News from MINOS and MINOS+

Karol Lang
University of Texas at Austin

On behalf of the MINOS+ Collaboration

Selected Topics:

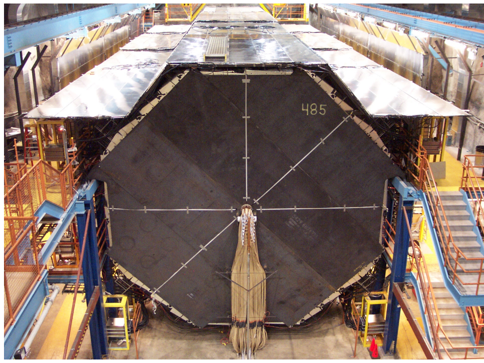
+ Beams and experiments
+ Standard oscillations
+ Sterile neutrinos
+ Large extra dimensions
+ Non-standard interactions

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
39th Course
Neutrinos in Cosmology,
in Astro-, Particle- and Nuclear Physics
Erice-Sicily: September 16-24, 2017

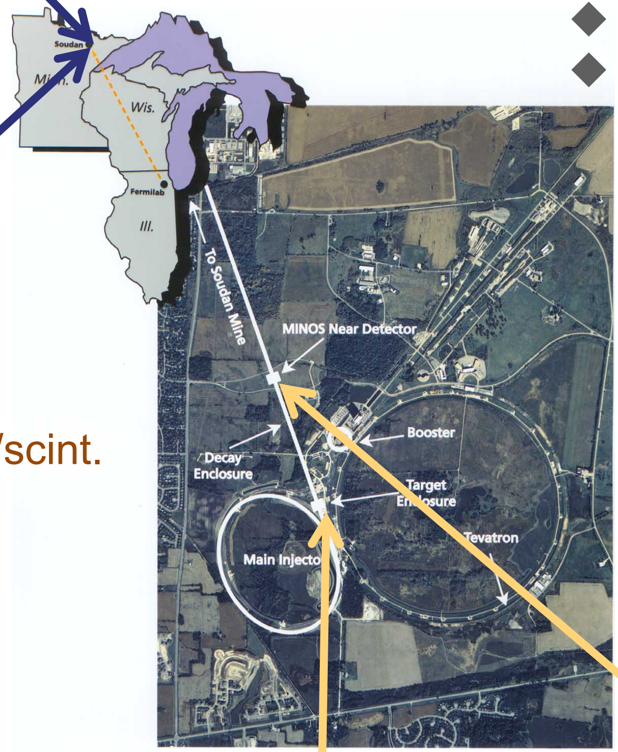
MINOS & MINOS+

BEAMS AND DETECTORS

MINOS, MINOS+, and NuMI



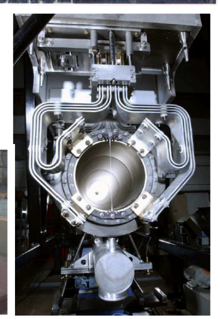
- Far Detector (FD) on axis
- 735 km from target
- 5.4 kt, 8m octagon
- ~1.2 T B field
- Segmented, sampling, iron/scint. tracking calorimeter

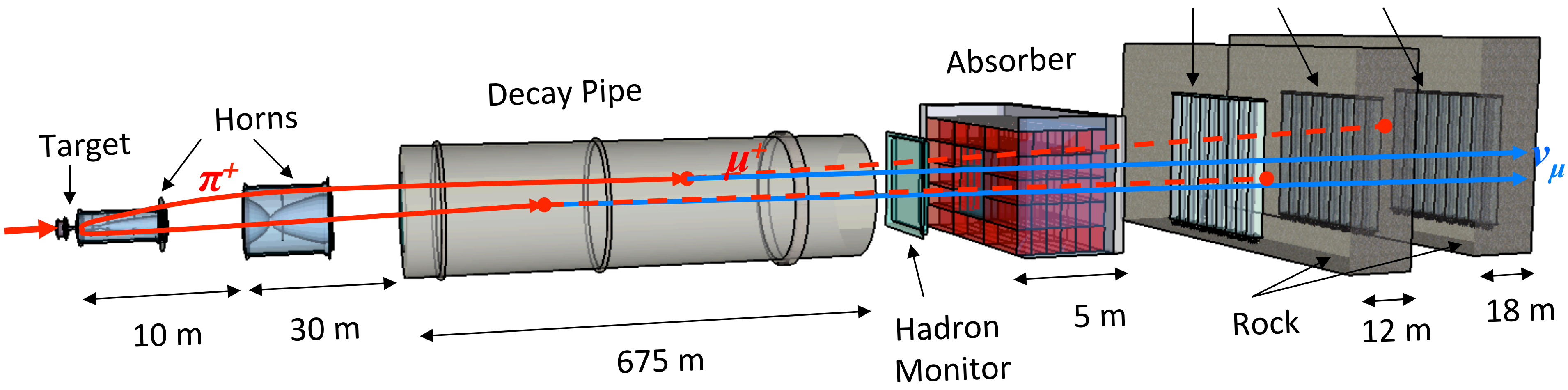


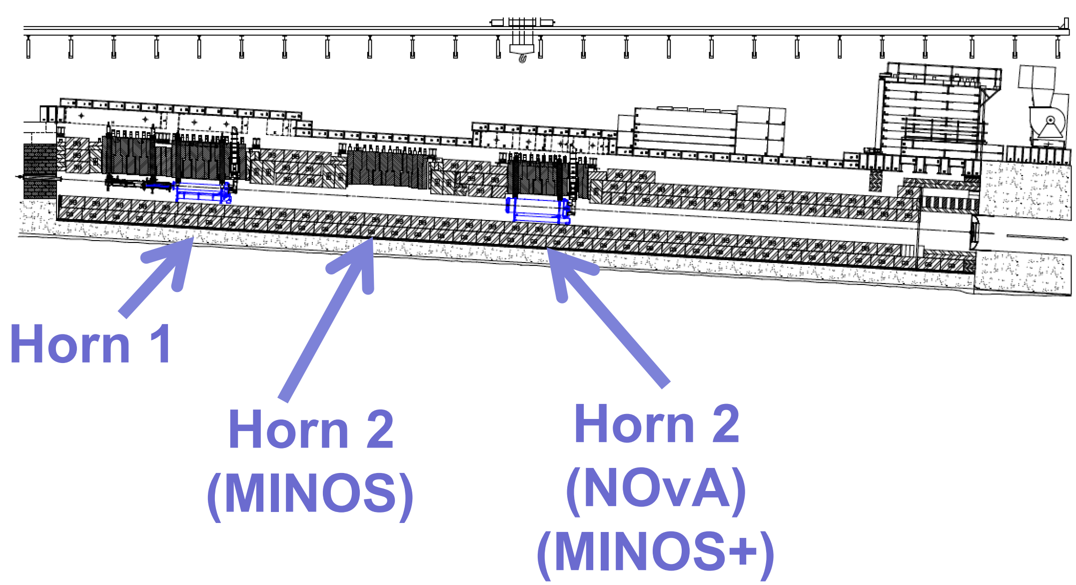
- MINOS Proposed 1995
- Main Injector 2000
- Beam data 2005-2012
- NuMI reconfigured for NOvA 2013
- MINOS+ 2013-2016

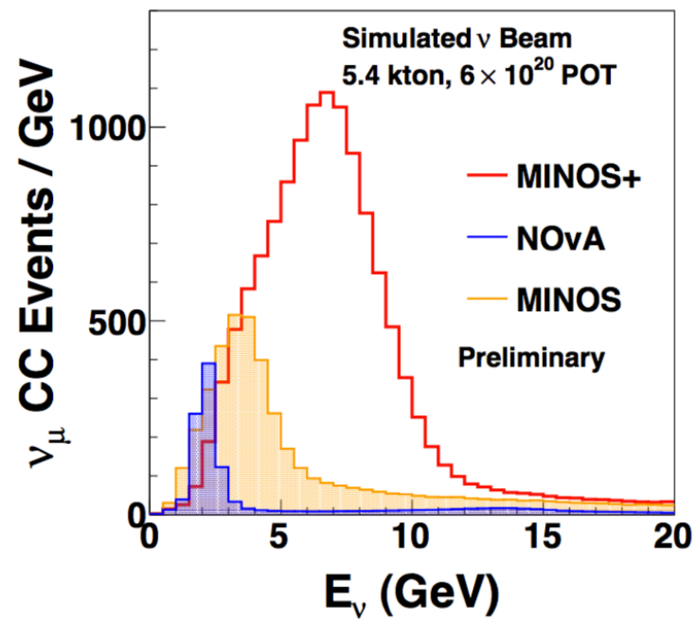
- Near Detector (ND) on axis
- 1,040 m from target
- 1kt, 4m `squeezed' octagon
- ~1.2 T B field
- Same technology as FD

- 2-horn focusing 185 kA
- 2λ graphite target (movable)
- Up to ~600 kW beam
- 3.5x10^{13} ppp
- 1.33 s cycle time

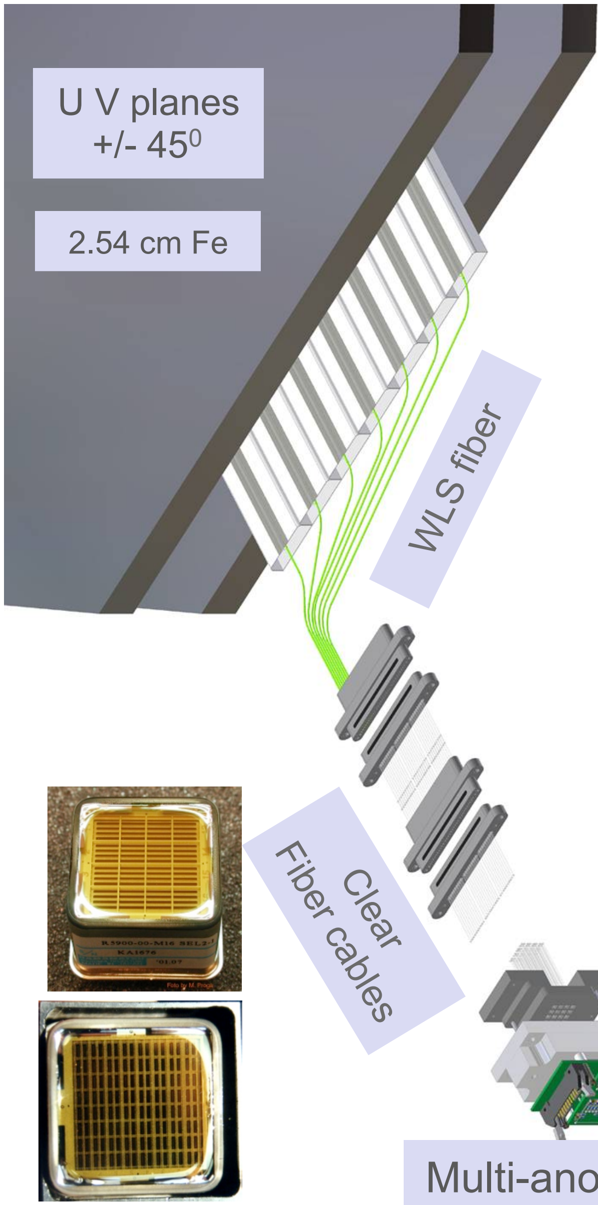


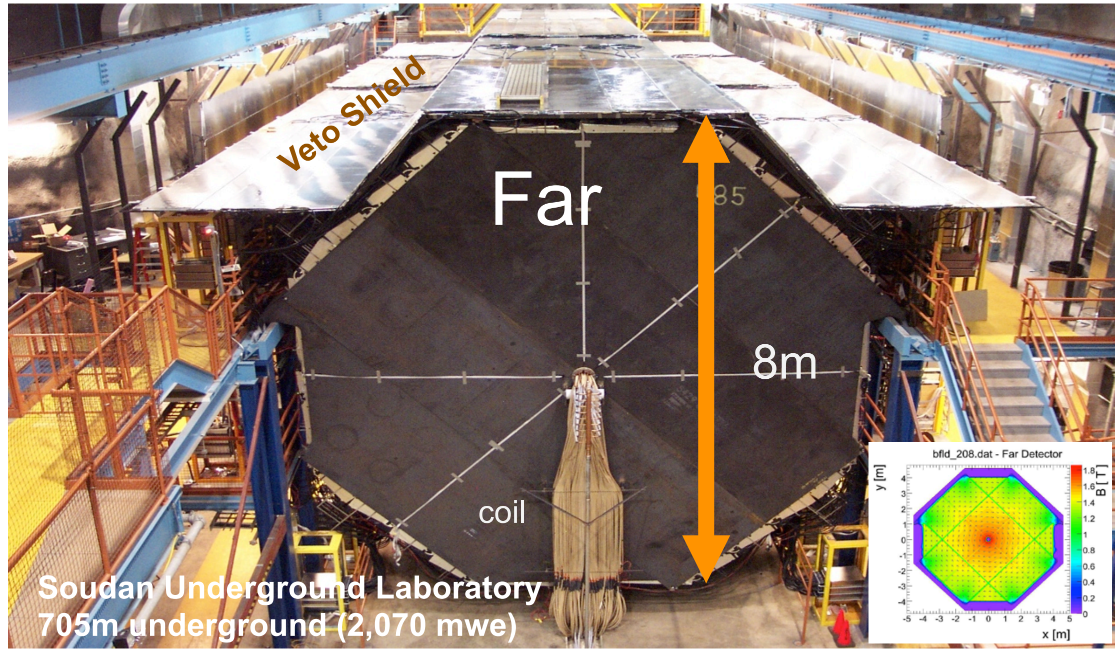

Target
Horns
π^+
Decay Pipe
μ^+
Absorber
ν_μ
Hadron Monitor
Rock
10 m
30 m
675 m
5 m
12 m
18 m

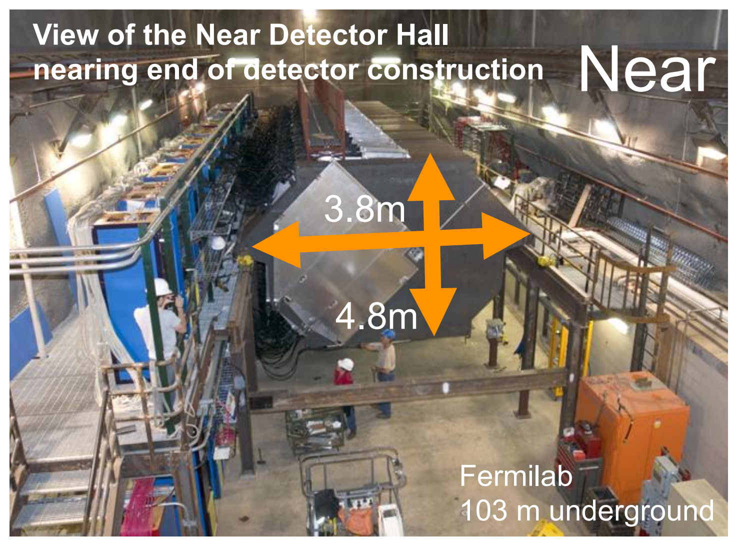

Horn 1
Horn 2 (MINOS)
Horn 2 (NOvA) (MINOS+)


Simulated ν Beam
5.4 kton, 6 × 10^20 POT
MINOS+
NOvA
MINOS
Preliminary
ν_μ CC Events / GeV
E_ν (GeV)
0
500
1000
5
10
15
20

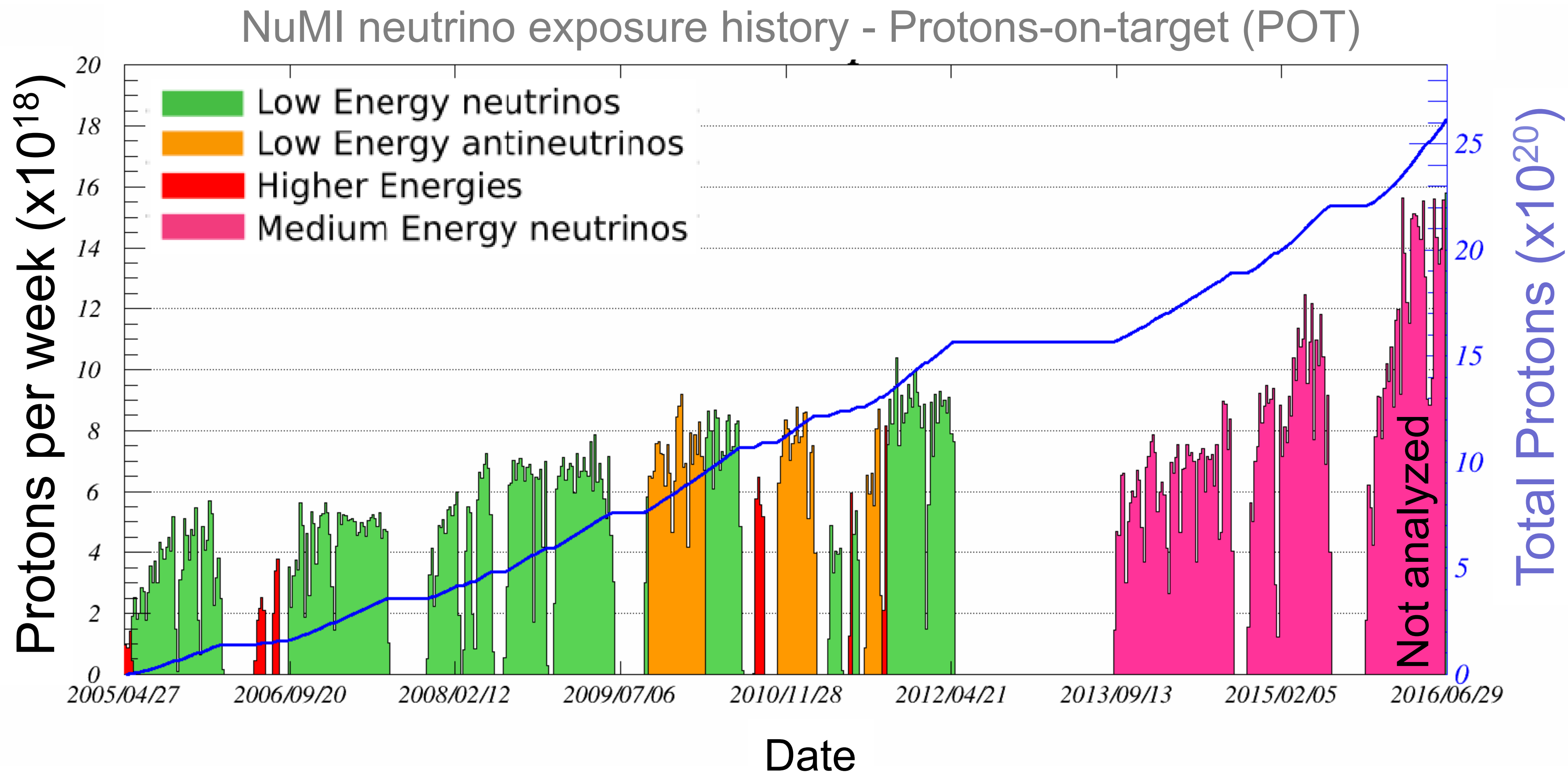
MINOS: Near and Far Detectors







MINOS and MINOS+ exposures
2005 → 2016



MINOS (2005-2012)

10.56×10^{20} POT

3.36×10^{20} POT

MINOS+ (2013-2016)

9.69×10^{20} POT

(5.80×10^{20} POT "processed")

MINOS & MINOS+

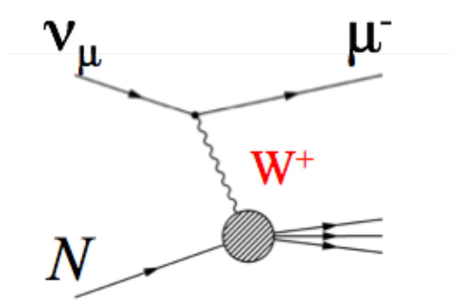
STANDARD OSCILLATIONS

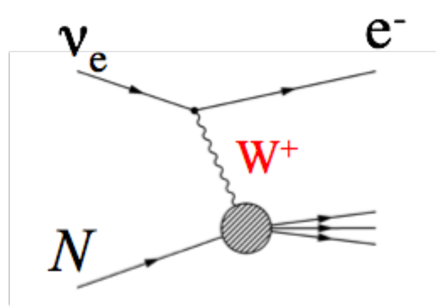
Event types in MINOS

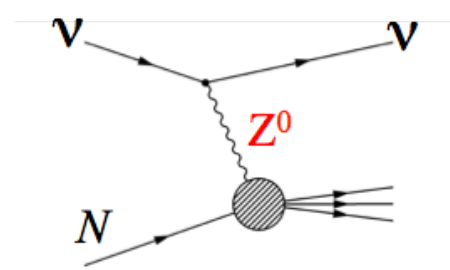
ν_μ Charged Current (ν_μ CC)

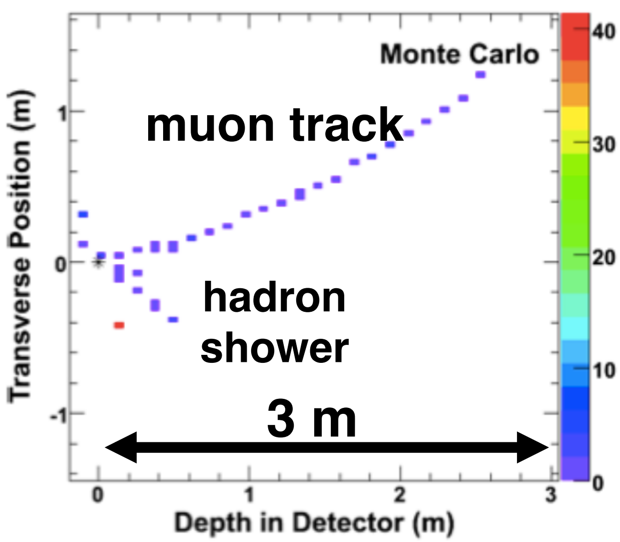
ν_e Charged Current (ν_e CC)

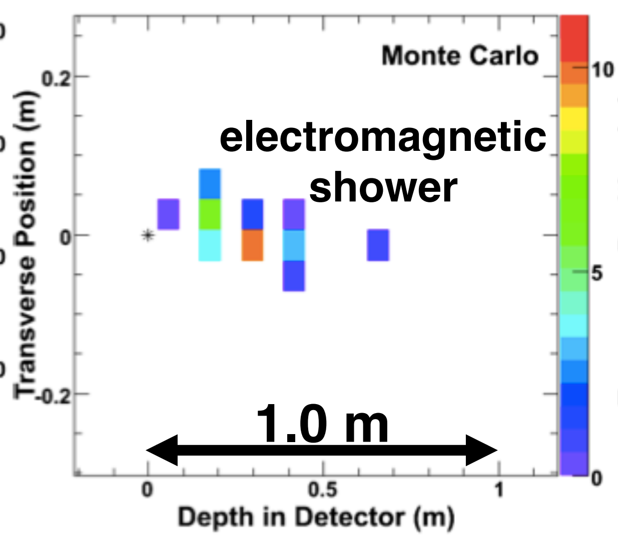
ν_x Neutral Current (NC)

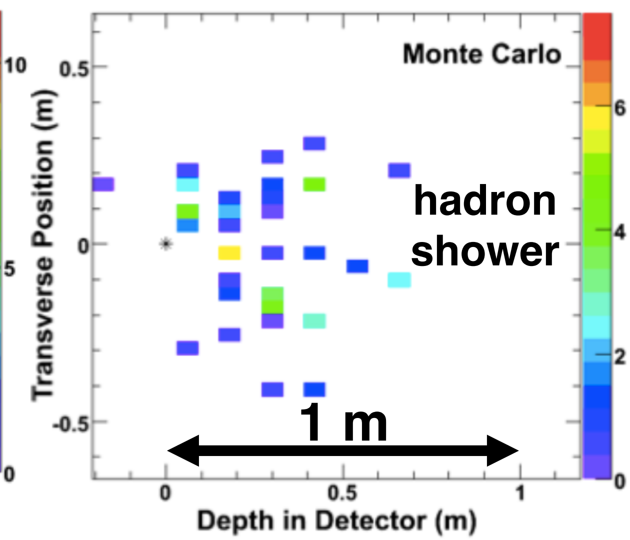






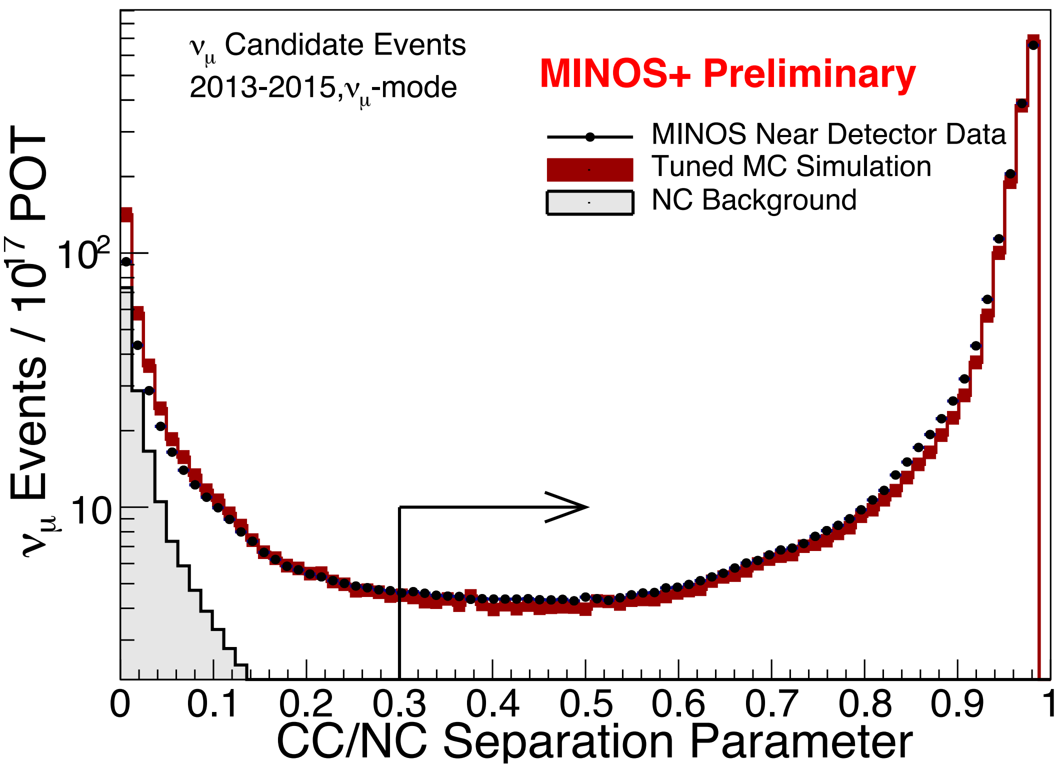






Charged current **(CC)** vs Neutral current **(NC)** classification

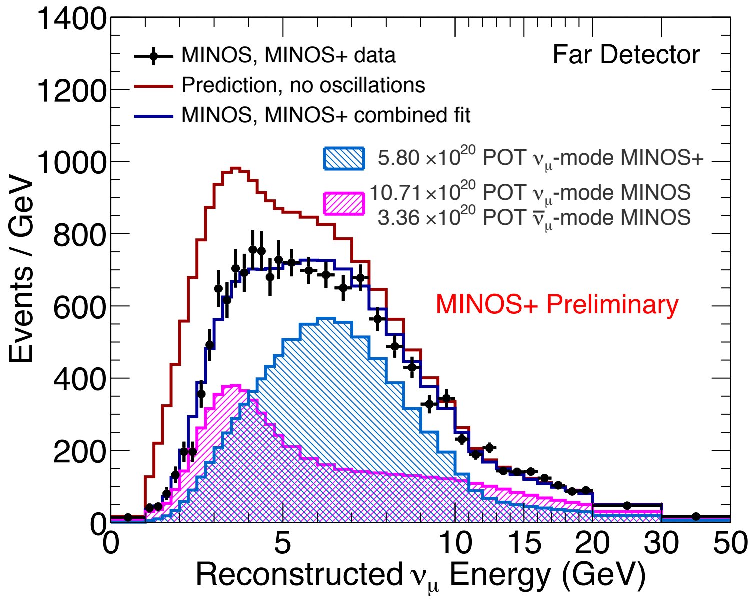
Event classification:
k Nearest-Neighbors (kNN)

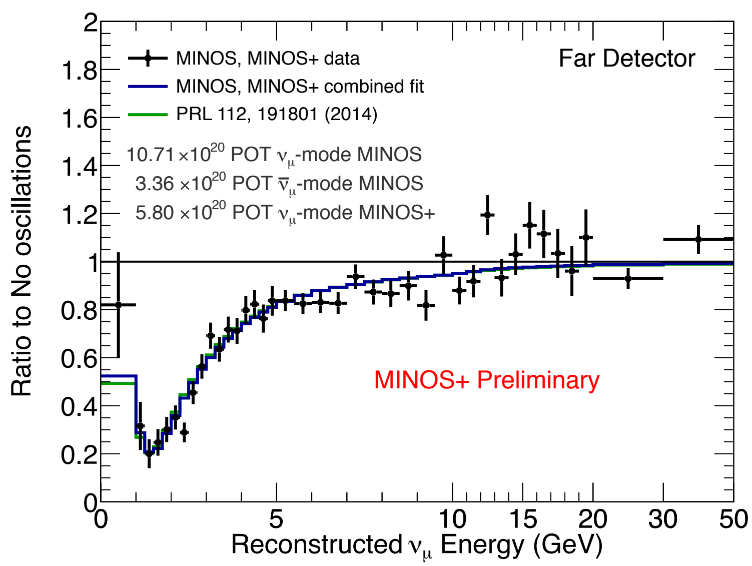


MINOS+ Far Detector

efficiency	85.9%
purity	99.3%

MINOS & MINOS+
Standard Oscillations Results (so far: 5.80×10^{20} POT)





Best fits, 68% C.L.

Normal $\Delta m^2_{32} = +\,2.42 \pm 0.09 \quad (\times 10^{-3} eV^2)$

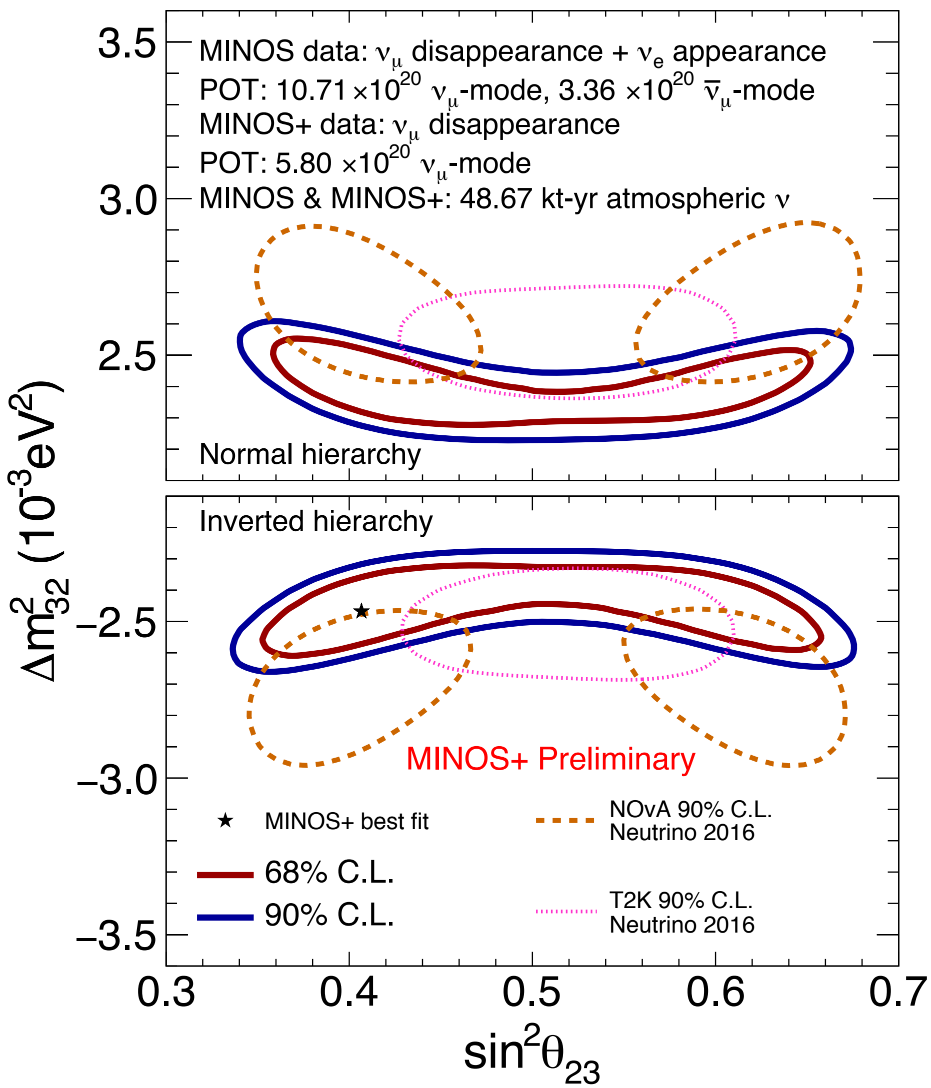
$\sin^2\theta^2_{23} = 0.41 \quad (0.37 \leftrightarrow 0.46)$

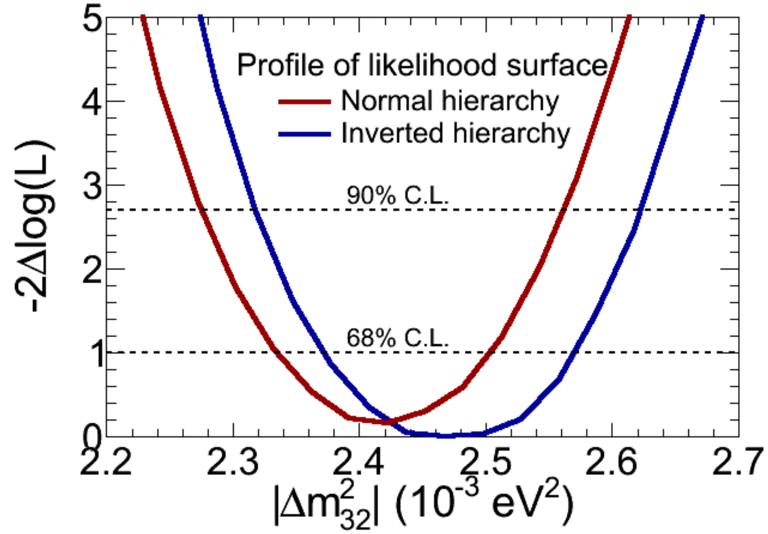
Inverted $\Delta m^2_{32} = -\,2.48 \pm 0.09 \quad (\times 10^{-3} eV^2)$

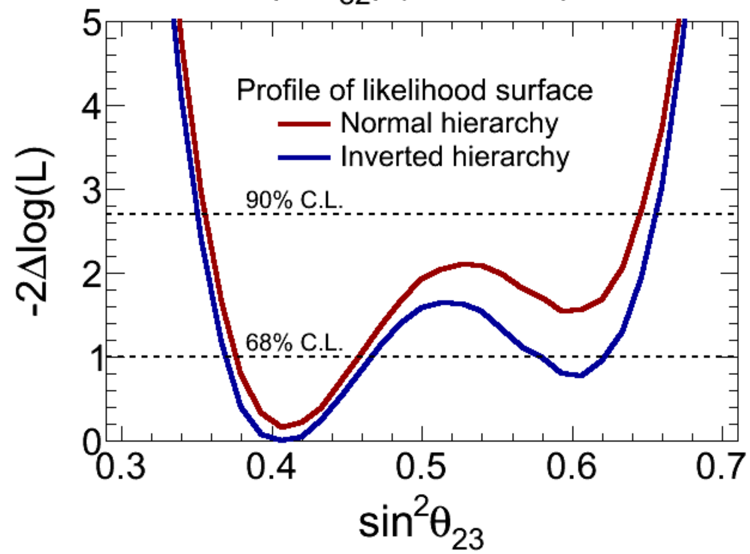
$\sin^2\theta^2_{23} = 0.41 \quad (0.37 \leftrightarrow 0.47)$

Data events		ν_μ	$\overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$	Atmospheric
MINOS	(2005-2012)	2579	538	152	20	2072
MINOS+	(2013-2015)	3692	179	–	–	551

MINOS contours bounds







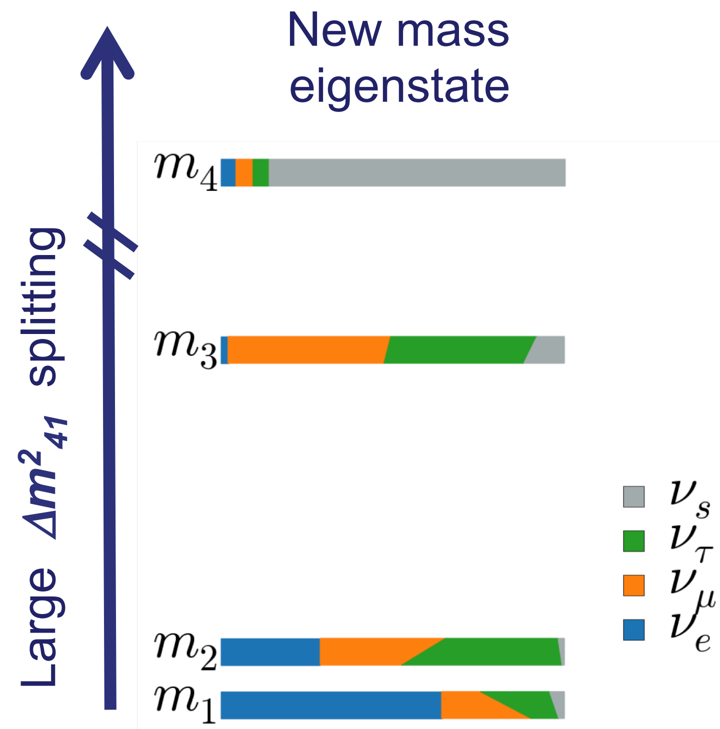
$\sin^2\theta_{13}$=0.0210 +- 0.0011 (PDG 2017)

MINOS & MINOS+

SEARCH FOR STERILE NEUTRINOS

The "3+1" mixing

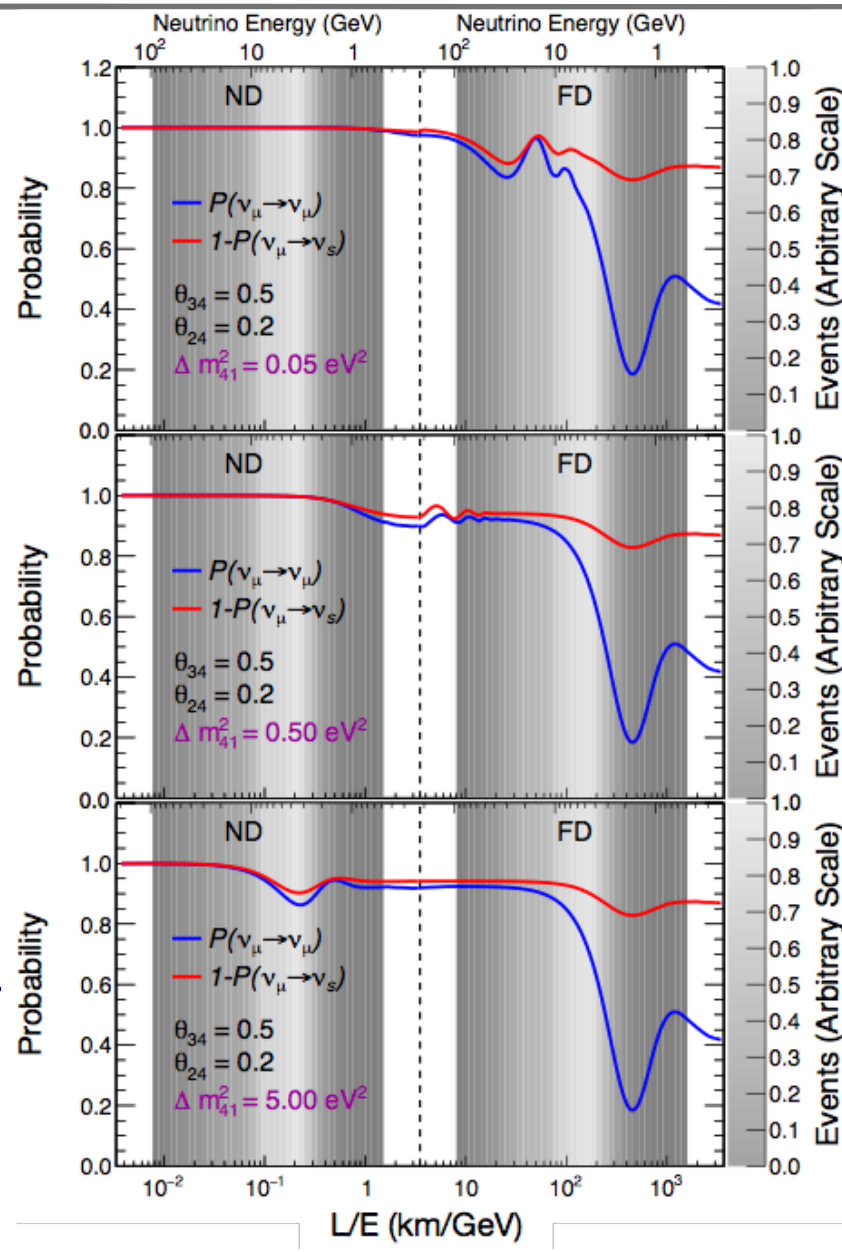
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



- (New) Oscillation parameters:
  - 3 mass scales: Δm^2_{21}, Δm^2_{32}, Δm^2_{41}
  - 6 mixing angles: θ_{12}, θ_{23}, θ_{13}, θ_{14}, θ_{24}, θ_{34}
  - 3 CP-violating phases: δ_{13}, δ_{14}, δ_{24}

4-flavor oscillations in MINOS

- MINOS is sensitive to three sterile neutrino parameters
  - ⇨ θ_{24} , θ_{34} and Δm^2_{41}
  - ⇨ **Small Δm^2_{41} < 0.05 eV²**
  - ⇨ Low Δm^2_{41} only affects FD
- Oscillations can cause effects in both detectors
  - ⇨ Rapid oscillations cause a constant deficit in FD
  - ⇨ **Medium Δm^2_{41} ~ 0.5 eV²**
- Can't use ND as a flux measurement in this analysis
  - ⇨ High Δm^2_{41} → oscillations in ND.
  - ⇨ **Large Δm^2_{41} > 5 eV²**
  - ⇨ Oscillations at the ND



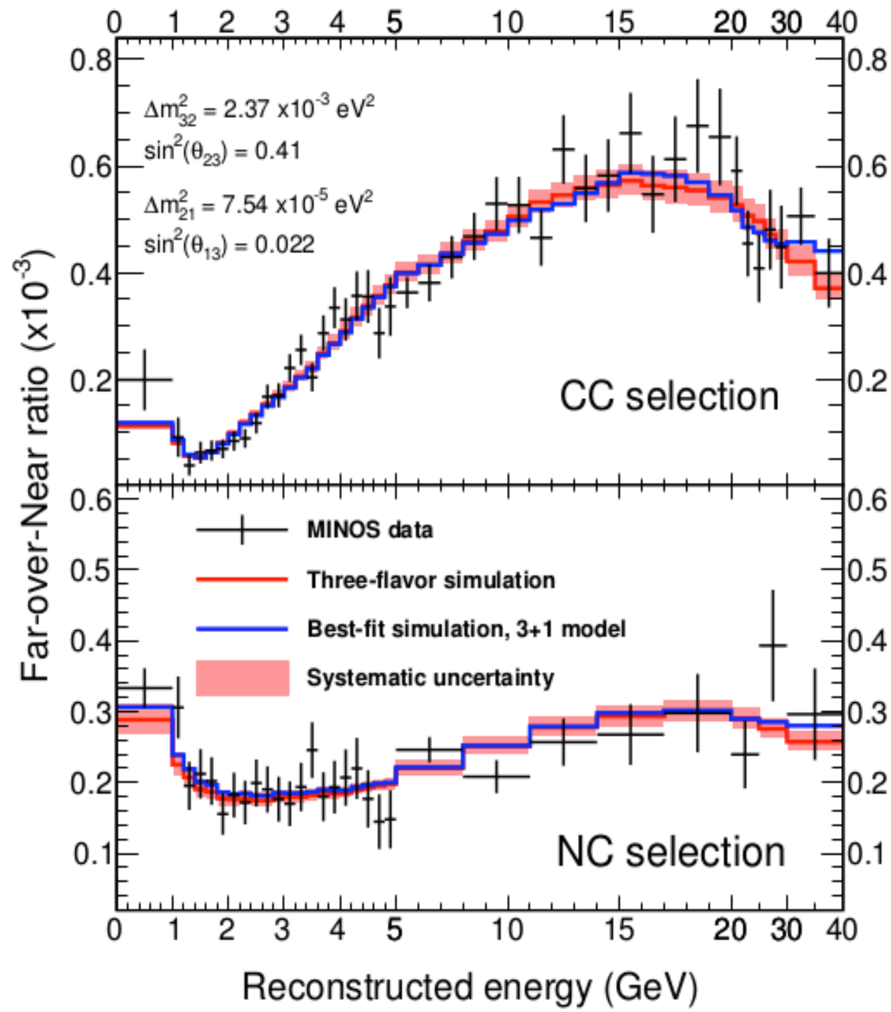
small

Δm^2_{41}

large

Use Far-over-Near energy spectra ratios

- The 2016 sterile neutrino analysis used the ratio of FD & ND energy spectra*
  - ⇨ Use both CC and NC channels
  - ⇨ Many systematics cancel in the ratio
- However:
  - ⇨ Ratio uncertainty dominated by FD statistics
  - ⇨ Effect of high-mass sterile neutrino cancels

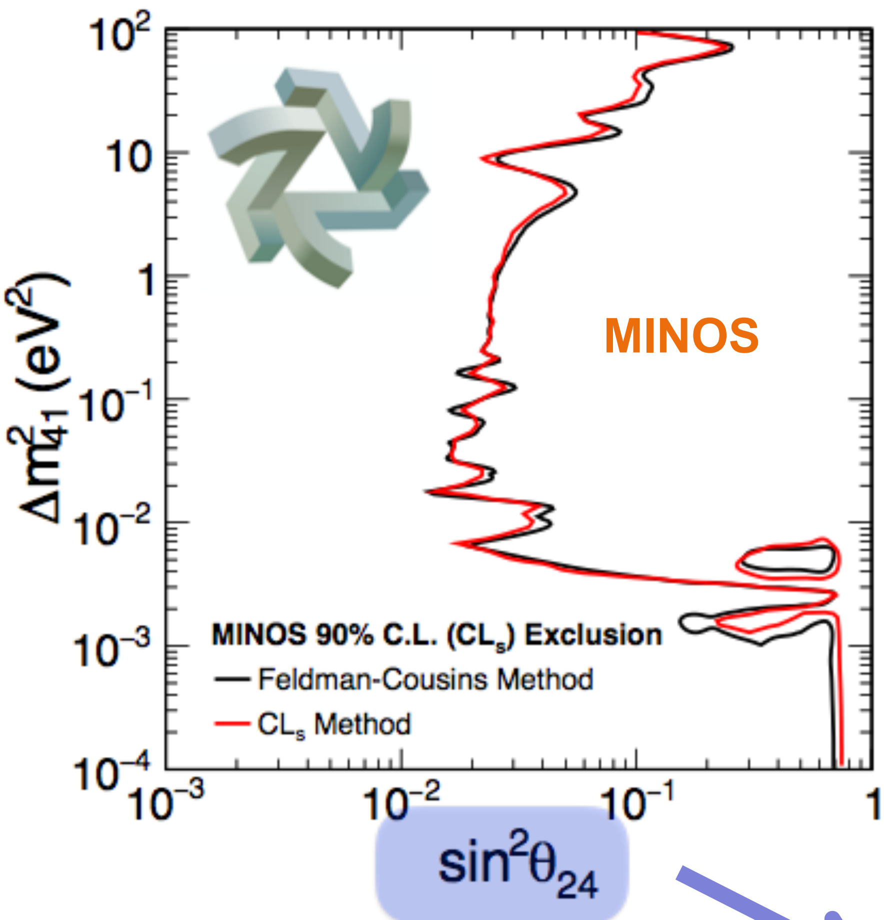


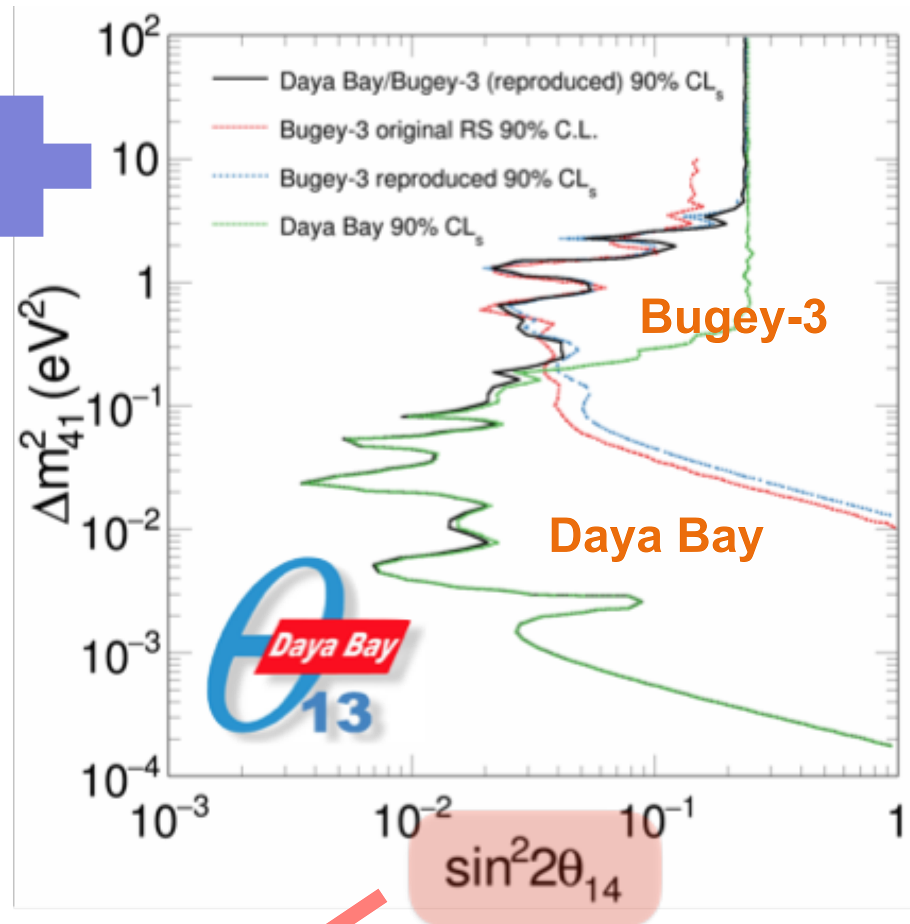
*P. Adamson *et al.*, Phys. Rev. Lett. 117, 151803 (2016)

MINOS (ν_μ disappearance) + Daya Bay (ν_e disappearance)

The 2016 results

Combined : Phys. Rev. Lett. 117, 151801
MINOS : Phys. Rev. Lett. 117, 151803
Daya Bay : Phys. Rev. Lett. 117, 151802

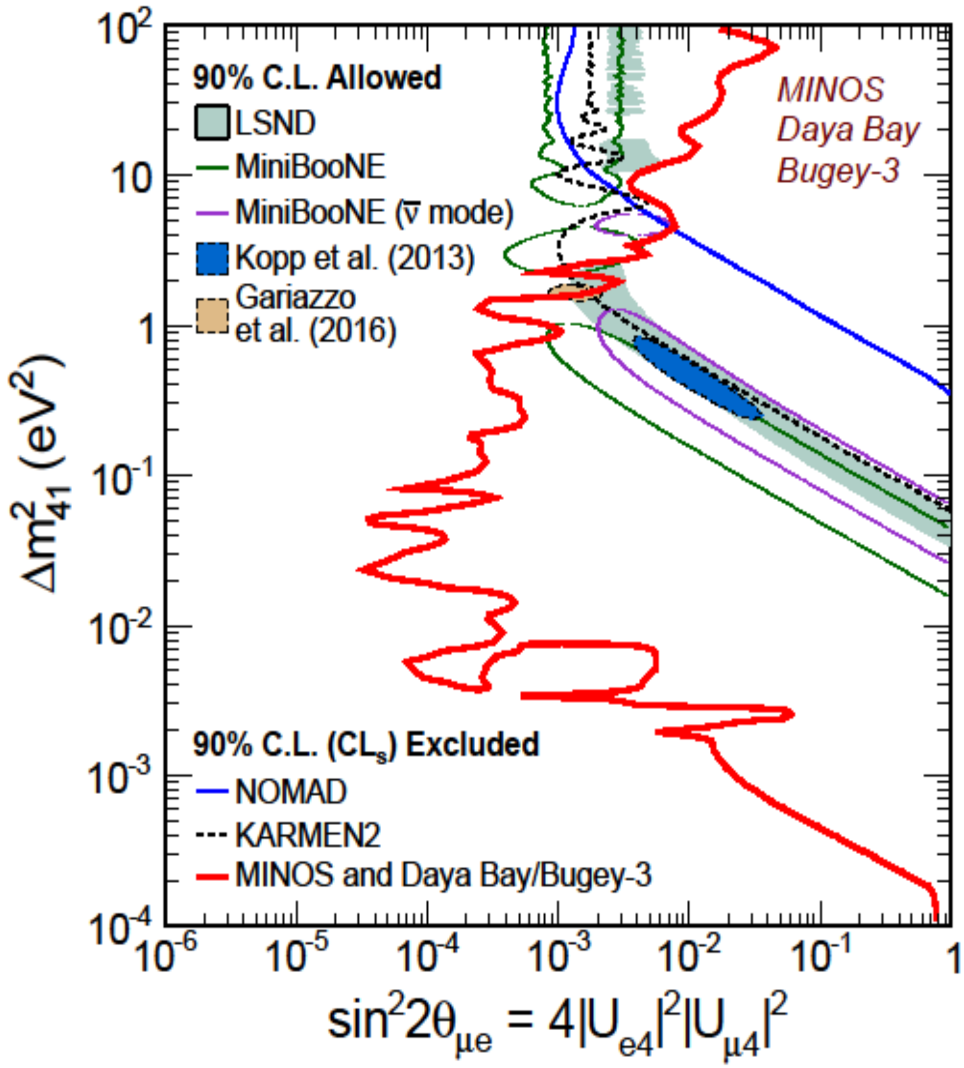




$$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$

MINOS & Daya Bay/Bugey-3

The 2016 results



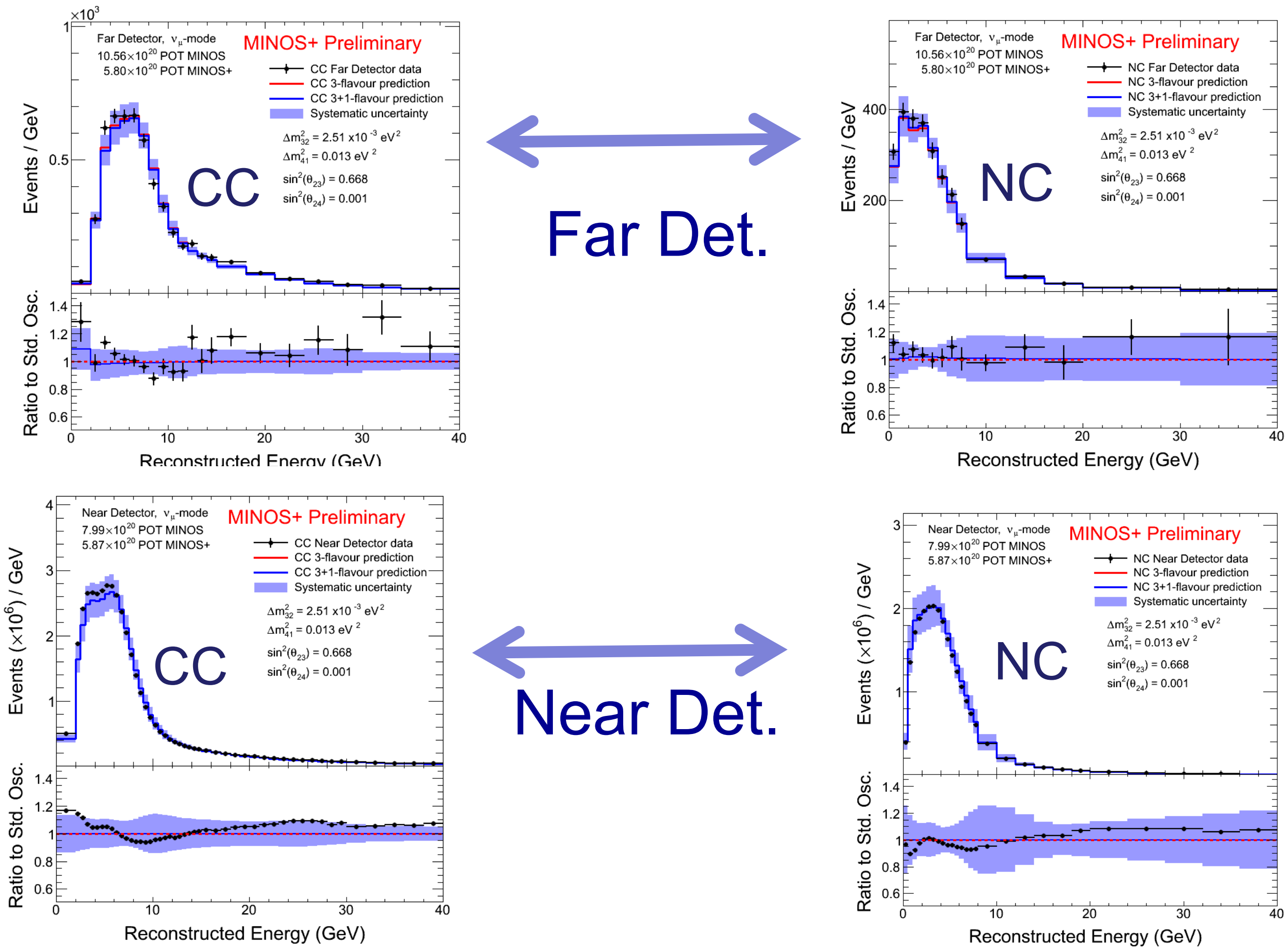
Combined : Phys. Rev. Lett. 117, 151801
MINOS : Phys. Rev. Lett. 117, 151803
Daya Bay : Phys. Rev. Lett. 117, 151802

- The 2016 combination of MINOS data with Daya Bay/ Bugey-3
- 90% C.L. limit excludes appearance allowed regions for

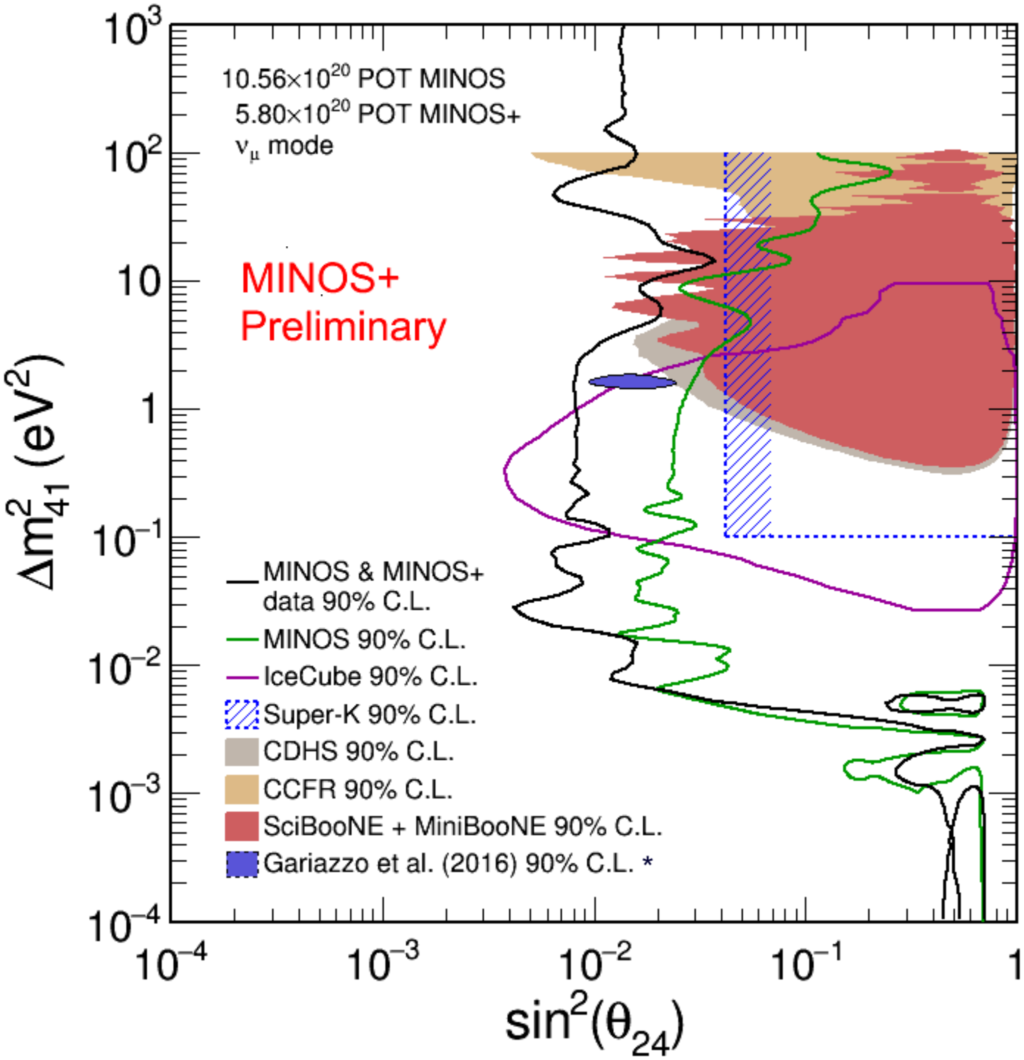
***S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J.Phys. G43 033001 (2016)**

Sterile Search - new method – two-detector fit

- The 2017 MINOS sterile analys1s uses Far and Near Detectors energy spectra directly rather than their ratios
- Systematics through the covariance matrix



The **2017** results



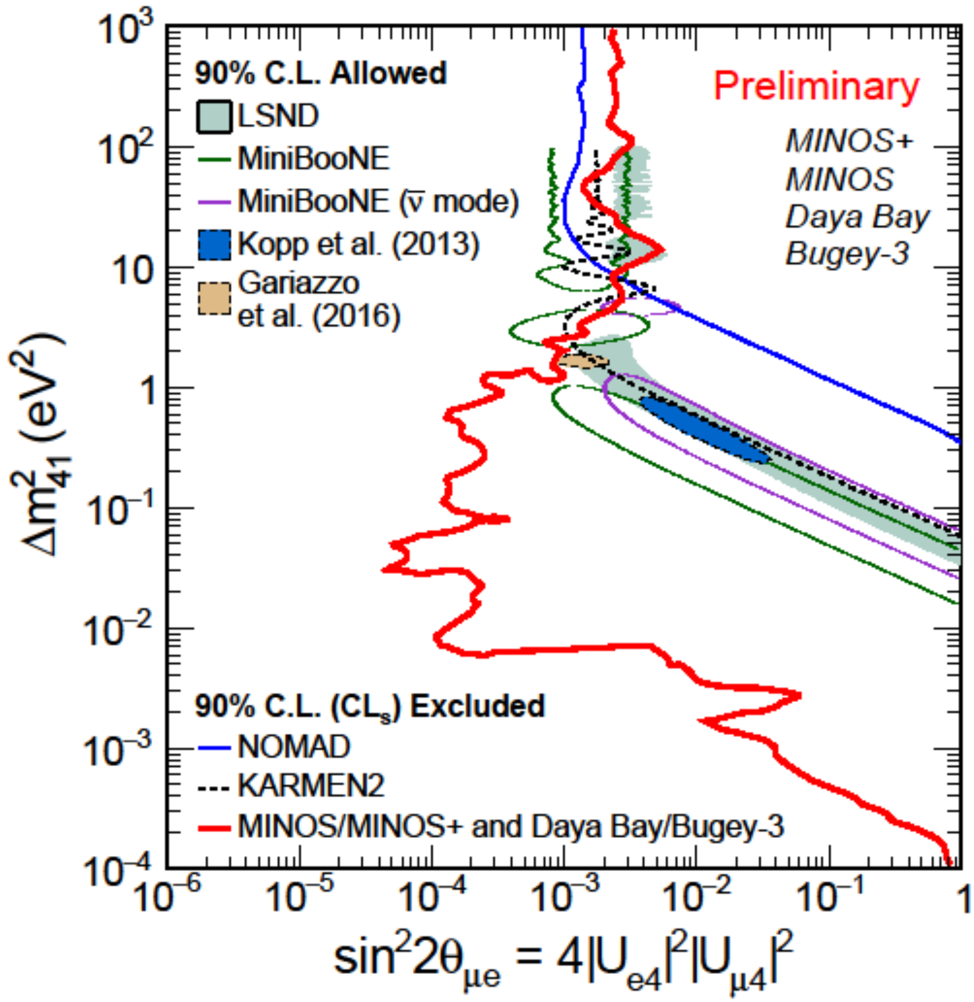
- New limit improves constraint of the previous MINOS analysis
- Constraint improved by Near Detector contribution for $\Delta m^2_{41} \sim 5$ eV^2
- Increased tension with global best fit

*S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J.Phys. G**43** 033001 (2016)

New Combined Result with Daya Bay

- ***Preliminary:*** ongoing effort between MINOS+/MINOS and Daya Bay and Bugey-3 data.
- Significant increase in the constraint at Δm^2_{41} > 10 eV^2 due to two-detector fit method.
- A new combination with a larger Daya Bay data later.

The **2017** results



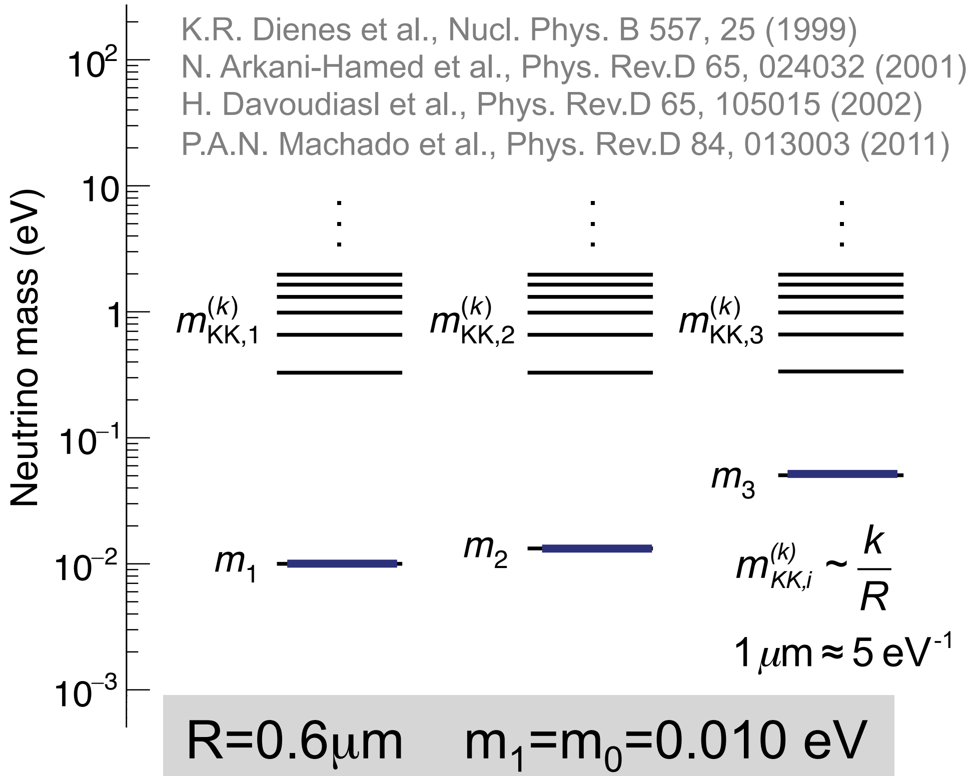
^J. Kopp, P. Machado, M. Maltoni, T. Schwetz, JHEP 1305:050 (2013)

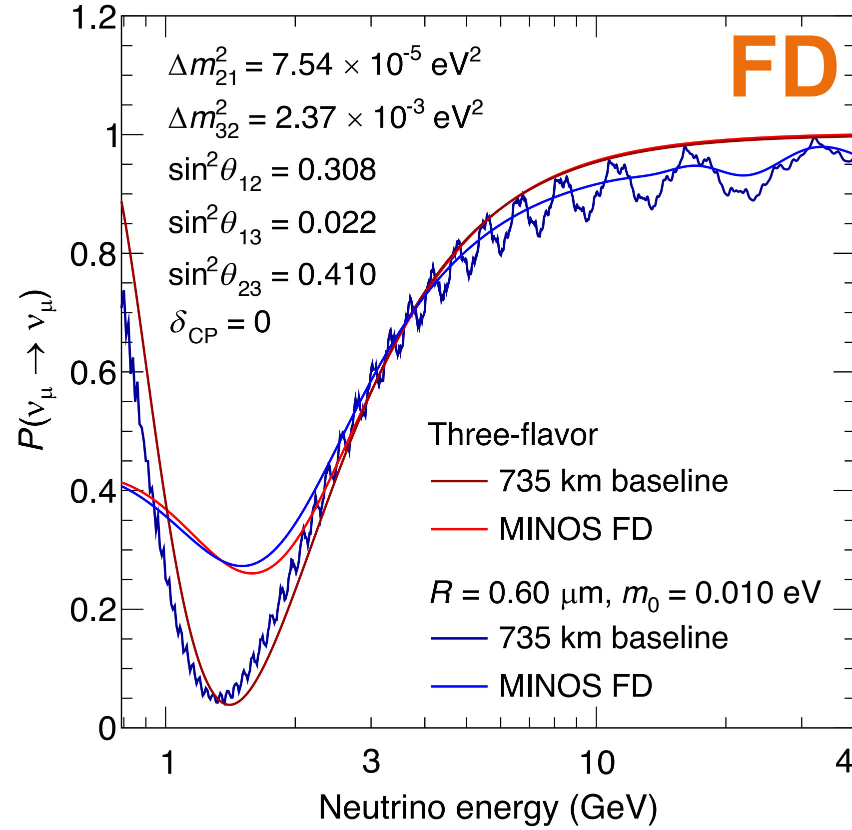
*S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J.Phys. G43 033001 (2016)

MINOS & MINOS+

LARGE EXTRA DIMENSIONS (LED)

LED ν_μ Disappearance Probability





- Introduce extra spatial dimension compactified on a circle with radius ***R***
- 3 sterile fields that live in the bulk
- Sterile fields act as **Kaluza-Klein towers** of infinite sterile neutrinos

$$P(\nu_\mu \to \nu_\mu) = \left| \sum_{j=1}^{3} \sum_{n=0}^{+\infty} U_{\mu j} U^*_{\mu j} \left(W_j^{(0n)} \right)^2 \exp\left[i \left(\frac{\lambda_j^{(n)}}{R} \right)^2 \left(\frac{L}{2E} \right) \right] \right|^2$$

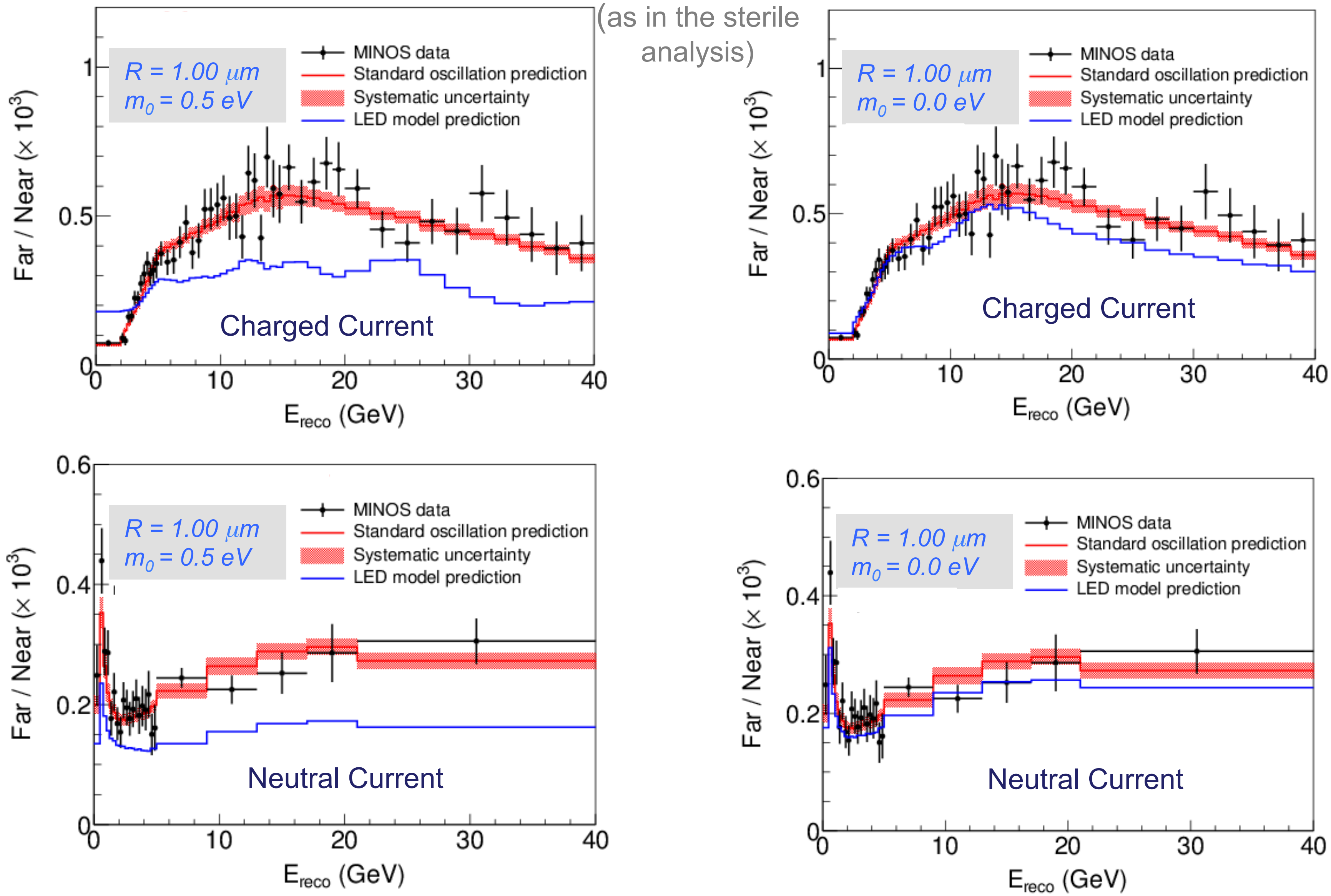
Mixing in towers

Neutrino masses

Large Extra Dimension: effect of ***R*** and ***m_0***

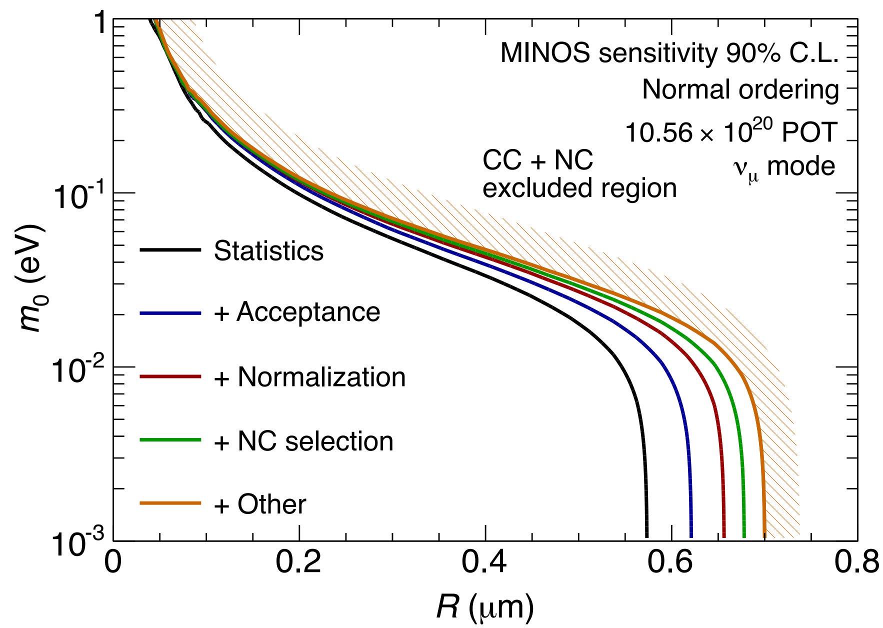
Ratios of energy spectra

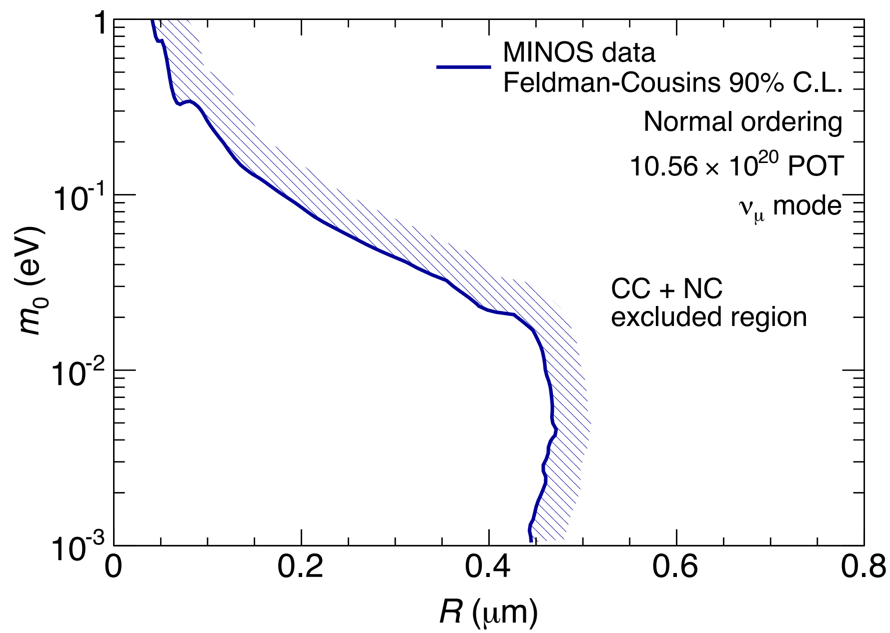
(as in the sterile analysis)



MINOS bounds

$$\chi^2 = \sum_{i,j=1}^{N} (o_i - p_i)[V^{-1}]_{ij}(o_j - p_j) + \left(\frac{N_{\text{data}} - N_{\text{MC}}}{\sigma_N}\right)^2$$





P. Adamson et al. [MINOS Collaboration], Phys.Rev. D94 (2016) no.11, 111101

Future:

- MINOS+ and MINOS data
- Two-detector method

MINOS & MINOS+

NON-STANDARD INTERACTIONS (NSI)

MINOS Non-Standard NSI bounds

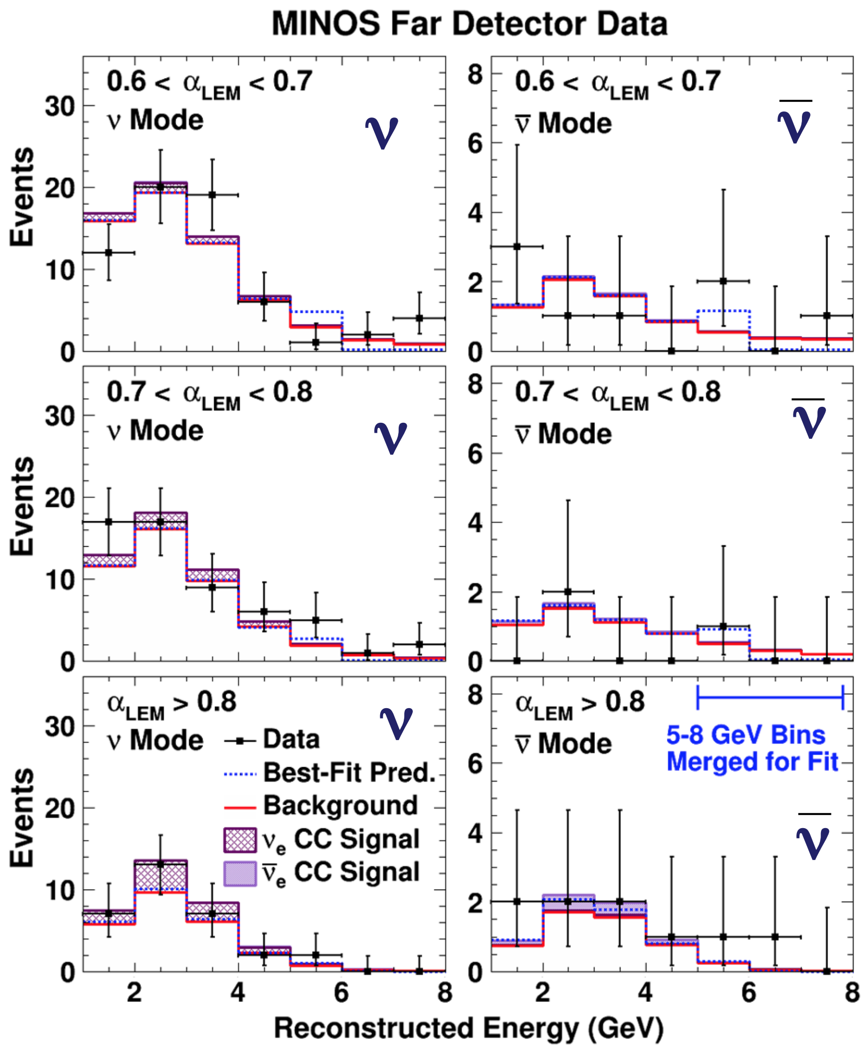
- MINOS also searches for non-standard matter effects
  - The Mikheyev-Smirnov-Wolfenstein (MSW) matter effect is an important consideration for electron neutrino appearance analyses
  - Hamiltonian modified with analogous potentials to address NC NSI scattering processes that could affect oscillation

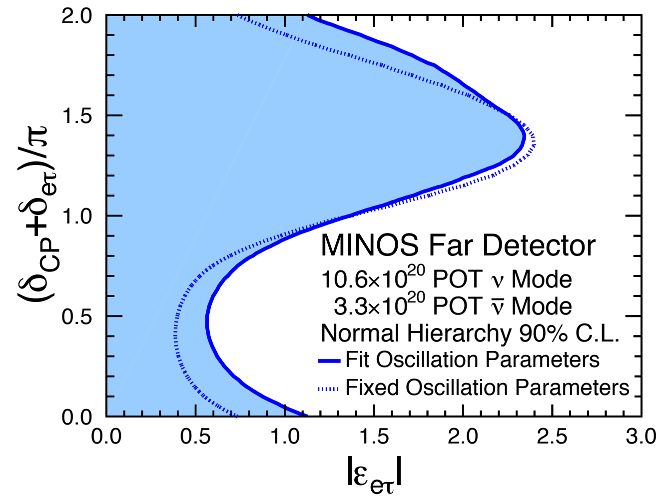
$$H_{matter} = \sqrt{2} G_F N_e \begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon^*_{e\mu} & \varepsilon^*_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon^*_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

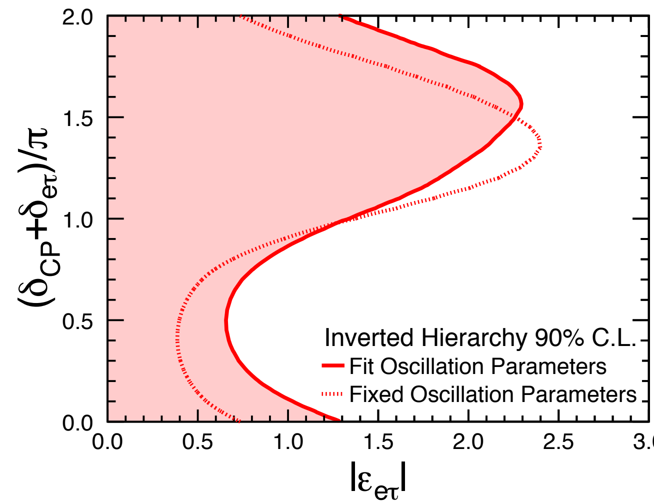
  - In particular, the MINOS appearance analysis is sensitive to $\varepsilon_{e\tau}$ and its associated complex phase

- Utilize many of the same tools as the standard appearance analysis
  - Modify the oscillation and extrapolation software to handle NSI parameters

NSI bounds using ν_e appearance







PHYSICAL REVIEW D **95**, 012005 (2017)

Search for flavor-changing nonstandard neutrino interactions using ν_e appearance in MINOS

MINOS & MINOS+

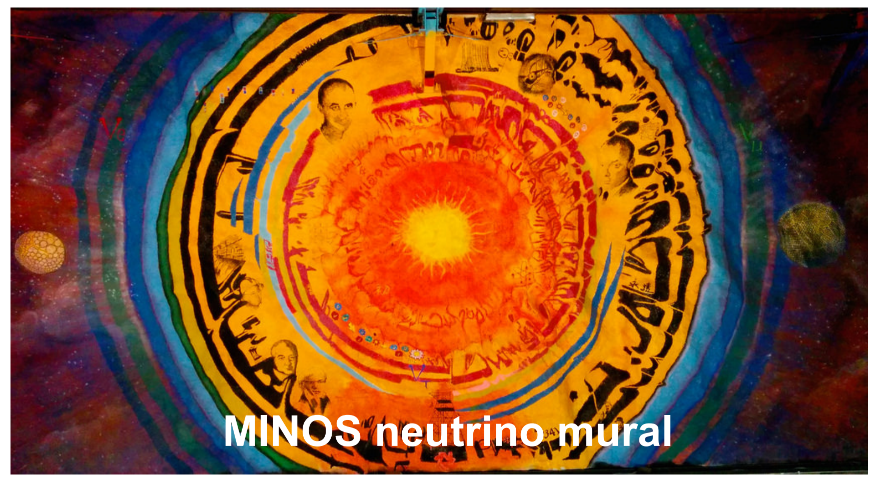
THE END GAME

MINOS & MINOS+

- 11 years of operations, 25 POT exposure, up to 600 kW beam
- Best to date Δm^2_{32} (68% CL), no octant preference at 90%CL for θ_{23}

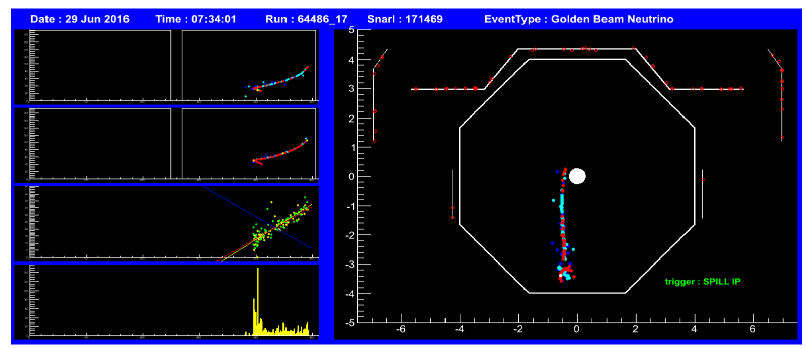
Normal	$\Delta m^2_{32} = +2.42 \pm 0.09 \quad (\times 10^{-3} eV^2)$	$\sin^2 \theta^2_{23} = 0.41 \quad (0.37 \leftrightarrow 0.46)$
Inverted	$\Delta m^2_{32} = -2.48 \pm 0.09 \quad (\times 10^{-3} eV^2)$	$\sin^2 \theta^2_{23} = 0.41 \quad (0.37 \leftrightarrow 0.48)$

- Some of the most stringent bounds on "3+1" sterile neutrinos
  - Muon disappearance
  - Joint analysis with Daya Bay for $\nu_\mu \rightarrow \nu_e$ appearance bounds
  - Increased tension with global fits
- Bounds on LED and NSI



- MINOS+ data still being analyzed
  - (Run 13 not used)
  - Final papers on all the above still to come …

Last MINOS+ FD event: 29 Jun 2016



Argonne · Athens · Brookhaven · Caltech · Cambridge · Campinas · Cincinnati · Fermilab · Goiás · Harvard · Holy Cross · Houston · IIT · Indiana · Iowa State · Lancaster · Manchester · Minnesota-Twin Cities · Minnesota-Duluth · Otterbein · Oxford · Pittsburgh · Rutherford · São Paulo · South Carolina · Stanford · Sussex · Texas A&M · Texas-Austin · Tufts · UCL · Warsaw · William & Mary