Long-baseline Sterile Neutrino Searches in the NOvA Experiment

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Outline

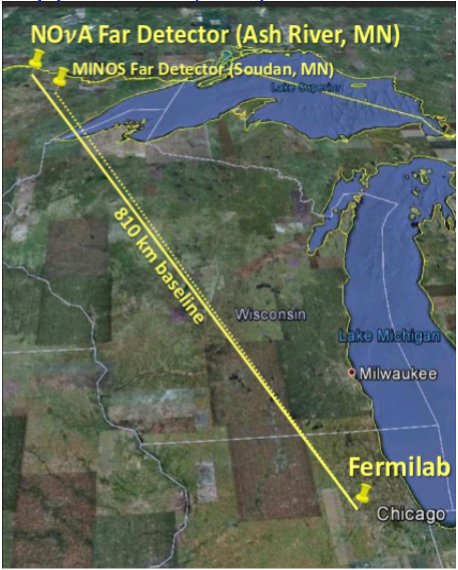
1. Research Outline
2. π^0 mass reconstruction
3. Long-baseline sterile neutrino search in the NOvA experiment

Introduction: Research highlights

- I have been collaborating with the NOvA Experiment at Fermilab, USA since 2015.
- Worked in the NOvA's calibration group and introduced a new method to cross-check the absolute calibration of the Far Detector (FD).
- Led NOvA's long-baseline sterile neutrino searches using neutrino beam and played a leading role in the antineutrino beam analysis.

The NOvA (NuMI Off-axis ν_e Appearance) Experiment

- A long-baseline neutrino experiment.
- Two functionally identical detectors- **Near Detector** at Fermilab and **Far Detector**, at Ash river, Minnesota.
- The detectors lie **14.6 mrad. off** from the Fermilab's NuMI (Neutrino at Main Injector) ν_μ **beam axis**, which provides a narrow-band beam **peaked at 2 GeV**



Outline

π^0 mass reconstruction

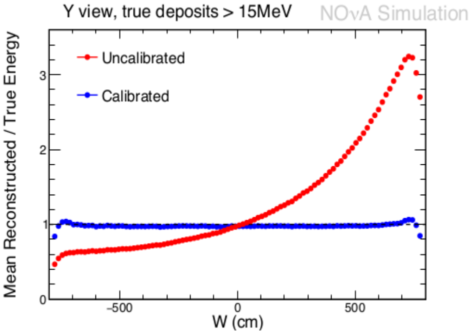
- The invariant π^0 mass can be used as a standard candle to cross-check the absolute calibration of the detectors.
- I have validated the reconstructed π^0 mass peak in the ND to make sure that the data and simulation are in good agreement (NOvA docdb-19242).
- Introduced a new method to identify cosmic induced π^0s to cross-check the absolute calibration in the FD[1]

[1] **S. Edayath**, **"pi0 mass reconstruction in the NOvA Far Detector"**, **http://meetings.aps.org/link/BAPS.2017.APR.S11.3**.

Calibration of NOvA Detectors: Relative Calibration

- Uniformity across cells is the output of the relative calibration procedure.
- Through going cosmic muons are used.

- Data response as a function of distance from a cell center is fitted with a curve.
- This function is used to correct the uncalibrated cell hits.

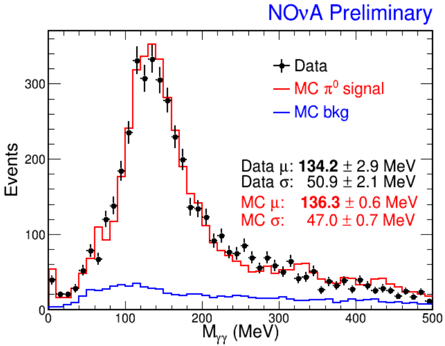


Calibration of NOvA Detectors: Absolute Energy Calibration

- To express the energy deposits in **physically meaningful units (GeV)**.

Standard Candles Used in NOvA

- **Near Detector**
  - Average energy lost per distance ($\frac{dE}{dx}$) of muons (μ)
  - π^0 invariant mass using beam π^0s.
- **Far Detector**
  - Average energy lost per distance ($\frac{dE}{dx}$) of muons (μ)
  - π^0 invariant mass using cosmic π^0s.

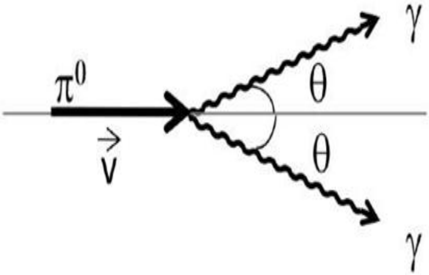


Reconstructed beam π^0 mass peak

Absolute calibration of FD using π^0s from cosmic rays

Challenges

- $\sim$ 140 kHz of cosmic rays.
- π^0s from cosmic origin are very rare.
- Events do not have any directional dependence.



Scheme

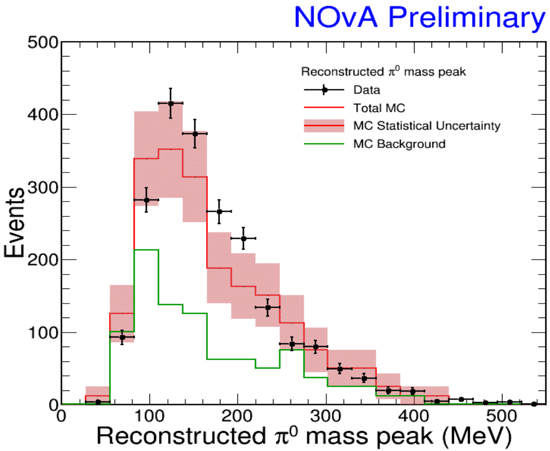
- Looking for **the two-γ decay of π^0.**
- The invariant π^0 mass is 135 MeV.

Reconstructed π^0 mass,

$$\mathbf{M_{\pi^0} = \sqrt{2E_{\gamma_1}E_{\gamma 2}\left(1 - \cos 2\theta\right)}}$$

- $\mathbf{E_{\gamma_1}}$ is the reconstructed energy of first cluster of hits (most energetic)
- $\mathbf{E_{\gamma_2}}$ is reconstructed energy of the second cluster (least energetic)
- 2θ is the opening angle between the two cluster of hits.

Reconstructed π^0 mass peak



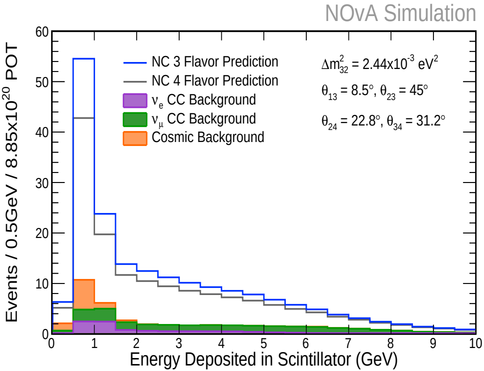
- **Purity in the event selection is 55%.**
- **2030 π^0 candidates are selected in data.**

Sample	Mean	σ
MC	**118.3 $\pm$ 17.1**	53.3$\pm$ 20.8
Data	**135.1 $\pm$ 2**	45.6 $\pm$ 3.4

Outline

NC Disappearance at the NOvA FD[2]

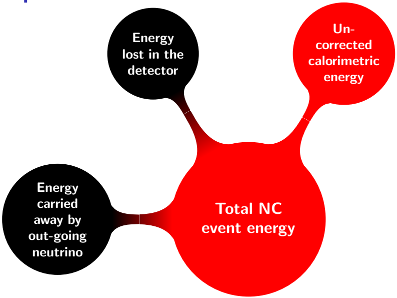
- In this analysis, we adopt a minimal "3+1" extension of three flavor neutrino model.
- NC events are not sensitive to three flavor oscillation.
- Looking for the depletion of NC spectrum due to active to sterile oscillation($\nu_\mu \rightarrow \nu_s$).



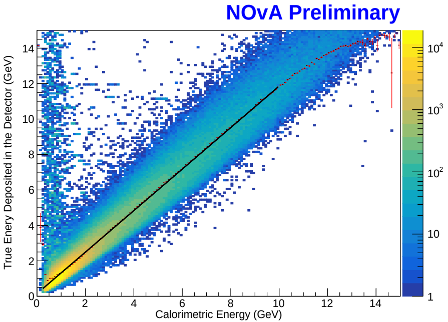
NC depletion at the FD as a function of energy.

[2]**P Adamson et al. (NOvA Collaboration)**, **"Search for active-sterile neutrino mixing using neutral-current interactions in NOvA" Phys. Rev. D 96**, **072006 (2017)**.

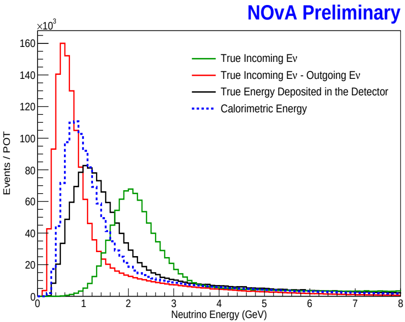
Updated calorimetric energy resolution of the detectors.



- The true energy deposited in the detector vs calorimetric energy plot is fitted with a line.
- The calorimetric energy is corrected with the slope of the fitted line.



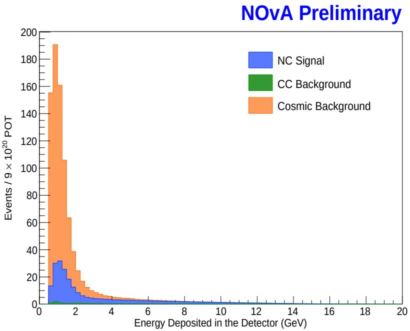
True energy deposited vs calorimetric energy, log-Z plot.



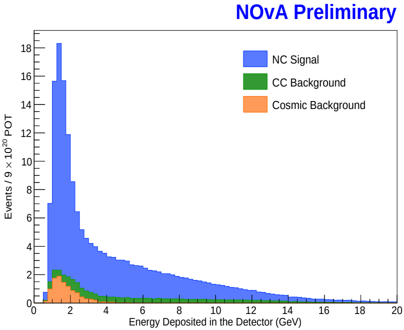
NC event Energy distribution in NOvA ND.

Improved Cosmic rejection BDT.

- Cosmogenic particles, predominantly muons and neutrons, mimic the NC signal in the NOvA FD (located on the ground surface).
- I have trained, tested and implemented a TMVA based particle classifier BDT.
- Reconstructed shower variables are input to the BDT algorithm.

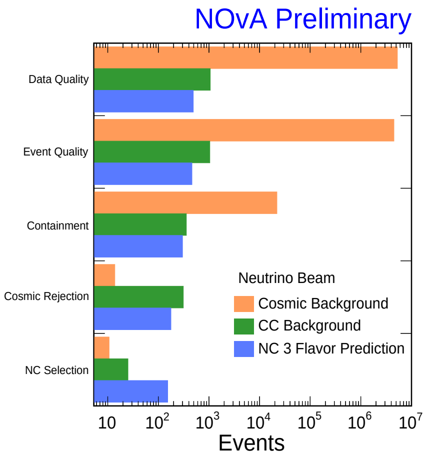


Energy deposited in the detector before cosmic rejection.



Energy deposited in the detector after final selection

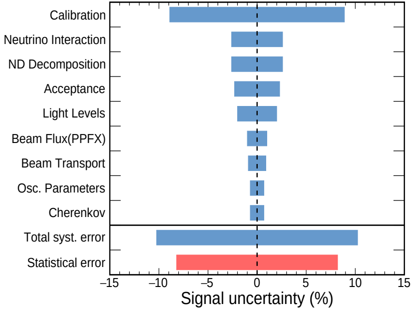
Summary of Analysis Selection Cuts



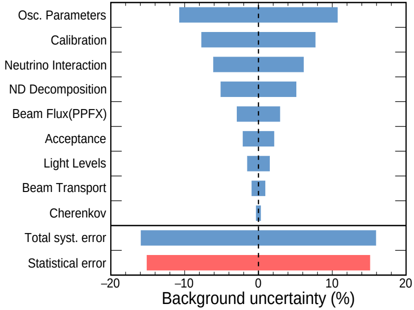
Neutrino analysis

Systematic Uncertainties in the Neutrino Analysis

- Systematic uncertainties accounts for the deviation of experimental simulation from the real world.
- Since NOvA NC disappearance analyses use the extrapolation technique, many systematic errors are reduced by the extrapolation method.



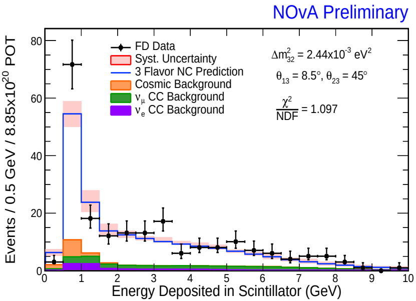
Systematic uncertainities that effect signal.



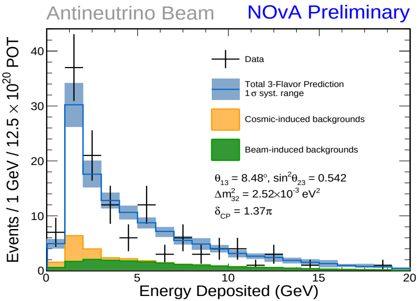
Systematic uncertainities that effect background.

FD Data - Simulation Distribution

Neutrino beam.



Antineutrino beam



- 214 data events are observed while the predicted events are $191^{\pm 13.8(stat)}_{\pm 22.0(syst)}$
- 120 data events are observed while the predicted events are $121^{\pm 11(stat)}_{\pm 18(syst)}$.

Analysis Deliverables

- A model-independent R-ratio that quantify the level of agreement between the data and 3-flavor simulated prediction.

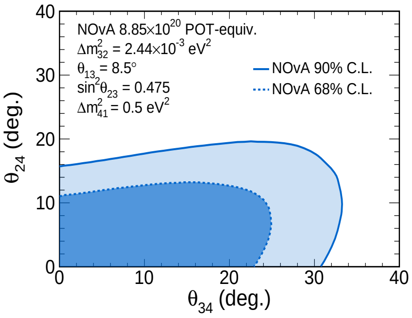
- Contribute to the global data on sterile mixing parameters by extracting measurements on θ_{24}, θ_{34}, $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$.
(Using $|U_{\mu 4}|^2 = \cos 2\theta_{14} \sin 2\theta_{24}$ and $|U_{\tau 4}|^2 = \cos 2\theta_{14} \cos 2\theta_{24} \sin 2\theta_{34}$)

R-ratio

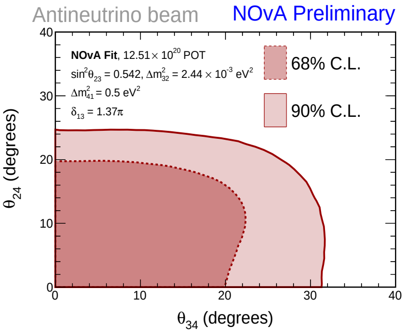
- The R-ratio is defined as, $R_{NC} = \frac{N_{Data} - \sum N_{Bkg}^{Pred}}{N_{NC}^{Pred}}$; where N_{Data} is number of data events, N_{Bkg}^{Pred} is the background prediction and N_{NC}^{Pred} is the NC signal prediction.
- R-ratio for the neutrino analysis is 1.15$\pm$0.14 (stat)$\pm$0.12 (syst), while for the antineutrino analysis is 0.99$\pm$0.12 (stat)$\pm$0.16 (syst).
- These are consistent with the three neutrino flavor hypothesis.

NC disappearance analysis results.

- I contributed significantly to the event selection and predicting the FD simulated spectrum that is to be fitted with the data to extract the sterile mixing parameters such as θ_{24} and θ_{34}.

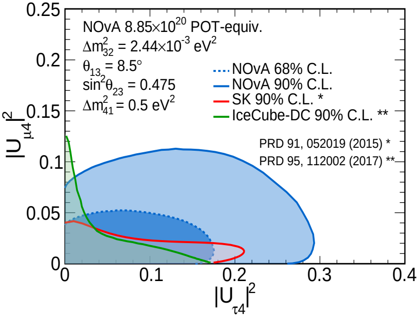


Neutrino beam limit on θ_{24} and θ_{34}.

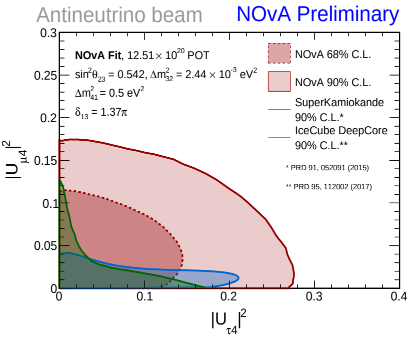


Antineutrino beam limit on θ_{24} and θ_{34}.

NOvA's Constraints on the Sterile Mixing Parameters



Neutrino beam limit on $|U_{\mu4}|^2$ and $|U_{\tau4}|^2$.



Antineutrino beam limit on $|U_{\mu4}|^2$ and $|U_{\tau4}|^2$.

1D 90% CL limit	θ_{24} (degree)	θ_{34} (degree)	$\lvert U_{\mu4}\rvert^2$	$\lvert U_{\tau4}\rvert^2$
NOvA 2019($\overline{\nu}$)	24.7	31.7	0.175	0.276
NOvA 2017(ν)	16.2	29.8	0.078	0.274
NOvA 2016(ν)	20.8	31.2	0.126	0.268
MINOS/MINOS+	4.4	23.6	0.06	0.160
SuperK	11.7	25.1	0.041	0.180
IceCube	4.1	-	0.05	-
IceCube-DeepCore	19.4	22.8	0.11	0.150

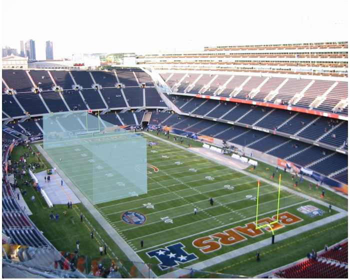
Conclusion

- In NOvA, I got an excellent opportunity to work independently and as a part of an analysis group.
- There are some exciting developments happening in the field of neutrino physics.
- Race towards the DUNE is prominent among them.
- The post-doc position at ANL will give an excellent opportunity to participate in the critical elements of this experiments, and contribute to the ANL experimental neutrino physics group's efforts in furthering our understanding of neutrino physics.

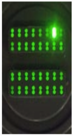
THANKS

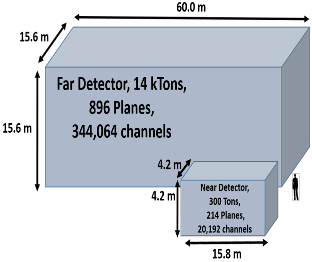
BACKUPS

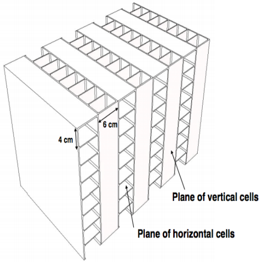
NOvA Detectors

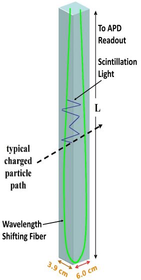


- **Far Detector**
  - 14 kton detector at the surface.
- **Near Detector**
  - Structurally identical to FD
  - 0.3 kton underground detector.

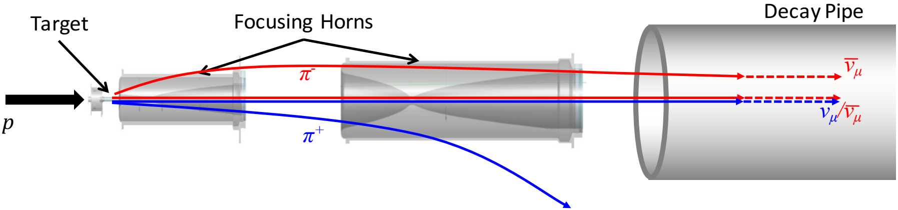








The NuMI Beam



- High energy protons ($\sim$ 120 GeV) colliding with the graphite target produced mesons mainly pions and kaons.
- Charged mesons are focused using magnetic horns.
- The focused particles decay in to *neutrinos* (*antineutrinos*) and tertiary particles in decay pipe.

Off-axis Detectors

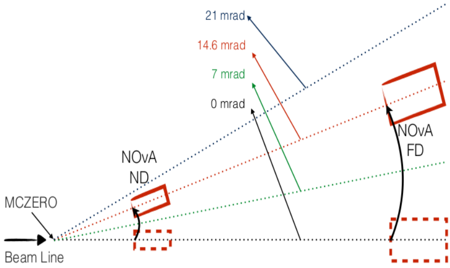
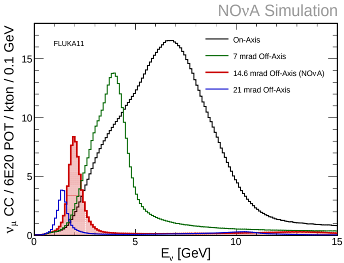


Figure showing the off-axis position of the NOvA detector.

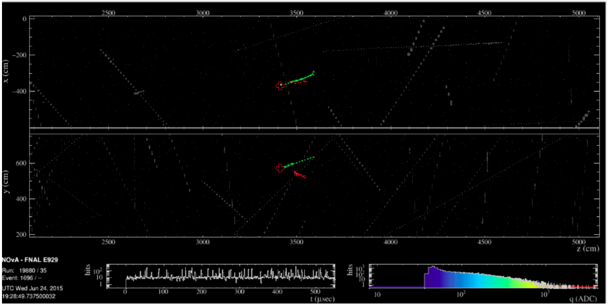


Beam profile as seen by the FD.

1. The off-axis position of the NOvA detector reduces the flux, but gets a narrow band beam.

2. The peak around 2 GeV is chosen so that the first oscillation maximum for the ν_μ disappearance lie near it.

Event Reconstruction



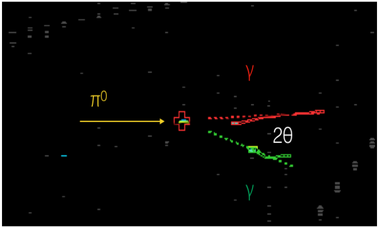
- It involves the series of algorithms that groups the calibrated cell hits that correlates in space and time, in to clusters.
- These clusters of cells hits are fed into algorithms that identifies the features in it.
- Analyses are performed using these features.

Event Selection

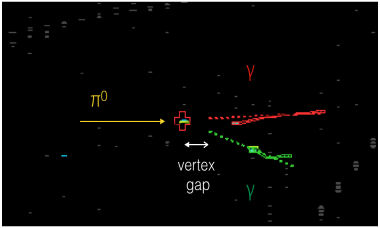
A cosmic π^0-specific reconstruction chain was implemented to reconstruct them.
The preliminary event selection was based on **variables of shower like cluster** such as,

1. **Number of hits** in each cluster.
2. **Opening angle** between the the cluster.
3. **The gap** between event vertex and the cluster starting position.

On top of these, a computer vision based particle identifier **convolutional visual networks (CVN)** is used to identify the γ's in this analysis.
(An adaptation of the CVN is implemented to identify the individual component of an event: the prong CVN)



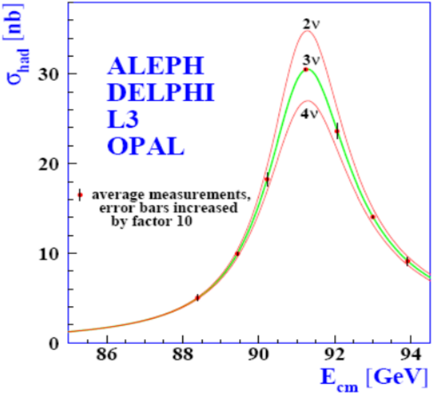
Opening angle between the the cluster.



The event vertex gap.

Sterile Neutrinos: The LEP Experiment Result

- The Large Electron Positron (LEP) measurements of the Z^0 boson decay is consistent with the presence of 3 active neutrinos.
- If a fourth neutrino exists, it does not participate in the standard model interactions or a Sterile Neutrino.
- It points to new physics beyond the standard model.

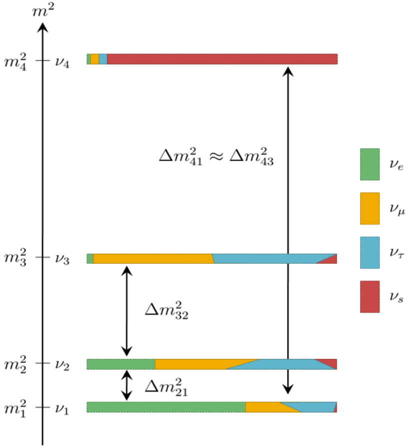


Sterile Neutrinos are a potential solution to open questions ranging from the neutrino sector to cosmology.

Sterile Neutrinos: The LSND (Liquid Scintillator Neutrino Detector) Anomaly

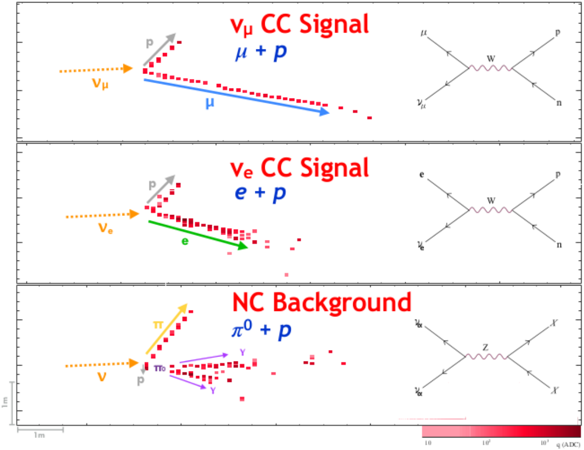
The LSND experiment measured an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam in the vicinity of $\frac{L}{E} = \frac{1m}{MeV}$. Another SBL experiment MiniBooNE saw similar excess.

1. This excess can be interpreted as **a result of oscillation** at a mass squared splitting 1 eV^2.
2. The presence of these three different Δm^2 demands the existence of at least 4 neutrinos.
3. But, the Large Electron Positron (LEP) measurements of the Z^0 boson decay is consistent with the presence of 3 active neutrinos.



The Event Topology in the NOvA Detector

- ν_μCC : Long-straight track.
- ν_eCC : Shorter, wider and fuzzy shower.
- NC events : Diffuse activity from nuclear recoil system.



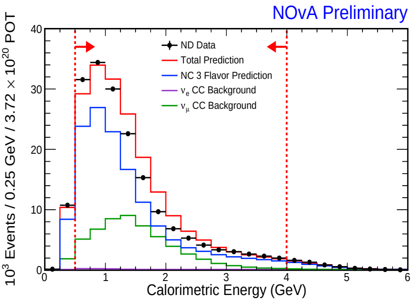
The Analysis Strategy: Far/Near Extrapolation Method

The process of predicting the FD Calorimetric energy spectrum using ND energy spectrum can be summarized as,

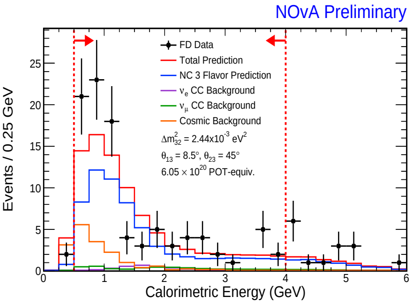
1. ND data is decomposed into different interaction types.
2. Each component is extrapolated to FD by

$$ND^{Data} \times \frac{FD^{MC}}{ND^{MC}} = FD^{Pred} \qquad (1)$$

3. Oscillation weights are applied to each FD predicted components. The MC prediction is compared with the FD data.



ND NC Calorimetric Energy spectrum.

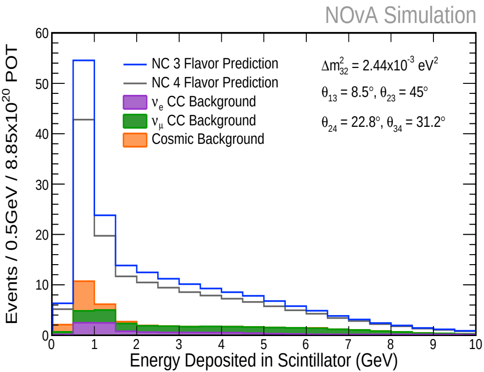


FD NC Calorimetric Energy spectrum.

Long-baseline Sterile Neutrino Searches in NOvA

- NC events are not sensitive to three flavor oscillation.
- Looking for the depletion of NC spectrum at the FD.
- Analyses using both neutrino beam (FHC) and antineutrino beam (RHC)

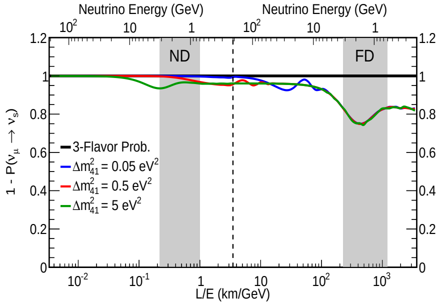
NC depletion as a function of energy.



$$
\begin{aligned}
1 - P\left(\nu_\mu \to \nu_s\right) \approx 1 &- c_{34}^2 sin^2 2\theta_{24} sin^2 \Delta_{41} \\
&- c_{34}^2 \left(c_{24}^2 - c_{24}^2 c_{34}^2\right) sin^2 2\theta_{23} sin^2 \Delta_{31} \\
&- \frac{1}{4} sin2\theta_{23} sin2\theta_{24} sin2\theta_{34} sin\delta_{24} sin2\Delta_{31}
\end{aligned} \quad (2)
$$

Long-baseline NC Disappearance Analyses in NOvA

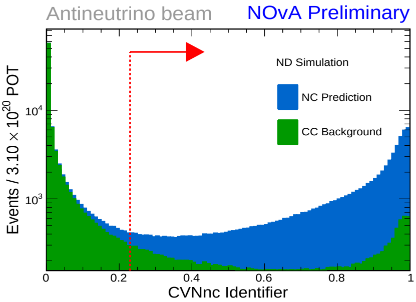
- Search for active to sterile neutrino mixing through NC disappearance.
- Two separate analyses.
  - With neutrino beam. Termed as Forward Horn Current (FHC) analysis.
  - With antineutrino beam. Termed as Reverse Horn Current (RHC) analysis.
- Considering a 3+1 model with 0.05 $eV^2 < \Delta m^2_{41} < 0.5\ eV^2$.



Minimal 3+1 model.

Convolutional Visual Network as the Particle Identifier.

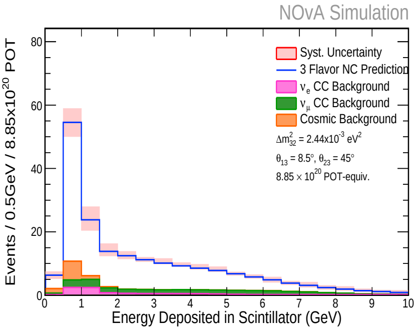
- A computer vision based particle identifier using convolutional neural networks (CVN) is used to identify the NC events.
- The events in the NOvA detector can easily be interpreted as two images, one for each view.
- Designed to classify events according to their likely neutrino flavor and interaction type.



Systematics study

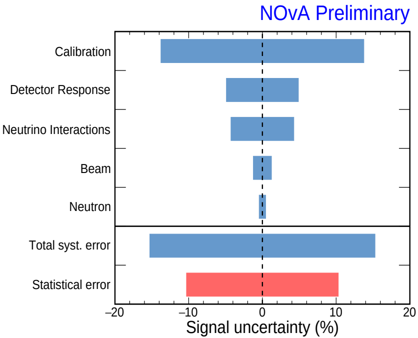
- The NOvA NC disappearance analysis is affected by several systematic uncertainties.
- I have tested and quantified systematic uncertainties for this analysis.

FD energy spectrum with the systematics band.

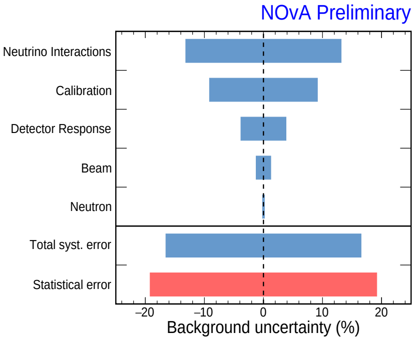


Systematic Uncertainties in the Antineutrino Analysis

- Systematics are included as a pull term in the neutrino oscillation fit.

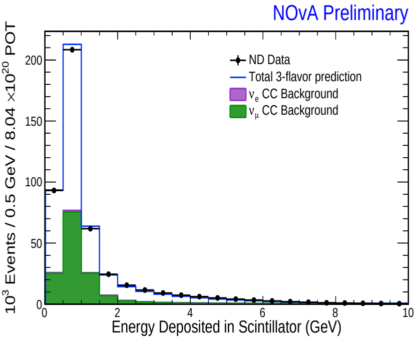


Systematic uncertainities that effect signal.

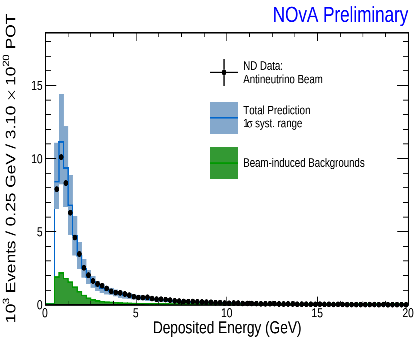


Systematic uncertainities that effect background.

ND Energy Spectrum



Neutrino beam.



Antineutrino beam.