Sterile neutrino search from disappearance measurements at Daya Bay and MINOS/MINOS+

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On behalf of the Daya Bay collaboration

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Outline

- Introduction to Sterile Neutrino Mixing
- Daya Bay Results
- Daya Bay + Bugey-3 Combination
- MINOS/MINOS+ Results
- Daya Bay + Bugey-3 + MINOS/MINOS+ Combination

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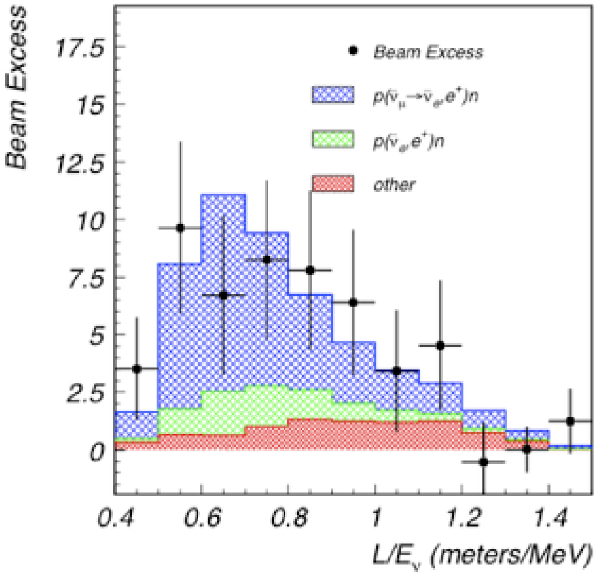
Sterile Neutrinos

Sterile neutrinos are hypothetical particles which do not participate in standard weak interactions.

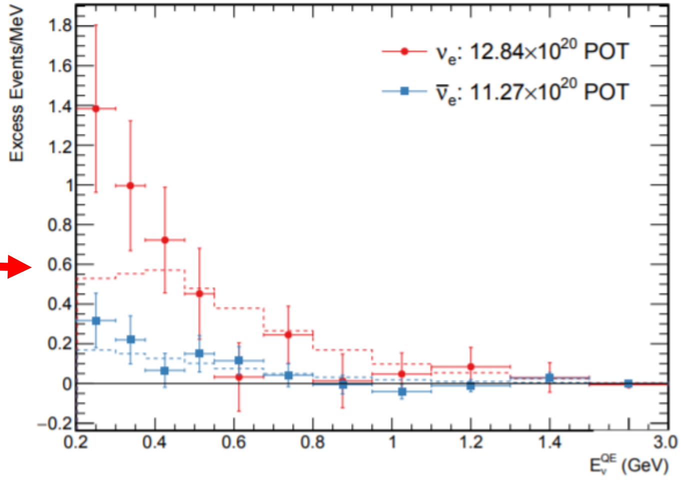
- Well-motivated from the theoretical standpoint
- Pratically unobservable, indirect search via oscillation measurements
- Candidates to resolve puzzles in astronomy and cosmology
- Could explain some experimental anomalies



Phys. Rev. D. ***64***(11), 112007 (2001)

LSND anomaly:
3.8σ excess of $\bar{\nu}_e$ in a
$\bar{\nu}_\mu$ beam (2001)

MiniBooNE anomaly:
4.7σ excess in combined
$\nu/\bar{\nu}$ appearance
measurements (2018)

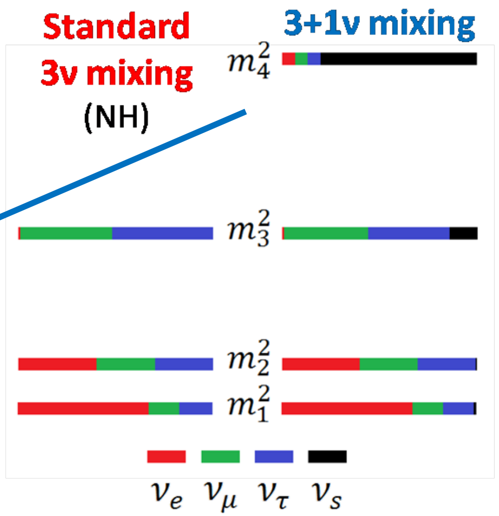


Phys. Rev. Lett. ***121***(22), 221801 (2018)

(3+1) Neutrino Oscillations

- Add an additional flavor and mass eigenstate:

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



For **Daya Bay** and **Bugey-3**:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \boxed{\sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}}$$

→ **Sensitive to sin^{2}2θ$_{14}$**

Probe (sin^{2}2θ$_{14}$, Δm$^2_{41}$)

For **MINOS/MINOS+**:

$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \boxed{\sin^2 2\theta_{24} \sin^2 \frac{\Delta m^2_{41} L}{4E}}$$

+

Sensitive to sin^{2}2θ$_{24}$

Probe (sin^{2}θ$_{24}$, Δm$^2_{41}$)

Directly probe regions allowed by **LSND** & **MiniBooNE** **(sin^{2}2θ$_{\mu e}$, Δm$^2_{41}$)**

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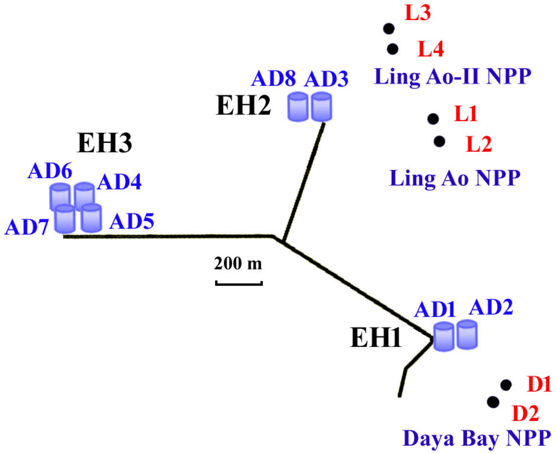
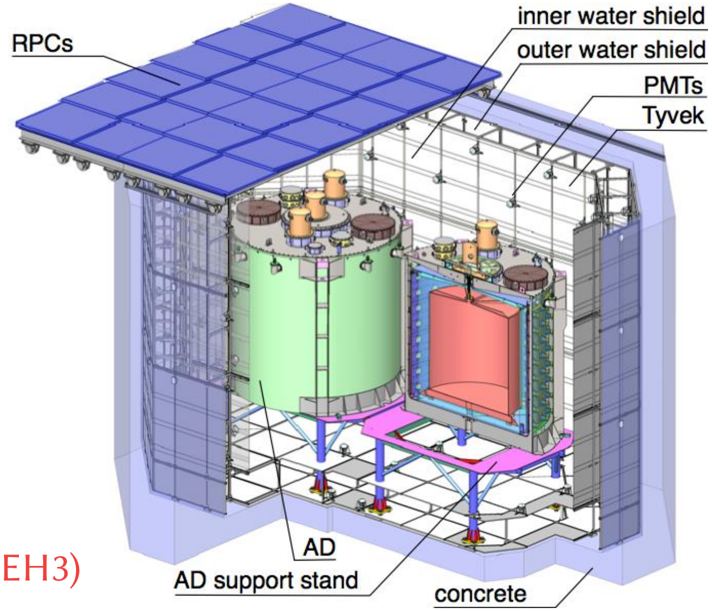


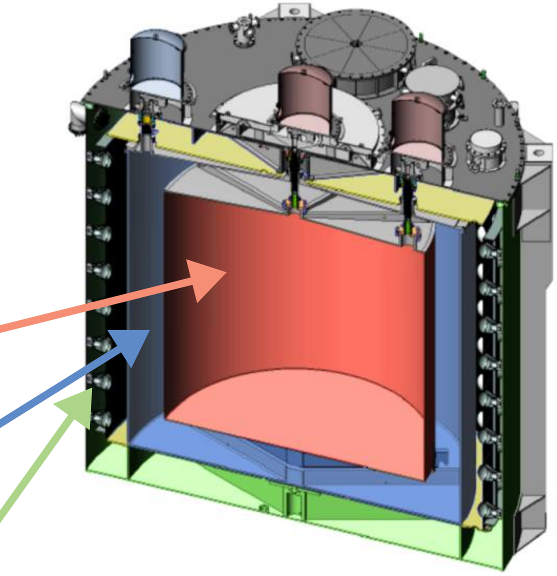
3 experimental halls (EHs)
2 near (EH1 & EH2); 1 far (EH3)



Nucl. Instrum. Meth. A ***733*** 8 (2015)

- Powerful reactor complex
  - Large statistics
- Relative near-far measurement & 8 identically designed detectors
  - Reduce systematic uncertainties
- Multiple shielding
  - Low background
- Inverse beta decay
  - Gadolinium doped (capture neutron)

	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding



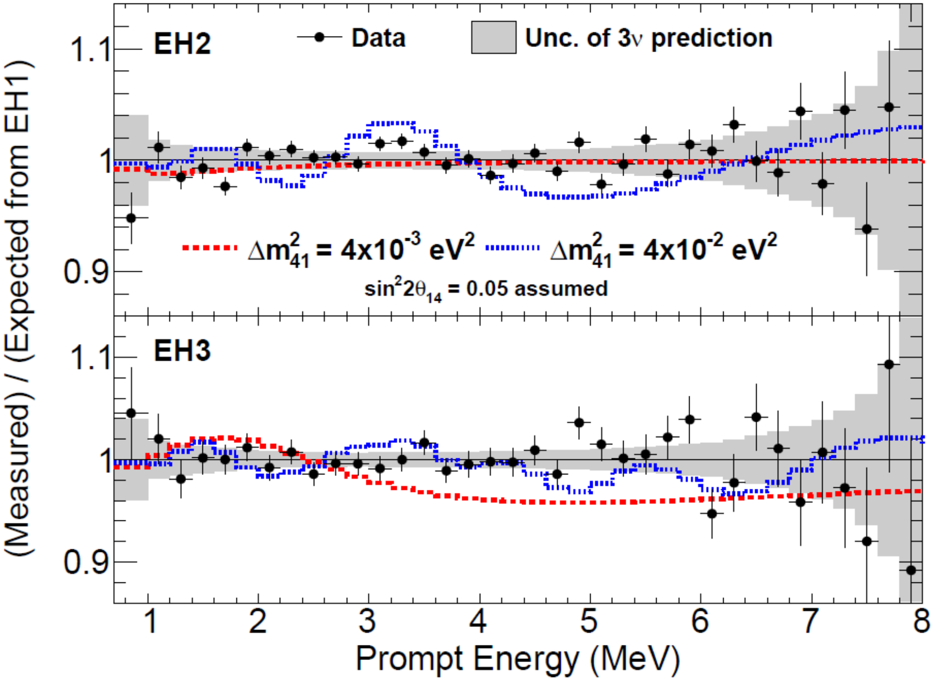
Nucl. Instrum. Meth. A ***811*** 133 (2016)

Details in the parallel talk: **New results from Daya Bay** by *Juan Pedro Ochoa-Ricoux*

Sterile Neutrino Search at Daya Bay

- Search for additional spectral distortion
  - frequency higher than standard three-flavor oscillations
- Multiple baselines
  - Sensitive to sterile neutrino for $2\mathrm{x}10^{-4}\mathrm{eV}^2 \leq |\Delta m^2_{41}| \leq 0.2\ \mathrm{eV}^2$
- Sensitivity at different $|\Delta m^2_{41}|$ regions
  - EH2/EH1: $|\Delta m^2_{41}| \approx 4\mathrm{x}10^{-2}\ \mathrm{eV}^2$
  - EH3/EH1: $|\Delta m^2_{41}| \approx 4\mathrm{x}10^{-3}\ \mathrm{eV}^2$

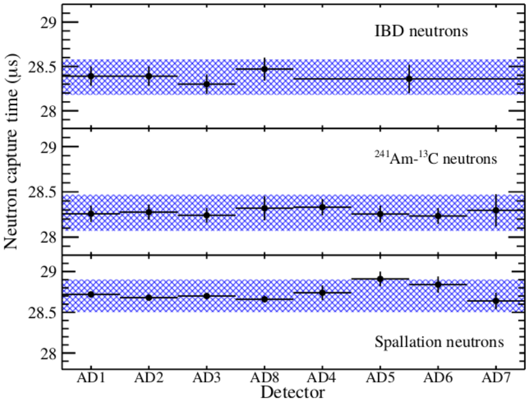
Phys. Rev. Lett, ***117***(15), 151802 (2016)



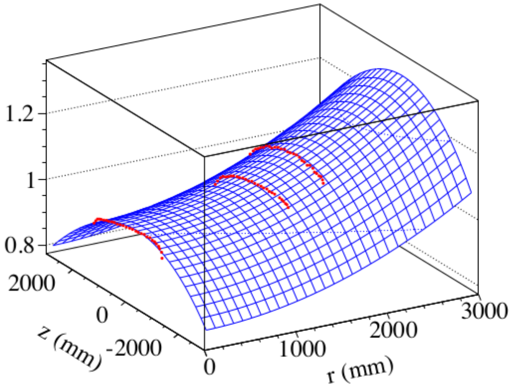
$$\text{Ratio} = \frac{\text{observed spectra at EH2 and EH3}}{3\nu \text{ best fit prediction EH1}}$$

New Search for Sterile Neutrinos

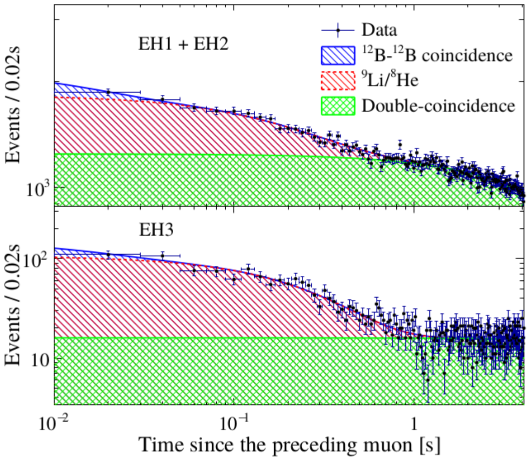
- New search with 1230 days-data (2.5 M events)
  - Twice the statistics w.r.t the previous search
- Reduced relative detection efficiency uncertainty (down to 0.13%)
- New spatial non-uniformity correction
  - Time-dependent spatial non-uniformity caused by small drift in light-yield now taken into account
- More precise background assessment
  - Muon-induced ^{9}Li/^{8}He & fast neutrons



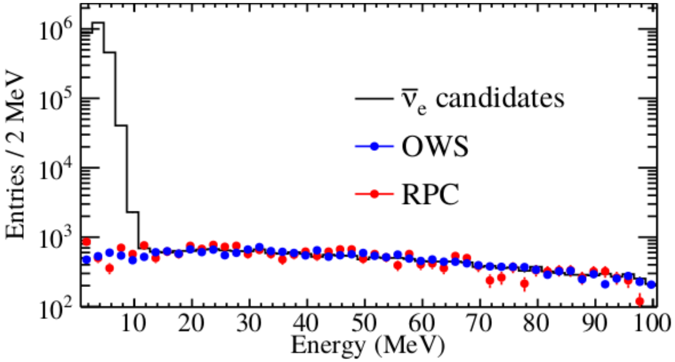
Relative Gd capture fraction < 0.1%
Relative detection efficiency 0.13%



Spatial variation in light yield



$\overline{\nu}_e$ candidates versus time since the preceding muon



$\overline{\nu}_e$ candidates compared to high purity fast-neutron sample

Phys. Rev. D. ***95***(7), 072006 (2017)

Sterile Neutrino Analysis

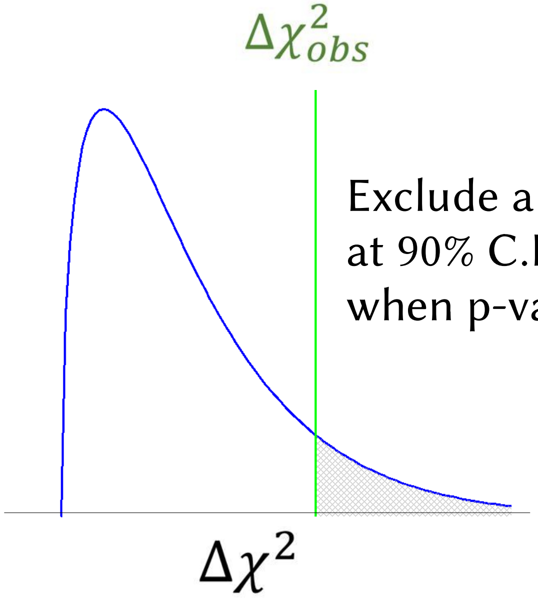
- Two independent analyses yield consistent results
  - Method A:
    - Predicts far spectra from near spectra
    - Covariance matrix for χ^2
  - Method B:
    - Simultaneously fit all energy spectra using predicted reactor flux
      - Huber-Mueller model with enlarged normalization uncertainty to 5%
    - A mixture of pull-terms and covariance matrix for χ^2

From *Phys. Rev. Lett.* ***112***(20), 202501 (2014)

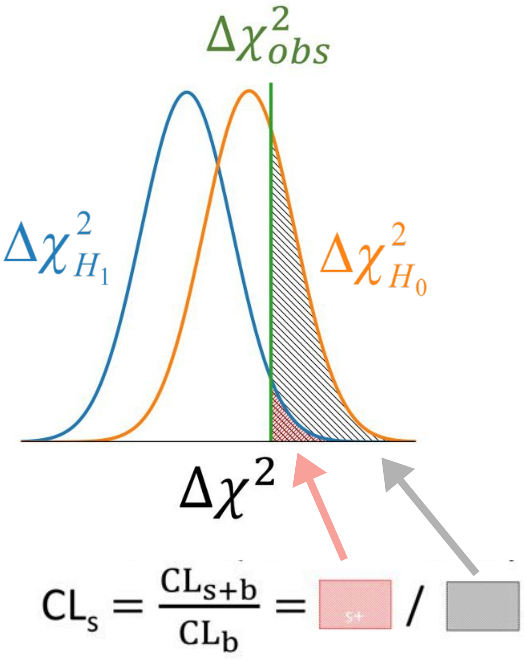
Statistical Methods

- **Feldman-Cousins**
  - compare one specific point for (3+1)ν model, to the best-fit for the same model

$$\Delta\chi^2=\chi^2_{4\,\nu,\,point}-\chi^2_{bestfit}$$



Exclude a point at 90% C.L. when p-value < 0.1



$\mathrm{CL_s} = \frac{\mathrm{CL_{s+b}}}{\mathrm{CL_b}} =$ 🟥 / ⬜

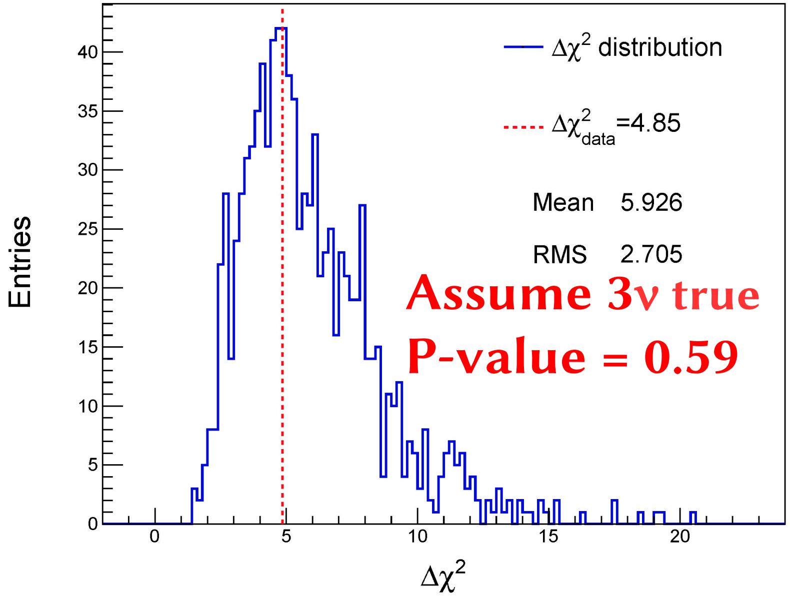
- **Gaussian CL$_s$**: two hypothesis test
  - H$_1$: {$\sin^2 2\theta_{14}$=a, Δm^2_{41}=b}, one specific point for (3+1)ν model
  - H$_0$: {$\sin^2 2\theta_{14}$=0, Δm^2_{41}=0}, standard 3ν model

$$\Delta\chi^2=\chi^2_{H_1}-\chi^2_{H_0}=\chi^2_{4\,\nu,\,point}-\chi^2_{3\,\nu}$$

Exclude a point at 90% C.L. (CL$_s$) when CL$_s$ ≤ 0.1

Gaussian CL$_s$ method: *Nucl. Instrum. Meth. A* ***827***, 63-78 (2016)

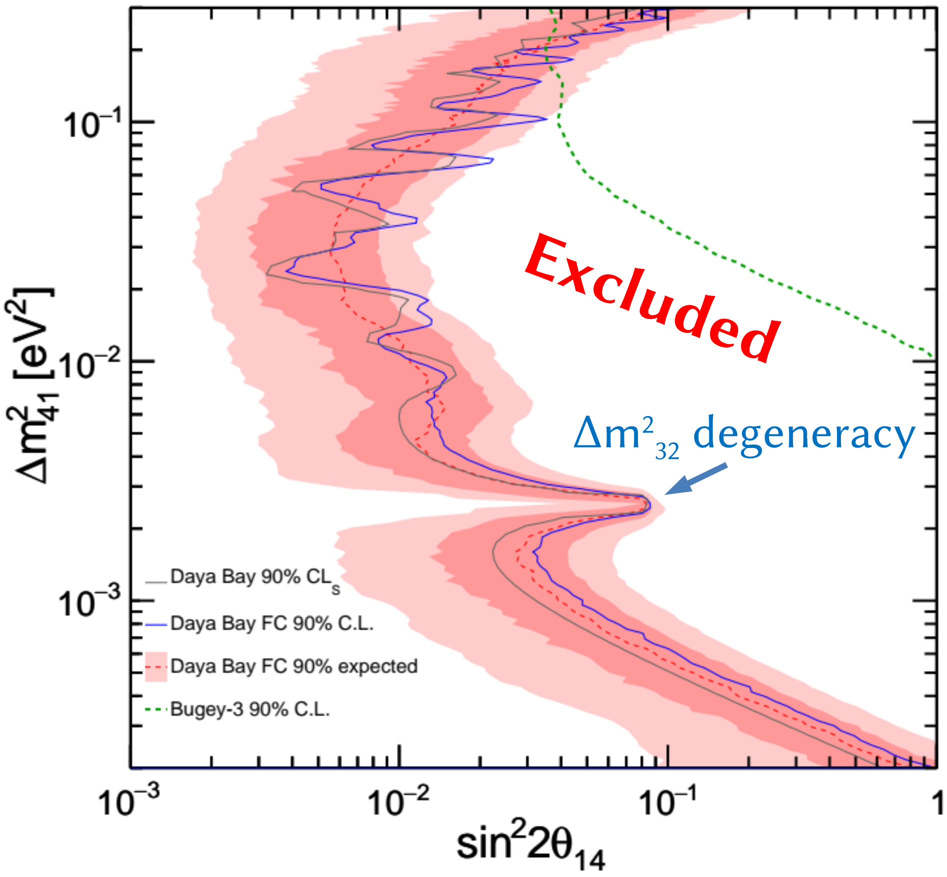
Sterile Neutrino Search at Daya Bay



Assume 3ν true

P-value = 0.59

Preliminary 1230 days



Excluded

Δm^2_{32} degeneracy

- No evidence of light sterile neutrino observed
- Method A and B yield consistent contours when using the same statistical approach (e.g. CL_s)
- World-leading limits for 2×10^{-4} eV^2<$|\Delta m^2_{41}|$ <0.2 eV^2

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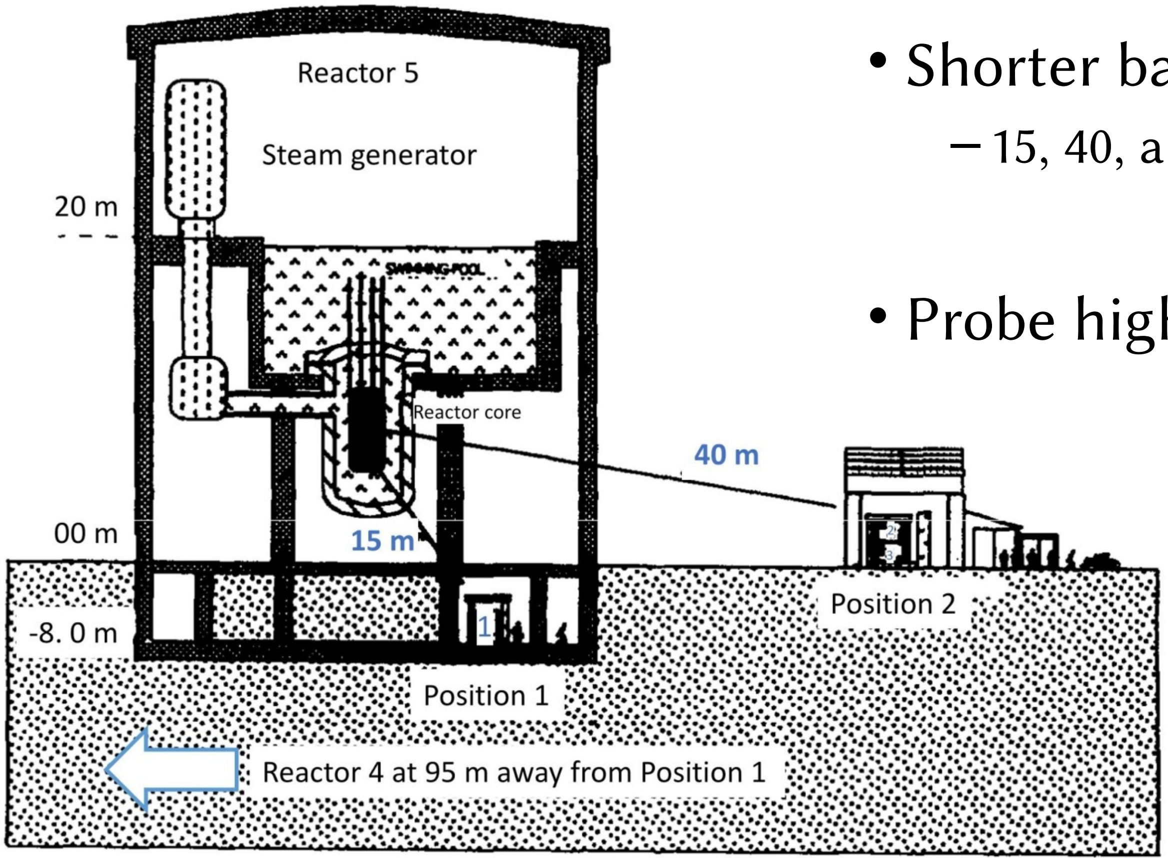
Bugey-3 Experiment

Bugey Nuclear Power Plant, France, 1984-1996

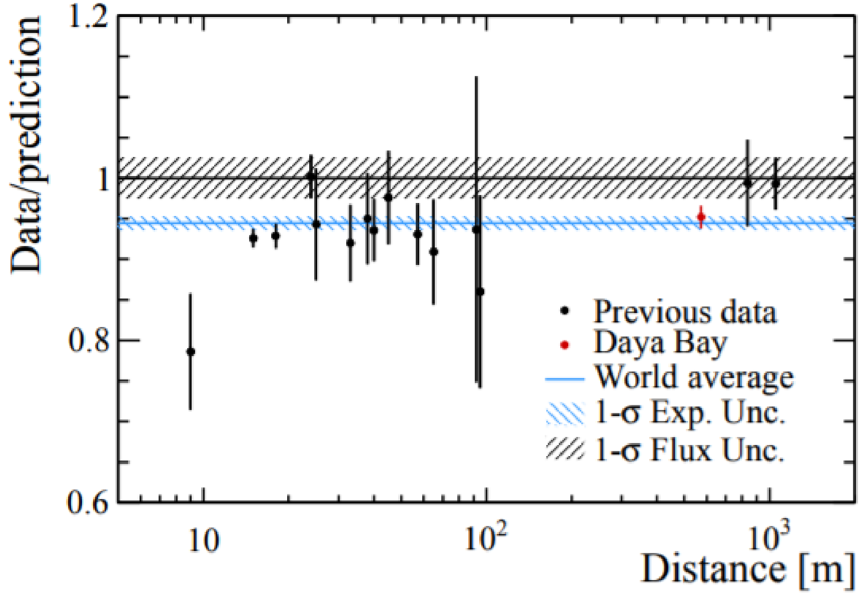
- 3 detectors at 2 position
- 150k events
- Shorter baselines
  - 15, 40, and 95 m
- Probe higher $|\Delta m^2_{41}|$ than Daya Bay



Nucl.Instrum. Meth. A ***374***(2) 164 -187 (1996)

Adjust Bugey-3 Prediction

For Daya Bay + Bugey-3 combined fit



arXiv: 1808.10836

- Use Huber-Mueller model instead of the original ILL-Vogel model for prediction

assume 5% normalization uncertainty

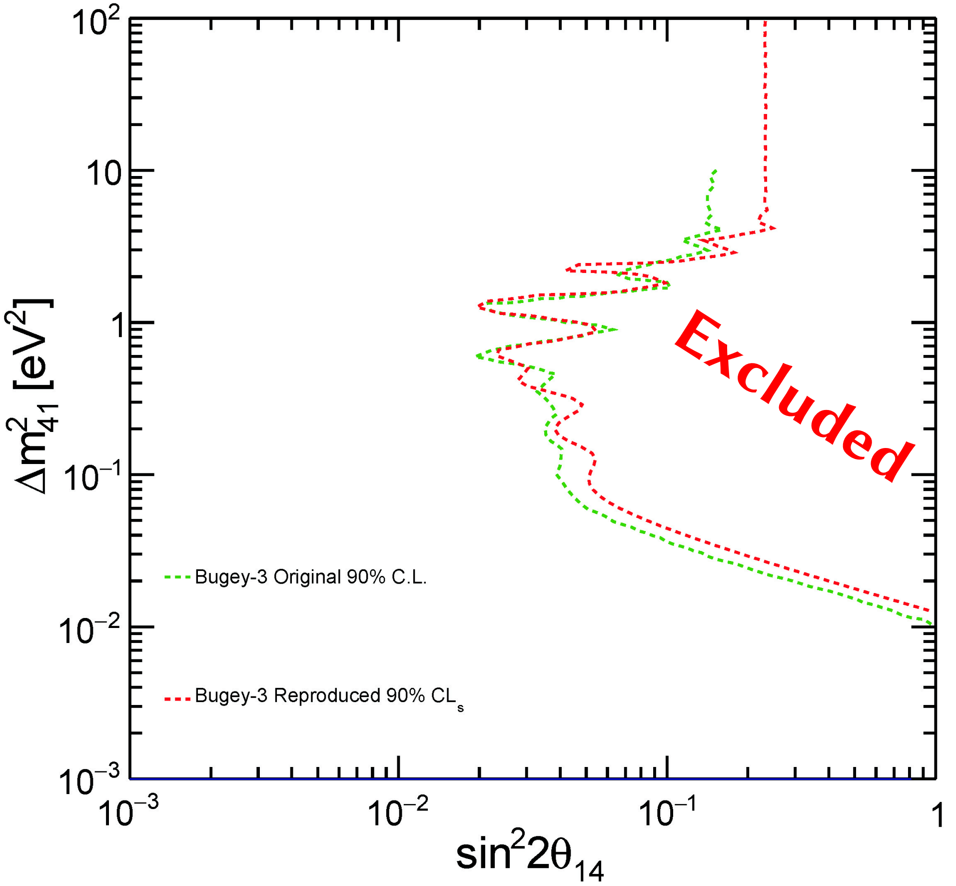
$$R^{obs} = \frac{data}{MC(ILL+Vogel)} \longrightarrow \overset{\text{Reactor flux Daya Bay is using}}{MC(Huber+Mueller)}$$

- Detection interaction (inverse beta decay) cross-section with updated neutron decay time

Bugey-3 Results (reproduced)

- Gaussian CL_s method applied to reproduce Bugey-3 results

- Consistent results between our reproduced contour and the original raster scan Bugey-3 contour



For Daya Bay + Bugey-3 combined fit

Daya Bay + Bugey-3

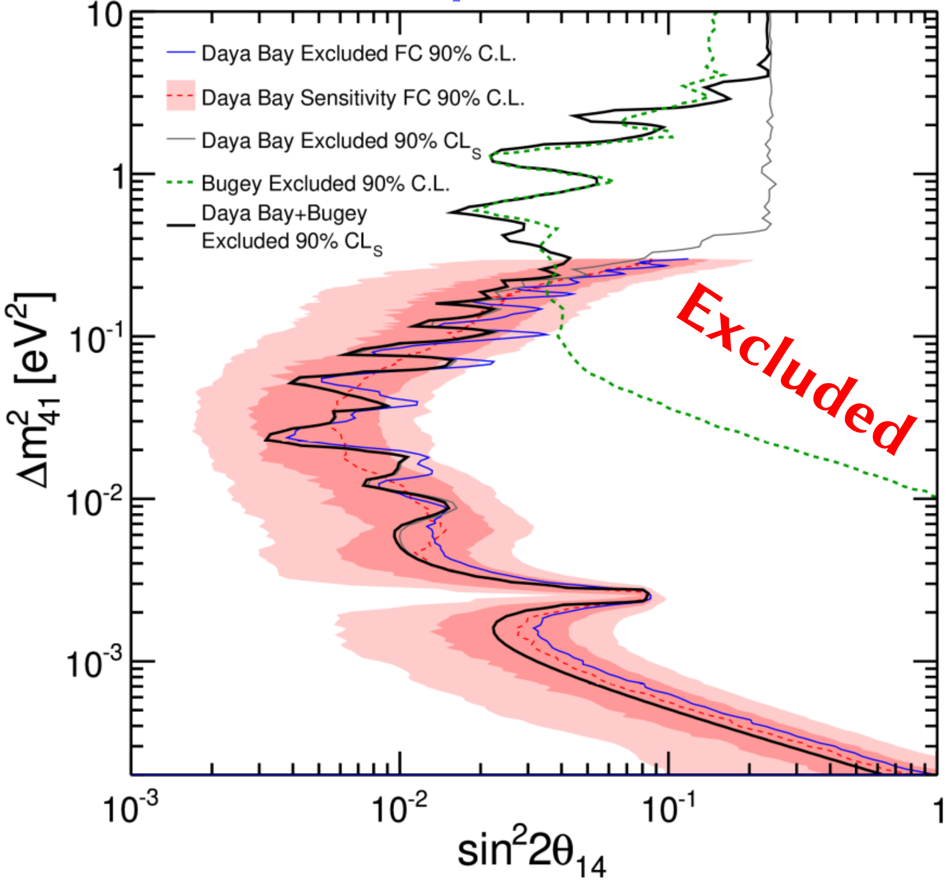
- Oscillation parameters and normalization factor are fully correlated

$$\chi^2 = \chi^2_{Daya\ Bay} + \chi^2_{Bugey-3} - \chi^2_{corr}$$

- Gaussain CL_s method

- Place leading limits for $2\times10^{-4}\ \mathrm{eV}^2 < |\Delta m^2_{41}| < 3\ \mathrm{eV}^2$

Preliminary



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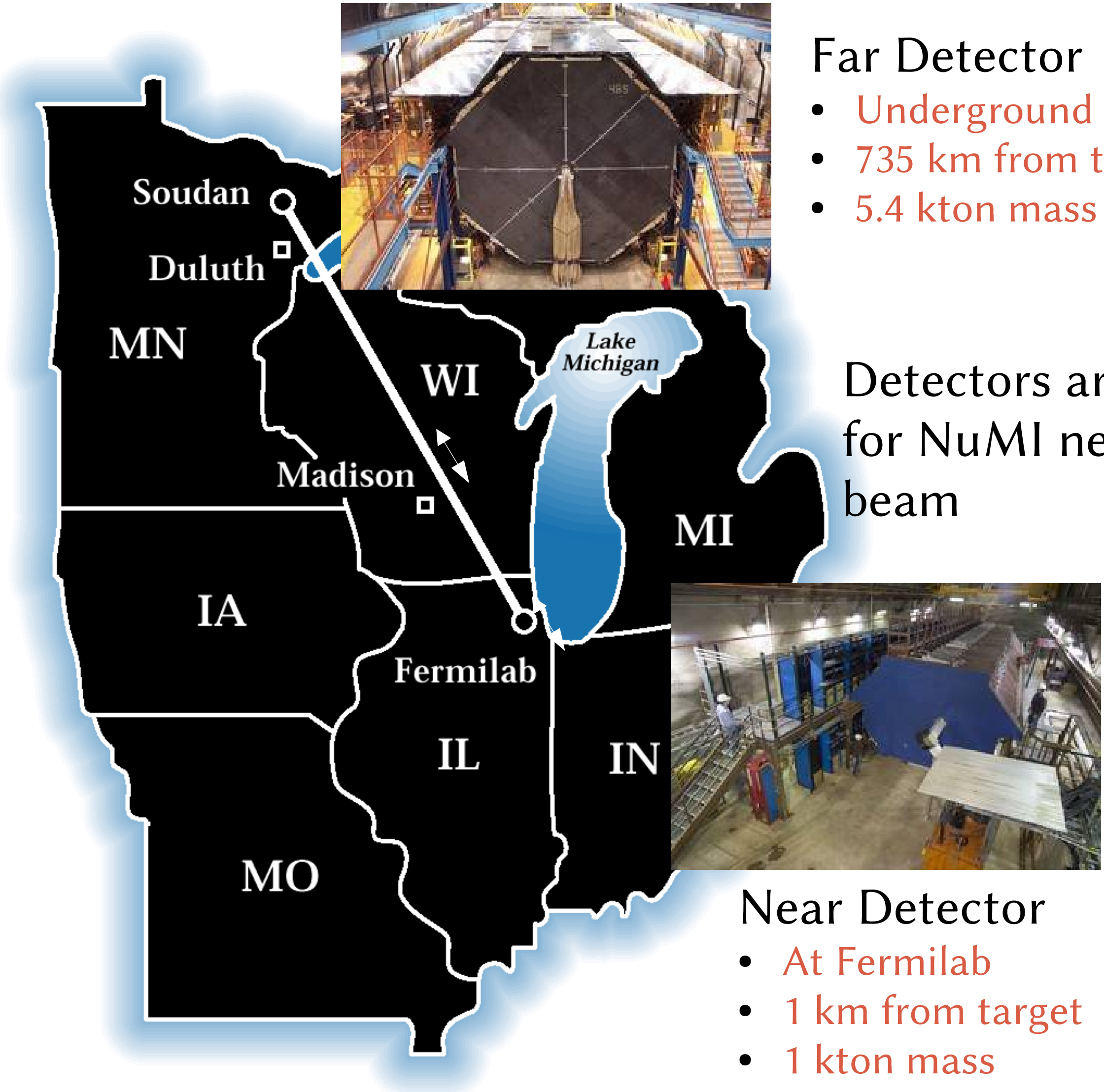
MINOS and MINOS+ Overview

- MINOS and MINOS+ were designed to study neutrino oscillations over long baselines using two detectors that are:
  - Iron-scintillator tracking calorimeters to contain muons
  - Functionally identical for systematic uncertainty reduction
  - Magnetized for sign selection and energy estimation



Far Detector

- Underground in Soudan mine
- 735 km from target
- 5.4 kton mass

Detectors are on-axis for NuMI neutrino beam

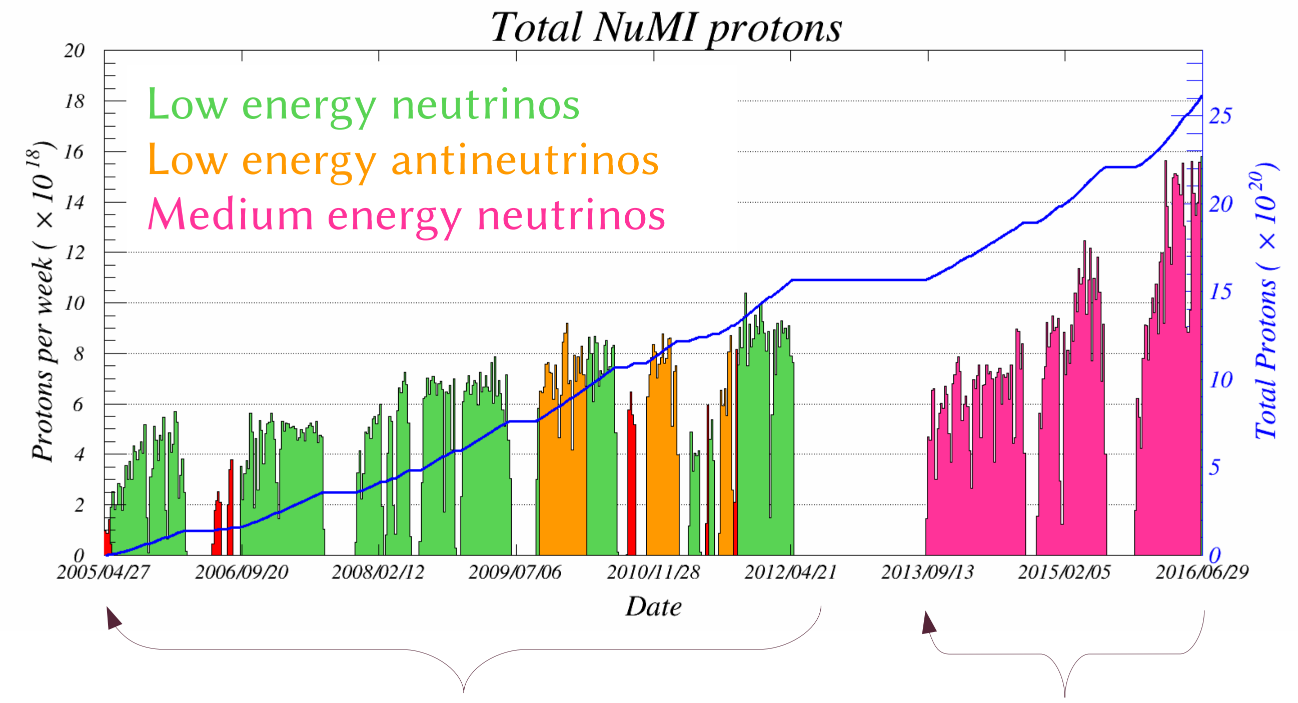
Near Detector

- At Fermilab
- 1 km from target
- 1 kton mass

MINOS and MINOS+ Beam

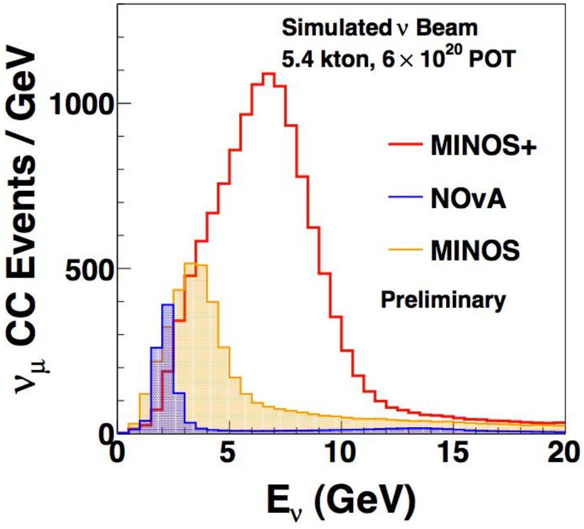
MINOS:
- ~3 GeV peak energy
- Study oscillations at atmospheric frequency

MINOS+:
- ~7 GeV peak energy
- Constrain deviations from 3 flavor paradigm



MINOS era:
- 10.56×10^{20} POT (neutrino-mode)
- 3.36×10^{20} POT (antineutrino-mode)

MINOS+ era:
- 9.69×10^{20} POT



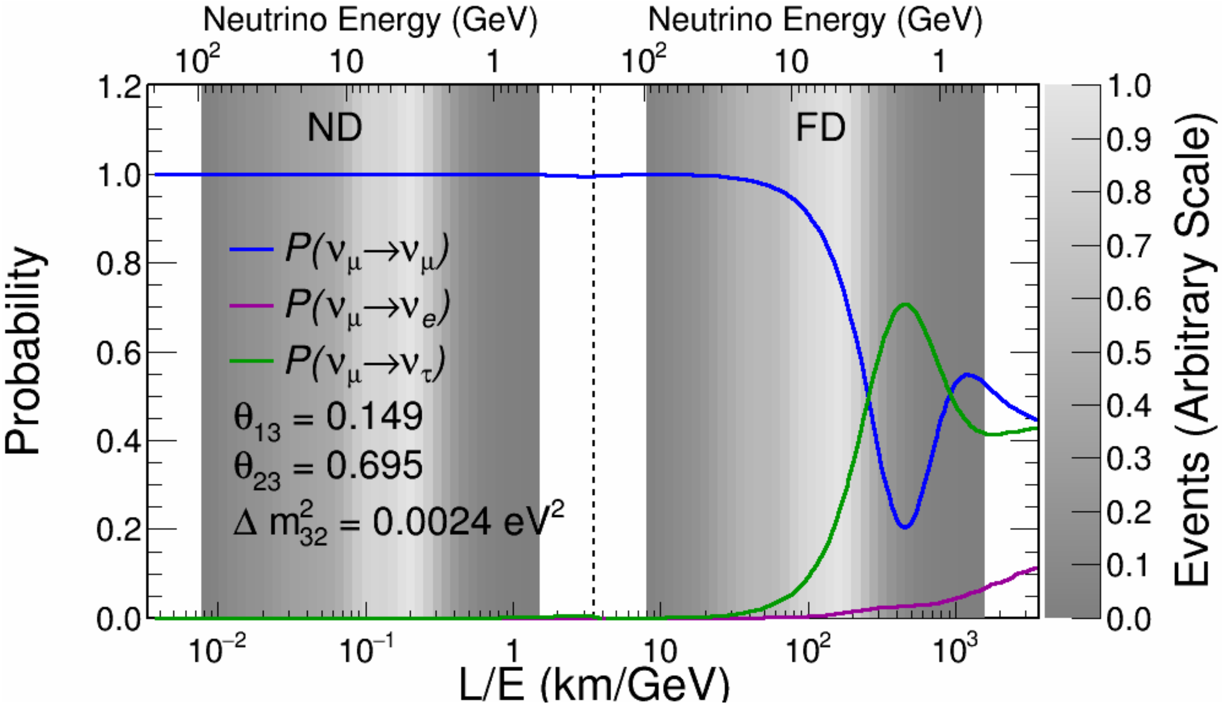
Total:
- ~25×10^{20} POT in 11 years of running

This analysis: MINOS 10.56×10^{20} POT MINOS+ 5.80×10^{20} POT

Sterile Neutrinos at MINOS/MINOS+

$\Delta m^2_{41} = 0 \longrightarrow$ 3-flavor oscillations

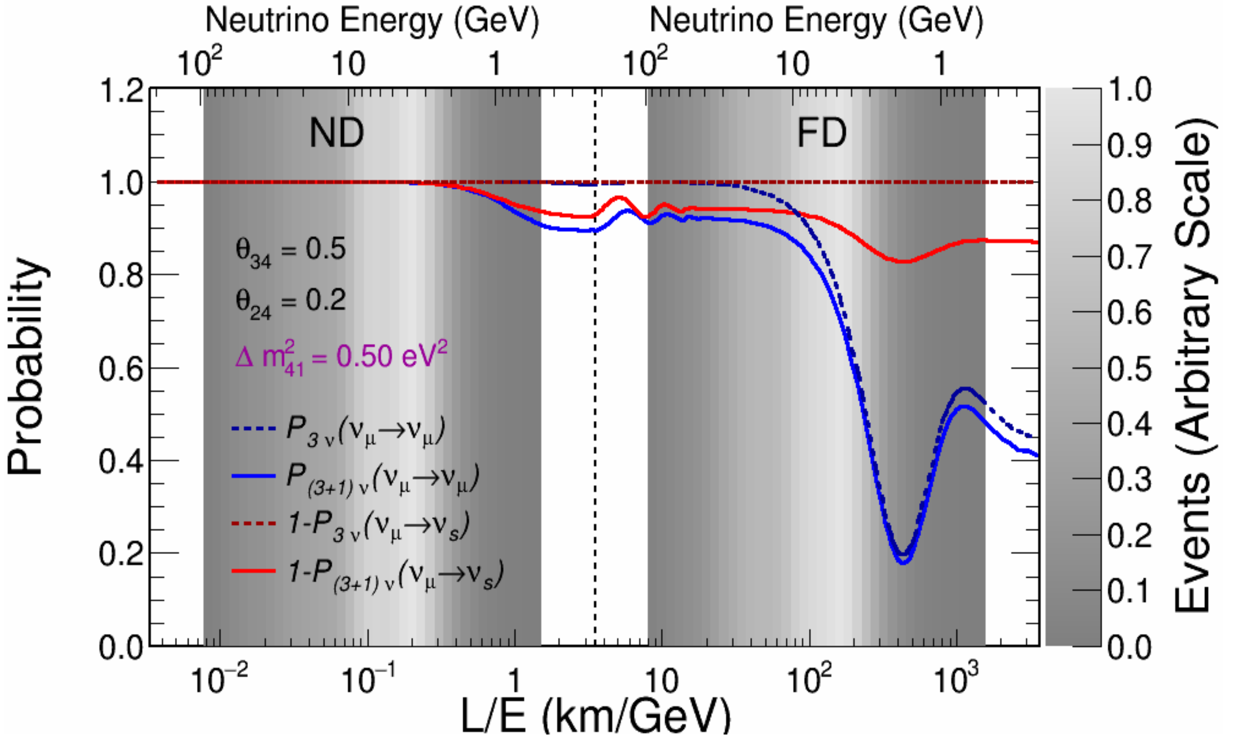
- Far Detector
  - ν_μ CC: single oscillation maximum
    - Position from Δm^2_{32}
    - Depth from θ_{23}
  - NC: no oscillations
    - NC interaction is flavor agnostic
- Near Detector
  - ν_μ CC: no oscillations
  - NC: no oscillations
  - ND constrains beam and cancels systematics



Sterile Neutrinos at MINOS/MINOS+

Small Δm^2_{41}

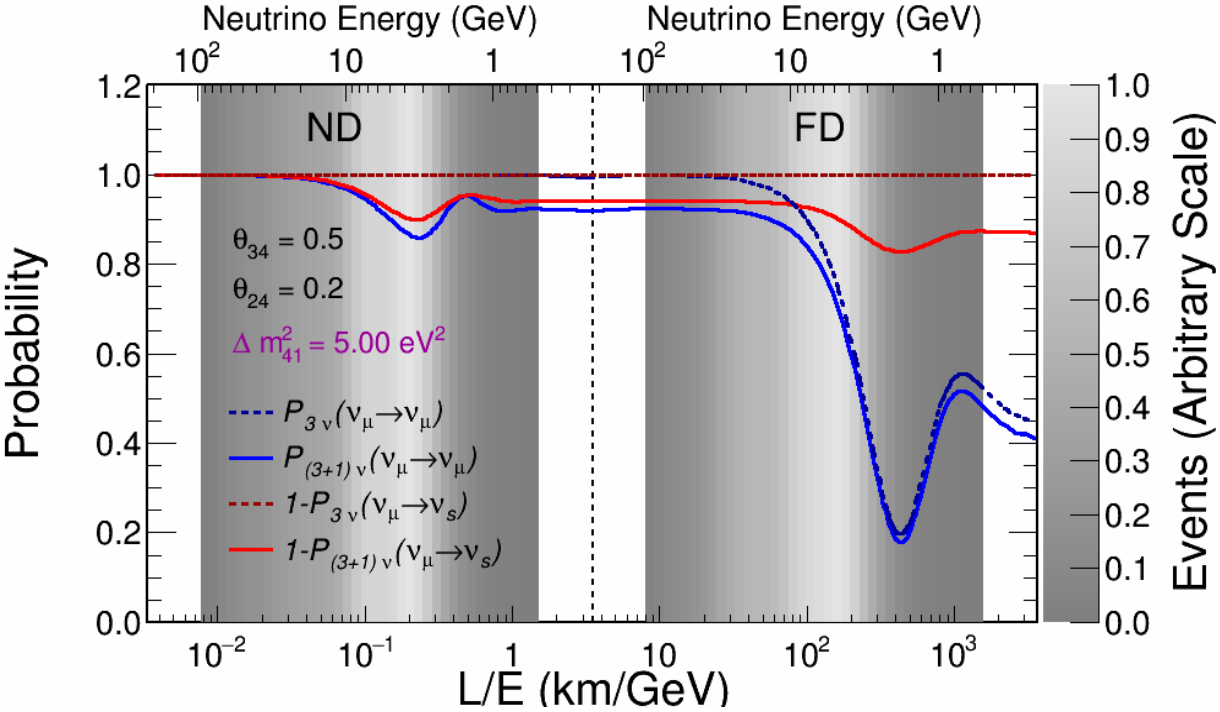
- Far Detector
  - ν_μ CC
    - Large disappearance at atmospheric maximum
    - Modulations at high energies
  - NC
    - Δm^2_{41} independent dip at atmospheric maximum
    - Modulations at high energies
- Near Detector
  - low energy disappearance



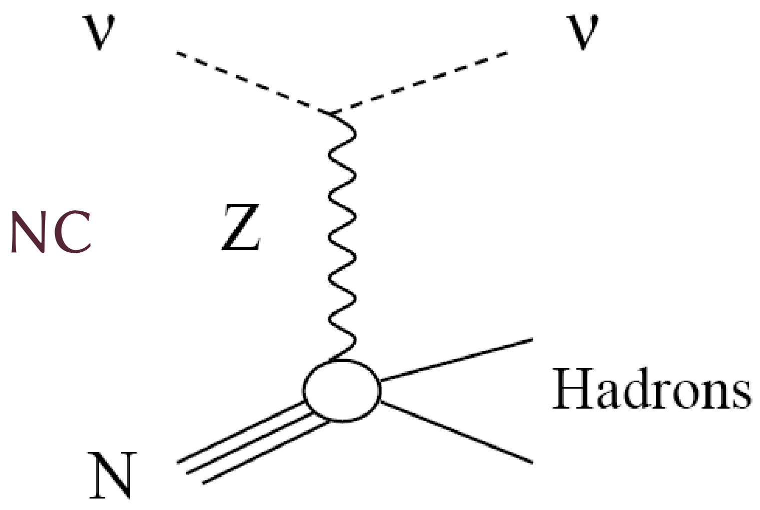
Sterile Neutrinos at MINOS/MINOS+

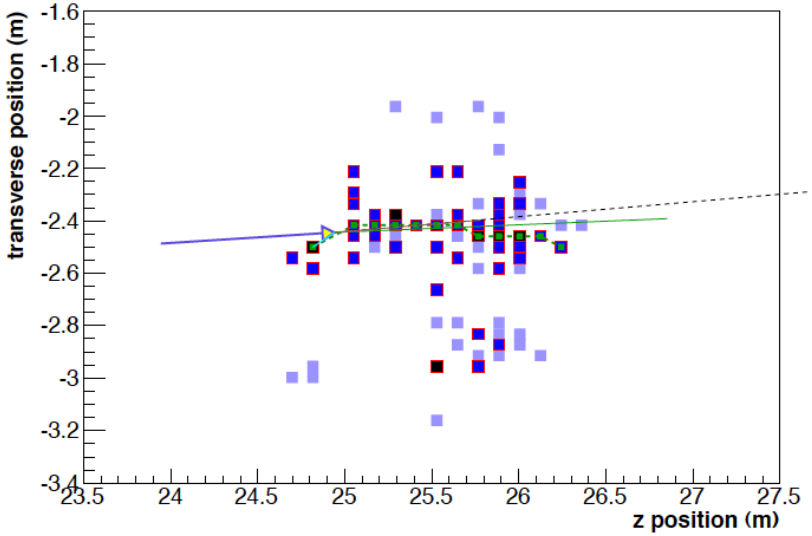
Large Δm^2_{41}

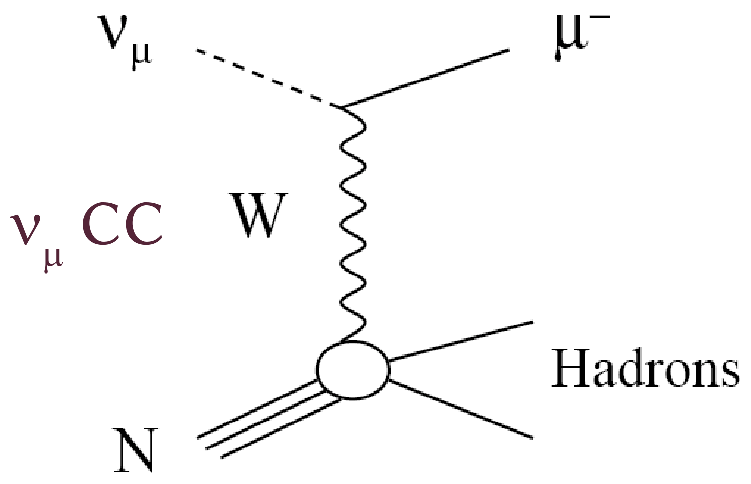
- Far Detector
  - ν_μ CC
    - Large disappearance at atmospheric maximum
    - Due to finite energy resolution, fast oscillations create constant offset away from maximum
  - NC
    - Δm241 independent dip at atmospheric maximum
    - Constant offset due to rapid oscillations
- Near Detector
  - Oscillations near the focusing peak in both samples

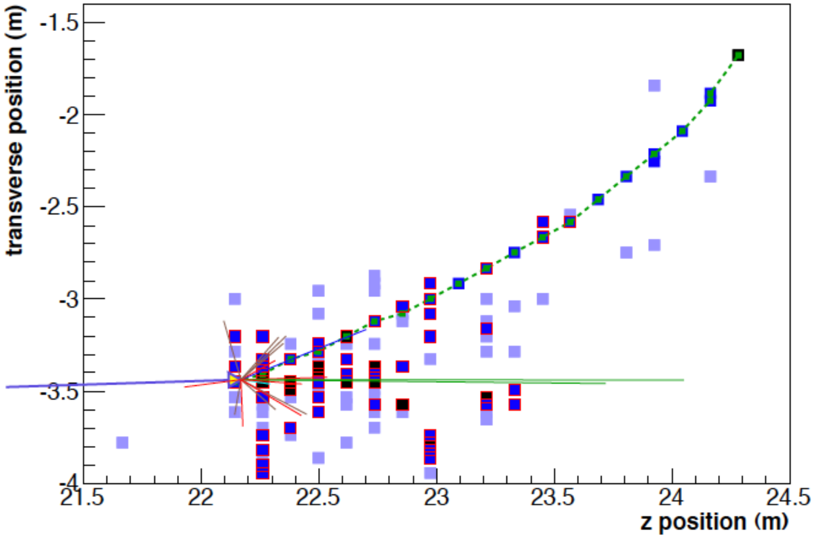


Event Topologies

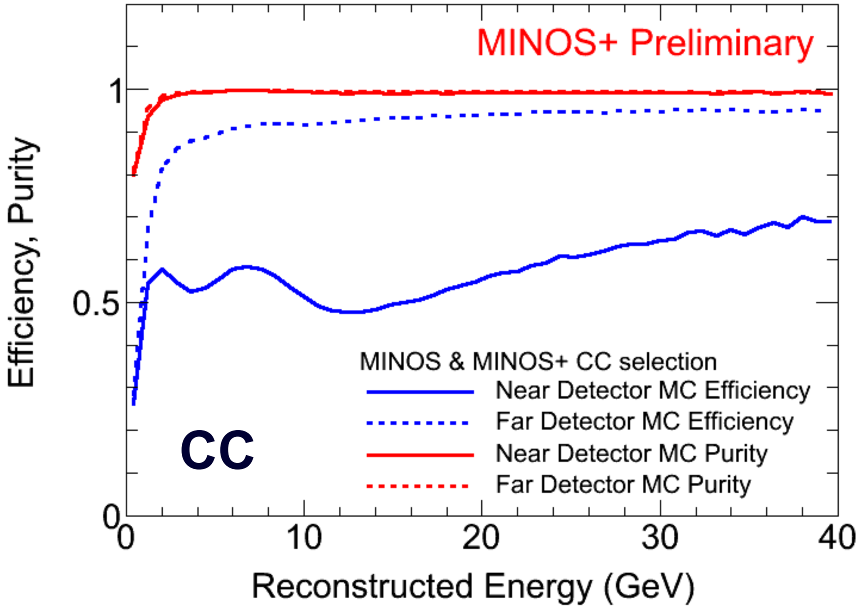


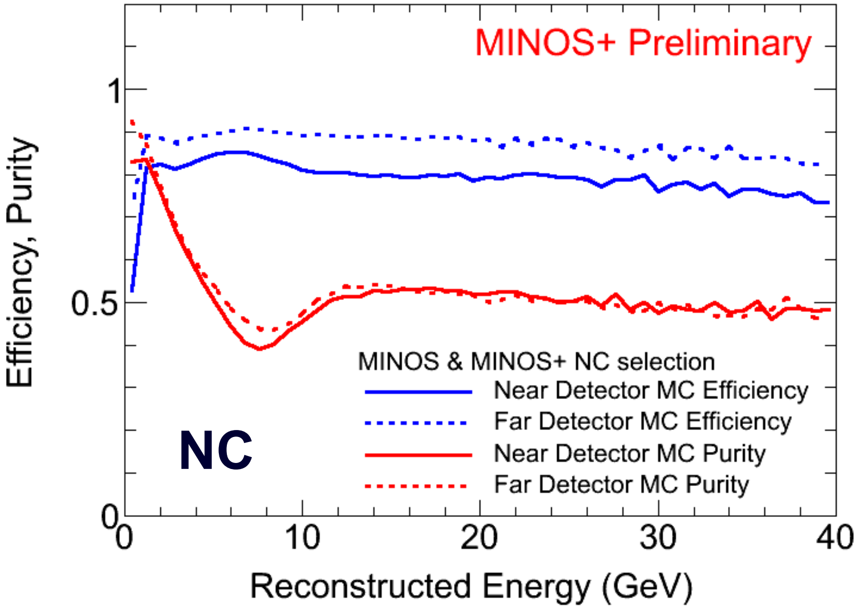






Event Selection





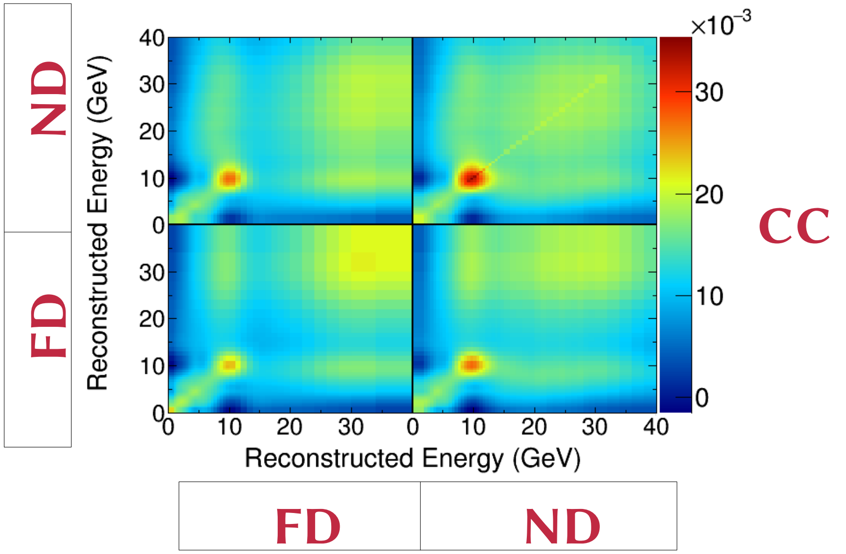
- ν_μ charged current selection
  - Use 4 variable kNN designed to distinguish muon from pion tracks
  - Applied to events failing NC selection
  - 86% efficiency, 99% purity at the FD

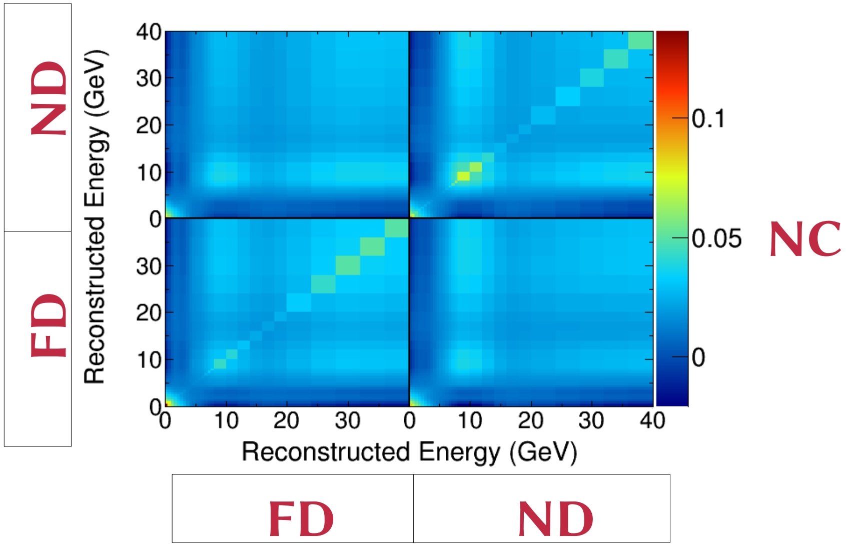
- Neutral current selection
  - Selection based on topological quantities
    - Require compact events
    - No long tracks extending out of shower
  - 89% efficiency and 61% purity at FD
  - Primary background is inelastic ν_μ
  - 97% of ν_e CC pass selection

Analysis Strategy

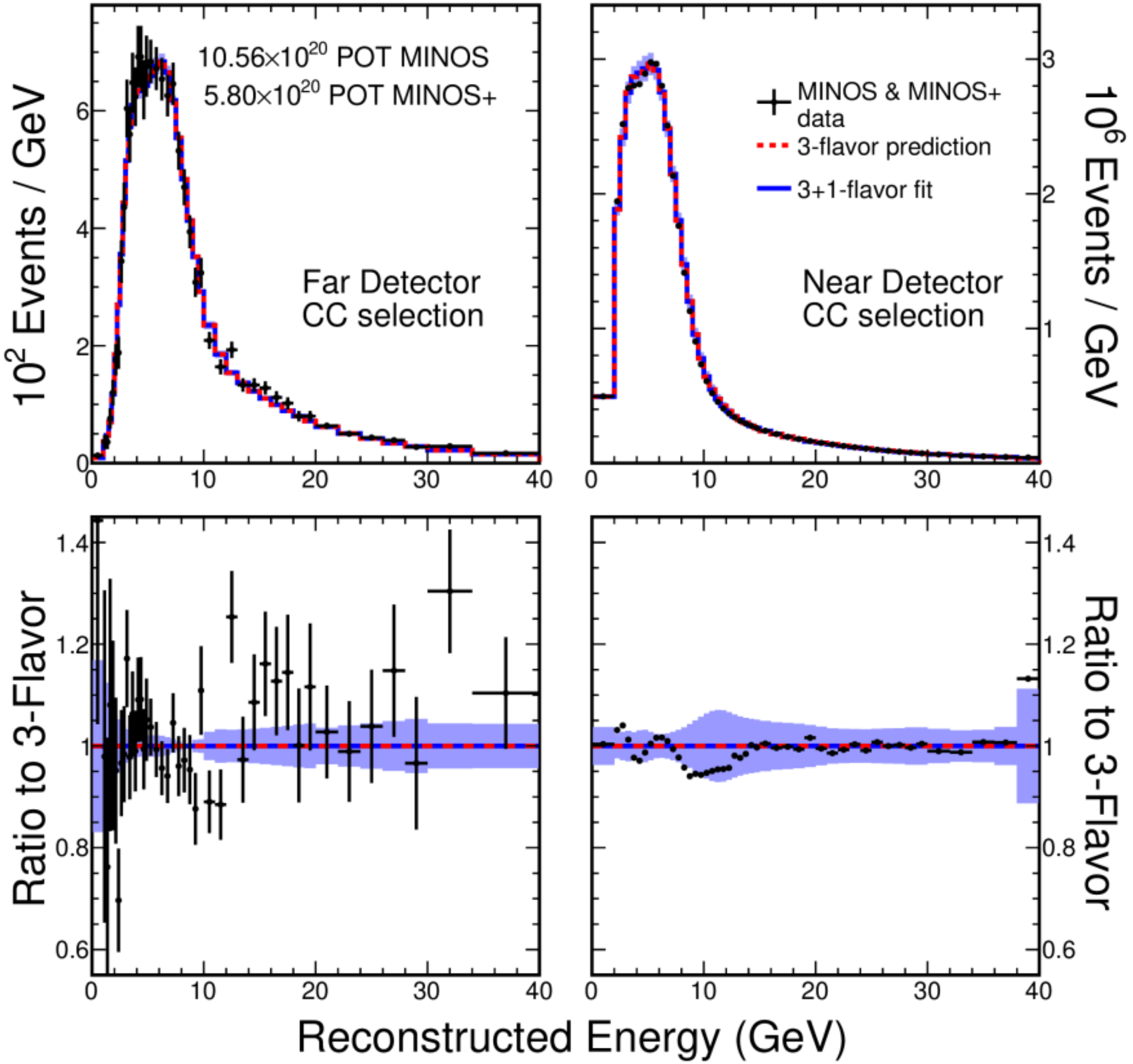
- Treat ND and FD on equal footing
  - Flux estimate derived from MINERvA PPFX method which uses only hadron production experiment data
- Joint fit for ν_μ CC and NC disappearance in ND and FD
  - Uses full statistical power of ND, unlike the Far-to-Near ratio dominated by FD statistics
- Encode correlations due to systematic uncertainties between energy bins and detectors with a covariance matrix
  - 26 systematic uncertainties considered
- Minimize covariance-matrix-based χ^2 function to allow for a high degree of cancellation of correlated shape uncertainties:

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



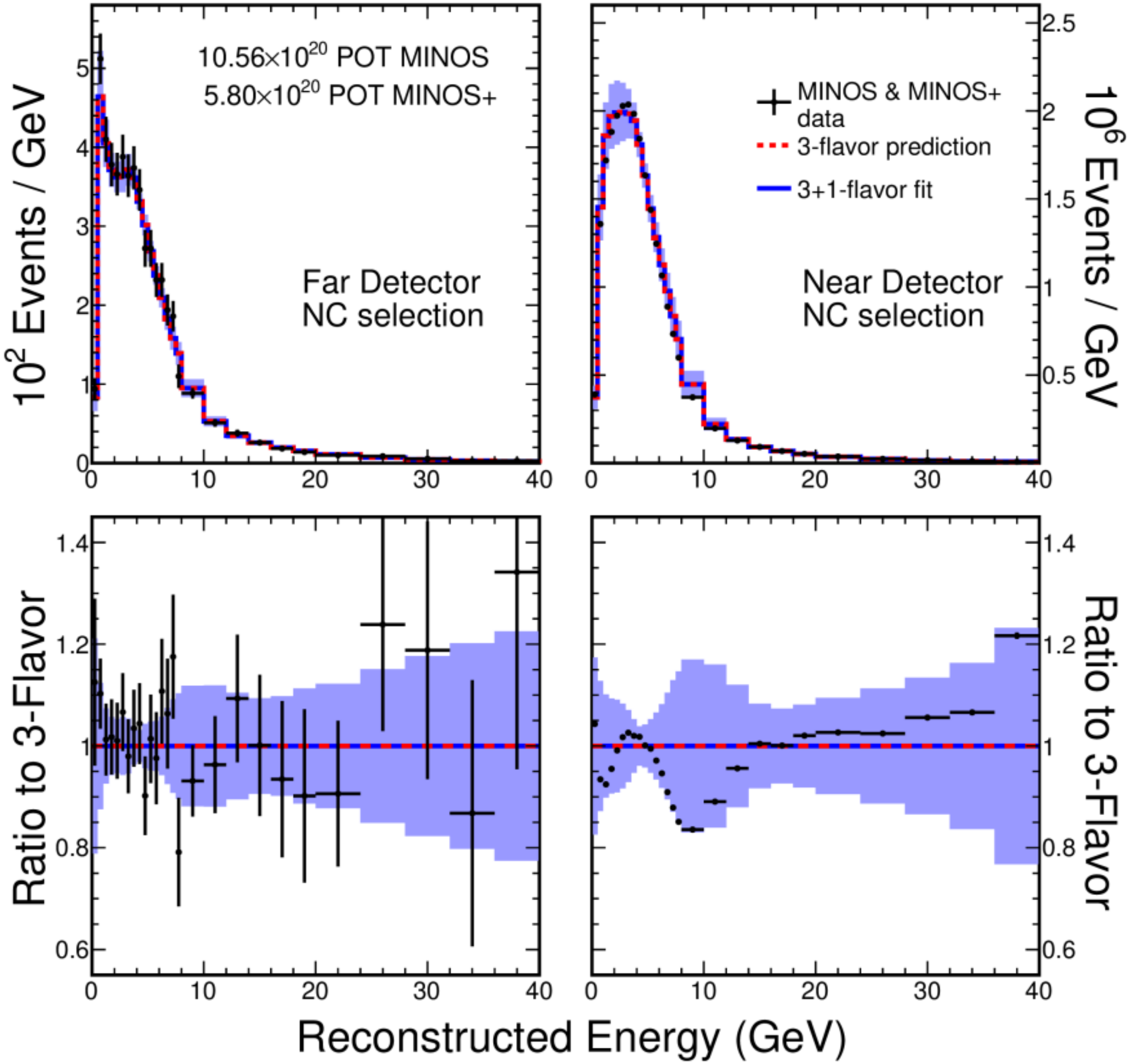


ν_μ CC Sample



- Covariance matrix fits do not include systematics as nuisance parameters
- The error bands and prediction account for off-diagonal elements to indicate the equivalent of post-fit agreement

NC Sample

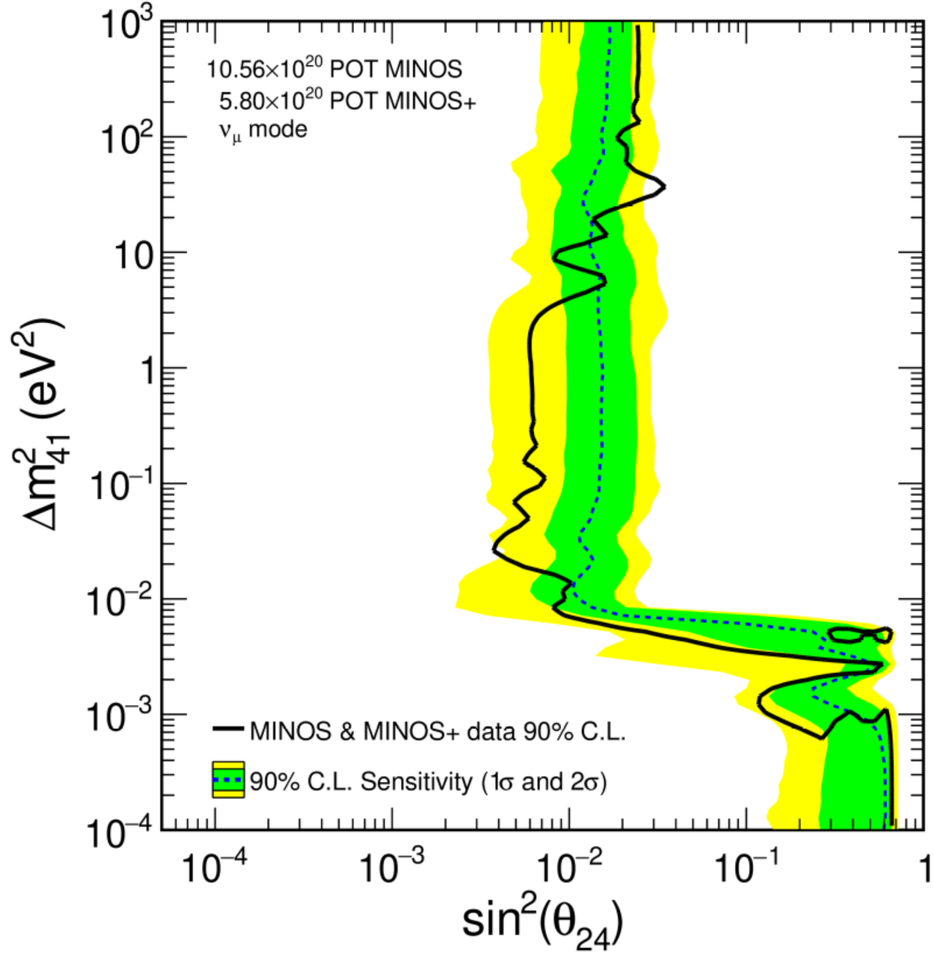


- Covariance matrix fits do not include systematics as nuisance parameters
- The error bands and prediction account for off-diagonal elements to indicate the equivalent of post-fit agreement

Sterile Disappearance Limit

- Use full NC and CC samples in both 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% C.L. contours from pseudo-experiments
- Best fit:
  - $\Delta m^2_{41} = 2.33\text{x}10^{-3}$ eV^2
  - $\sin^2\theta_{24} = 1.1\text{x}10^{-4}$
  - $\theta_{34} < 8.4\text{x}10^{-3}$
  - $\sin^2 2\theta_{23} = 0.92$
  - $\chi^2_{min}/\text{dof} = 99.3/140$
  - $\chi^2(4\nu) - \chi^2(3\nu) = 0.01$

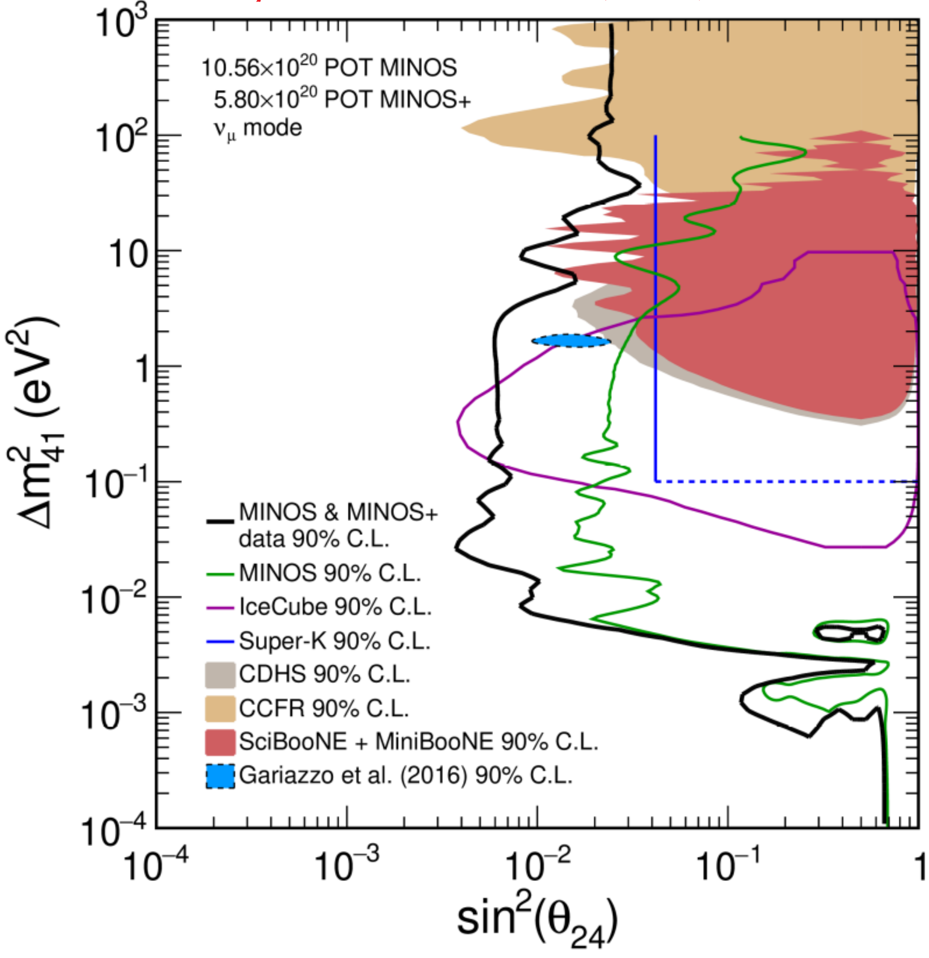
Phys. Rev. Lett, **122** (2019) 091803



Sterile Disappearance Limit

- 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
  - Covariance matrix systematic uncertainty cancellations
  - Improved binning around atmospheric dip in Far Detector
- Increased tension with global best fit
- Final year of data is still to be analyzed
  - Represents 50% more data in MINOS+ spectrum
- See ancillary materials at arXiv:1710.06488 for more details

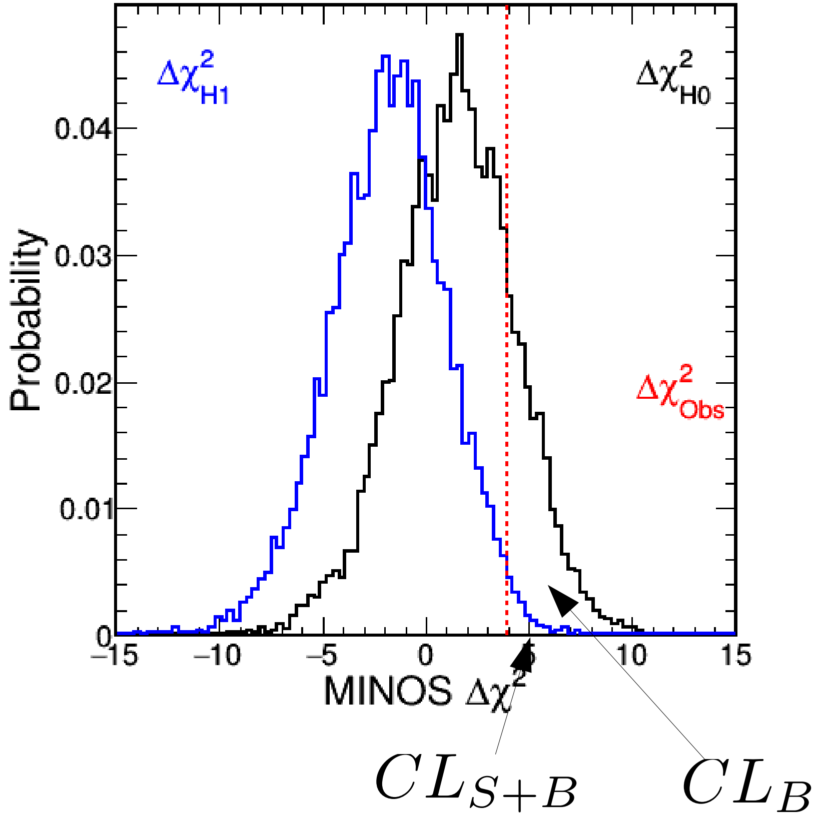
Phys. Rev. Lett, **122** (2019) 091803



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

CL_s at MINOS/MINOS+

- MINOS/MINOS+ treats θ_{34} as a nuisance parameter
  - Cannot use Daya Bay's Gaussian CL_S method
  - Use fake experiments
- For each (Δm^2_{41}, θ_{24}) point:
  - Generate 3-flavor fake experiments using PDG parameters
  - Generate (3+1)-flavor fake experiments using the current (Δm^2_{41}, θ_{24}) point
    - θ_{23}, θ_{34}, and Δm^2_{32} set to the best fit at each grid point
  - Statistically and systematically fluctuate fake experiments
- Fit each fake experiment to both the 3-flavor and (3+1)-flavor hypotheses to build the $\Delta\chi^2$ distributions

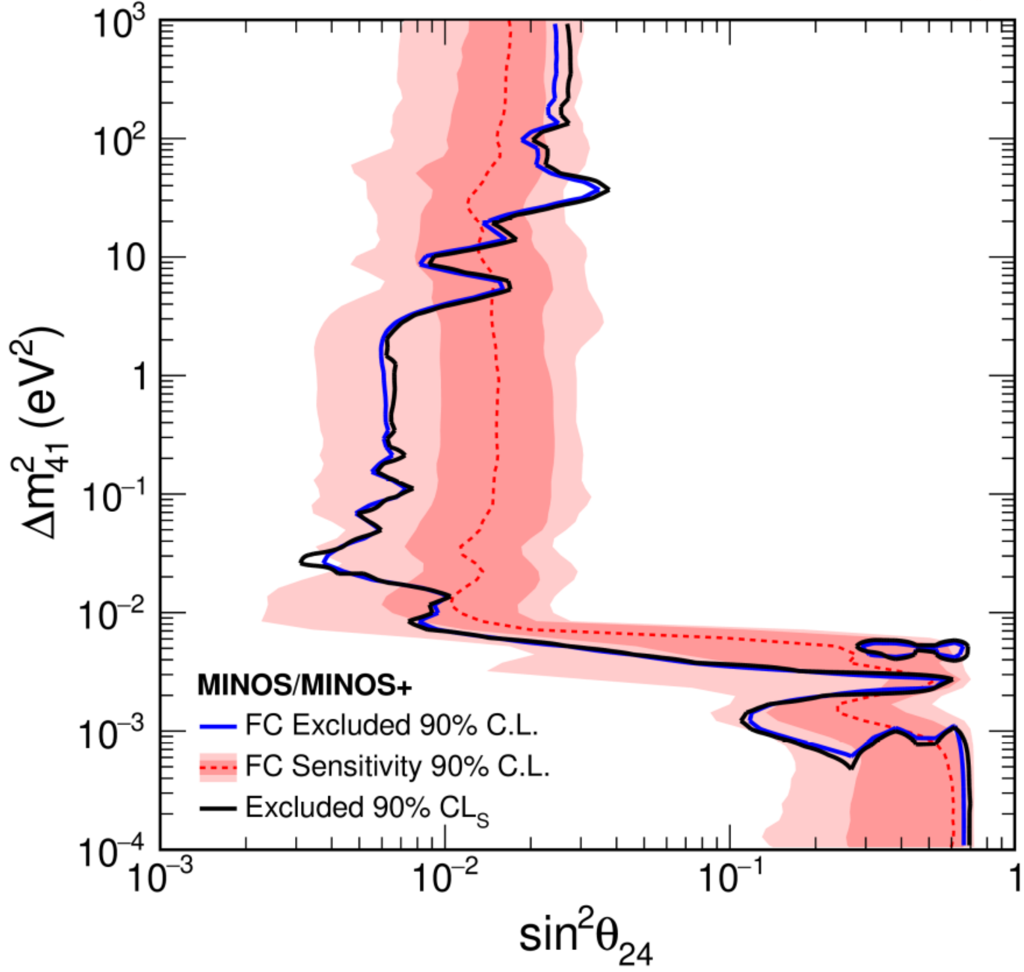


$$CL_S = \frac{CL_{S+B}}{CL_B}$$

CL_s Cross Check

90% C.L. contours generated using the CL_s method are consistent with the limit constructed using the Feldman-Cousins method.

MINOS+ Preliminary



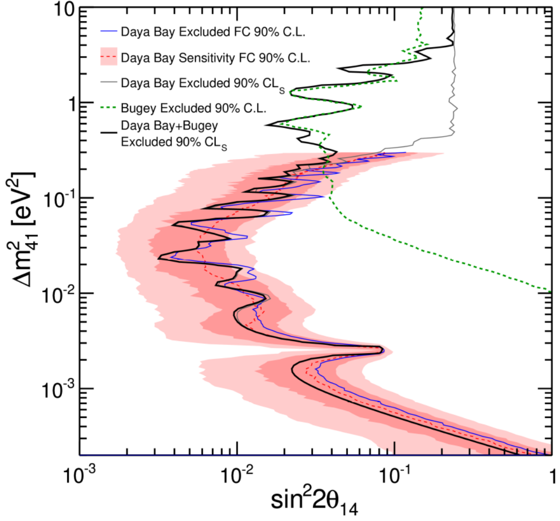
Outline

- Introduction to Sterile Neutrino Mixing
- Daya Bay Results
- Daya Bay + Bugey-3 Combination
- MINOS/MINOS+ Results
- Daya Bay + Bugey-3 + MINOS/MINOS+ Combination

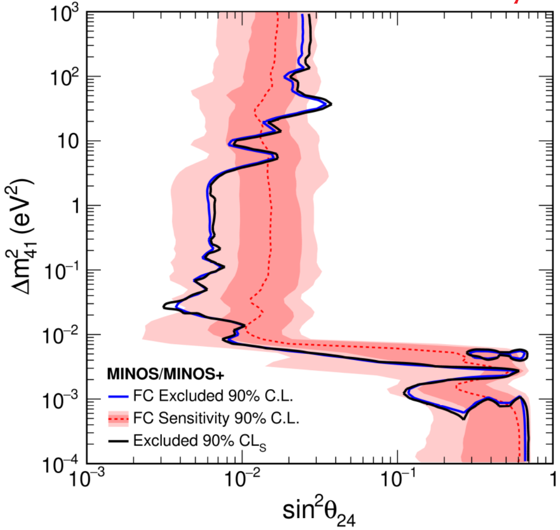
Combination Method

- Combining two disappearance experiments to set limits on $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$
  - Surfaces from each experiment share the same y-axis but have different x-axes
- Feldman-Cousins involves a best fit with all parameters free
  - Constraining each experiment to a common Δm^2_{41} would be difficult without a full joint fit framework
- $\mathrm{CL_S}$ is an ideal solution
  - A local method
    - Δm^2_{41}, $\sin^2 2\theta_{14}$, and $\sin^2\theta_{24}$ are always fixed

Daya Bay Preliminary

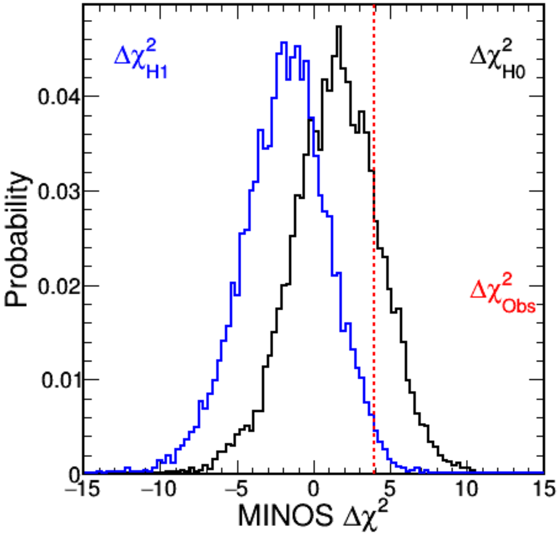


MINOS+ Preliminary

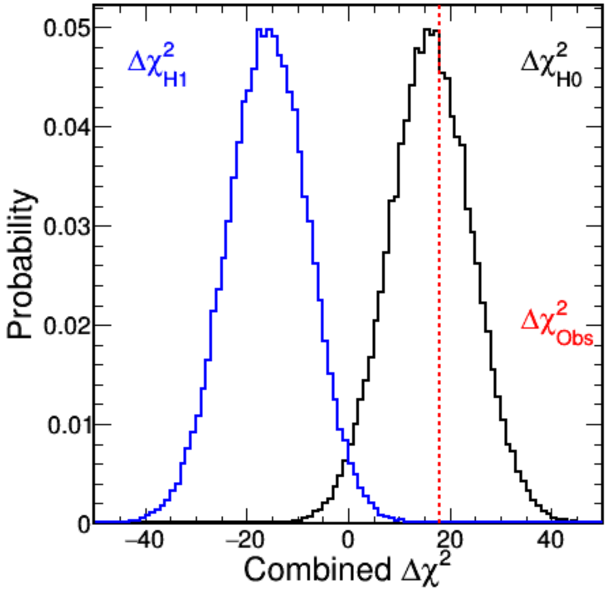


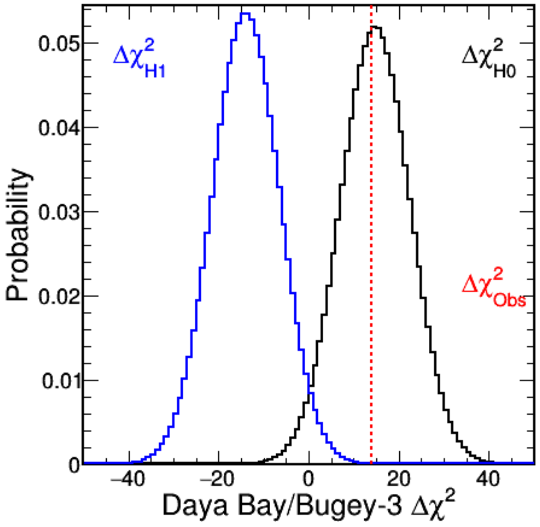
Combining a Single Point

Need to be able to calculate CL_S at a single ($\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$, Δm^2_{41}) point



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



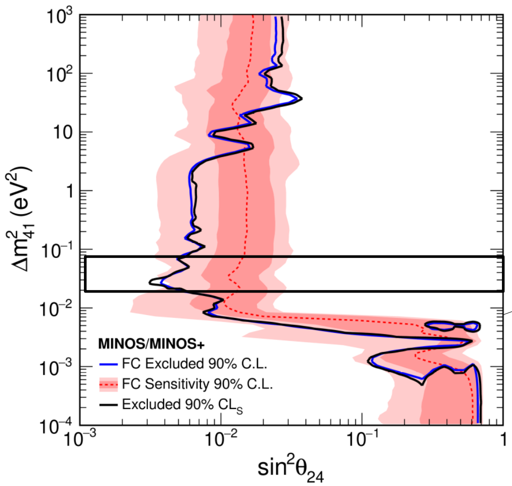


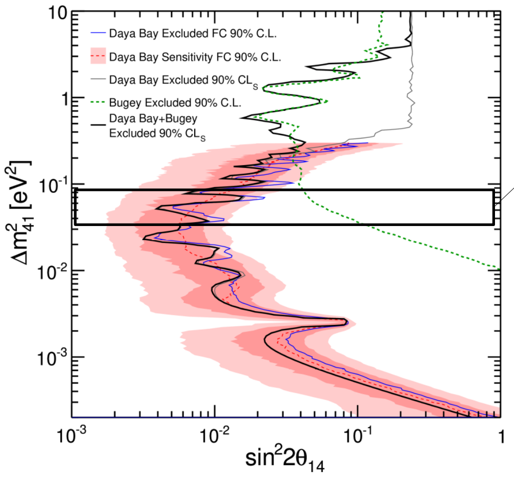
Draw Daya Bay/Bugey-3 $\Delta\chi^2$ values from Gaussian distributions

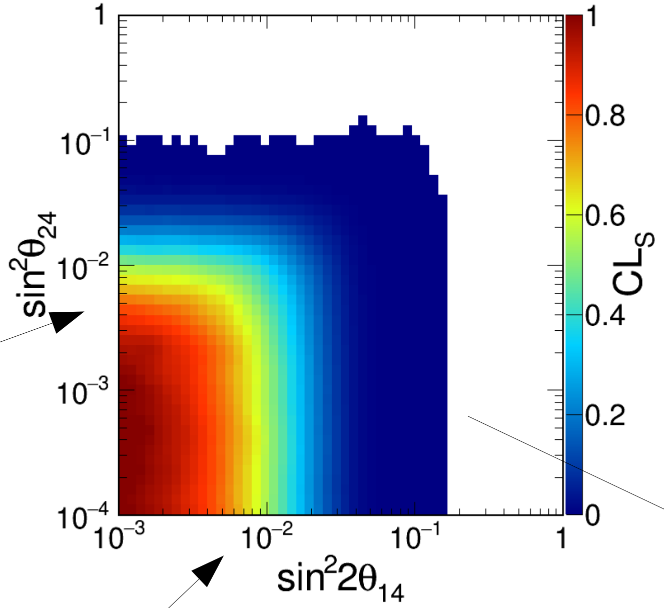
Since MINOS/MINOS+ has uncorrelated systematics from Daya Bay/Bugey-3

$\Delta\chi^2_{\text{combo}} = \Delta\chi^2_{\text{MINOS}} + \Delta\chi^2_{\text{DB/Bugey-3}}$

Combining a Δm^2_{41} Row

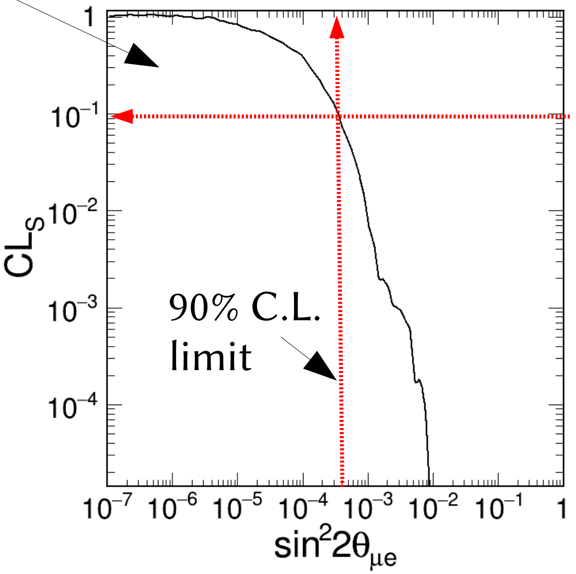






- Convert CL_S from a 2D function of ($\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$) to 1D function of $\sin^2 2\theta_{\mu e}$
- Multi-values, so pick the largest CL_S per bin as a conservative choice

For a fixed Δm^2_{41}, calculate CL_S at each ($\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$) point

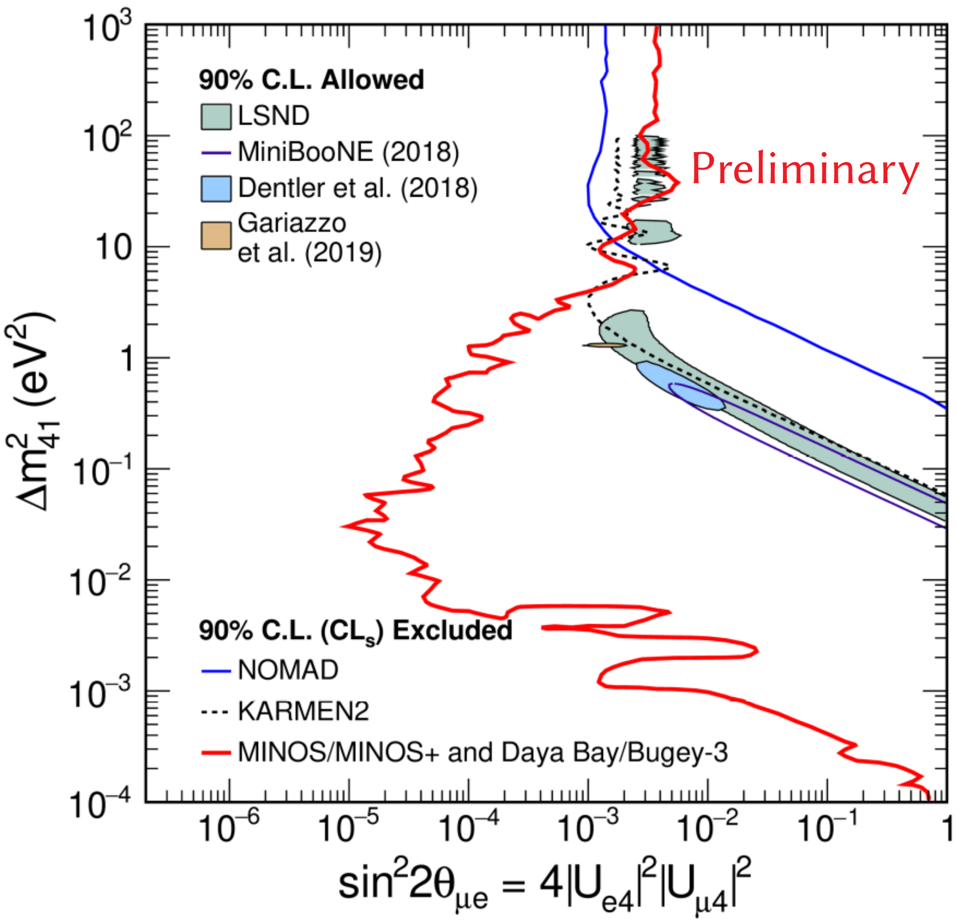


Combined – 90% C.L.

The combined 90% C.L. limit excludes entire lower lobe ($\Delta m^2_{41} < 10\ \mathrm{eV}^2$) of appearance allowed regions and two global fits

The Dentler *et al.* fit to appearance data was updated to include the 2018 MiniBooNE appearance result

The Gariazzo *et al.* global fit shown was modified to not include any MINOS/MINOS+, Daya Bay, or Bugey-3 data



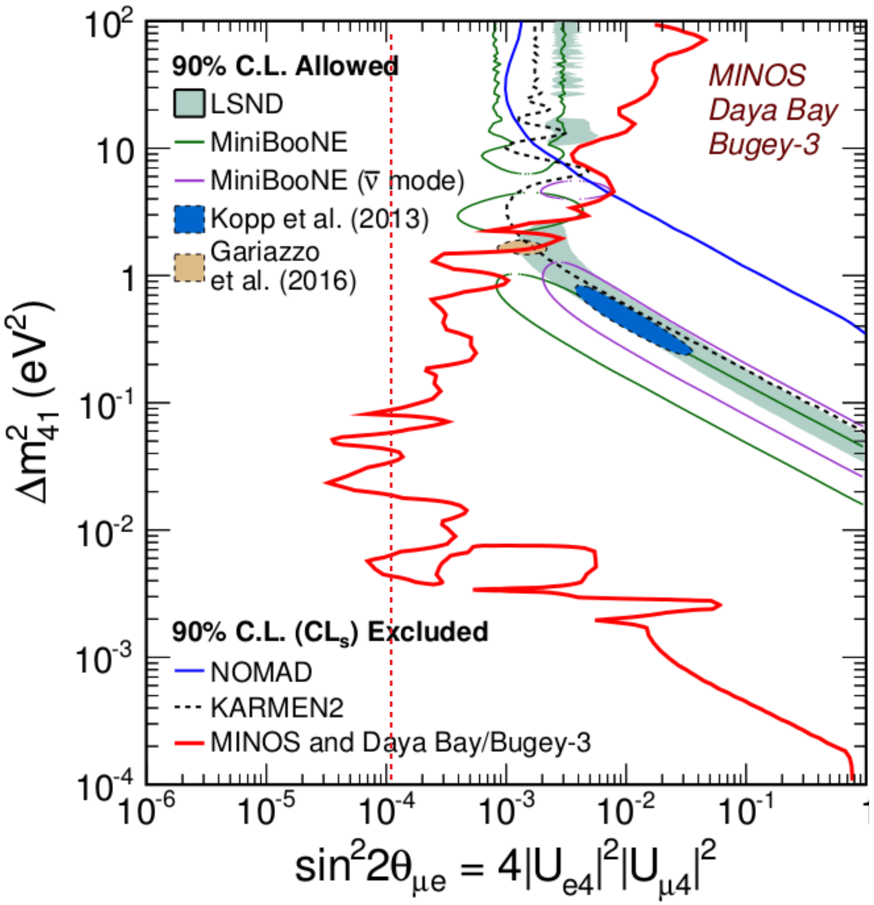
*M. Dentler, A. Hernandez-Cabezudo, J. Kopp, P. A. N. Machado, M. Maltoni, I. Martinez-Soler, T. Schwetz, JHEP **08**, 010 (2018)

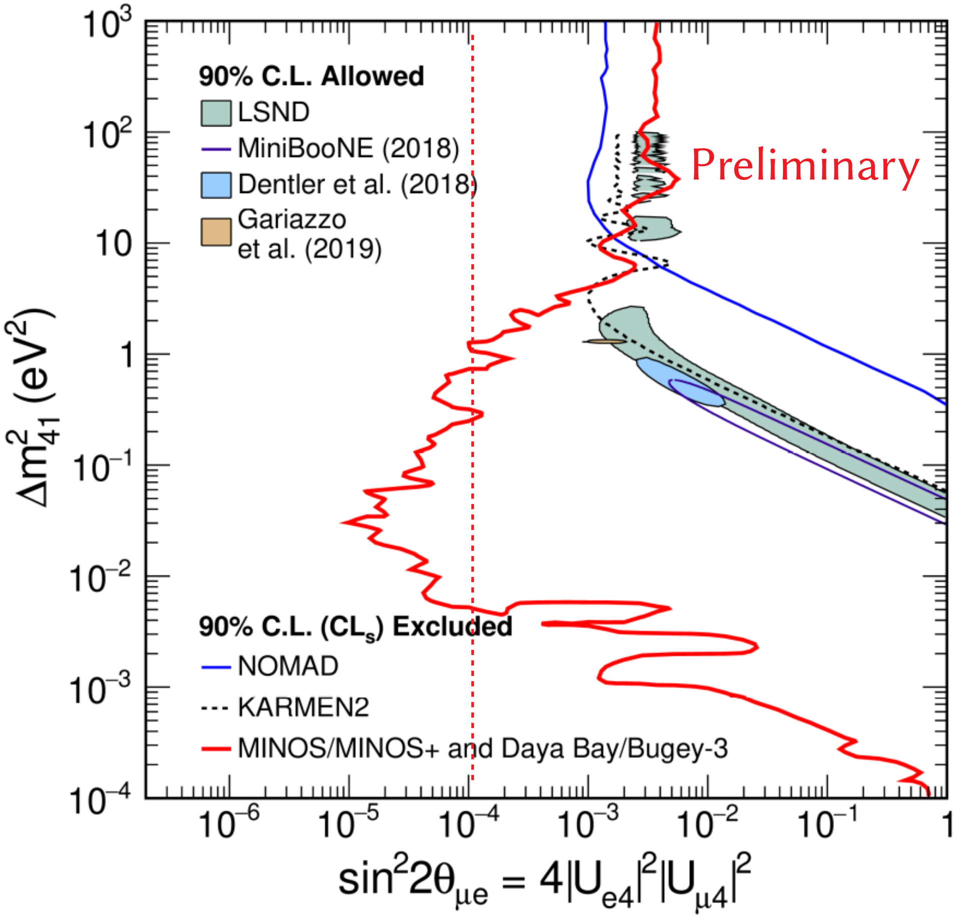
S. Gariazzo, C. Giunti, M. Laveder, Y. F. Li, Phys. Lett. **B782, 13 (2018)

Combined – 90% C.L.

Previous result:
Phys. Rev. Lett. 117 (2016) 151801

This result





Combined – 99% C.L.

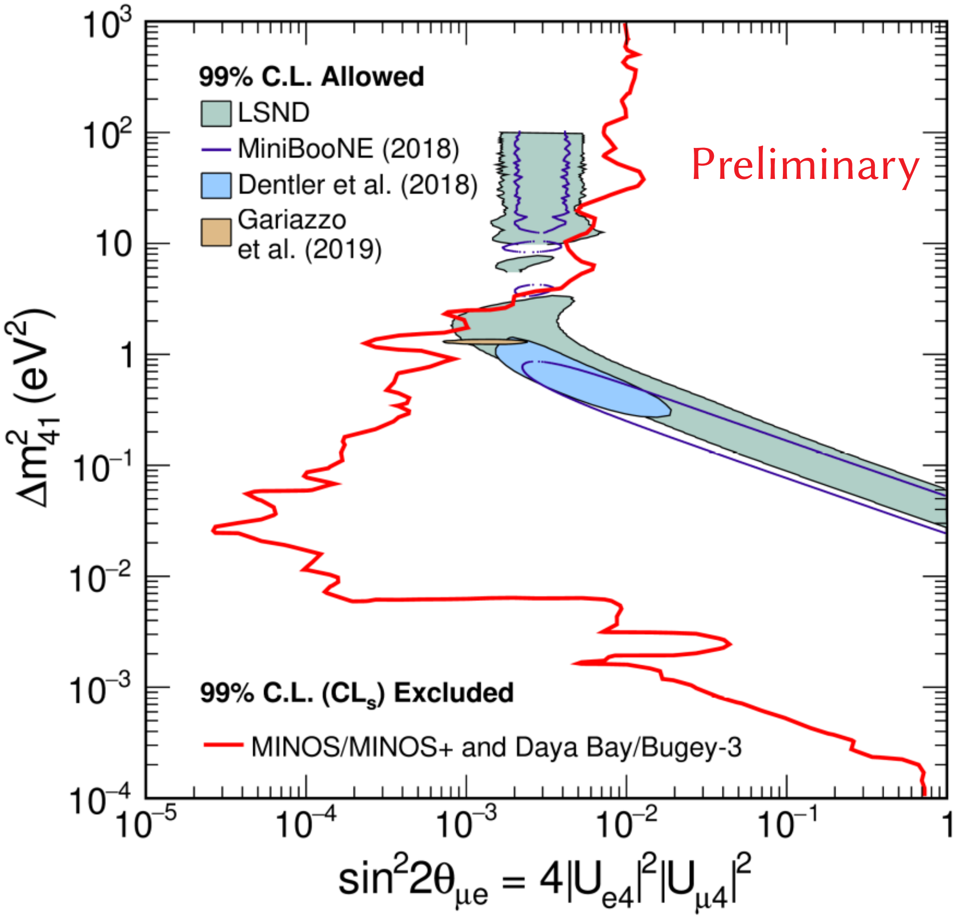
The combined 99% C.L. limit excludes all appearance allowed regions with $\Delta m^2_{41} < 2\ \text{eV}^2$, as well as two global fits

The Dentler *et al.* fit to appearance data was updated to include the 2018 MiniBooNE appearance result

The Gariazzo *et al.* global fit shown was modified to not include any MINOS/MINOS+, Daya Bay, or Bugey-3 data

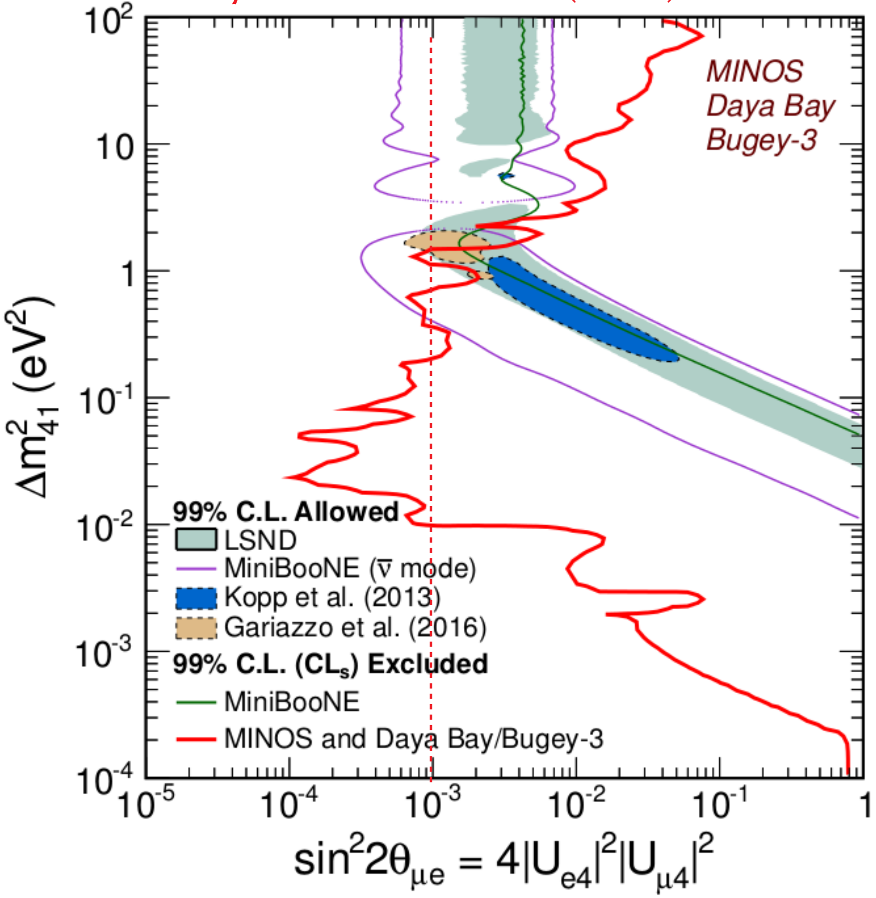
*M. Dentler, A. Hernandez-Cabezudo, J. Kopp, P. A. N. Machado, M. Maltoni, I. Martinez-Soler, T. Schwetz, JHEP **08**, 010 (2018)

S. Gariazzo, C. Giunti, M. Laveder, Y. F. Li, Phys. Lett. **B782, 13 (2018)

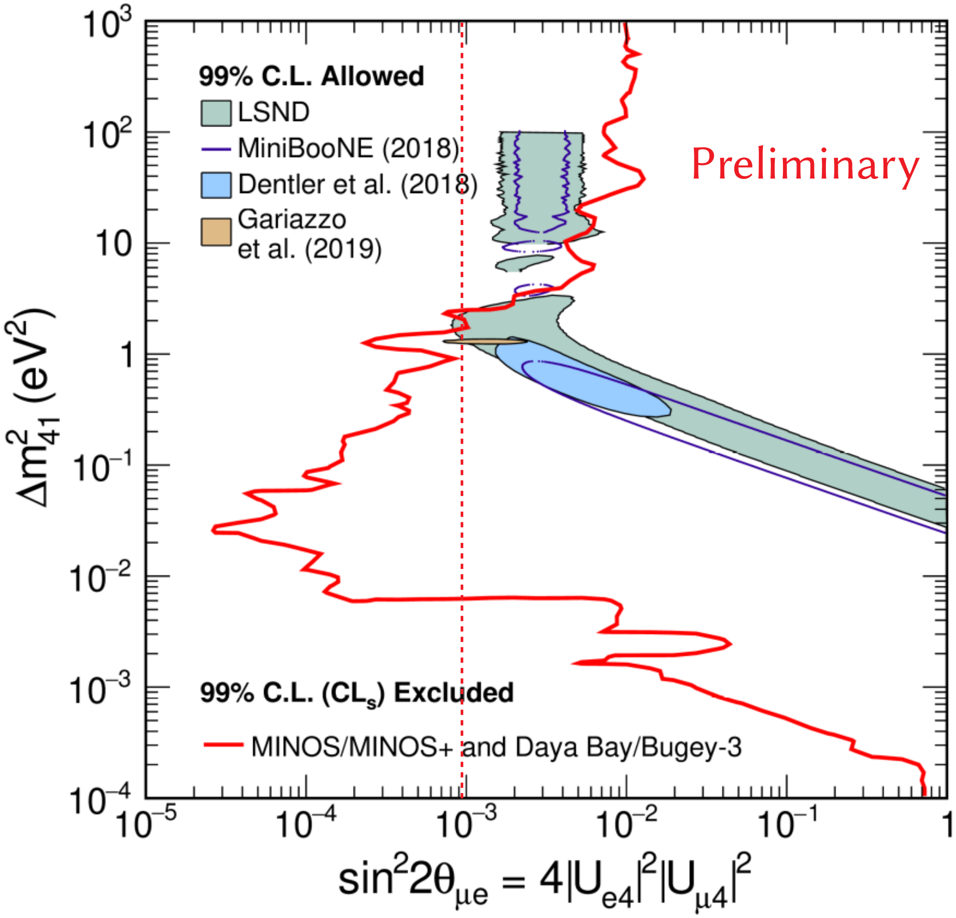


Combined – 99% C.L.

Previous result:
Phys. Rev. Lett. 117 (2016) 151801



This result



Conclusions

Daya Bay

- Using 1230 days of data (2x more than previous analysis), Daya Bay sets world-leading limits on $\sin^2 2\theta_{14}$ for $2\mathrm{x}10^{-4}\ \mathrm{eV}^2 < |\Delta m^2_{41}| < 0.2\ \mathrm{eV}^2$

MINOS/MINOS+

- Using a new two-detector fit technique, MINOS/MINOS+ sets world-leading limits on sterile neutrino mixing, especially in the critical $1\ \mathrm{eV}^2 < \Delta m^2_{41} < 10\ \mathrm{eV}^2$ region

MINOS/MINOS+ and Daya Bay/Bugey-3 Combination

- Through close collaboration, Daya Bay and MINOS were able to use the CL_s technique to combine their disappearance limits to extract equivalent appearance limits, assuming the (3+1)-flavor model
- Stringent limits on excess disappearance in both ν_e and ν_μ channels are incompatible with ν_e appearance evidence when interpreted in a pure sterile neutrino mixing framework

Thank you!


The Daya Bay Collaboration

The Daya Bay experiment is supported in part by the Ministry of Science and Technology of China; the U.S. Department of Energy; the Chinese Academy of Sciences; the CAS Center for Excellence in Particle Physics; the National Natural Science Foundation of China; the Guangdong provincial government; the Shenzhen municipal government; the China General Nuclear Power Group; the Research Grants Council of the Hong Kong Special Administrative Region of China; the Ministry of Education in Taiwan; the U.S. National Science Foundation; the Ministry of Education, Youth and Sports of the Czech Republic; the Joint Institute of Nuclear Research in Dubna, Russia; the NSFC-RFBR joint research program;and the National Commission for Scientific and Technological Research of Chile.

The MINOS/MINOS+ experiment is supported by the U.S. Department of Energy; the United Kingdom Science and Technology Facilities Council; the U.S. National Science Foundation; the State and University of Minnesota; and Brazil's FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo), CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior). We are grateful to the Minnesota Department of Natural Resources and the personnel of the Soudan Laboratory and Fermilab. We thank the Texas Advanced Computing Center at The University of Texas at Austin for the provision of computing resources.

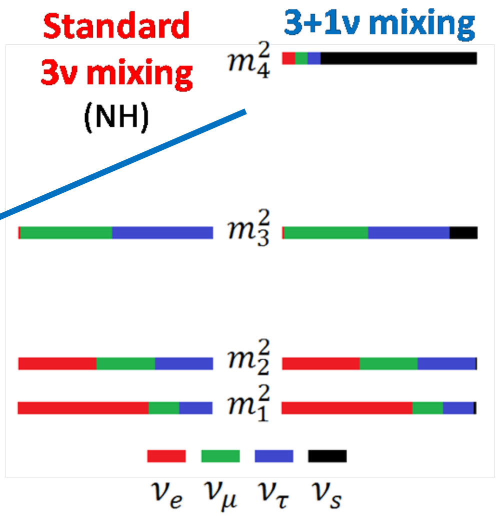

The MINOS+ Collaboration

BACKUP

(3+1) Neutrino Oscillations

- Add an additional flavor and mass eigenstate:

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



For **Daya Bay** and **Bugey-3**:

$$P_{\overline{\nu}_e \to \overline{\nu}_e} \approx 1 - 4|U_{e3}|^2\left(1 - |U_{e3}|^2 - |U_{e4}|^2\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) - \boxed{4|U_{e4}|^2\left(1 - |U_{e4}|^2\right)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)}$$

→ **Sensitive to $|U_{e4}|^2$**

For **MINOS/MINOS+**:

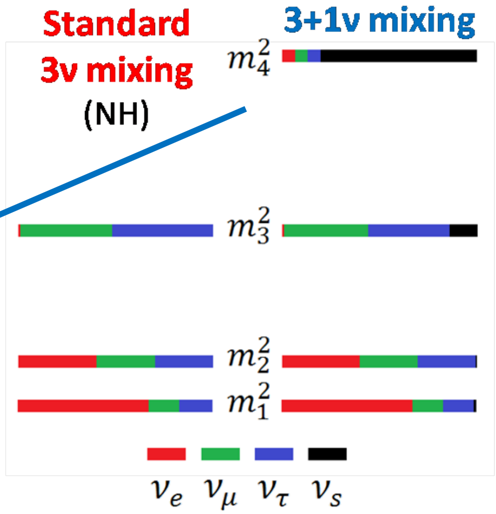
$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu} \approx 1 - 4|U_{\mu 3}|^2\left(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) - \boxed{4|U_{\mu 4}|^2\left(1 - |U_{\mu 4}|^2\right)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)}$$

→ **Sensitive to $|U_{\mu 4}|^2$**

(3+1) Neutrino Oscillations

- Add an additional flavor and mass eigenstate:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



Adopting the parameterization :

$$U = R_{34}R_{24}R_{14}R_{23}R_{13}R_{12}$$

$$\begin{aligned} |U_{e4}|^2 &= \sin^2\theta_{14}, \\ |U_{\mu4}|^2 &= \sin^2\theta_{24}\cos^2\theta_{14}, \\ 4|U_{e4}|^2|U_{\mu4}|^2 &= \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \boxed{\sin^2 2\theta_{\mu e}}. \end{aligned}$$

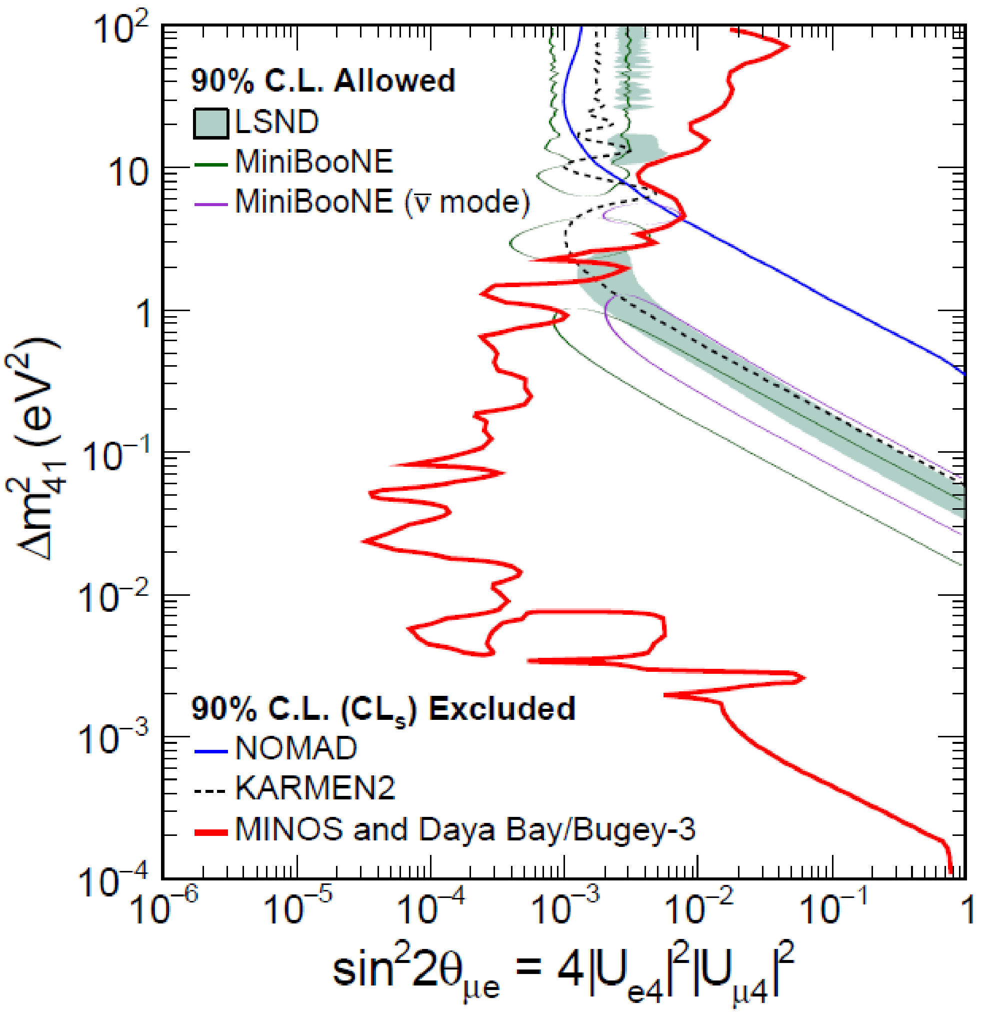
Daya Bay

MINOS/MINOS+

LSND & MiniBooNE

The joint analysis places limits in the ($\sin^2 2\theta_{\mu e}$, Δm^2_{41}) parameter space.

Previous exclusion limits:
Daya Bay + Bugey-3 + MINOS



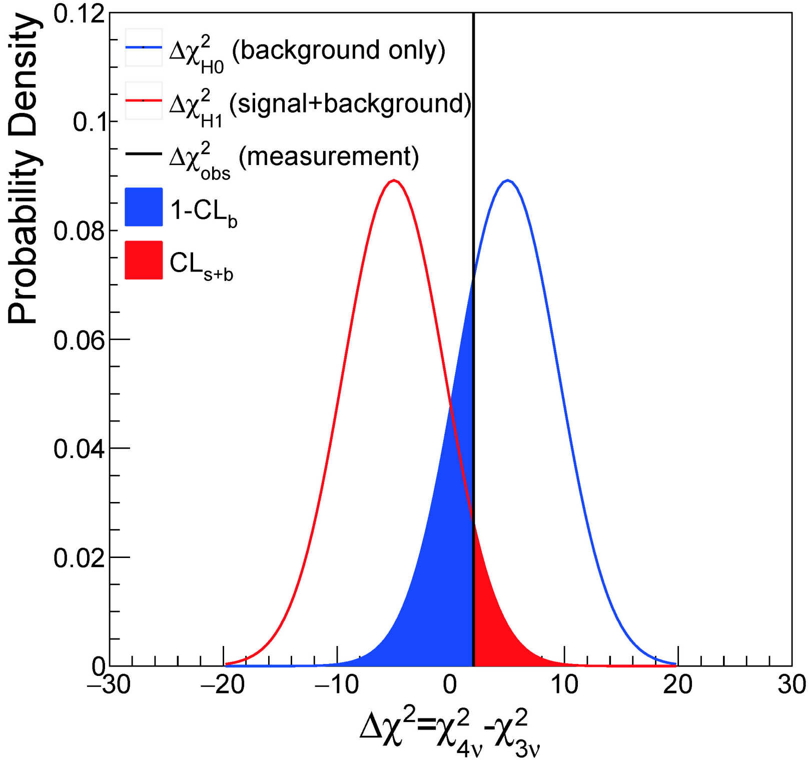
Phys. Rev. Lett. 117, 151801 (2016)

- Combined $\bar{\nu}_e$ disappearance of Daya Bay and Bugey-3 with ν_μ disappearance of MINOS
- Constrain $\sin^2 2\theta_{\mu e}$ over 6 order s of magnitude in Δm^2_{41}
- Parameter space allowed by LSND & MiniBooNE excluded for $\Delta m^2_{41} < 0.8\text{eV}^2$

BACKUP

CLs vs. F-C

CL_s definition



We are using different notation, however, the calculated CL_s values are identical.

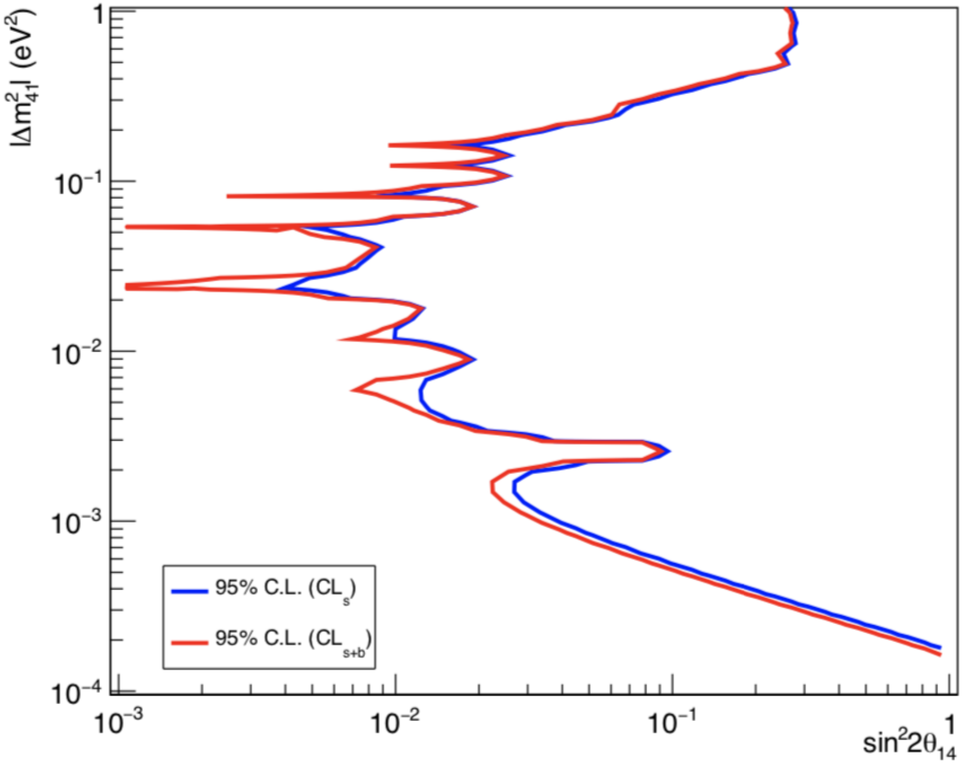
$$CL_s = \frac{\textit{solid red area}}{\textit{blank blue area}}$$

If we switch to the PDG notation, it can cause some confusion since we have used our notation since the very first sterile neutrino publication.

PDG: $CL_s = \frac{p_\mu}{1-p_b}$ p_μ: The solid red region.
p_b: The solid blue region.

Our: $CL_s = \frac{1-p_{4\nu}}{1-p_{3\nu}} = \frac{CL_{s+b}}{CL_b}$ CL_{s+b}: The solid red region.
CL_b: The blank blue region.

Conservativeness of $\mathrm{CL_s}$



- From the PDG CLs definition $CL_s = \dfrac{p_\mu}{1-p_b}$
- Since $1-p_b$ is always less than or equal to 1, the $\mathrm{CL_s}$ value is always larger than or equal to p_μ, the p-value of $\mathrm{H_1}$ hypothesis, so it is conservative by definition.

Gaussian CL_s vs. F.C.

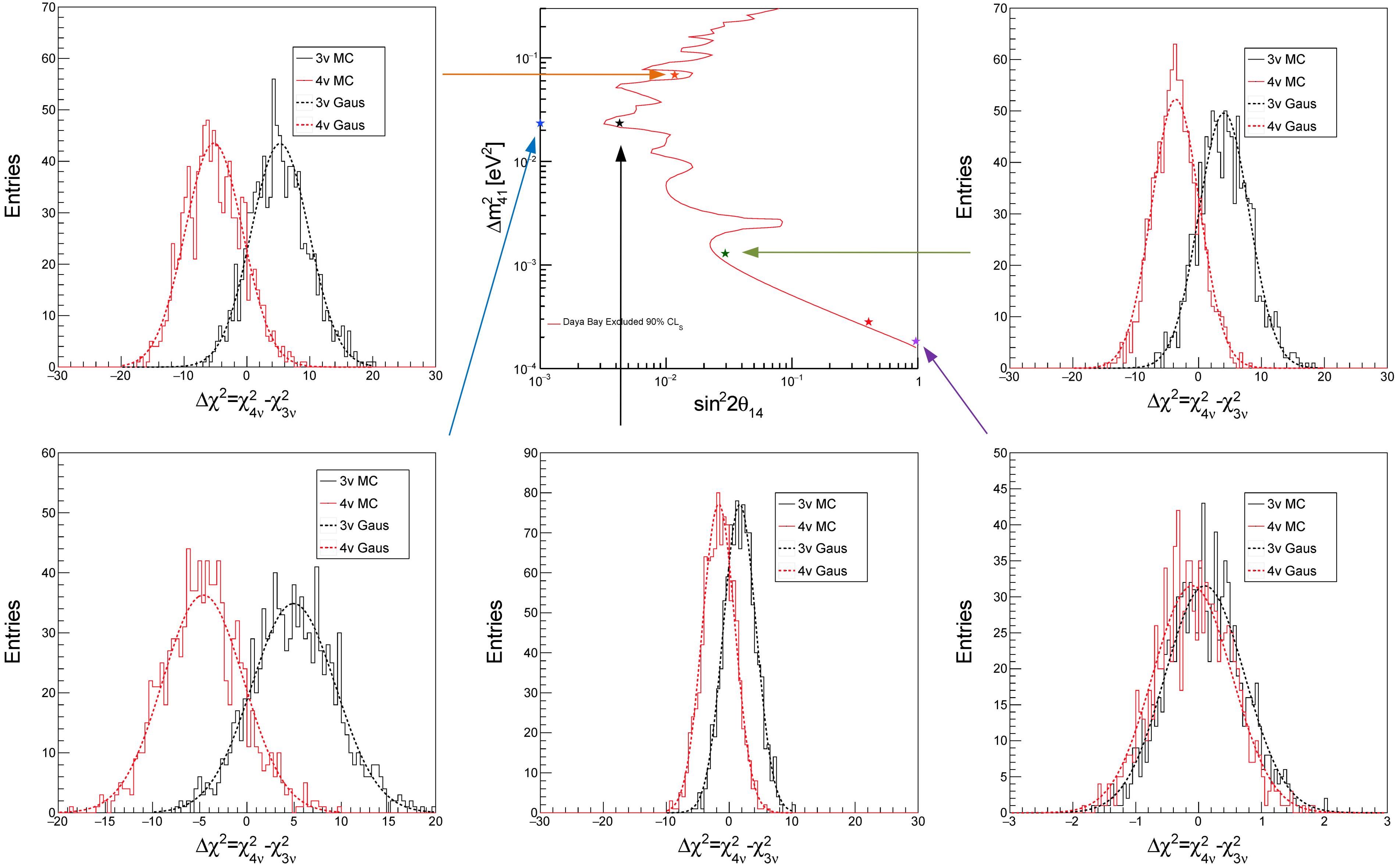
- For Gaussian CLs, we are doing two hypothesis test w.r.t.
  - H_1: $\{\sin^2 2\theta_{14}=a, \Delta m^2_{41}=b\}$, one specific point for 4ν model
  - H_0: $\{\sin^2 2\theta_{14}=0, \Delta m^2_{41}=0\}$, standard 3ν model

- For Feldman-Cousins
  - H_1: $\{\sin^2 2\theta_{14}=a, \Delta m^2_{41}=b\}$, one specific point for 4ν model
  - H_0: $\{\sin^2 2\theta_{14}\neq a$, or $\Delta m^2_{41}\neq b\}$, any other point for 4ν model

Clearly the H_0 hypothesis are different for Gaussian CL_s and F.C.

More details can check Barlow, R. J. (2019). Practical Statistics for Particle Physics. arXiv preprint arXiv:1905.12362

‘Gaussianity’ of $\Delta\chi^2$ distribution



BACKUP

Bugey-3 reproduction

Overview: Bugey-3 Reproduction

- No info. about reactor power, fission fractions of each isotope
- Input : Measured / MC ratio (cancel out reactor info.)
  - ILL + Vogel model
  - Mean fission fraction values in Bugey-4

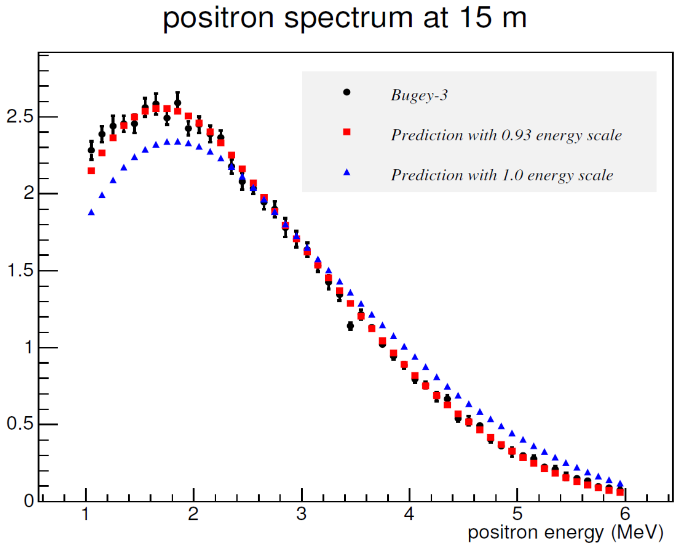
- Oscillation effects:
  - Finite bin size effect: sterile ν driven fast oscillation
    - need to integrate over each bin for fast oscillation
  - Baseline smearing: not provided
    - Assume 1.26 and 1.0 meter Gaussian smearing to 15 and 40m baseline detectors

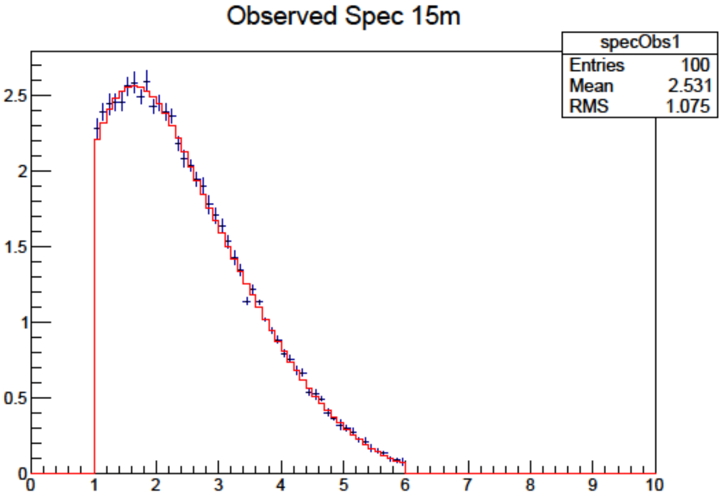
Overview: Bugey-3 Reproduction

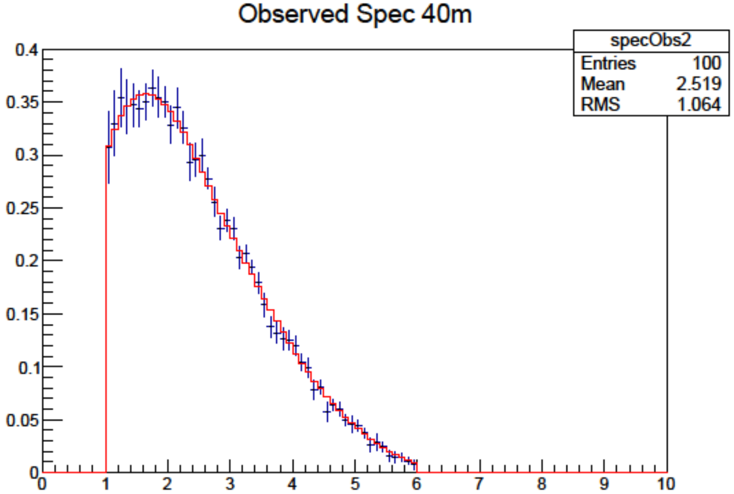
- Energy scale: not provided
  - indirectly extract from published positron spectra

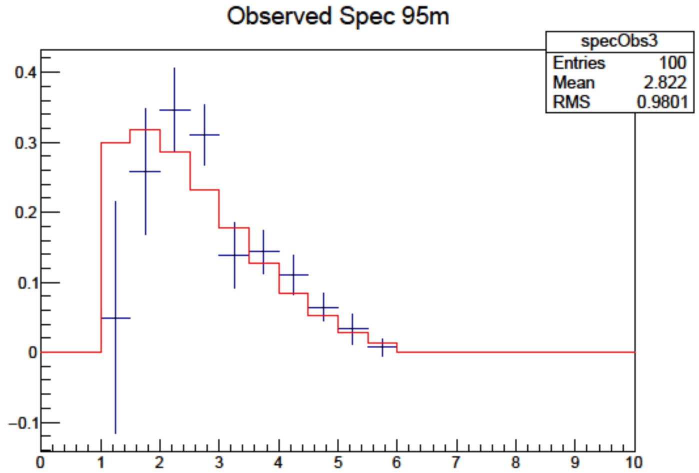
- Energy resolution: 6% at 4.2 MeV
  - 6% at 4.2 MeV
  - Neutron capture peak (assume Gaussian, extract σ)
  - Bi peak (assume Gaussian, extract σ)

Bugey-3 Positron Spectrum Prediction



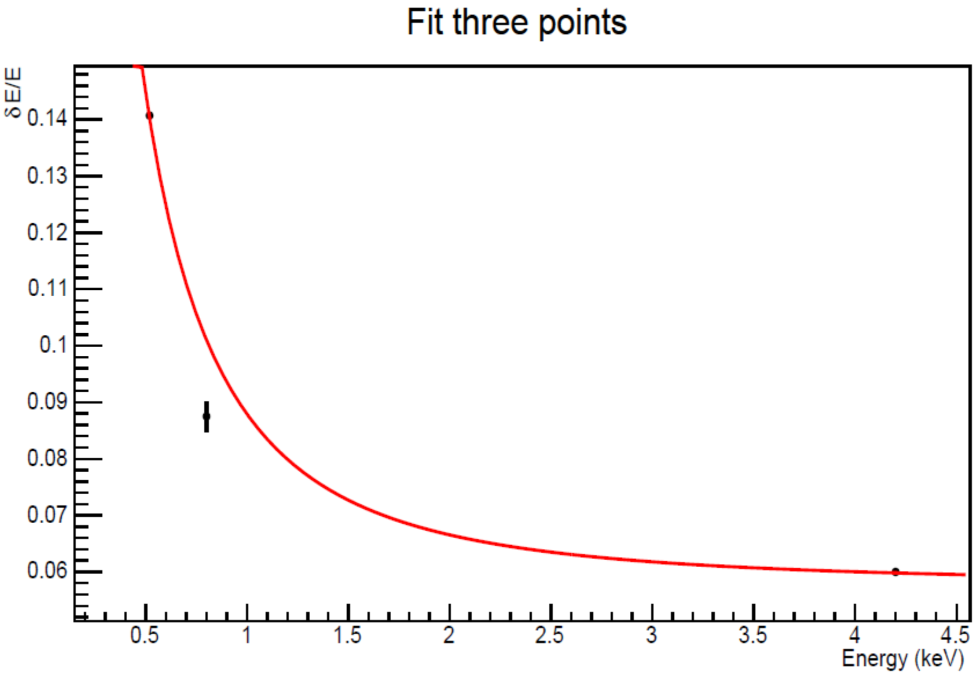


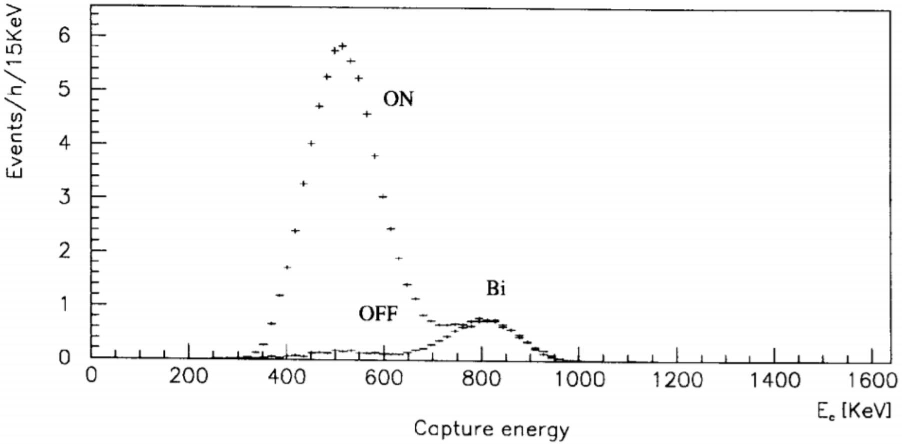




- We applied energy response correction.

Bugey-3 Energy Smearing





neutron capture peak and Bi peak

3 points are chosen (neutron capture peak, Bi peak, and 6% at 4.2 MeV)

$$\frac{\delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

$a = 5.769 \times 10^{-2}$

$b=2.354 \times 10^{-7}$

$c=6.633 \times 10^{-2}$

Reproduction of Bugey-3

$$\chi_i^2 = \sum_{j=1}^{nbins} \frac{\left(\left((1-a_0)(1+a_i)+b\left(E_j-1.0\right)\right)R_j^{pre}-R_j^{obs}\right)^2}{\sigma_j^2}$$

$$\chi^2 = \sum_{i=1}^{3} \chi_i^2 + \sum_{j=4}^{4} \frac{a_j^2}{\sigma_{a_i}^2} + \frac{b^2}{\sigma_b^2}$$

R_j^{pre} : predicted ratio R_j^{obs} : observed ratio

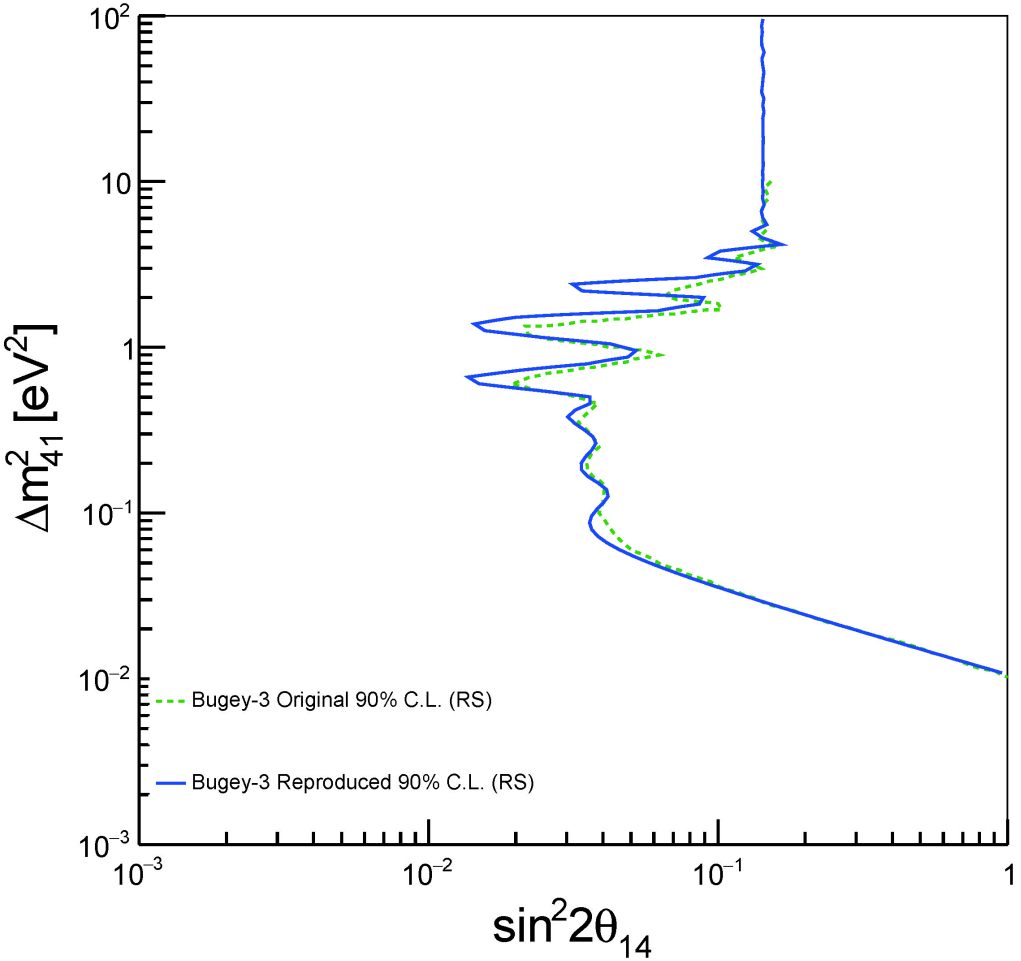
a_0 : overall normalization (constrain to 5%)

a_i : normalization for each baseline

$b(E_j - 1.0)$: systematic uncertainties for energy scale

Repro. of Bugey-3 Results (raster scan)

- Reproduced Bugey-3 raster scan contour (blue)
- Consistent with Bugey-3 original raster scan exclusion contour (green dash)



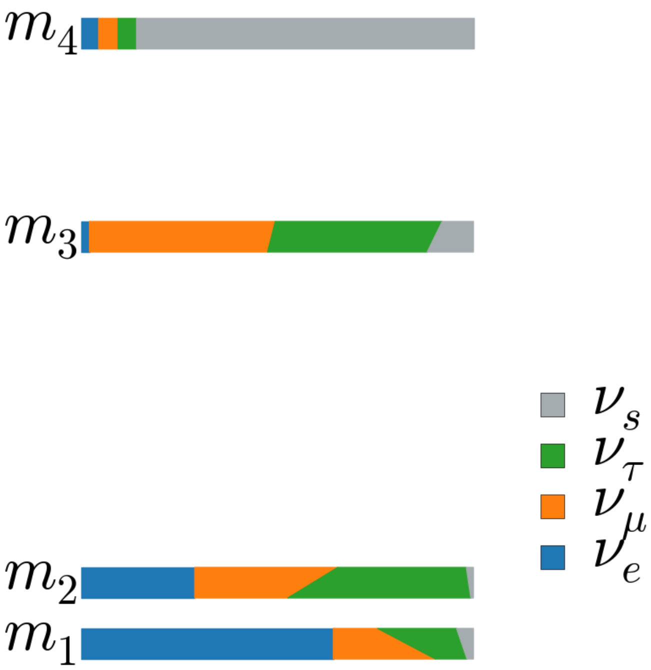
BACKUP

MINOS/MINOS+

3+1 Model

- Anomalous short-baseline results consistent with new mass state and new sterile flavor
- Expand PMNS matrix from 3x3 ⟶ 4x4
- 6 new parameters
  - One mass scale (Δm^2_{41})
  - Three mixing angles (θ_{14}, θ_{24}, θ_{34})
  - Two CP-violating phases (δ_{14}, δ_{24})
- Search in two modes
  - Neutral current disappearance
    - NC rate is insensitive to 3 flavor mixing
    - Sterile neutrinos do not couple to the Z boson
    - Sensitive to Δm^2_{41}, θ_{24}, θ_{34}
  - ν_μ charged current disappearance
    - Three flavor oscillations are modulated by the higher frequency sterile oscillations
    - Sensitive to Δm^2_{41} and θ_{24}

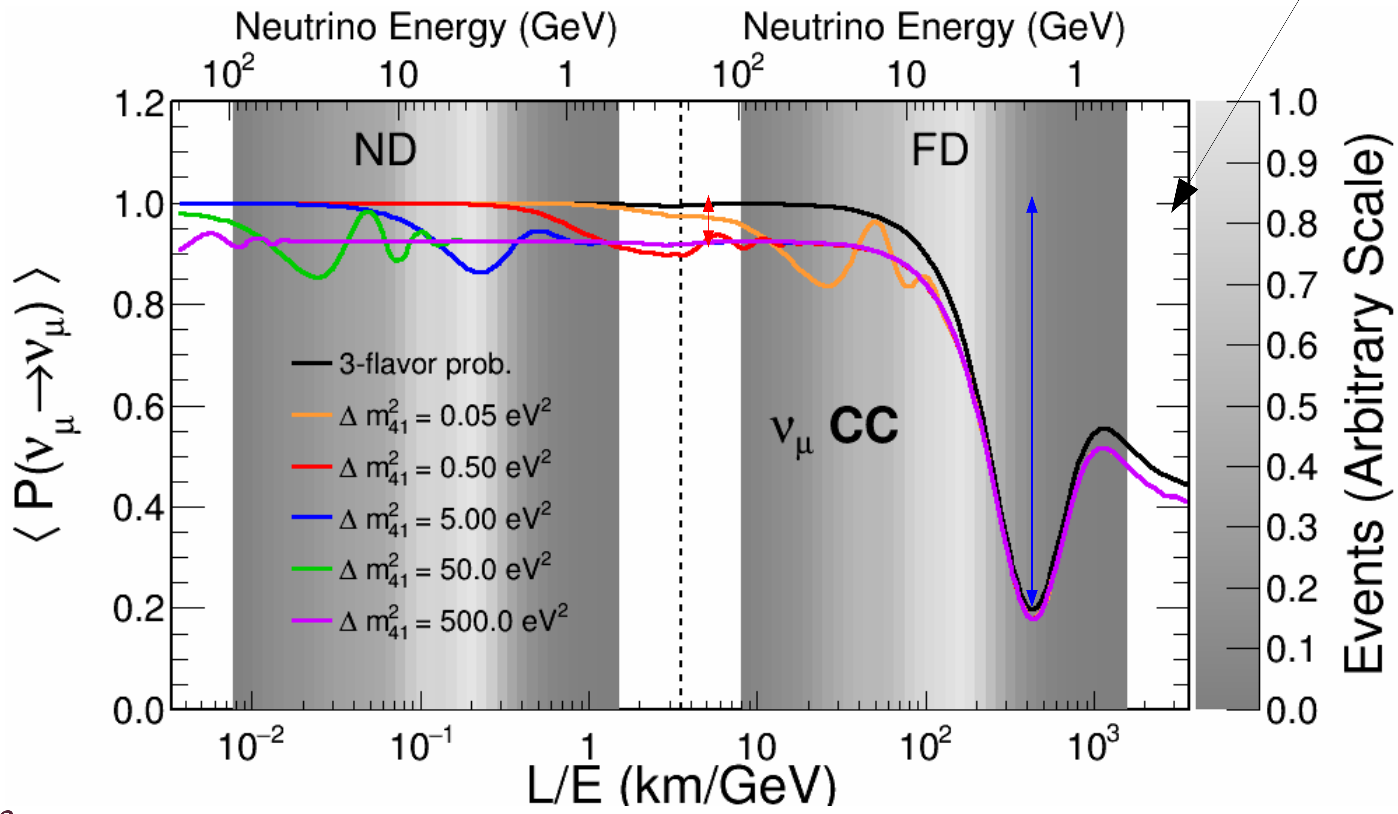
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



Oscillations at Very Large Δm^2_{41}

Interplay between shape and normalization gives strong constraints even at very large Δm^2_{41}

Independent of Δm^2_{41}

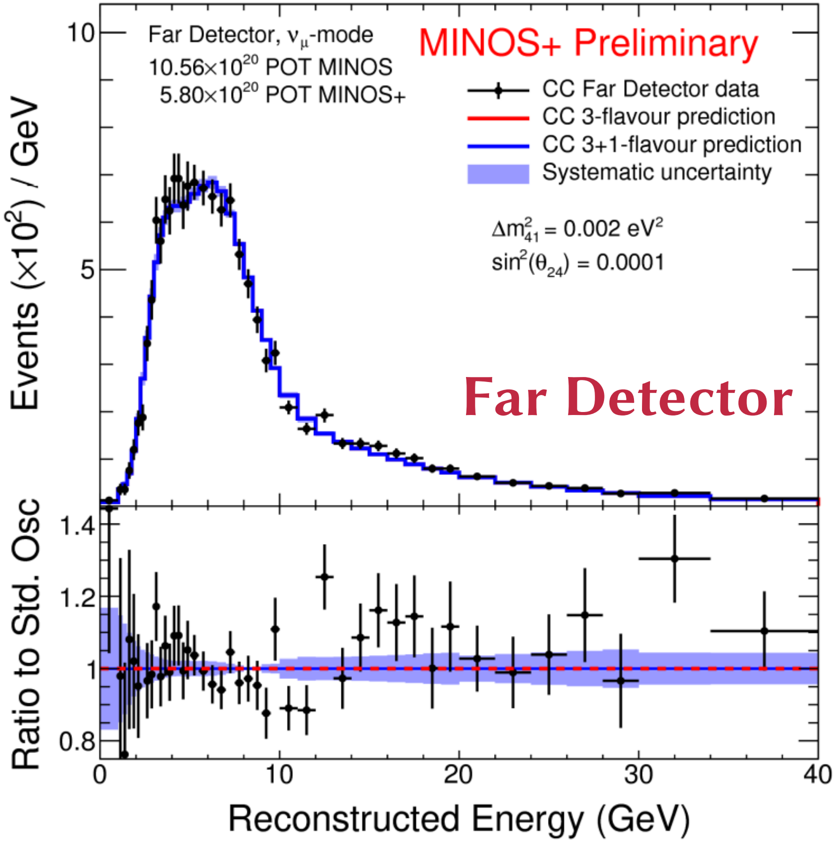


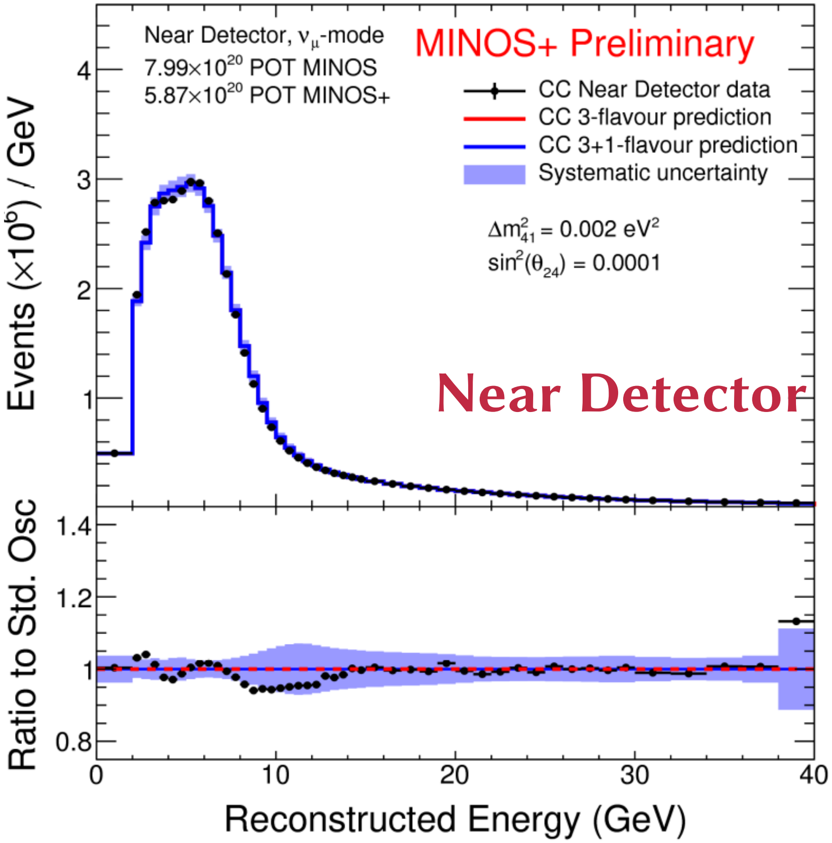
Rapid oscillation regime causes normalization shifts

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

Already constrained by near-maximal mixing

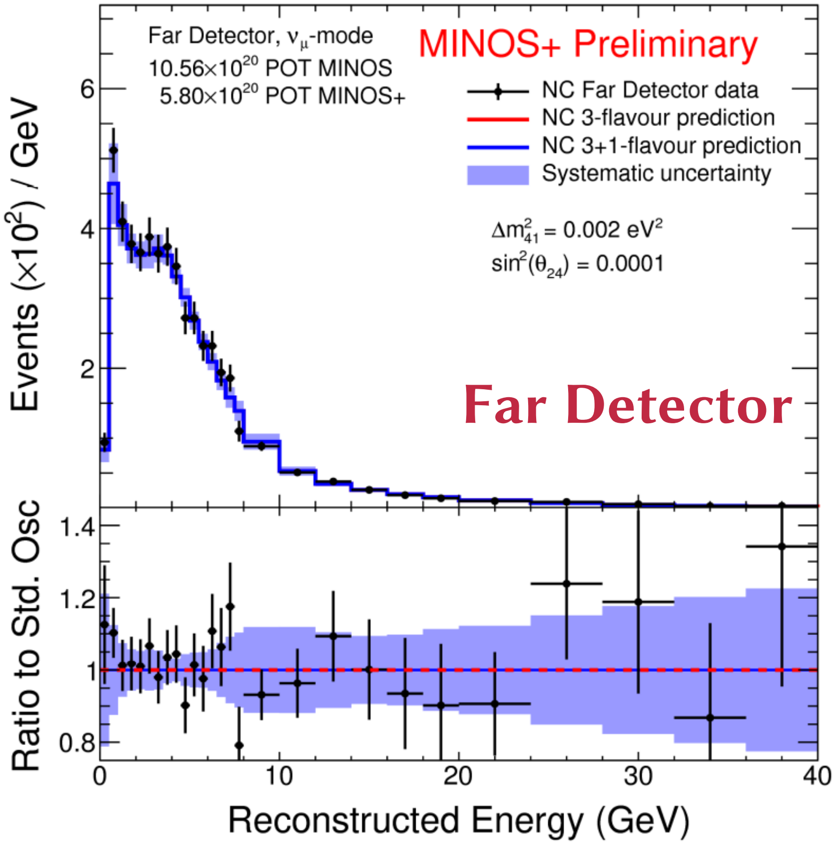
ν_μ CC Sample

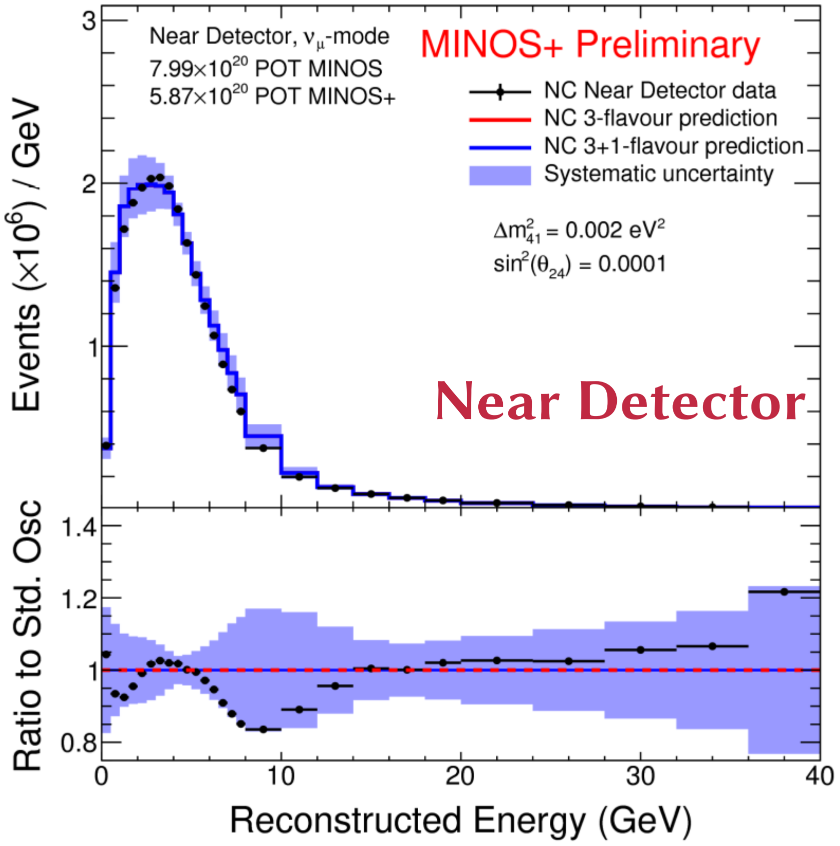




- Covariance matrix fits do not include systematics as nuisance parameters
- The error bands and prediction account for off-diagonal elements to indicate the equivalent of post-fit agreement

NC Sample





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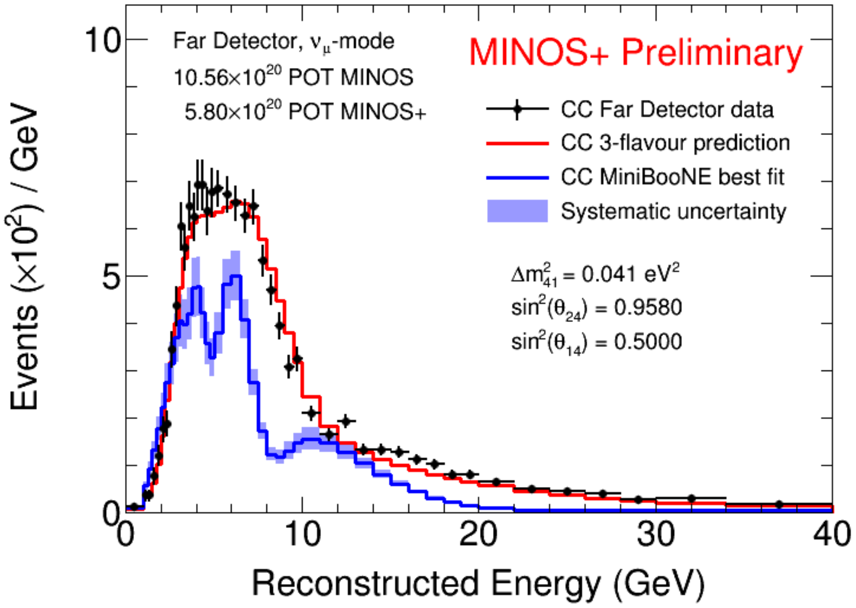
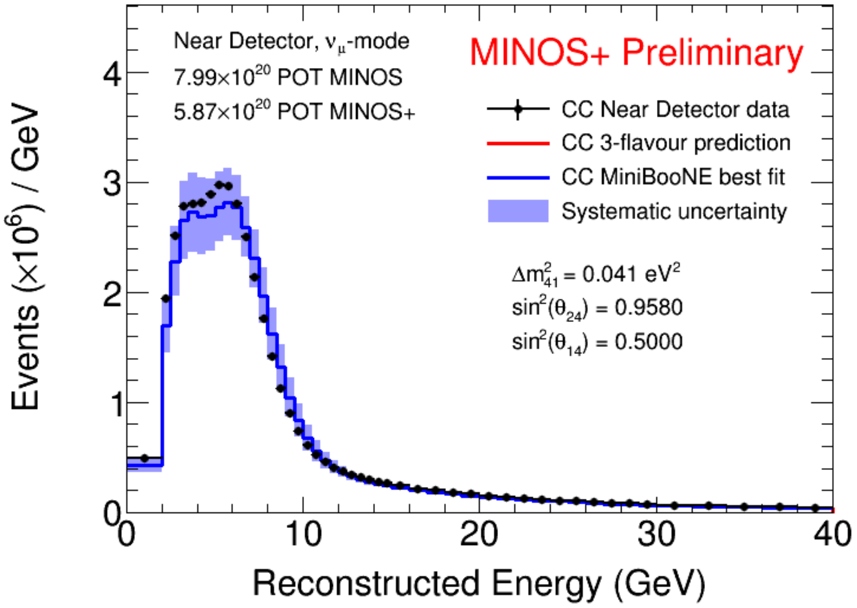
Comparison to MiniBooNE + LSND Best Fit: CC Selected Events

Far Detector



Near Detector



New MiniBooNE paper – arXiv:1805.12028

Best fit: $\Delta m^2 = 0.041$ eV^2 and $\sin^2 2\theta_{\mu e} = 0.958$

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

Take $\sin^2 2\theta_{14} = 1$ to minimize ν_μ disappearance

Comparison to MiniBooNE + LSND Best Fit: NC Selected Events

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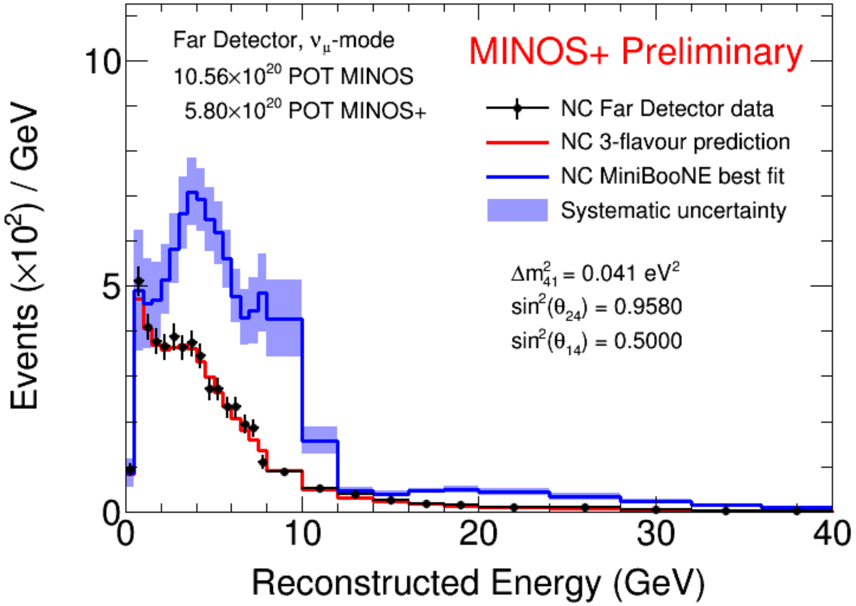
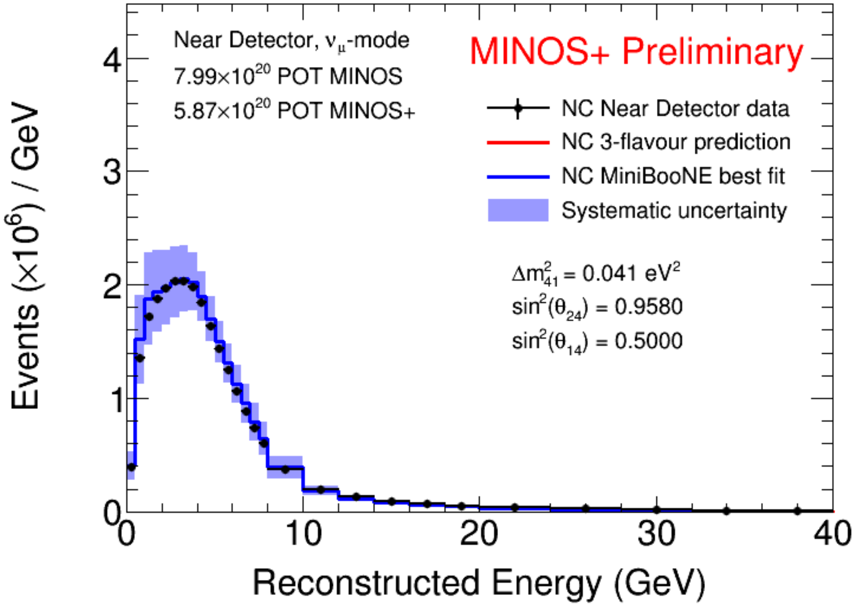


Near Detector



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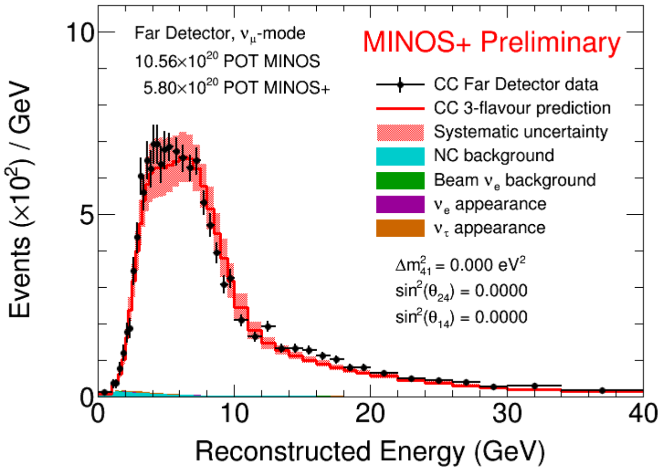
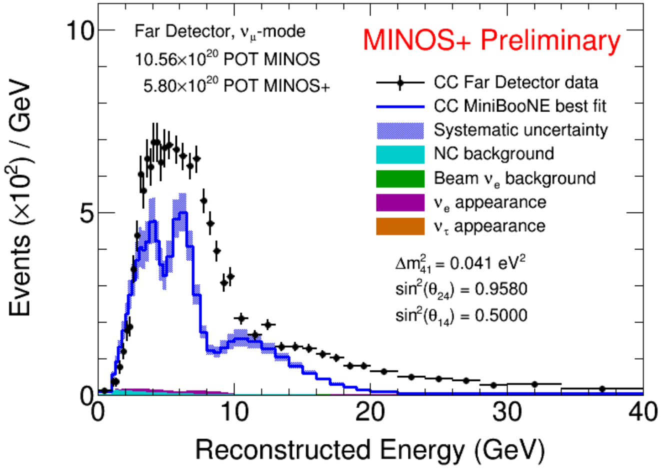
Comparison to MiniBooNE + LSND Best Fit: CC Selected Events

Three-flavor Oscillations

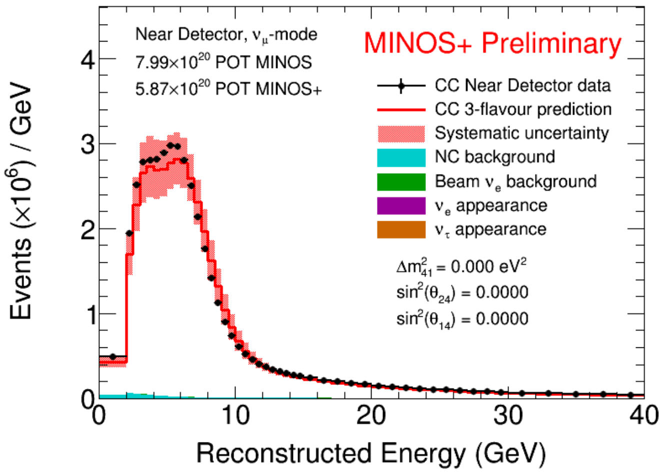
MiniBooNE + LSND Best Fit

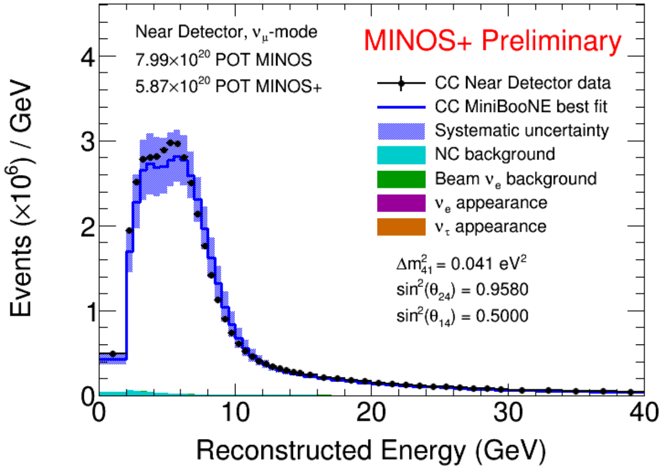
FD





ND



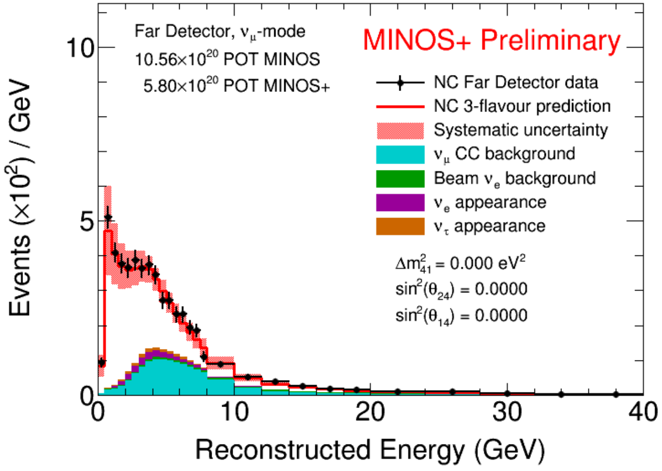


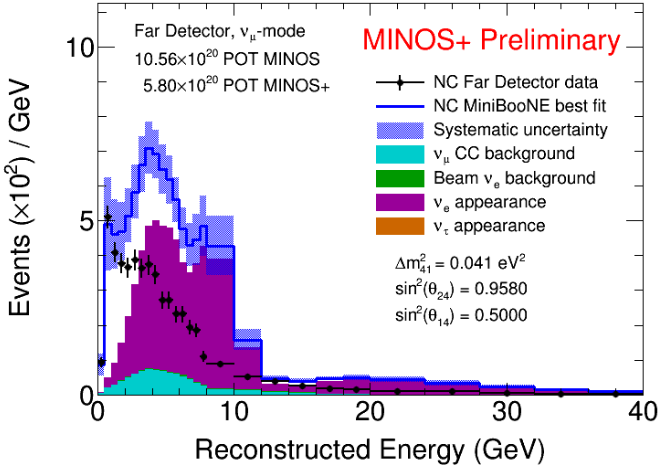
Comparison to MiniBooNE + LSND Best Fit: NC Selected Events

Three-flavor Oscillations

MiniBooNE + LSND Best Fit

FD





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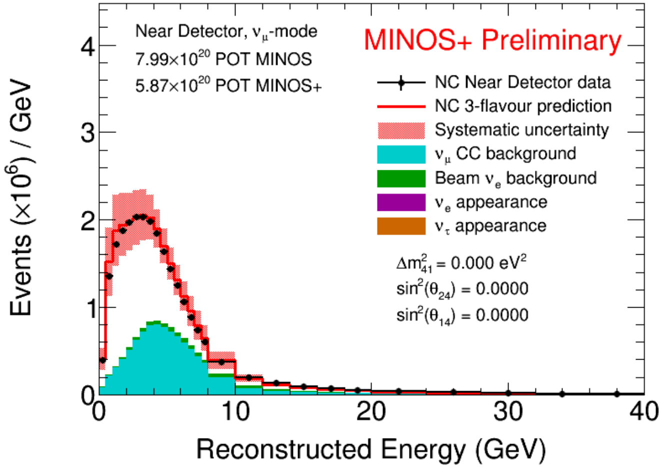
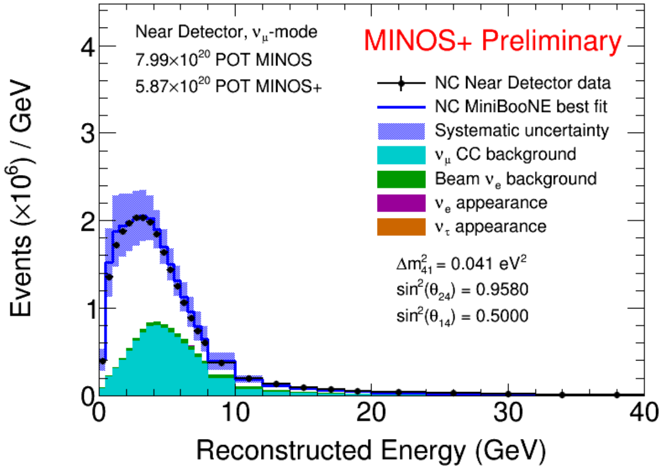
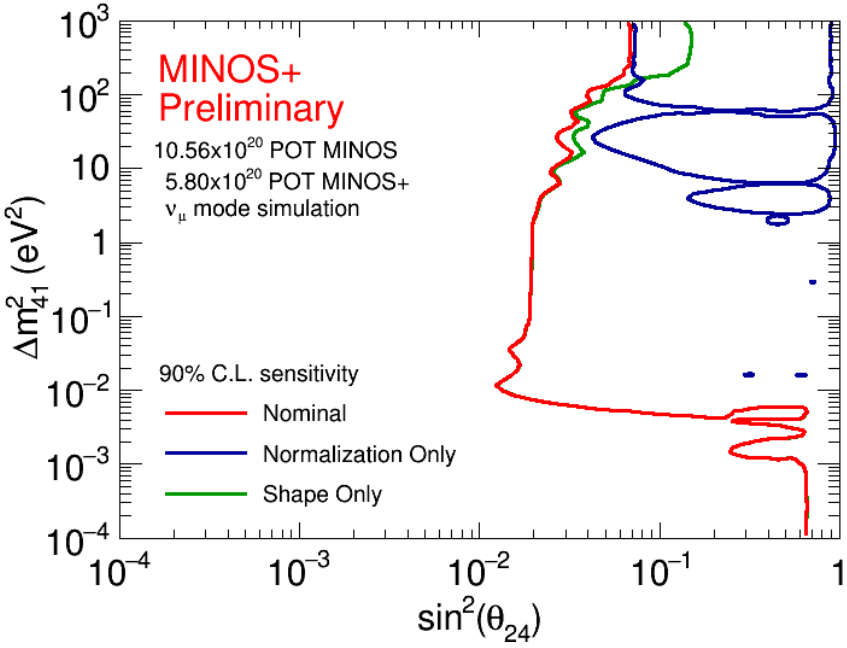


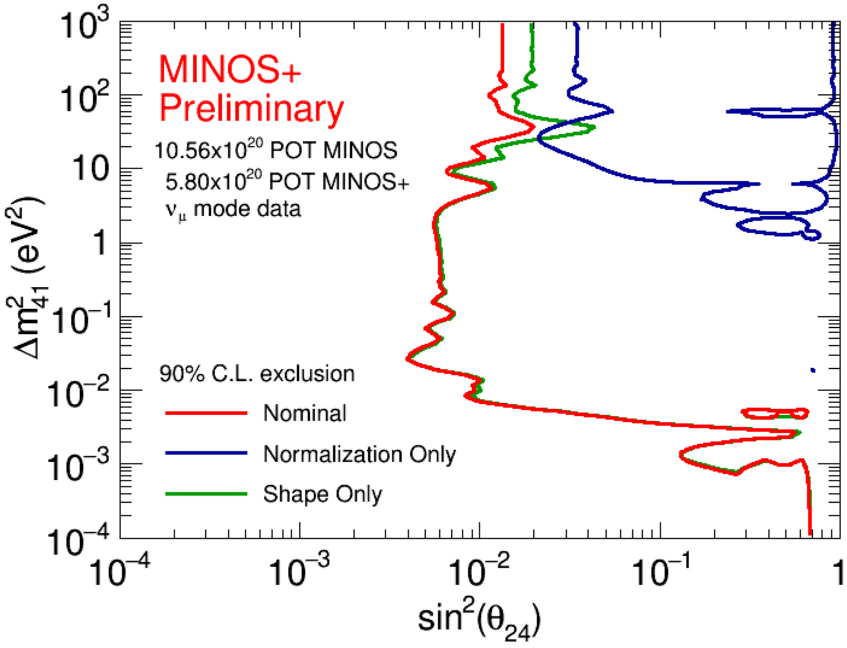


Shape/Normalization Factorization

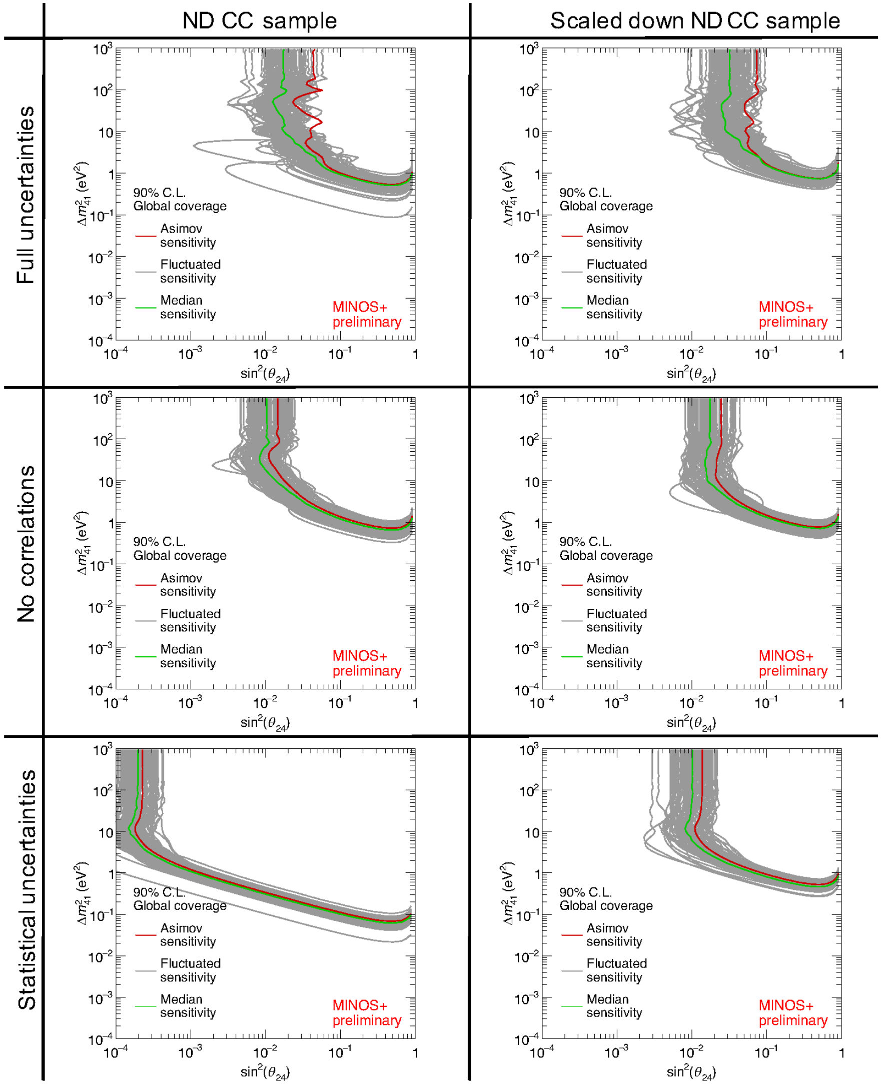
Asimov Sensitivity



Data Limit

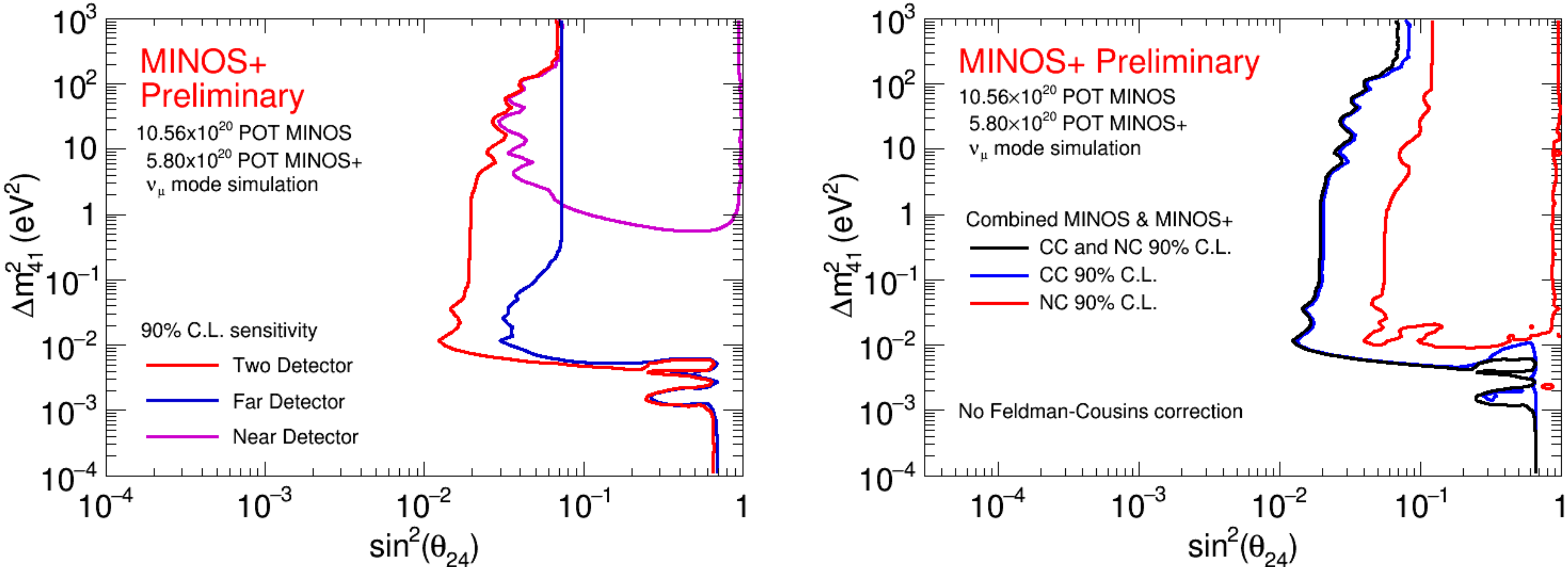


Median vs. Asimov Sensitivity

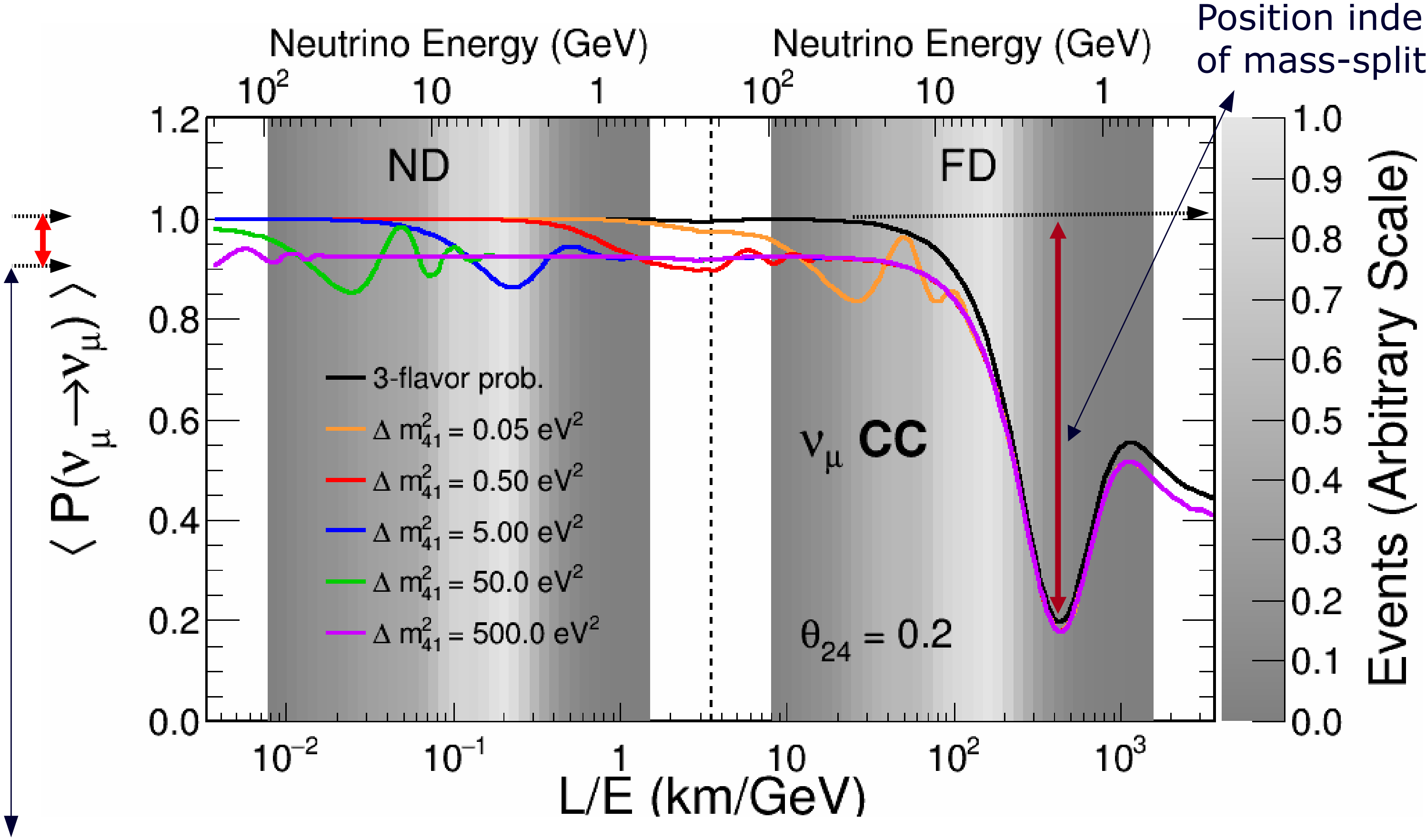


Detector and Sample Contributions

Asimov Sensitivities



(3+1)-Flavor Oscillations



Position independent of mass-splitting

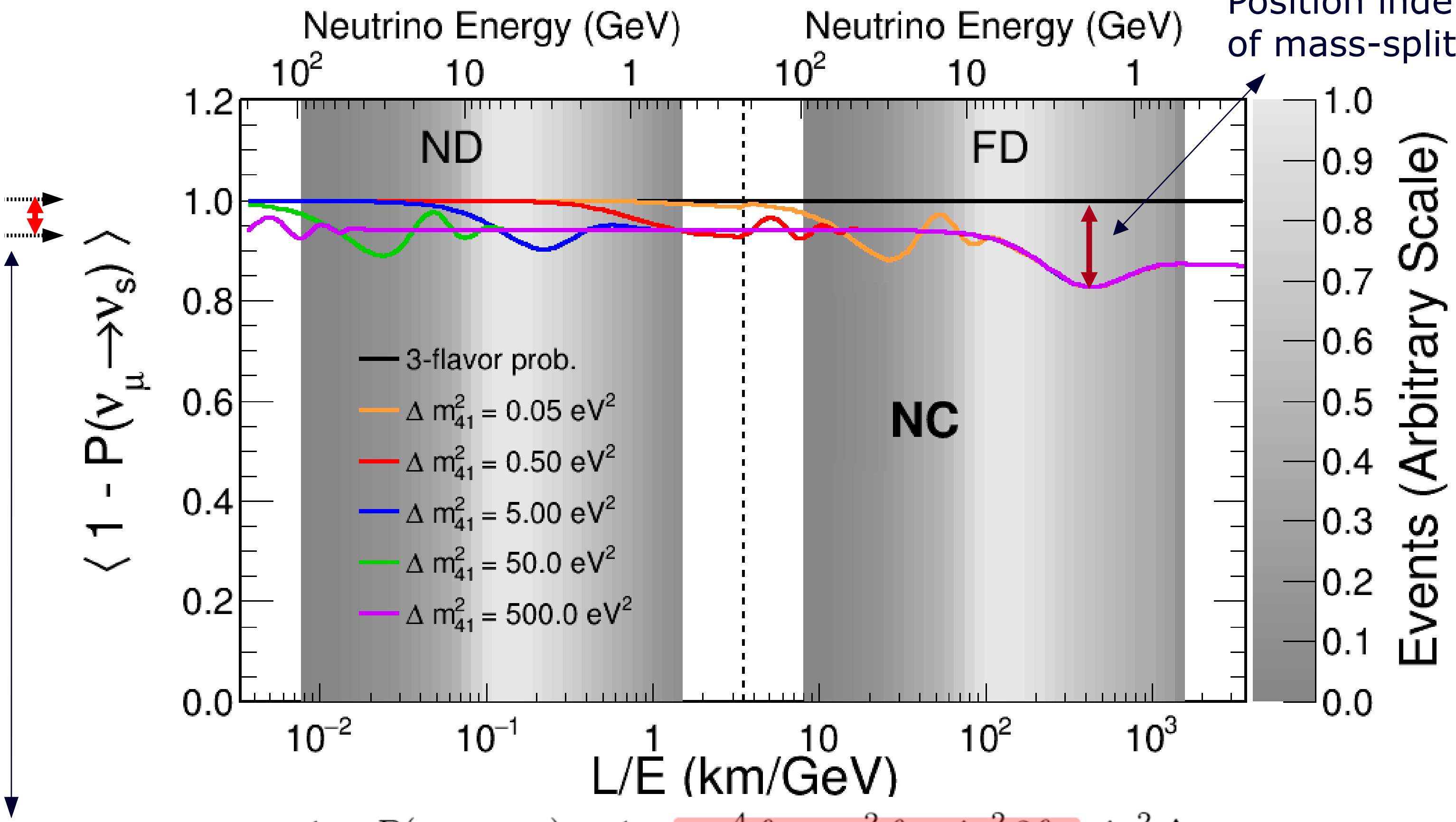
Rapid oscillations regime causes normalization shifts

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

Constrained by observation of near-maximal mixing

(3+1)-Flavor Oscillations

Position independent of mass-splitting



$$1 - P(\nu_\mu \rightarrow \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}$$

$$- \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}$$

$$\cancelto{0}{+ \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin\Delta_{31}}$$

Rapid oscillations regime causes normalization shifts

Constrained by observation of near-maximal mixing

(3+1)-Flavor Degeneracies

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\left|U_{\mu 3}\right|^2\left(1 - \left|U_{\mu 3}\right|^2 - \left|U_{\mu 4}\right|^2\right)\sin^2\Delta_{31} - 4\left|U_{\mu 4}\right|^2\left|U_{\mu 3}\right|^2\sin^2\Delta_{43} - 4\left|U_{\mu 4}\right|^2\left(1 - \left|U_{\mu 3}\right|^2 - \left|U_{\mu 4}\right|^2\right)\sin^2\Delta_{41}$$

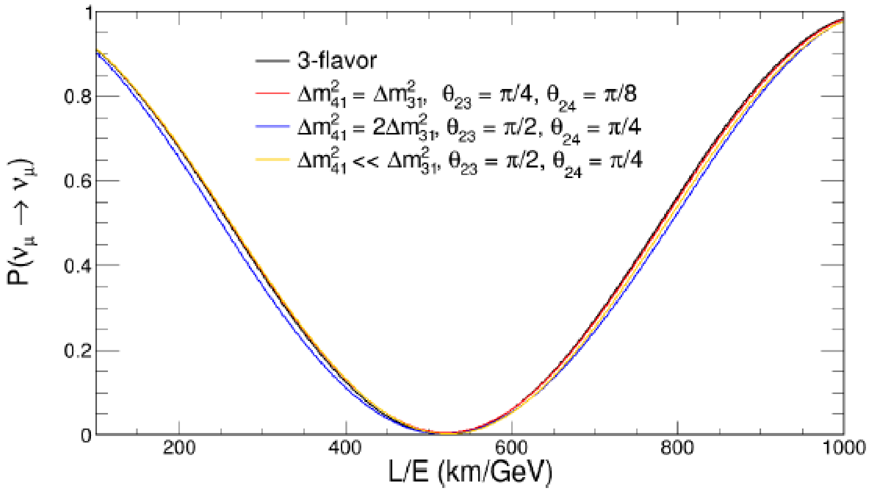
where $\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$

If:

- $\Delta m^2_{41} \approx \Delta m^2_{31}$
- $\Delta m^2_{41} \approx 2\Delta m^2_{31}$
- $\Delta m^2_{41} \ll \Delta m^2_{31}$

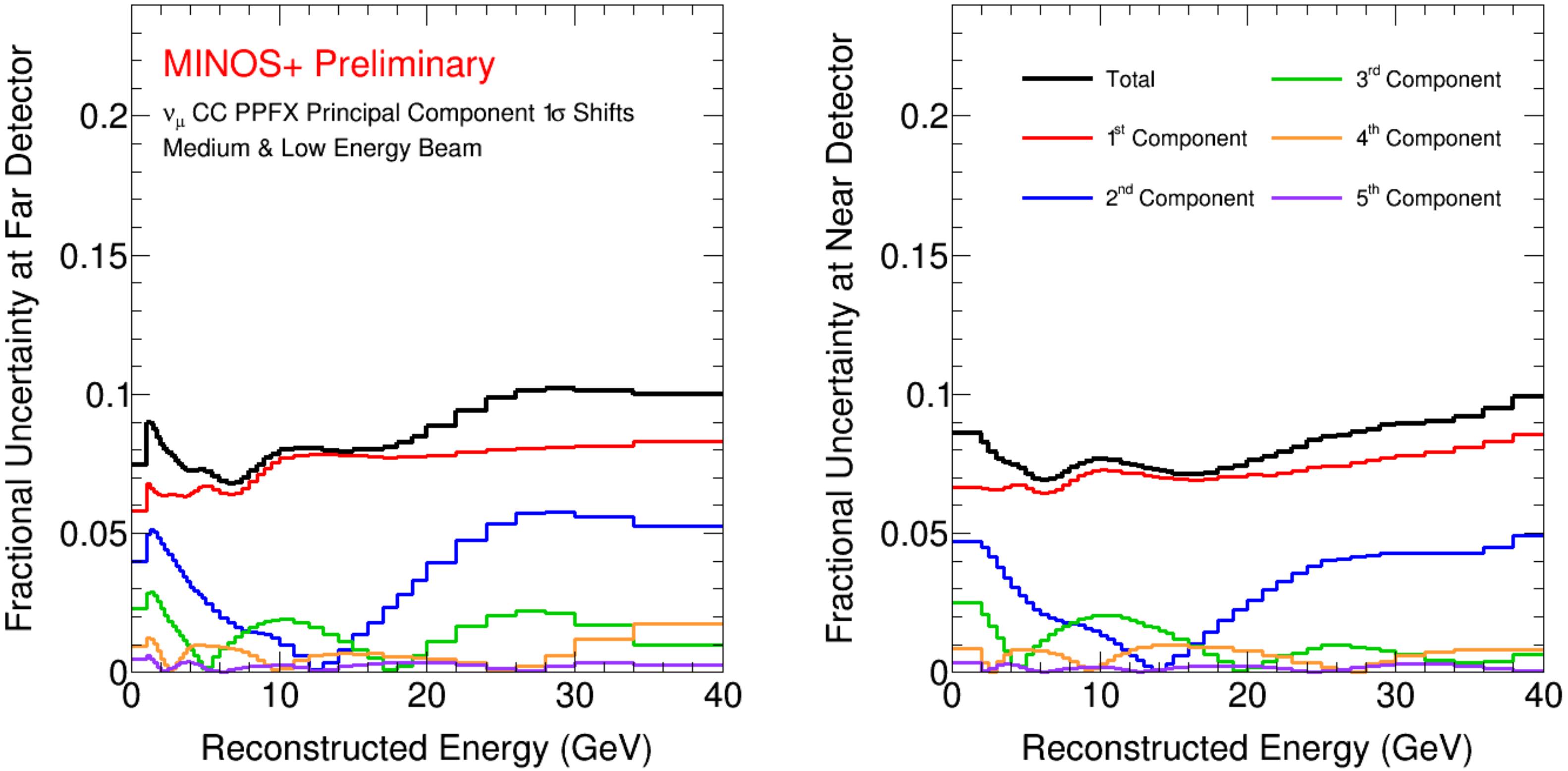
Certain combinations of θ_{23}, θ_{24}, and θ_{34} can produce 4-flavor solutions nearly indistinguishable from 3-flavor.

Run each fit five times → each θ_{23} octant and mass hierarchy choice and the degenerate region.

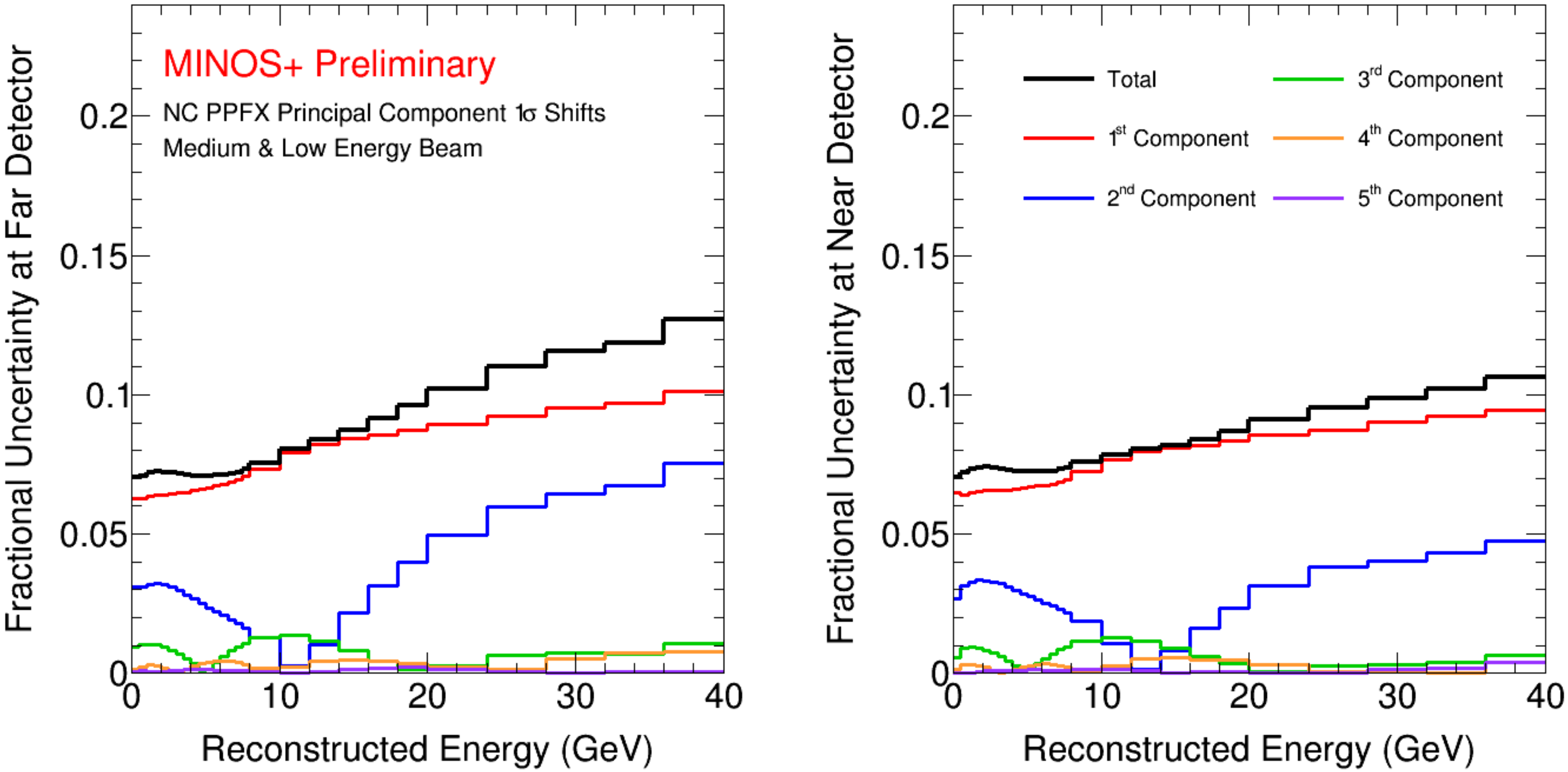


Example degenerate scenarios

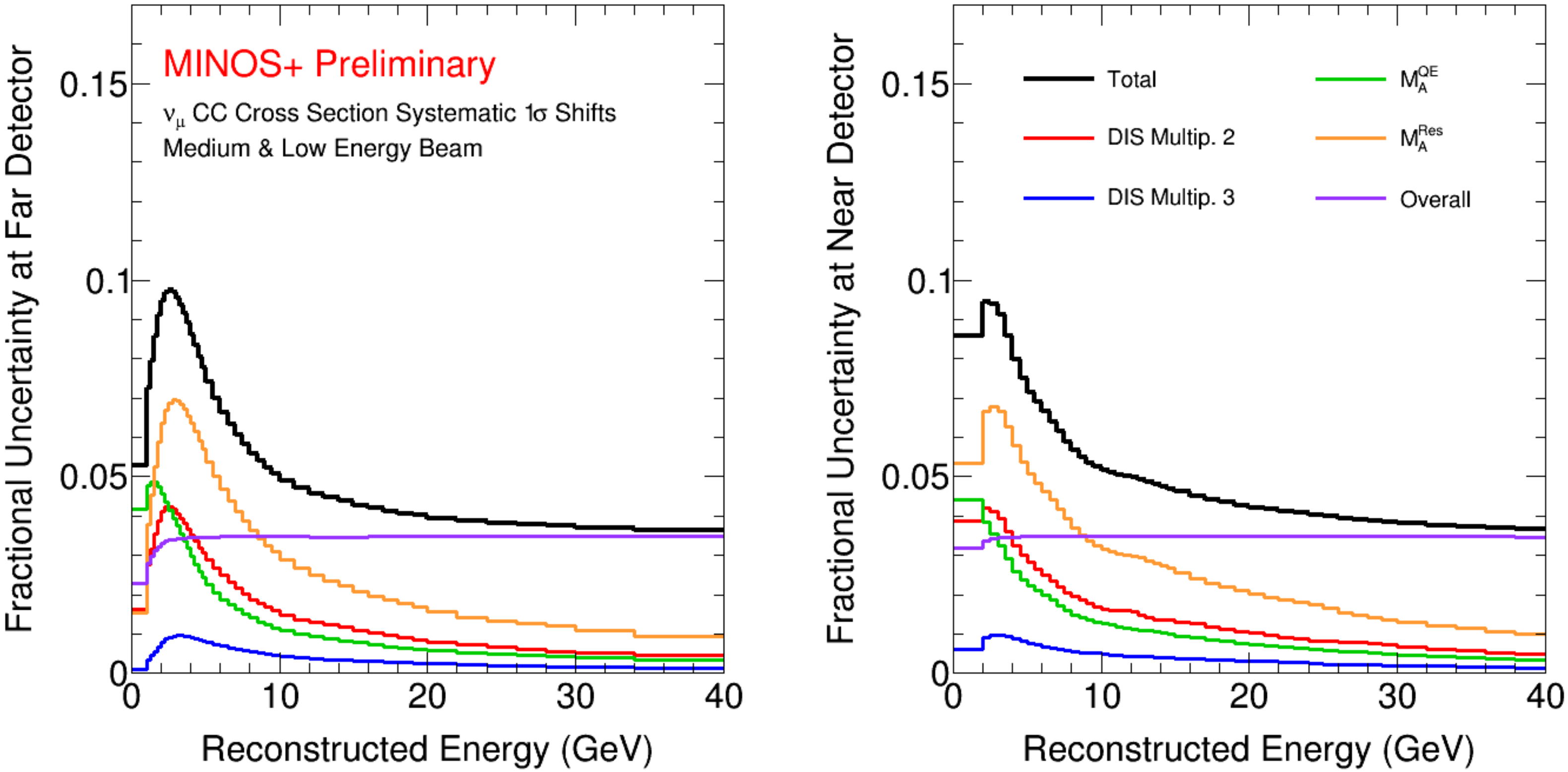
Sterile Systematics: CC Hadron Production



Sterile Systematics: NC Hadron Production



Sterile Systematics: CC Cross Sections



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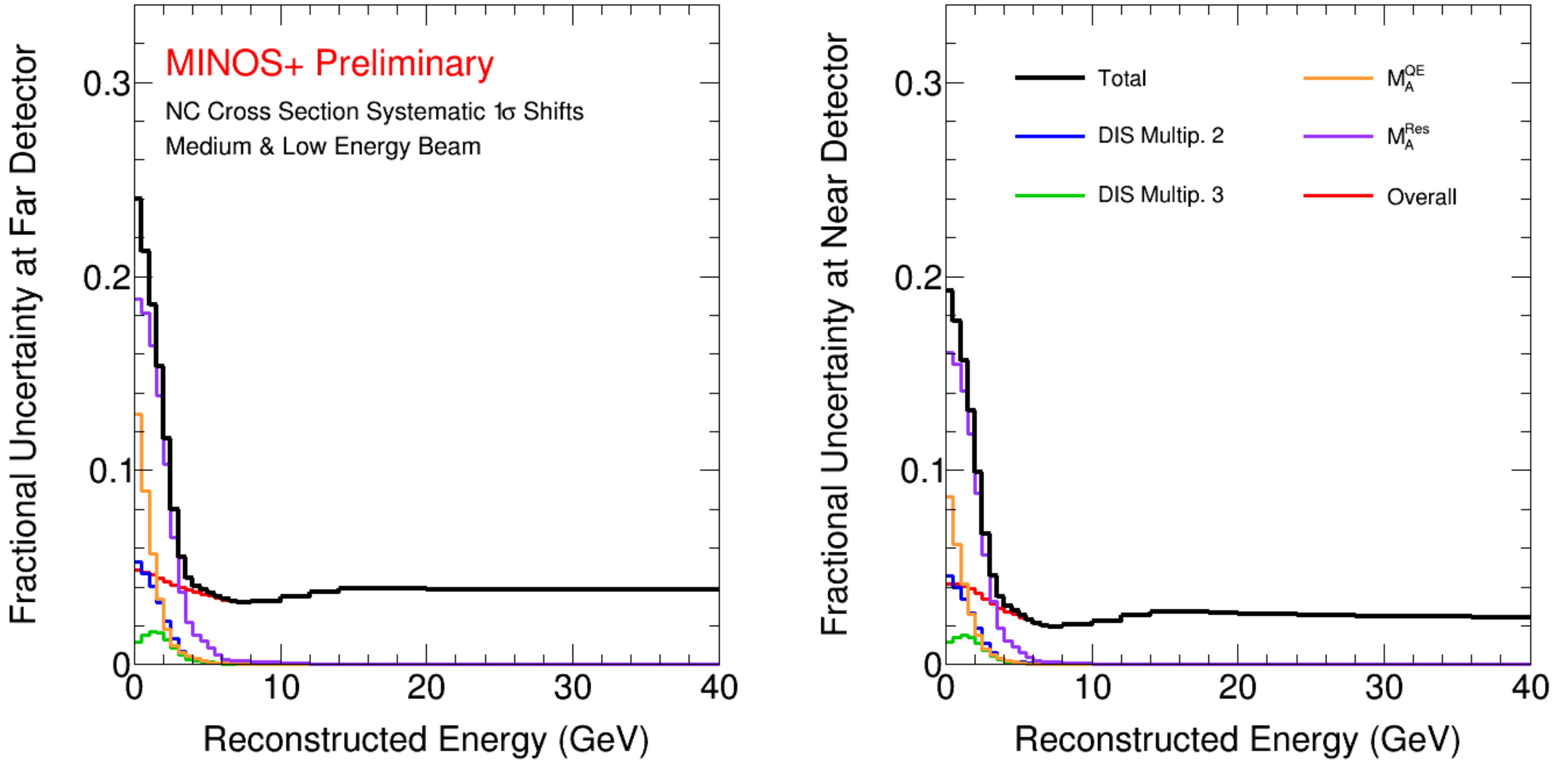
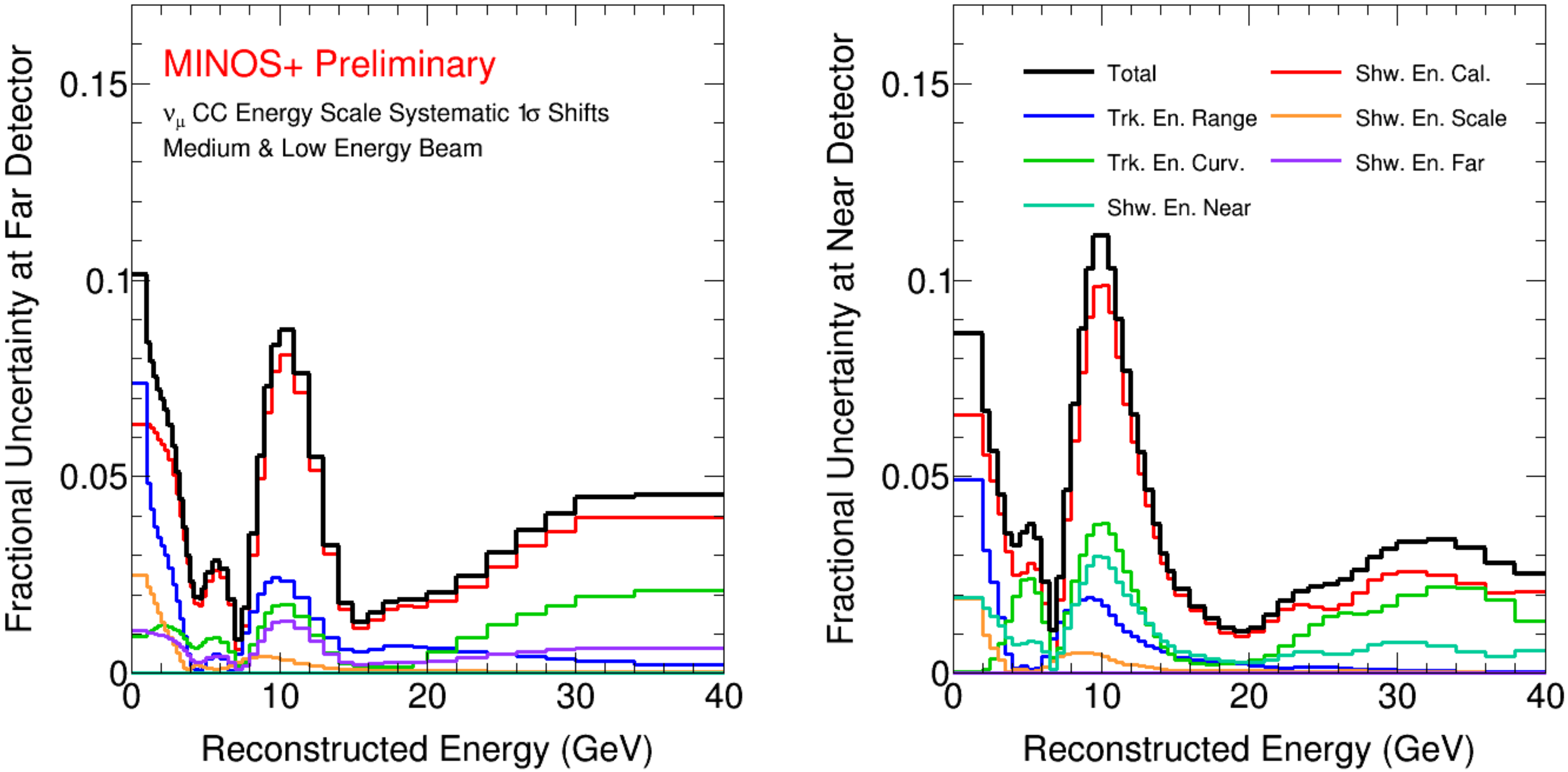
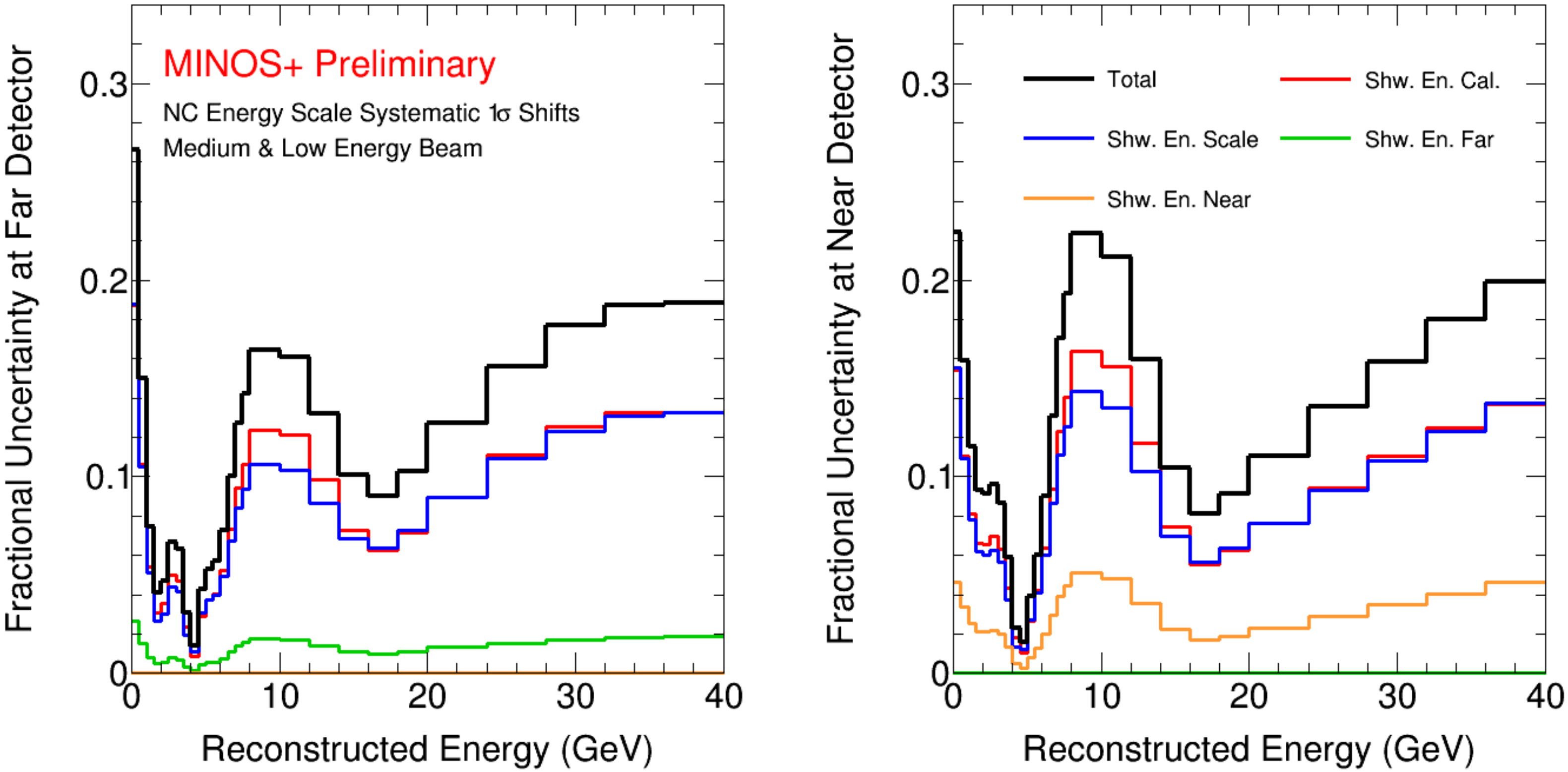


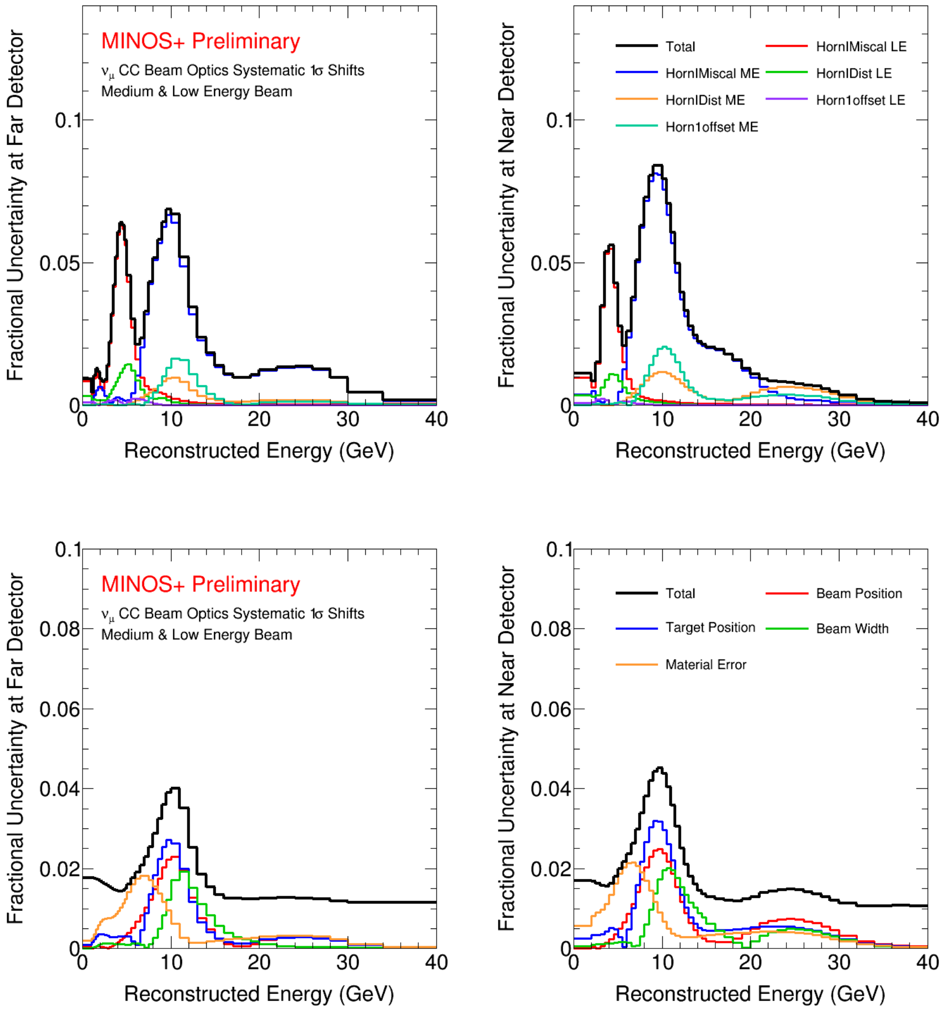
Sterile Systematics: CC Energy Scale



Sterile Systematics: NC Energy Scale



Sterile Systematics: CC Beam Optics



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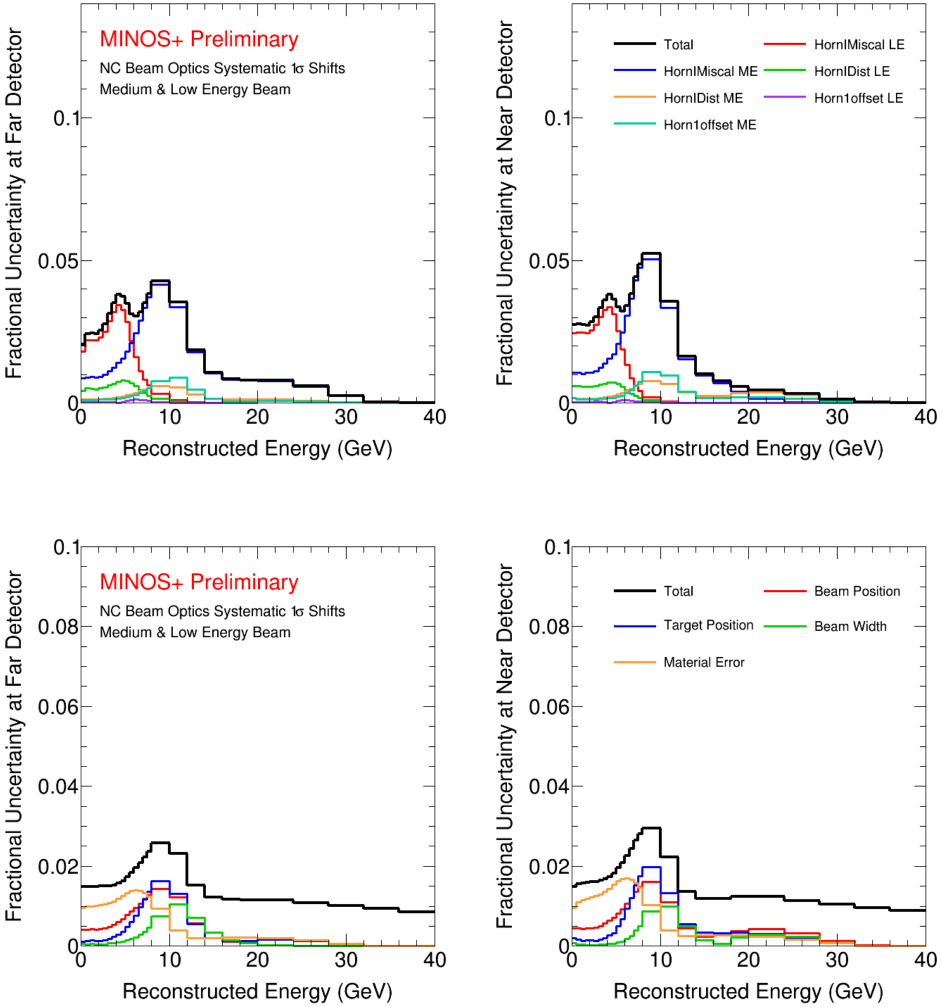

Sterile Systematics: Acceptance