# Results from the MINOS Experiment

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*University of Minnesota*

**Heavy Quarks and Leptons 2016**

# Standard Oscillation Physics

**Standard 3-flavor oscillation physics**

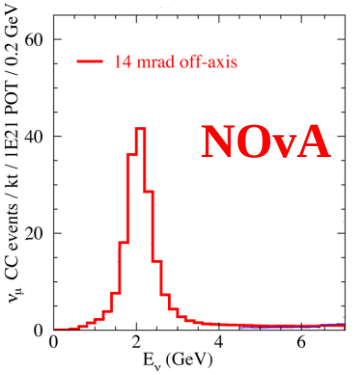
Governed by $\Delta m^2_{21}$ and $\Delta m^2_{32}$

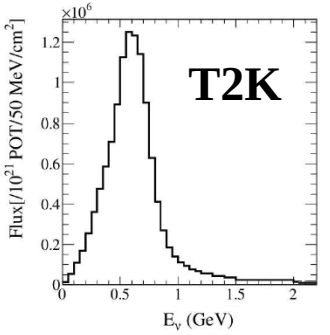
**Current generation of experiments (NOvA, T2K)**

Tuned L/E for $\Delta m^2_{32}$

Sensitive to $\delta_{CP}$, $\theta_{23}$, and sign of $\Delta m^2_{32}$

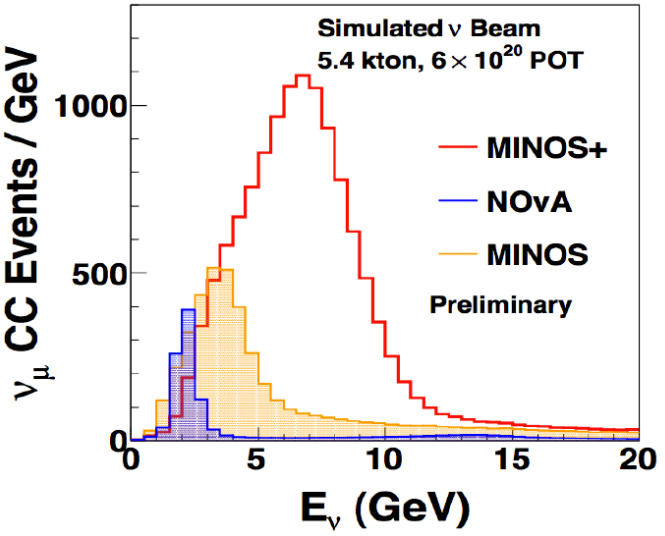
Narrow band beam




**What about new physics?**

MINOS/MINOS+ can explore higher energy neutrino phenomena that can affect $\nu_\mu$ disappearance and $\nu_e$ appearance outside the $\Delta m^2_{32}$ oscillation maximum



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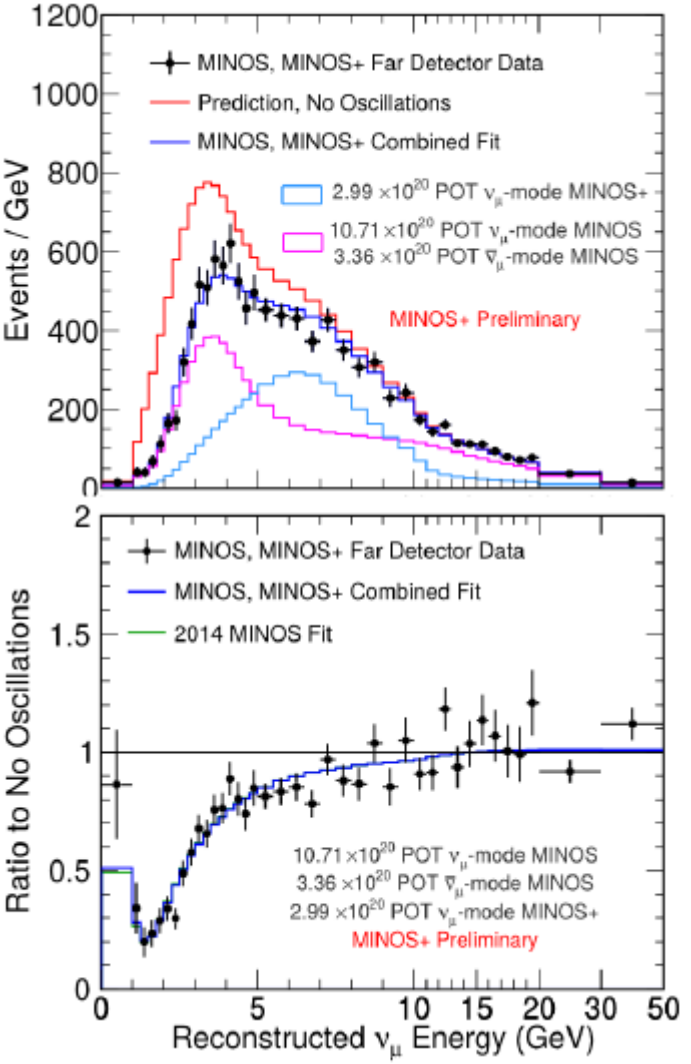


# What can be out there …

## Sterile neutrinos

**4th mass state**

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

**Parameterized into angles**

$$|U_{e4}|^2 = \sin^2\theta_{14},$$
$$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

Oscillation at different $\Delta m^2$

$\nu_\mu \rightarrow \nu_s$

Anomalous disappearance of CC events

Anomalous disappearance of NC events

$\nu_\mu \rightarrow \nu_e$

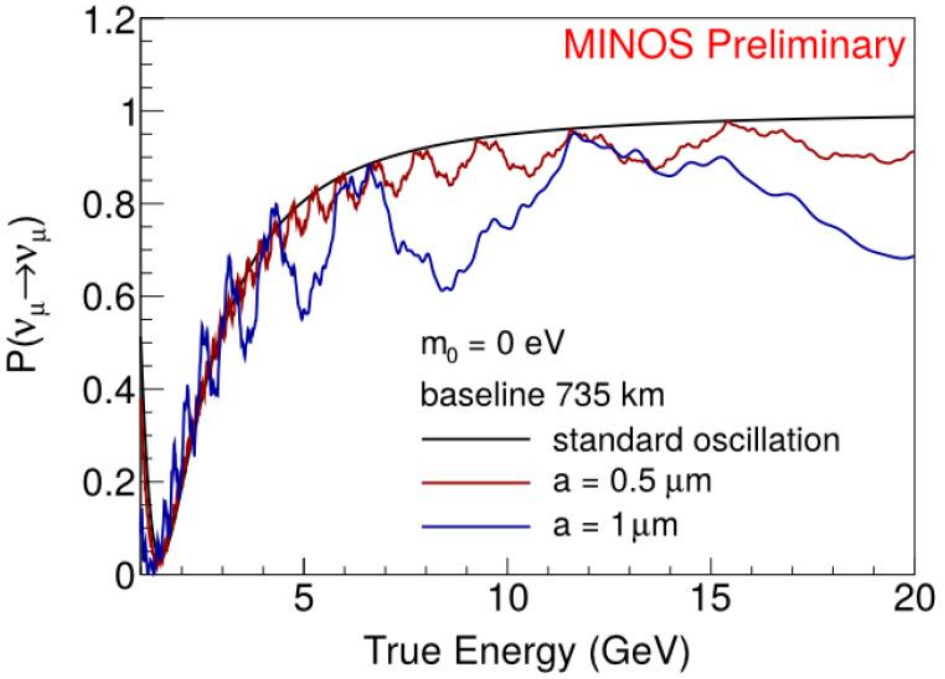
Anomalous $\nu_e$ appearance (LSND like)

# What can be out there …

## Large Extra Dimensions

KK modes of right handed neutrino states allow for extra oscillations

- Anomalous disappearance of CC events
- Anomalous disappearance of NC events




Depends on size of LED and mass of active neutrinos

# What can be out there …

## Nonstandard Neutrino Interactions

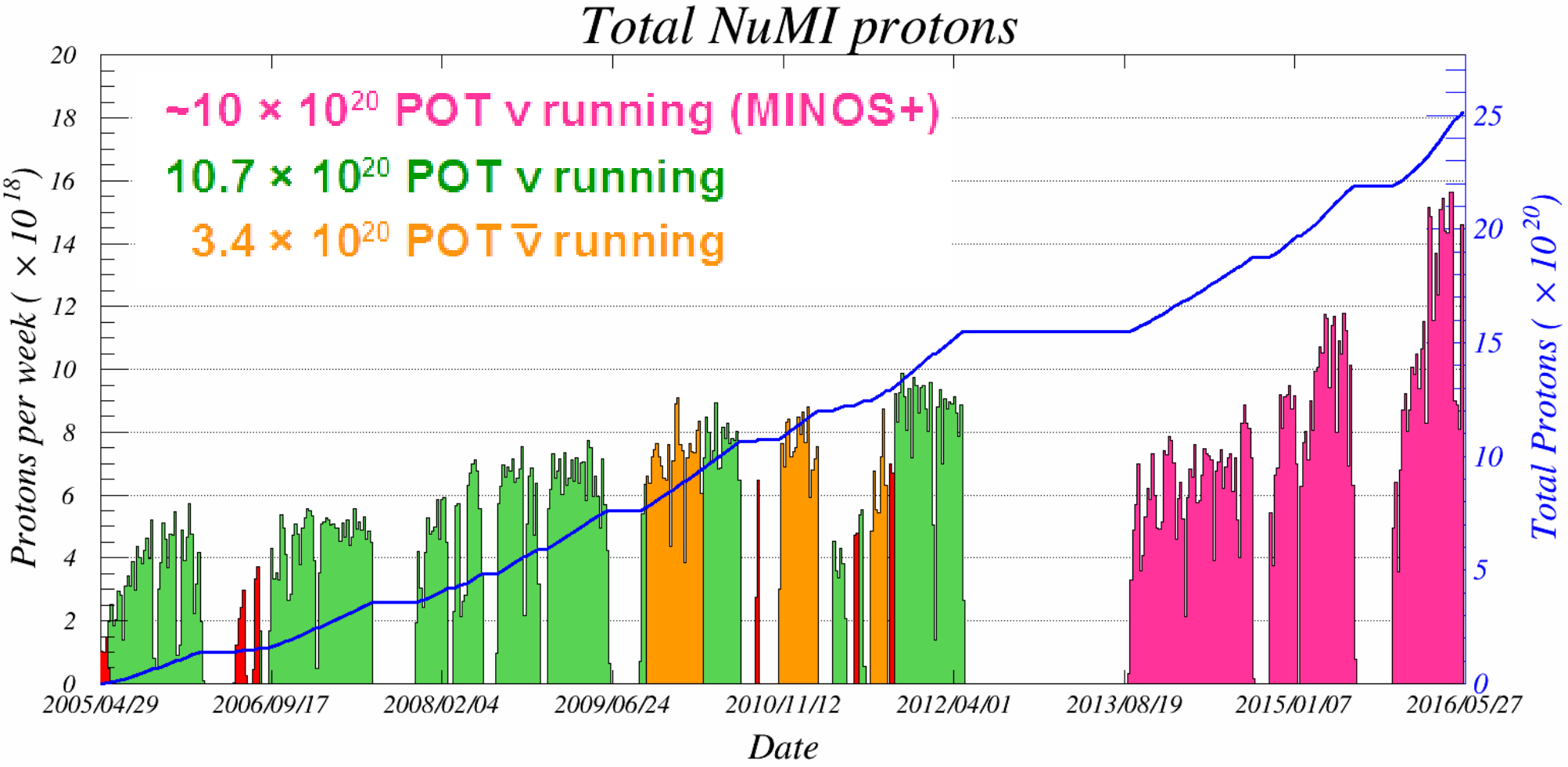
Some new interaction between neutrinos and matter

$$H = U_{\text{PMNS}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^{\dagger}_{\text{PMNS}} + \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}$$

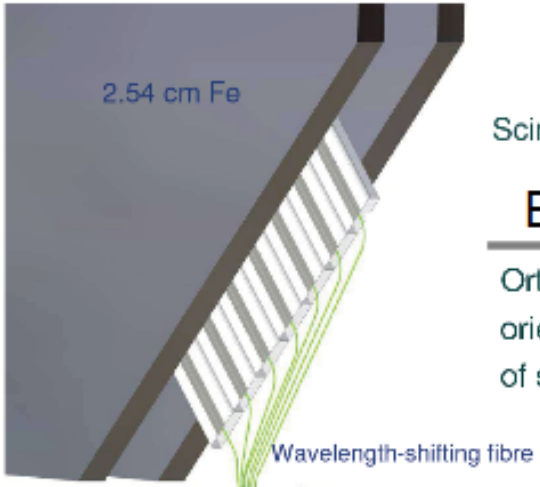
Neutrinos interact with matter as travel through Earth

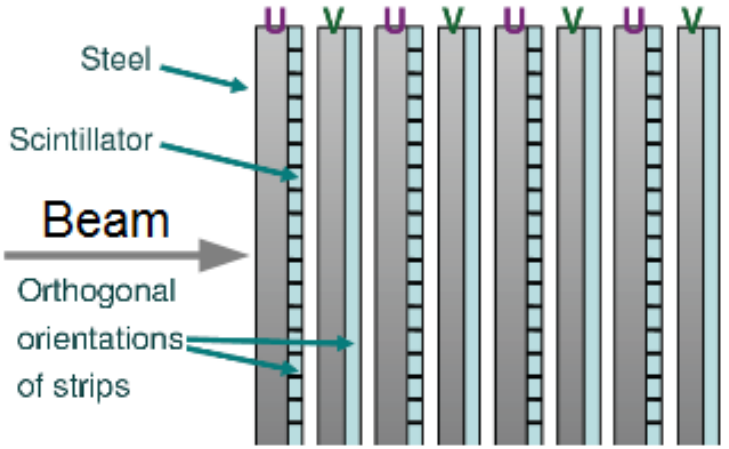
Anomalous matter effect

# Data Set

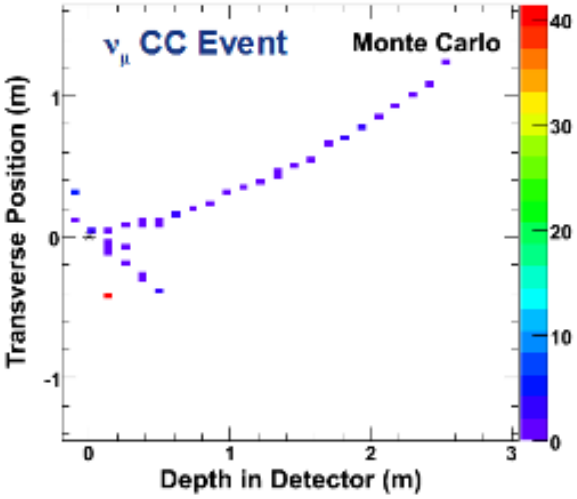

Total NuMI protons
~10 × 10^20 POT ν running (MINOS+)
10.7 × 10^20 POT ν running
3.4 × 10^20 POT ν̄ running
Protons per week ( × 10^18 )
Total Protons ( × 10^20 )
0
2
4
6
8
10
12
14
16
18
20
0
5
10
15
20
25
2005/04/29
2006/09/17
2008/02/04
2009/06/24
2010/11/12
2012/04/01
2013/08/19
2015/01/07
2016/05/27
Date

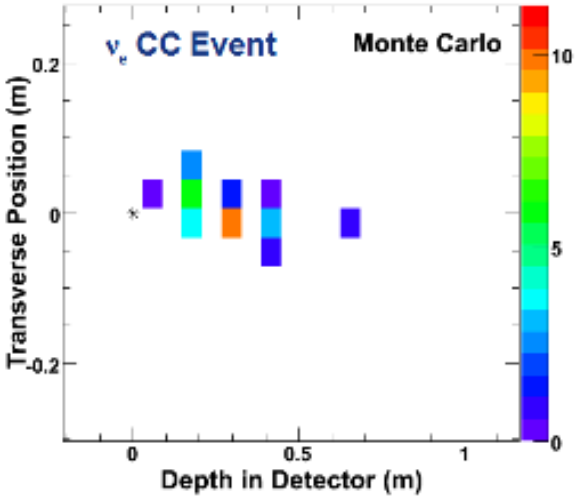
# Event Topologies

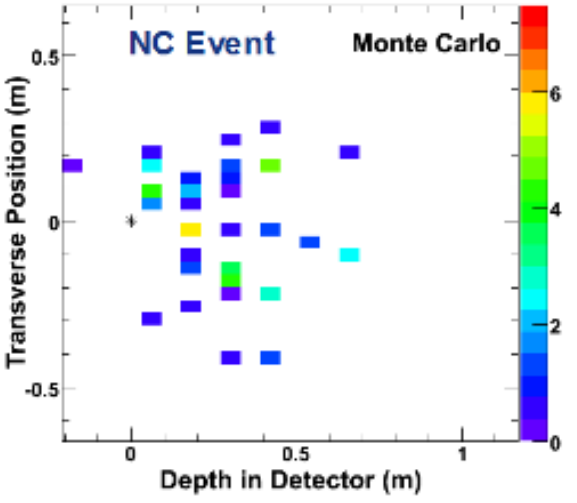






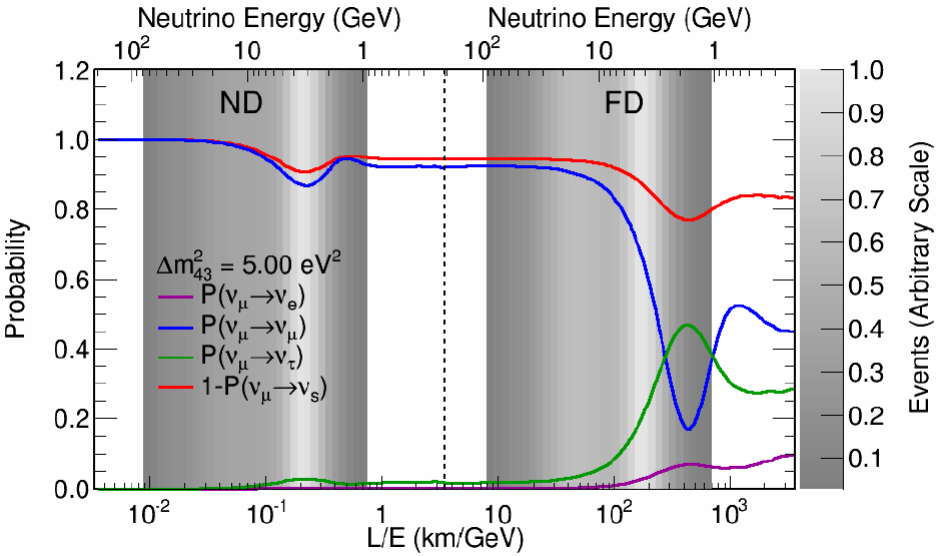
# Sterile Neutrino Search

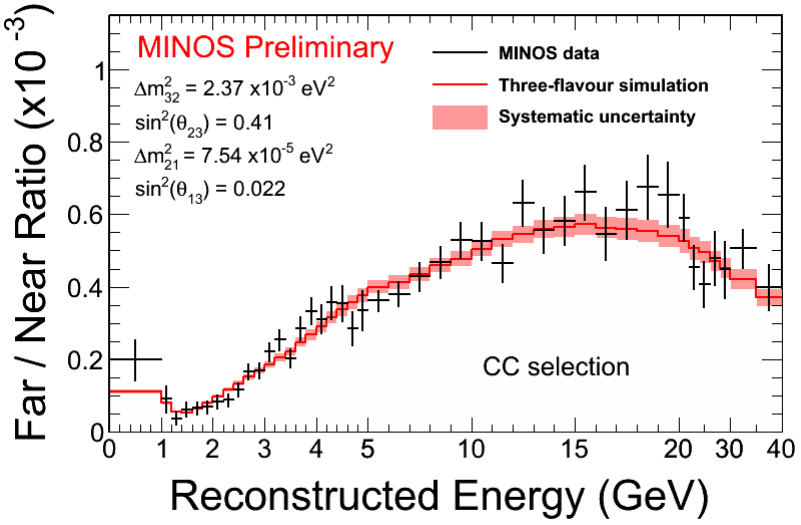
**Assume 3+1 model**

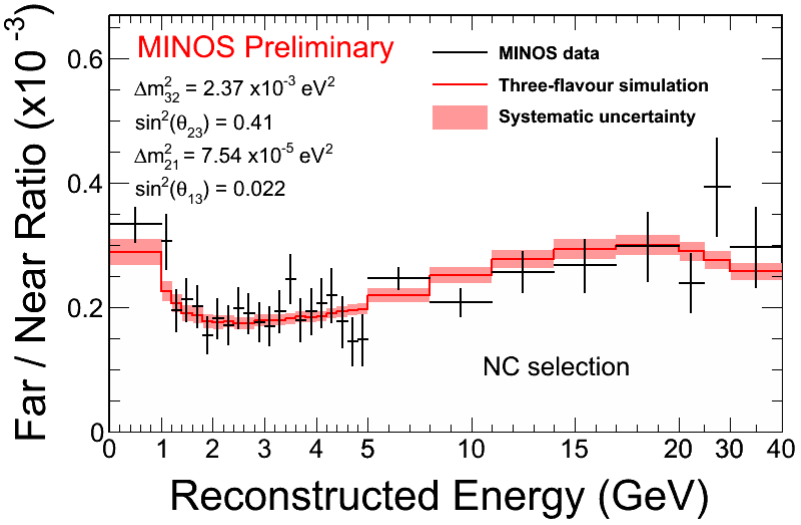
**Look for deficit in $\nu_\mu$ CC and NC**

**Oscillation can occur in ND**

- **Depends on $\Delta m^2$**
- **Fit Far/Near ratio**



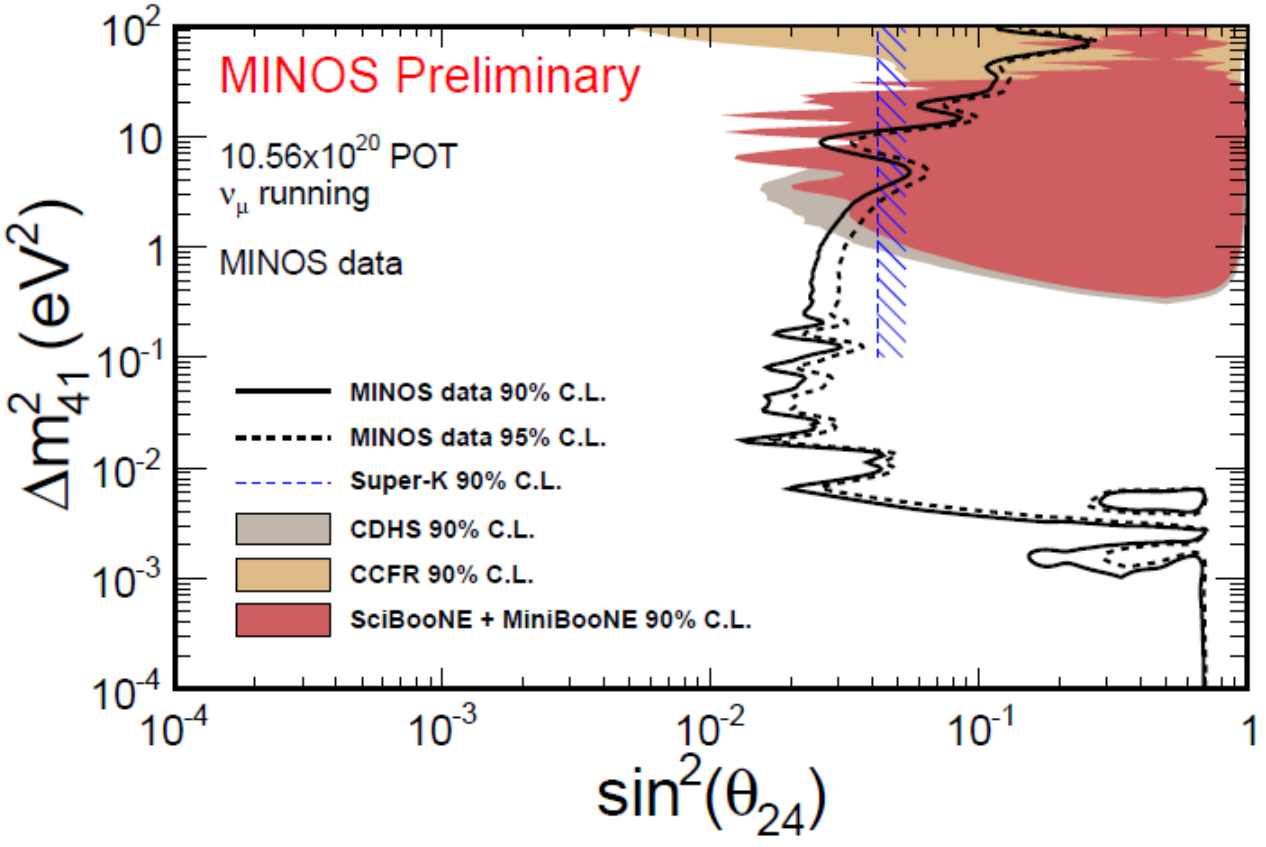



# Sterile Neutrino Search

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\cos^2(2\theta_{24})\sin^2(\Delta_{31}) - \sin^2(2\theta_{24})\sin^2(\Delta_{41})$$

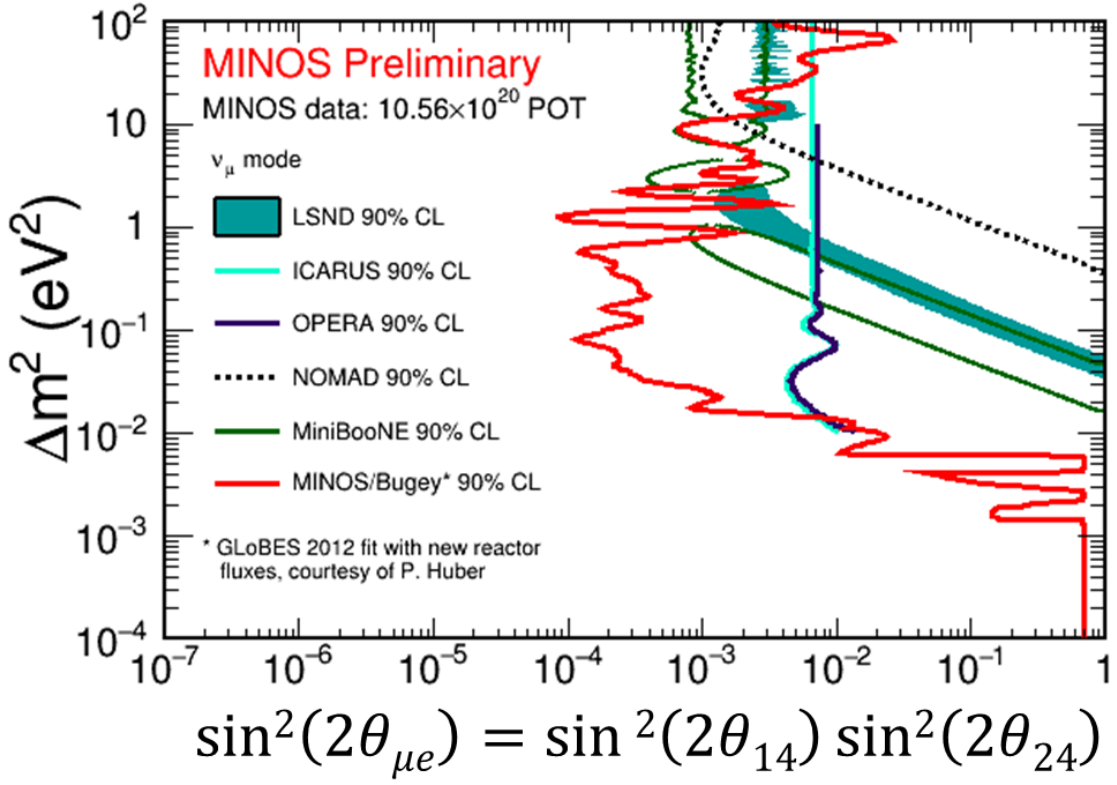
Use full 4-flavor probability and NC and CC samples




**Tightest experimental limits at low $\Delta m^2$**

# Sterile Neutrino Search

Combine with $\theta_{14}$ constraints from Bugey ( $\bar{\nu}_e$ disappearance )



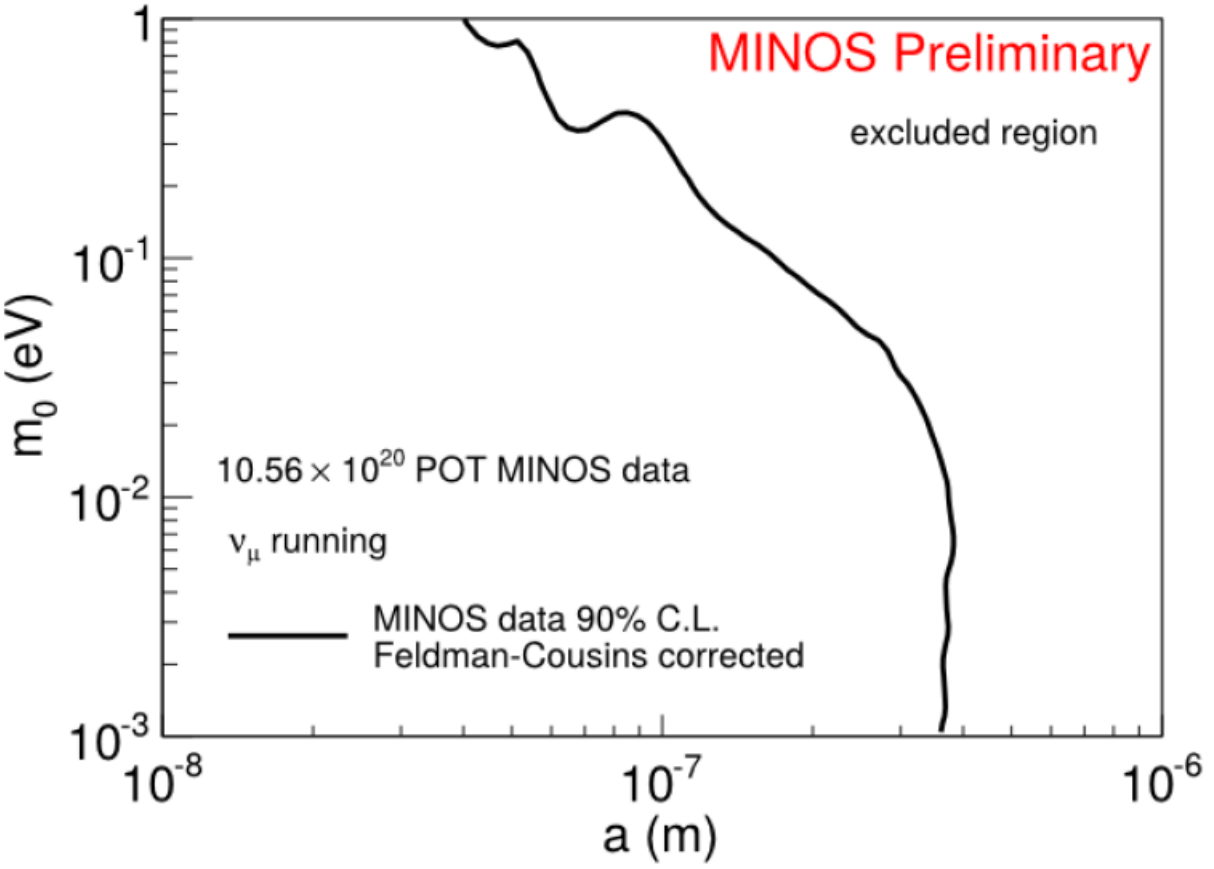

**Exclude much of LSND allowed parameter space**

Future results will use Daya Bay constraints

# Large Extra Dimensions

Take previous 3+1 sterile analysis and fit data using LED hypothesis

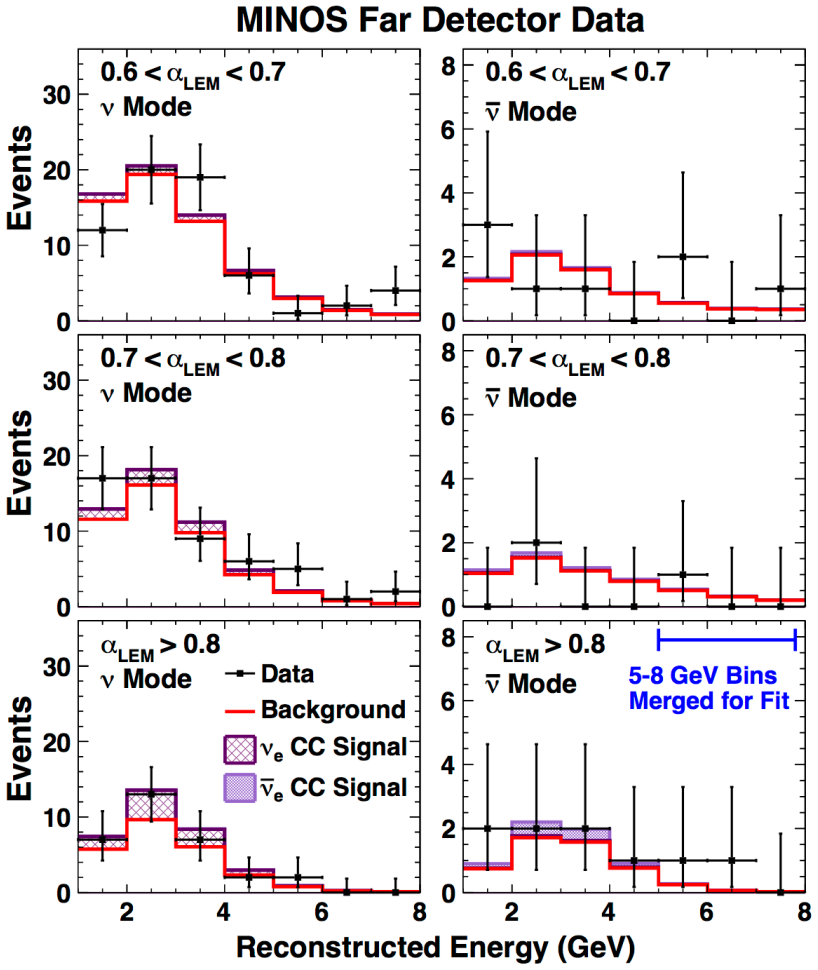
Assume 1 extra dimension is much larger than others

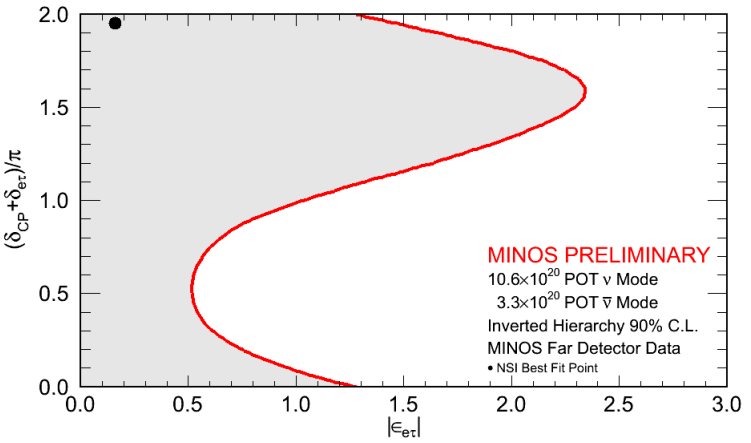


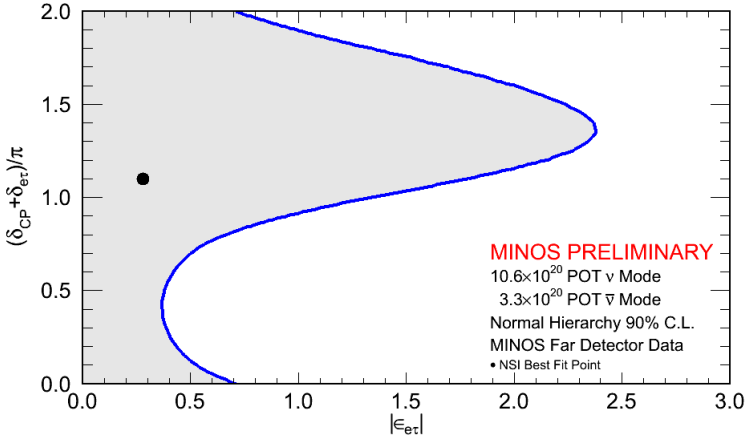
# Nonstandard Interactions

**Look for indication of nonstandard neutrino interactions in $\nu_e$ appearance data**

**Data consistent with no NSI**

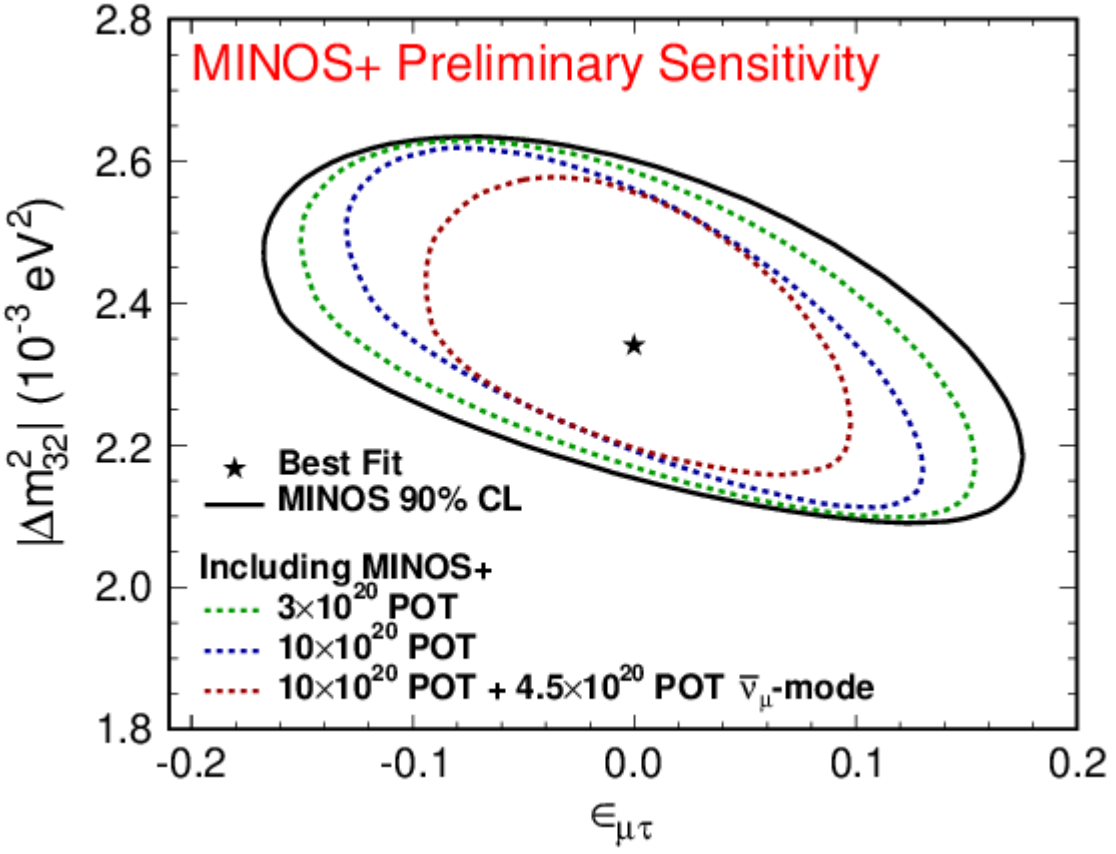


# The Near Future

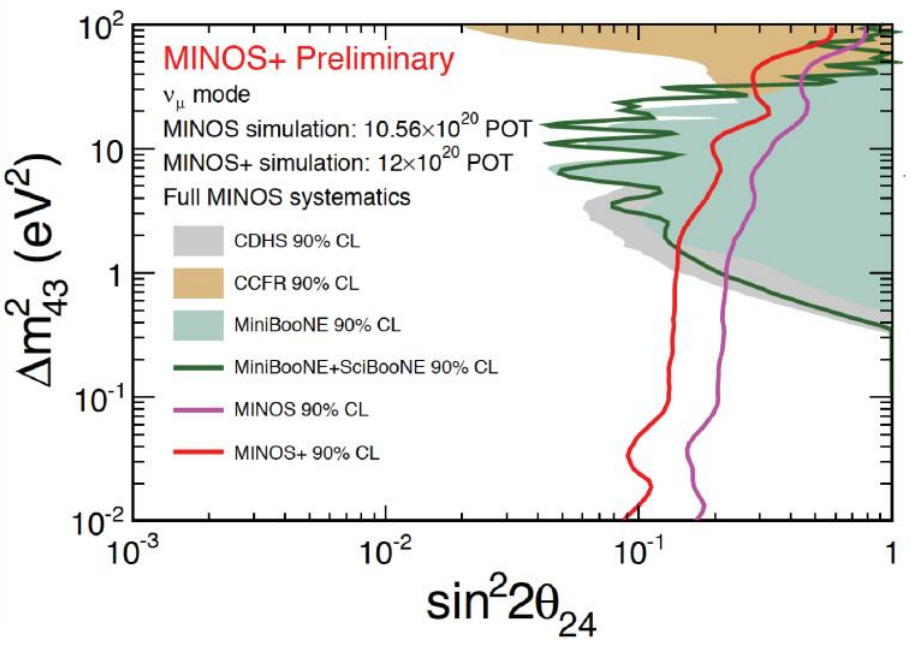
**MINOS+ data will be used to place further constraints on NSI**



# The Near Future

**MINOS+ data will be used to place further constraints on sterile ν**

## Disappearance channels




## Appearance channel