Sterile Neutrino Searches with MINOS+

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Birmingham HEP Seminar

29/04/20

UNIVERSITY OF CAMBRIDGE

MINOS

Outline

- Introduction
- MINOS+ Experiment
- Three flavour oscillation results
- Four flavour oscillation results

Neutrinos

- Neutrino oscillations have become a well-established and well-described phenomenon over the last 20 years.
  - The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

- Oscillations arise from the quantum mechanical interference between the neutrino mass states.
  - At least two of the neutrinos must be massive!

- The neutrino eigenstates of the weak interaction are not the same as the mass eigenstates.

Neutrinos

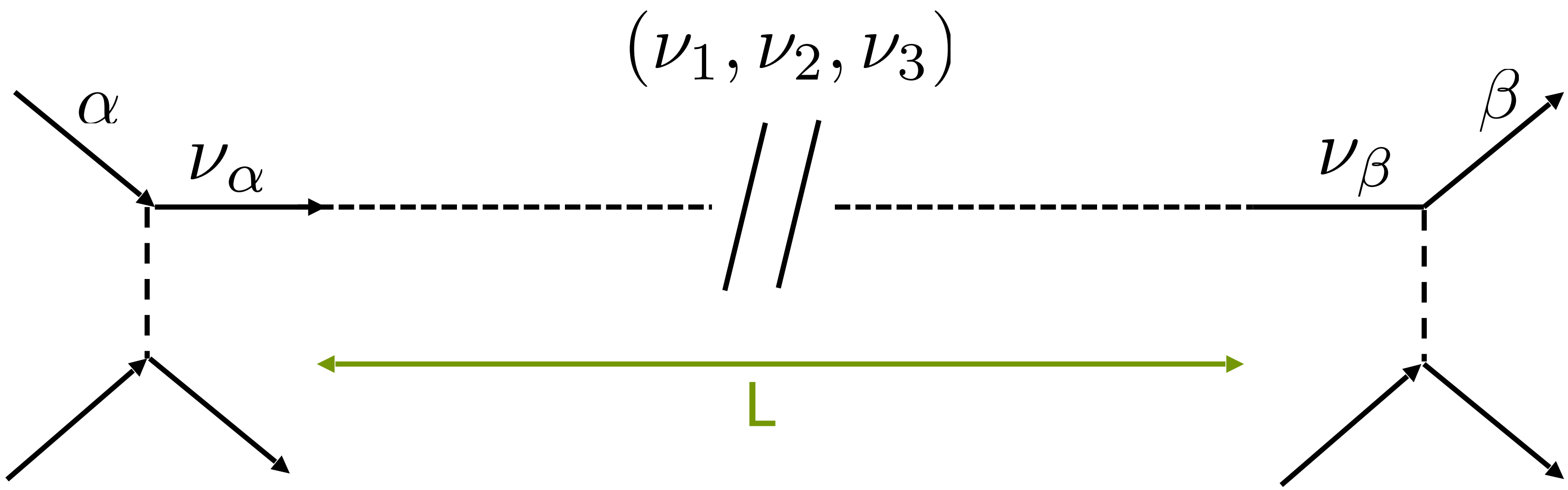
- For three neutrino flavours:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i$$

Flavour eigenstates: ν_e, ν_μ, ν_τ

Mass eigenstates: ν_1, ν_2, ν_3

3x3 unitary matrix – the PMNS matrix



Neutrinos

- For three neutrino flavours: $c_{jk} = \cos\theta_{jk}, s_{jk} = \sin\theta_{jk}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Muon neutrino disappearance (accelerator and atmospheric)

Electron antineutrino disappearance (reactor)
Electron neutrino appearance (accelerator)

(Anti)electron neutrino disappearance (solar and reactor)

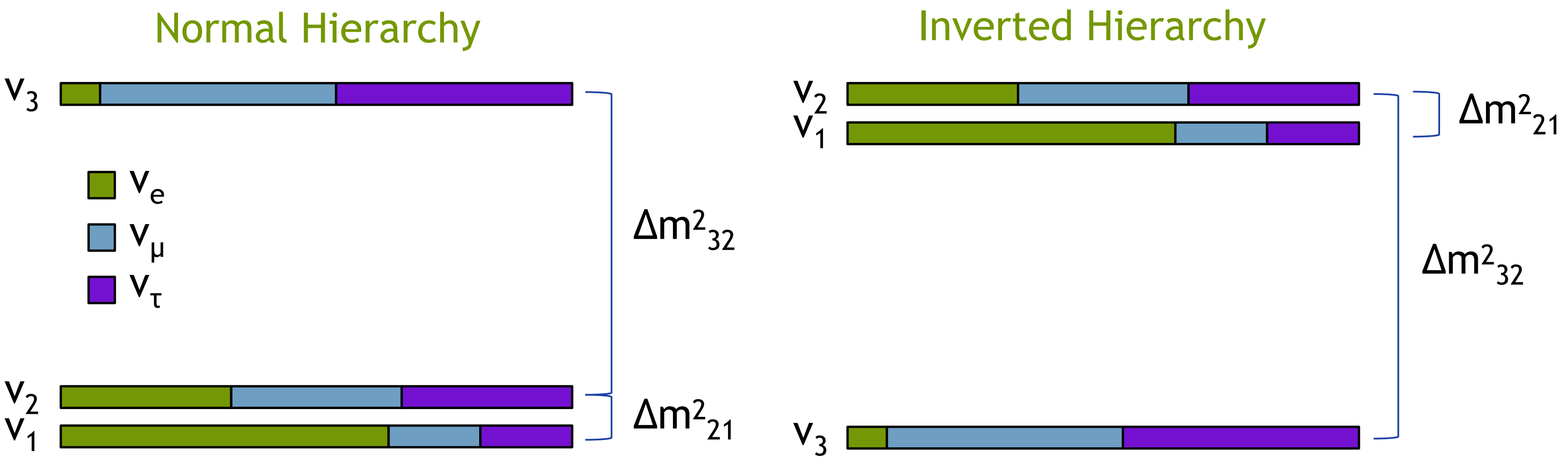
- Three mixing angles and a CP violating phase.

- Oscillations are driven by mass-squared splittings

$$P\left(\nu_\mu \to \nu_\mu\right) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31} L}{E}\right)$$

Mass Hierarchy

- The order of all the mass states isn't completely known.



- The sign of Δm^2_{21} is known from matter effects in the Sun and from the definition of ν_1 having the largest ν_e component.
- The sign of Δm^2_{32} is still unknown.

Current State of Measurements

- Very successful programme of measurements.

- The remaining unknowns:
  - Is the mass-hierarchy
    - Normal Δm^2_{32} > 0?
    - Inverted Δm^2_{32} < 0?
  - Is θ_{23} = 45°?
    - If not, is it higher or lower?
  - What is the value of δ ?
    - Is there CP violation in the neutrino sector?
  - How many neutrinos are there?

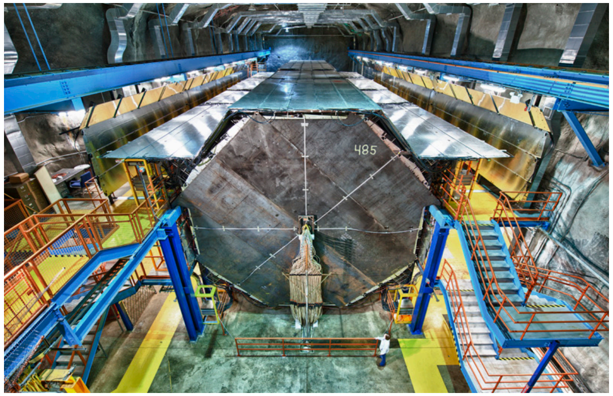
Nu-Fit v4.0

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

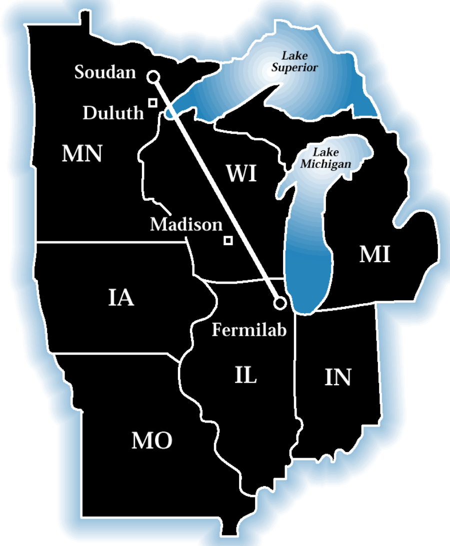
Esteban, I., Gonzalez-Garcia, M.C., Hernandez-Cabezudo, A. et al. J. High Energ. Phys. (2019) 2019: 106. https://doi.org/10.1007/JHEP01(2019)106

MINOS and MINOS+

The MINOS+ Experiment



Far Detector
735 km from beam target
5.4 kton mass

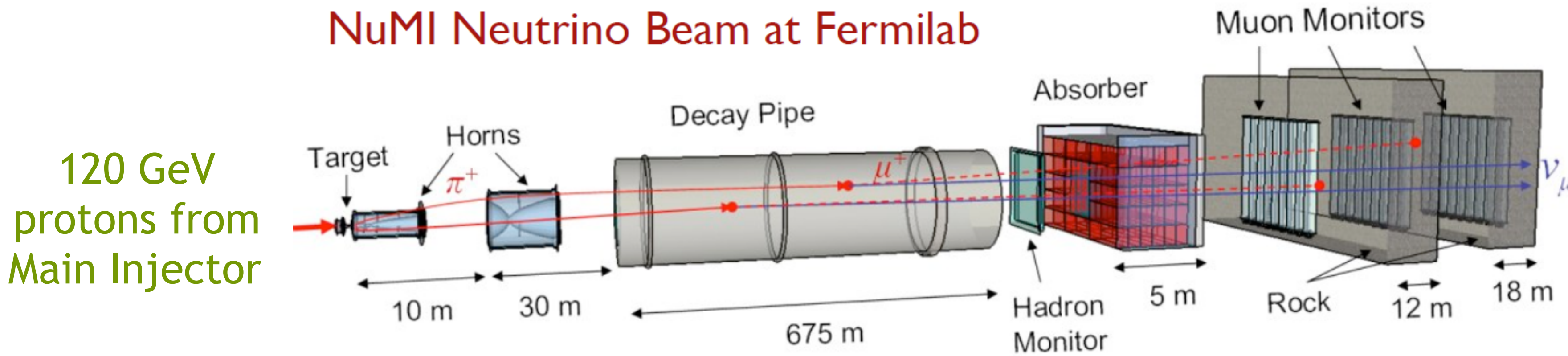


Near Detector
1 km from beam target
1 kton mass

- MINOS/MINOS+ had two functionally identical, magnetised, tracking, sampling calorimeters.
  - Can distinguish muon charge from the curvature.
- Exposed by the NuMI beam at Fermilab.
- MINOS+ is the continuation of MINOS into the NOvA era at FNAL.

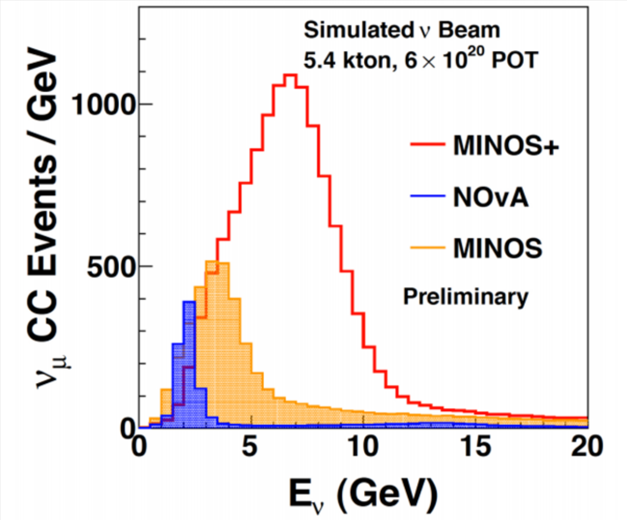
The NuMI Beam

- MINOS+ collected neutrinos from the NuMI beam at Fermilab.

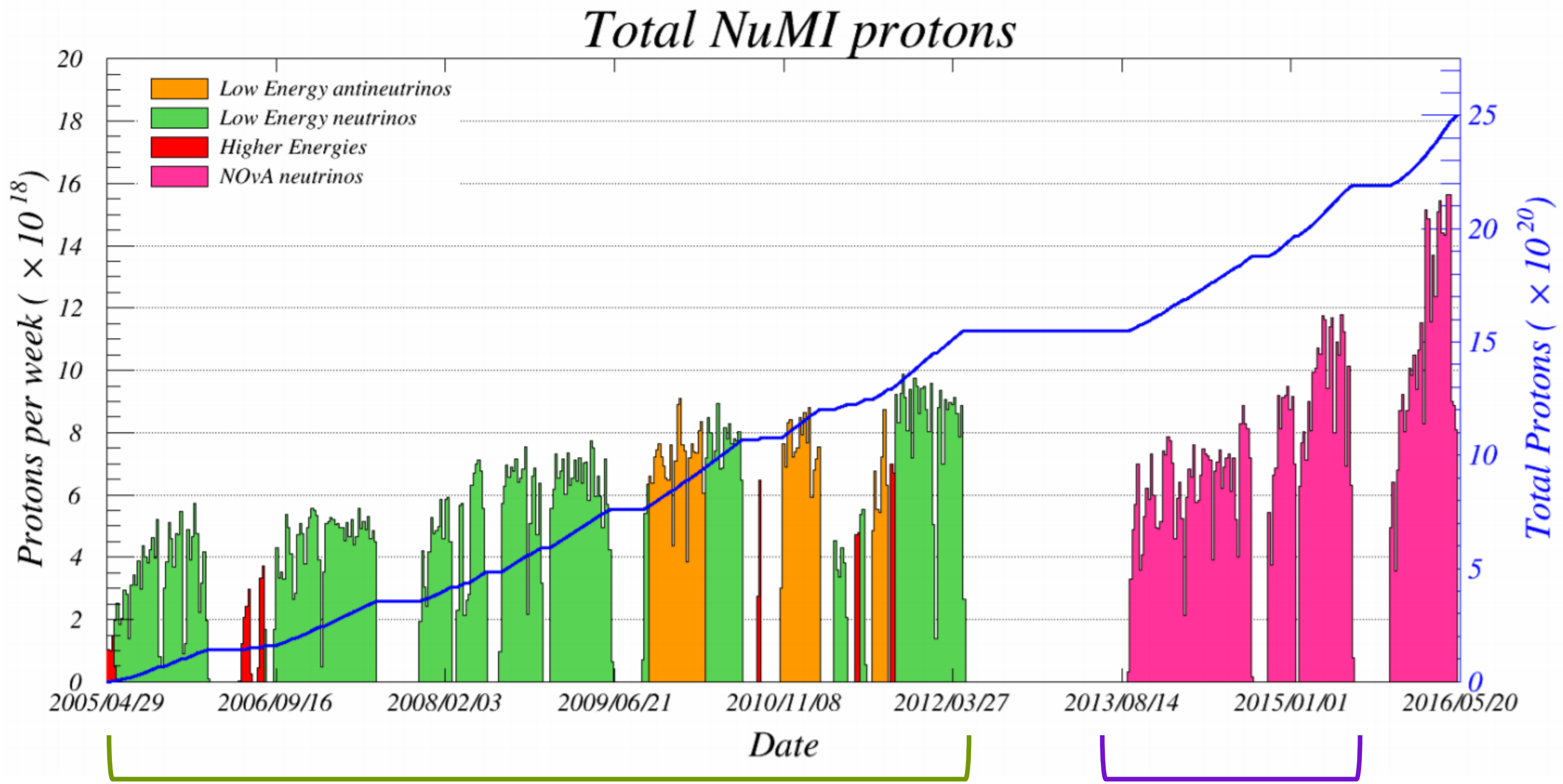


- Neutrinos produced by decay of focused mesons produced in the target.

- Polarity of the horns can be reversed to produce an antineutrino beam.



Data Samples



10.56 x 10^{20} POT MINOS

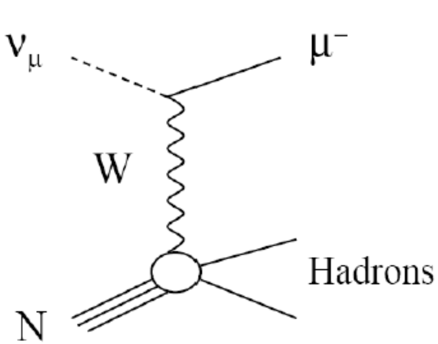
5.80 x 10^{20} POT MINOS+

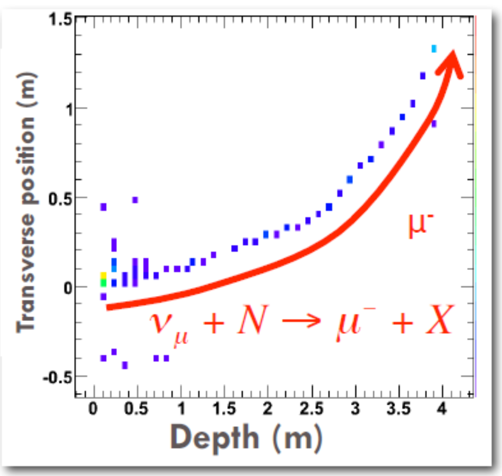
- Results shown today use all MINOS and 2/3 years of MINOS+ data

Neutrino Interactions in MINOS+

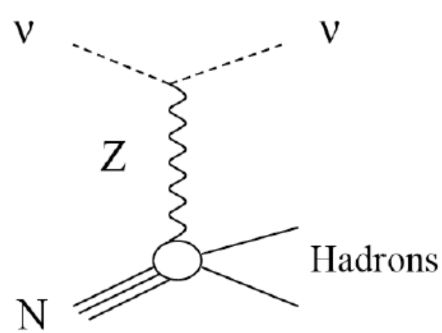
- There are three main types of interactions seen in MINOS+

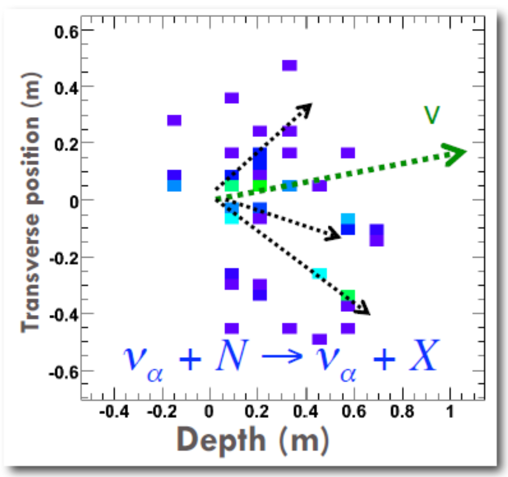
ν_μ charged-current



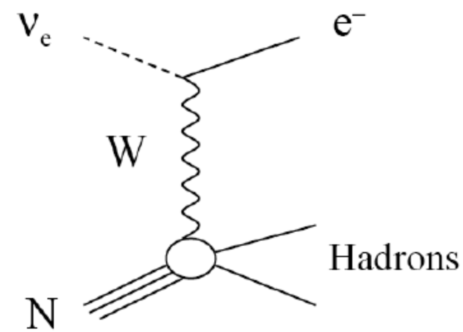


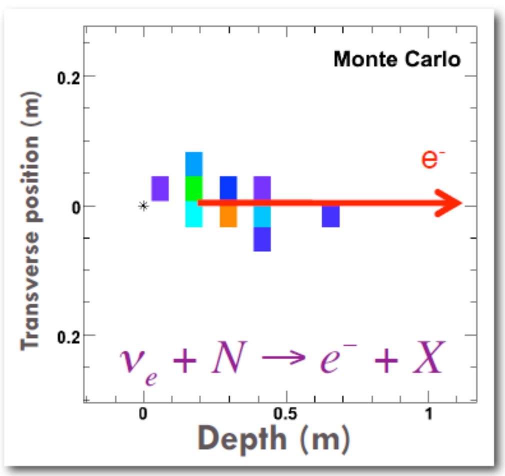
ν neutral-current





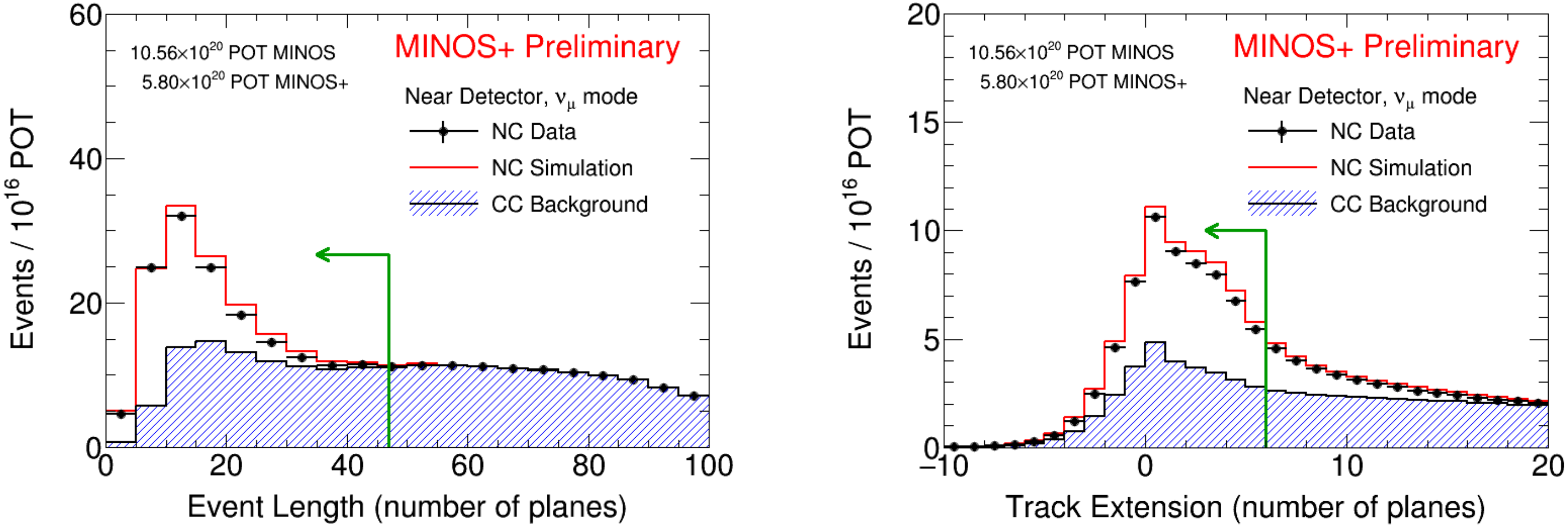
ν_e charged-current





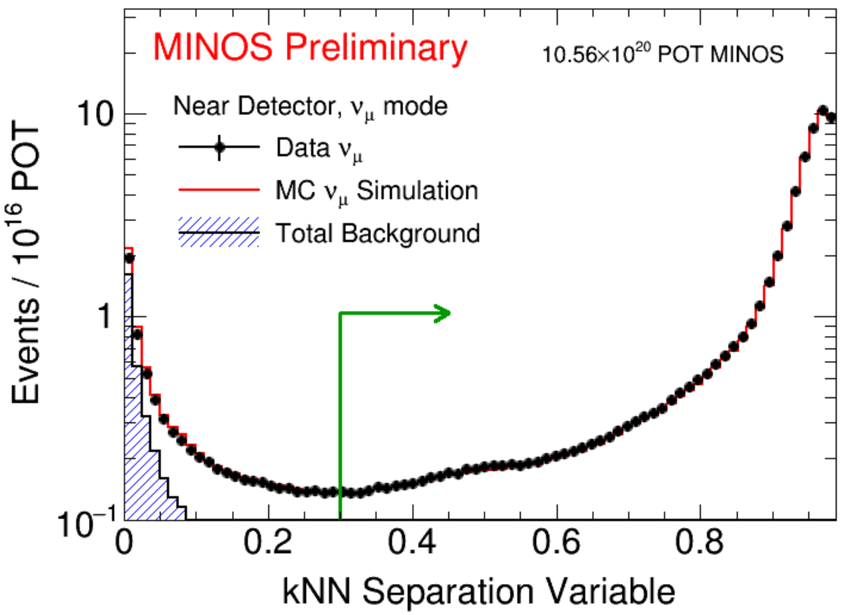
NC Event Selection

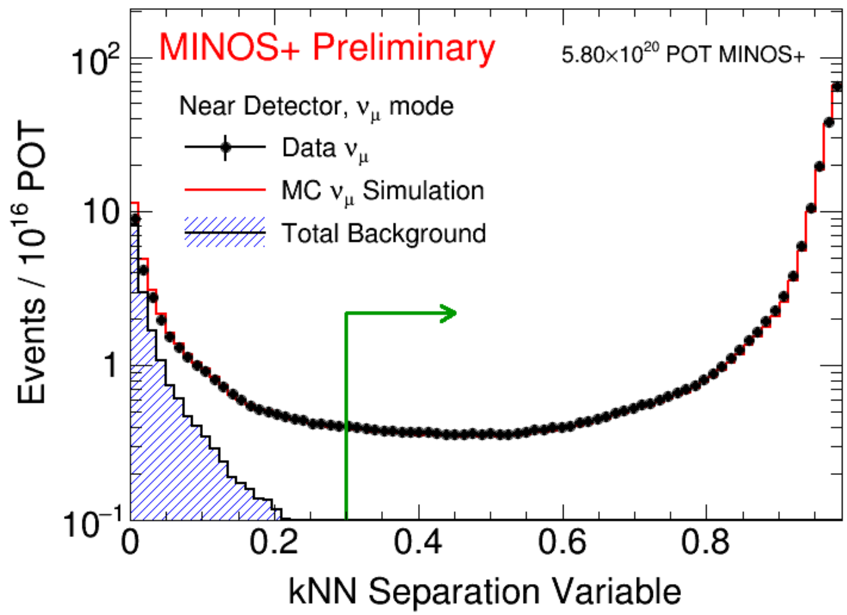
- The first step is to select the neutral current interactions.
- Two main selection criteria:
  - Event length and the extension of the track beyond the hadronic shower.



CC Event Selection

- Charged current interactions are selected from those that do not pass the neutral current selection.
  - Use a kNN to select CC interactions from the backgrounds.
    - Uses four topological and energy deposition variables as input.



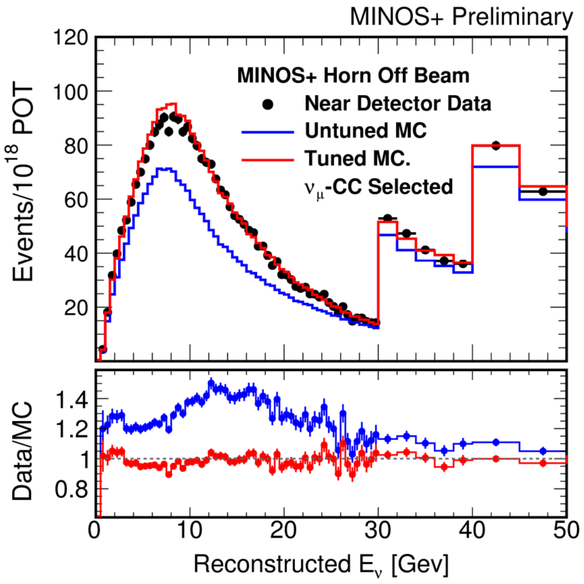


Three Flavour Oscillation Analysis

Beam Neutrinos - Flux Prediction

- In our three-flavour analysis we use the ND to tune the MC

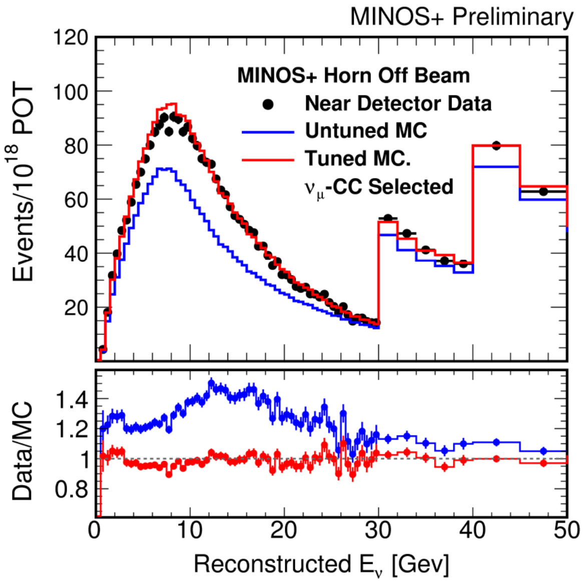
- A special sample with the magnetic horns switched off allows us to probe hadron production effects

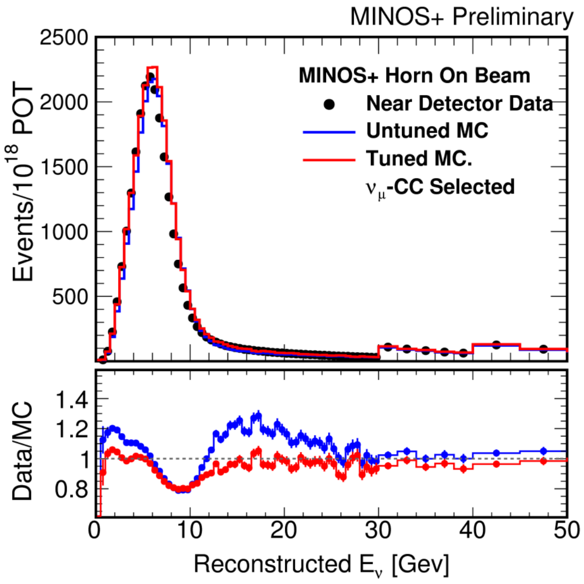


Beam Neutrinos - Flux Prediction

- In our three-flavour analysis we use the ND to tune the MC

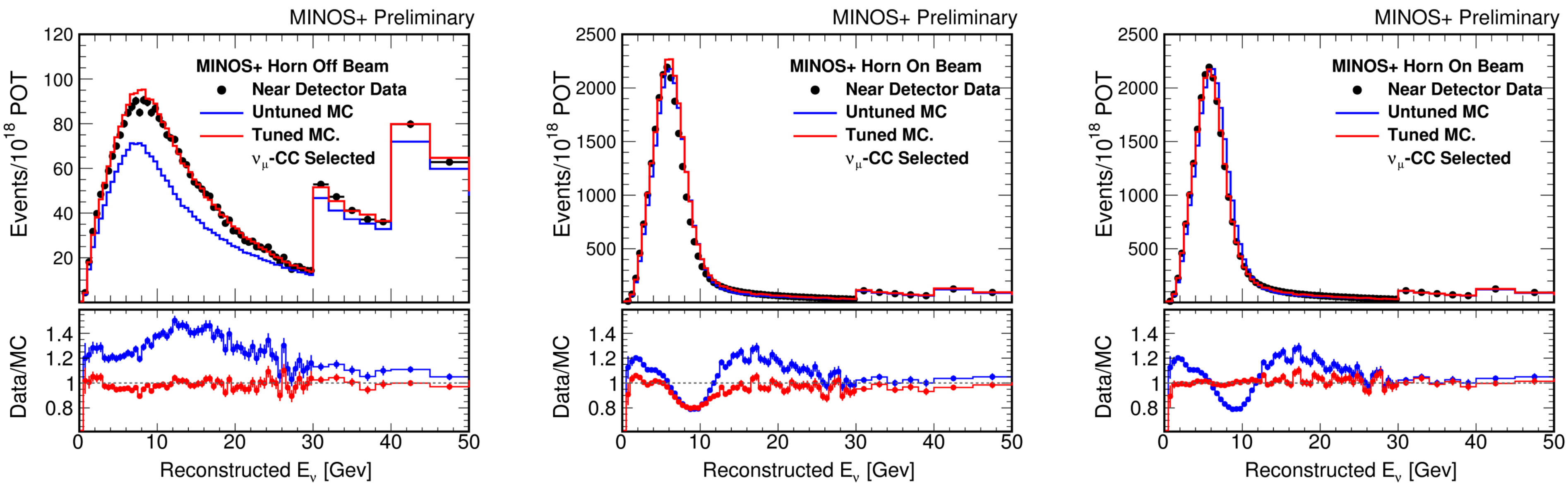
- We then apply these hadron production weights to the standard horn on MC





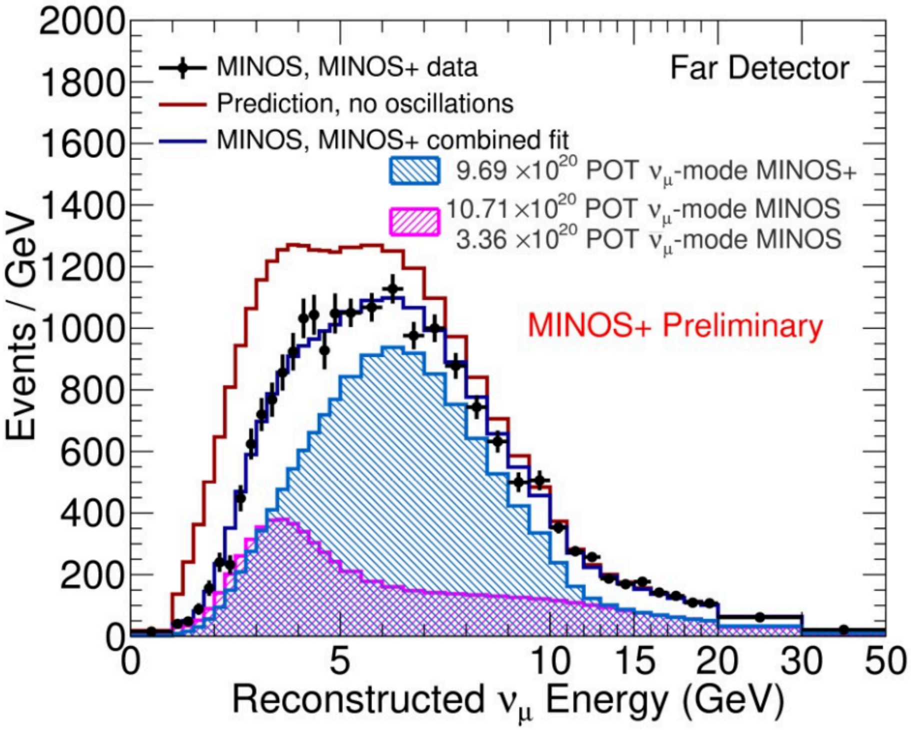
Beam Neutrinos - Flux Prediction

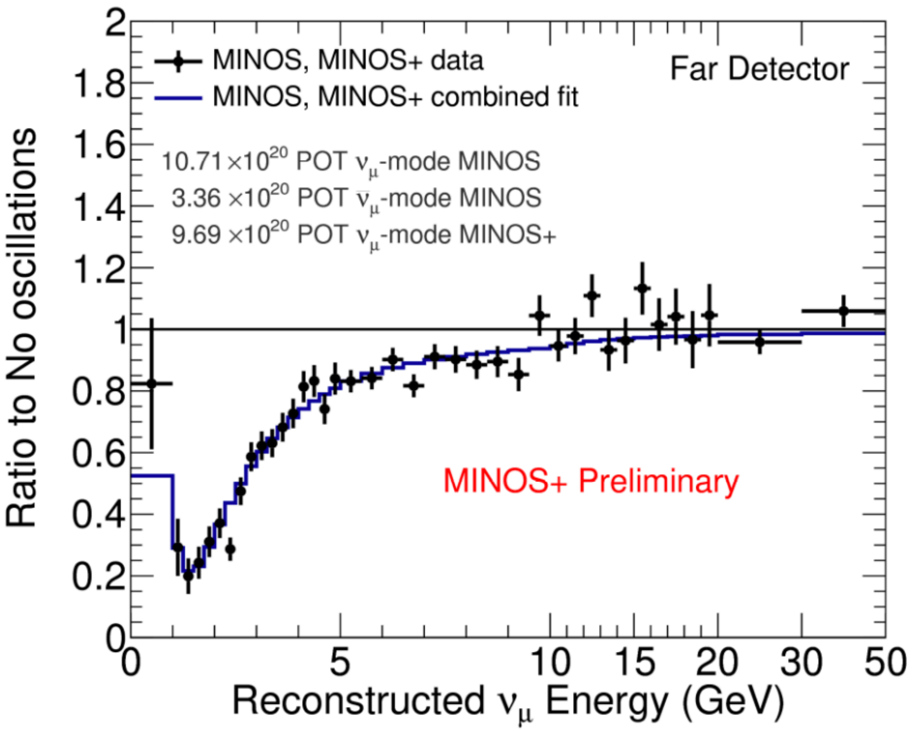
- In our three-flavour analysis we use the ND to tune the MC
- Finally, we fit the standard hour on MC to tune the beam focussing component of the flux prediction



Beam Neutrinos

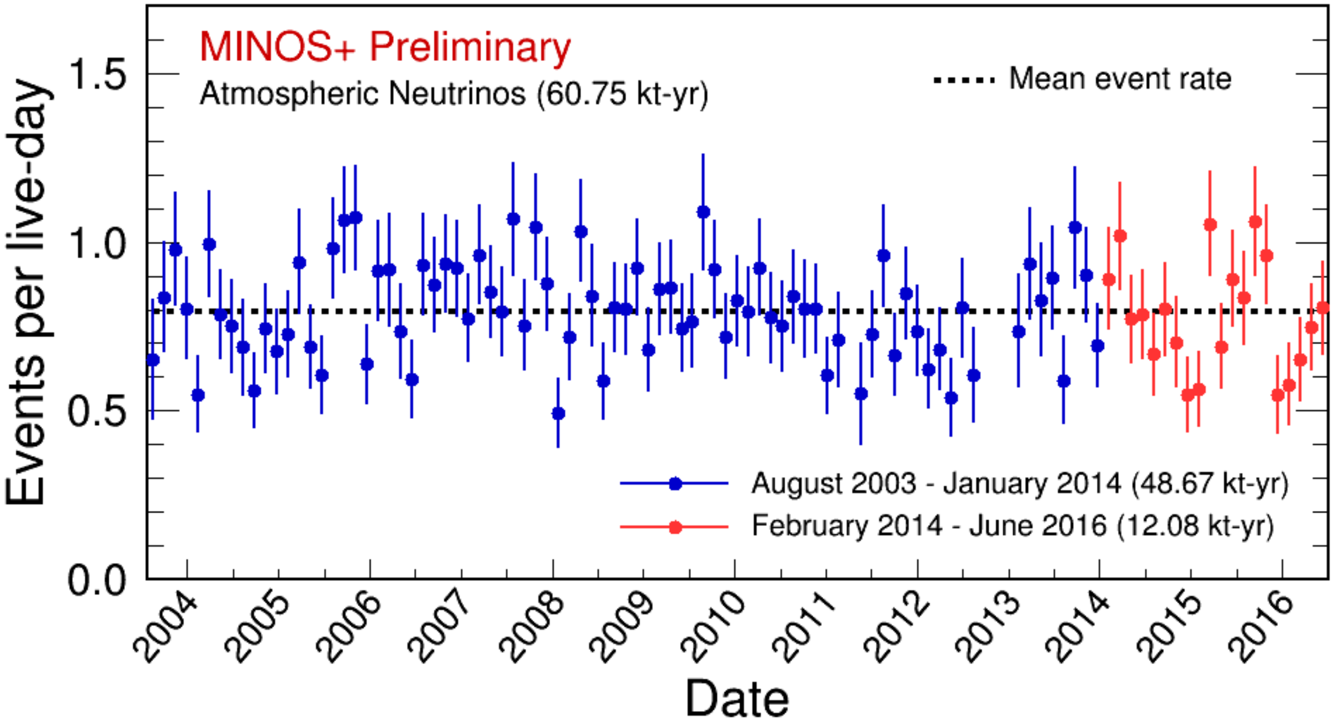
- MINOS was designed to measure the atmospheric scale oscillation parameters.
  - Look for disappearance of muon neutrinos in the FD relative to ND.
  - Measure muon neutrinos through charged current interactions.





Atmospheric Neutrinos

- The MINOS+ Far Detector has collected a large number of atmospheric neutrinos over 12 years
  - Neutrinos and anti-neutrinos separated by curvature in the magnetic field



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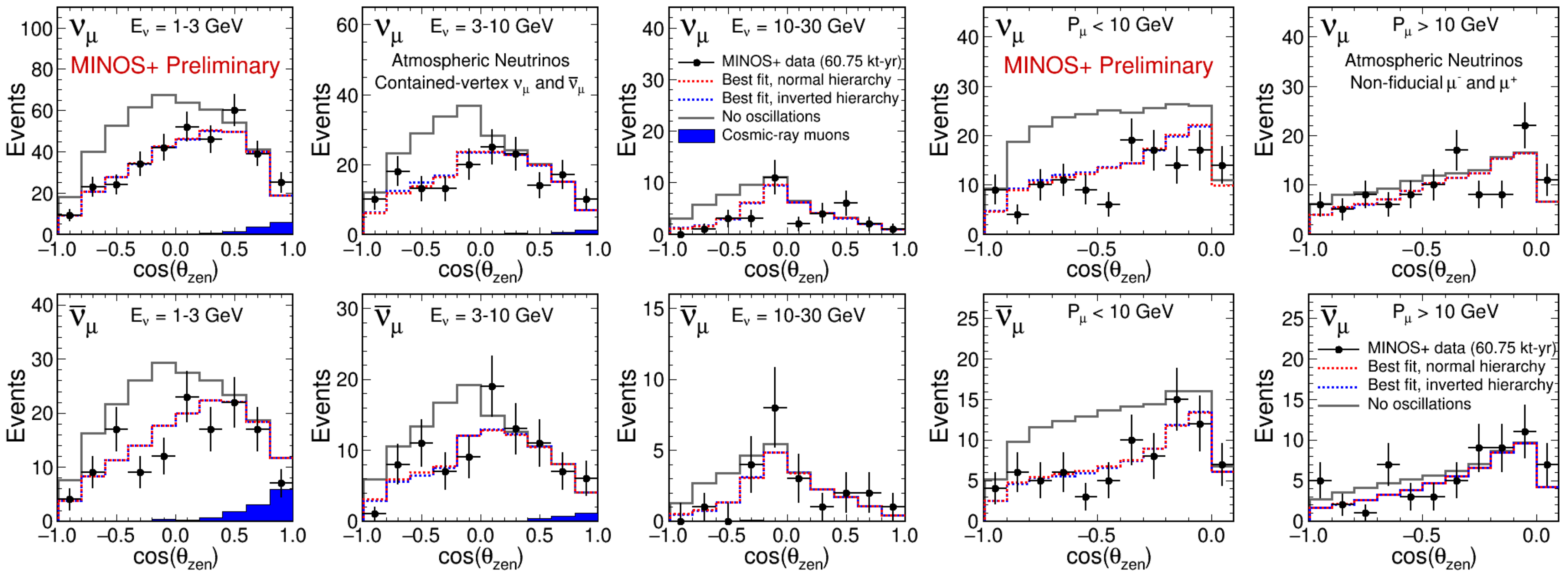
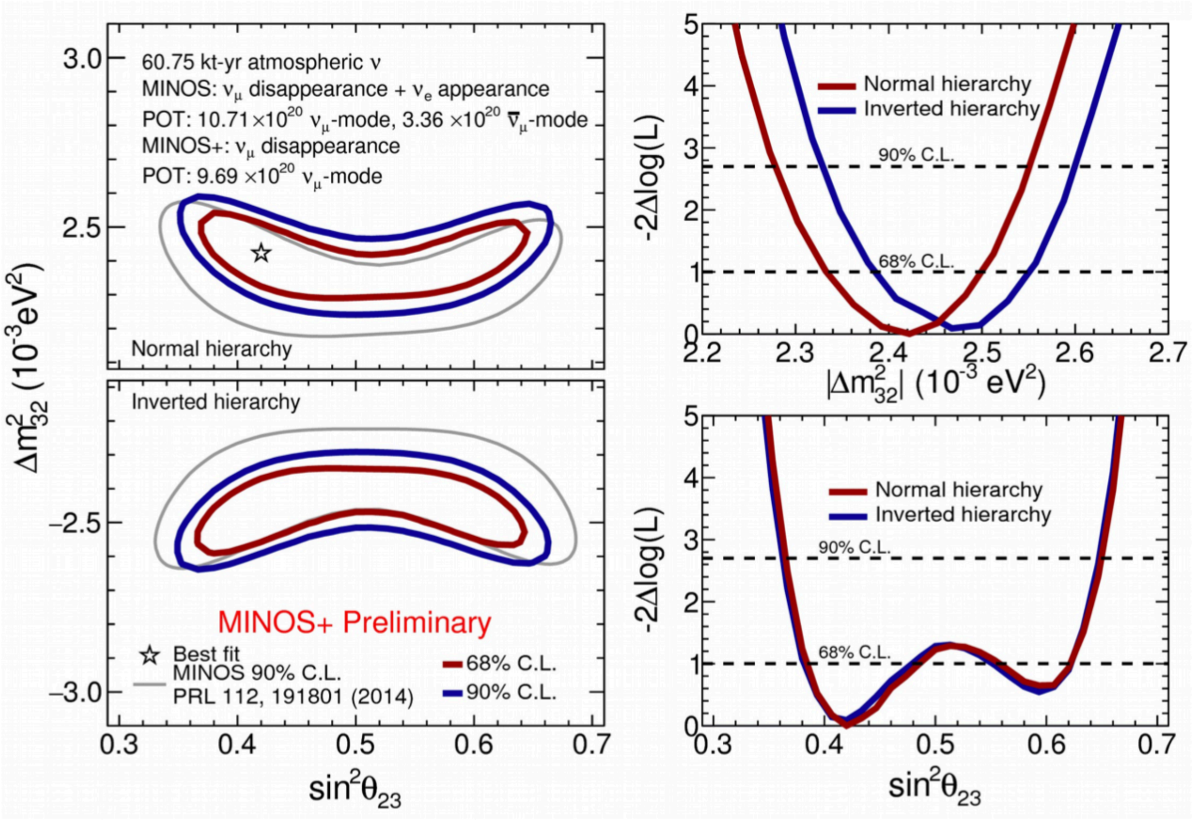


Three Flavour Oscillations

- Fit gives 1D and 2D contours



Best fit

$\Delta m^2_{32} = 2.42\times10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.42$

$|\Delta m^2_{32}|$ 90% C.L. intervals

NH: $(2.28 - 2.55) \times 10^{-3}$ eV^2

IH: $(2.33 - 2.60) \times 10^{-3}$ eV^2

Measured to ~3.5% at 68% C.L.

$\sin^2\theta_{23}$ 90% C.L. interval

0.36 – 0.65

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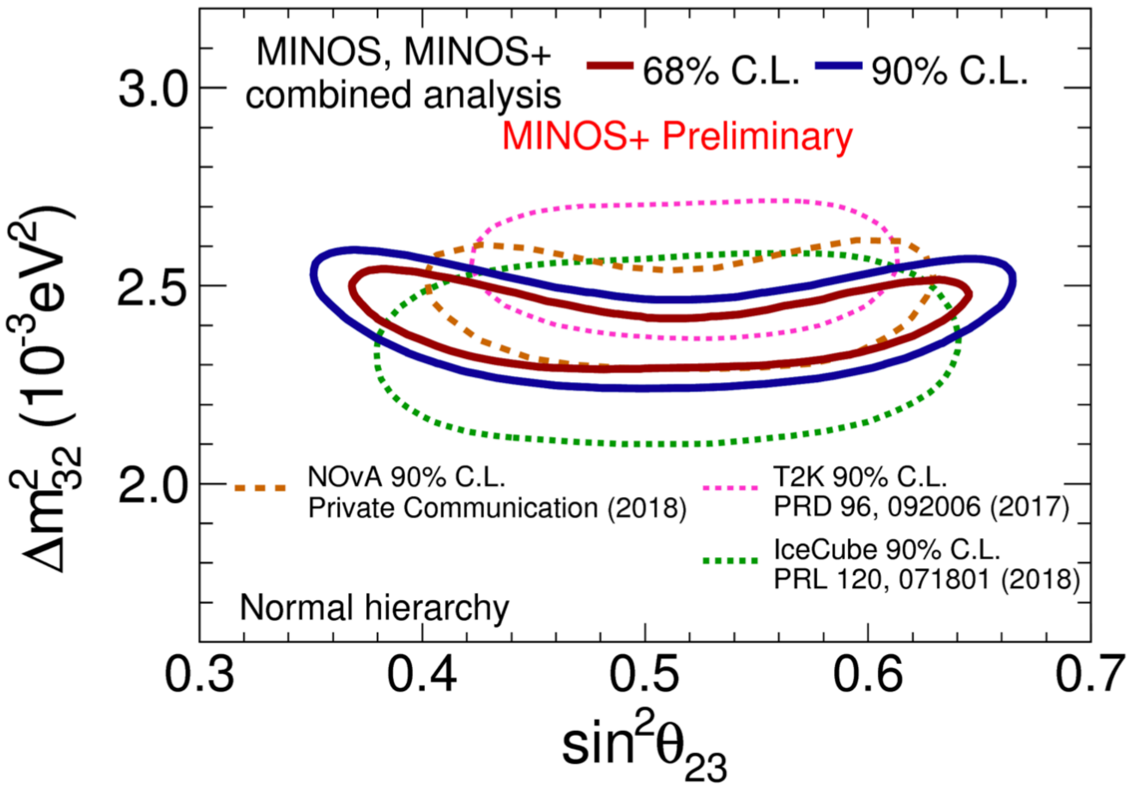

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Beyond Three Neutrino Flavours

How Many Neutrinos?

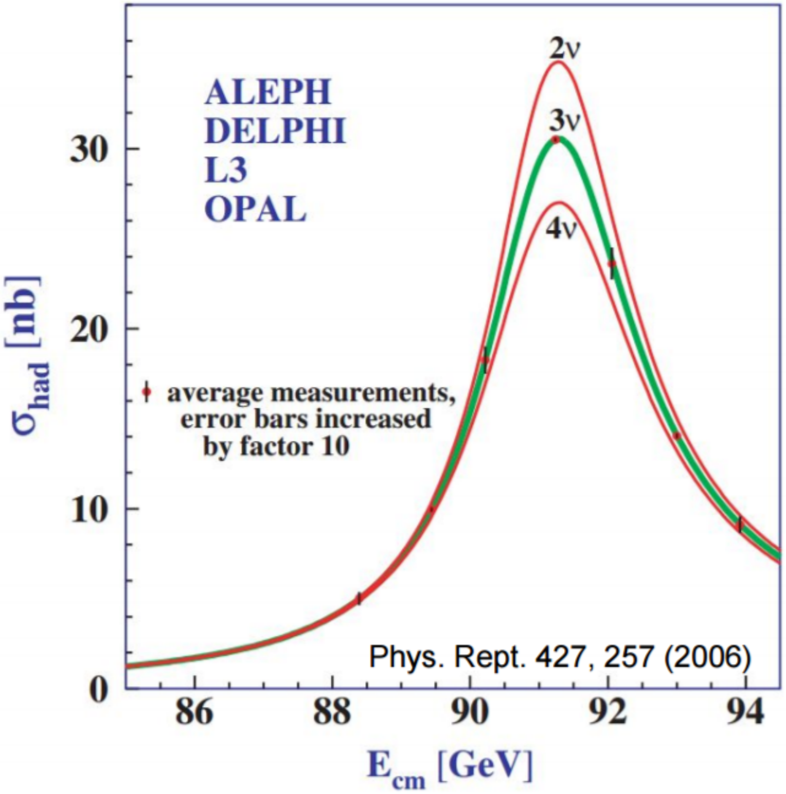
- Invisible width of the Z-boson from LEP very strongly measured that there are 3 neutrinos.

- For $m_\nu < \frac{1}{2} m_Z$ fourth neutrino must not couple to the Z-boson.
  - Hence the name *sterile*.

- Results from Planck:

$$\left.\begin{aligned} N_{\rm eff} &= 3.2 \pm 0.5 \\ \sum m_\nu &< 0.32\ \text{eV} \end{aligned}\right\} \quad 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+BAO}.$$

P. A. R. Ade, et al. (2016) Astron. Astrophys. 594, arXiv 1502.01589



Some Anomalies

- The majority of neutrino oscillation data is well described by the three flavour model.
  - However, there are some outliers.

- Anomalous appearance of ν_e in short-baseline ν_μ beams.

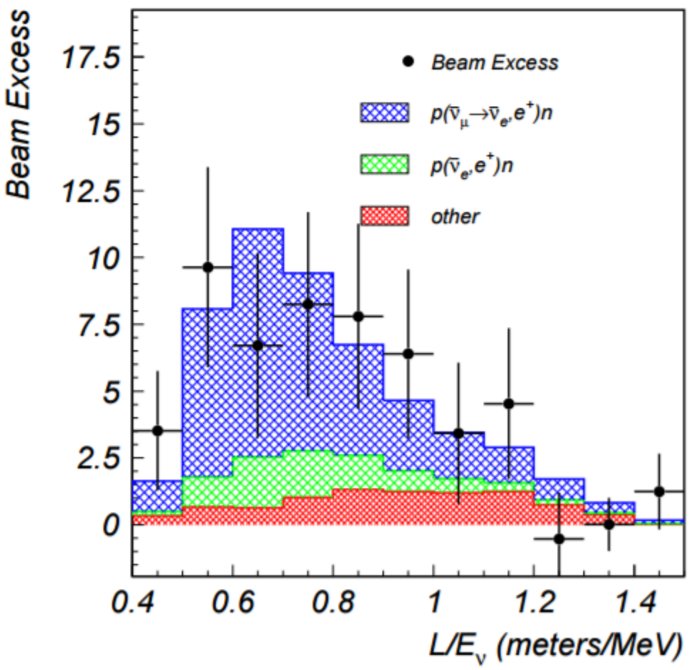
- Gallium experiment calibration sources.

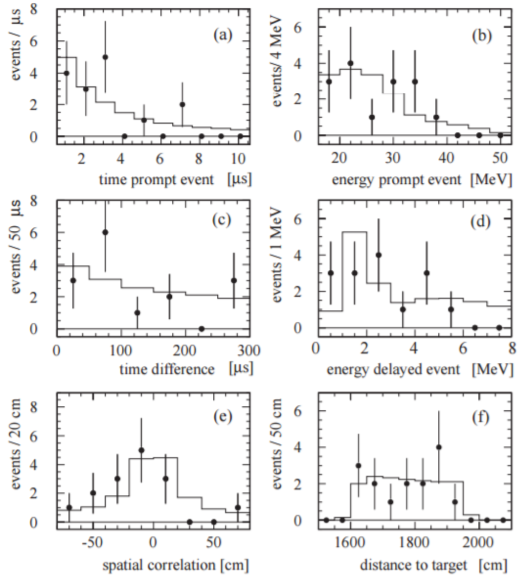
- Reactor neutrino flux deficit.

- The main point is that all three anomalies were consistent with oscillations at a mass-splitting scale of approximately 1 eV^2

Some Anomalies - 1

- LSND saw an excess of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
  - Could be interpreted as oscillations at a mass-splitting scale of approximately 1 eV^2
- However, KARMEN2 saw results consistent with expectation.



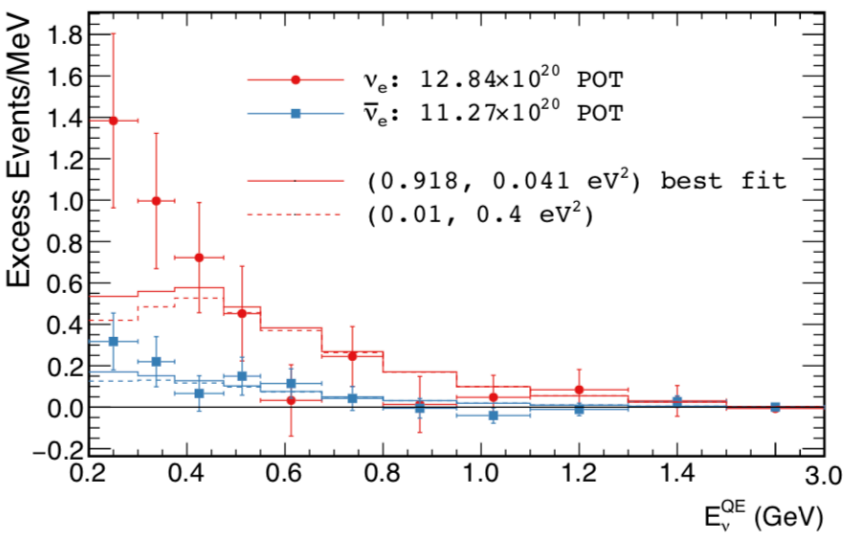


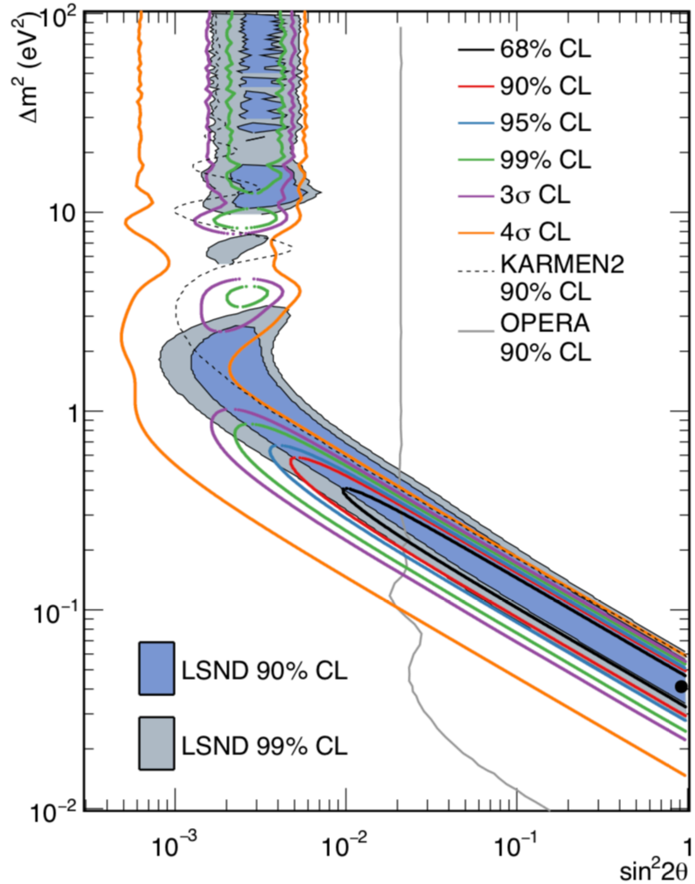
- The MiniBooNE experiment was devised to investigate these differing results…
  - Looked at $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$

Some Anomalies - 1

- MiniBooNE saw excess appearance in both neutrino and anti neutrino channels.

- Not identical to LSND, but allowed similar regions of phase-space.

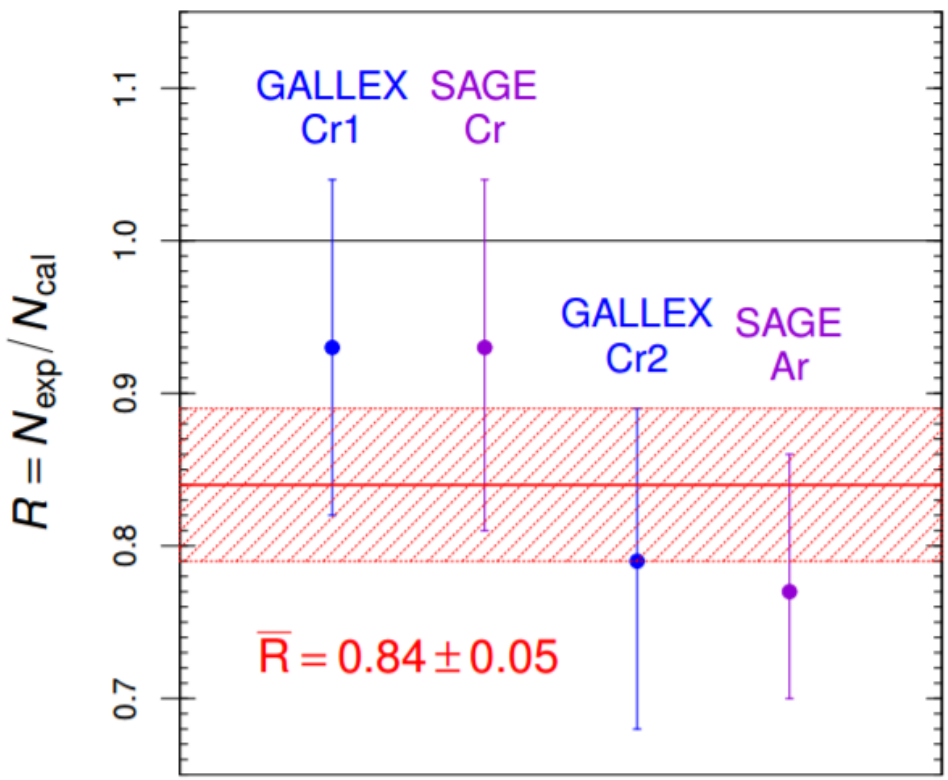




A. Aguilar-Arevalo et al. Phys. Rev. Lett. 121 (2018), p. 221801.

Some Anomalies - 2

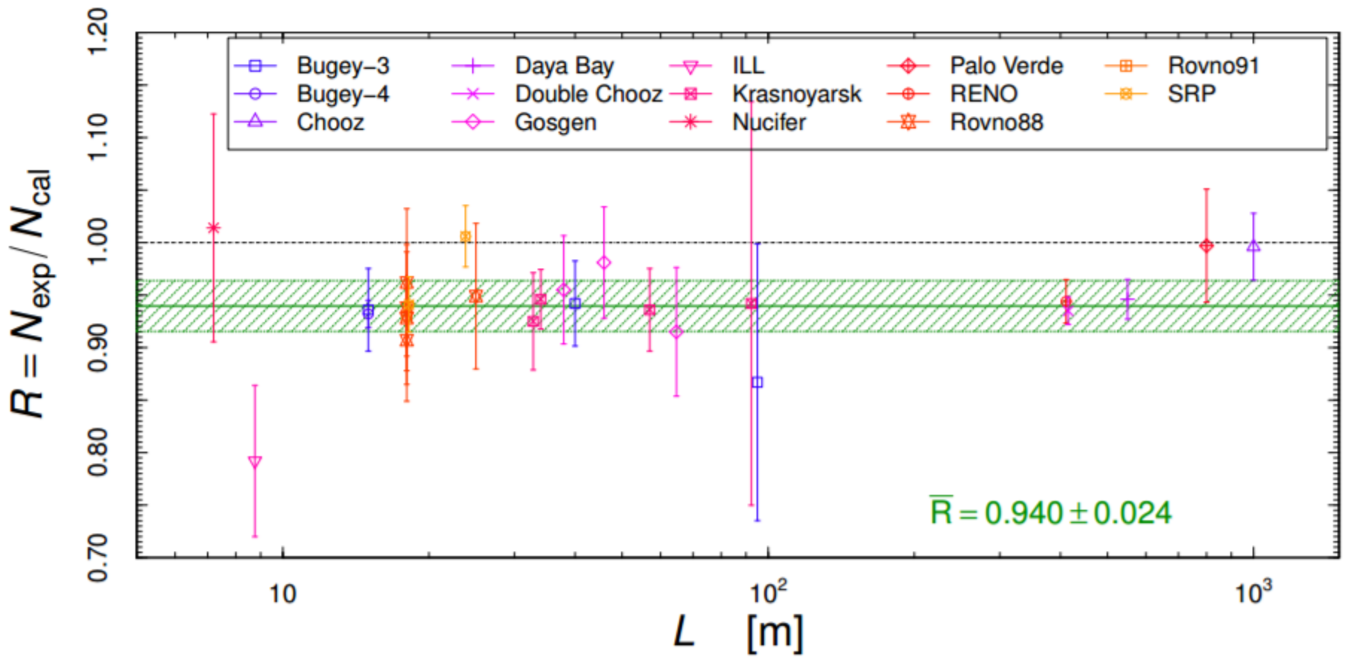
- GALLEX and SAGE were two solar neutrino experiments.
- Calibrated using radioactive sources.
- Measured rates from the calibration sources showed consistent deficits.
- Again, consistent with a 1 eV^2 mass-splitting.



Gariazzo et al. J.Phys. G43 (2016) 033001
DOI:10.1088/0954-3899/43/3/033001

Some Anomalies - 3

- The majority of reactor neutrino experiments have seen a deficit of $\overline{\nu}_e$.

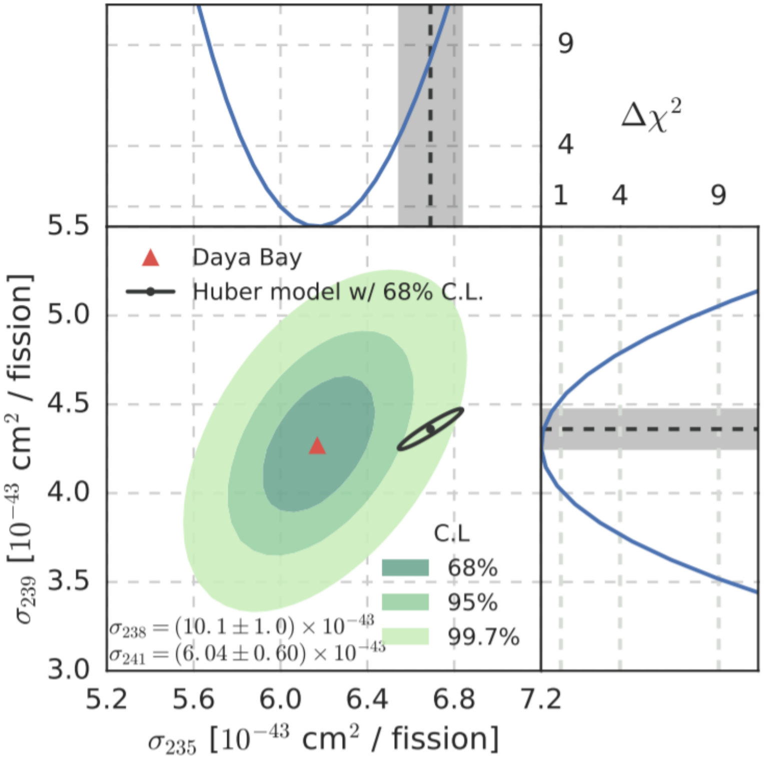


Gariazzo et al. (2017). arXiv: 1703.00860 [hep-ex]

- Again, consistent with a 1 eV^2 mass-splitting, but…

Some Anomalies - 3

- Daya Bay released results from studying their flux as a function of reactor fuel cycles to extract information on the uranium and plutonium components.
- Flux deficit appears to only come from the uranium flux.
- The sterile neutrino hypothesis for the reactor anomaly is: “incompatible with Daya Bay’s observation at 2.6σ”.

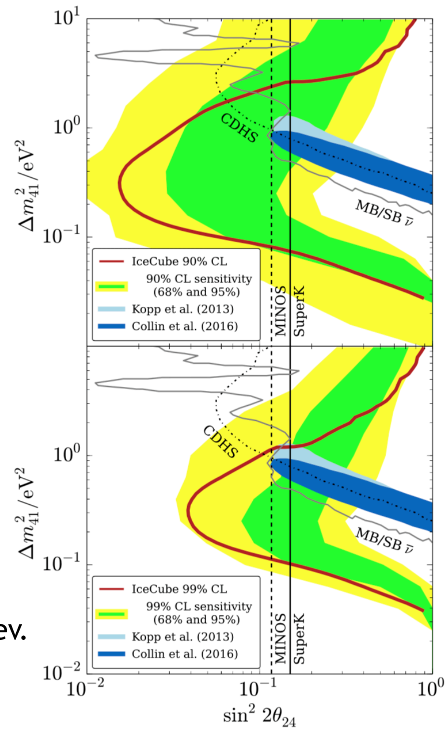


An et al. (2017). arXiv: 1704.01082 [hep-ex]

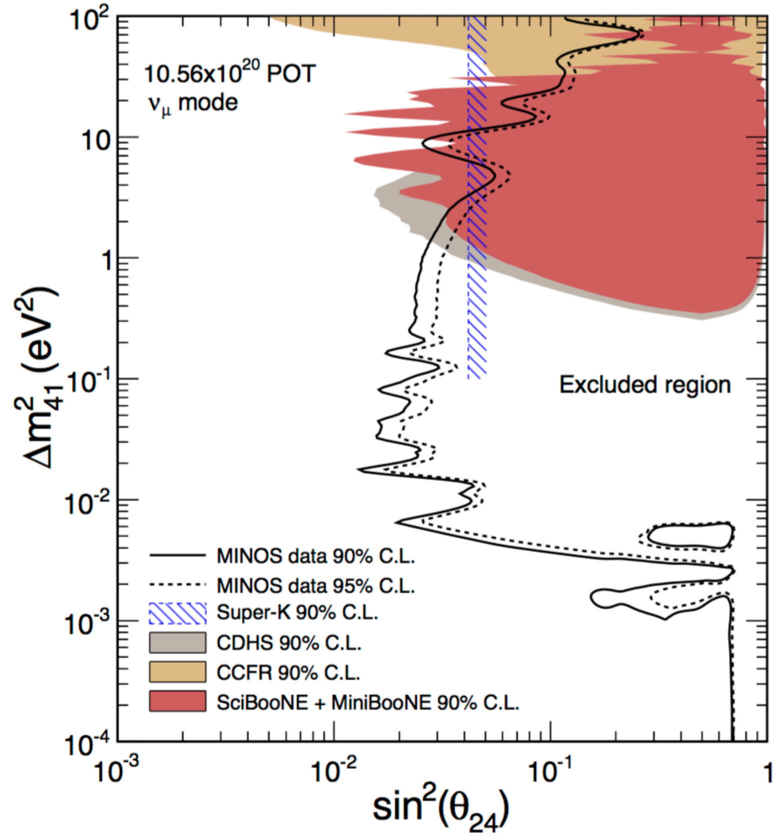
Null Results

- A number of muon neutrino disappearance experiments see no evidence of a sterile neutrino.

- MiniBooNE + SciBooNE
- MINOS
- IceCube
- CDHS
- CCFR
- Super-K
- …



M. G. Aartsen et al. Phys. Rev. Lett. 117, 071801 (2016)



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

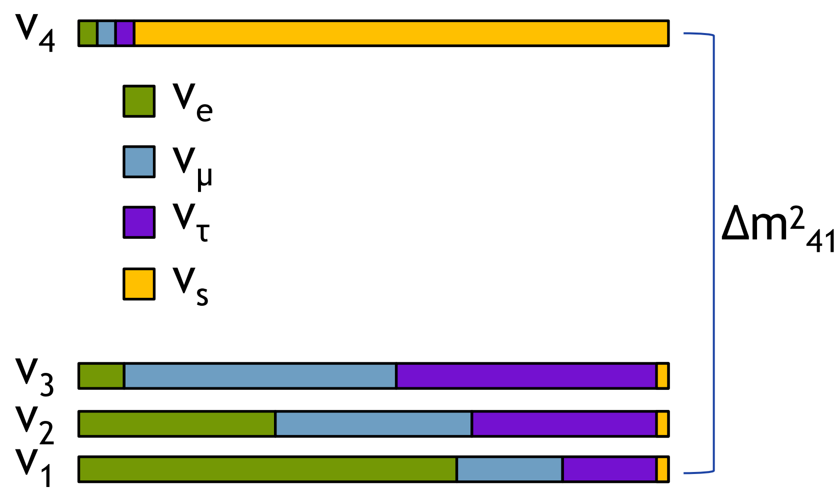
Four Flavour Formalism

- Most common extension to include a 4th neutrino is the 3+1 model.

$$\begin{pmatrix} & U_{PMNS} & & U_{e4} \\ & & & U_{\mu 4} \\ & & & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- PMNS matrix becomes 4 x 4
  - Three new mixing angles: θ_{14} , θ_{24} and θ_{34}
  - Two new CP phases: δ_{14} and δ_{24}

- Three new mass-splittings, but only one is independent.
  - Δm^2_{41}



MINOS+ Four Flavour Oscillation Analysis

Sterile Oscillations in MINOS+

- MINOS+ is sensitive to three of the sterile oscillation parameters.

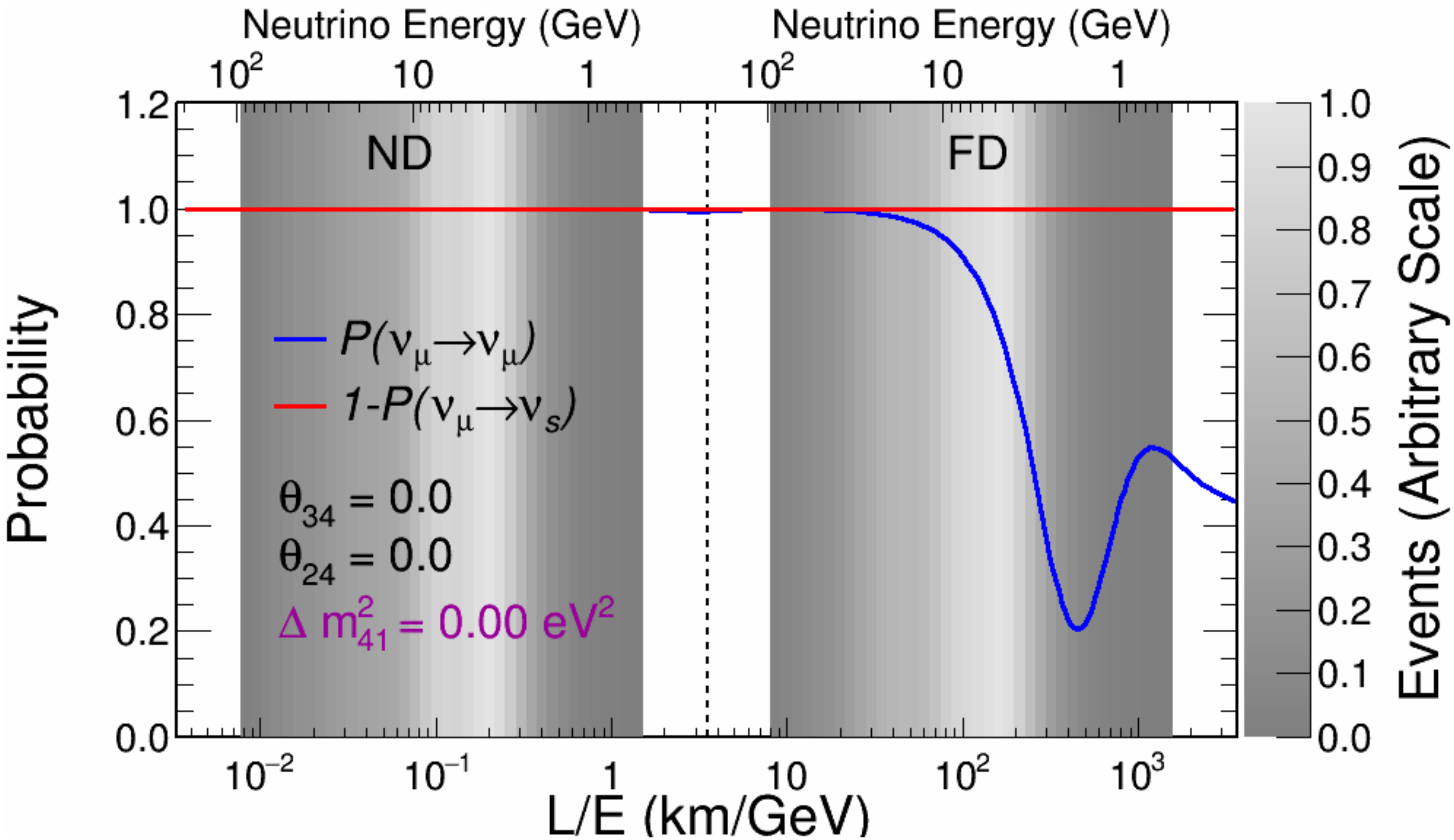
- Muon neutrino disappearance: θ_{24} and Δm^2_{41}
  - Measured with muon neutrino charged-current events.

- Active neutrino disappearance: θ_{24} , θ_{34} and Δm^2_{41}
  - Measured using neutral-current interactions.
  - Sensitivity reduced compared to CC due to worse energy resolution and lower cross-section.

- Oscillations can cause effects in both detectors depending on the value of Δm^2_{41}

Sterile Oscillations in MINOS+

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



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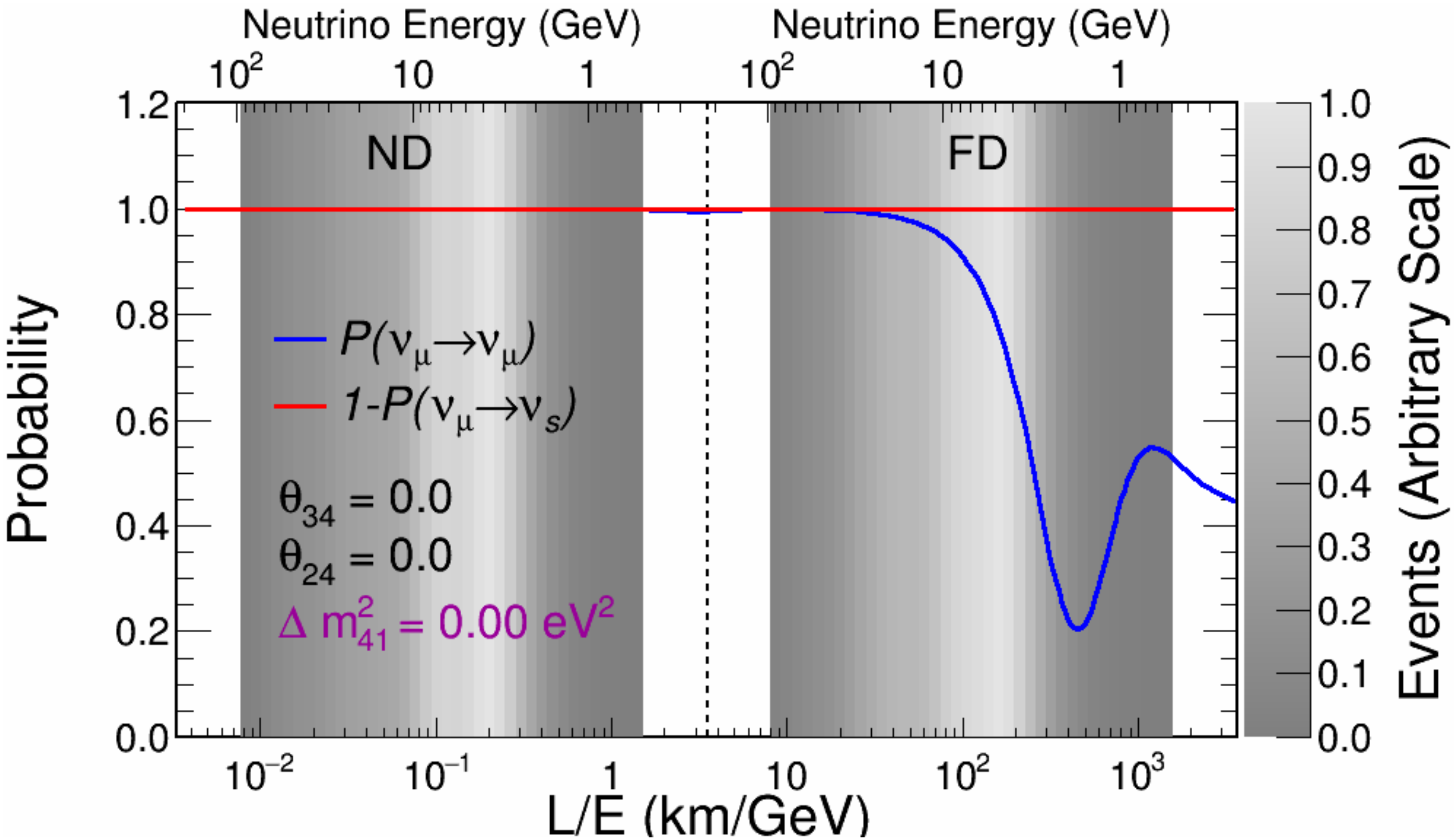

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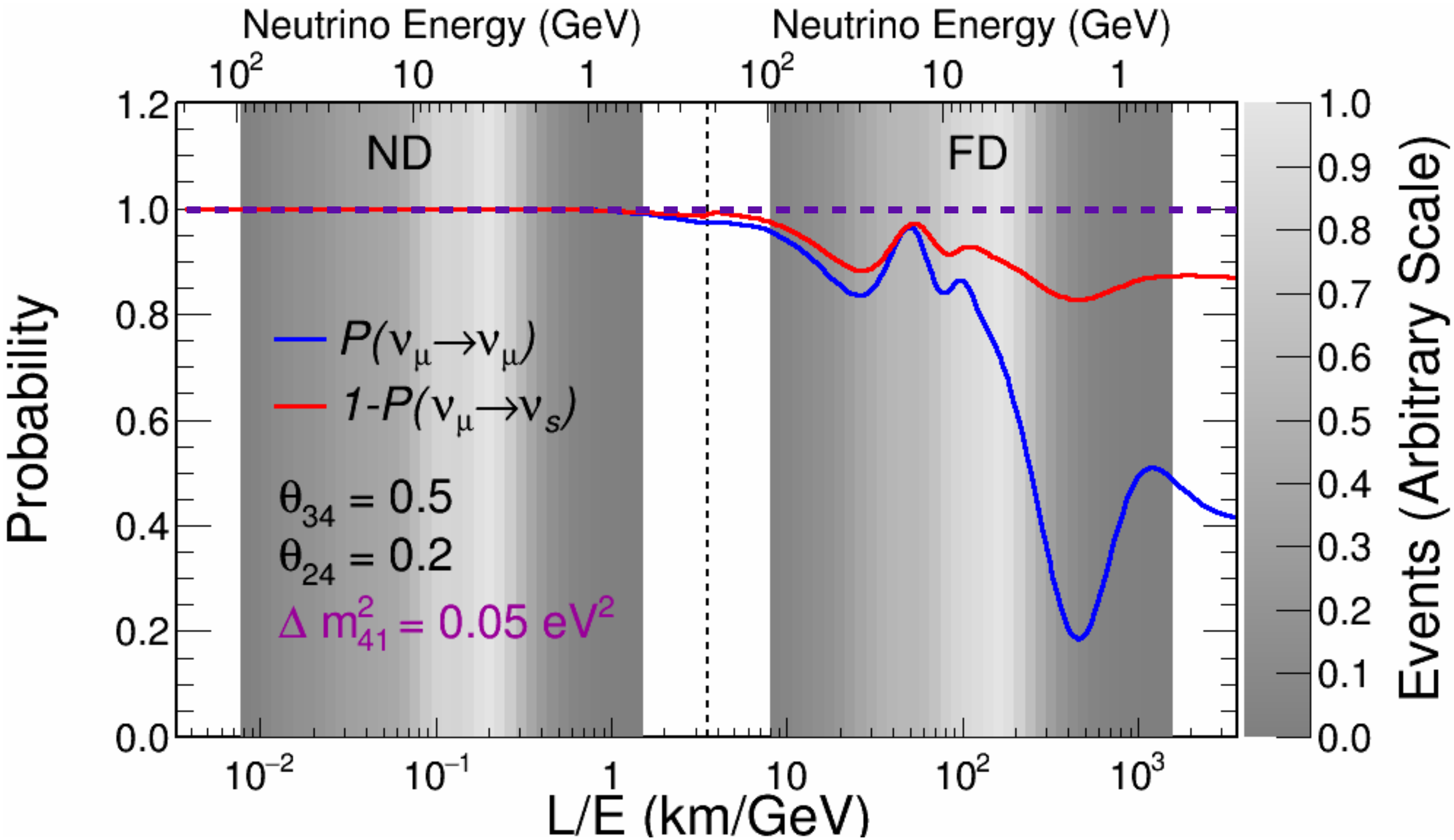
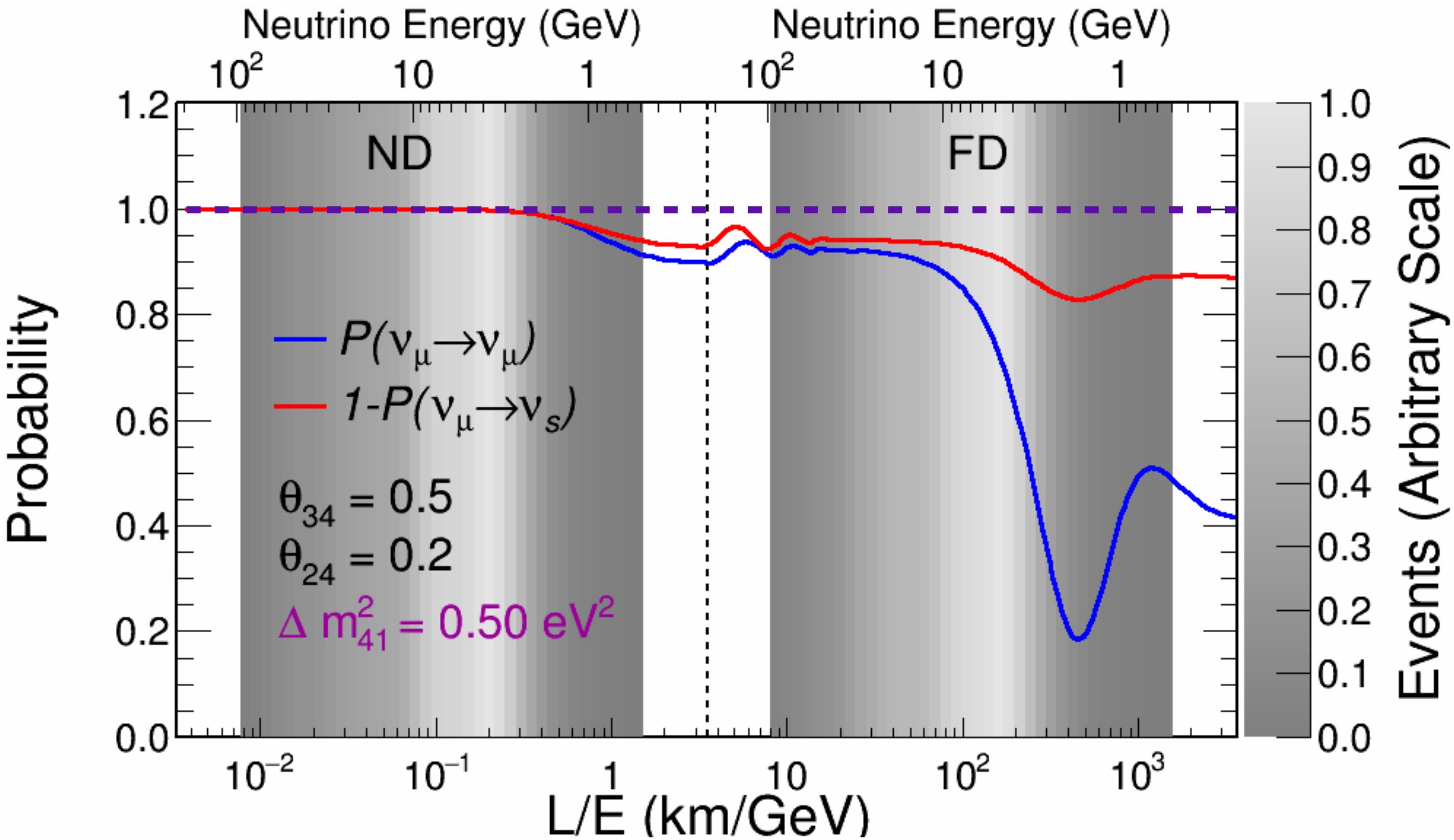


Sterile Oscillations in MINOS+

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



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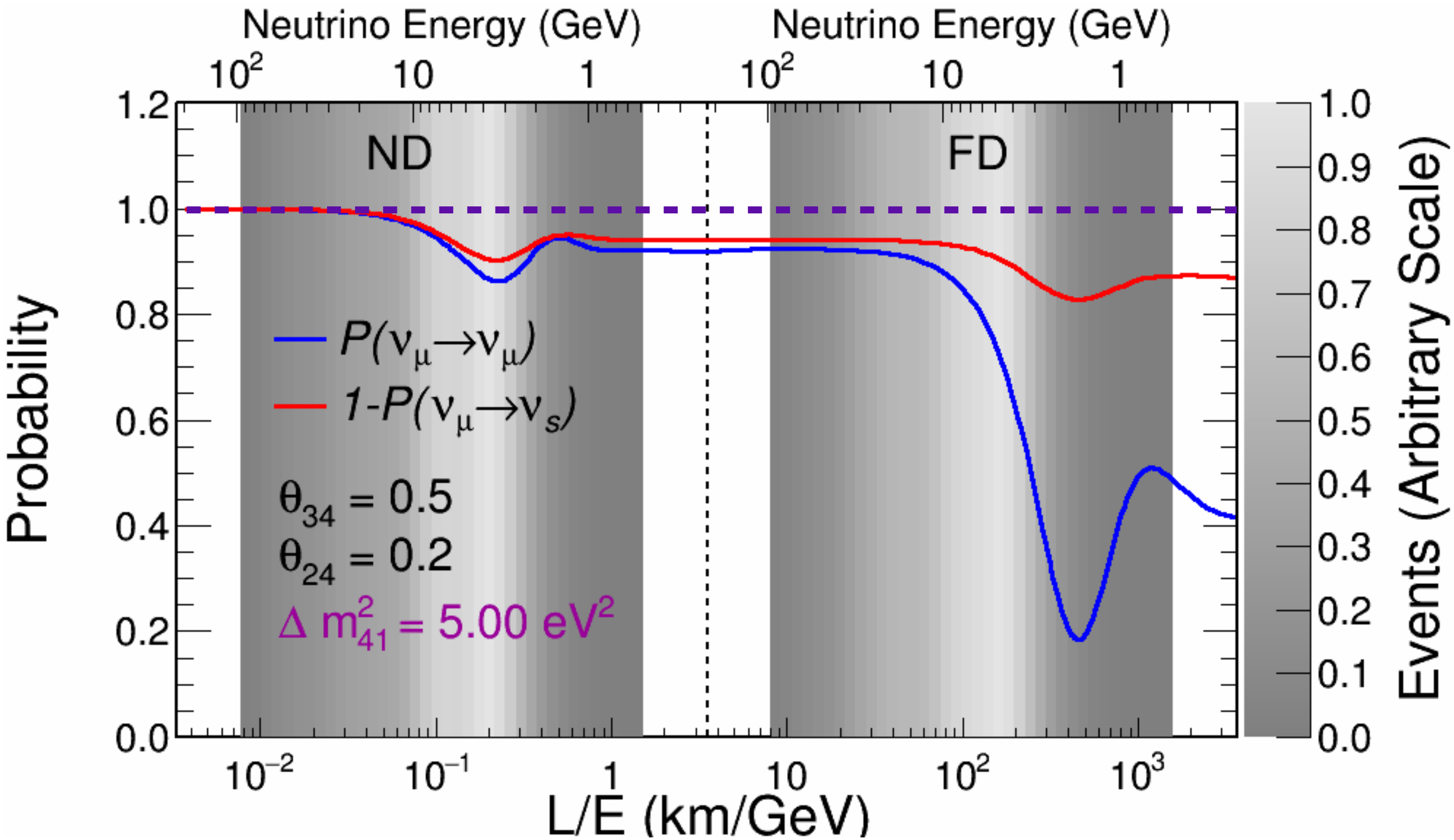
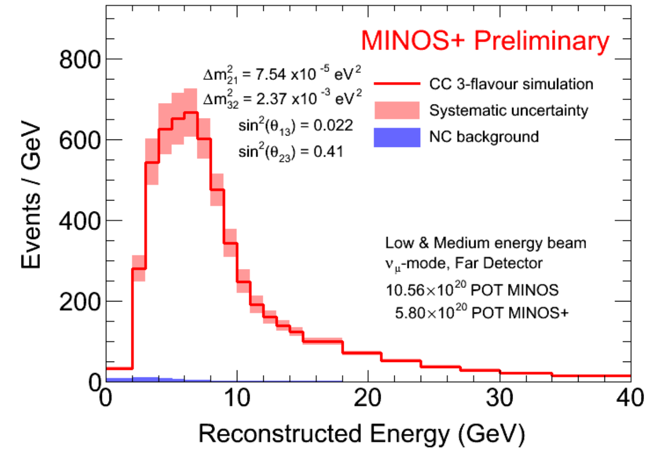
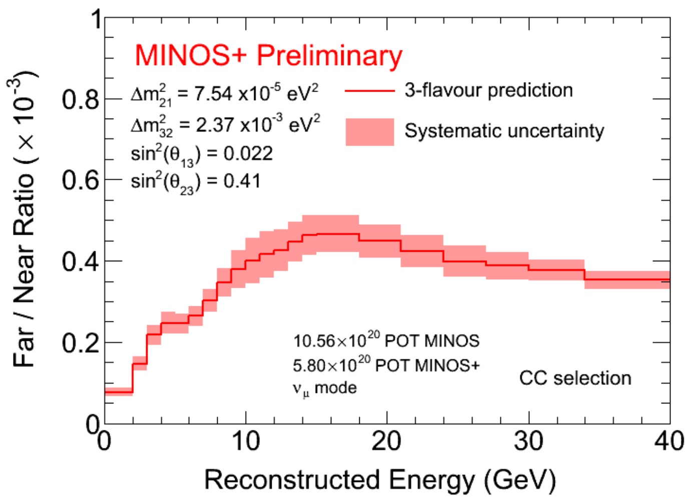
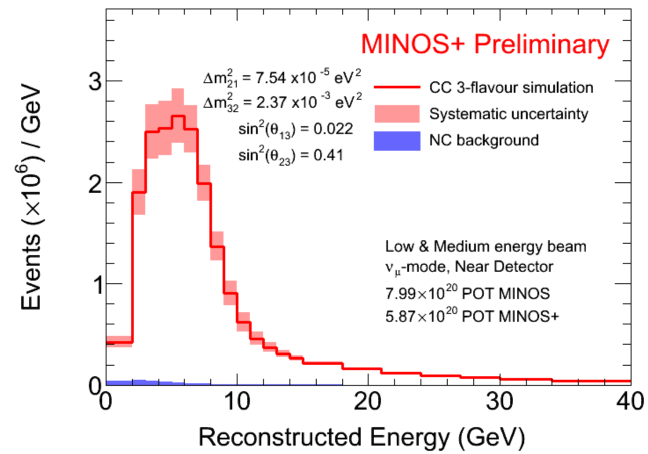


Analysis Method

- The previous MINOS sterile neutrino analysis used the ratio of the Far and Near spectra.
  - Can't use the ND to tune the MC like in our three-flavour analysis.
  - Many systematics cancel in the ratio.







- Uncertainty in the ratio was dominated by FD statistics.

The Two Detector Fit

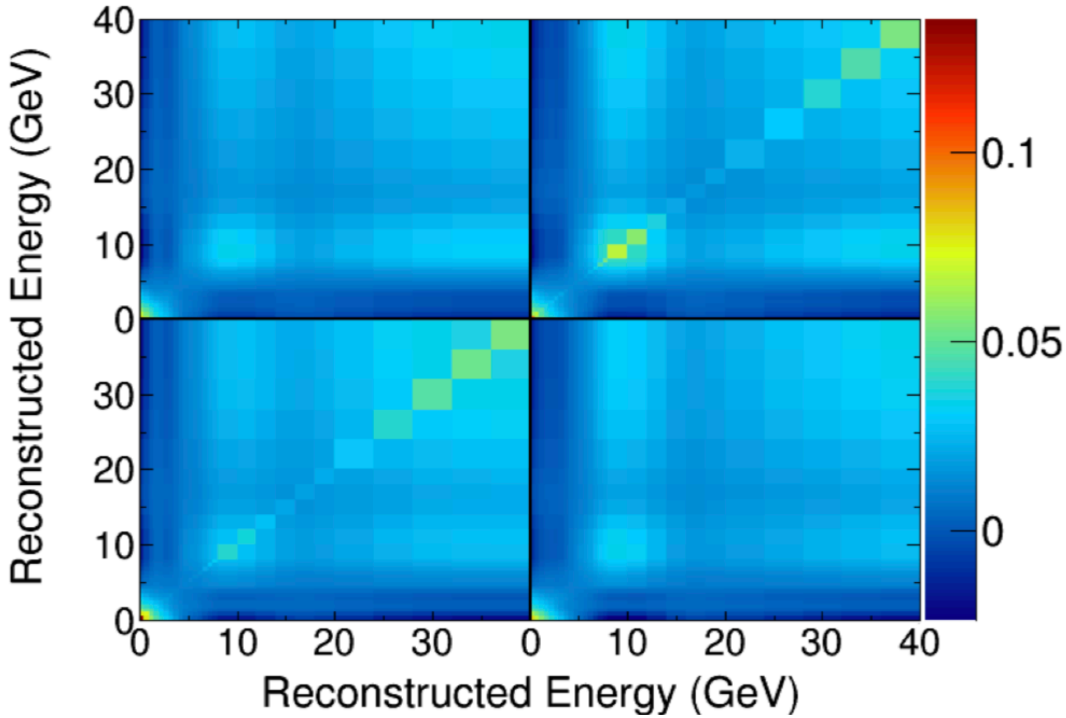
- We have now moved to a simultaneous two detector fit.
  - Use the a-priori flux prediction from MINERvA [1]

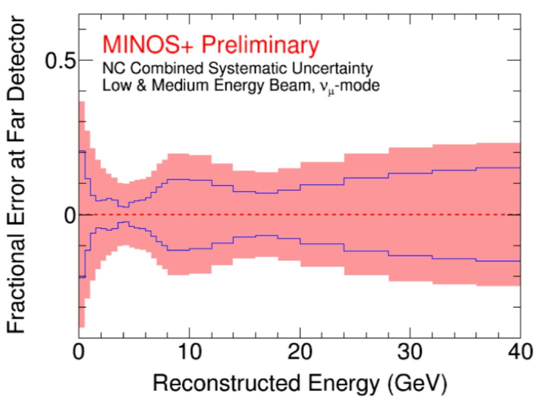
- We use a single covariance matrix that encapsulates the correlations between the systematic uncertainties.
  - This still enables us to have some cancellation of the systematic uncertainties without using the Far-over-Near ratio.

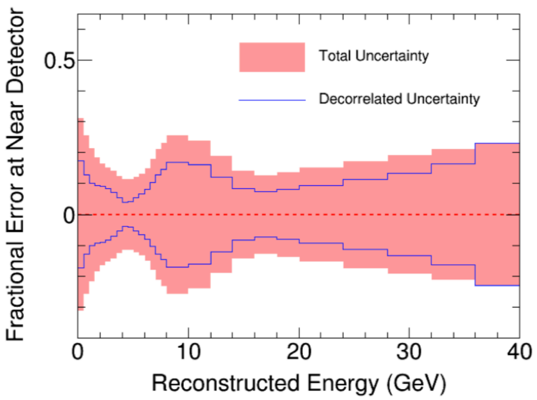
- Consider a total of 44 systematic uncertainties across the different event selections.

[1] L. Aliagia, et al, Phys. Rev. D 94, 092005, 2016

Systematic Uncertainties: NC

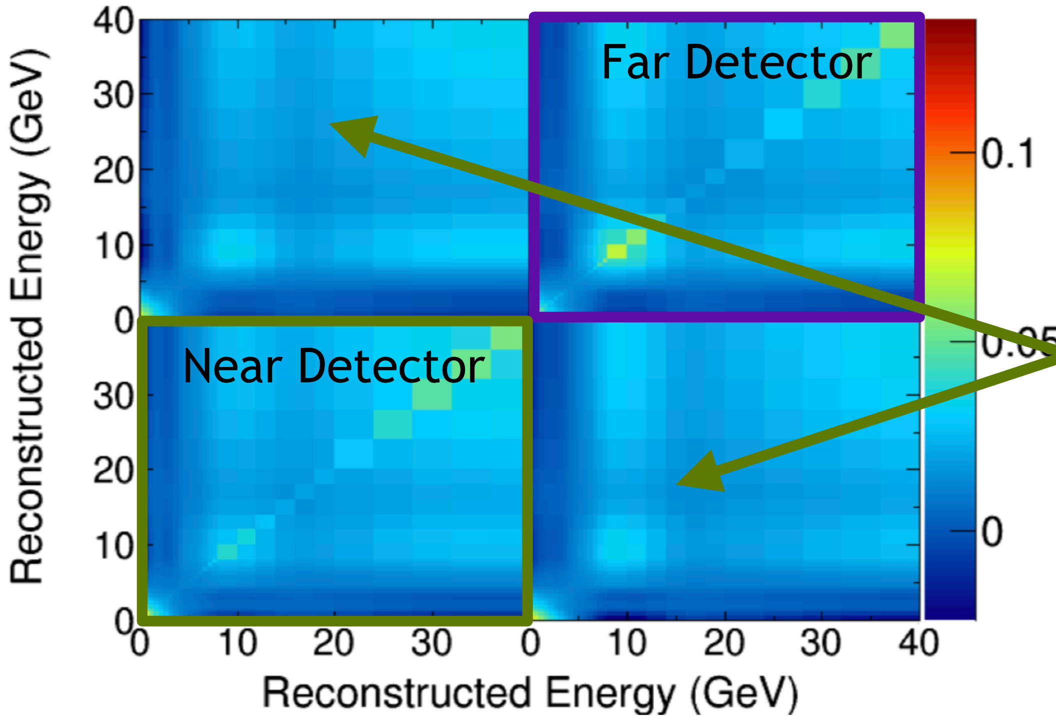






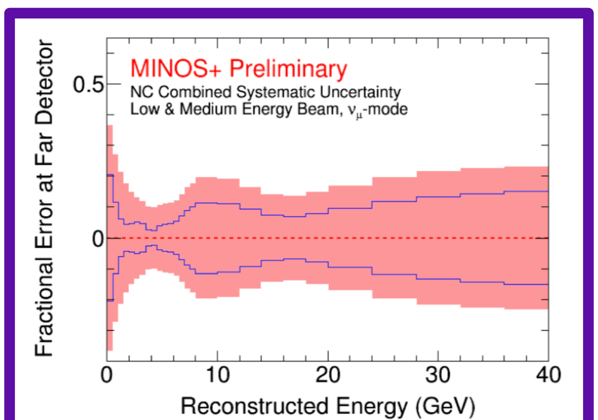
Systematic Uncertainties: NC

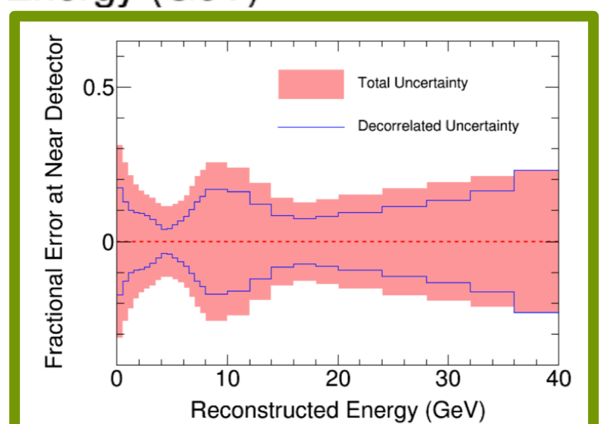
Diagonal components form the bands below



Correlations between the two detectors

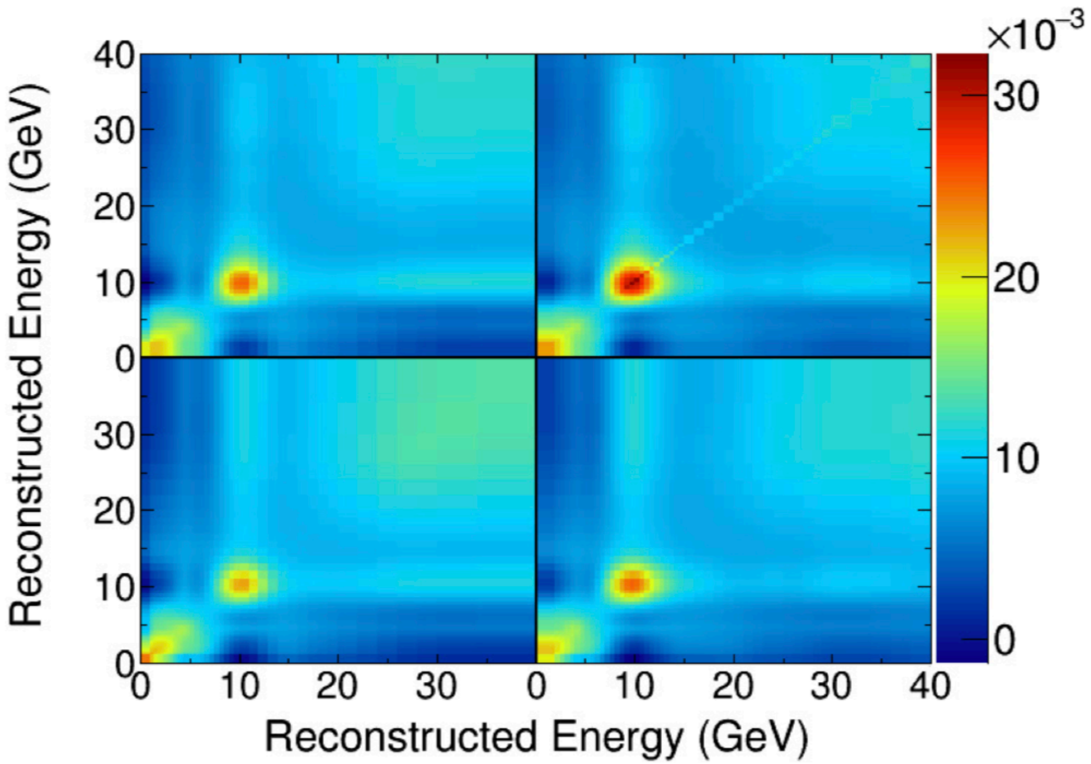
Far Detector



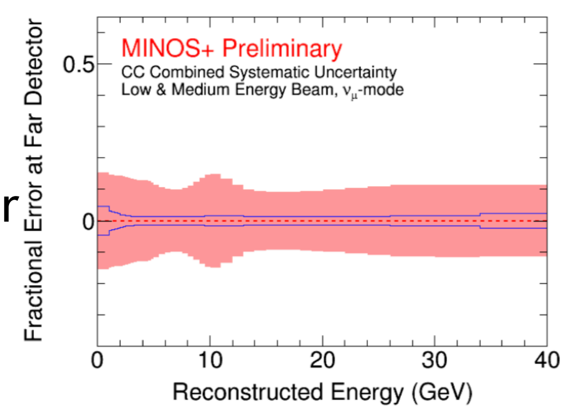


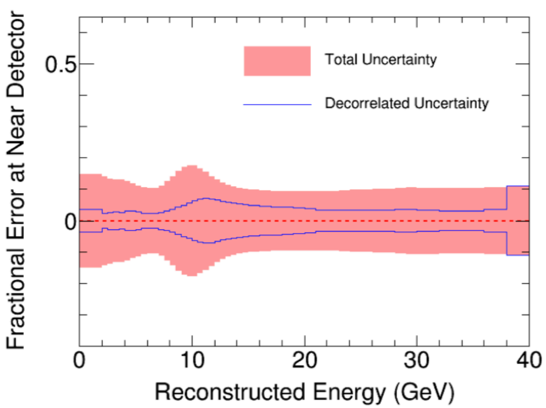
Near Detector

Systematic Uncertainties: CC



Far Detector





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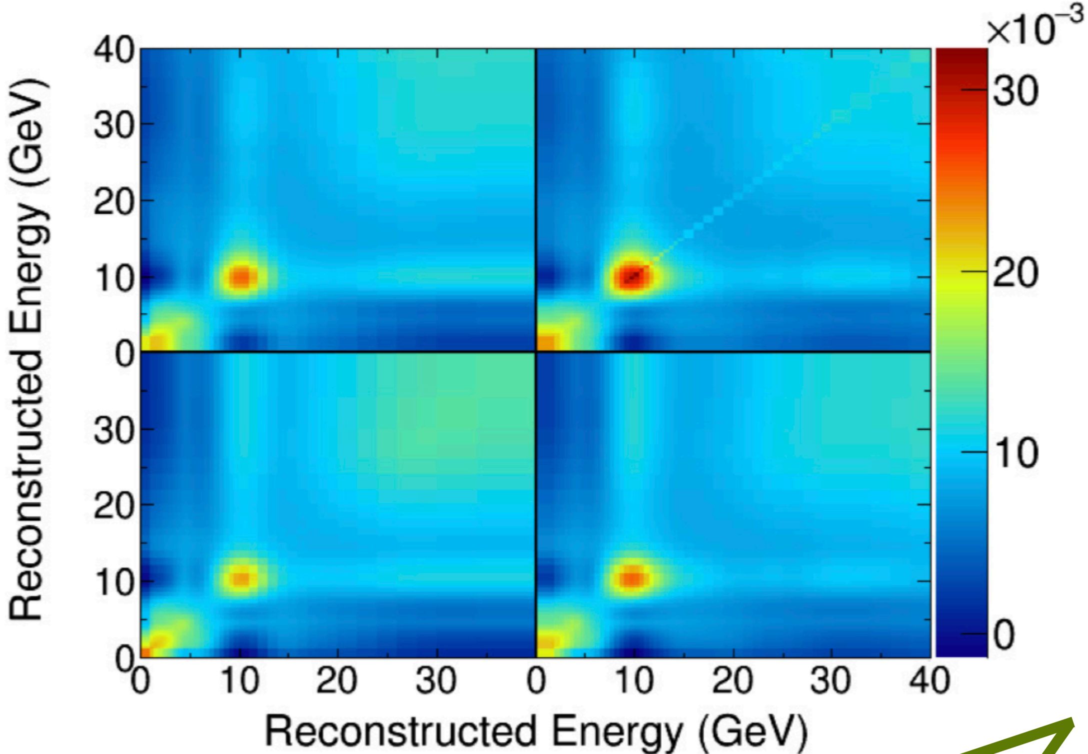
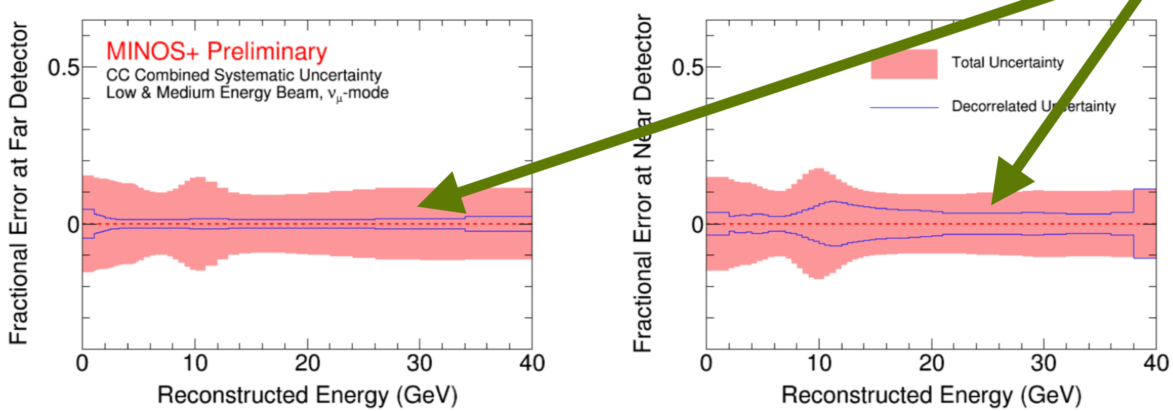




Strong correlations between the detectors gives strong cancellation of systematic uncertainties

The Fit Procedure

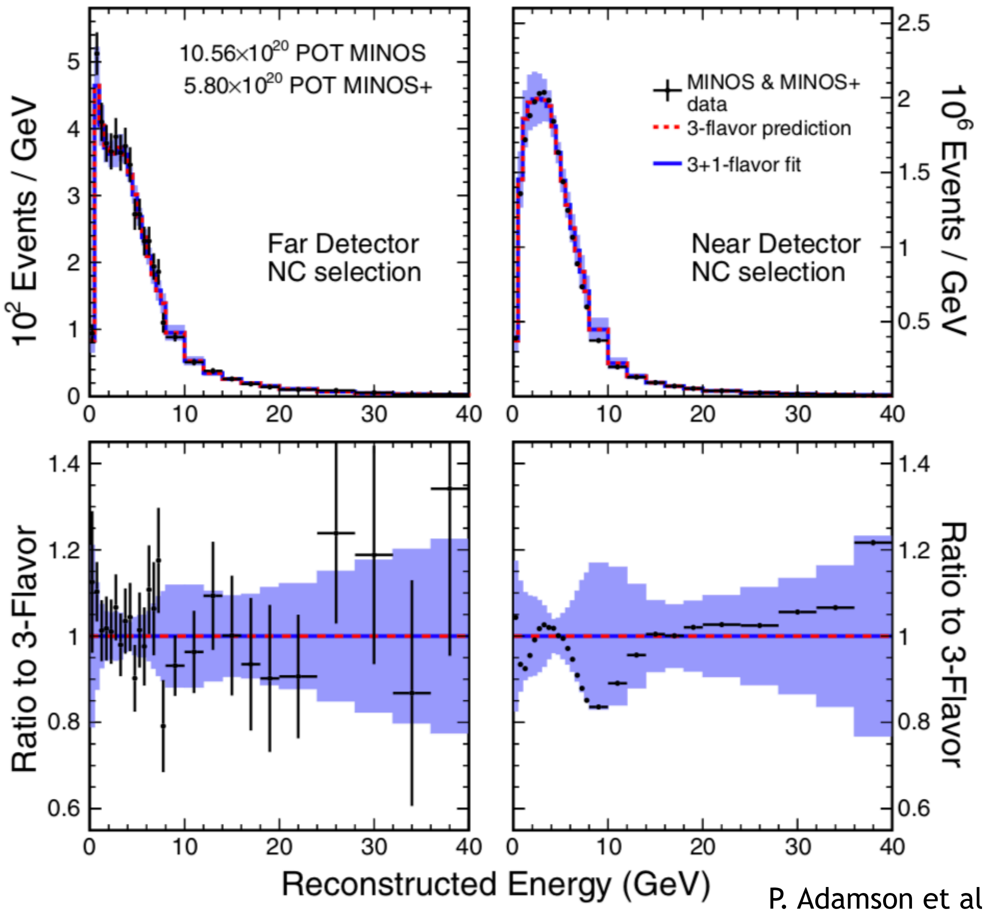
- Perform a fit to minimise the following for both the CC and NC samples

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(x_i - \mu_i)\left[V^{-1}\right]_{ij}(x_j - \mu_j) + \text{penalty}$$

- We fit for Δm^2_{41}, Δm^2_{32}, θ_{23}, θ_{24} and θ_{34}
- Global best fit values are used for Δm^2_{21}, θ_{12} and θ_{13}
- The other parameters have a negligible effect on the analysis and are set to zero: θ_{14}, δ_{13}, δ_{14} and δ_{24}
- Penalty term prevents from Δm^2_{32} becoming degenerate with Δm^2_{41}

Event Spectra: NC Selection

- Spectra shown after correcting the prediction after decorrelation of the covariance matrix



P. Adamson et al., Phys. Rev. Lett. 122, 091803 (2019).

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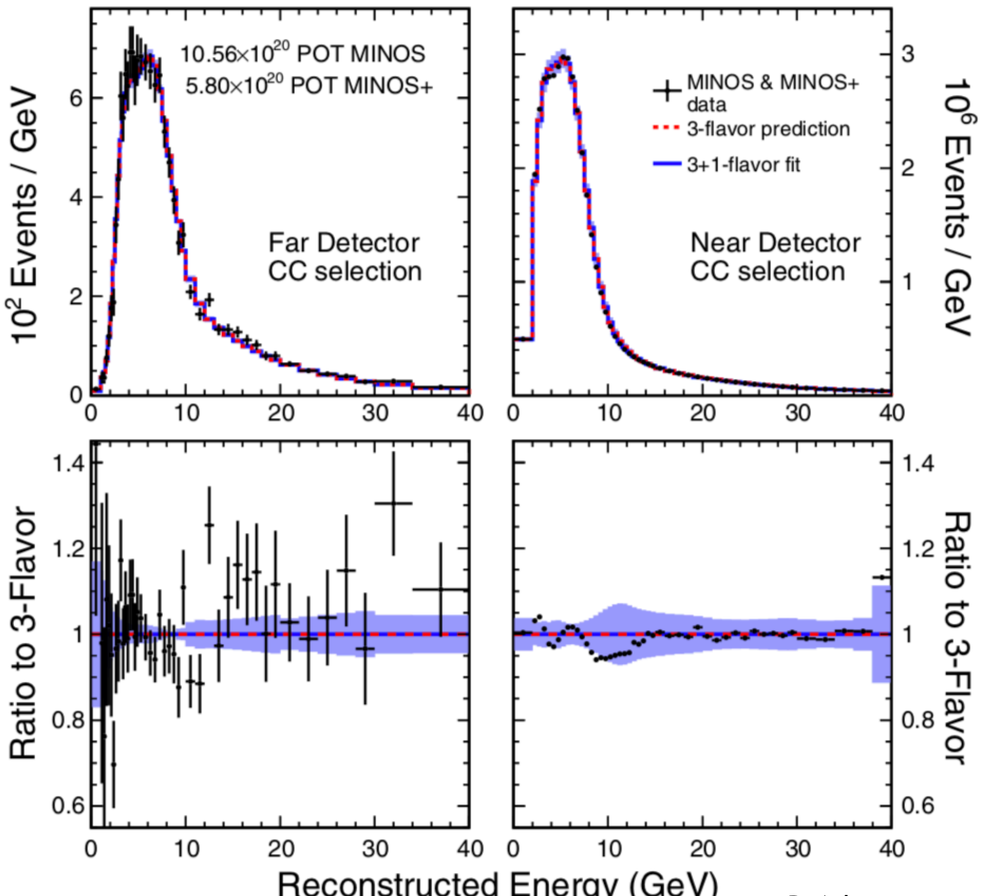


P. Adamson et al., Phys. Rev. Lett. 122, 091803 (2019).

The Fit Result

- Best fit point:

$\Delta m^2_{41} = 2.33\text{x}10^{-3}\ eV^2$

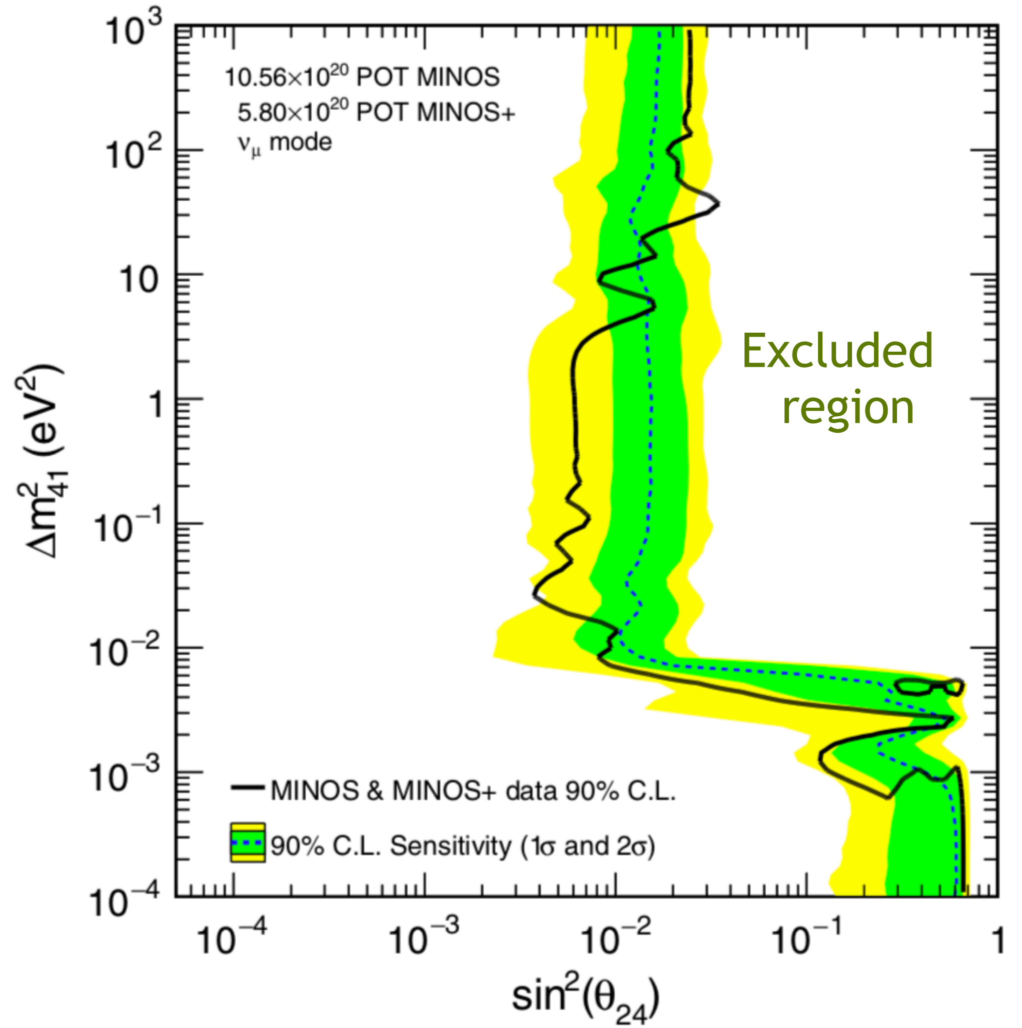
$\sin^2\theta_{24} = 1.1\text{x}10^{-4}$

$\theta_{34} < 8.4\text{x}10^{-3}$

$\sin^2 2\theta_{23} = 0.92$

$x^2_{min}/dof = 99.3/140$

$x^2(4\nu) - x^2(3\nu) = 0.01$



P. Adamson et al., Phys. Rev. Lett. 122, 091803 (2019).

Comparison with Other Results

- Best fit point:

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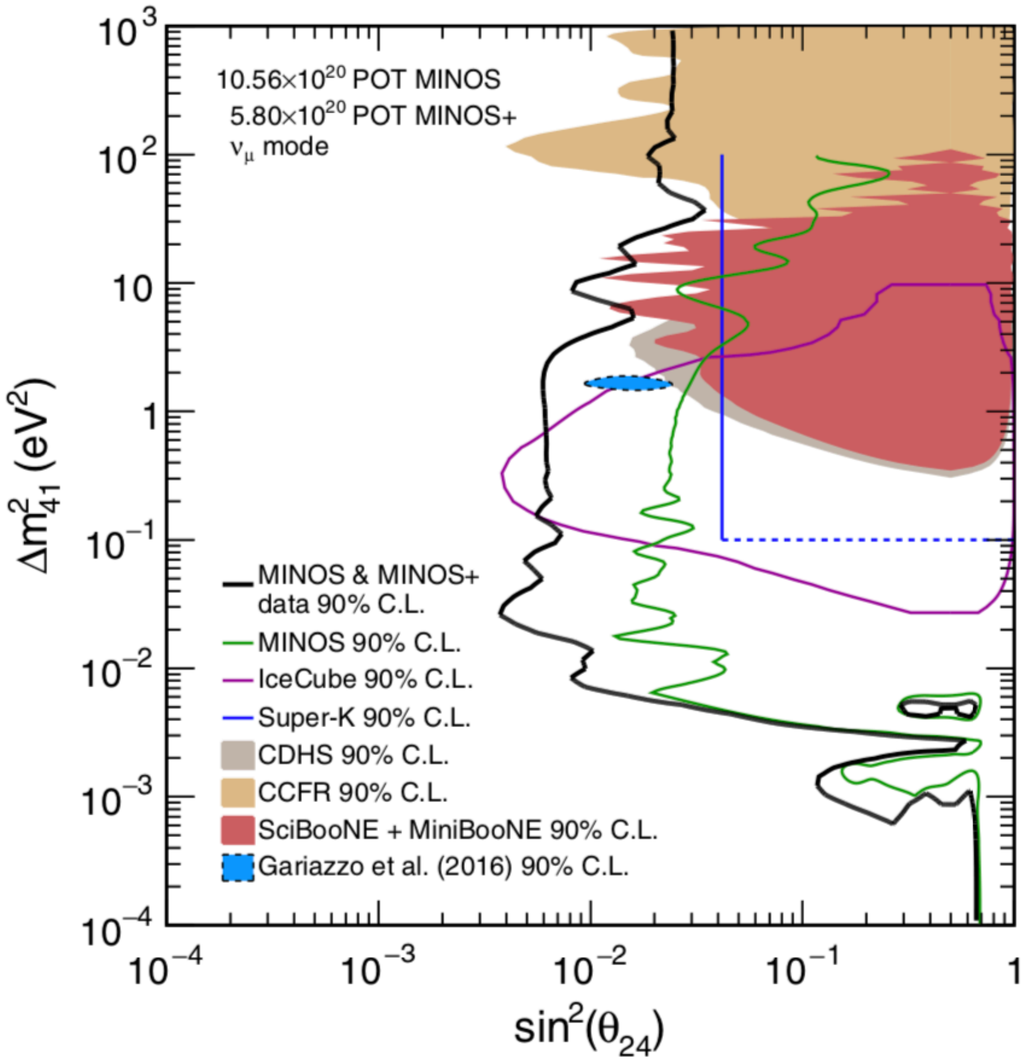
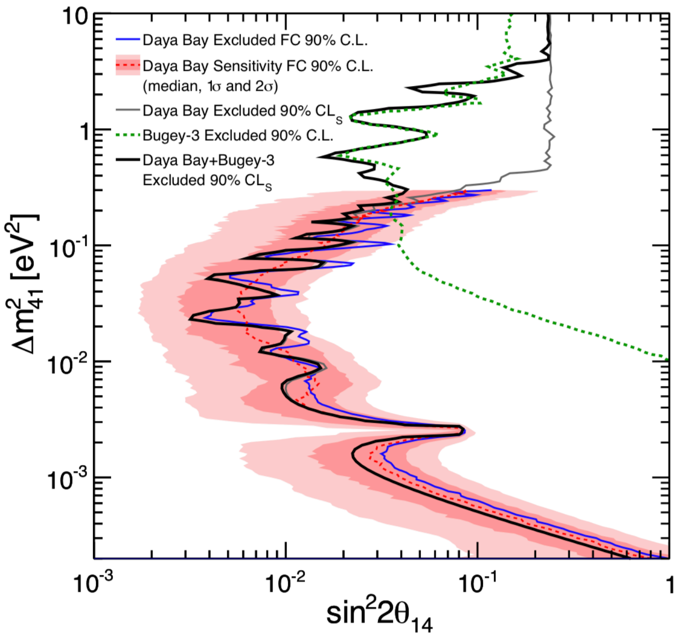
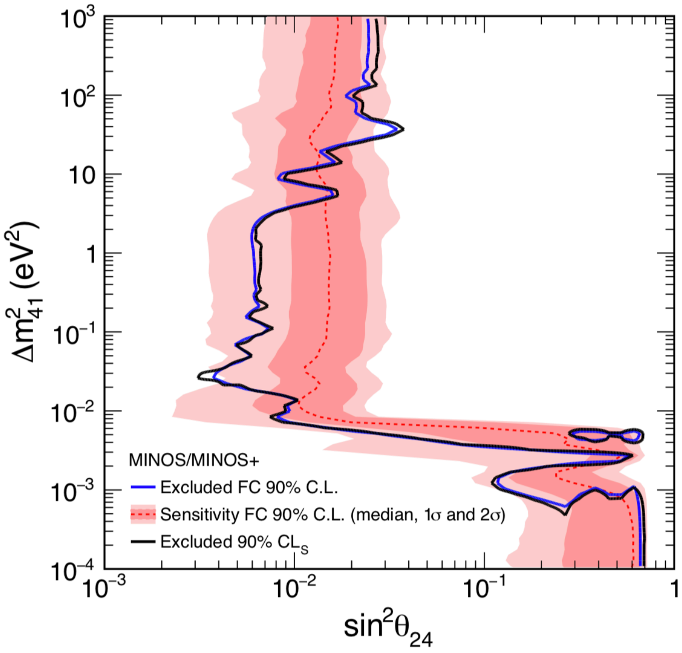


P. Adamson et al., Phys. Rev. Lett. 122, 091803 (2019).

Combination with Daya Bay

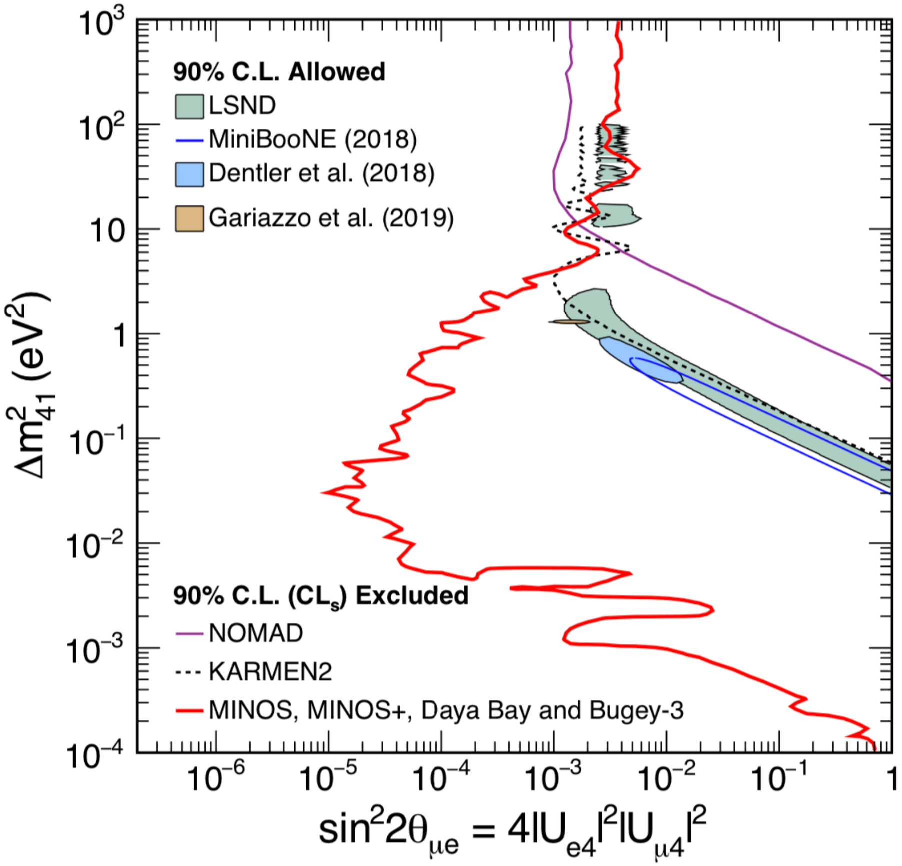
- MINOS+ sensitive to $|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$
- Daya Bay ν_e disappearance sensitive to $|U_{e4}|^2 = \sin^2\theta_{14}$

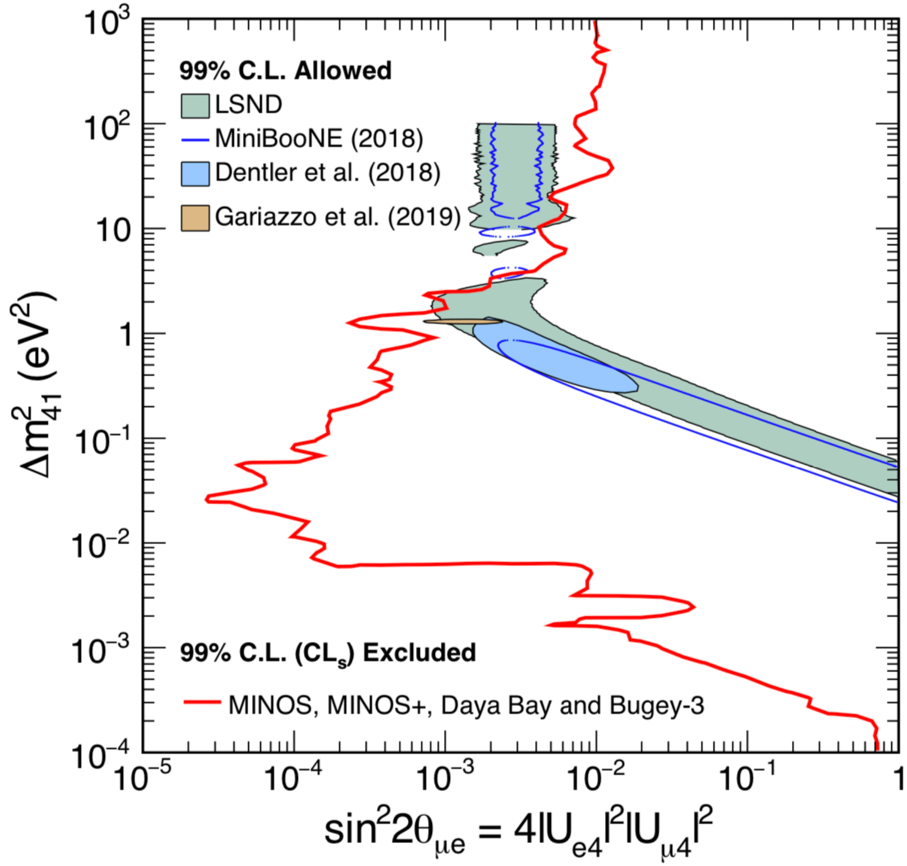




- Combine to probe the same parameter-space as LSND and MiniBooNE: $4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$

Combination with Daya Bay

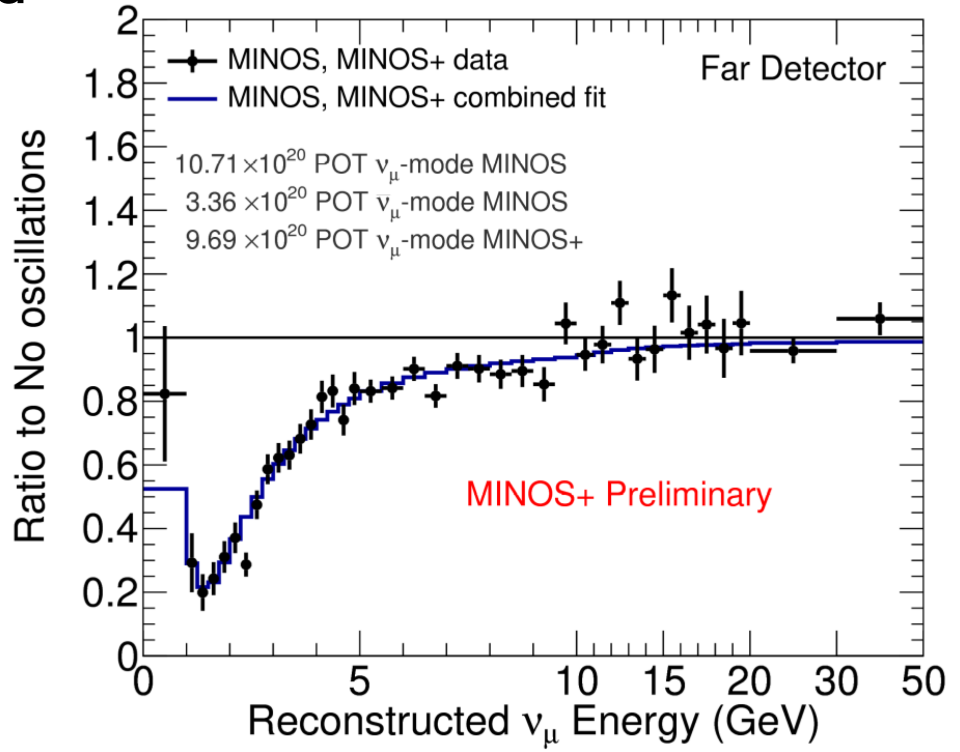




P. Adamson, et al., https://arxiv.org/abs/2002.00301

Summary

- MINOS/MINOS+ has produced its final three flavour muon neutrino disappearance result
  - Very high statistics covering the entire oscillation dip
  - Measured Δm^2_{32} to 3.5%



- The four-flavour analysis gives a leading exclusion on the sterile neutrino hypothesis over many orders of magnitude in Δm^2_{41}

Thank You!

Any Questions?