MINOS+ Sterile Neutrino Studies

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Different experiments

- Reactor experiments (ν_e disappearance): θ_{14}
- MiniBooNE and LSND (ν_e appearance):$\theta_{14}+\theta_{24}$
- MINOS (NC and ν_μ disappearance) $\theta_{24}+\theta_{34}$
- MiniBooNE and LSND, CDHS, CFFR (ν_μ dis):θ_{24}
- **MINOS+ (ν_μ disappearance) : θ_{24}**
- **MINOS+ (NC disappearance) : $\theta_{24}+\theta_{34}$**

Improvements

- MINOS+ Monte Carlo used for this analysis
  - Previous used reweighted LE events
- Oscillations at the Near Detector are incorporated
- A complete 4-flavour oscillation formula is used to allow lower reach in Δm^2_{43}
  - Down to where interference with atmospheric oscillations occurs ($\Delta m^2_{43} = 2.5 \times 10^{-3} eV^2$)

MINOS+ advantages

- MINOS+ will have very high statistics
- 2 detector experiment
  - Normalisation measurement at FD rather than shape only (MiniBoone, CDHS, CCFR)
  - Two baselines : 1km and 735km

Some Mathematics

And helpful assumptions (but these not implemented in simulation)

Some Maths

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= \delta_{\alpha\beta} - 4\sum_{j>i} \mathcal{R}(U^*_{\alpha j} U_{\beta j} U_{\alpha i} U^*_{\beta i}) \sin^2 \Delta_{ji} \\ &\quad + 2\sum_{j>i} \mathcal{I}(U^*_{\alpha j} U_{\beta j} U_{\alpha i} U^*_{\beta i}) \sin(2\Delta_{ji}), \end{aligned}$$

$$\Delta_{ji} = (m_j^2 - m_i^2) L/(4E)$$

Thought Simplifications

- Δm^2_{21} dependence can be neglected at this L and E, so

$$\sin^2 \Delta_{21} = \sin(2\Delta_{21}) = 0$$

$$\Delta_{42} = \Delta_{41} \text{ and } \Delta_{32} = \Delta_{31}$$

$$\begin{aligned} P_{\nu_\mu \to \nu_\mu} = 1 \quad - \quad & 4\{|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2)\sin^2 \Delta_{31} \\ & + |U_{\mu 4}|^2 |U_{\mu 3}|^2 \sin^2 \Delta_{43} \\ & + |U_{\mu 4}|^2(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2)\sin^2 \Delta_{41}\} \end{aligned}$$

Thought simplifications

$$U_{\mu 3} = -\sin\theta_{14}\sin\theta_{13}e^{-i\delta_1}\sin\theta_{24}e^{-i\delta_2} + \cos\theta_{13}\sin\theta_{23}\cos\theta_{24},$$
$$U_{\mu 4} = \cos\theta_{14}\sin\theta_{24}e^{-i\delta_2}.$$

- θ_{13} is small (set to 0), and so δ_1 irrelevant
- θ_{14} is also small (~9°) : $\sin\theta_{24}\cos\theta_{14} \approx \sin\theta_{24}$
- End up with:

$$U_{\mu 3} = \sin\theta_{23}\cos\theta_{24}, \qquad U_{\mu 4} = \sin\theta_{24}e^{-i\delta_2}$$

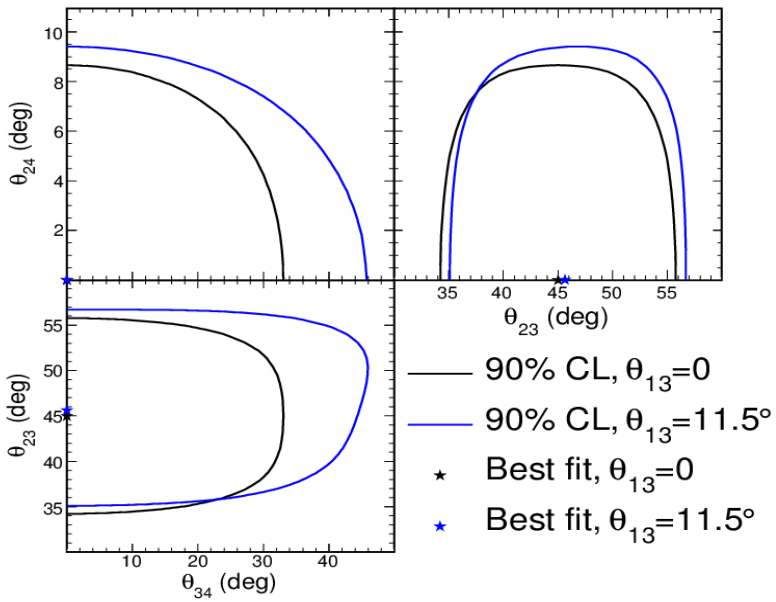
- Above Δm^2_{43} of 10^{-1}eV^2 $\sin^2\Delta_{41}$ and $\sin^2\Delta_{43}\approx 0.5$
- And Probability at FD:

$$= 1 - \sin^2(2\theta_{23})\cos^4\theta_{24}\sin^2\Delta_{31} - \frac{1}{2}\sin^2 2\theta_{24}.$$

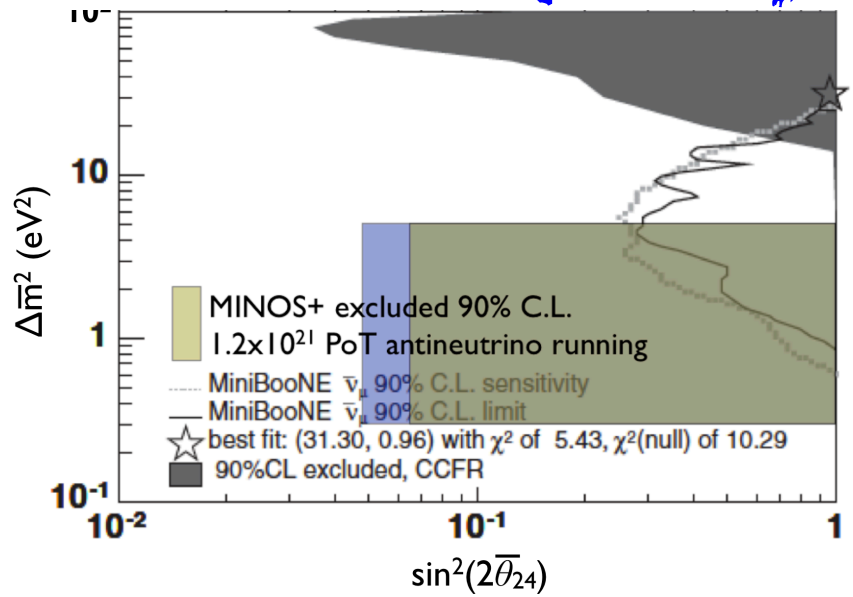
The Limits from Last PAC

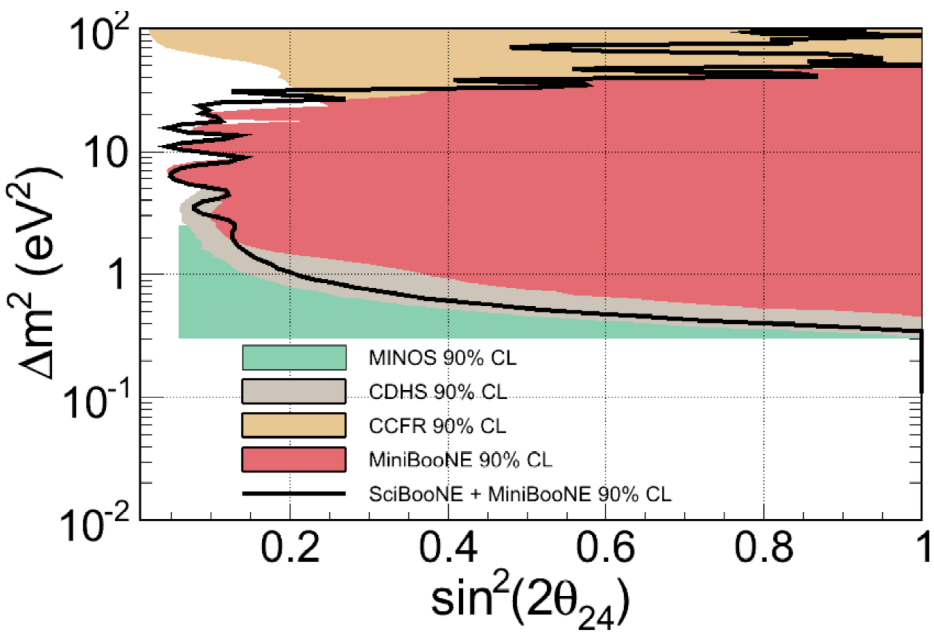
MINOS AND MINOS+

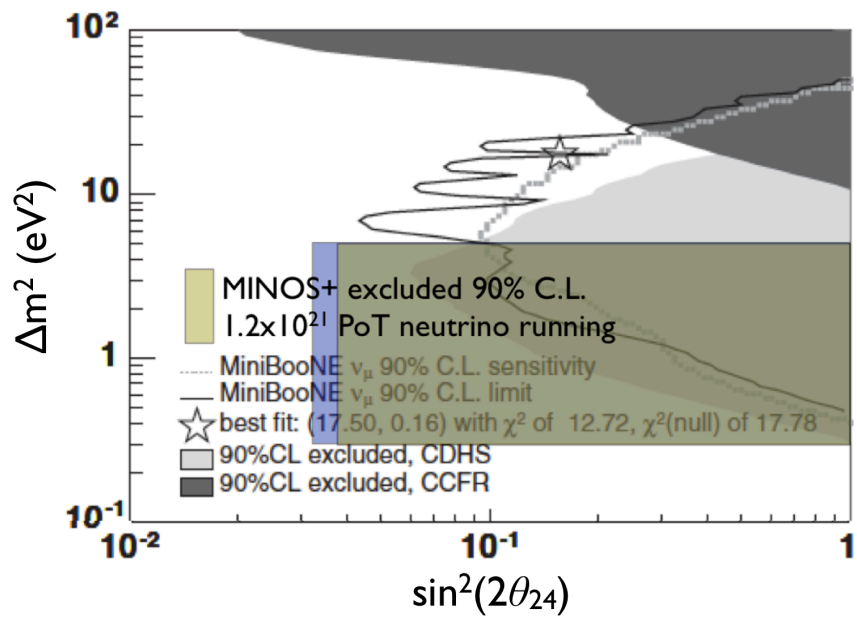
MINOS



MINOS+(old)



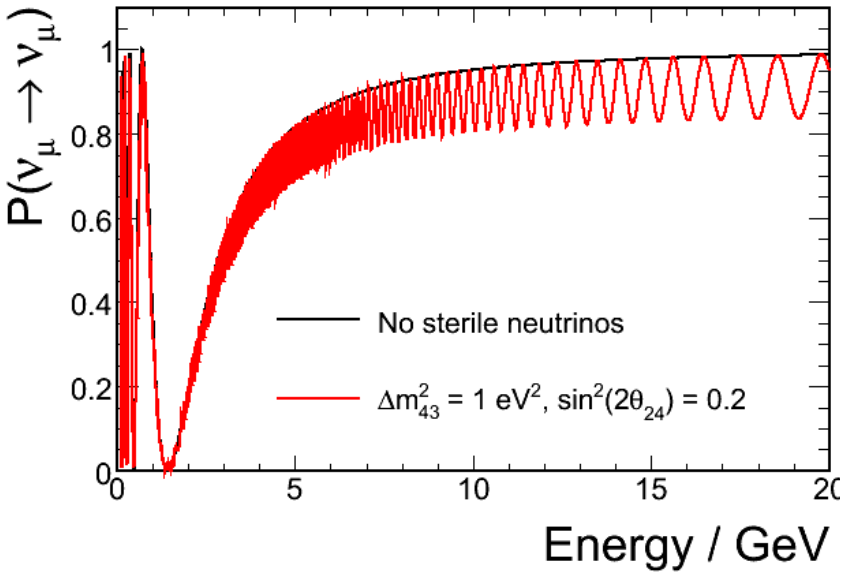


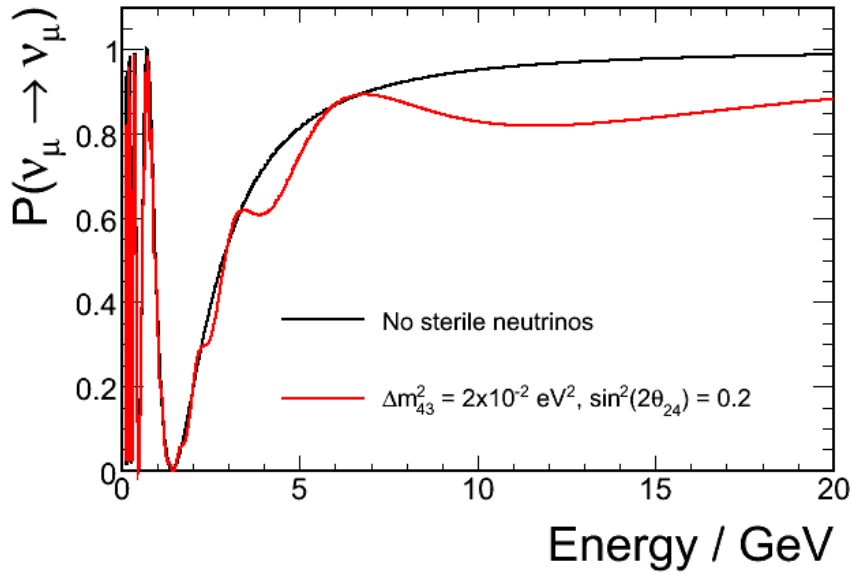


Characteristics of Limits

- $10^{-1}<\Delta m^2_{34}<1eV^2$: FD in fast oscillation mode and probability averages to ½, so no sensitivity to exact value of Δm^2_{34}
- Δm^2_{34} greater than $1eV^2$ Near Detector spectrum affected leading to more structure to the exclusion region
- As Δm^2_{34} goes above $10eV^2$ ND and FD both see fast oscillations, so comparison cancels the effect

FD sterile example

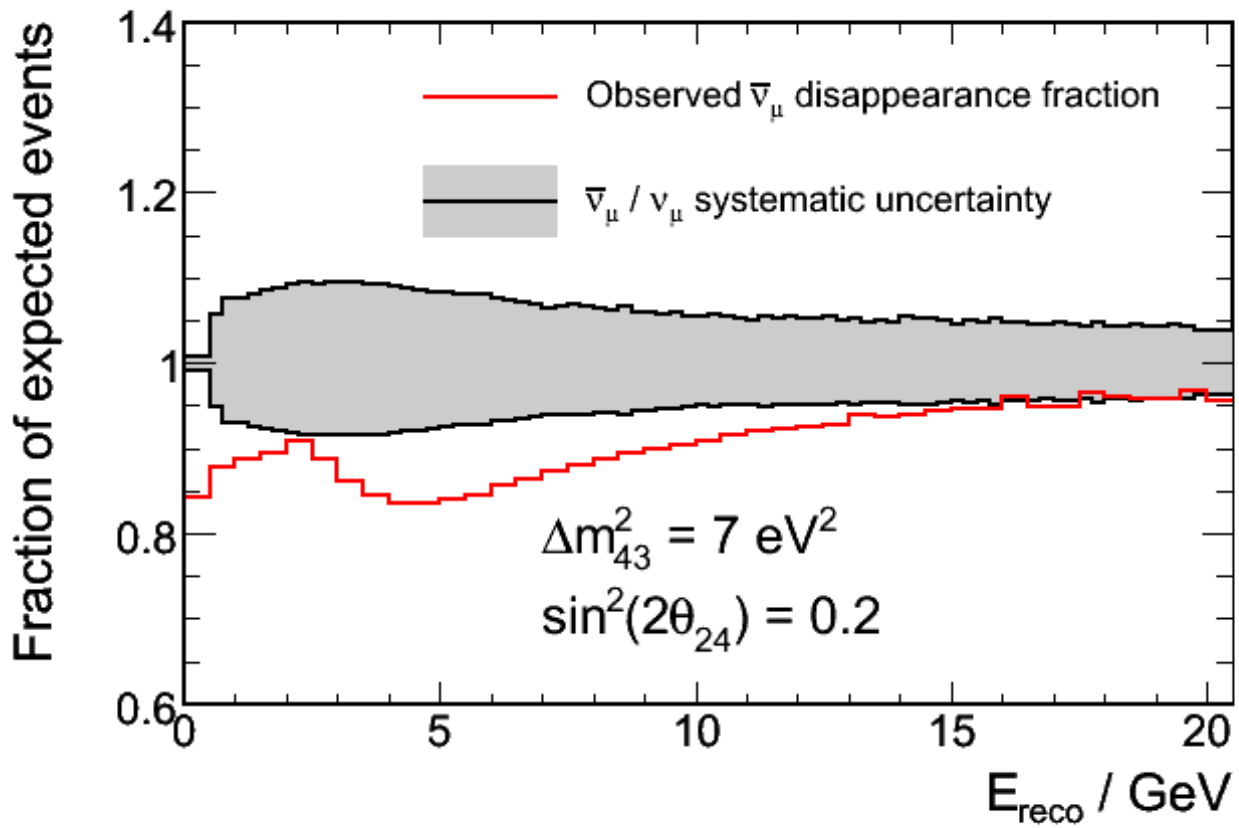




DM2 factor averages to 0.5

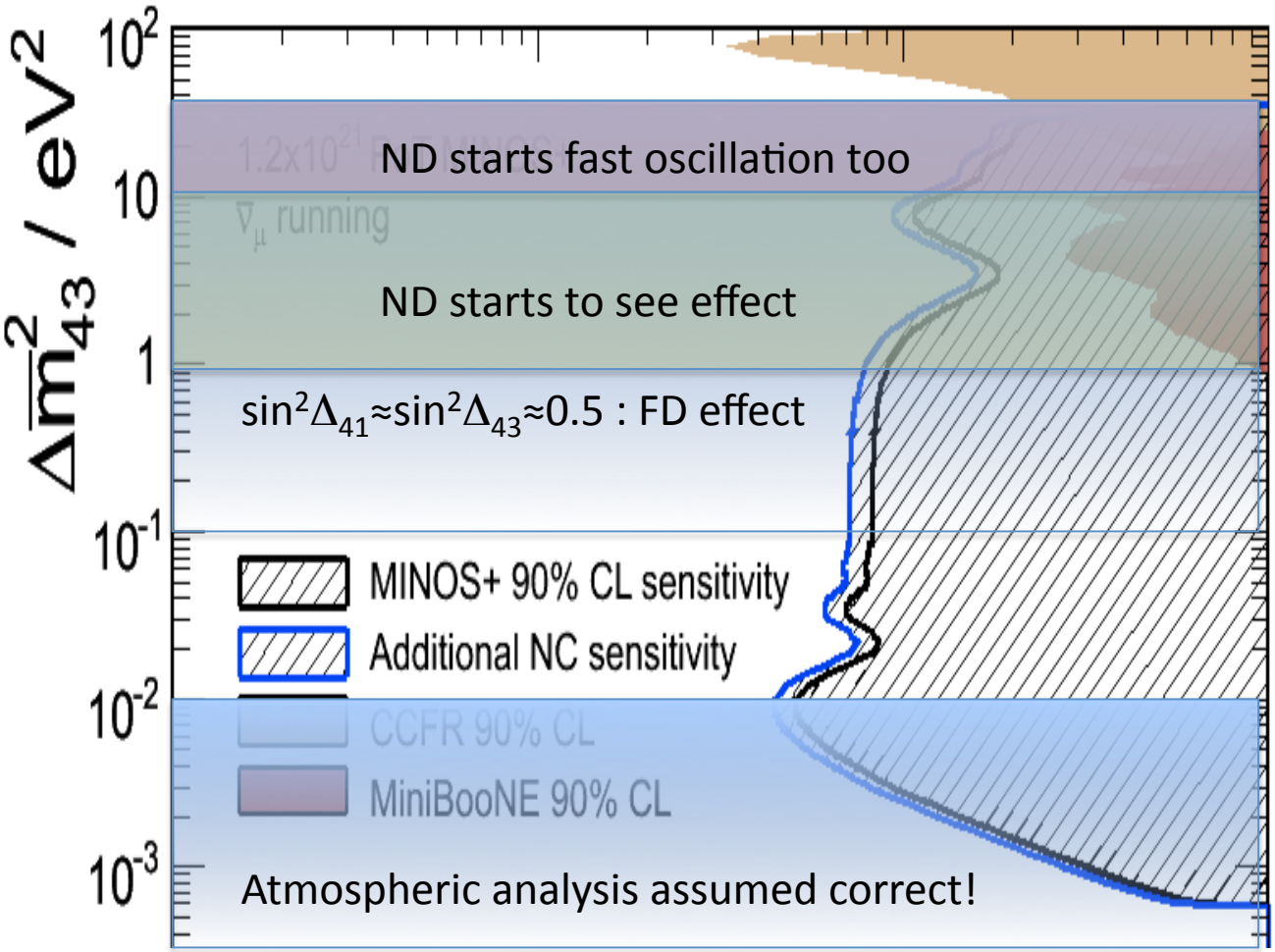
Both atmospheric and sterile dips apparent here

Near Detector Example

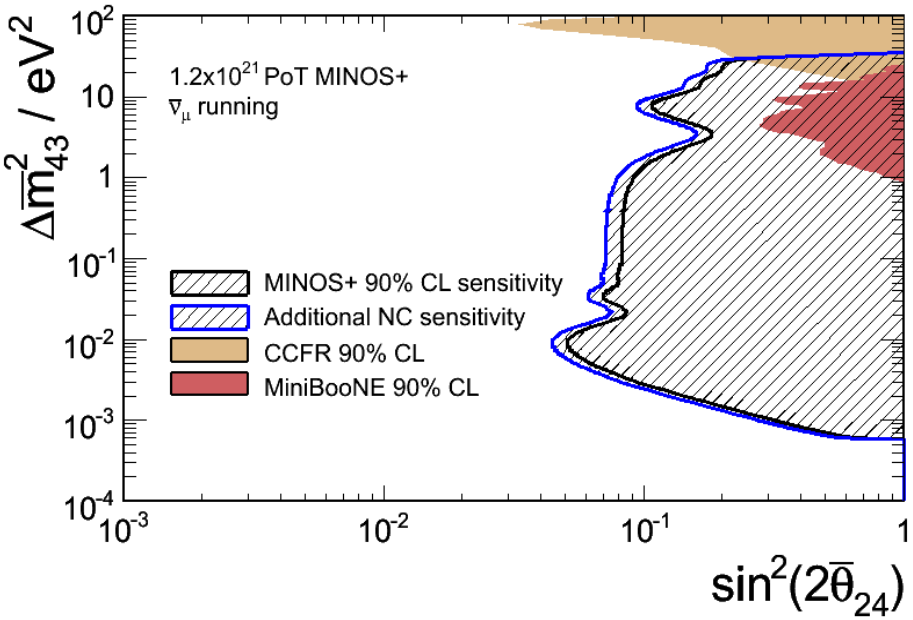


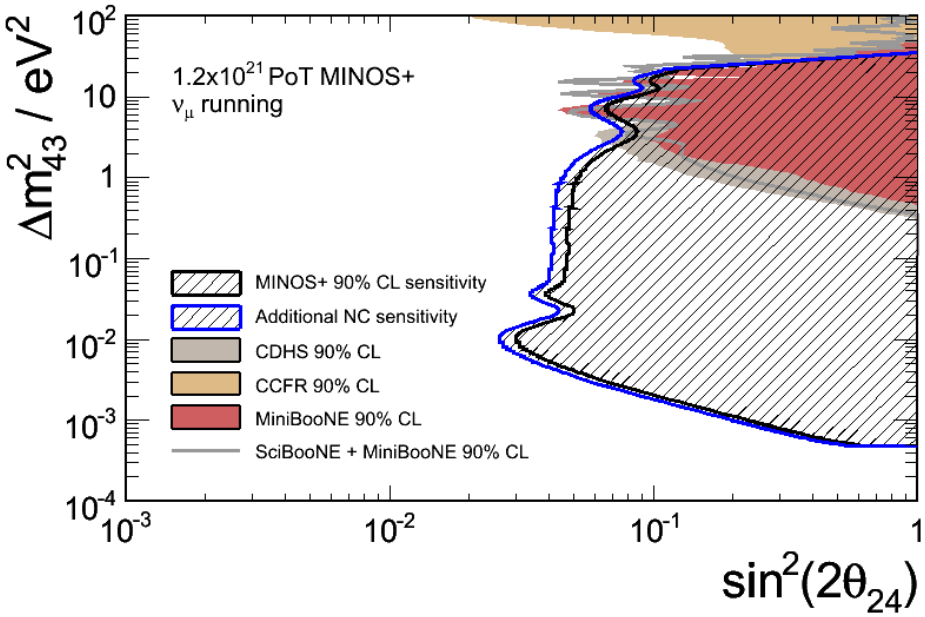
Systematic error is on ratio
of numu to numubar

MINOS+ $\overline{\theta}_{24}$



Bottom Line





anti-neutrinos

neutrinos

Summary

- More careful job results in much larger reach
- NC additional analysis not yet complete but improvement expected between $10^{-2}eV^2$ and $10^{-3}eV^2$.
- **MINOS+ has a world-beating sensitivity to this sterile search for both neutrinos and antineutrinos over large range of mass splitting**