Results from MINOS and MINOS+

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On behalf of the MINOS+ Collaboration

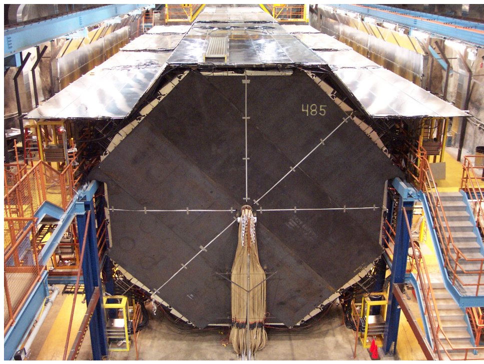
Selected Topics:
+ Beams and detectors
+ Standard oscillations
+ Sterile neutrinos
+ Large extra dimensions

MINOS & MINOS+

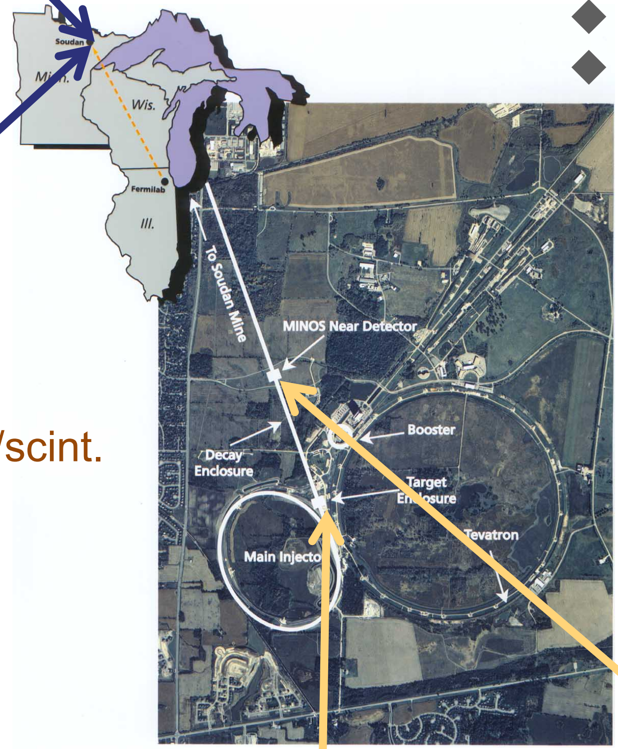
BEAMS AND DETECTORS

MINOS, MINOS+, and NuMI

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

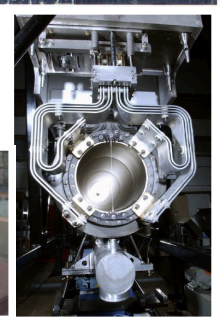


- Far Detector (FD) on axis
- 735 km from target
- 5.4 kt, 8m octagon
- ~1.2 T B field
- Segmented, sampling, iron/scint. tracking calorimeter



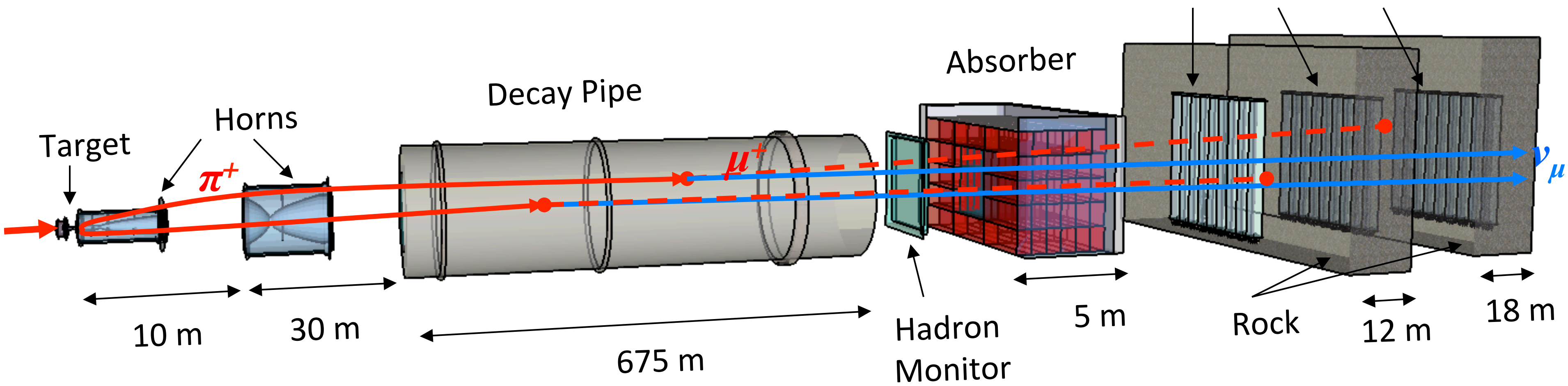
- Near Detector (ND) on axis
- 1,040 m from target
- 1kt, 4m `squeezed’ octagon
- ~1.2 T B field
- Same technology as FD

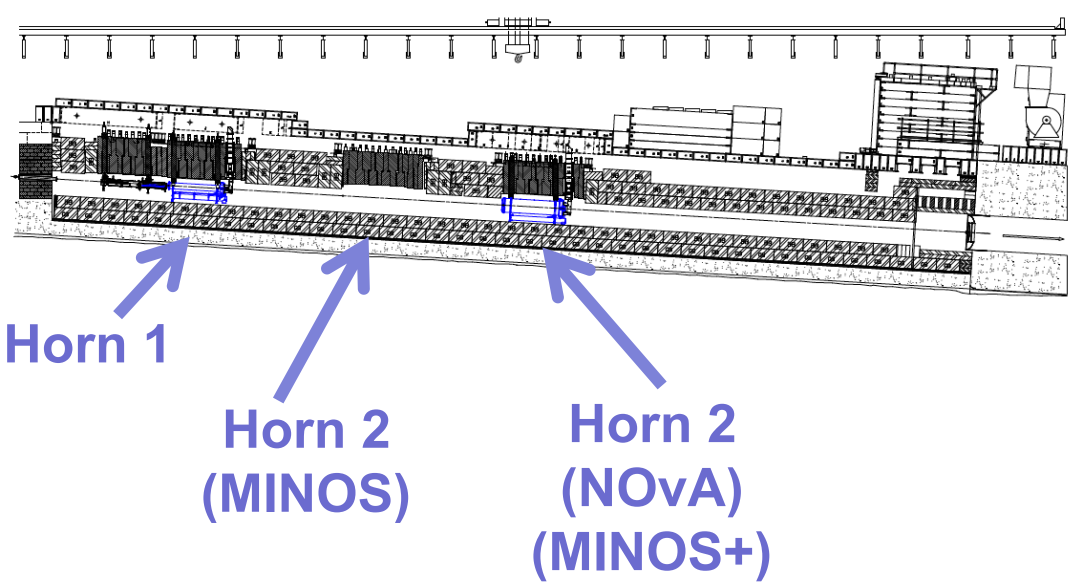
- 2-horn focusing 185 kA
- 2λ graphite target (movable)
- Up to ~600 kW beam
- 3.5×10^{13} ppp
- 1.33 s cycle time

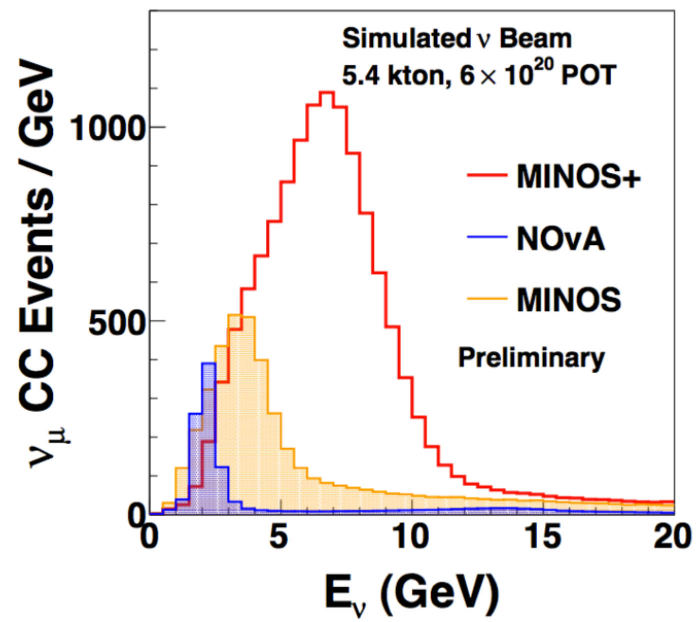


NuMI Neutrino Beams

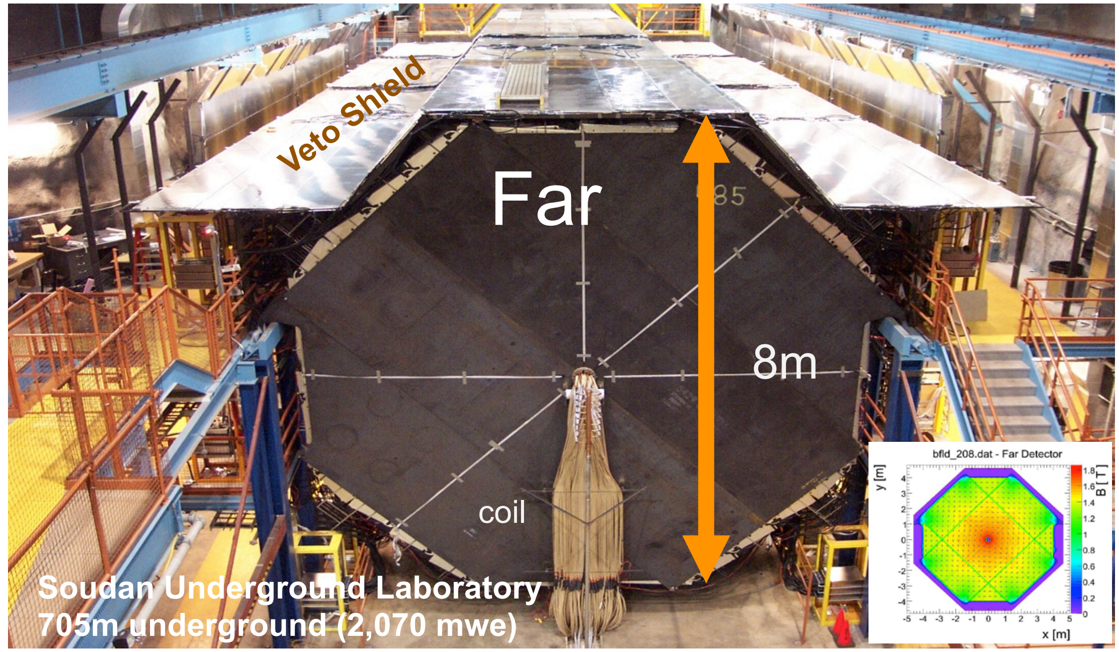
(Neutrinos from the Main Injector)

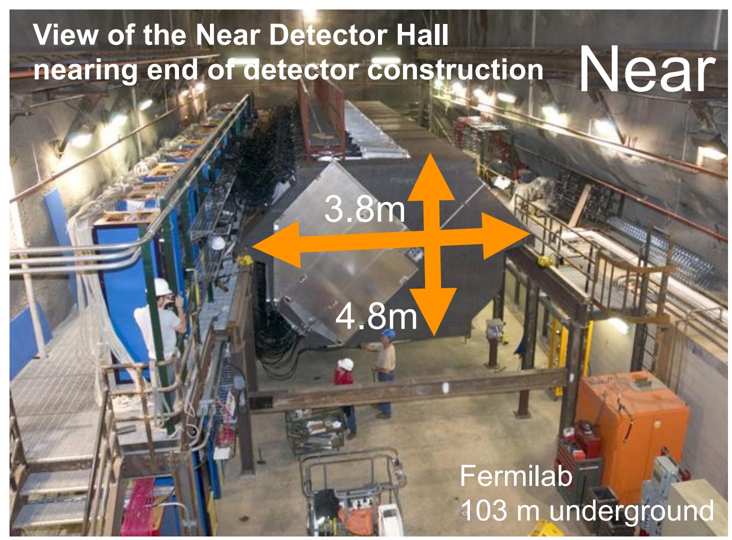




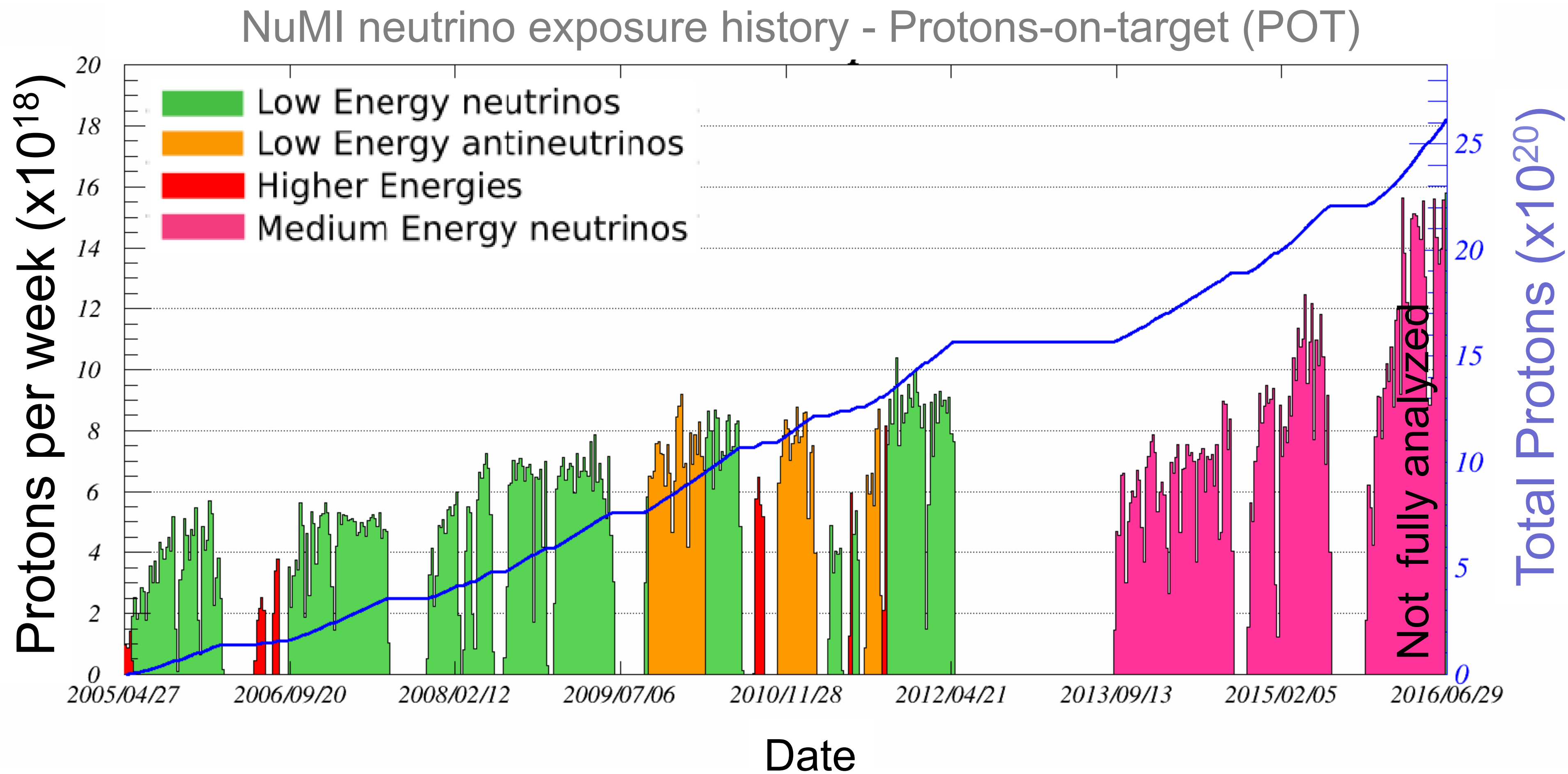


MINOS: Near and Far Detectors





MINOS and MINOS+ exposures
2005 → 2016



MINOS (2005-2012)

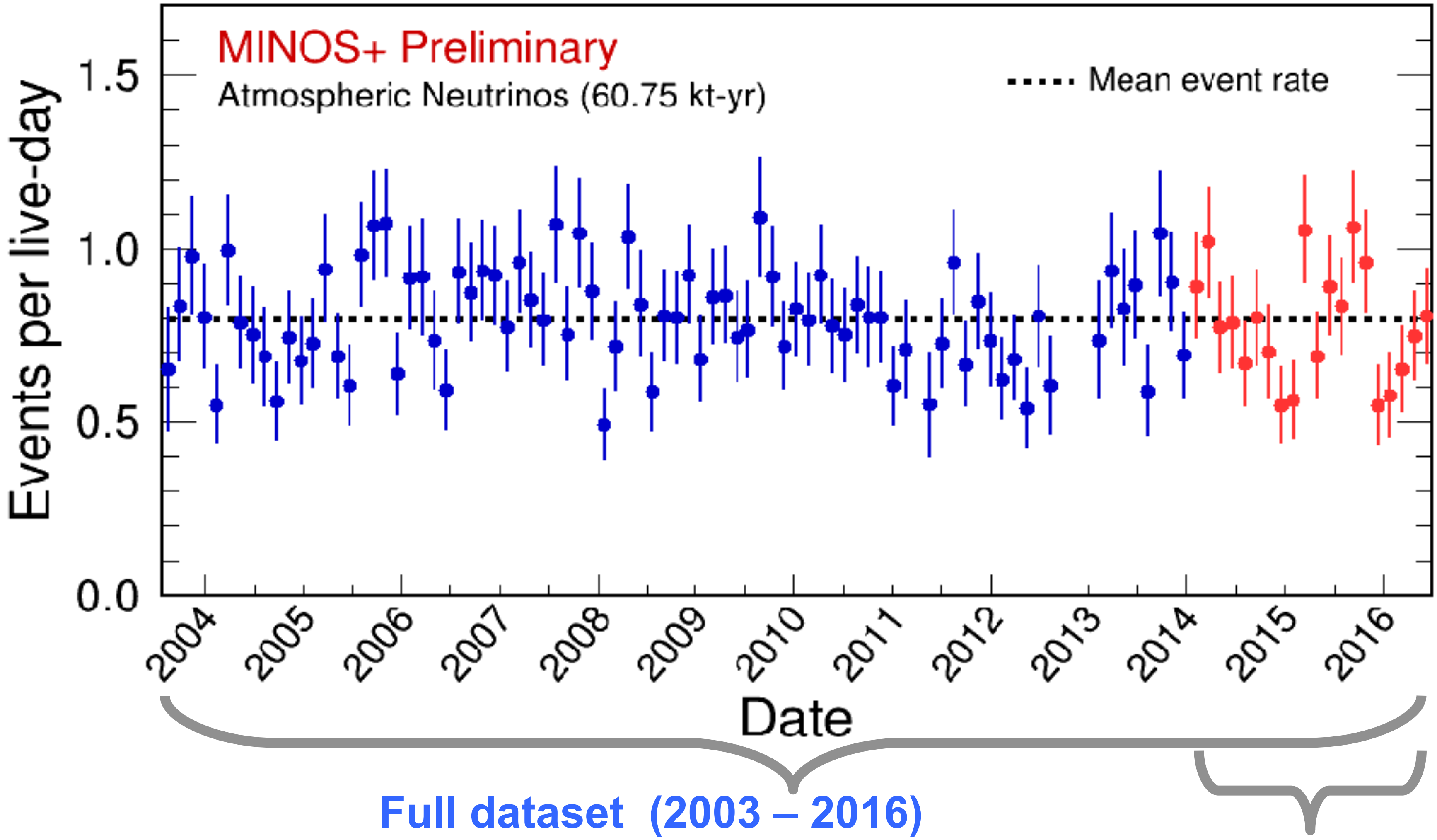
10.56×10^{20} POT

3.36×10^{20} POT

MINOS+ (2013-2016)

9.69×10^{20} POT

MINOS & MINOS+ atmospheric neutrinos



Full dataset (2003 – 2016)
60.8 kt-yr

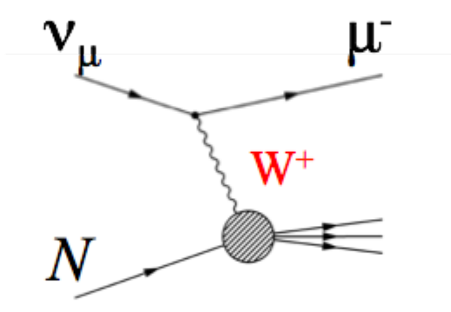
New: **12.1 kt-yr**
(~20% of total sample)

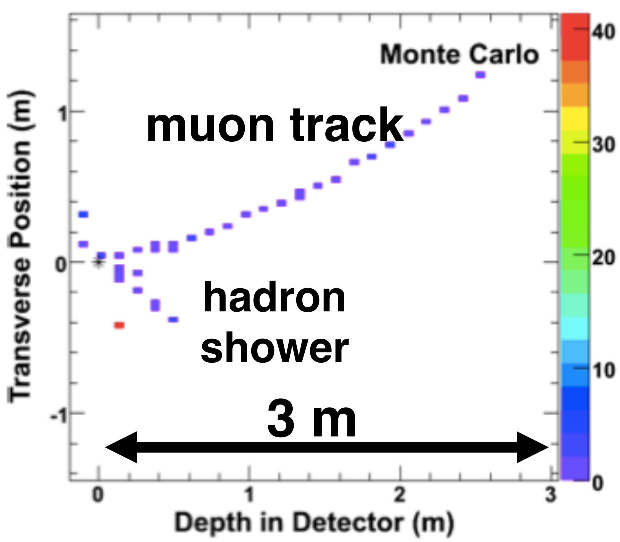
MINOS & MINOS+

STANDARD OSCILLATIONS

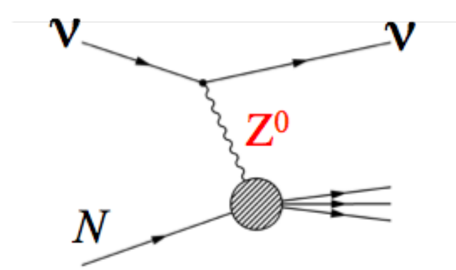
Event types in MINOS

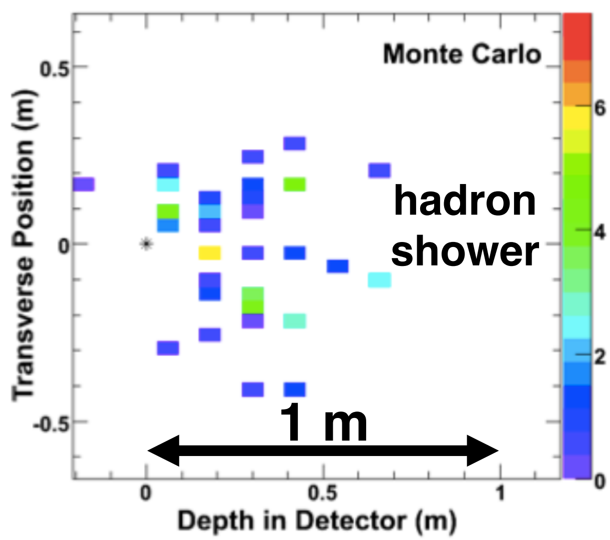
ν_μ Charged Current (ν_μ CC)



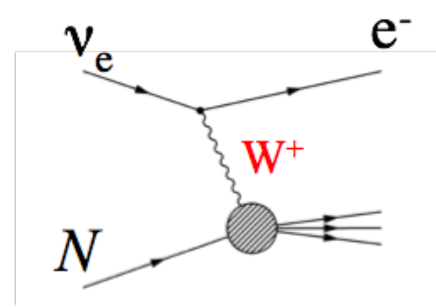


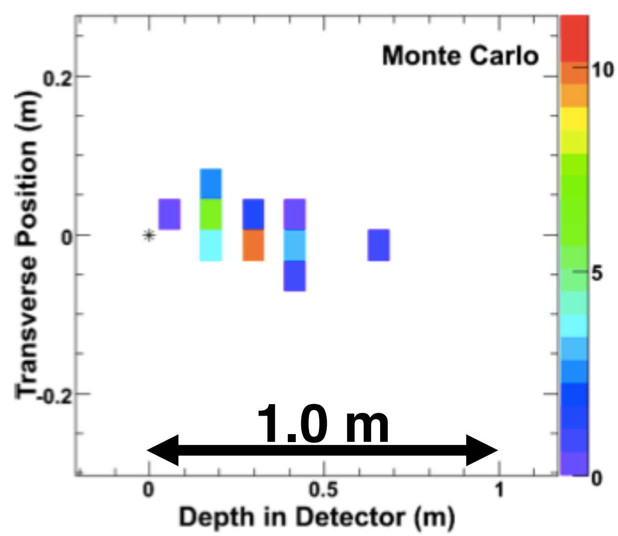
ν_x Neutral Current (NC)





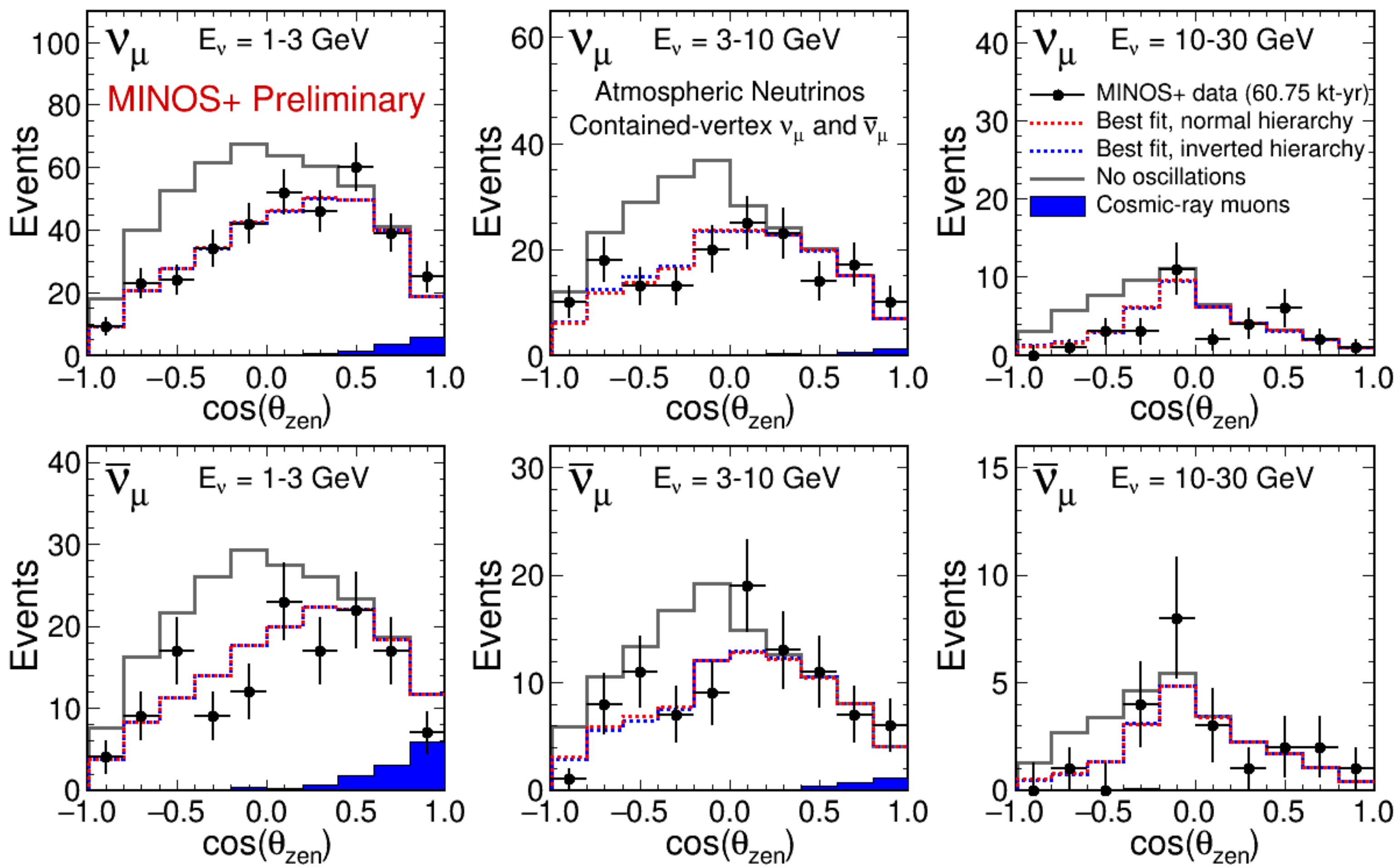
ν_e Charged Current (ν_e CC)



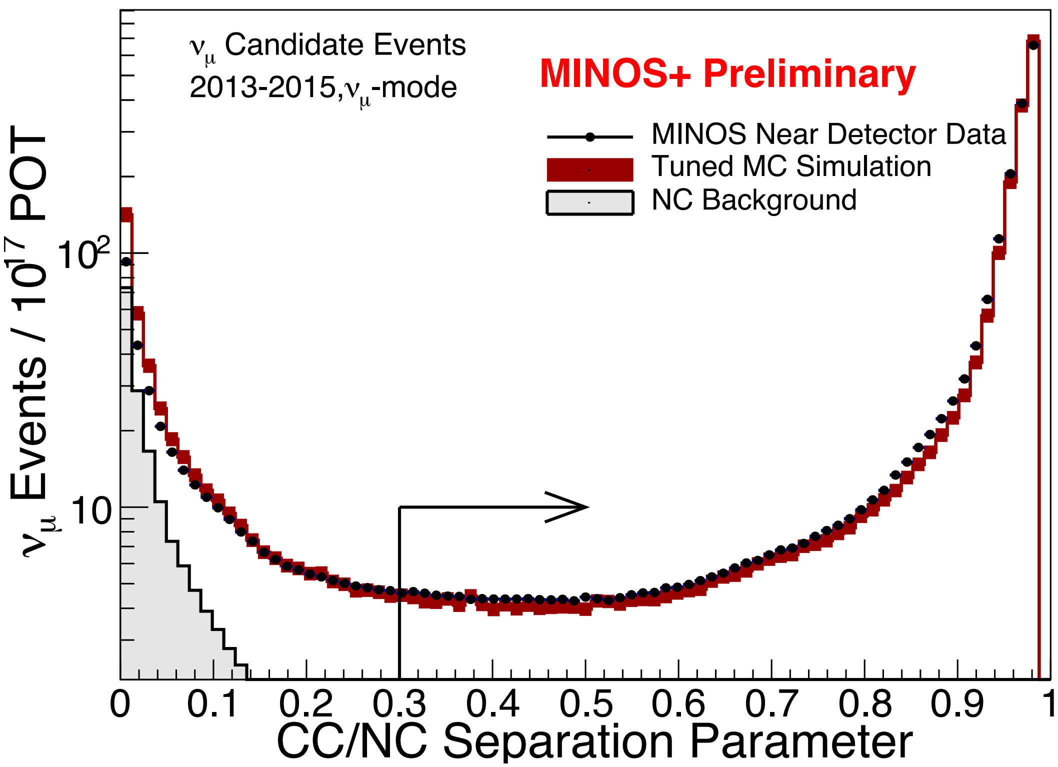


Atmospheric neutrinos and antineutrinos

- Fit in bins of cos(θ_{zen}) and energy
- Separate neutrino and antineutrino (mass hierarchy discrimination)
- Complements beam neutrino samples



Event classification:
k Nearest-Neighbors (kNN)

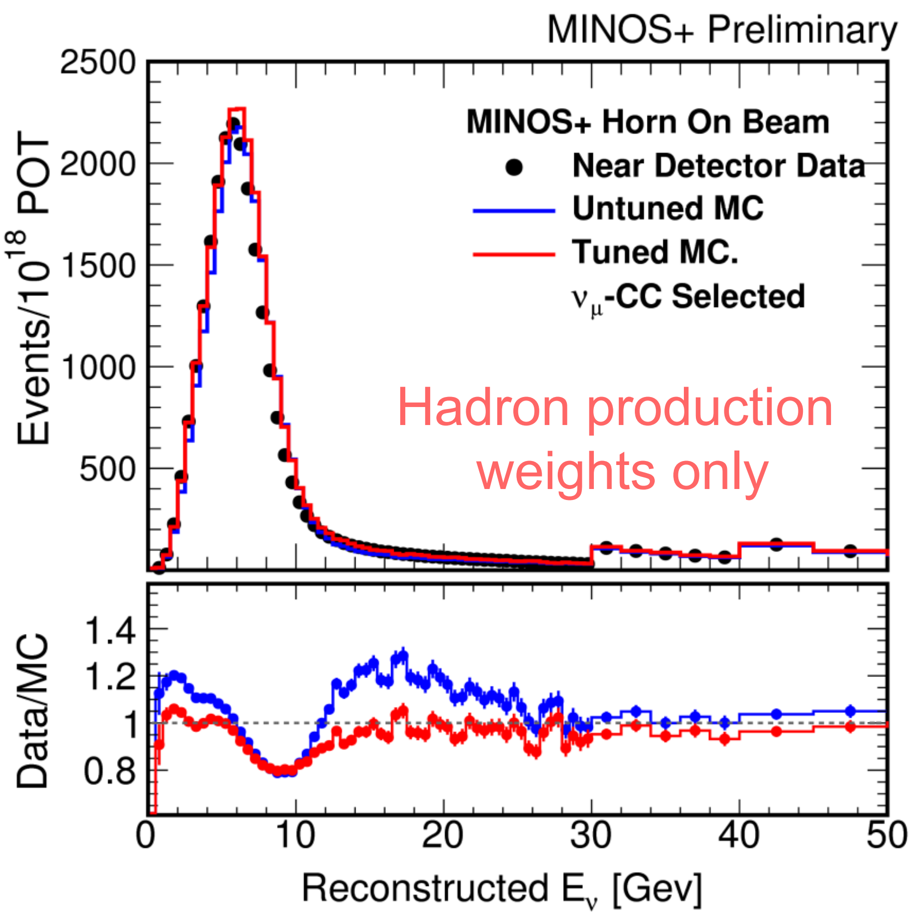


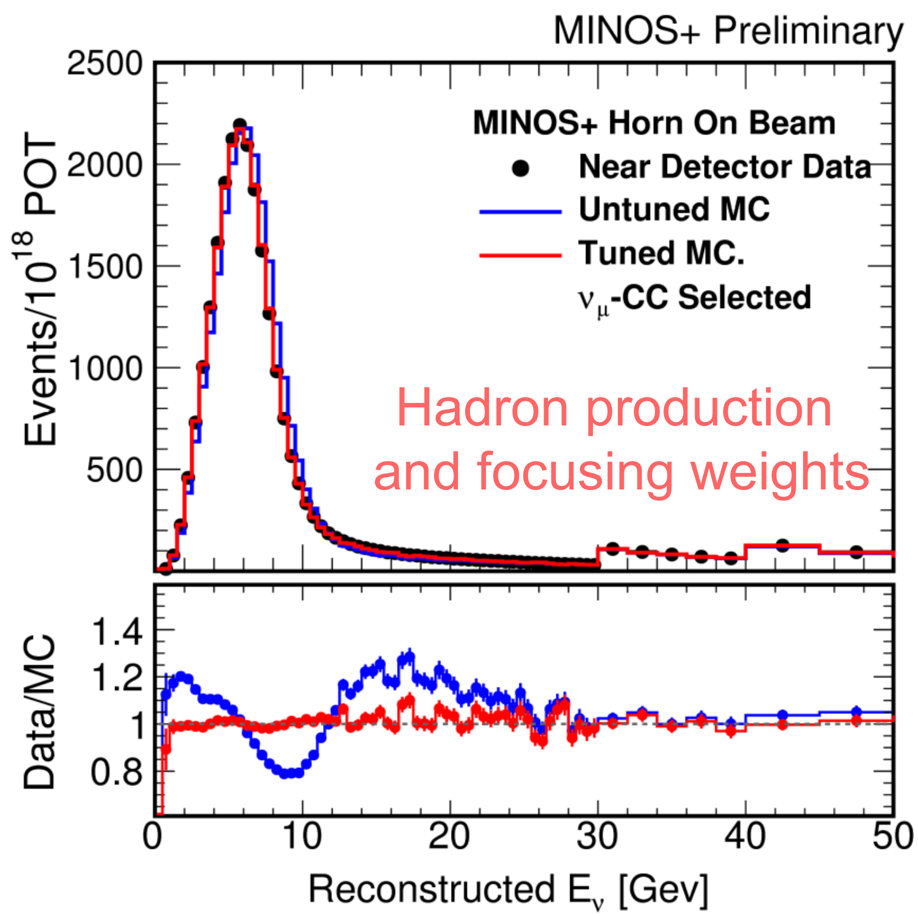
MINOS+ Far Detector ν_μ-CC

efficiency	85.9%
purity	99.3%

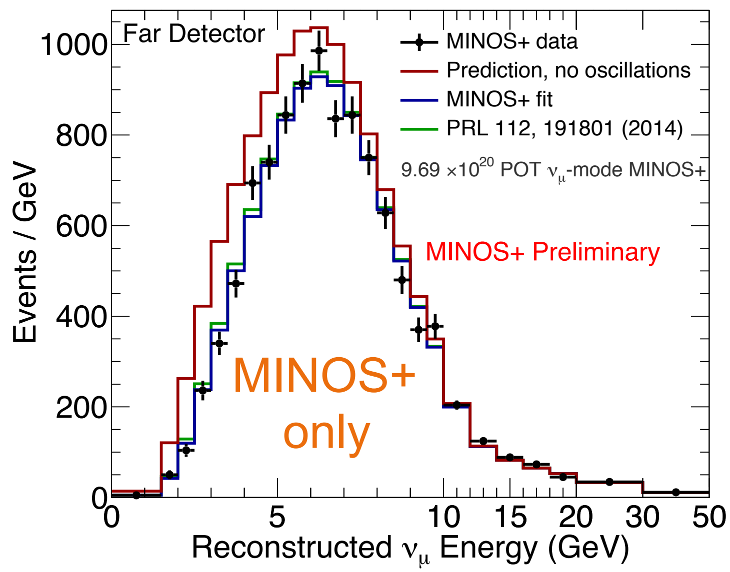
Improved beam flux calculations

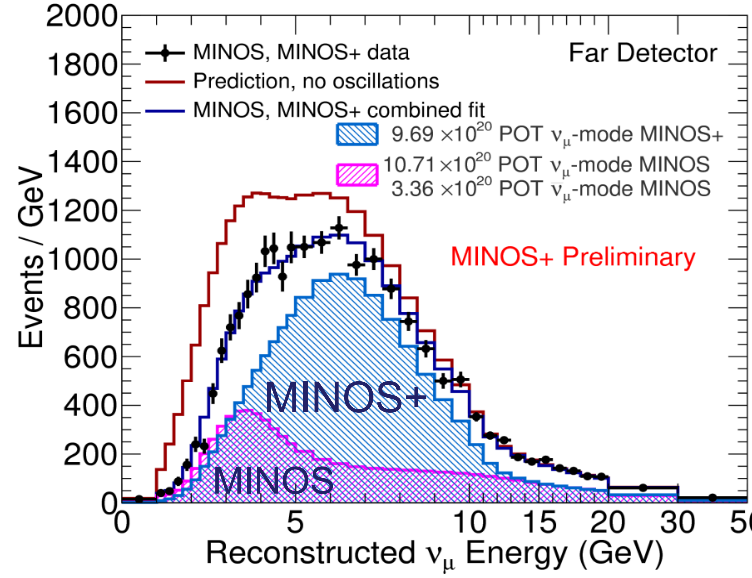
- Fit hadron production from HORNS OFF (i.e., no focusing B-field)
- Fit for focusing effects in HORNS ON (i.e., with focusing B field)

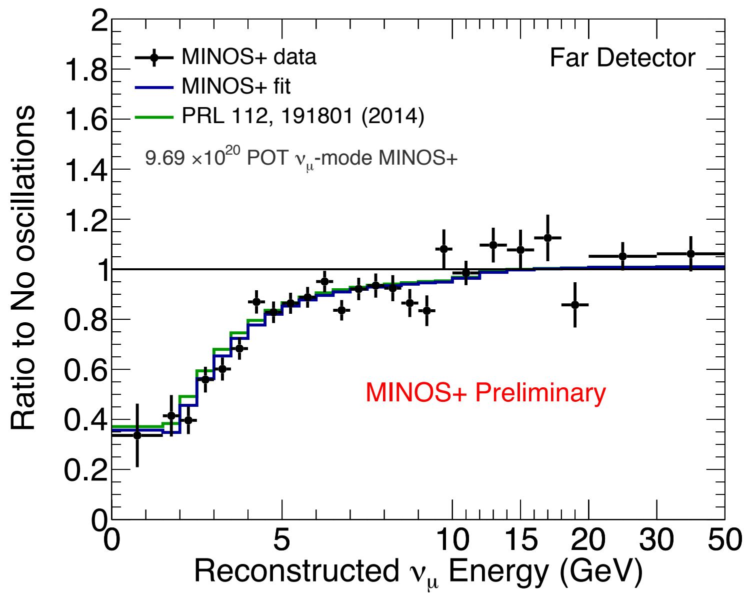


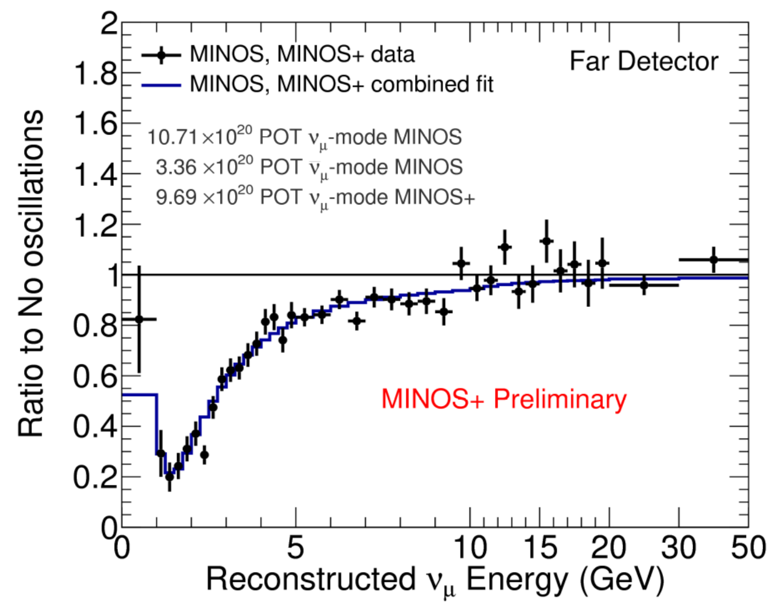


Combined fit MINOS & MINOS+ (beam + atmospheric)

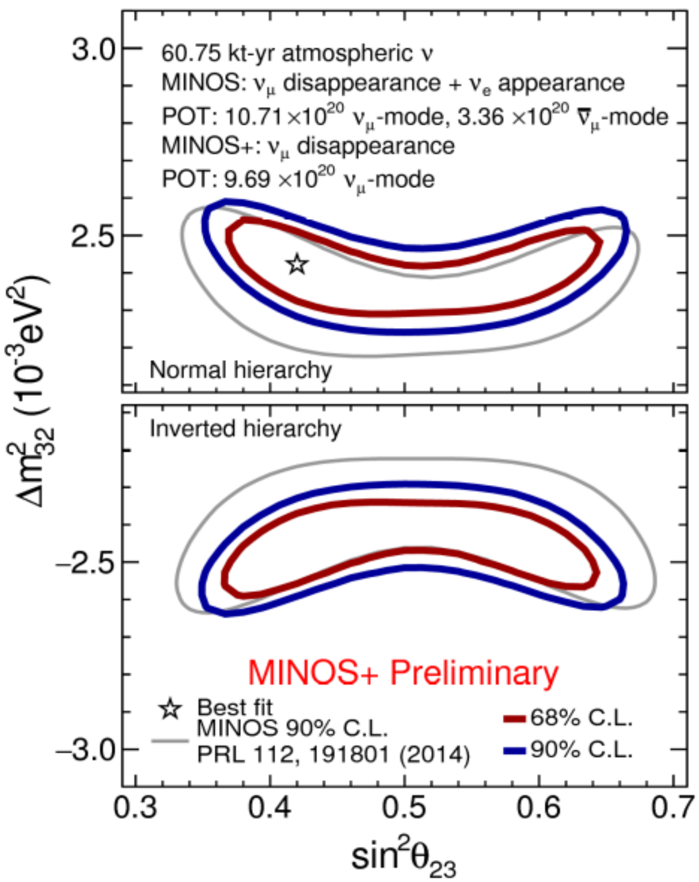


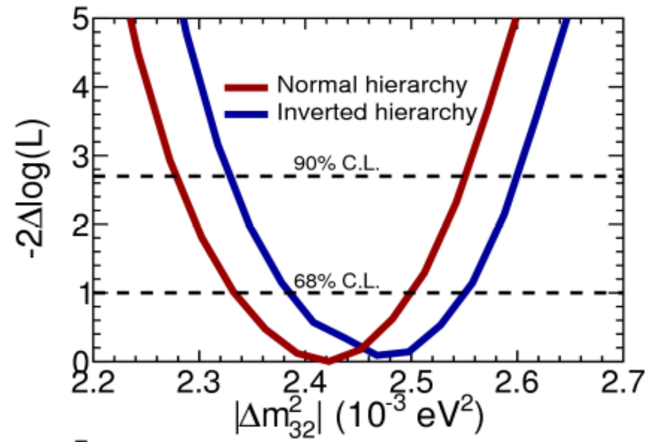


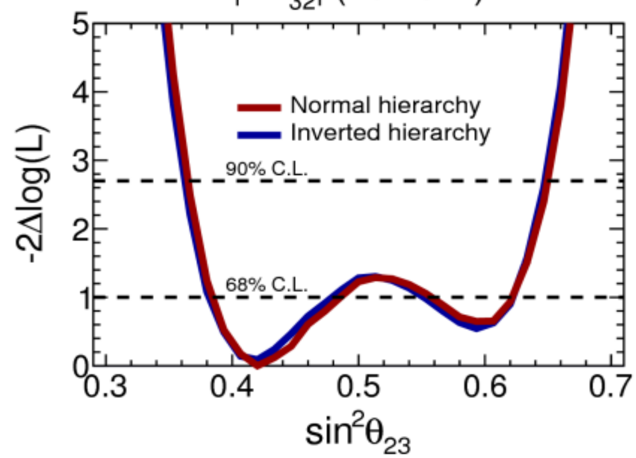




χ^2 contours and projections







Best fit: $\Delta m^2_{32} = +\,2.42 \quad (\times 10^{-3}\,eV^2)$

$\sin^2\theta^2_{23} = 0.42$

90% CL

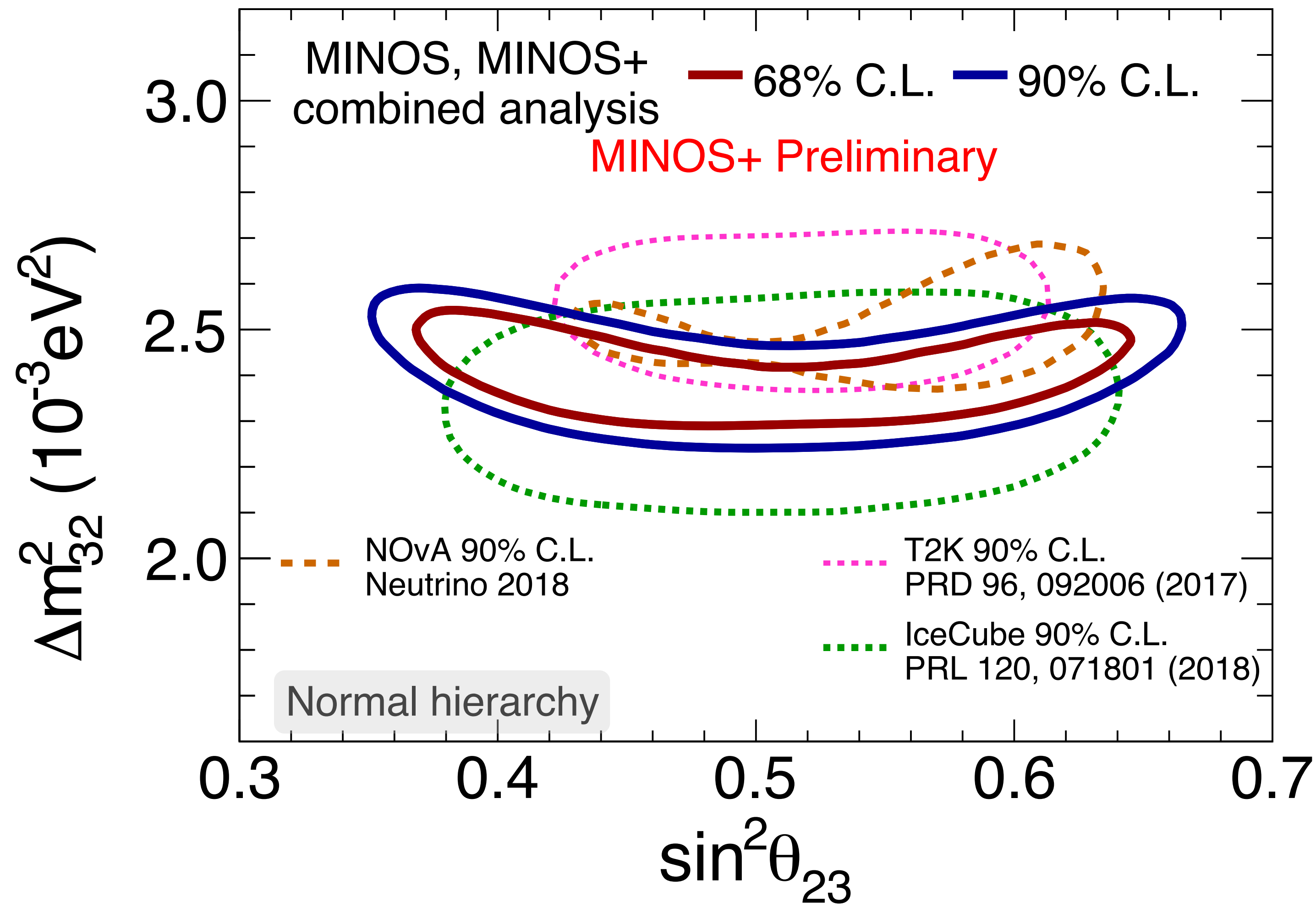
Normal $\Delta m^2_{32} = +\,(2.28 \leftrightarrow 2.55) \quad (\times 10^{-3}\,eV^2)$

$\sin^2\theta^2_{23} = (0.37 \leftrightarrow 0.65)$

Inverted $\Delta m^2_{32} = -\,(2.33 \leftrightarrow 2.60) \quad (\times 10^{-3}\,eV^2)$

$\sin^2\theta^2_{23} = (0.36 \leftrightarrow 0.65)$

Comparison of latest results

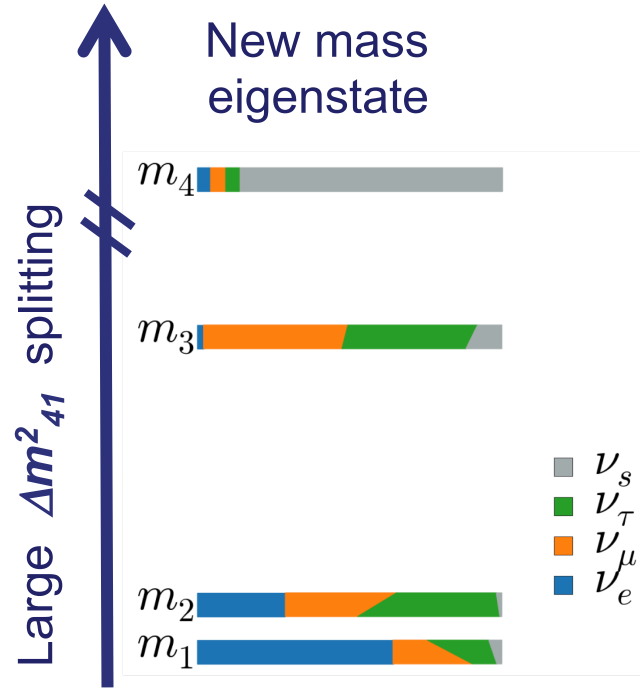


MINOS & MINOS+

SEARCH FOR STERILE NEUTRINOS

The “3+1” mixing

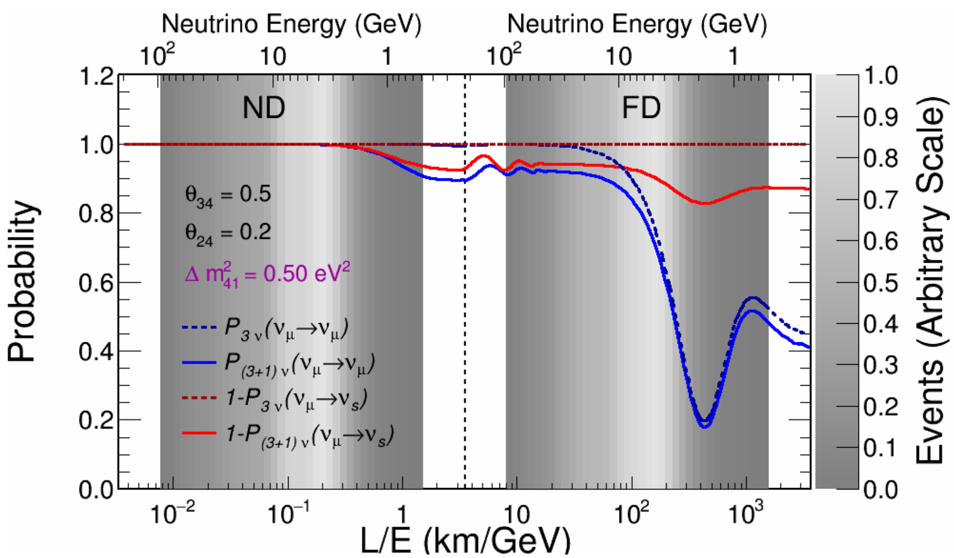
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



- (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}

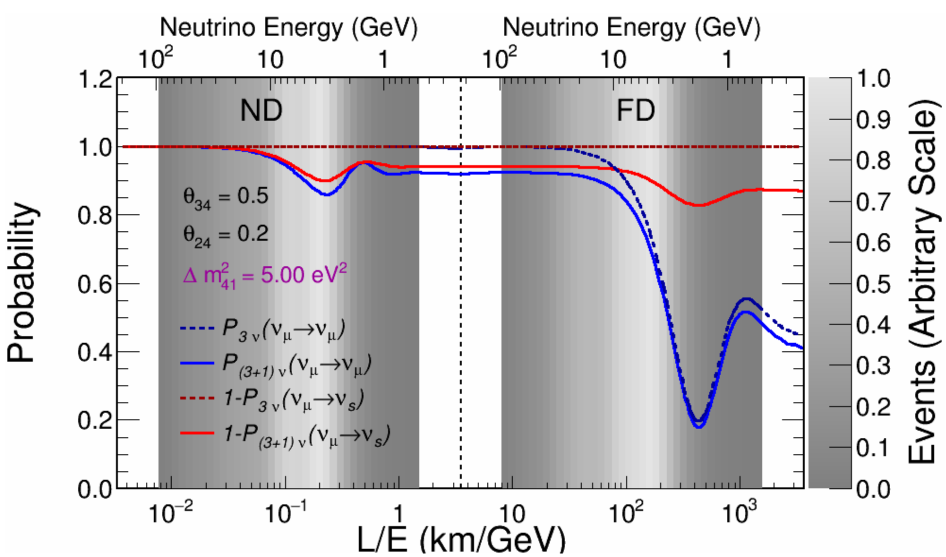
- Search for
  - ⇨ neutral current disappearance → sensitive to Δm^2_{41} *and* θ_{24}, θ_{34}
  - ⇨ ν_μ-charged current disappearance → sensitive to Δm^2_{41} *and* θ_{24}

"3+1" oscillations



Small Δm^2_{41} ~ 0.5 eV^2

- Almost no oscillations at the ND
- Oscillations at high E at the FD

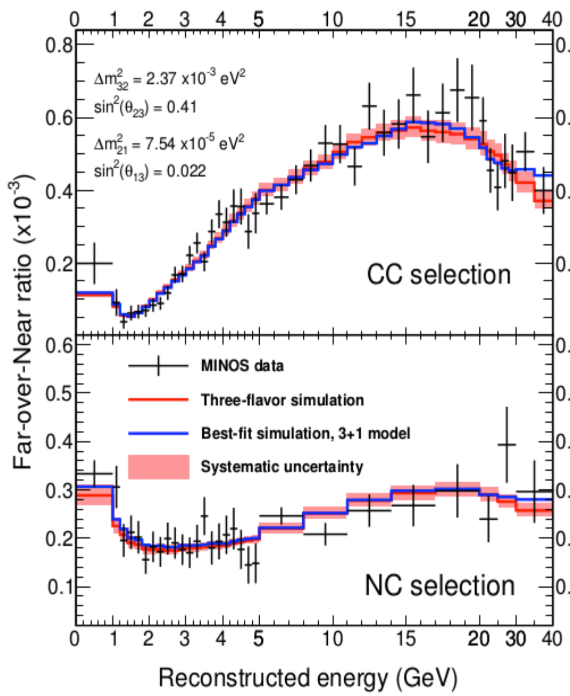


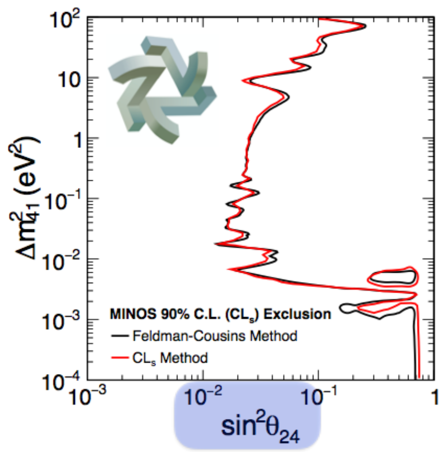
Large Δm^2_{41} ~ 5 eV^2

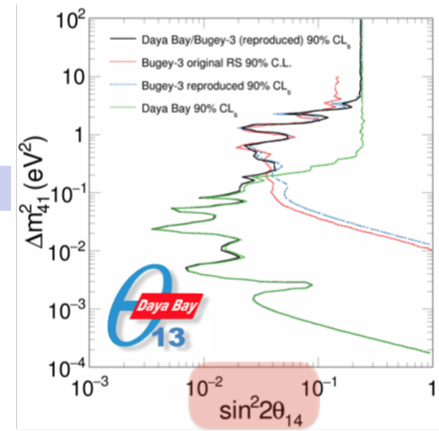
- Oscillations at the ND
- Finite energy resolution averages out rapid oscillations at the FD

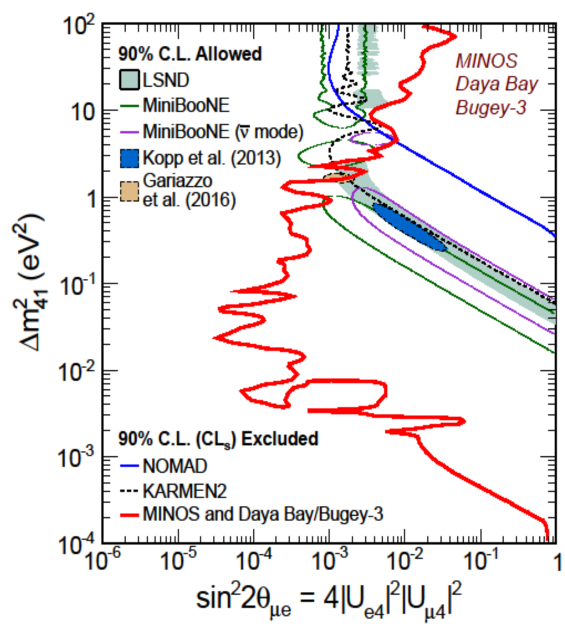
Previous results:
used Far-over-Near energy spectra ratios

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









- The 2016 sterile neutrino analysis used the ratio of FD & ND energy spectra*
  - Many systematics cancel in the ratio
  - Ratio uncertainty dominated by FD statistics
  - Effect of high-mass sterile neutrino cancels

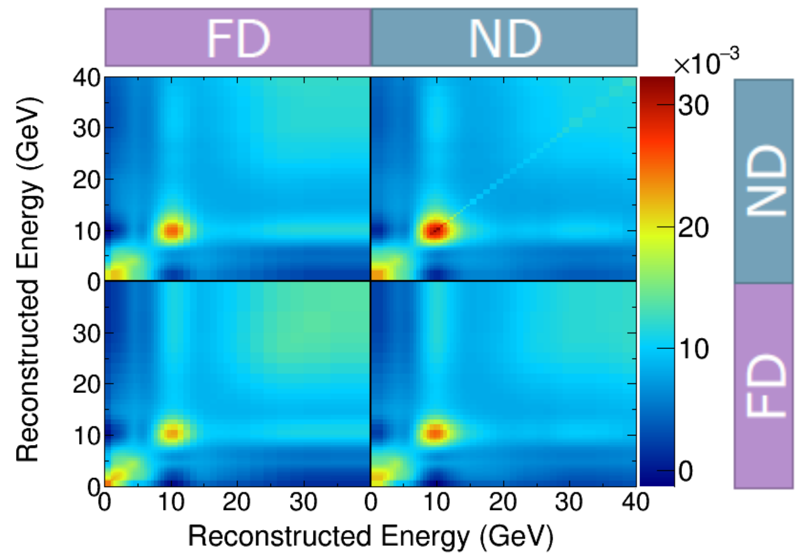
$$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$

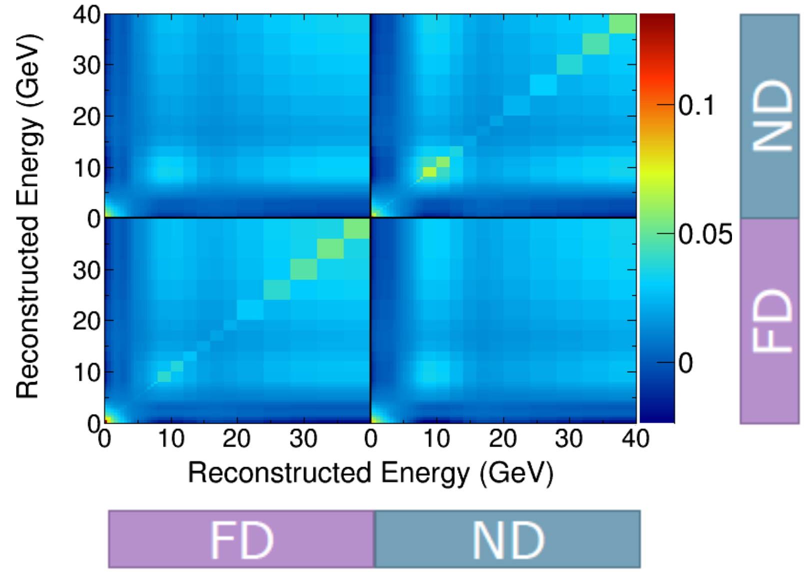
*P. Adamson *et al.*, Phys. Rev. Lett. 117, 151803 (2016)

Two-detector fit strategy

- ND and FD fits simultaneously
- Flux derived using MINERvA PPFX method (uses hadron production data)
- Systematic uncertainties encoded in the covariance matrices
  - ⇨ 26 sources of systematic uncertainties
  - ⇨ Accounts for correlations
- Use ν_μ-CC and NC spectra in a joint χ^2 fit

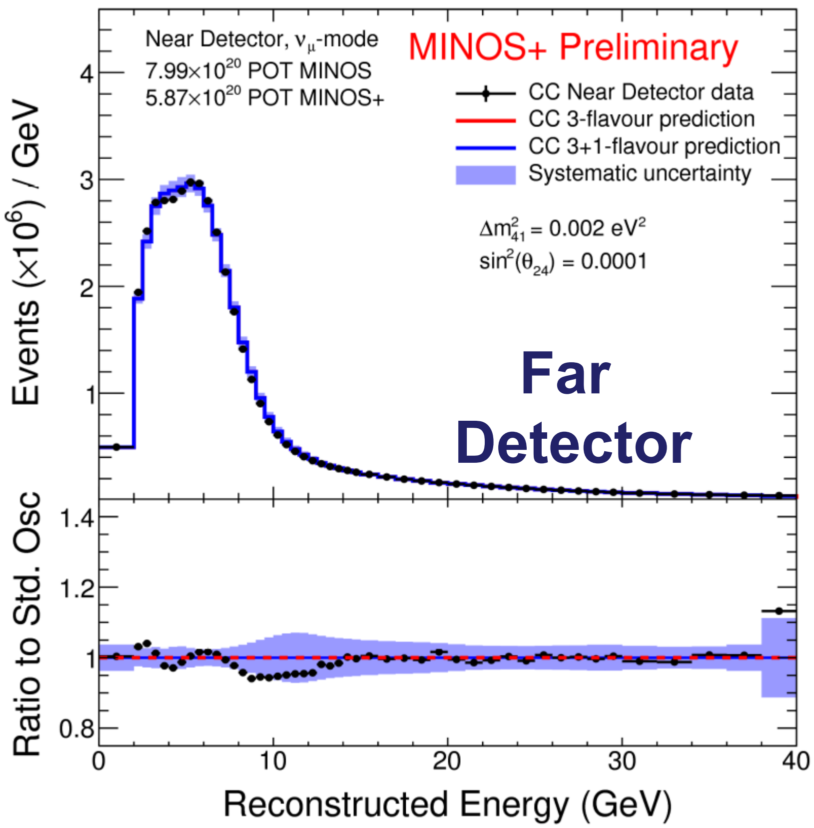
$$\chi^2 = \sum_{i,j=1}^{N} (\text{obs}_i - \text{pred}_i)[V^{-1}]_{ij}(\text{obs}_j - \text{pred}_j)$$

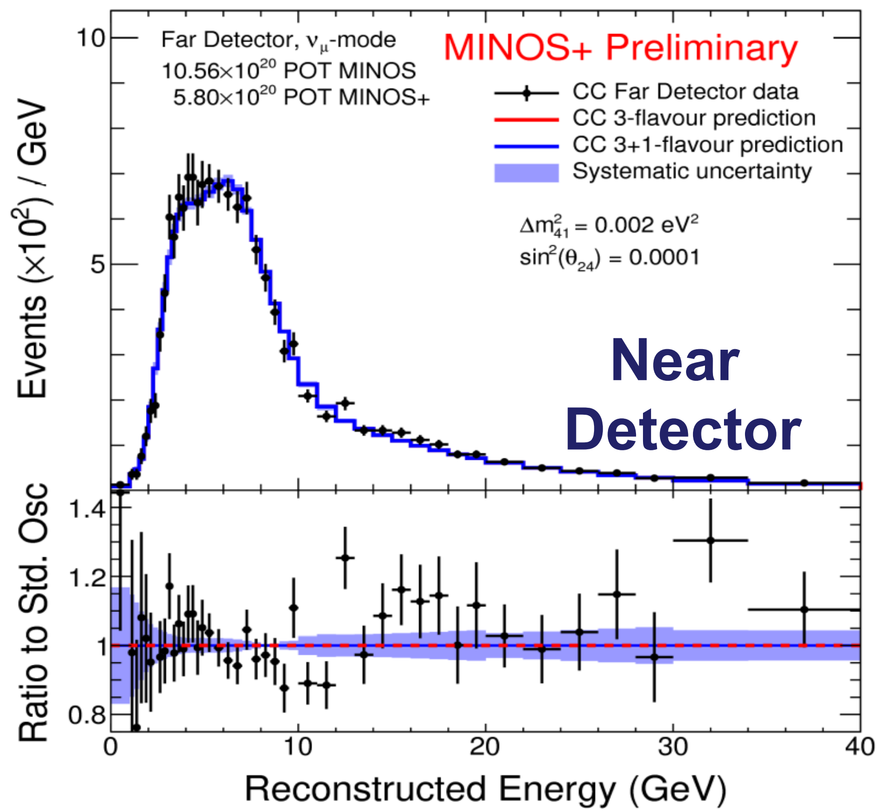




ν_μ Charged Current energy spectra

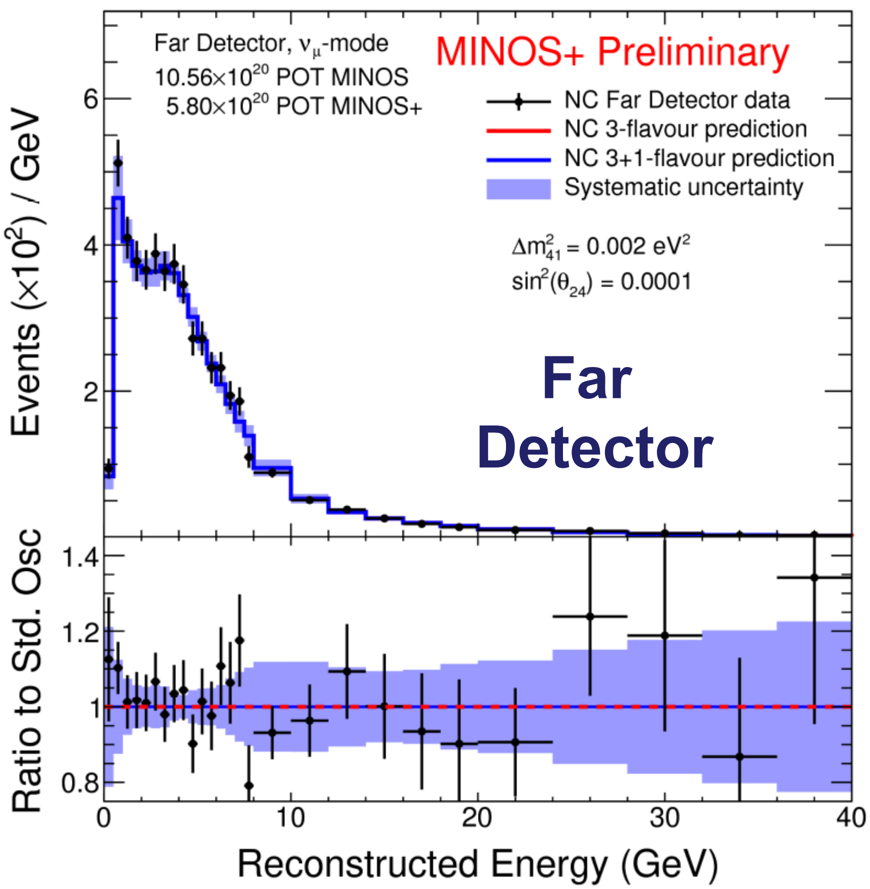
- Covariance matrix fits do not include systematics as nuisance parameters
- The error bands and prediction account for off-diagonal

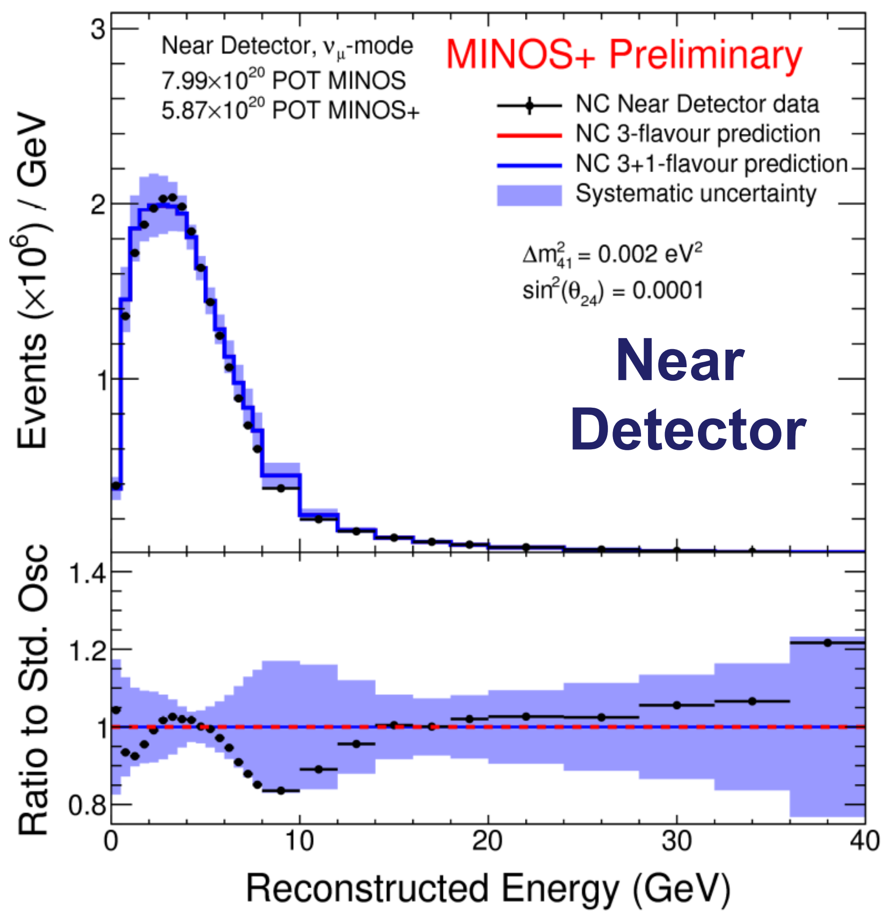




Neutral Current energy spectra

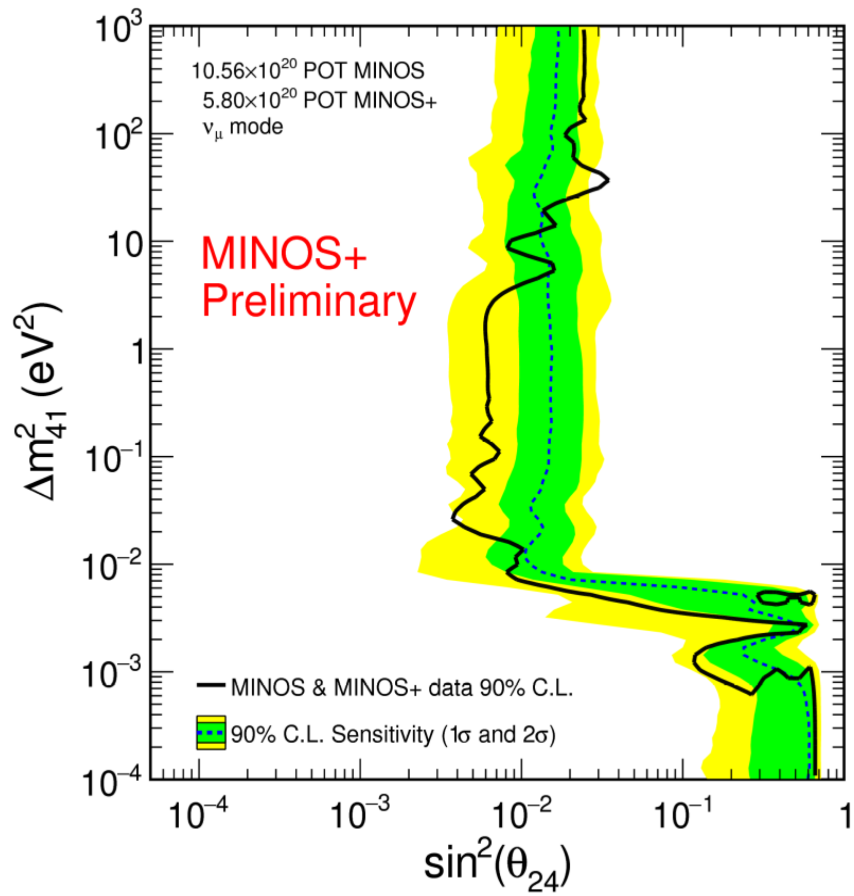
- Covariance matrix fits do not include systematics as nuisance parameters
- The error bands and prediction account for off-diagonal





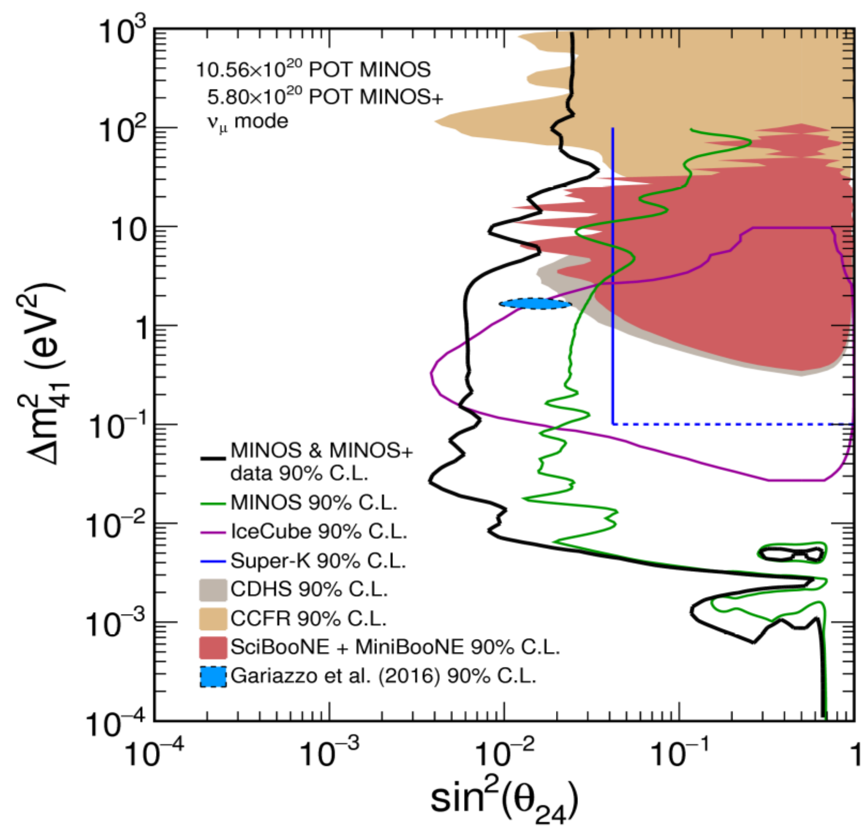
Fit and contour results

- Use full NC and CC samples in two detectors
- Fit for θ_{23}, θ_{24}, θ_{34}, Δm^2_{32}, and Δm^2_{41}
- Fix δ_{13}, δ_{14}, δ_{24}, and θ_{14} to zero
- Median sensitivity from Feldman-Cousins corrected 90% CL contours from pseudo-experiments
- Best fit:
  - $\Delta m^2_{41} = 2.33\times10^{-3}$ eV^2
  - $\sin^2\theta_{24} = 1.1\times10^{-4}$
  - $\theta_{34} < 8.4\times10^{-3}$
  - $\sin^2 2\theta_{23} = 0.92$
  - χ^2_{min}/dof = 99.3/140
  - $\chi^2(4\nu) - \chi^2(3\nu) = 0.01$

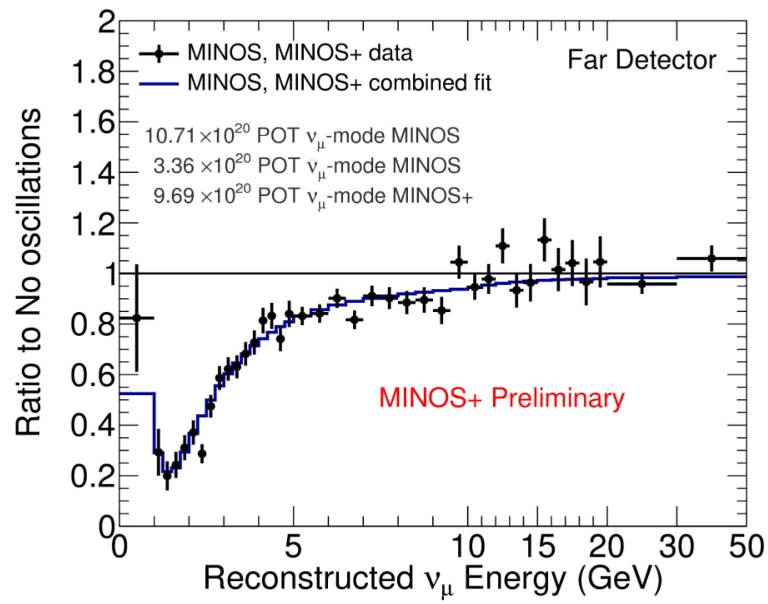


Sterile neutrino bounds

- MINOS and MINOS+ 90% C.L. exclusion limit over 7 orders of magnitude in Δm^2_{41}
- Improvement at large Δm^2_{41} over previous MINOS result due to:
  - Near Detector statistical power
  - Sensitivity to normalization shifts
  - Improved binning around atmospheric dip in Far Detector
- Increased tension with global best fit
  - Displayed here with $|U_{e4}|^2 = 0.023$
- Posted to arXiv:1710.06488 and submitted to PRL
  - See arXiv paper and ancillary materials for more details
- Final year of data is still to be analyzed



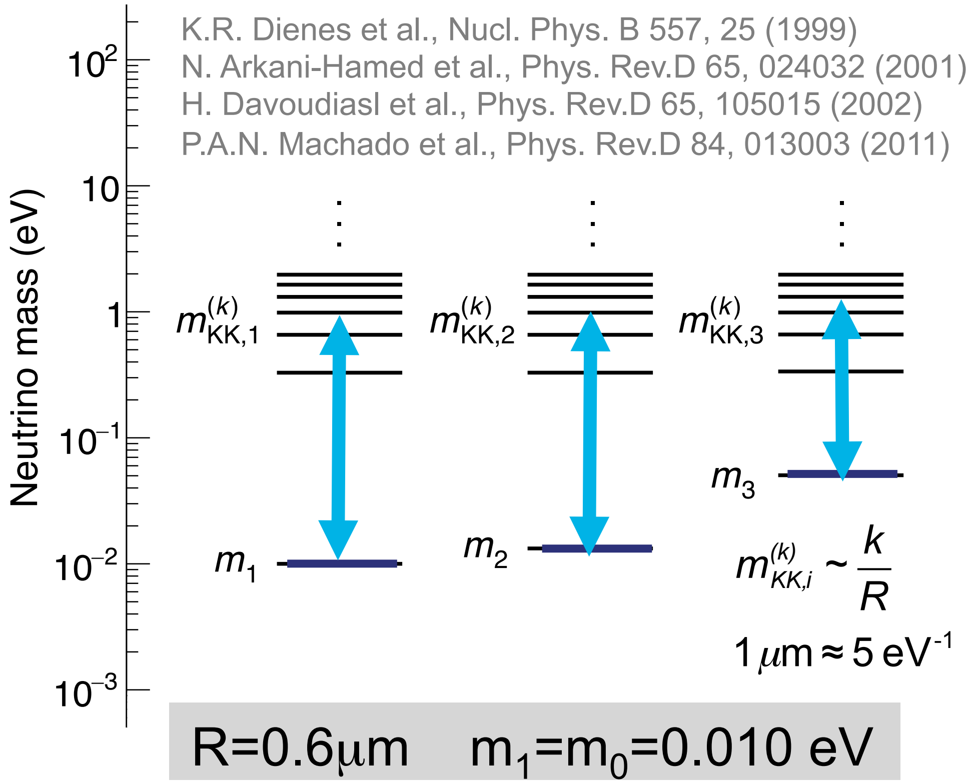
^S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J.Phys.G43, 033001 (2016)

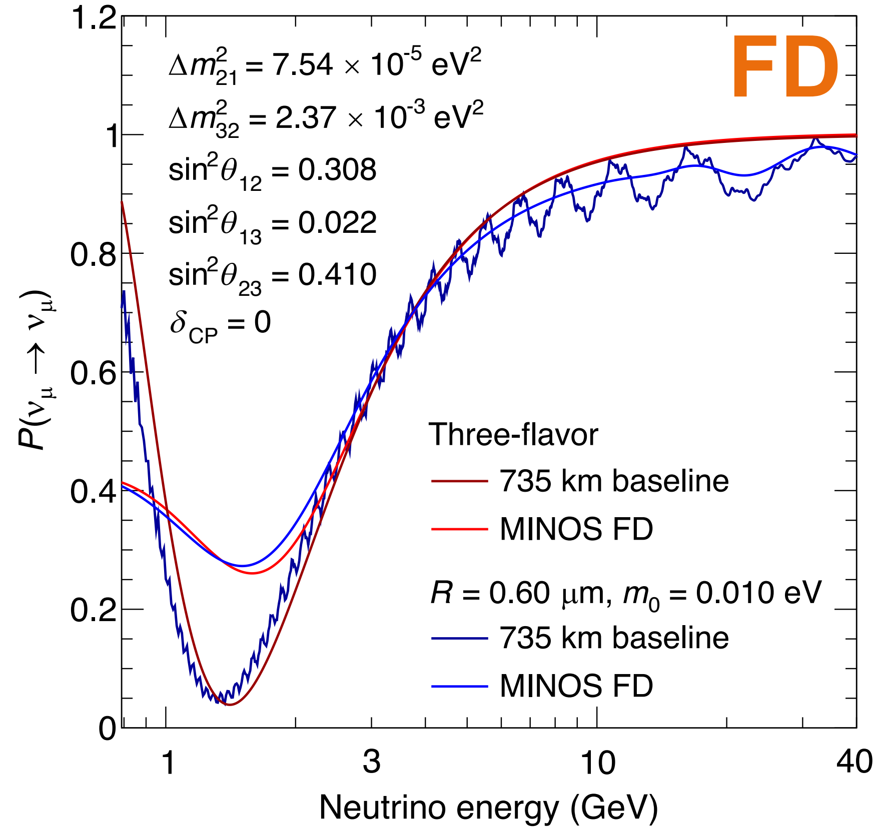


MINOS & MINOS+

LARGE EXTRA DIMENSIONS (LED)

LED ν_μ Disappearance Probability





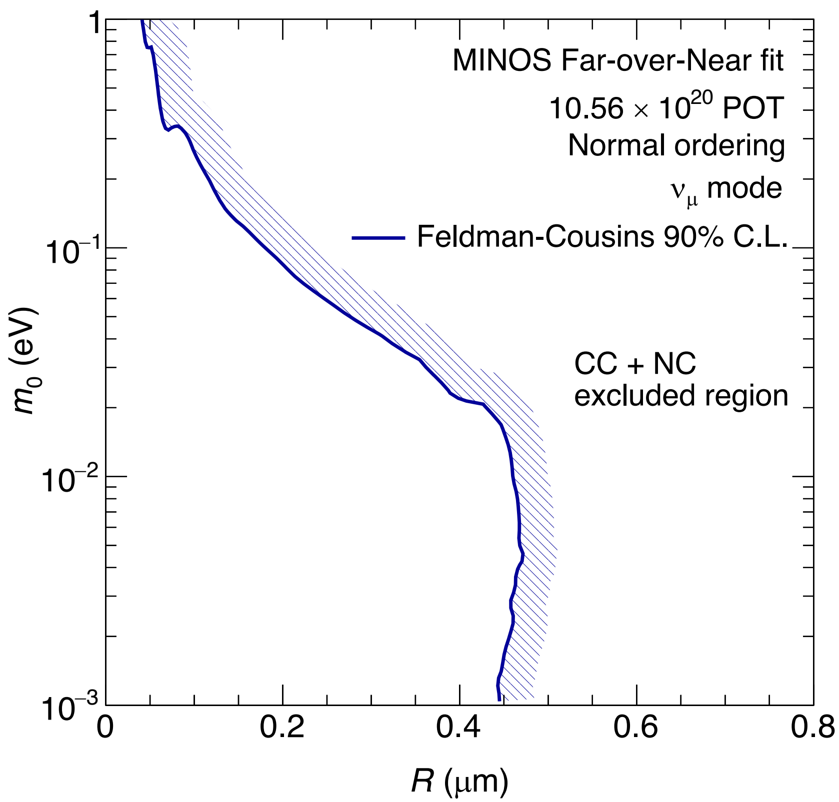
- Introduce extra spatial dimension compactified on a circle with radius ***R***
- 3 sterile fields that live in the bulk
- Sterile fields act as **Kaluza-Klein towers** of infinite sterile neutrinos

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

Mixing in towers   Neutrino masses

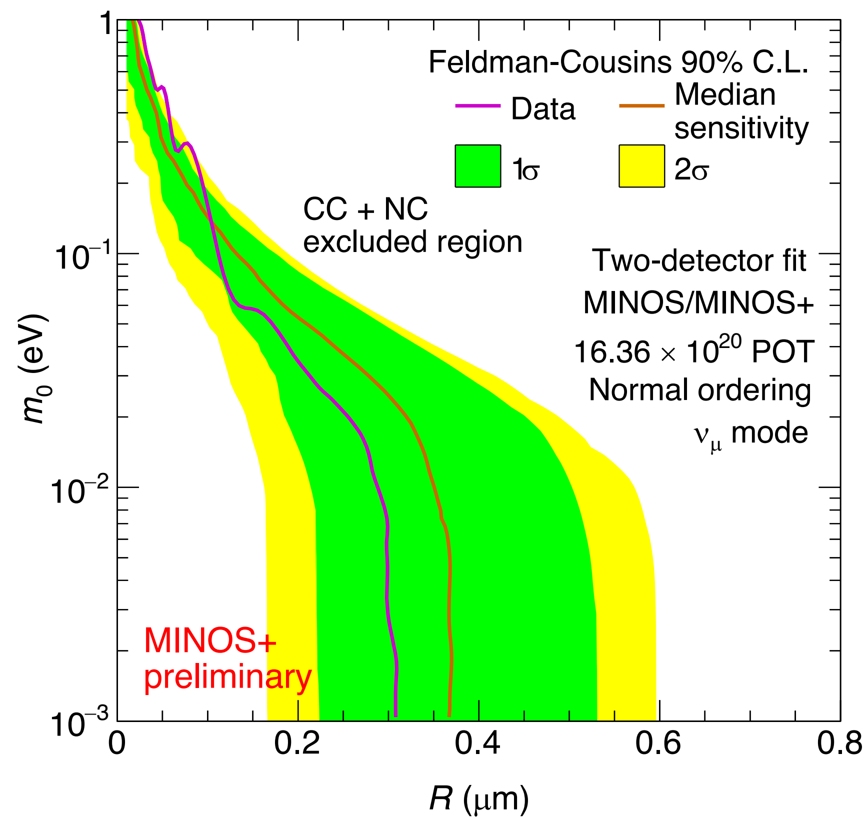
MINOS and MINOS+ LED bounds

- Previous results:
  Far-over-Near method



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

- MINOS+ and MINOS data
- Two-detector method



R < 0.30 μm at 90% C.L. for vanishing m_0

MINOS & MINOS+

THE END GAME

MINOS & MINOS+

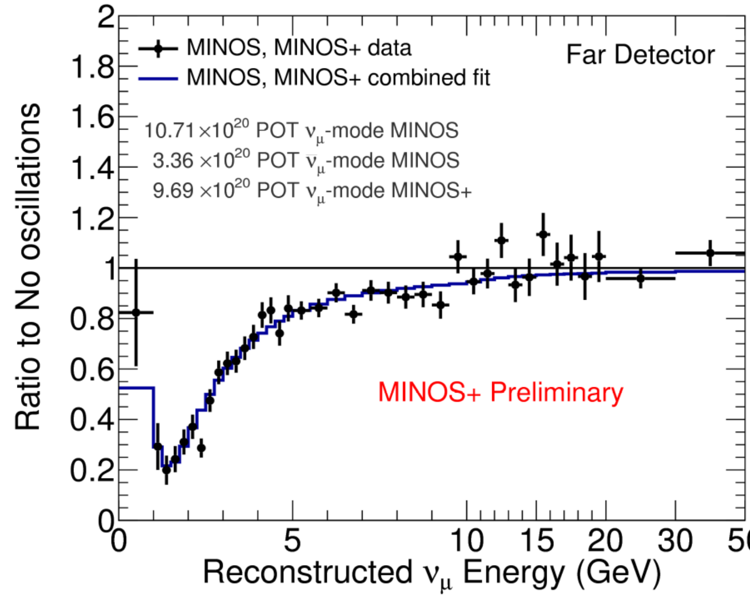
- 11 years of operations, 25 POT exposure, up to 600 kW beam
- Best to date Δm^2_{32} (68% CL), no octant preference at 90%CL for θ_{23}

Normal $\Delta m^2_{32} = +2.42^{+0.08}_{-0.09} \quad (\times 10^{-3} eV^2)$

$\sin^2\theta^2_{23} = 0.42 \quad (0.37 \leftrightarrow 0.65 \quad [90\% C.L.])$

Inverted $\Delta m^2_{32} = -2.48^{+0.10}_{-0.07} \quad (\times 10^{-3} eV^2)$

$\sin^2\theta^2_{23} = 0.42 \quad (0.36 \leftrightarrow 0.65 \quad [90\% C.L.])$



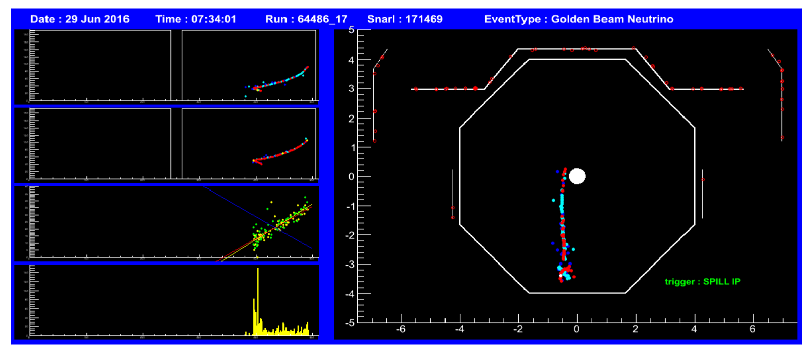
- Some of the most stringent bounds on "3+1" sterile neutrinos
  - ⇨ Muon neutrino disappearance
  - ⇨ Joint analysis with Daya Bay for $\nu_\mu \rightarrow \nu_e$ appearance bounds
  - ⇨ Increased tension with global fits

- Bounds on LED and NSI (soon)

Then and now


Ely, MN, June 2012 (the proposal era)

Last MINOS+ FD event: 29 Jun 2016



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MINOS

EXTRA IMAGES

Systematic Uncertainties

- We consider 44 total sources of systematic uncertainty in five categories
- Largest contributions arise from energy calibration uncertainty for NC events and cross-section uncertainties for CC events
- Statistical and systematic uncertainties are incorporated via covariance matrix
- Covariance matrix cross-terms allow for cancellation of uncertainties

Sources of Systematic Uncertainty

Uncertainty source	Maximum uncertainty (%)			
	ND CC	FD CC	ND NC	FD NC
Hadron production	7%	7%	7%	7%
Cross-sections	10%	10%	11%	13%
Backgrounds	1%	1%	10%	5%
Energy scale	10%	8%	20%	18%
Other	6%	3%	6%	3%
Total	15%	12%	25%	20%

$$\chi^2 = \sum_{i,j=1}^{N} (\text{obs}_i - \text{pred}_i)[V^{-1}]_{ij}(\text{obs}_j - \text{pred}_j)$$

CC and NC probabilities/ uncertainties

$$P\left(\nu_\mu \to \nu_\mu\right) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right). \qquad (1)$$

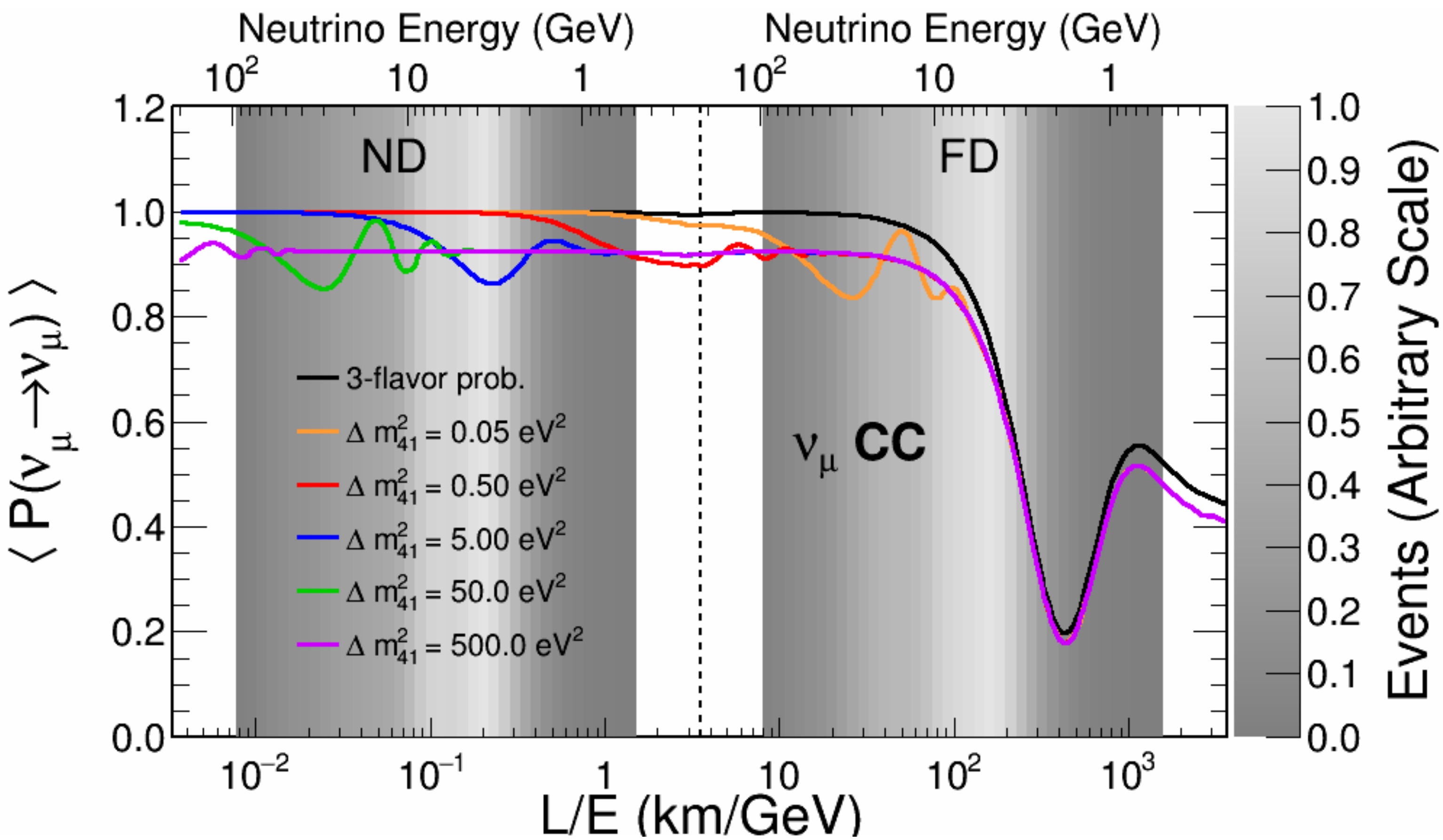
$$P_{\mathrm{NC}} = 1 - P\left(\nu_\mu \to \nu_s\right) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) - \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin\left(\frac{\Delta m^2_{31} L}{2E}\right) \qquad (2)$$

Uncertainty	Sensitivity to $\sin^2\theta_{24}$ at: $\Delta m^2_{41} = 1\,\mathrm{eV}^2$	$\Delta m^2_{41} = 1000\,\mathrm{eV}^2$
Statistics only	0.0008	0.0002
+Energy scale	0.0054	0.0003
+Hadron production	0.0131	0.0063
+Cross section	0.0138	0.0103
+Background	0.0141	0.0112
+Beam	0.0143	0.0128
+Other	0.0153	0.0165

Table I. The reduction in $\sin^2\theta_{24}$ exclusion sensitivity caused by accumulation of systematic sources at two values of Δm^2_{41}. The systematic uncertainty sources are given in Eq. (4).

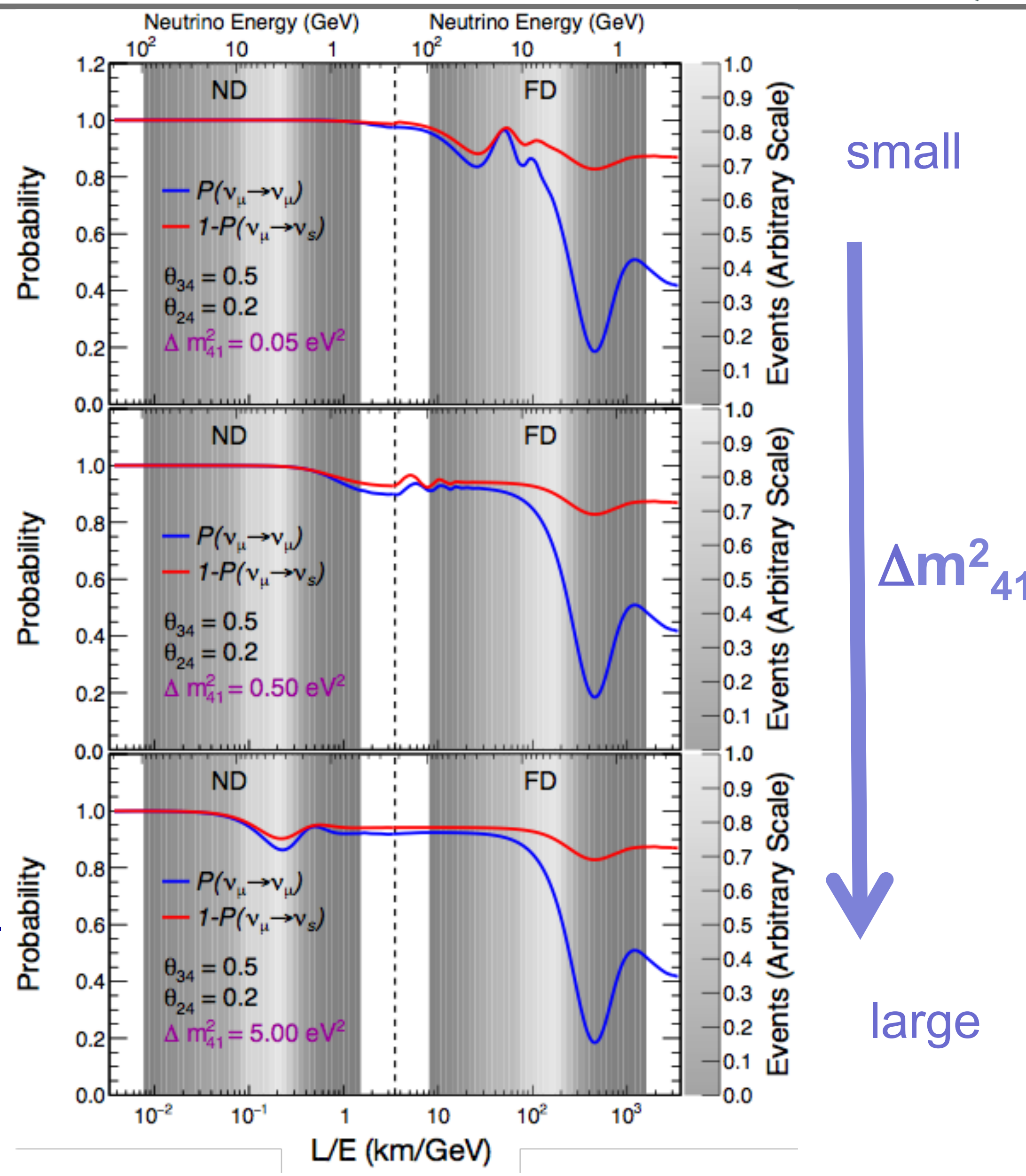
The “3+1” oscillations in two detetors

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



4-flavor oscillations in MINOS

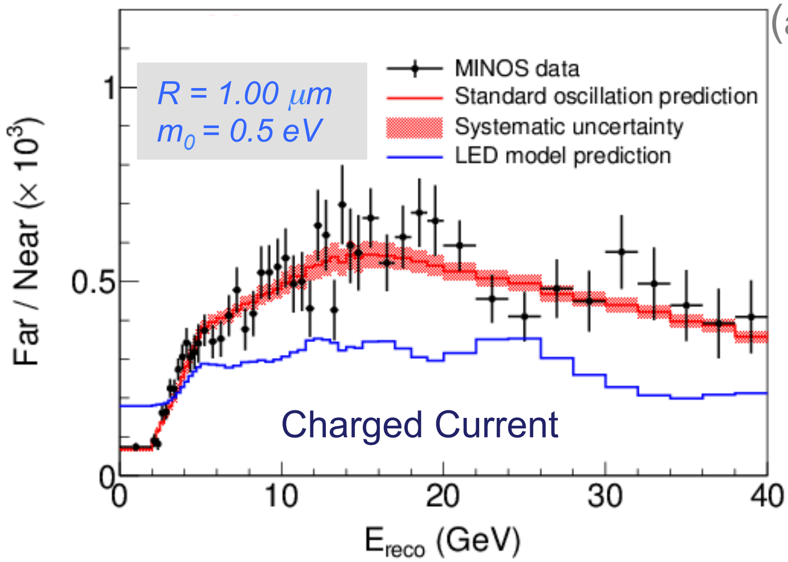
- MINOS is sensitive to three sterile neutrino parameters
  - ⇨ θ_{24} , θ_{34} and Δm^2_{41}
  - ⇨ **Small Δm^2_{41} < 0.05 eV^2**
  - ⇨ Low Δm^2_{41} only affects FD
- Oscillations can cause effects in both detectors
  - ⇨ Rapid oscillations cause a constant deficit in FD
  - ⇨ **Medium Δm^2_{41} ~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

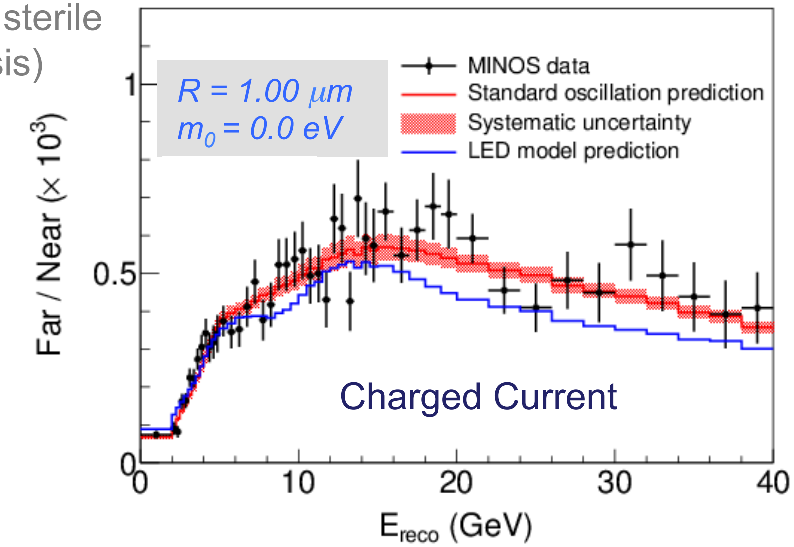


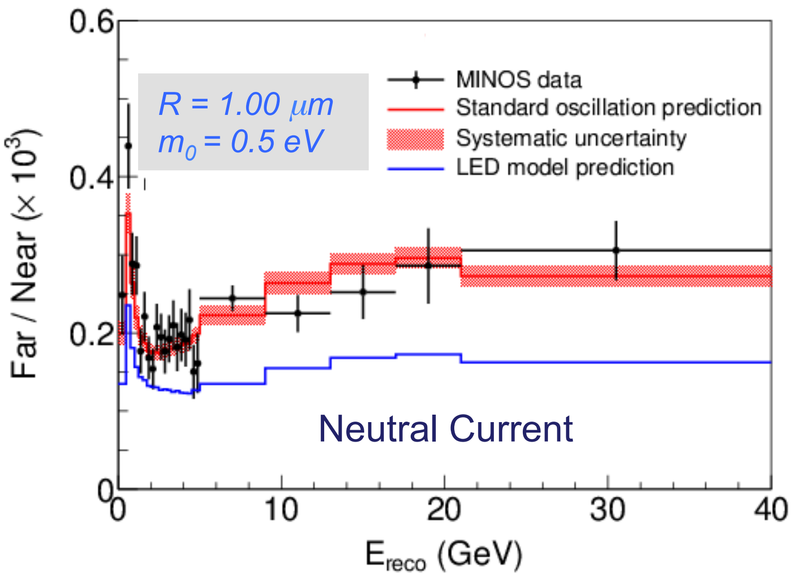
Large Extra Dimension: effect of ***R*** and ***m_0***

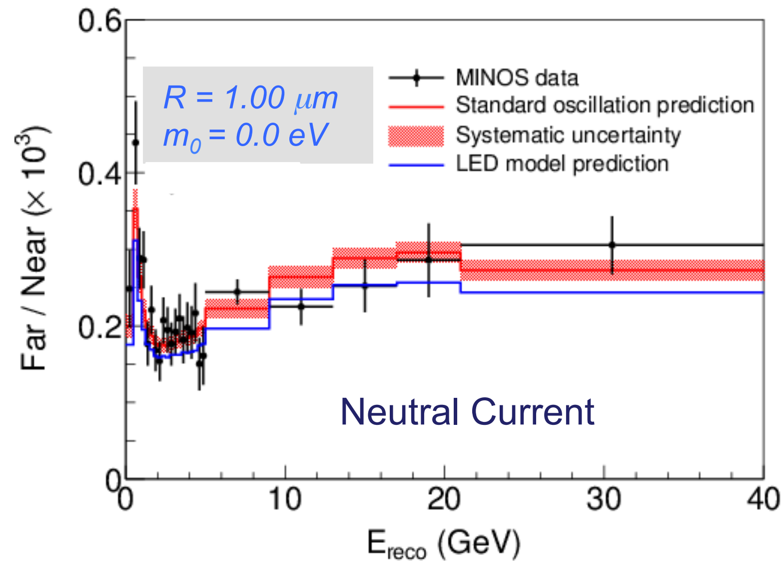
Ratios of energy spectra

(as in the sterile analysis)

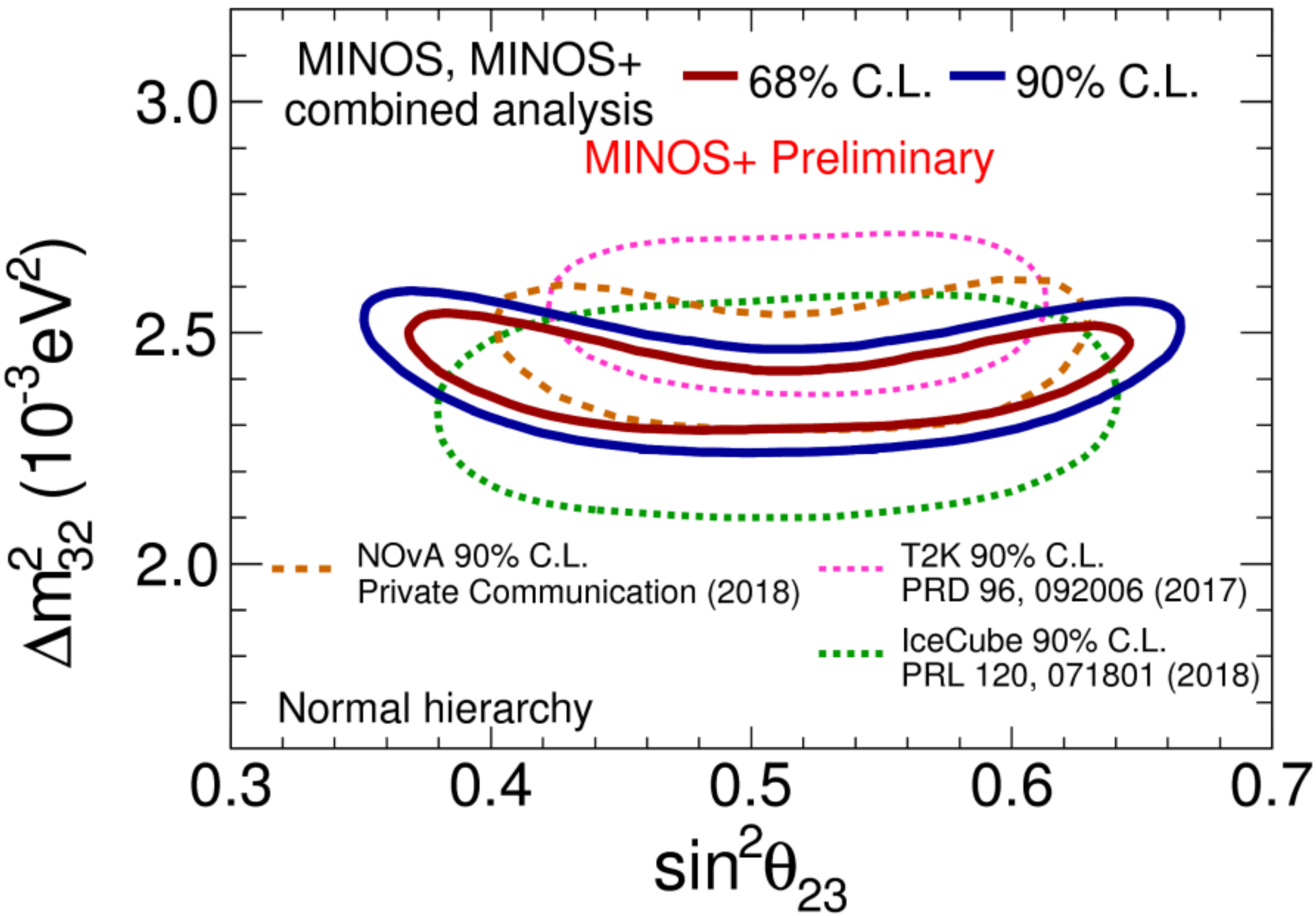






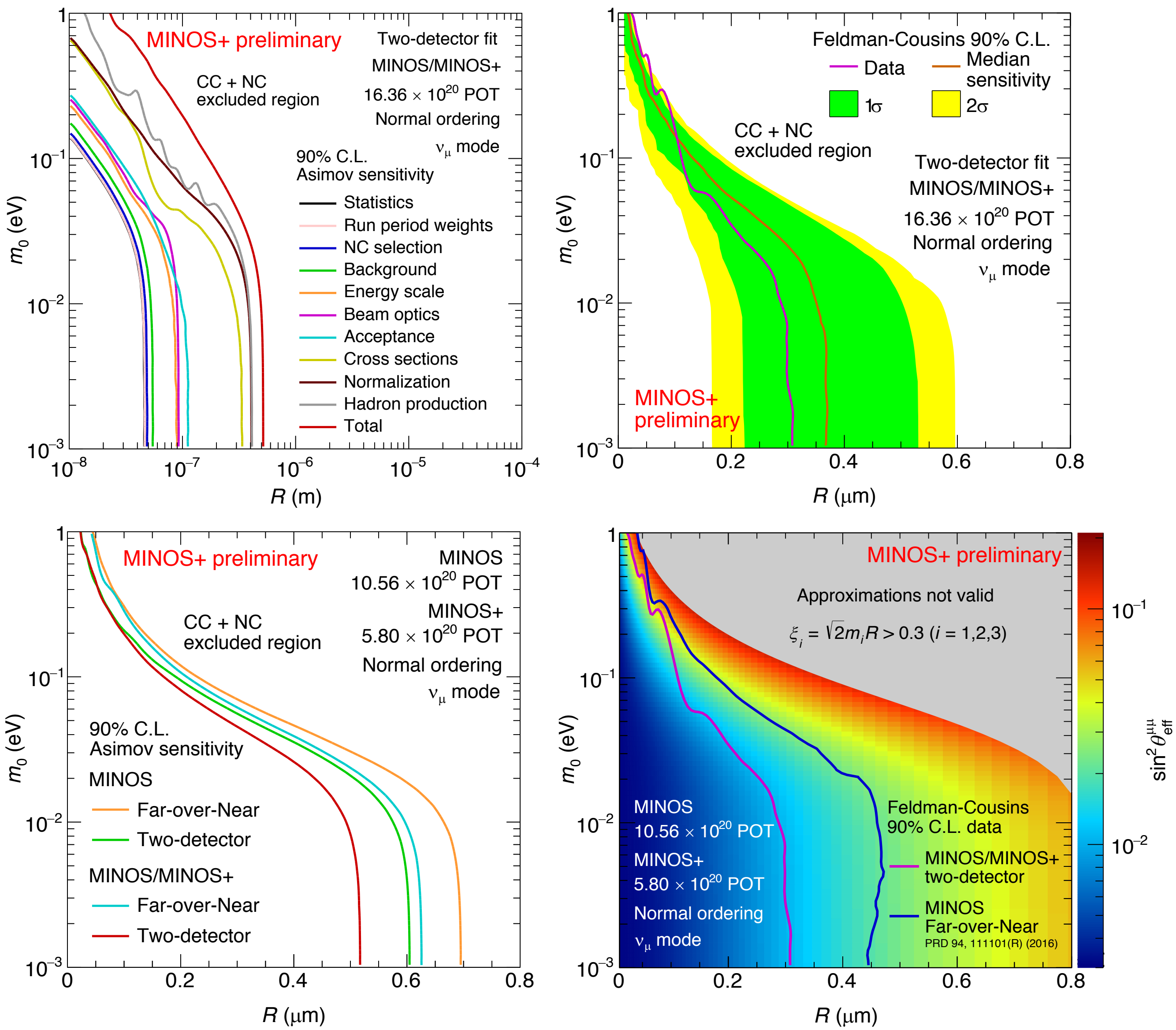


Comparison of latest results

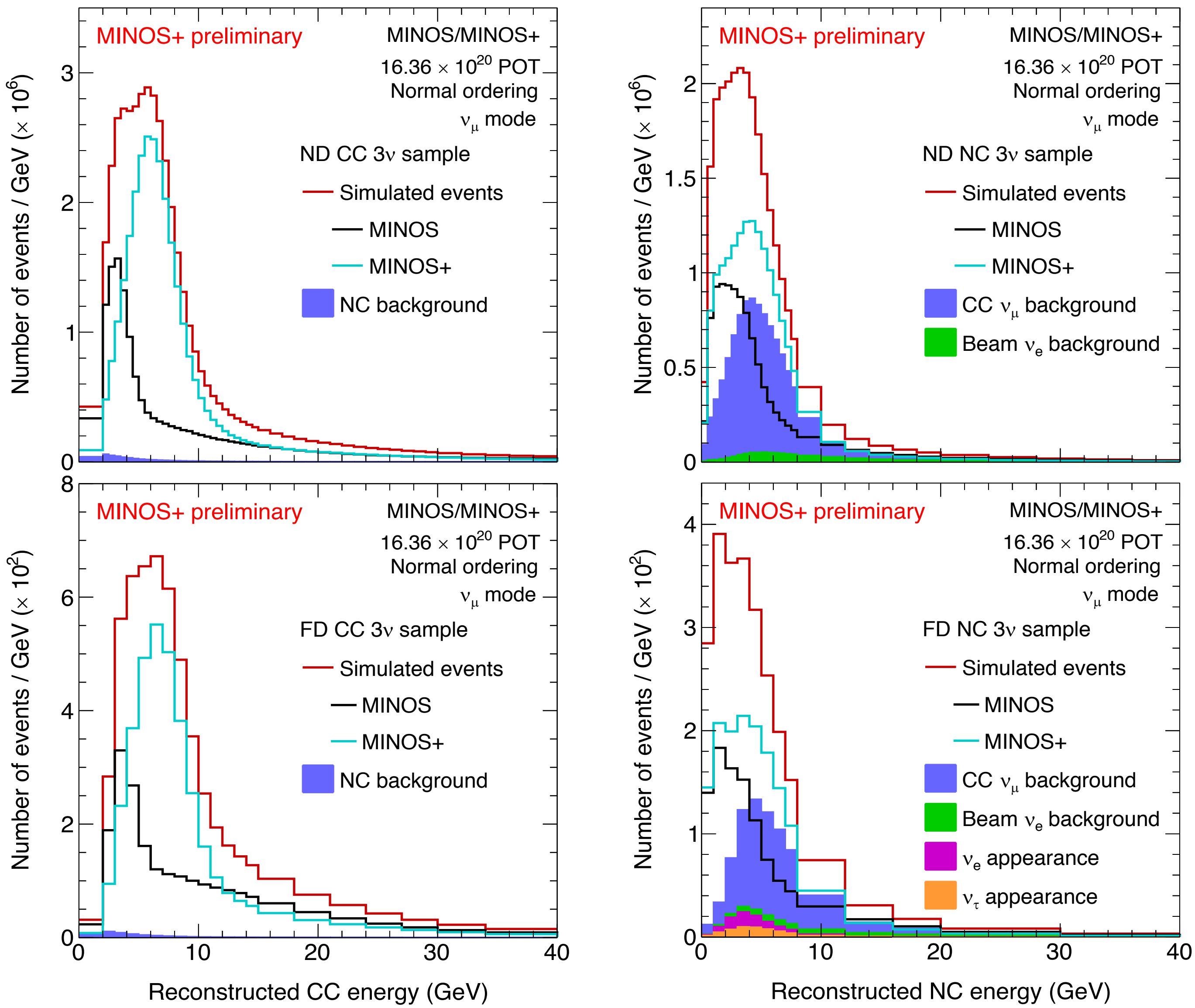


LED analysis details

- LED
- MINOS
- MINOS+
- Neutrino 2018

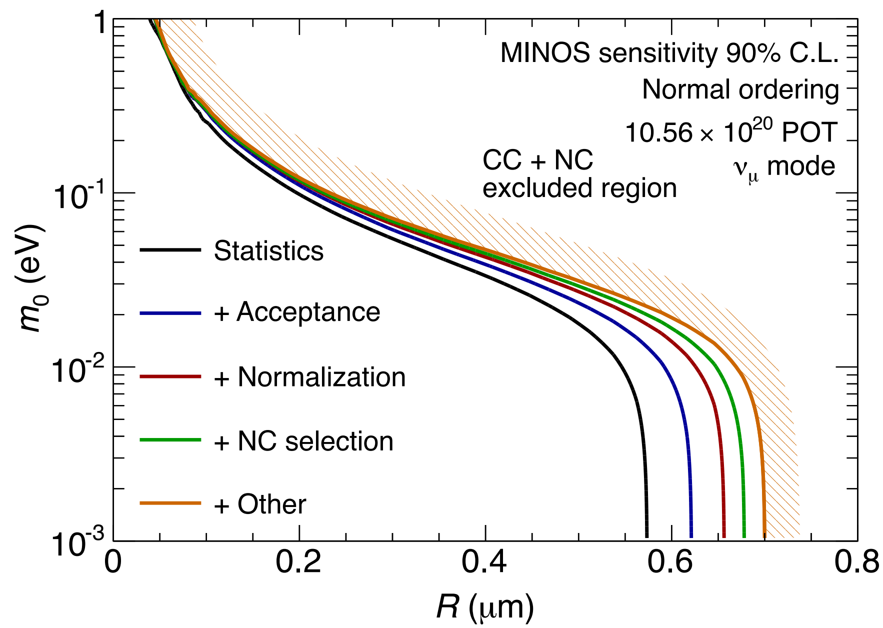


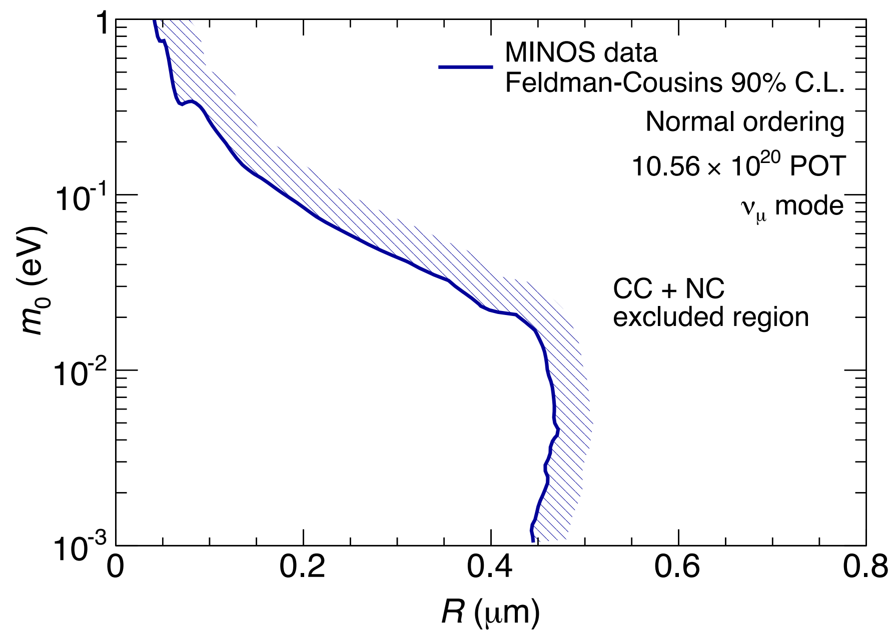
LED analysis details



MINOS bounds

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





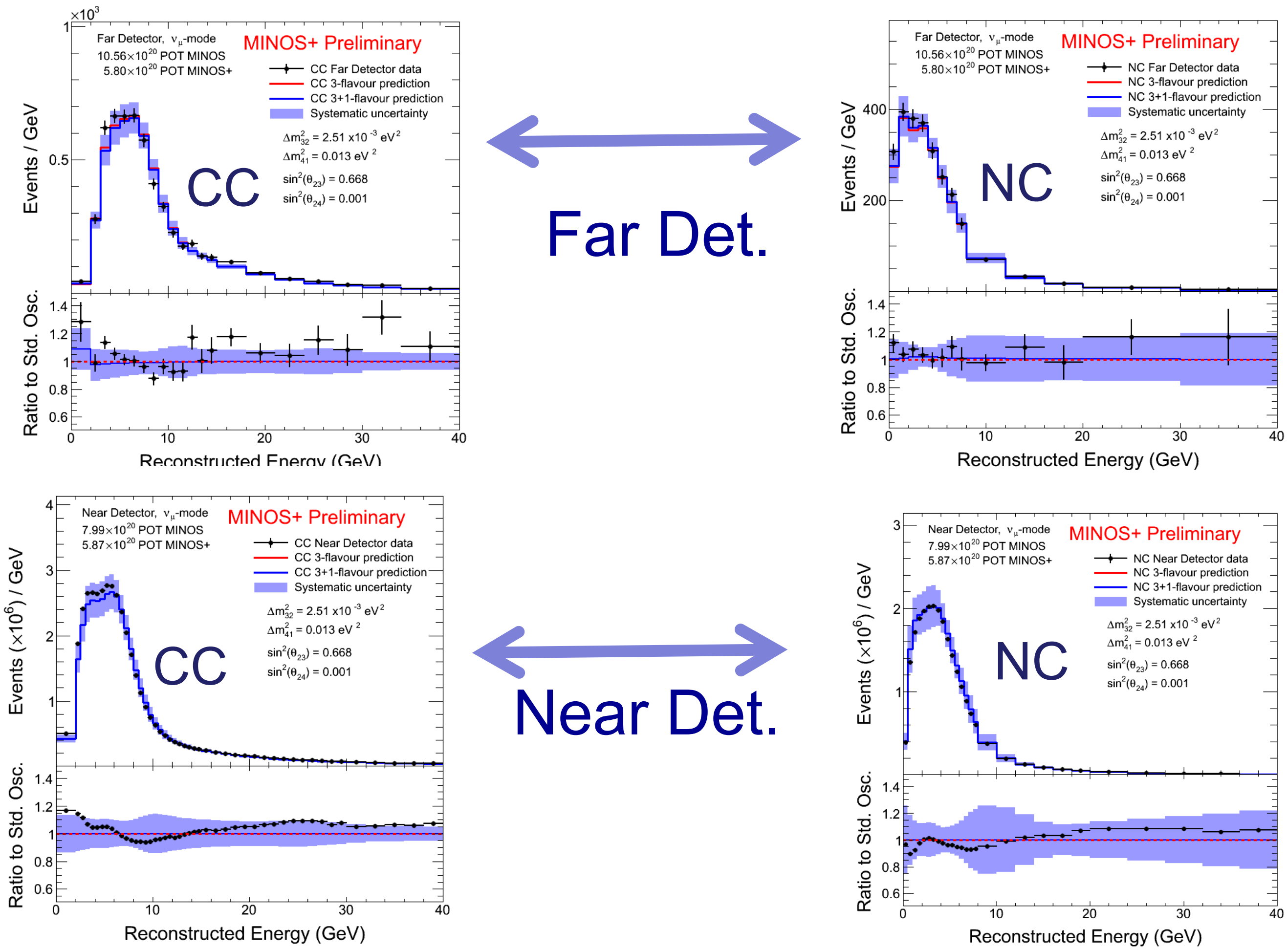
P. Adamson et al. [MINOS Collaboration], Phys.Rev. D94 (2016) no.11, 111101

Future:

- MINOS+ and MINOS data
- Two-detector method

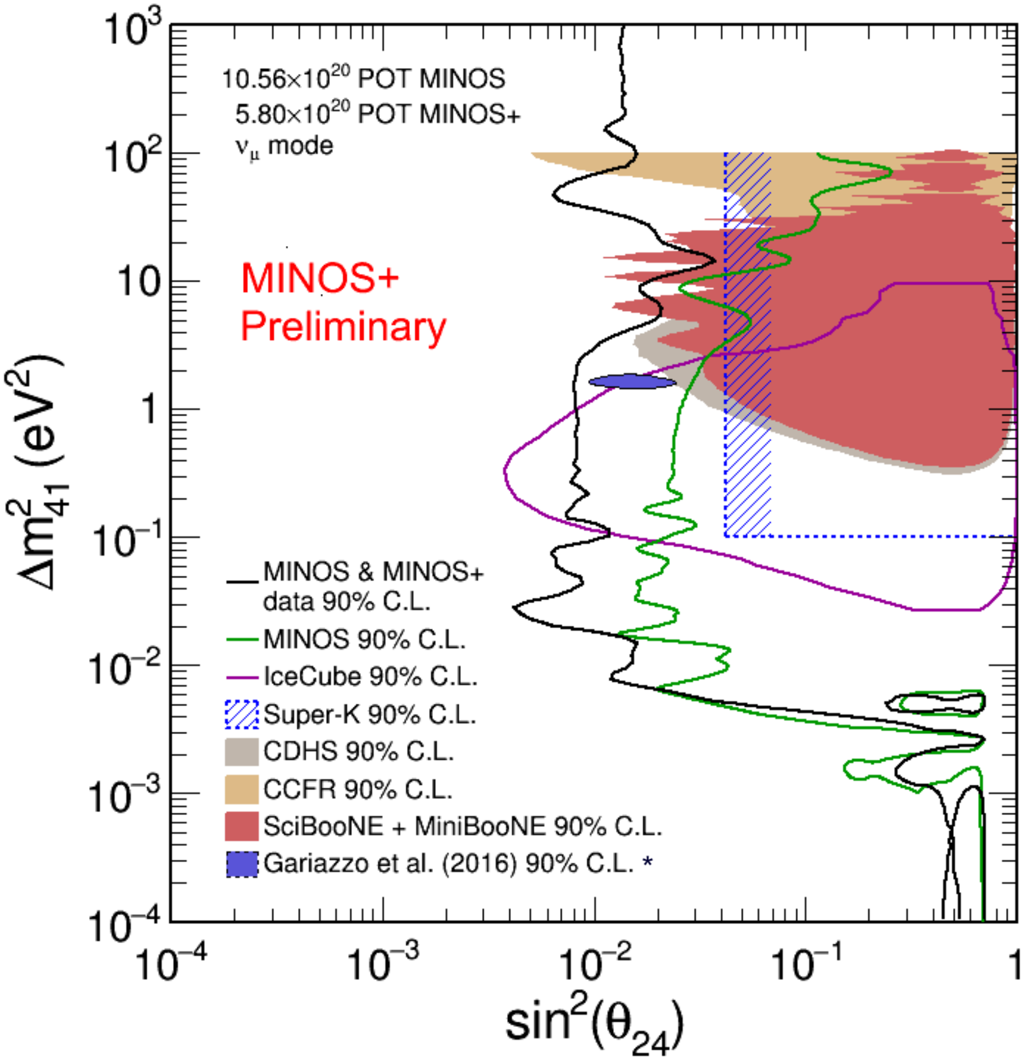
Sterile Search - new method – two-detector fit

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



Comparison with Other Experiments

The **2017** results



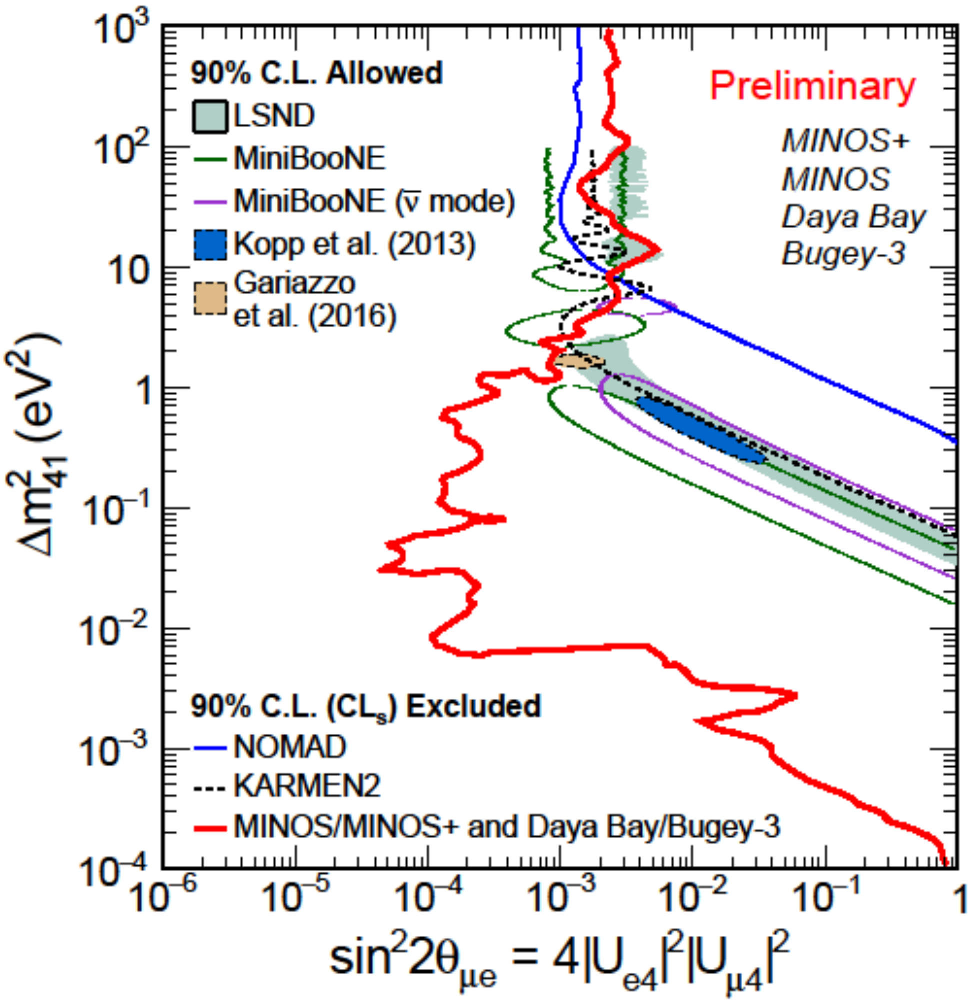
- New limit improves constraint of the previous MINOS analysis
- Constraint improved by Near Detector contribution for $\Delta m^2_{41} \sim 5\ eV^2$
- Increased tension with global best fit

*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.

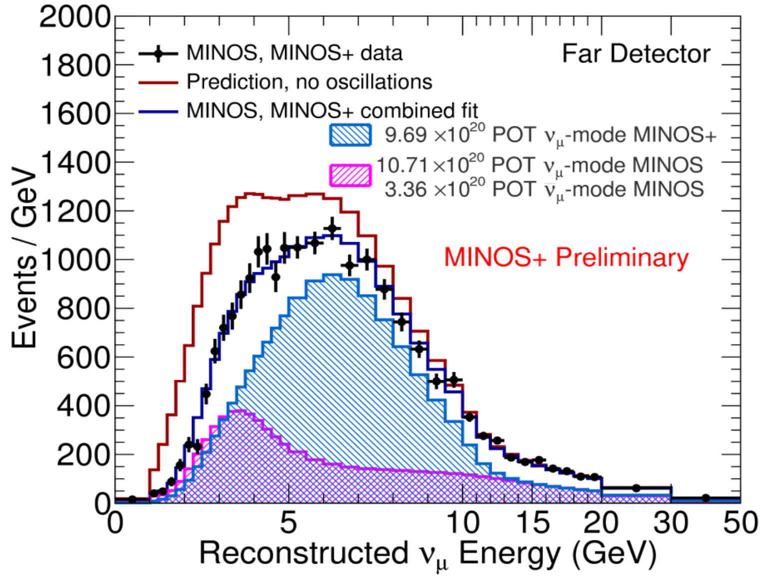
The **2017** results

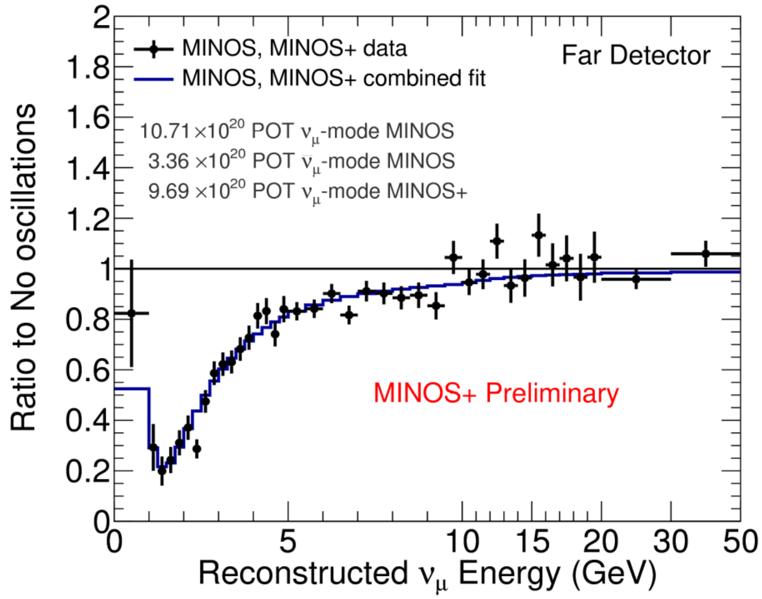


^J. Kopp, P. Machado, M. Maltoni, T. Schwetz, JHEP 1305:050 (2013)

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

Combined fit MINOS & MINOS+ (beam + atmospheric)





Best fits, 90% C.L.

Best fit: $\Delta m^2_{32} = +\ 2.42 \quad (\times 10^{-3} eV^2)$

$\sin^2\theta^2_{23} = 0.42$

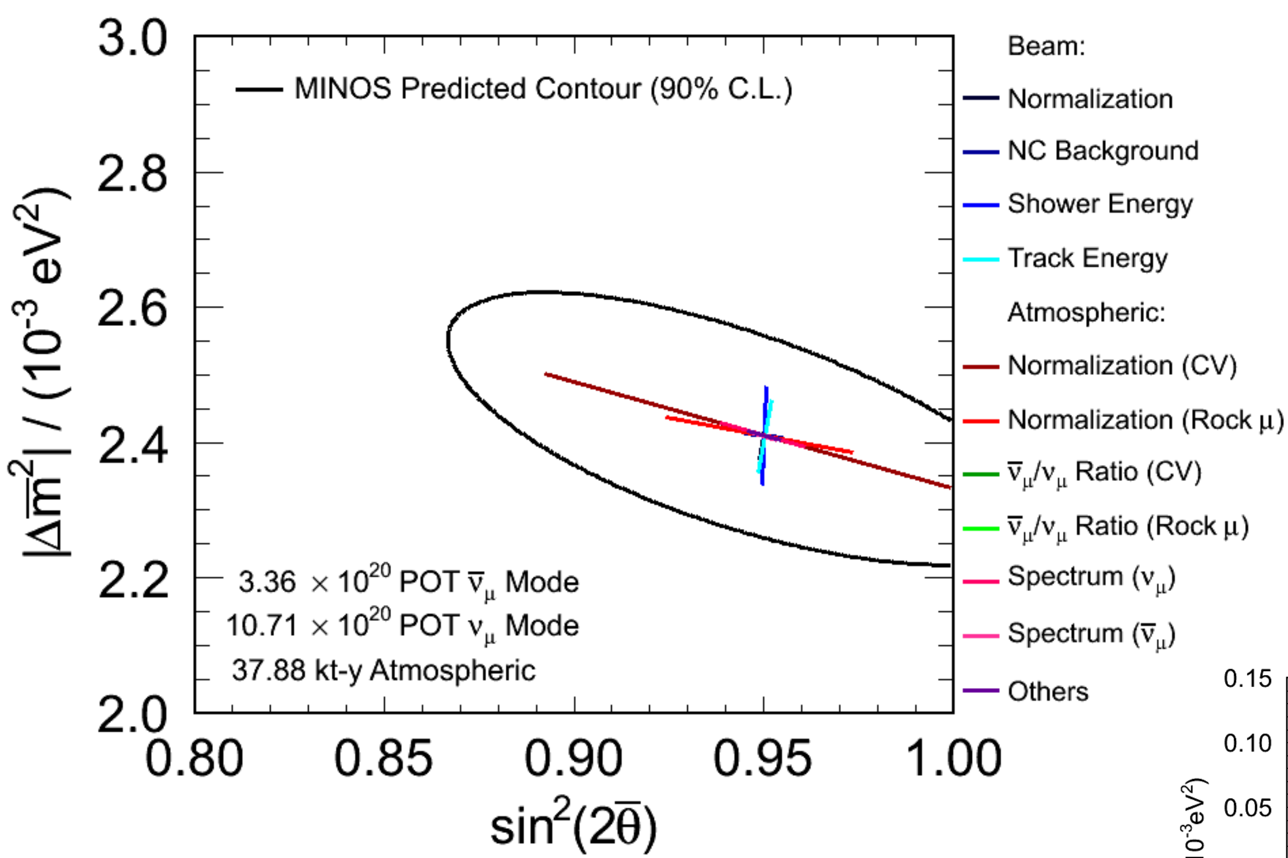
Normal $\Delta m^2_{32} = +\ (2.28 \leftrightarrow 2.55) \quad (\times 10^{-3} eV^2)$

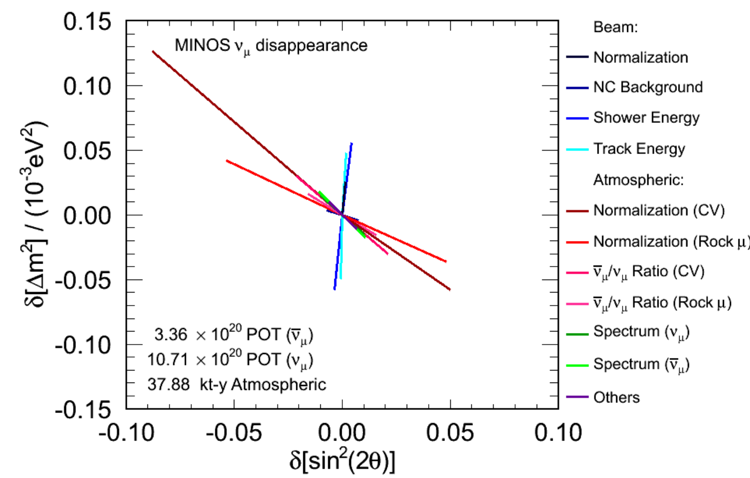
$\sin^2\theta^2_{23} = (0.37 \leftrightarrow 0.65)$

Inverted $\Delta m^2_{32} = -\ (2.33 \leftrightarrow 2.60) \quad (\times 10^{-3} eV^2)$

$\sin^2\theta^2_{23} = (0.36 \leftrightarrow 0.65)$

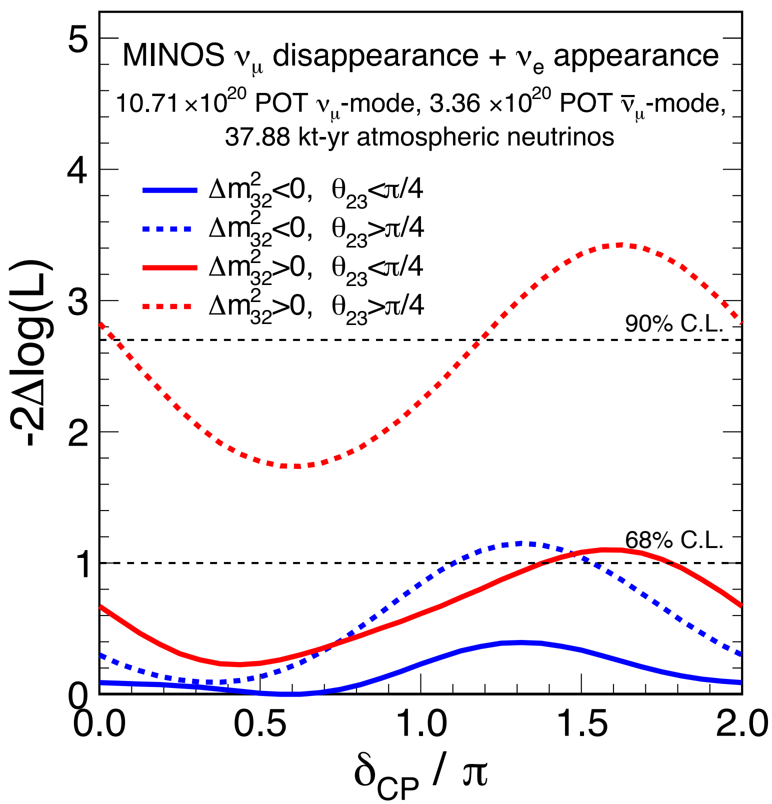
Systematics



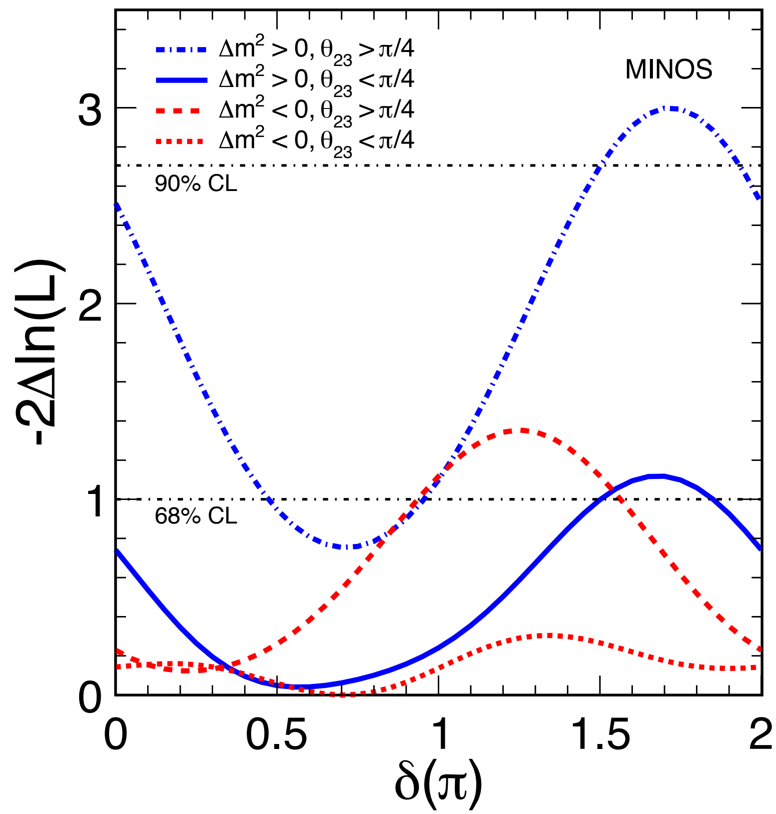


MINOS disappearance and appearance

P. Adamson et al. Phys. Rev. Lett. 112, 191801



Disappearance
&
Appearance only



Appearance only

MINOS

END-OF EXTRA IMAGES