Search for Sterile Neutrino at NOvA Experiment

Shivam, Bipul Bhuyan

Indian Institute of Technology Guwahati
India

December 14, 2022

XXV DAE-BRNS HEP Symposium

Outline

- Introduction:: NOvA Experiment
- Sterile Neutrino
- Analysis Strategy
- Results
- Future Work

NOvA Experiment

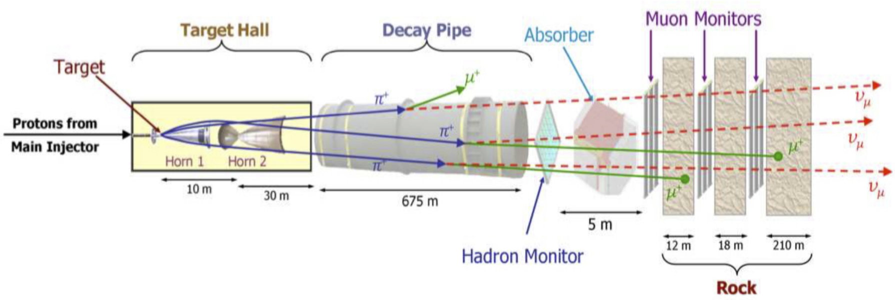
The NOvA(NuMI Off-axis ν_e Appearance) experiment was set up to understand the most mysterious particles neutrinos with the aim of::

- Whether $\nu_\mu \rightarrow \nu_e$ oscillation happens?
- What is Neutrino Mass Hierarchy?
- Why matter dominates antimatter?

NOvA uses an intense beam of muon neutrinos to look for the possibility of $\nu_\mu \rightarrow \nu_e$ oscillation.

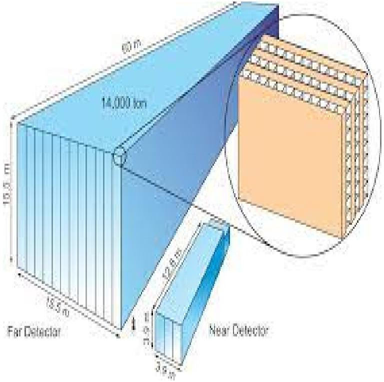
- Overall, NOvA consists of three main components:: NuMI beam, Near, and Far detector.

NOvA Experiment



- Schematic diagram of NuMI (**N**eutrino at **M**ain **I**njector) beam.
- Protons of energy 120GeV are allowed to hit on the graphite, which produces hadrons, including pions and kaons.
- These pions are then allowed to pass through the decay tunnel where they decay to produce muon and muon neutrino.
- Later, muon gets absorbed by the shields, and neutrinos will pass, giving a highly intense neutrino beam.

NOvA Experiment

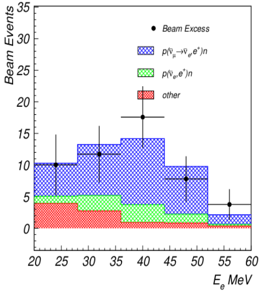


- The two detectors are functionally identical except the Far Detector(FD) is much larger than the near(ND) one.
- Each detector consists of horizontal and vertical planes giving it the form of cells filled with scintillating material.
- The detectors are 14*mrad* off-axis in order to get the correct flux required for the maximum oscillation probability for this baseline.

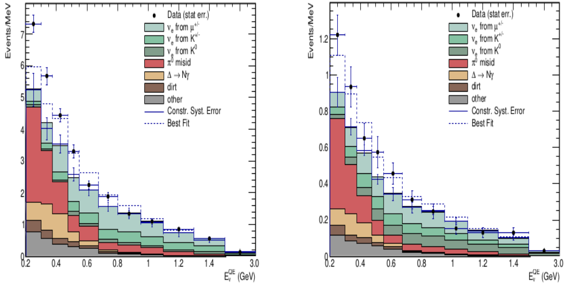
$$F = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi L^2} \quad (1)$$

$$E_\nu = \frac{E_h}{1+\gamma^2\theta^2}\left(1 - \frac{m_\mu^2}{m_h^2}\right) \quad (2)$$

Sterile Neutrino



(a) LSND Result



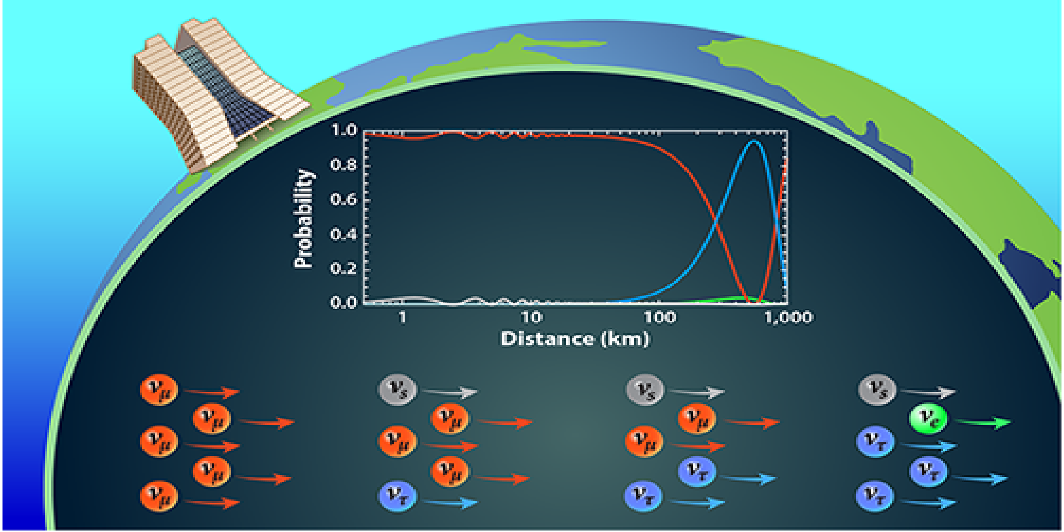
(b) MiniBooNE Result

- LSND results observed a 3σ excess over the estimated background.
- Similarly, MiniBooNE also observed a 4.7σ excess for neutrino mode and 4.8σ excess for combined mode(neutrino and antineutrino).

Sterile Neutrino

- One possible solution to solve the above experimental anomalies is to include an extra flavor of neutrinos, making it four in total.
- But the W and Z decay width doesn't allow an extra neutrino flavor suggesting that the extra new flavor is completely non-interacting with the known standard model interactions.
- No interaction suggests zero electric charges, zero hypercharges, and zero color charge.
- Neutral Current(NC) interaction will be used to study the active-sterile neutrino oscillation because the neutral current events are not affected by three-flavor oscillation.
- So, we will count an overall number of neutral current events and look for any deficit or excess.

Sterile Neutrino



Sterile Neutrino

- Addition of extra neutrino flavor includes an extra mass eigenstate and an extra dimension to the PMNS matrix. The fourth flavor state (sterile neutrino state) can be expressed as the linear combination of four mass eigenstates such that

$$|\nu_s\rangle = \sum_{i=1}^{4} U_{si}^{*}|\nu_i\rangle \tag{3}$$

- Furthermore, under the long baseline approximation, to be used in NOvA, the disappearance oscillation probability will be given by

$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \frac{1}{2}\cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24} + \tag{4}$$

$$A\sin^2\Delta_{31} - B\sin 2\Delta_{31} \tag{5}$$

- $\Delta_{31} = \frac{\Delta m_{31}^2 L}{4E}$, and the factor of $1/2$ results from the rapid oscillations driven by Δm_{41}^2.

Analysis Strategy

Selection Criteria

- The basic selection criteria are almost identical for both detectors, including **preselection**, **event quality**, **containment**, and **CVN**(Convolutional Visual Network).
- Apart from these, **Vertex cuts** are applied only to ND, while these cuts are a part of FD selection.
- In addition to all these, **BDT**(Boosted Decision Tree) cut is also applied to FD to reject the cosmic background because FD is on the surface, which is highly exposed to cosmic rays.
- Since the NC events have been characterized by shower only, for BDT training, shower information variables have been used.

Analysis Strategy

- CVN score is usually applied to select a particular type of interaction (CC or NC).
- No BDT cut is required in the ND as it is underground, and we assume no cosmic interactions.
- A joint fit approach b/w ND and FD is used to determine these values simultaneously by maximizing the FOM.
- For this, the fractional covariance matrix is used

$$F_{ij} = \frac{C_{ij}}{N_i \times N_j}$$

Analysis Strategy

- For each combination of ND CVN, FD CVN, and FD BDT, separate ND and FD spectra are produced. These are then concatenated into a single spectrum.
- Using the Fractional Covariance matrix and concatenated spectrum, the total covariance matrix is determined.
- Using simulated cosmic spectra and total systematic uncertainties in each bin, a FOM is calculated across the two detectors::

$$FOM = \frac{1}{N} \sum_{i}^{N} \frac{S_i}{\sqrt{S_i + B_i + \sigma_i^2}} \tag{6}$$

- This FOM is drawn as a func. of ND and FD for selected values of BDT score. The projected FOM vs each of these three variables gives the optimum cut value.

Event Display

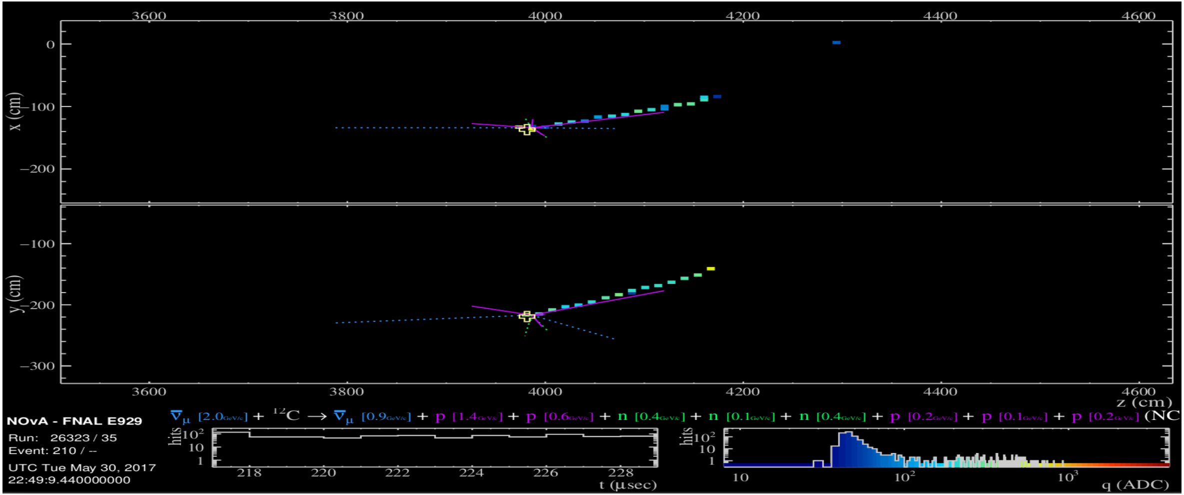


Figure: Event Display for true NC Signal Event

Event Display

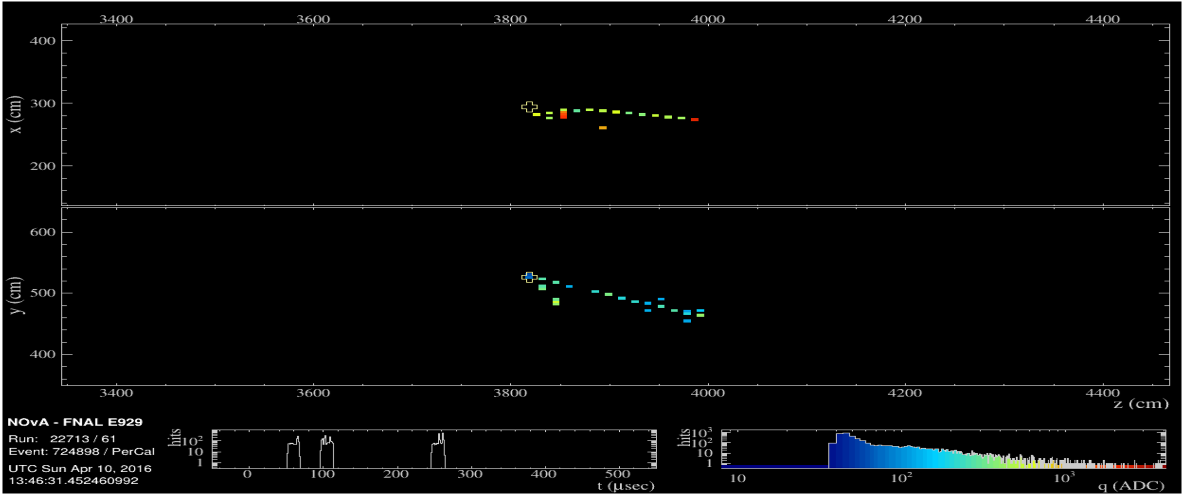
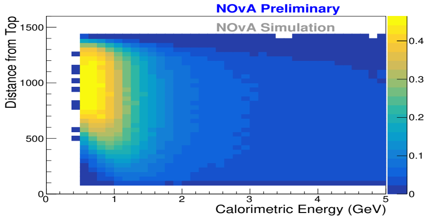
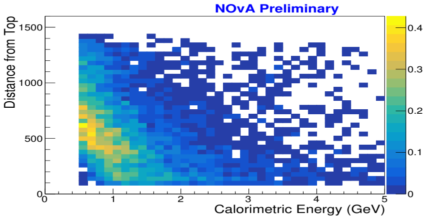


Figure: Event Display for Cosmic Event

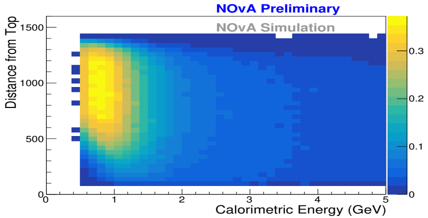
Results



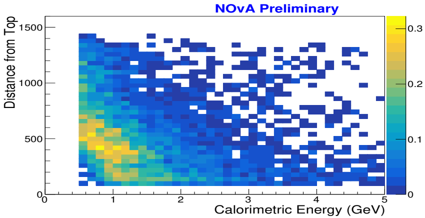
(a) True MC without extra cut



(b) Cosmic without extra cut

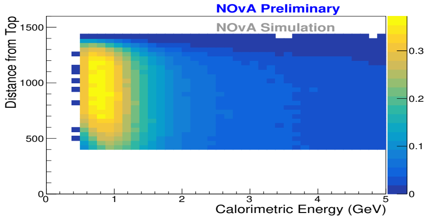


(c) MC with Cut 1

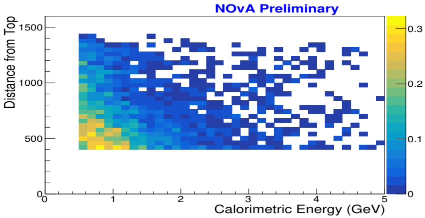


(d) Cosmic with cut 1

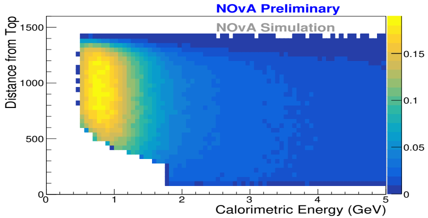
Results



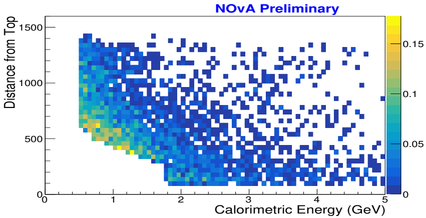
(a) MC with Cut 2



(b) Cosmic with cut 2



(c) MC with 2D Cut



(d) Cosmic with 2D Cut

Results

- Cut 1 :: kTrkCalEPerNHit > 0.01
- Cut 2 :: kTrkCalEPerNHit > 0.01 & kDistAllTop > 400

Events	No Cut	Cut 1	Cut 2
Total events	203.838	186.754	141.73
True NC Signal(%)	126.428 (62.02)	118.444 (63.42)	98.0755 (69.20)
MC Bkg (%)	24.1604 (11.85)	23.7928 (12.74)	18.2318 (12.86)
Cosmic Bkg (%)	53.2498 (26.12)	44.5174 (23.84)	25.4224 (17.94)

Table: Effect of Cuts on Signal Selection and Cosmic Rejection (POT Normalised)

Results::2D Cuts

- Distance≥600 && $0.5 \leq$ Energy ≤ 0.6
- Distance≥560 && $0.6 \leq$ Energy ≤ 0.7
- Distance≥480 && $0.7 \leq$ Energy ≤ 0.9
- Distance≥440 && $0.9 \leq$ Energy ≤ 1.0
- Distance≥400 && $1.0 \leq$ Energy ≤ 1.2
- Distance≥360 && $1.2 \leq$ Energy ≤ 1.4
- Distance≥320 && $1.4 \leq$ Energy ≤ 1.6
- Distance≥280 && $1.6 \leq$ Energy ≤ 1.8
- Distance>100 && Energy ≥ 1.8

Events	No Cut (%)	2D Cut (%)
Total Events	203.838	164.579
NC Signal	126.428 (62.01)	110.771 (67.31)
MC Bkg	24.1604 (11.85)	22.817 (13.86)
Cosmic	53.2498 (26.12)	30.9911 (18.83)

Table: Effect of 2D Cut on events

Results

Events	Total Events	NC Signal(%)	MC Bkg (%)	Cosmic (%)
FHC	520.0	344.7(**66.29**)	75.7(14.56)	99.6 (**19.15**)
No Cut(RHC)	203.838	126.428(62.02)	24.1604(11.85)	53.2498(26.12)
Cut 1	186.754	118.444 (**63.42**)	23.7928 (12.74)	44.5174 (**23.84**)
Cut 2	141.73	98.0755 (**69.20**)	18.2318 (12.86)	25.4224 (**17.94**)
2D Cut + Cut 1	164.579	110.771 (**67.31**)	22.817 (13.86)	30.9911 (**18.83**)

Table: Statistics to compare with previous FHC(Forward Horn Current) results.

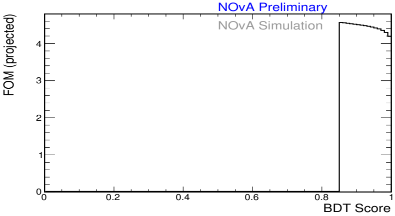
- We have seen that there is an improvement in the signal purity and cosmic rejection using the three sets of cuts independently.
- Cut 2 looks to give the highest purity but it also leaves less number of signal events so we decided to stay with the 2D cut.

Future Work

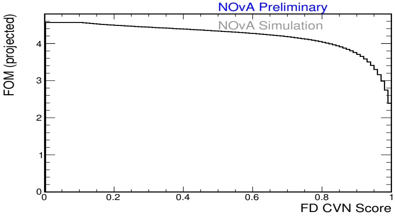
- This is a preliminary study showing the positive effect of the new 2D Cut on the NC event selection.
- We will be looking forward to the effect of these extra cuts on the sensitivity and systematic studies.
- We will finally calculate the oscillation parameters, including $\theta_{24}, \theta_{34}, \Delta m^2_{41}$.
- In addition to this, we have also been planning to use a joint high and low purity covariance approach which gives us the liberty to make use of the maximum available neutral current events.

Backup Slides

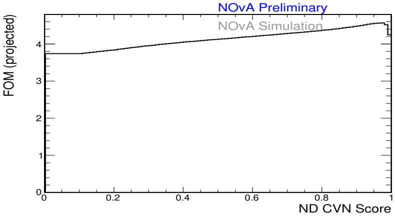
FOM Distributions



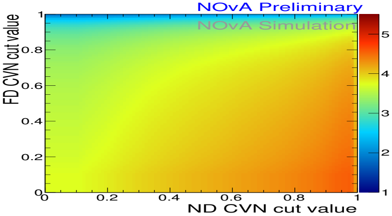
(a) BDT Projection



(b) Projection of FD CVN value



(c) Projection of ND CVN value



(d) FOM distribution with ND FD CVN

FOM Statistics

- Using the approach mentioned above, the CVN value of 0.97 for ND, 0.1 for FD, and BDT value of 0.85 will maximize the FOM to give a value of 4.28228.

Cuts	All Events	True NC Events	MC Backgrounds	Cosmic
PreSelection	50600.8	322.94(0.64%)	96.3436(0.19%)	50181.5(99.17%)
Quality	50253.5	322.328(0.64%)	96.3102(0.19%)	49834.8(99.17%)
Fiducial	6321.06	185.075(2.93%)	29.0584(0.46%)	6106.93(0.46%)
All Cuts	203.838	126.428(62.02%)	24.1604(11.85%)	53.2498(26.12%)

Table: NC events for Far Detector for cosrej BDT=0.85 and FD CVN=0.1 value.

- From the above table, we can see that the present cuts applied for FHC analysis are not sufficient for RHC analysis because even after applying a tight BDT cut of 0.85, there is still $\sim$ 26% cosmic events which is large number.
- So the first task is to look out for any other variable that can be used for cosmic rejection.

Results

Events	Total Events	NC Signal(%)	MC Bkg (%)	Cosmic (%)
No Cut(RHC)	203.838	126.428	24.1604	53.2498
Cut 1	186.754	118.444 (**93.68**)	23.7928 (98.48)	44.5174 (**83.60**)
Cut 2	141.73	98.0755 (**77.57**)	18.2318 (75.46)	25.4224 (**47.74**)
2D Cut + Cut 1	164.579	110.771 (**87.62**)	22.817 (94.44)	30.9911 (**58.20**)

Table: Statistics to compare with previous FHC results (Retained events)

- We have seen that there is an improvement in the signal purity and cosmic rejection using the three sets of cuts independently.
- Cut 2 looks to give the highest purity but it also leaves less number of signal events so we decided to stay with the 2D cut.

References

- Modern Particle Physics, Mark Thomson.
- Standard Model https://texample.net/media/tikz/examples/PDF/model-physics.pdf
- Searching for Light Sterile Neutrinos with NOvA Through Neutral-Current Disappearance https://novaexperiment.fnal.gov/theses/
- A. Aurisano *et.al*., JINST **11**, P09001(2016).
- Results and Prospects from NOvA, arXiv:1812.09585
- https://targets.fnal.gov/NuMI_neutrino_beam.html
- Pierre Baldi *et.al*. Phys. Rev. D **99**, 012011 (2019).
- https://indico.cern.ch/event/677667/contributions/2999601/attachments/1662374/2663786/1_cremonesi.pdf
- A. Lister and H. Hausner, NOvA Technote on Event Selection (2020).