Search for exotic transitions of muon neutrinos to electron neutrinos with MINOS

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Outline

Oscillation Phenomenon

Neutrino oscillations arise because two fundamentally distinct eigenstates characterize the neutrino.

- Mass eigenstates (ν_1, ν_2, ν_3): Describe the propagation of the neutrino.
- Flavor eigenstates (ν_e, ν_μ, ν_τ): Describe the interaction behavior of the neutrino.
- Two basis are related by Pontecorvo–Maki–Nakagawa–Sakata (PMNS) unitary mixing matrix.

  $|\nu_\alpha\rangle = \sum U_{\alpha j} |\nu_j\rangle$, where $\alpha = e, \mu, \tau$ and $j = 1, 2, 3$

Oscillation Phenomenon

PMNS mixing matrix is characterized by 4 free parameters: three Euler angles $\theta_{12}, \theta_{23}, \theta_{13}$ as well as the CP-violating phase, δ.

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

where $s_{ij} = sin[\theta_{ij}]$ and $c_{ij} = cos[\theta_{ij}]$.

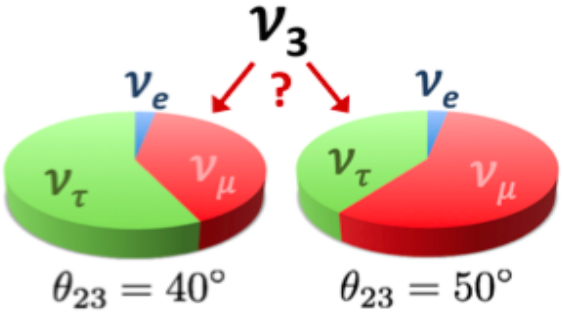
- Measured three mixing angles: θ_{12}, θ_{23} and θ_{13}
- Measured two mass splittings: $|\Delta m^2_{32}|$ and Δm^2_{21}

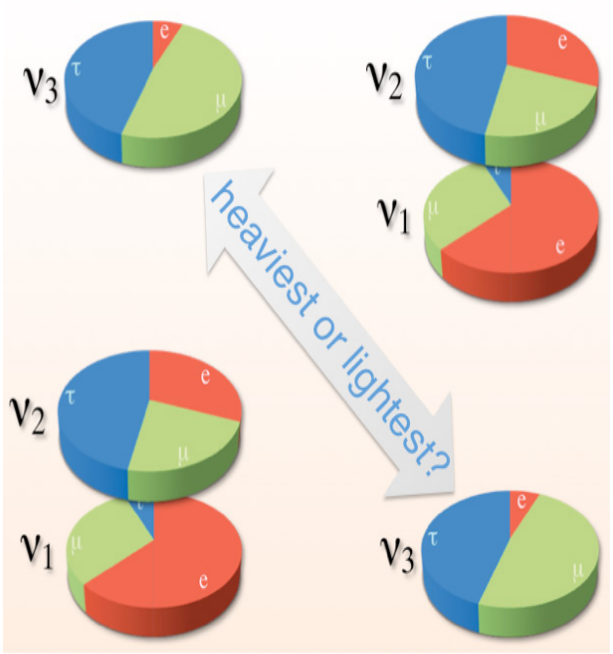
Parameter	*Best Fit Value*
Δm^2_{21}	$(7.60 \pm (-0.18, +0.19)) \times 10^{-5} eV^2$
Δm^2_{32}	$(2.40 \pm (-0.07, +0.05)) \times 10^{-3} eV^2$
θ_{12}	0.60 ± 0.02
θ_{23}	$0.85 \pm (-0.13, +0.03)$
θ_{13}	0.15 ± 0.03

Neutrino Physics: Open Questions

Neutrino mass is the first experimentally confirmed case of Physics beyond the Standard Model.

- Mass hierarchy (sign of Δm^2_{32})
- CP violation in lepton sector (magnitude of δ_{CP})
- θ_{23} octant: Nature of ν_3 and contributions of ν_μ and ν_τ



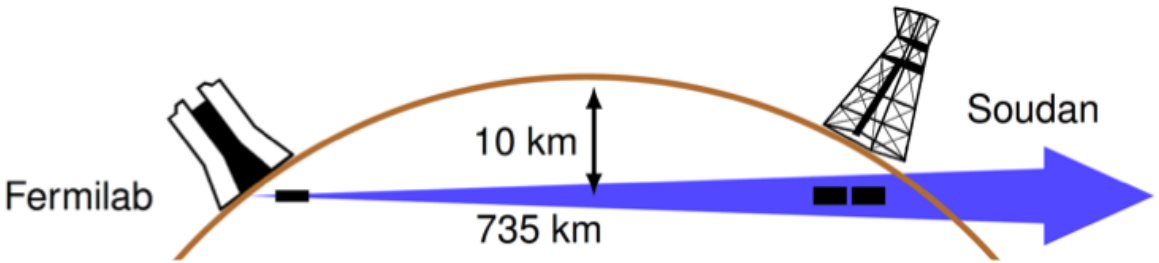


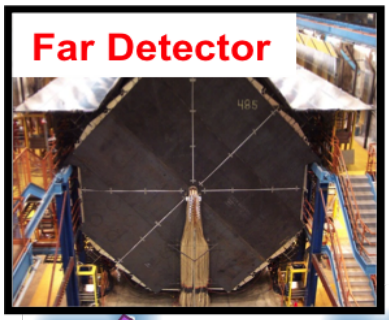
This Talk

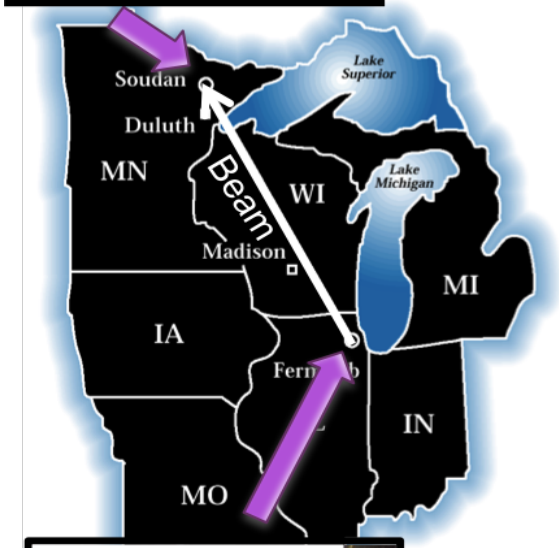
- Is there more to this picture: additional neutrino flavors, new types of interactions ?

MINOS: Main Injector Neutrino Oscillation Search

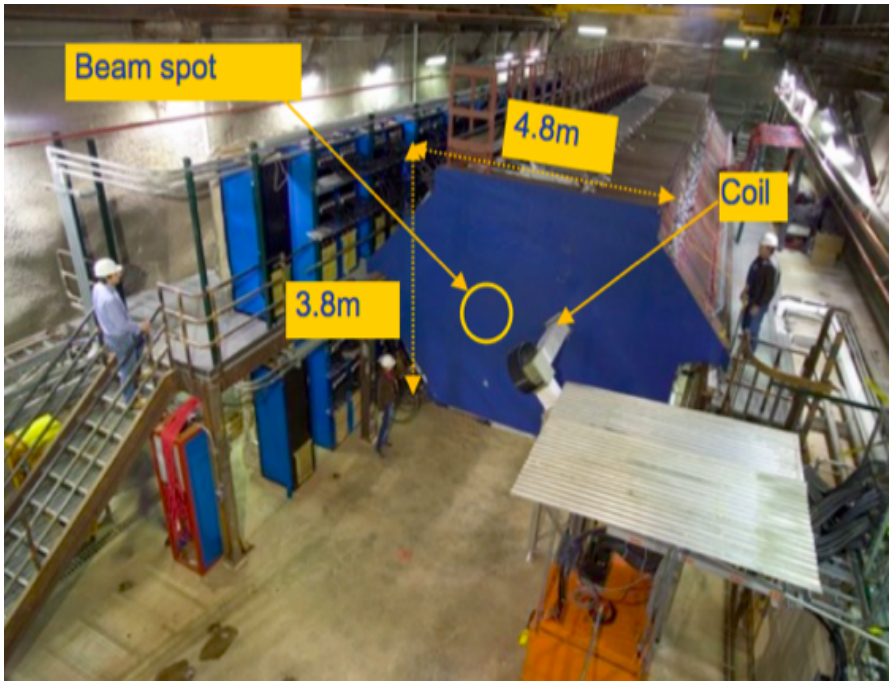
- Long Baseline Experiment, utilizing the Fermilab NuMI ν_μ beam
- Two functionally identical magnetized tracking calorimeter detectors to study neutrino flux
- Cancellation of neutrino beam flux and cross-section uncertainties.
- Measure NuMI Neutrino beam energy and flavor composition with two detectors over 735 km ($L/E \sim 500 km/GeV$)

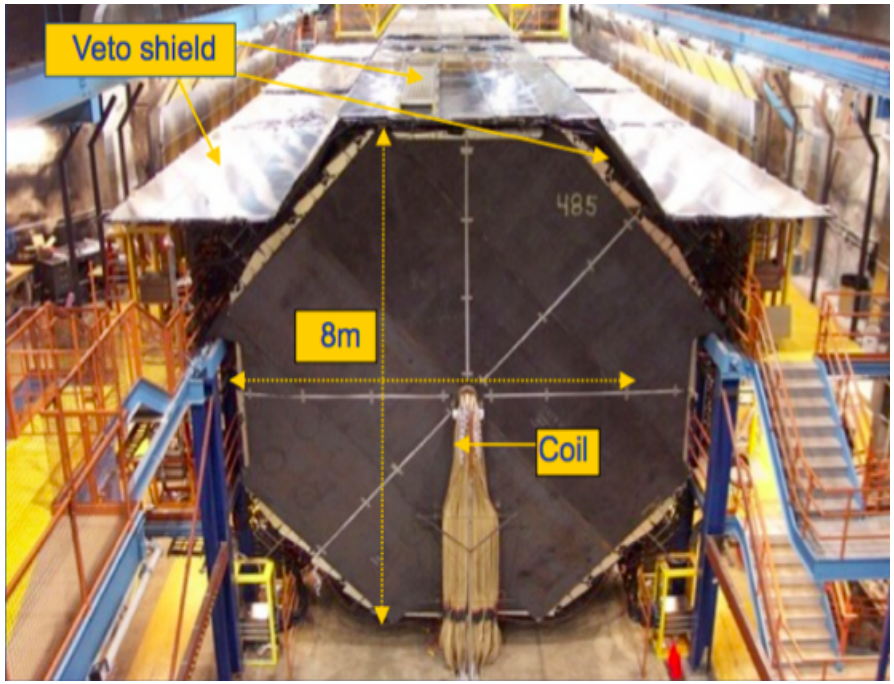






MINOS Detector Designs





Near Detector

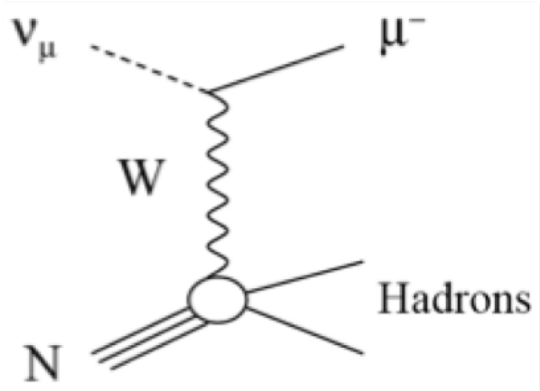
- 1 kton, 100 m Underground
- 1 km away from NuMI target
- Steel / Scintillator planes, $\sim$ 1.3T field

Far Detector

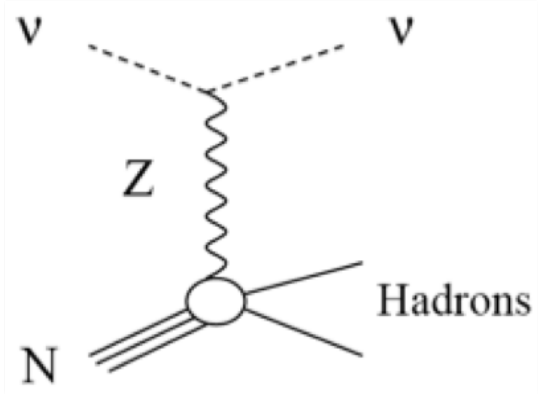
- 5.4 kt, 714 m underground
- 735 km away from NuMI target
- Steel / Scintillator planes, $\sim$ 1.3T field

Event Topology

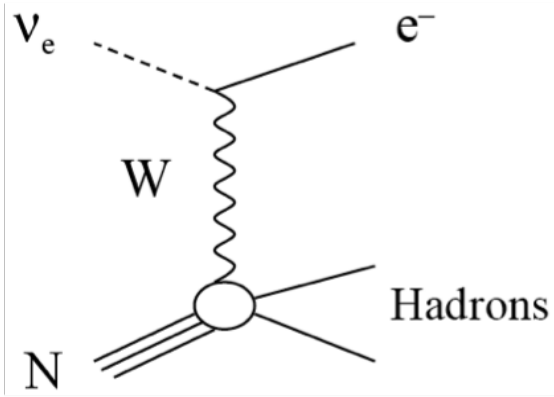
ν_μ Charged Current (CC)

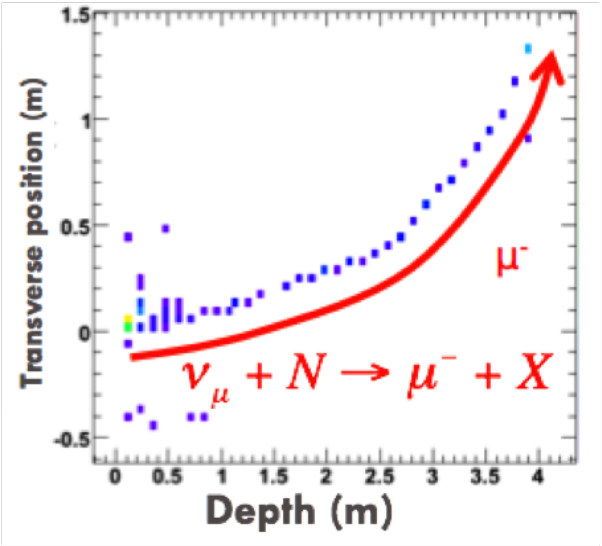


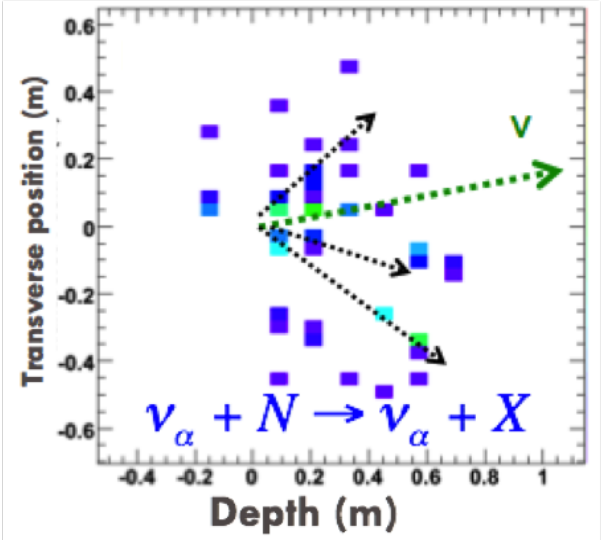
Neutral Current (NC)

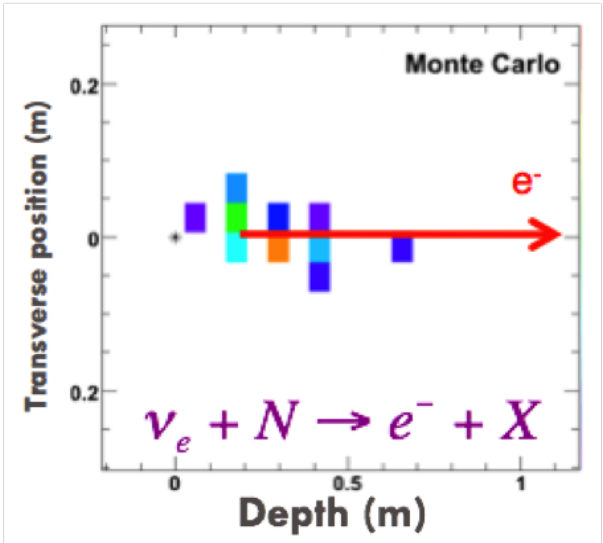


ν_e Charged Current (CC)

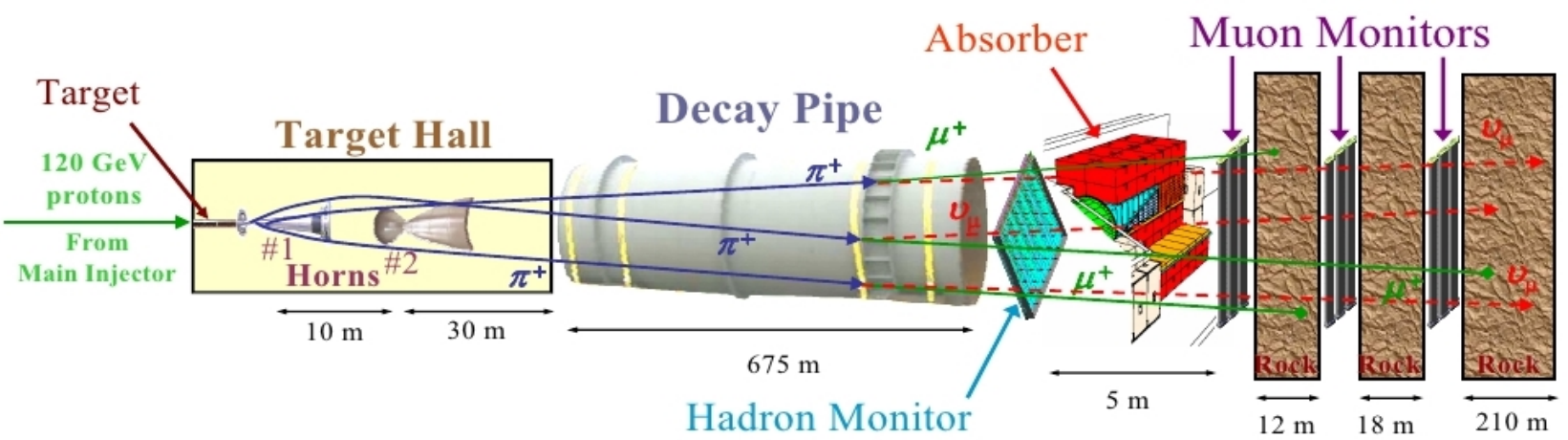








NuMI Beamline



Production: 120 GeV proton beam from Main Injector collides with graphite target.

Focusing:

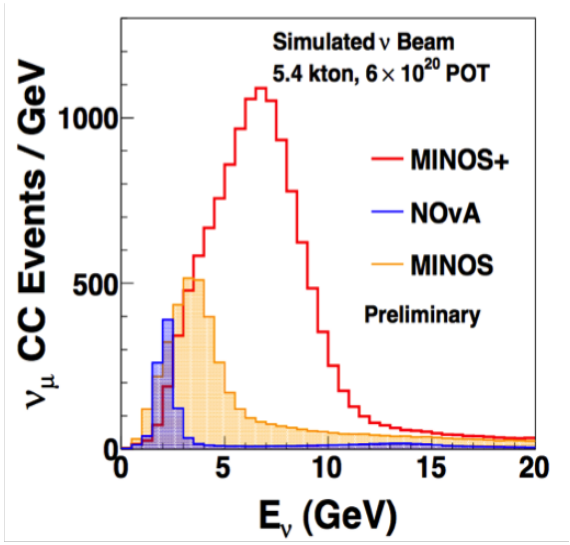
- Focus π^+/K^+ for neutrino beam
- Focus π^-/K^- for antineutrino beam

Decay: Hadrons decay in the 675m long decay pipe

Result: Wide-band on-axis ν_μ beam

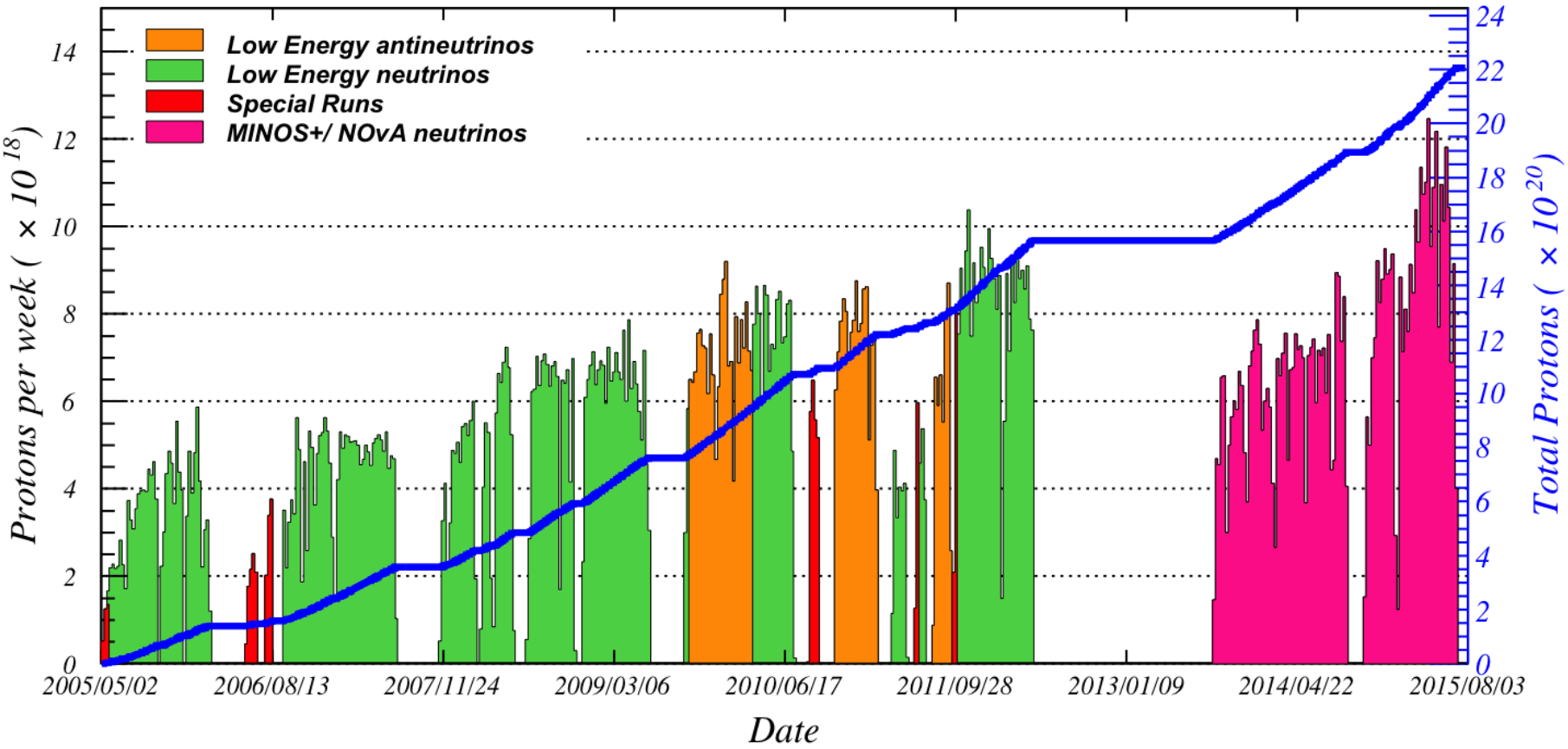
MINOS+: Will take advantage of the upgraded medium energy beam for NOνA ($\sim 700kW$)

Result: Higher intensity, higher energy ν_μ beam



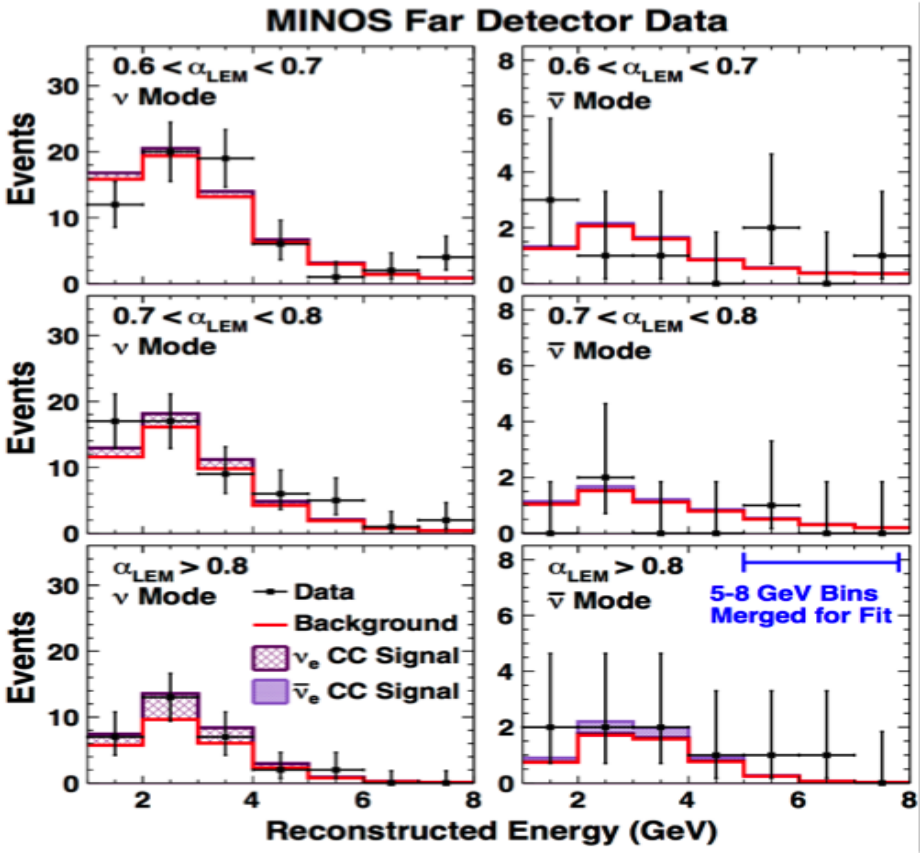
Protons On Target (POT) History

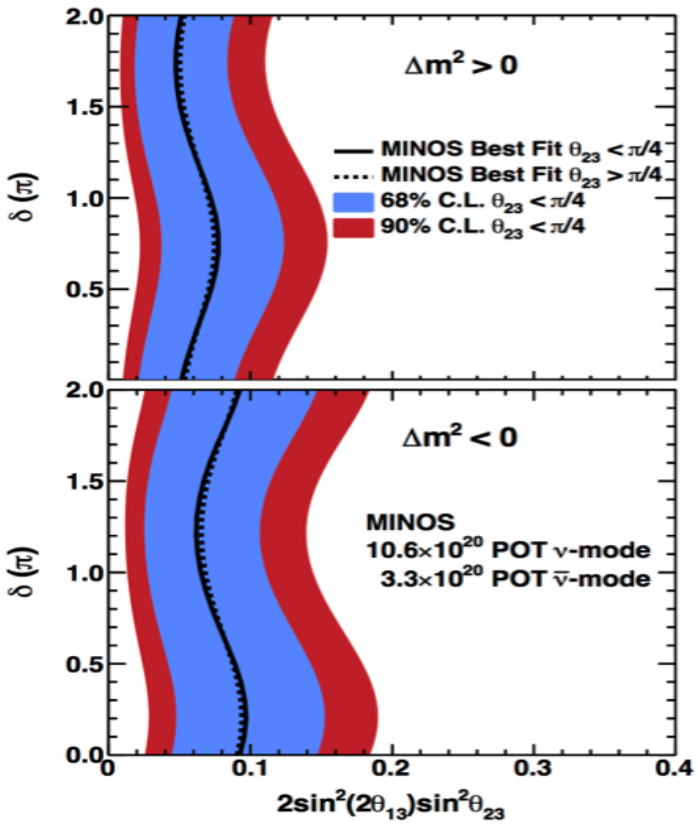
- MINOS *Neutrinos* $= 10.71e^{20}$
- MINOS *Antineutrinos* $= 3.36e^{20}$
- MINOS+/NOνA *Neutrinos* $= 6.4e^{20}$



MINOS ν_e Appearance

- ν_e appearance provides sensitivity to θ_{13}, θ_{23} octant, mass hierarchy and δ_{CP}
- ν_e signal events separated from NC background by selecting electromagnetic showers
- Extrapolated ND to FD predictions



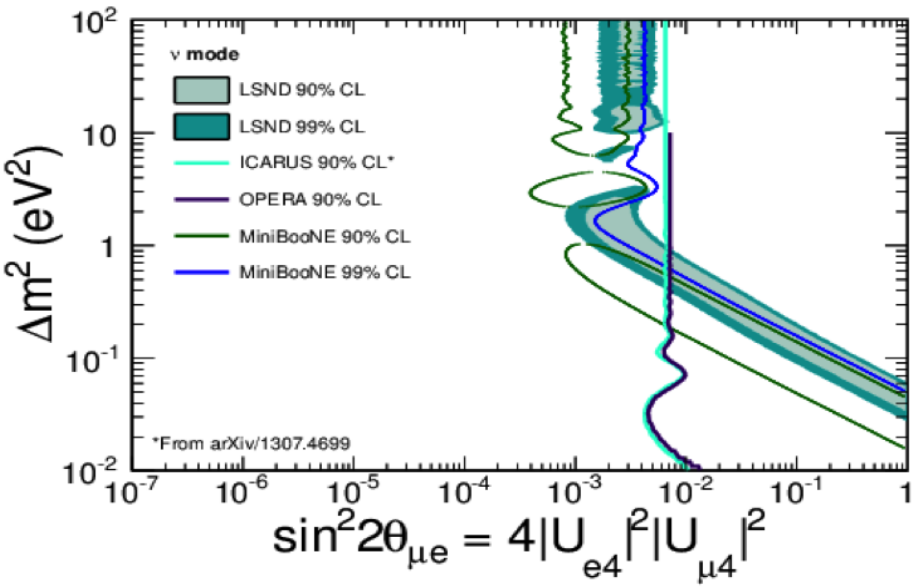


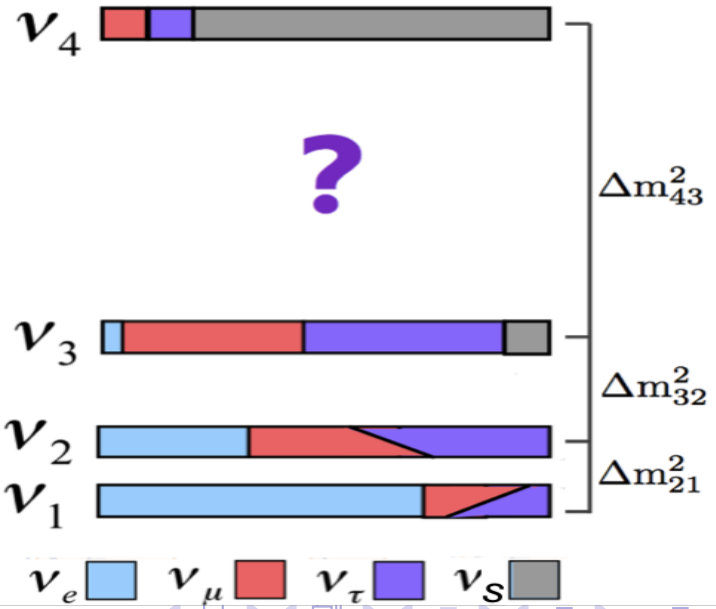
MINOS+ Physics Goals

- Concurrent run with NOνA experiment with updated NuMI beam.
- Precision measurement of the three-flavor oscillation parameters.
- Higher statistics: Expected $\sim$ 4000 ν_μ CC events/year at the Far Detector.
- The only wide-band beam long-baseline experiment currently running.
- Search for new exotic phenomena
  - Sterile neutrino mixing
  - Non-standard interactions

Sterile Neutrino Search in ν_e Appearance

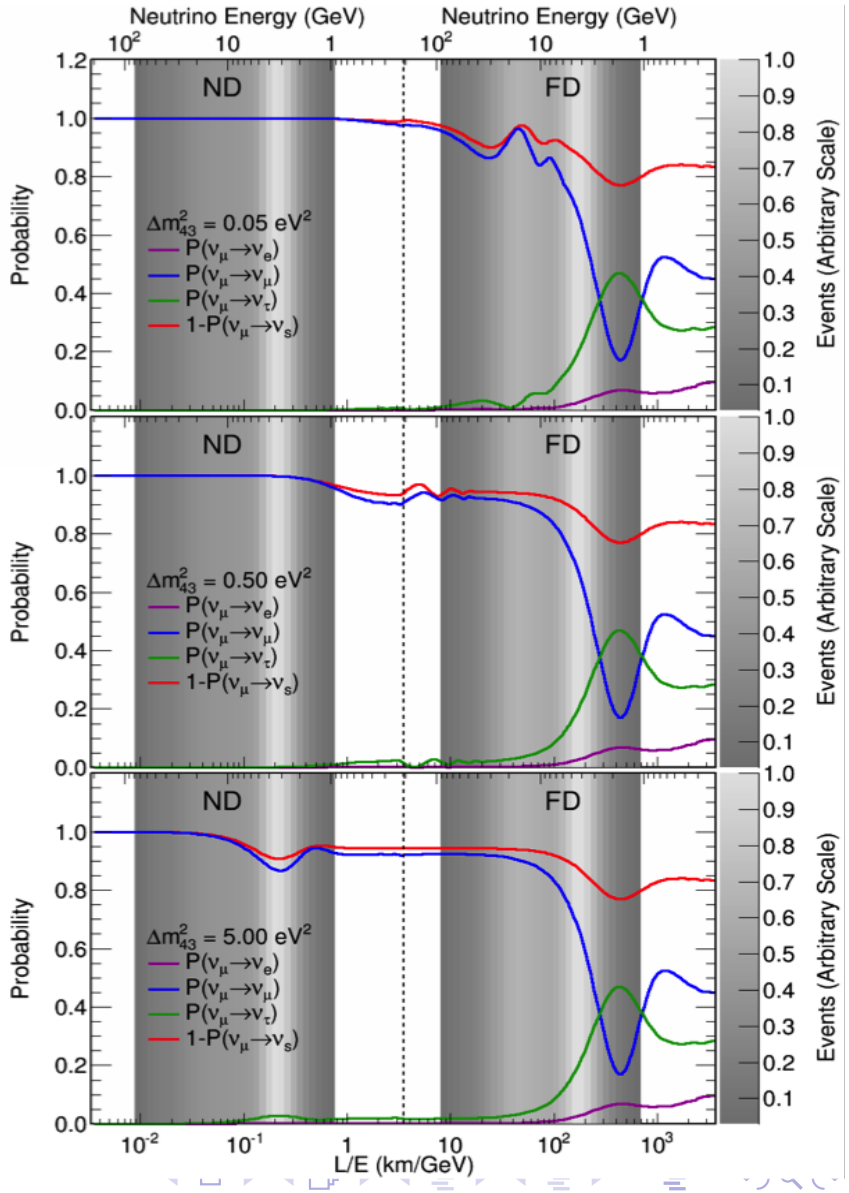
- Possibility of one or more additional light sterile neutrino states
  - Add 1 new flavor state (ν_s)
  - Add 1 new mass state (ν_4)
  - Additional 4 parameters: $\theta_{14}, \theta_{24}, \theta_{34}$ and Δm^2_{43}
- Anomalies were observed in:
  - Short baseline neutrino experiments
  - Reactor neutrino experiments
  - Radiochemical experiments



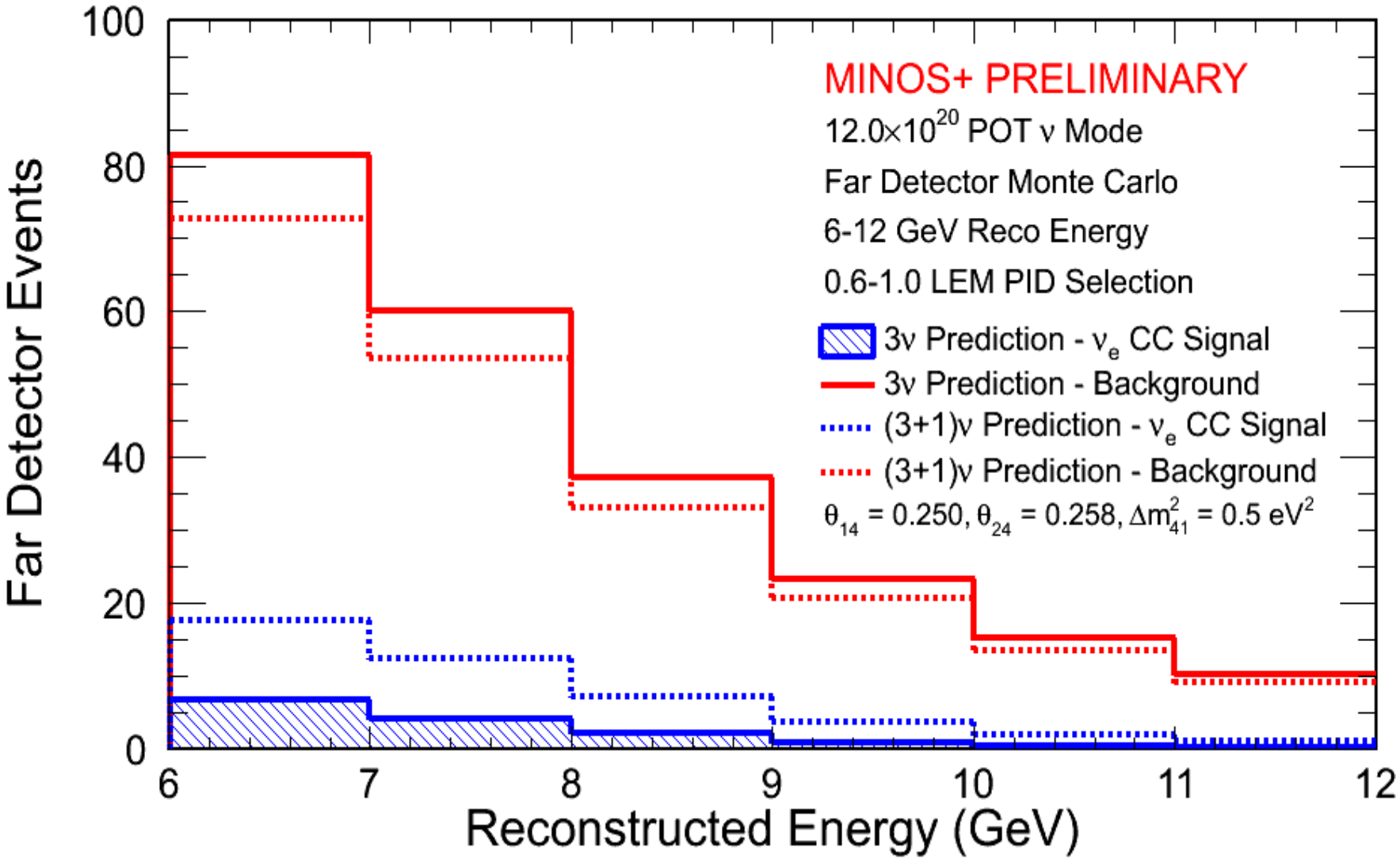


MINOS+ Sterile Oscillations

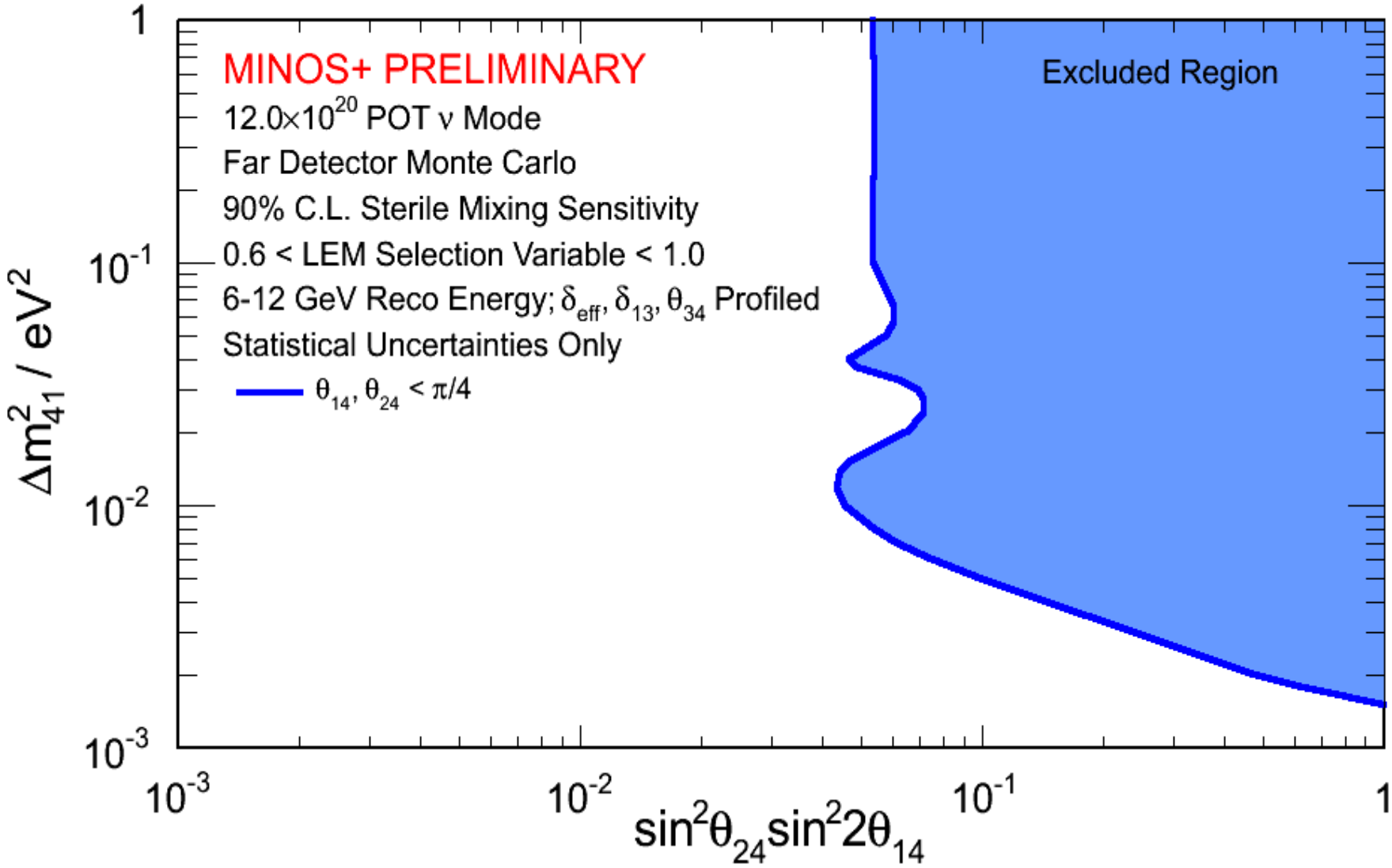
- Signature of $\nu_\mu \rightarrow \nu_s$ in MINOS:
  Energy-dependent depletion in both NC and ν_μ-CC energy spectra
- Small Δm^2_{43} : $(10^{-3} - 10^{-1} eV^2)$
  - FD: Additional oscillations above 3-flavour oscillation maximum
  - ND: unaffected
- Medium Δm^2_{43} : $(10^{-1} - 1 eV^2)$
  - FD: Rapid oscillations average out resulting in constant depletion
  - ND: unaffected
- Large Δm^2_{43} : $(1 - 10^2 eV^2)$
  - FD: Constant depletion
  - ND: oscillations must be accounted for when extrapolating to FD



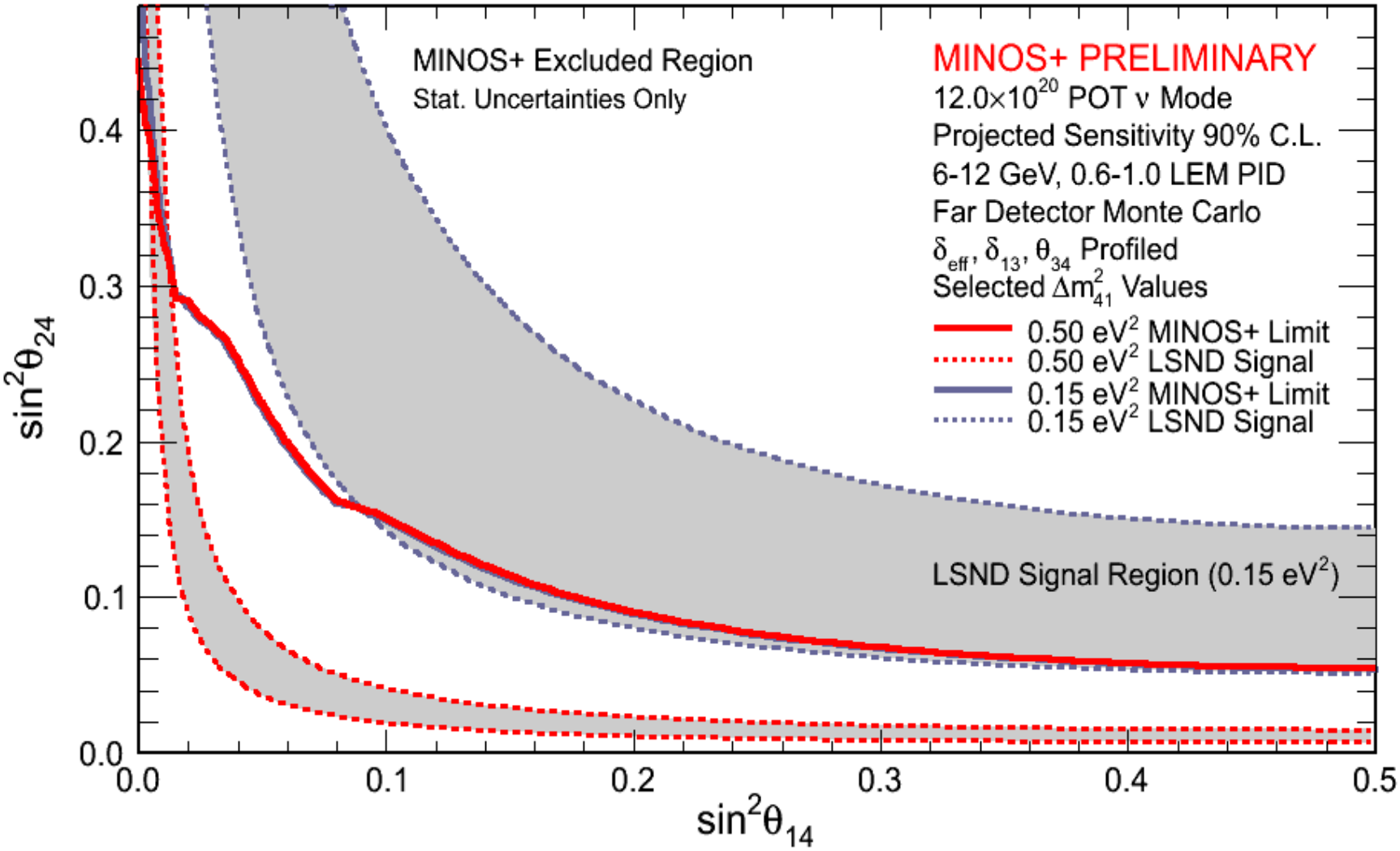
MINOS+: Sterile Neutrino Sensitivity



MINOS+: Sterile Sensitivity Contours



MINOS+: Sterile Sensitivity Contours



Summary

- NuMI beamline is being upgraded to increase the power to 700kW
- MINOS+ is collecting new high-statistics data with medium energy beam
  - New precision measurements of 3-flavor oscillation parameters in an unexplored energy range
  - Sterile neutrino search
- MINOS ν_e appearance can be used to set new constraints on low-mass sterile mixing parameters

THANK YOU!

Accelerator Upgrades

Fermilab accelerator complex is upgrading to go from 250 kW to 700 kW for NOνA experiment.

- First stage: Use Recycler for 'slip stacking' protons (250 kW $\rightarrow$ 500 kW).
- Second stage: Upgrading RF cavities to reduce the cycle time from 2.2 s to 1.33 s. (500 kW $\rightarrow$ 700 kW).
- Upgrade the target station to safely handle the increase power.
- Assuming overall complex efficiency of 61% and a running time of 44 weeks per year, 700 kW corresponds to 6.0×10^{20} protons per year.

ν_e Appearance

Measure $\nu_\mu \to \nu_e$ Oscillation

Probability in the Vacuum

$$P(\nu_\mu \to \nu_e) \approx sin^2 2\theta_{13} sin^2 \theta_{23} sin^2 \Delta$$
$$- \alpha sin2\theta_{13} sin\delta_{CP} sin2\theta_{12} sin2\theta_{23} \Delta sin\Delta sin\Delta$$
$$+ \alpha sin2\theta_{13} cos\delta_{CP} sin2\theta_{12} sin2\theta_{23} \Delta sin\Delta cos\Delta$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \qquad \Delta = \Delta m^2_{31} L/(4E)$$

Appearance Probability $P(\nu_\mu \to \nu_e)$ is sensitive to:
θ_{13}, θ_{23} Octant, δ_{CP}

ν_e Appearance

Measure $\nu_\mu \to \nu_e$ Oscillation

Probability in the Matter

$$P(\nu_\mu \to \nu_e) \approx sin^2 2\theta_{13} sin^2\theta_{23} \frac{sin^2(A-1)\Delta}{(A-1)^2}$$

$$- \alpha sin2\theta_{13} sin\delta_{CP} sin2\theta_{12} sin2\theta_{23} \frac{sinA\Delta}{A} \frac{sin(A-1)\Delta}{(A-1)} sin\Delta$$

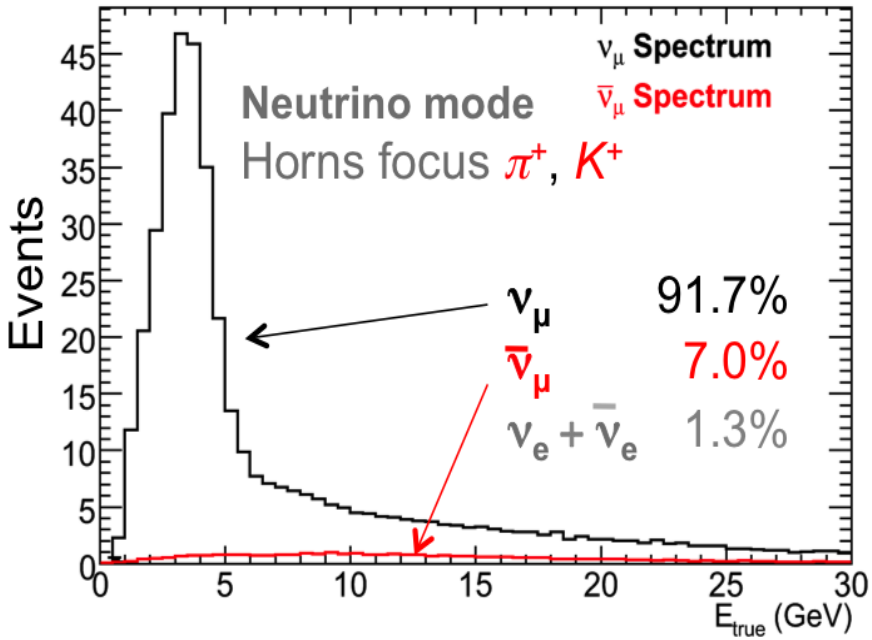
$$+ \alpha sin2\theta_{13} cos\delta_{CP} sin2\theta_{12} sin2\theta_{23} \frac{sinA\Delta}{A} \frac{sin(A-1)\Delta}{(A-1)} cos\Delta$$

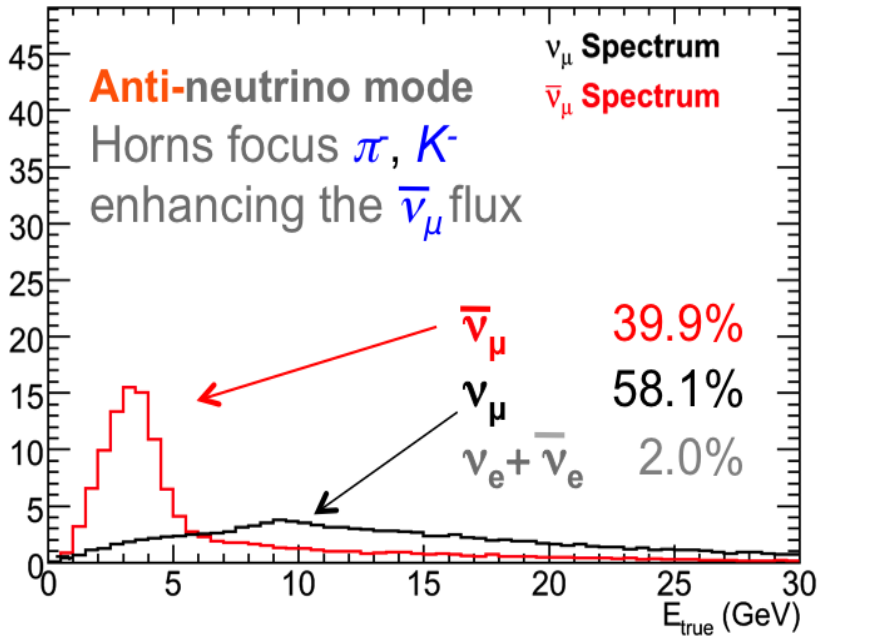
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}, \qquad \Delta = \Delta m^2_{31} L/(4E), \qquad A = G_f n_e L/(\sqrt{2}\Delta)$$

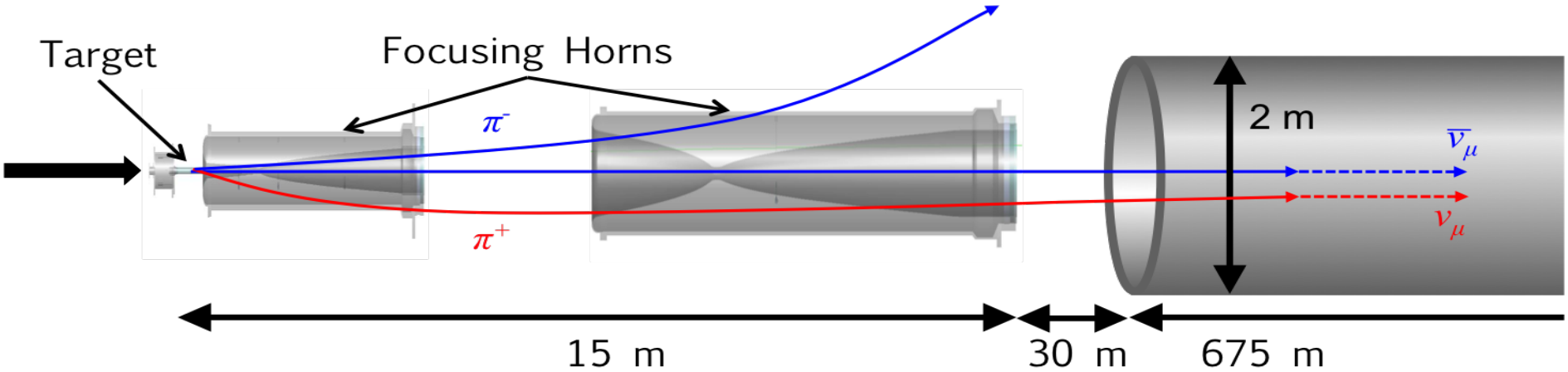
Appearance Probability $P(\nu_\mu \to \nu_e)$ is sensitive to:

Mass hierarchy and matter effects

NuMI Beam Composition

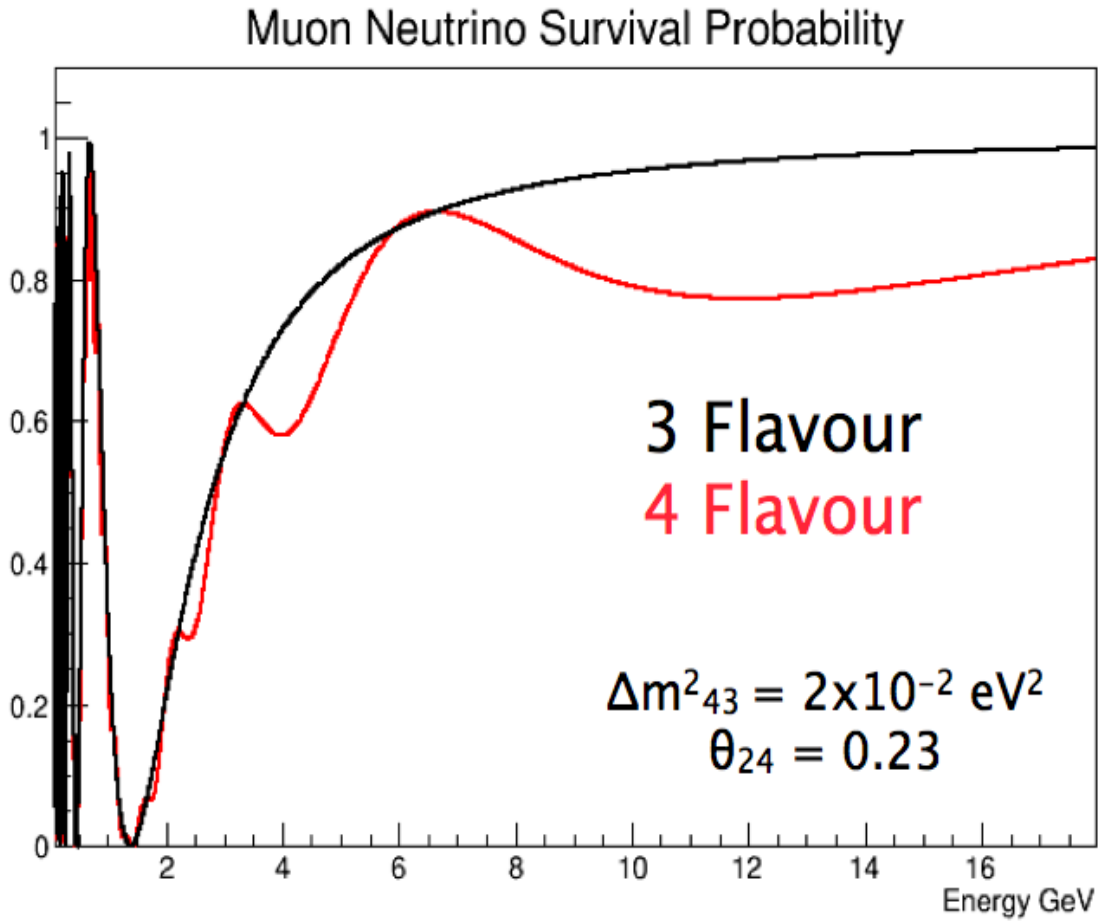


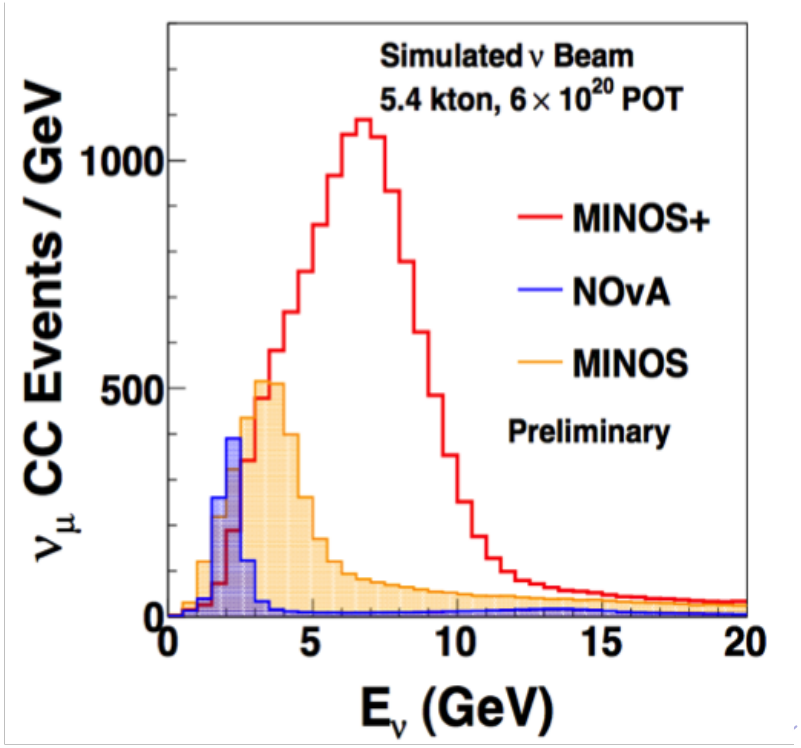




Sterile Oscillations

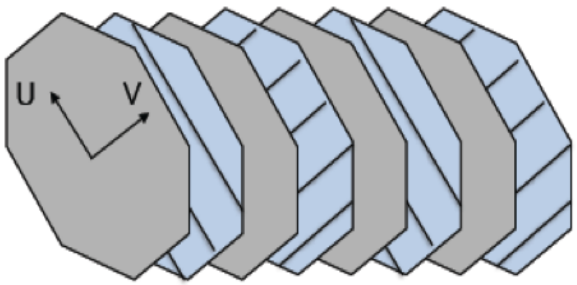
- Sterile Neutrino oscillation is high energy phenomenon
- MINOS+ allows access to higher energy region to study Sterile Neutrino oscillations

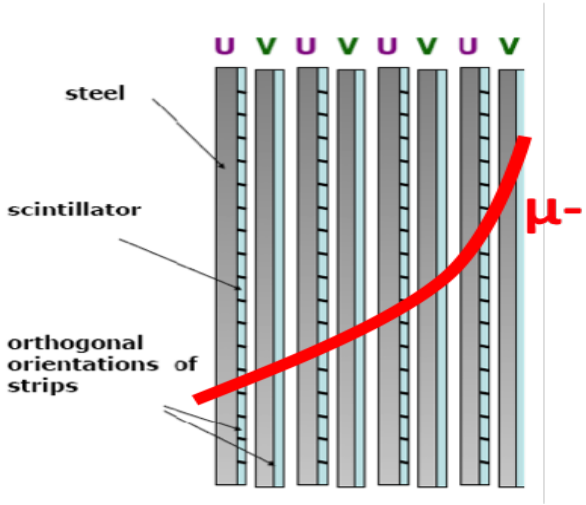


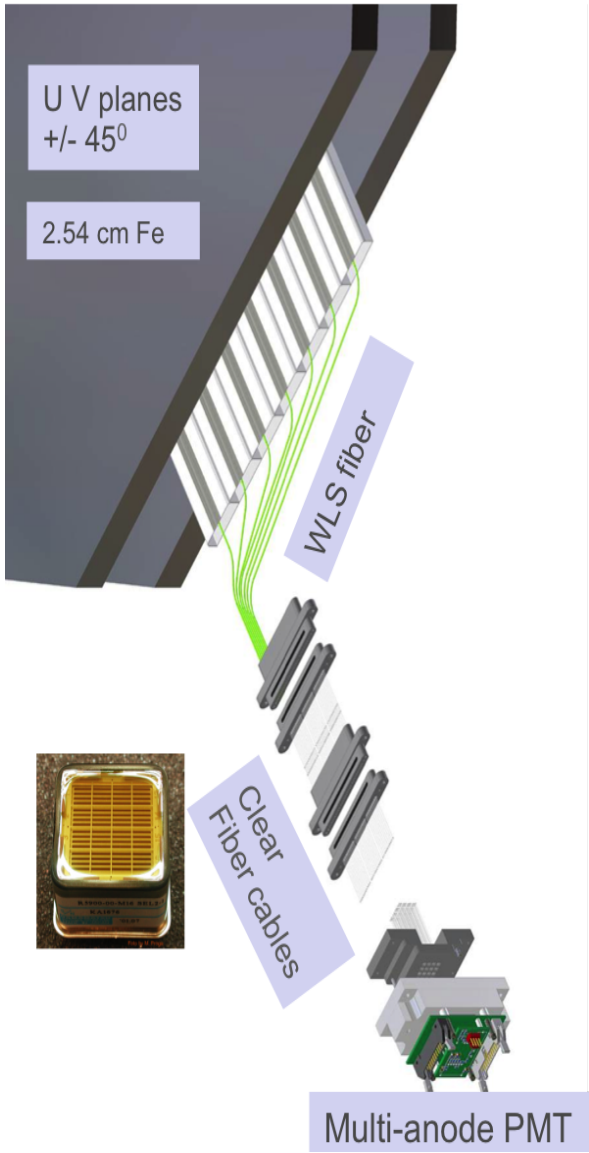


Detector Redout

- Series of octagonal planes
- Each plane consists of 1 in steel, 1 cm thick, 4.1 cm wide plastic scintillator
- Optimized for μ^+/μ^- detection
- Magnetized to $\sim$ 1.3 T for neutrino - antineutrino separation.







Particle Identification: LEM= Library Event Matching

- Large number of Signal and Background events are generated by Monte Carlo simulations to create Event Library
- Compact Electromagnetic showers are selected as ν_e-CC event candidates.
- ν_e-CC candidates are matched to Library Events
- 50 best matches are fed to Artificial Neural Network (ANN)
- Statistical selection algorithm generates α_{LEM} parameter value for particle selection.
- As $\alpha_{LEM} \rightarrow 1$, more ν_e-CC signal like events