Prospects for a MINOS+ sterile ν search using ν_e appearance events

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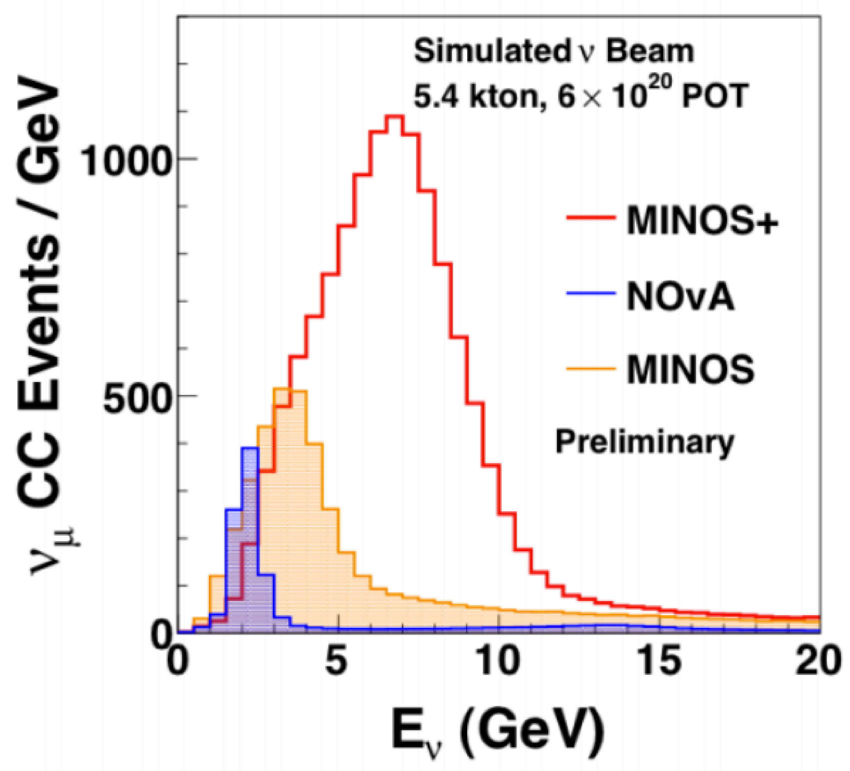
The MINOS+ Experiment and Sterile Search Motivations

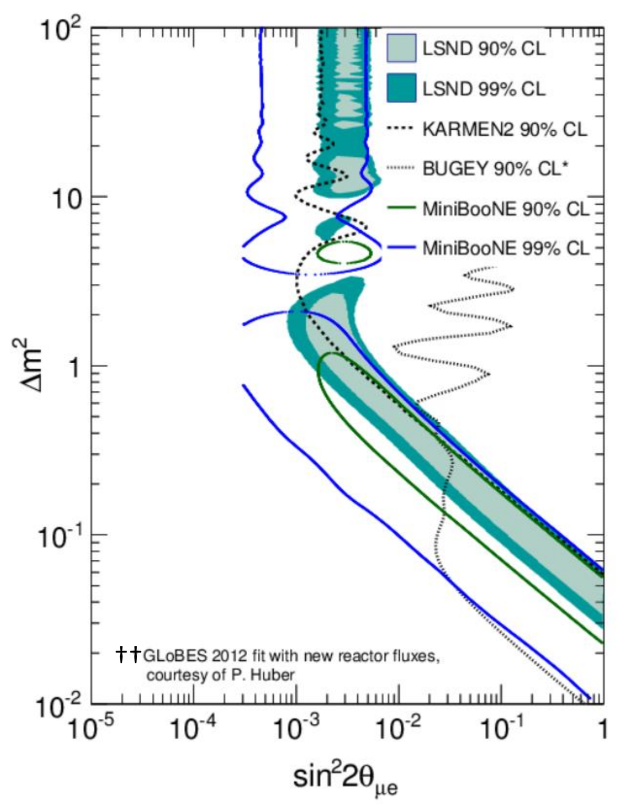
Functionally identical MINOS near and far detectors

➢ **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 with the medium-energy NOνA era NuMI beamline**
- Increased beam power in addition to higher energy beam optics
- Appearance channel has not been explored in an accelerator experiment with the current NuMI energy spectrum
- Focus on high energy window, shifted from oscillation maximum, could put constraints on sterile parameters

➢ **LSND and MiniBooNE observed neutrino oscillation in $\nu_\mu \rightarrow \nu_e$ at L/E inconsistent with standard formalism ~ 1 eV^2**
- Sterile neutrino model possible explanation for this result
- 3+N sterile models add additional mass splittings, mixing angles, and phases to the oscillation framework
- Requires further study and MINOS+ is in position to contribute



➢ **MINOS studied $\nu_\mu \rightarrow \nu_e$ oscillation in the standard oscillation framework**
- 10.6 ×10^{20} protons-on-target (POT) neutrino mode data and 3.3 ×10^{20} POT antineutrino mode†
- Shift to medium-energy beam yields increased rate of backgrounds (NC events) and decreased rate of appearance in the standard oscillation model
- However, changes in the oscillation probability due to the existence of sterile neutrinos can lead to beneficial shifts in the expected event rates

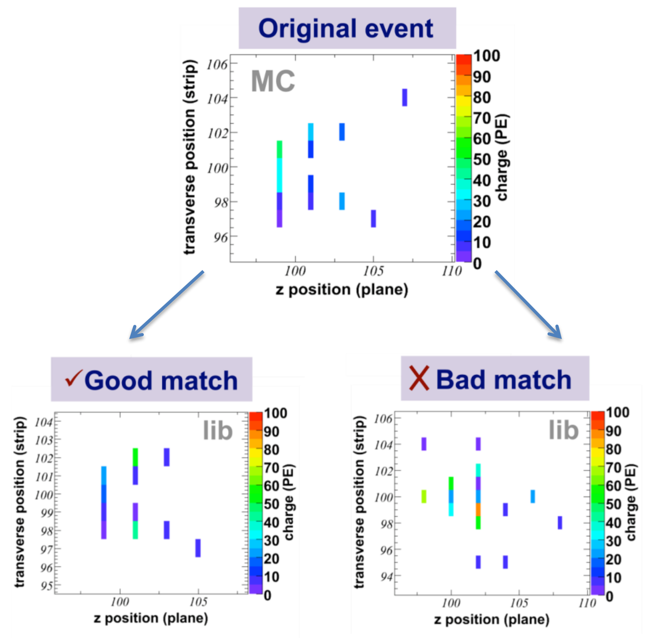
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(1.27\Delta m^2 L/E)$$

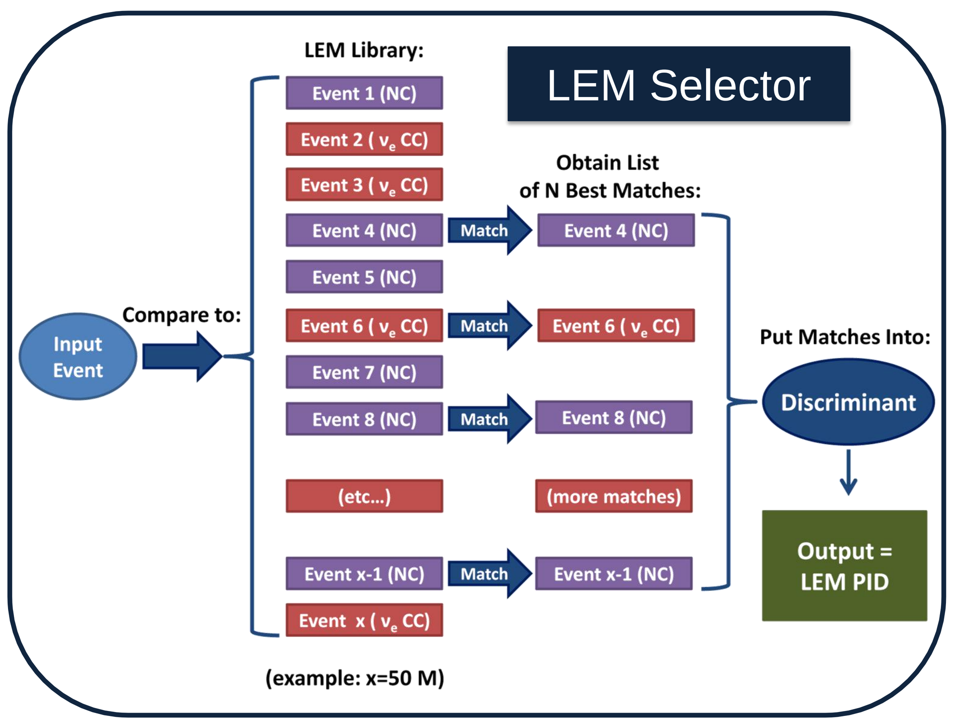
$$+$$

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

➢ **High-energy region (6-12 GeV) selection improves sensitivity to new physics**
- Complements sterile neutrino focus of MINOS+ experiment
- Vetted appearance signal selection technique available for MINOS+ study

Updated ν_e 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 neutral current Far Detector events
  - Information from set of the 50 best matches to the candidate gets fed to an artificial neural network that returns single value discriminant
- Previous matching process returned four variables that served as neural network inputs
  - 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
- Two variables added that yield 5-10% improvement in signal-to-background
  - Mean inelasticity of NC events in best 50
  - Mean matched charge of NC events in best 50
- This architecture change did not negatively impact computational resources

➢ **New artificial neural network trained based upon the new variable inputs and reconstructed energy region of interest**
- Performance and signal-background separation assessed – as shown in lower right panel

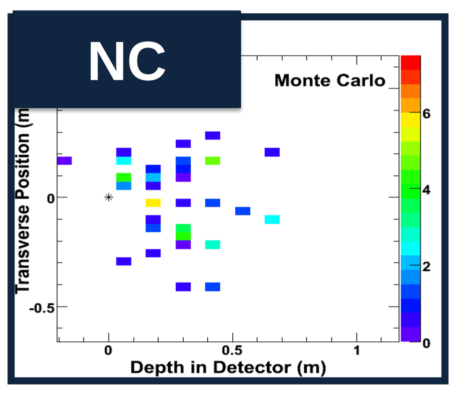
➢ **Four flavor model investigated in this study**
- Appearance channel sensitive to sterile mass splitting as well as θ_{14} and θ_{24}
- Shape fit performed using 3 bins of the LEM selection variable and 6 bins of reconstructed energy
- Log-likelihood calculated at various points in parameter space and compared to Far Detector prediction to generate sensitivity

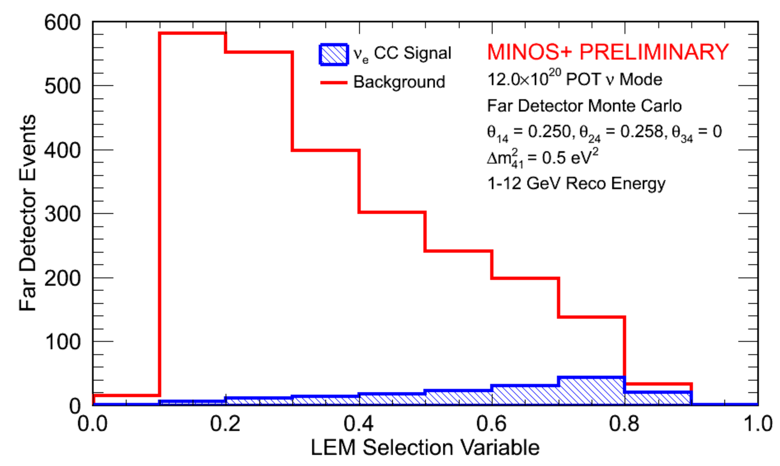
References

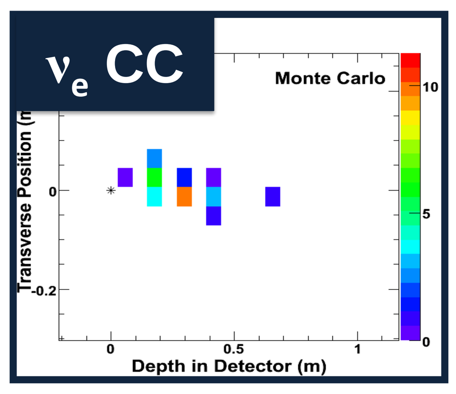
†Electron neutrino and antineutrino appearance in the full MINOS data sample, P. Adamson et al. (MINOS), Phys. Rev. Lett. 110 (2013) 171801, arXiv:1108.0015.
††P. Huber, Phys. Rev. C 85 029901 (2011) (*fit and reactor flux update*)
A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 110, 161801 (2013) (*MiniBooNE contours*)

Selector Performance and Sensitivities

➢ **Assessing Signal-Background Separation**
- Basic pre-selection cut restricts reconstructed energy range to 1-12 GeV window
- Examine LEM selection performance in beam peak and signal tail regions

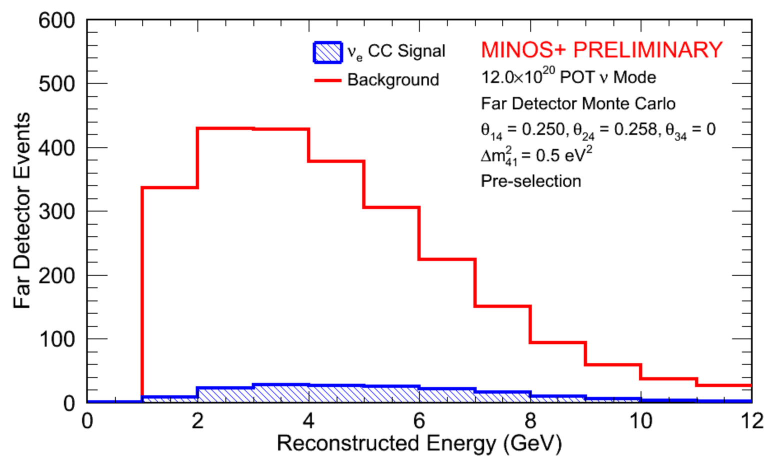




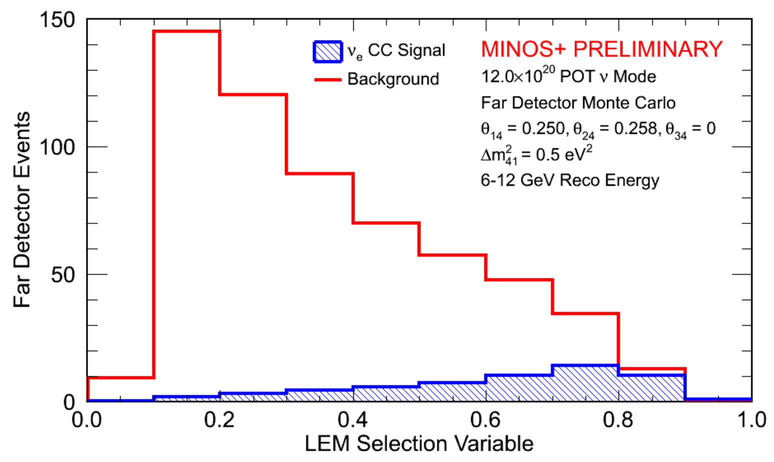


- Distribution acquired with selected oscillation parameters
  - 369.35 background events expected with 96.11 ν_e CC events (65.64 events from standard oscillations, 30.47 from sterile model inclusion)
  - Figure of Merit (FOM) ≡ (ν_e CC excess from sterile model inclusion) / √(Background + ν_e CC expected from standard oscillations) = 1.46

- Substantial portion of background events sit at lower reconstructed energies
- Background rate diminishes more rapidly as a function of energy
- Aim to use this feature to increase sensitivity



➢ **Energy cut check**
- Test cut of 6-12 GeV on reconstructed energy applied as proof of principle
- Signal-Background clearly improved
- What about FOM?
  - 95.54 background events
  - 35.18 ν_e CC events
    - 18.20 from standard oscillation
    - 16.98 from sterile model
  - FOM = 1.59
- Additional cut tuning planned to check for further improvements in sensitivity



➢ **Monte Carlo driven sensitivities:**
- 90% C.L. generated for normal mass hierarchy
- Log-likelihood computed for various values of $\sin^2\theta_{24}\sin^2 2\theta_{14} = \sin^2 2\theta_{\mu e}$ for a given slice of Δm^2
- Observed events in each analysis bin set to the Far Detector prediction, in which $\sin^2\theta_{24}\sin^2 2\theta_{14} = 0$
- Point along horizontal axis at which $-2\Delta\ln L = 2.71$ defines 90% C.L.
- Cutoff at 1 eV^2 driven by need to handle Near Detector Oscillations
- **More developments in the near future!**