Sterile Neutrino Search via Neutral-Current Disappearance with NOvA

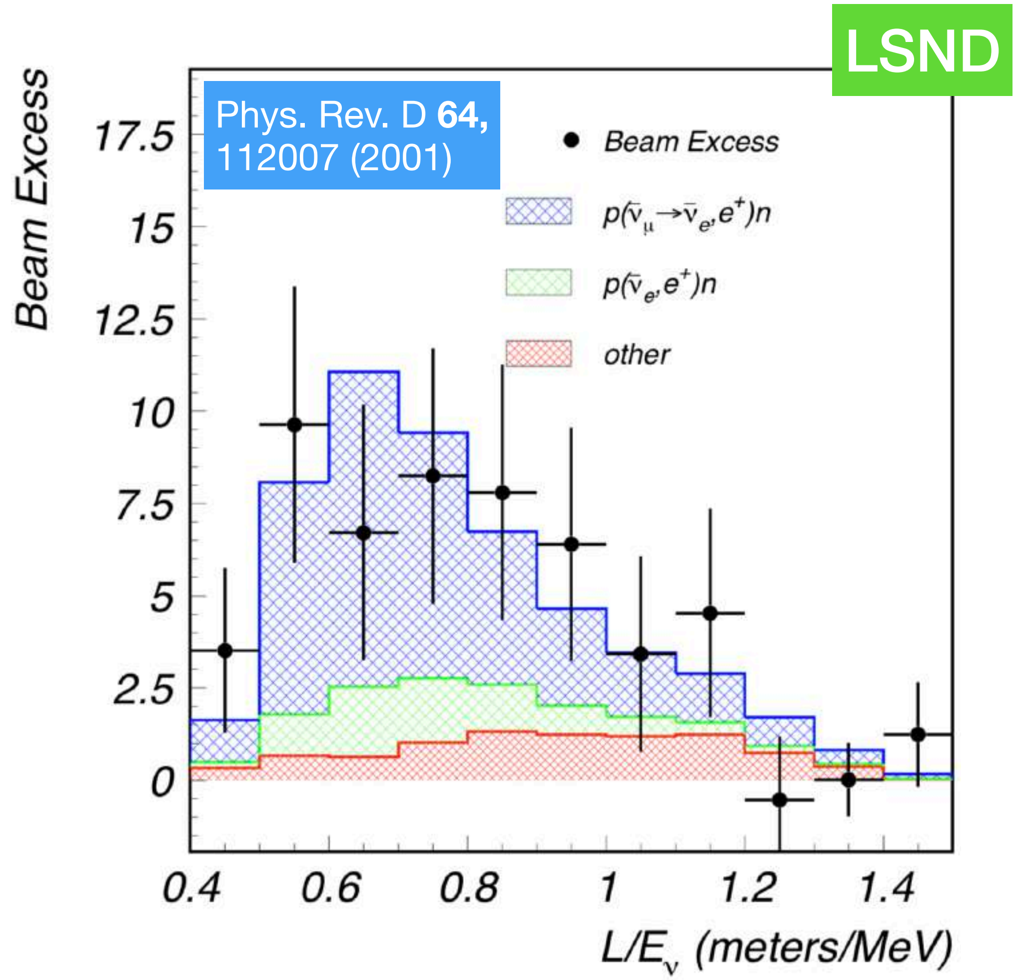
Mike Wallbank, University of Cincinnati
on behalf of the NOvA collaboration

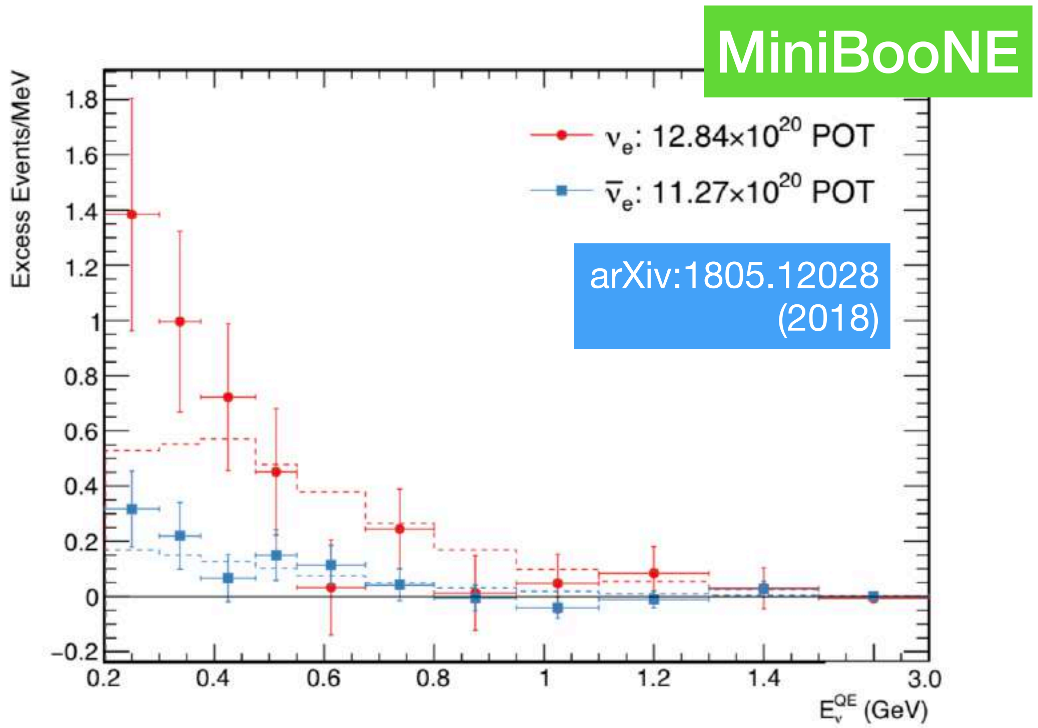
The 20th International Workshop on Neutrinos from Accelerators
August 17, 2018

Sterile Neutrinos

- Short-baseline neutrino oscillation experiments (LSND, MiniBooNE) observed an excess of ν_e ($\bar{\nu}_e$) events in ν_μ ($\bar{\nu}_\mu$) beams.

- Inconsistent with oscillations between three neutrino flavors; may be explained through oscillations by introducing a fourth neutrino with a mass splitting $\Delta m^2 \sim 1\ \mathrm{eV}^2$.





Sterile Neutrinos

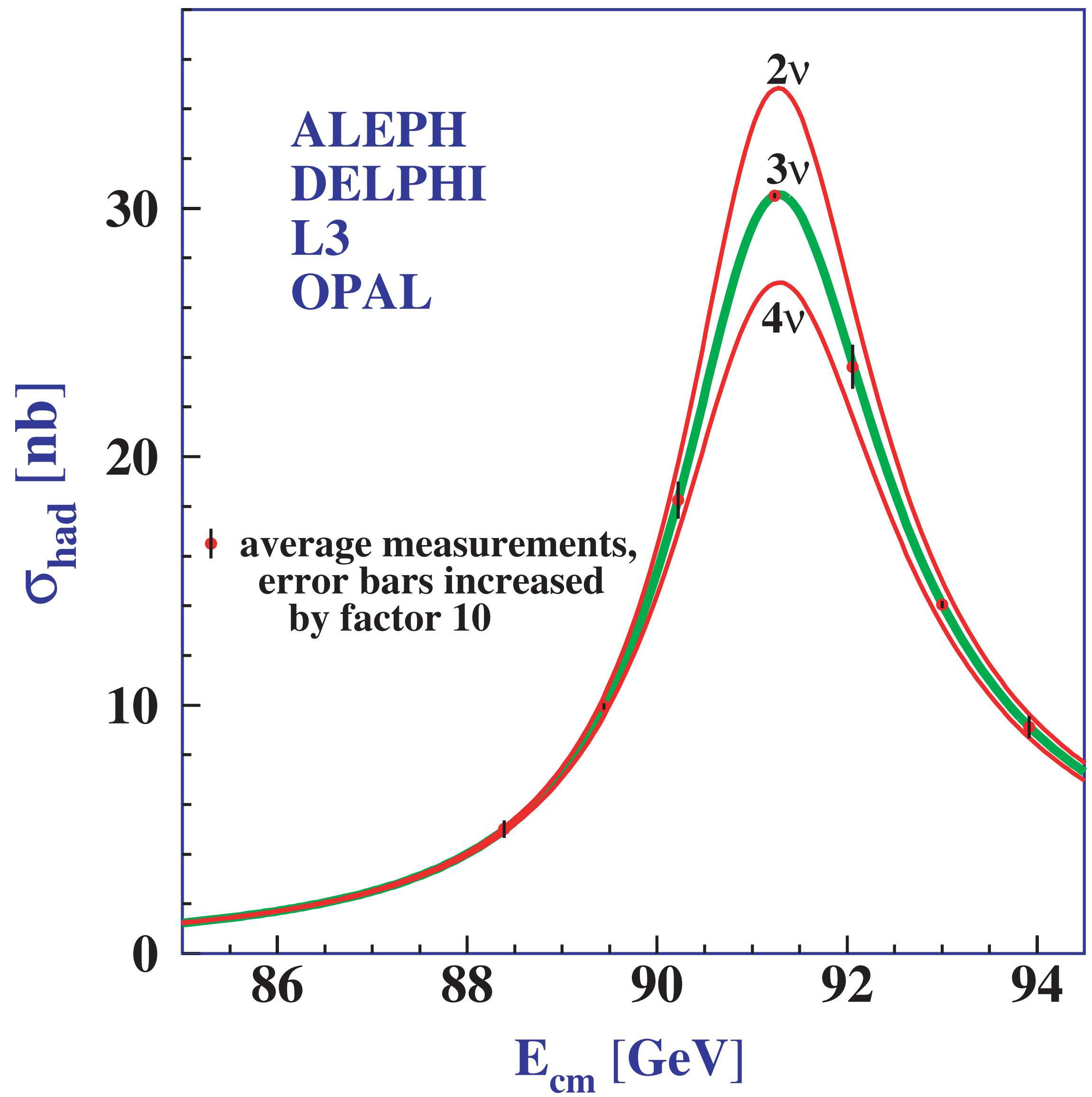
- Short-baseline neutrino oscillation experiments (LSND, MiniBooNE) observed an excess of ν_e ($\bar{\nu}_e$) events in ν_μ ($\bar{\nu}_\mu$) beams.

- Inconsistent with oscillations between three neutrino flavors; may be explained through oscillations by introducing a fourth neutrino with a mass splitting $\Delta m^2 \sim 1\ \text{eV}^2$.

- Measurements of the Z-boson decay width at LEP placed strict limits on the number of light neutrinos:

    - Any additional neutrinos must be *sterile*.

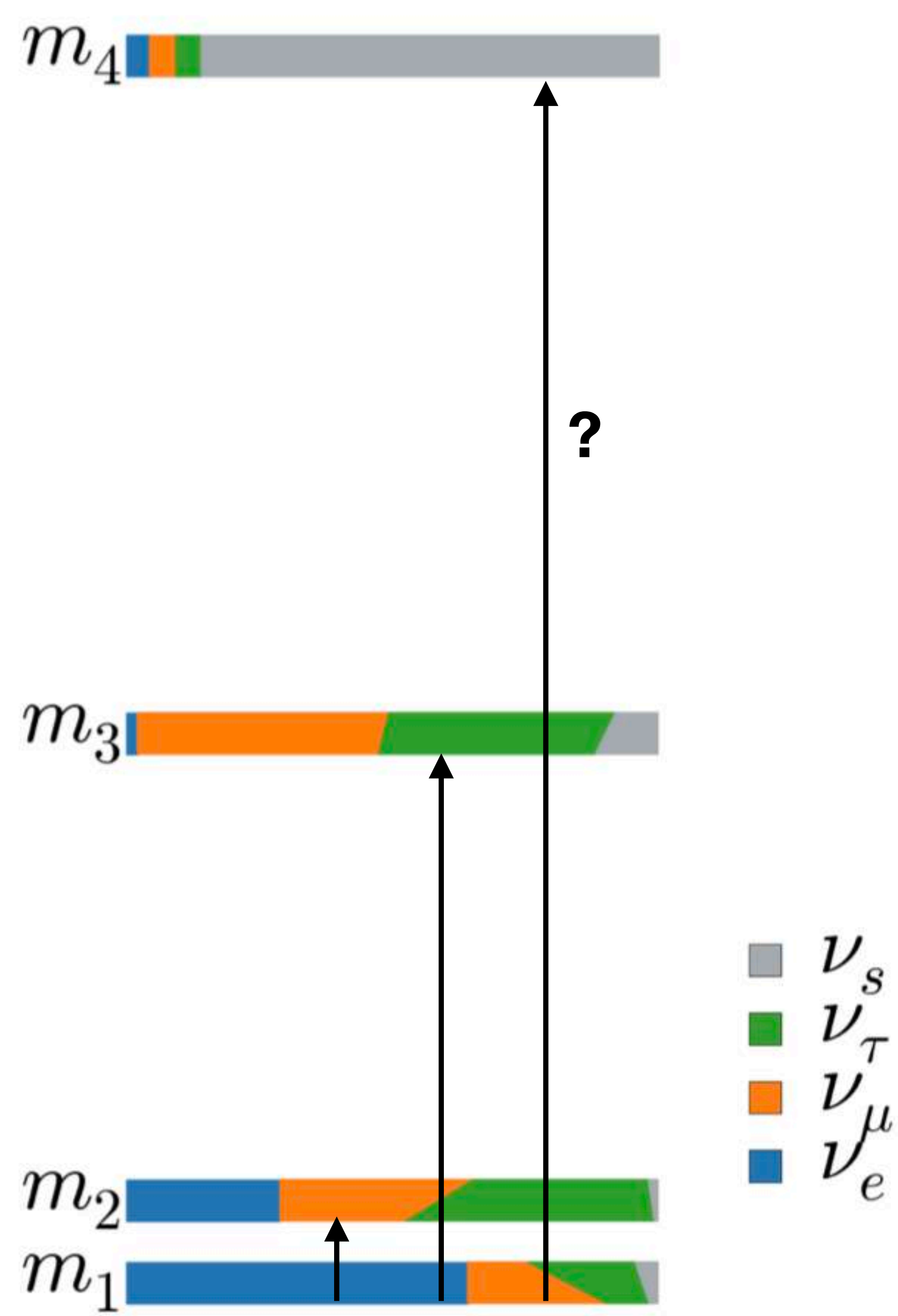
Phys. Rept. **427**, 257-454 (2006)



3+1 Model

- Simplest model adds a single additional neutrino — PMNS matrix increases from 3x3 to 4x4:

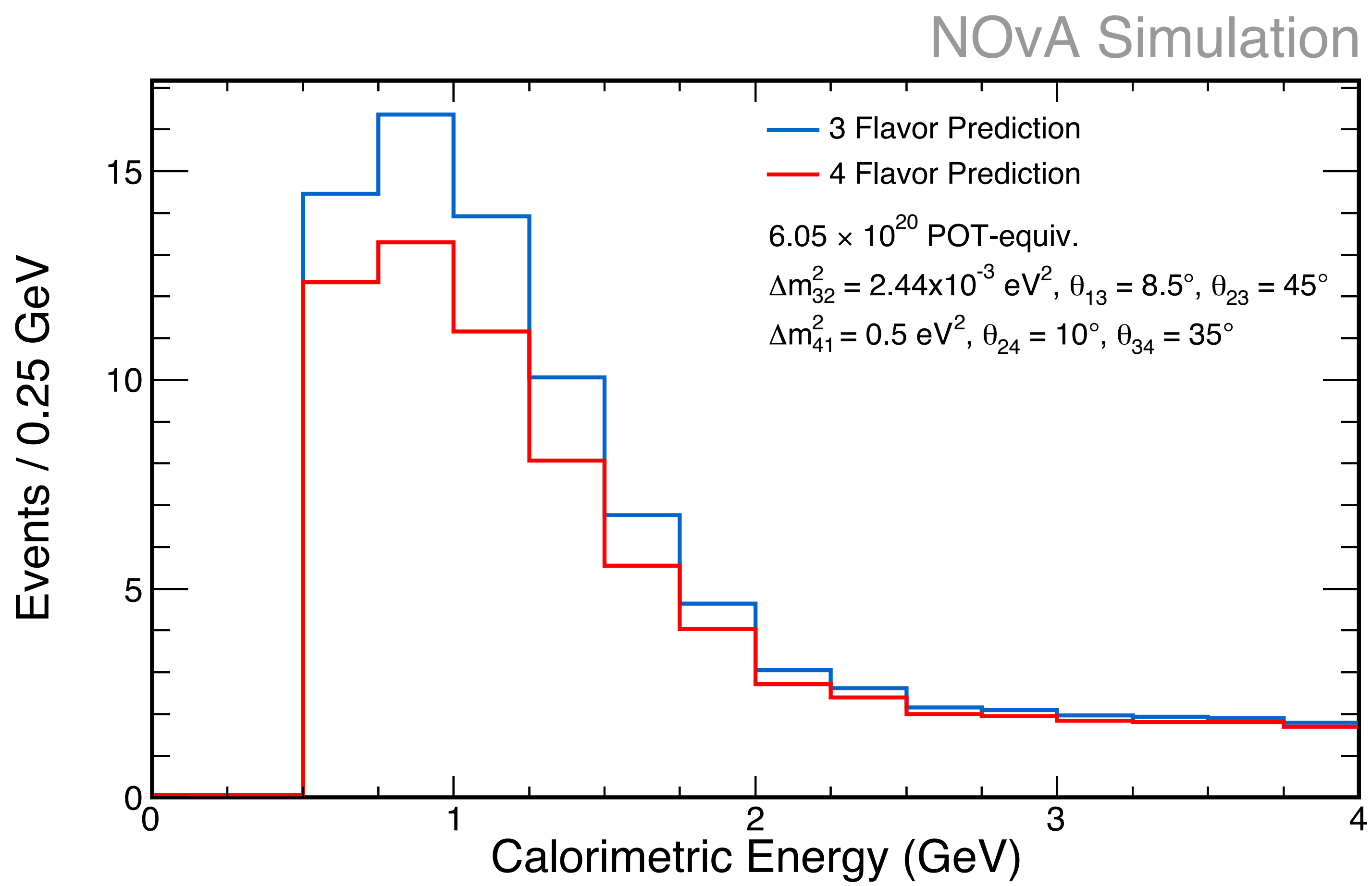
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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



- Six additional parameters:
  - One mass splitting, Δm^2_{41};
  - Three mixing angles, θ_{14}, θ_{24}, θ_{34};
  - Two CP-violating phases, δ_{14}, δ_{24}.

Long-Baseline Neutral Current Disappearance

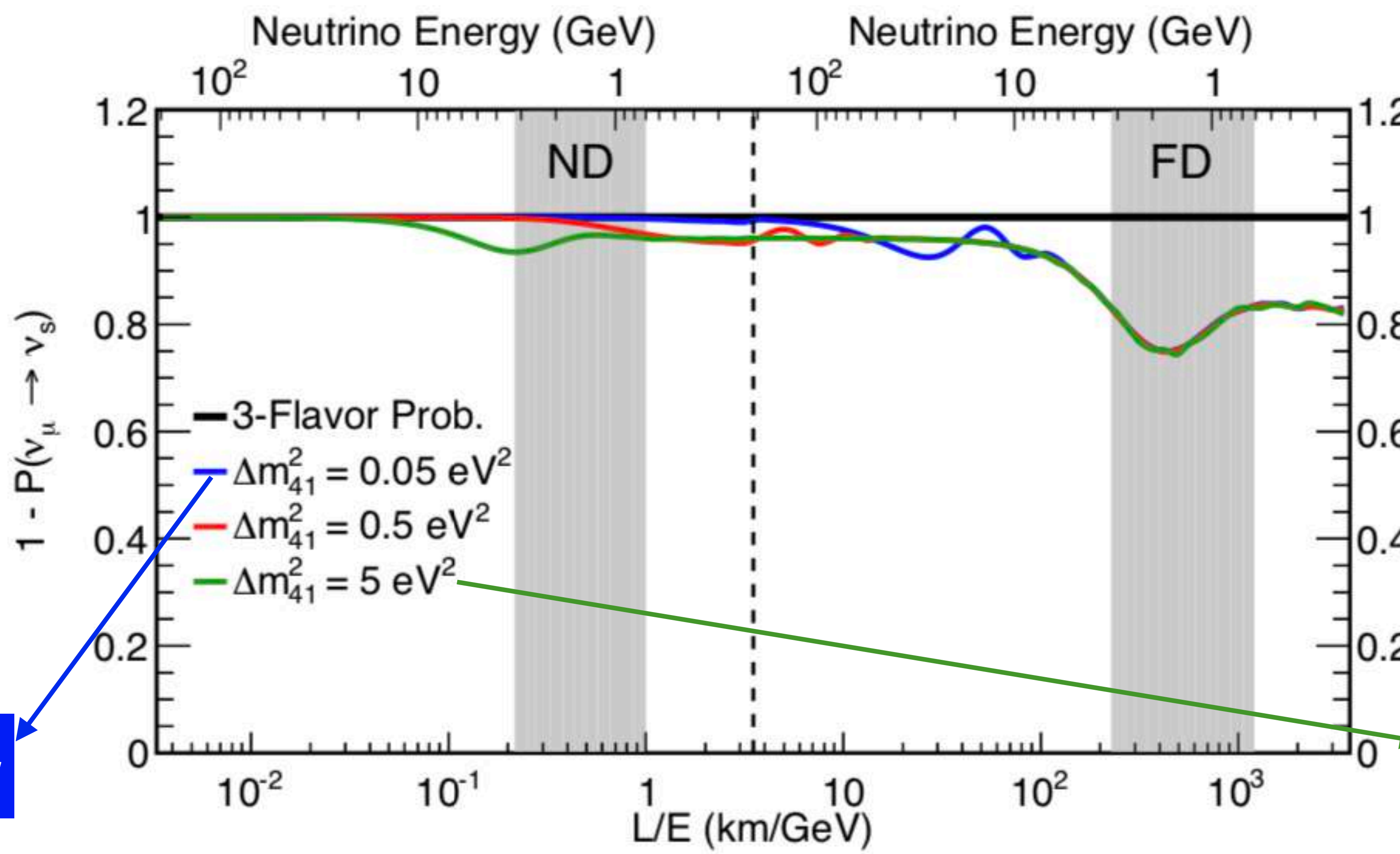
- Neutral Current (NC) interaction rate is the same for the 3 active neutrino flavors — insensitive to 3-flavor oscillations.
- Oscillations to sterile neutrino states will result in deficit in the NC interaction rate.
- Sensitive to mixing parameters θ_{24}, θ_{34}, Δm^2_{41}, δ_{24} (assume small δ_{14}).



$$1 - P^{LBL,3+1}_{\nu_\mu \to \nu_s} \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}$$
$$+\sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}$$
$$-\frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin 2\Delta_{31}$$

Approximate disappearance probability
(Exact formalism used in the fit)

Long-Baseline Neutral Current Disappearance



$\Delta m^2_{41} < 0.5$ eV^2

$\Delta m^2_{41} > 0.5$ eV^2

- Region $0.05 < \Delta m^2_{41}$ (eV^2) < 0.5;
  - No significant ND oscillations,
  - Rapid oscillations in FD — independent of Δm^2_{41}.

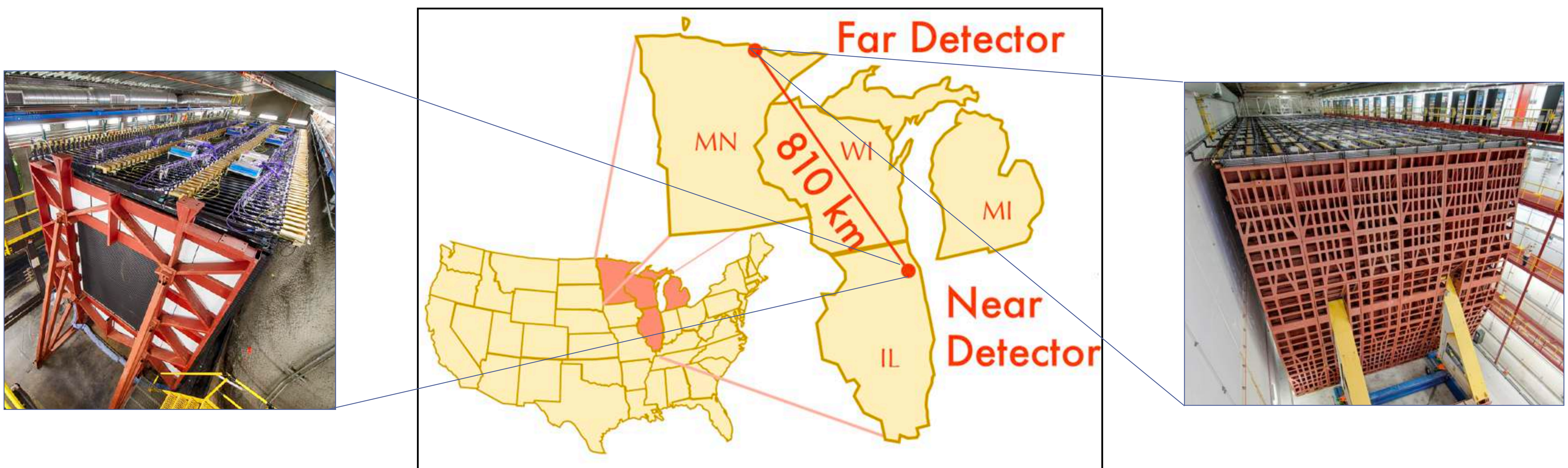
- $\Delta m^2_{41} > 0.5$ eV^2;
  - ND oscillations become significant,
  - Dependence on Δm^2_{41}.

NOvA

The NOvA Experiment

- The NOvA (NuMI Off-Axis ν_e Appearance) experiment is a long-baseline neutrino oscillation experiment based at Fermi National Accelerator Laboratory.

- Rich physics program:
  - Precision Standard Model measurements, mass ordering, leptonic CPV: ν_μ, $\overline{\nu}_\mu$ disappearance, ν_e, $\overline{\nu}_e$ appearance.
  - Sterile neutrino searches: NC disappearance, short-baseline studies.
  - Other searches: supernovae, exotics, cross-sections.



The NOvA Experiment

- The NOvA (… oscillation experiment …
- Rich physics …
  - Precision … isappearance, ν_e, $\overline{\nu}_e$ app…
  - Sterile ne…
  - Other se…

NOvA @ NuFACT 2018

Posters

F. Psihas: Neutrino Physics with Deep Learning on NOvA

A. Sutton: The NOvA Test Beam Program

Monday

M. Judah, WG2: NOvA Cross Section Results

Tuesday

J. Bian, Plenary III: Results and Prospects from NOvA

Thursday

E. Smith, WG1: Details of the NOvA Oscillation Analyses

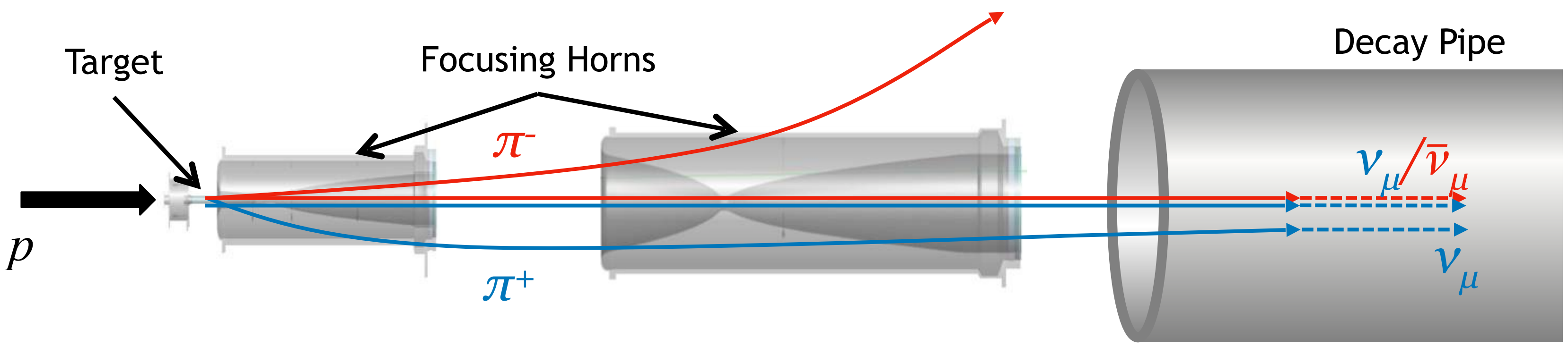
Friday

J. Wolcott, WG2: NOvA Cross Section Model / Oscillation Needs

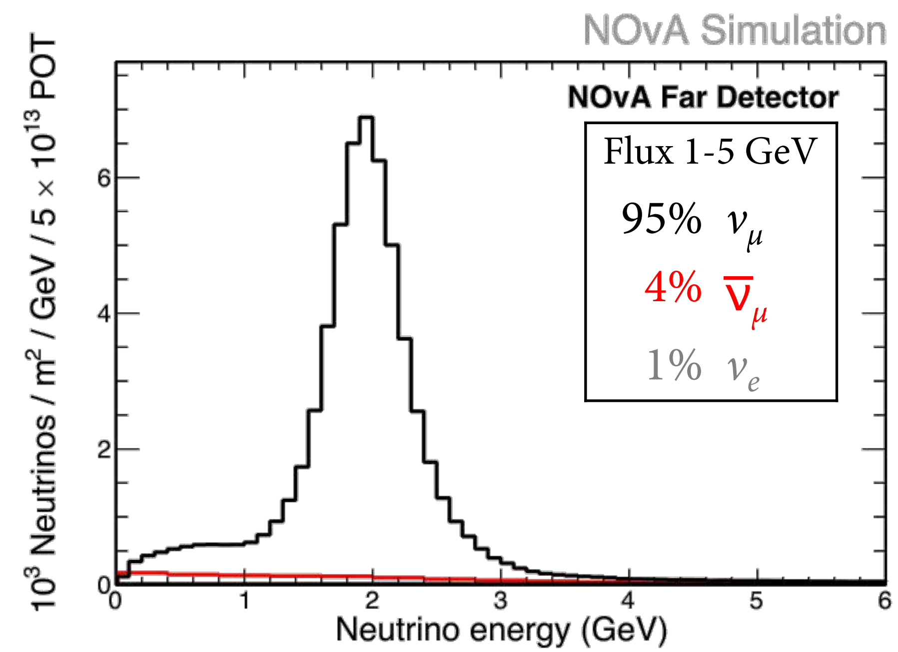
M. Wallbank, WG1+WG5: Sterile Neutrinos Search via NC disappearance at NOvA

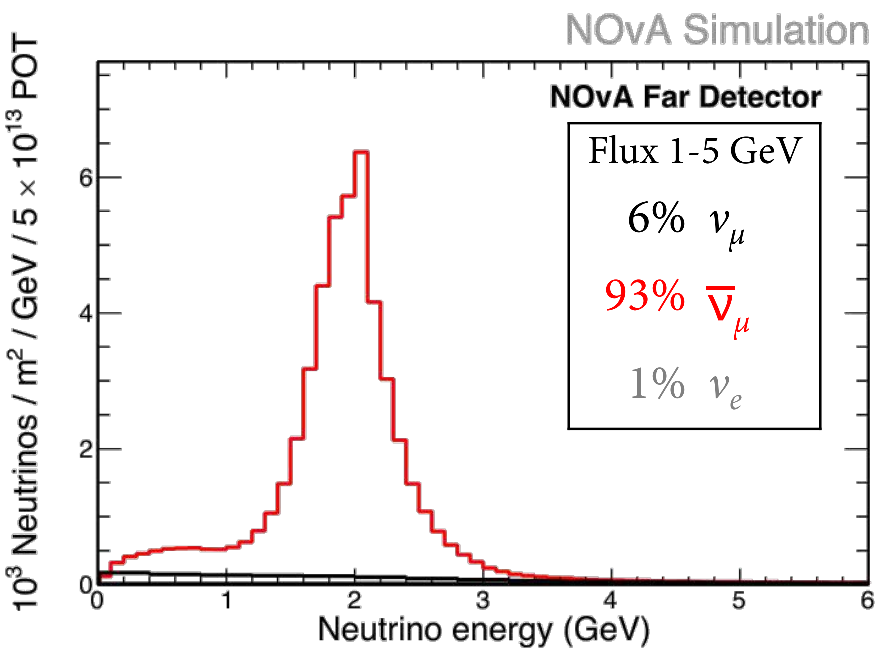
The NuMI Beam

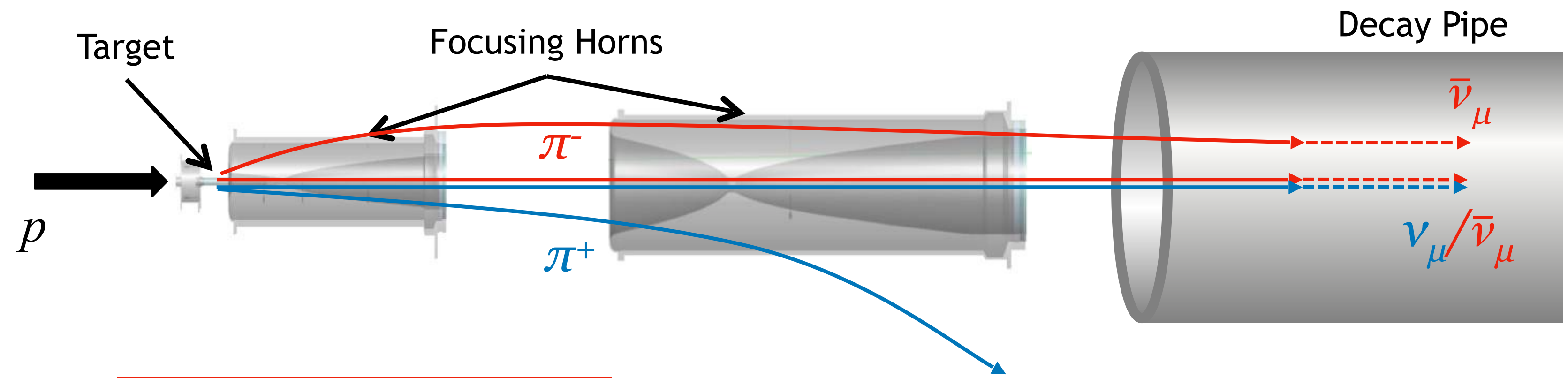
- Can use horn polarity to preferentially select positively or negatively charged pions — **neutrino**- or **antineutrino**-dominated beam.



Neutrino Beam





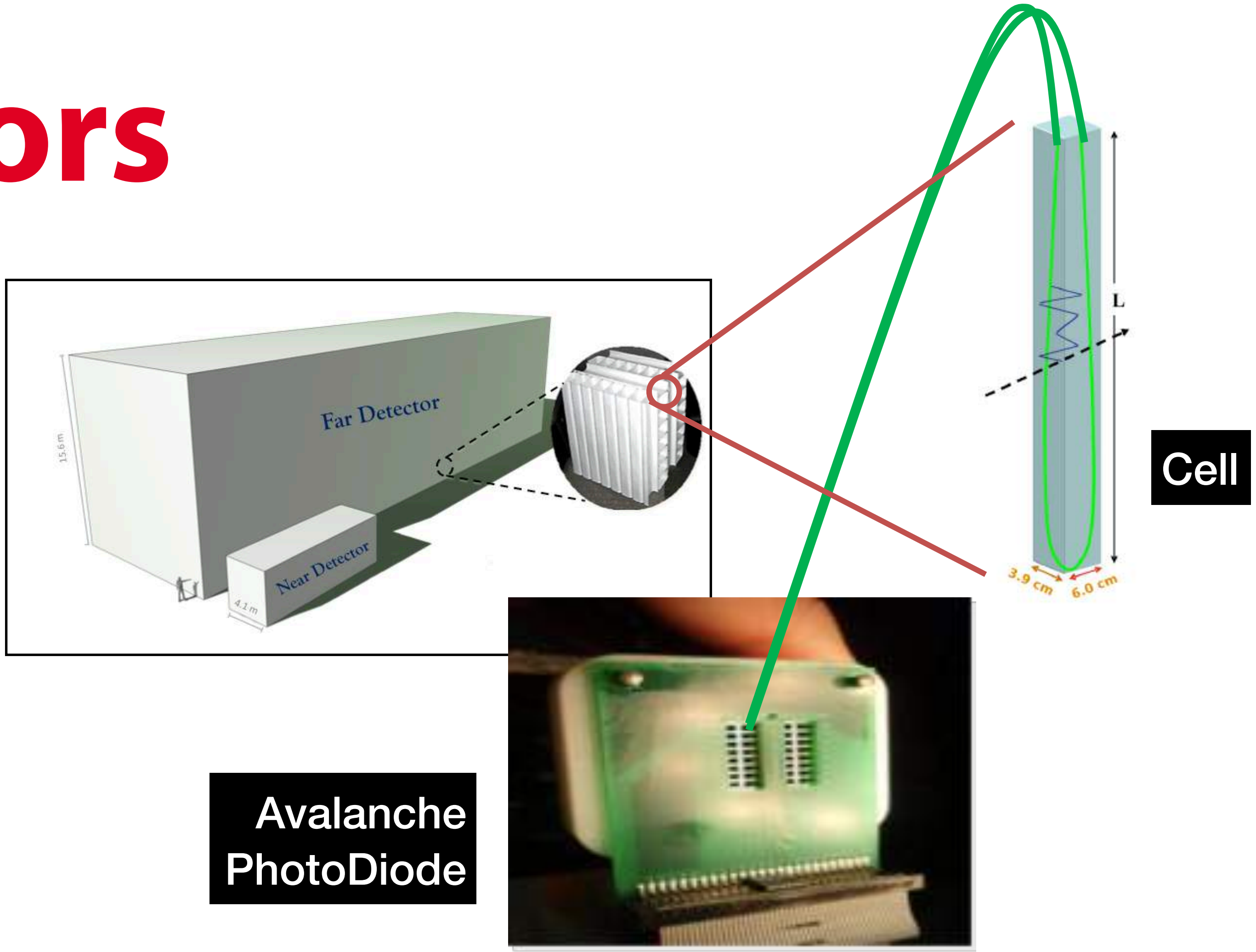


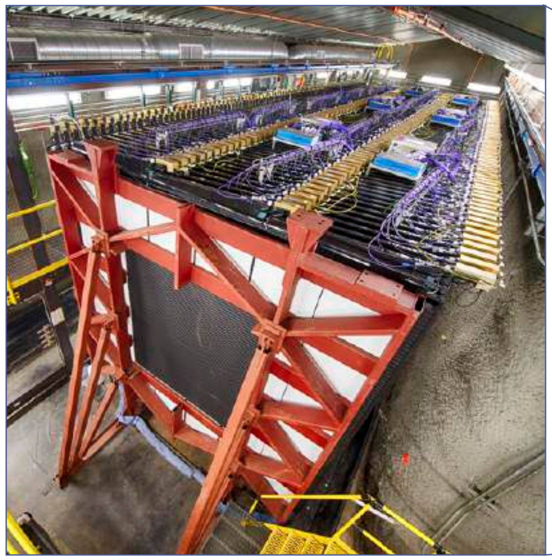
Antineutrino Beam

The NOvA Detectors

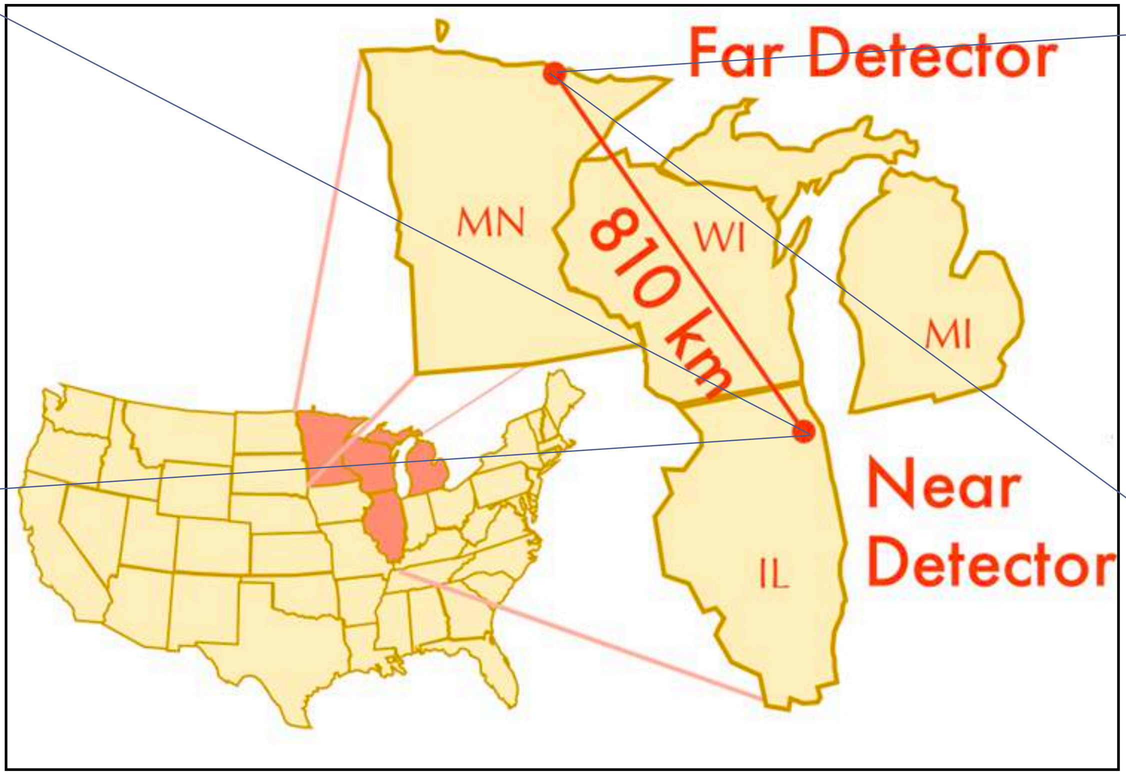
- Neutrinos sampled 14.6 mrad off-axis at 1 km and 810 km by two functionally identical detectors.

- Low Z tracking calorimeter composed of alternating horizontal and vertical planes of liquid filled scintillator, read out out by photodiodes.



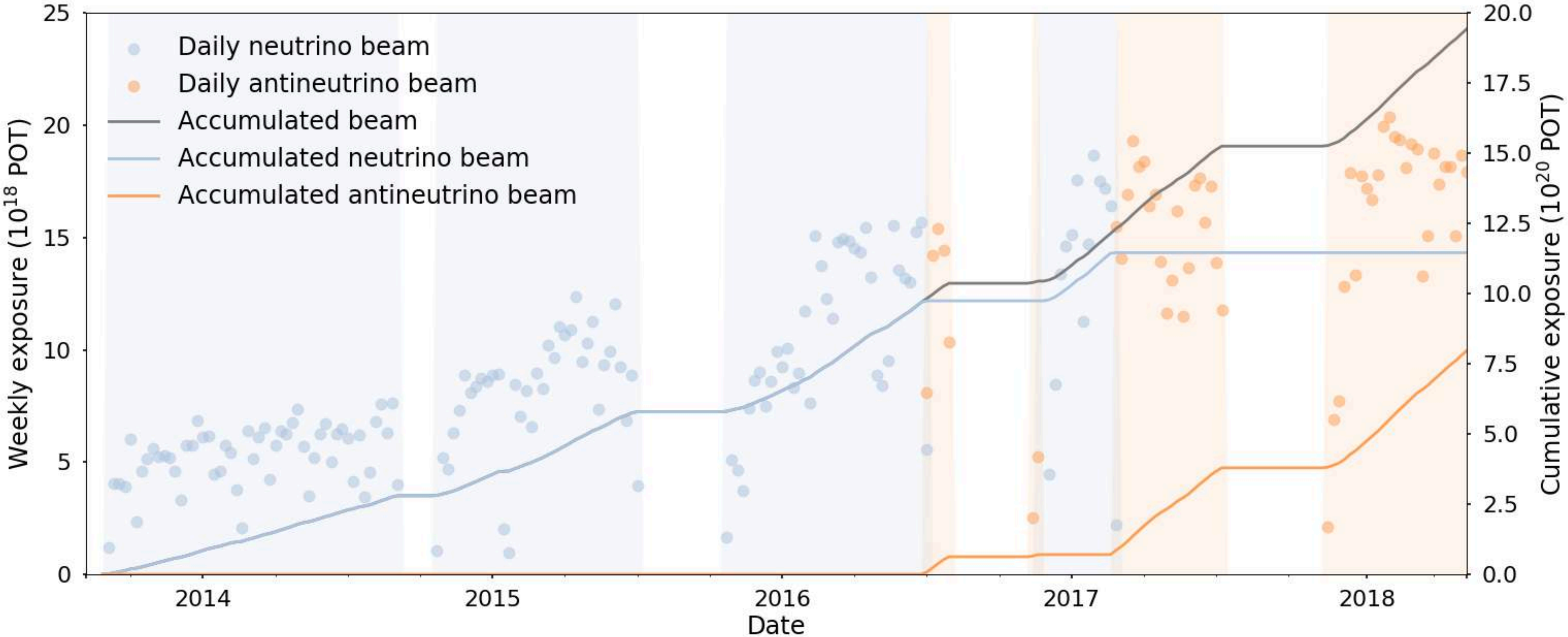


Near Detector
300 tons
14.3 m x 4.1 m x 4.1 m
214 layers, ~20,000 channels



Far Detector
14 kton
60 m x 15.6 m x 15.6 m
896 layers, ~344,000 channels

Accumulated Dataset



Neutrino data, 8.85×10^{20} POT

NEW!

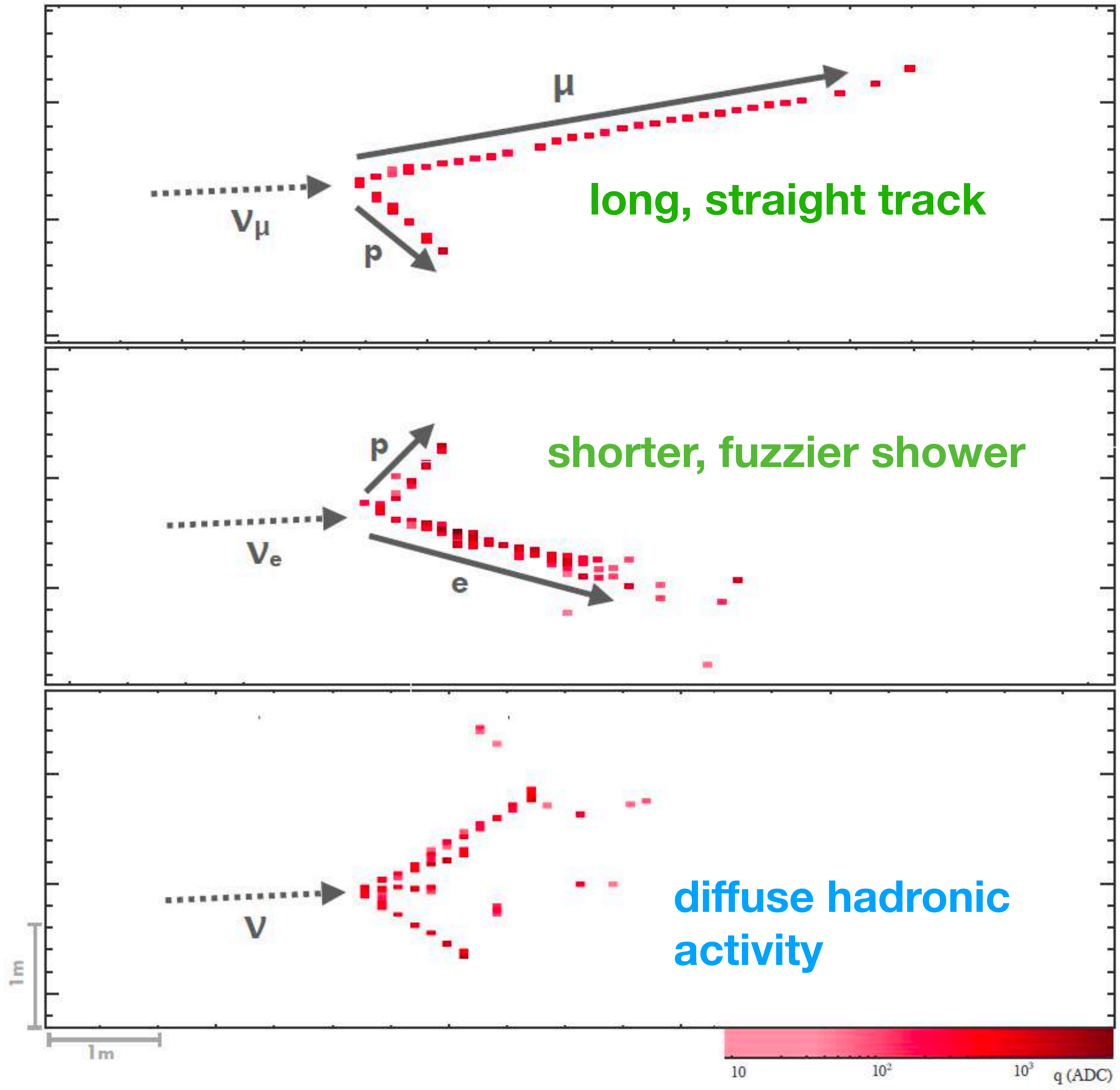
Antineutrino data, 6.9×10^{20} POT

Event Classification

ν_μCC (background)

ν_eCC (background)

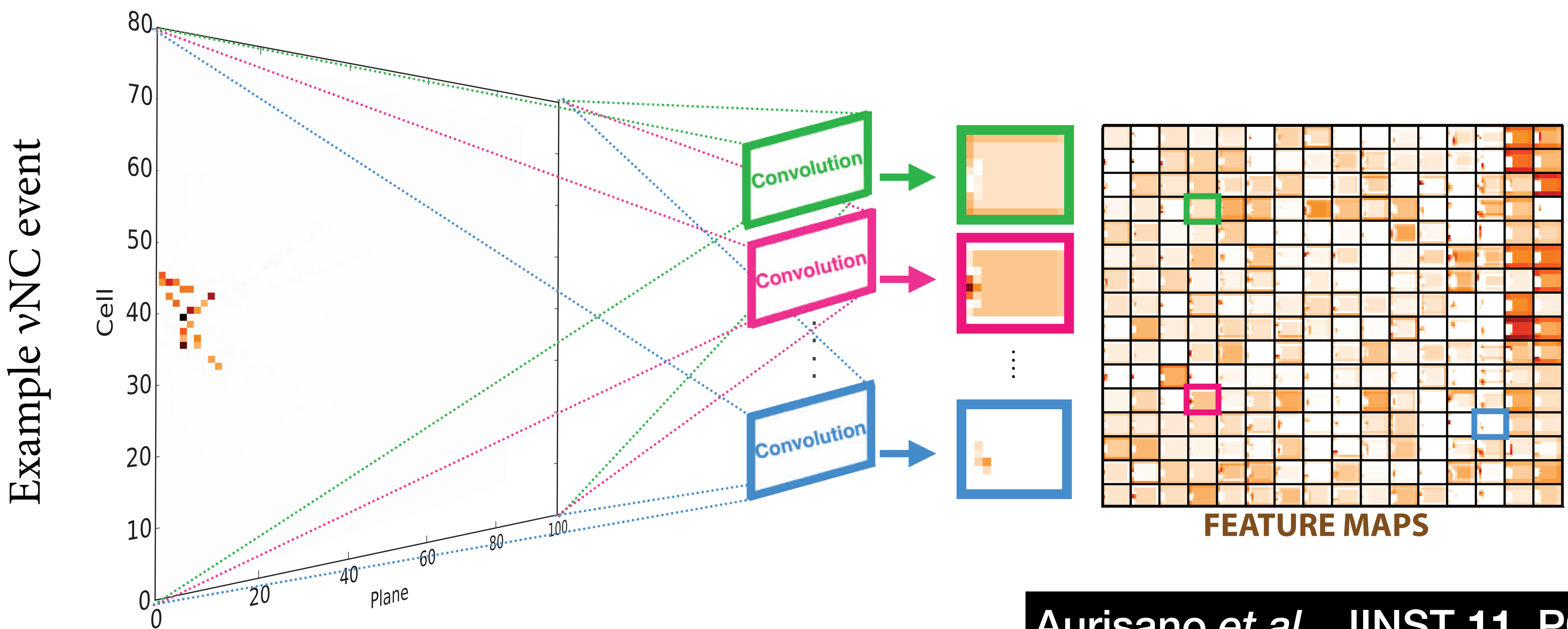
νNC (signal)



Event Classification

Poster: 'Neutrino Physics with Deep Learning on NOvA', F. Psihas

- Utilize deep-learning techniques to perform event classification — NOvA's **convolutional visual network**.
  - Multipurpose classifier used to identify ν_μCC, ν_eCC, ν_τCC and NC events.
- Treat minimally-reconstructed events as feature maps and use convolutional layers which learn filters to extract discriminating features from the events.

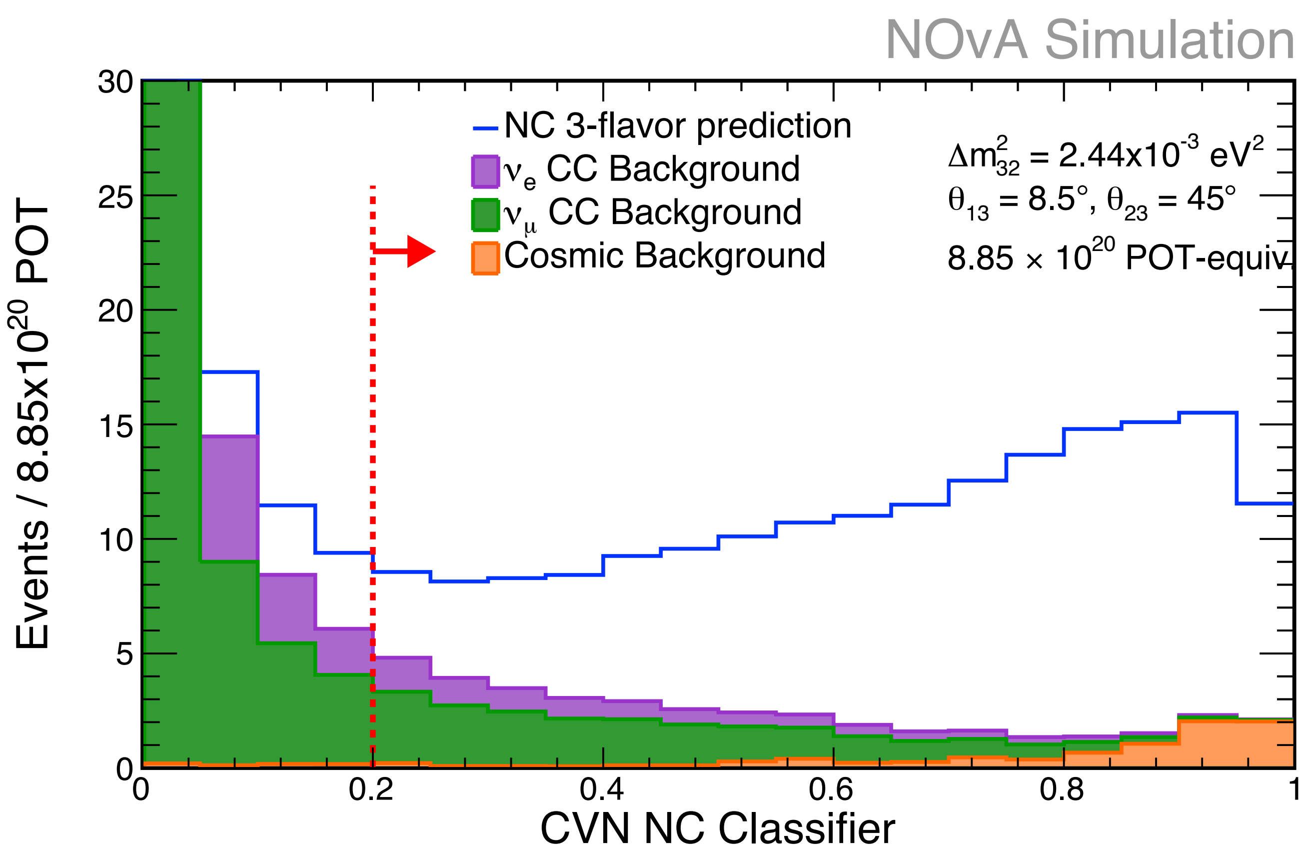


Aurisano *et al.*, JINST 11, P09001 (2016)

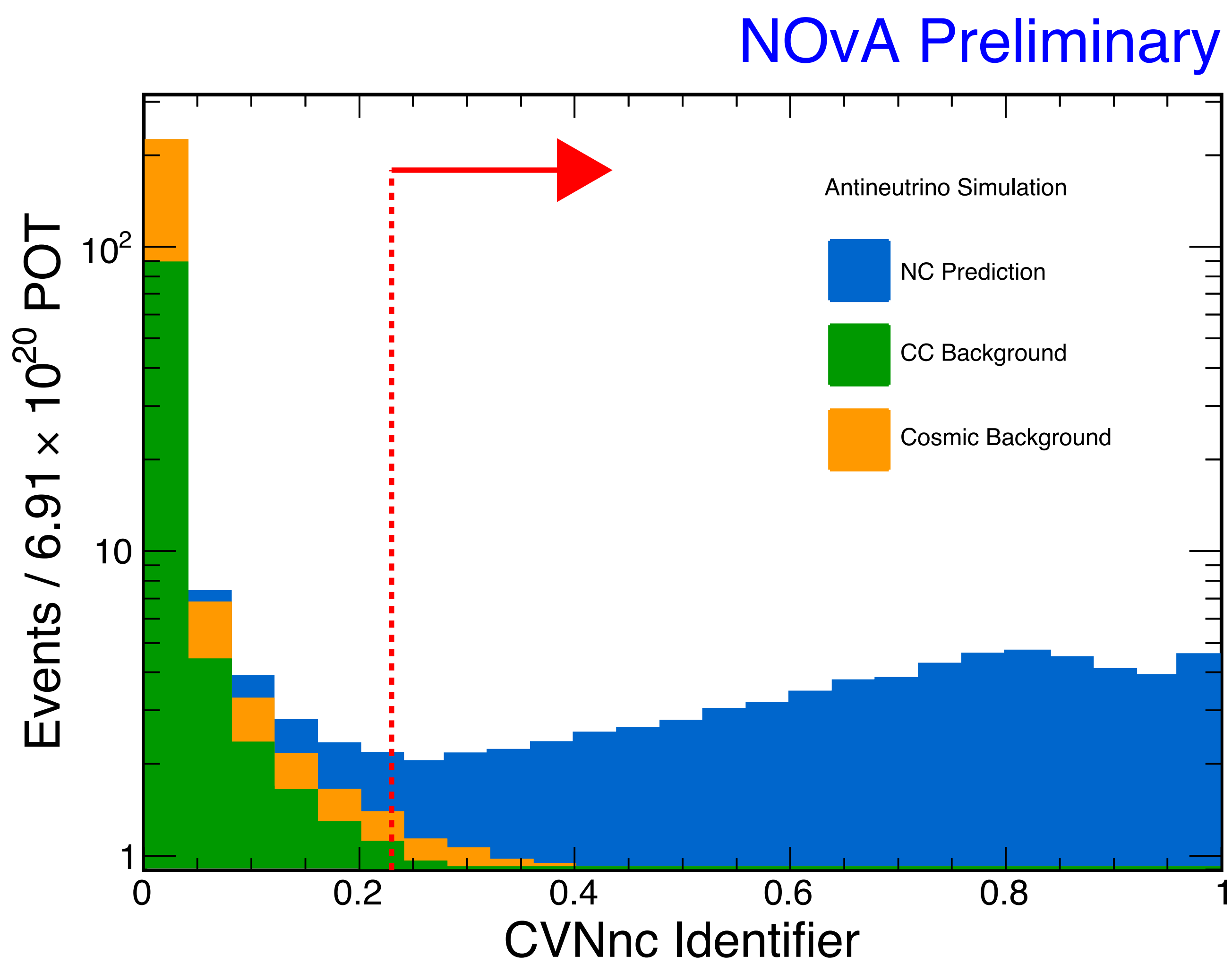
Neutral Current Disappearance Analysis

Neutral Current Selection

- The CVN classifier is trained separately for **neutrino** and **antineutrino** data and gives good separation between NC signal and CC backgrounds.



Neutrino Beam

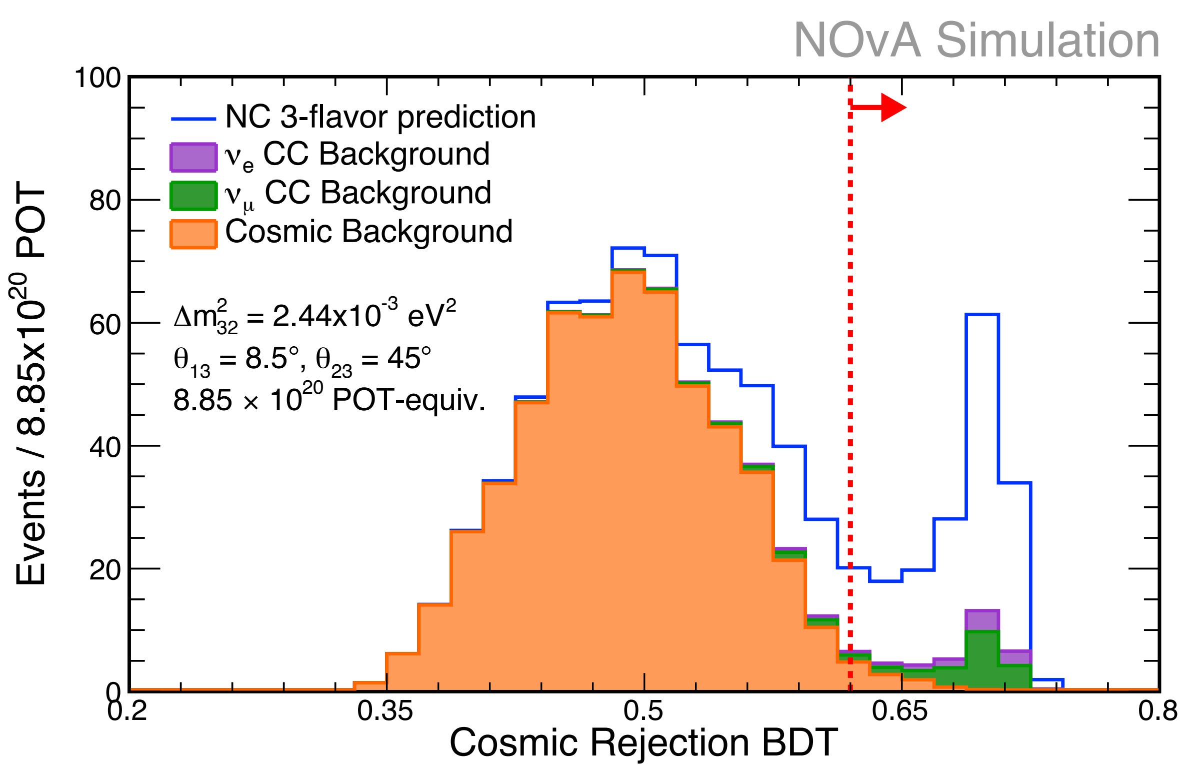


Antineutrino Beam

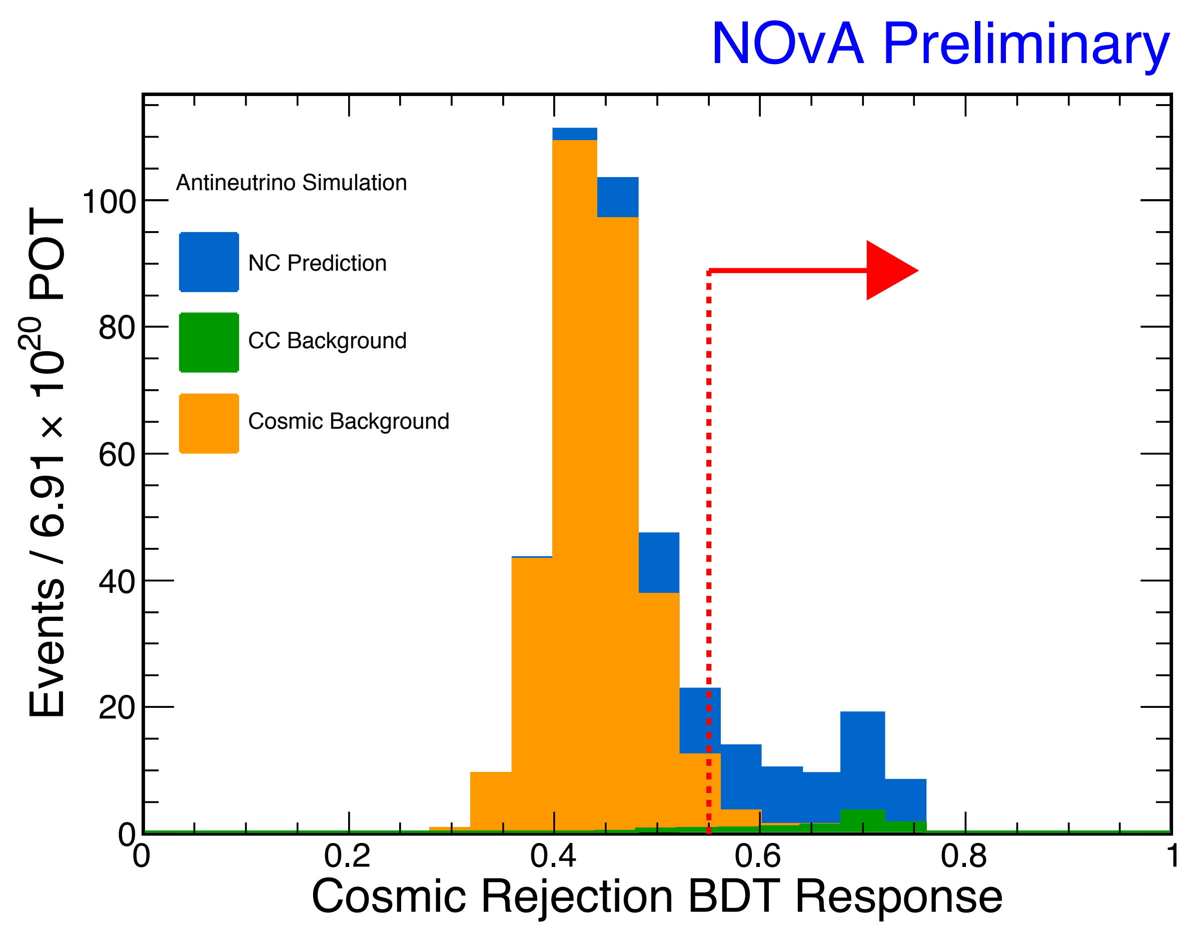
Cosmic Rejection

- The NOvA far detector is on the surface and is exposed to cosmic muons at a rate of 11 billion a day. Neutrons from cosmic induced interactions are a large background to NC events in NOvA.

- Remove cosmic events by cutting on directionality of showering particles, transverse momentum, activity in events close in temporal and spatial proximity, and using an NC-specific Boosted Decision Tree (BDT) trained on 13 shower variables.



Neutrino Beam



Antineutrino Beam

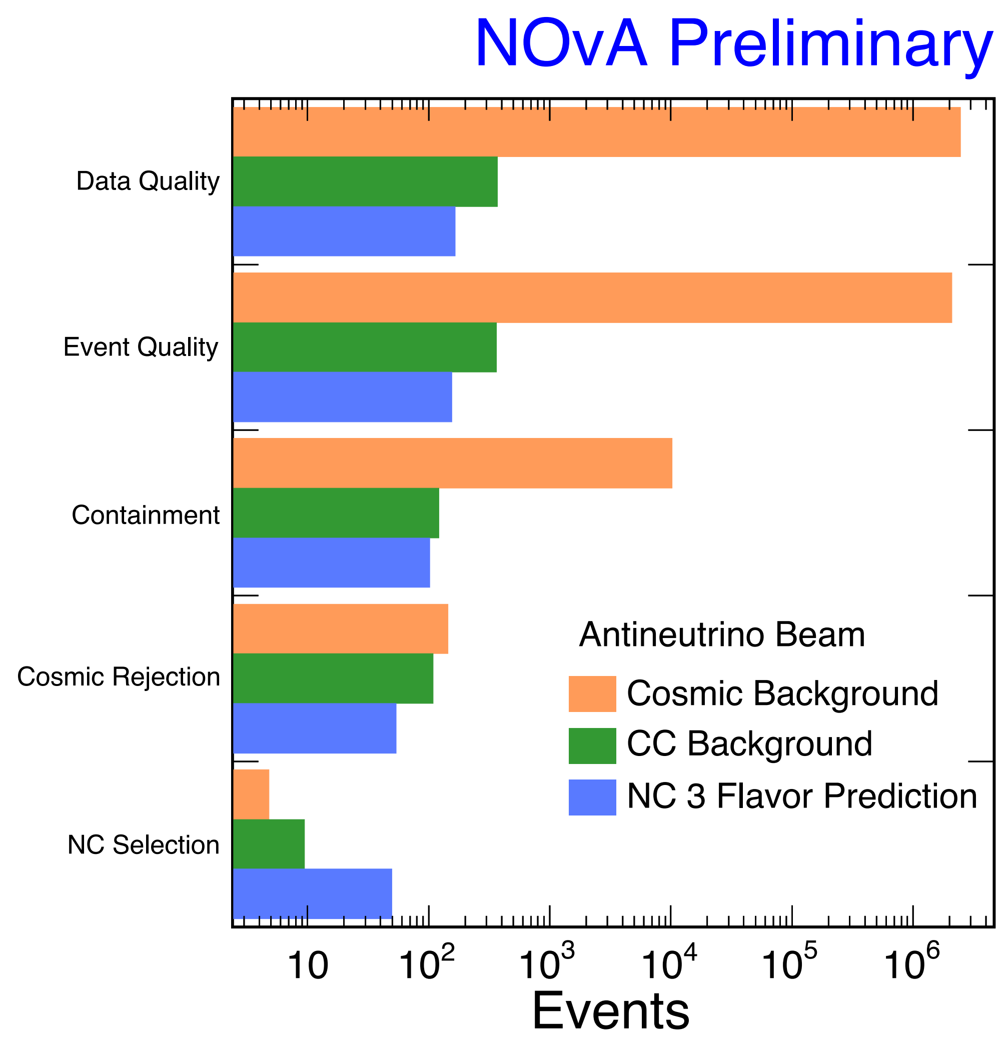
Event Selection

Neutrino Data

- 191 events selected
  (148 NC, 35 CC bg, 7.9 cosmic bg).
- Overall selection efficiency of 52% and purity 77%.

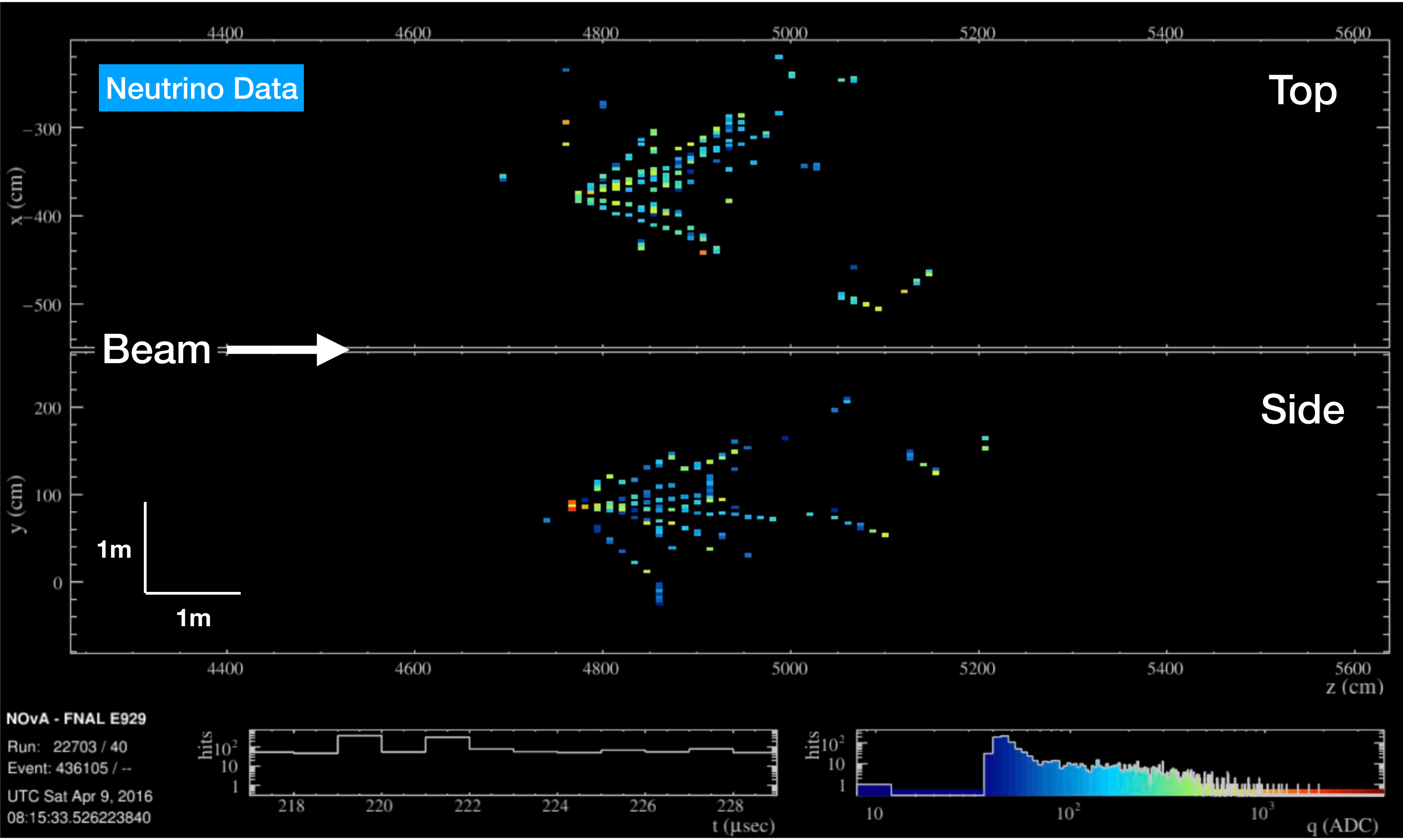
Antineutrino Data

- 68.9 events selected
  (53.4 NC, 10.2 CC bg, 5.3 cosmic bg).
- Overall selection efficiency of 50% and purity 78%.



Antineutrino Cut Flow

Candidate Selected Event



Extrapolation

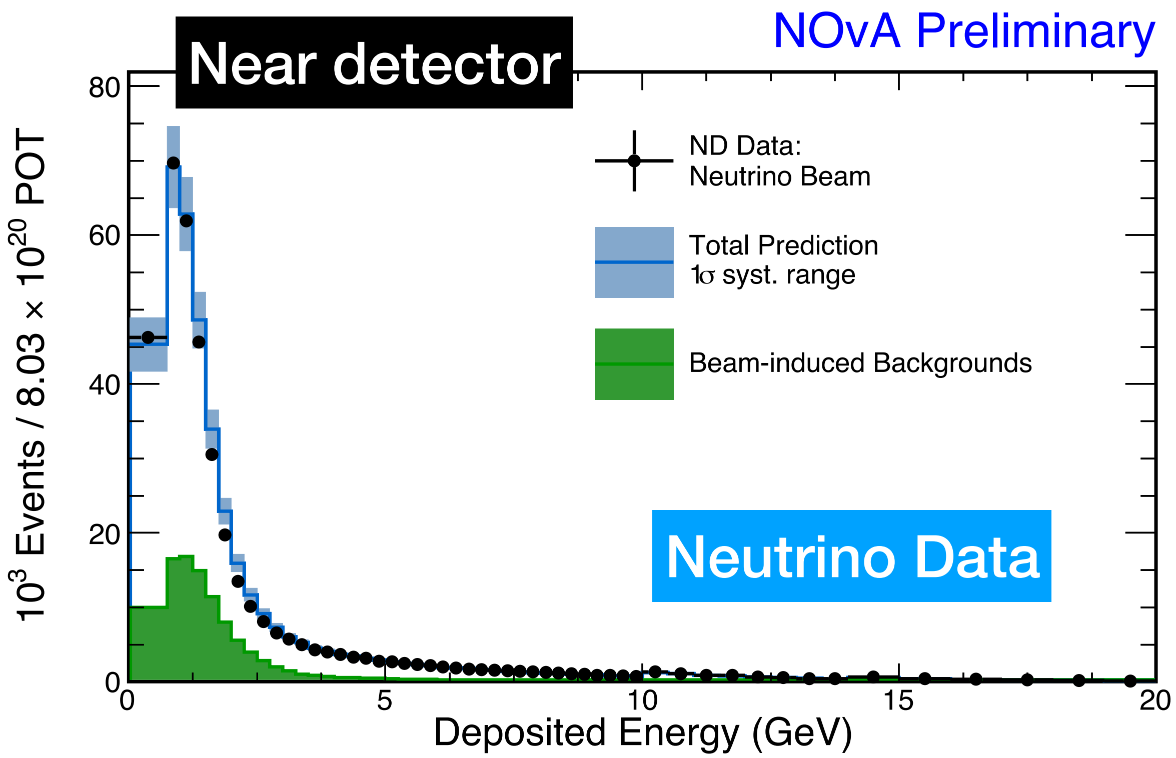
- Assuming a small mass-splitting such that there are no ND oscillations, can produce a FD 'prediction' using ND data.

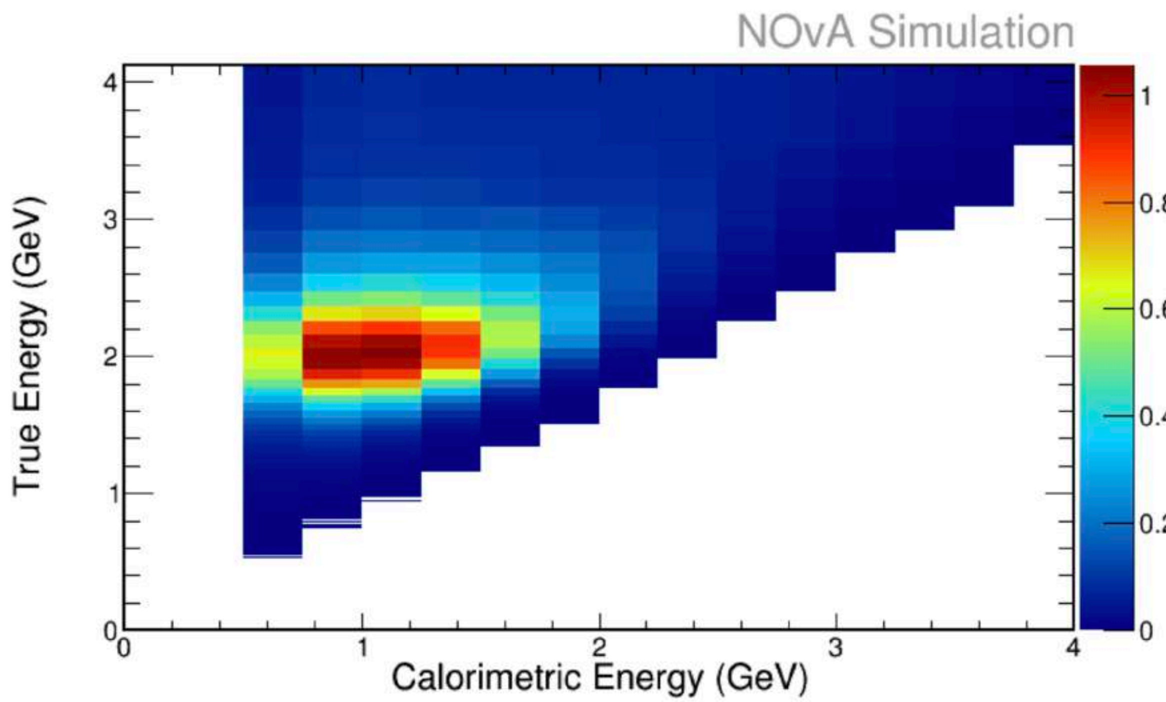
- Constrain the ND simulation with data and convolve with the predicted ratio of the FD and ND distributions, taking into account geometrical differences, beam dispersion and the effect of oscillations.

    - Partially cancels correlated systematic uncertainties between two detectors.

- Since each component oscillates differently, decompose observed ND spectrum according to simulated proportions.

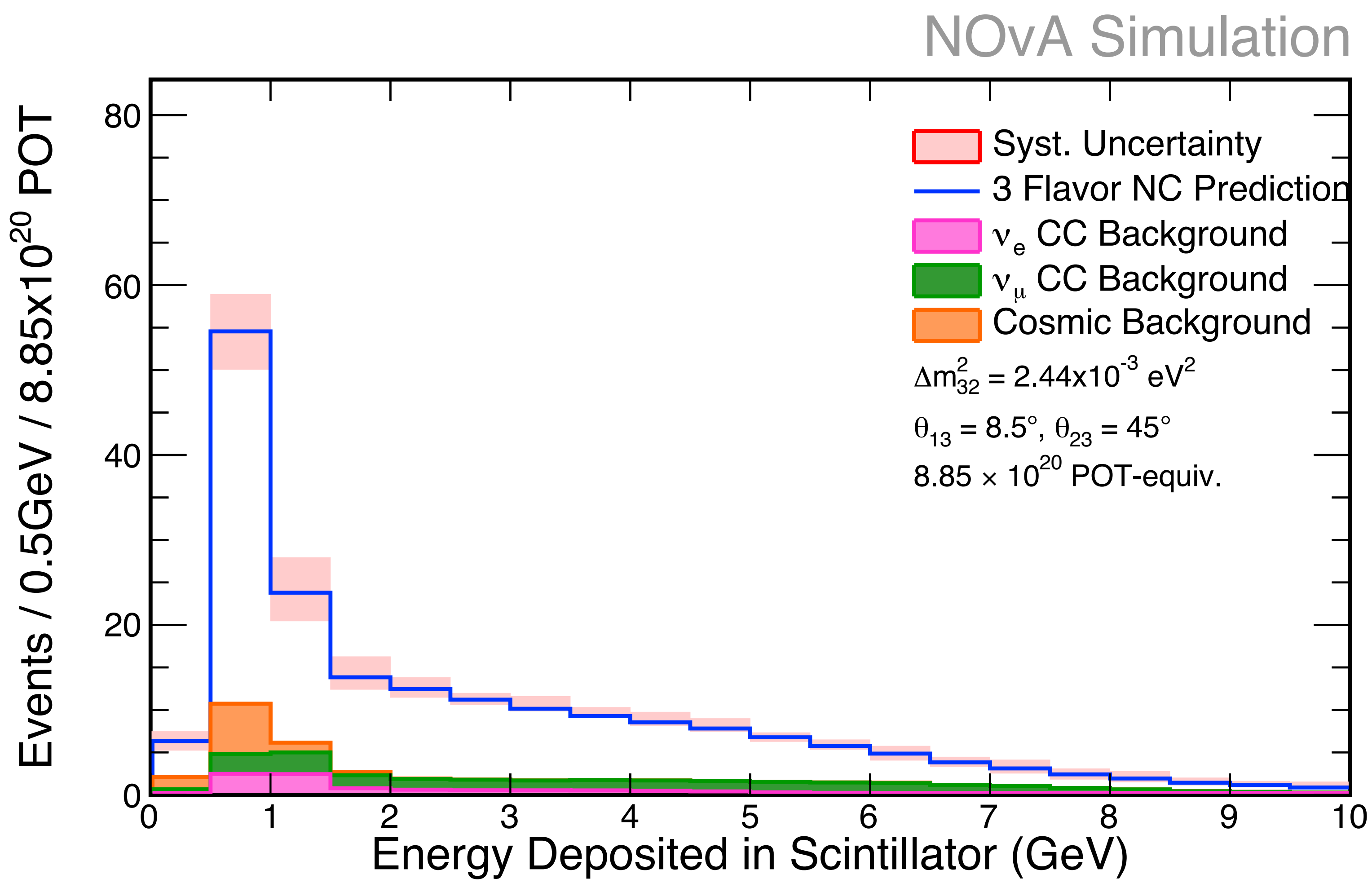
- Use migration matrix to convert reconstructed energy to true energy, apply oscillations and migrate back to reconstructed energy.





Far Detector: Neutrino Prediction

- Use NOvA best fit point from the joint ν_μ-ν_e analysis:
  - $\sin^2\theta_{23} = 0.558 \pm 0.042$,
  - $\delta_{13} = 1.21\pi$,
  - $\Delta m^2_{32} = 2.44\times10^{-3}$ eV^2.
- Used for both **neutrino** and **antineutrino** analyses.

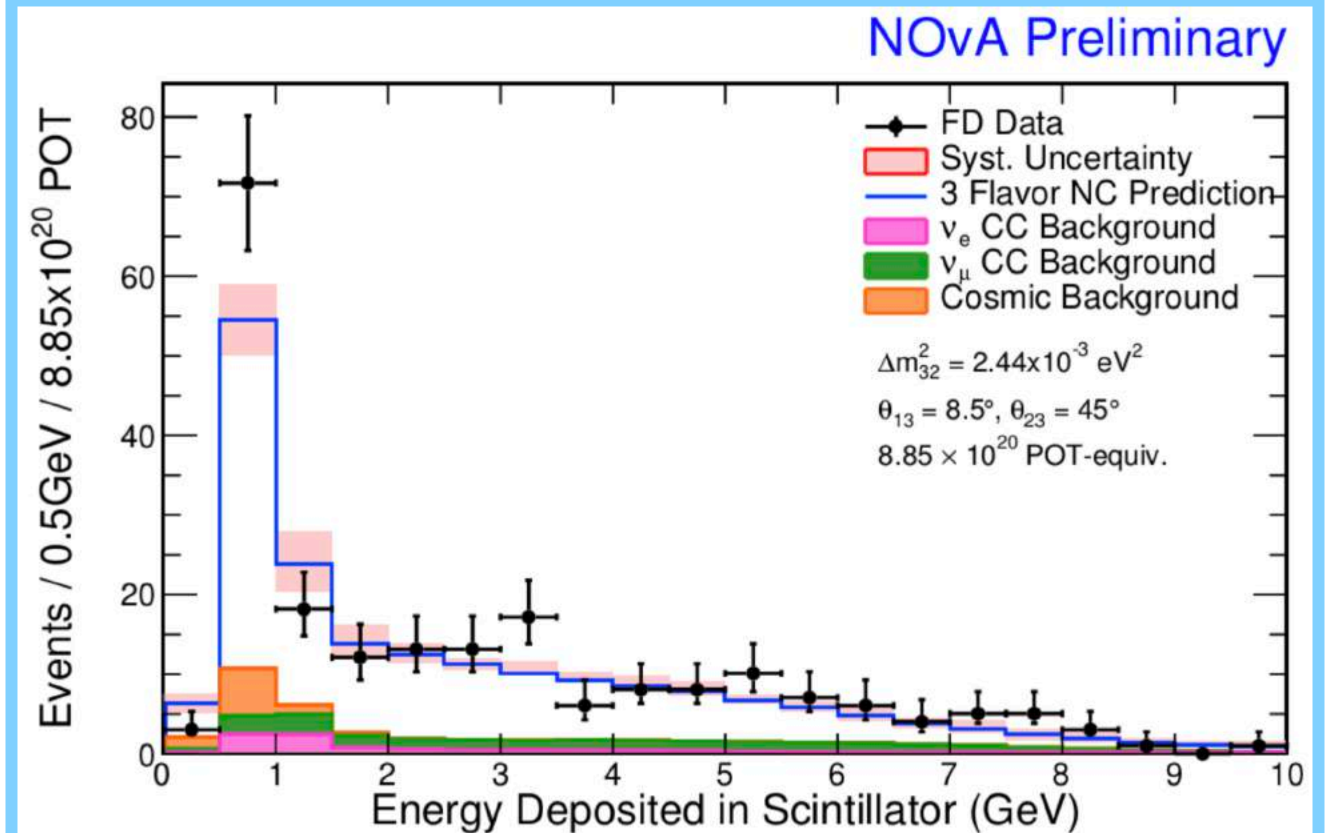


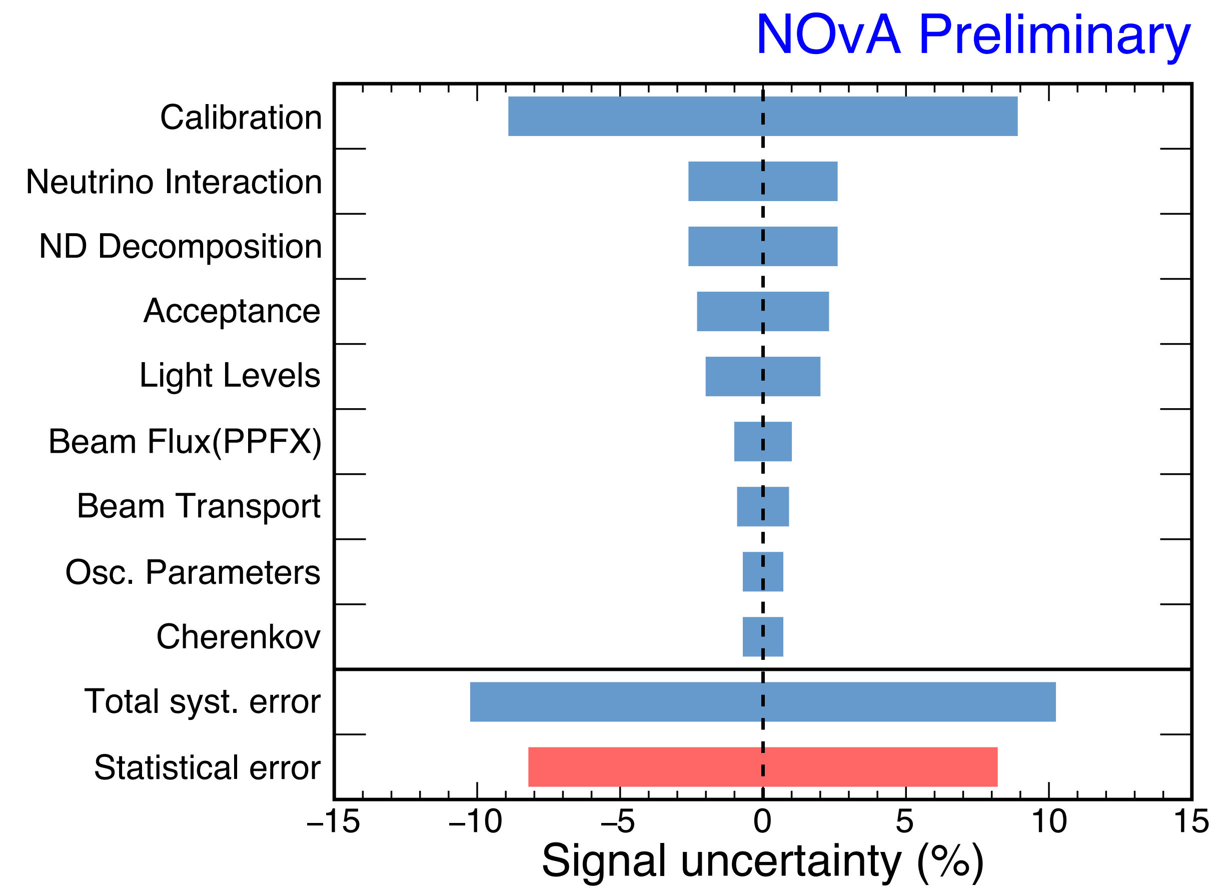
Neutrino Simulation

Far Detector Neutrino Data

Neutrino Data

- Observed **214** events, with prediction of **191.2 ± 13.8 (stat) ± 22.0 (syst)**.





No evidence of neutral current disappearance

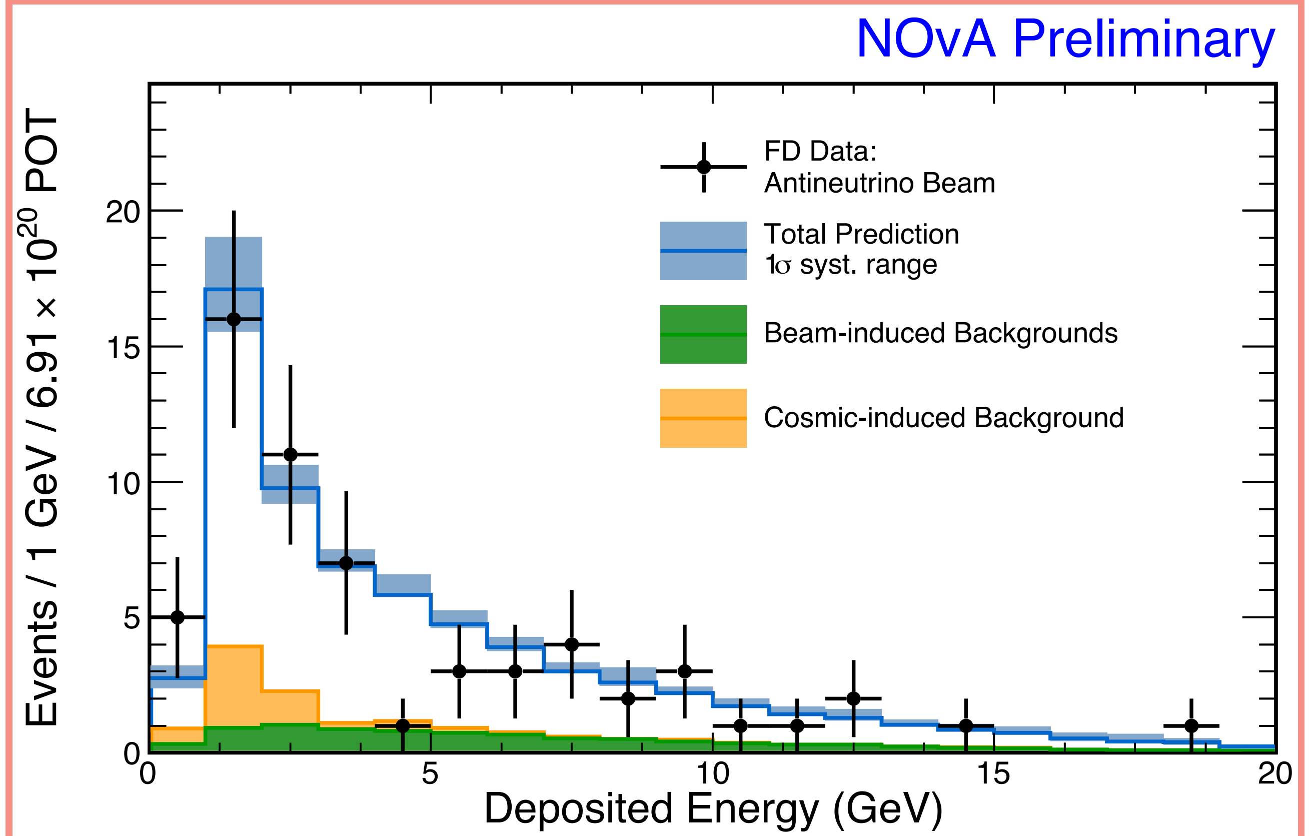
$$R_{NC} \equiv \frac{N^{Data} - \sum N^{Pred}_{Bkg}}{N^{Pred}_{NC}} = 1.19 \pm 0.14(\text{stat.}) \pm 0.12(\text{syst.})$$

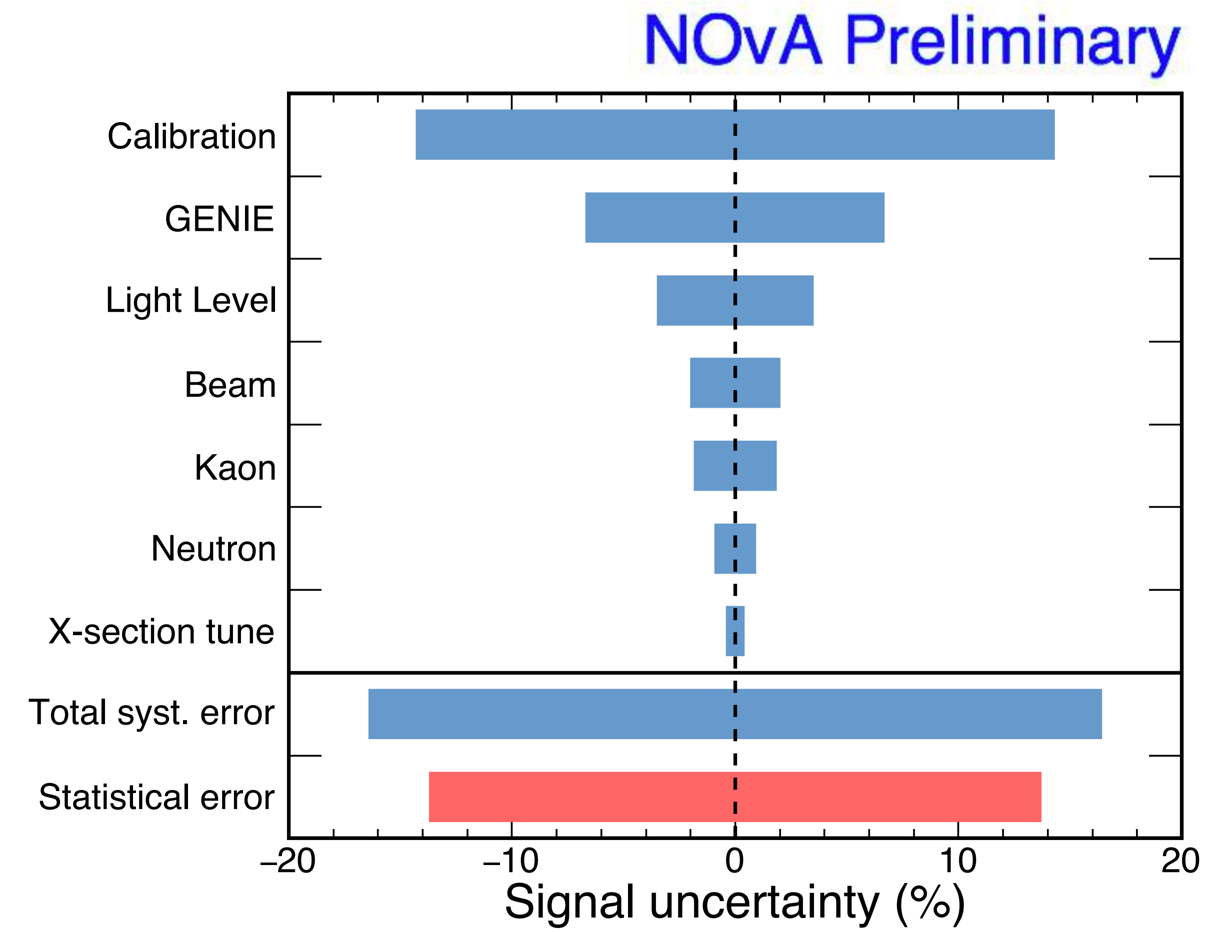
- Uncertainties dominated by calibration and interaction systematics.
- Future work, in particular the NOvA test beam program, will aim to reduce these uncertainties for future analyses.

Far Detector Antineutrino Data

Antineutrino Data

- Observed **61** events, with prediction of **69 ± 8 (stat.) ± 10 (syst.)**.





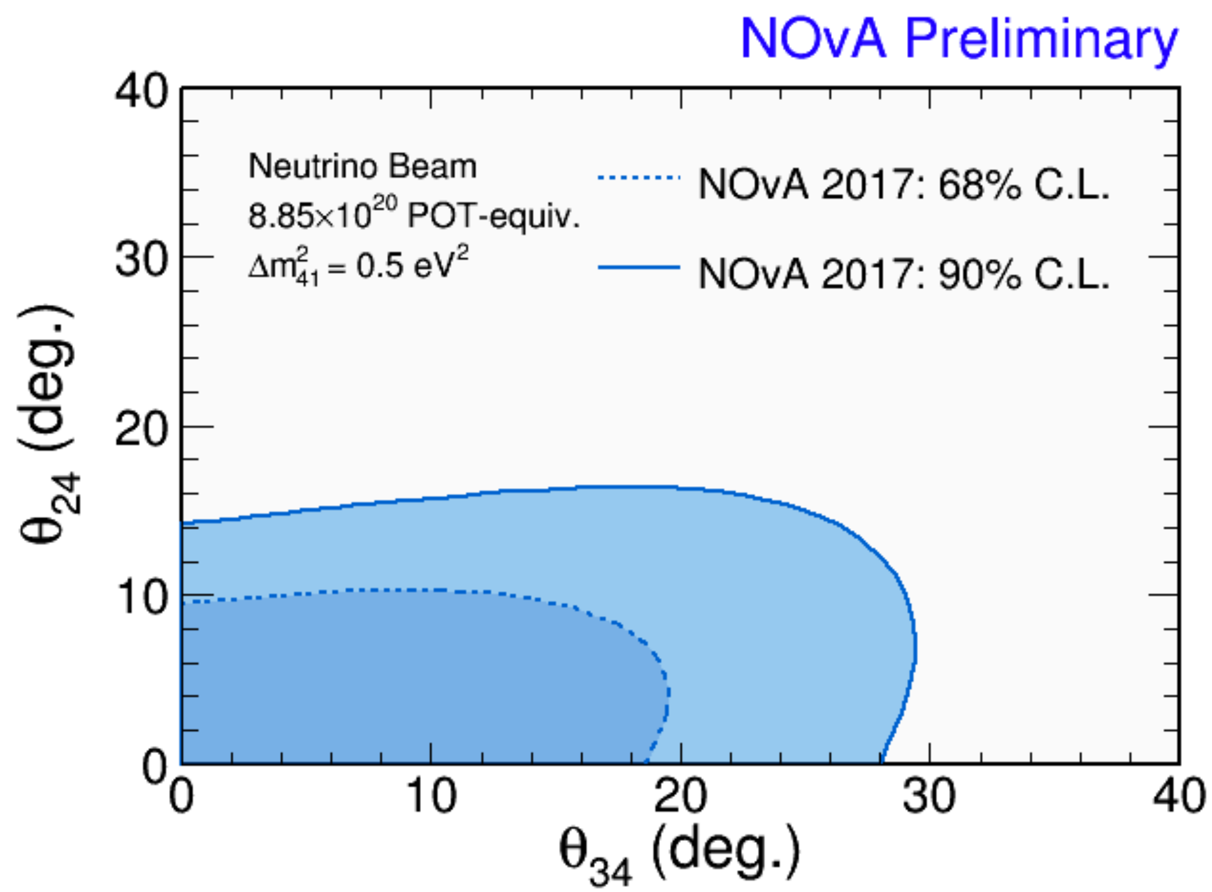
- Similarly large experimental uncertainties to the neutrino analysis.

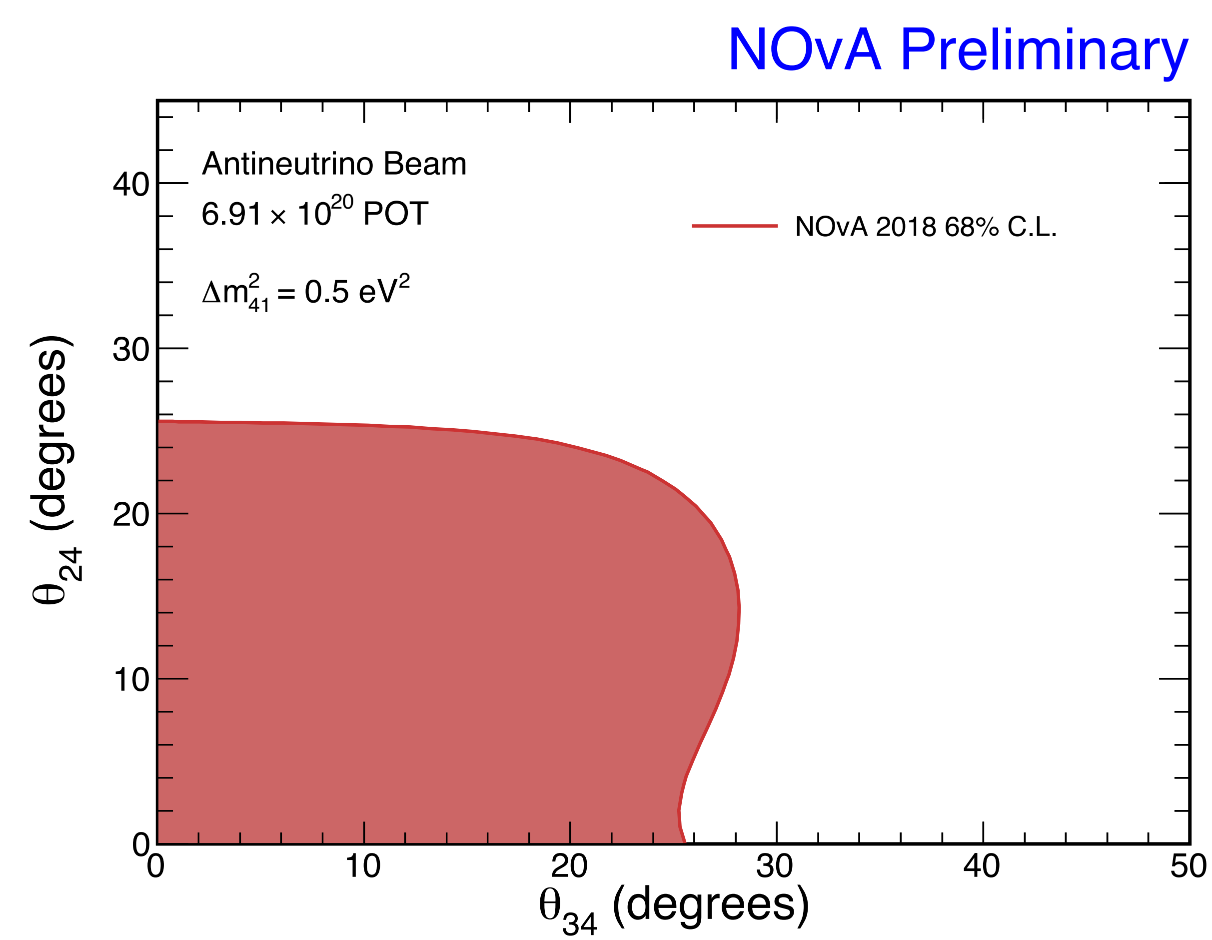
Again consistent with oscillations in 3-flavor framework.

$$R_{NC} \equiv \frac{N^{Data} - \sum N^{Pred}_{Bkg}}{N^{Pred}_{NC}} = 0.86 \pm 0.15(\text{stat.})^{+0.09}_{-0.12}(\text{syst.})$$

Limits

- Perform shape-based fits to create allowed regions in θ_{24}-θ_{34} parameter space:
  - Valid for $0.05 < m^2_{41}$ (eV^2) < 0.5;
  - Profile over θ_{23} and δ_{14}.
  - Assume $\theta_{14} = 0$ and $\delta_{14} = 0$ (solar and reactor constrains $\sin^2\theta_{41} < 0.04$).
- 1D limits from neutrino data:
  - $\theta_{24} < 16.2°$, $\theta_{34} < 29.8°$ (90% C.L.).
- 1D limits from antineutrino data:
  - $\theta_{24} < 25.5°$, $\theta_{34} < 31.5°$ (68% C.L.).

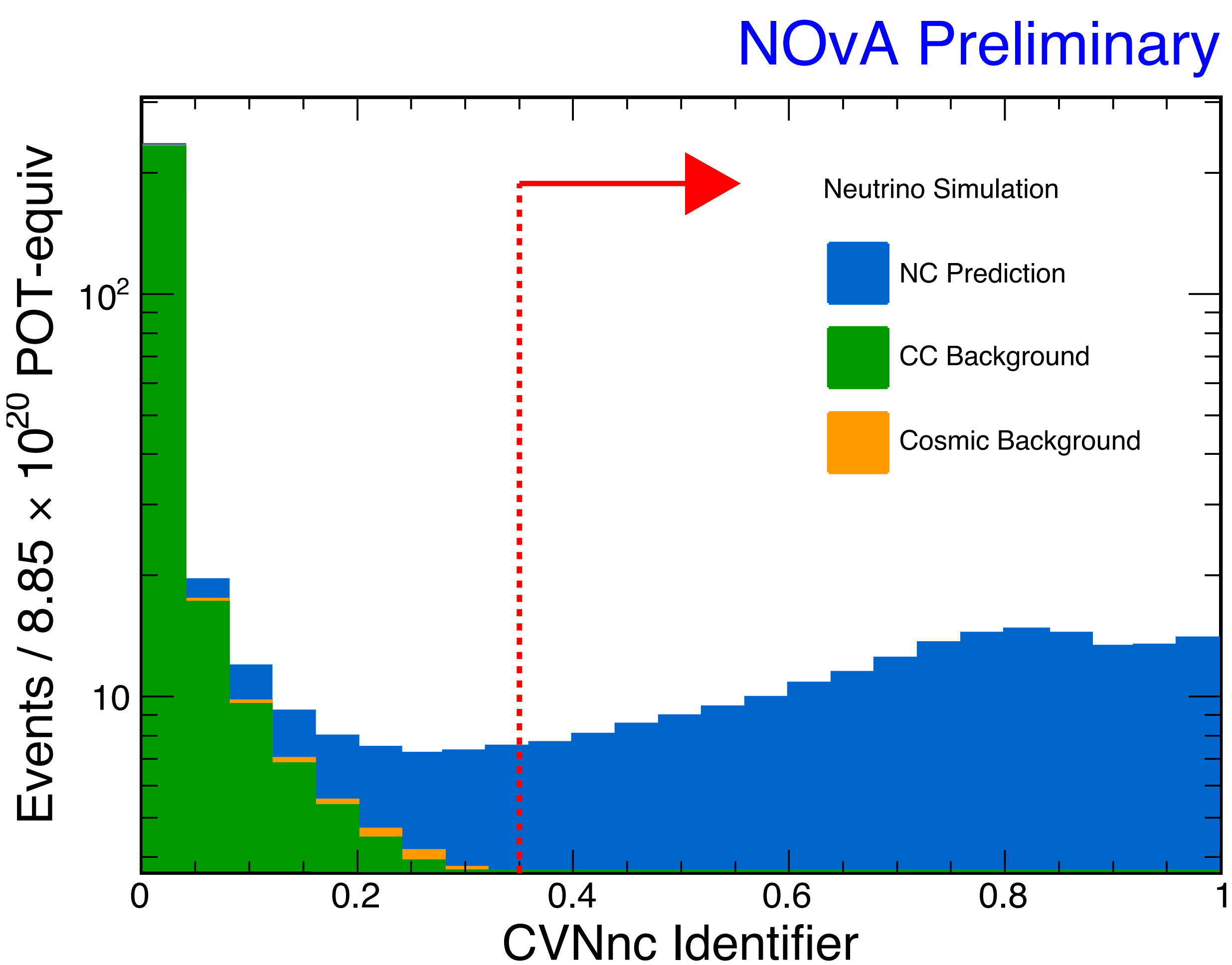


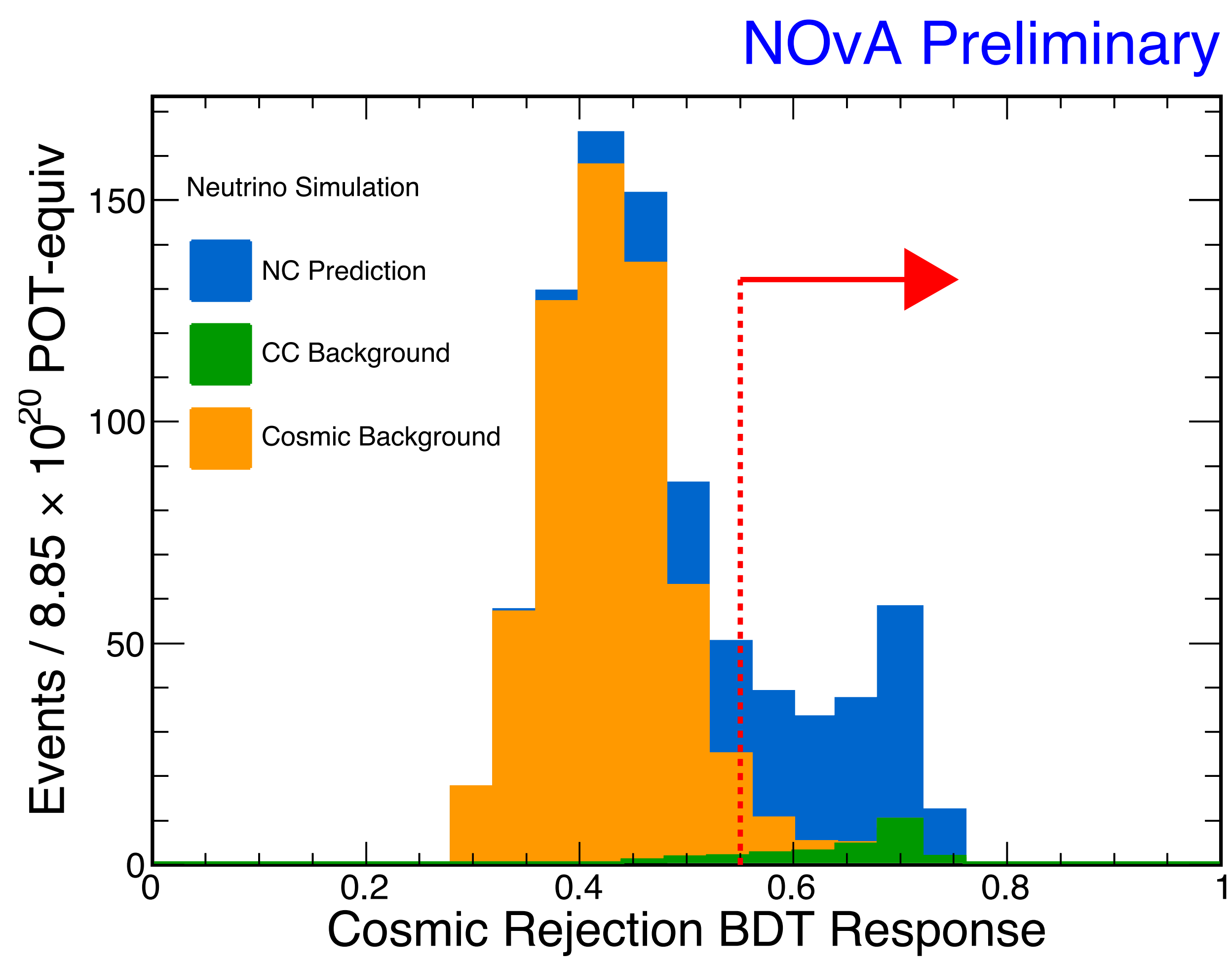


Future Improvements

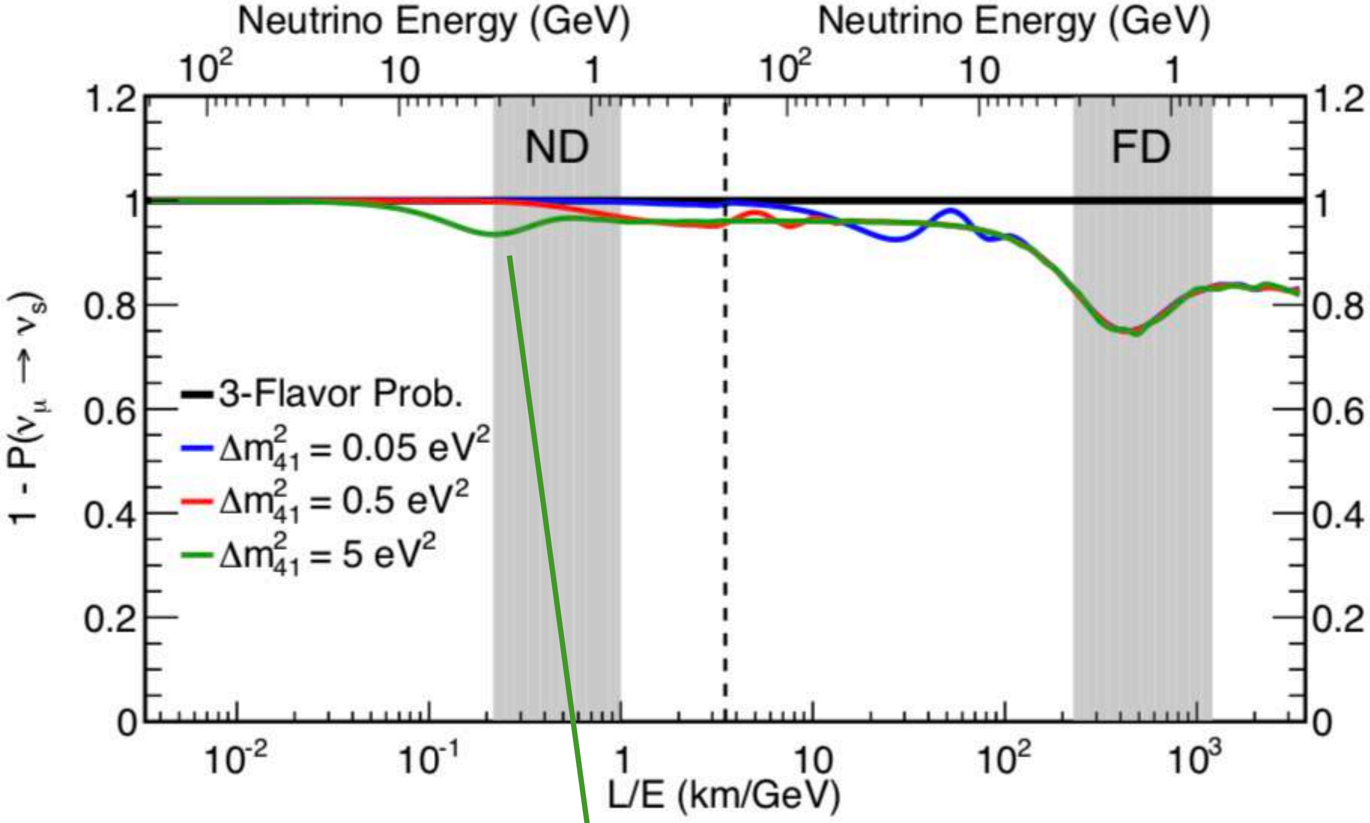
Improved Selection for Neutrino Analysis

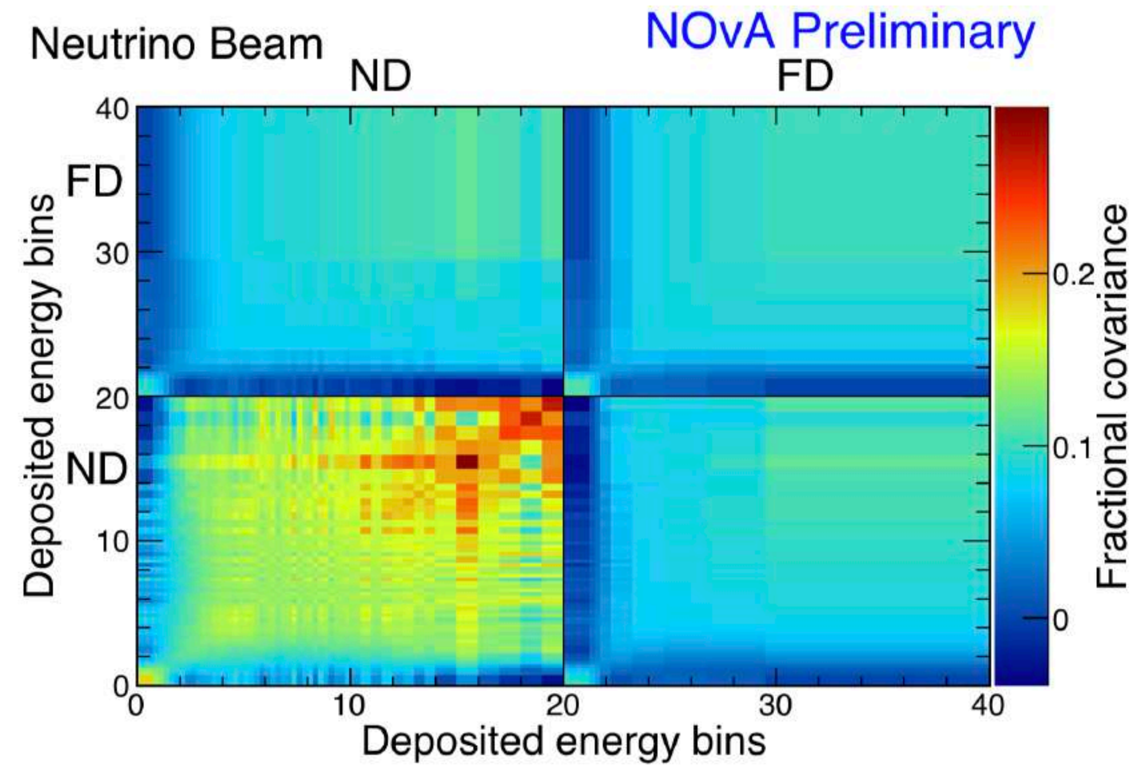
- Retrain CVN for improved event classification.
- Train the cosmic rejection BDT separately on different data-taking running conditions.
- Selection purity increased to 81% from 77%, maintaining 52% efficiency.





Fitting for Sterile Mass Splitting





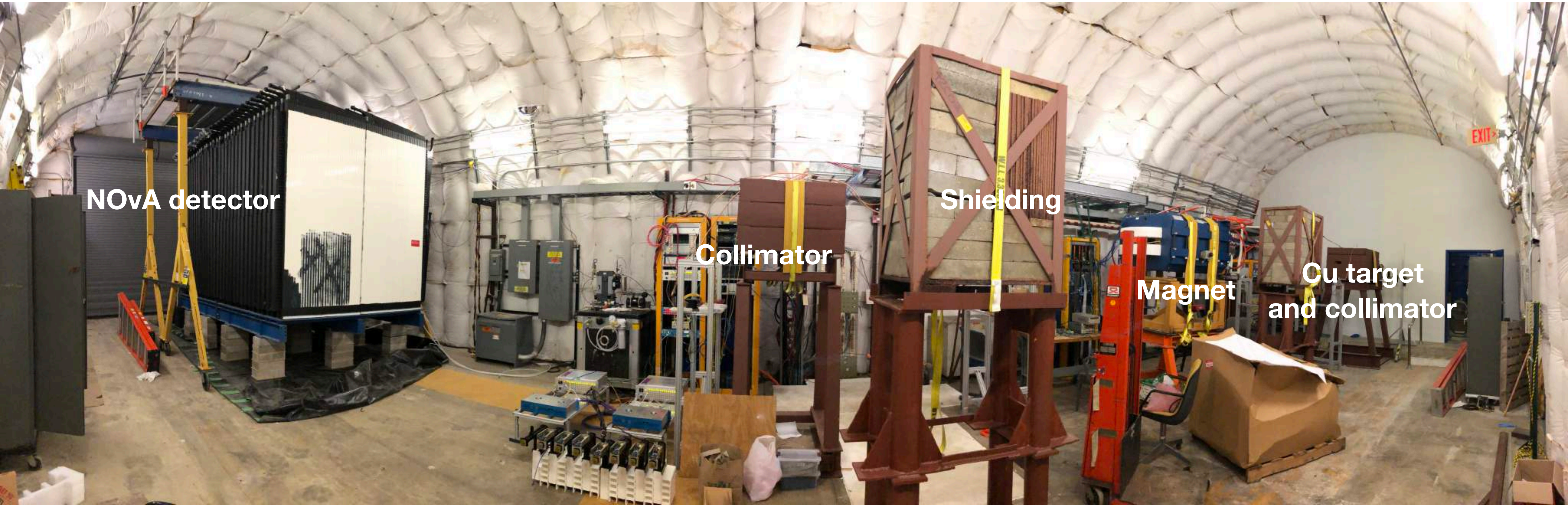
$\Delta m^2_{41} > 0.5$ eV^2

- Oscillations in both ND and FD, can no longer treat Δm^2_{41} as constant.
- Must perform joint fit in both ND and FD to properly account for these effects.

- Use covariance matrix to track correlated systematics between two detectors, maintaining the cancellation of uncertainties.
- Technique recently used by MINOS/MINOS+ (arXiv:1710.06488v2), this will be the first use in NOvA.

Test Beam Program

Poster: 'The NOvA Test Beam',
A. Sutton

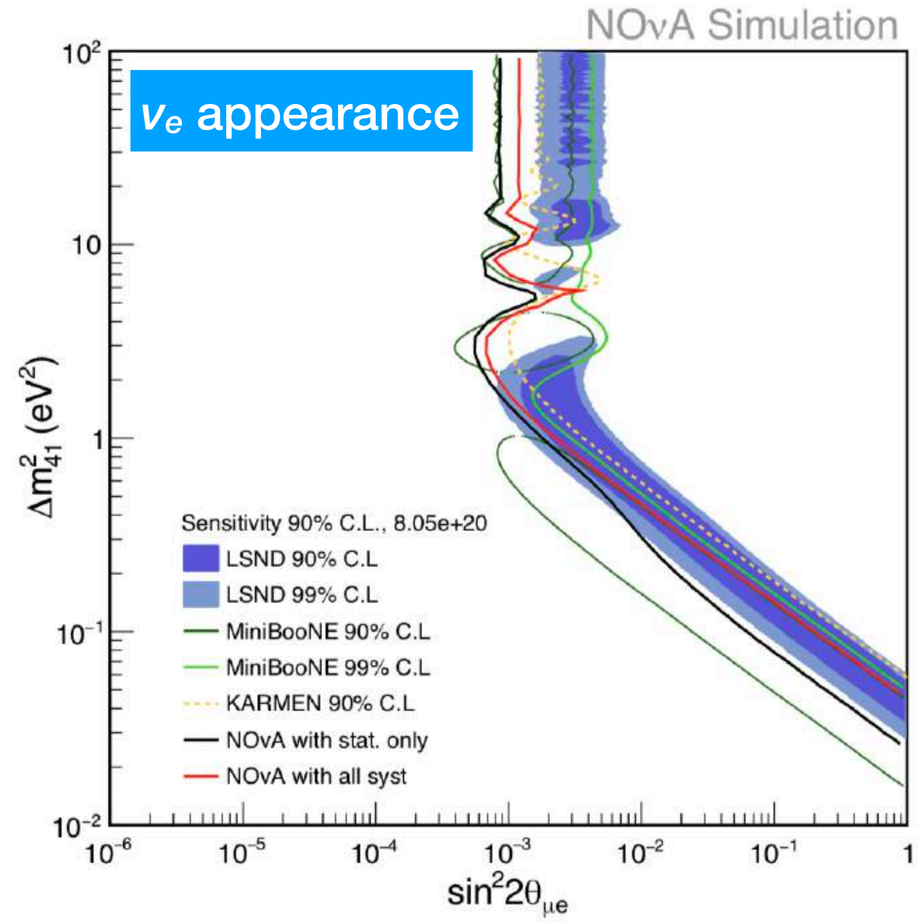


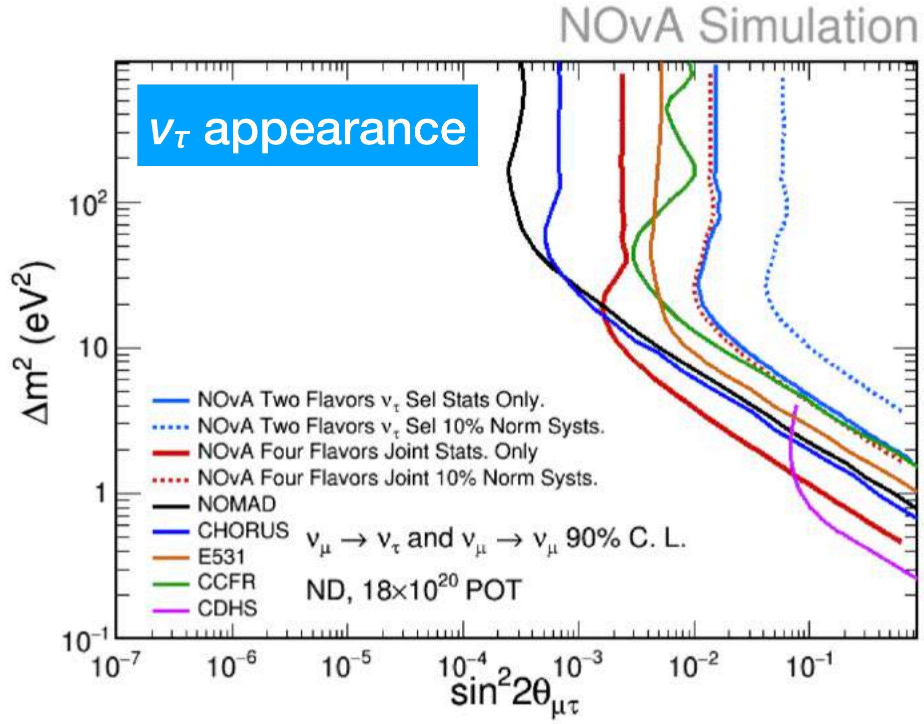
- Six-month test beam run scheduled January — June 2019, currently under construction and commissioning at Fermilab Test Beam Facility.

- Will use a scaled-down (30 ton) NOvA detector to sample beams of tagged electrons, muons, pions, and protons in the momentum range of 0.3 to 2 GeV and will further the NOvA physics reach by precisely measuring the detector's muon energy scale and electromagnetic and hadronic response.

Short-Baseline Analyses

- With sterile neutrino oscillations, electron neutrino and tau neutrino appearance must be consistent with muon neutrino disappearance.
- Joint analysis of ν_e, ν_τ appearance with ν_μ disappearance allows partial cancellation of systematics.
- Short-baseline oscillations at the NOvA near detector covers L/E range of LSND and allows searching for high-energy ν_τs in the tail above the beam peak.
- Results coming soon!





Summary

- Searched for deficit in Neutral Current neutrino events in the NOvA detectors with
  - 8.85×10^{20} POT neutrino data;
  - 6.91×10^{20} POT antineutrino data (new analysis!).
- Results for both analyses consistent with no sterile oscillations;
  - For $0.05 < m^2_{41}$ (eV^2) < 0.5:
    - 1D limits (90% C.L.) from neutrino data: $\theta_{24} < 16.2°$, $\theta_{34} < 29.8°$;
    - 1D limits (68% C.L.) from antineutrino data: $\theta_{24} < 25.5°$, $\theta_{34} < 31.5°$.
  - Limits from the new two-detector joint-fit with neutrino data coming later this year.
- Two short-baseline sterile searches are nearing completion.

Thank You!

http://novaexperiment.fnal.gov

Back-Ups

Short-Baseline Oscillations

$$P^{SBL,3+1}_{\nu_\mu \to \nu_\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2\Delta_{41}$$
$$= 1 - \cos^2\theta_{14}\sin^2\theta_{24}\sin^2\Delta_{41}$$

Extrapolation

$$F^{\textbf{pred}}_{jk\beta} = \sum \frac{N^{\textbf{data}}_{jk\alpha}}{N^{\textbf{sim}}_{jk\alpha}} F^{\textbf{sim}}_{jk\beta} P(\nu_\alpha, \nu_\beta)$$

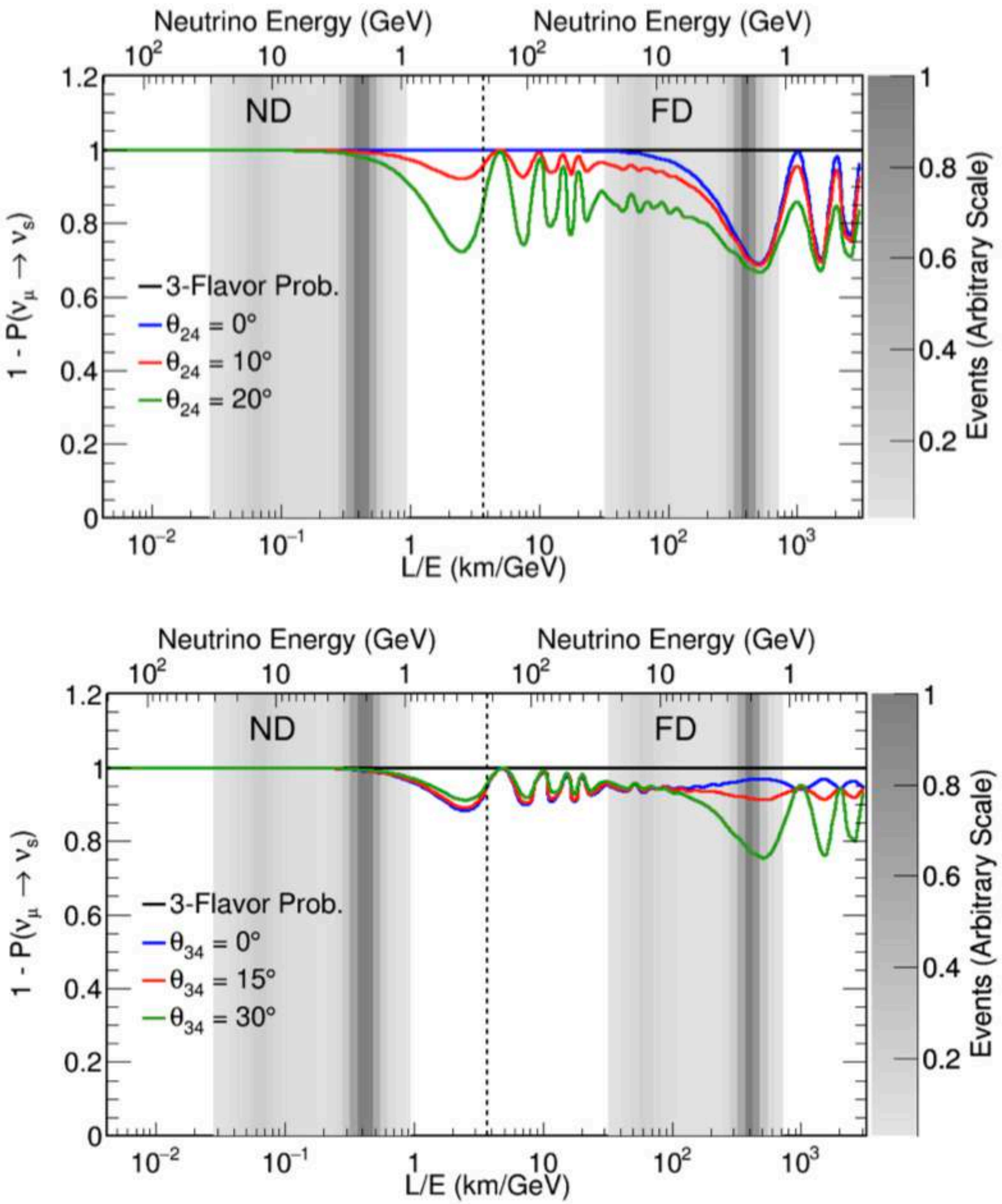
Covariance Matrix Fit

$$V_{ij,syst} = \frac{\sum_{n=1}^{U}(S_{n,i} - \mu_i)(S_{n,j} - \mu_j)}{U - 1}$$

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(x_i - \mu_i)[V^{-1}]_{ij}(x_j - \mu_j)$$

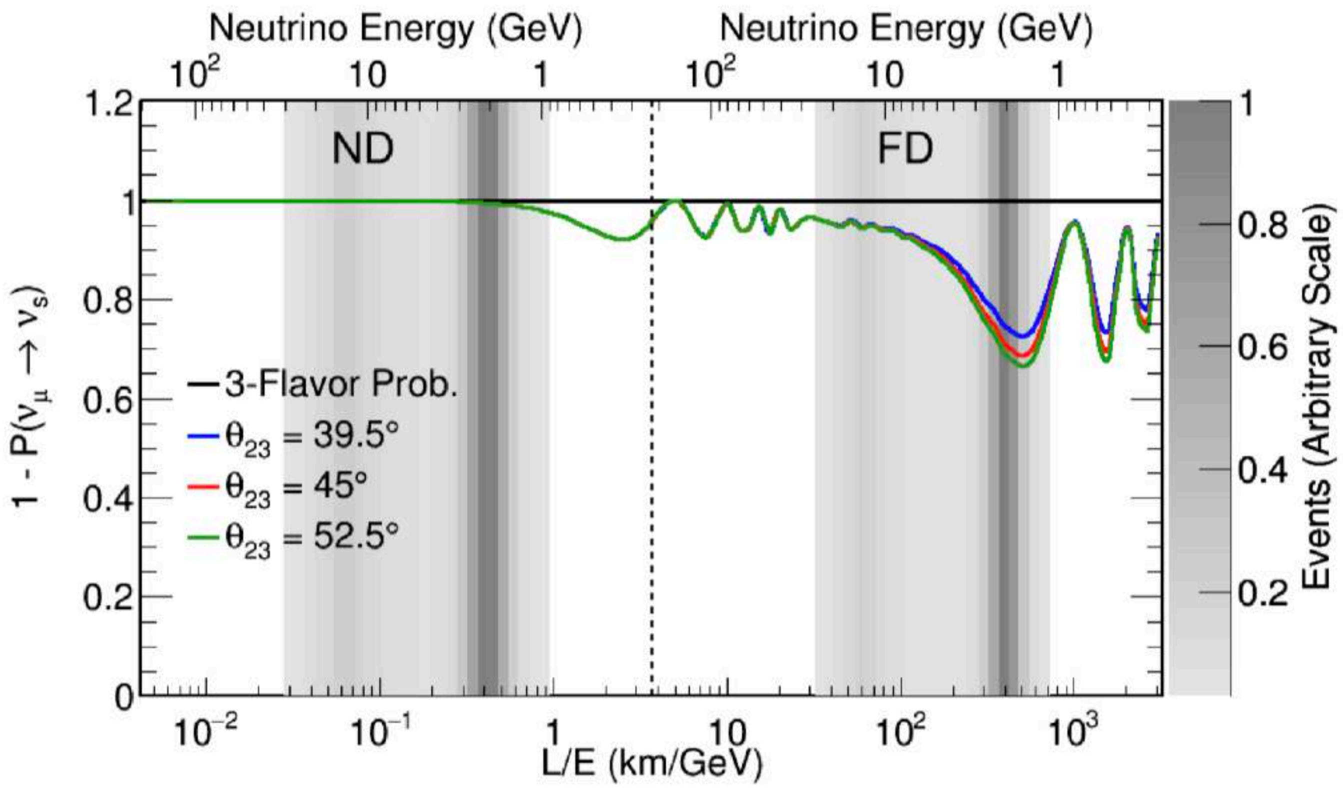
Long-Baseline Neutral Current Disappearance

- Mixing angles, θ_{24}, θ_{34}:
  - Depth of oscillations at maximum controlled by θ_{34},
  - Shape of decent controlled by θ_{24}.



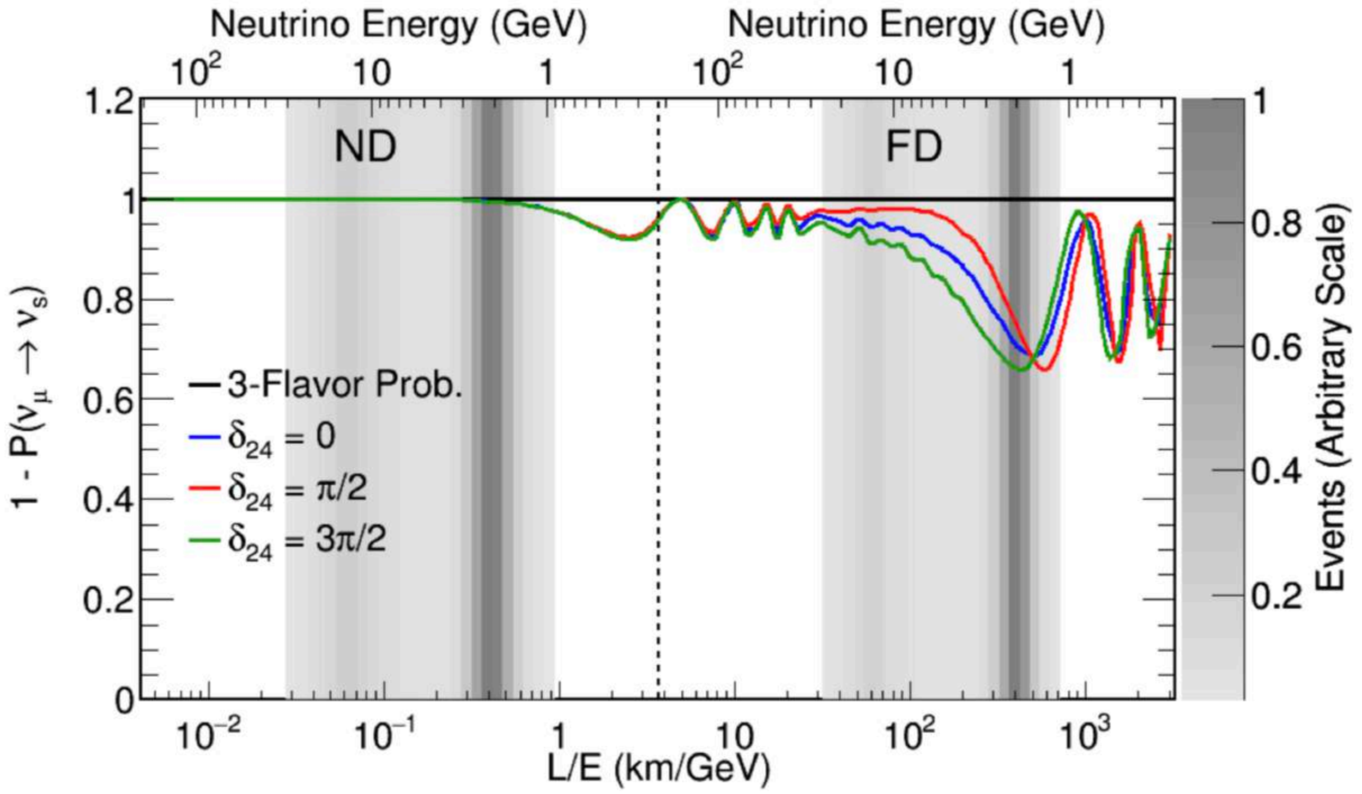
Long-Baseline Neutral Current Disappearance

- Mixing angle θ_{23}:
  - Also affect depth of oscillations, fix to NOvA best fit from ν_e/ν_μ analysis.

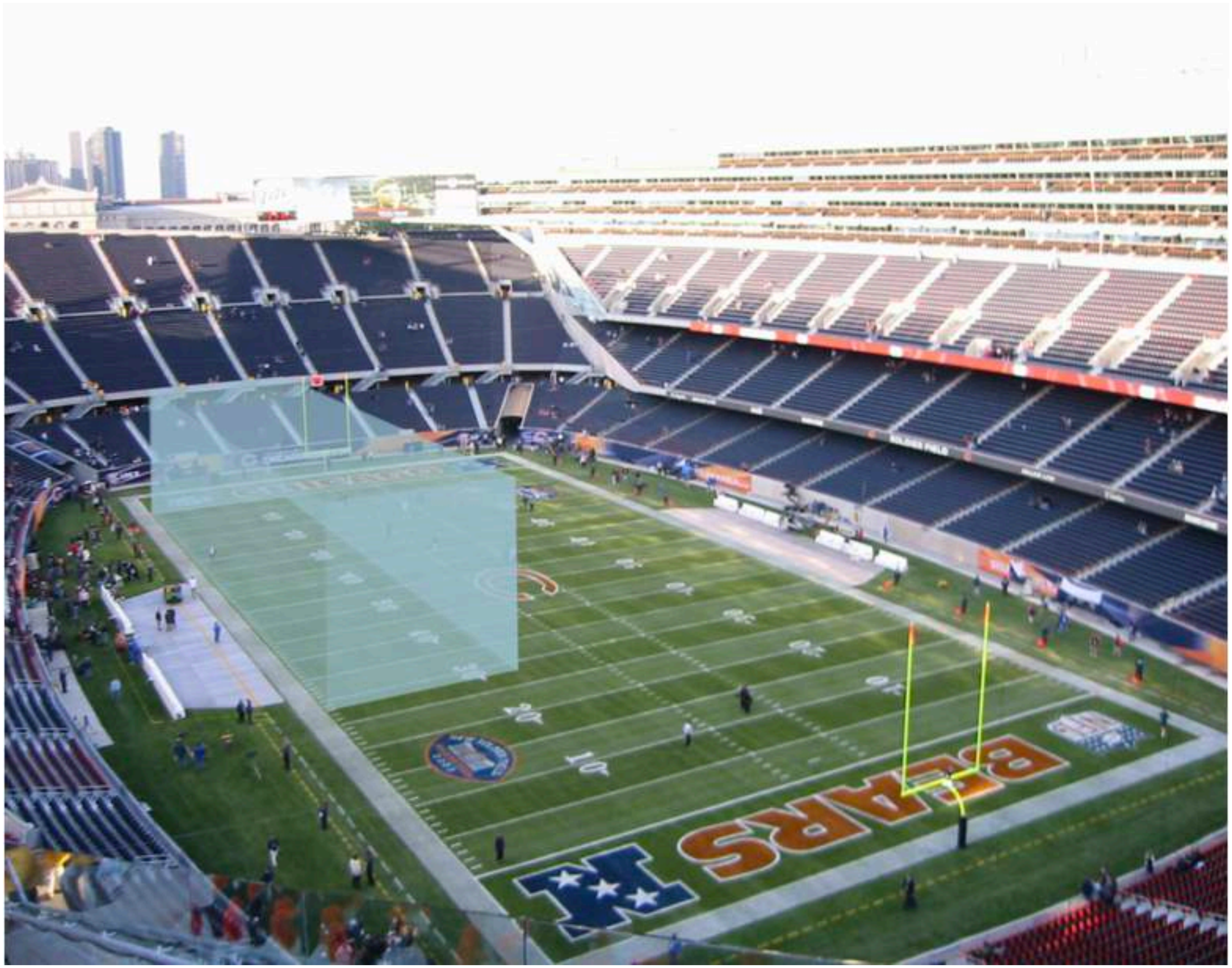


Long-Baseline Neutral Current Disappearance

- CP-violating phase δ_{24} can also affect NC disappearance.
- Profile over this in fit, slightly degrade our resolution.

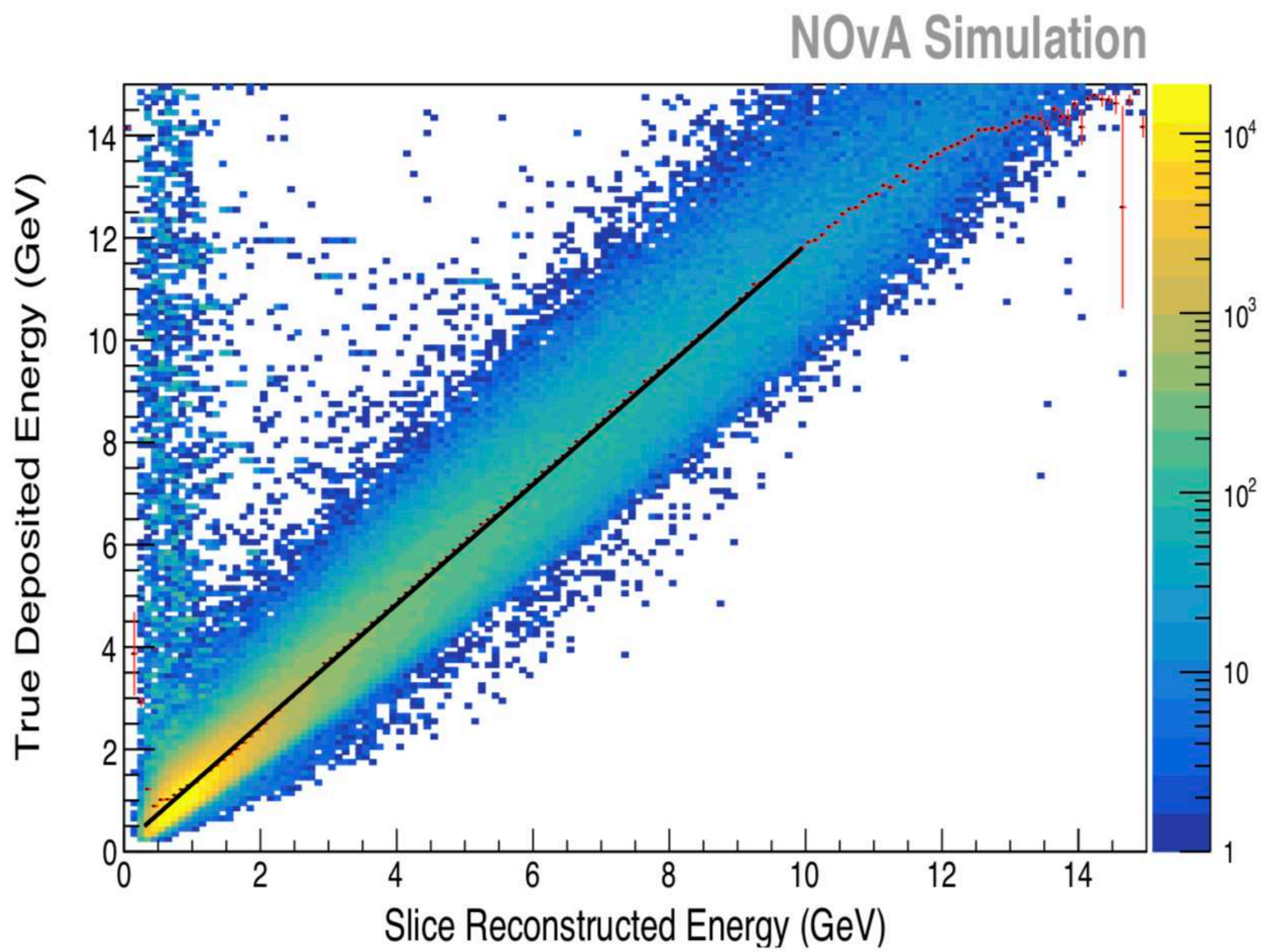


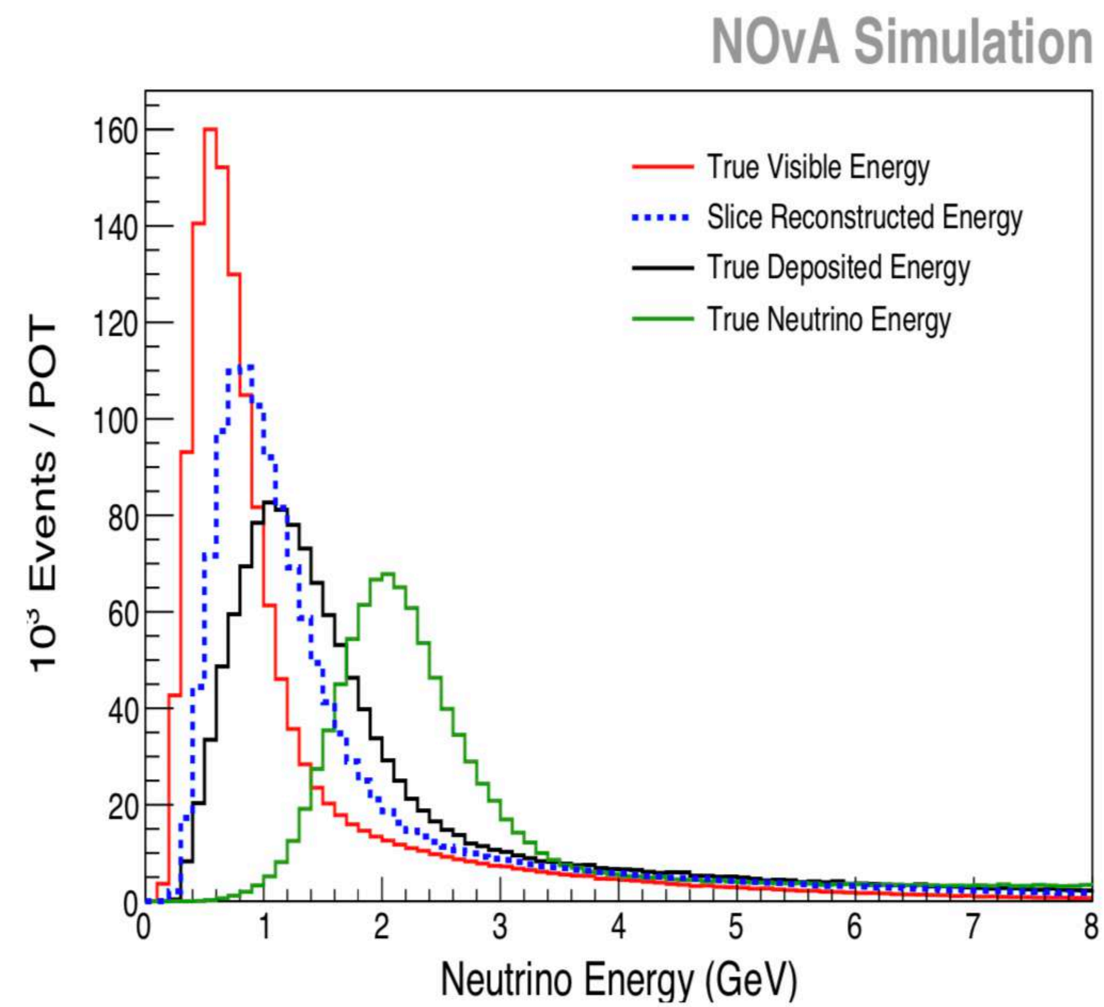
NOvA Playing Left Field?



Energy Reconstruction

- Determine 'calorimetric energy' based on calibrated charge collected in detector.
- Use simulation to convert reconstructed energy into 'true deposited energy' in the event.
- Final energy resolution ~25%.





Cosmic Rejection BDT

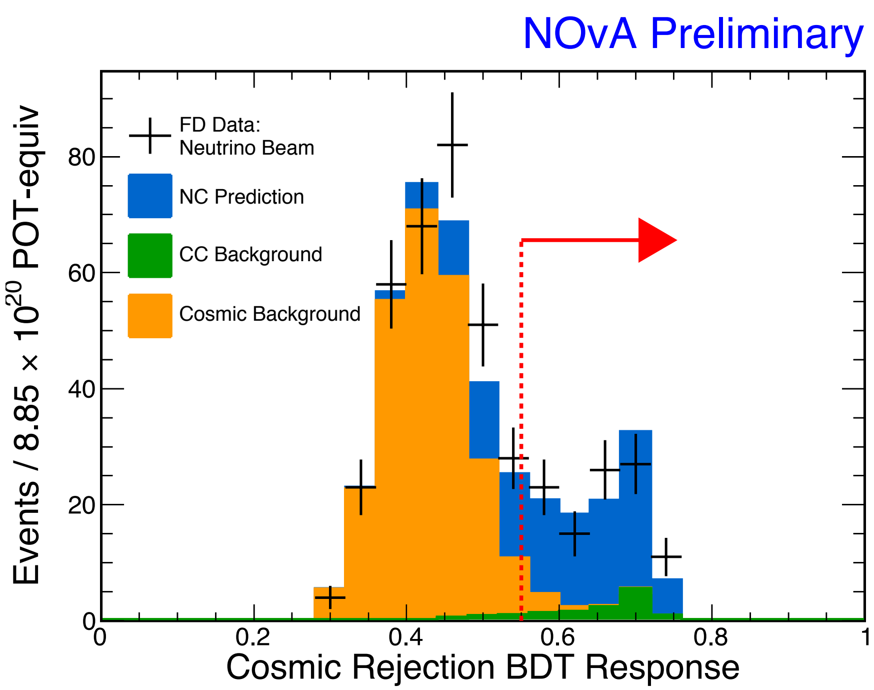
- Variables:
  - CVN cosmic,
  - Number of showers,
  - Leading shower direction,
  - Leading shower length,
  - Transverse momentum fraction,
  - Leading shower number of hits [4] (each view separately, sum and difference),
  - Leading shower number of hits (X-Y)/(X+Y) view,
  - Leading shower width,
  - Leading shower gap,
  - Number of MIP hits in slice,
  - ‘Calorimetric energy’ for leading shower.

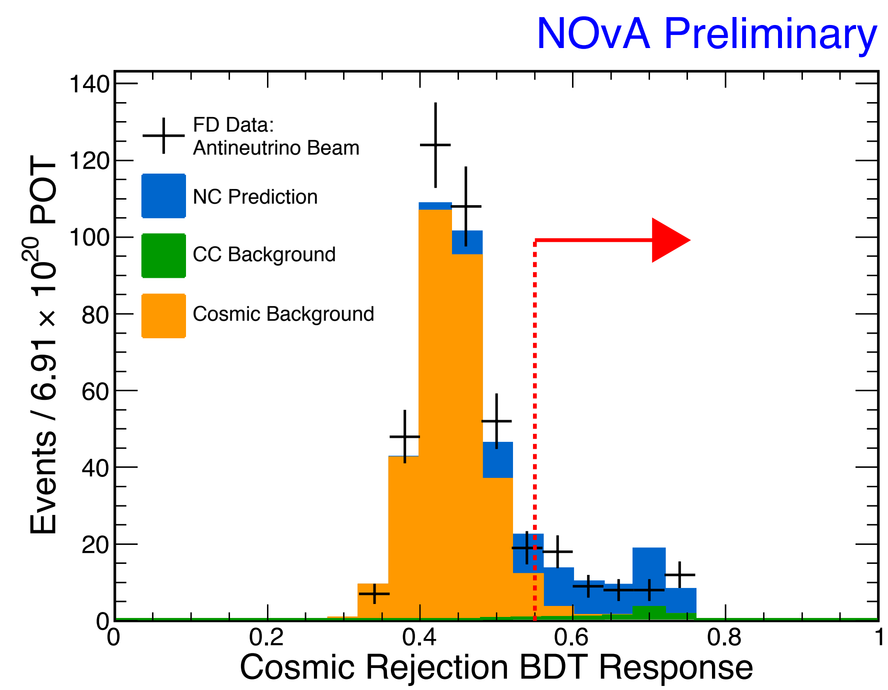
- Three running periods:
  - Coarse timing, low gain;
  - Low gain, fine timing;
  - High gain, fine timing.

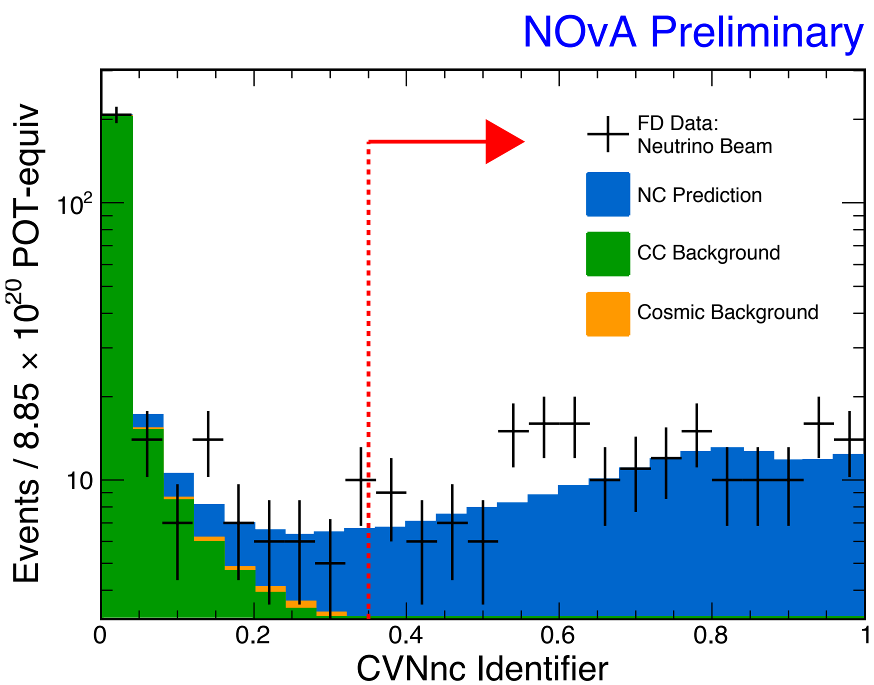
New NOvA NC Disappearance Analyses

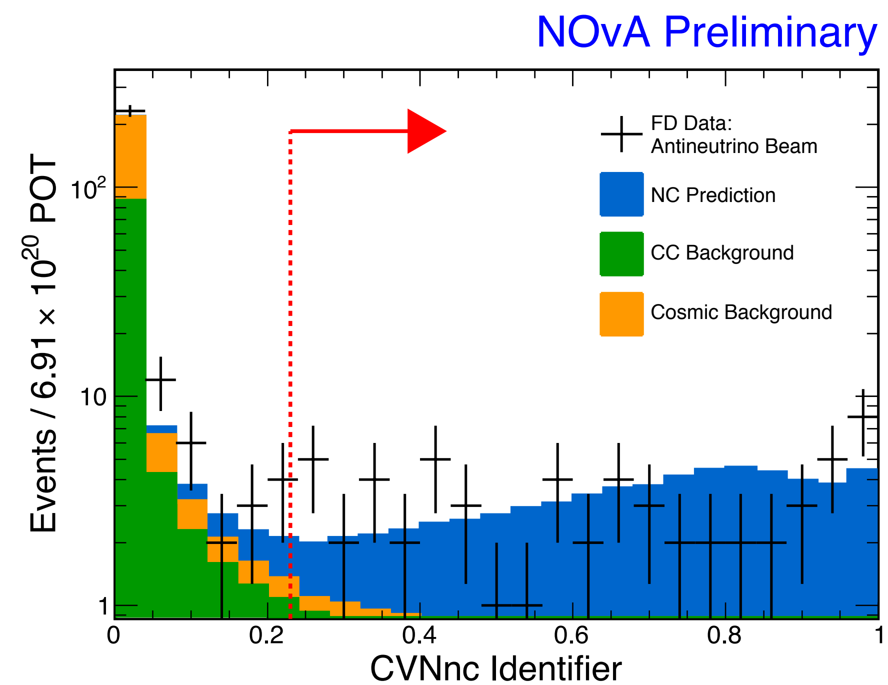
- Two new analyses for 2018:
  - Reanalysis of neutrino dataset with improved selection and a new two-detector joint fit method;
  - First analysis of NOvA's antineutrino dataset with the traditional extrapolation technique (first NC disappearance analysis with long-baseline antineutrino data).
- Analysis improvements:
  - NOvA CVN retrain, include first training for antineutrino data;
  - Retrained BDT used for cosmic rejection, now separated by different detector running conditions.

Selection Plots





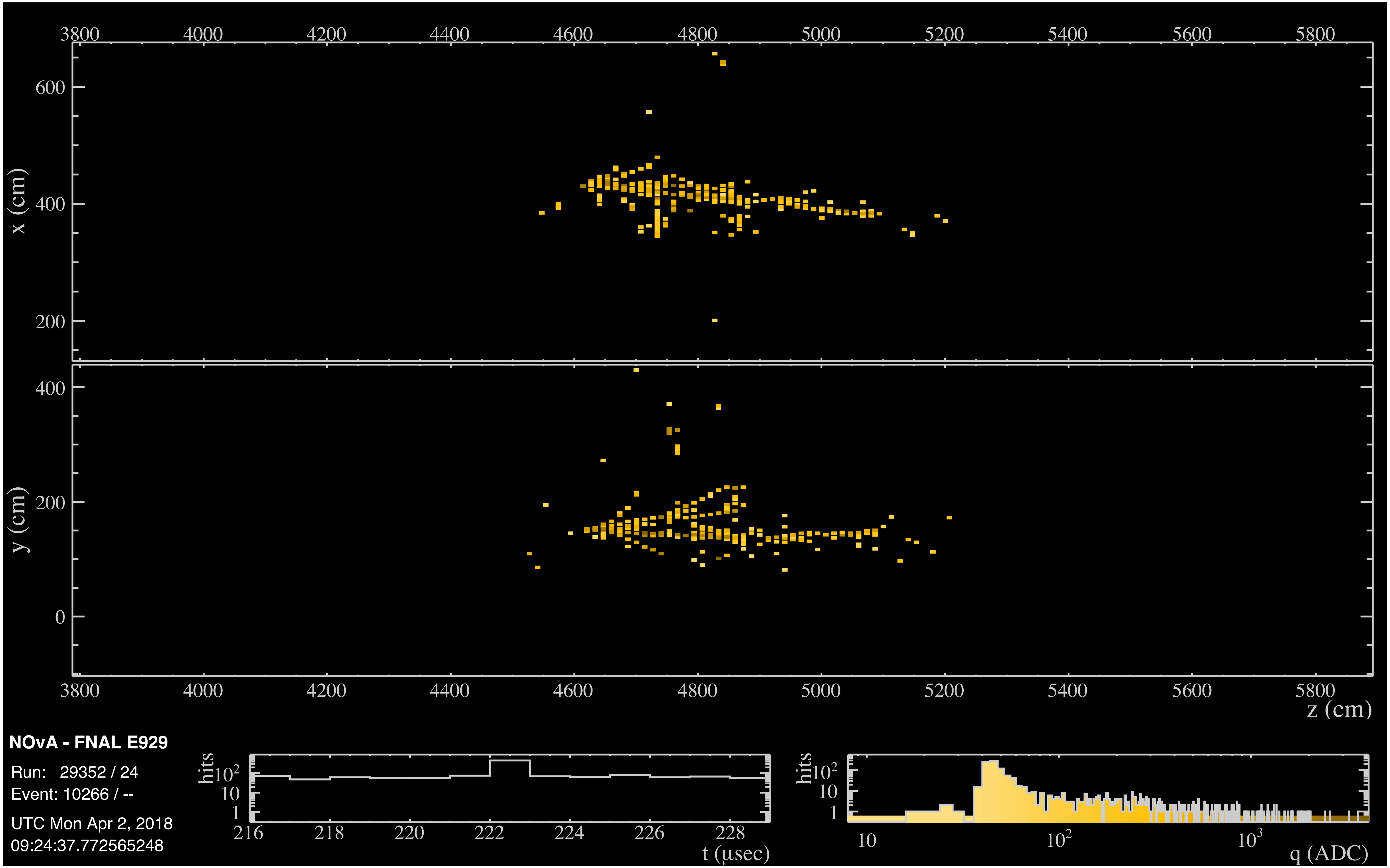




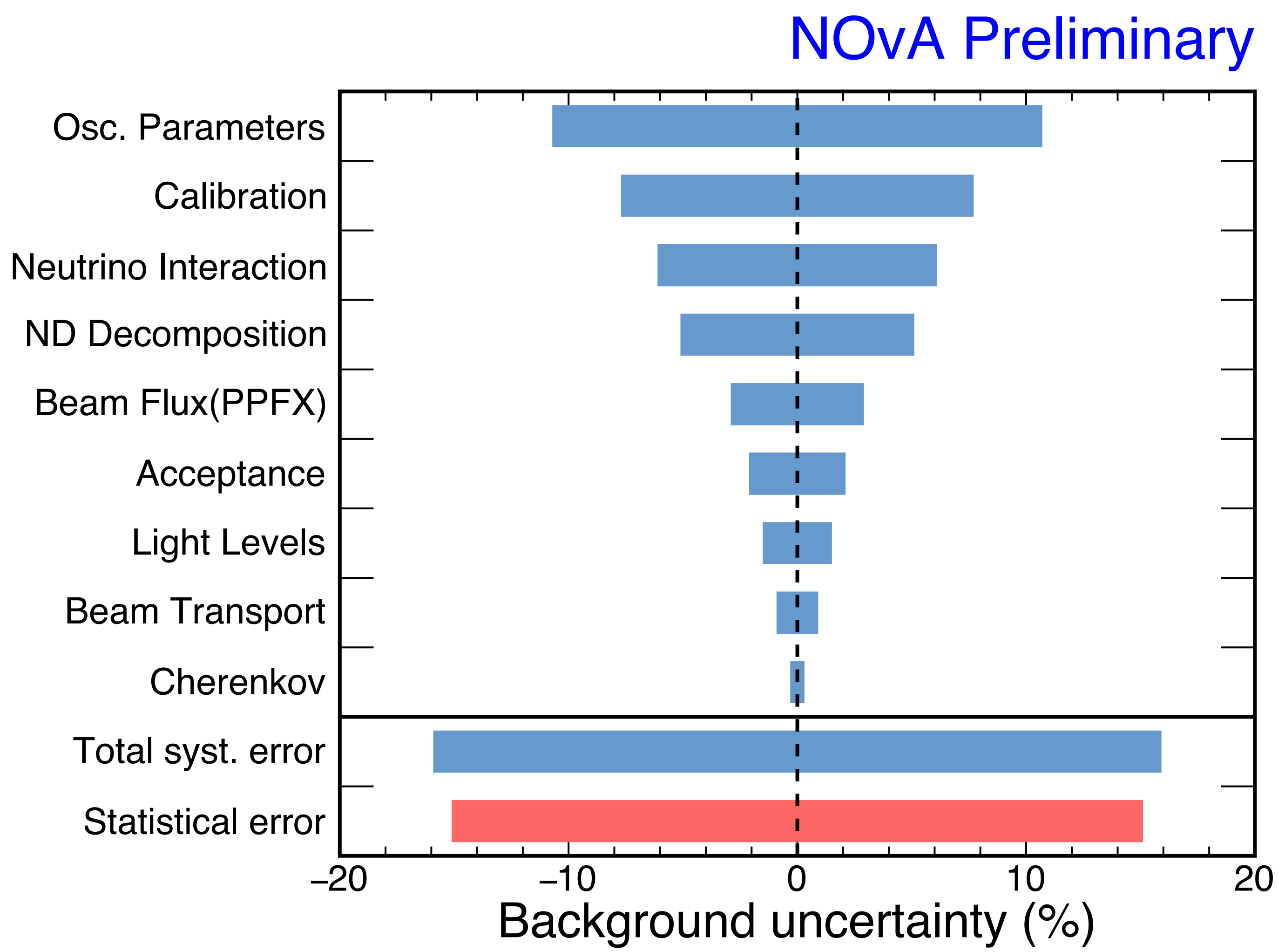
Neutrino

Antineutrino

Antineutrino Candidate Event



Background Uncertainties



Neutrino Analysis

Comparison

	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

MINS/MINOS+ 2018 (0.5 eV^2): 4.05 23.6