Recent Results from the MINOS Experiment

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24th Rencontres de Blois, May 28 – June 1, 2012

Overview

- Introduction
- MINOS
  (The Main Injector Neutrino Oscillation Search):
  - NuMI Beam & MINOS Detectors
  - Muon Neutrino Disappearance ($\nu_\mu \rightarrow \nu_\mu$)
  - Muon Anti-Neutrino Disappearance ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)
  - Electron Neutrino Appearance ($\nu_\mu \rightarrow \nu_e$)
- Outlook

Neutrino Mixing

PMNS Matrix (Pontecorvo-Maki-Nakagawa-Sakata)

analogue to CKM-Matrix in quark sector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

weak "flavour" eigenstates

Unitary mixing matrix:
3 mixing angles & complex phases

mass eigenstates

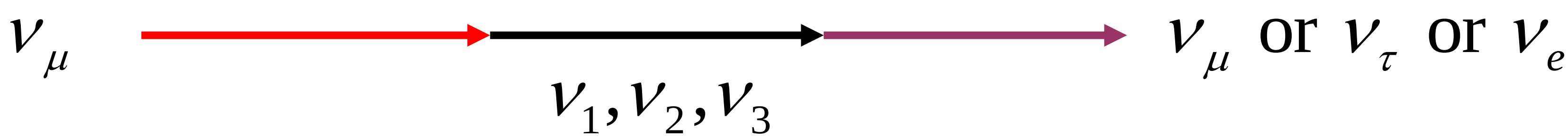
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

accessible by MINOS — solar sector — Majorana phases

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle

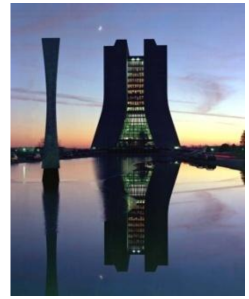
Neutrino Oscillation

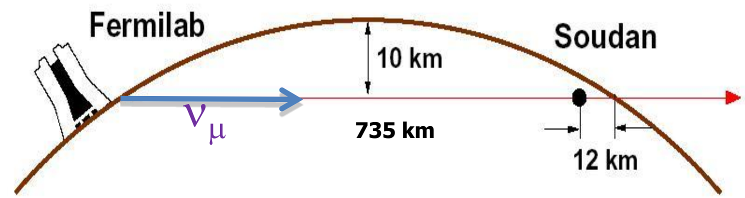
- Neutrino is produced in one of the weak eigenstates (ν_e , ν_μ , ν_τ)
- It propagates a distance L in a mixture of mass eigenstate (ν_1, ν_2, ν_3)
- It will be detected in one of the weak eigenstates with certain probability



The MINOS experiment

- MINOS - Main Injector Neutrino Oscillation Search
- High intensity high purity ν_μ beam
- Near Detector
  - 1 km from target
  - 94 m underground, 225 mwe
  - measures the energy spectrum
  - and beam composition
- Far Detector
  - 735 km from target
  - 700 m underground, 2070 mwe
  - remeasures the neutrino beam composition
- Two functionally identical detectors to reduce systematics

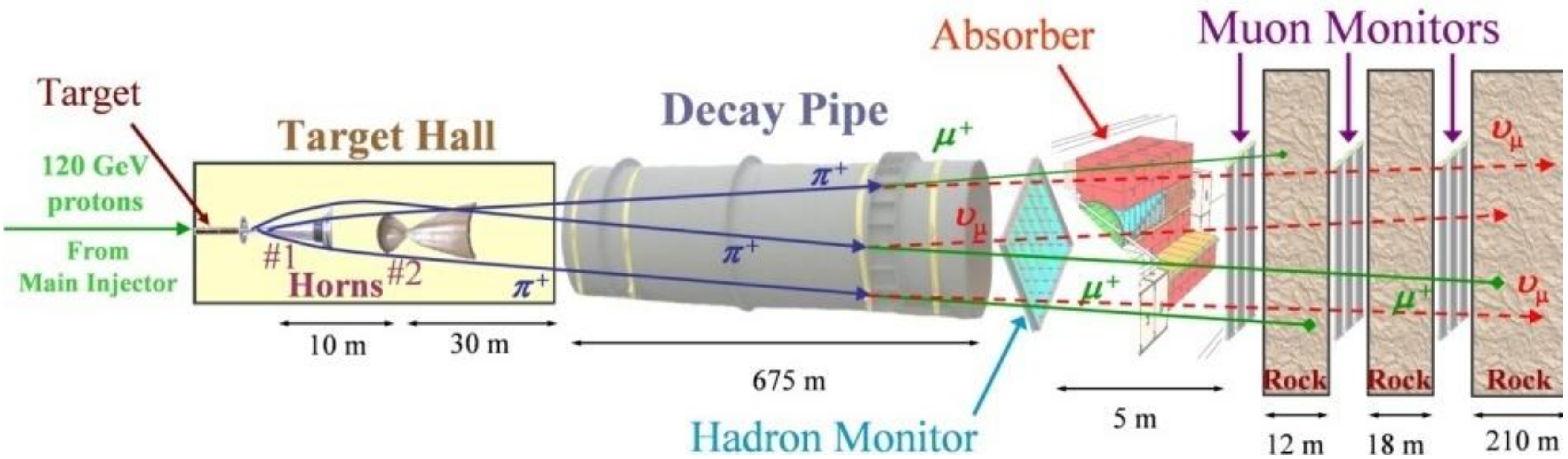




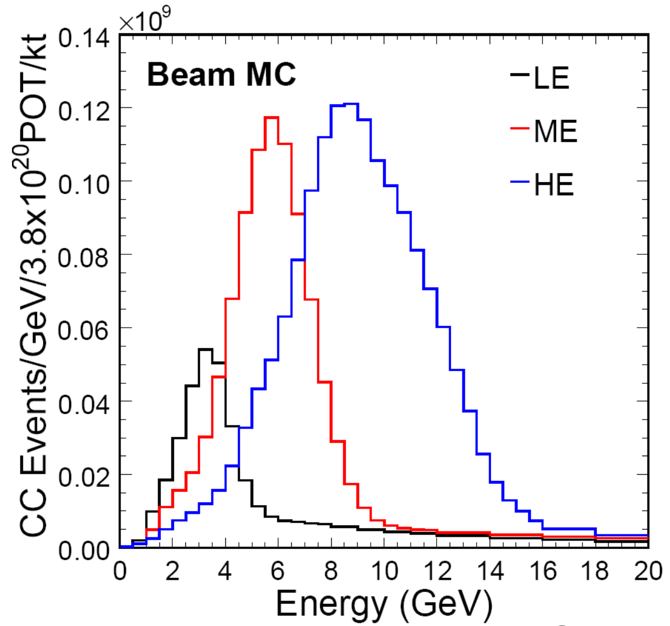
Near Detector
980 tons

Far Detector
5,400 tons

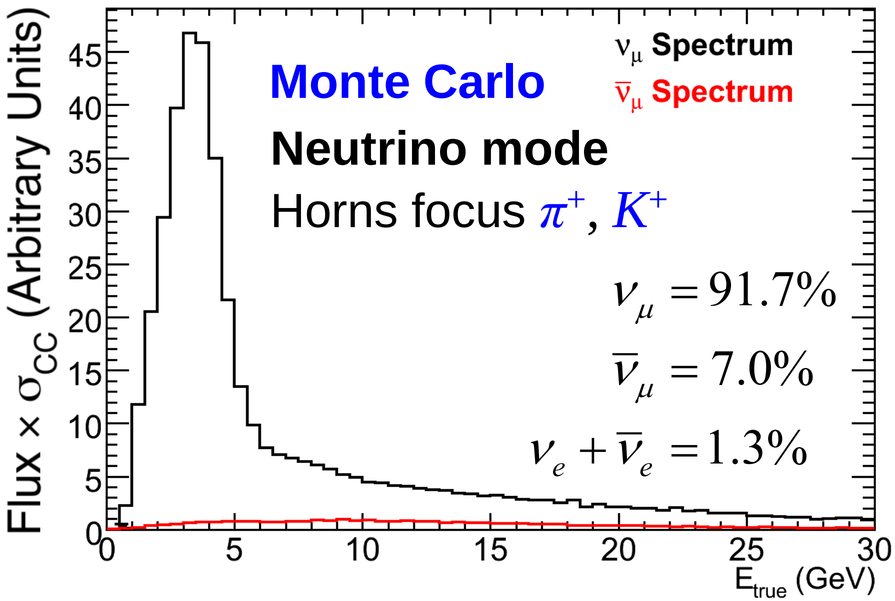
NuMI Beam

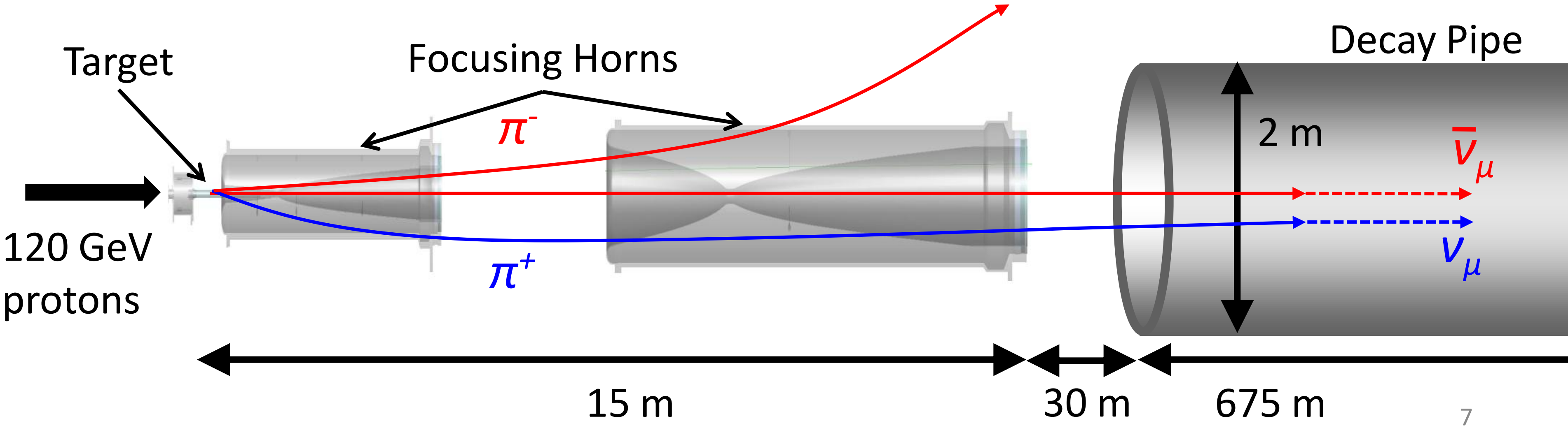


- Accelerate protons in the Main Injector
- 10 μs spill of 120 GeV protons every 2.2 s
- Collide with a graphite target to produce mesons (π's and K's)
- Decay into neutrinos in the 675 m decay pipe
- Neutrino spectrum changes with target position

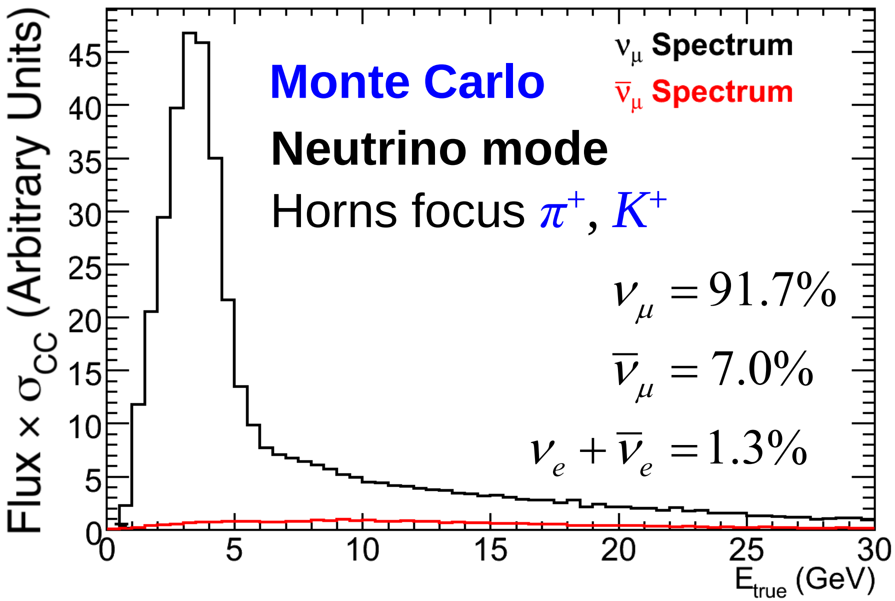


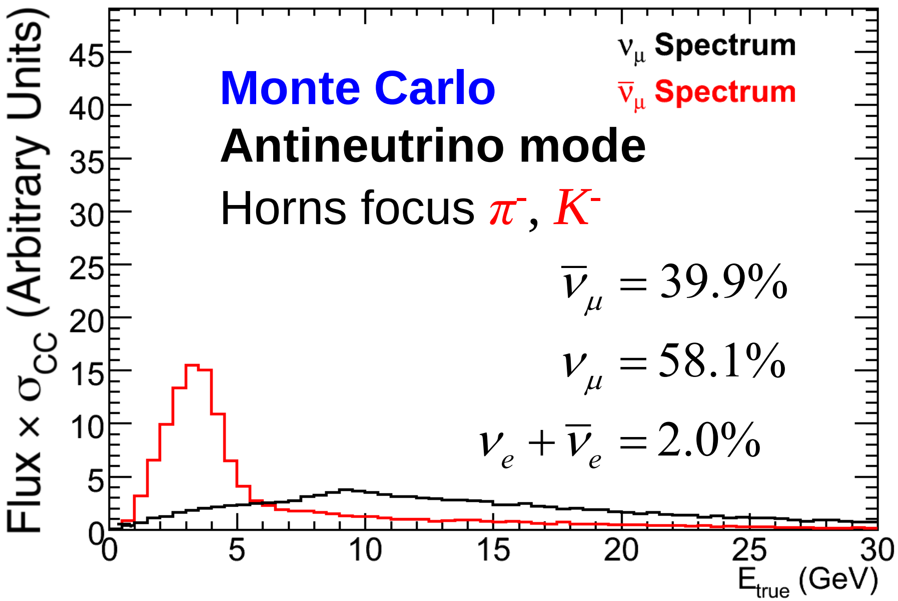
Neutrino Mode

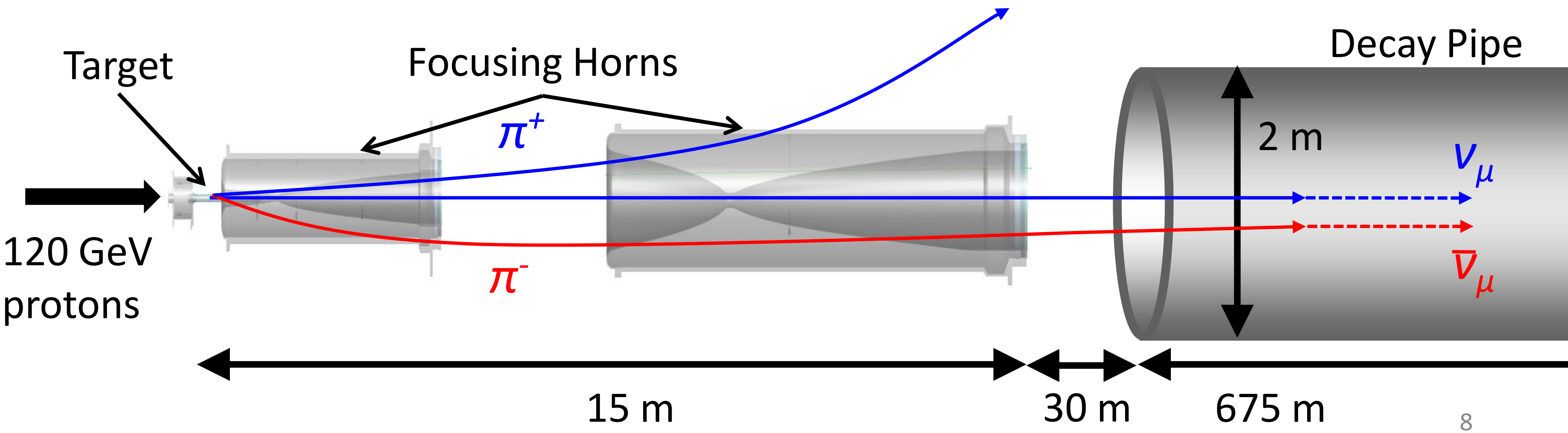




Antineutrino Mode







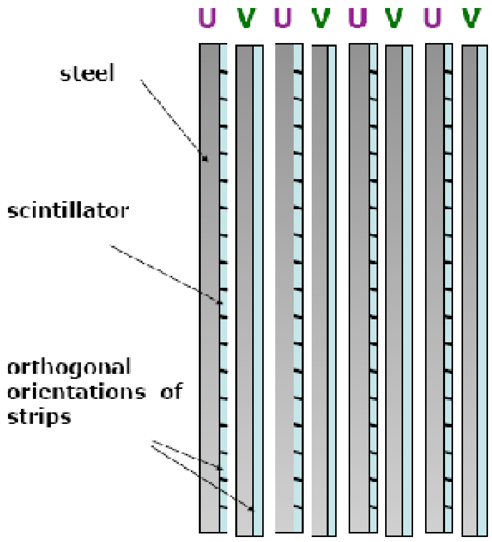
Detector Technology

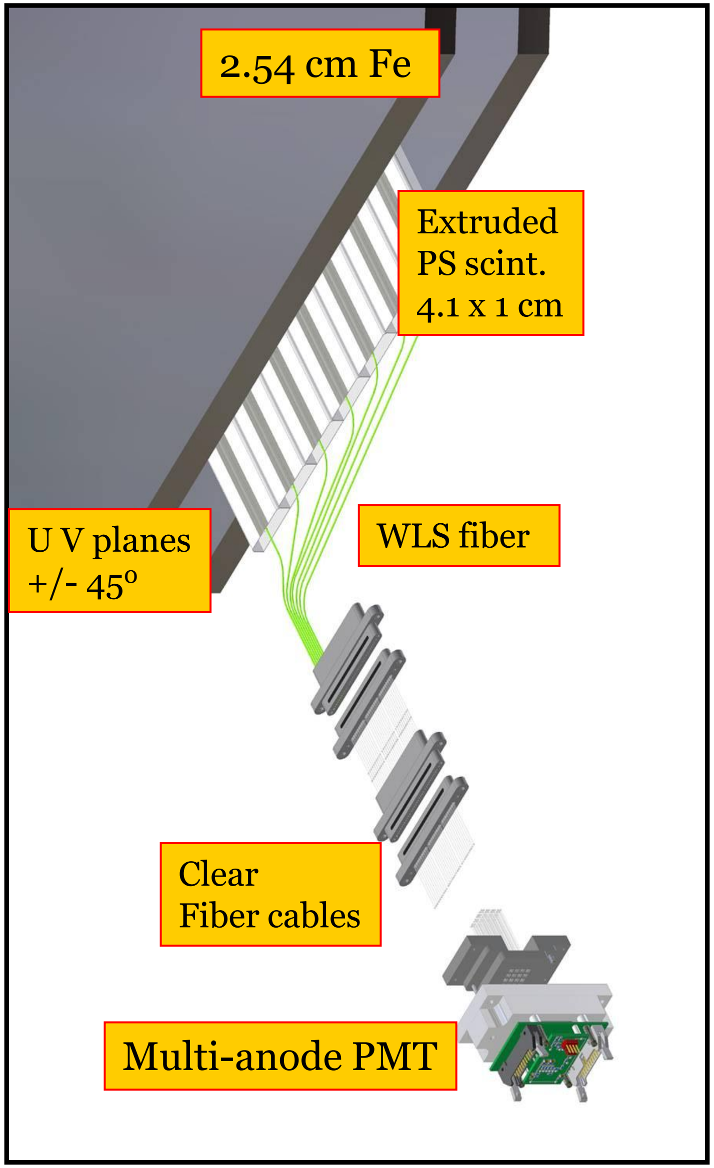
Steel/scintillator tracking calorimeters

- Alternate orthogonal orientation planes
- Steel absorber 2.54 cm thick
- Scintillator strips 4.1 cm wide, 1.0 cm thick
- 1 GeV muons penetrate 28 layers
- Optical fibre readout to multi-anode PMTs

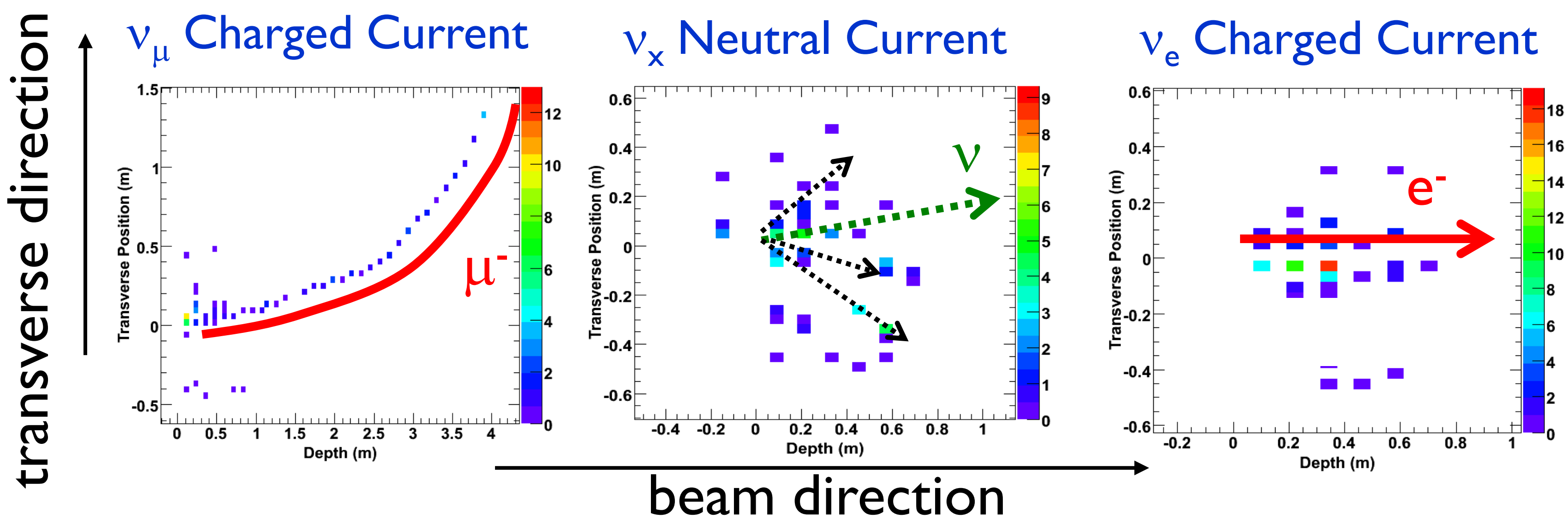
Magnetized

- Muon energy from range/curvature
- Distinguish μ^+ from μ^- tracks

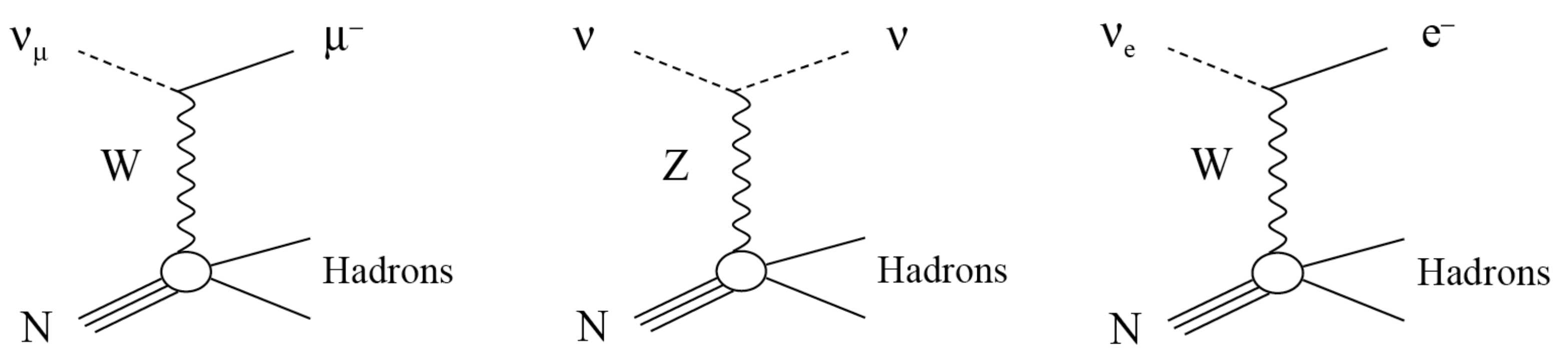




Neutrino Interactions in Detectors



color scale represents energy deposition



long μ track & hadronic activity at vertex

short with diffuse shower

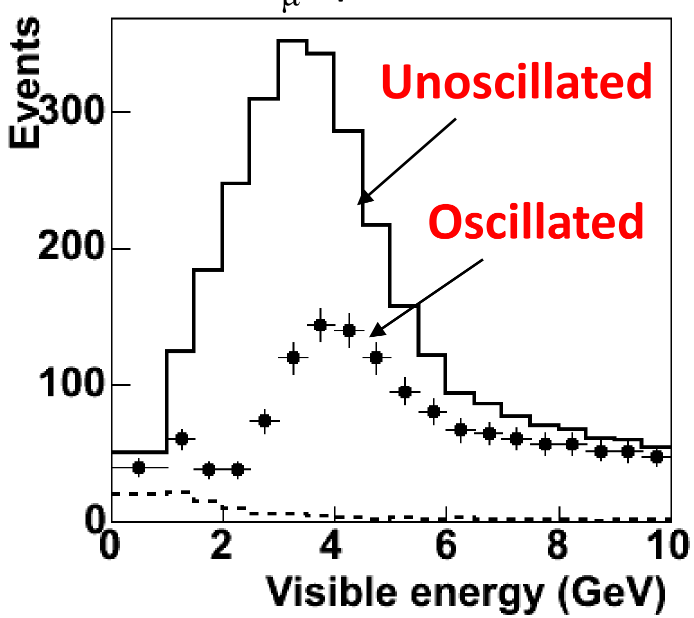
short with compact EM shower profile

ν_μ Disappearance Measurement

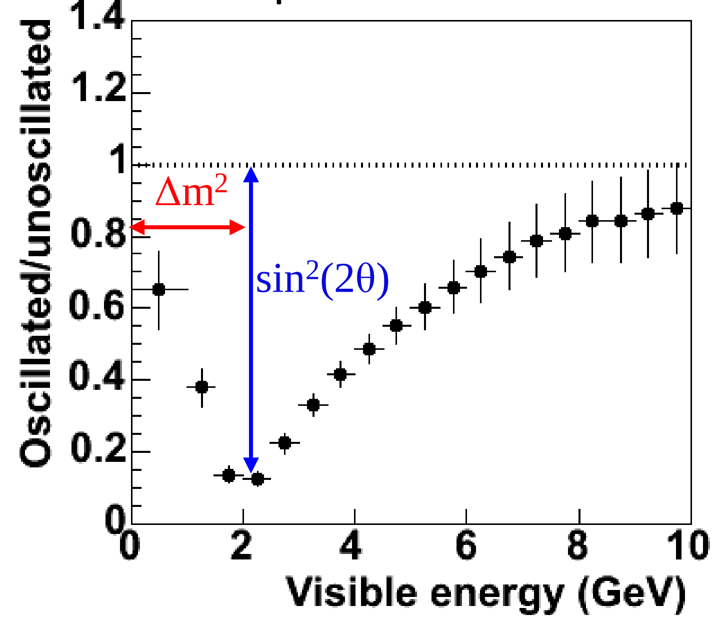
$$P\left(\nu_\mu \to \nu_\mu\right) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.267\ \Delta m_{32}^2 [ev^2] L[km]}{E[GeV]}\right)$$

$$P\left(\bar{\nu}_\mu \to \bar{\nu}_\mu\right) = 1 - \sin^2 2\bar{\theta}_{23} \sin^2\left(\frac{1.267\ \Delta \bar{m}_{32}^2 [ev^2] L[km]}{E[GeV]}\right)$$

ν_μ spectrum



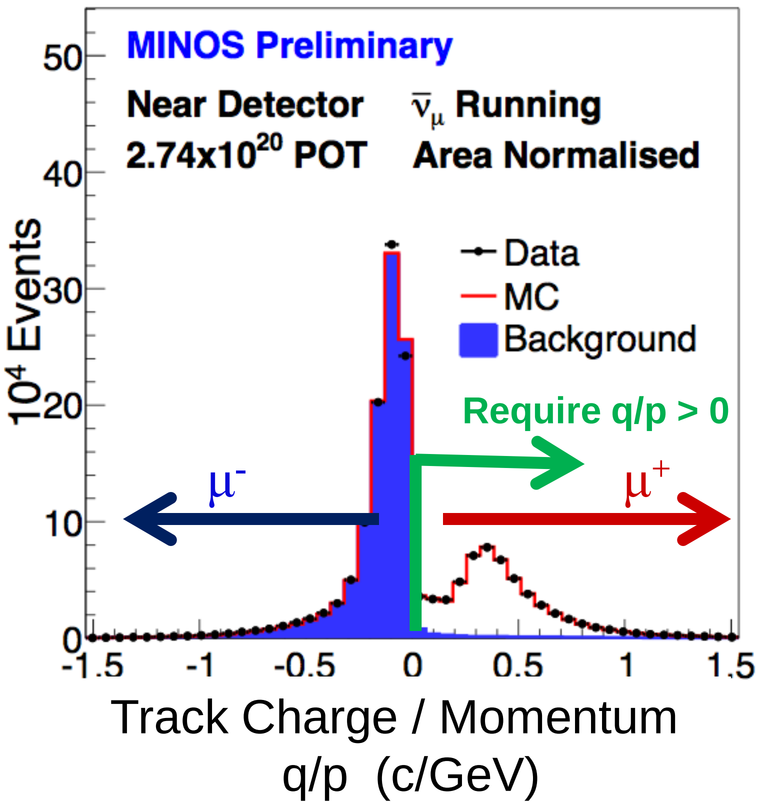
Spectrum ratio

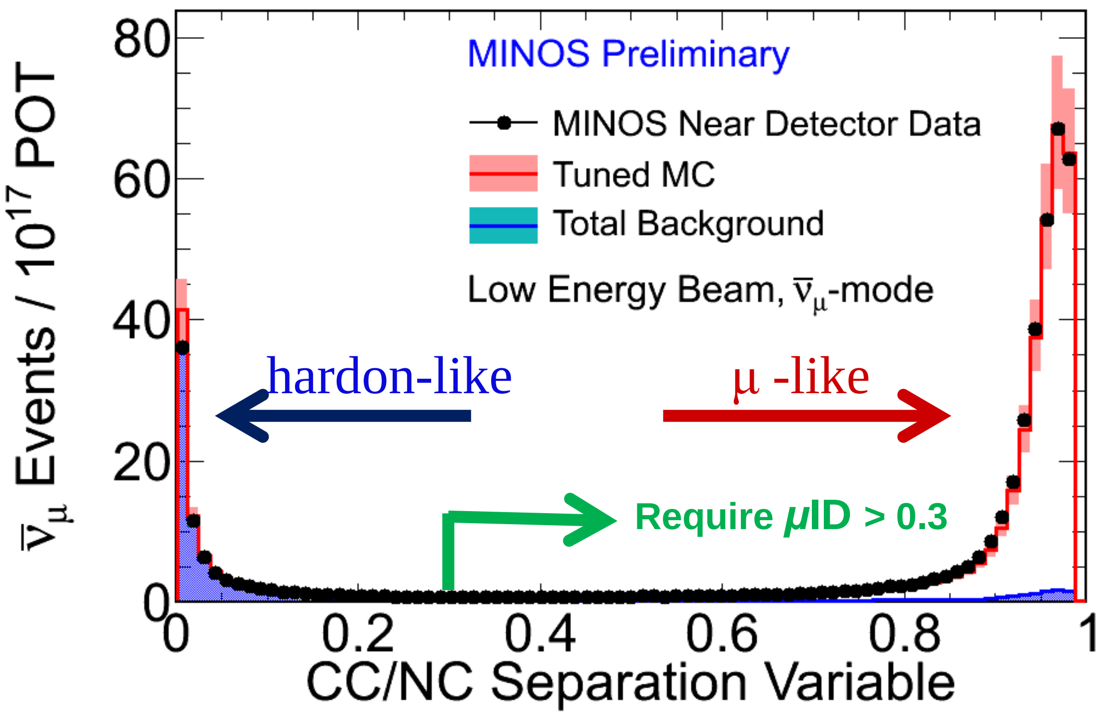


Charge Identification and CC-NC Separation

Charge identification via magnetic field bending and track fitting

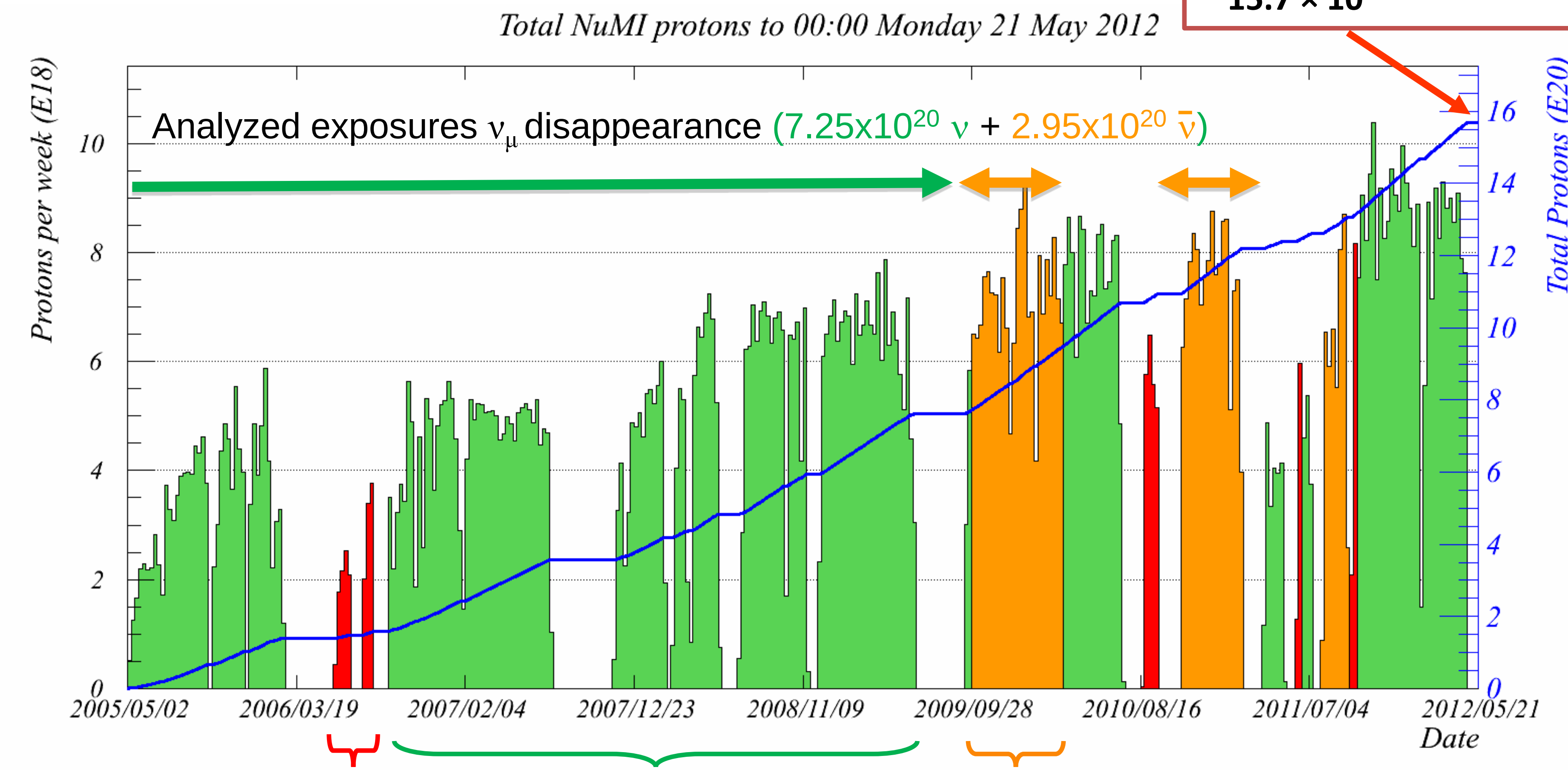
CC-NC separation via a kNN (k-Nearest-Neighbors) algorithm





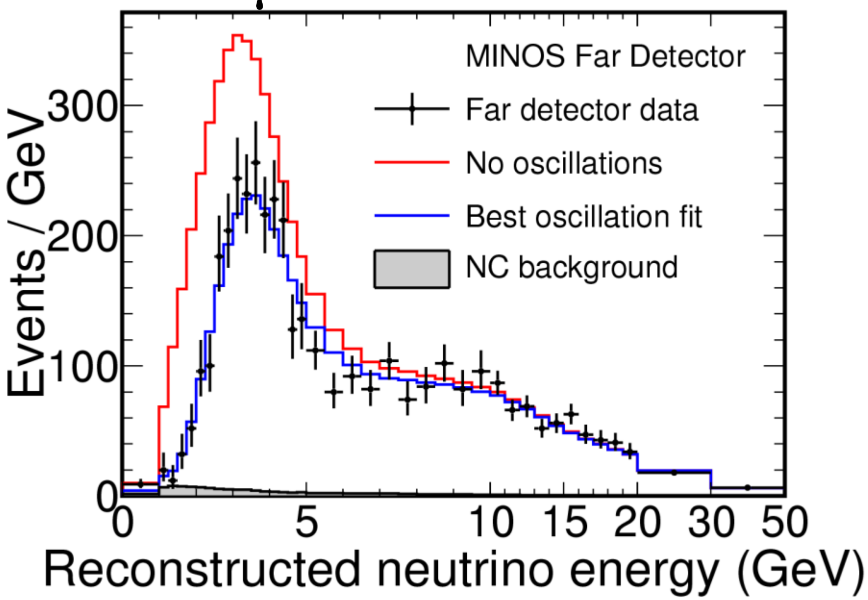
Analyzed Data for ν_μ Disappearance

Total Protons delivered: ~ 15.7×10^{20}



HE beam **nuetrino beam** **anti-nuetrion beam**

ν_μ Disappearance Measurement

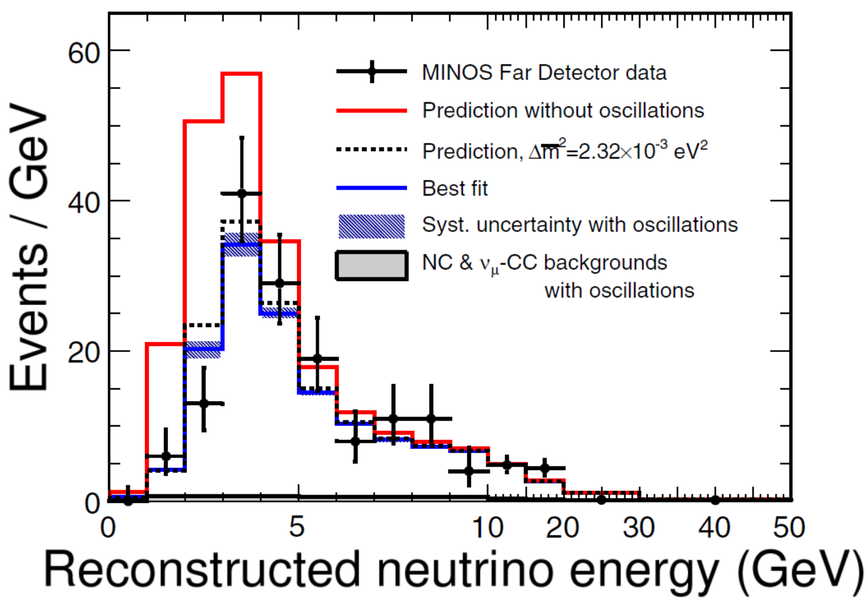


muon neutrinos

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

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

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



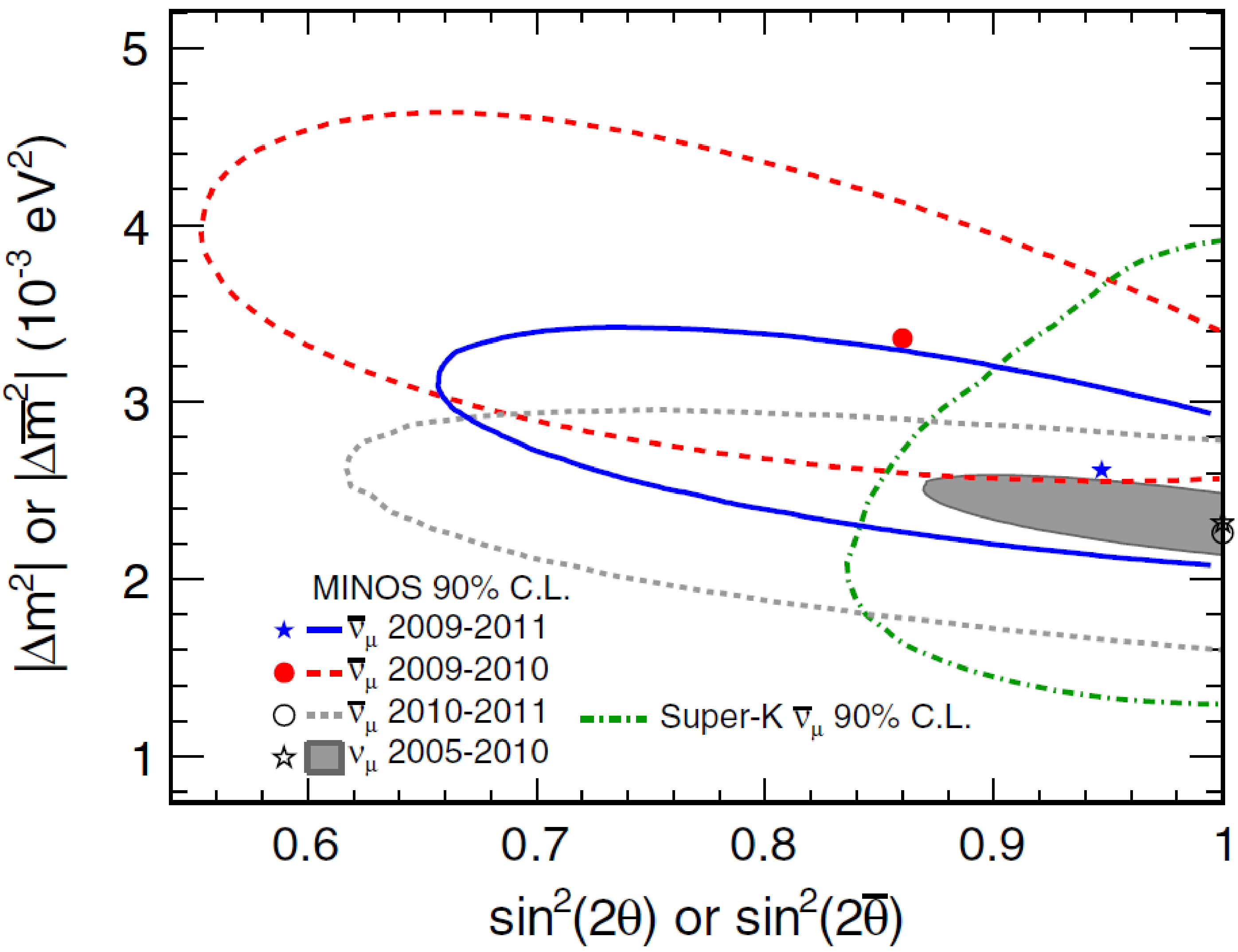
muon antineutrinos

$$|\Delta \bar{m}^2| = [2.62^{+0.31}_{-0.28}(stat) \pm 0.09(syst)] \times 10^{-3} eV^2$$

$$\sin^2(2\bar{\theta}) = 0.95^{+0.10}_{-0.11}(stat) \pm 0.01(syst)$$

Phys. Rev. Lett. 108, 191801 (2012)

Confidence Contours for the ν_μ and $\bar{\nu}_\mu$ Oscillation Parameters



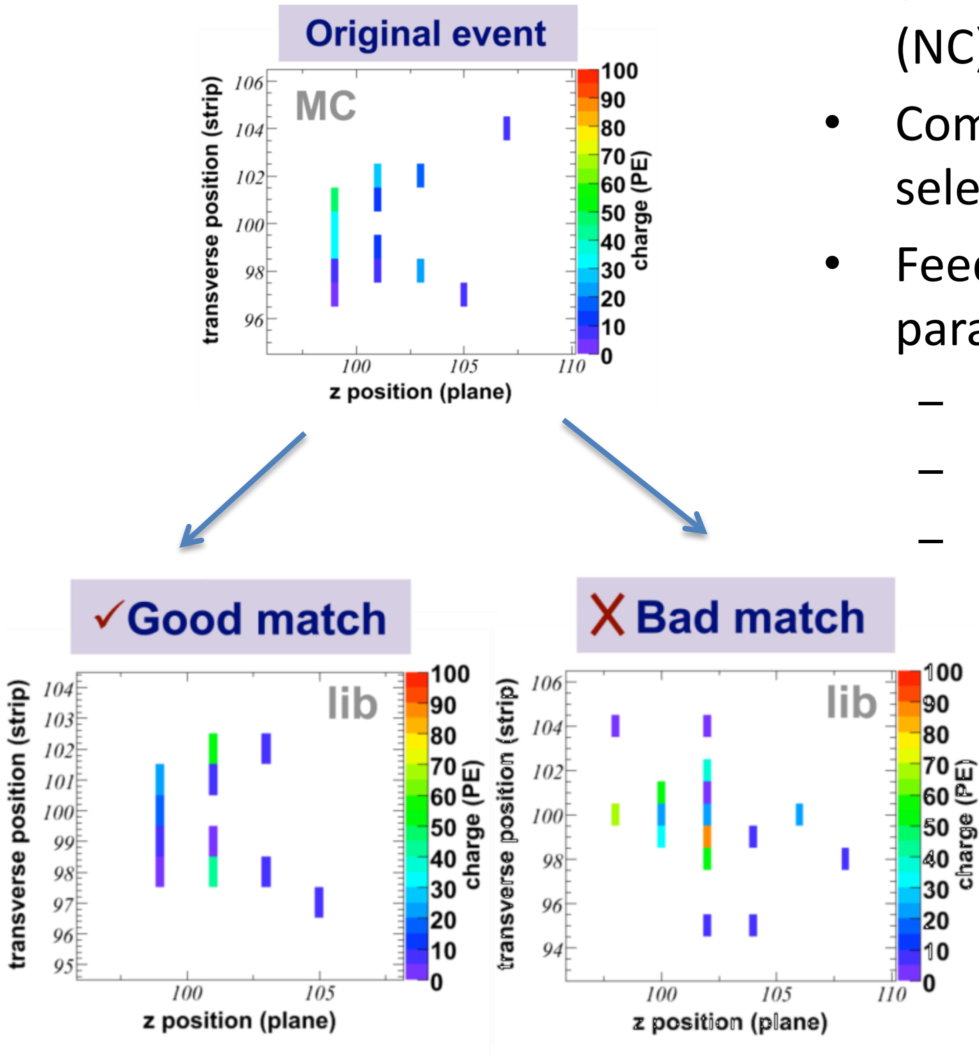
ν_e Appearance Measurement

$$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(\frac{1.267\ \Delta m^2_{31} L}{E}\right) + \cdots$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx \sin^2(\bar{\theta}_{23}) \sin^2(2\bar{\theta}_{13}) \sin^2\left(\frac{1.267\ \Delta \bar{m}^2_{31} L}{E}\right) + \cdots$$

- $\boldsymbol{\theta_{13}}$ measurement
- Dependent on assumptions on
  - ❑ $\sin^2(\theta_{23})$,
  - ❑ δ_{CP},
  - ❑ sign of Δm^2, mass hierarchy (normal or inverted):
- CP-violating δ and matter effects included in fits

Library Event Matching (LEM) Particle ID

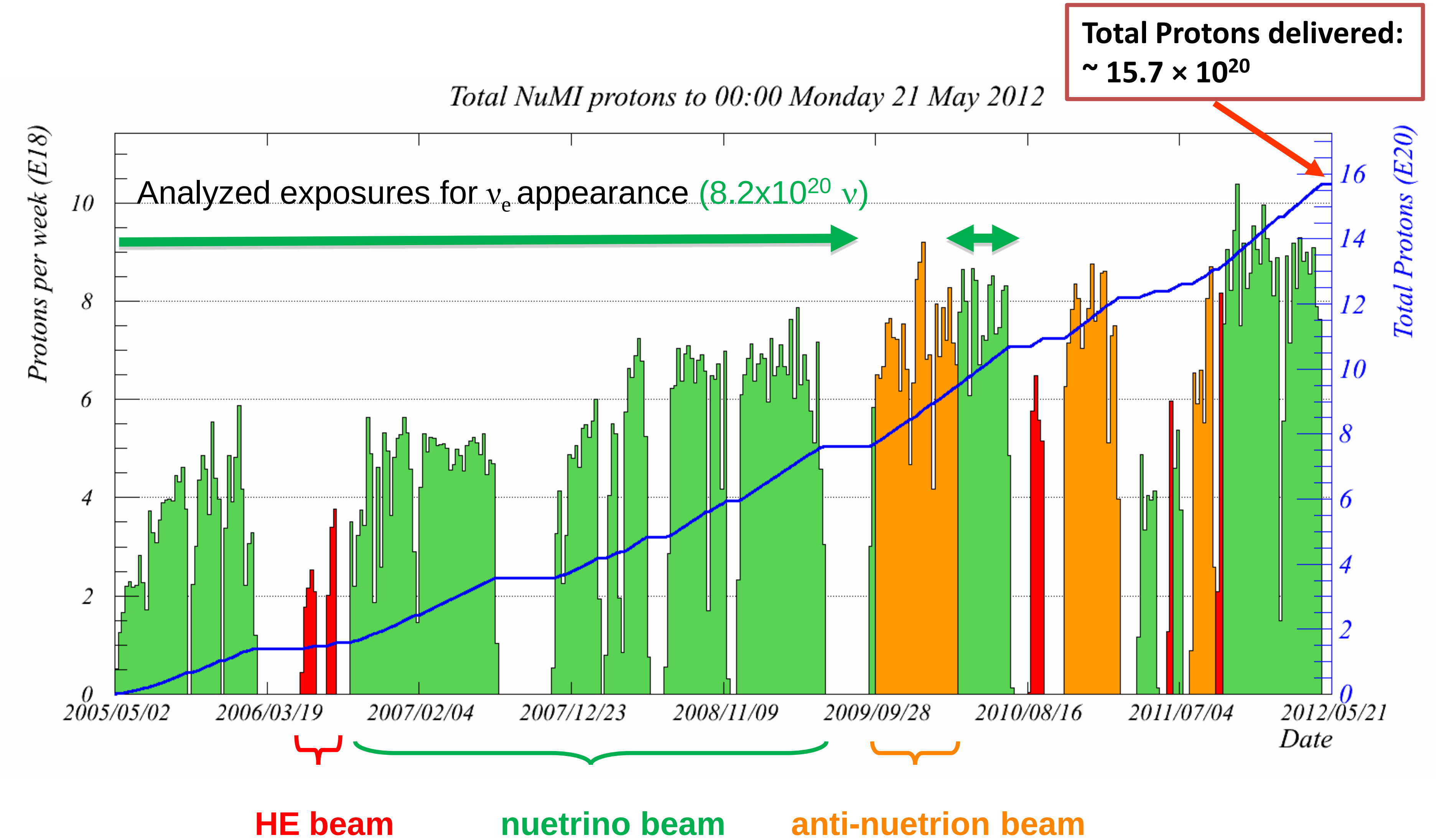


- Simulate of 20M Signal + 30M Background (NC) Far Detector MC events library
- Compare candidate event to library and select a list of 50 “best matches”
- Feed information from best matches as input parameters into a neural network (NN)
  - true ν_e CC events fraction
  - average inelasticity <y>
  - average charge fraction overlapping the input event and each ν_e CC event

Advantage:

- detector hits information rather than higher level variables
- no loss of information from the construction
- gain 15% in sensitivity over previous NN only technique

Analyzed Data for ν_e Appearance



ν_e Appearance Results

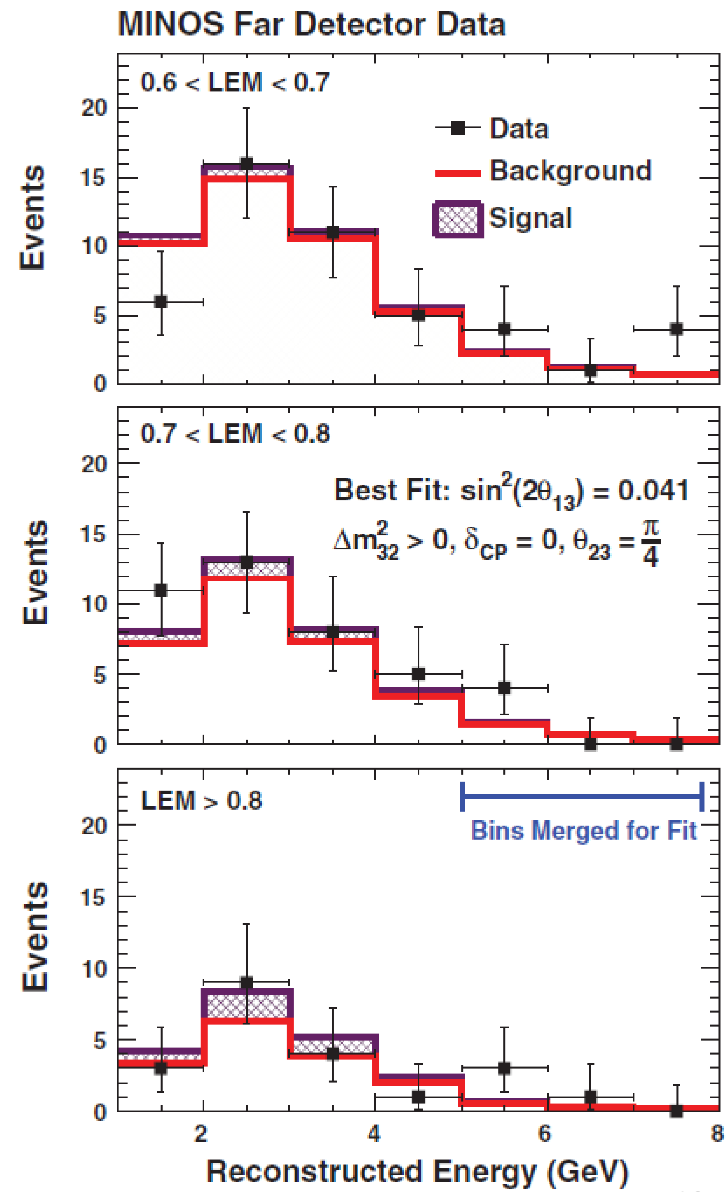
8.2 x 10^{20} protons on target (POT)

Predicted background :

49.6 ± 7.0(stat.) ± 2.7(syst.),

(if $\theta_{13} = 0$)

Observed : **62** events



ν_e Appearance Results

- 90% C.L. Feldman-Cousins Contours (including systematics), assuming

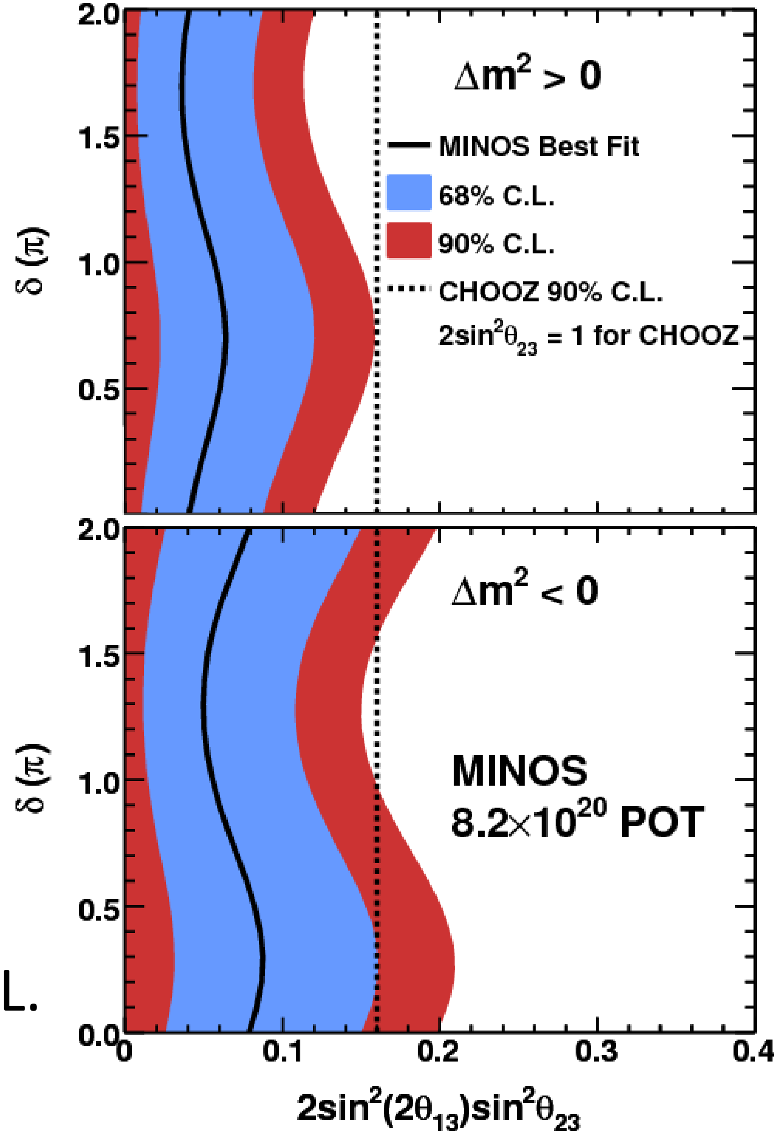
$$|\Delta m^2_{32}| = (2.32^{+0.12}_{-0.08}) \times 10^{-3} eV^2$$
$$\Delta m^2_{21} = (7.59^{+0.19}_{-0.21}) \times 10^{-5} eV^2$$
$$\theta_{23} = 0.785 \pm 0.100$$
$$\theta_{12} = 0.60 \pm 0.02$$

- $\delta_{CP} = 0$, at 90% C.L.

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

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

- $\theta_{13} = 0$ hypothesis disfavored by 89% C.L.



Outlook

- New Result this summer coming soon
  - Top off with new data
  - Improved ν_μ and $\bar{\nu}_\mu$ disappearance result
  - Improved θ_{13} sensitivity
  - Combined result from beam neutrino with atmospheric neutrino
  - Improved neutrino Time of Flight measurement
- MINOS -> MINOS+
  - Beam power: 320 kW -> 700 kW
  - Collect large sample of 4-10 GeV neutrino and anti-neutrino during NOvA running

Acknowledgments

- The MINOS Collaboration would like to thank the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the MINOS experiment.
- We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and the Minnesota DNR for hosting us.

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