A search for muon neutrino to electron neutrino oscillation mediated by sterile neutrinos in MINOS+

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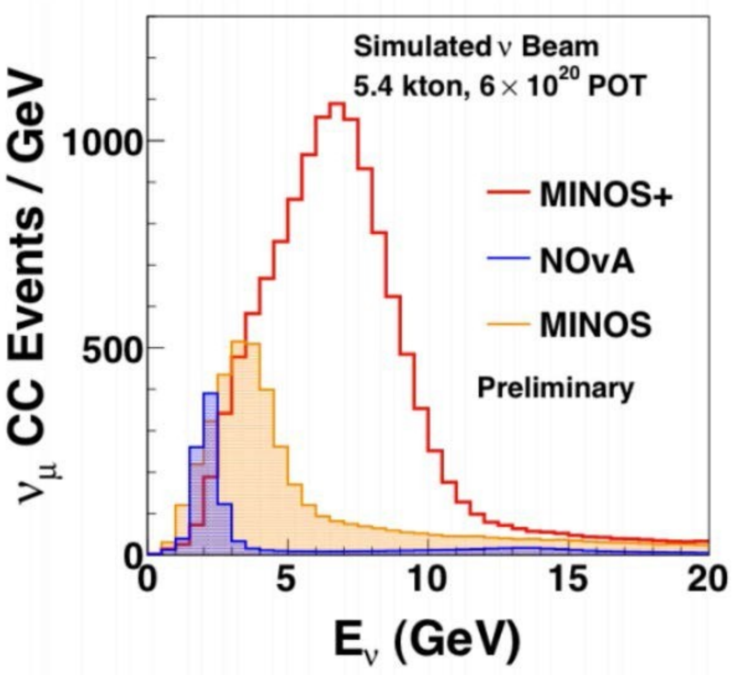
The MINOS+ Experiment and Sterile Search Motivations

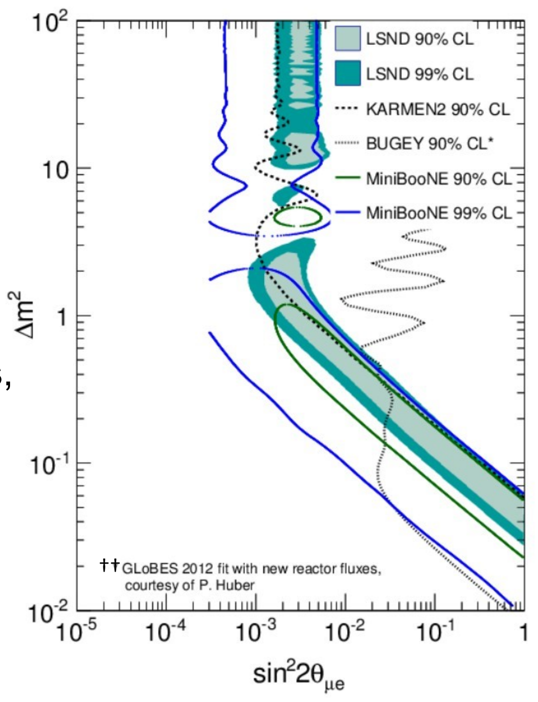
Functionally identical MINOS Near and Far Detectors

- **MINOS+ is an on-axis, long-baseline experiment studying neutrino oscillations in the medium-energy NuMI beam**
  - Extension of MINOS experiment that studied neutrino and antineutrino oscillations in the low-energy NuMI beam mode



- **Opportunities from using higher energy NuMI beam**
  - Increased beam power in addition to new beam optics
  - $\nu_\mu \rightarrow \nu_e$ appearance has not been explored in an accelerator experiment with current NuMI on-axis energy spectrum
  - <u>Search for exotic oscillation phenomena</u> by focusing on energies shifted from oscillation maximum

- **LSND and MiniBooNE observed electron neutrino and antineutrino appearance inconsistent with standard three-flavor formalism**
  - Sterile neutrino model possible explanation for this result
  - We consider 3+1 model in MINOS+, which adds additional oscillation parameters



- **The MINOS+ Impact**
  - Compared to MINOS, there is an increased rate of background events, particularly neutral currents (NC), and a decreased rate of ν_e charged current (CC) appearance
  - However, 3+1 model can lead to beneficial shifts in the expected event rates

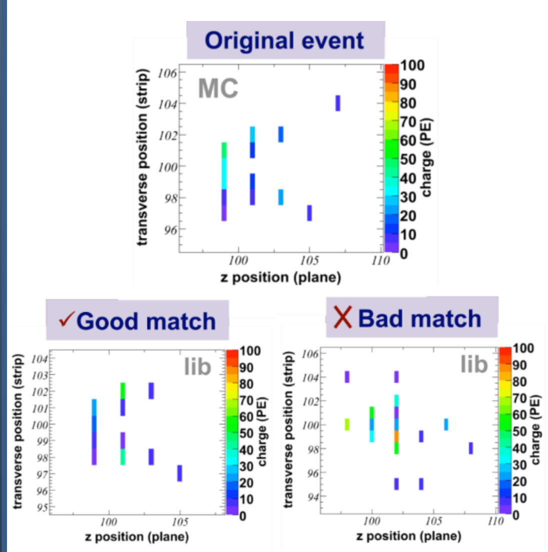
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(1.27\Delta m^2 L/E)$$

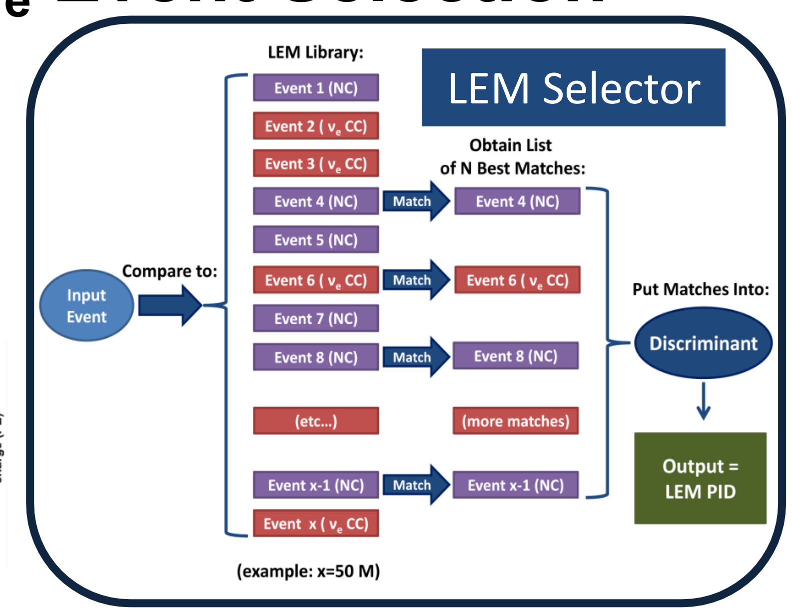
$$+$$

$$\sin(\theta_{23})\sin(2\theta_{13})\sin(2\theta_{24})\sin(\theta_{14})\sin^2\Delta_{32} + \sin^2(2\theta_{14})\sin^2(\theta_{24})\sin^2\Delta_{43} + \ldots$$

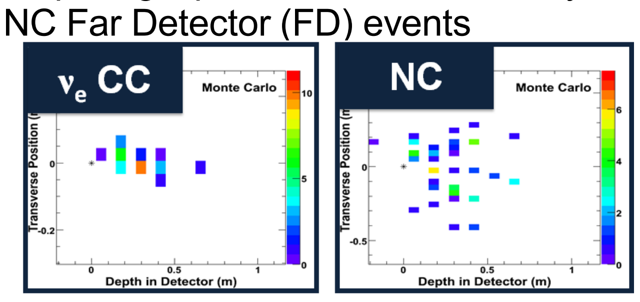
- **MINOS+ builds upon the vetted MINOS appearance analysis techniques to probe for new physics in 6-12 GeV region**
- **Still two additional years of data to analyze!**

Updated ν_e Event Selection

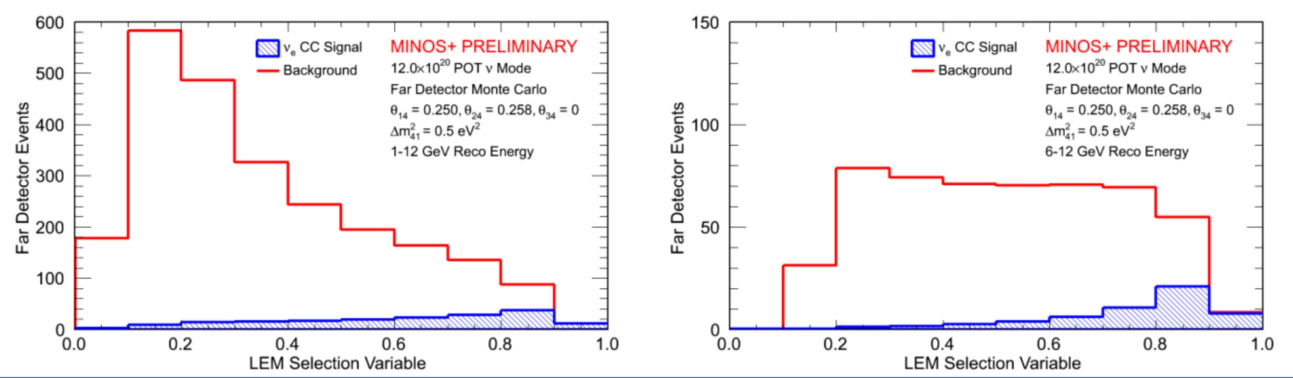




- **Library Event Matching(LEM) signal selection method used in the past**[†]
  - Single discriminant produced by comparing input candidates to library of simulated 20M signal and 30M NC Far Detector (FD) events
  - Compare topologies of events to select compact ν_e CC showers from hadronic activity

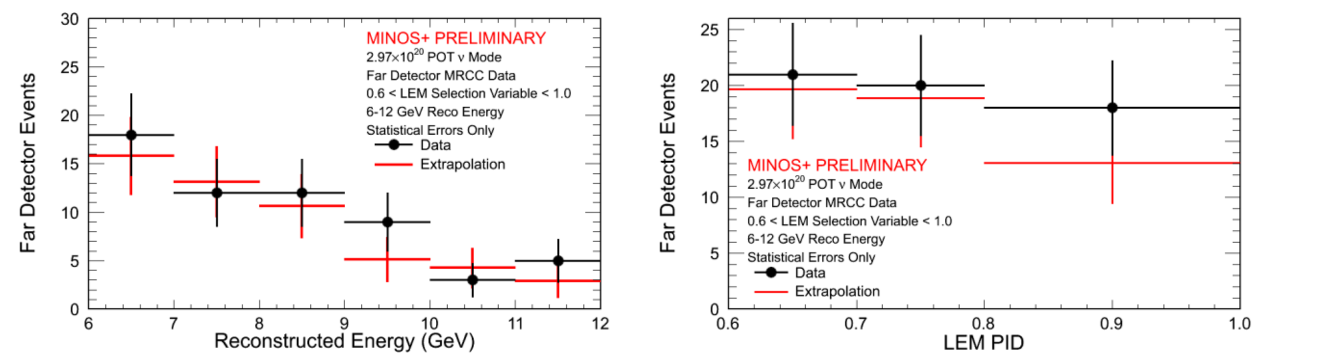


  - Four variables from matching process input to artificial neural network that yields discriminant
    - Fraction of best 50 that were signal matches
    - Mean inelasticity of signal events in best 50
    - Mean matched charge of signal events in best 50
    - Reconstructed energy of input candidate
  - **Artificial neural network trained using Monte Carlo optimized for MINOS+ energy spectrum**
- **Selector provides clear shape difference between background and signal events in 3+1 parameter space**
  - Cut between 6-12 GeV reduces background and improves signal-to-background in the signal-selected region (LEM > 0.6)



Analysis Crosschecks

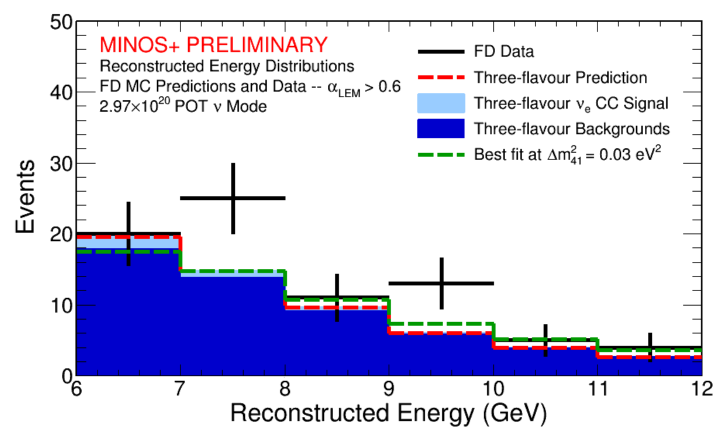
- **Comparisons between FD predictions and data place limits upon the parameter space of interest**
  - Before looking at the signal-selected region, several crosschecks are performed to verify the LEM selection algorithm and the prediction method
  - **AntiPID** – compares the three-flavor FD prediction and data with LEM < 0.5
    - No ν_e CC excess is expected in this region
    - <u>**Predicted 64.5 ± 8.0(stat. only), observe 62**</u>
  - **MRCC** – assesses the handling of NC events in the analysis region (LEM > 0.6) by making a prediction using an NC-like sample created from ν_μ CC events in data and simulation



- **Both sideband FD predictions were statistically indistinguishable from the data**

MINOS+ First-Year Results

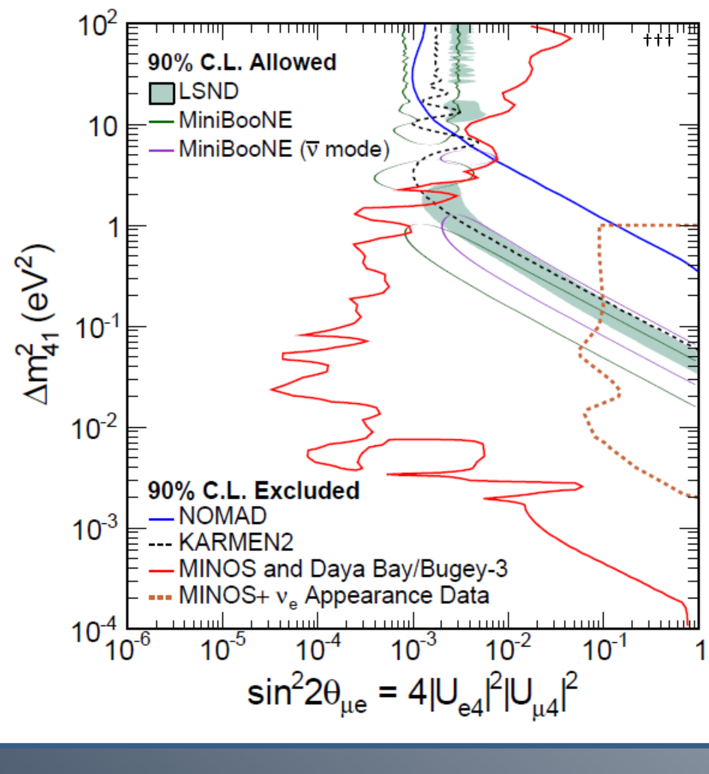
- **Analysis performed on first 2.97 × 10^{20} Protons-on-Target (POT) delivered to MINOS+**
  - Expected 56.7 events in the FD data given a three-flavor oscillation prediction using global best values
  - We observed 78 events, corresponding to a 2.3σ excess



Fit to 3+1 model done in 3 bins of LEM PID and 6 bins of reconstructed energy

This analysis is sensitive to both θ_{14} and θ_{24}, and there are additional dependencies to θ_{13}, θ_{23}, θ_{34}, δ_{13}, and $\delta_{24} - \delta_{14}$

Likelihood surfaces spanning θ_{14} and θ_{24} are produced at various values of Δm^2_{41} to produce the 90% C.L. exclusion shown – θ_{34}, δ_{13}, and $\delta_{24} - \delta_{14}$ are profiled



Analysis complements MINOS disappearance result through a robust treatment of the 3+1 model parameters

Offers immediate and independent comparison to LSND and MiniBooNE

References

†Electron neutrino and antineutrino appearance in the full MINOS data sample, P. Adamson et al. (MINOS), Phys. Rev. Lett. 110 (2013) 171801, arXiv:1108.0015.
††P. Huber, Phys. Rev. C 85 029901 (2011) (*fit and reactor flux update*); A. Aguilar et al. (LSND), Phys. Rev. D 64, 112007 (2001); A.A. Aguilar-Arevalo et al. (MiniBooNE), Phys. Rev. Lett. 110, 161801 (2013).
†††B. Armbruster et al. (KARMEN), Phys. Rev. D 65, 112001 (2002); P. Astier et al. (NOMAD), Phys. Lett. B 570, 19 (2003).