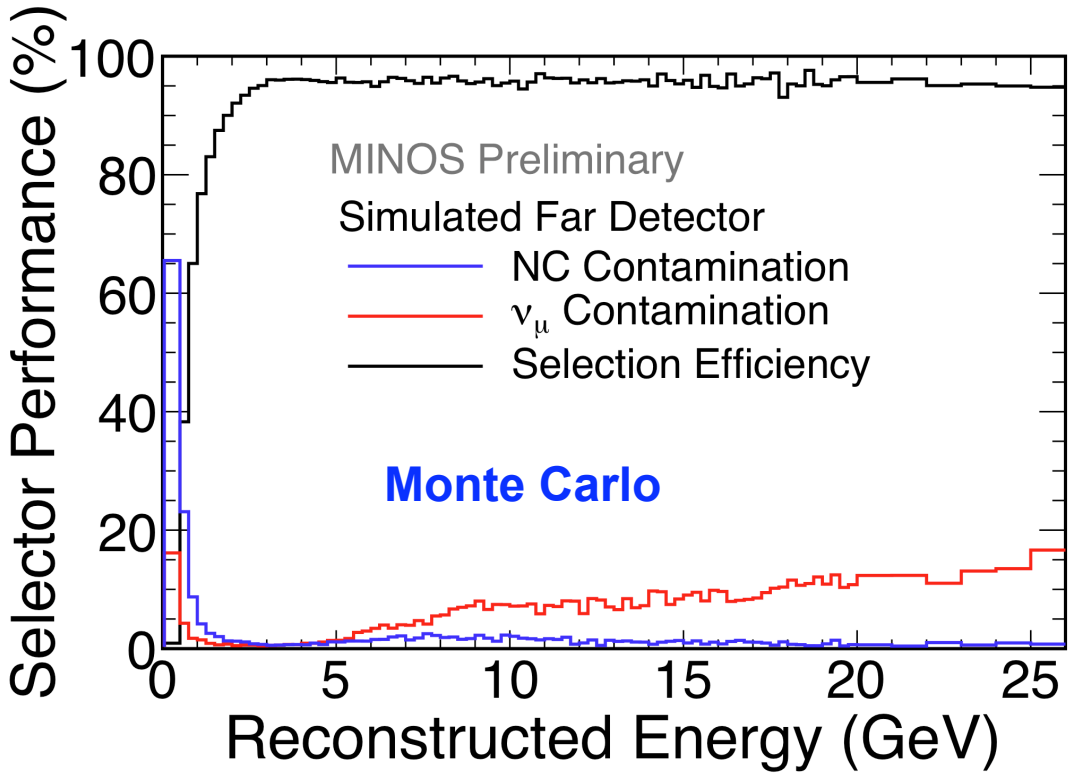


Common Selection

- 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



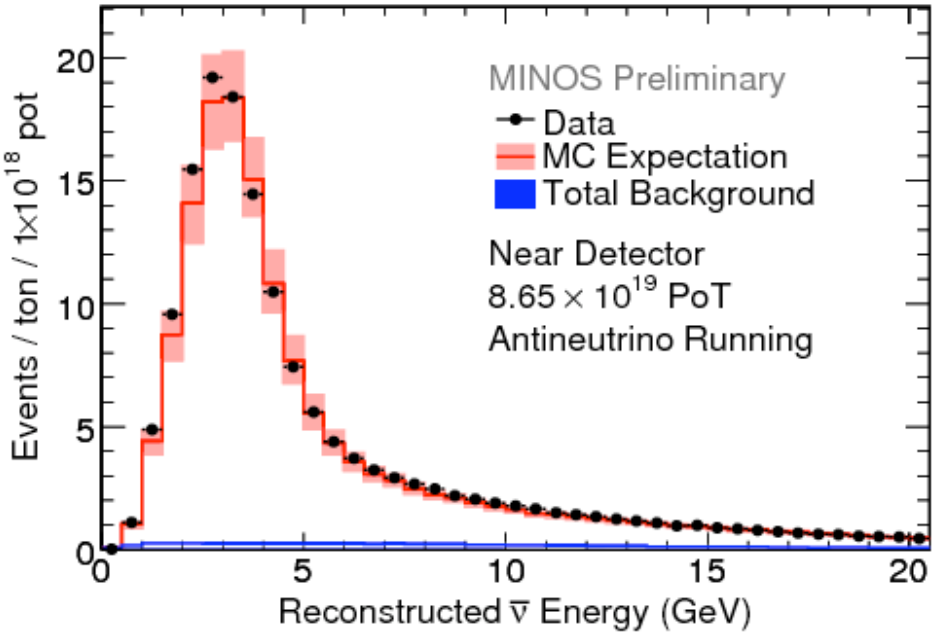
Antineutrino Efficiency & Purity

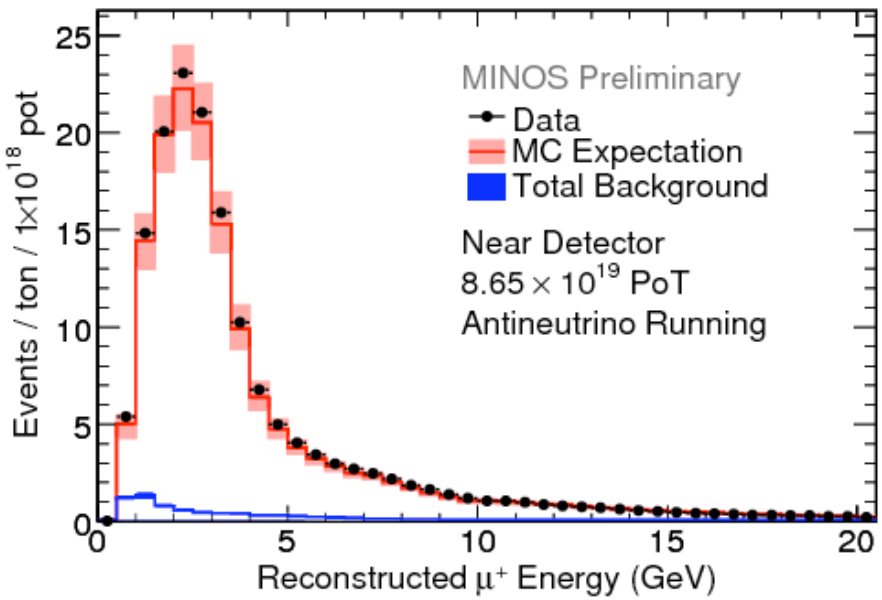


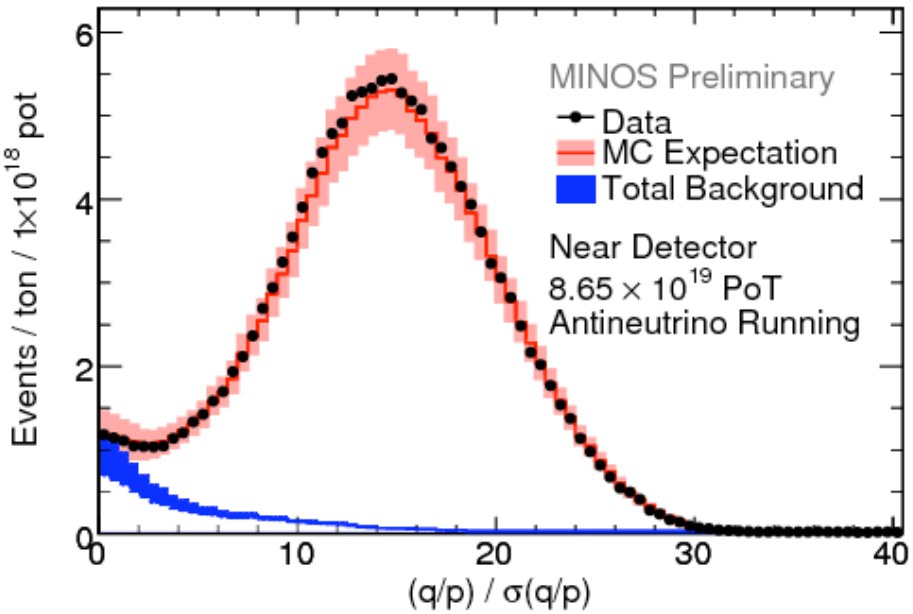
	Signal	Bkgd.
0-6 GeV	106	1.9
6-20 GeV	38	4.3
> 20 GeV	8	3.0

High energy ν_μ contamination does not affect the oscillation result

Near Detector Data





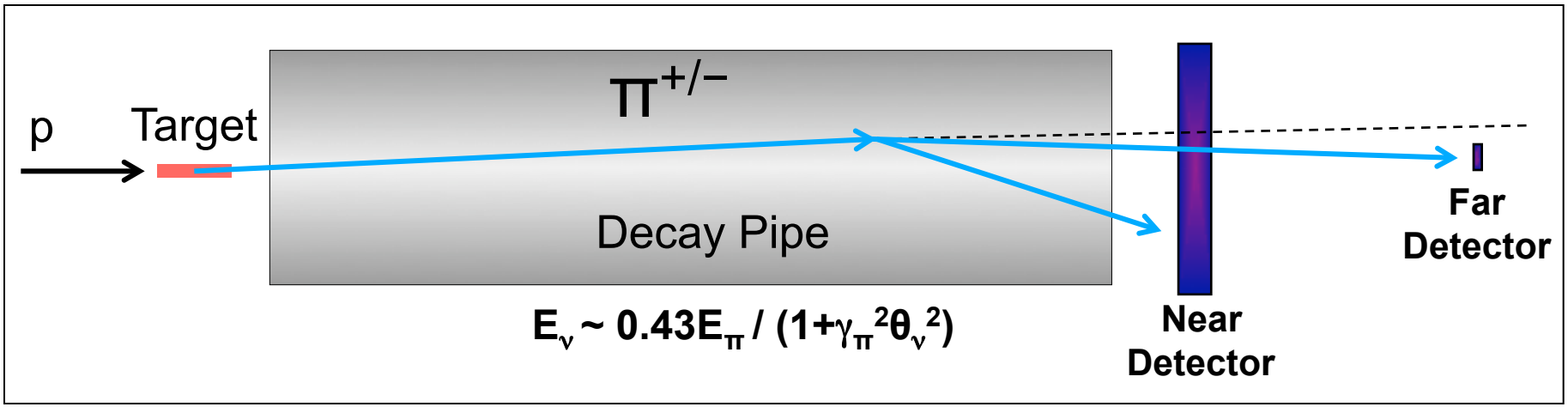


- Data/MC agreement comparable to neutrino running

P. Vahle, Neutrino 2010

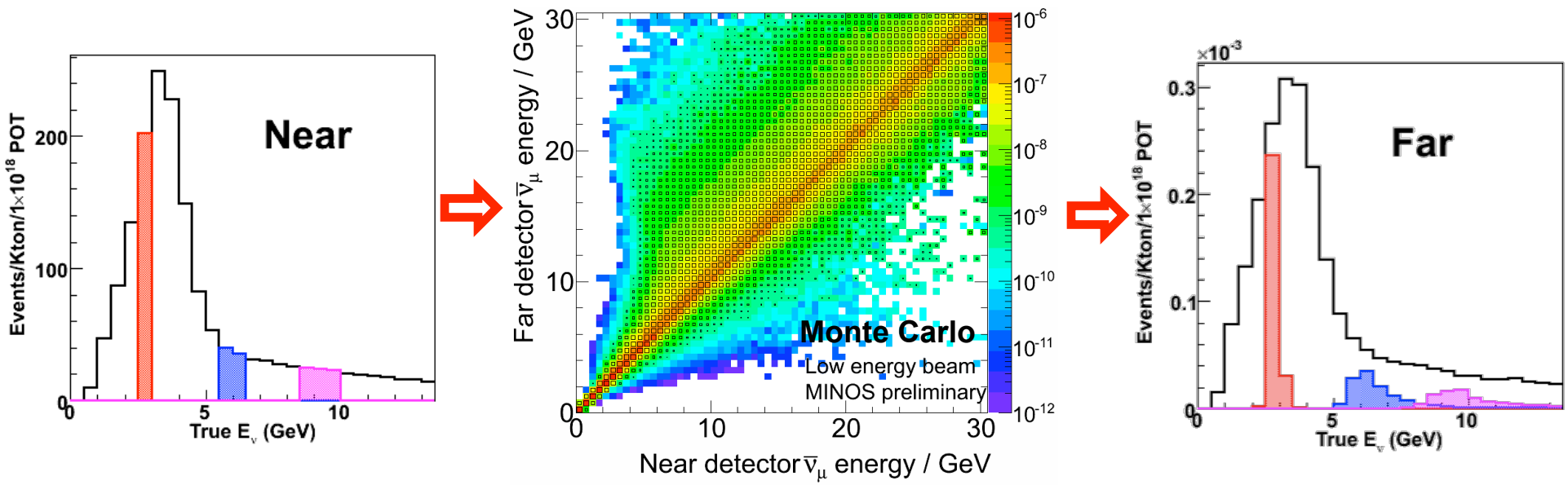
Near to Far Extrapolation

- Near detector spectrum ≠ Far detector
  - Project different solid angles
  - Non-point source for Near detector
  - π/K decay kinematics
    - average neutrino energy varies with angle

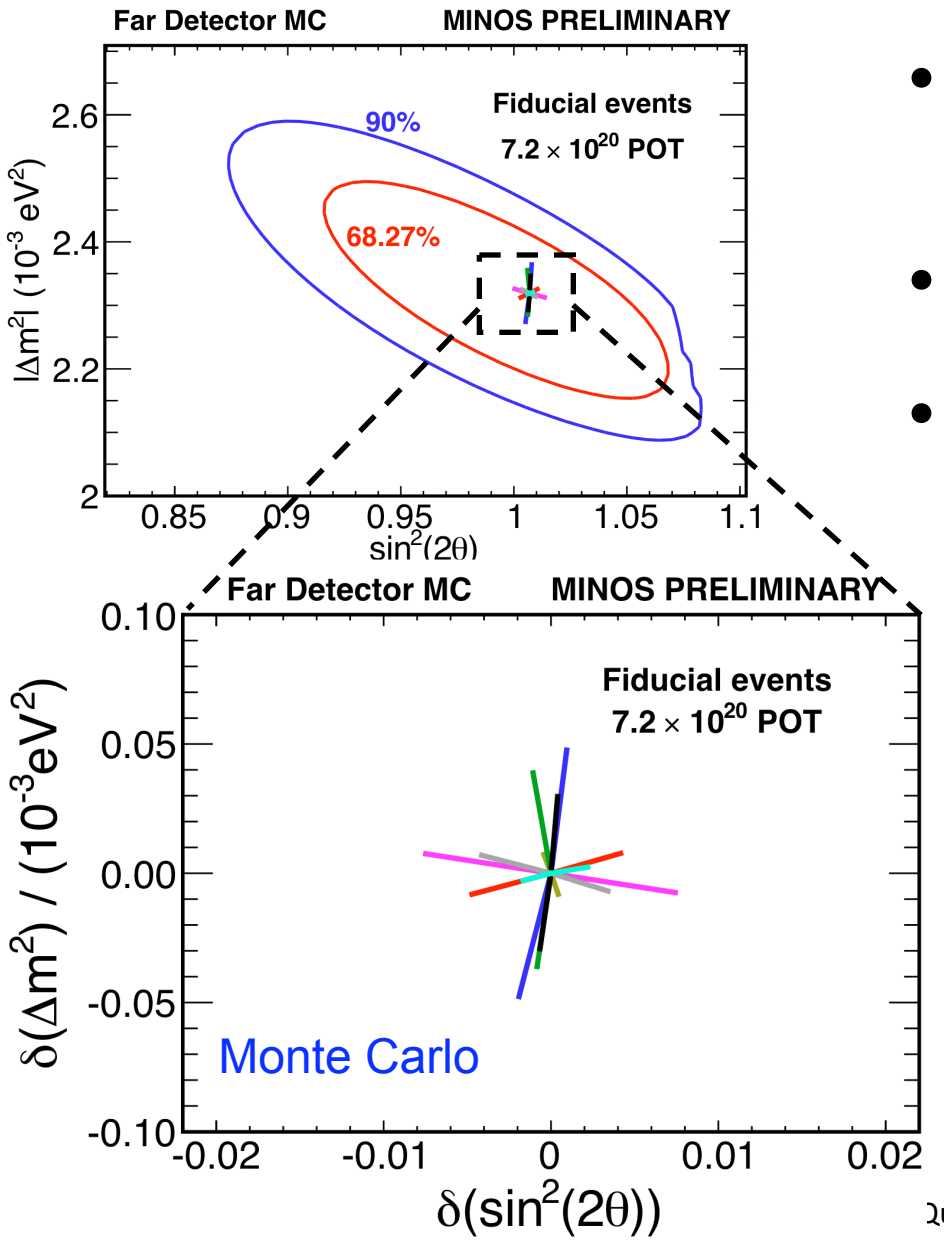


Beam Matrix Extrapolation

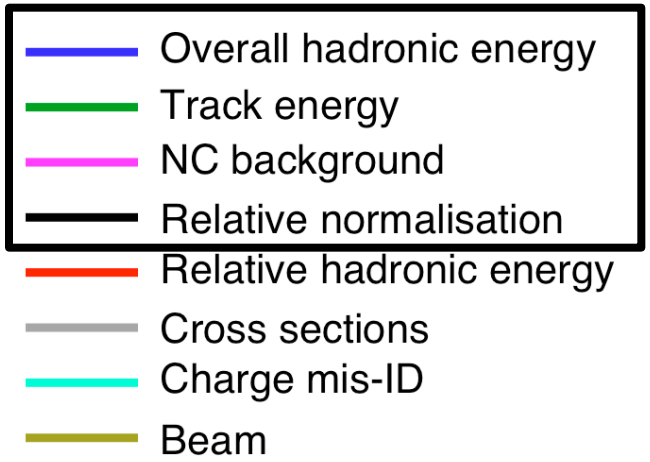
- A beam matrix transports measured Near spectrum to Far
  - ν_μ and $\bar{\nu}_\mu$ are extrapolated independently
- Matrix encapsulates knowledge of meson decay kinematics and beamline geometry
  - Matrix element M_{ij} reflects the probability of obtaining a Far event with energy E_j given the observation of a Near event with energy E_i
- MC used to correct for energy smearing and acceptance



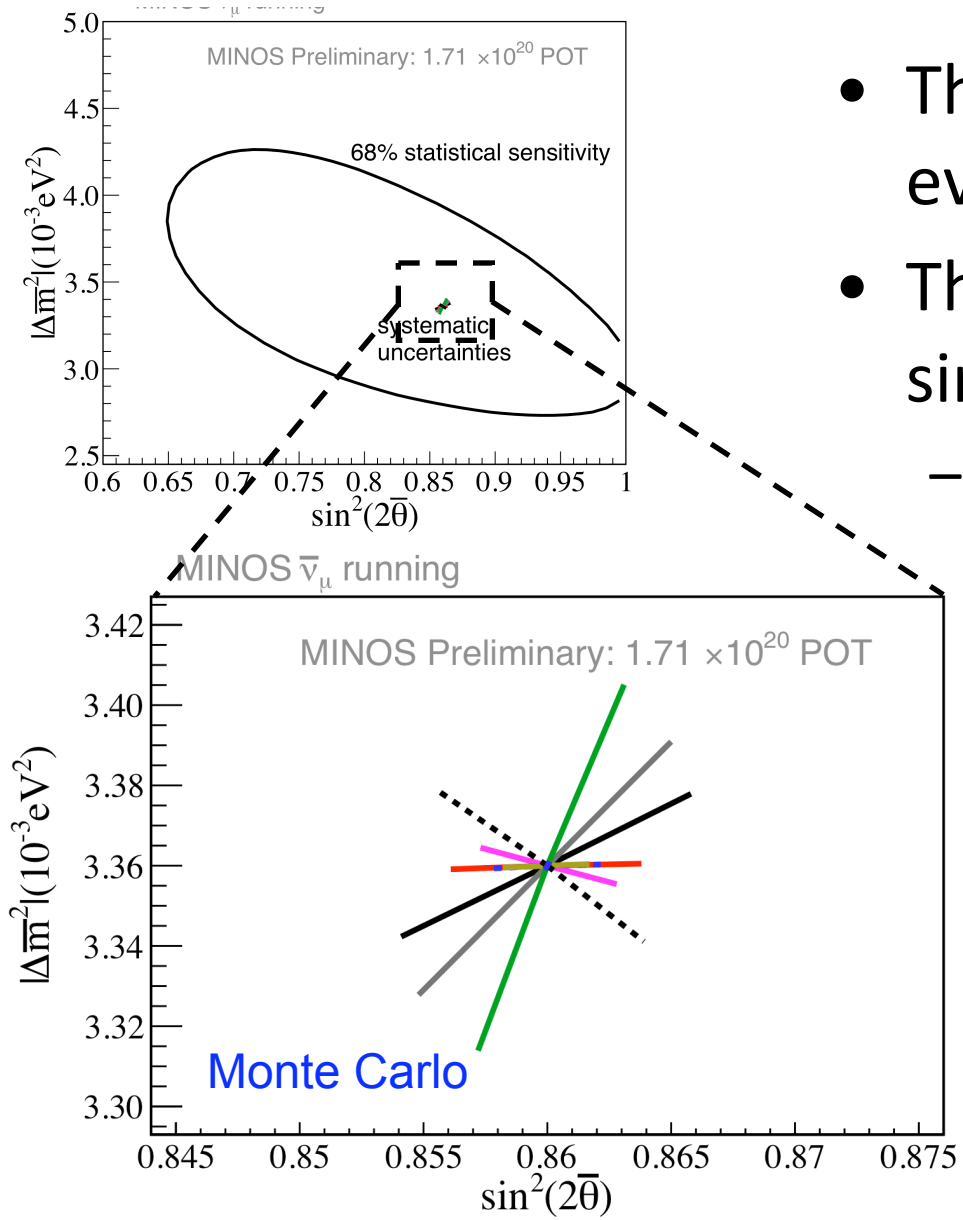
Neutrino Systematics



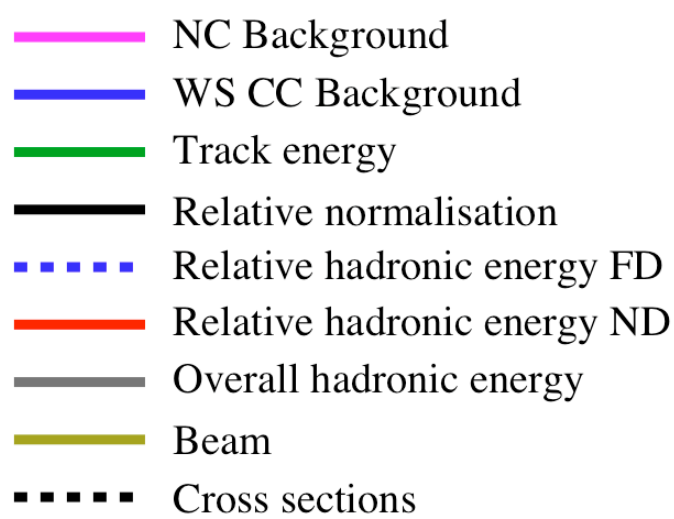
- Effect of uncertainties estimated by fitting systematically shifted MC
- Analysis is still statistically limited
- The 4 largest systematics are included as penalty terms in the fit.



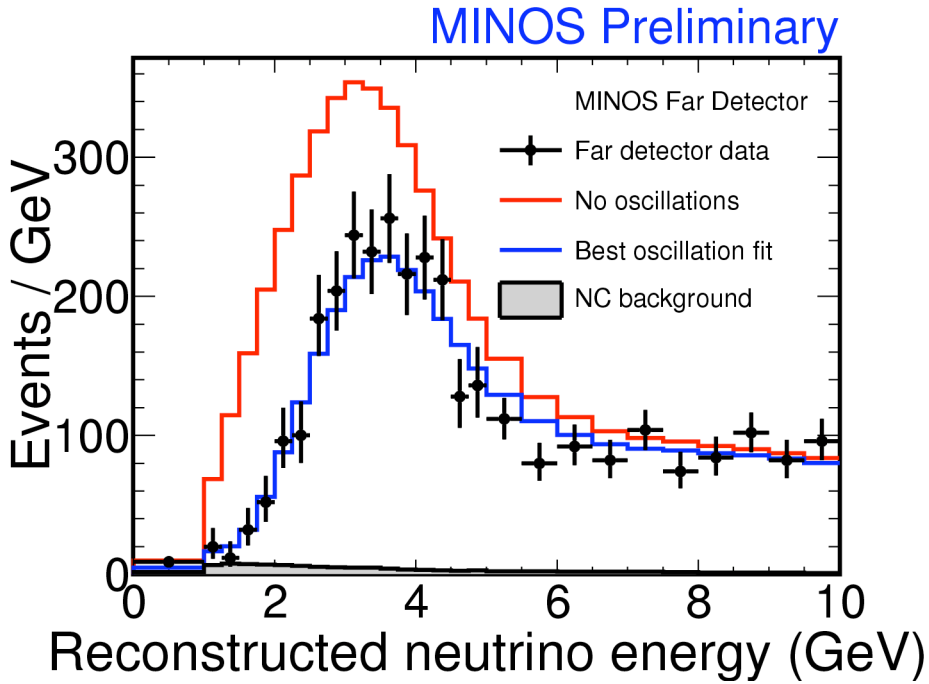
Anti-neutrino Systematics

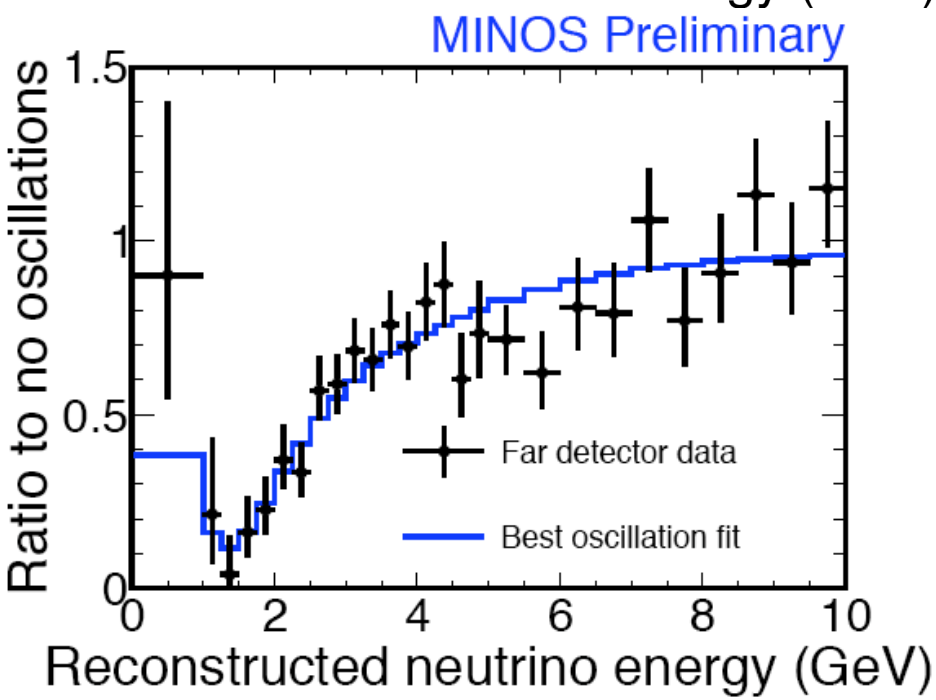


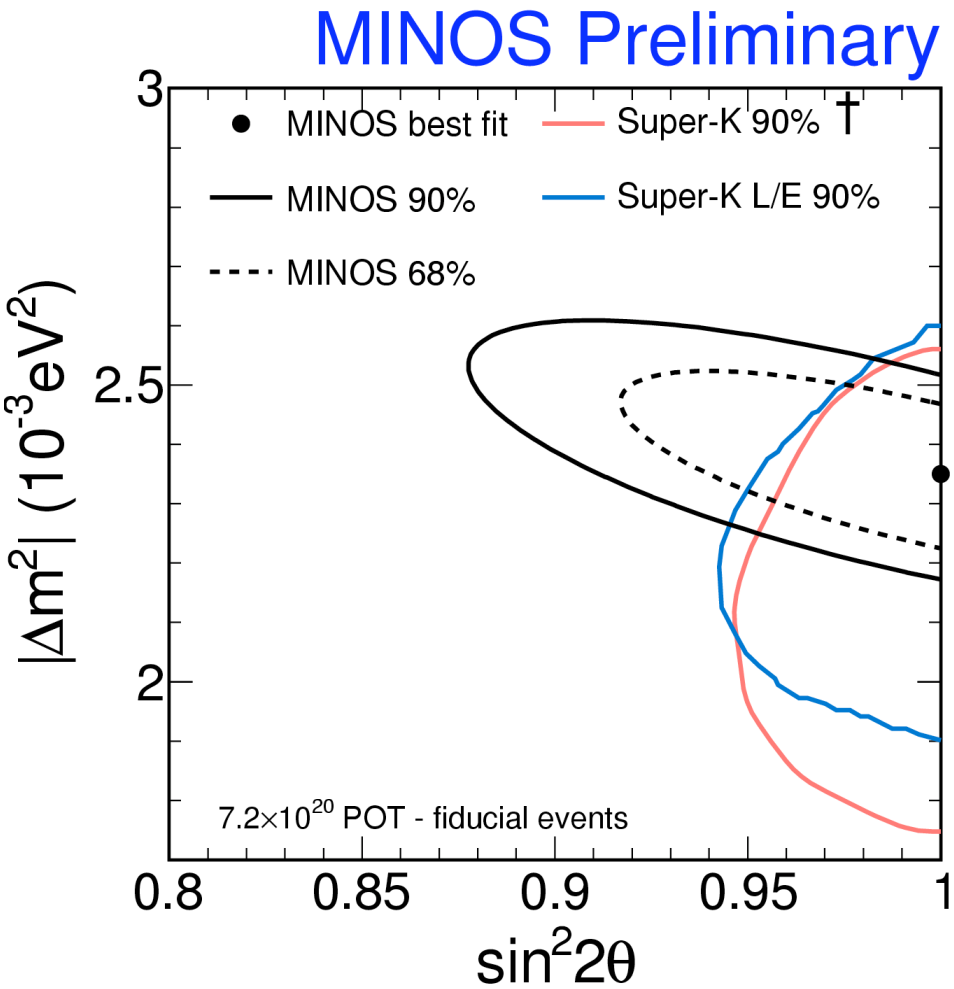
- The antineutrino analysis is even more statistically limited.
- The two analyses have very similar systematics
  - Though sizes of the effects are not the same.



Neutrino Results







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

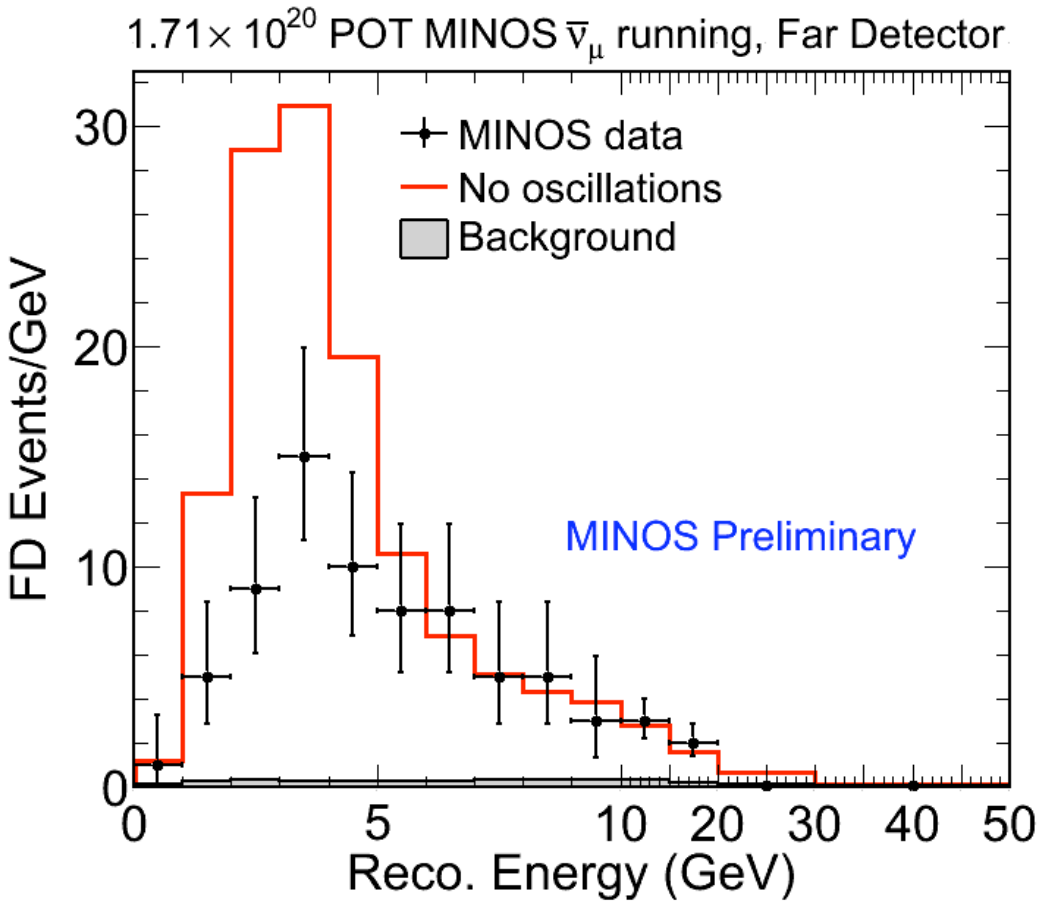
$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

†Super-Kamiokande 2-flavour (preliminary)

[Vahle, Nu2010]

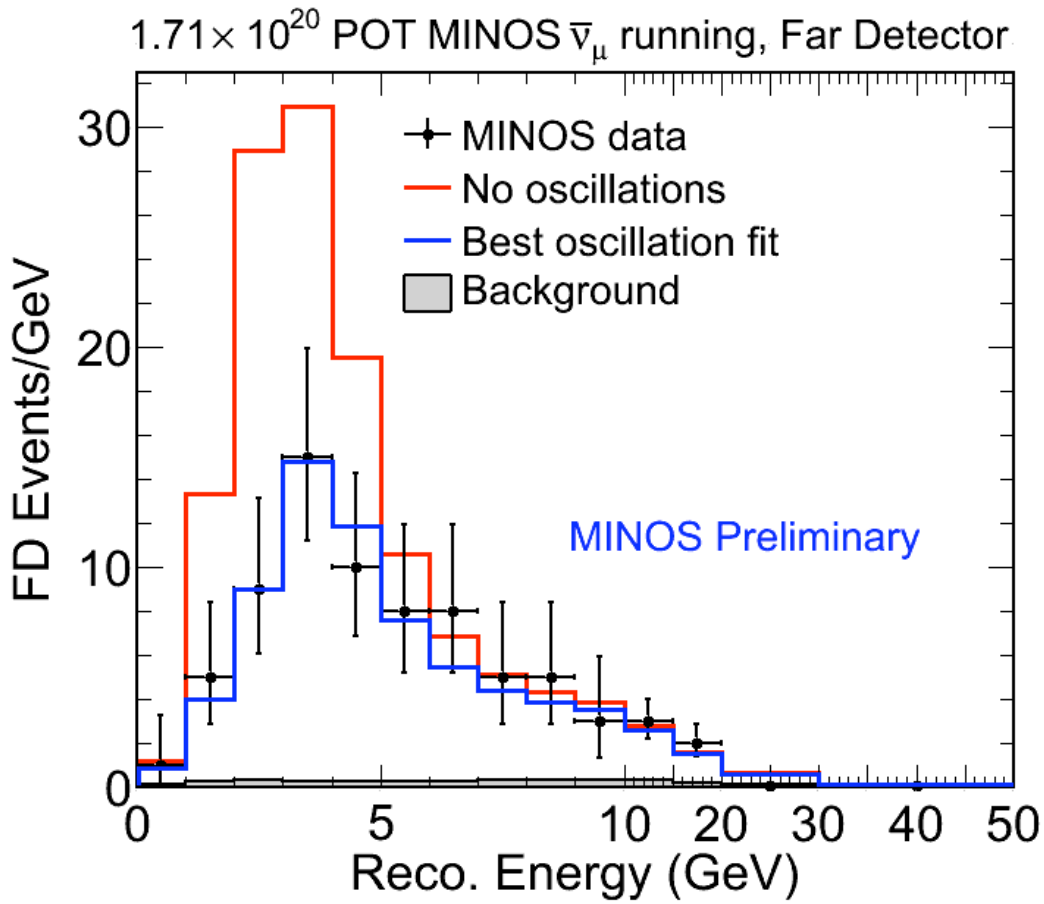
Anti-neutrino Results

Far Detector Data



- No oscillation Prediction: **155**
- Observe: **97**
- No oscillations disfavored at 6.3σ

Far Detector Data

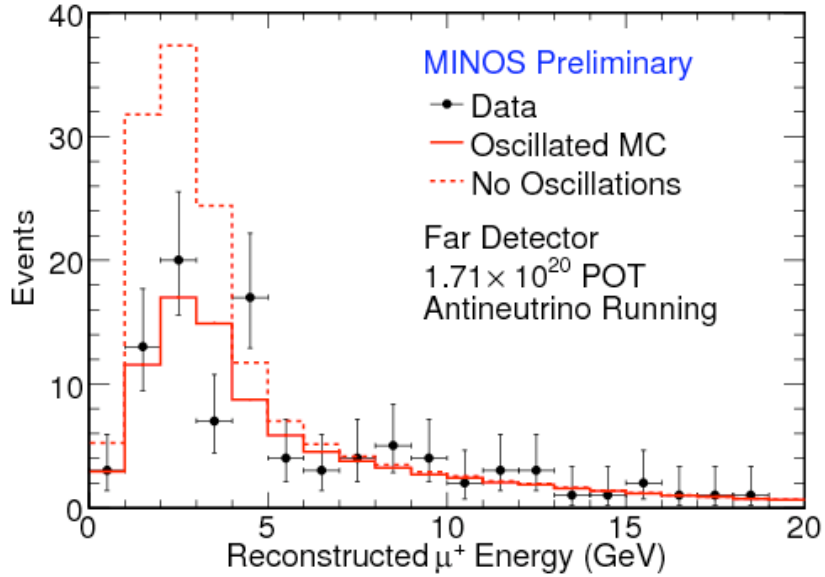


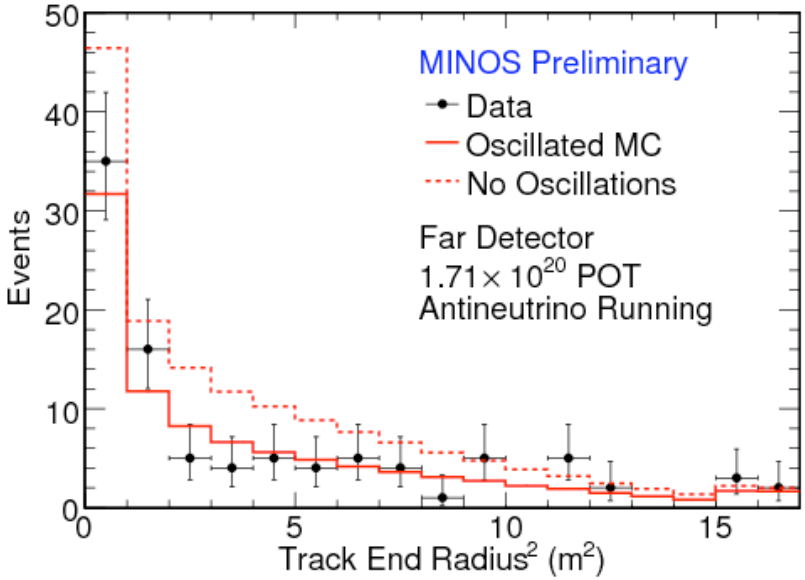
- No oscillation Prediction: **155**
- Observe: **97**
- No oscillations disfavored at 6.3σ

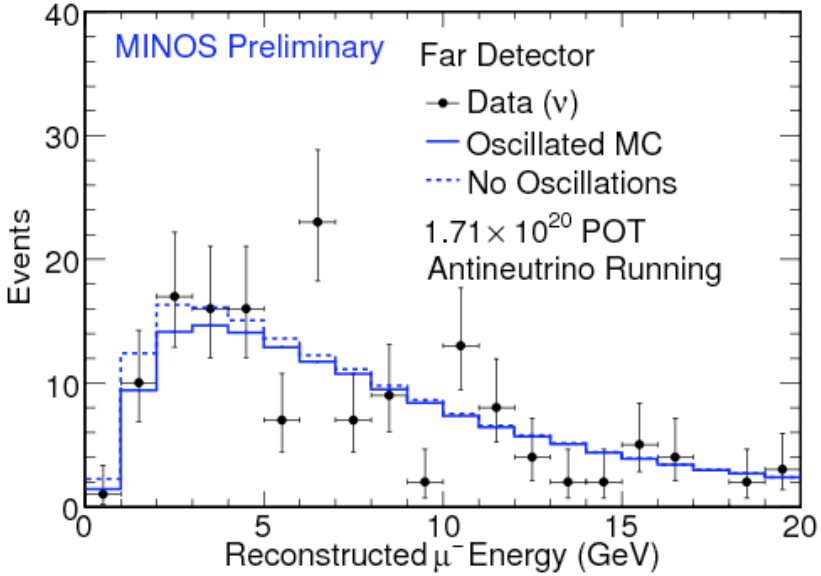
$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

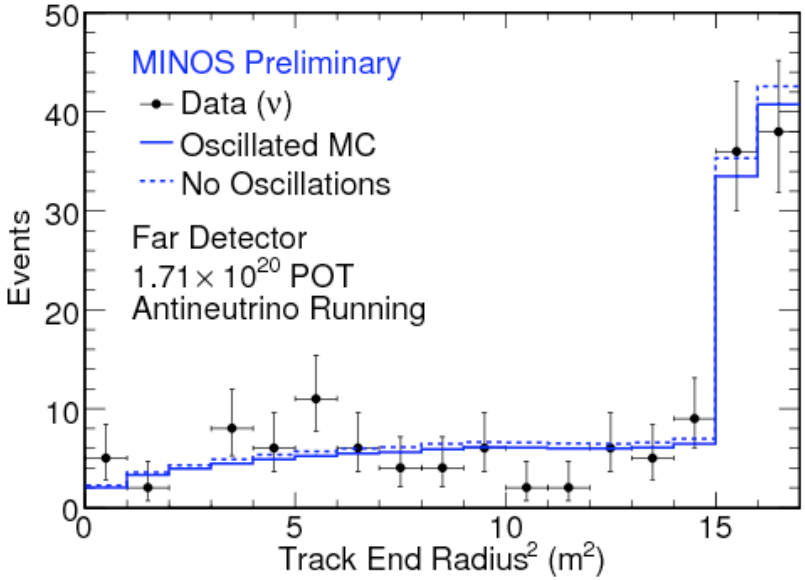
$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

Far Detector Data



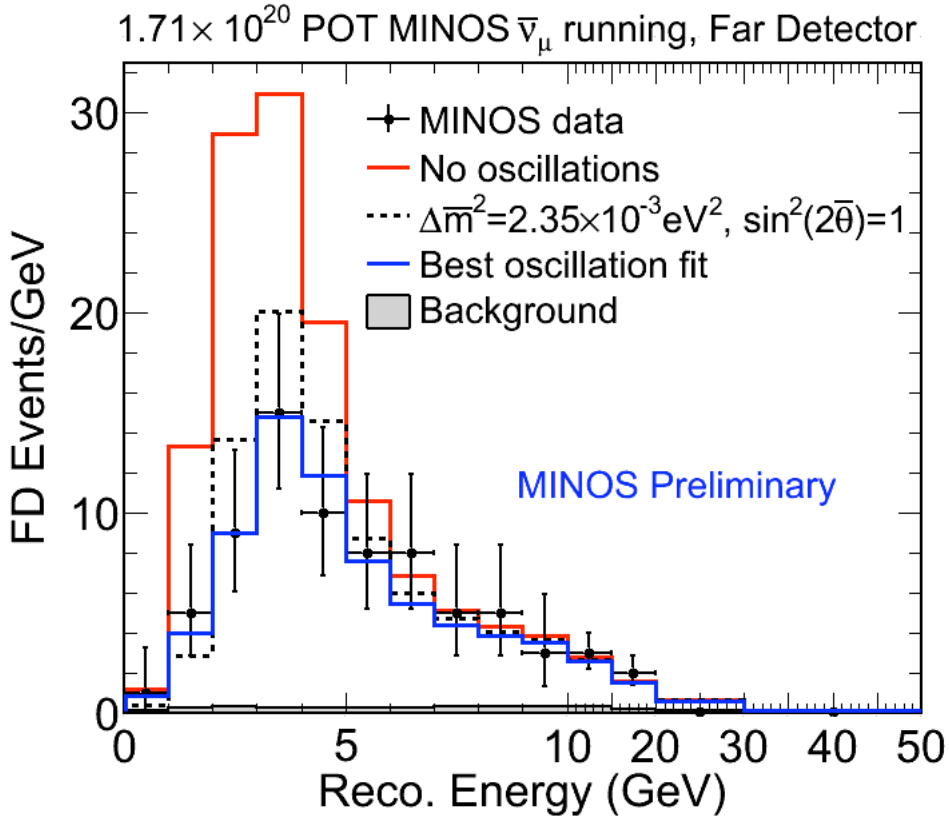


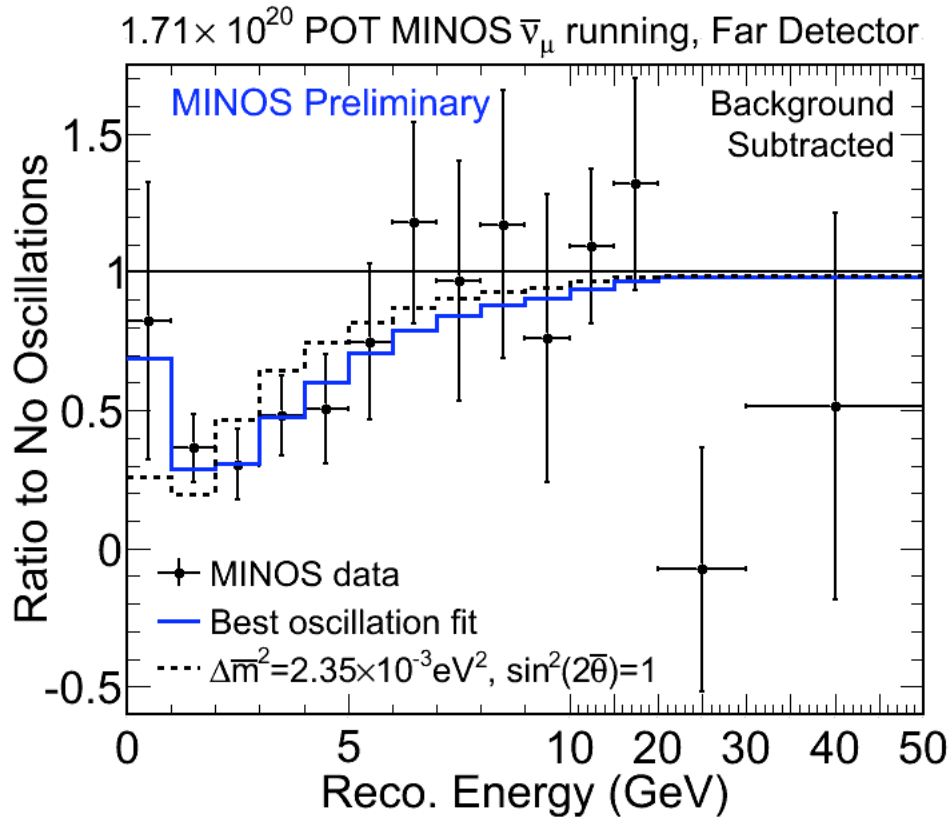




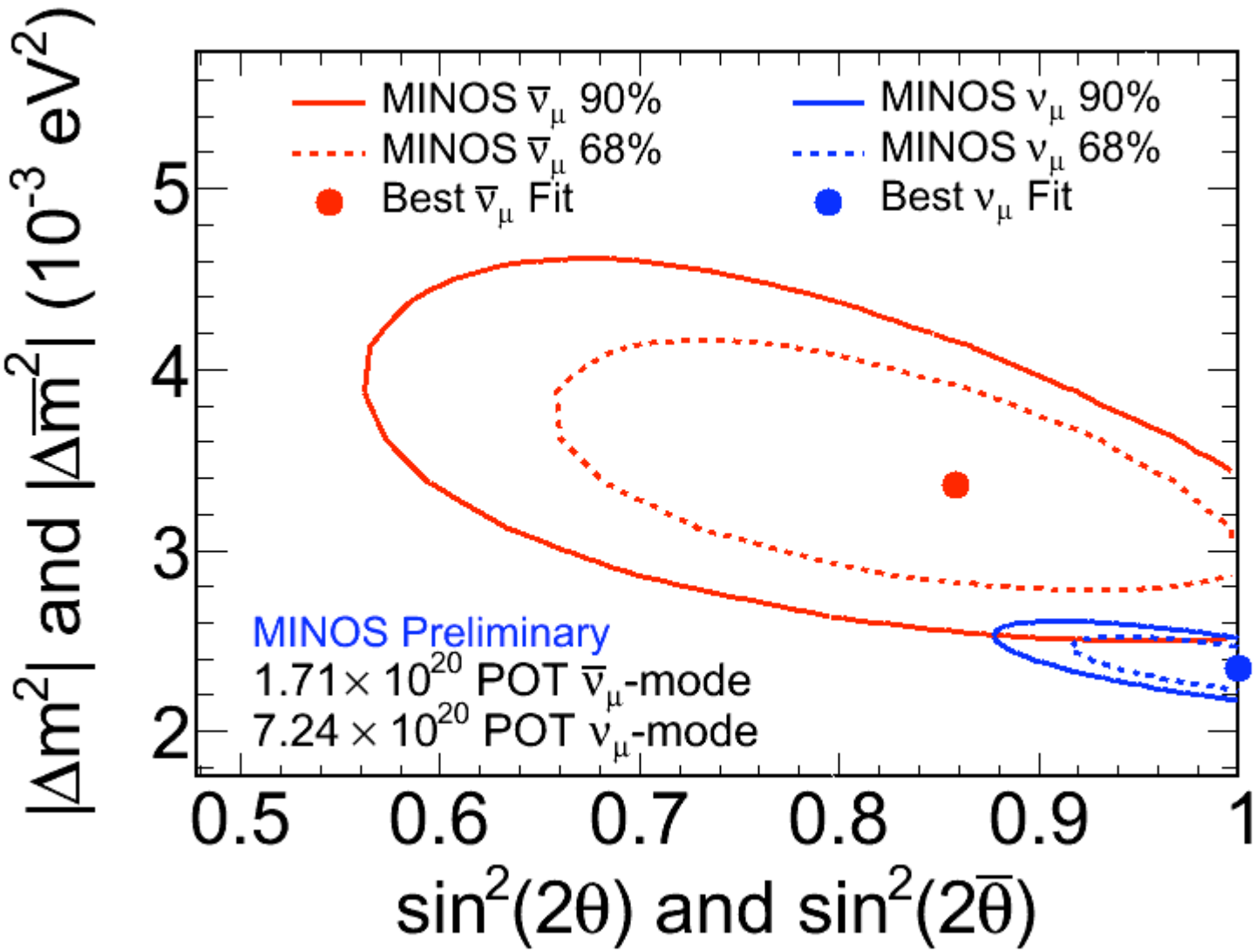
P. Vahle, Neutrino 2010

Comparisons to Neutrinos





Comparisons to Neutrinos



P. Vahle, Neutrino 2010

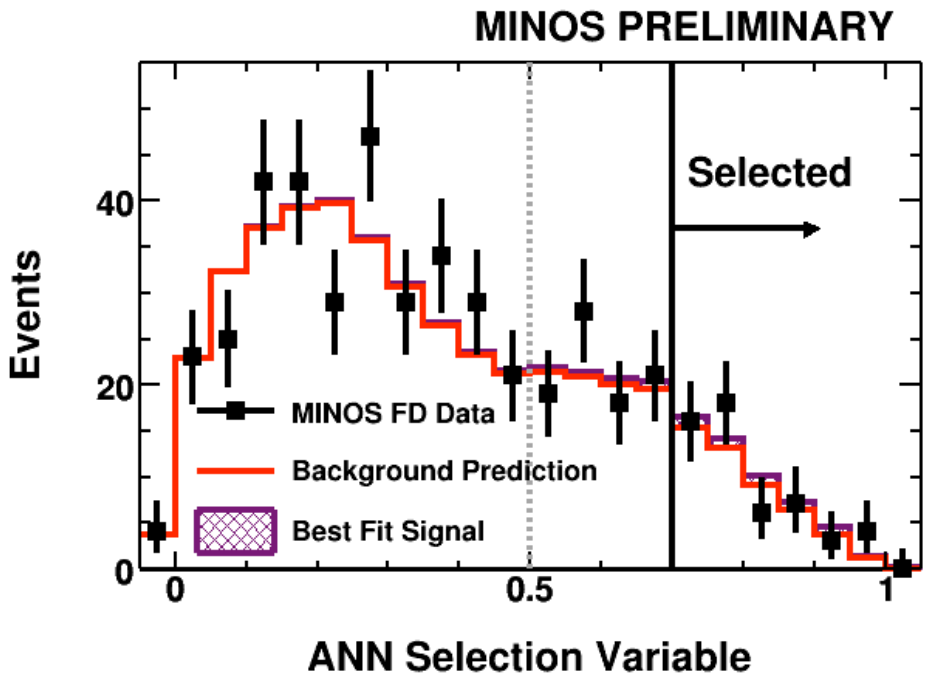
Electron Neutrino Appearance Analysis

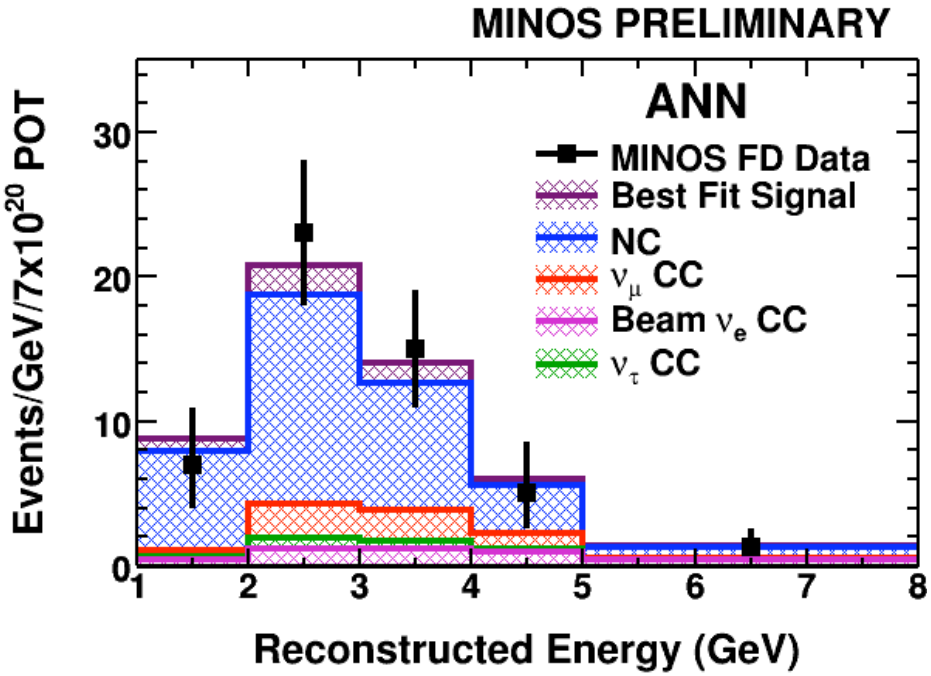
$\nu_\mu \rightarrow \nu_e$ Oscillation Search Overview

- Sub-dominant neutrino oscillations
  - Look for ν_e appearance at Far detector
    - $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$
      - also CPv and matter effects: not shown here but included in fit
  - Electron neutrino events only 2% of total (at Chooz limit)
- Select events w/ compact shower, typical EM profile
  - MINOS optimised for ν_μ
  - ν_e signal selection is harder
    - Steel thickness 2.5 cm = 1.4 X_0
    - Strip width 4.1cm ~ Molière radius (3.7cm)
- Use the Near detector to determine the background

ν_e Appearance Results

- Based on ND data, expect: **49.1±7.0(stat.)±2.7(syst.)**
- Observe: **54** events in the FD, a 0.7σ excess





P. Vahle, Neutrino 2010

ν_e Appearance Results

for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

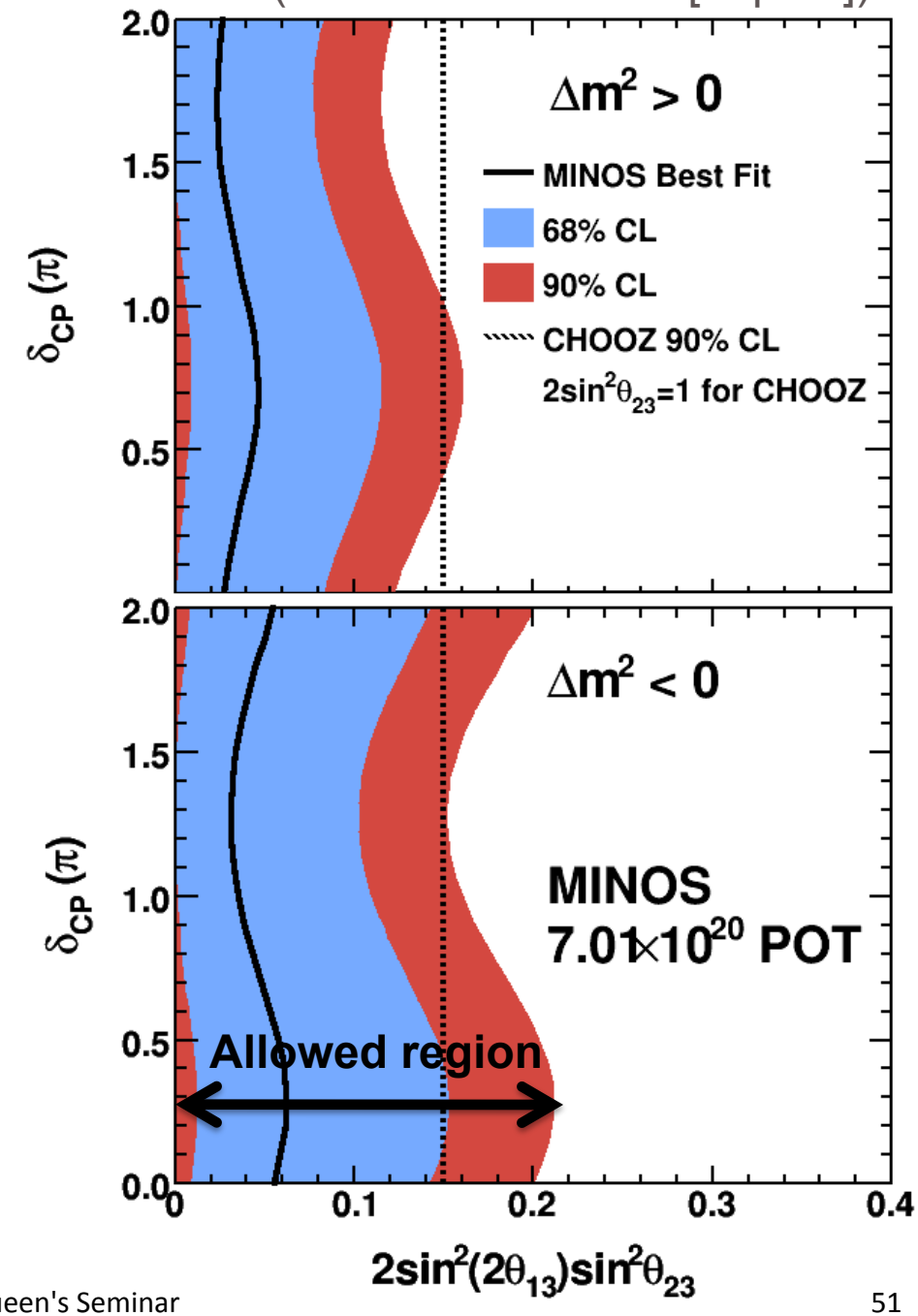
$$\left|\Delta m^2_{32}\right| = 2.43 \times 10^{-3}\ \mathrm{eV}^2$$

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

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

at 90% C.L.

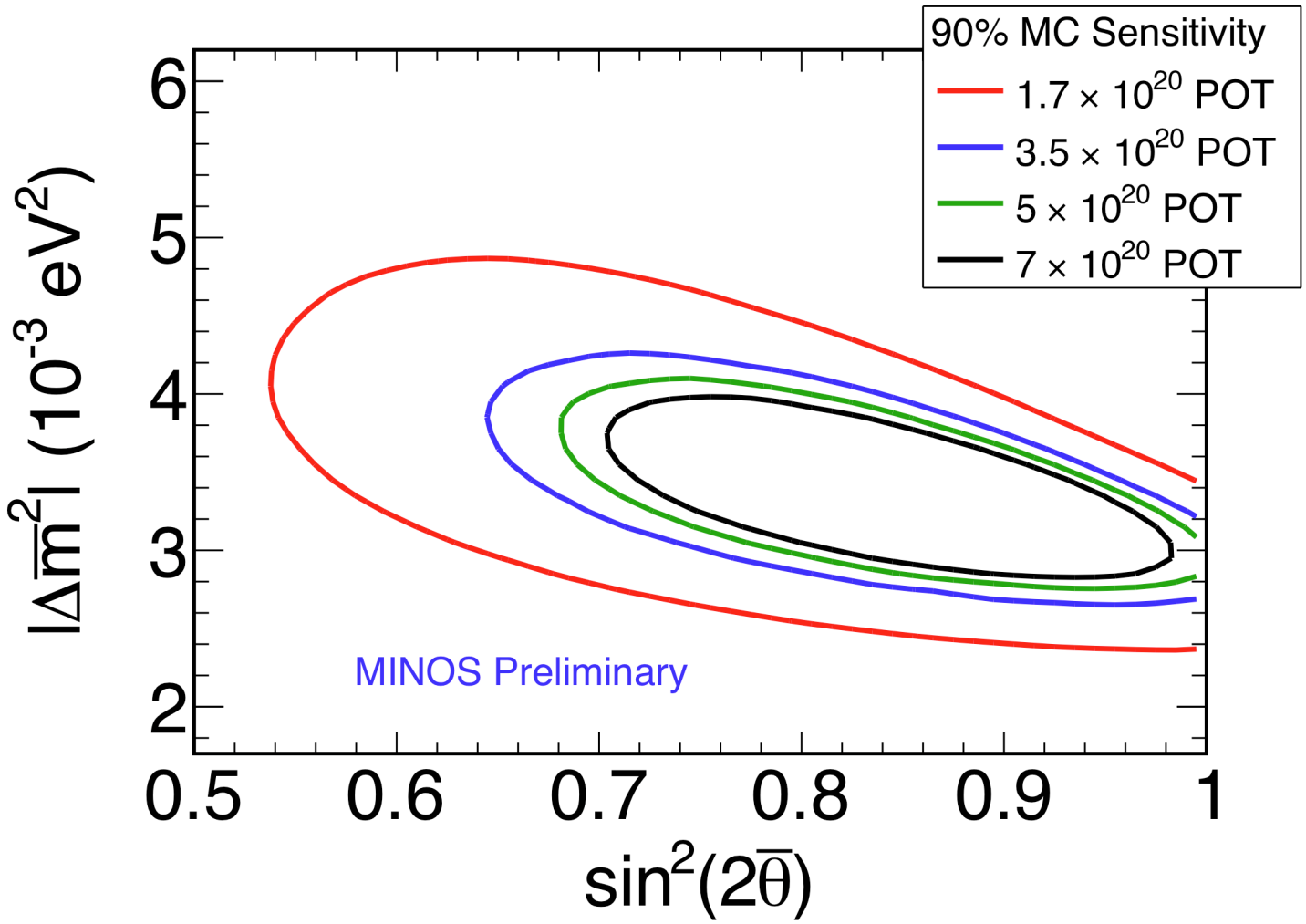
(arXiv:1006.0996v1 [hep-ex])



[Vahle, Nu2010]

Future Plans

More anti-neutrinos…



Neutrino Physics Program

Latest Fermilab-PAC Report

Please comment on

1. *Status and plans for the Fermilab neutrino program.*

2. *The significance of the recent antineutrino results from MiniBooNE and MINOS and relevance for possible further antineutrino-mode running in the Booster Neutrino Beam and NuMI beam.*

Neutrino Beam Operations and Experiments

The PAC commends the Fermilab Accelerator Division for the superb operation of both the NuMI and Booster Neutrino Beam programs. The Committee was pleased to see the exciting new results from both the MINOS and MiniBooNE experiments on their antineutrino running and first events from the completed MINERνA detector. The PAC looks forward to the upcoming results from the SciBooNE and ArgoNeuT experiments. The Committee is also impressed with the progress that has been made on the construction of the NOνA experiment.

NuMI Beamline Running

Given the two-sigma difference currently observed between neutrinos and antineutrinos in the mass difference vs. mixing angle plane [Δm_{23}^2 and $\sin^2(2\ \theta_{23})$], the Committee recommends further antineutrino running for MINOS. For the NuMI beamline, there is a short-fall in the total number of protons on target (POT) required to satisfy the requested additional 2.5×10^{20} POT by MINOS with antineutrino running and the requested 4.9×10^{20} POT by MINERνA with neutrino running before the NOνA shutdown in March 2012. The Committee recommends sharing the short-fall of POT such that MINOS receives ~90% of the total requested POT for antineutrino running and MINERνA receives ~90% of the total requested POT for neutrino running - assuming the current operation capabilities of the NuMI beamline.

Conclusions

- MINOS has most precise measurement of $|\Delta m^2_{\text{atm}}|$
- First direct, precision measurement $|\Delta \bar{m}^2_{\text{atm}}|$

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

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

- World's best limit on electron neutrino appearance
  - improves Chooz bound in the normal hierarchy
- Will more than double the antineutrino data set
  - watch this space!

Backup slides

What about the Muon **Anti-**Neutrinos…

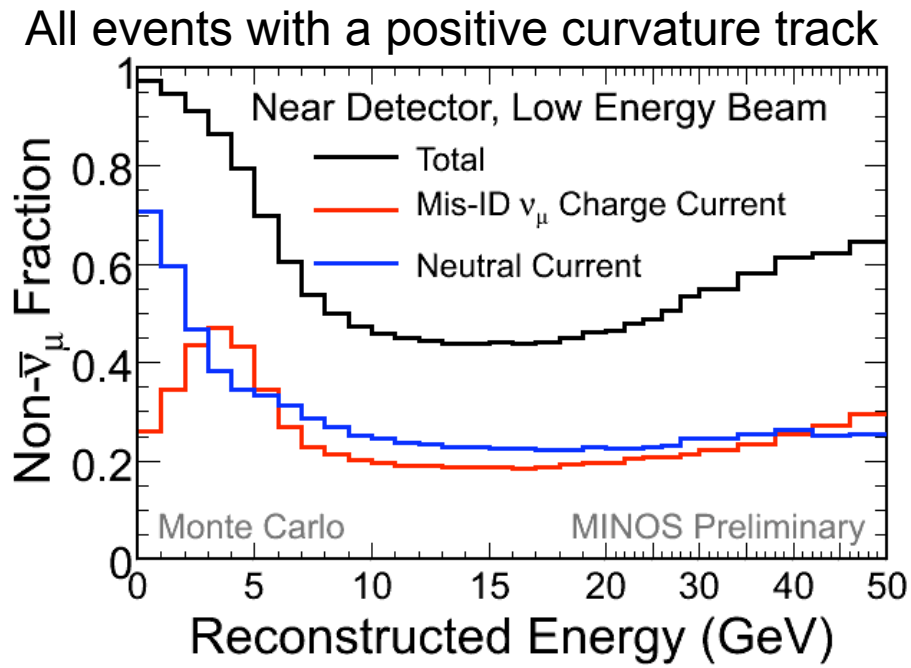
$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons}$$

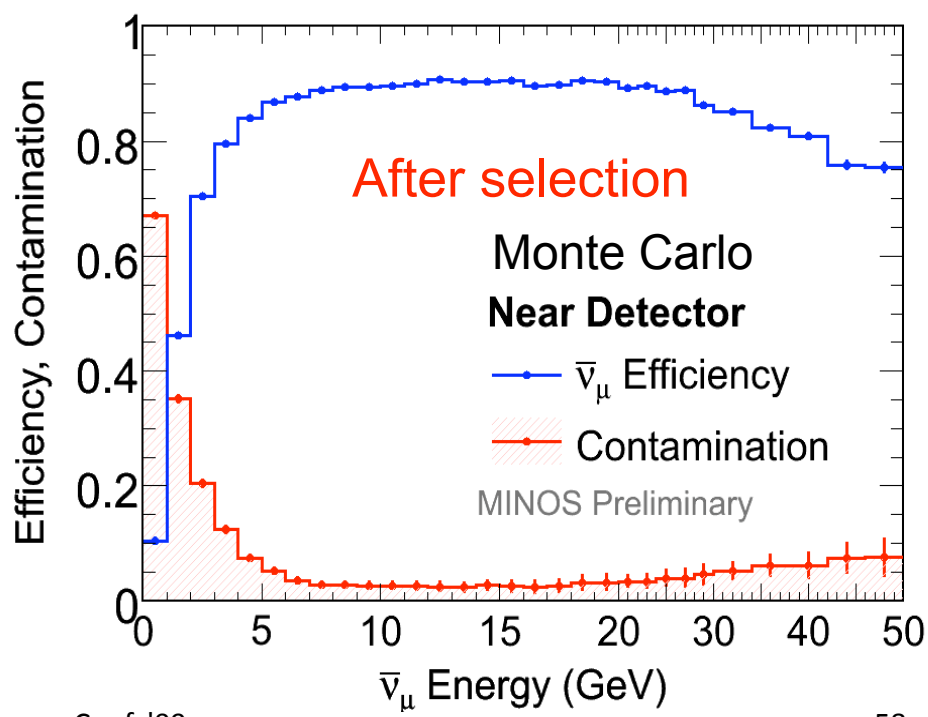
$$\nu_\mu + N \rightarrow \mu^- + \text{hadrons}$$

(NEW: Preliminary results released in May ’09)

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

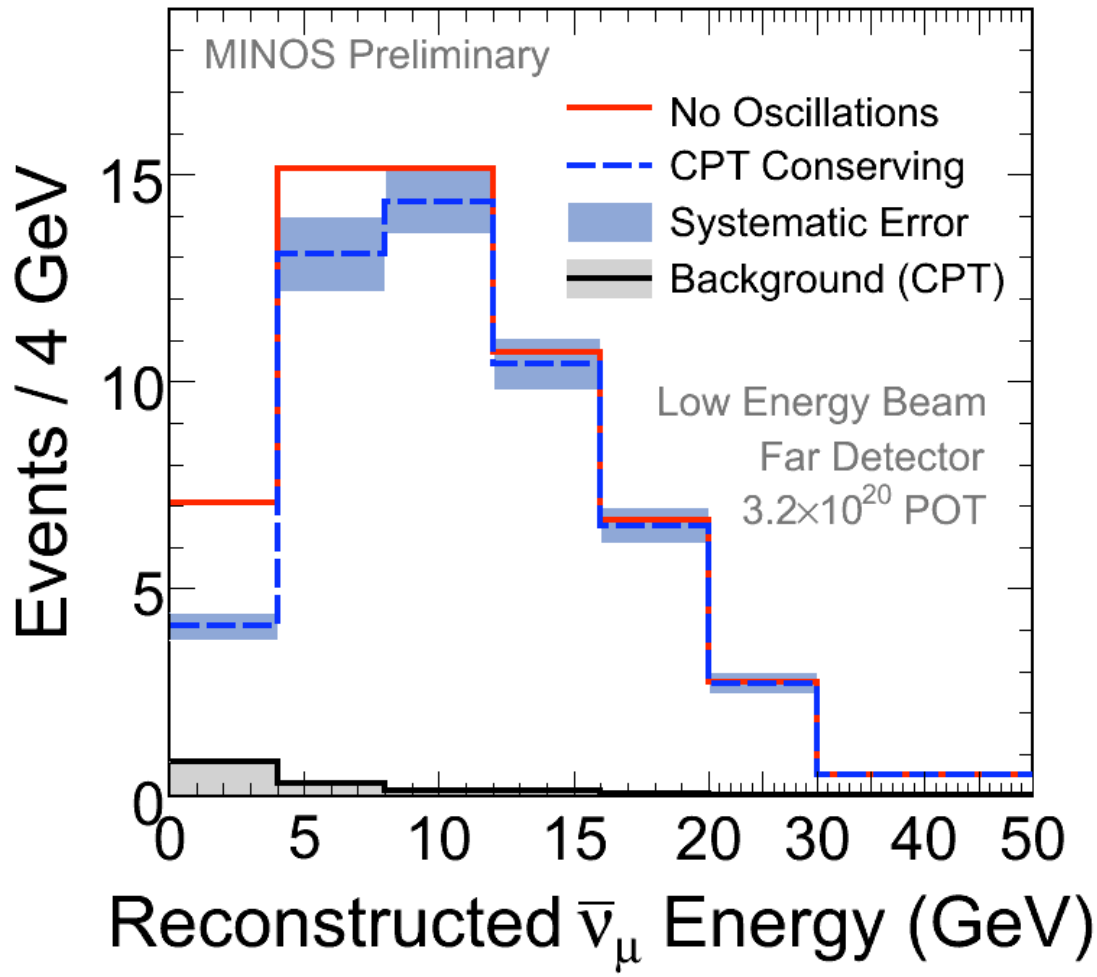
- $\bar{\nu}_\mu$ CC events are 7% of beam
- Searching for $\bar{\nu}_\mu$ CC amongst a large sample of other events:
  - Mis-identified ν_μ CC where μ charge sign is wrong
  - Neutral Current (NC) events where another particle fakes a μ^+ track
- NC events with a track are ~50:50, positive:negative charge sign
- Cut on additional variables to achieve:
  - Efficiency of 87%
  - Contamination of 5%





Predicted Far Detector Spectrum

(follow an analogous procedure as for the muon neutrinos)

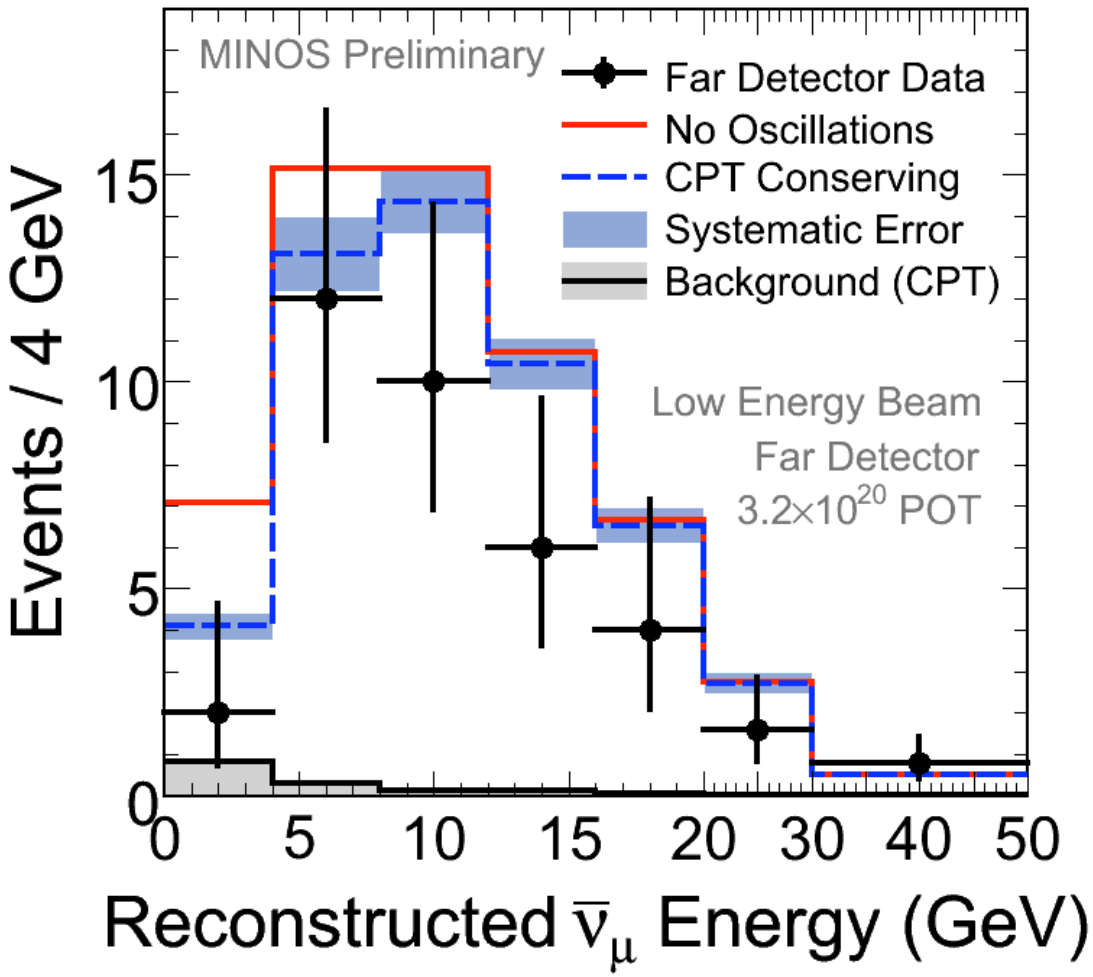


- Predicted events with CPT conserving oscillations:
  - 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - 64.6 ± 8.0 (stat.) ± 3.9 (syst.)

Far Detector Spectrum

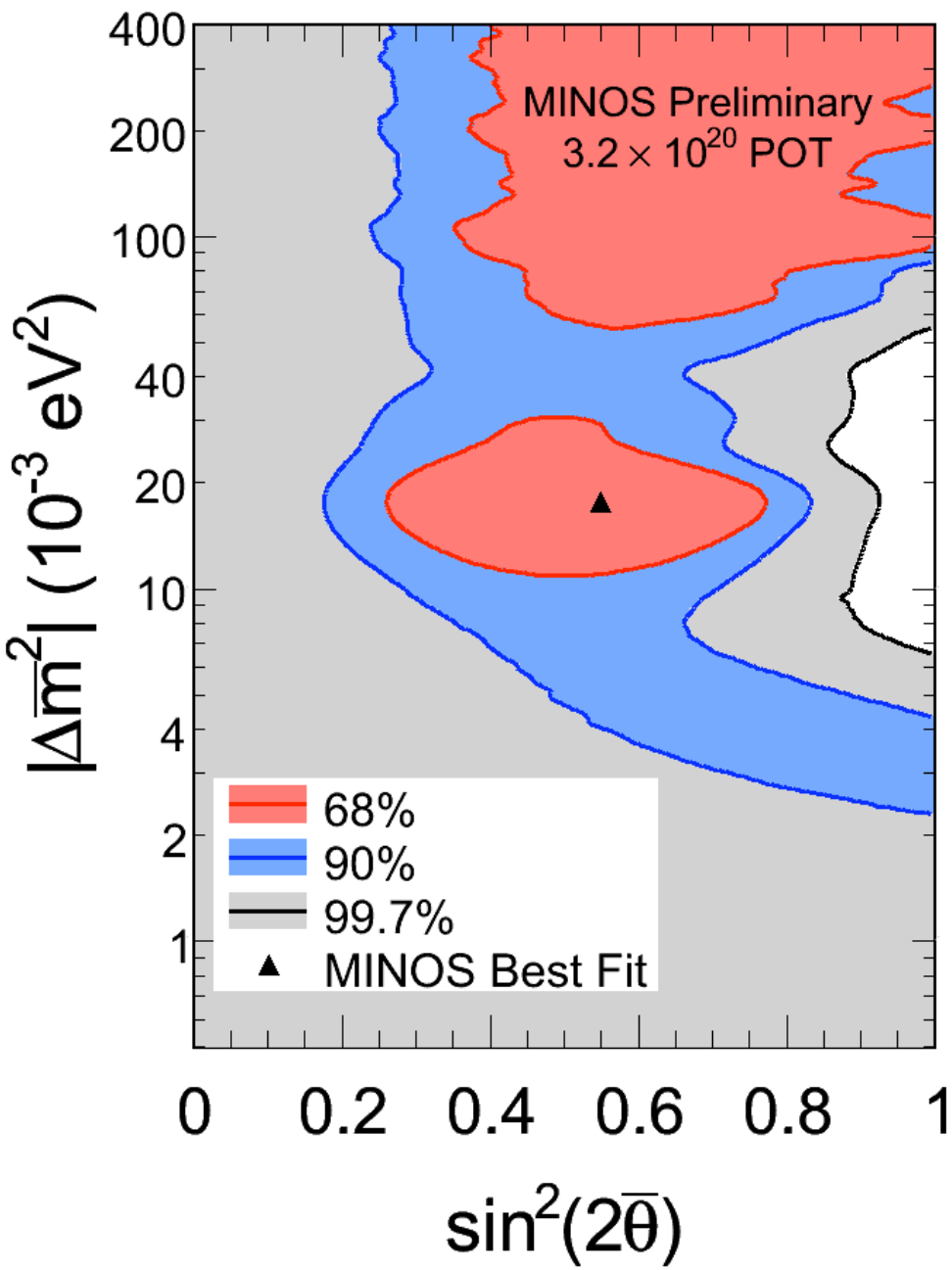
- Observe **42 events** in the Far detector
- First direct observation of $\bar{\nu}_\mu$ in an accelerator long-baseline experiment

- Predicted events with CPT conserving oscillations:
  - 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - 64.6 ± 8.0 (stat.) ± 3.9 (syst.)



Allowed Region

- Null oscillation hypothesis excluded at 99%
- CPT conserving point from the MINOS neutrino analysis is within 90% contour
- $\bar{\nu}_\mu$ best fit is at high value, due to deficit at high energy
- At maximal mixing **exclude**:
  - $(5.0 < \Delta\bar{m}^2 < 81)\times10^{-3}$ eV^2 (90% C.L.)



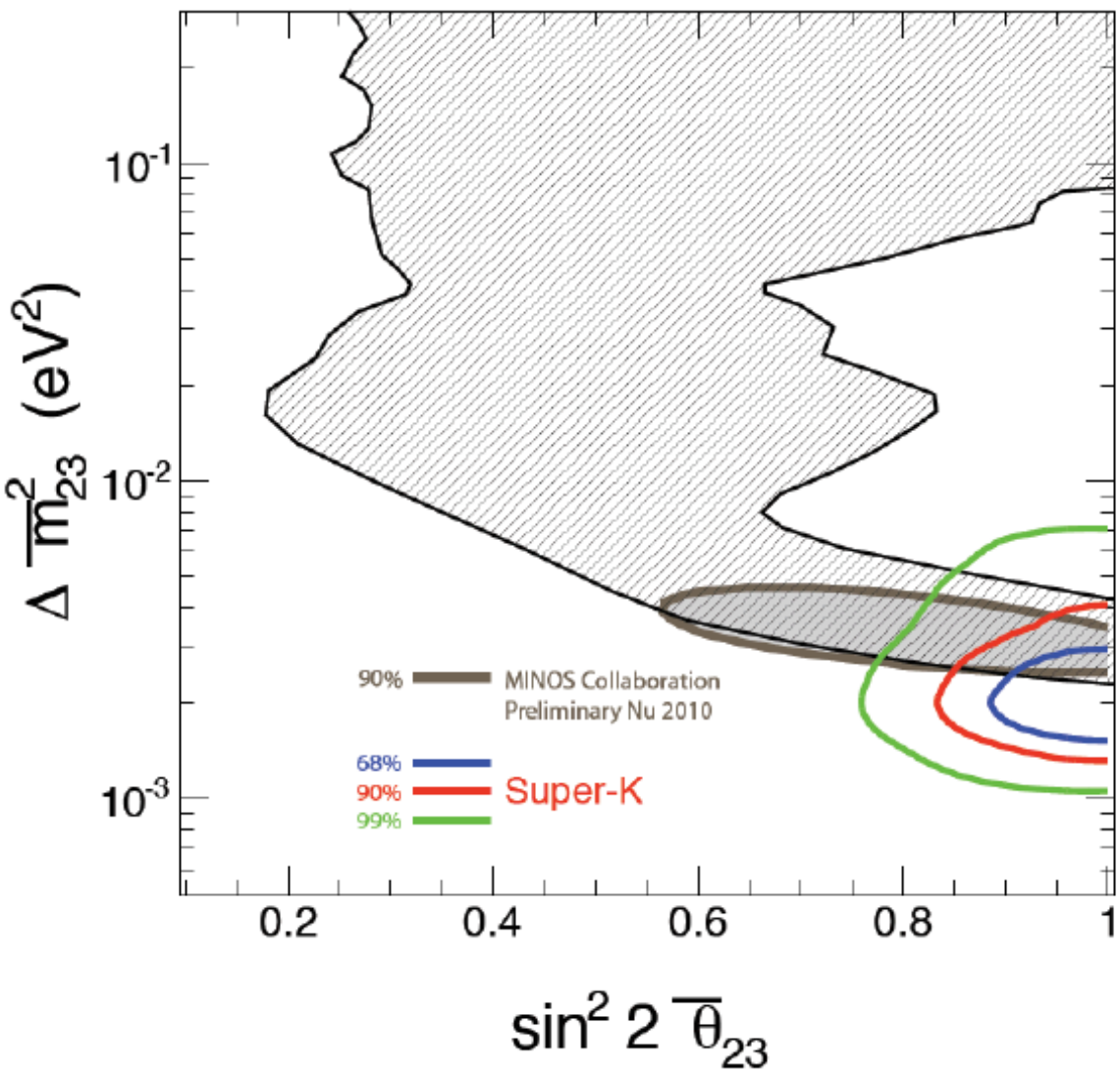
Search for CPT violation in atm. ν

Jun 2009

- Under the CPT theorem, $P(\nu \rightarrow \nu)$ and $P(\bar{\nu} \rightarrow \bar{\nu})$ should be same.
- Test ν oscillation or $\bar{\nu}$ oscillation separately.

SK-I+II+III

Preliminary



Neutrino:

$\Delta m_{23}^2 = 2.2 \times 10^{-3} eV^2$

$\sin^2 2\theta_{23} = 1.0$

Anti-neutrino:

$\Delta \bar{m}_{23}^2 = 2.0 \times 10^{-3} eV^2$

$\sin^2 2\bar{\theta}_{23} = 1.0$

No evidence for CPT violating oscillations is found

Poster-79 by Roger Wendell

[Takeuchi, Nu2010]