Looking for Sterile Neutrinos via Neutral-Current Disappearance with NOvA

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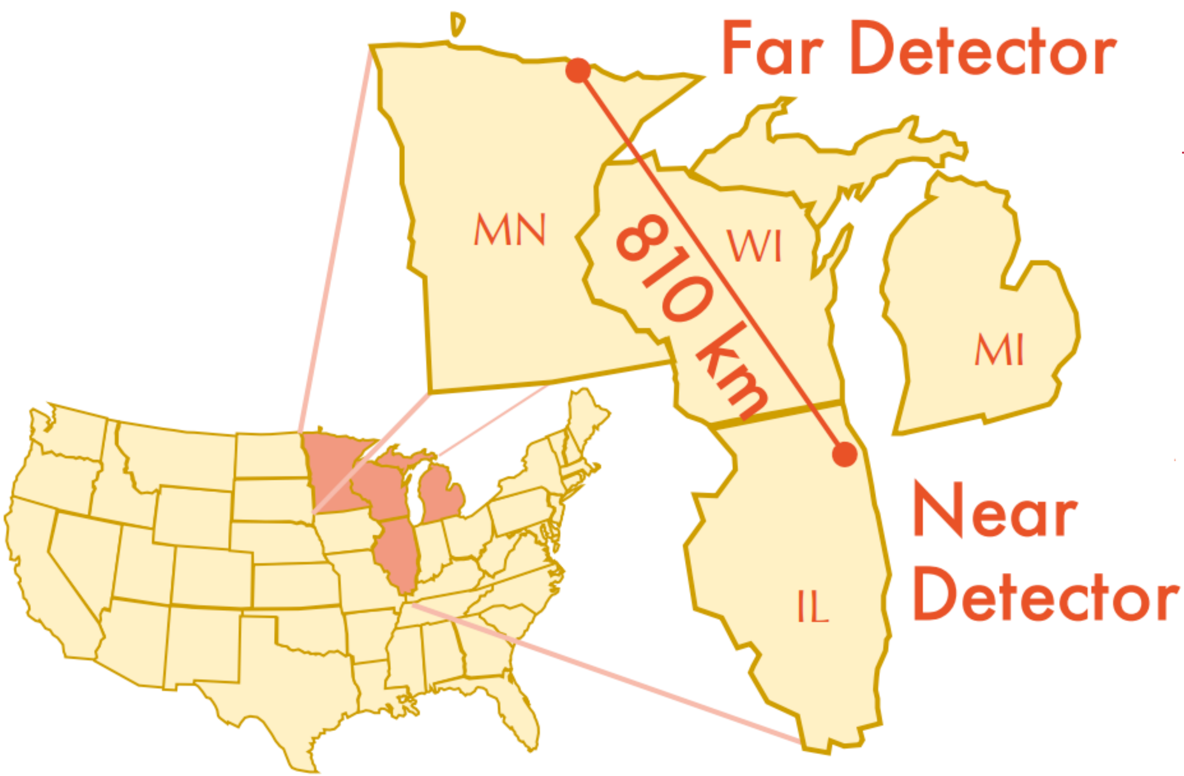
26 September 2017

NuMI Off-Axis ν_e Appearance Experiment

NOvA is a long-baseline neutrino oscillation experiment located 14 mrad off-axis from the NuMI beam designed to measure:



ν_e appearance

- Mass hierarchy
- θ_{23} octant
- CP violation

ν_μ disappearance

- Improved precision on $|\Delta m^2_{32}|$ and θ_{23}

NC disappearance

- Search for sterile neutrinos
- Constrain θ_{34} and θ_{24}

Others

- Short-baseline steriles
- Cross sections
- Supernovae
- Exotics

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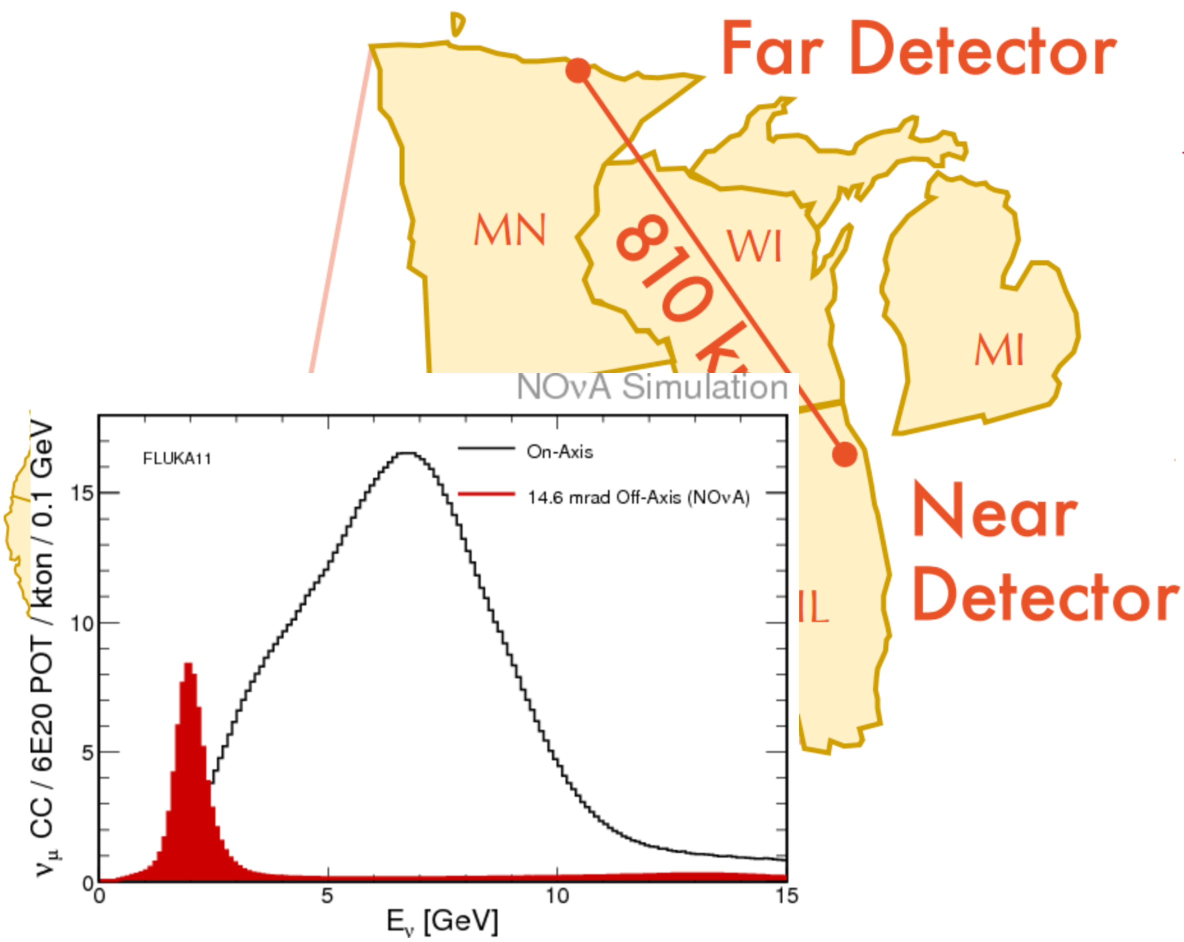

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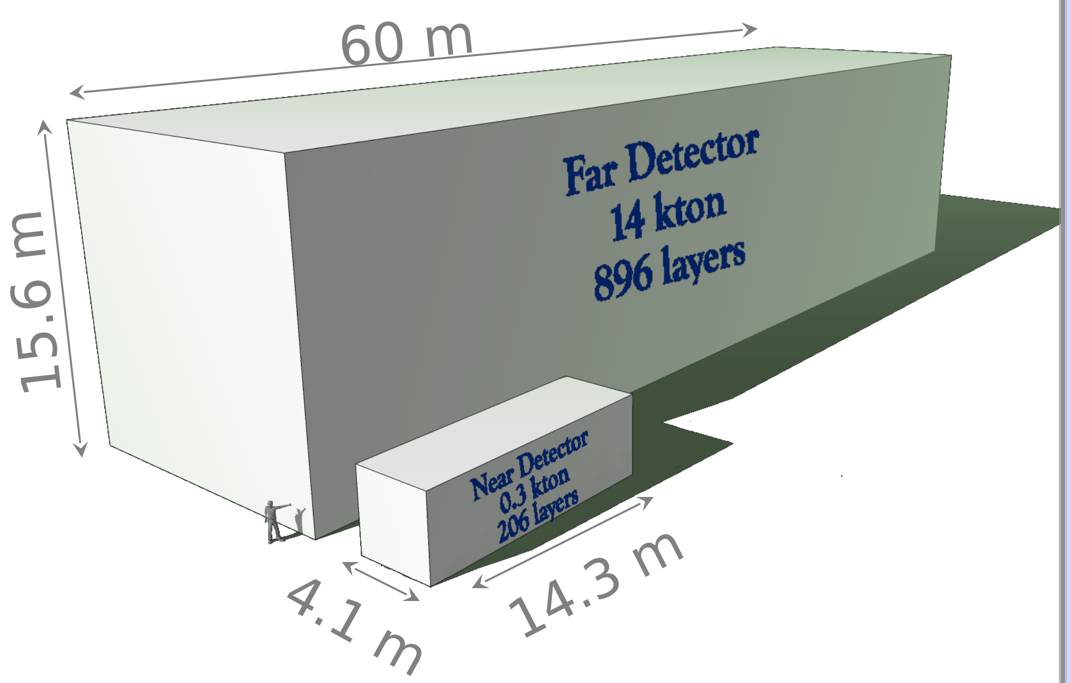
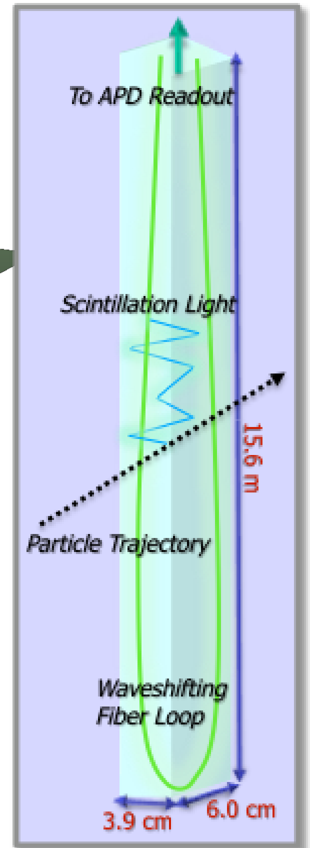
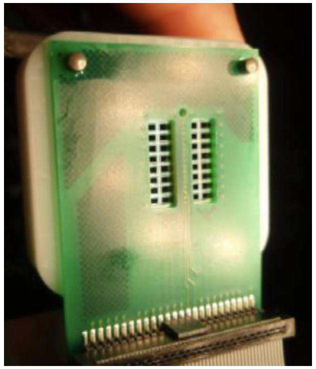
NOvA Detector Design





Low Z tracking calorimeter composed of alternating horizontal and vertical planes of liquid scintillator filled cells.



Far detector (FD)

- 14 kton
- 65% active mass
- ~344,000 channels

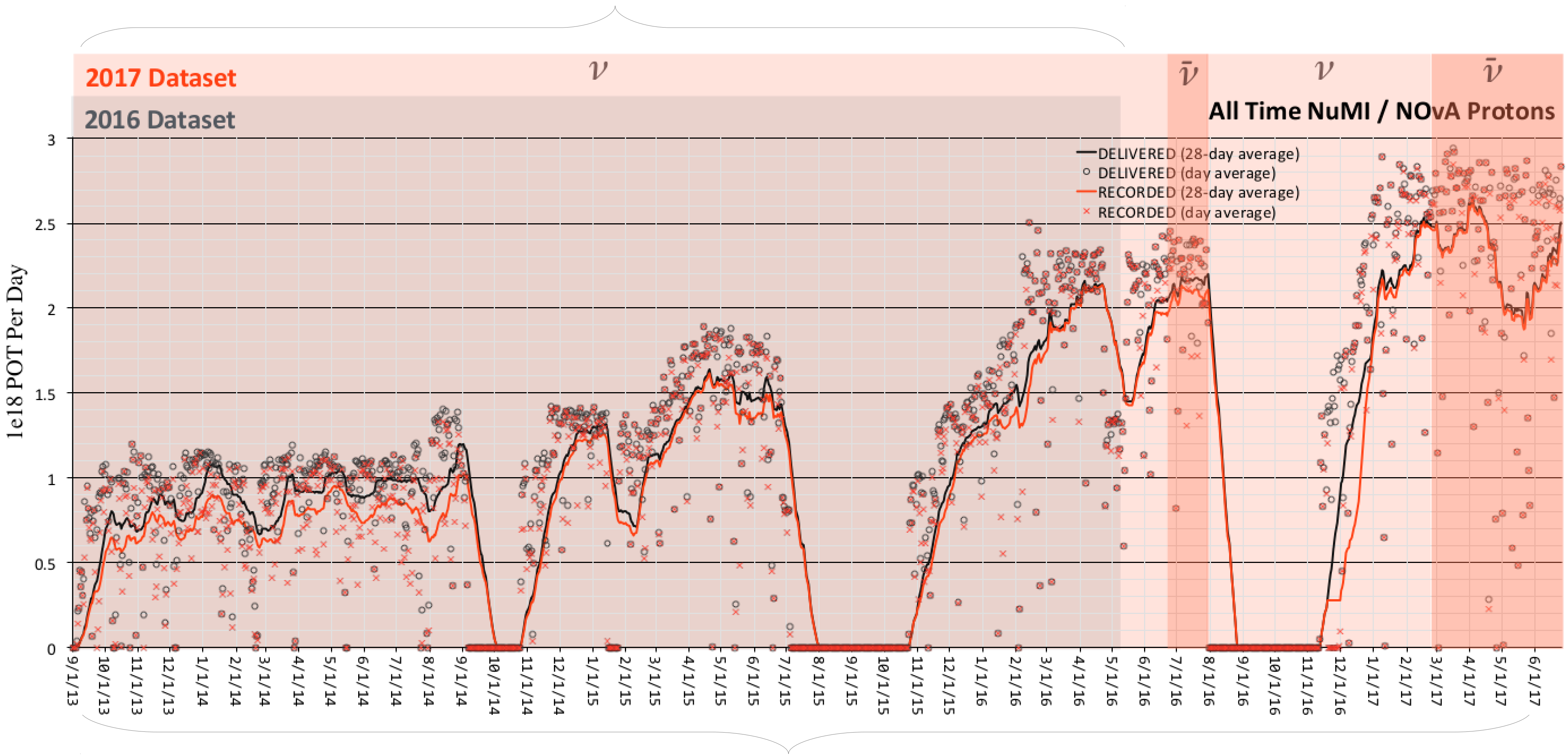
Near detector (ND)

- 0.3 kton
- Functionally equivalent to FD for systematic uncertainty reduction
  - Faster electronics
  - Muon catcher to contain muons
- ~20,000 channels

Wavelength shifting fibers carry light out of the cells to APDs.

Accumulated Dataset

2016 analysis: 6 Feb 2014 – 1 May 2016 ⟶ 6.05×10^{20} POT

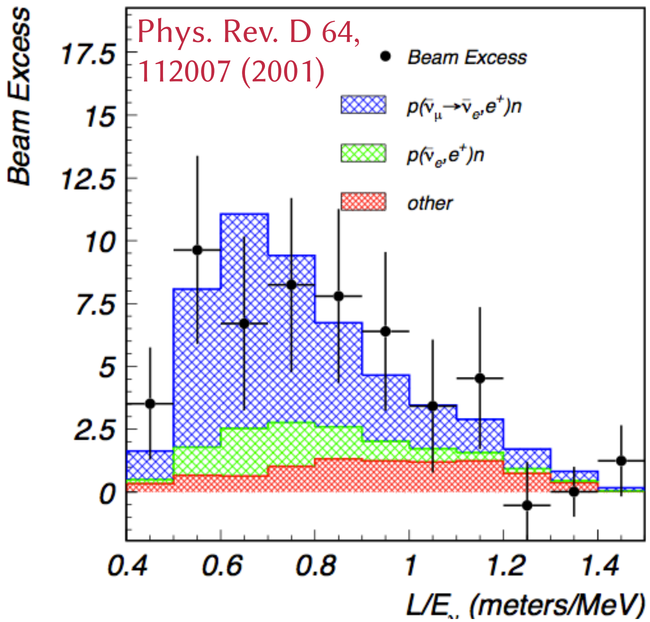


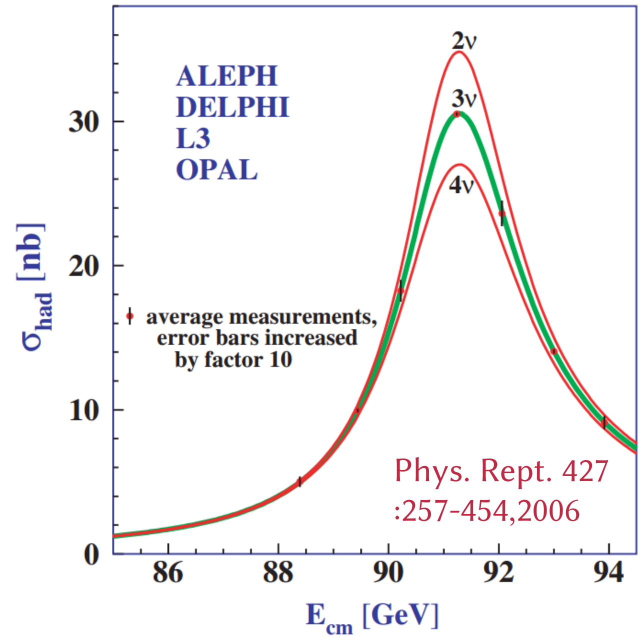
2017 analysis: 6 Feb 2014 – 20 Feb 2017 ⟶ 8.85×10^{20} POT

~50% increase in exposure

Sterile Neutrinos

- Short-baseline experiments (LSND, MiniBooNE) observed anomalous excesses of ν_e ($\bar{\nu}_e$) appearance in ν_μ ($\bar{\nu}_\mu$) beams
- Observed rate from calibration sources used at gallium radiochemical solar neutrino experiments produced results consistent with ν_e or $\bar{\nu}_e$ disappearance over short baselines
- The anomalies could all be explained by oscillations driven by a mass splitting $\Delta m^2 \sim 1\ \mathrm{eV}^2$
  - Not consistent with three known flavors
- Measurement of Z decays at LEP only allows for three light active neutrinos
  - Any extra light neutrino must be sterile





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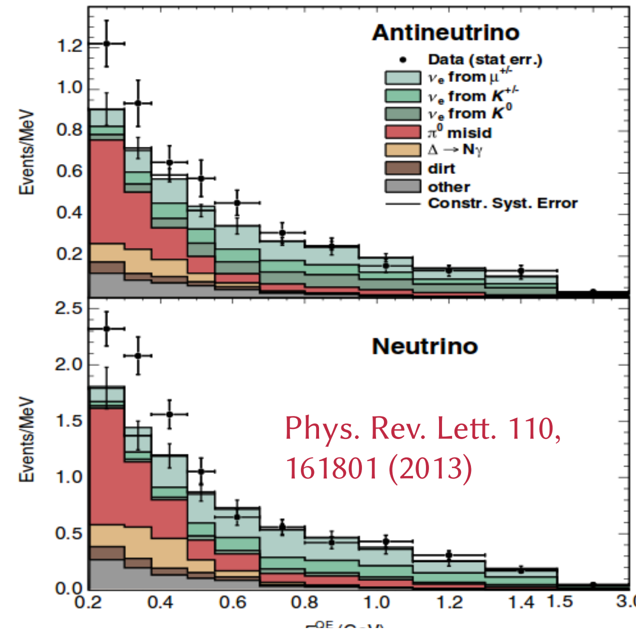
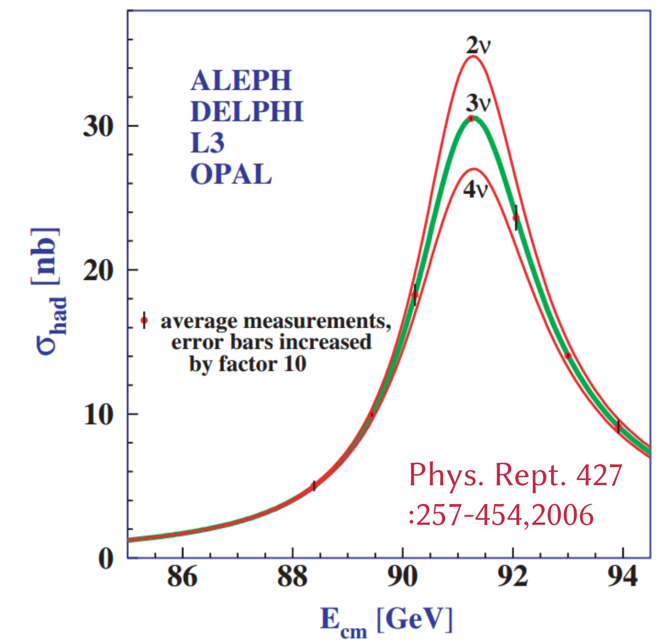


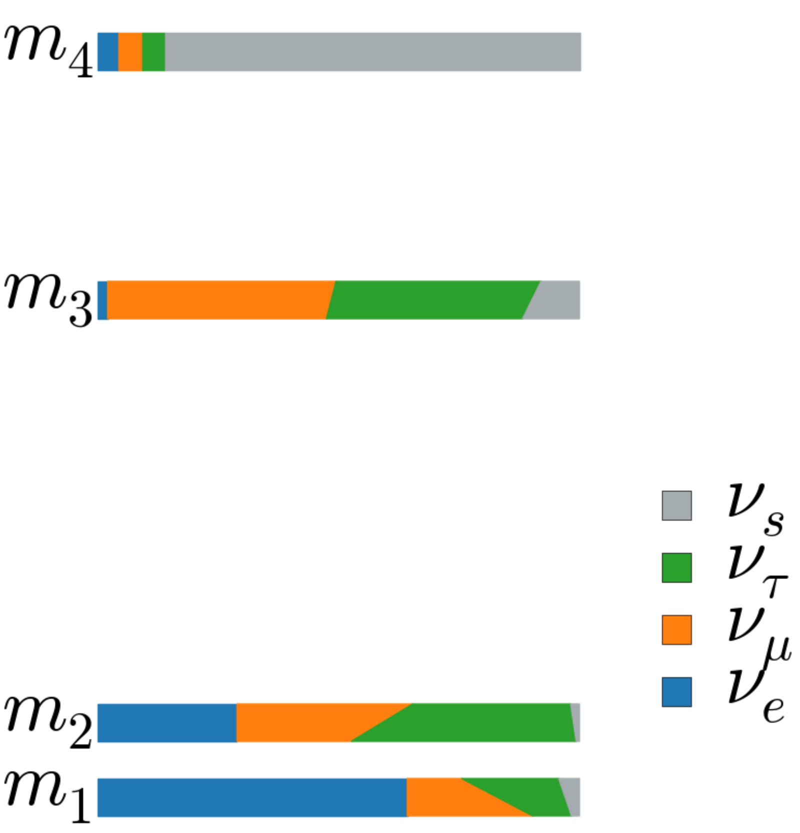
Phys. Rev. Lett. 110, 161801 (2013)



Phys. Rept. 427 :257-454,2006

3+1 Model

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



- Simplest model adds one sterile neutrino
- 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 for Sterile Neutrinos Using Neutral Currents

- Neutral current interaction rate is the same for 3 active neutrinos
  - NC rate is insensitive to 3 flavor oscillations
- Sterile neutrino do not interact in the detector
  - $\nu_\mu \longrightarrow \nu_s$ reduce the NC rate at the FD
- One oscillation term for $\nu_\mu \longrightarrow \nu_s$ oscillations at atmospheric frequency
- Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum

$$
\begin{aligned}
& 1 - P(\nu_\mu \to \nu_s) \approx \\
& 1 - 4\left|U_{\mu 3}\right|^2\left|U_{s3}\right|^2 \sin^2\Delta_{31} \\
& \quad - 4\left|U_{\mu 4}\right|^2\left|U_{s4}\right|^2 \sin^2\Delta_{41} \\
& \quad - 8\,\mathrm{Re}\left(Z\right)\sin\Delta_{31}\cos\Delta_{43}\sin\Delta_{41} \\
& \quad - 8\,\mathrm{Im}\left(Z\right)\sin\Delta_{31}\sin\Delta_{43}\sin\Delta_{41} \\
& Z = U^*_{\mu 4}U_{s4}U_{\mu 3}U^*_{s3}
\end{aligned}
$$

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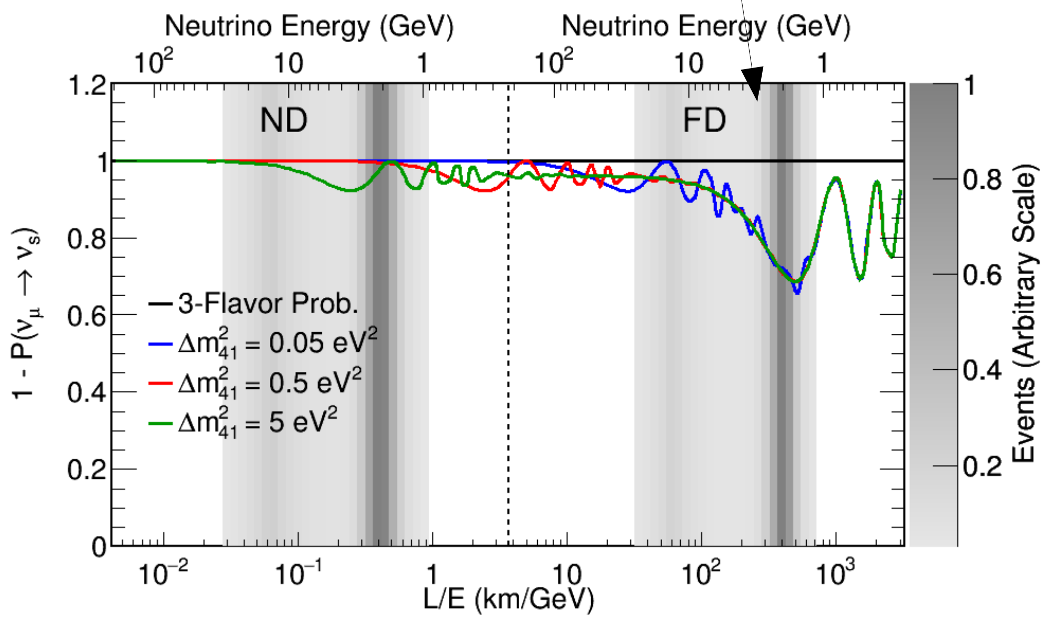
- Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum
- Search in $0.05\ \mathrm{eV}^2 < \Delta m^2_{41} < 0.5\ \mathrm{eV}^2$
  - No significant ND oscillations
  - Rapid oscillations at FD $\longrightarrow$ no Δm^2_{41} dependence

$$
\begin{aligned}
1 - P(\nu_\mu \to \nu_s) \approx 1 &- \frac{1}{2}\cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24} \\
&+ \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31} \\
&- \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin 2\Delta_{31}
\end{aligned}
$$

Rapid oscillation approximation
(exact formula used for fitting)



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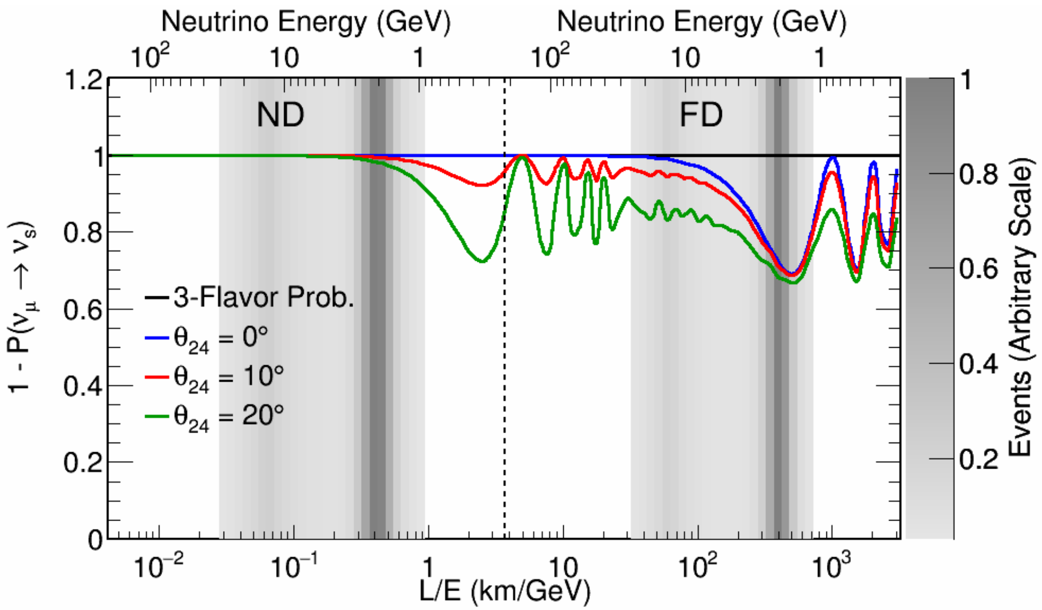
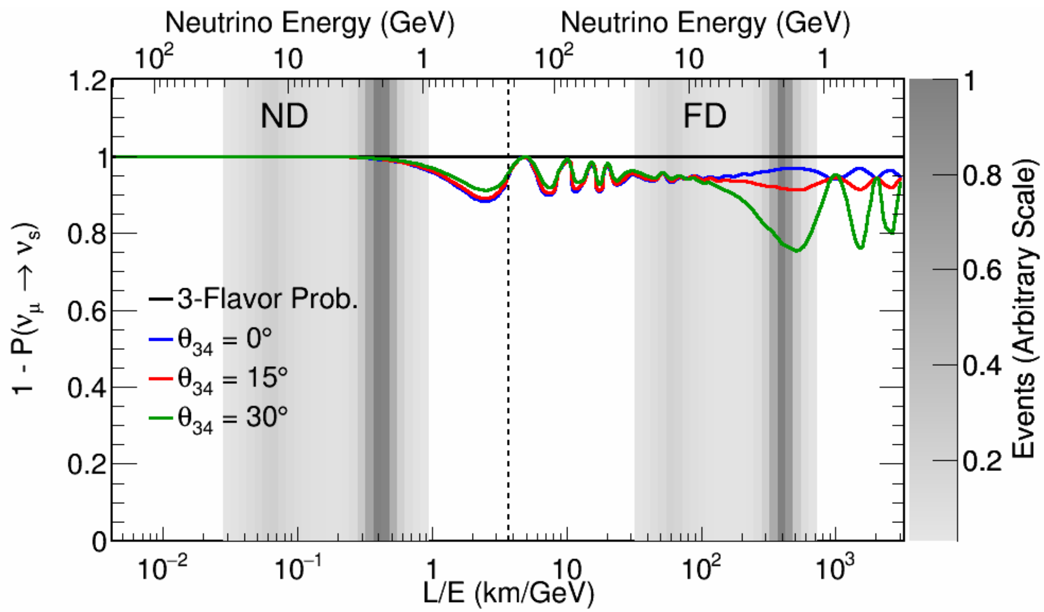
- One oscillation term for $\nu_\mu \rightarrow \nu_s$ oscillations at atmospheric frequency
- Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum
- Depth of oscillations at the oscillation maximum is primarily controlled by θ_{34}
- θ_{24} scales shape of descent into the oscillation maximum





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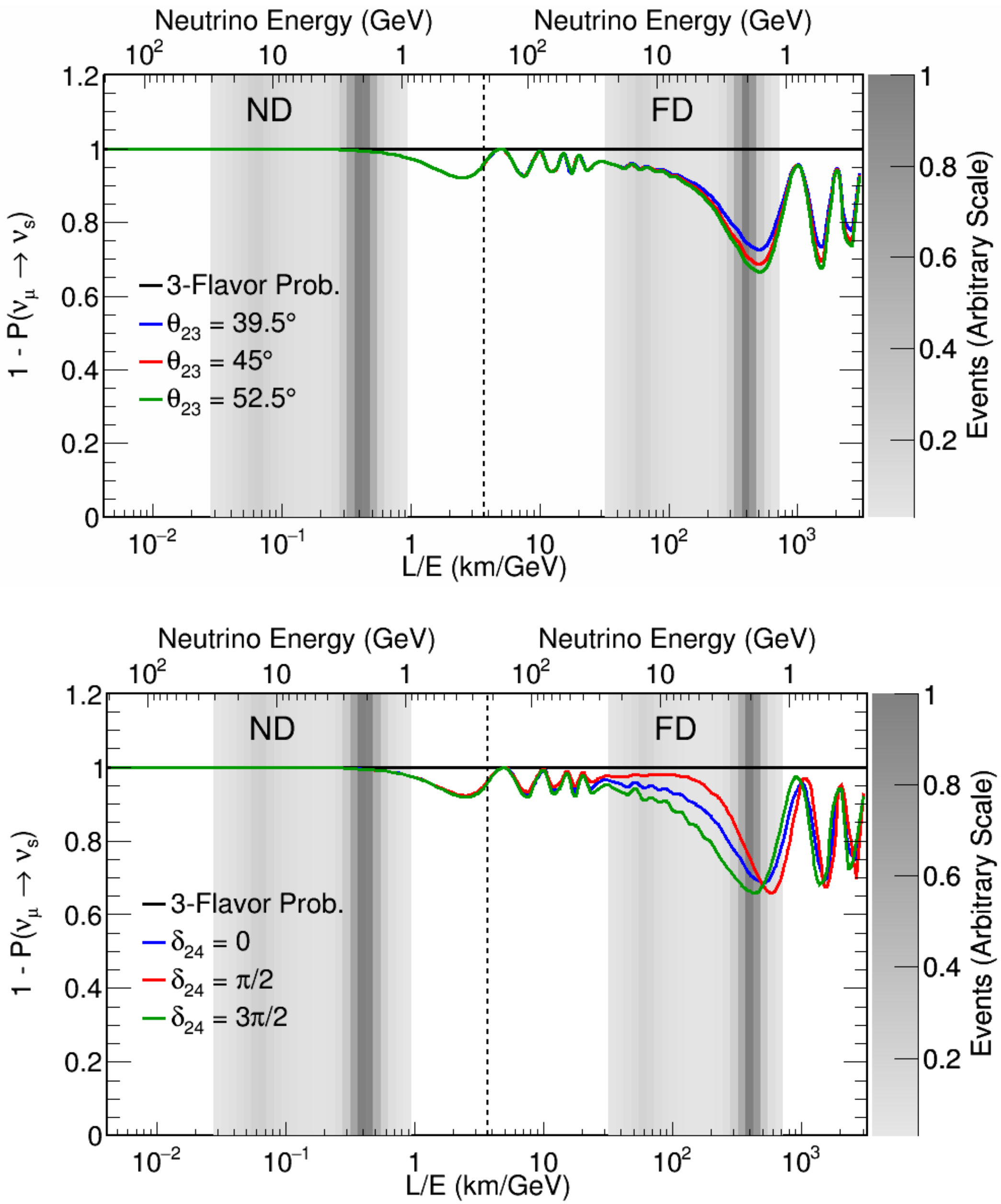
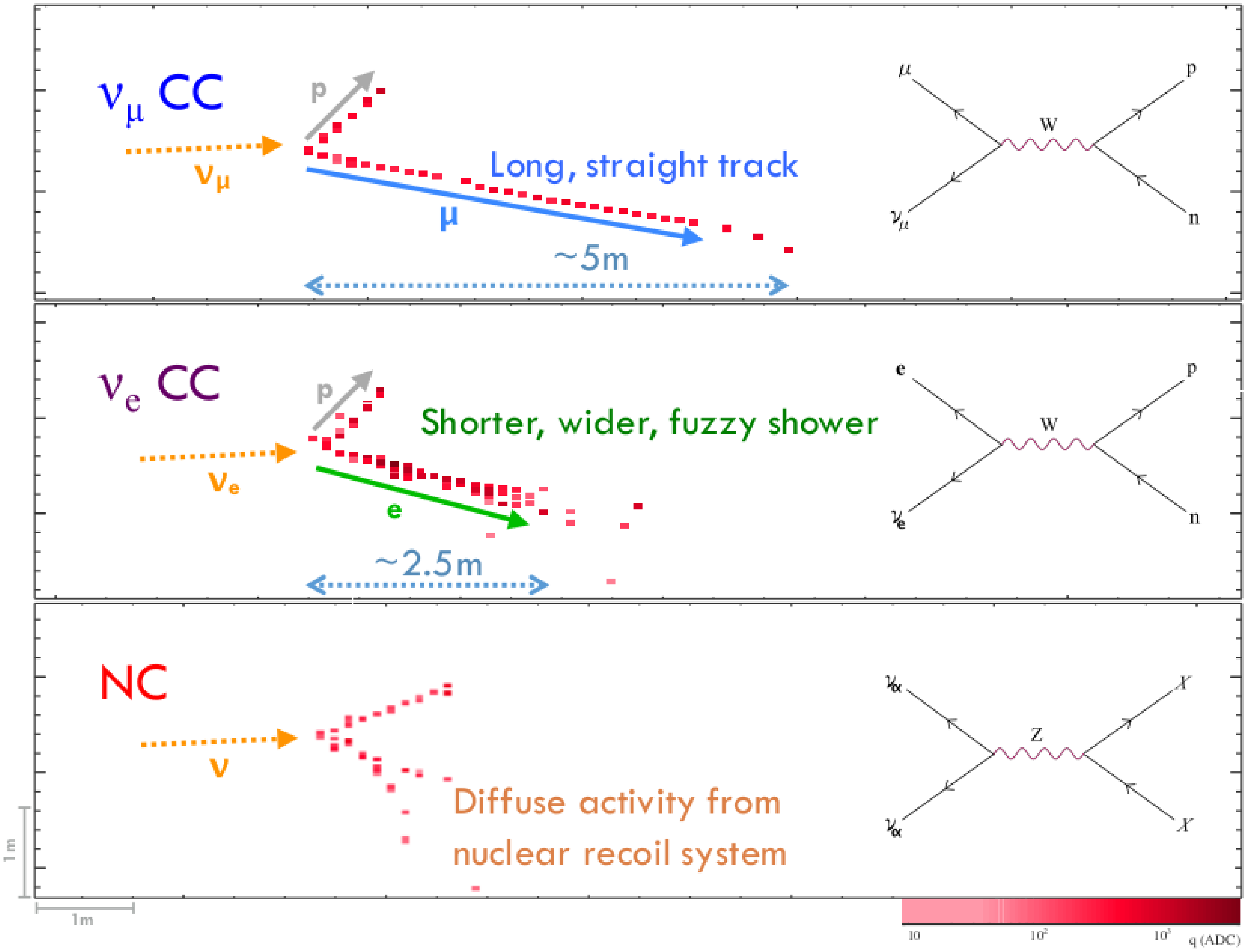
  - $\nu_\mu \rightarrow \nu_s$ reduce the NC rate at the FD
- One oscillation term for $\nu_\mu \rightarrow \nu_s$ oscillations at atmospheric frequency
- Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum
- θ_{23} also controls the depth of the oscillation maximum
  - Constrain to the NOvA degenerate minima
- The CP-violating phase, δ_{24}, can reduce NC disappearance even as θ_{24} and θ_{34} become large.



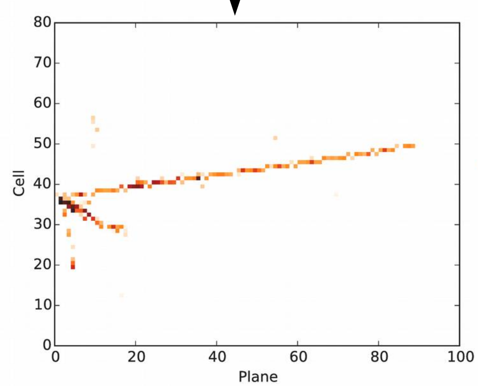
Event Topologies



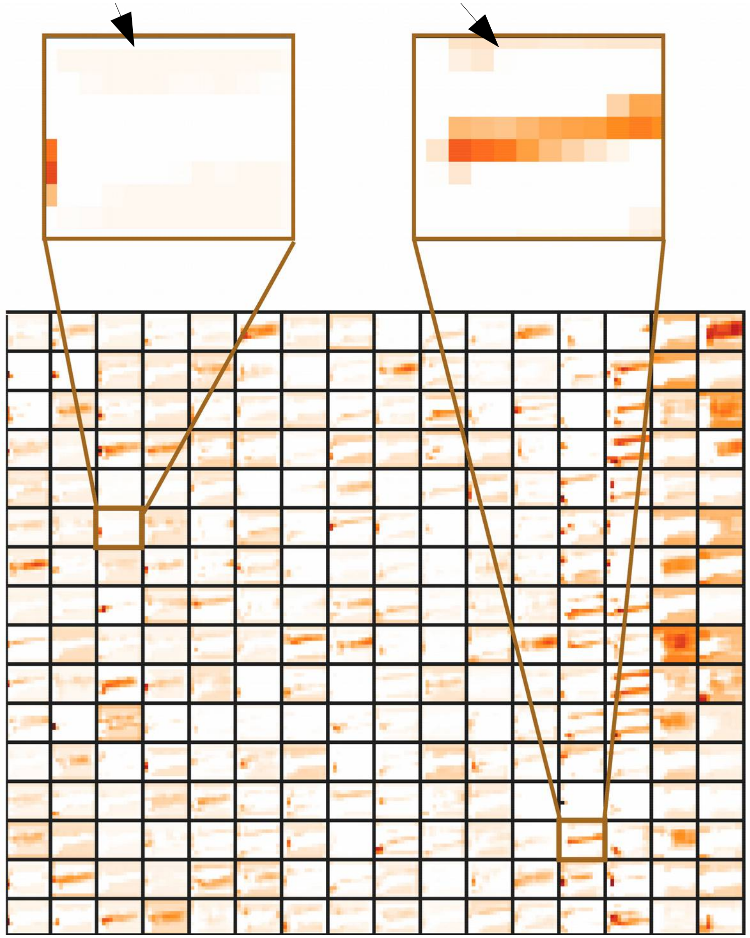
Convolutional Visual Network

- Convolutional Visual Network (CVN) is a selection algorithm based on Deep-Learning techniques
- Uses all information in minimally reconstructed events
- Is a multi-purpose classifier
  - Capable of selecting ν_e, ν_μ, ν_τ, and NC

Treat each event as an image with cells as pixels and charge as color value



Individual learned filters are sensitive to physics: e.g. hadronic activity or muon tracks

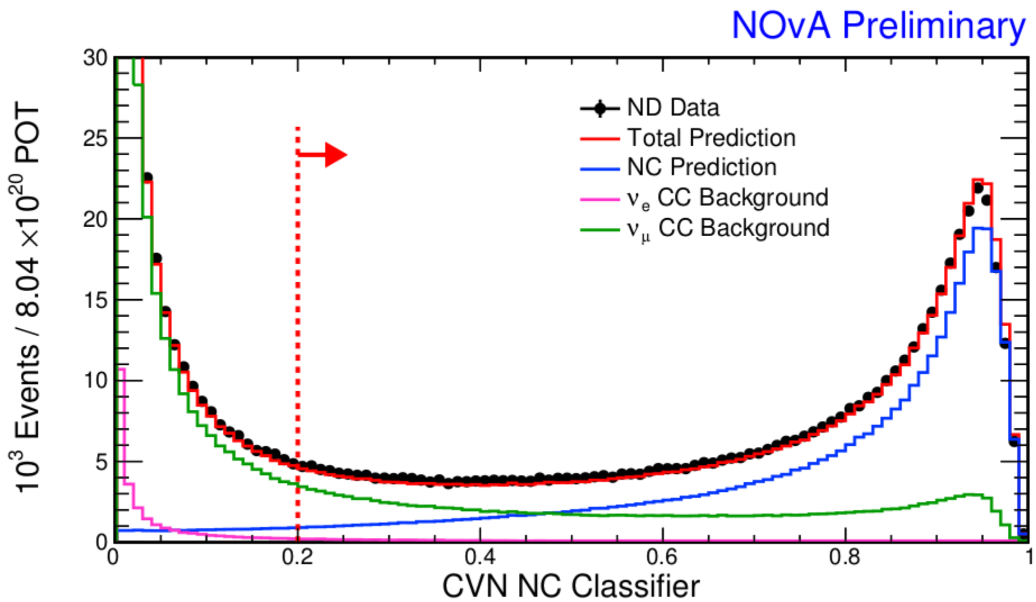


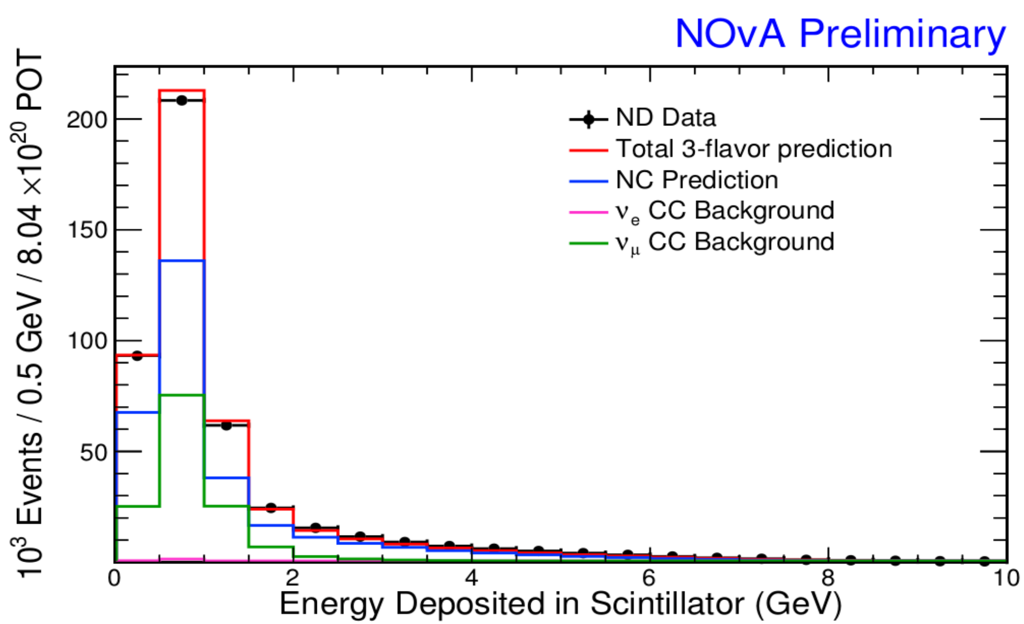
Convolutional layers learn filters to optimally extract features from the data

JINST 11 (2016) P09001

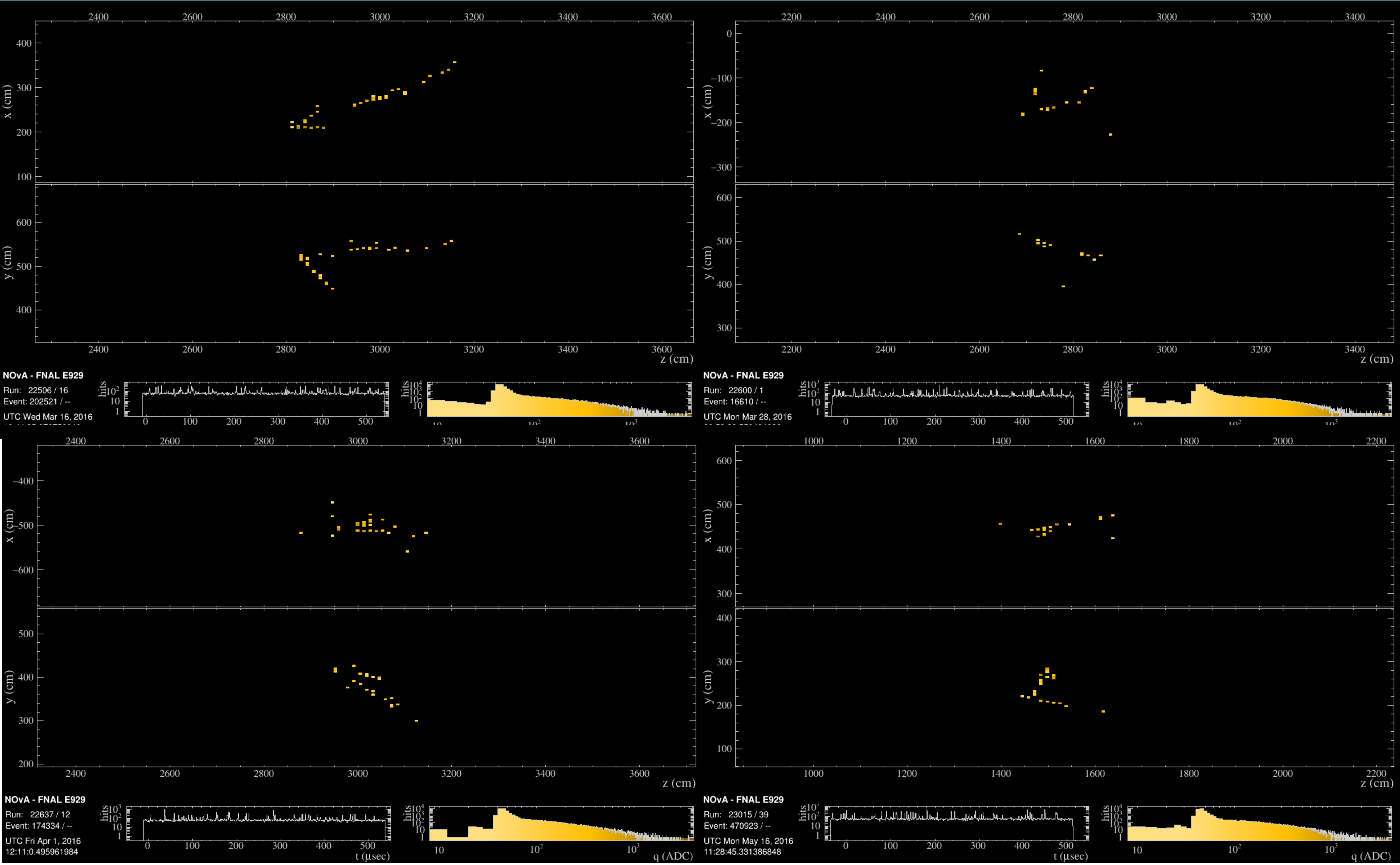
NC/CC Separation

- The CVN NC classifier is excellent at separating NC events from beam background
- Good data/MC agreement in the ND



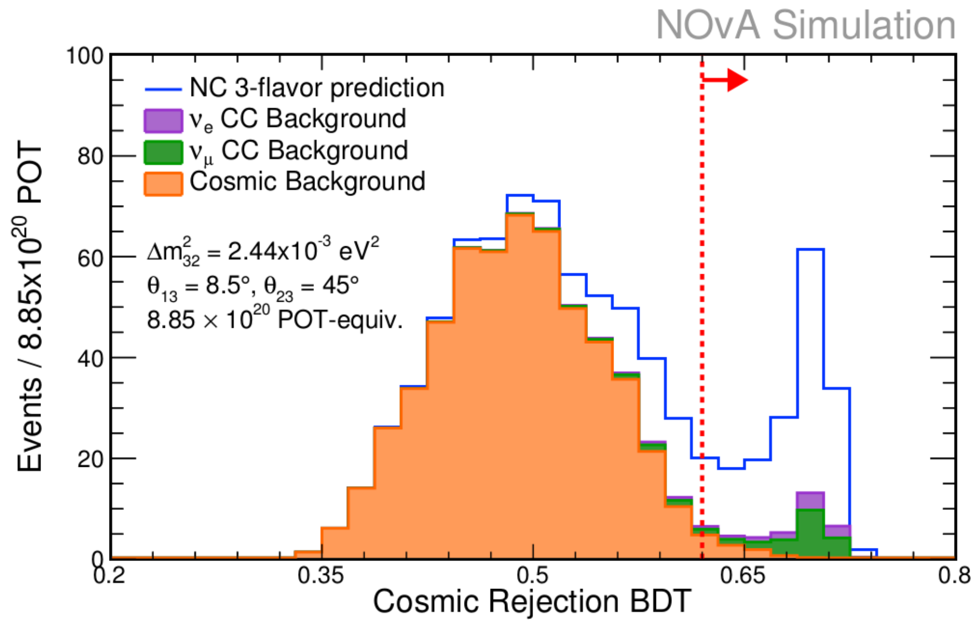


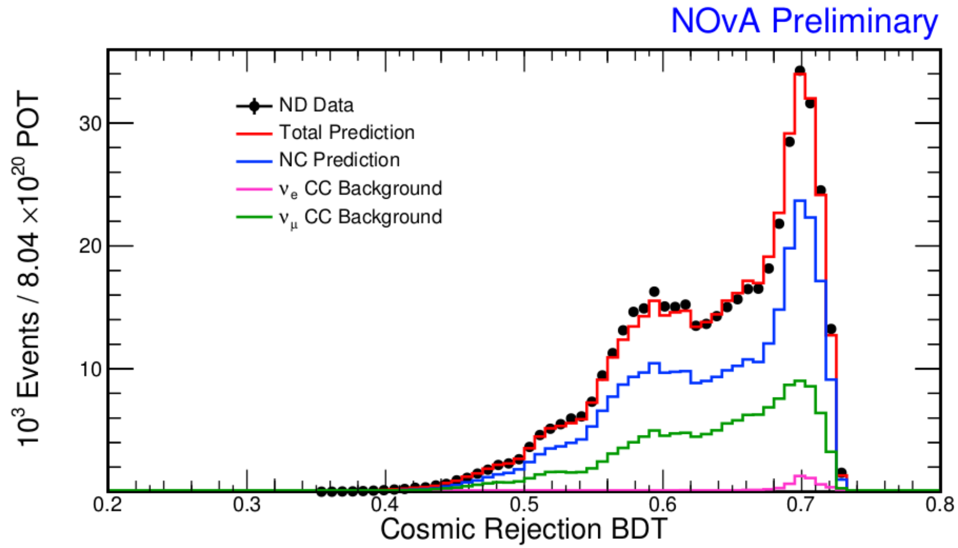
Rejecting Cosmic Events



Rejecting Cosmic Events

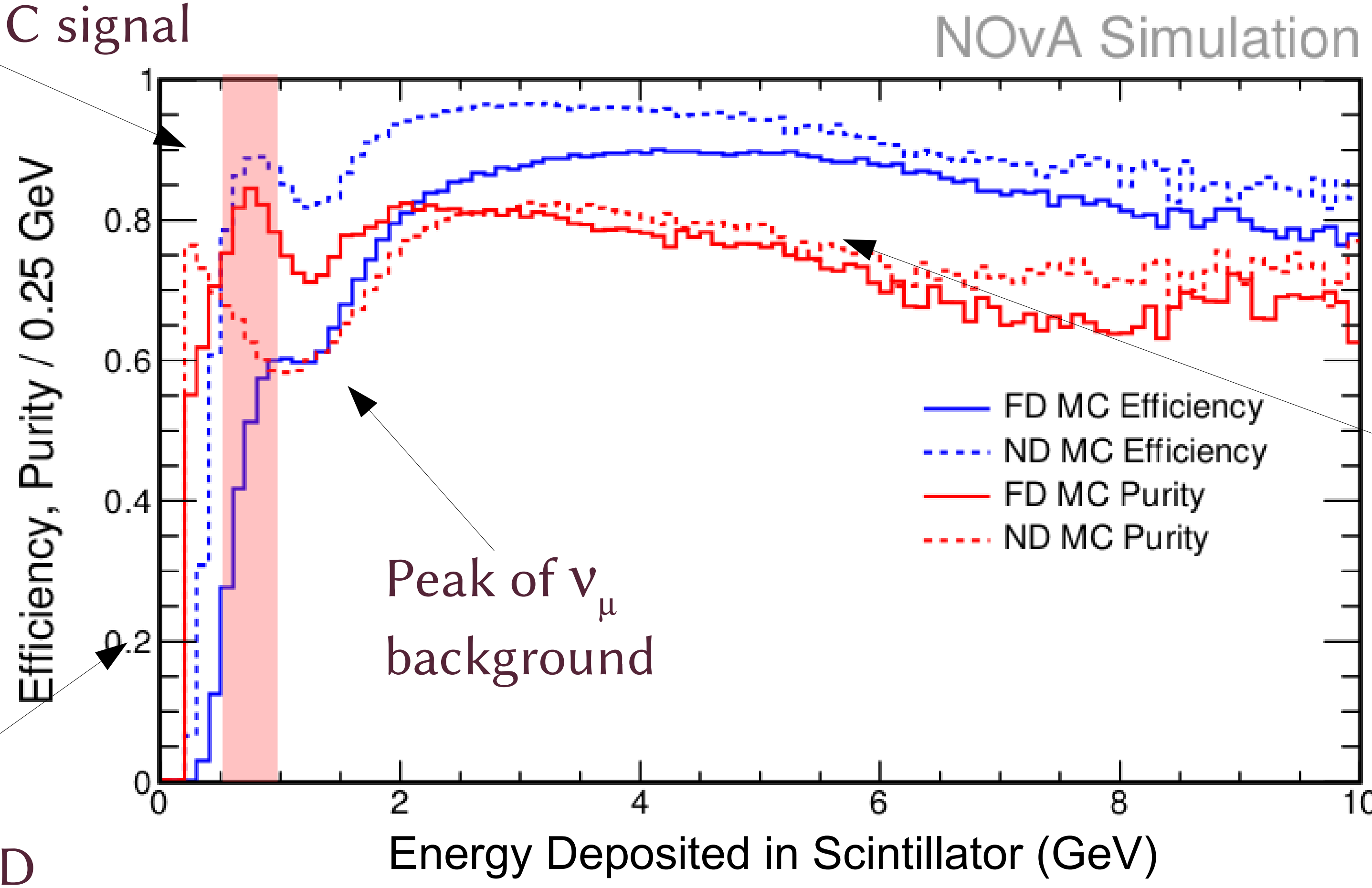
- The FD sees ~150,000 cosmic rays/second
- Cosmogenic neutrons can be difficult to separate from NC events
- In 2016 analysis, removed all events in the top 5 m of the FD
- Replacing this cut with a BDT designed to separate cosmogenic neutrons and NC events using reconstructed shower variables
- Reduces the cosmic rate by 50% compared to the 2016 analysis





NC Selection: Efficiency and Purity

Peak of NC signal



Peak of ν_μ background

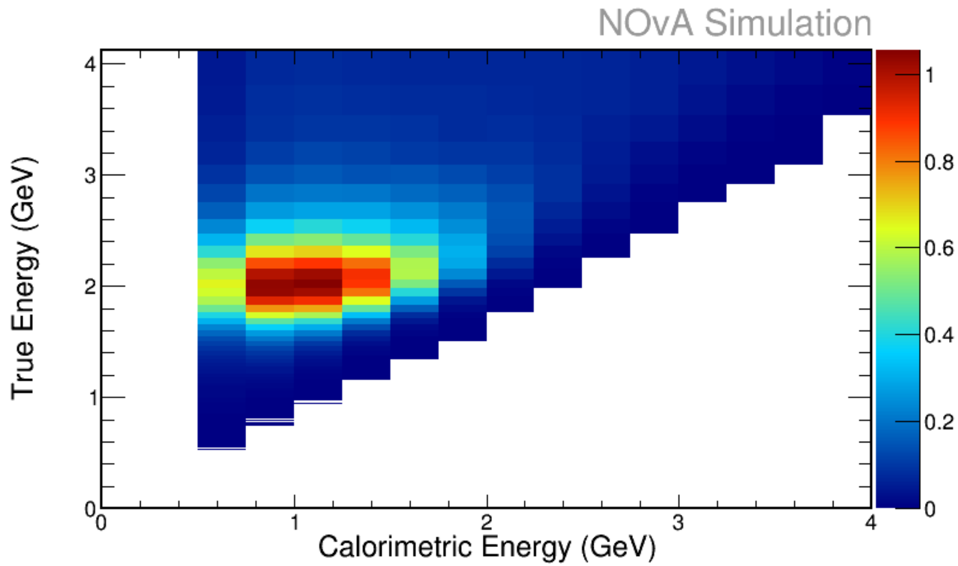
Flat efficiency and purity above the ν_μ background peak

Drop in FD efficiency at low energy due to cosmic rejection

	Efficiency	Purity
ND	50%	67%
FD	52%	77%

Extrapolation

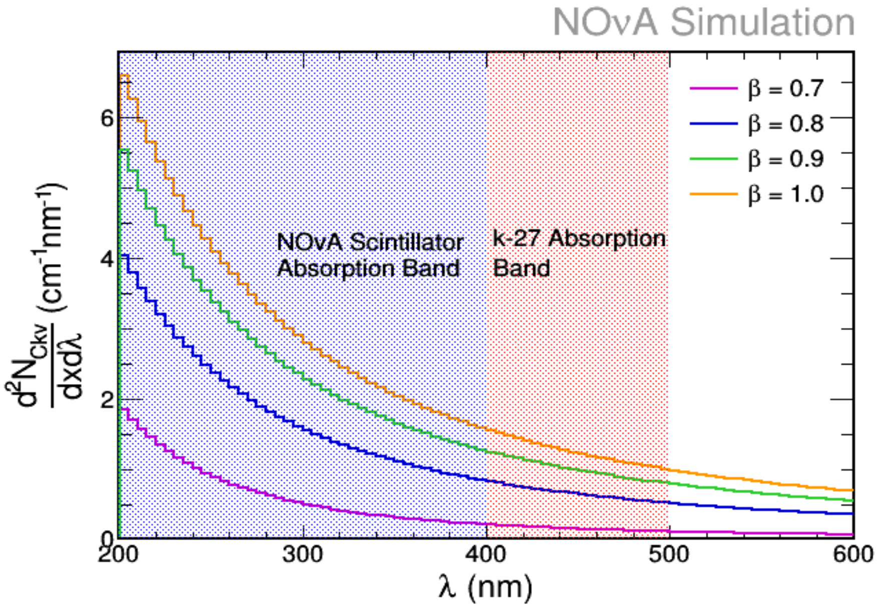
- The FD prediction is generated using the extrapolation process
  - Partially cancels systematics uncertainties that are correlated between the ND and FD
- Since each component oscillates differently, decompose observed ND spectrum according to simulated proportions
- Use a migration matrix to convert reconstructed energy to true energy
- The data and MC ND components are used to correct the corresponding FD component
- Apply oscillations and unfold back to reconstructed energy

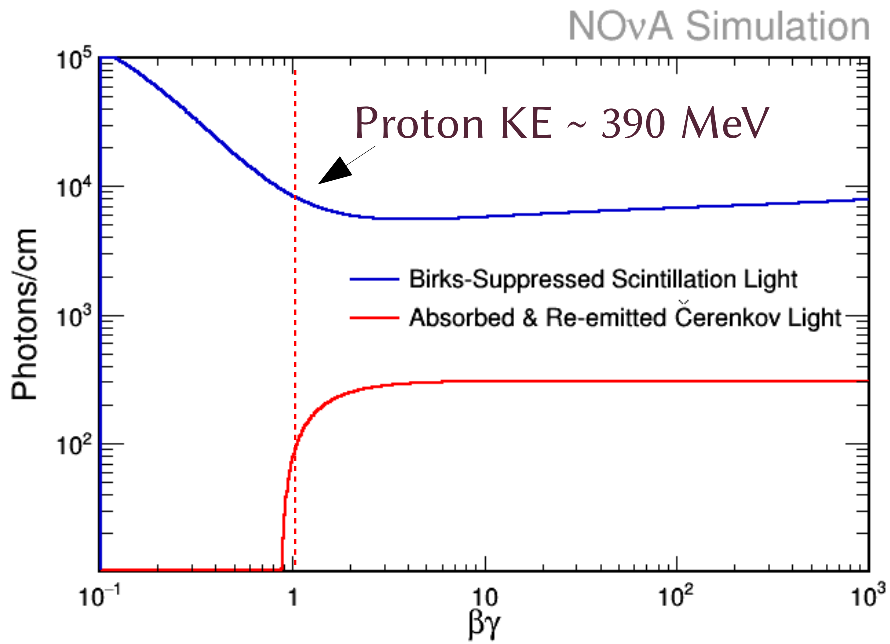


$$F_{jk\beta}^{\text{pred}} = \sum_{\alpha} \frac{N_{jk\alpha}^{\text{data}}}{N_{jk\alpha}^{\text{sim}}} \, F_{jk\beta}^{\text{sim}} \, P(\nu_\alpha, \nu_\beta).$$

Improvements to Detector Response Modeling

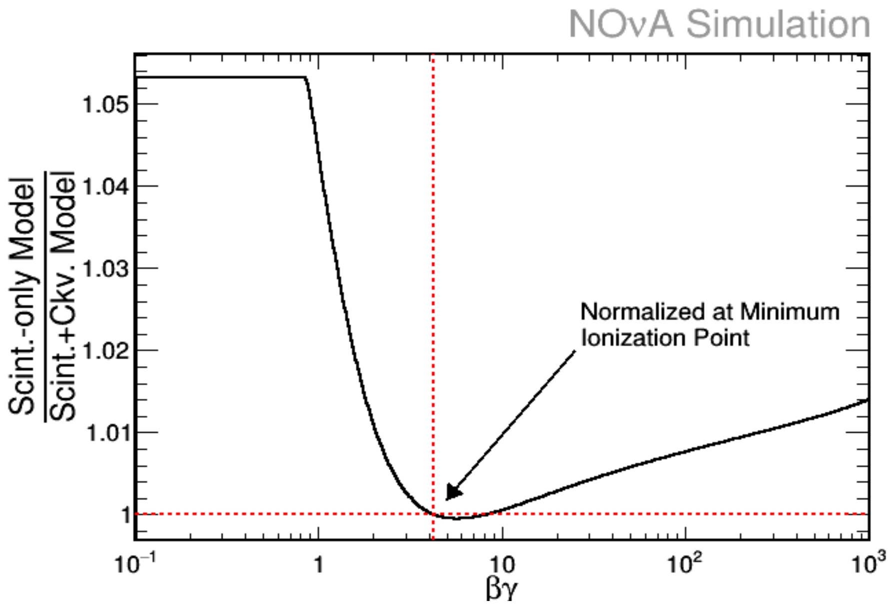
- In scintillation-based experiments, Cerenkov light is often neglected
- Scintillation yields are very large compared to Cerenkov light yields
- Most Cerenkov light is produced at short wavelengths that cannot be absorbed by the NOvA
- However, short wavelength light can be absorbed by the pseudocumene, PPO, and bis-MSB in scintillator
- Absorbed and re-emitted Cerenkov light is a small but important signal that is particularly important for the modeling of the detector response to hadronic activity

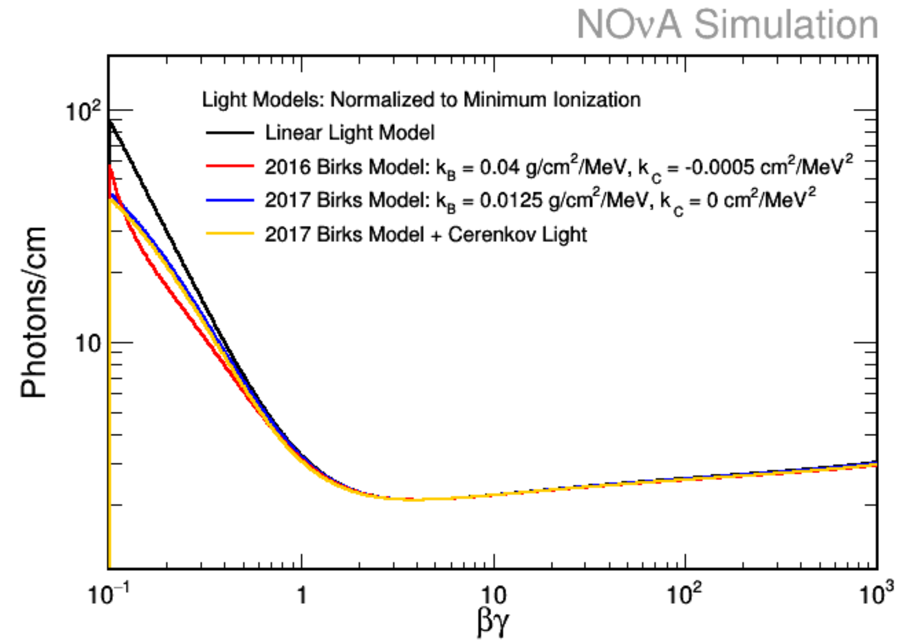




Improvements to Detector Response Modeling

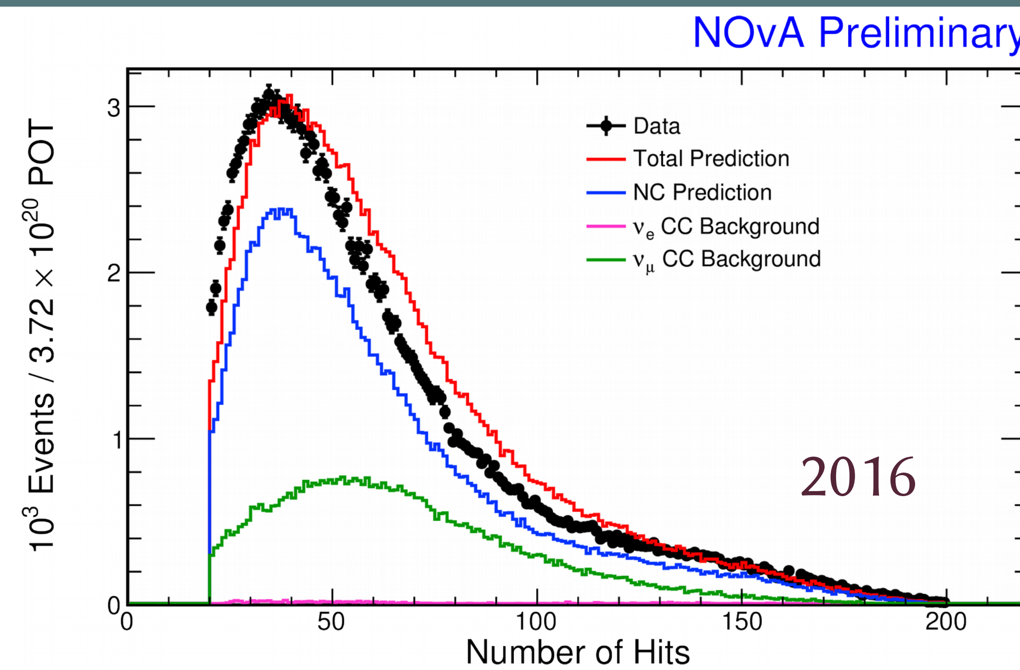
- The detector energy response is calibrated using the energy deposited by stopping cosmic muons at their minimum ionization point
- Failing to account for Cerenkov light biases the calibration of slow particles by ~ 5%
- In previous analyses, the resulting hadronic data/MC disagreement was minimized by tuning scintillator quenching, requiring significant systematic uncertainties

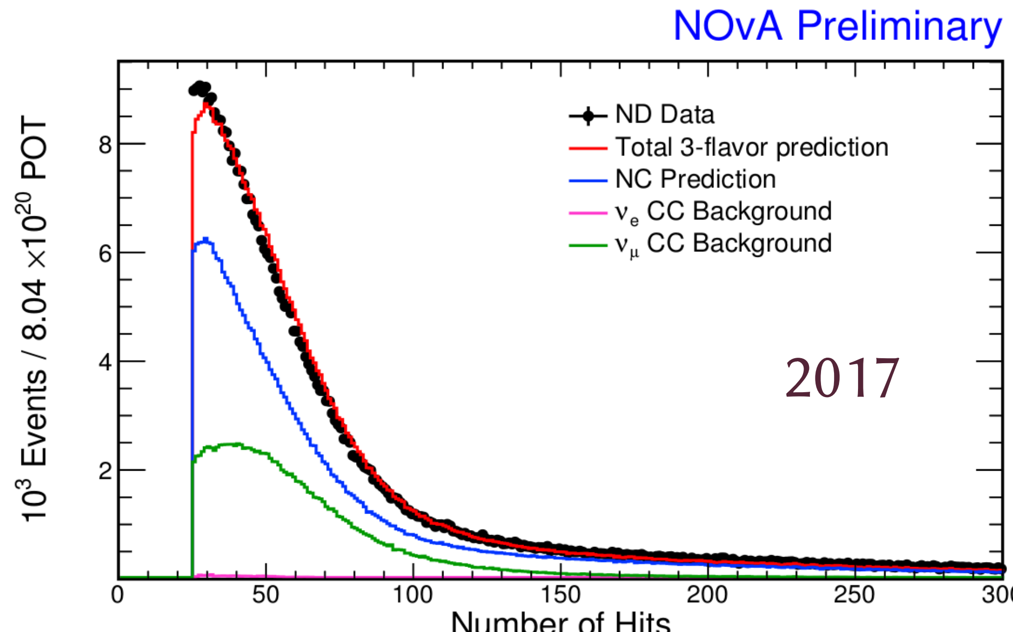




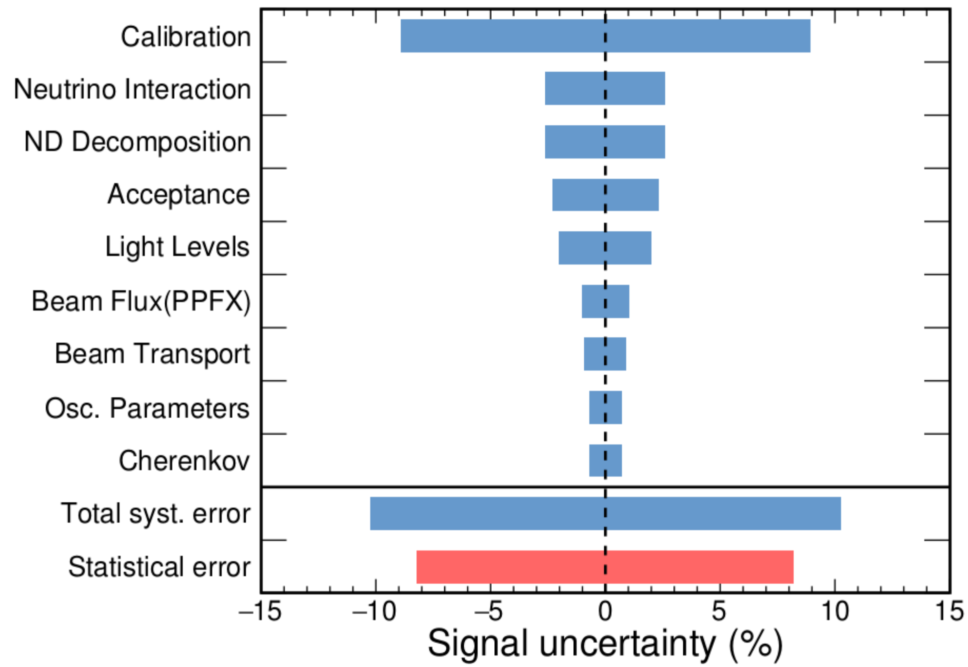
Improvements to Detector Response Modeling

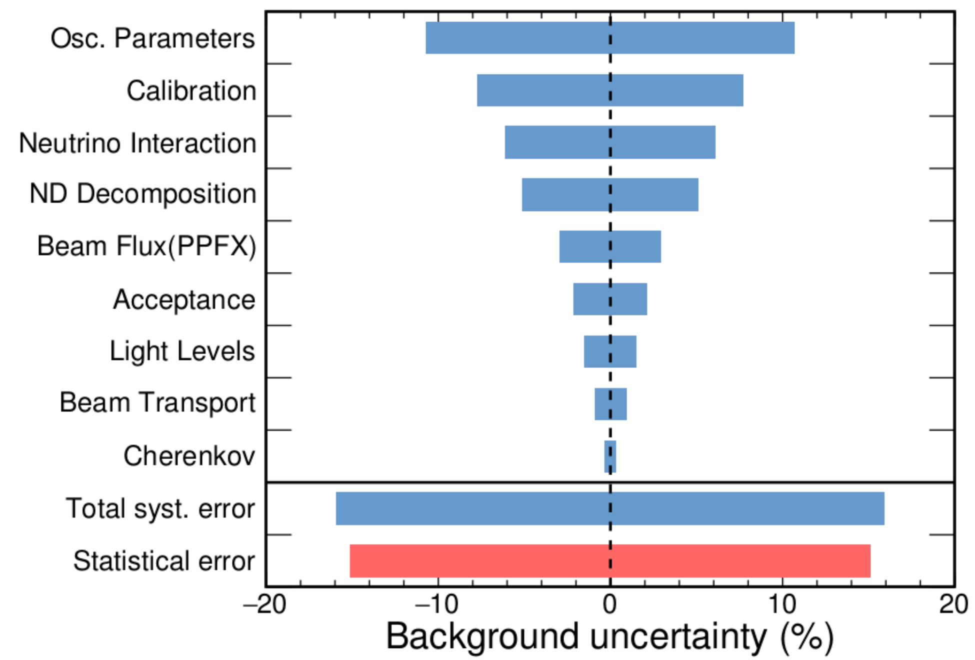
- Modeling the absorption and re-emission of Cerenkov light produced significant improvements in data/MC agreement, especially for:
  - Number of hits
  - Energy/hit
- Allows for a reduction in systematic uncertainties





Systematics





- ND Composition systematic is determined by extrapolating the ND data/MC disagreement differently
- Previously the largest systematic (7% for signal, 10% for background)
- Due to improved modeling of the hadronic system, this uncertainty is halved

FD Prediction

- Predictions depend on the choice of three flavor parameters
- NOvA's combined ν_e and ν_μ analysis found two degenerate best fits
  - Lower octant
    - $\sin^2\theta_{23} = 0.404 \pm 0.030$
    - $\delta_{13} = 1.48\pi$
    - $\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3}\ \mathrm{eV}^2$
  - Upper octant
    - $\sin^2\theta_{23} = 0.623 \pm 0.030$
    - $\delta_{13} = 0.74\pi$
    - $\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3}\ \mathrm{eV}^2$
- In the 2016 analysis, cosmics were the dominant background
- After analysis improvements, ν_μ CC is the dominant background

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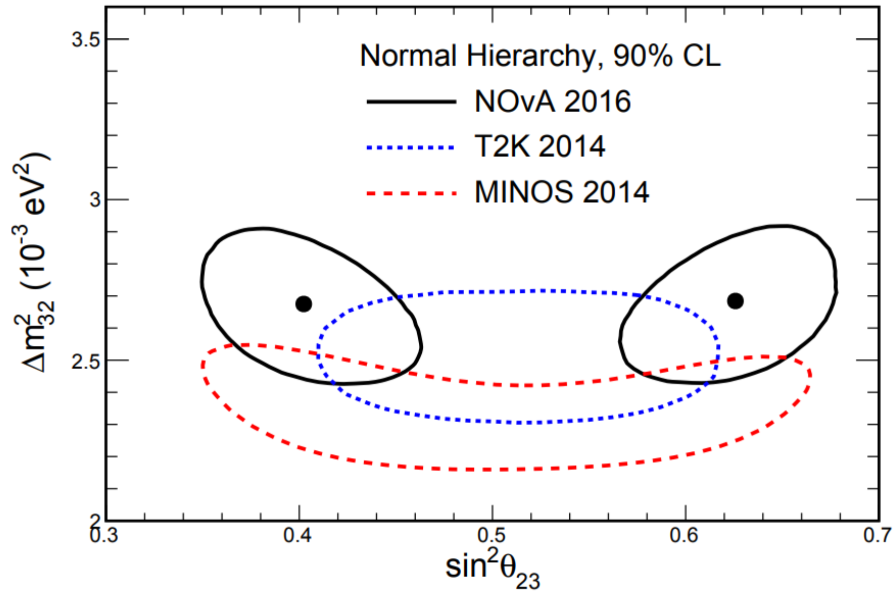
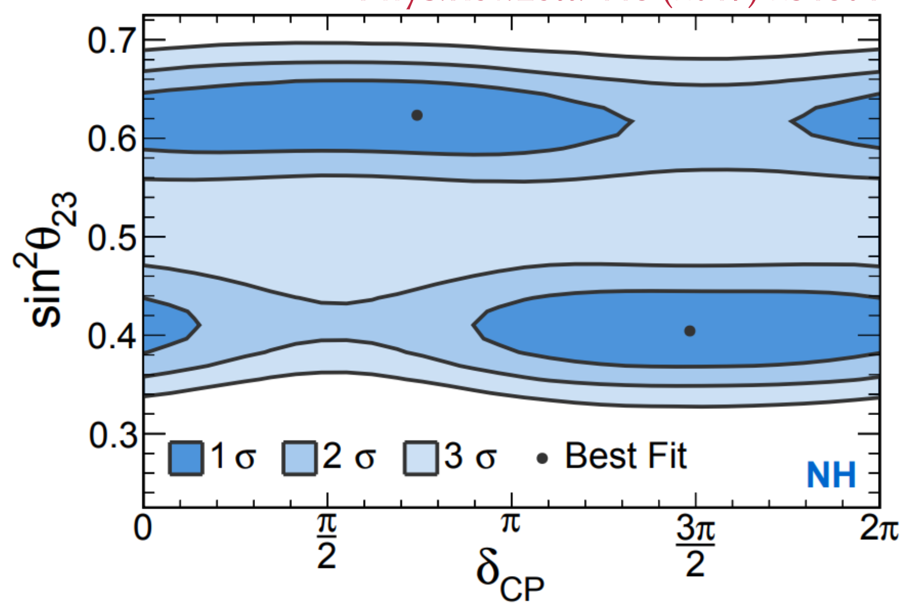


Phys.Rev.Lett. 118 (2017) 231801



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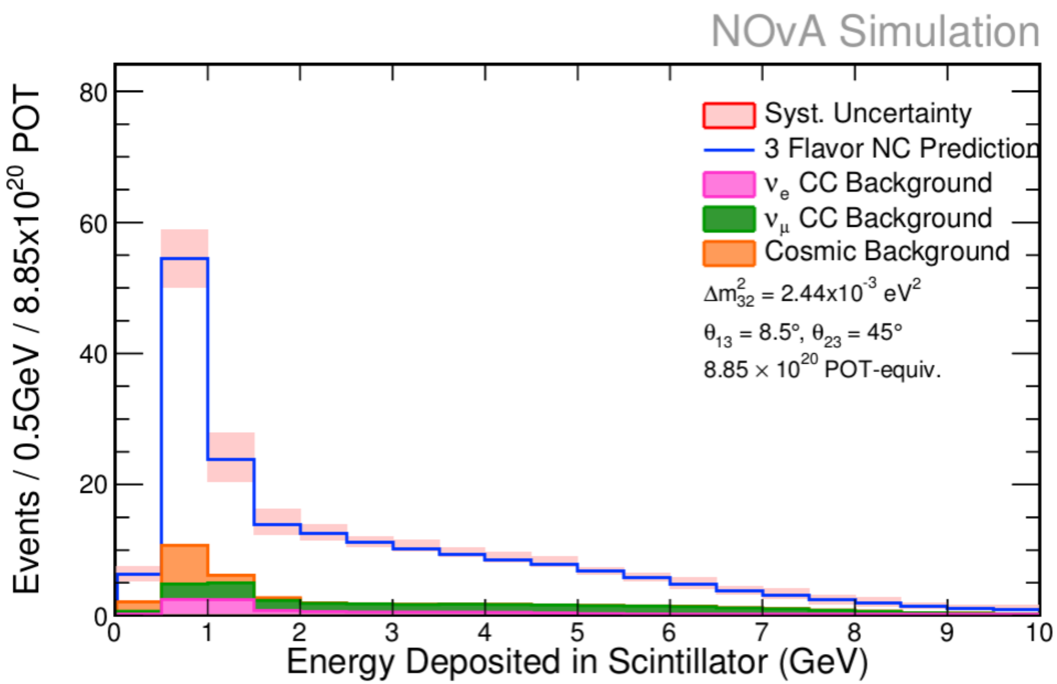
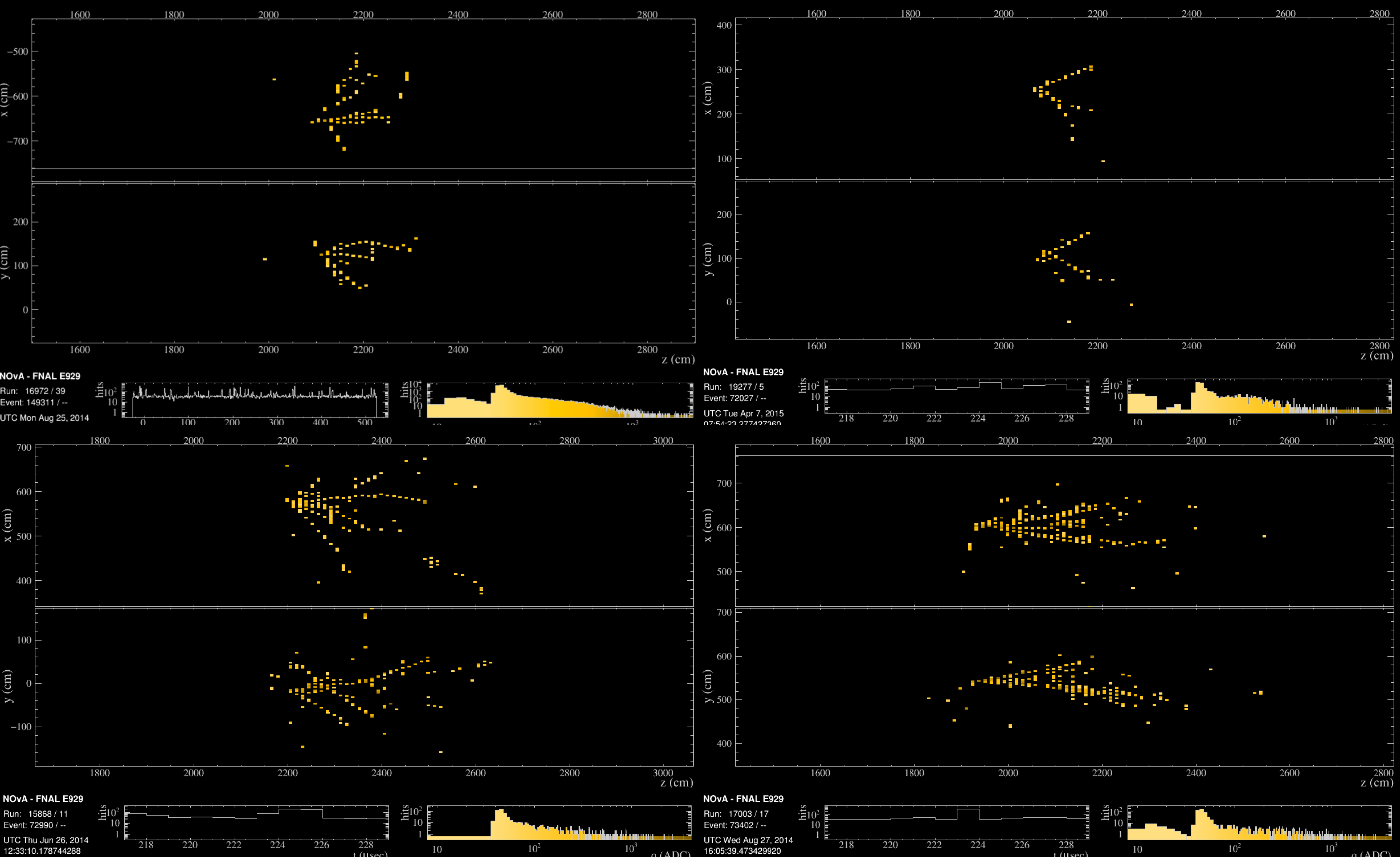


	NC Signal	CC Bkg	Cosmics
Upper oct.	148.3	36.3	7.9
Lower oct.	148.3	36.0	7.9
Max. Mixing	148.3	34.9	7.9

NC Disappearance Data

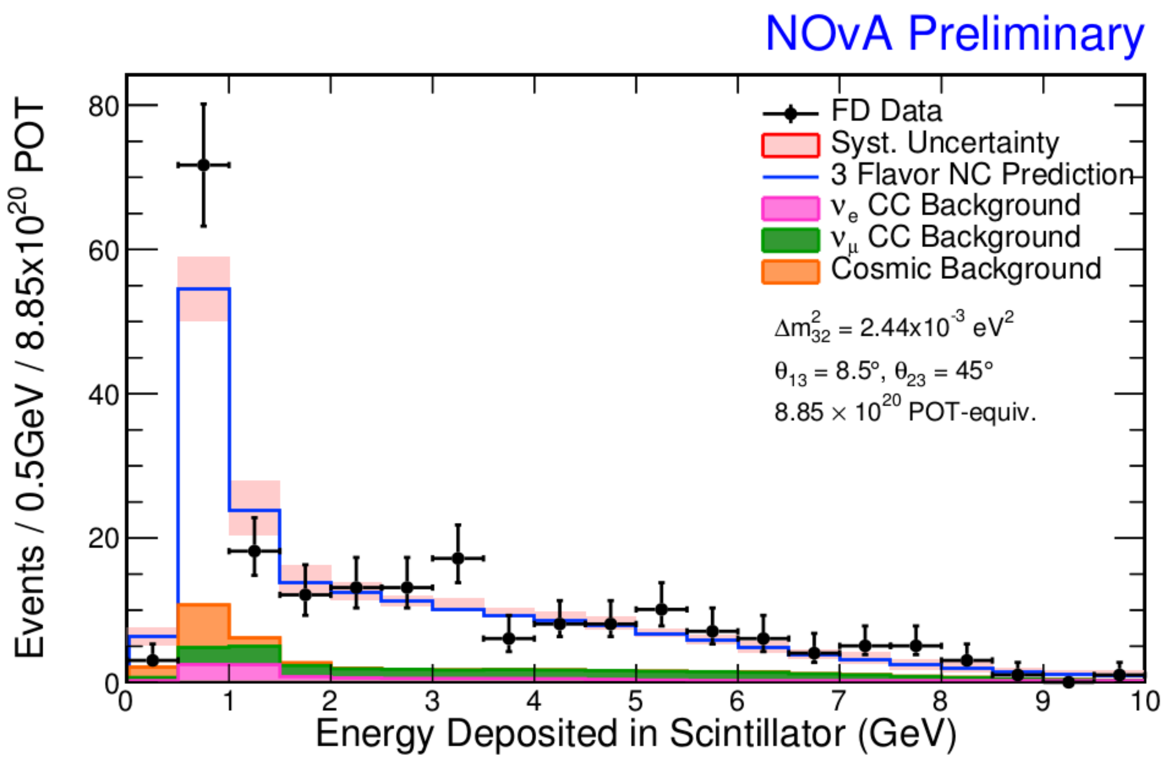


FD Data

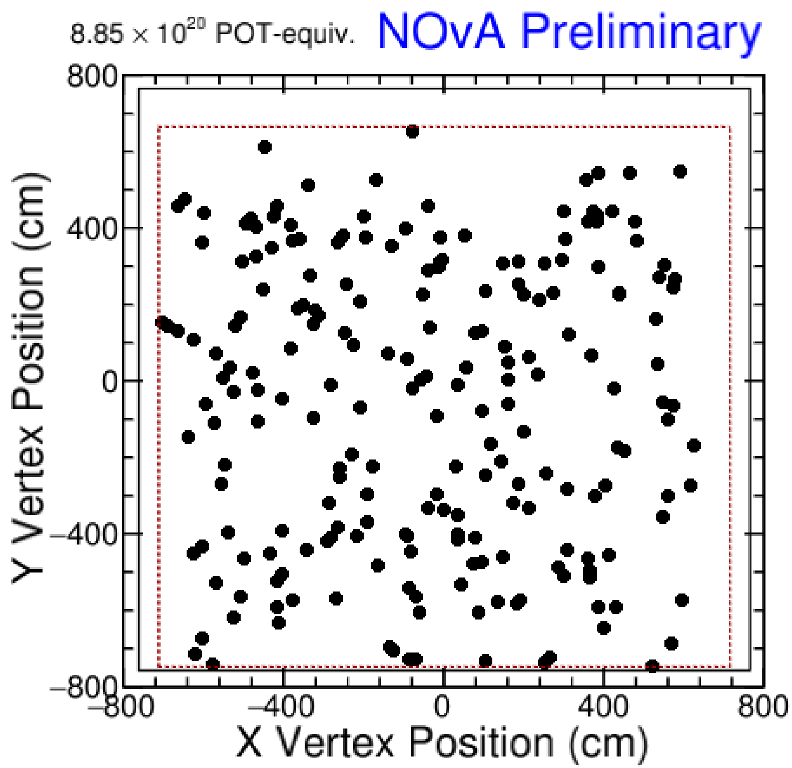
Expected: 191.2 ± 13.8 (stat)
± 22.0 (syst)

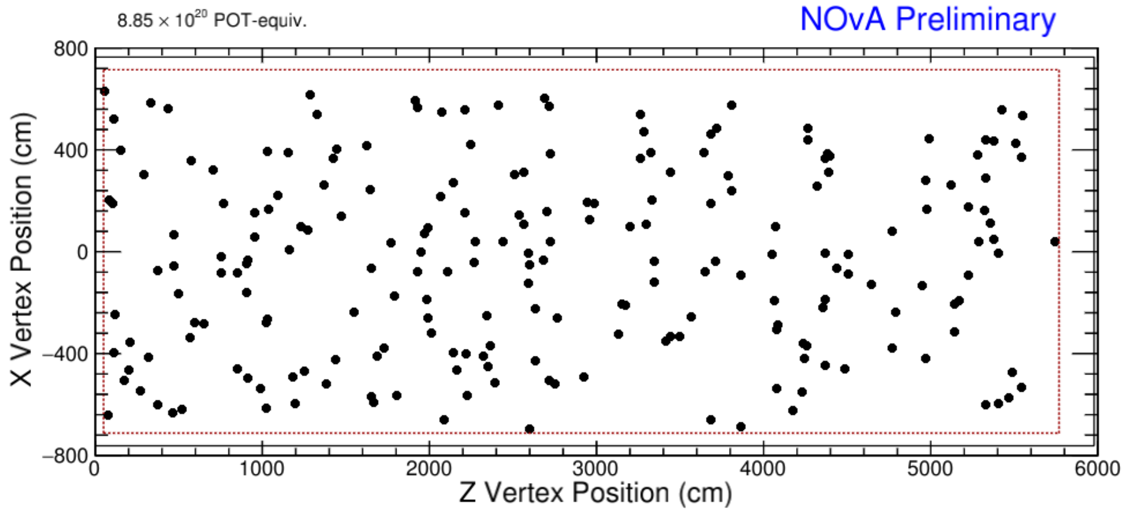
Observed: 214

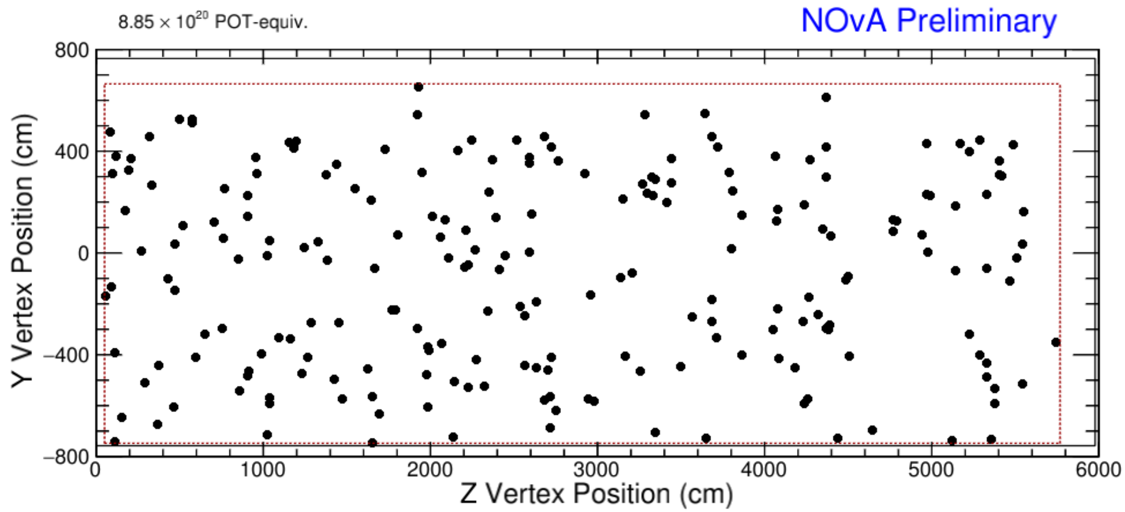
No depletion of neutral current events observed



Event Distributions







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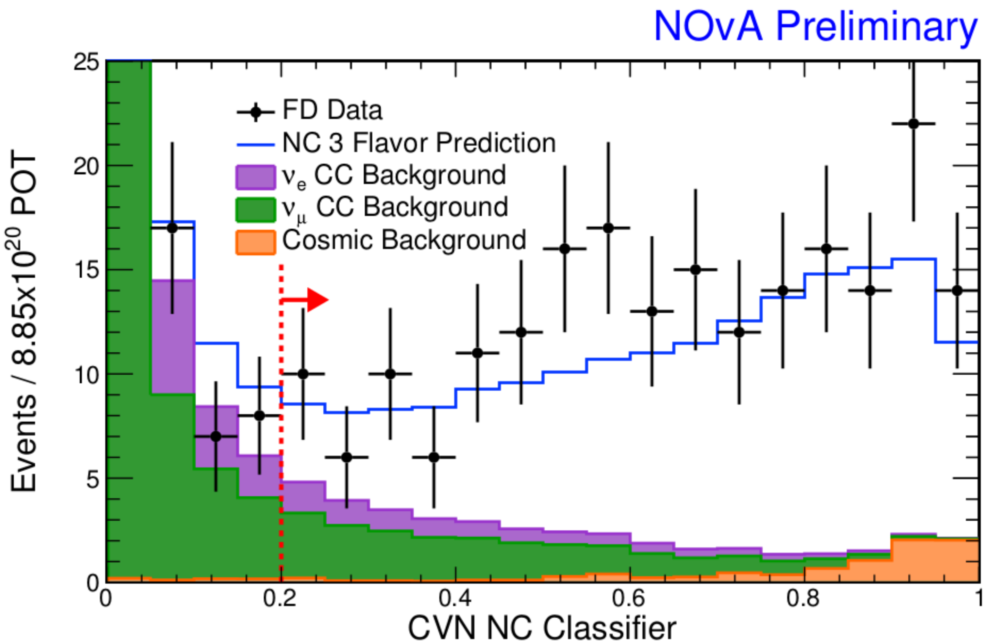
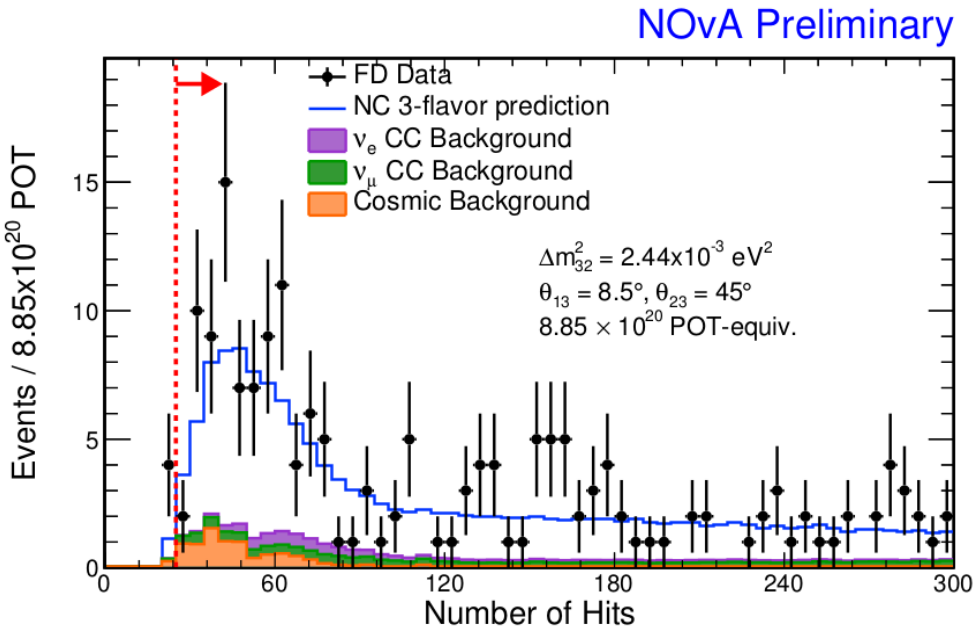
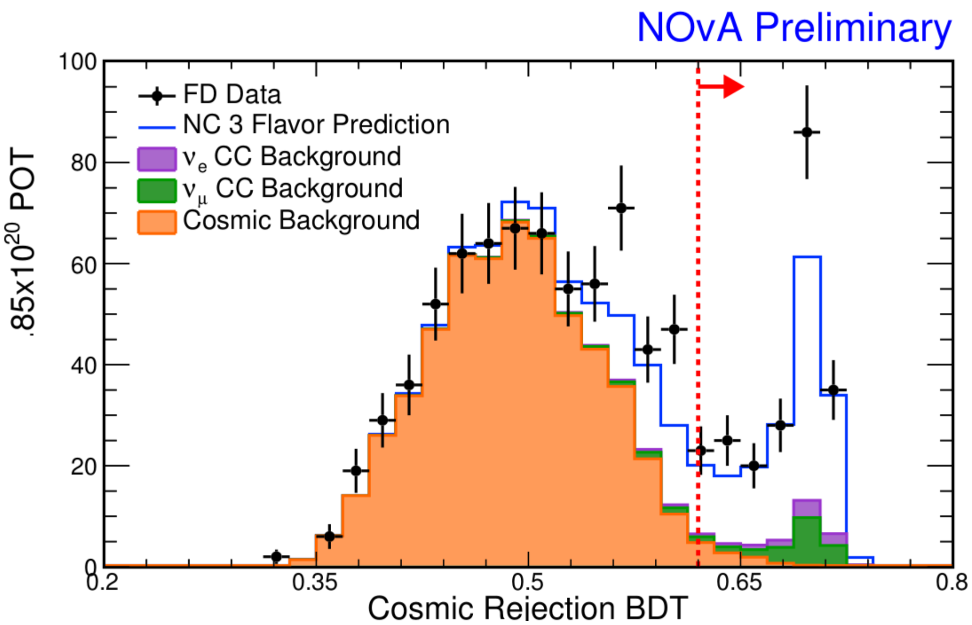






Comparison to Three-Flavor Predictions

$$R_{\mathrm{NC}} \equiv \frac{F^{\mathrm{data}} - \sum F^{\mathrm{pred}}(\mathrm{bkg})}{F^{\mathrm{pred}}(\mathrm{NC})}$$

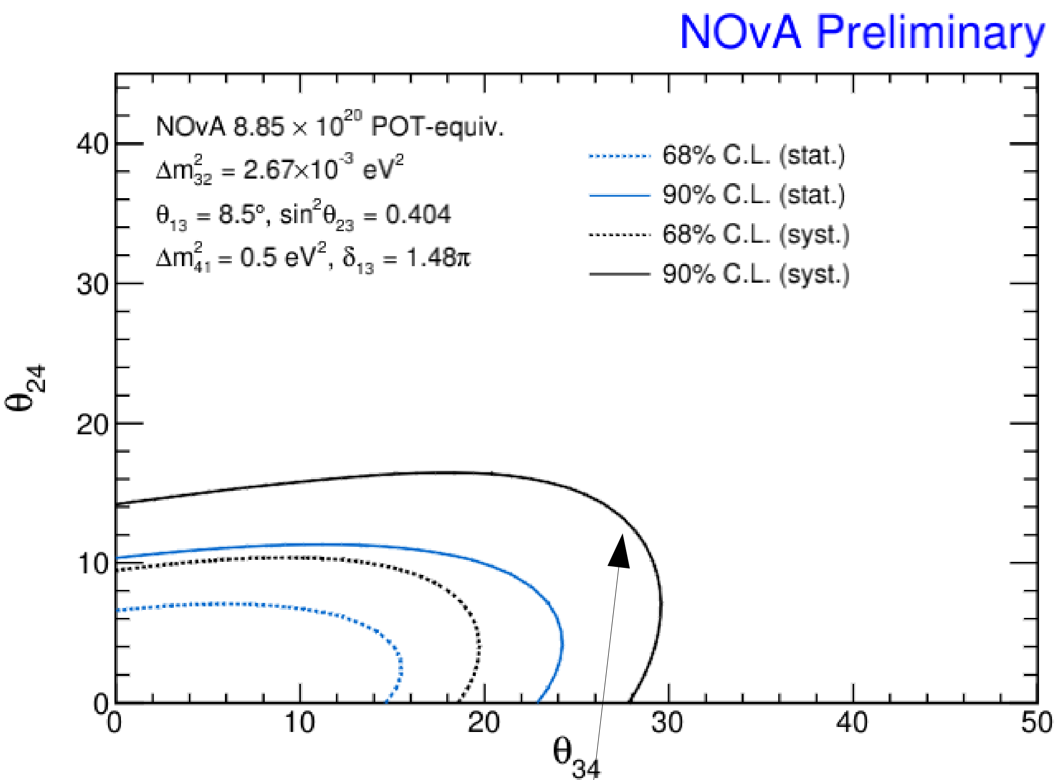
- R-ratio is a model independent measure of NC disappearance
  - No NC disappearance → R = 1
- Calculate in two energy regions
  - 0 – 2.5 GeV
    - 119 events observed
  - 2.5 – 10 GeV
    - 95 events observed

	0-2.5 GeV	2.5-10 GeV
Upper octant	1.18 ± 0.14 ± 0.12	1.07 ± 0.14 ± 0.12
Lower octant	1.18 ± 0.14 ± 0.12	1.08 ± 0.14 ± 0.12
Max. mixing	1.19 ± 0.14 ± 0.12	1.08 ± 0.14 ± 0.12

2016 analysis: R = 1.19 ± 0.16 ± 0.10

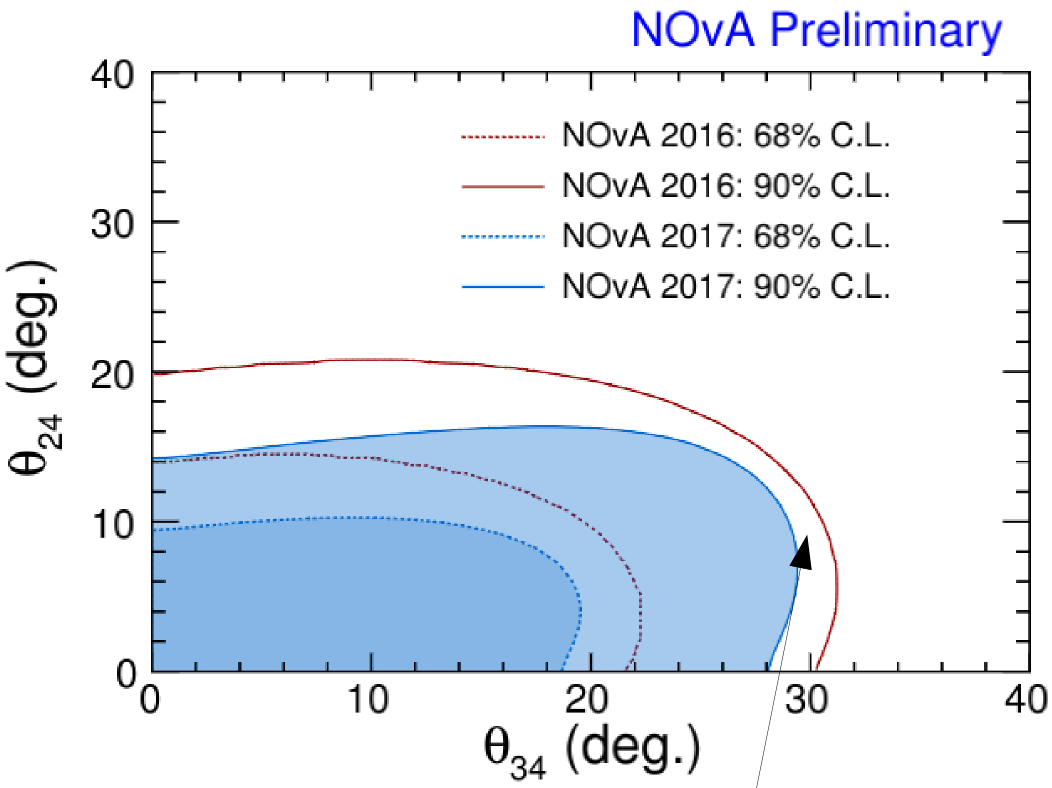
Shape Fit: 2D 90% C.L. Limits

- Constrain θ_{23}, Δm^2_{32}, and δ_{13} to NOvA's degenerate best fit points
  - Fit separately for each three-flavor degenerate solution and take the least constraining result
- Solar and reactor data constrains $\sin^2\theta_{14} < 0.041$
  - Assume $\theta_{14} = 0$ and $\delta_{14} = 0$
- Profile over θ_{23},, Δm^2_{32}, δ_{24}
- Limit Δm^2_{41}:
  - $0.05\ \text{eV}^2 < \Delta m^2_{41} < 0.5\ \text{eV}^2$
  - No significant ND oscillations
  - Rapid oscillations in FD
- Perform a shape-based fit for θ_{24} and θ_{34}



Stretching at large θ_{24} and θ_{34} is due to profiling over δ_{24}

Shape Fit: 2D 90% C.L. Limits



2016 analysis was a rate only analysis

	θ_{24}	θ_{34}	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
NOvA 2016	20.8°	31.2°	0.126	0.268
NOvA 2017	16.2°	29.8°	0.078	0.228
MINOS	7.3°	26.6°	0.016	0.20
SuperK	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

Fit in the lower octant is the least constraining

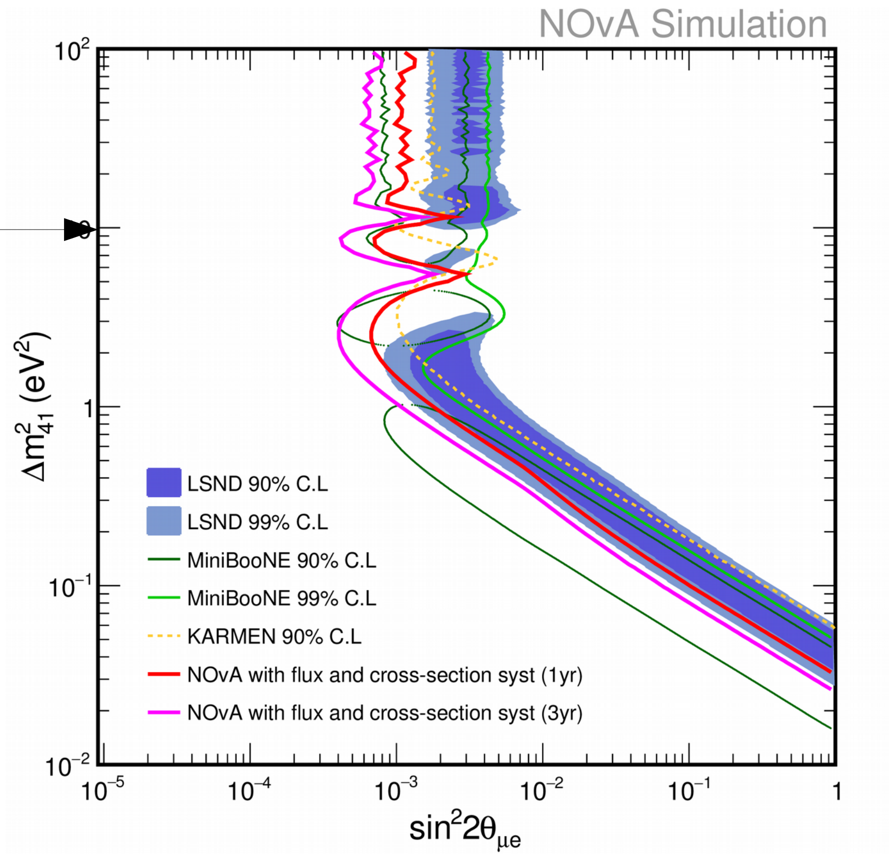
NOvA 2017 analysis improves over the NOvA 2016 limit

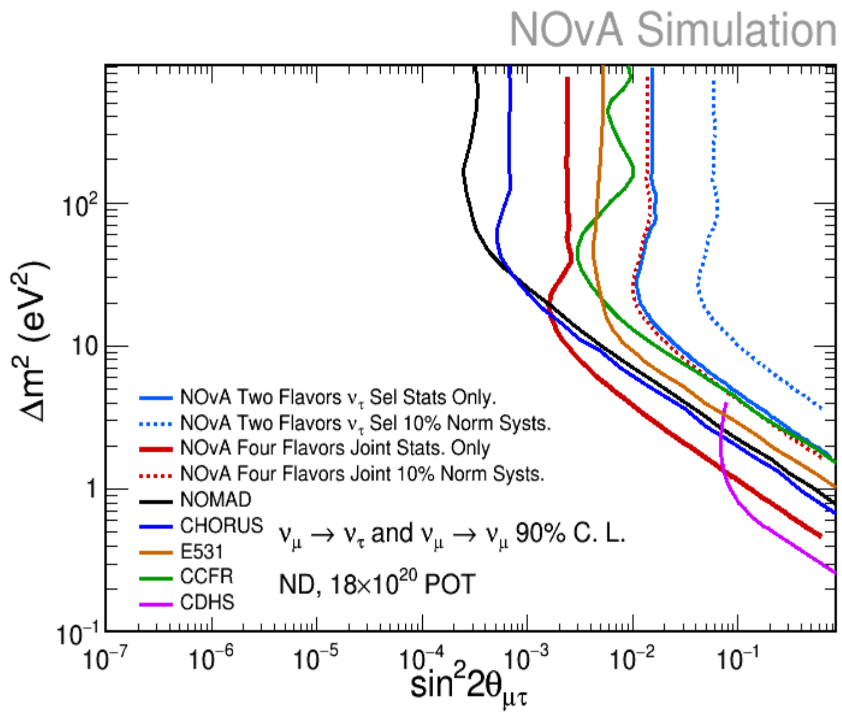
$\longrightarrow \theta_{24}$ by 4.6°

$\longrightarrow \theta_{34}$ by 1.4°

Future of NOvA Sterile Results: Short-Baseline Searches

- NOvA short-baseline ν_e appearance – ν_μ disapperance joint fit
  - Correlated uncertainties between the ν_e and ν_μ samples partially cancel
  - Probes LSND and MiniBooNE allowed regions with one year of NOvA data





- NOvA short-baseline ν_τ appearance
  - Search for ν_τ produced by oscillations in the high energy tail
  - NOvA will be competitive with previous experiments after 3 years of running

Summary

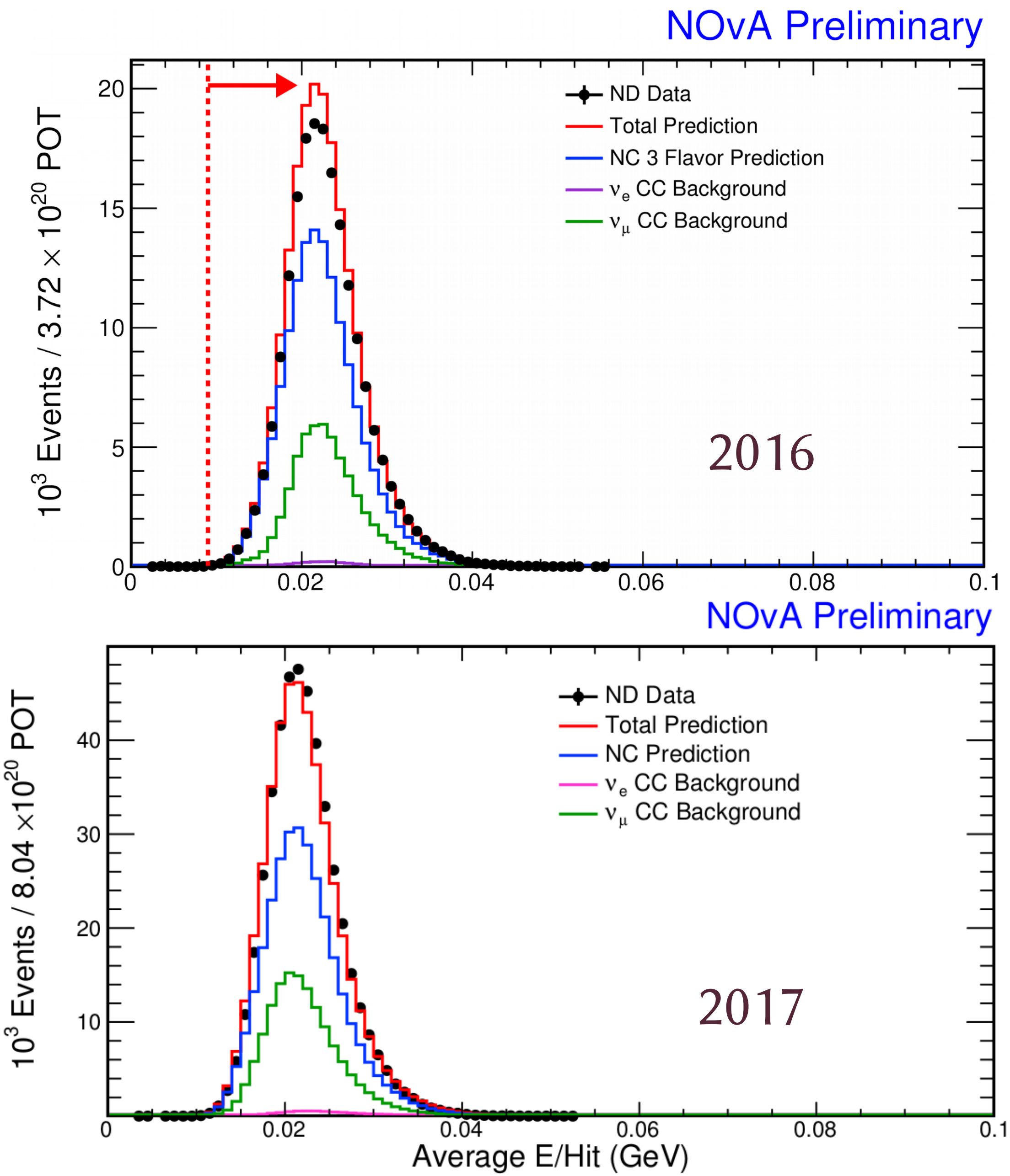
- Performed a search for a depletion in the NC rate at the NOvA FD with 8.85×10^{20} POT
  - Significant analysis improvements over the 2016 analysis
    - 50% increase in statistics
    - Improved cosmic rejection lead to a 50% reduction in the cosmic rate
      - Allowed for an increase in usable FD mass, increasing the NC selection efficiency
    - Significant modeling improvements halved the systematic error due ND data/MC disagreements and allowed for a shape-based fit
- Results are consistent with no sterile oscillations
- For $0.05\ \mathrm{eV}^2 < \Delta m^2_{41} < 0.5\ \mathrm{eV}^2$:
  - $\theta_{24} < 16.2^{\circ}$ and $\theta_{34} < 29.8^{\circ}$
  - Competitive with other experiments with 1/3 of planned exposure
- Short-baseline sterile neutrinos searches are in progress
- Analysis improvements to allow for fitting a wider range of Δm^2_{41} are in progress
- Stay tuned!

Thank You!

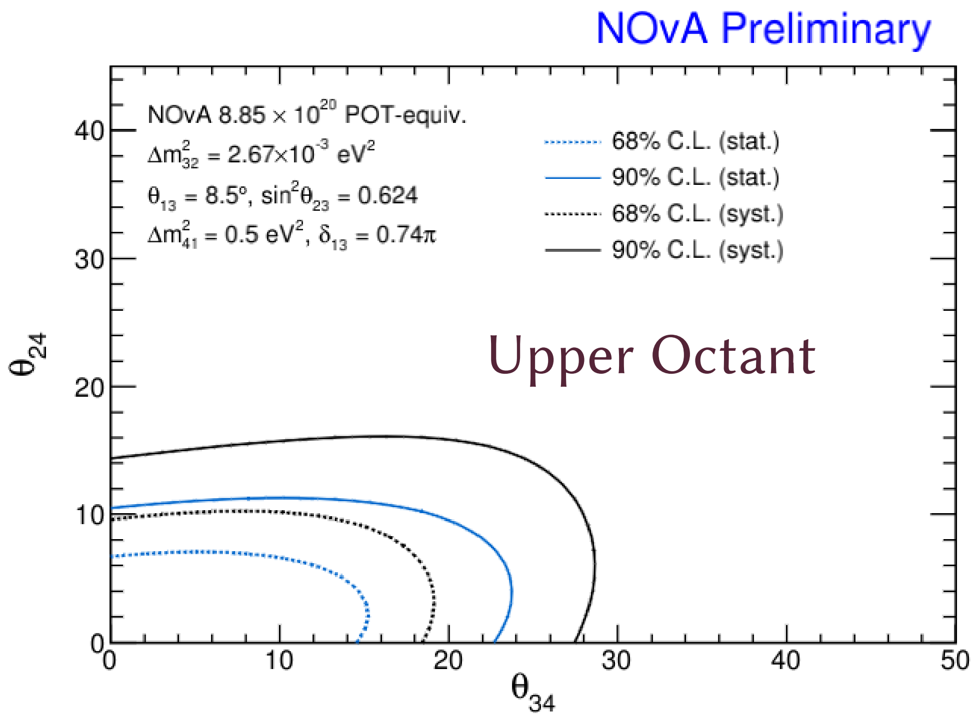
Backup Slides

Improvements to Detector Response Modeling

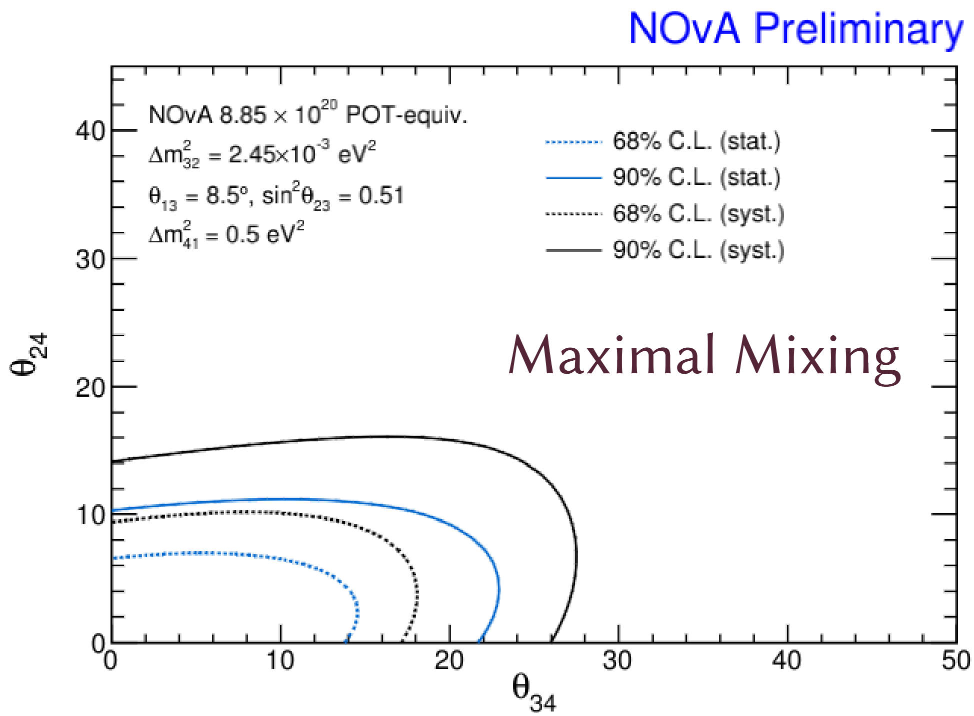
- In previous analyses, the scintillator non-linearity was tuned to minimize the data/MC disagreement energy lost by protons
- Recently, Cerenkov light was uncovered as an extra source of scintillator non-linearity
  - Short-wavelength Cerenkov light can be absorbed and re-emitted by the scintillator at detectable wavelengths
- Modeling this process produced significant improvements in data/MC agreement, especially for:
  - Energy/hit
  - Number of hits



2D Limits



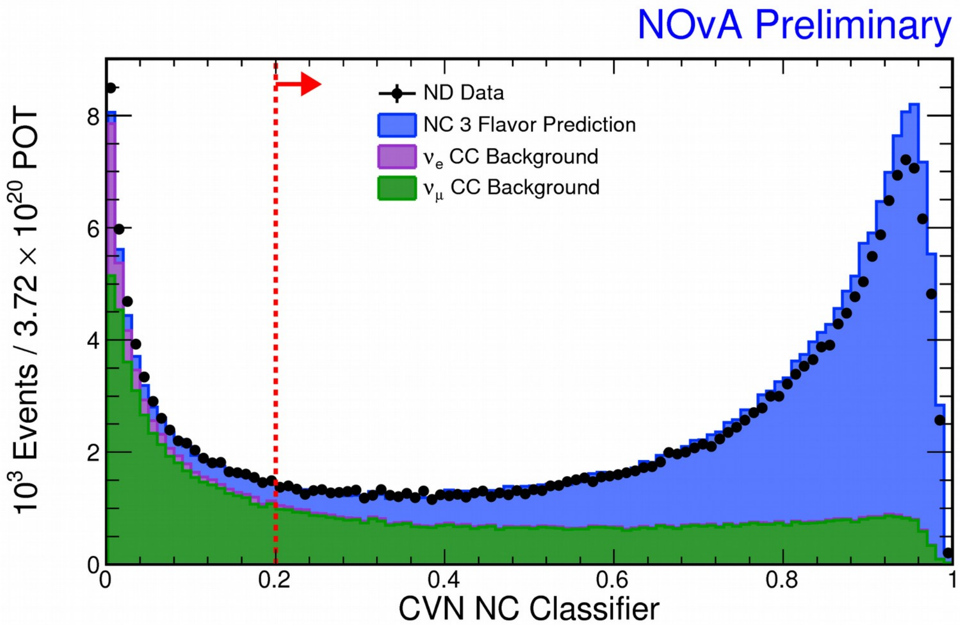
NOvA Preliminary
NOvA 8.85 × 10[20] POT-equiv.
$\Delta m^2_{32} = 2.67\times10^{-3}$ eV^2
$\theta_{13} = 8.5°$, $\sin^2\theta_{23} = 0.624$
$\Delta m^2_{41} = 0.5$ eV^2, $\delta_{13} = 0.74\pi$
68% C.L. (stat.)
90% C.L. (stat.)
68% C.L. (syst.)
90% C.L. (syst.)
Upper Octant
θ_{24}
θ_{34}



NOvA Preliminary
NOvA 8.85 × 10[20] POT-equiv.
$\Delta m^2_{32} = 2.45\times10^{-3}$ eV^2
$\theta_{13} = 8.5°$, $\sin^2\theta_{23} = 0.51$
$\Delta m^2_{41} = 0.5$ eV^2
68% C.L. (stat.)
90% C.L. (stat.)
68% C.L. (syst.)
90% C.L. (syst.)
Maximal Mixing
θ_{24}
θ_{34}

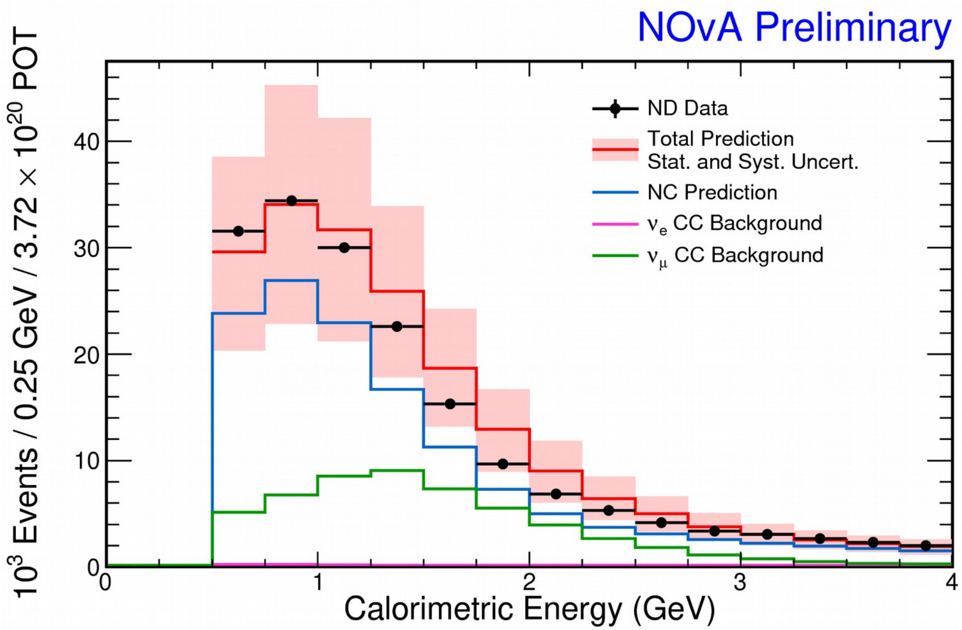
NOvA NC Disappearance

- Events classified with CVN
- Near detector spectrum agrees well within large NC cross-section uncertainties
- Extrapolate ND data to FD assuming no ND oscillations
  - Restrict analysis to small Δm_{41}^2 values



Far detector predictions

Total	NC	ν_μ CC	Beam ν_e	Cosmics
83.7 ±8.3	60.6	4.8	3.6	14.3



NOvA NC Disappearance

Observe 95 events

Compare to three-flavor:

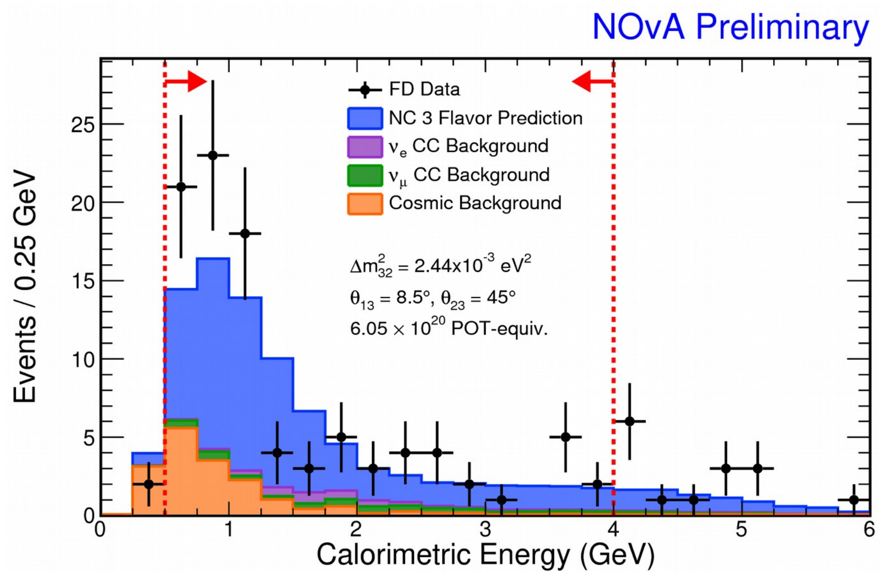
$$R = \frac{N_{data} - BG}{S_{NC}}$$
$$= 1.19 \pm 0.16(stat.) \pm 0.11(syst.)$$

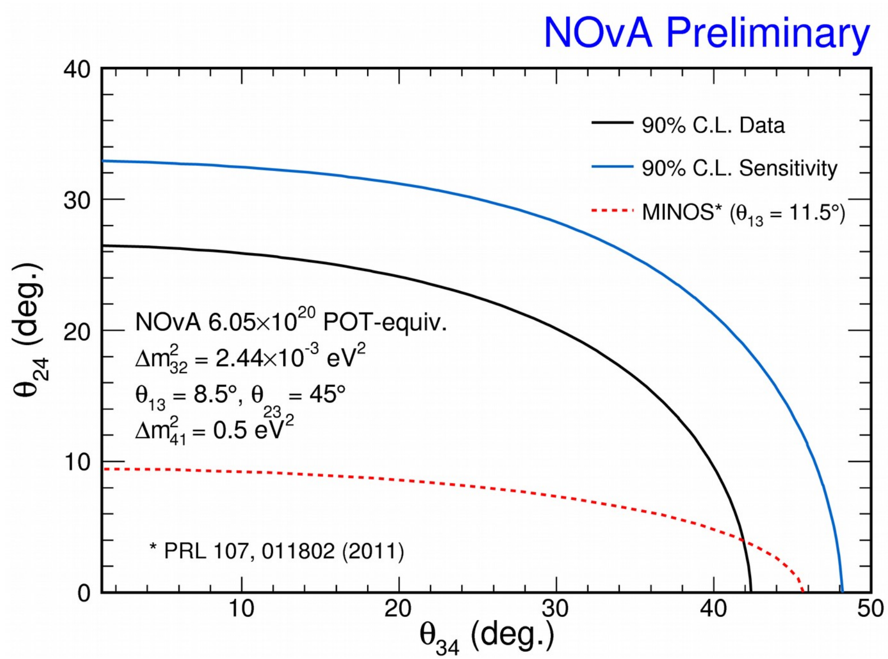
No evidence for sterile neutrino mixing

Fitting NC rate with the 3+1 model:

For $0.05\ \text{eV}^2 < \Delta m_{41}^{\ 2} < 0.5\ \text{eV}^2$

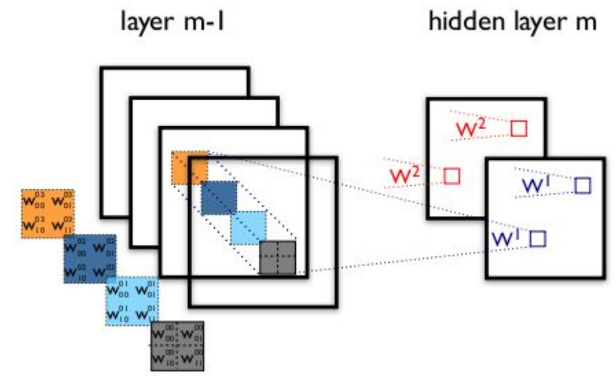
$\theta_{34} < 35^\circ$, $\theta_{24} < 21^\circ$

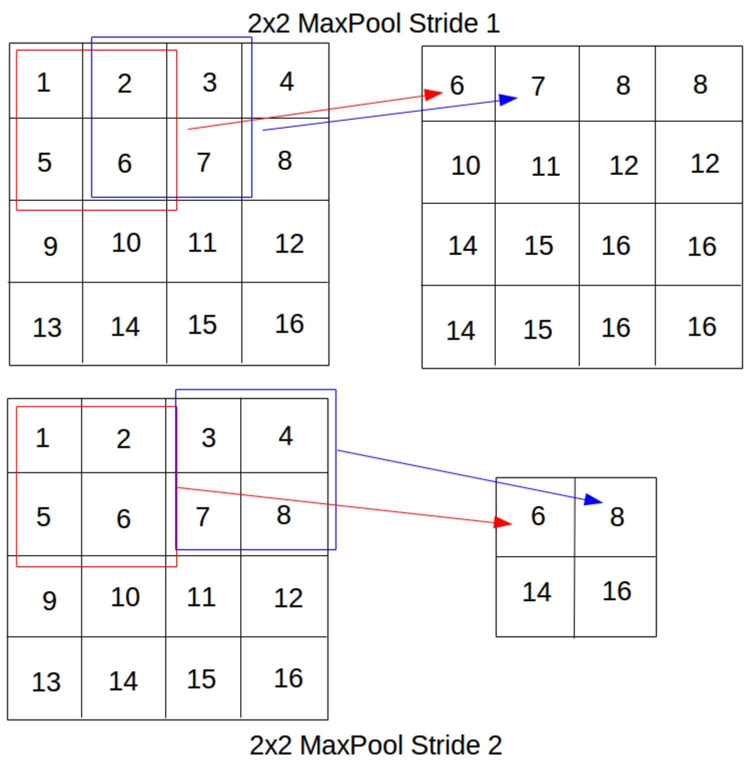




Convolutional Neural Networks

- Deep learning is a new paradigm that has caused a renaissance in the machine learning community.
  - Made possible by better activation functions, better weight initialization, and the advent of cheap GPUs.
- One variant – the convolutional neural network has been highly successful at image recognition tasks.
- Two basic type of layers:
  - Convolutional layers – apply discrete convolutions using learned kernels to extract features from the image.
  - Pooling layers – downsample the image and increase translational invariance in the final output.
- Stacked structure of convolutional and pooling layers extract increasingly abstract features from the input raw data encoding both local and global structure.
- Relatively new:
  - LeNet – one of the first (1998)
  - AlexNet – the one that started the revolution (2012)





Understanding the Network: Feature Embedding with t-SNE