Results From the Joint Fit to ν_e Appearance and ν_μ Disappearance in NOvA

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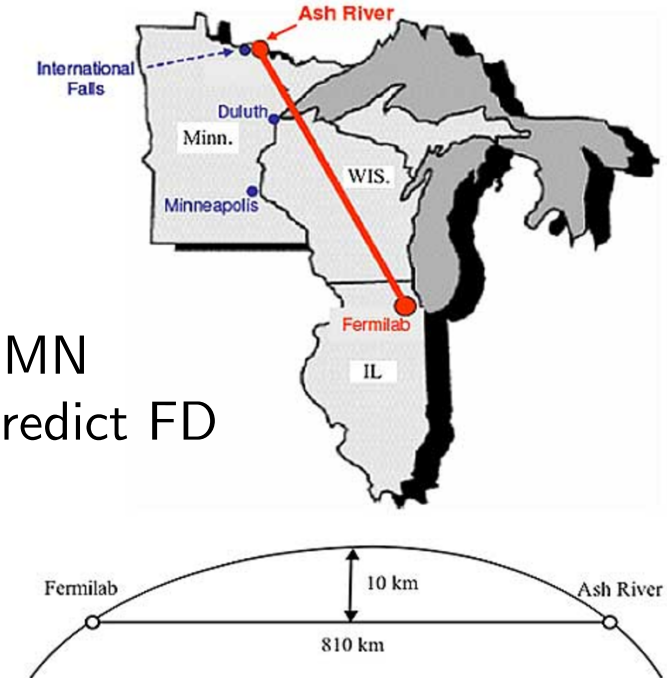
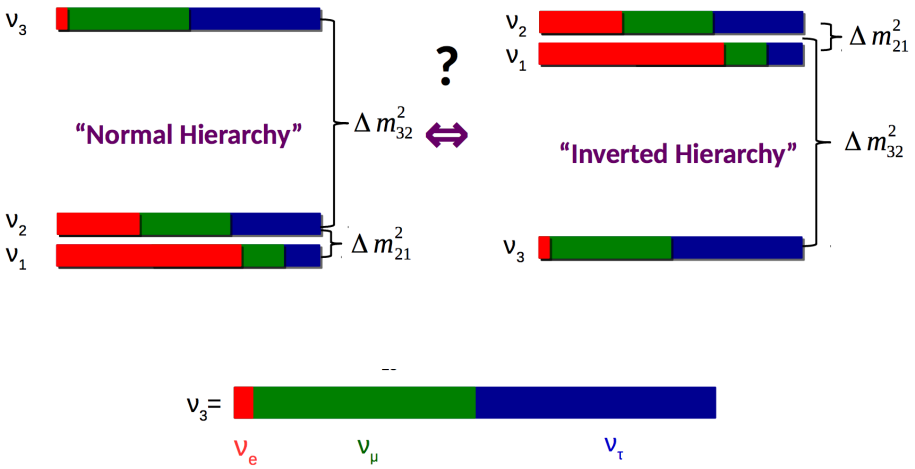
June 5, 2017

NuMI Off-axis ν_e Appearance, Overview

- Long-baseline, off-axis neutrino oscillation experiment;
- Study neutrinos from NuMI beam at Fermilab;
- 14 mrad off-axis, energy peaked at 2 GeV;
- Functionally identical detectors
  - Near Detector on site at Fermilab
  - Far Detector 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD



Physics Background



- 3 flavor states are superpositions of 3 mass eigenstates.
- Superpositions are described by the unitary matrix, U_{PMNS}
- Parameterized in 3 mixing angles($\theta_{12}, \theta_{13}, \theta_{23}$) and δ_{CP}

Physics Goal

- Disappearance of ν_μ Charged Current Events

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

  - Measure precise values of $|\Delta m^2_{32}|$, $sin^2(2\theta_{23})$
  - PRL.118.151802
  - *For more details on ν_μ CC event classifier, see Jose S.'s Exploring the ν_μ charged-current uncontained sample at the NOvA Far Detector talk.*

- Appearance of ν_e Charged Current Events
  - Determine θ_{23} octant, Mass Hierarchy
  - Constrain CP violation parameter δ_{cp}.
  - Joint fit of results from ν_μ analysis:
    - $|\Delta m^2_{32}|$, $sin^2(2\theta_{23})$;
    - uncertainties,
    - extrapolation and prediction.
  - PRL.118, 231801

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1^2)}$$

note sign flip for antineutrinos

$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$

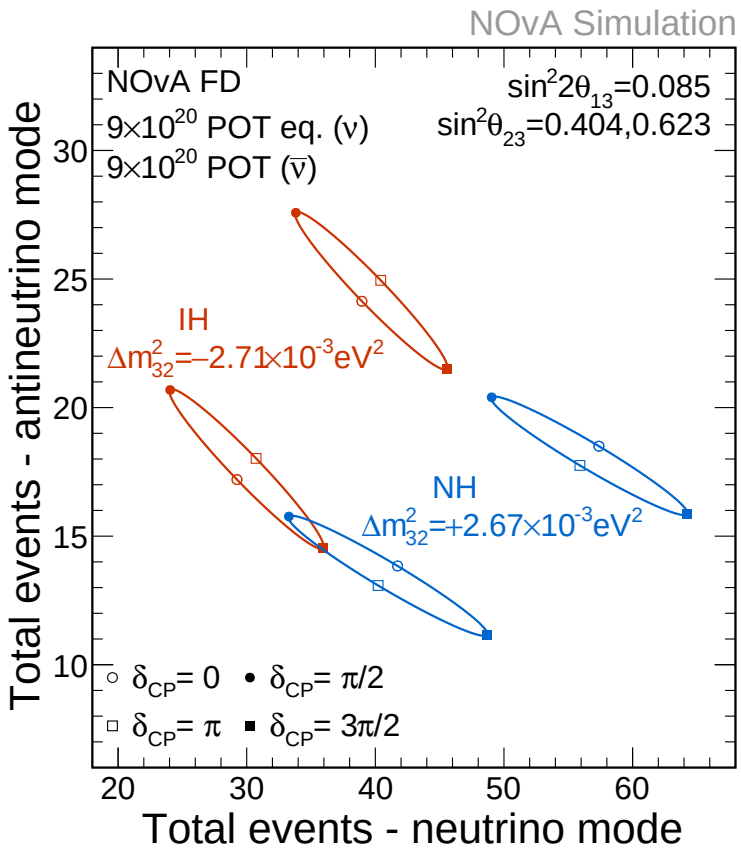
$$+ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos\Delta$$

Where: $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$ $\Delta = \Delta m^2_{31} \frac{L}{4E}$ $A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$

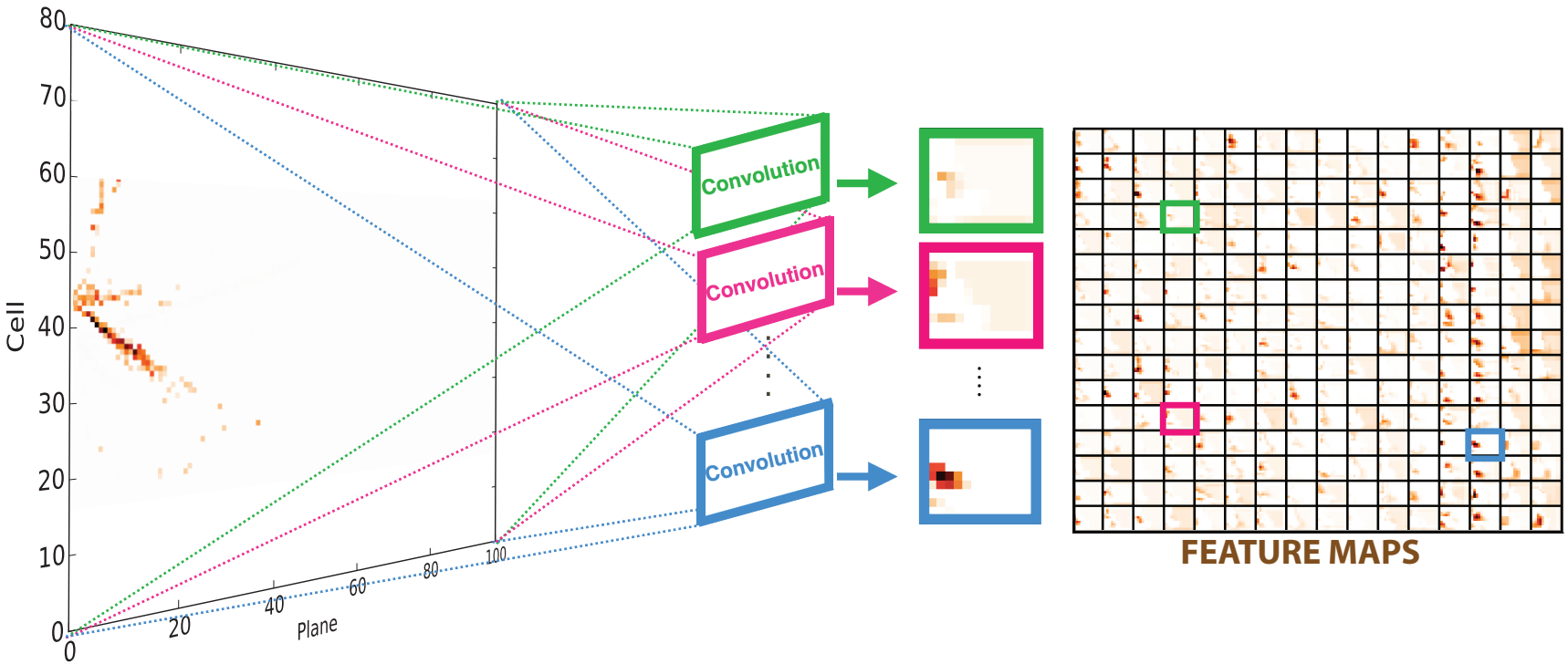
- Other Goals
  - cross section studies, searches for exotic phenomena, non-beam physics studies
  - *Coming talk : Sterile neutrino search in the NOvA Far Detector by Sijith E.*

Physics Goal

- For antineutrinos, the mass hierarchy and CP phase have the opposite effect on the oscillation probability;
- Increasing values of $sin^2\theta_{23}$ increase the appearance probabilities for ν_e and $\bar{\nu_e}$ alike.



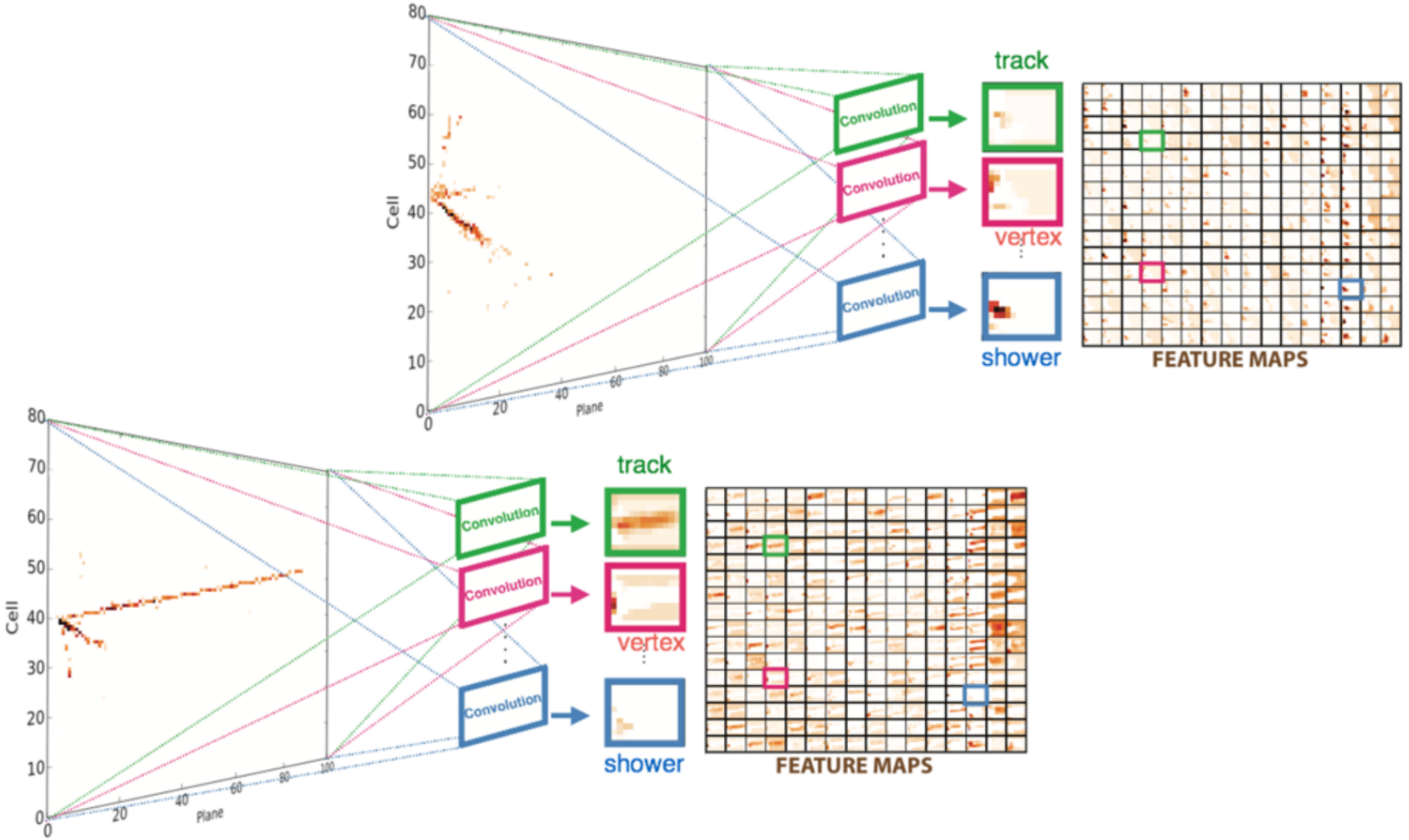
ν_eCC Event Classifier : CVN



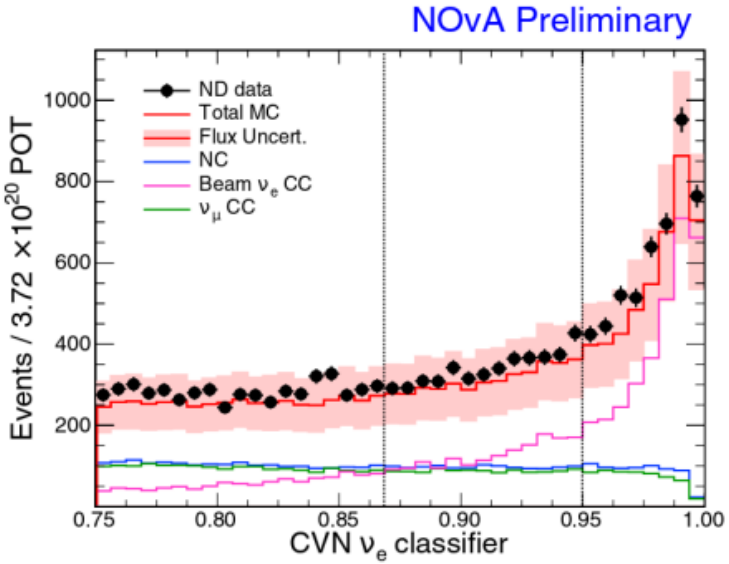
Convolutional neural network neutrino event classifier (CVN):

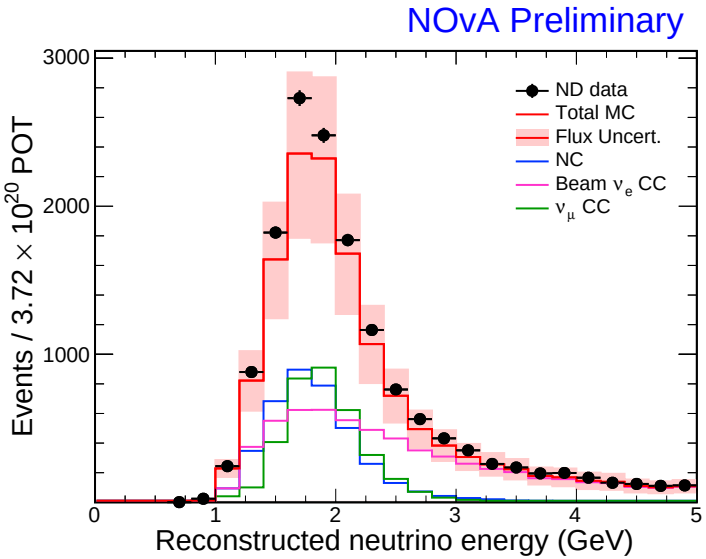
- Based on ideas from computer vision and deep learning;
- Calibrated hit maps are inputs;
- Series of image processing transformations applied to extract abstract features;
- Extracted features used as inputs to a conventional neural network to classify the event.

ν_eCC Event Classifier : CVN



ν_e Appearance $\nu_\mu \rightarrow \nu_e$, ND

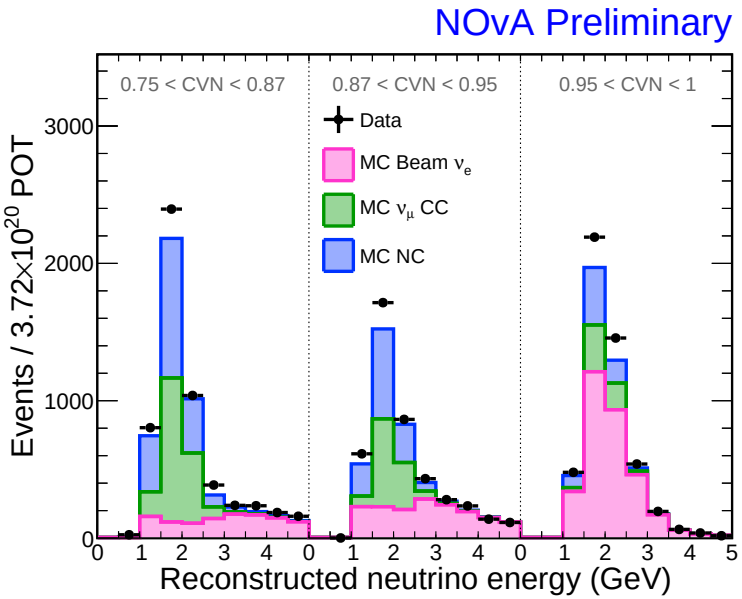




CVN ν_e classifier and energy distribution of ν_e classifier selected events.

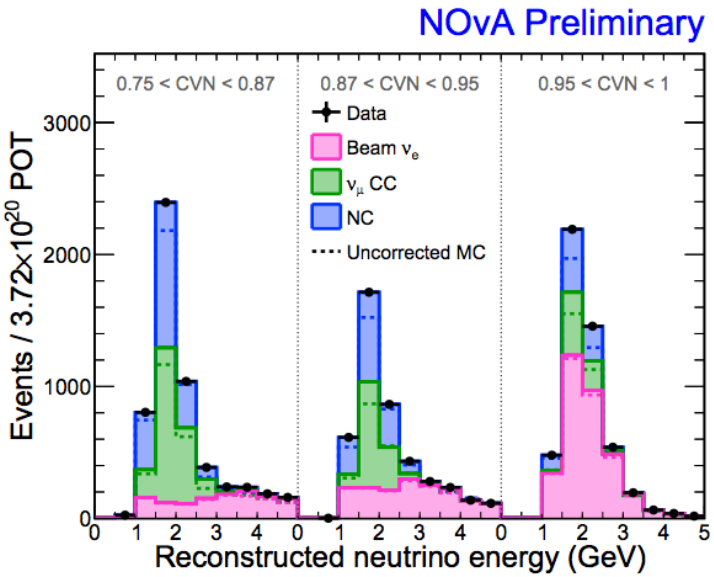
- Selection reoptimized to favor parameter measurement
  - improve both cosmic rejection and classifier cut;
  - increased signal efficiency, including lower purity bins.

ν_e Appearance $\nu_\mu \rightarrow \nu_e$, Prediction



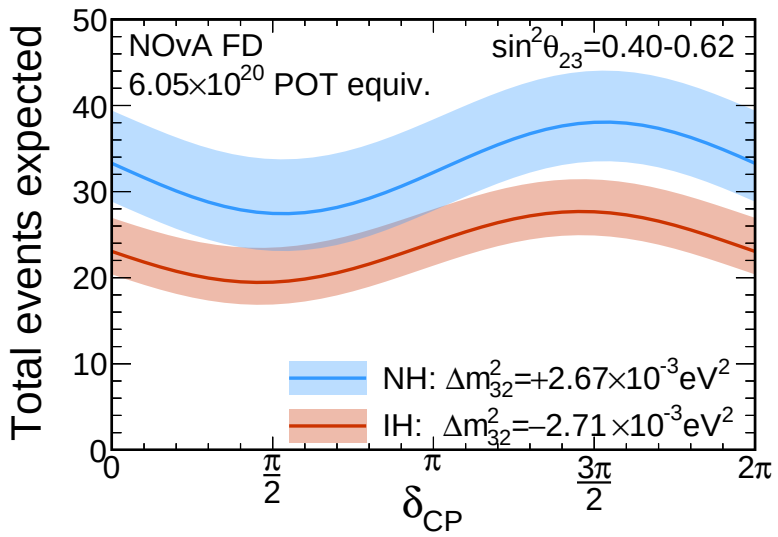
Least ν_e - like $\Longrightarrow$ Most ν_e - like
(Divided into bins of event classifier)
Used ND spectrum to predict background in FD

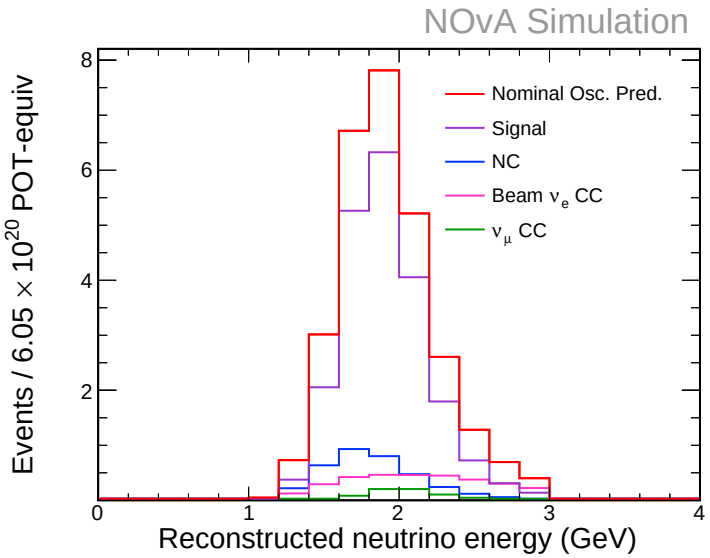
- Decompose ND spectrum and predict signal at FD using a data-driven method as Nitish talked about earlier.



- Extrapolate each background component in bins of energy and CVN output;
- *For more details see Nitish N.'s Decomposition Methods for the ν_e Appearance analysis in the NOvA Near Detector talk.*

ν_e Appearance $\nu_\mu \rightarrow \nu_e$,FD Prediction





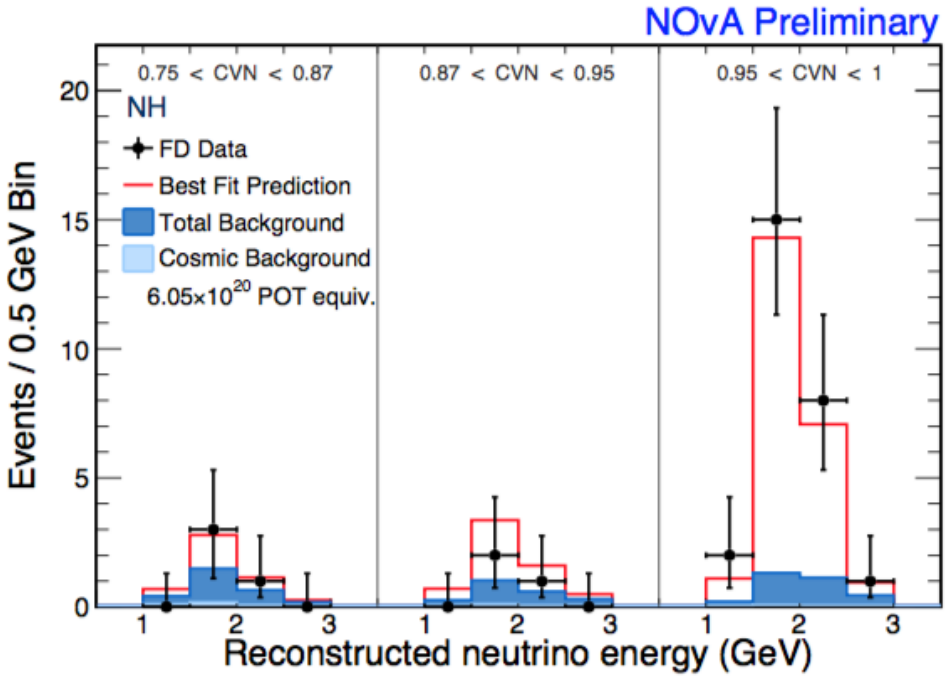
Total events (±5% systematic uncertainty):	NH, 3π/2,	IH, π/2,
	36.4	19.4

Background by component (±10% systematic uncertainty):

Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5

Signal is quite a lot bigger than the background;
Expected event counts depend on the oscillation parameters.

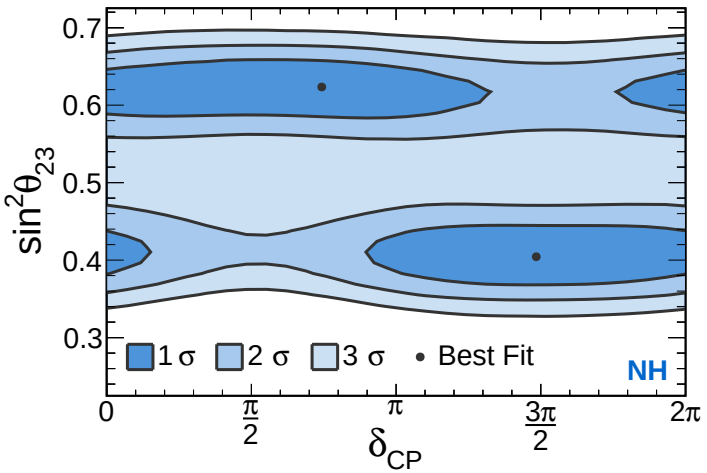
ν_e Appearance $\nu_\mu \rightarrow \nu_e$,FD Data

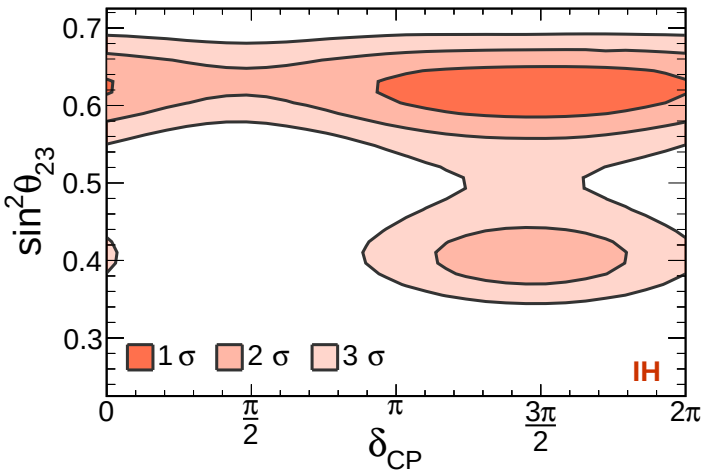


After the event selection criteria and analysis procedures were finalized:

- Observed 33 events in FD,
- background 8.2$\pm$0.8
- $> 8\ \sigma$ electron neutrino appearance signal

ν_e Appearance $\nu_\mu \rightarrow \nu_e$,Contours





- Fit for mass hierarchy, δ_{CP}, $sin^2\theta_{23}$
  - Constrain $sin^2(\theta_{23})$ and Δm^2_{32} with ν_μ disappearance results;
  - Results are full joint fit, systematics and other oscillation parameters are correlated.
- Global best fit Normal Hierarchy:

  $\delta_{CP} = 1.49\pi$

  $sin^2(\theta_{23}) = 0.404$
  - Best fit of IH-NH $\Delta\chi^2$=0.47
  - Both octants and hierarchies allowed at 1σ
  - In some regions of IH, lower octant around $\delta_{CP} = \pi/2$ is excluded at 3σ

Summary

With 6.05×10^{20} POT, NOvA finds:

- Electron neutrino appearance:
  - Electron neutrinos appear at $> 8\sigma$
  - Data prefer NH at low significance
  - Region in IH, lower octant around $\delta_{CP} = \pi/2$ is excluded at 3σ.
- We started running antineutrino mode in February, and the data will help to resolve degeneracies.
- Looking forward to Fall 2017 with 50% more data.


NOvA collaboration
meeting @ANL
Summer 2016
Thank you!

Backup

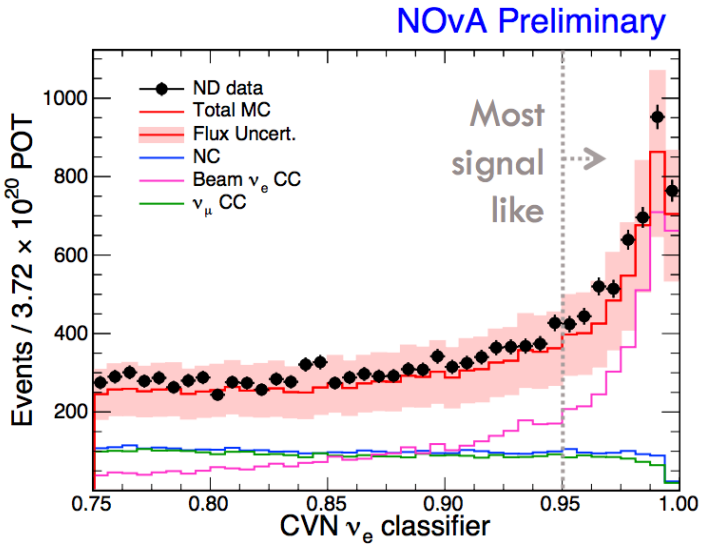
Event Classifiers

ν_μ-CC events classifier:

- k-nearest neighbor (kNN)
  - $\frac{dE}{dx}$ *likelihood*
  - total track length
  - scattering likelihood
  - fraction of planes along the track

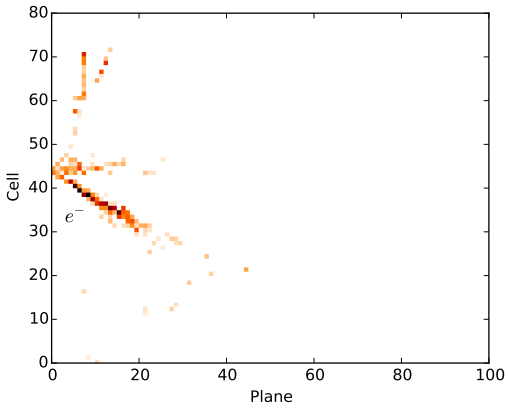
ν_e-CC events classifier:

- Convolutional Visual Network(CVN)
  - hits from clusters
  - applies trained linear operations
  - extract complex, abstract classifying features



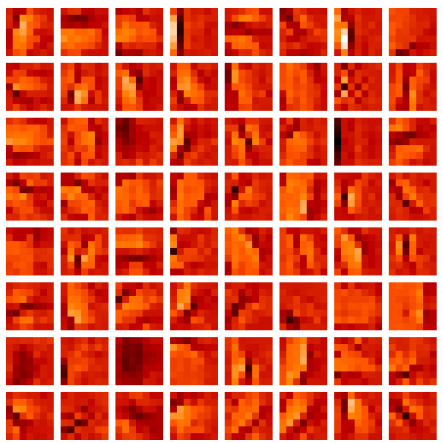
ν_eCC Event Classifier : CVN

a true ν_e CC interaction



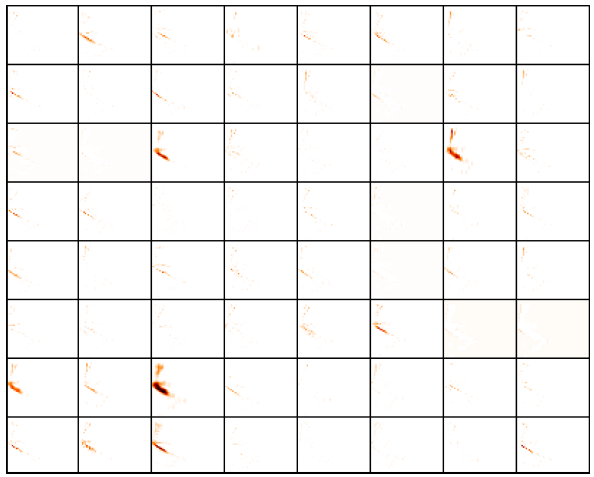
$\rightarrow$

the first convolutional layer



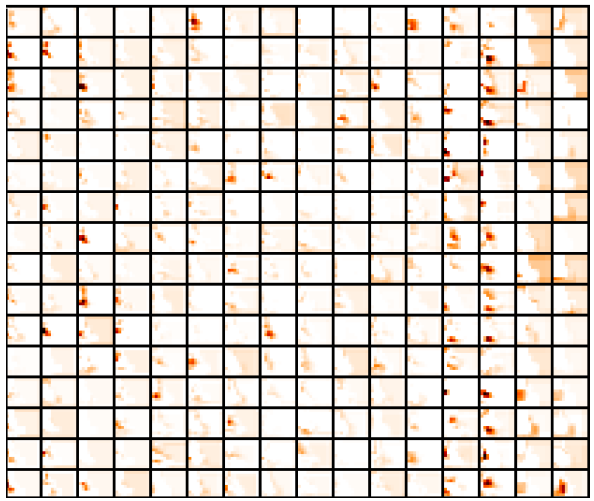
$\rightarrow$

Result after the first convolutional layer



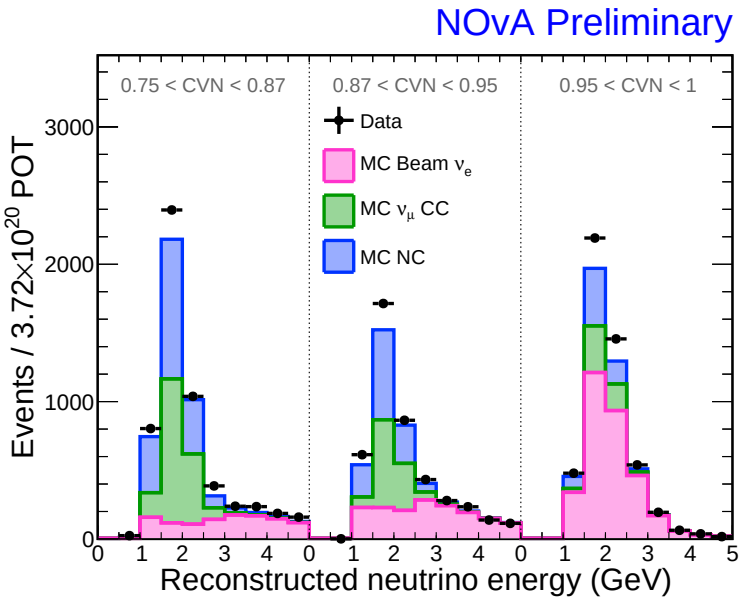
input to the next layer.. and the next ...

$\downarrow$



the feature maps by the end of the first inception module of the CVN network

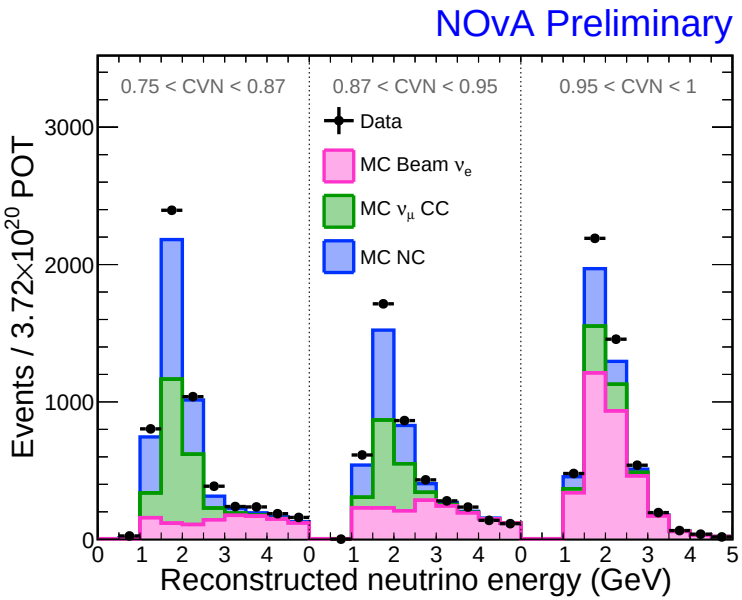
ν_e Appearance $\nu_\mu \rightarrow \nu_e$,ND



Least ν_e - like $\Longrightarrow$ Most ν_e - like
(Divided into bins of event classifier)

- Use ND spectrum to predict background in FD
  - BEN + Michel constraints together tell us how to use the ND information to correct each component in the FD spectrum.

ν_e Appearance $\nu_\mu \rightarrow \nu_e$,ND Decomposition



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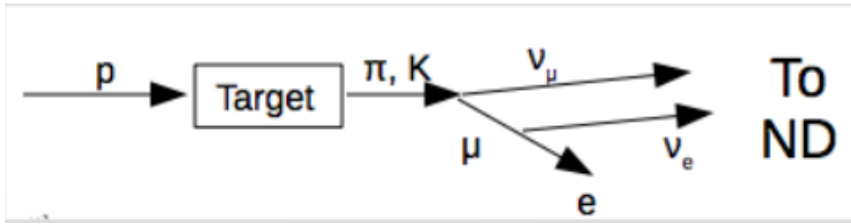
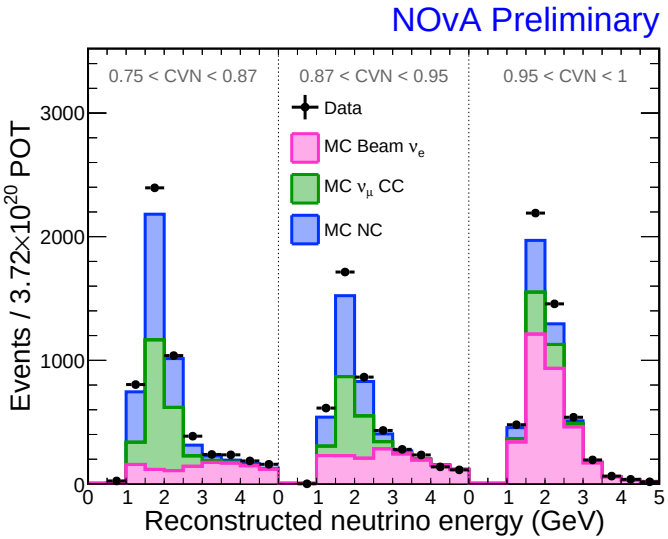


- Constrain beam ν_e using selected ND ν_μCC spectrum

ν_e Appearance $\nu_\mu \rightarrow \nu_e$,ND Decomposition



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(Divided into bins of event classifier)

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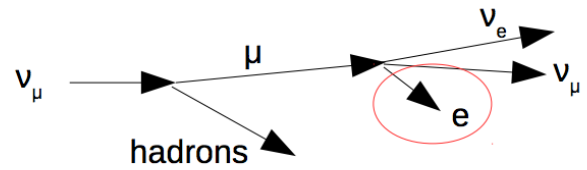
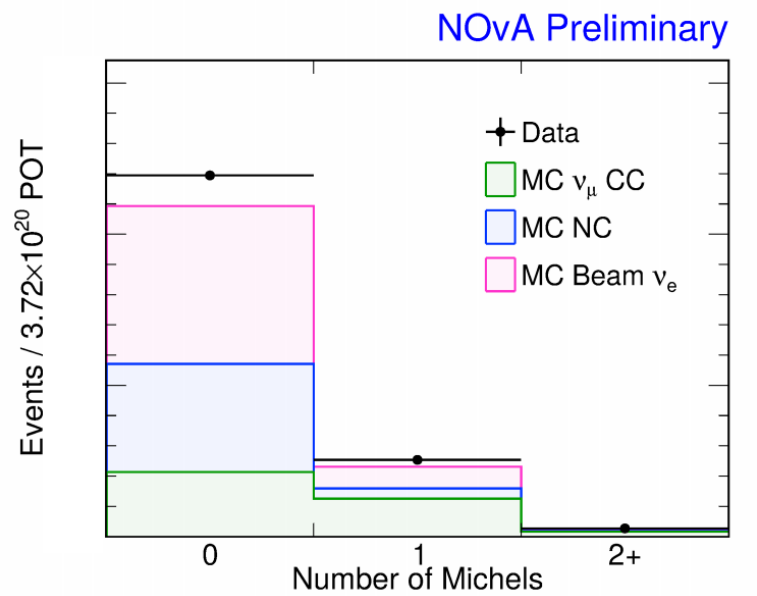
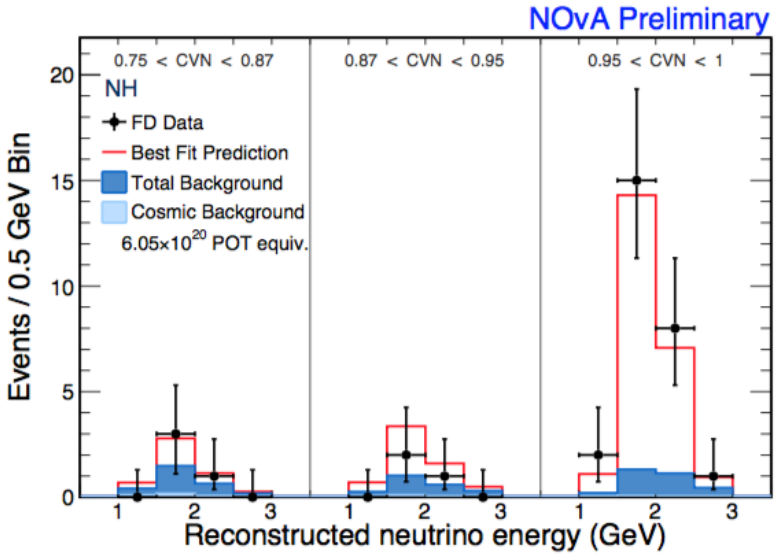




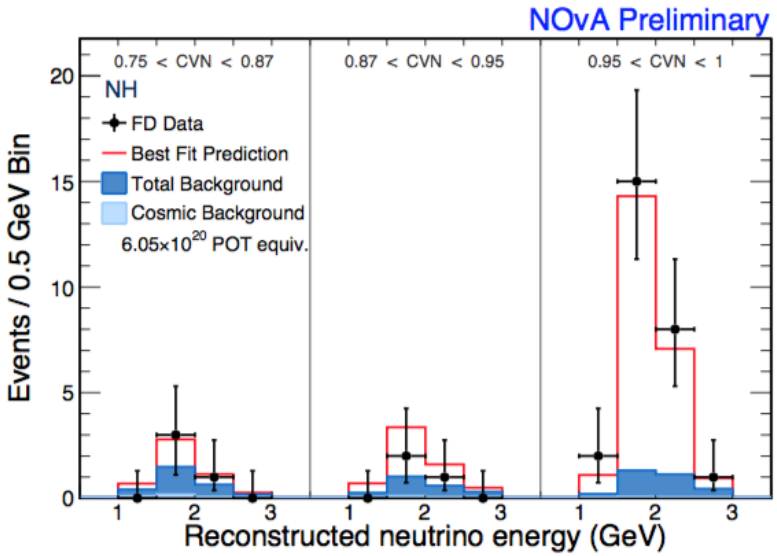
- Constrain ν_μ-CC using Michel Electron distribution;
- NC, ν_μCC, Beam ν_e each component propagates differently;

ν_e Appearance $\nu_\mu \rightarrow \nu_e$,Prediction



- Use ND spectrum to predict background in FD
  - This extrapolation is carried out for the energy spectra in all three ν_e classifier bins.
  - The variation in the number of FD events predicted as a function of the assumed oscillation parameters.

ν_e Appearance $\nu_\mu \rightarrow \nu_e$,FD Data

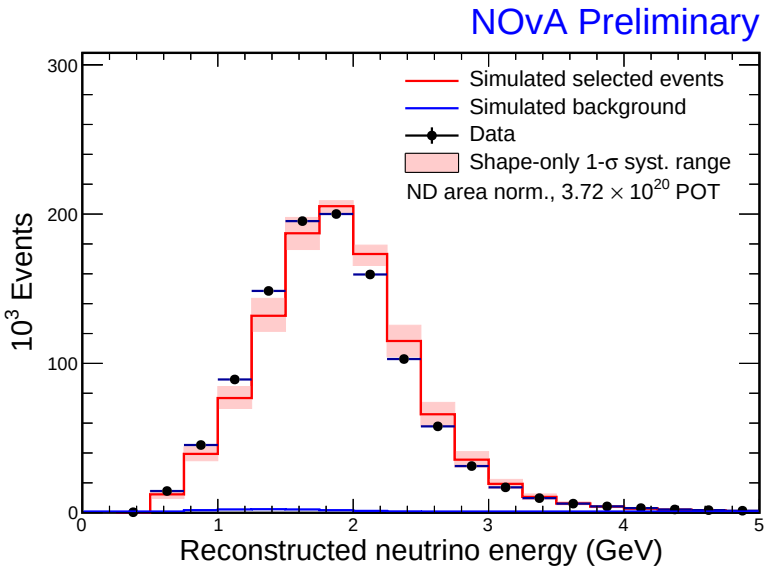


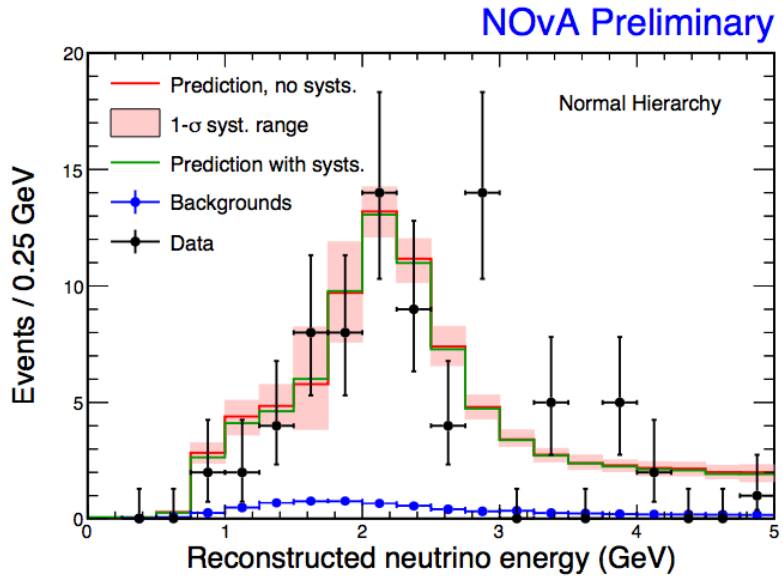
After the event selection criteria and analysis procedures were finalized:

- $> 8\ \sigma$ electron neutrino appearance signal
- Observed 33 events in FD,
- background 8.2$\pm$0.8

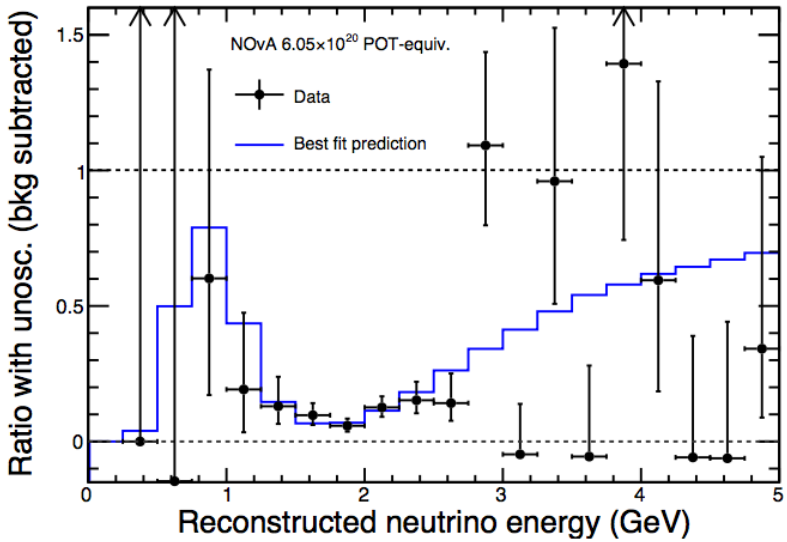
- Event distribution with the expectations at the best fit point :
- Apply constraint from reactor experiments for θ_{13};
- Perform joint analysis with preceding ν_μ result to constrain θ_{23} and Δm^2_{32}

ν_μ Disappearance $\nu_\mu \rightarrow \nu_\mu$, FD Extrapolation



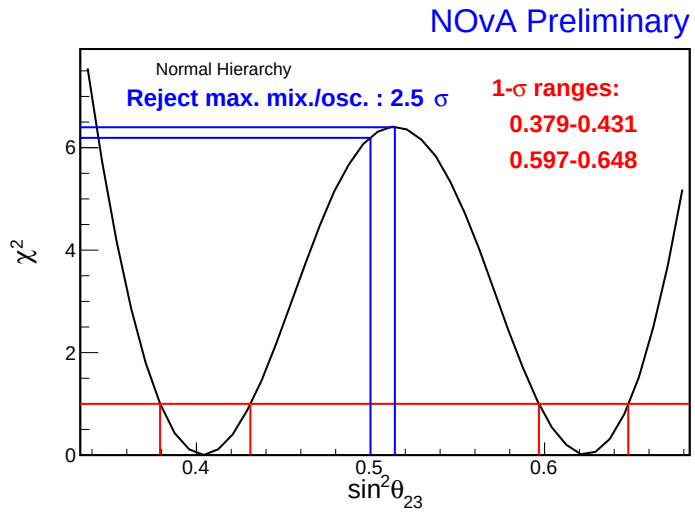


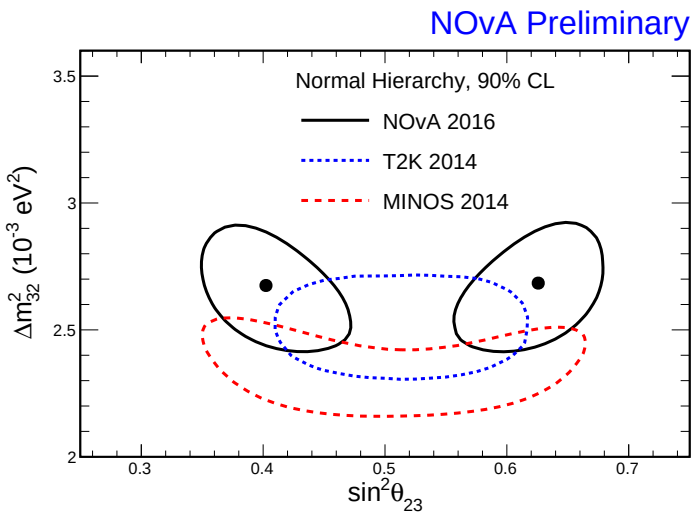
- 78 ν_μ -CC candidate events observed in the FD
- In the absence of oscillations 473±30 events are predicted.
- At the best-fit parameters, 82.4 events are expected.
- 3.7 beam background and 2.7 cosmic-ray-induced events



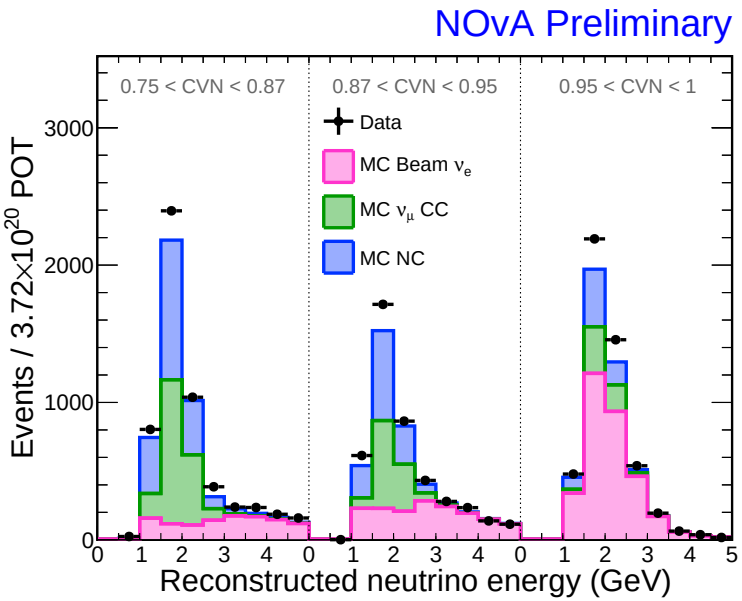
ν_μ Disappearance $\nu_\mu \rightarrow \nu_\mu$, Contours

- Best fit to the data at 68% C.L. gives :
  - $\Delta m^2_{32} = (+2.67 \pm 0.11) \times 10^{-3} eV^2$
  - $sin^2\theta_{23} = 0.404^{+0.030}_{-.022} (0.624^{+0.022}_{-0.030})$
- Maximal mixing, where $sin^2\theta_{23} = 0.5$, is disfavored by the data at 2.6σ
- The dashed curves show MINOS and T2K 90% C.L. contours.



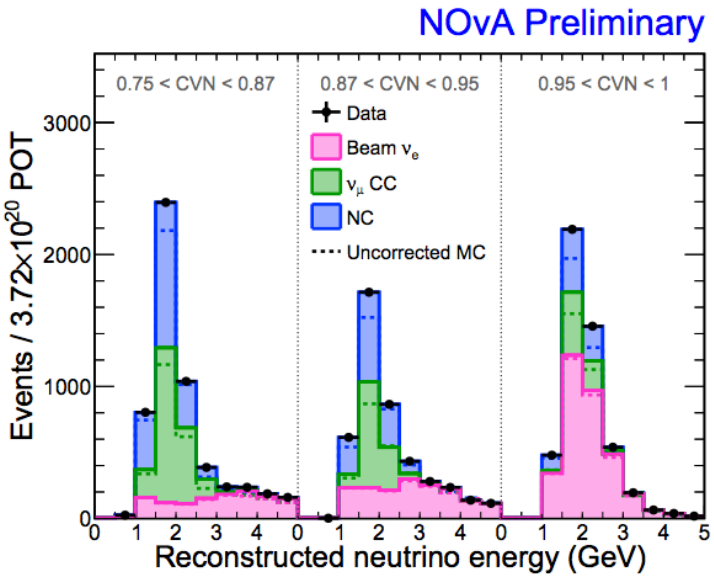


ν_e Appearance $\nu_\mu \rightarrow \nu_e$, Prediction



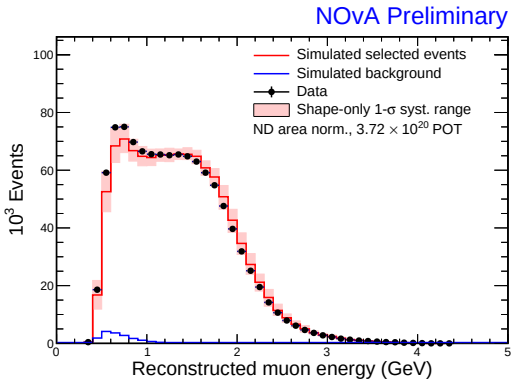
Least ν_e - like $\Longrightarrow$ Most ν_e - like
(Divided into bins of event classifier)
Used ND spectrum to predict background in FD

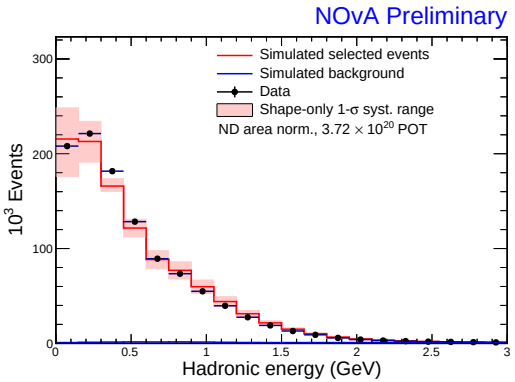
- NC, ν_μCC, beam ν_e each propagates differently;
- constrain beam ν_e using selected ν_μCC spectrum;
- constrain ν_μCC using Michel Electron distribution.

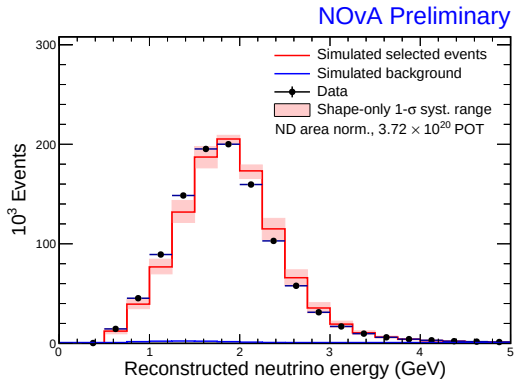


- Extrapolate each background component in bins of energy and CVN output;
- Expected event counts depend on oscillation parameters ;
- *For more details see Nitish N.'s Decomposition Methods for the ν_e Appearance analysis in the NOvA Near Detector talk.*

ν_μ Disappearance $\nu_\mu \to \nu_\mu$ at ND







+nue energy reconstructions

- Hadronic energy scale uncertainty reduced (14% to 5%)
- Reconstructed neutrino energy unfolded, to extrapolate ND spectrum for a FD prediction