Search for Sterile Antineutrinos in MINOS

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for the MINOS Collaboration

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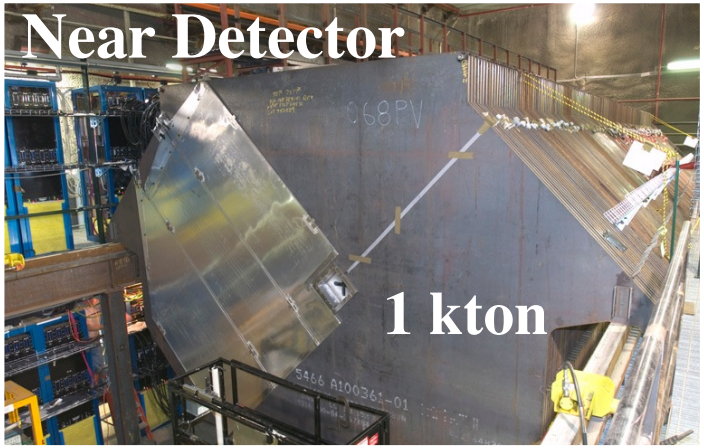
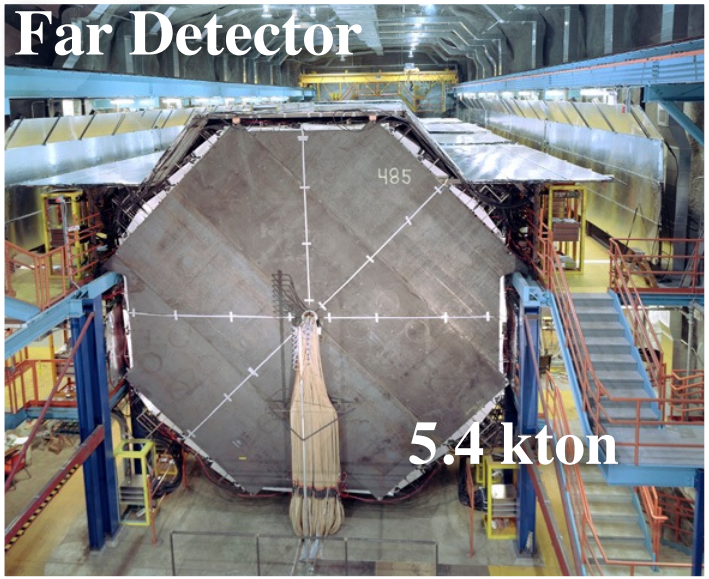
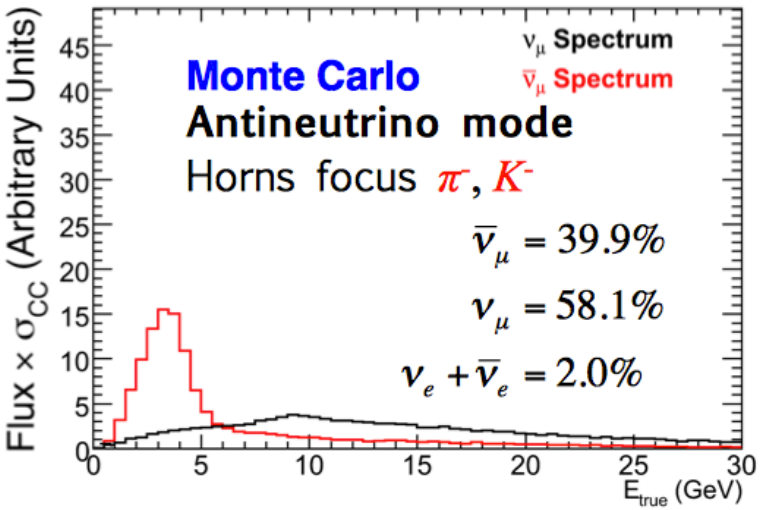
The MINOS Experiment



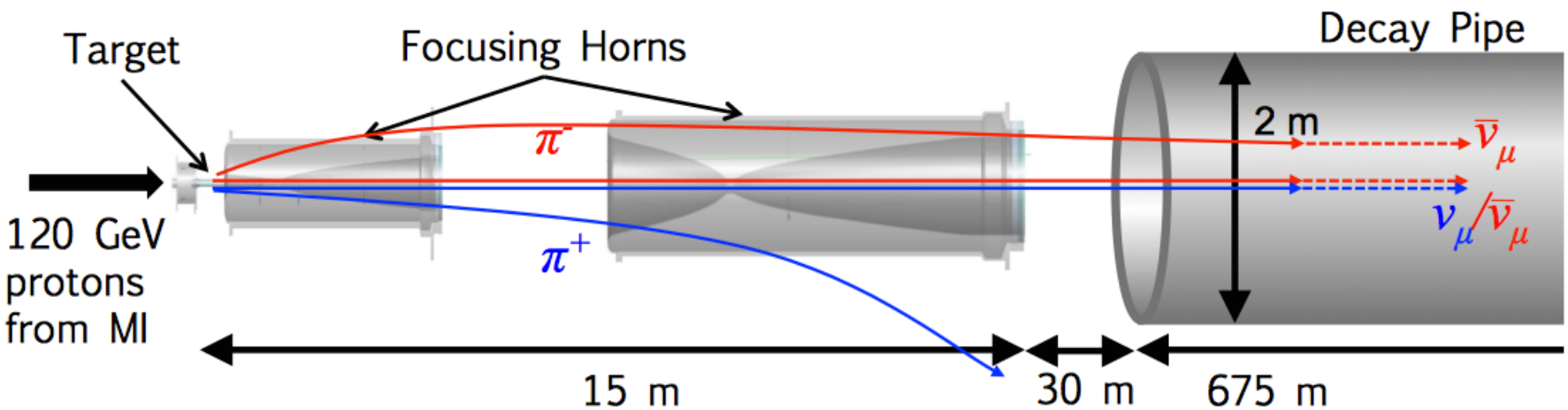
- High Intensity, flexible NuMI beam at Fermilab (320 kW, 120 GeV)
- **Near Detector**
  - At Fermilab, 1km away from the source
  - 1 kton, measures the energy spectra and beam composition
- **Far Detector**
  - At Soudan mine, 735km away from the source
  - 5.4kton and 700m deep, functionally identical to the Near Detector
- Alternating layers of 2.54cm steel and 1cm plastic scintillator with WLS and clear fibers
- 1.3T magnetic field



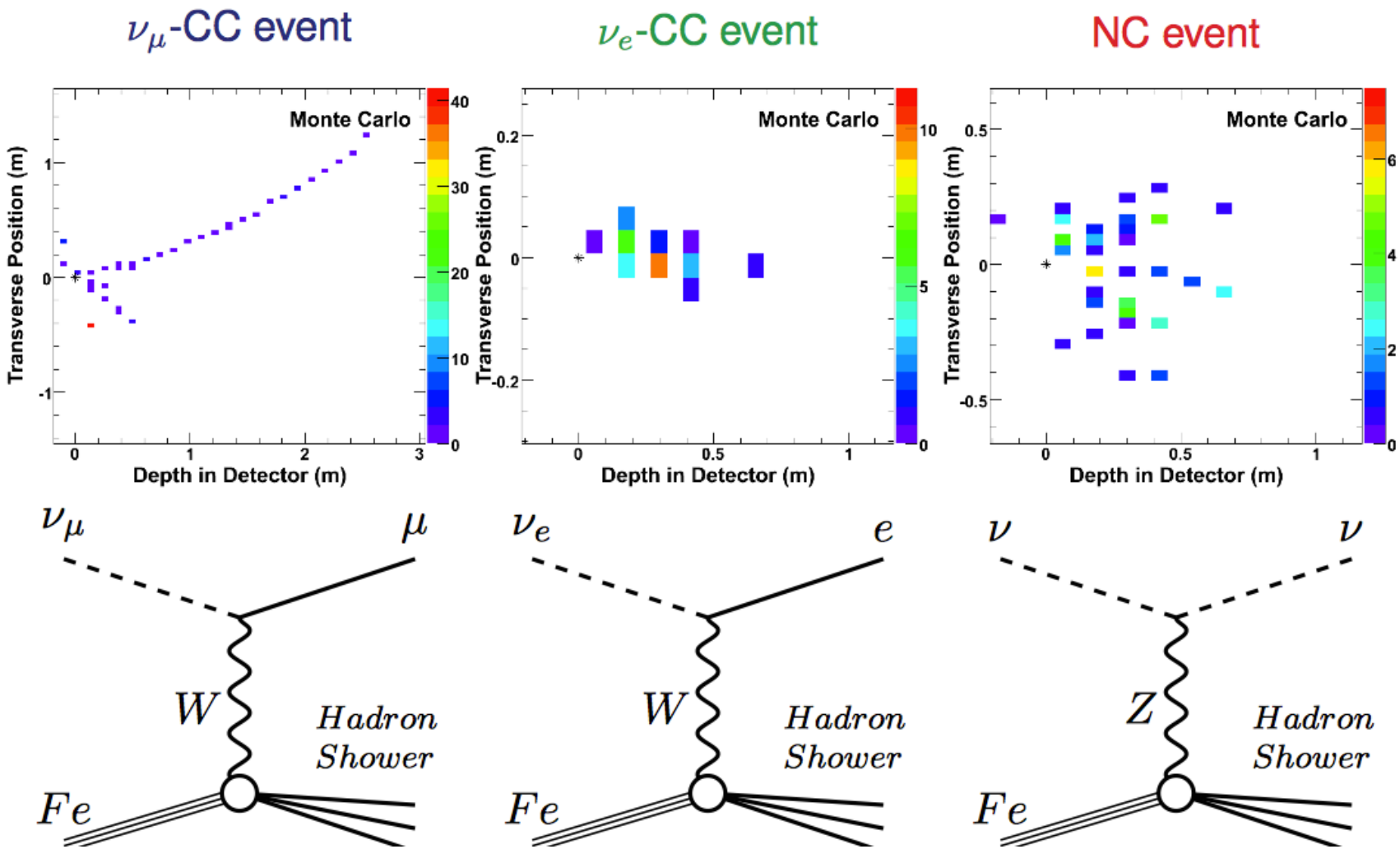
MINOS Antineutrino Beam



- MINOS has taken data in antineutrino mode between 2009-2011
- Collected 3.36 x10^{20} PoT antineutrino data
- Bombard graphite target with 120 GeV protons from the Main Injector: produce pions and kaons
- Focus π^+/K^+ for neutrinos and π^-/K^- for antineutrinos



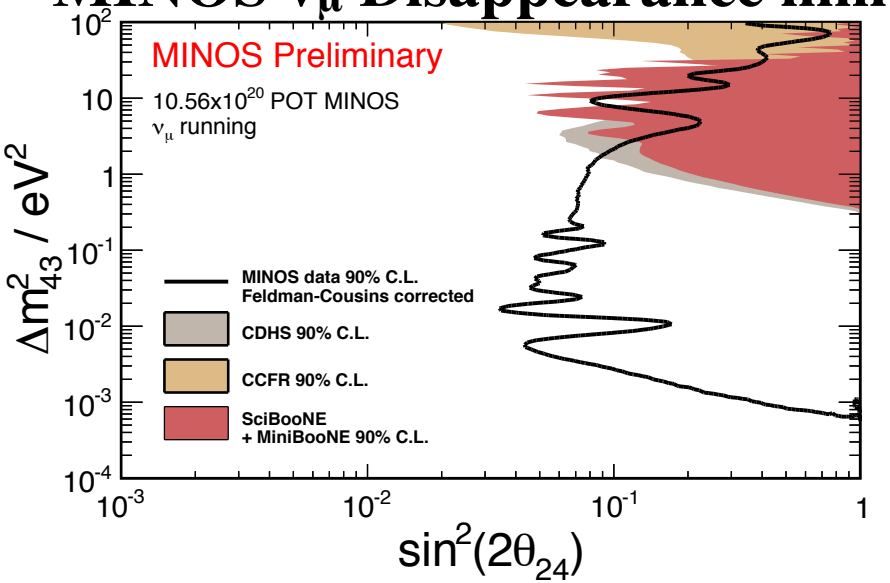
MINOS Event Topology

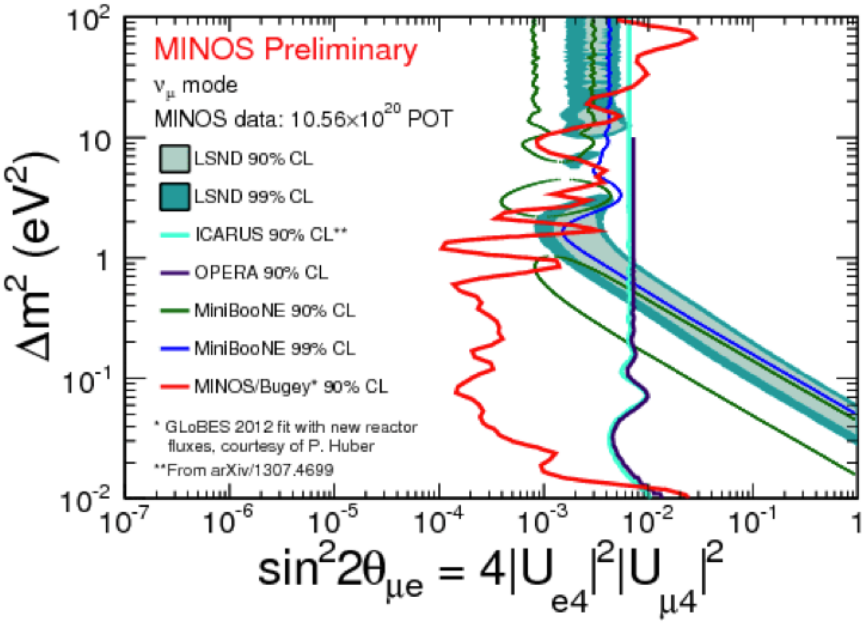


Sterile Neutrinos

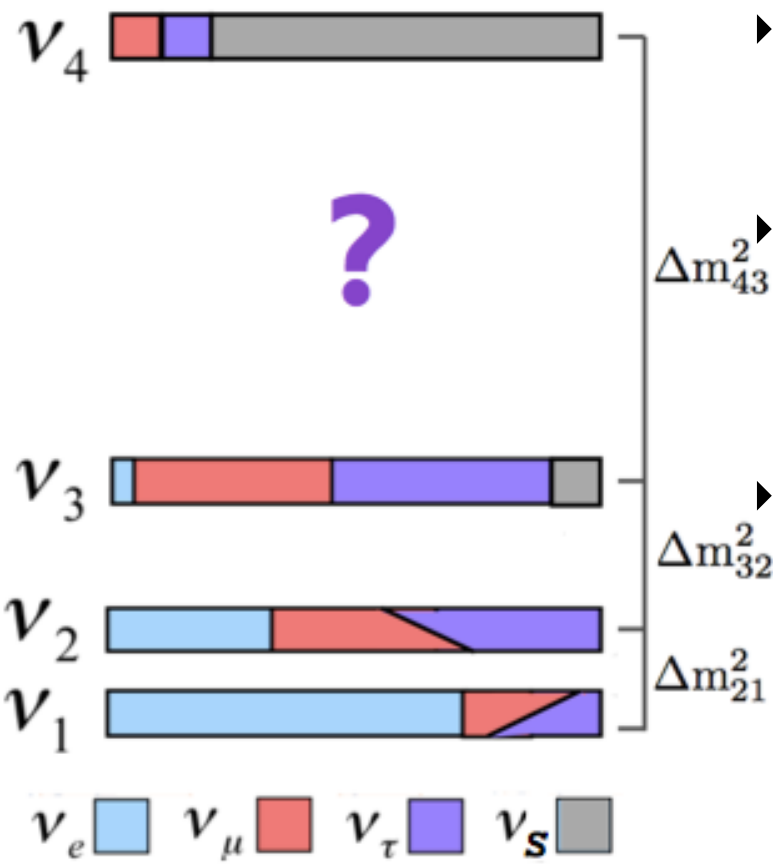
- Many anomalies from reactor, radio-chemical, short-baseline, may be explained with oscillation to light sterile neutrinos
- Evidence is not yet conclusive
- MINOS can probe sterile neutrinos through ν_μ and **$\bar{\nu}_\mu$ disappearance**
- MINOS ν_μ limit combined with Bugey can be compared with LSND and MiniBooNE allowed region. Will explore this with $\bar{\nu}_\mu$ disappearance

MINOS ν_μ Disappearance limit





Sterile Neutrinos



- 3+1 Sterile neutrino model is used in the study
- 3 active neutrinos (ν_e, ν_μ, ν_τ) and one sterile neutrino (ν_s) and additional mass eigen state (ν_4) => 4x4 mixing matrix
- We assume $\bar{\nu}_\mu$ and ν_μ disappearance due to oscillations are governed by the same mixing parameters, deviations from this would be an indication of CPT violation.
- Oscillation is described by

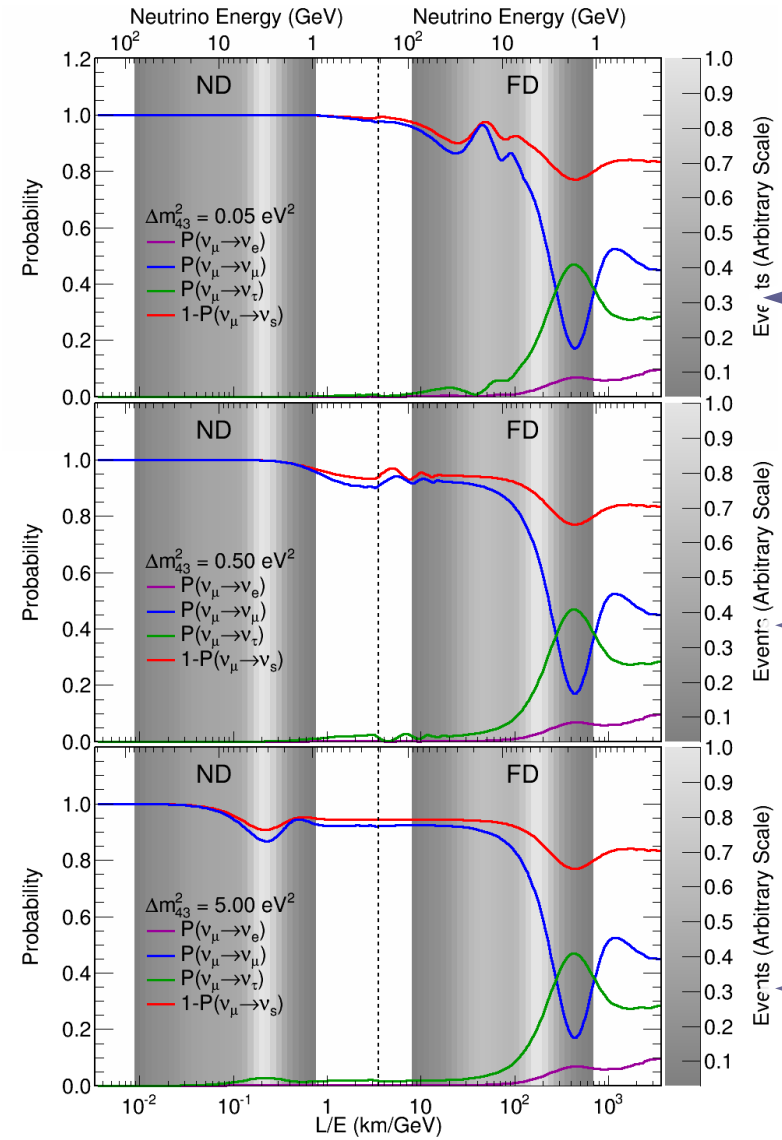
Standard three flavor parameters

- **Δm^2_{32}, Δm^2_{21}, θ_{12}, θ_{23}, θ_{13}**
- **$\delta 13$**

Sterile parameters

- **Δm^2_{43}, θ_{14}, θ_{24}, θ_{34}**
- **$\delta 24$, $\delta 14$**

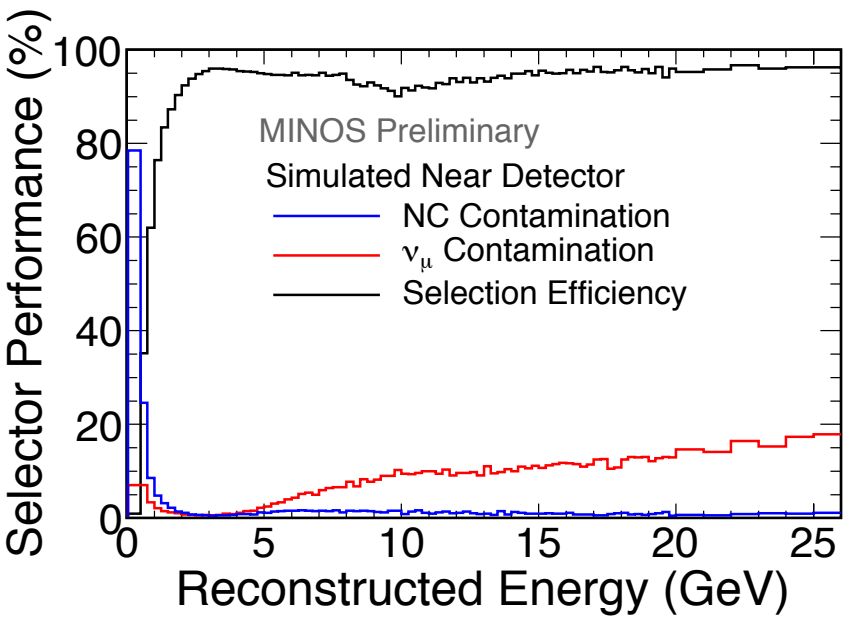
Sterile Neutrinos in MINOS

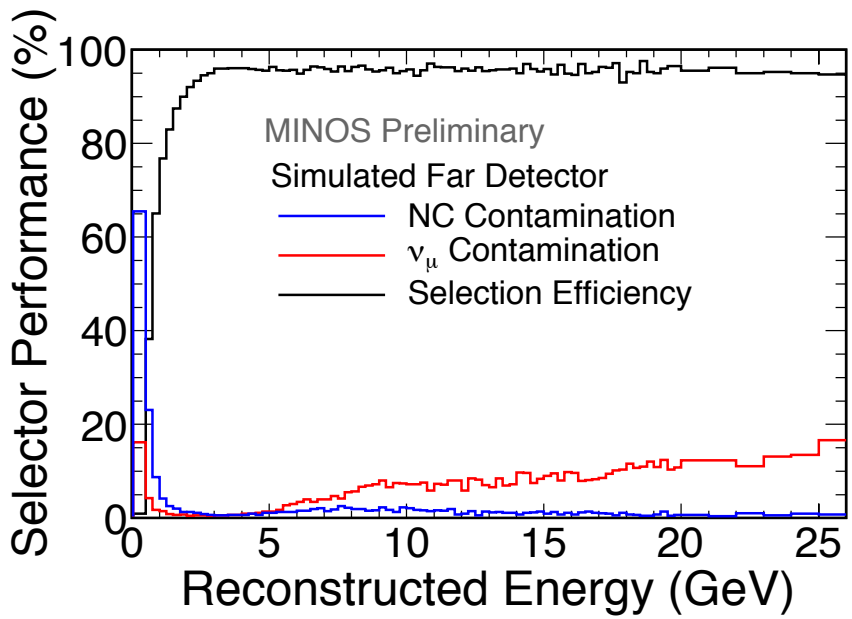


- Oscillation to sterile neutrinos can be seen in both detectors
  - **Small $\Delta m^2_{43} \ll 0.5$ eV^2**
    - No ND oscillation
    - Distortion at FD spectrum
  - **Medium $\Delta m^2_{43} \sim 0.5$ eV^2**
    - No ND oscillation
    - Fast oscillation in FD average out
    - Effectively a counting experiment
  - **Higher $\Delta m^2_{43} \gg 0.5$ eV^2**
    - Oscillations at both detectors
    - Spectral distortion at ND
    - Constant depletion in FD

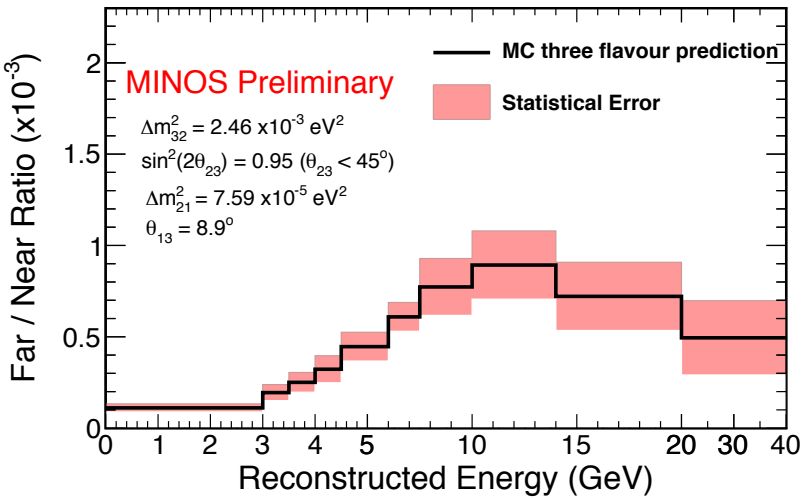
Selection of Antineutrino Events

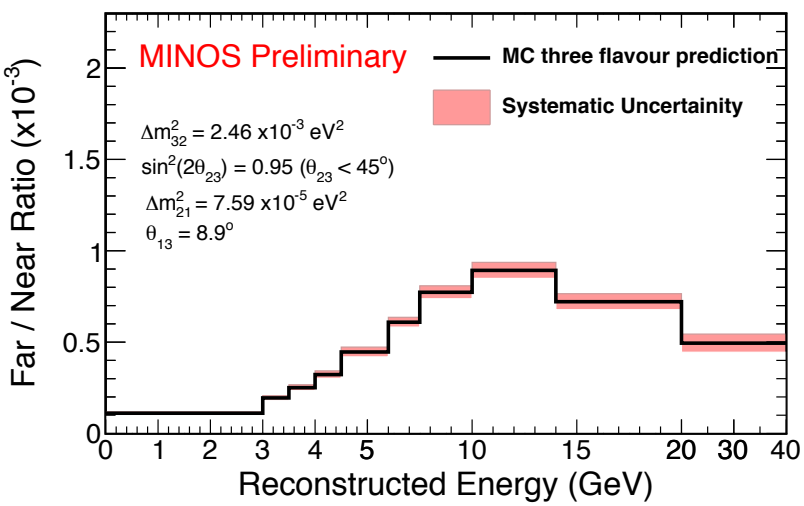
- Selects only the muon track with positive charge sign
- High efficiency ~ 95 %
- Very low wrong sign contamination and NC background





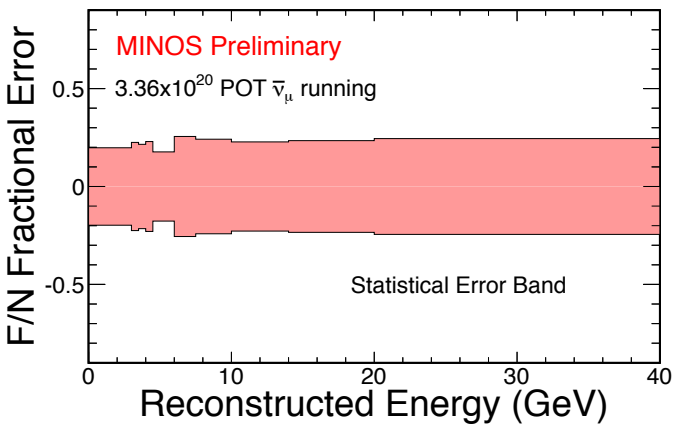
Far-over-near Ratio

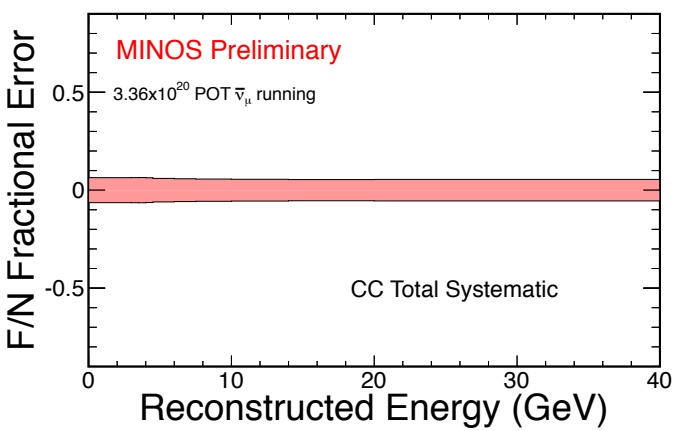




- Using only antineutrino CC samples
- We look for the perturbation from the standard oscillation signature
- Fit to F/N ratio incorporates oscillations in both detectors into the fit
- Systematics uncertainties cancel out in the ratio
- Fit 4 parameters $\Delta m^2_{32}, \theta_{23}, \theta_{24}, \Delta m^2_{41}$ (fix all other parameter)

Systematic Uncertainties





- Incorporate different systematics in to the χ^2 function for the fit thorough a covariance matrix
  - Detector Acceptance
  - Normalisation
  - Hadron Production
  - Beam optics
  - Cross sections
  - Energy Scale
  - Background

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T[V^{-1}]_{ij}(o_j - e_j)$$

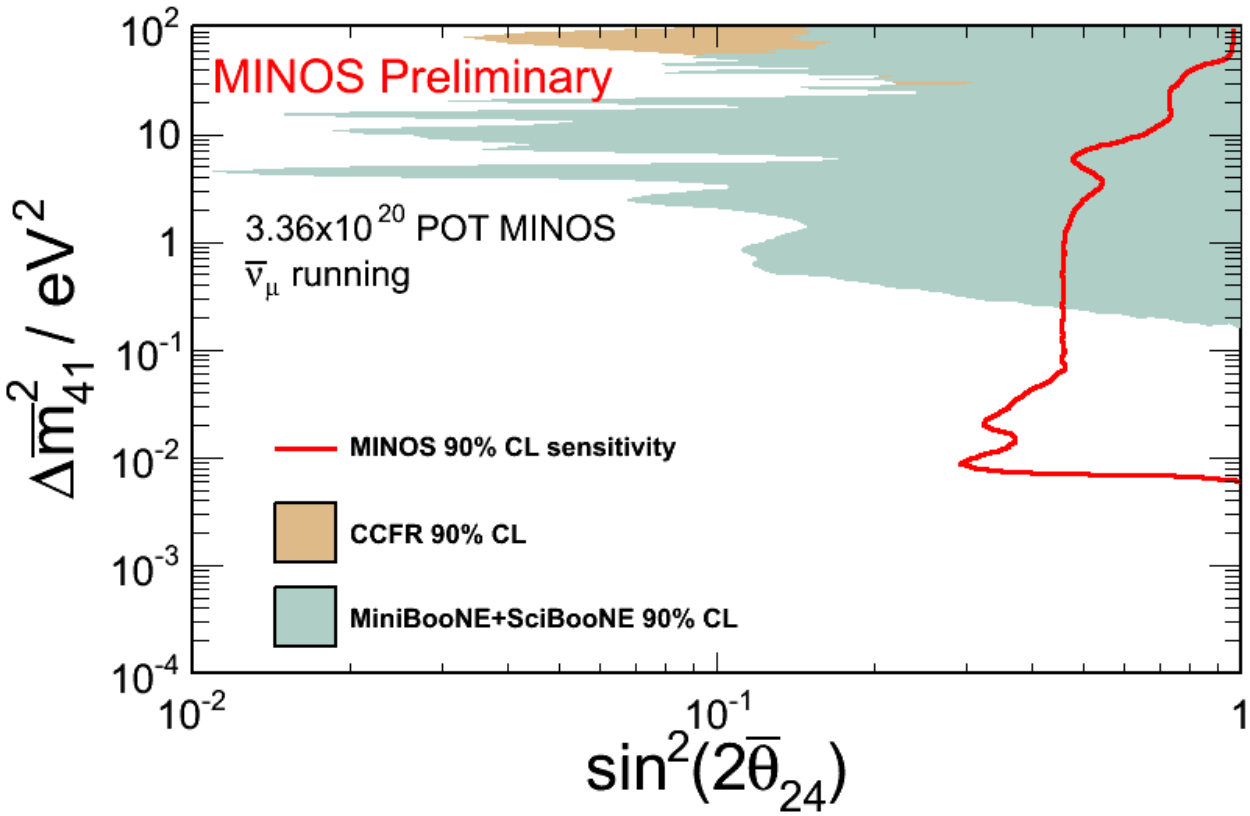
o_i : Observed events in bin i

e_i : Predicted events in bin i

V : Covariance matrix

- V is the total covariance matrix, sum of statistical and systematics matrices
- MINOS $\bar{\nu}_\mu$ sample is statistically limited

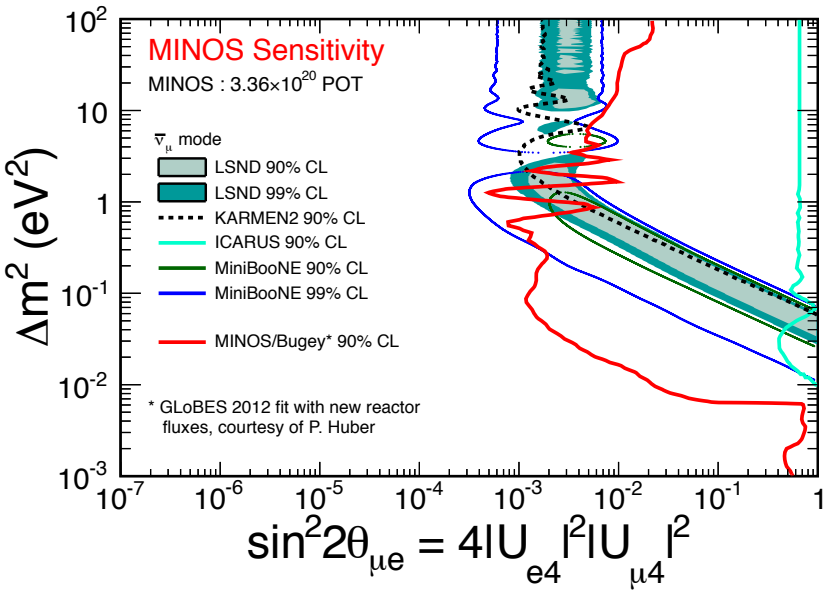
MINOS Sensitivity for Sterile Antineutrino



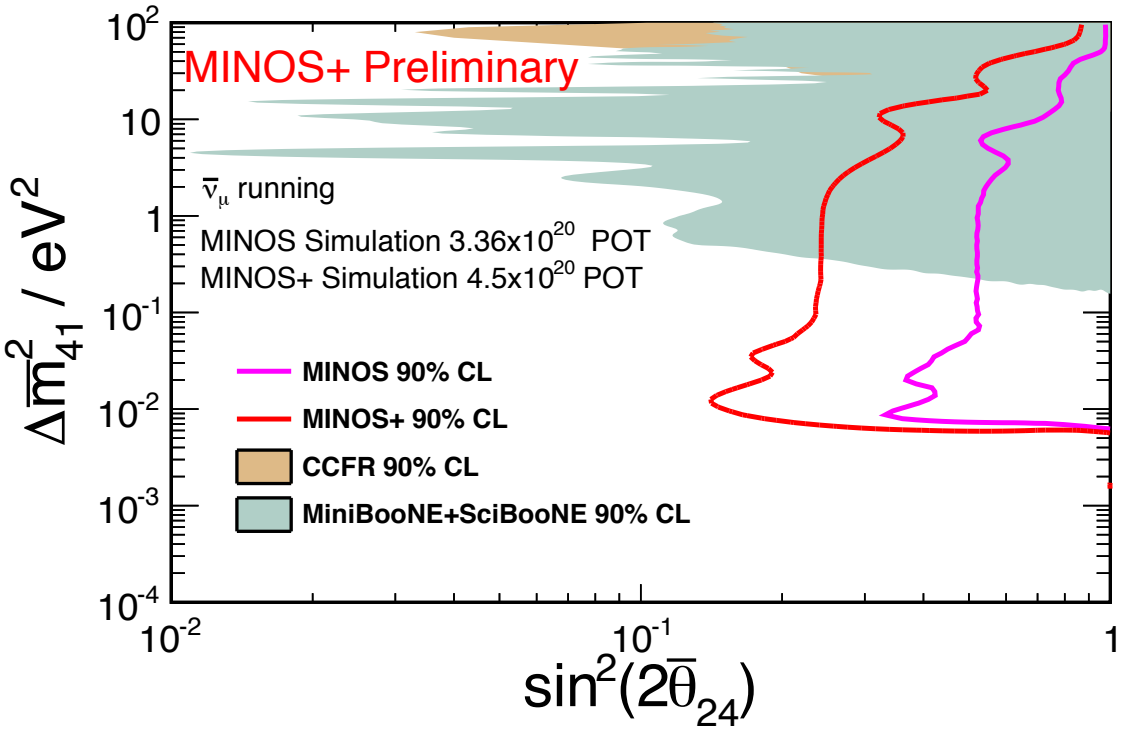
- Spans 3 orders of magnitude in Δm^2_{41}
- Exploring the region below 0.5eV^2 for the first time with antineutrinos
- Excludes the region right to the curve

Combination with Bugey

- Combine our $\bar{\nu}_\mu$ disappearance sensitivity with $\bar{\nu}_e$ disappearance limit from Bugey reactor experiment
- Both are antineutrinos, it is a more direct comparison
- MINOS 90% C.L on θ_{24} and Bugey 90% C.L in θ_{14}, combined sensitivity on $\mathbf{\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}}$
- Combined sensitivity can be compared with the appearance allowed region from MiniBooNE, LSND



+ Future Sensitivity with MINOS +



- Projected sensitivity for MINOS+ one year of antineutrino running, combined with the MINOS antineutrino mode
- MINOS+ is in 2nd year of running in ν_μ mode
- MINOS+ $\bar{\nu}_\mu$ mode running improves the sterile antineutrino limit significantly

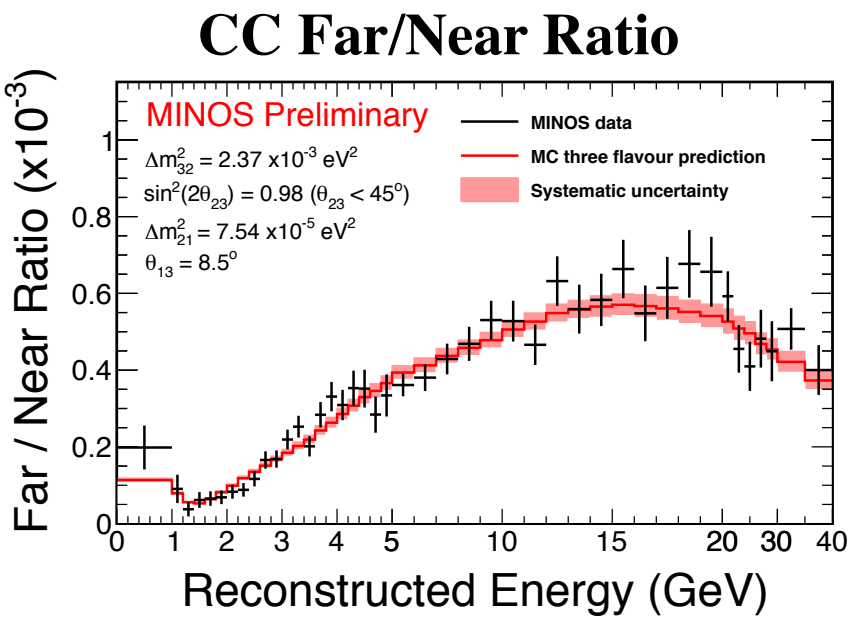
Summary

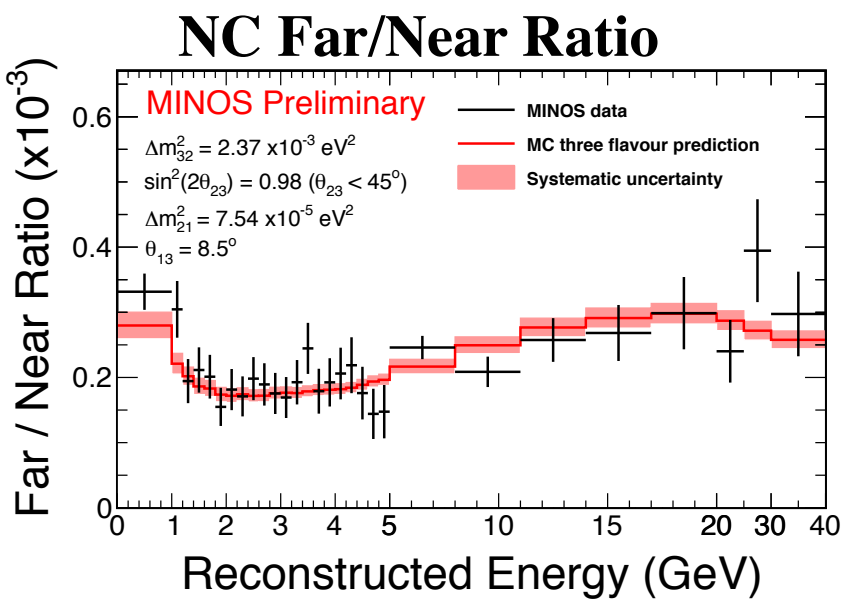
- MINOS has set limit on sterile neutrino parameters, which is 3 orders of magnitude in Δm^2_{41}
- We also have the ability to look at the sterile antineutrinos, presented our sensitivity to sterile antineutrinos and results are coming soon
- Combination with Bugey allow us for a direct comparison to the existing hints for sterile neutrinos
- We have other set of antineutrino data, the NC sample and antineutrinos from neutrino mode, together will produce a stronger limit
- Expecting more exciting results on sterile antineutrinos

THANK YOU

Backup

MINOS ν_μ Disappearance Results



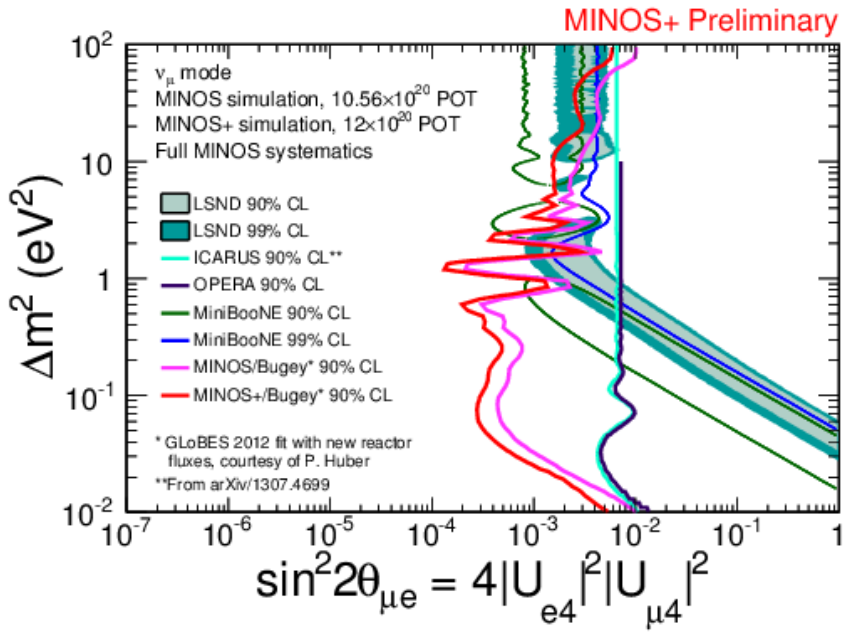


- Far-over- ratio binned as a function of reconstructed energy. Fit the distribution to get the oscillation parameter
- F/N ratio - many systematics cancels out

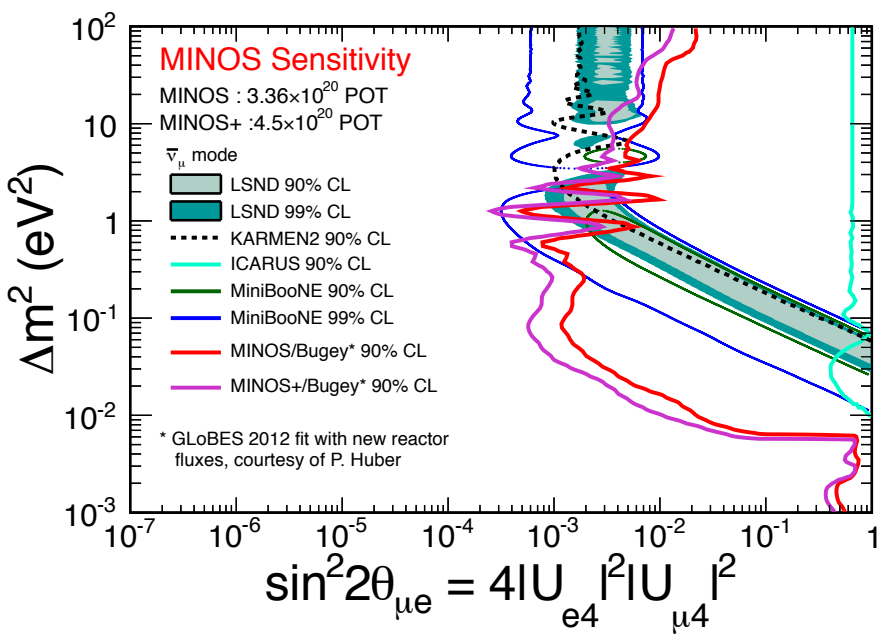
Comparison to the ν_e Signal

- Bugey limit combined with MINOS and MINOS+ sensitivity

Neutrino Mode



Antineutrino Mode



$$|U_{e4}|^2 = \sin 2\theta_{14}$$

$$|U_{\mu4}|^2 = \cos 2\theta_{14} \sin 2\theta_{24}$$

$$\Rightarrow \sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$$