Sterile Neutrino Searches with MINOS and MINOS+

Leigh Whitehead

UCL HEP Seminar

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Outline

- Neutrino Oscillations
- The MINOS/MINOS+ Experiment
- Three-flavour results
- Sterile neutrino searches

Neutrino Oscillations

- 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.

Neutrino Oscillations

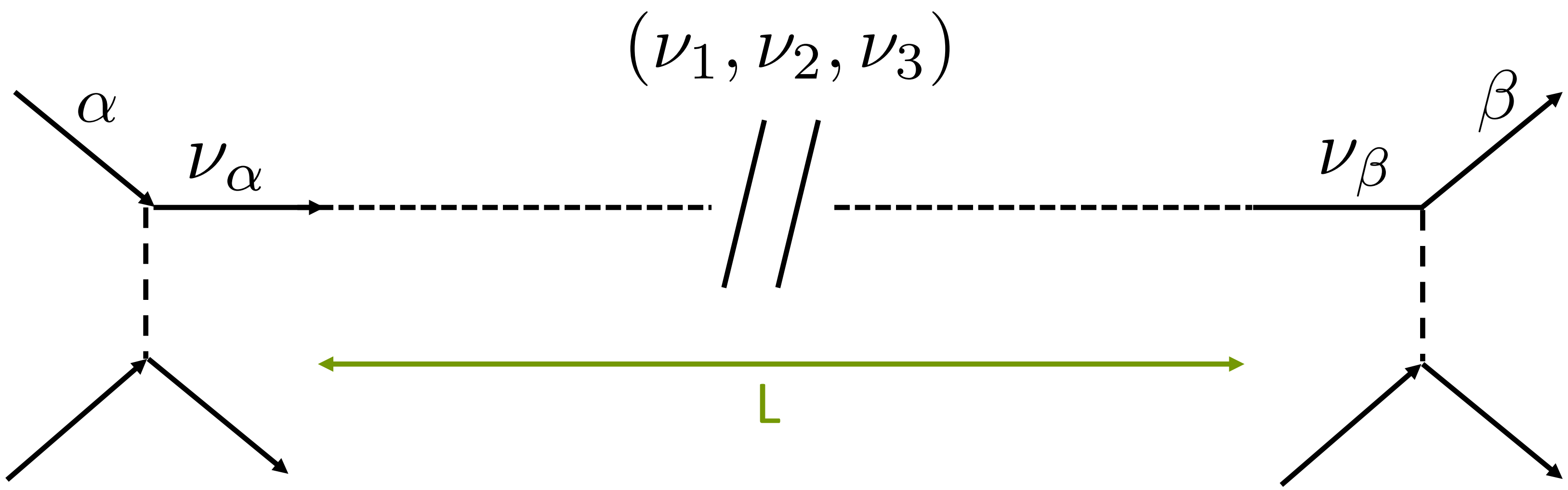
- For three neutrinos:

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

Flavour eigenstates: ν_e, ν_μ, ν_τ

Mass eigenstates: ν_1, ν_2, ν_3

3x3 unitary matrix – the PMNS matrix



The PMNS Matrix

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

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

Muon neutrino disappearance (accelerator and atmospheric)

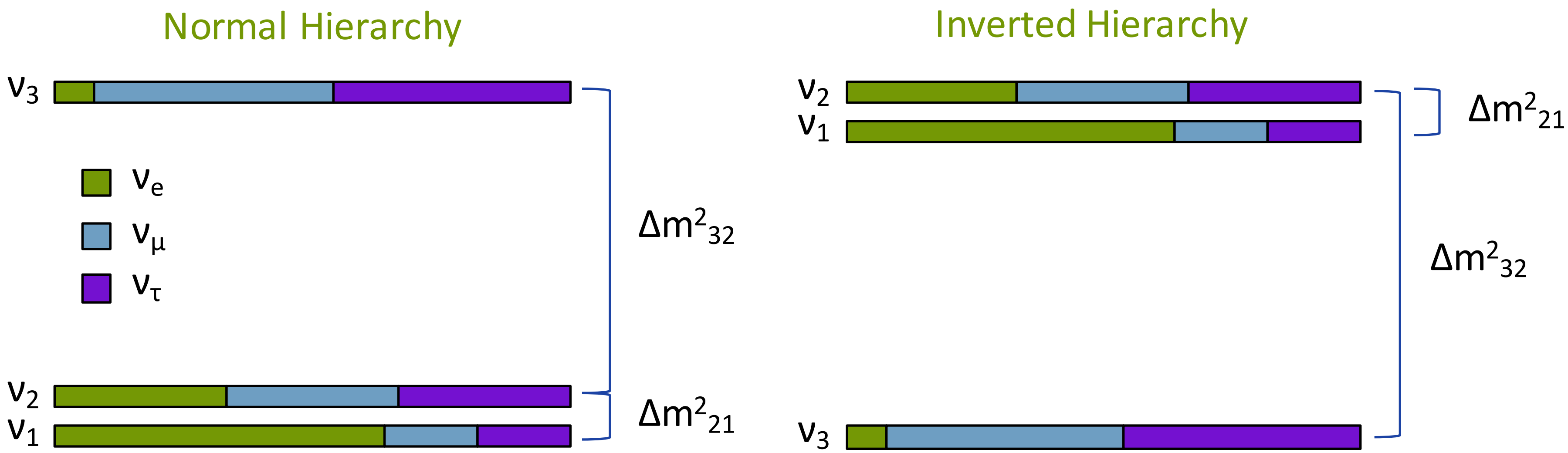
Electron antineutrino disappearance (reactor)
Electron neutrino appearance (accelerator)

(Anti)electron neutrino disappearance (solar and reactor)

- Four parameters – three mixing angles and a CP violating phase.
- Oscillations themselves are driven by mass-squared splittings:
  - With three neutrinos you can write down three of these, but only two are independent.

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 $\Delta m^2_{32} > 0$?
    - Inverted $\Delta m^2_{32} < 0$?
  - Is $\theta_{23} = 45^o$?
    - If not, is it higher or lower?
  - What is the value of δ?
    - Is there CP violation in the neutrino sector?

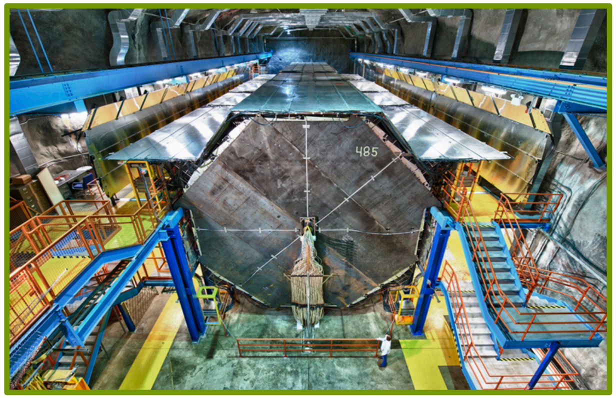
K. A. Olive et al. (Particle Data Group), Chin. Phys. C 38, 090001 (2014).

Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$
$\|\Delta m^2\|$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ ($1.31^{+0.29}_{-0.33}$)

$$\Delta m^2 = m_3^2 - \frac{(m_2^2 + m_1^2)}{2}$$

MINOS and MINOS+

The MINOS/MINOS+ Experiment



Far Detector
735 km from beam target
5.4 kton mass

Near Detector
1 km from beam target
1 kton mass

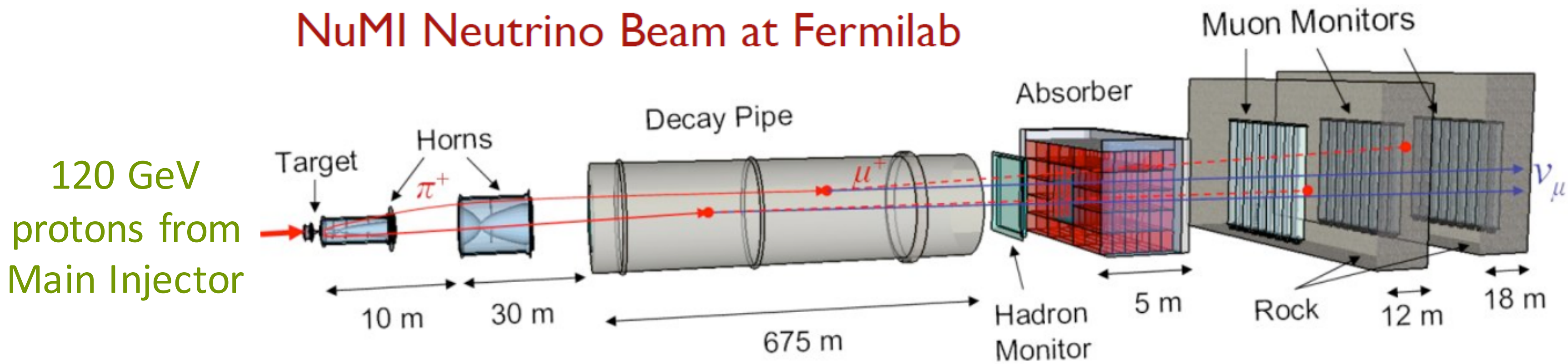
- MINOS/MINOS+ had two functionally identical, magnetised, tracking, sampling calorimeters.
  - Can distinguish muon charge from the curvature.
- Exposed by the NuMI beam at Fermilab.
- MINOS+ is the continuation of MINOS into the NOvA era at FNAL.

Note the Past Tense

- After 14 years, the MINOS FD has been removed from Soudan.
- The ND has been handed over to MINERvA.

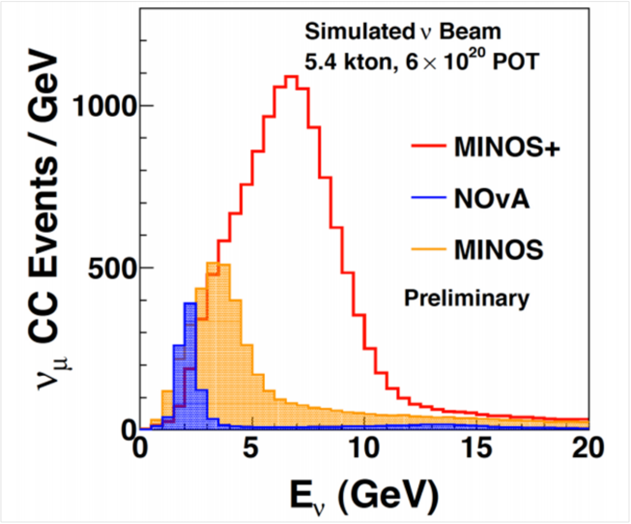
The NuMI Beam

- MINOS collected neutrinos from the NuMI beam at Fermilab.

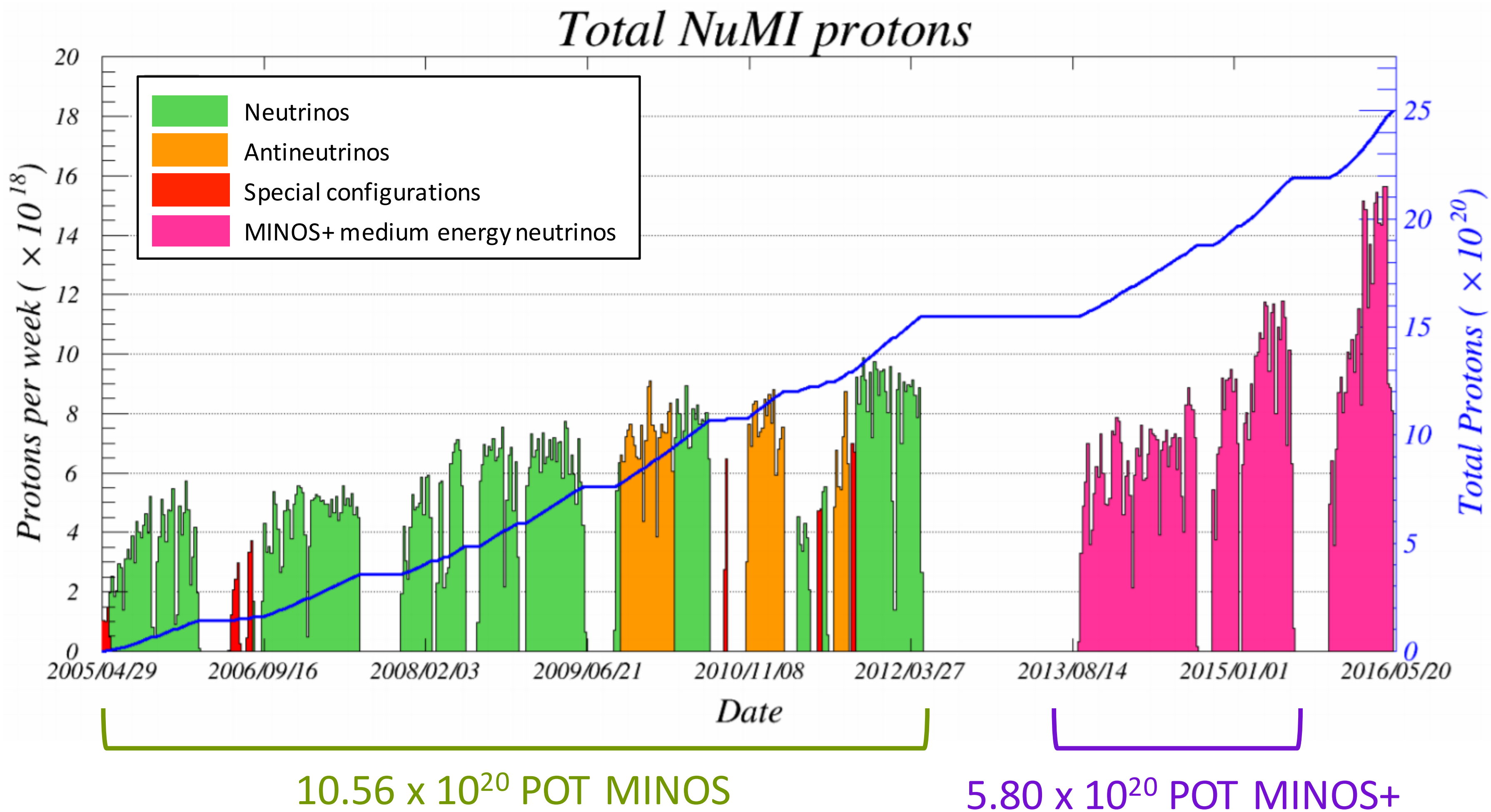


- Neutrinos produced by decay of focused mesons produced in the target.

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



Data Samples

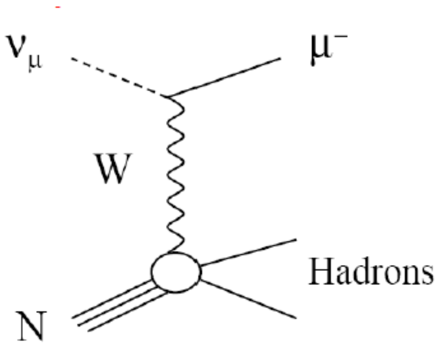


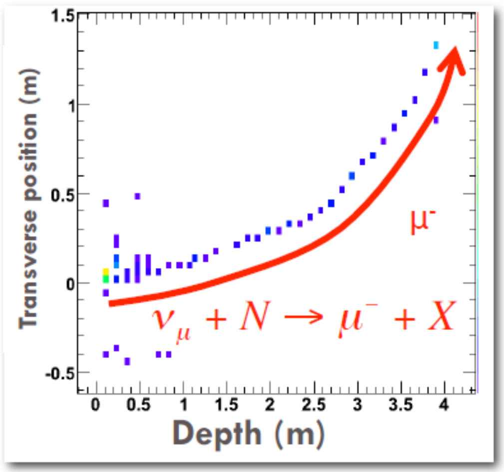
- Results shown today use all MINOS and 2 years of MINOS+ data

Neutrino Interactions in MINOS

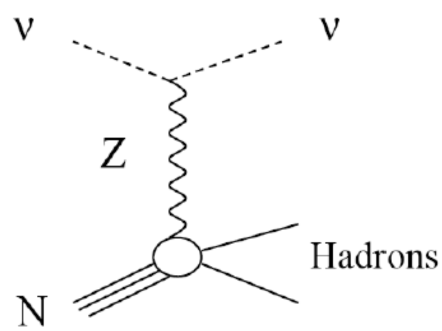
- There are three main types of interactions seen in MINOS.

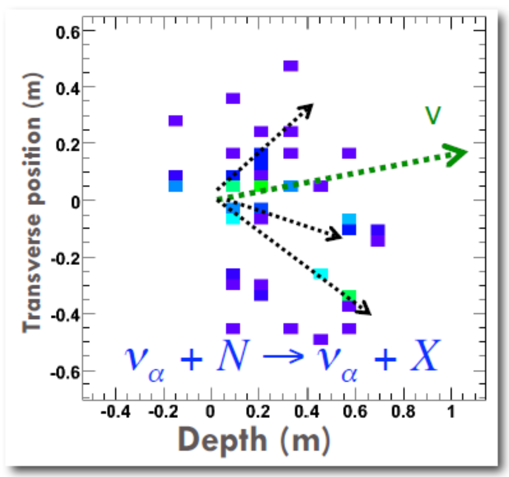
ν_μ charged-current



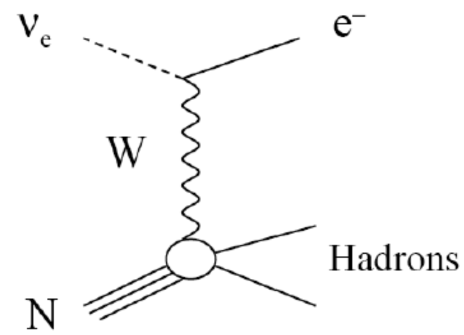


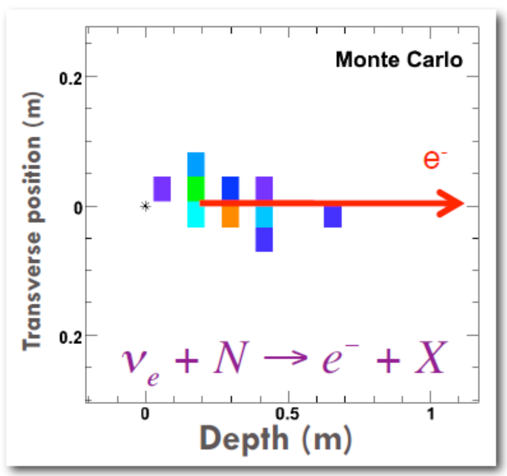
ν neutral-current





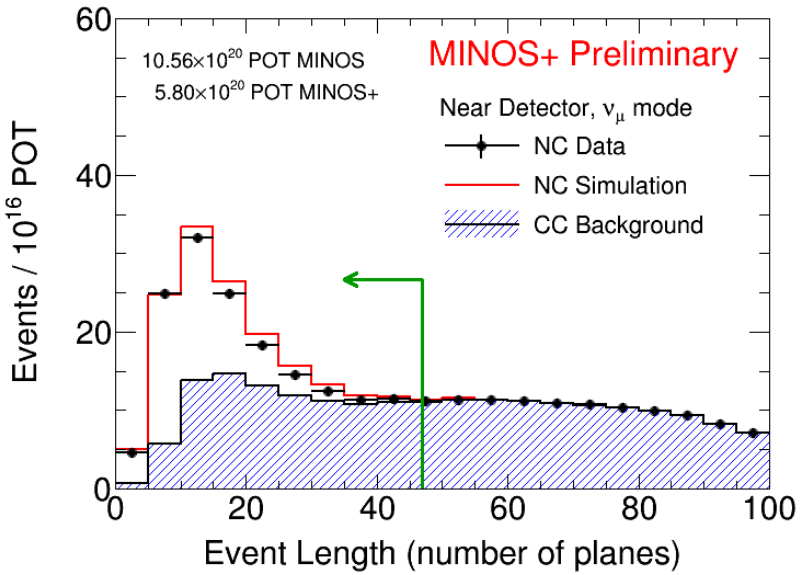
ν_e charged-current

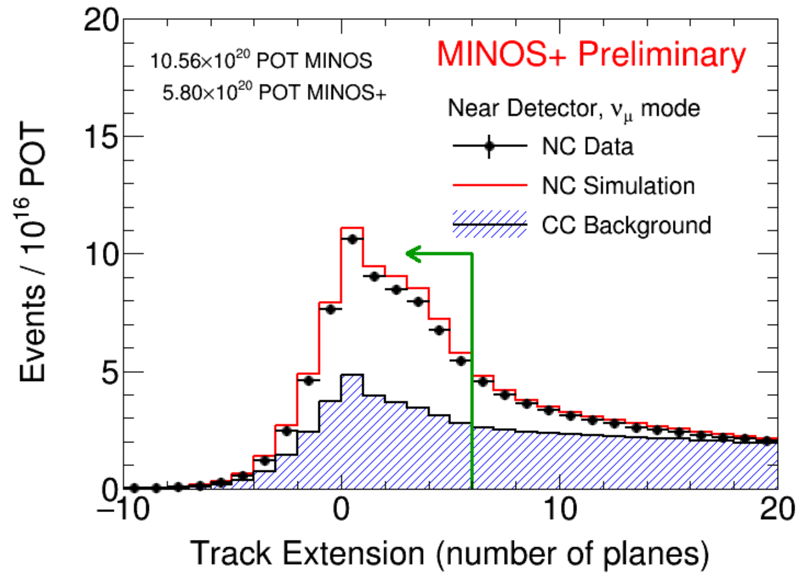




NC Event Selection

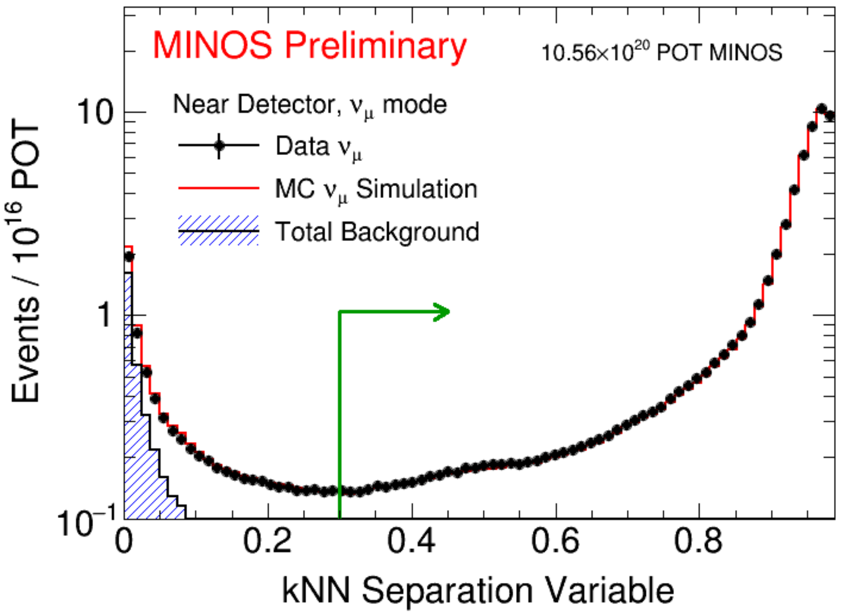
- The first step is to select the neutral current interactions.
- Two main selection criteria:
  - Event length and the extension of the track beyond the hadronic shower.

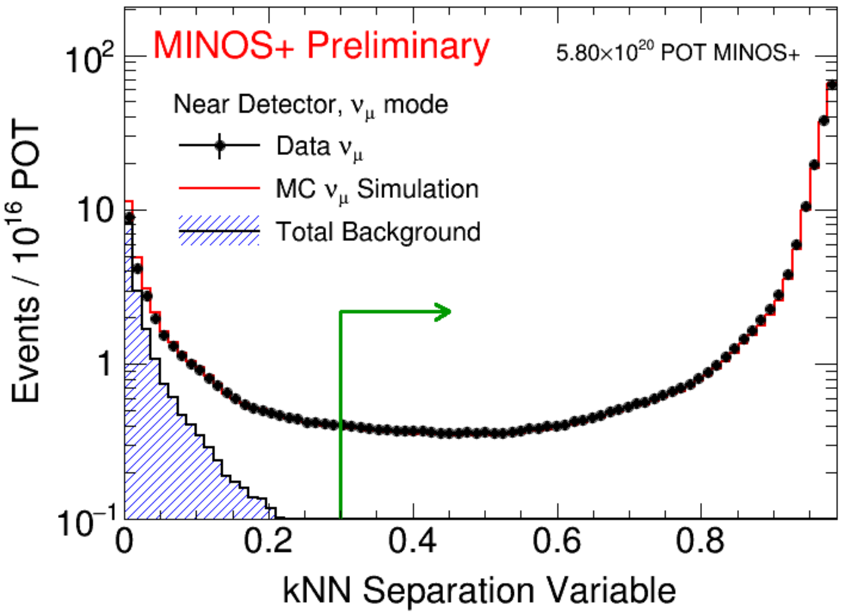




CC Event Selection

- 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.

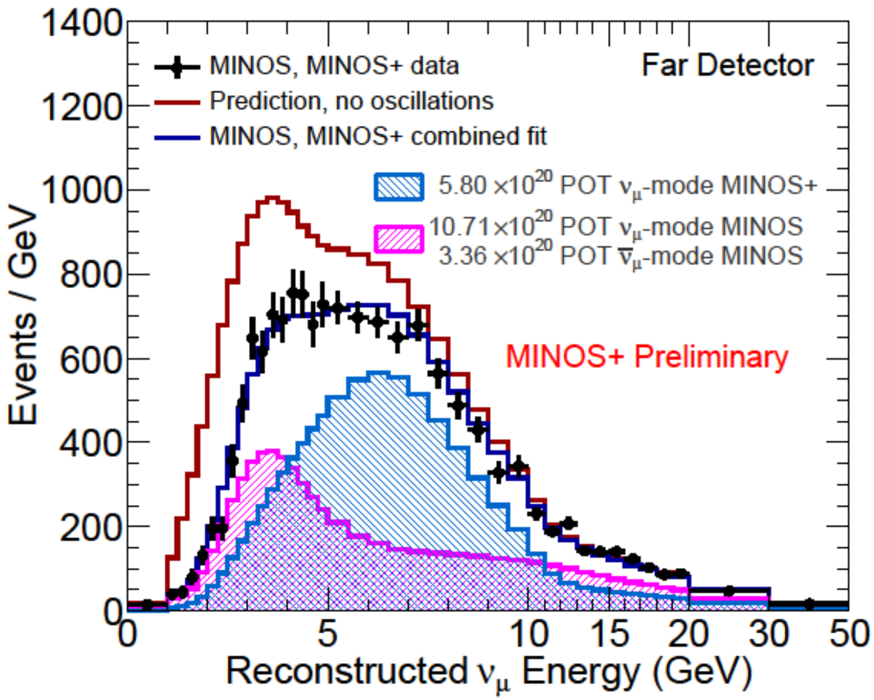


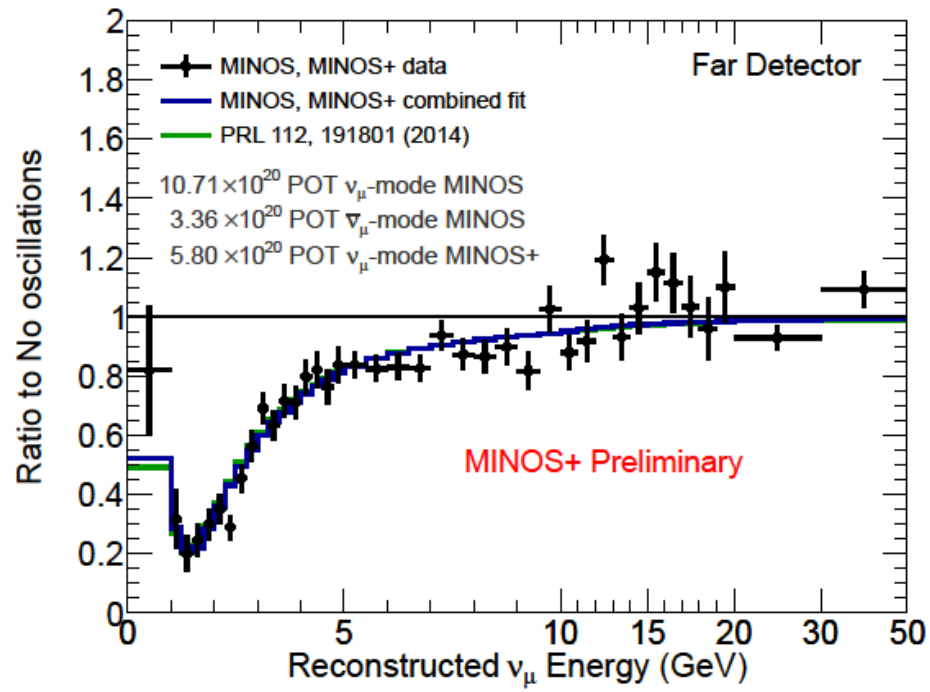


Three Flavour Oscillation Results

Three Flavour Oscillations

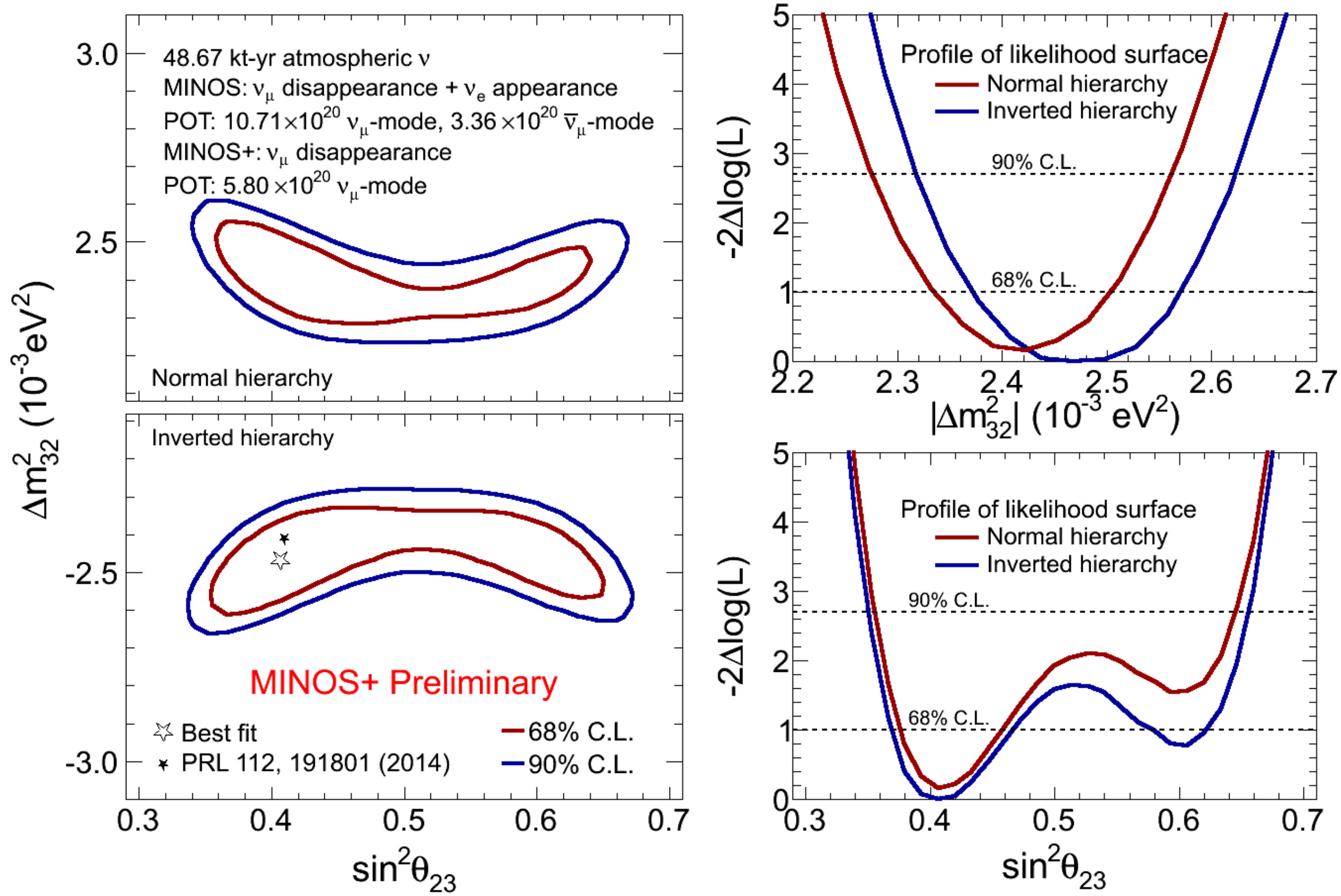
- MINOS was designed to measure the atmospheric scale oscillation parameters.
  - Look for disappearance of muon neutrinos in the FD relative to ND.
  - Measure muon neutrinos through charged current interactions.





Three Flavour Oscillations

- Obtain the following contours.



Three Flavour Oscillations

- This is a very competitive measurement of Δm^2_{32}.

Normal Hierarchy

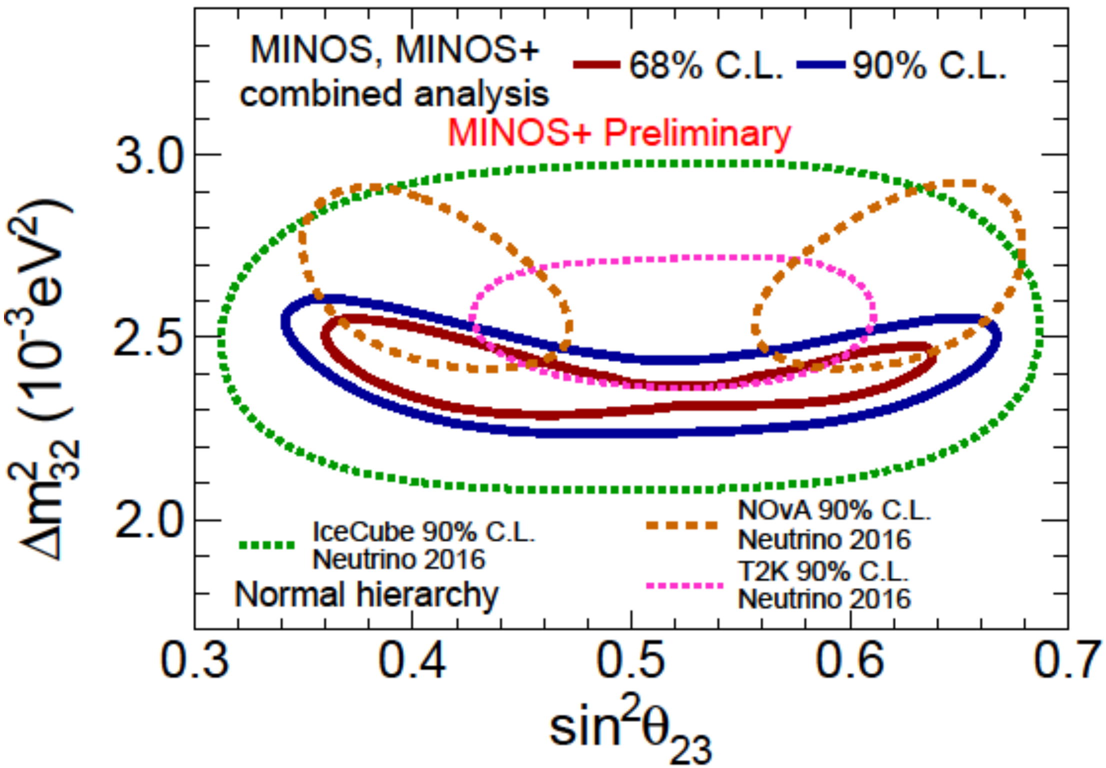
$$\Delta m^2_{32} = 2.42 \pm 0.09 \times 10^{-3} \text{ eV}^2 \text{ (68\% C.L.)}$$

$$\sin^2\theta_{23} = 0.35 - 0.65 \text{ (90\% C.L.)}$$

Inverted Hierarchy

$$\Delta m^2_{32} = -2.48^{+0.09}_{-0.11} \times 10^{-3} \text{ eV}^2 \text{ (68\% C.L.)}$$

$$\sin^2\theta_{23} = 0.35 - 0.66 \text{ (90\% C.L.)}$$



Beyond Three

Neutrino Flavours

How Many Neutrinos?

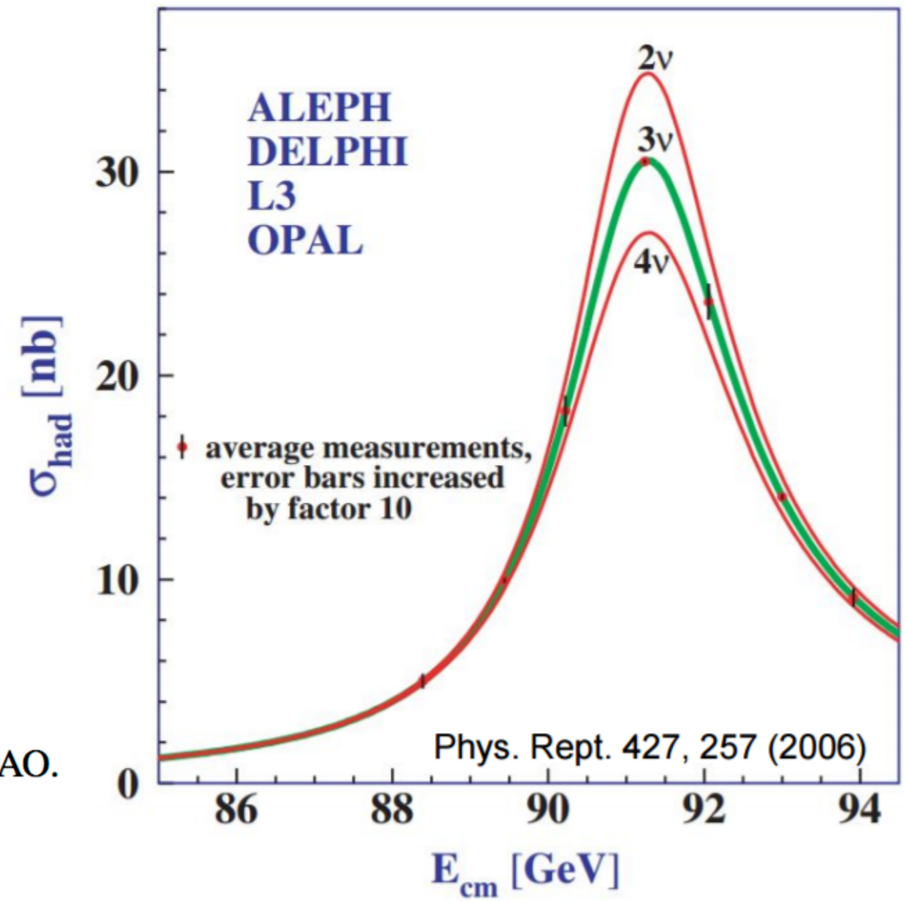
- Invisible width of the Z-boson from LEP very strongly measured that there are 3 neutrinos.

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

- Results from Planck:

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

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

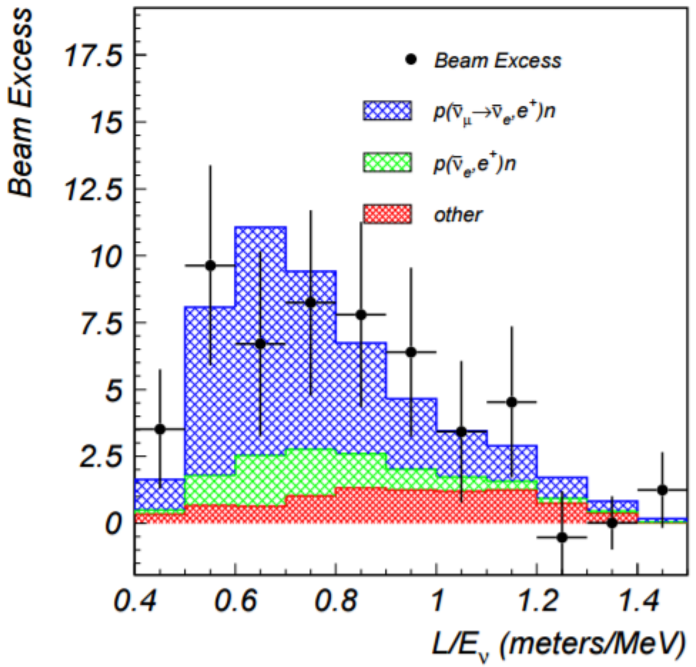


Some Anomalies

- 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

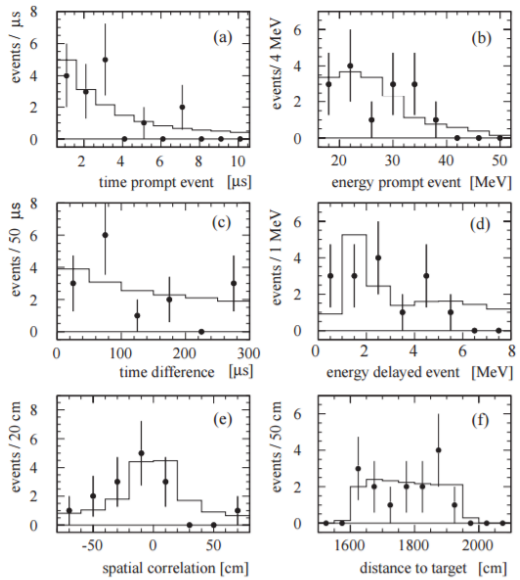
Some Anomalies - 1

- 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



A. Aguilar-Arevalo et al. Phys. Rev. D64 (2001), p. 112007.

- However, the KARMEN2 experiment saw results consistant with expectation.

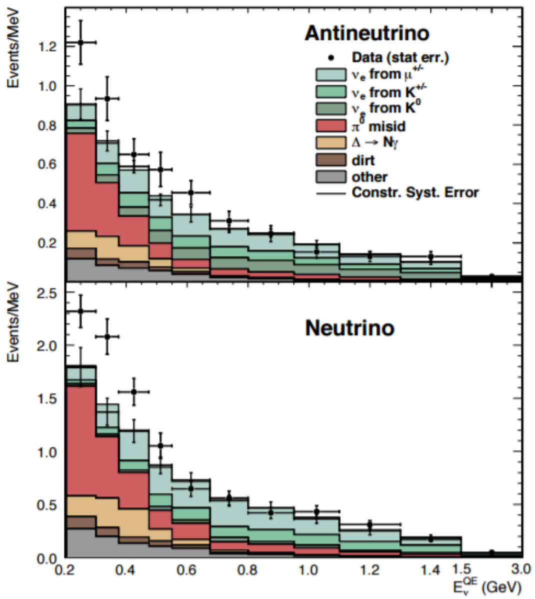


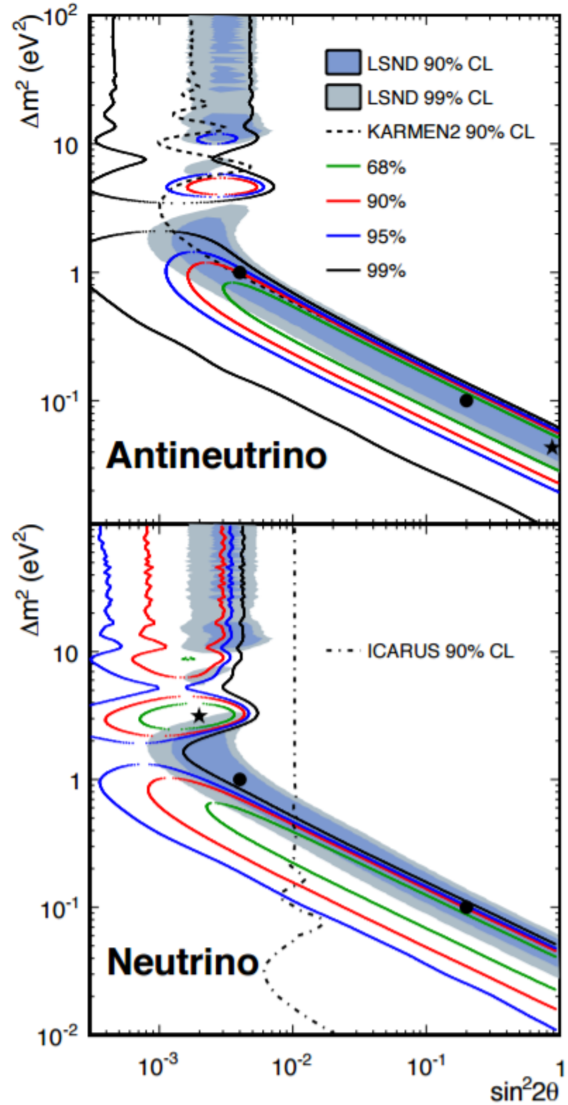
Church et al. Phys. Rev. D66 (2002), p. 013001.

- 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.

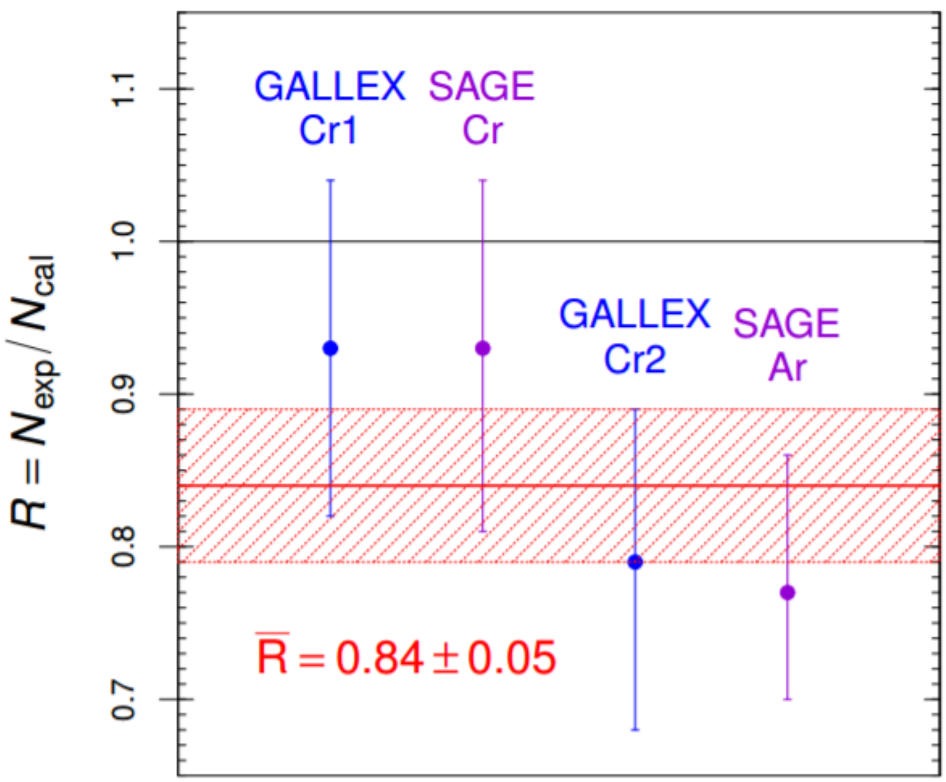




A. Aguilar-Arevalo et al. Phys. Rev. Lett. 110 (2013), p. 161801.

Some Anomalies - 2

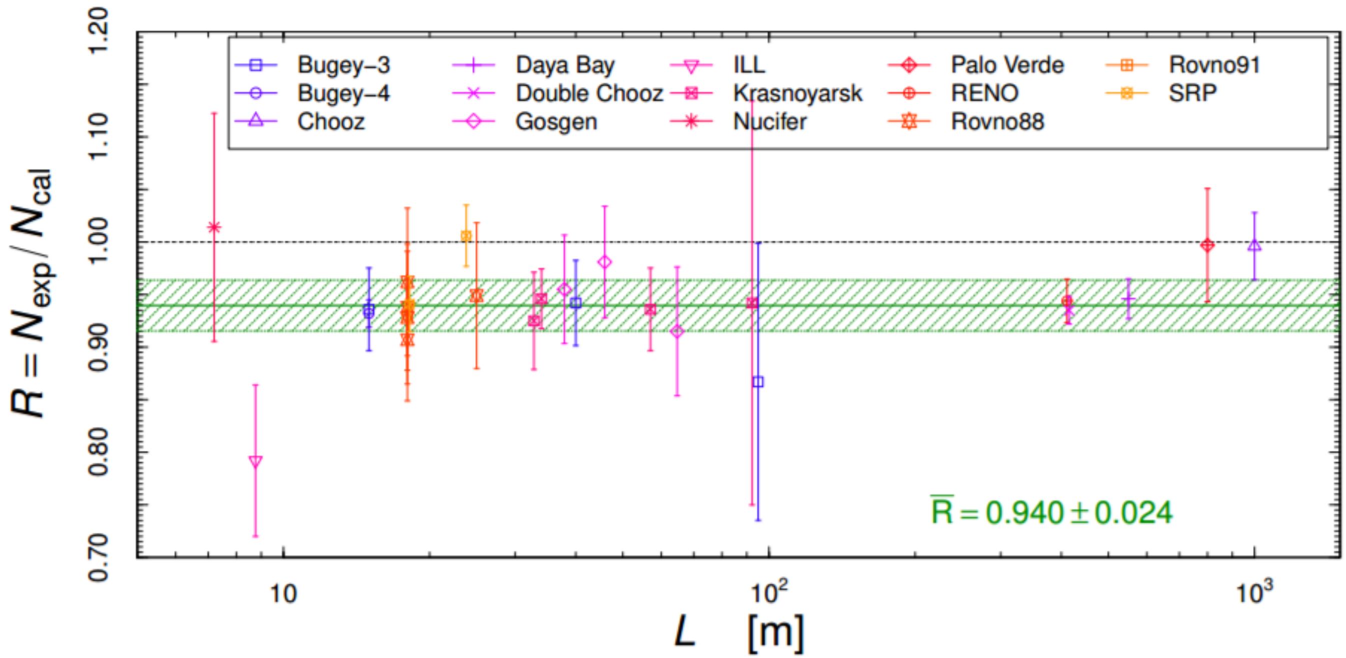
- GALLEX and SAGE were two solar neutrino experiments.
- Calibrated using radioactive sources.
- Measured rates from the calibration sources showed consistent deficits.
- Again, consistent with a 1 eV^2 mass-splitting.



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 $\overline{\nu}_e$.

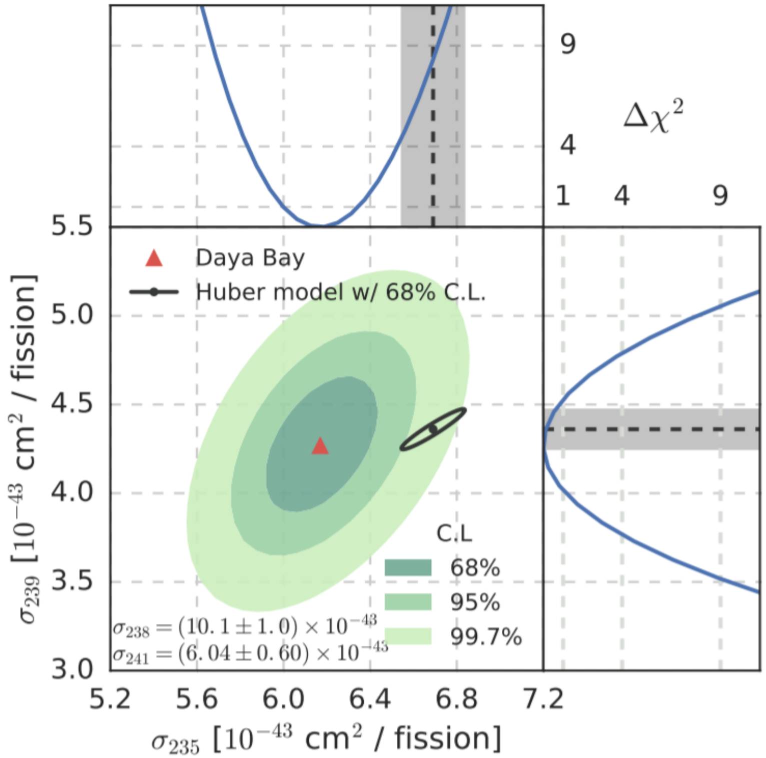


Gariazzo et al. (2017). arXiv: 1703.00860 [hep-ex]

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

Some Anomalies - 3

- Daya Bay recently 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".

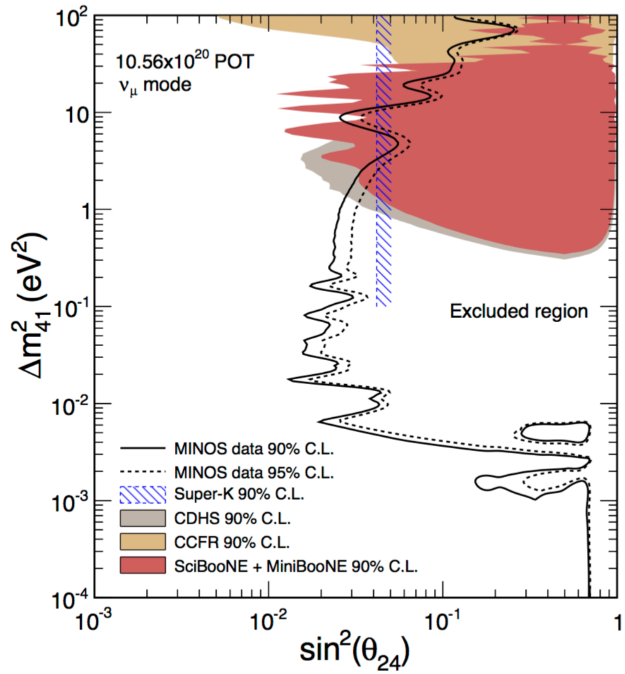


An et al. (2017). arXiv: 1704.01082 [hep-ex]

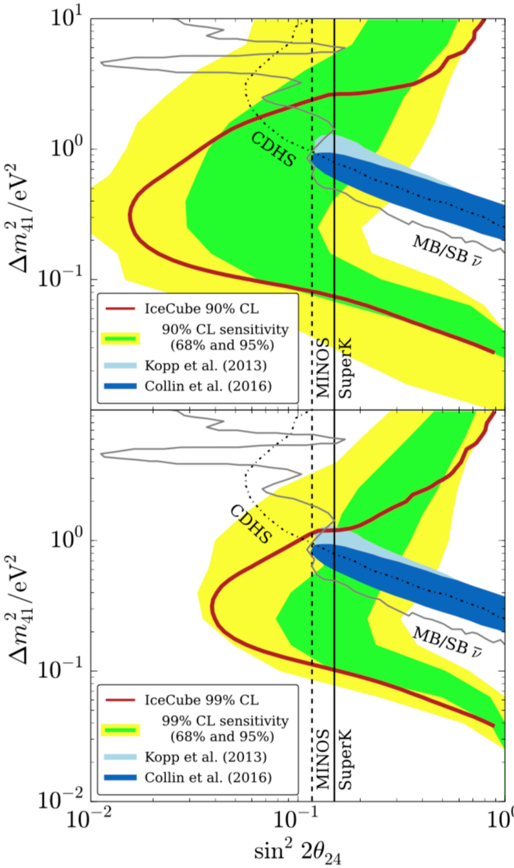
Null Results

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

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



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

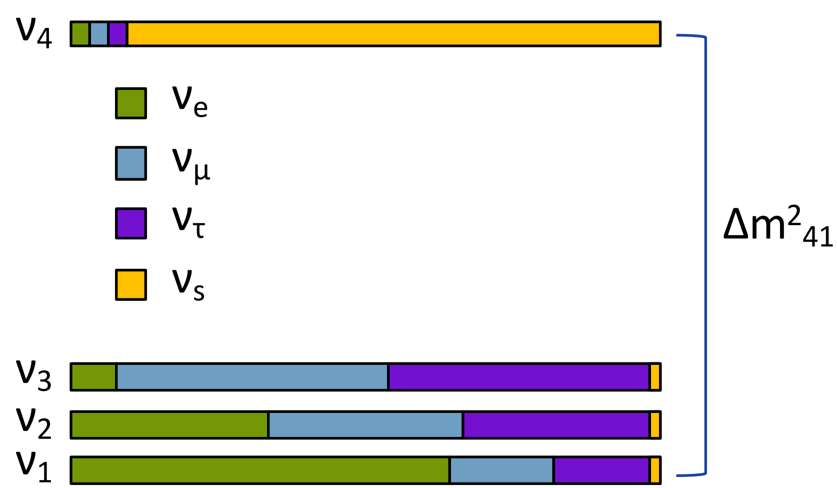


M. G. Aartsen et al. Phys. Rev. Lett. 117, 071801 (2016)

Four Flavour Formalism

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

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



MINOS+ Four Flavour Oscillation Analysis

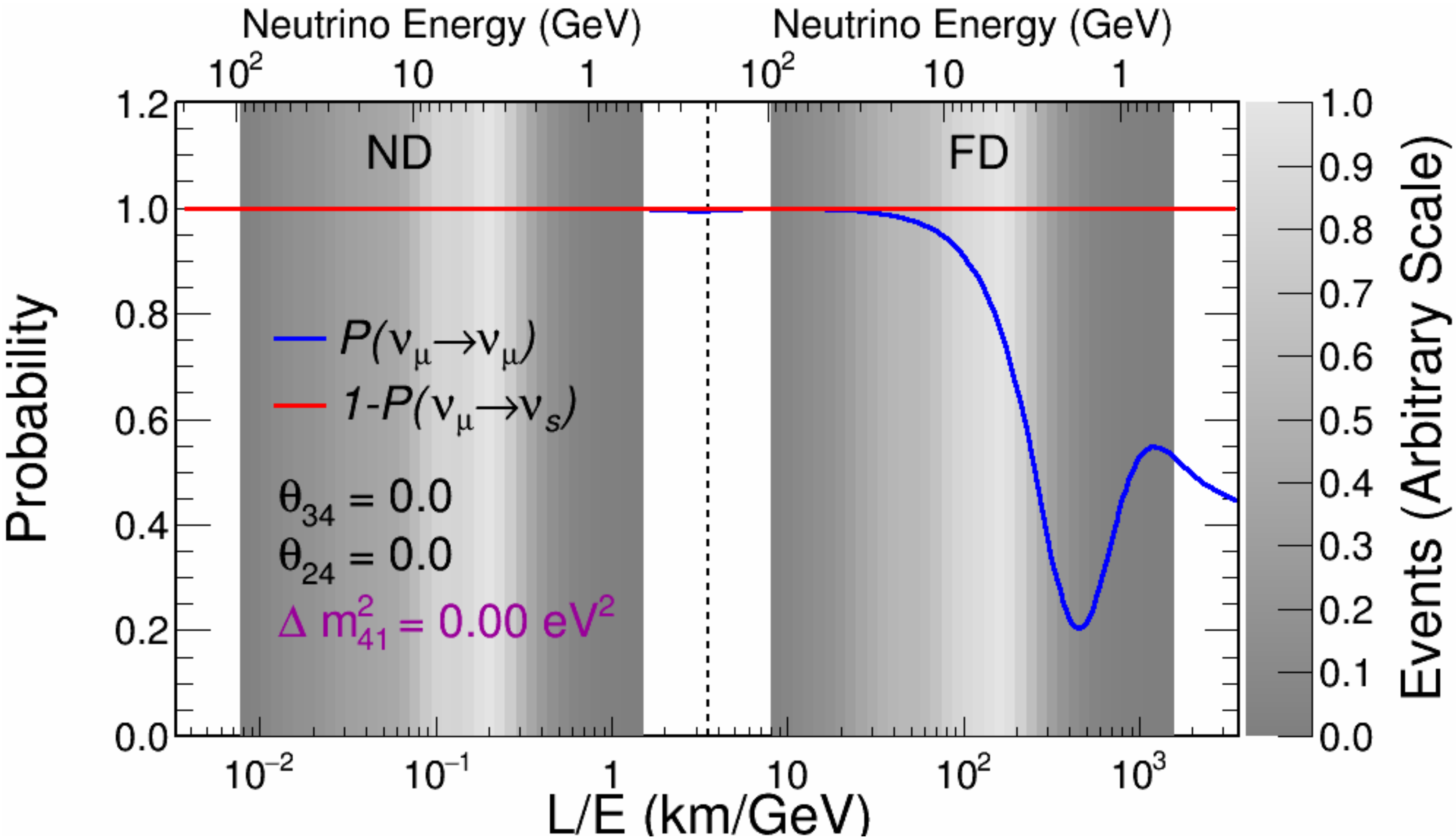
Sterile Oscillations in MINOS

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



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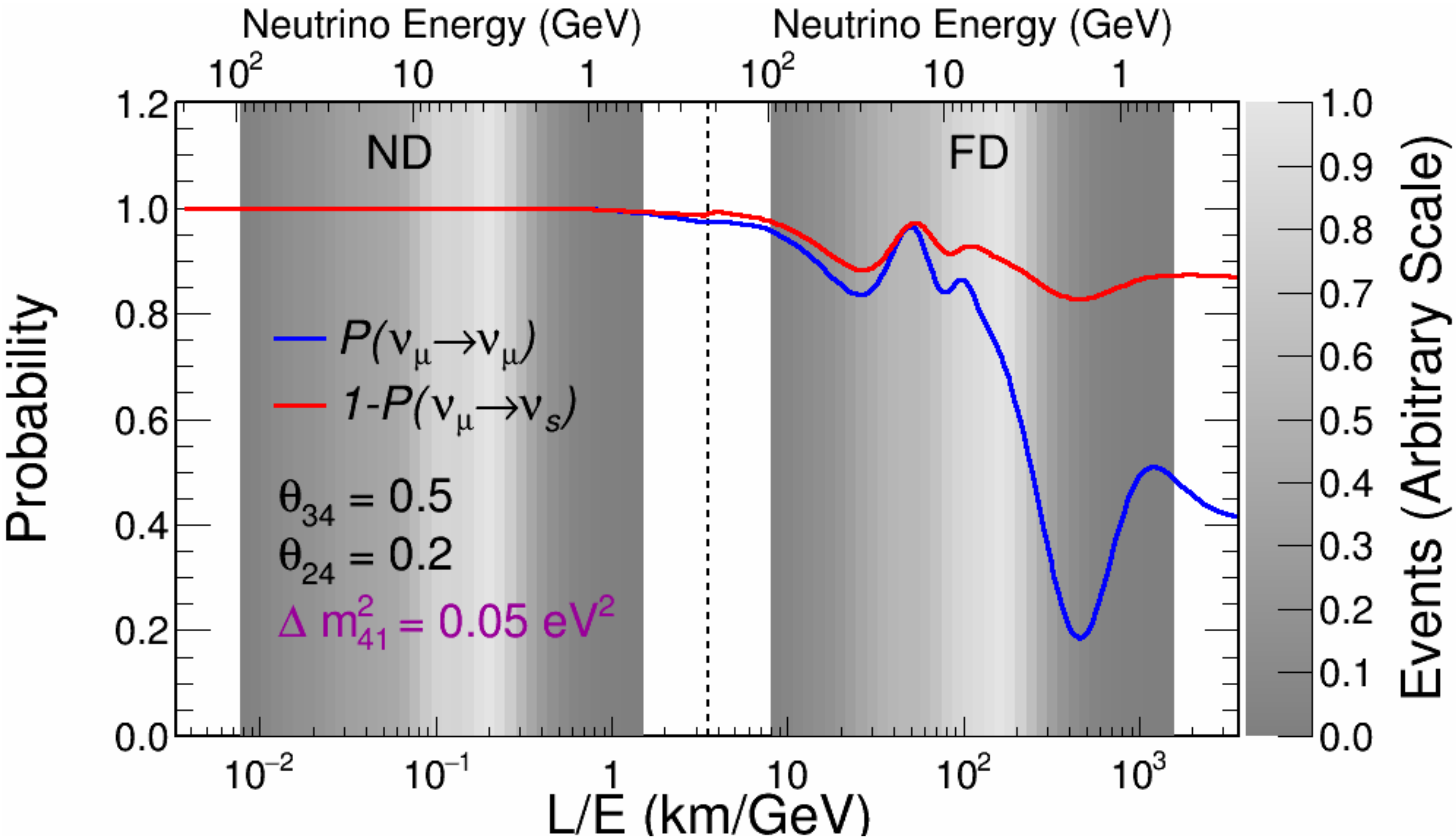
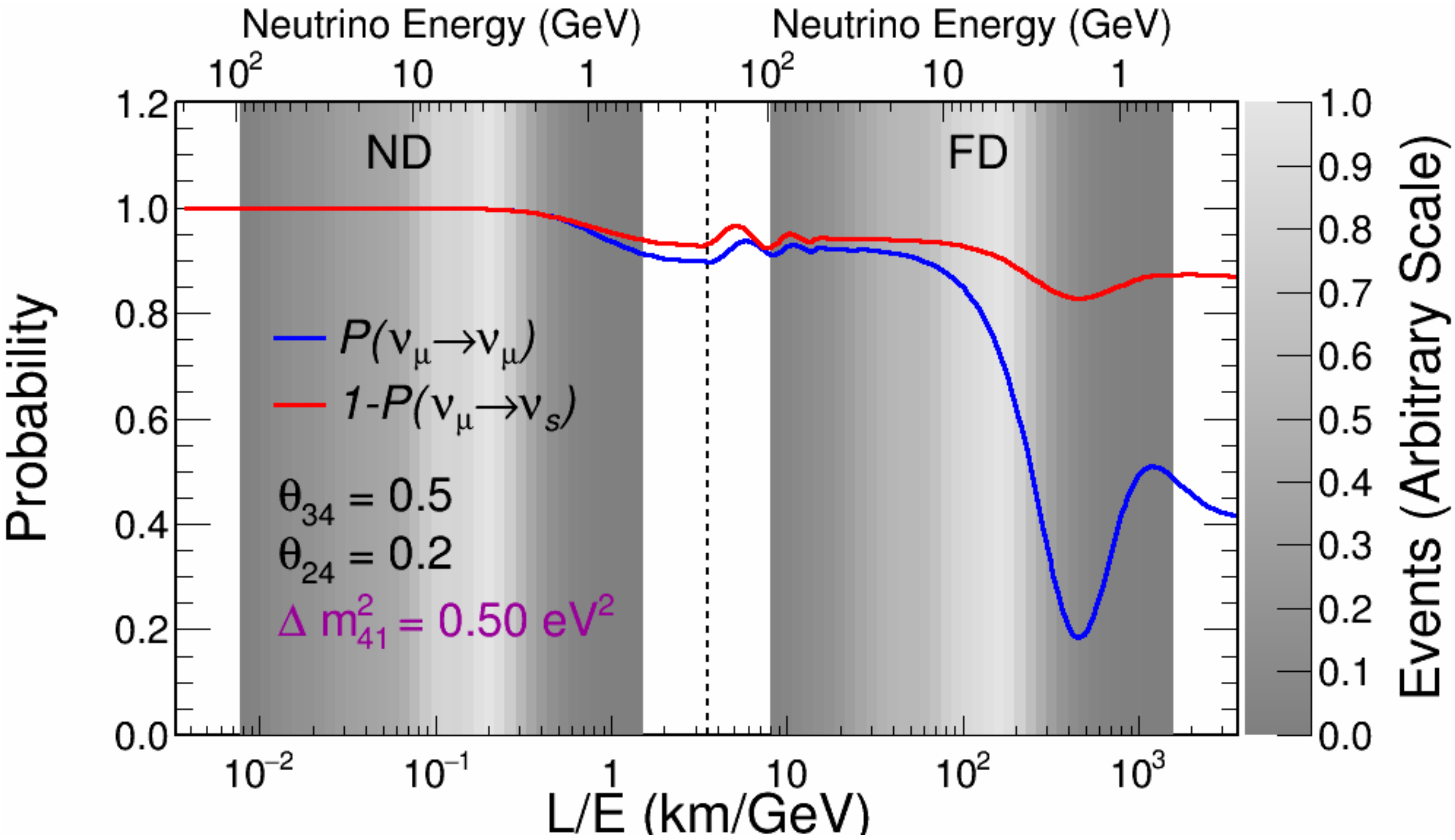
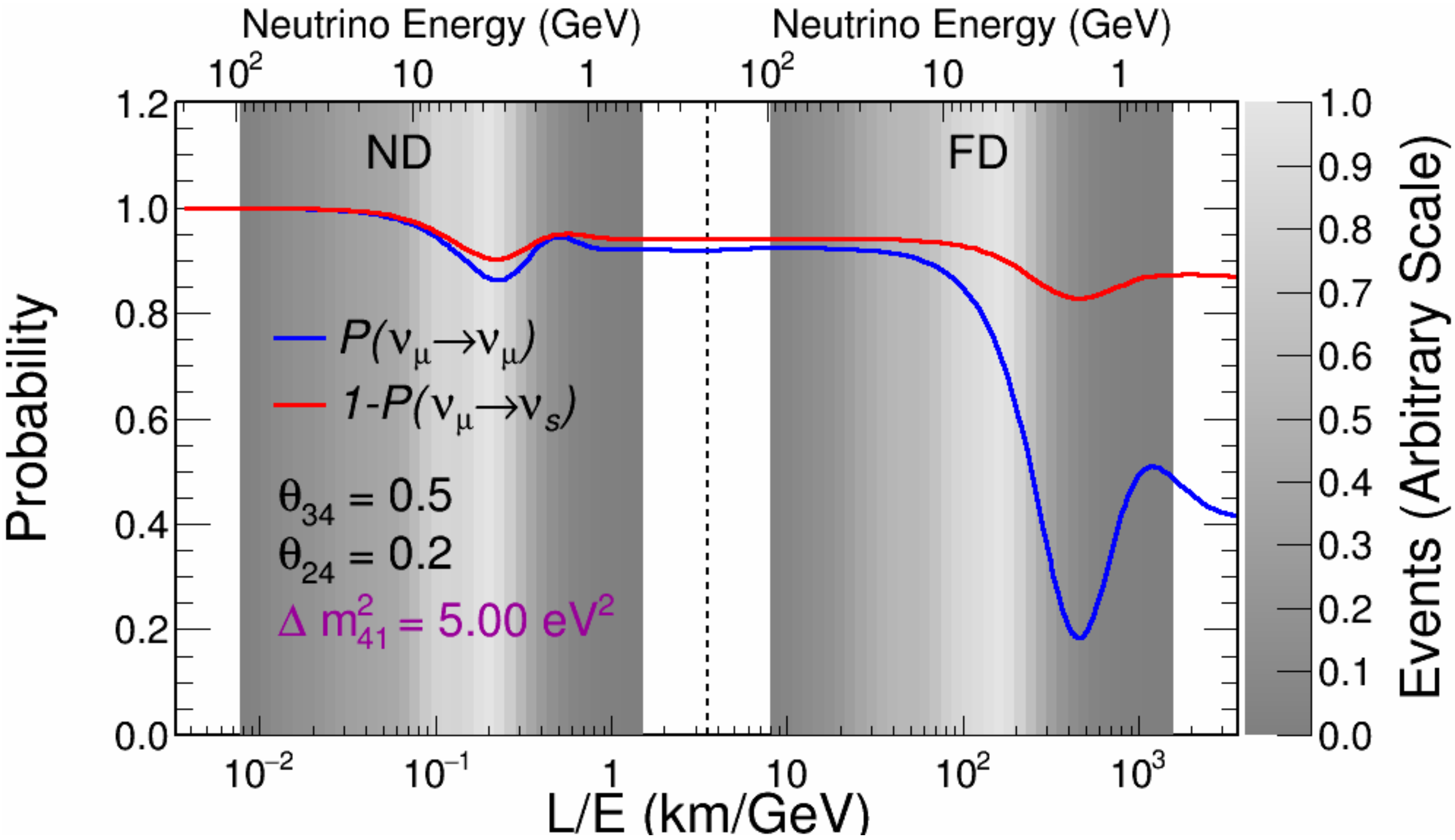


Sterile Oscillations in MINOS

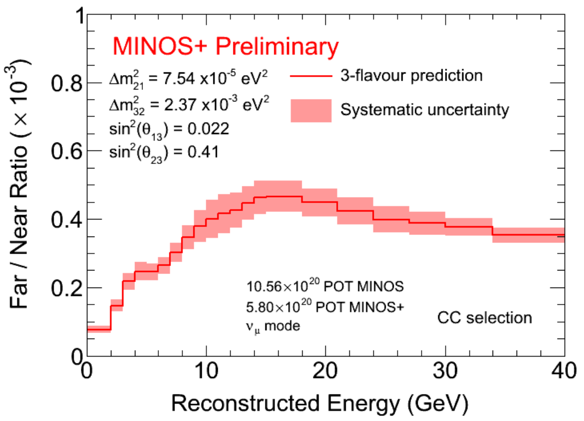


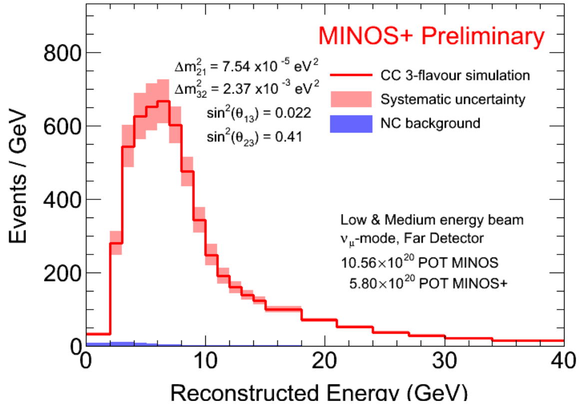
Sterile Oscillations in MINOS

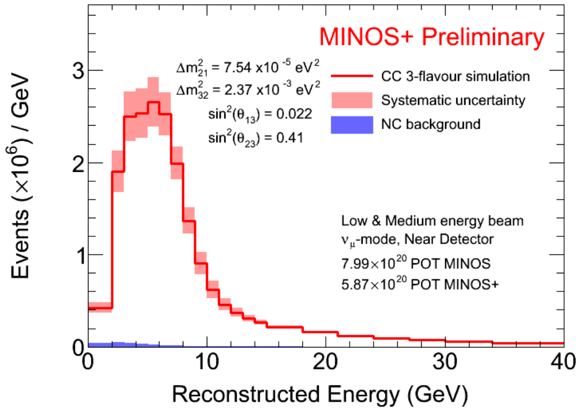


Analysis Method

- 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 anaylsis.
  - Many systematics cancel in the ratio.







- However, uncertainty in the ratio was dominated by FD statistics.

Analysis Method

- The previous MINOS sterile neutrino analysis used the ratio of the Far and Near spectra.
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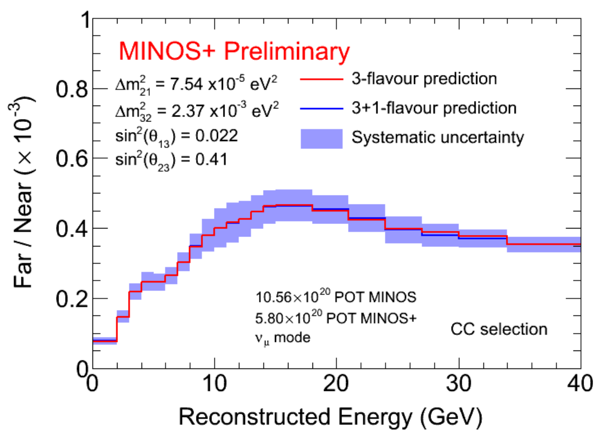
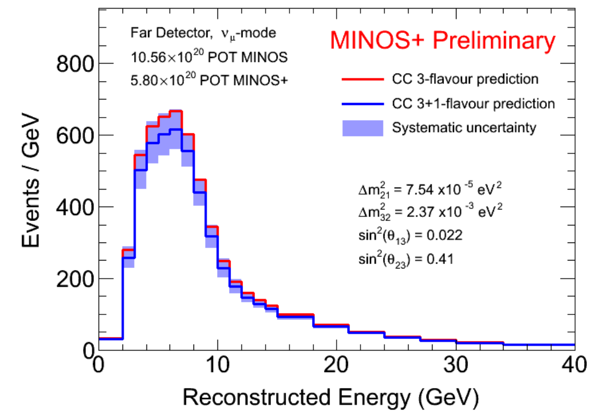
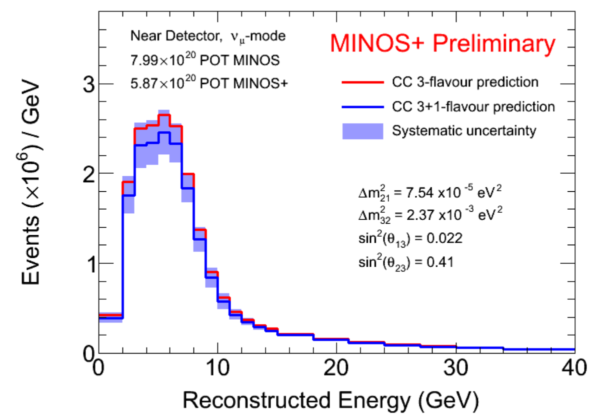
  - Many systematics cancel in the ratio.







Sample Parameters: $\theta_{24} = 0.2$, $\Delta m^2_{41} = 80.0$ eV^2

- Also, high mass-splitting effect cancels in the ratio.

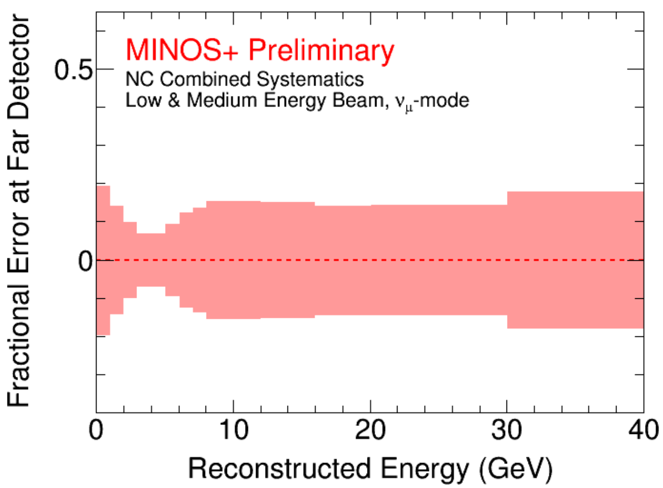
The Two Detector Fit

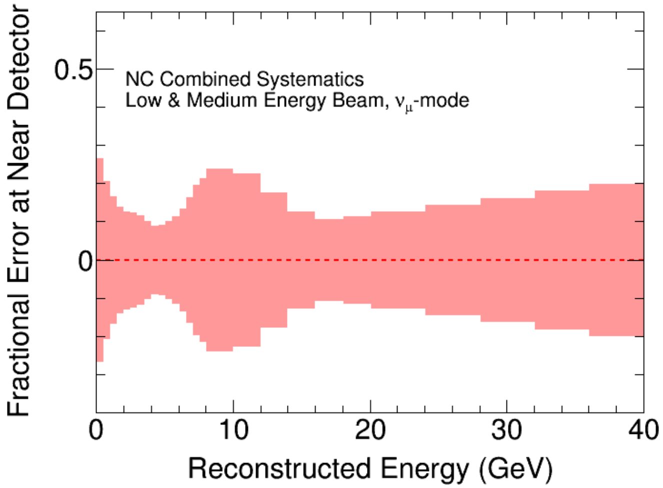
- We have now moved to a simultaneous two detector fit.
  - Use the a-priori flux prediction from MINERvA [1]
- We use a single covariance matrix that encapsulates the correlations between the systematic uncertainties.
  - This still enables us to have some cancellation of the systematic uncertainties without using the Far-over-Near ratio.
- Consider a total of 44 systematic uncertainties across the different event selections.

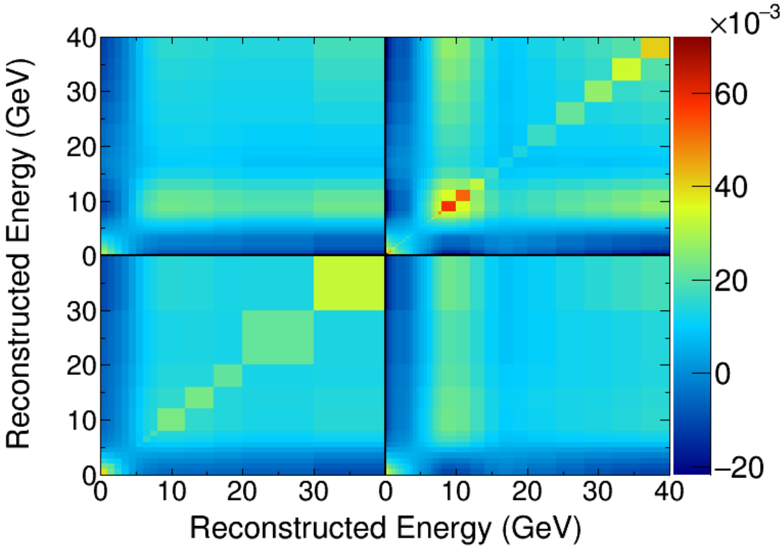
Uncertainty source	Maximum uncertainty (%)			
	ND CC	FD CC	ND NC	FD NC
Hadron production	7%	7%	7%	7%
Cross-sections	10%	10%	11%	13%
Backgrounds	1%	1%	10%	5%
Energy scale	10%	8%	20%	18%
Other	6%	3%	6%	3%
Total	15%	12%	25%	20%

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

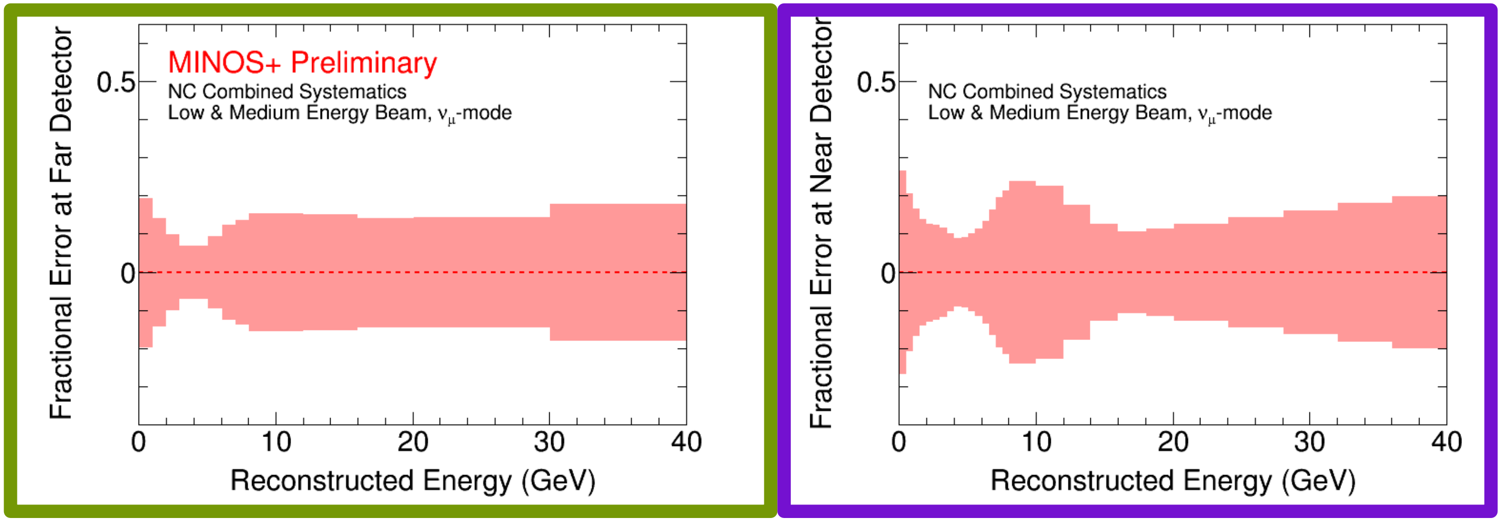
NC Systematic Uncertainties



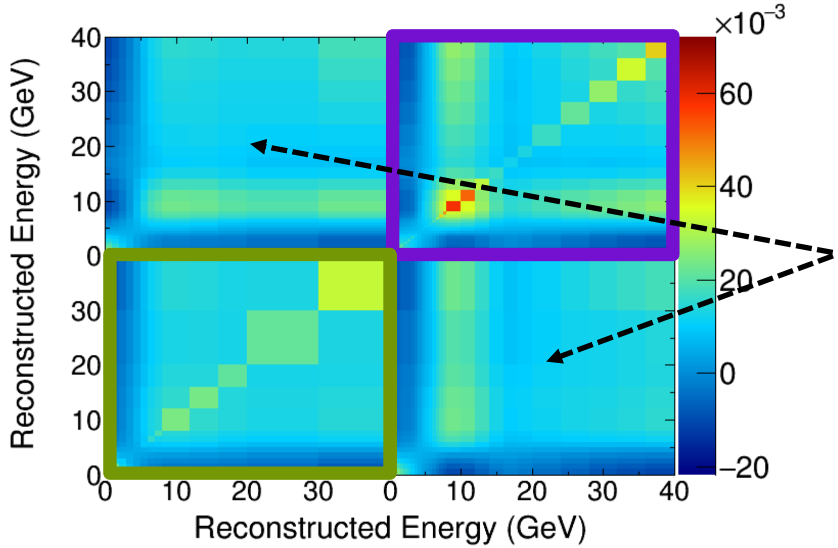




NC Systematic Uncertainties

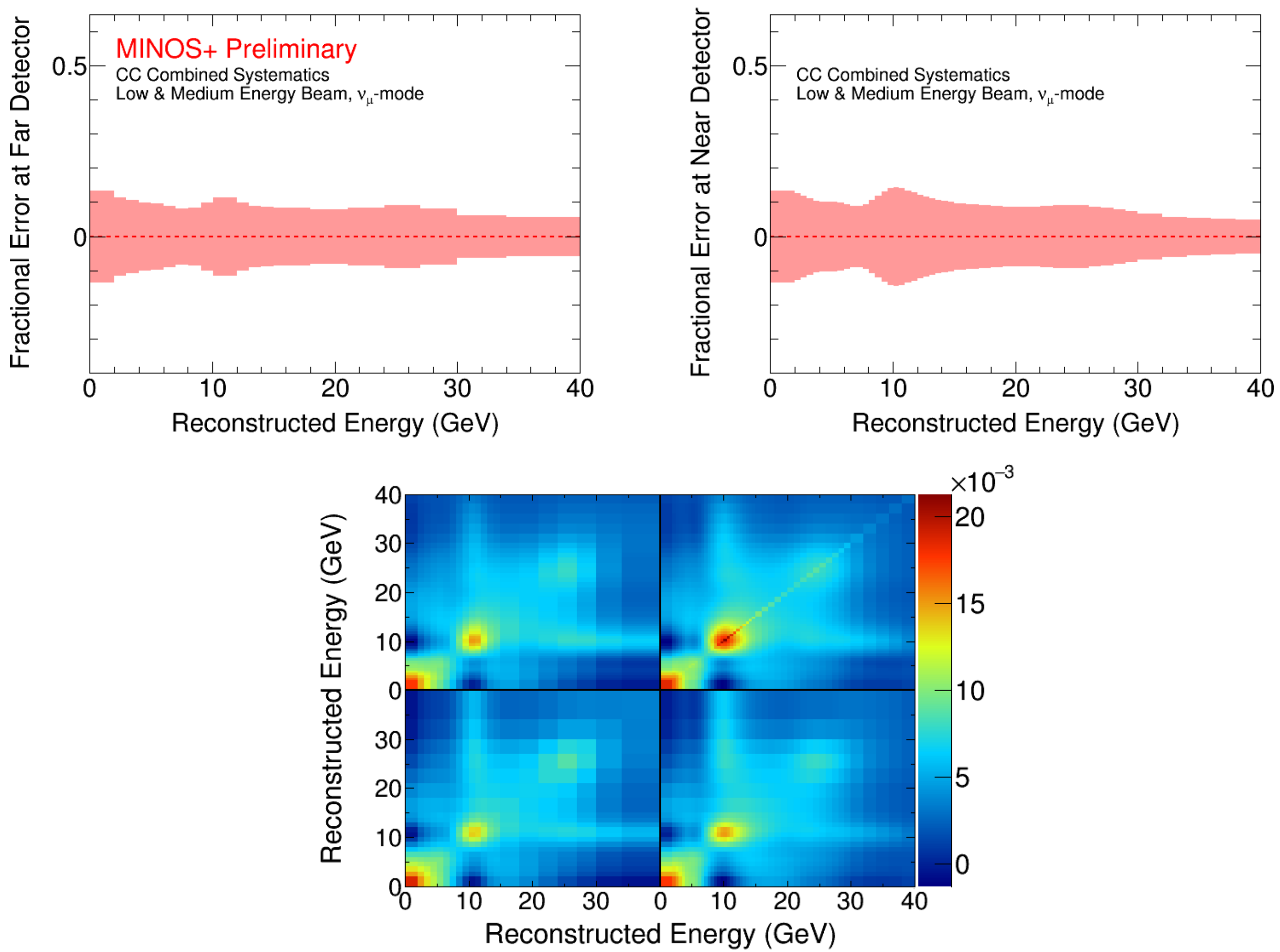


Diagonal components form the bands above

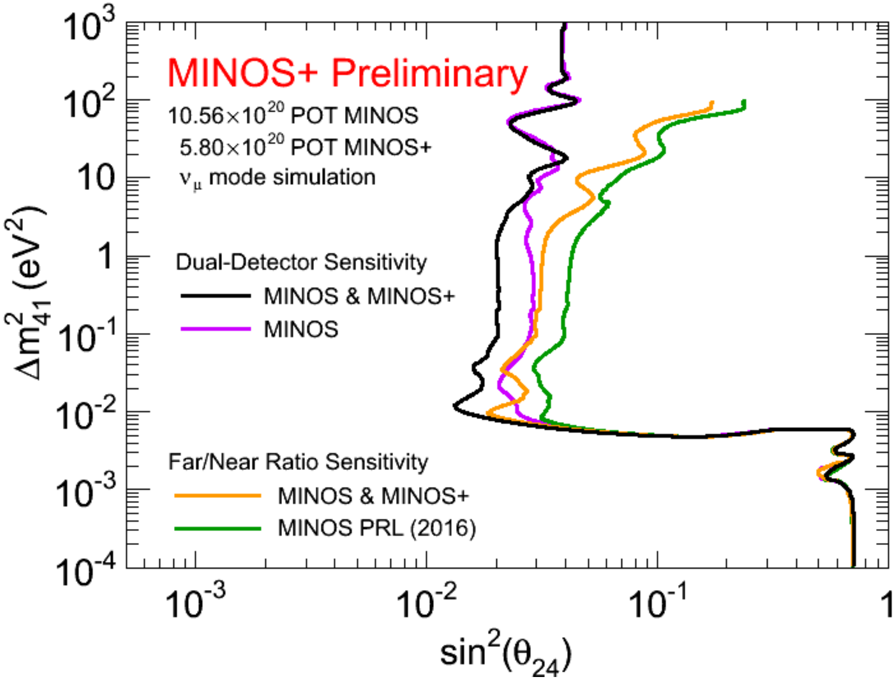


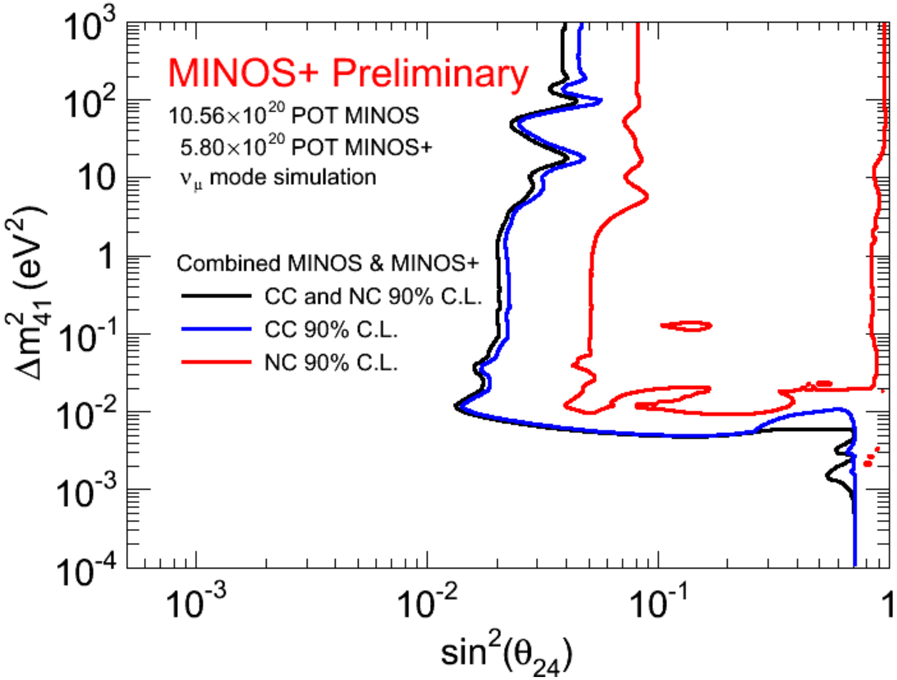
Correlations between the detectors

CC Systematic Uncertainties



Sensitivity

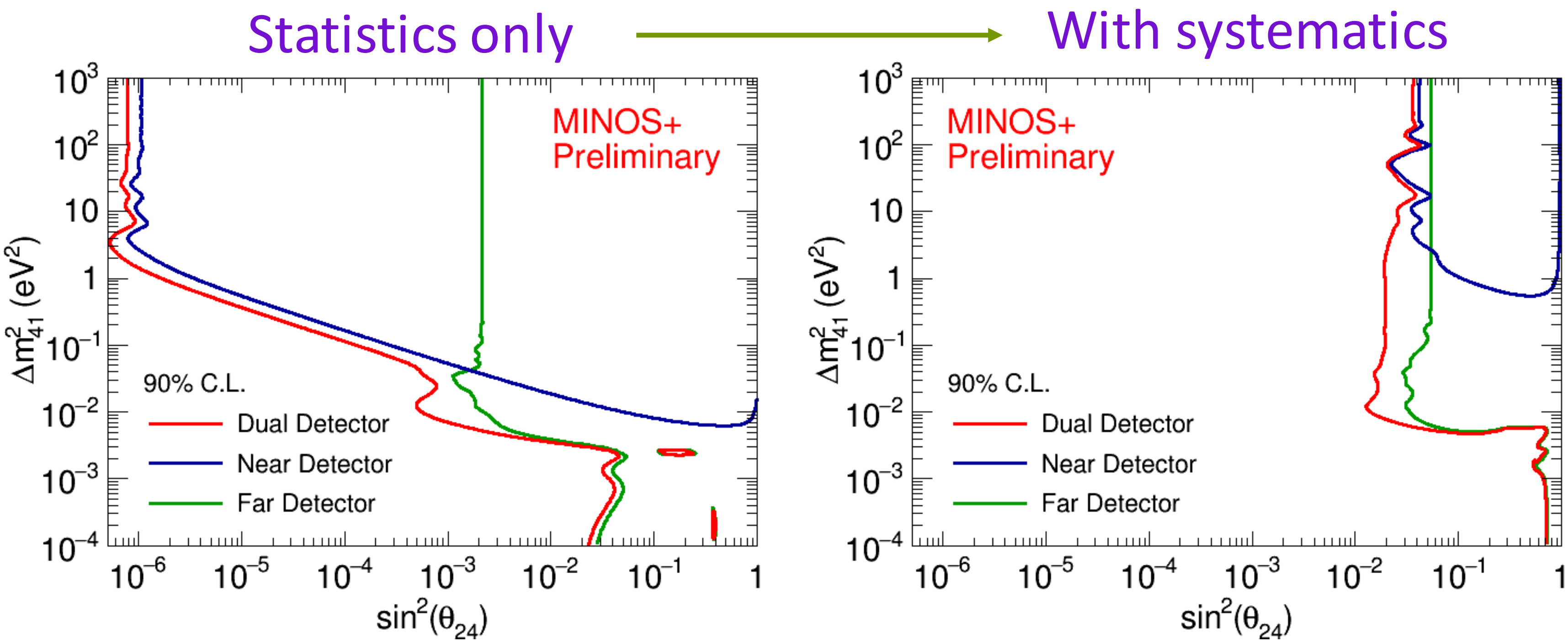




- Much improved sensitivity for $\Delta m^2_{41} > 10$ eV^2 with new method

MINOS PRL 2016: Phys. Rev. Lett. **117**, 209901 (2016)

Detector Contributions



- Very high stats in the ND – clearly systematics limited.
- Can see the effect of the correlations in the systematic uncertainties.

The Fit Procedure

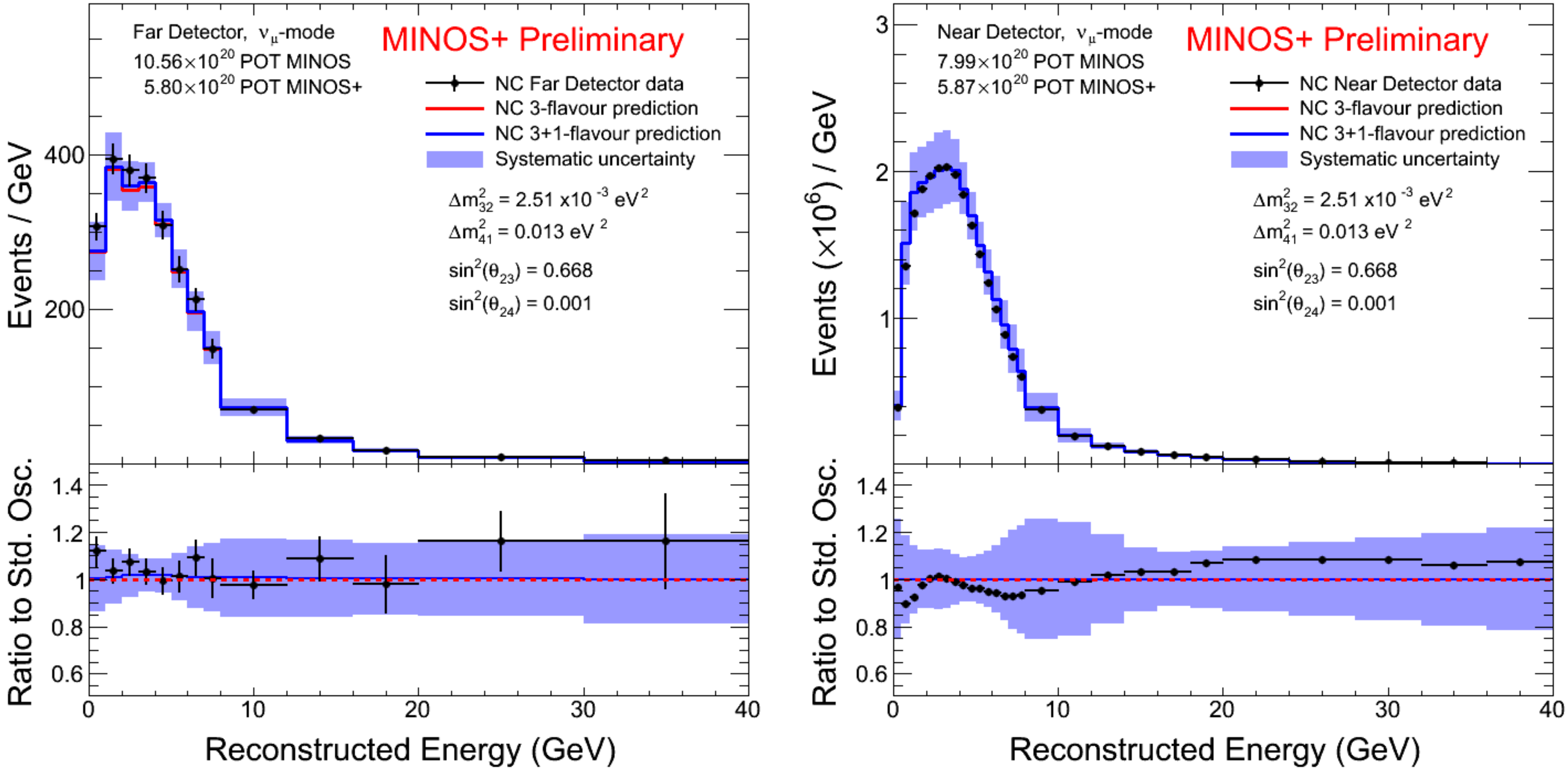
- Perform a maximum likelihood fit to minimise the following for both the CC and NC samples

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(x_i - \mu_i)[\mathbf{V}^{-1}]_{ij}(x_j - \mu_j) + \mathrm{const}$$

- 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}

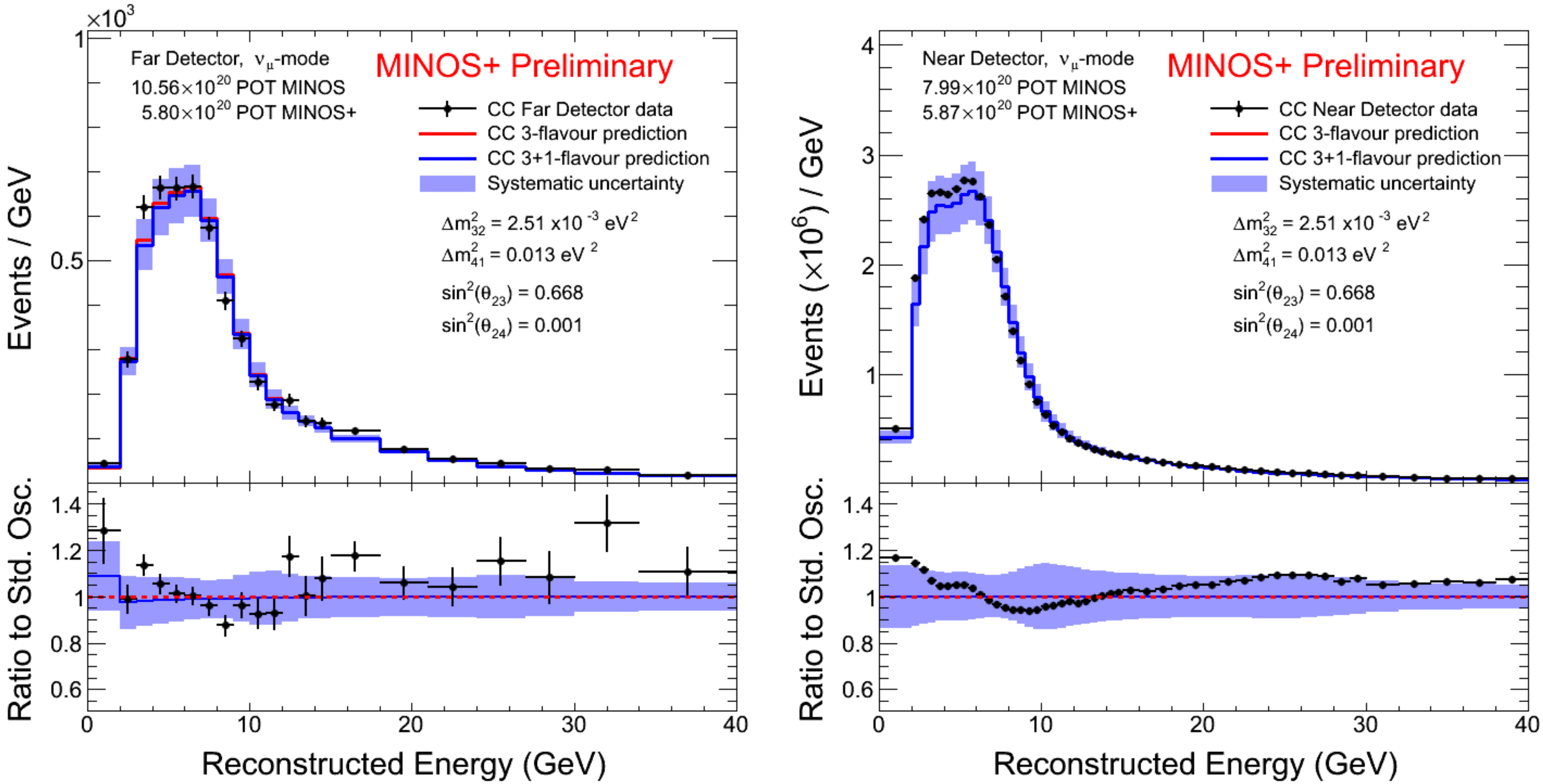
Selected NC Interactions

- The first step is to select the neutral current interactions.



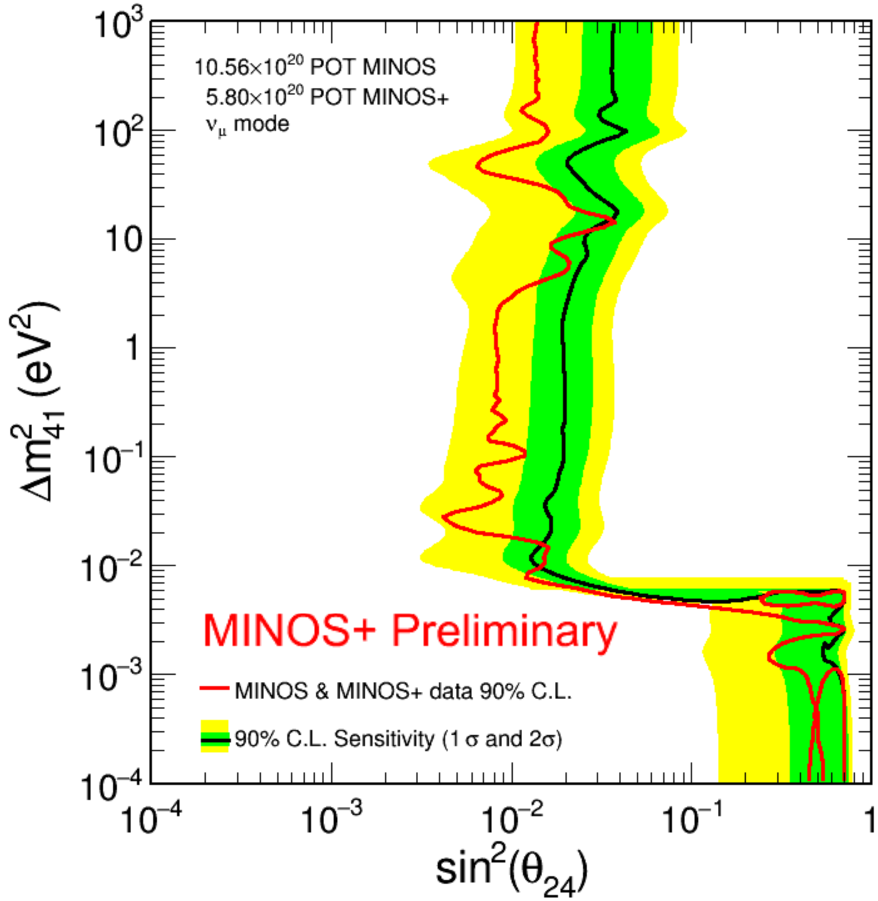
Selected CC Interactions

- Charged current interactions are selected from those that do not pass the neutral current selection.

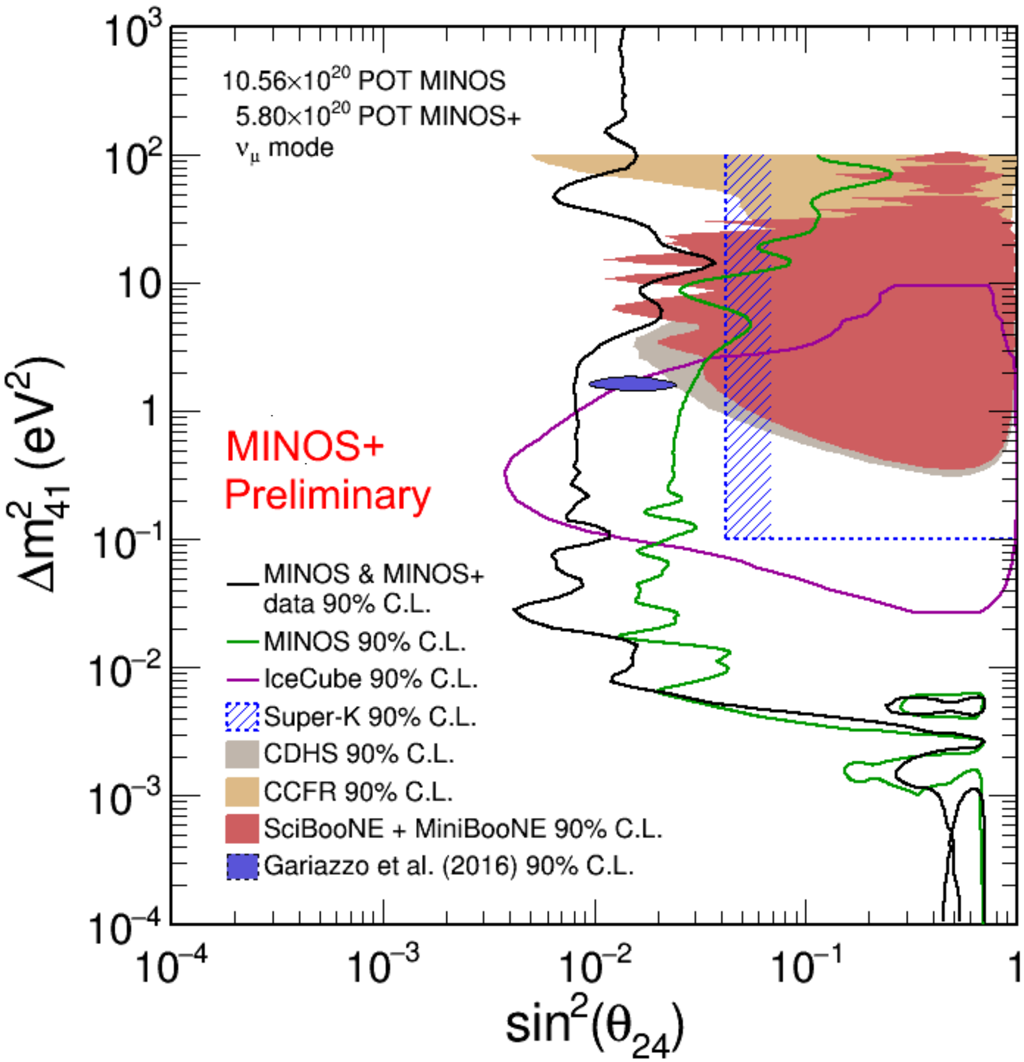


Exclusion Contour

- For each bin in $(\Delta m^2_{41}, \theta_{24})$ space, minimise with respect to the other parameters.
- Limit constructed using the Feldman-Cousins approach.
- Strong limit on θ_{24} set over seven orders of magnitude in Δm^2_{41}.
- Limit falls within expected 2σ sensitivity band.



Comparison with Other Experiments



- Comparison with various experiments
  - Very strong exclusion limit.
- Gariazzo region is from a global fit.
  - Shown under the assumption $|U_{e4}| = 0.023$

Comparing to the LSND phase-space

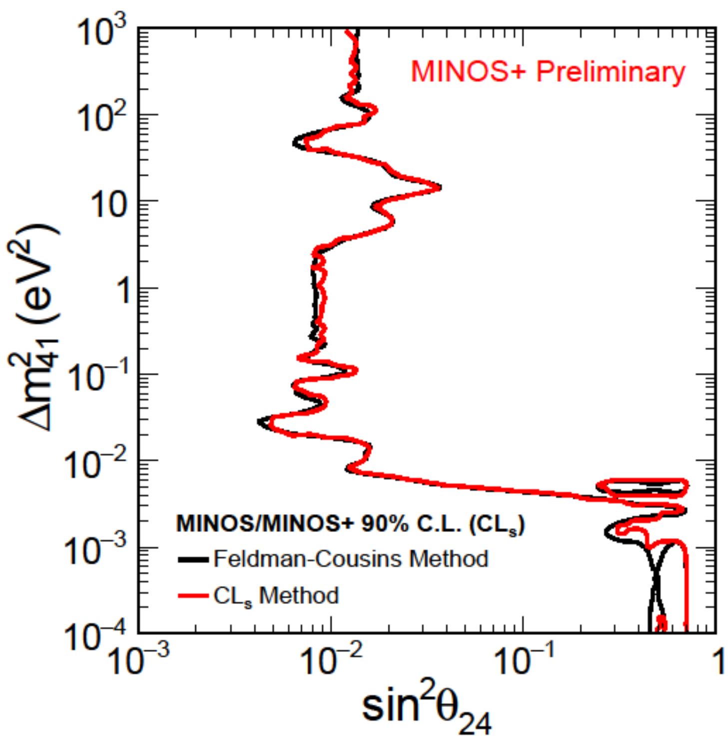
- MINOS/MINOS+ has main sensitivity to $|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$
- We want to be able to compare to LSND / MiniBooNE that measure $4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$
- Reactor experiments such as Daya Bay measure $|U_{e4}|^2 = \sin^2\theta_{14}$
- By combining MINOS/MINOS+ with Daya Bay (and Bugey-3) we can populate the same phase-space.

Combination with Daya Bay

- Performed preliminary new combination with Daya Bay.

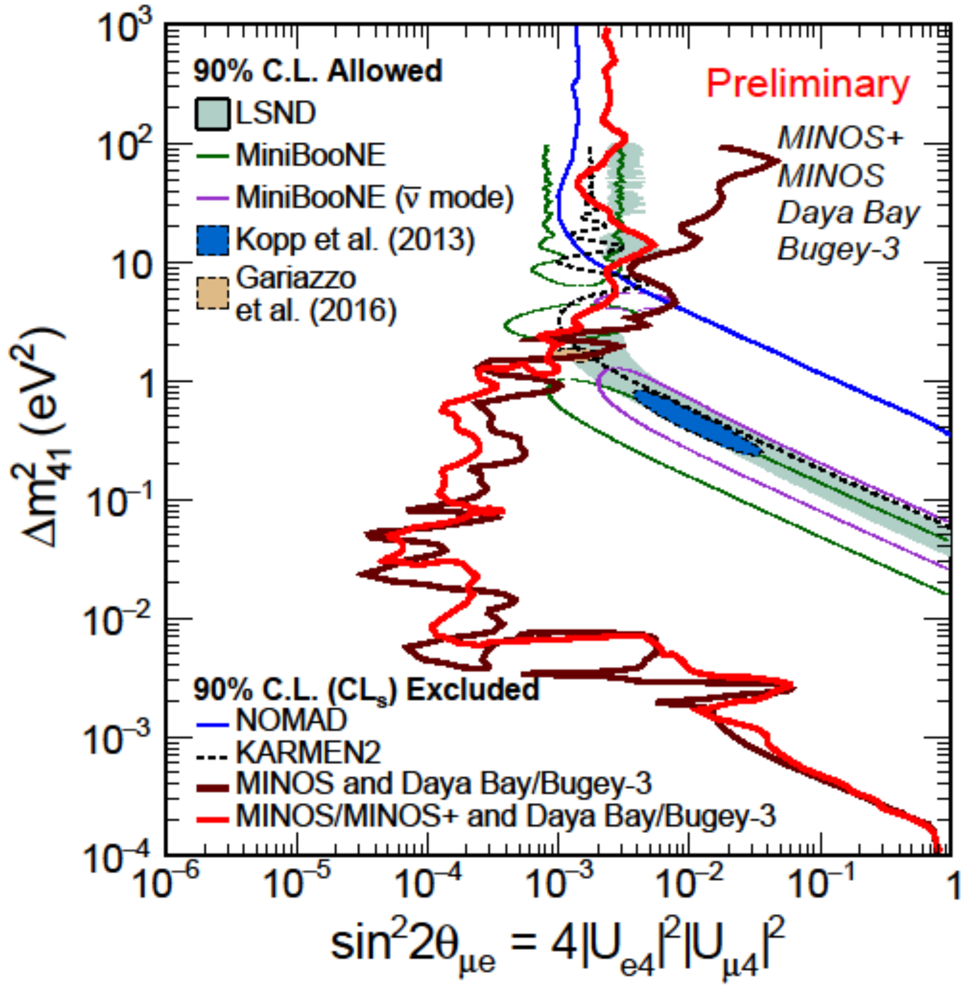
- Daya Bay data remains the same as in the previous combination
  - Phys. Rev. Lett. 117, 151801

- Re-compute new MINOS+ limit using the CLs technique.
  - Agrees well with the Feldman-Cousins procedure.



Combination with Daya Bay

- Preliminary result of the ongoing collaborative effort between MINOS+/MINOS and Daya Bay (with inclusion of Bugey-3 data)
- Significant increase in the constraint at $\Delta m^2_{41} > 10$ eV^2 due to two-detector fit method, as expected
- Final combination with a larger Daya Bay data set is planned



Summary

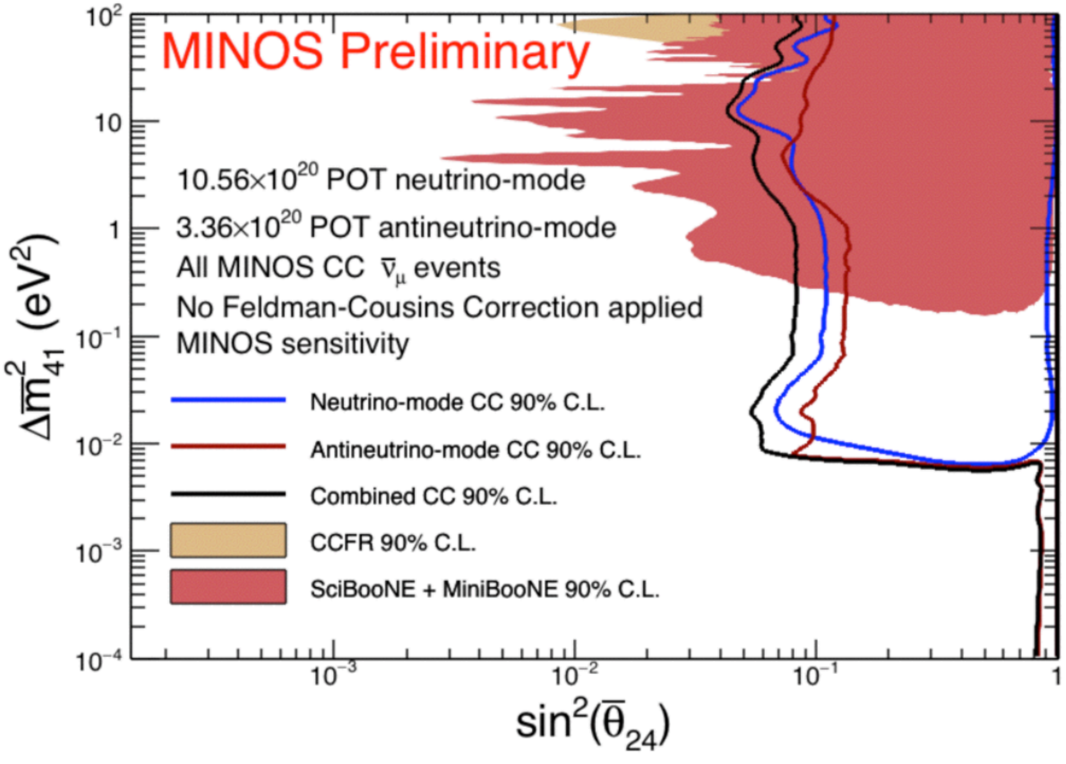
- MINOS/MINOS+ sets a new strong limit on the existence of a sterile neutrino over seven orders of magnitude in Δm^2_{41}.
- Further increases the tension between appearance and disappearance searches.
- Analysis of the other 50% of MINOS+ data underway.
- Corresponding searches using muon antineutrino disappearance and electron neutrino appearance under development.

Thank You

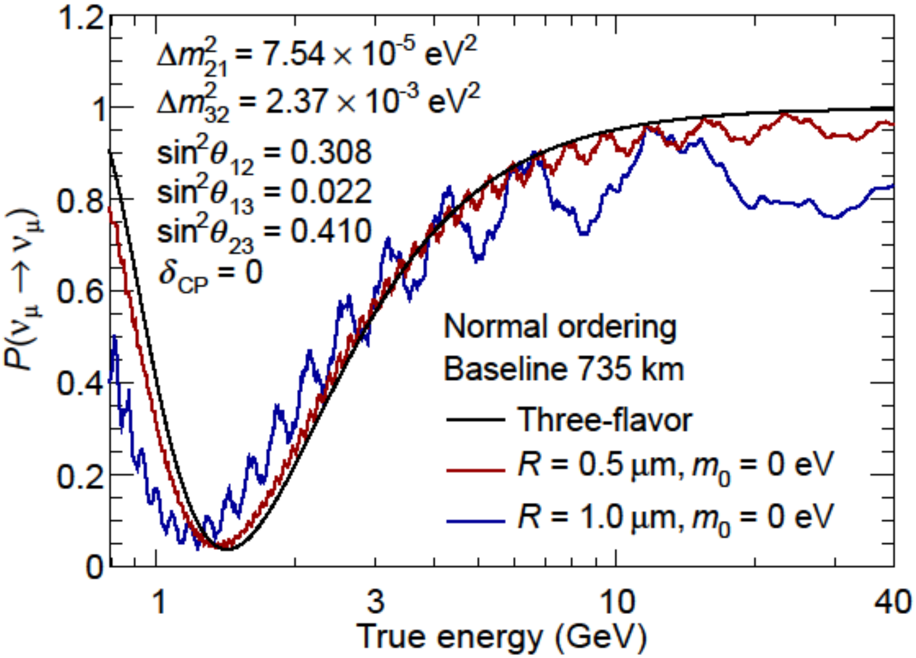
Any Questions?

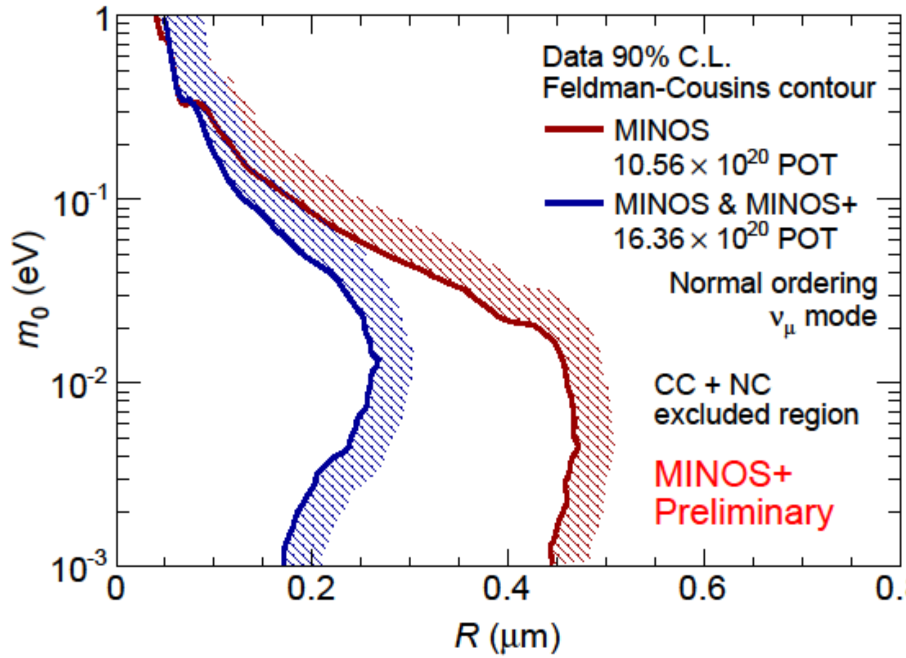
Sterile Antineutrino Sensitivity

- Select CC muon antineutrino interactions from:
  - The antineutrino component of the neutrino mode beam
  - The antineutrino beam

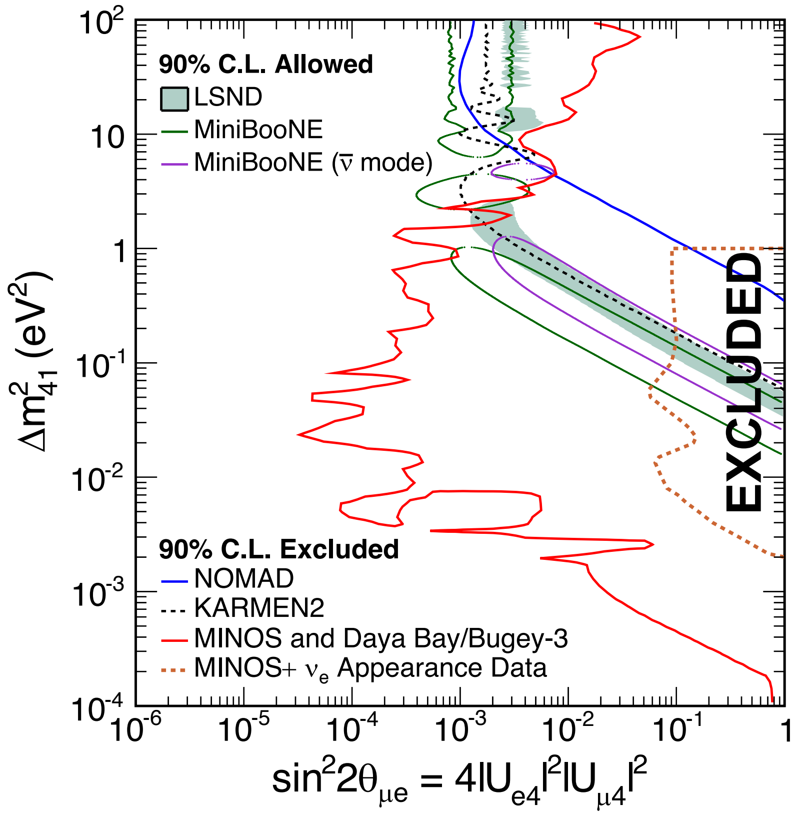


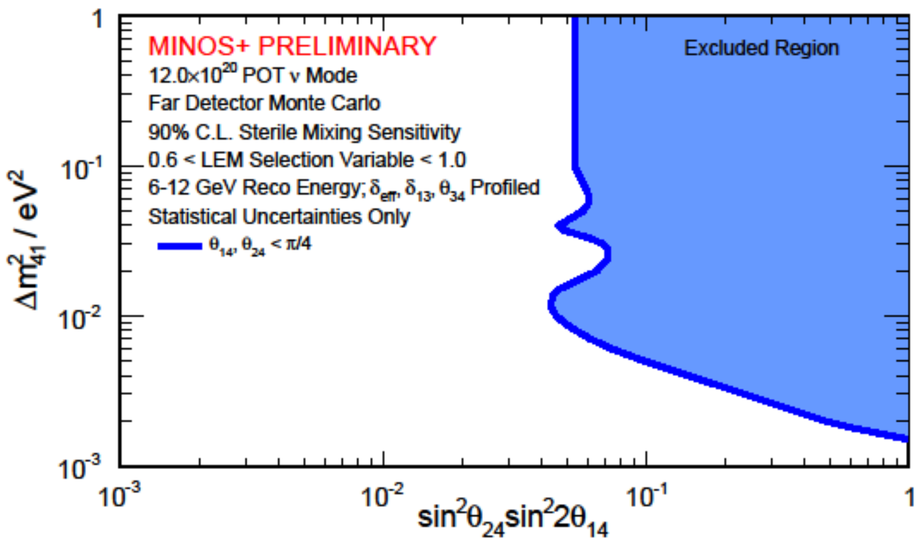
Large Extra Dimensions





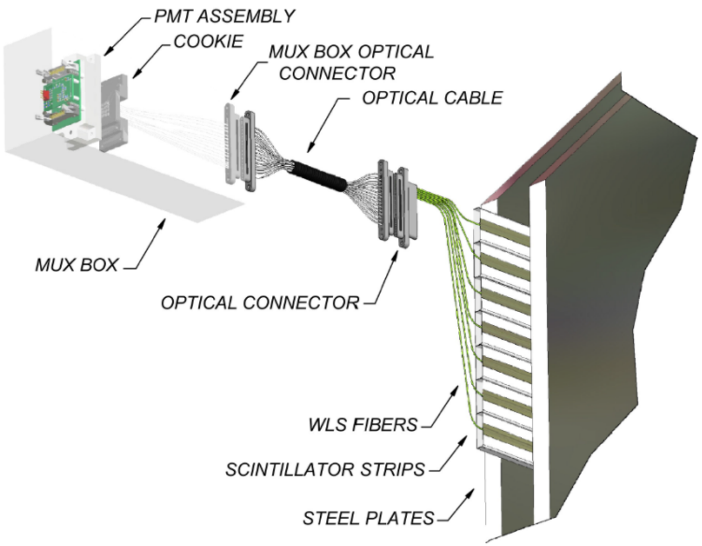
Sterile Neutrino Appearance

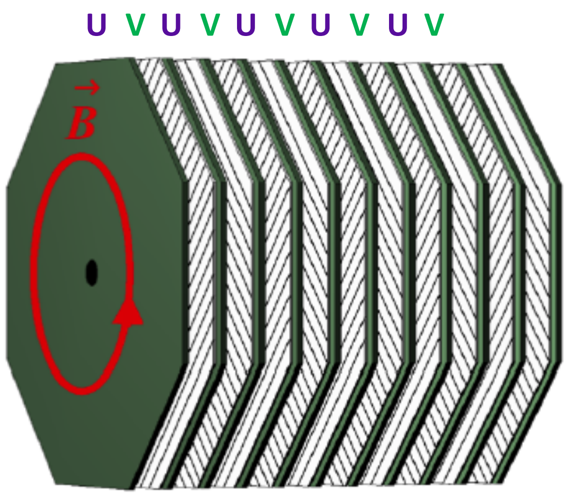


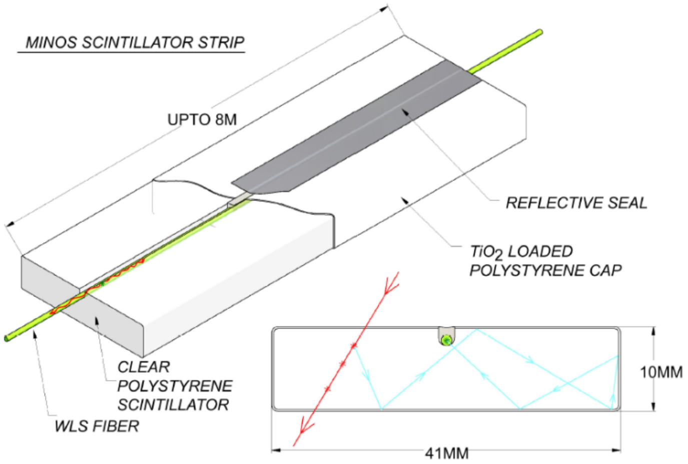


Detector Details

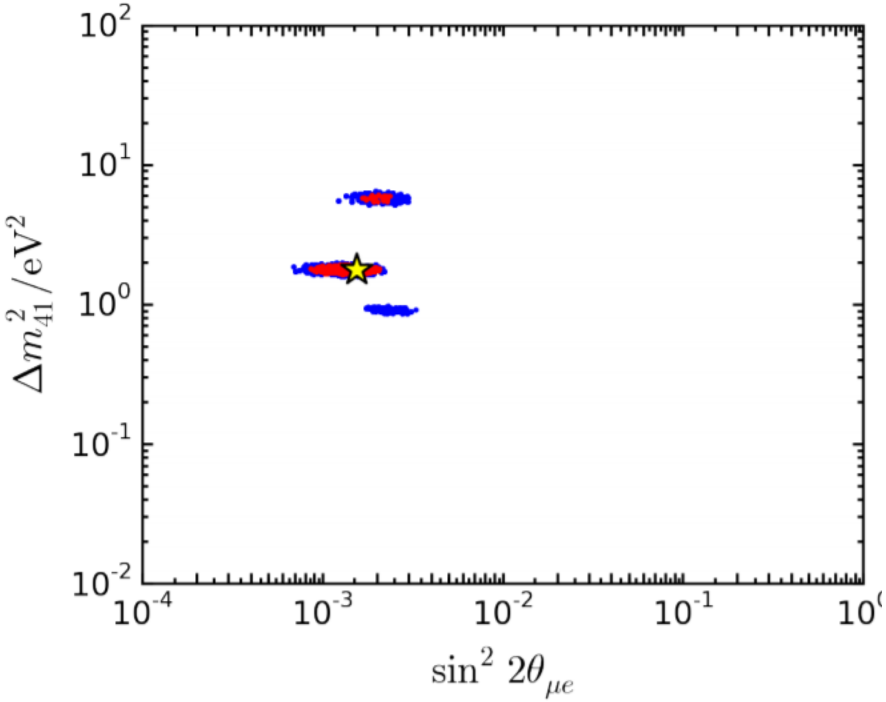
- Magnetized steel plates with scintillator strip and PMT instrumentation
  - Steel thickness: 2.54 cm
  - Intraplane distance: 5.96 cm
- Magnetized with a B-field ~1.3T
  - Range and curvature energy estimation for μ tra
  - Distinguish between μ+ and μ- tracks



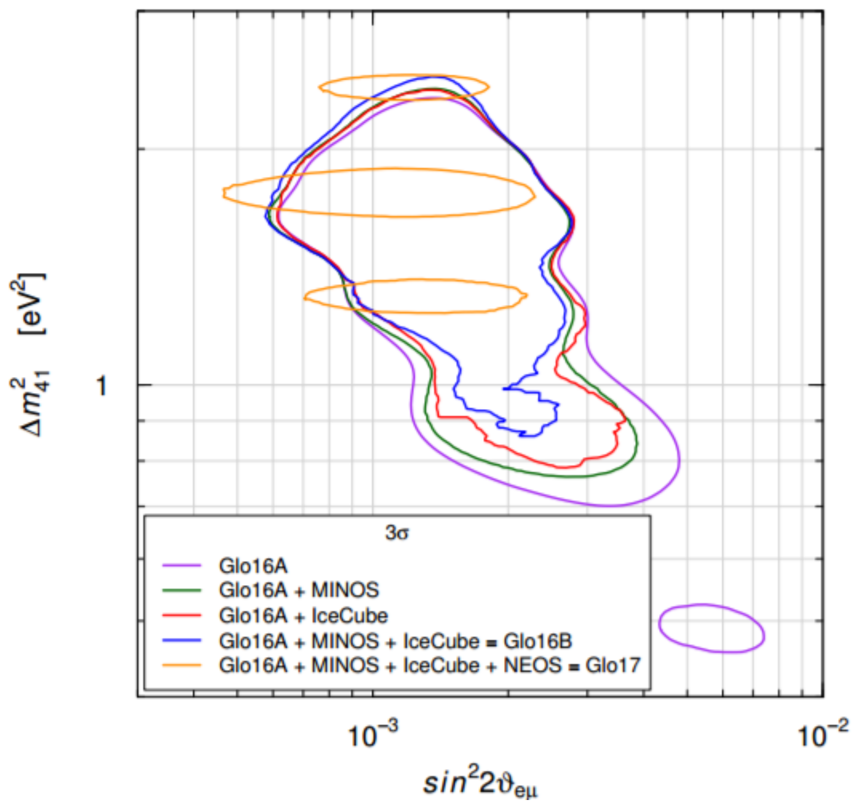




Global Fits including MINOS 2016



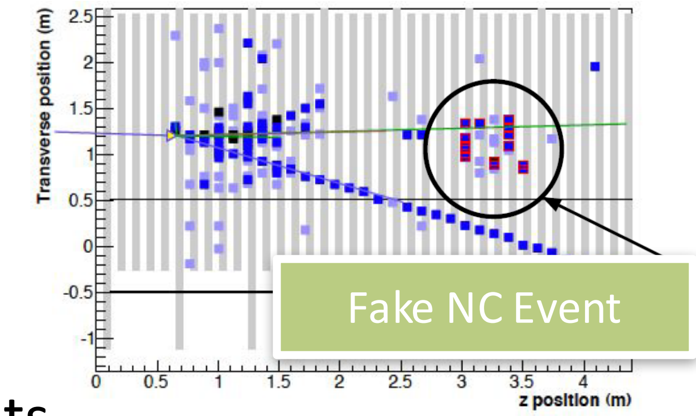
Phys. Rev. Lett. 117, 221801 (2016)
DOI: 10.1103/PhysRevLett.117.221801



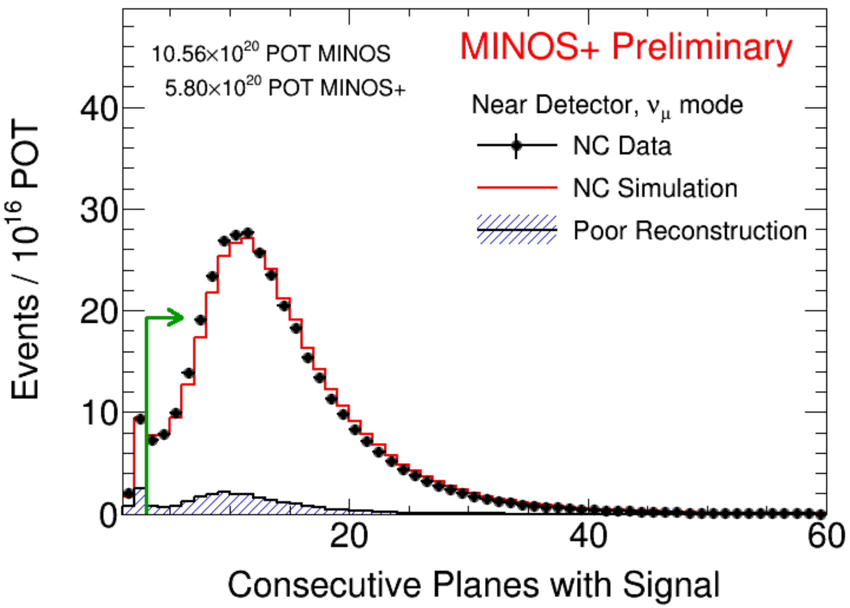
Gariazzo et al. (2017). arXiv: 1703.00860 [hep-ex]

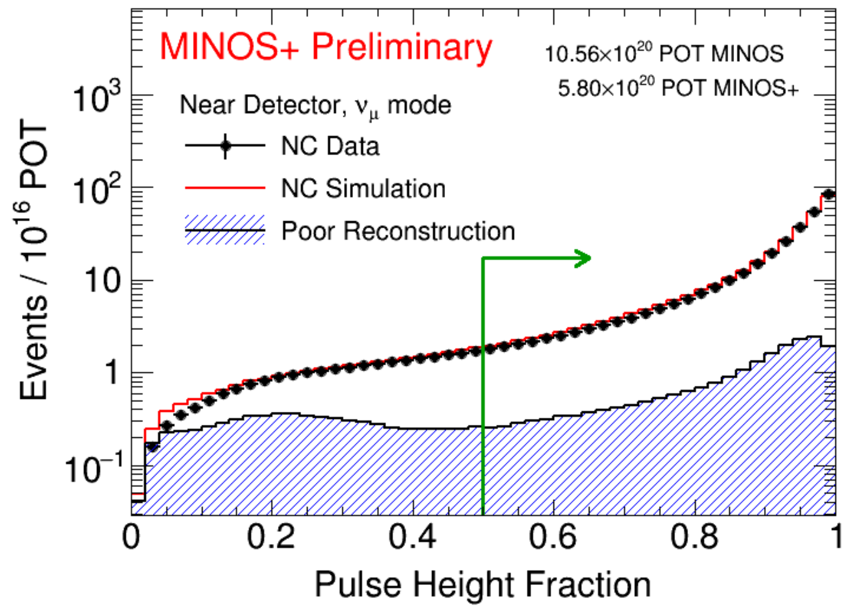
Near Detector Event Pile Up

- High event rate in the ND can cause the reconstruction to mistakenly separate showers from the main event.



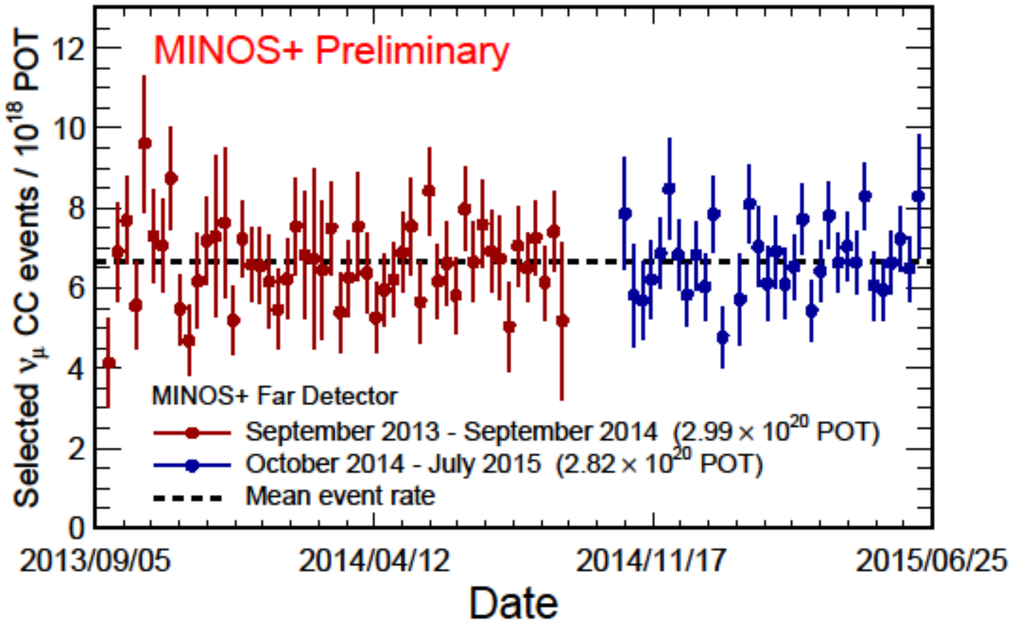
- Use a preselection to clean up these events

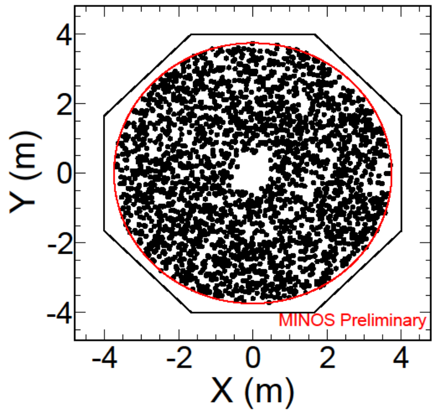


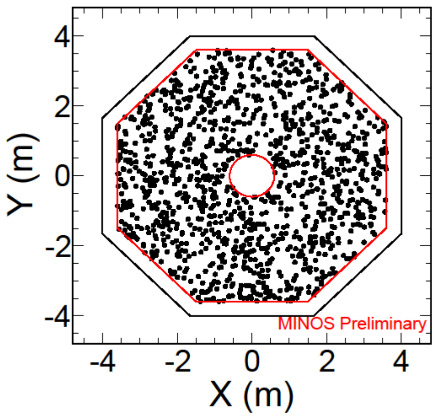


MINOS+ Data Stability

- MINOS / MINOS+ FD data rate over the two year period.

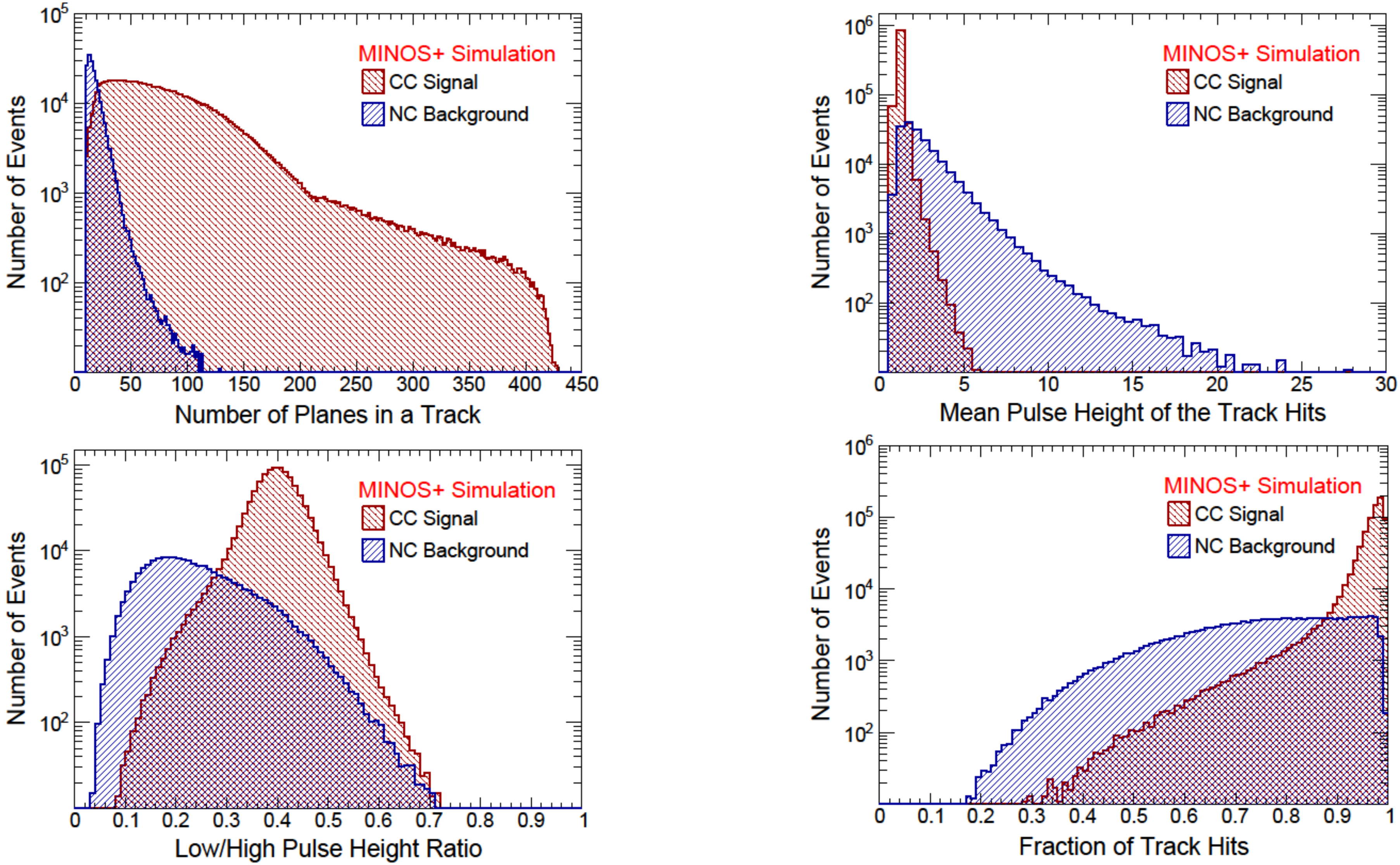




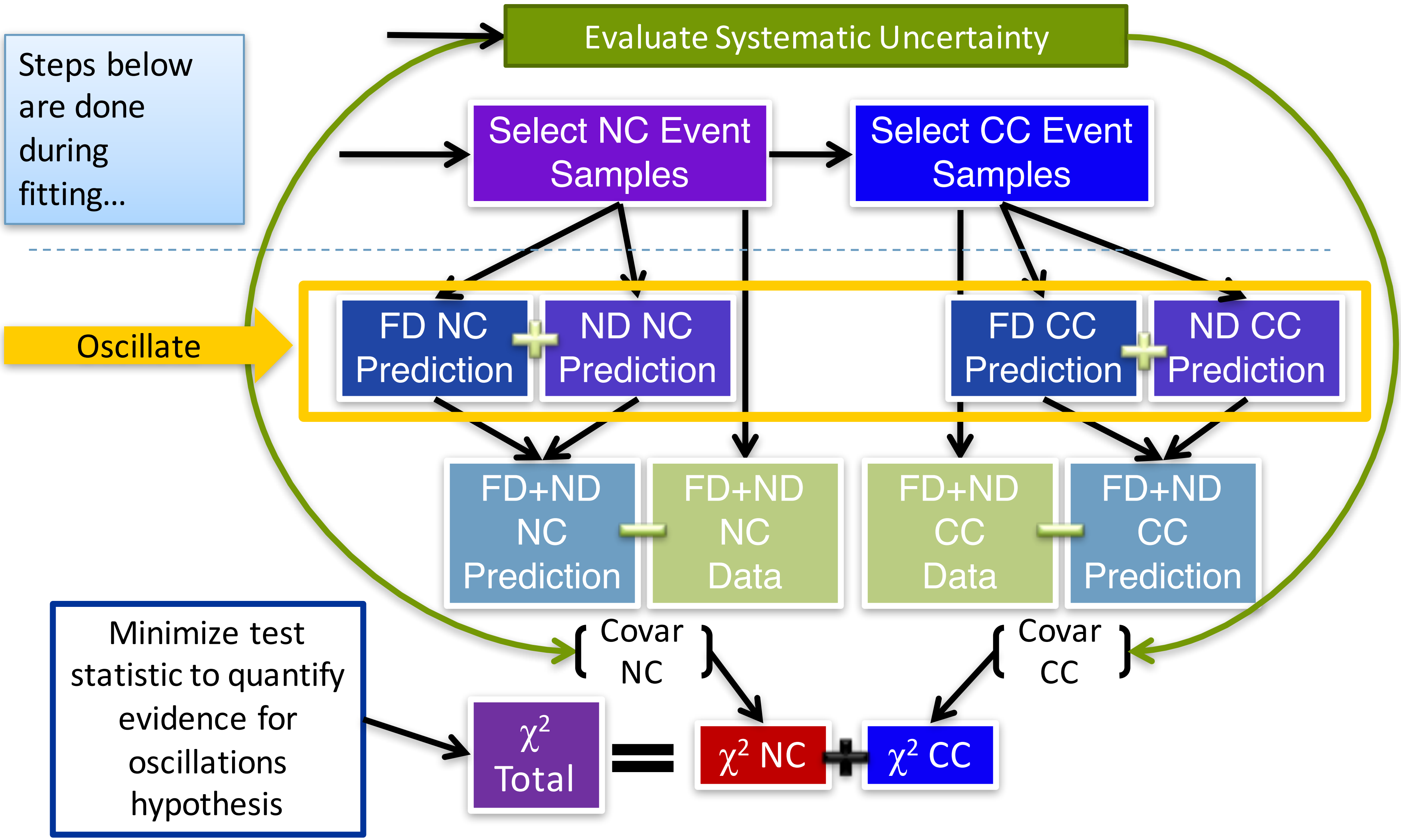


- Uniform event distribution across the FD for both CC and NC interactions.

CC kNN Inputs



Analysis Flow Chart

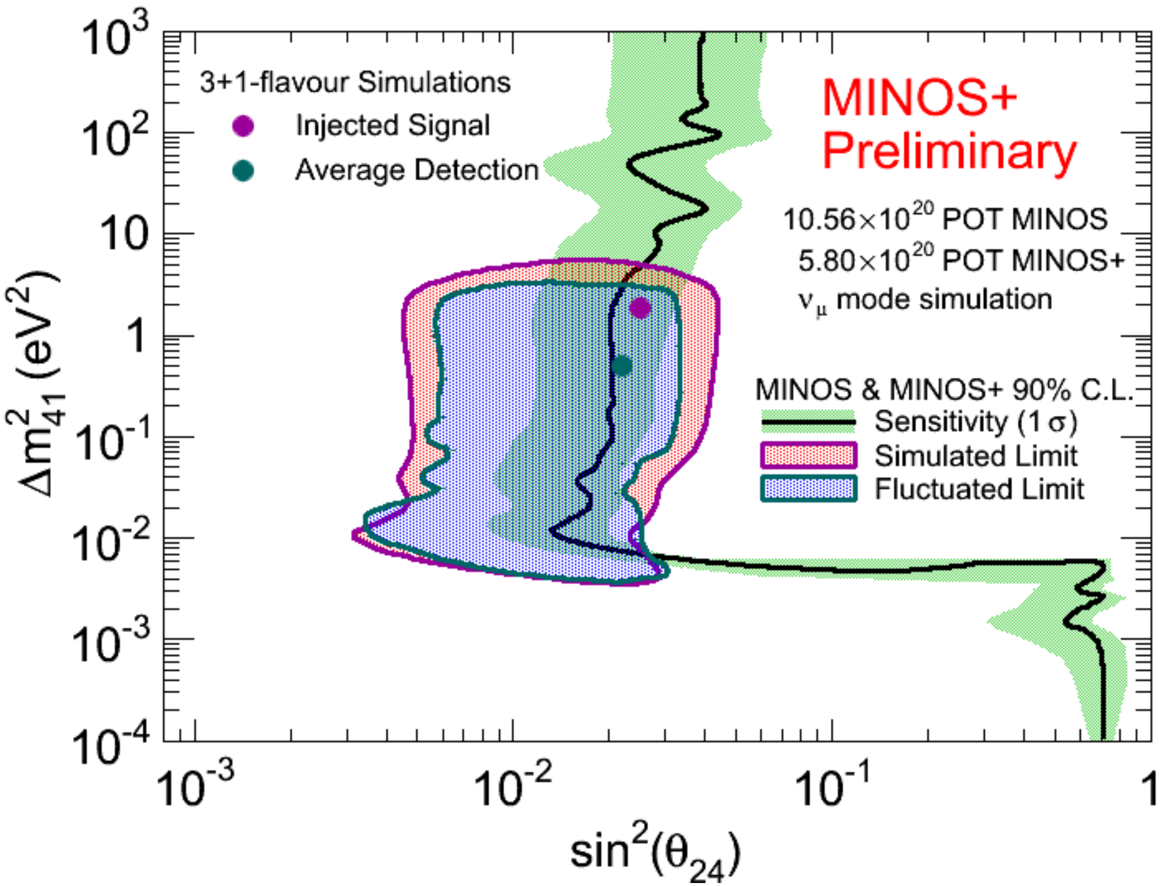


Signal Injection Test

- Tested signal injection at the global best fit point.

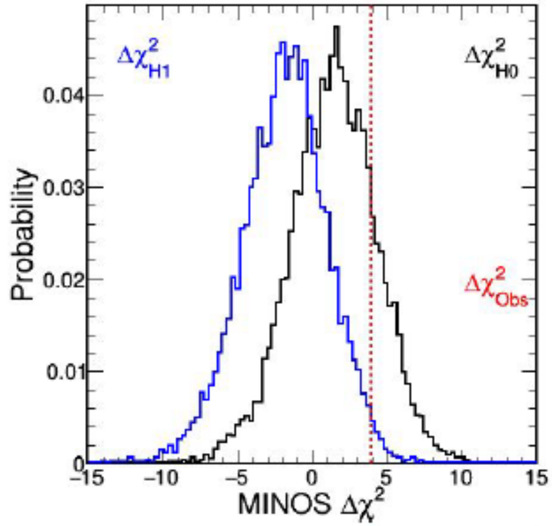
- This shows what MINOS+ should see if a sterile neutrino exists at
  $\theta_{24} = 0.15$
  $\Delta m^2_{41} = 1.65\ eV^2$

- See allowed region with and without systematic fluctuations.

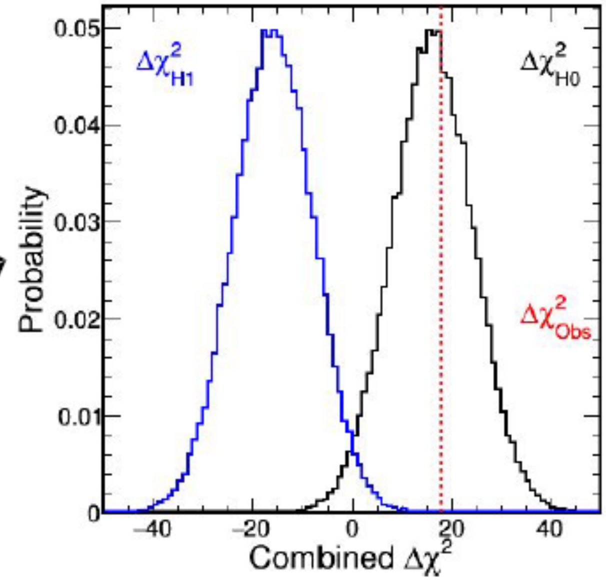


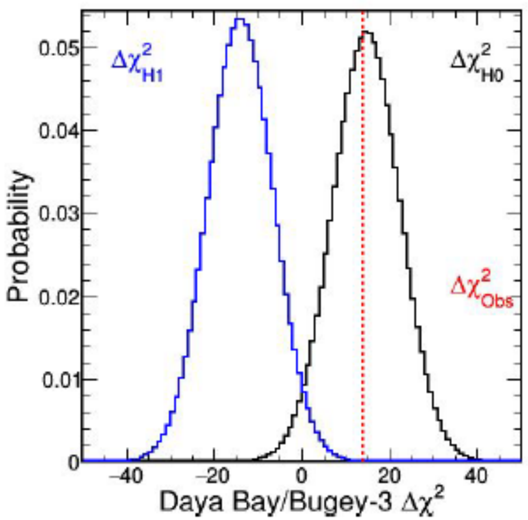
Combination Technique

For each point in the parameter space, combine $\Delta\chi^2$ distributions



Draw MINOS $\Delta\chi^2$ values from fake experiments.





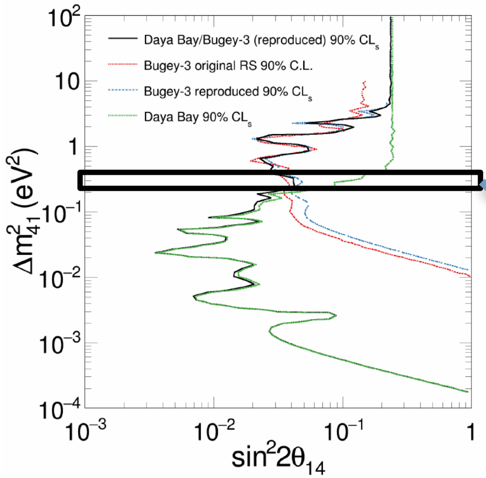
Draw Daya Bay/Bugey-3 $\Delta\chi^2$ values from Gaussian distributions.

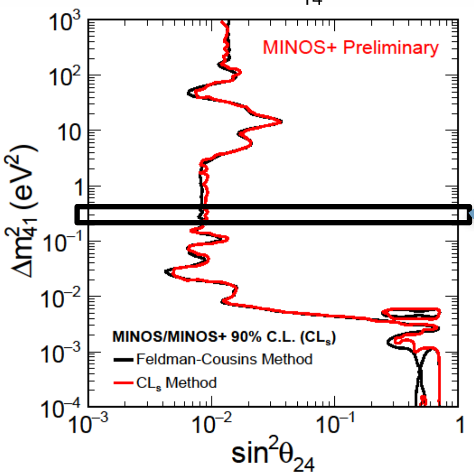
MINOS and Daya Bay/Bugey-3 have uncorrelated systematics so:

$\Delta\chi^2_{combo} = \Delta\chi^2_{DB} + \Delta\chi^2_{MINOS}$

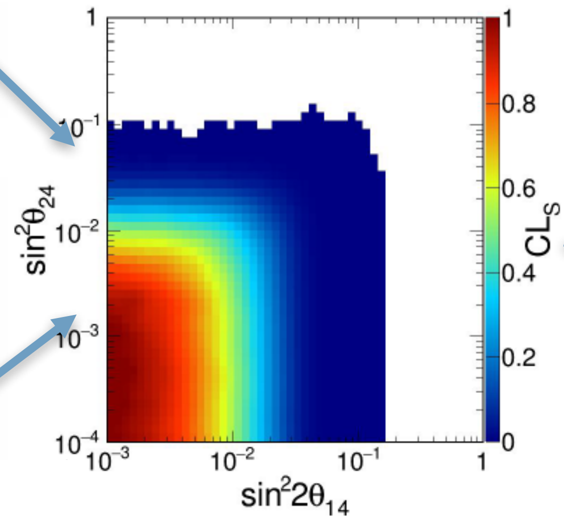
Combination Technique

- For fixed Δm^2_{41}, compute combined limit in the appearance parameter space

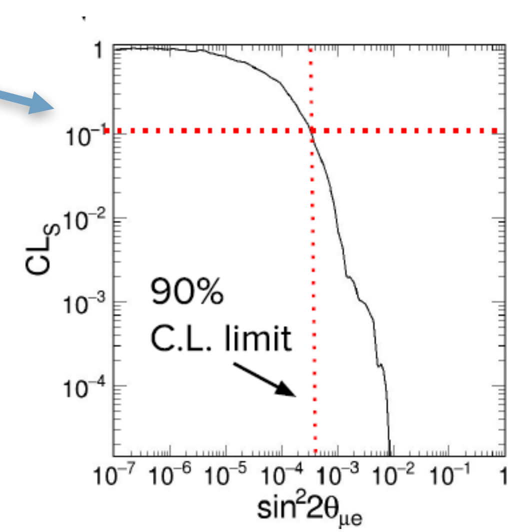




- Convert CL$_s$ from a surface in the 2D space ($\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$) to a 1D space in $\sin^2 2\theta_{\mu e}$
  - $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$



- Largest CLs value is the conservative choice



- For each fixed Δm^2_{41}, calculate CL$_s$ for all combinations in the space ($\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$)