Happy 50th Anniversary..!

Search For Sterile Neutrinos At The NOvA Near Detector

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For The NOvA Collaboration
New Perspectives | Fermilab
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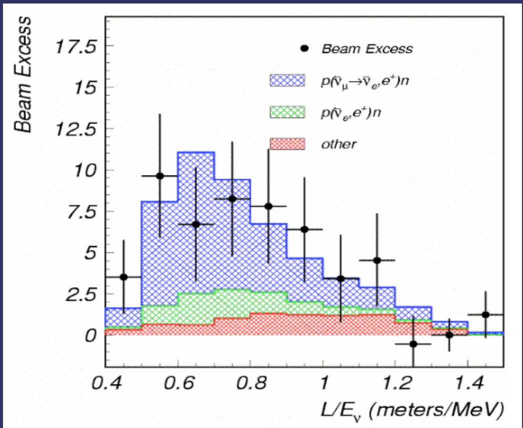
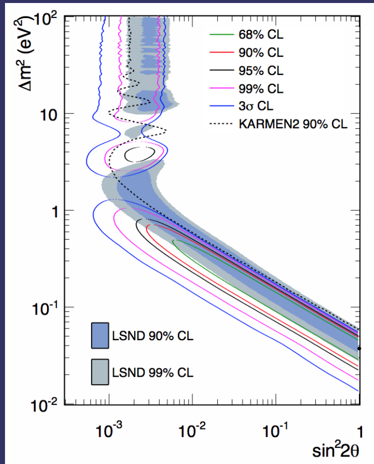
LSND/MiniBooNE Excess

- The excess can be interpreted as "Sterile Neutrinos" with $\Delta m^2 \geq 1$ eV^2.
- In the 2-flavor neutrino oscillation model, the excess can be expressed as

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L}{E}$$



A. Aguilar et al., Phys. Rev. D 64, 112007 (2001).



(3+1) Model

- For our analysis, we consider (3+1) model. The PMNS matrix is given by

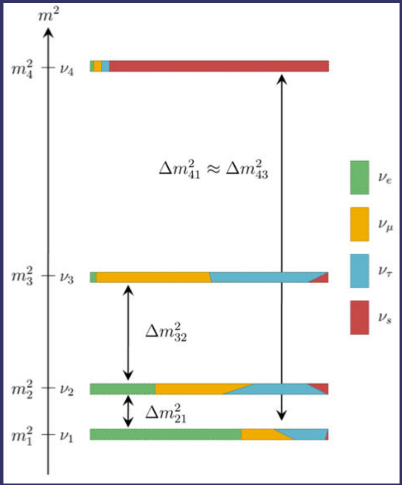
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

- ν_e Appearance Probability

$$P^{SBL,3+1}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

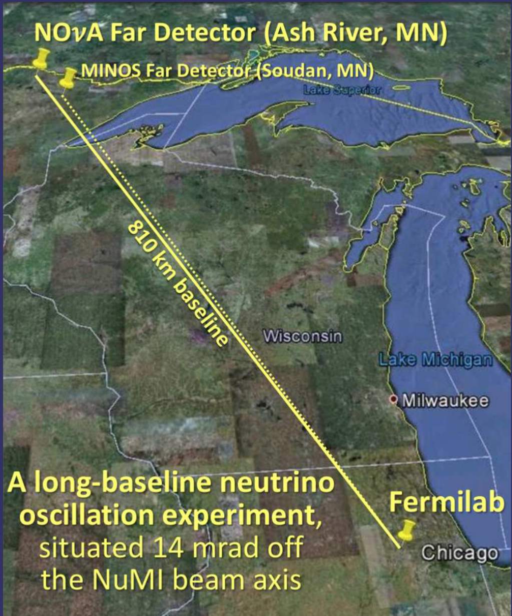
- ν_μ Disappearance Probability

$$P^{SBL,3+1}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu} = 1 - 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2) \sin^2 \frac{\Delta m^2_{41} L}{4E} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$



$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24} \text{ and } \sin^2 2\theta_{\mu\mu} = \cos^2 \theta_{14} \sin^2 \theta_{24}$$

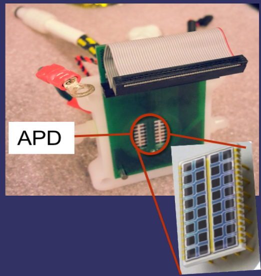
NOvA Experiment

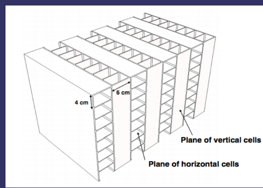


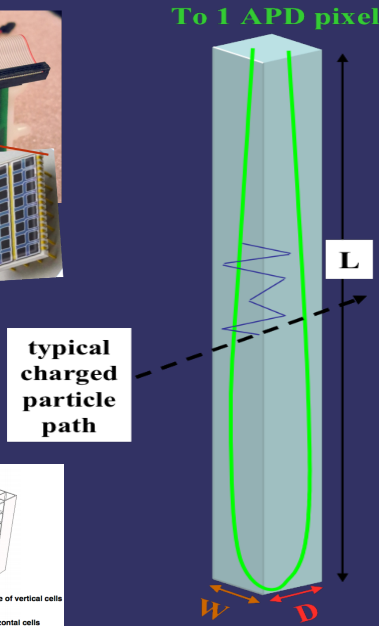
- NOvA (NuMI Off-Axis Electron Neutrino Appearance) is an accelerator based neutrino oscillation experiment.
- Near Detector
  - 1 km from source, 100 meter deep underground
  - 0.3 kton in mass.
- Far Detector
  - 810 km from Fermilab on surface.
  - 14 kton in mass.
- This analysis is done with the near detector alone.

NOvA Detectors

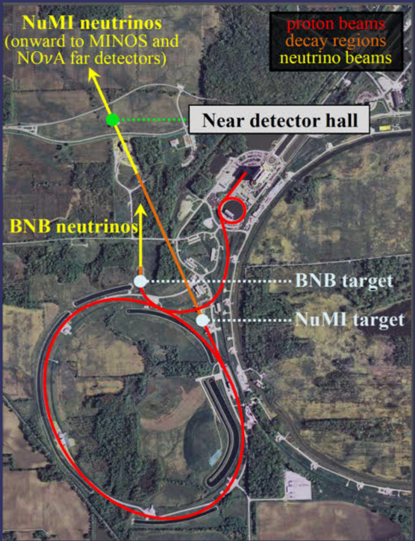
- NOvA detectors are made of plastic PVC cells which are glued together in vertical and horizontal planes.
- Each cell is filled with mineral oil based scintillator with the liquid scintillant.
- Each cell has a Wavelength Shifting Fiber inside to carry light photons to the Avalanche Photodiode read out.

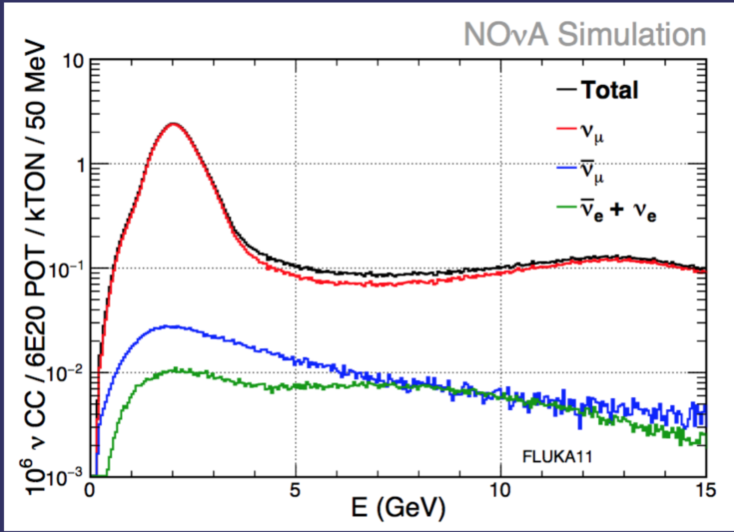






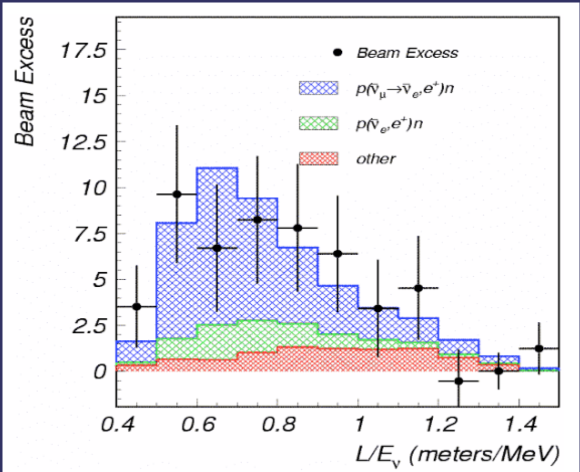
NuMI Beam in NOvA



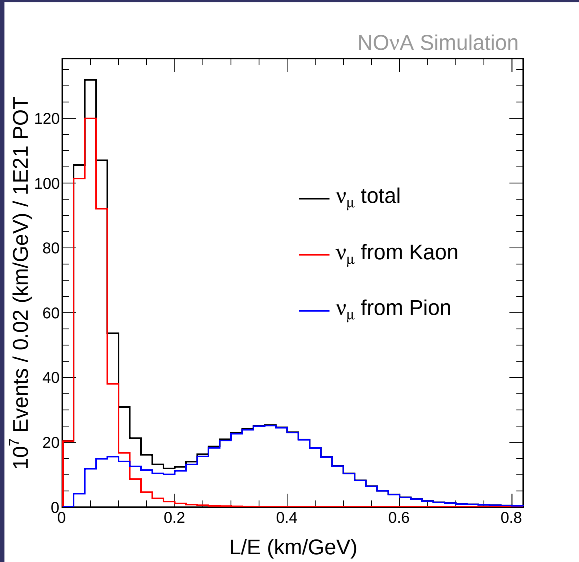


- Both detectors use the same NuMI beam which peaks at 2 GeV, at 14.6 mrad off-axis.
- NuMI beam composition: $\approx$ 98% ν_μ's and $\approx$ 2% ν_e's.
- NOvA is operating at it's designed NuMI power, 700 kW.

What NOvA Can Do?

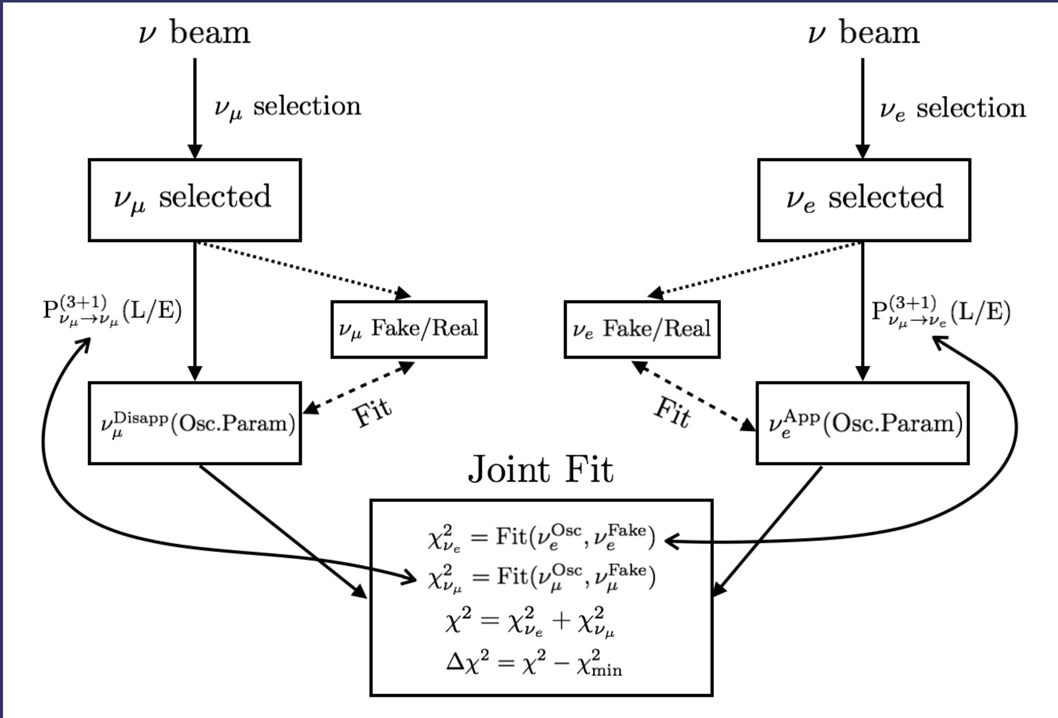


LSND excess with L/E



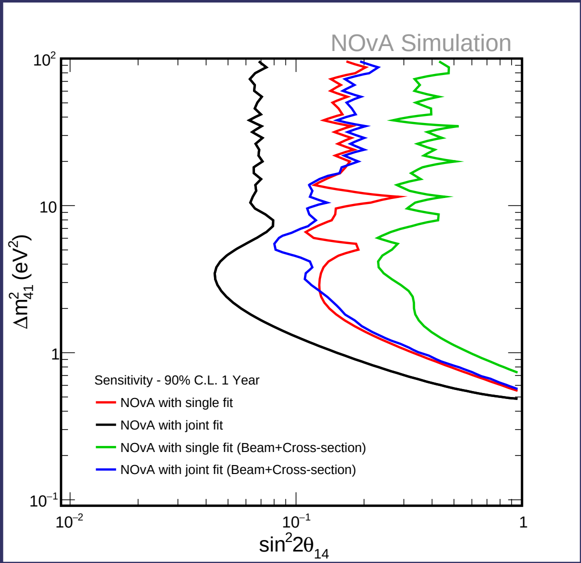
NOvA Near Detector is well placed to probe the Short-Baseline Neutrino Oscillations with $\Delta m^2 \geq 1 eV^2$.

Analysis Strategy



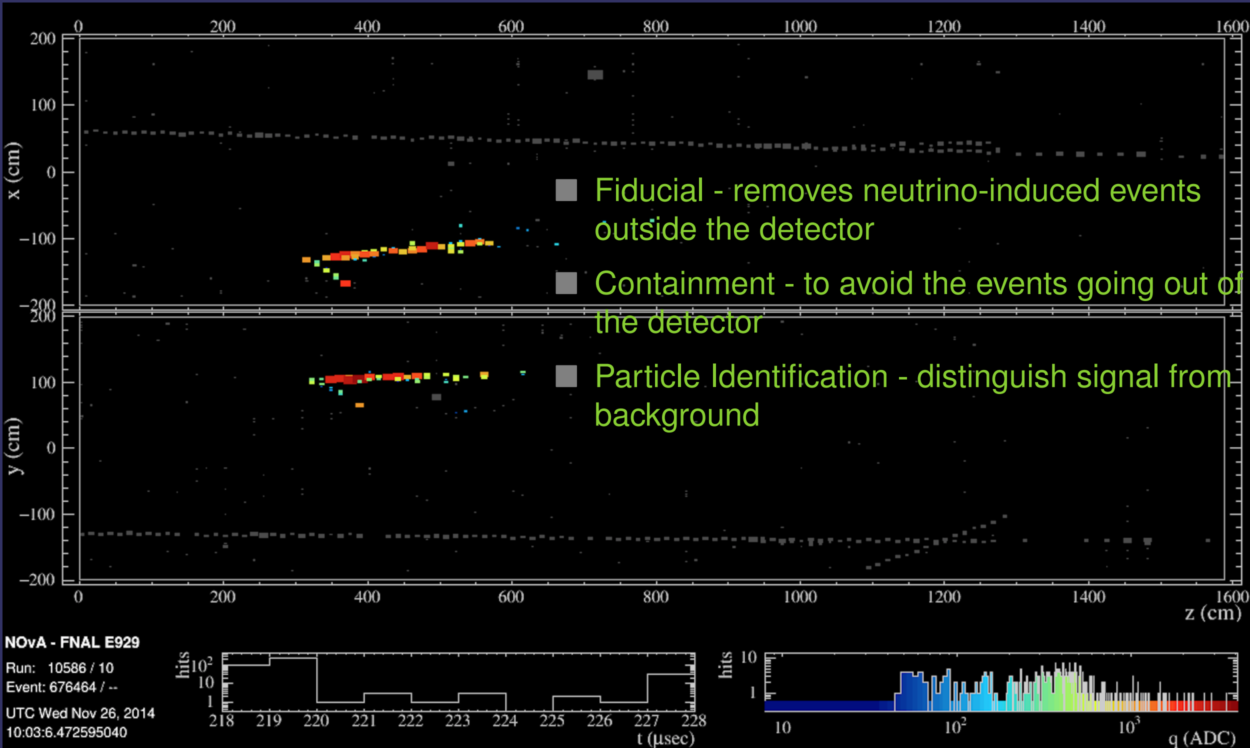
Joint Fit Method Sensitivities

- Comparison of joint fit sensitivities with the independent ν_μ and ν_e fits.
- Joint Fit allows for the partial cancellation of systematic uncertainties, significantly improving sensitivity of the analysis.



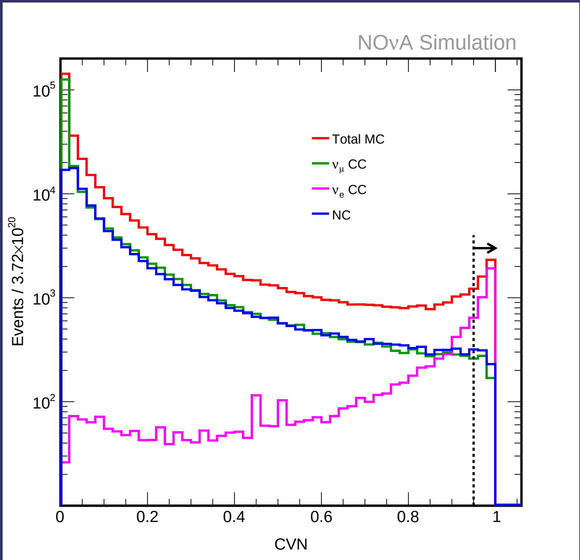
$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}.$$

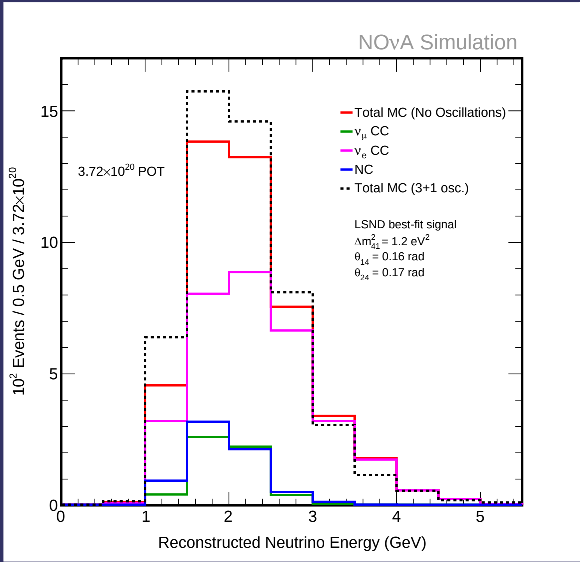
Event Selection



- Fiducial - removes neutrino-induced events outside the detector
- Containment - to avoid the events going out of the detector
- Particle Identification - distinguish signal from background

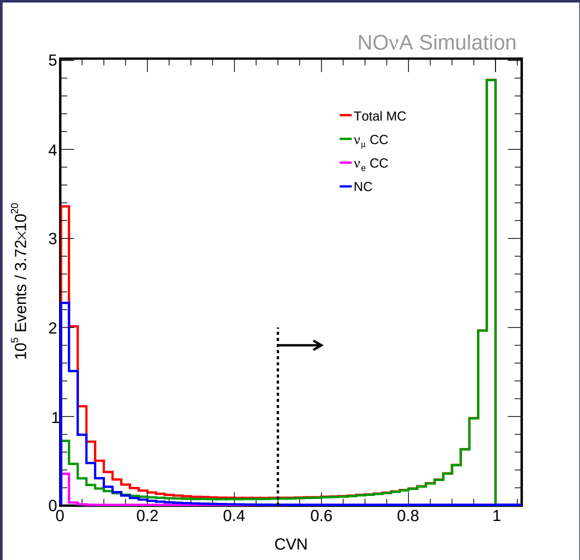
EVENT SELECTION - ν_e

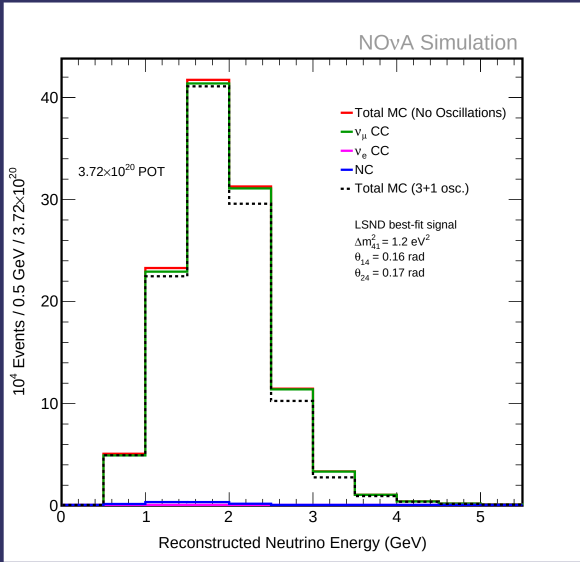




Selection efficiency of ν_e's with CVN > 0.95 is 49% and purity is 86%.

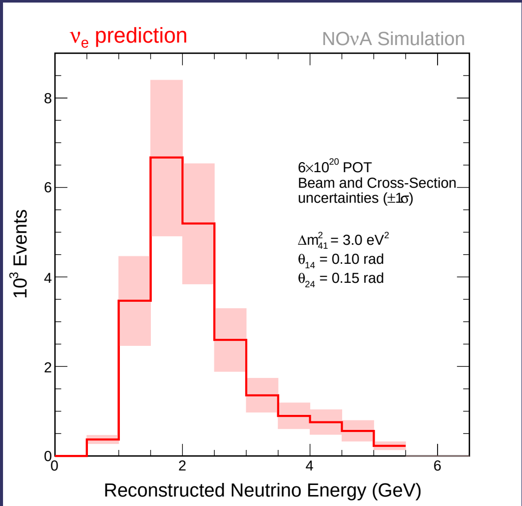
Event Selection - ν_μ

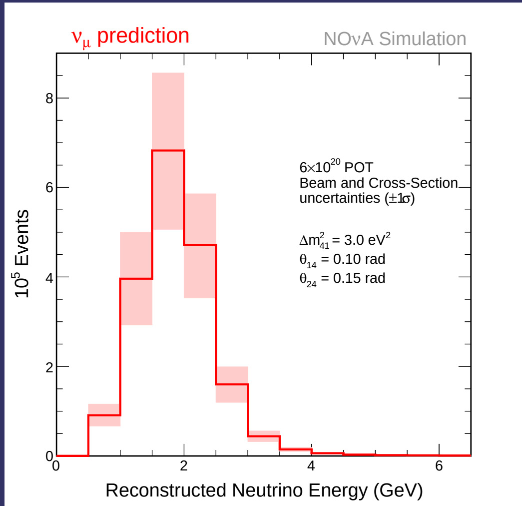




Selection efficiency of ν_μ's with CVN > 0.5 is 58% and purity is 96%.

Prediction With Systematics

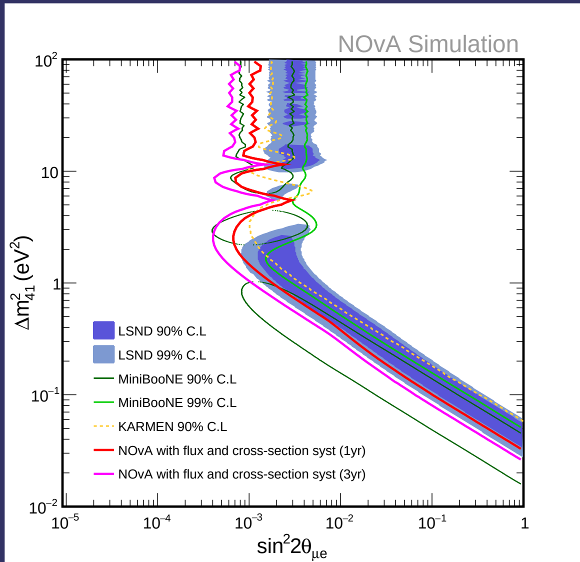




- Predictions for both ν_e (left) and ν_μ (right) after including the flux and cross-section uncertainties added in quadrature at $\pm 1\sigma$.
- Any correlated systematics will be cancelled in the joint fit, e.g cross-section systematics.

Sensitivity - $\theta_{\mu e}$

- Fitting simultaneously both ν_e and ν_μ prediction with ν_e and ν_μ selected MC spectrum with no (3+1) oscillations.
- Fit for $\theta_{\mu e}$, profiling θ_{14}, θ_{24} and θ_{34}, and keeping all other parameters fixed.
- Included flux and cross-section uncertainty into the fit.



$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}.$$

Summary

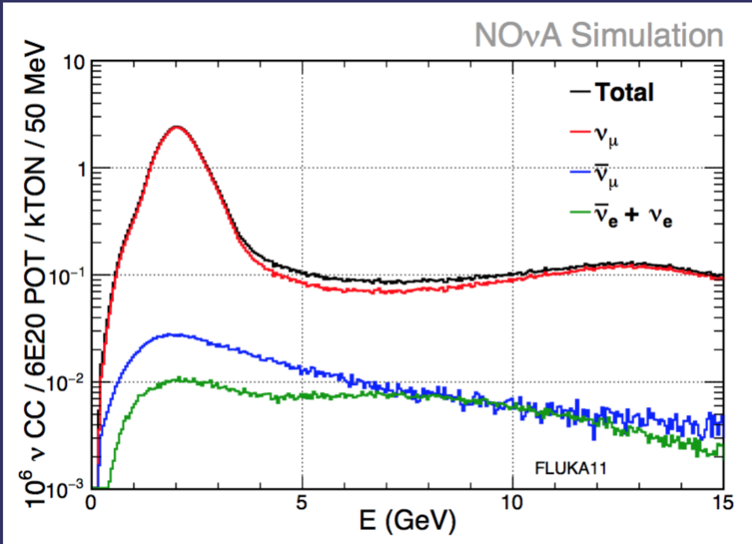
- NOvA is well positioned to search for the sterile neutrinos with $\Delta m^2 \geq 1$ eV^2 at its baseline with the NuMI beam.
- Joint fit provides significant improvement in sensitivities over the individual fits.
- Current NOvA sensitivities are competitive with the on-going and future experiments like Short-Baseline Near Detector program at Fermilab etc.
- Stay tuned for the exciting results.

Thank You

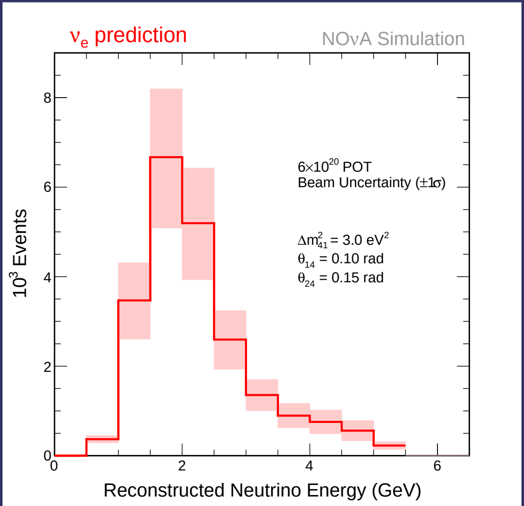

www-nova.fnal.gov

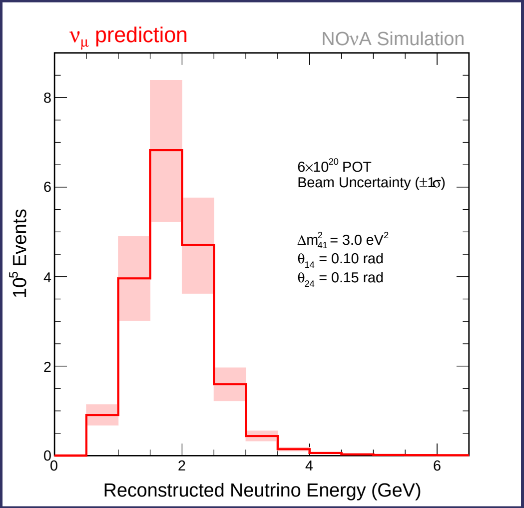
BACKUP

NuMI Beam Composition - FHC

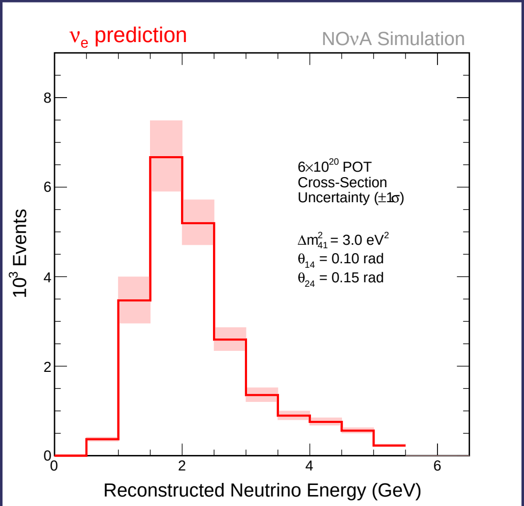


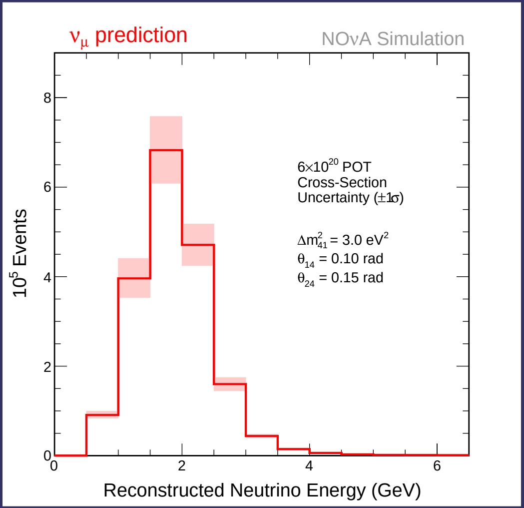
Prediction With Flux Systematics



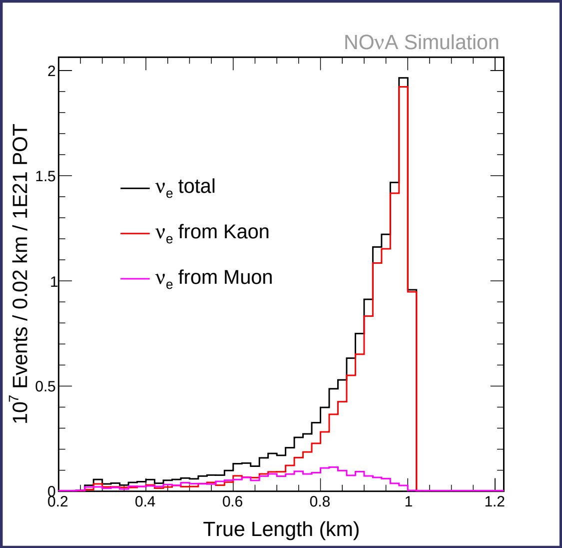


Prediction With Cross-section Systematics

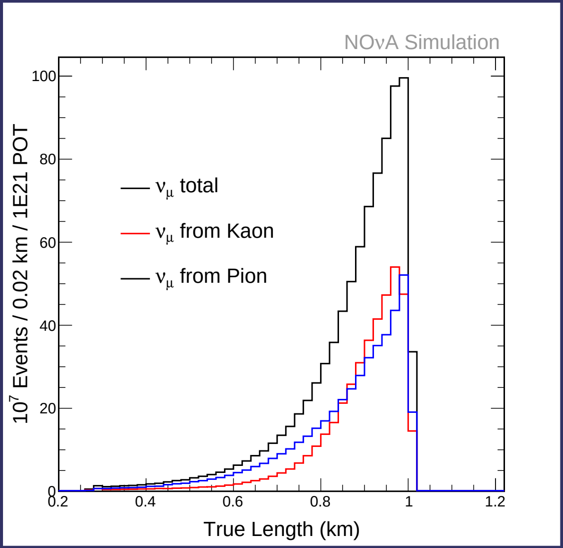




TRUE LENGTH

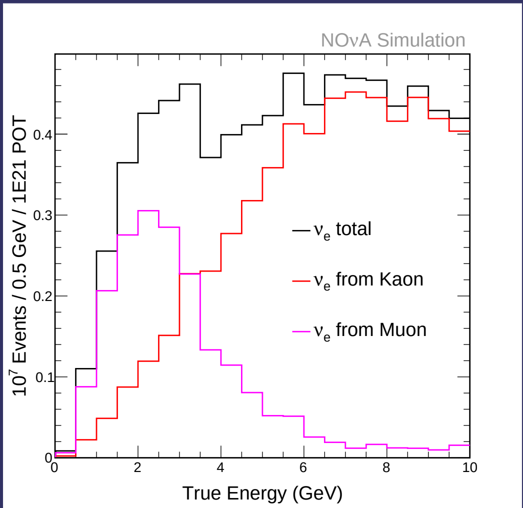


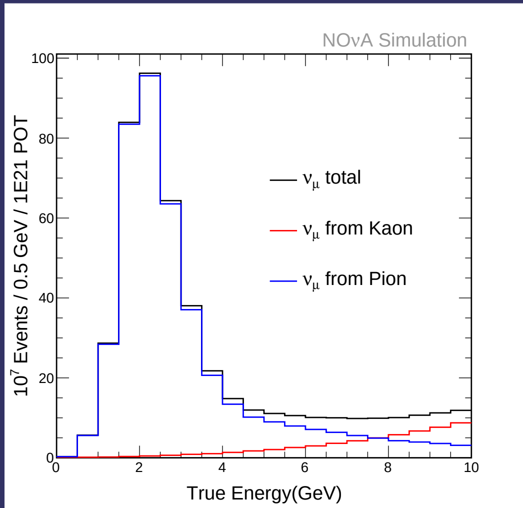
NOvA Simulation
10^7 Events / 0.02 km / 1E21 POT
ν_e total
ν_e from Kaon
ν_e from Muon
True Length (km)
0
0.5
1
1.5
2
0.2
0.4
0.6
0.8
1
1.2



NOvA Simulation
10^7 Events / 0.02 km / 1E21 POT
ν_μ total
ν_μ from Kaon
ν_μ from Pion
True Length (km)
0
20
40
60
80
100
0.2
0.4
0.6
0.8
1
1.2

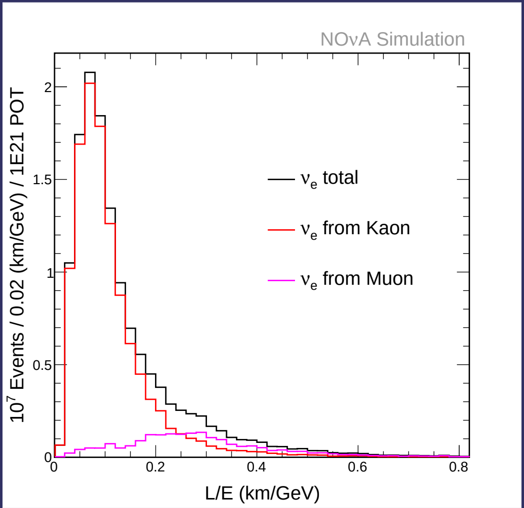
True Energy

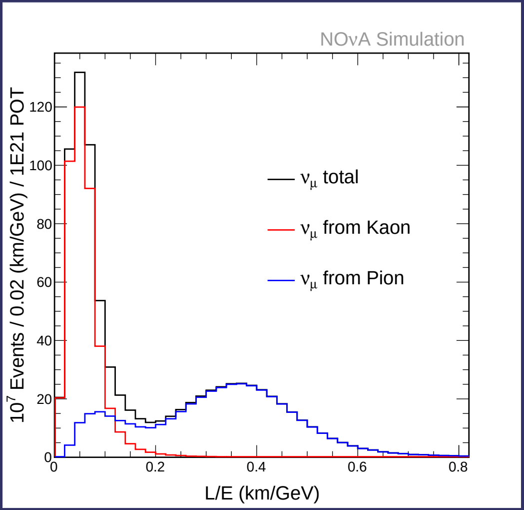




- Distribution of true energy of neutrinos break down by their parents in the near detector.

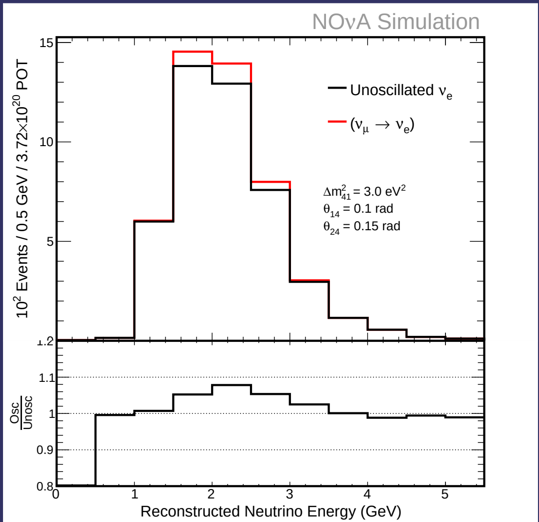
True Length Over True Energy

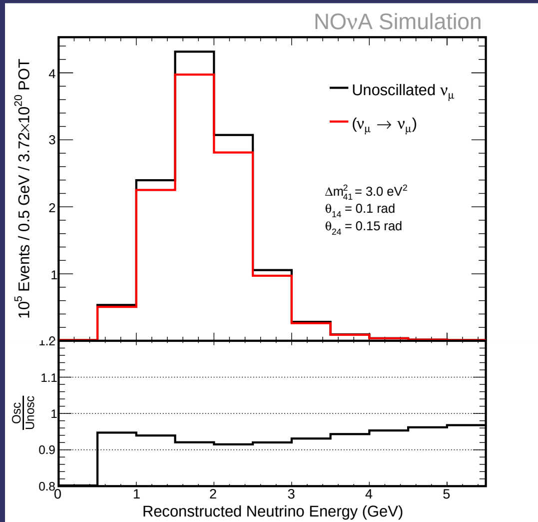




- Distribution of true length over true energy of neutrinos break down by their parents in the near detector.

Signal Prediction





- Predictions, Left: ν_e prediction and Right: ν_μ prediction, after applying the ν_e and ν_μ selection respectively, for the oscillation parameters Δm^2_{41} = 3.0 eV^2 ; θ_{14} = 0.1(rad) ; θ_{24} = 0.15(rad).

Selection

ν_e selection

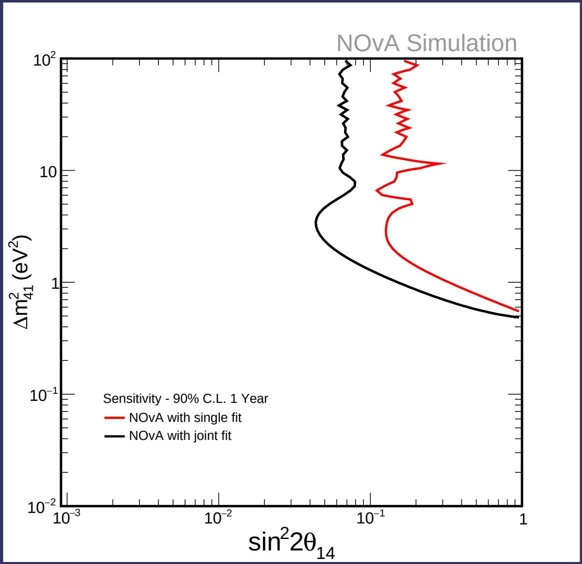
- DQ: flasher cut (hits per plane <= 8)
- Reco: each slice has a vertex and 1 3D FuzzyK prong and one shower
- Vertex containment: abs(vX)<140, abs(vY)$<$140, 100$<$vZ$<$700
- Energy: Slice calorimetric energy $<$ 5 GeV
- Loose containment and nplanestofront $>$ 6
- Hits: 20 < nhits < 200
- Length: 140 < longest fuzzyk prong < 500 cm
- Gap: Shower start to vertex gap $<$ 100 cm
- LID > 0.95

ν_μ selection

- kNumuQuality
- kNumuContainND
- kNumuNCRej (ReMID > 0.75)

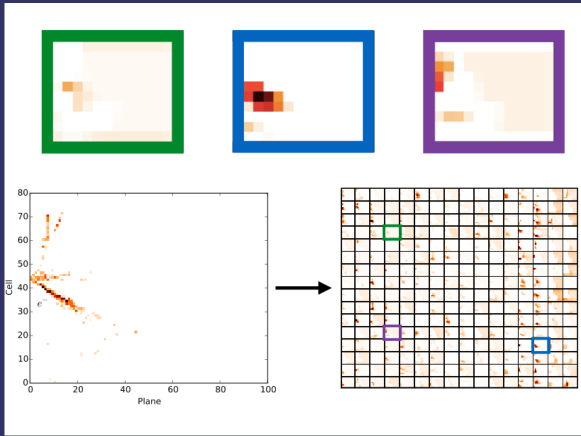
$\sin^2 2\theta_{14}$ Vs Δm^2_{41}

- Single Fit: Performed fit for only ν_e appearance.
- Joint Fit: Performed fit for both ν_e appearance and ν_μ disappearance.
- Fitting ν_e/ν_μ prediction with ν_e/ν_μ selected MC spectrum with no (3+1) oscillations.
- Fit for θ_{14}, profiling θ_{24}, and keeping all parameters fixed.
- No systematics included.



Convolutional Visual Network

- This analysis is based on using the new algorithm for particle identification, Convolutional Visual Network.
- Based on machine learning and deep learning methods.
- No other information is needed except initial hit clustering and energy deposited in hits.
- All interactions with at least 15 hits are used for training.
- CVN achieves the figure of merit equivalent to collecting 30% more exposure



A. Aurisano et al., arXiv:1604.01444.

Cut Flow Table

Selection	Total MC	ν_μ	ν_e	NC
No Cut	2.749e+08	2.279e+08	4.062e+06	4.289e+07
Data Quality	3.812e+07	3.366e+07	4.339e+05	4.029e+06
Fiducial	2.703e+06	1.998e+06	5.393e+04	6.516e+05
Containment	7.801e+05	4.525e+05	2.012e+04	3.075e+05
FrontPlanes	7.764e+05	4.505e+05	2.001e+04	3.059e+05
# Hits	7.242e+05	4.354e+05	1.654e+04	2.723e+05
Energy	7.213e+05	4.353e+05	1.469e+04	2.714e+05
ProngLength	5.96e+05	3.862e+05	1.406e+04	1.958e+05
Ptp	5.163e+05	3.412e+05	1.337e+04	1.617e+05
CVN > 0.95	7242	944.1	5171	1127

For ν_e for 6e+20 POT.

Selection	Total MC	ν_μ	ν_e	NC
No Cut	2.749e+08	2.279e+08	4.062e+06	4.289e+07
Data Quality	6.81e+07	6.212e+07	5.978e+05	5.382e+06
Containment	3.565e+06	2.484e+06	5.777e+04	1.022e+06
CVN > 0.5	1.908e+06	1.889e+06	365.4	1.894e+04

For ν_e for 6e+20 POT.

Joint Fit Method

- The formalism to combine several measurements by performing a joint maximum-likelihood fit of different datasets. This analysis is done using log-likelihoods.

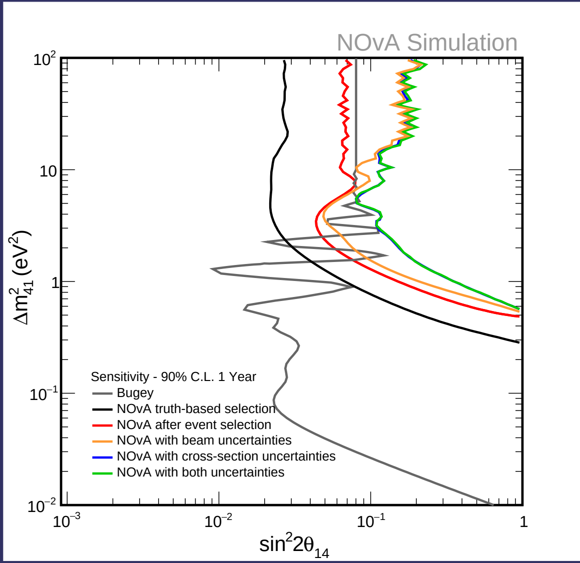
$$\mathcal{L}_{\text{Joint}} = \mathcal{L}_A + \mathcal{L}_B$$

  where $\mathcal{L}$ is Log-likelihood. A and B are datasets.

- Combine ν_μ disappearance and ν_e appearance performing a joint fit for the datasets after applying ν_μ and ν_e selection.

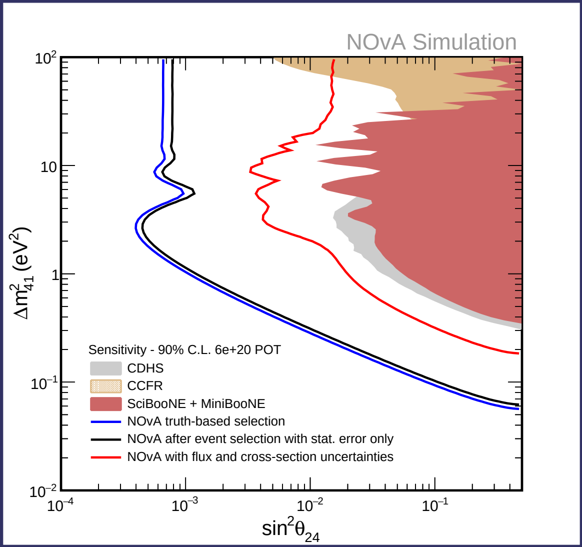
Sensitivity - θ_{14}

- Fitting ν_e/ν_μ prediction with ν_e/ν_μ selected MC spectrum with no (3+1) oscillations.
- Fit for θ_{14}, profiling θ_{24}, and keeping all parameters fixed.
- Included flux and cross-section uncertainty.
- With the improved selection and understanding of systematics, improves the sensitivity in a better way.



Sensitivity - θ_{24}

- Fitting ν_e/ν_μ prediction with ν_e/ν_μ selected MC spectrum with no (3+1) oscillations.
- Fit for θ_{14}, profiling θ_{24}, and keeping all parameters fixed.
- Included flux and cross-section uncertainty.
- With the improved selection and understanding of systematics, improves the sensitivity in a better way.



Sensitivity - $\theta_{\mu e}$

- Fitting simultaneously both ν_e and ν_μ prediction with ν_e and ν_μ selected MC spectrum with no (3+1) oscillations.
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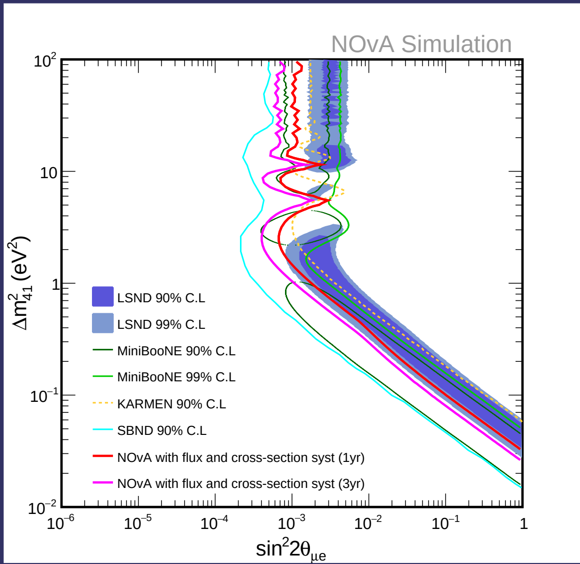

$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}.$$