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Searches for new physics with MINOS+

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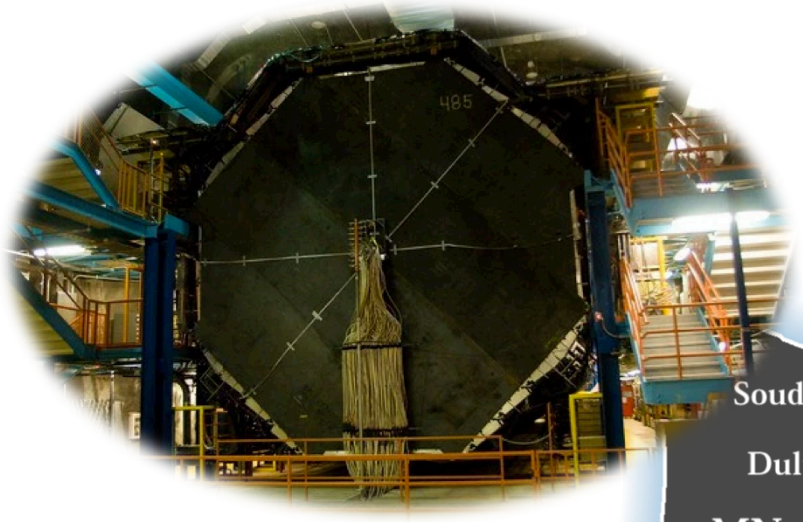
University of Manchester

MINOS



Near and Far Detectors

Comparison of the two tells us about oscillation

- Appearance and disappearance

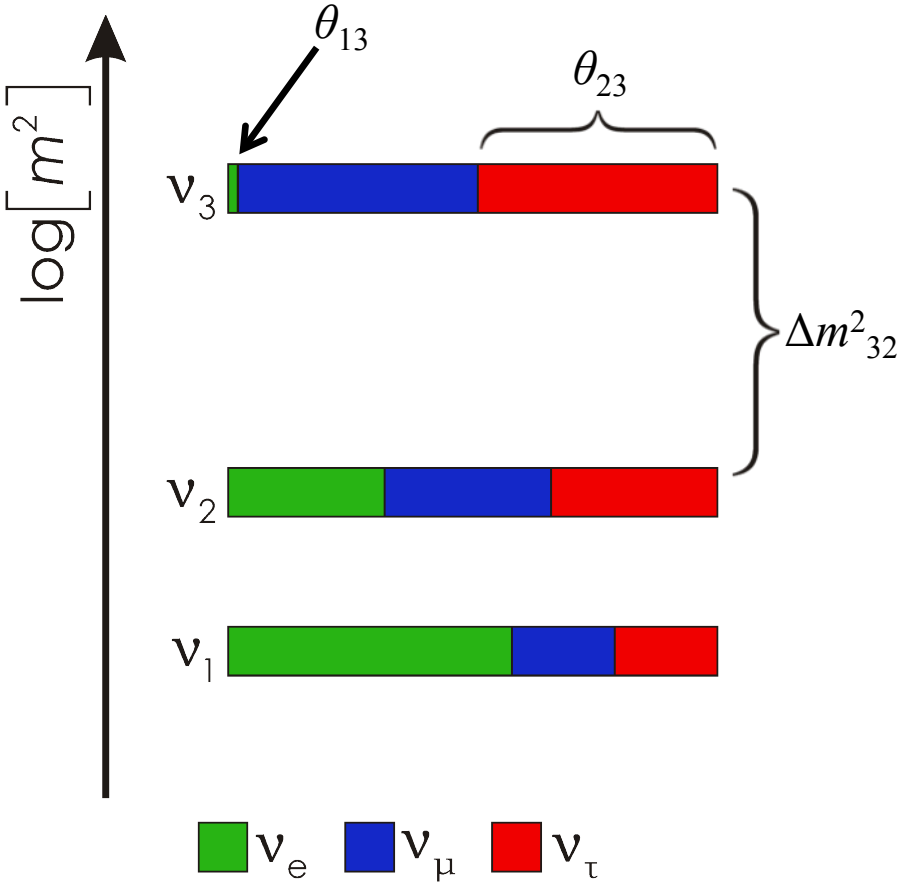
Physics

Designed to be sensitive to the mass splitting Δm^2_{32}

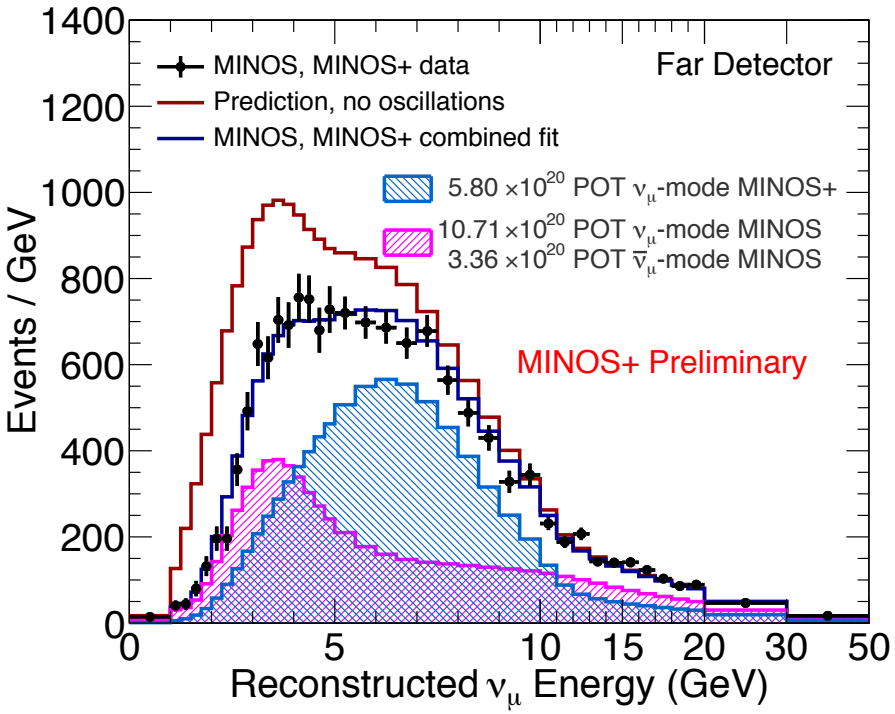
- θ_{23} – ν_μ disappearance
- θ_{13} – ν_e appearance

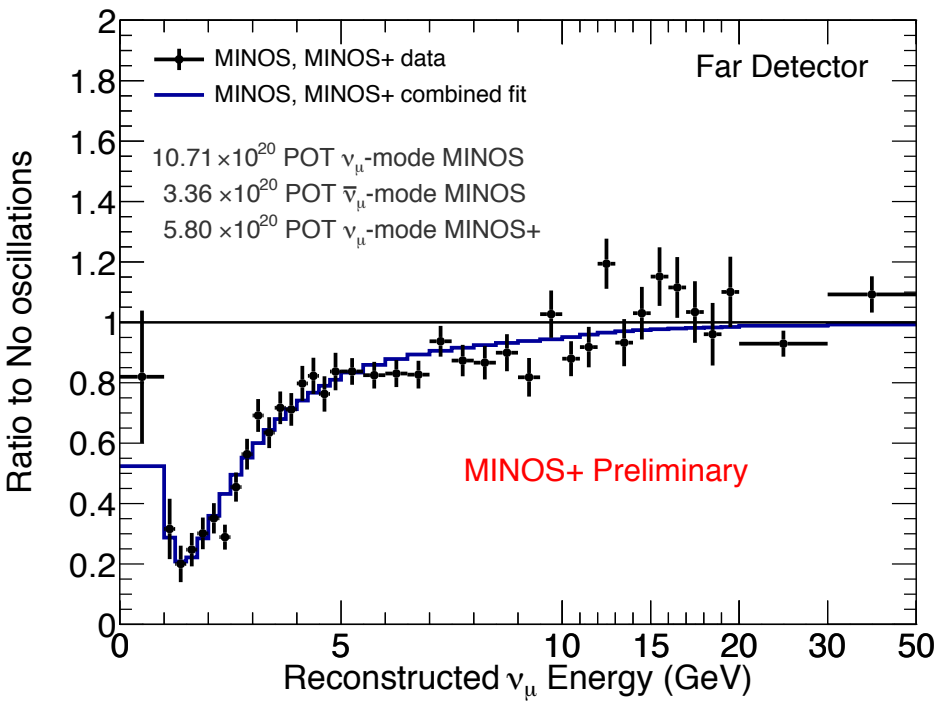
Is there physics beyond three-flavour oscillations?

- Non-standard interactions
- Large extra dimensions
- Sterile neutrinos



Oscillations





'Classic' two-baseline technique

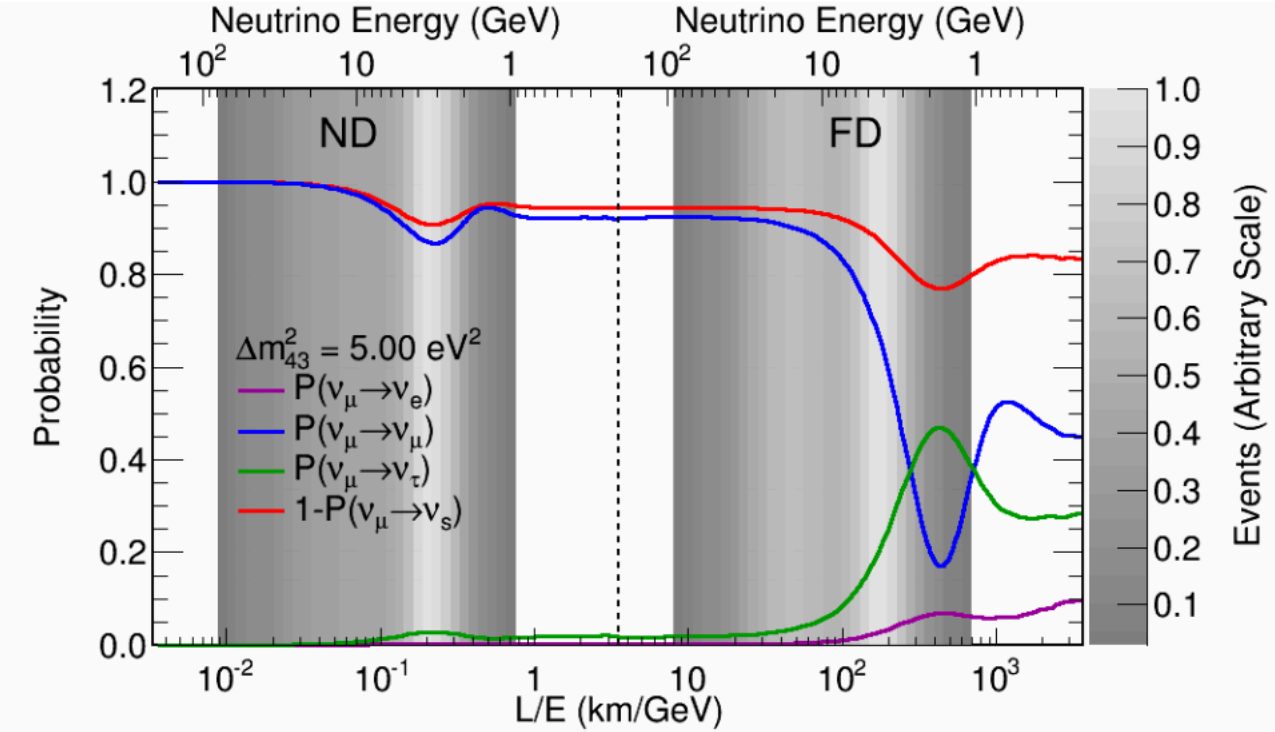
- Predict the Far Detector energy spectrum using the Near Detector

But this doesn't work for many new physics models

- Neutrinos can change flavour **before** reaching the Near Detector

A dual-baseline experiment

3+1 model

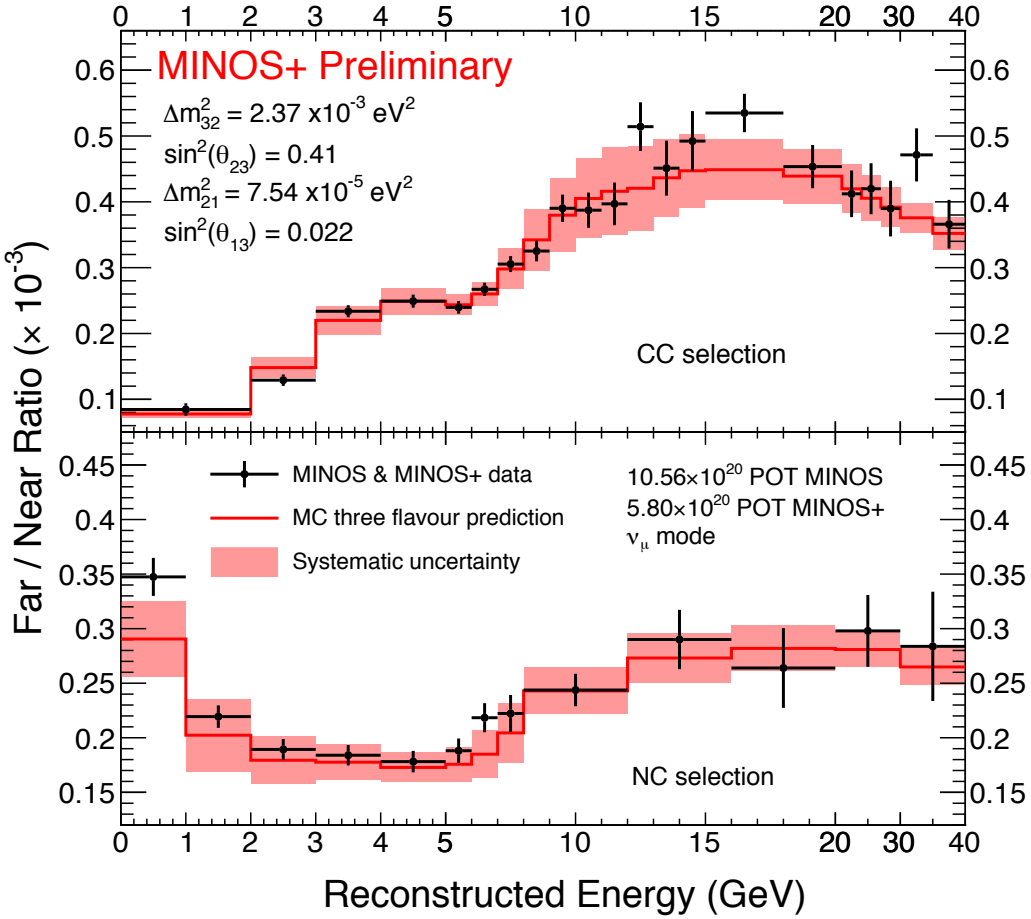


ν_μ disappearance on top of that from standard oscillations

- At both the Near and Far Detectors
- Seen in both NC and CC ν_μ events

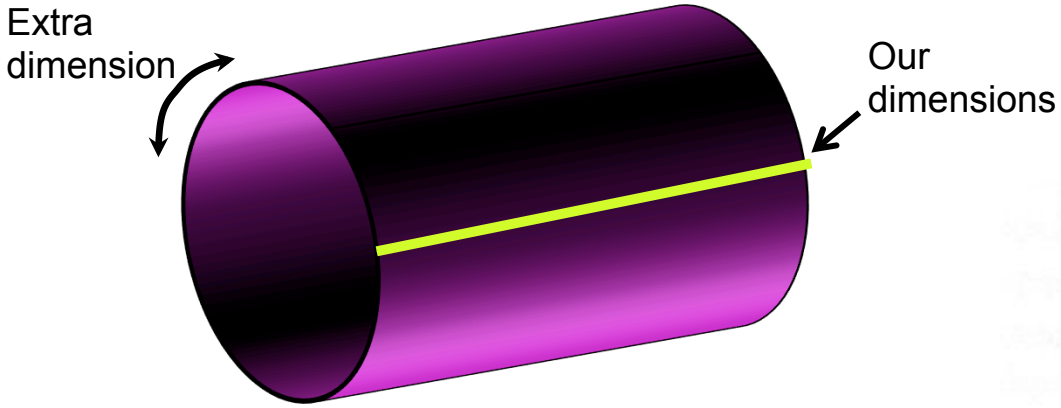
Look at the Far-to-Near Detector ratio

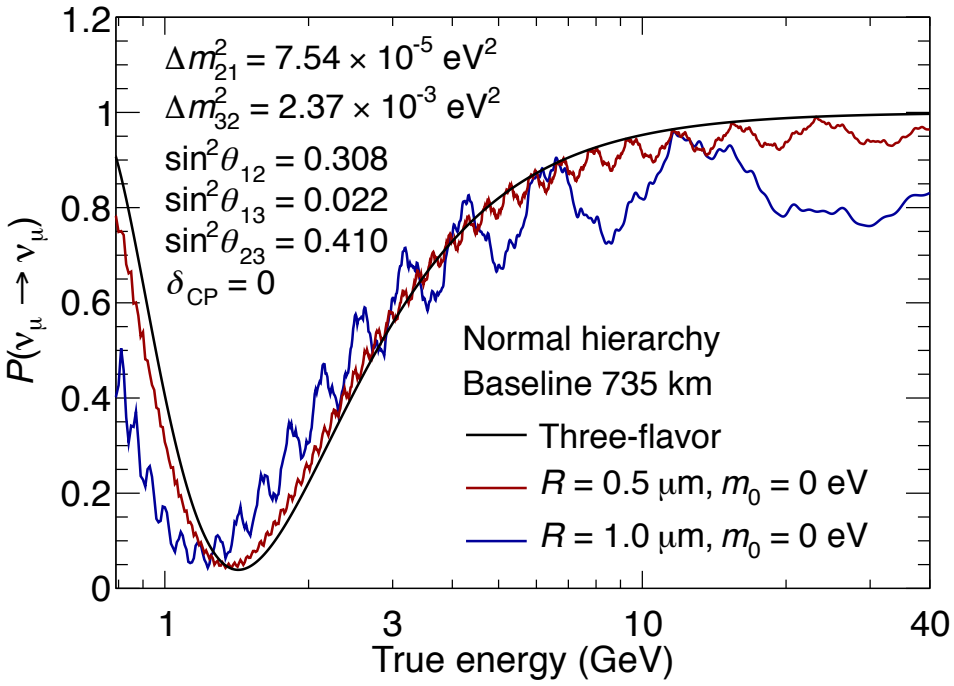
The Far / Near ratio

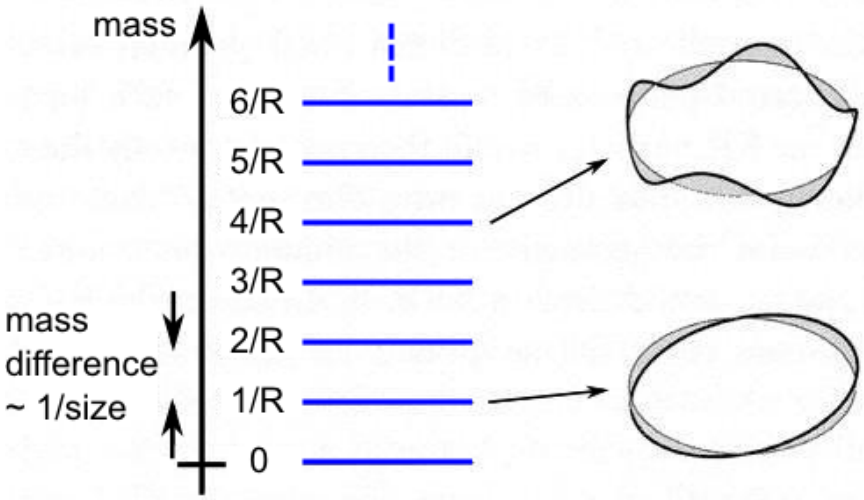


- Test for consistency with the standard three-flavour oscillation hypothesis

Large extra dimensions



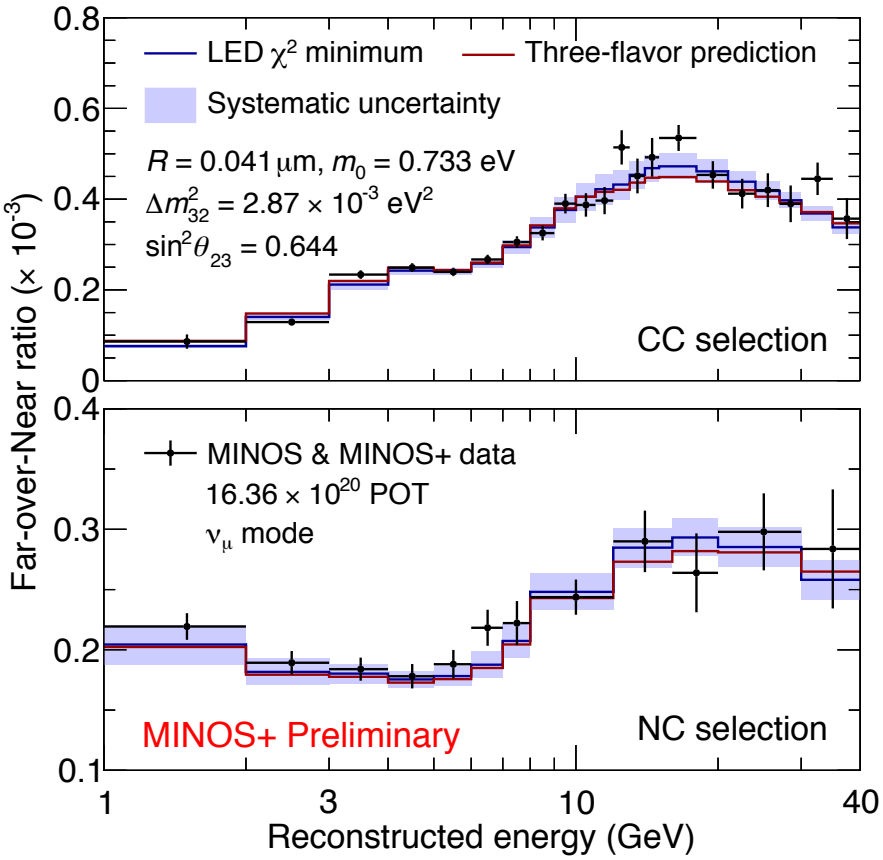


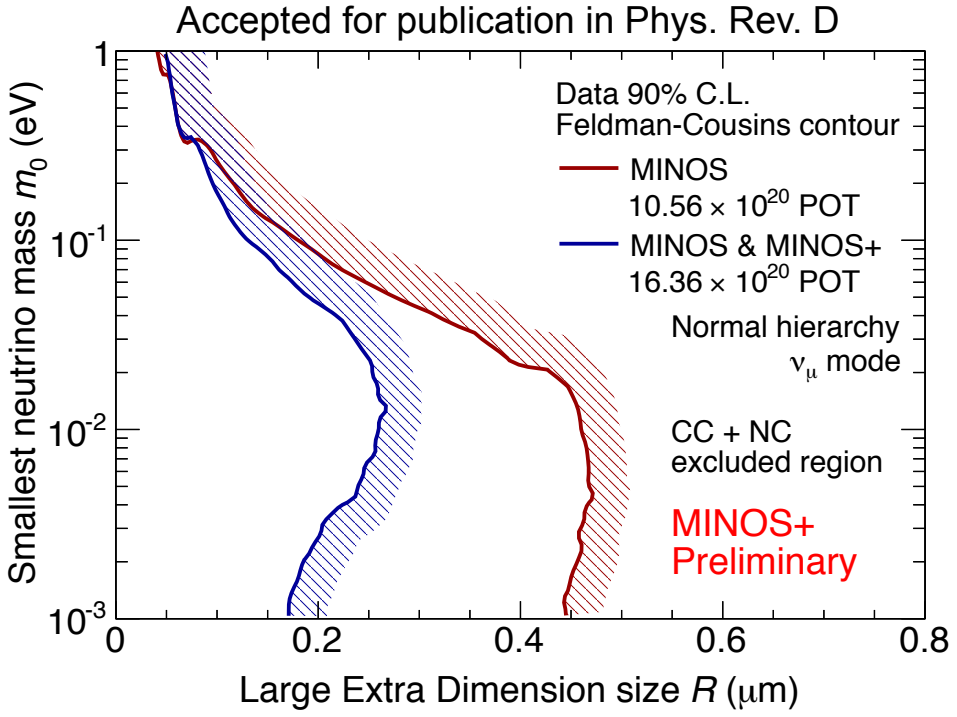


Three singlet, sterile neutrinos in the bulk

- N. Arkani-Hamed *et al.*, Phys. Rev. D **65**, 024032 (2002)
- H. Davoudiasl *et al.*, Phys. Rev. D **65**, 105015 (2002)
- P.A.N. Machado *et al.*, Phys. Rev. D **84**, 013003 (2011)

Large extra dimensions





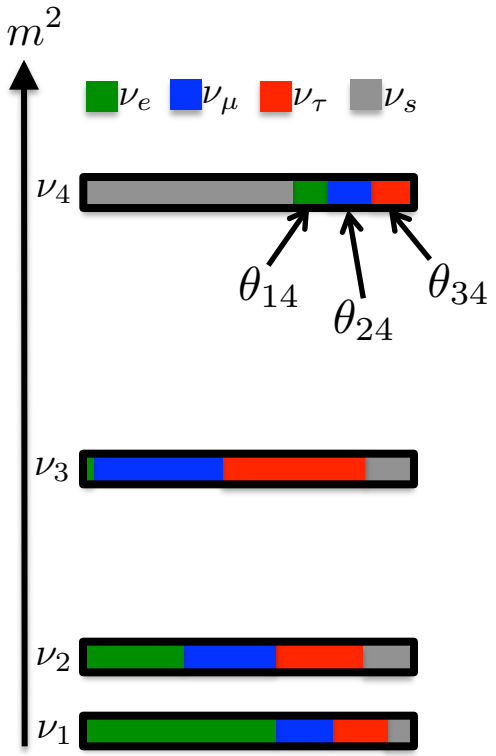
$R < 0.17$ μm at 90% C.L. for vanishing m_0

- Best limit on R from a neutrino oscillation experiment

Sterile neutrinos

Test a 3+1 hypothesis

- A single additional mass state and a single additional, sterile flavour state

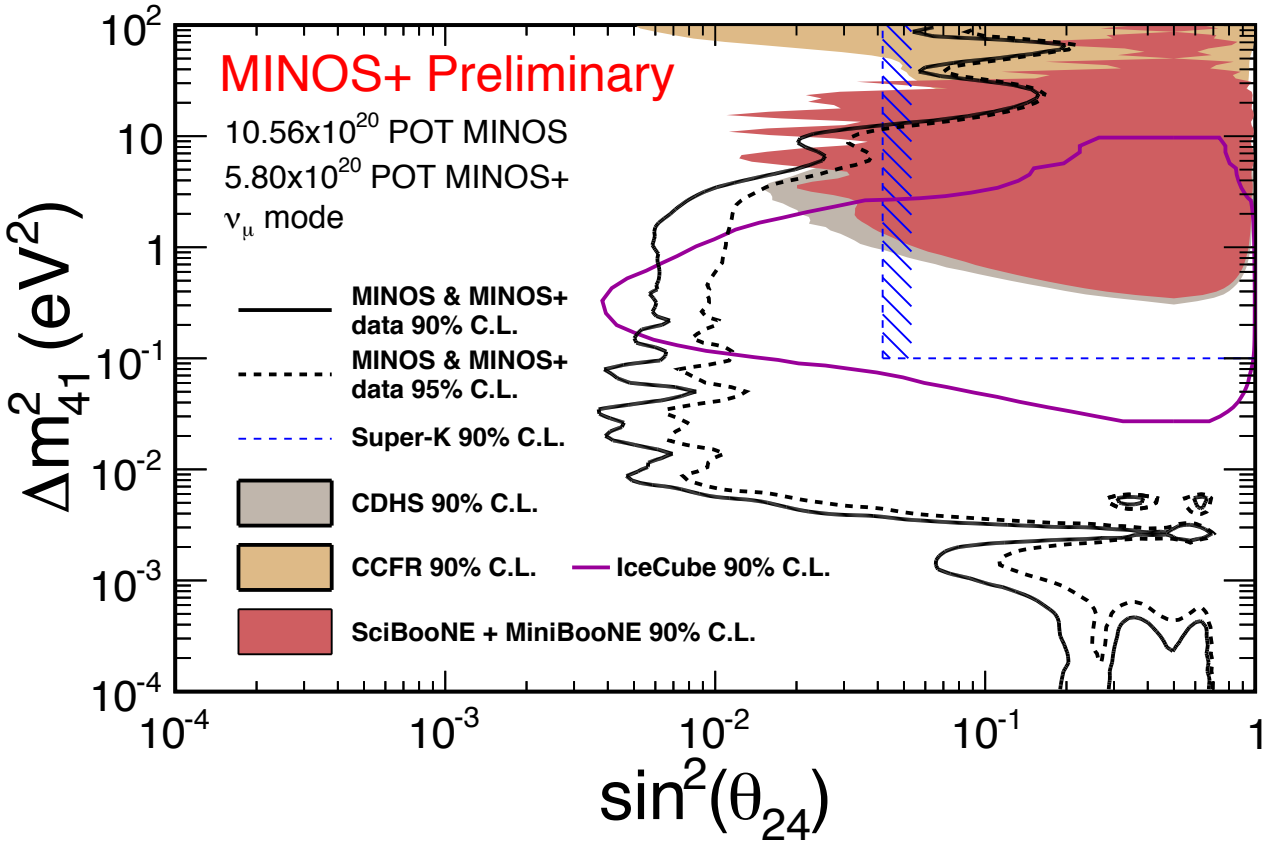


$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Three new mixing angles

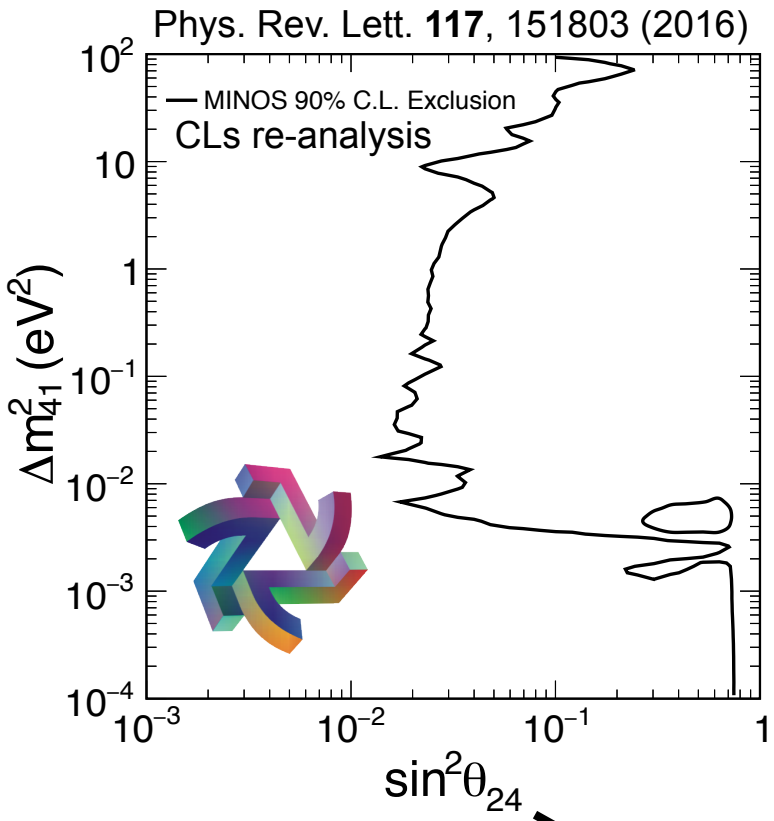
- MINOS, through a ν_μ disappearance search, measures θ_{24}

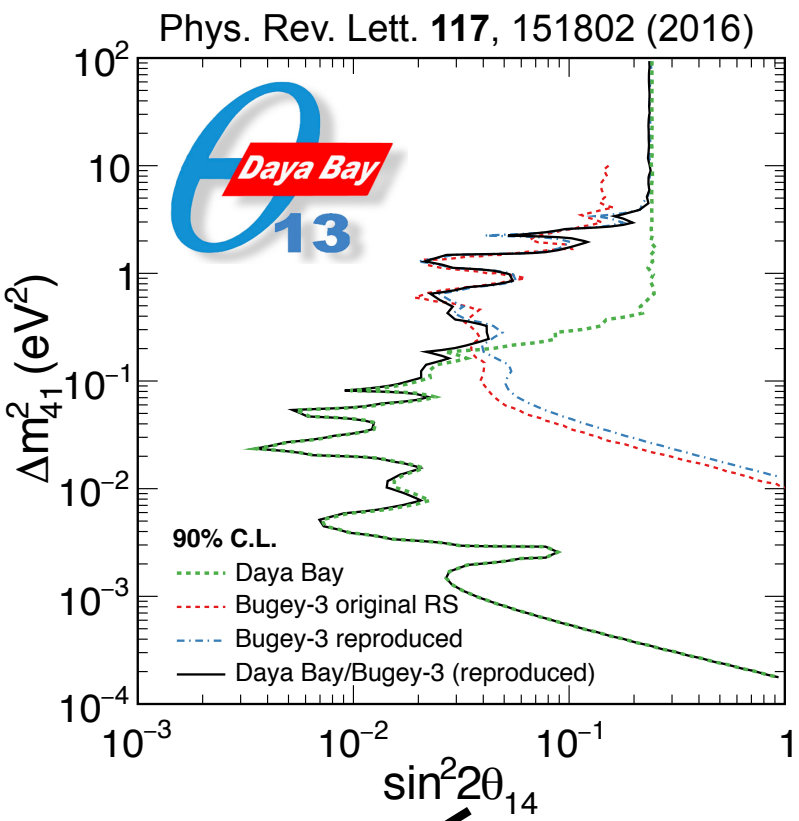
Sterile neutrinos



A similar amount of MINOS+ data still to be analysed

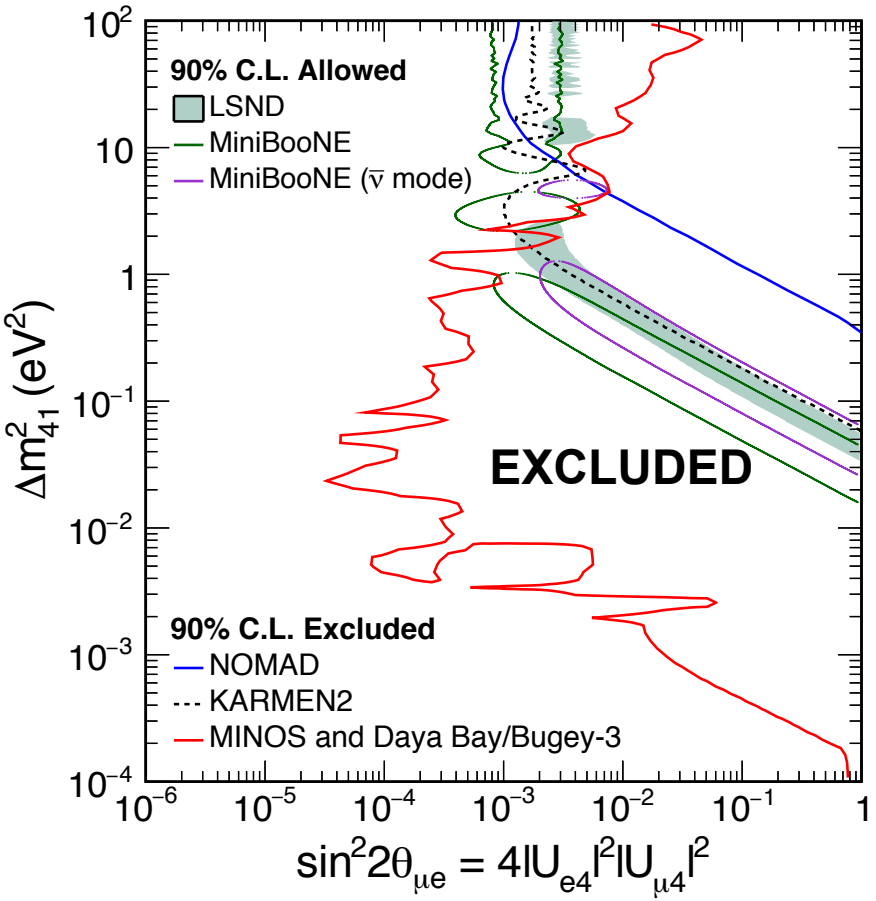
Sterile neutrinos: MINOS, Daya Bay and Bugey-3





$$4|U_{\mu 4}|^2|U_{e4}|^2 = \sin^2\theta_{24}\sin^2(2\theta_{14}) \equiv \sin^2(2\theta_{\mu e})$$

MINOS, Daya Bay and Bugey-3



Parameter space allowed by LSND and MiniBooNE is excluded for $\Delta m^2_{41} < 0.8$ eV^2 at 95% C.L.

- Phys. Rev. Lett. **117**, 151801 (2016)

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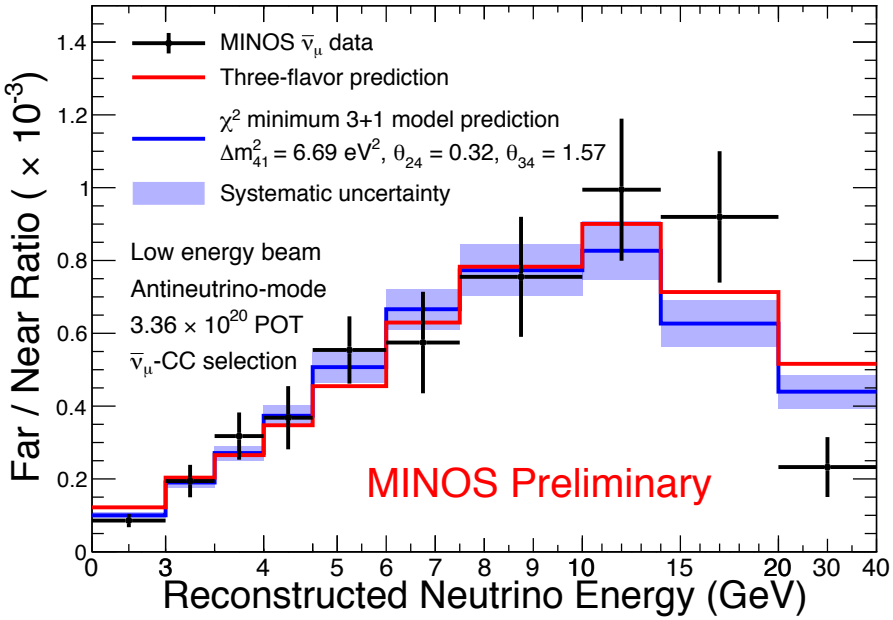
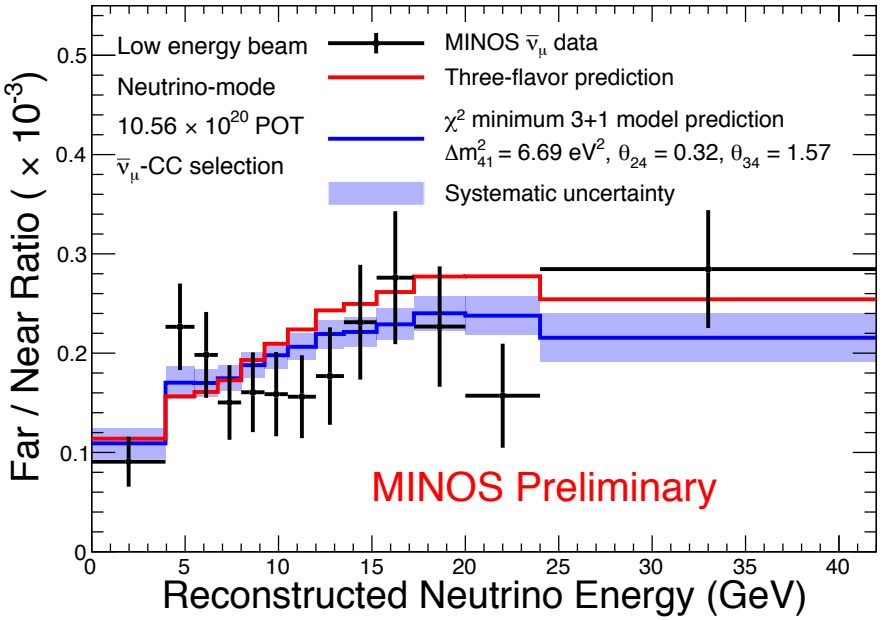
Antineutrinos

Antineutrino beam

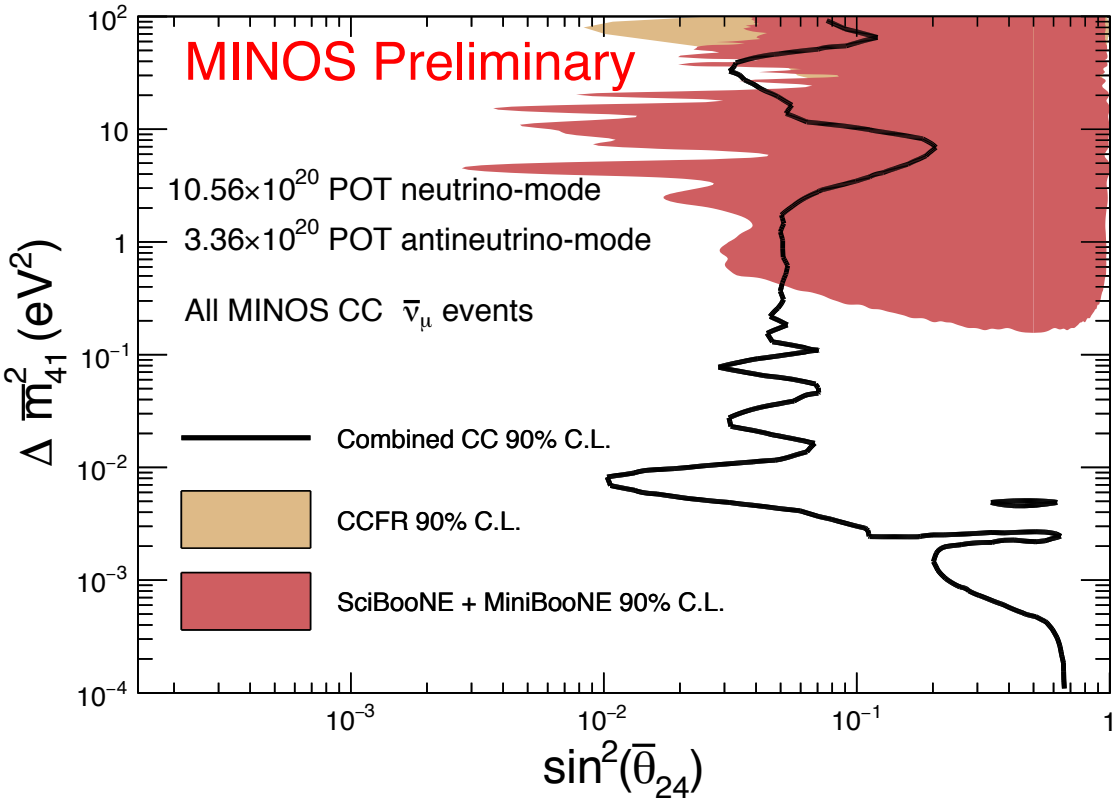


Antineutrinos in the neutrino beam



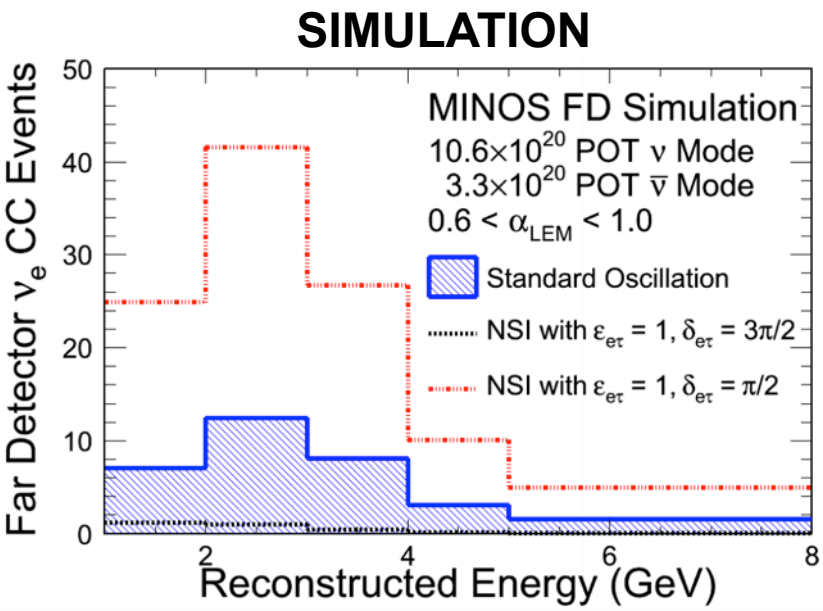
- Dedicated antineutrino running
- Significant numbers of higher-energy antineutrinos in the neutrino-mode beam

Sterile antineutrinos



Limits set by searching for $\bar{\nu}_\mu$ disappearance

Non-standard interactions



Introduce non-standard interaction terms into the Hamiltonian:

$$H_{NSI} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Also gives rise to three new phases

- $\delta_{e\tau}, \delta_{e\mu}, \delta_{\mu\tau}$

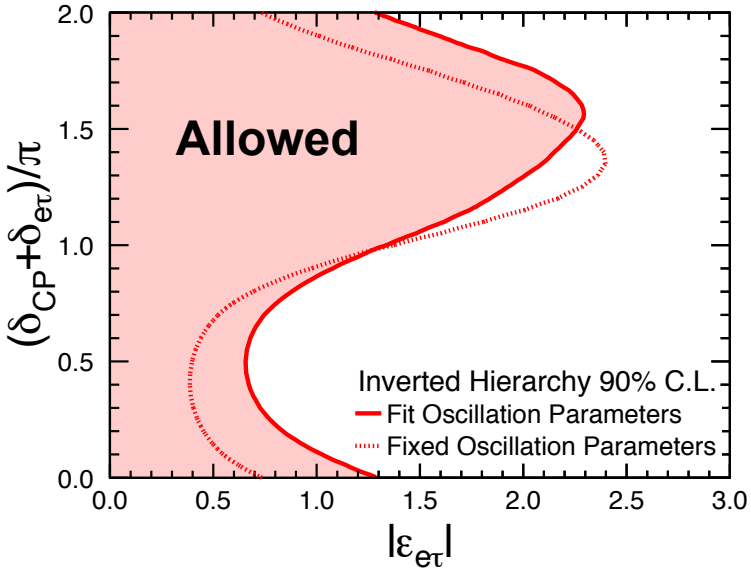
A search for non-standard ν_e appearance analysis sets limits on

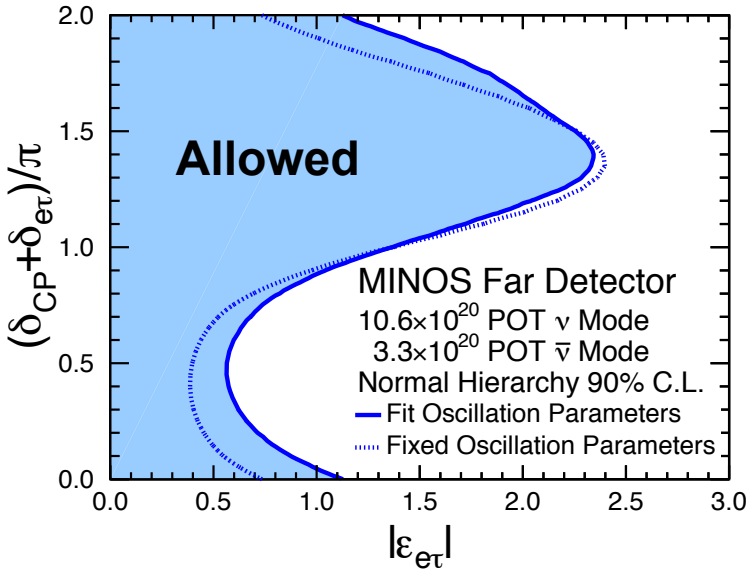
- $\varepsilon_{e\tau}$
- The combination $(\delta_{\mathrm{CP}} + \delta_{e\tau})$

MINOS: arXiv:1605.06169

- Submitted to Phys. Rev. D

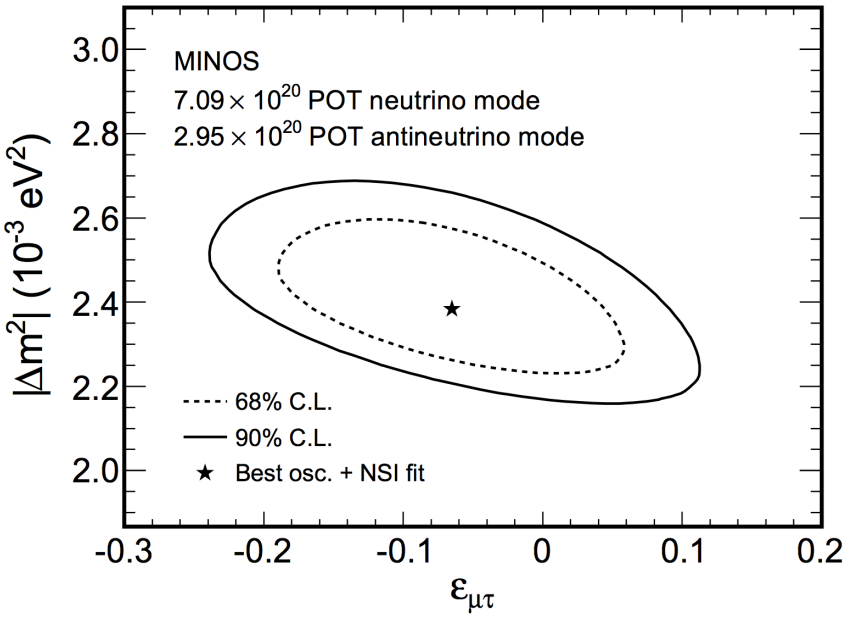
Non-standard interactions





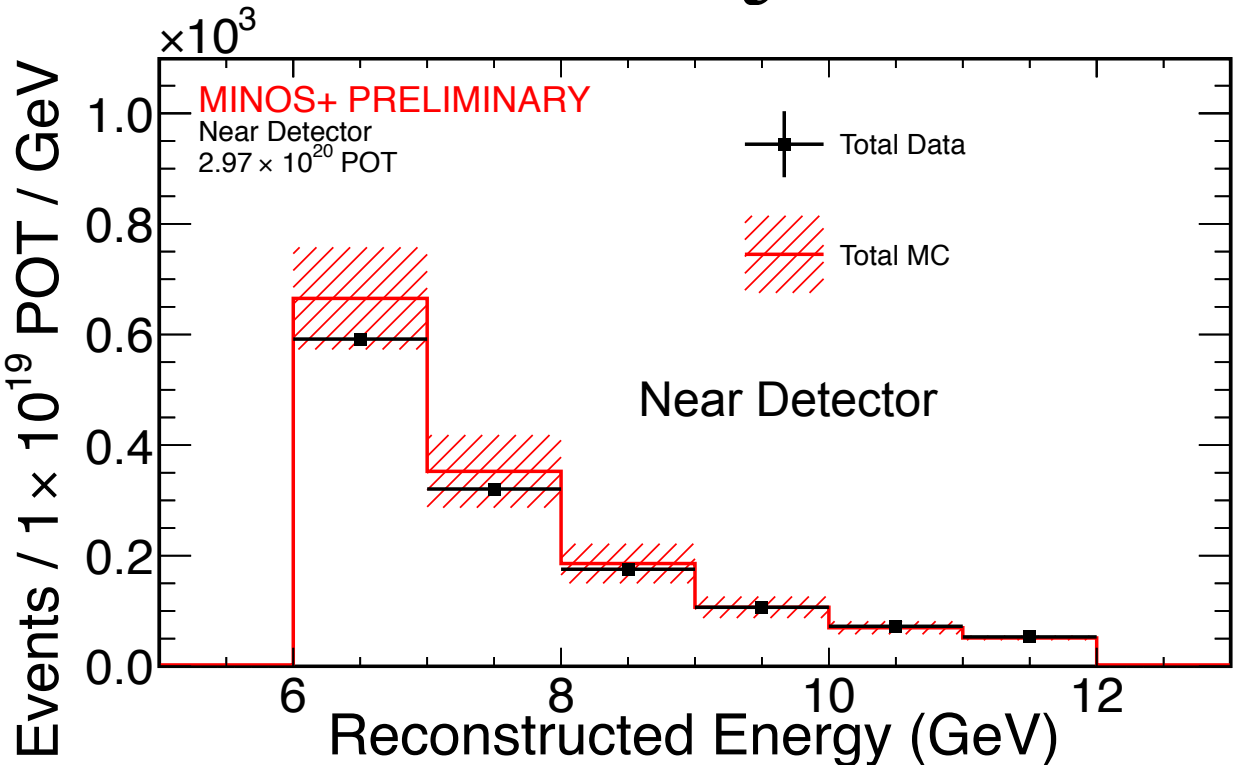
MINOS: arXiv:1605.06169
Submitted to Phys. Rev. D

MINOS ν_μ disappearance channel sets limits on $\varepsilon_{\mu\tau}$



MINOS: arXiv:1303.5314
Phys. Rev. D **88**, 072011 (2013)

Sterile-driven ν_e appearance

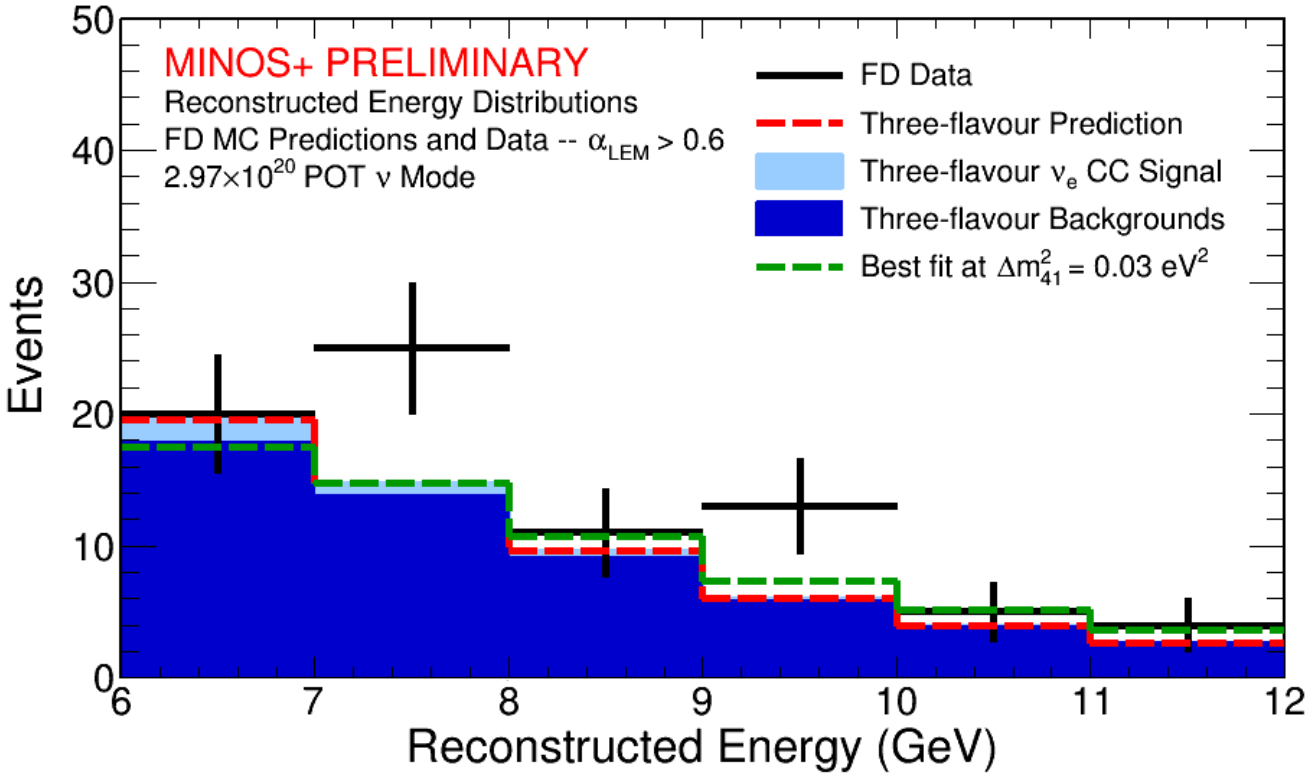


Look for non-standard ν_e appearance in the 6-12 GeV region

- Identify CC ν_e interactions with efficiency of 78%

A direct probe of the $\nu_\mu \rightarrow \nu_e$ channel

Sterile-driven ν_e appearance



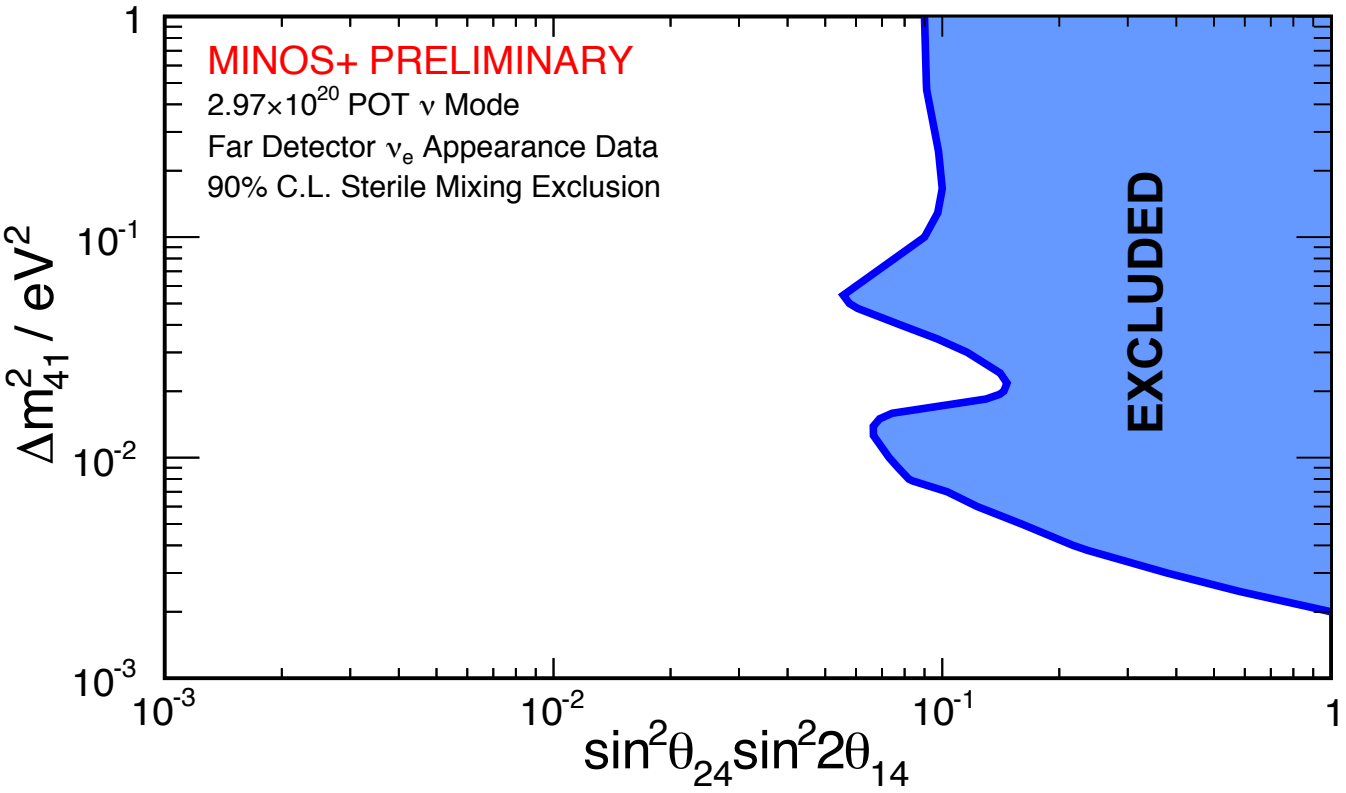
Near detector used to produce a Far Detector prediction

Expect 56.7 events, observe 78

- 2.3σ excess

Three times more data to come

Sterile-driven ν_e appearance



- Profiled over θ_{34}, δ_{13} and $(\delta_{24} - \delta_{14})$
- 24 systematics included via a covariance matrix

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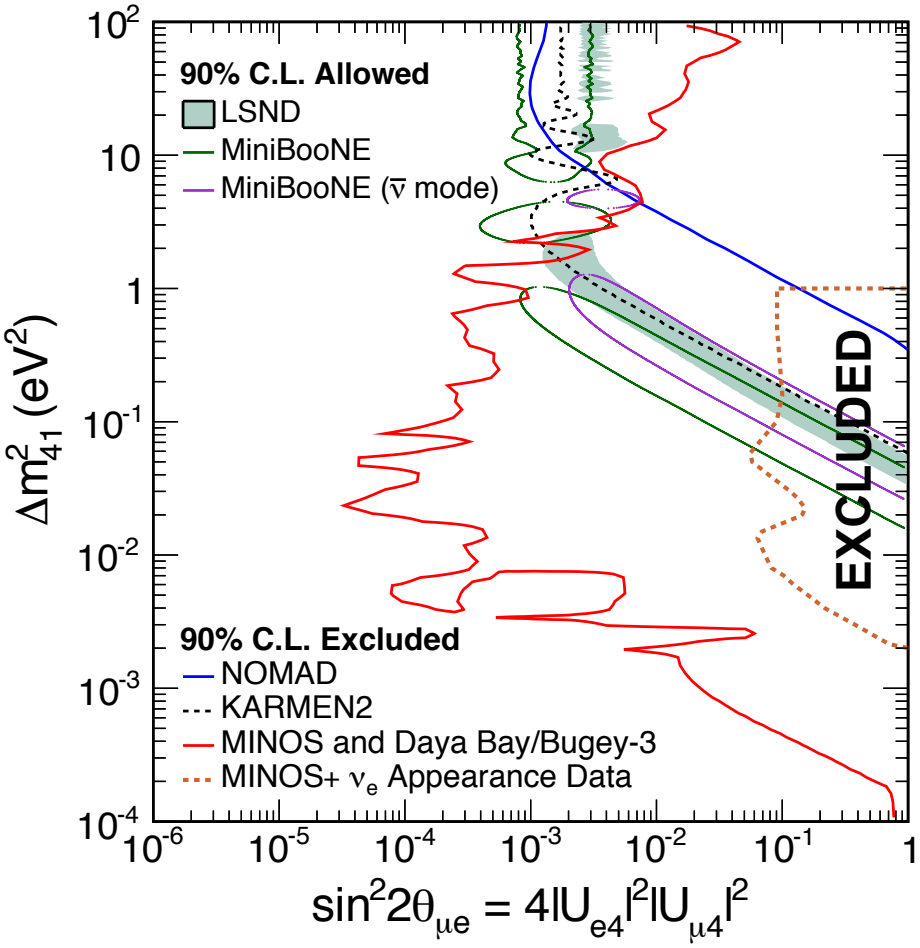
Sterile neutrinos



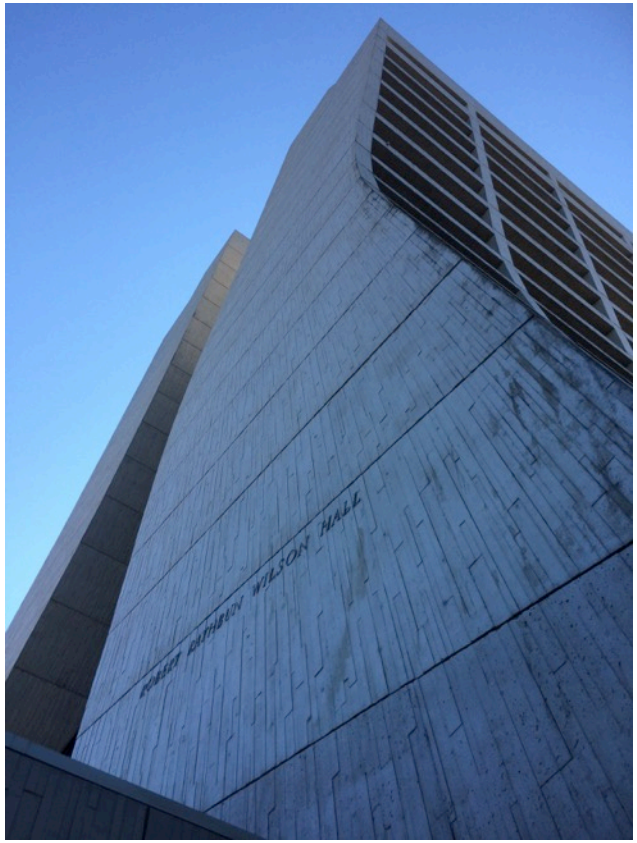
Consistent appearance and disappearance exclusions

- Three times as much appearance data still to analyse

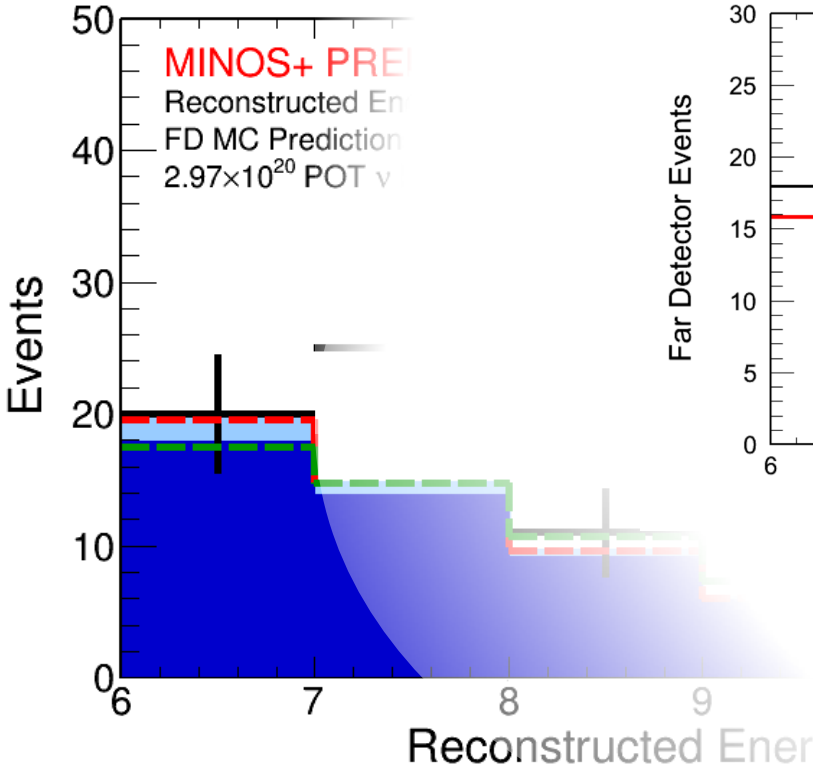
Conclusion

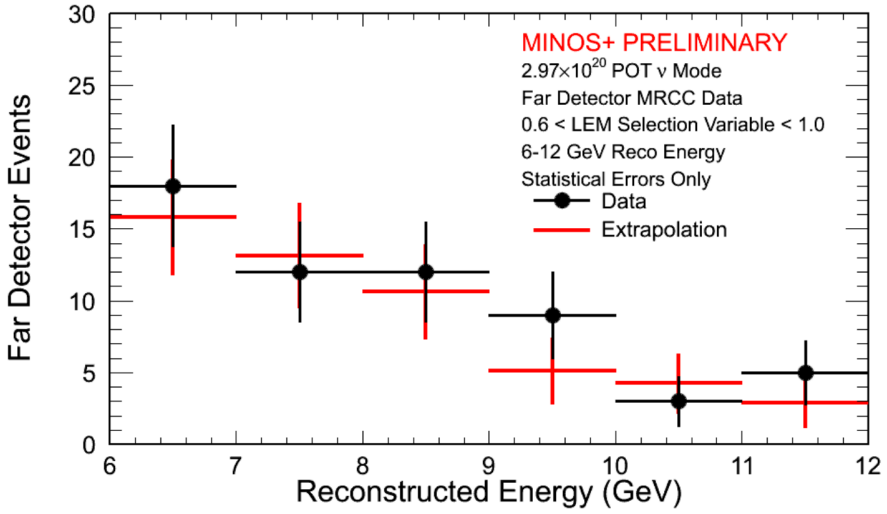
MINOS can search for physics beyond standard oscillations

- Sterile neutrinos
- Sterile antineutrinos
- Non-standard interactions
- Large extra dimensions



Sterile-driven ν_e appearance





Hadron-shower modeling cross-checked with Muon-Removed Charged-Current events

Near detector used to produce a Far Detector pre

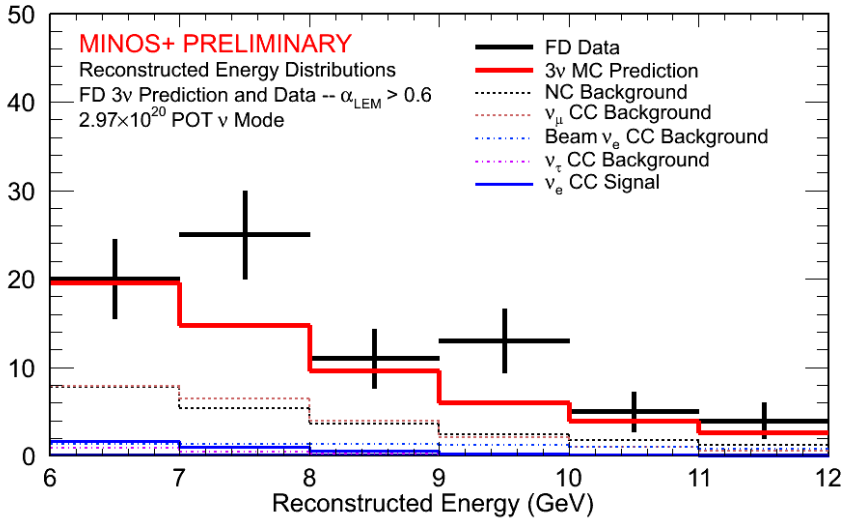
Expect 56.7 events, observe 78

- 2.3σ excess

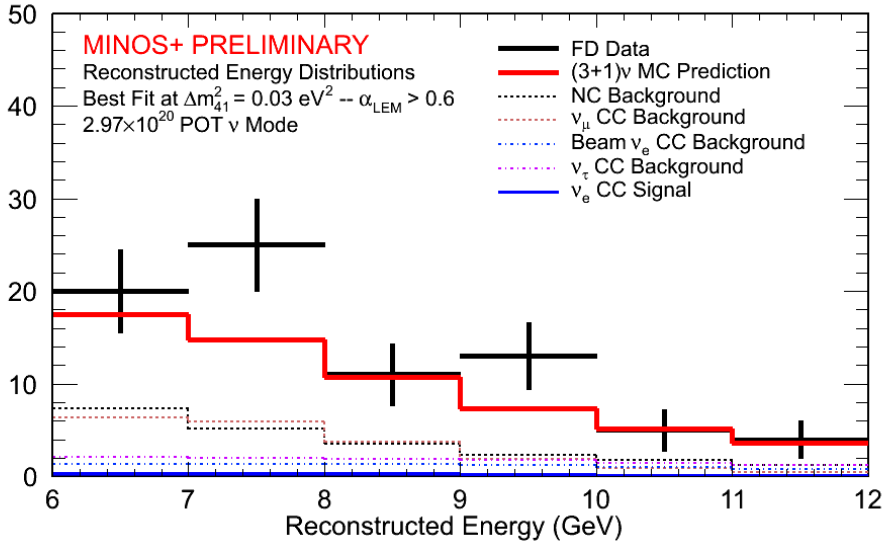
Three times more data to come

Sterile-driven ν_e appearance

Three-neutrino hypothesis



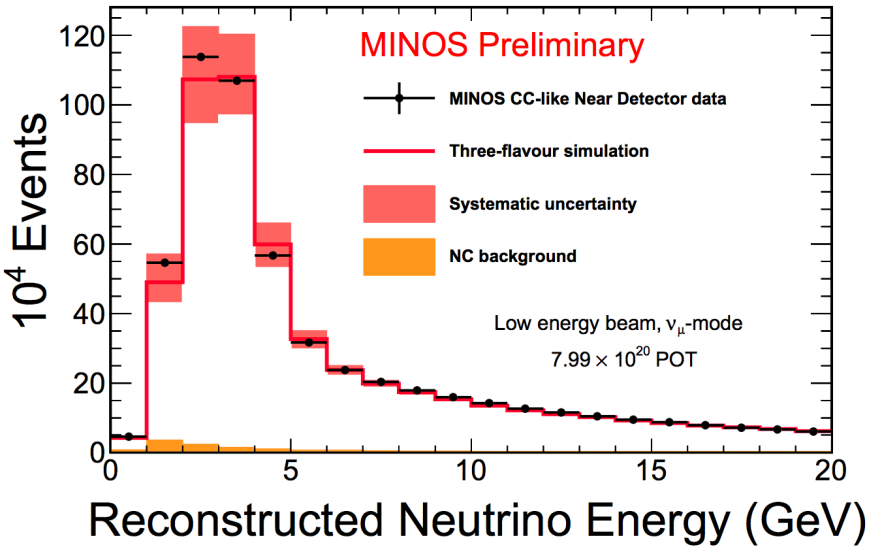
Best fit

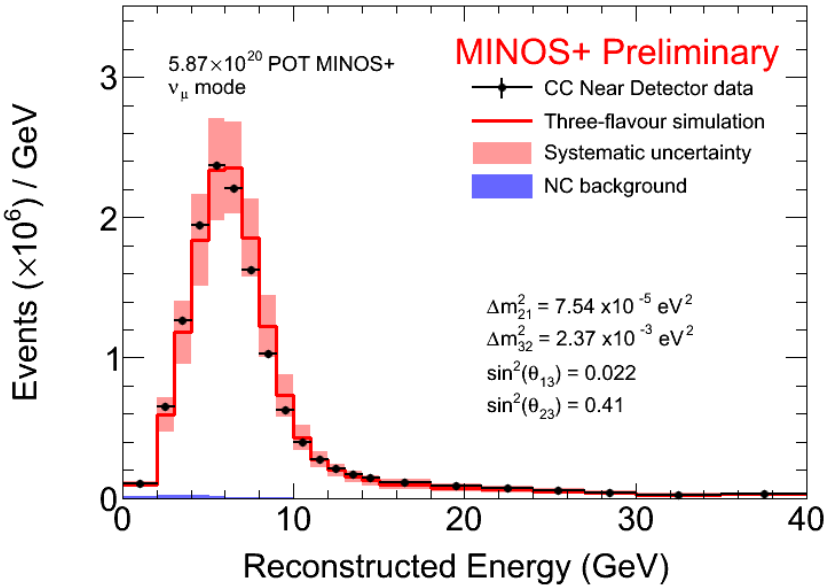


Our data does not favour ν_e appearance

- Obtain a marginally better χ^2 by varying the backgrounds with θ_{34}

MINOS ν MINOS+





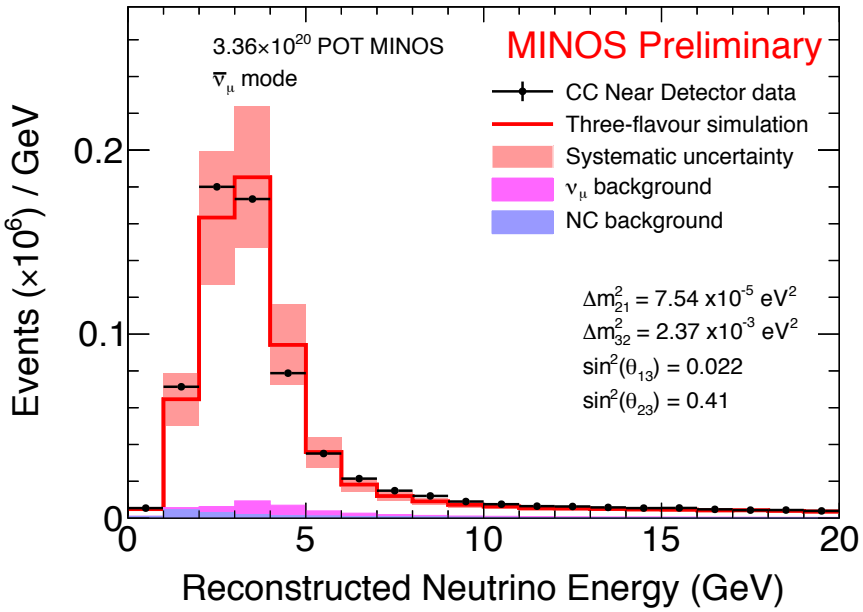
Low-energy MINOS beam optimised for measuring Δm^2_{32}

- Oscillation maximum at ~1.5 GeV

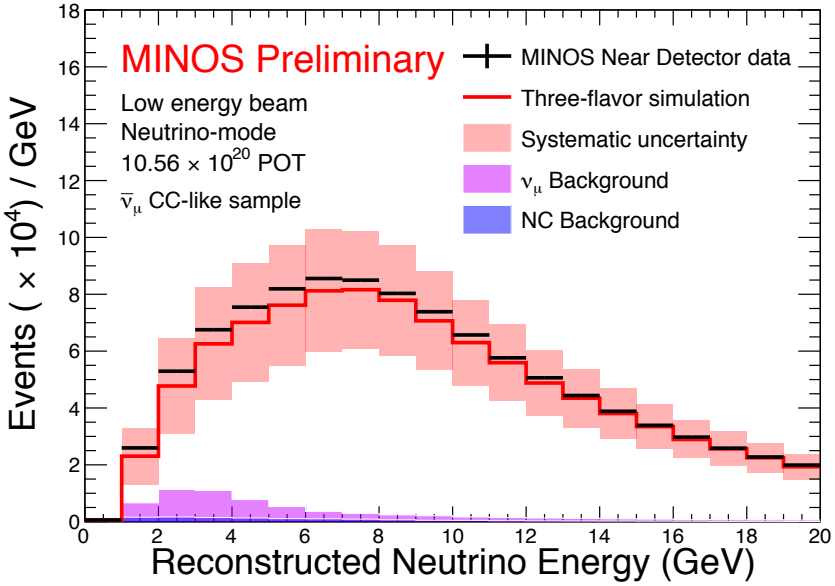
Higher-energy MINOS+ beam allows us to study the region at energies above standard oscillations

Antineutrinos

Antineutrino beam

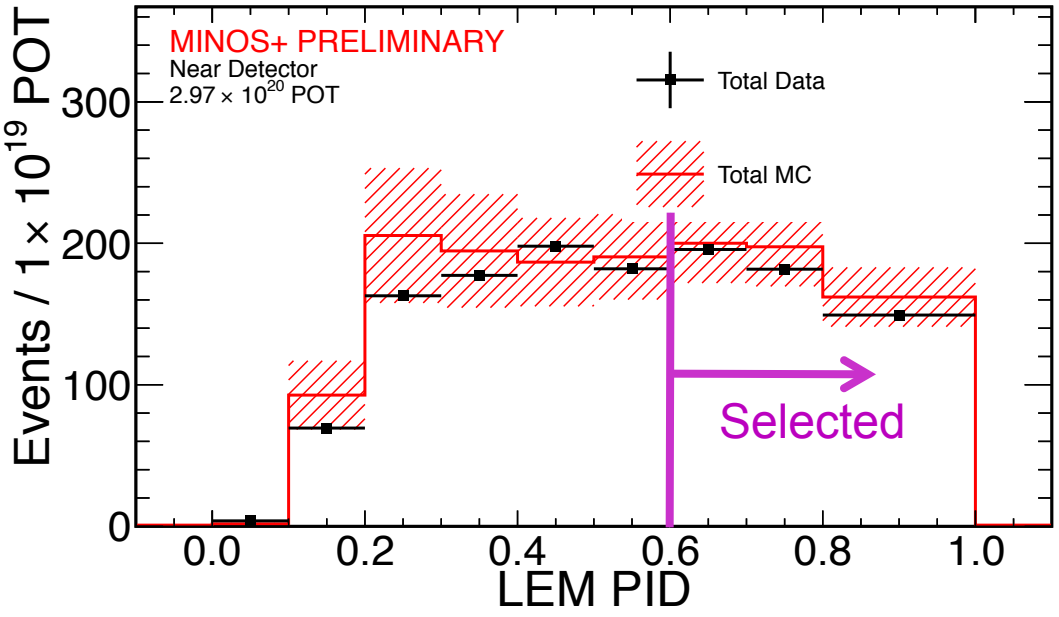


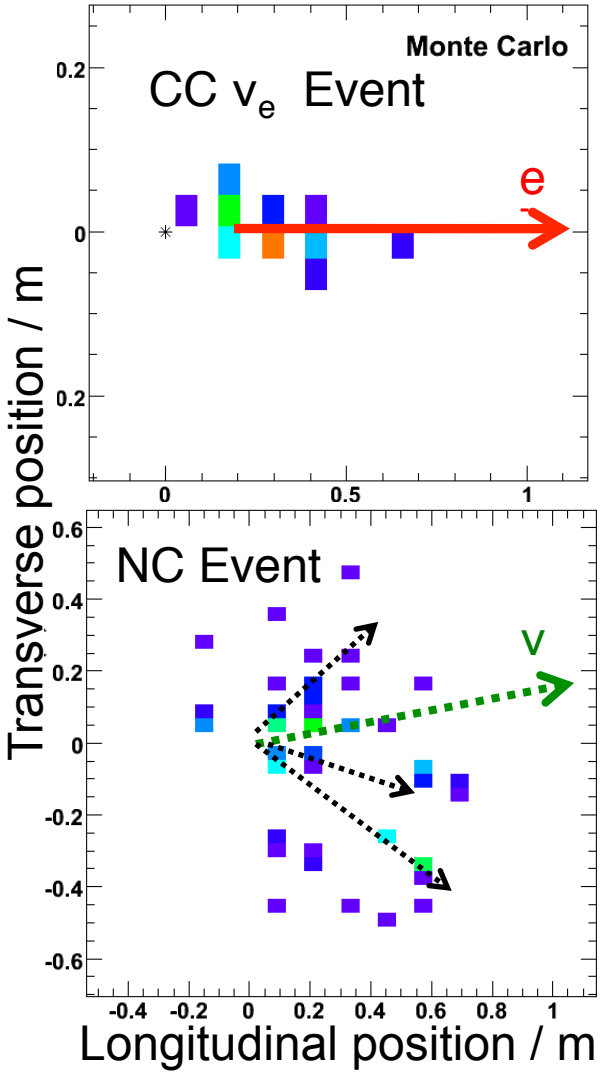
Antineutrinos in the neutrino beam



- Dedicated antineutrino running
- Significant numbers of higher-energy antineutrinos in the neutrino-mode beam

Sterile-driven ν_e appearance





Look for non-standard ν_e appearance in the 6-12 GeV region

- Library event matching allows identification of CC ν_e events
- Total selection efficiency is 78%

A direct probe of the $\nu_\mu \rightarrow \nu_e$ channel