Physics Results from NOνA Neutrino Oscillation Experiment (for the NOνA Collaboration)

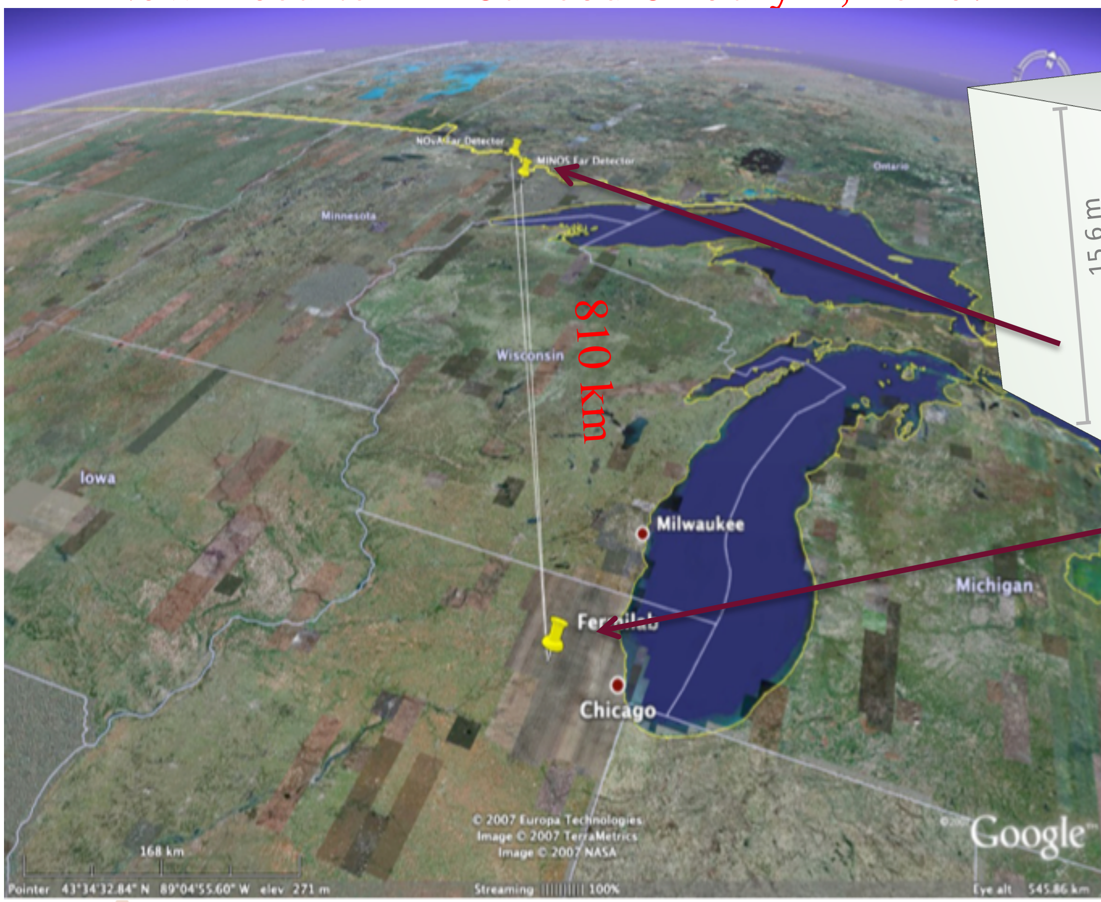
Zelimir Djurcic
Argonne National Laboratory

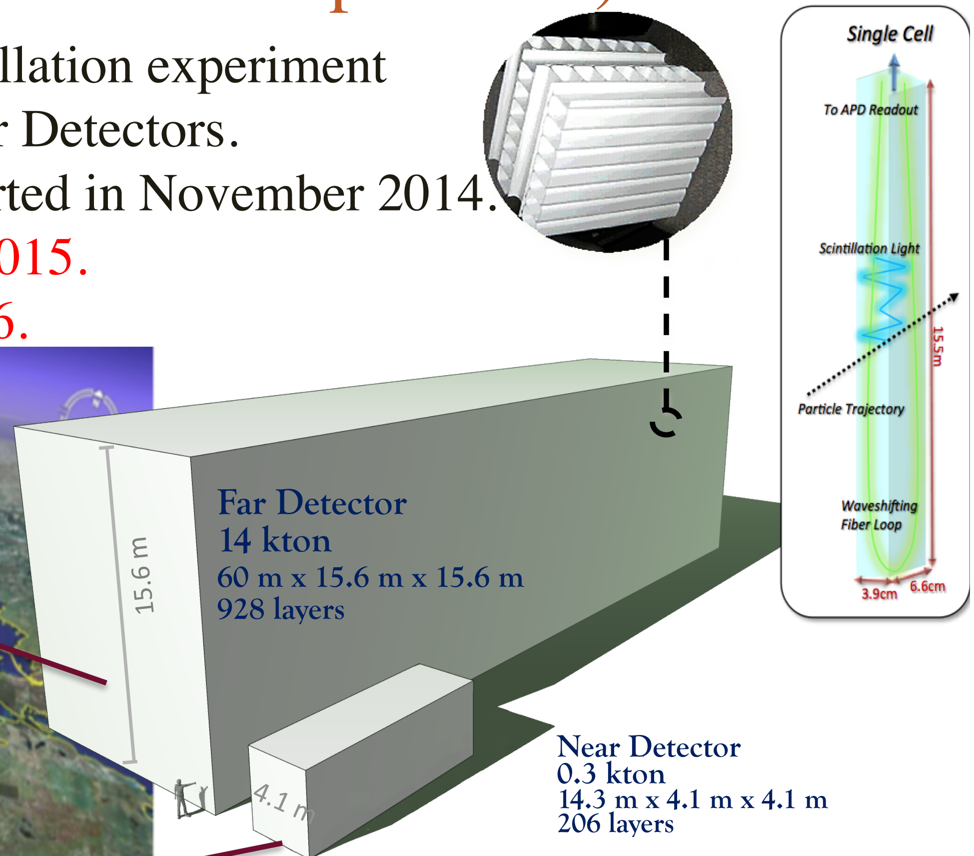
Plan of the Talk

- Introduction to NOνA
- The Goals of NOνA Experiment
- ν_μ Disappearance Search
- ν_e Appearance Search
- Other Oscillation Physics Results from NOνA
- Summary

NOνA (NuMI Off-axis ν_e Appearance Experiment)

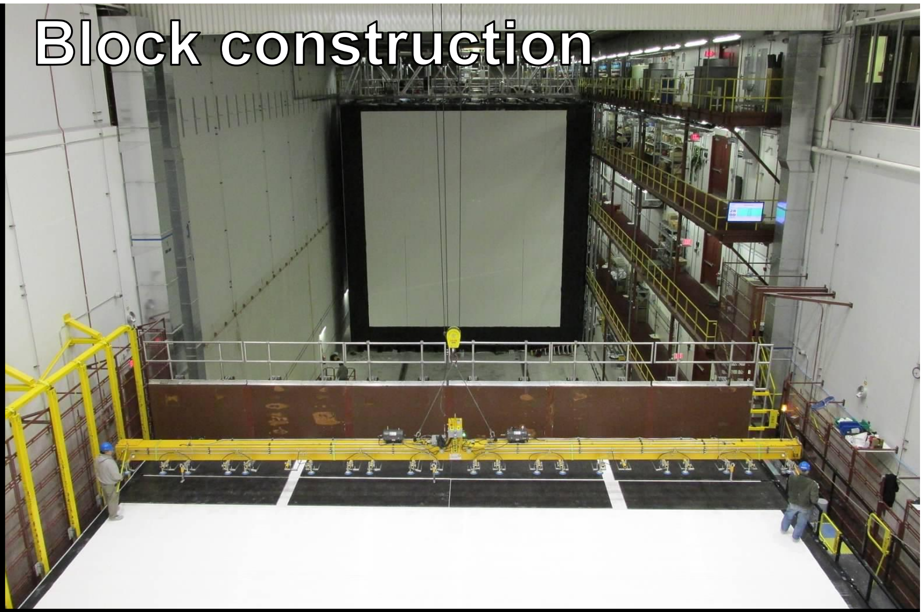
- The long-baseline off-axis neutrino oscillation experiment with functionally identical Near and Far Detectors.
- Data taking with complete detectors started in November 2014.
- First Results Announced on August 6, 2015.
- New Results Announced on July 4, 2016.



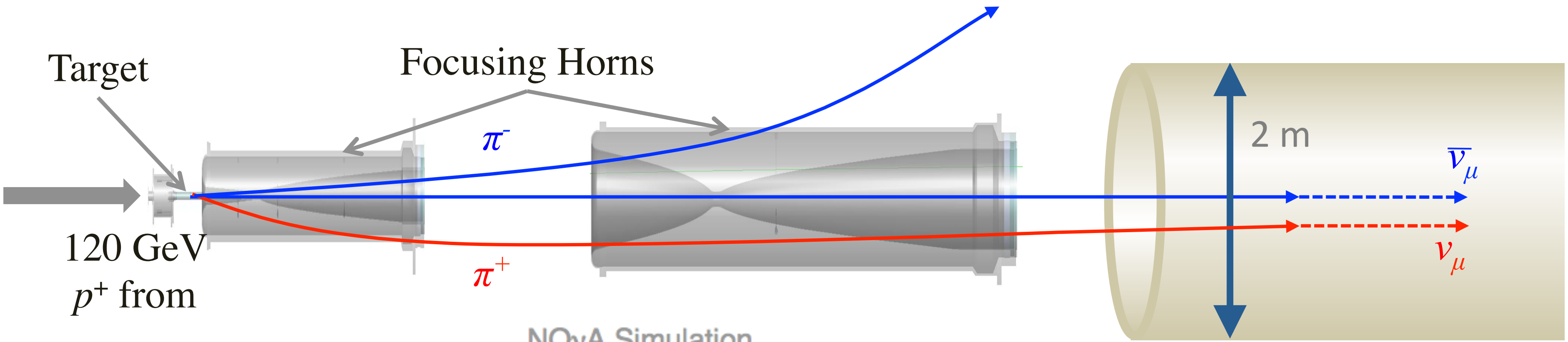


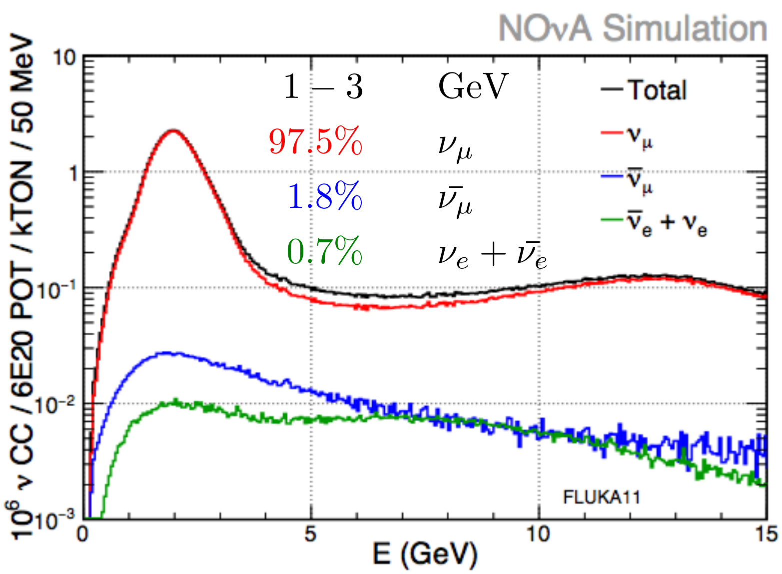
- Low-Z tracking calorimeters
- High power NuMI beam
  - -upgraded for NOνA to take the power 350 – 700 kW
  - -this result: 6.05×10^{20} POT, 700 kW peak intensity.
- Detectors are 14 mrad off-axis.

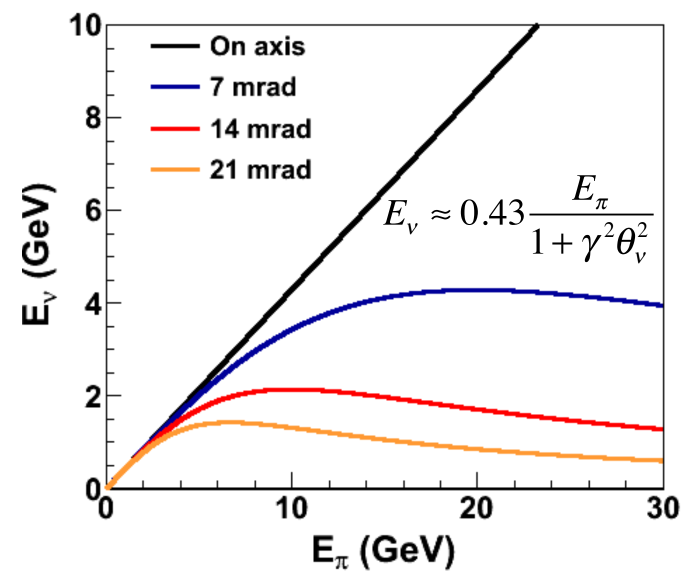
NOνA Detectors



NOνA Off-axis Neutrino Beam







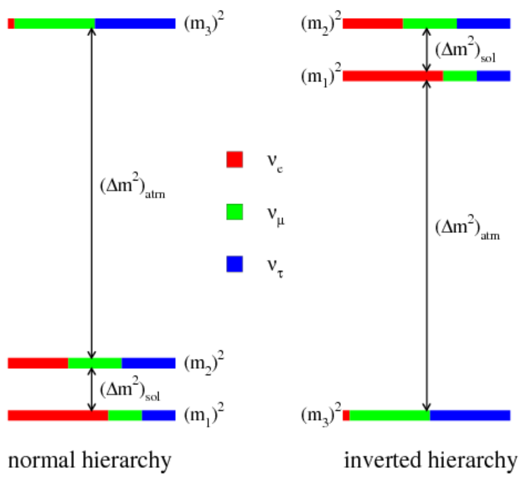
- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events

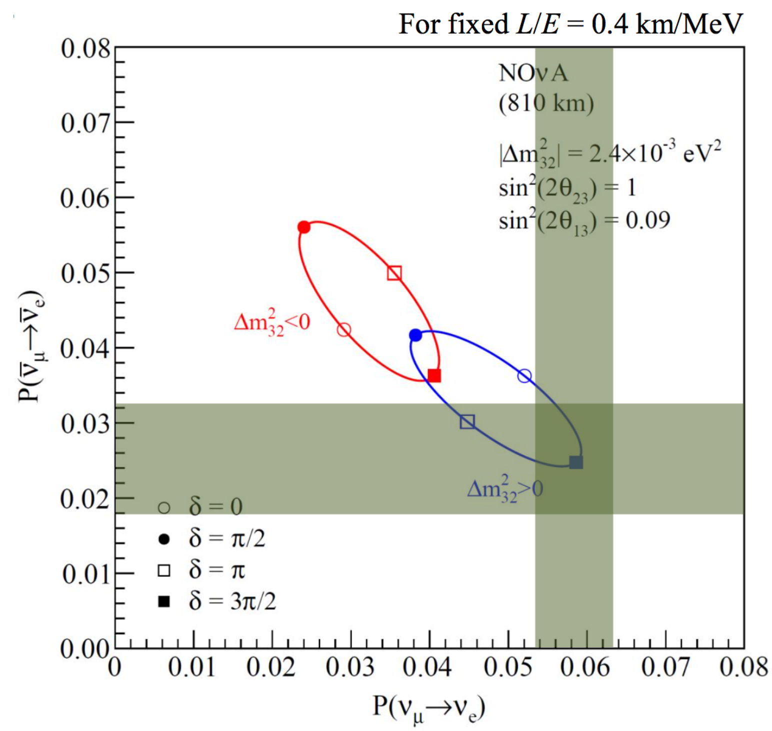
The Goals of NOνA Experiment

- Measure the oscillation probabilities of
  a) appearance channels: $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
  b) disappearance channels: $\nu_\mu \rightarrow \nu_\mu$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$

$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta)\ ?$$

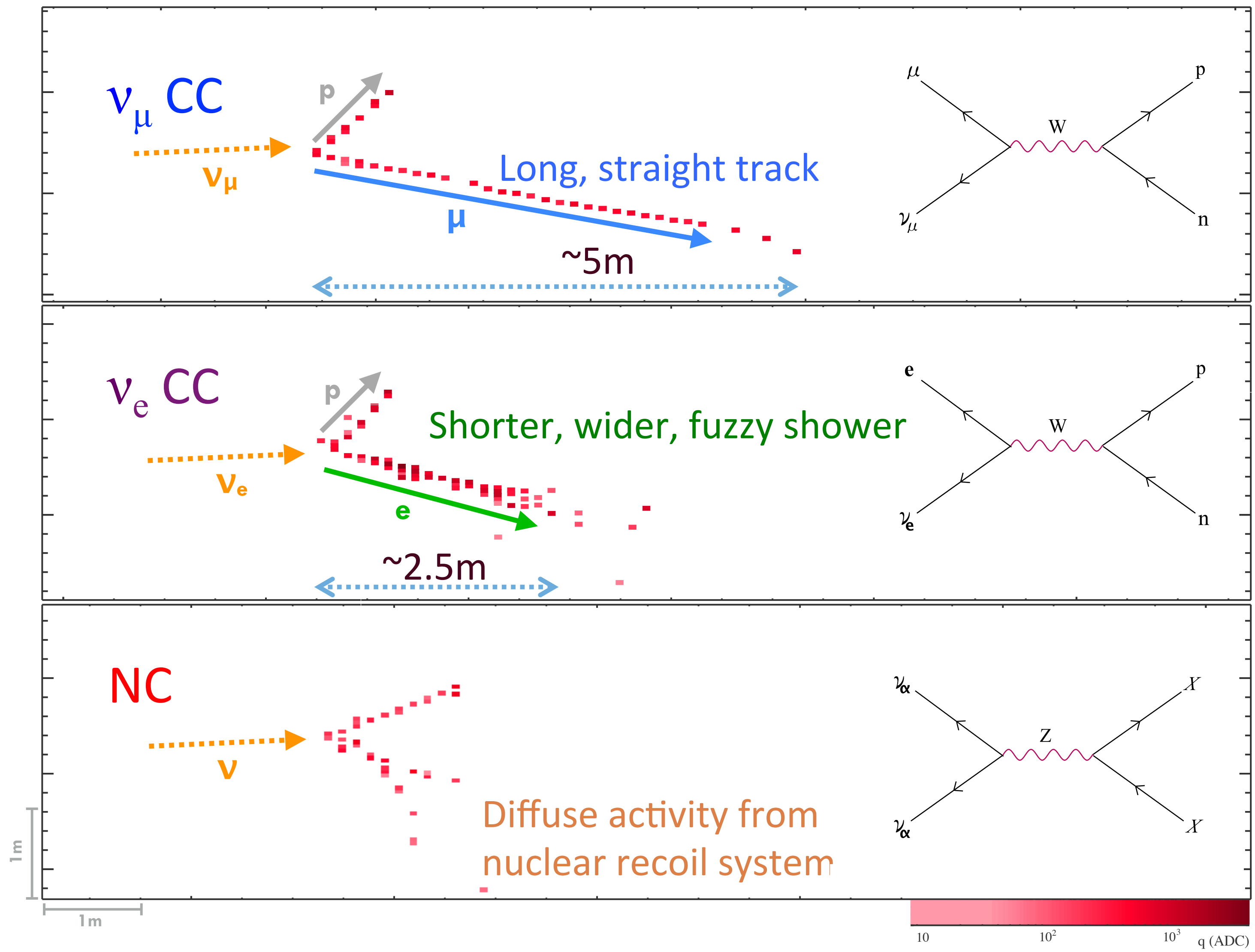
- Precision measurements of θ_{13}, Δm^2_{32}, θ_{23}
- Probe the neutrino mass hierarchy
- Study the CP violation parameter δ



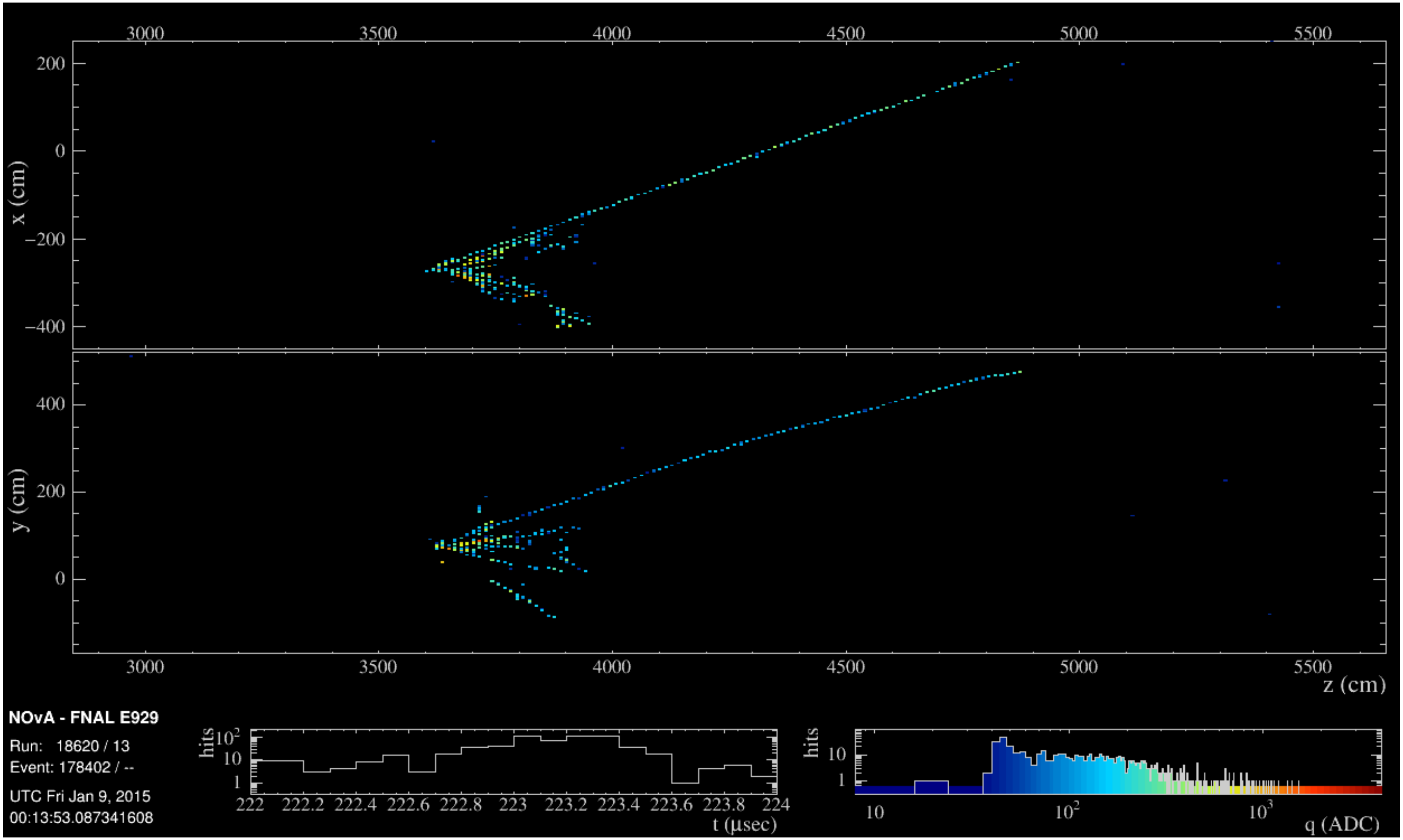


- Additional Physics Goals:
  -Neutrino cross-sections and interaction physics
  -Sterile Neutrinos
  -Supernovae and Exotic Searches

NOνA Event Topologies



Neutrino Interaction the NOνA Far Detector



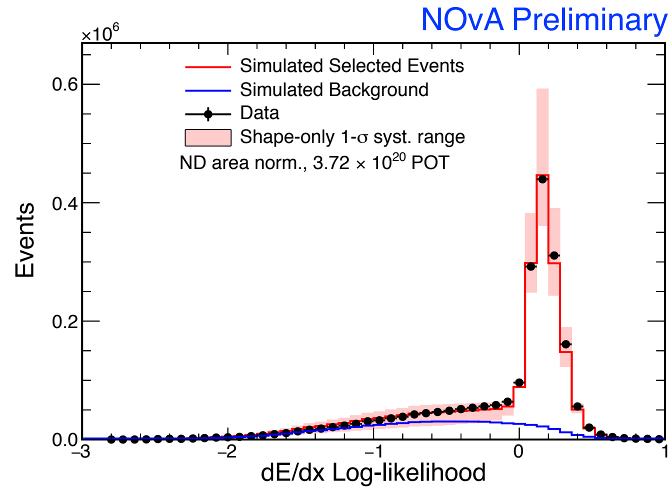
ν_μ Disappearance Search

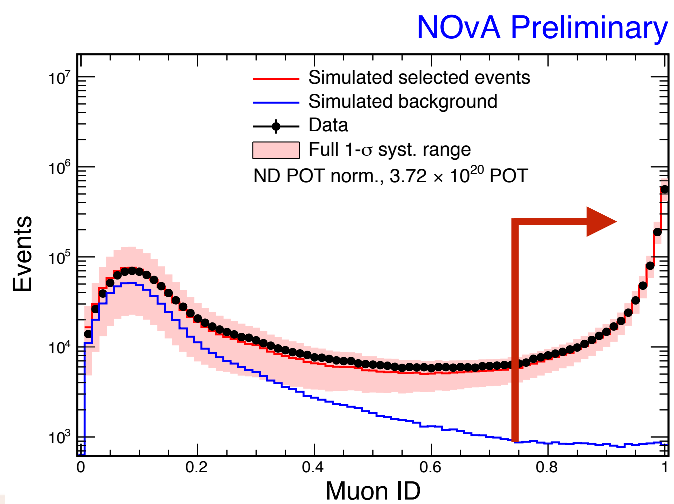
ν_μ Disappearance Search

- Identify contained ν_μ CC events in both Near and Far Detector
- Measure Energy
- Extract oscillation information from differences between the Far and Near energy spectra

ν_μ Event Selection

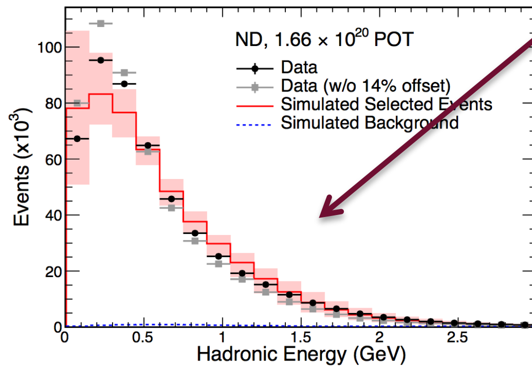
- Isolate a pure sample of ν_μ CC events less than 5GeV
  – Select events with long tracks
  – Suppress NC and cosmic backgrounds
- 4-variable kNN used to identify muon based on
  – track length
  – dE/dx along track
  – scattering along track
  – track-only plane fraction
- ND data matches simulation well for muon variables





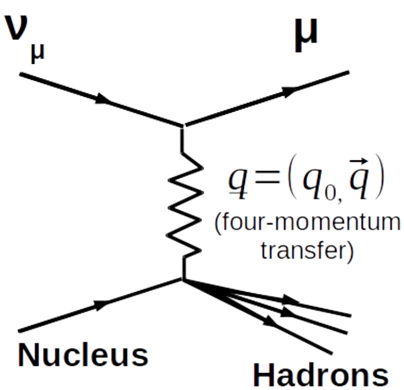
Energy Measurement

- The reconstructed neutrino energy E_ν of a contained ν_μ CC event is given by $E_\nu = E_\mu + E_{had}$
- Near detector hadronic energy distribution suggests un-simulated process between quasi-elastic and delta production

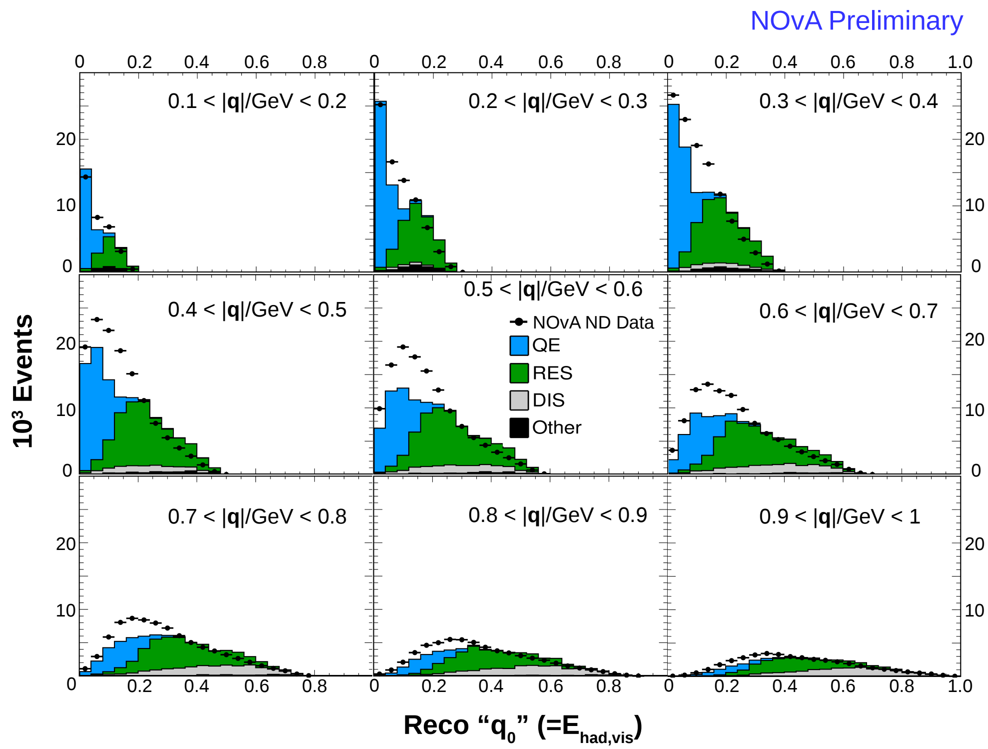


Reconstructed hadronic energy in ND ν_μ CC interactions

NOvA 1st ν_μ result: PRD 93 (2016) 051104



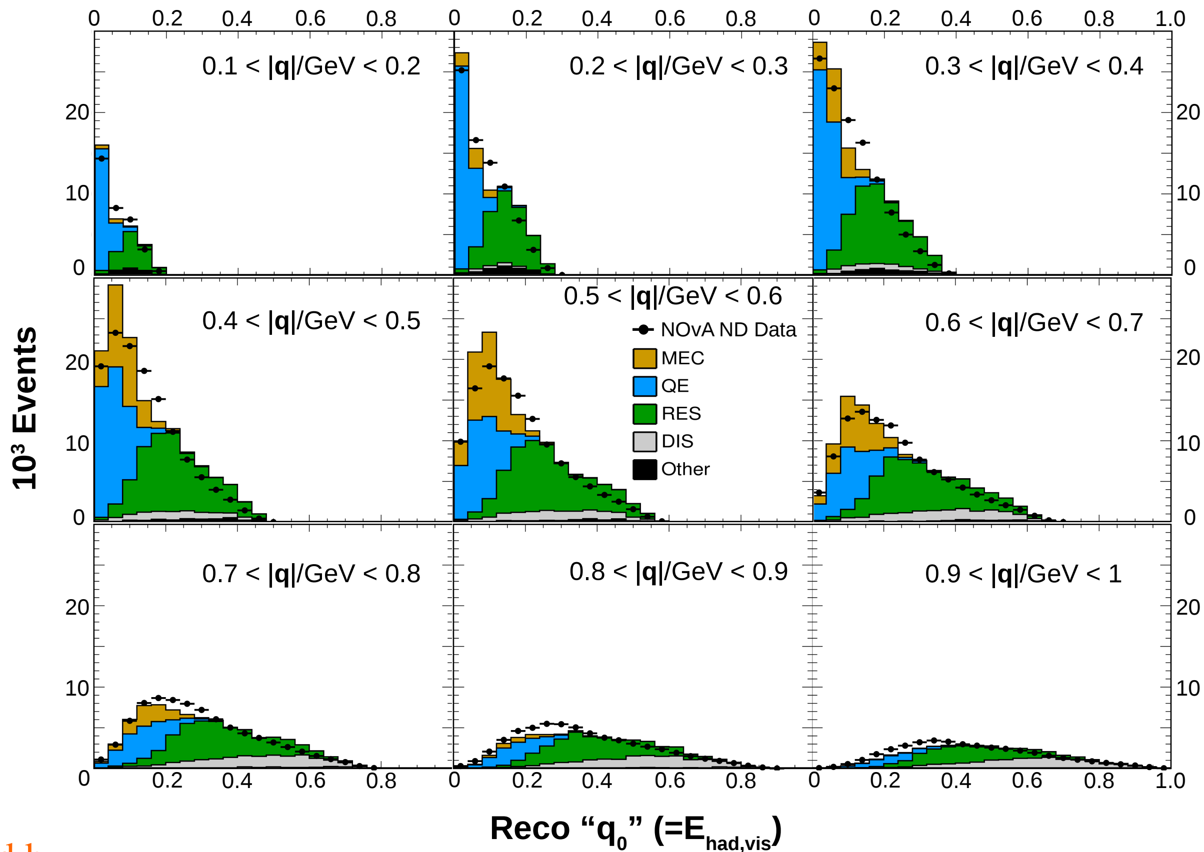
Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802



Scattering in a Nuclear Environment

- Approach: Enable GENIE empirical Meson Exchange Current Model
- Reweight to match NOvA excess as a function of 3-momentum transfer

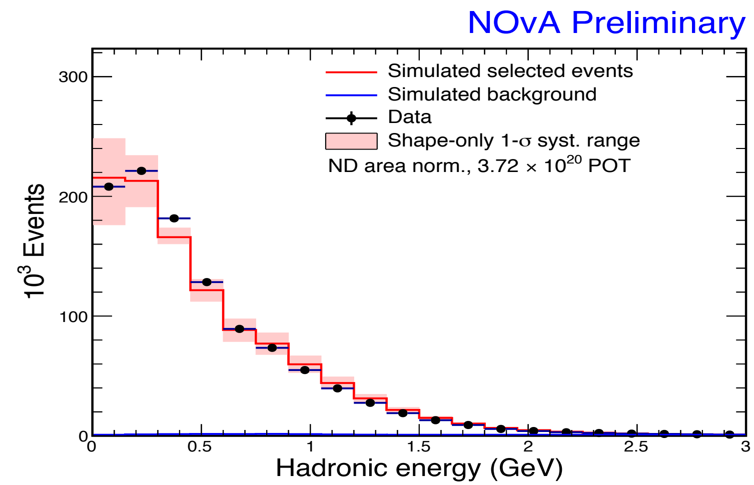
- 50% systematic uncertainty on MEC component
- Reduces largest systematics
  - hadronic energy scale
  - QE cross section modeling
- Reduce single non-resonant pion production by 50% (P.A. Rodrigues et al, arXiv:1601.01888.)

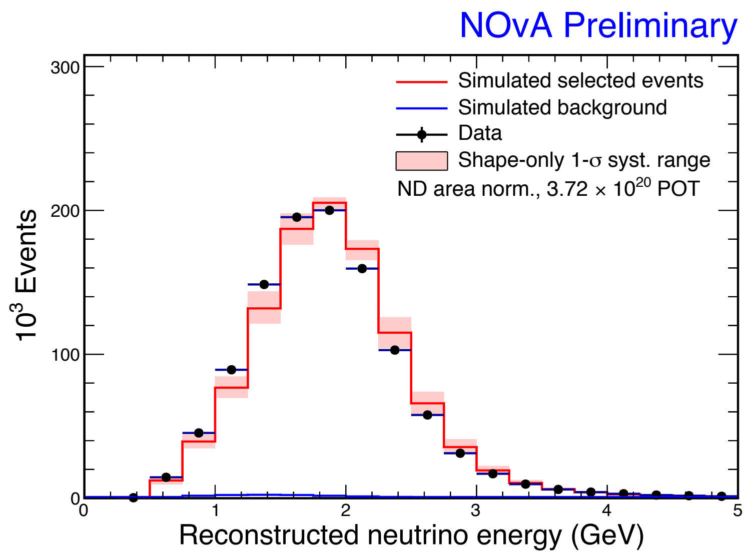


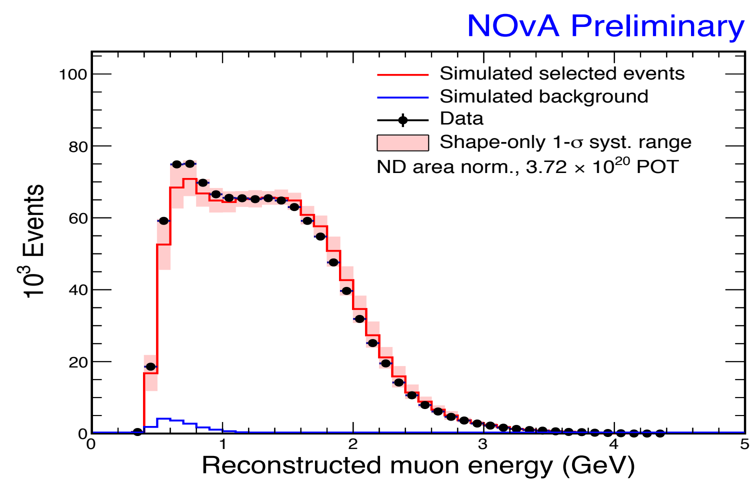
MEC model by S. Dytman, inspired by
J. W. Lightbody, J. S. O'Connell, Computers in Physics 2 (1988) 57.

NOvA ν_μ Disappearance Search

- Addition of MEC events substantially improves simulated hadronic energy distribution
  - hadronic energy scale uncertainty reduced (14% to 5%)







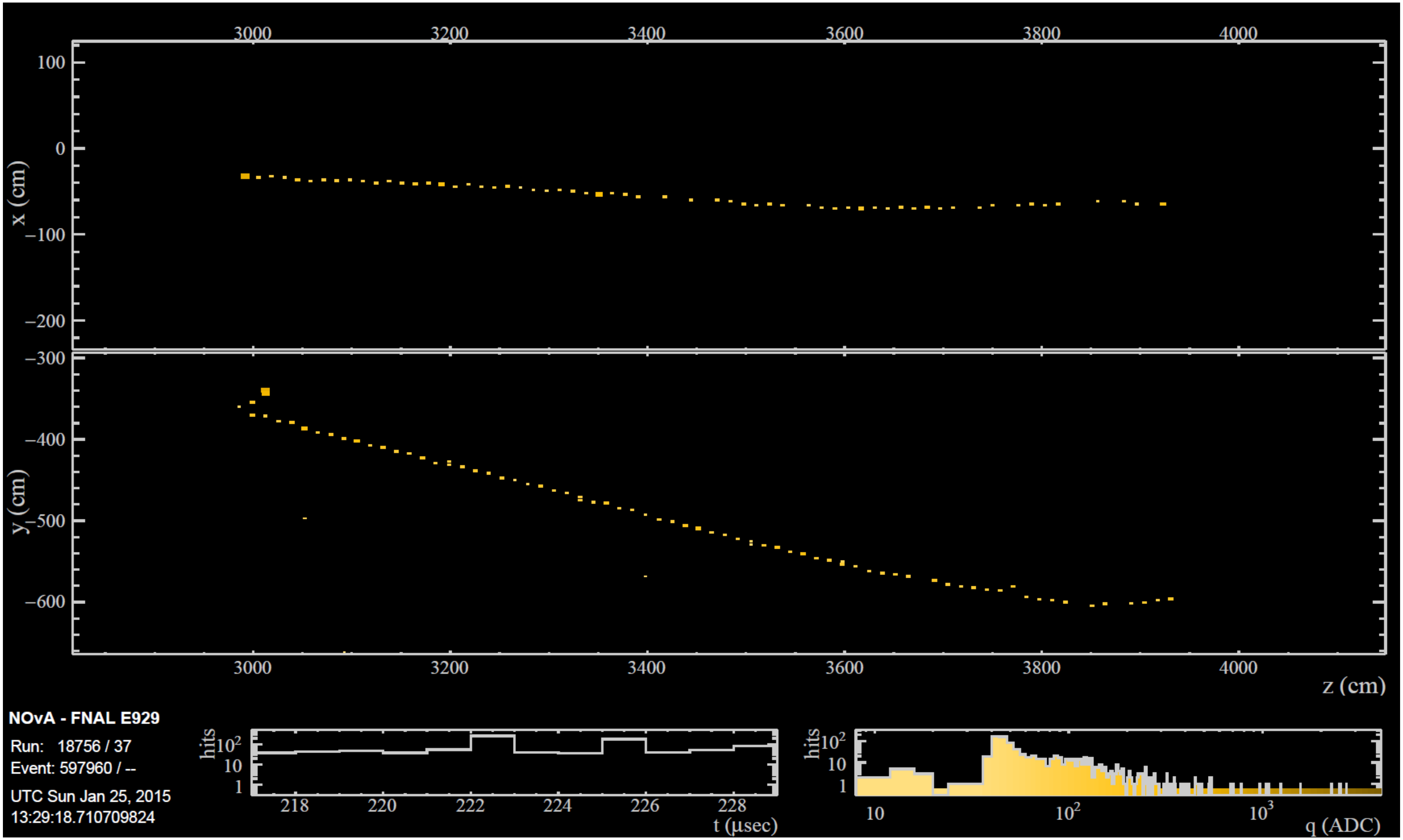
- Reconstructed neutrino energy unfolded, true Far/Near ratio used to extrapolate ND data for a FD prediction

- Far Detector Prediction with no oscillations:

-473±30 events expected without oscillations

-Background: 3.7 beam, 2.9 cosmic

NOvA Far Detector Selected ν_μ CC Candidate



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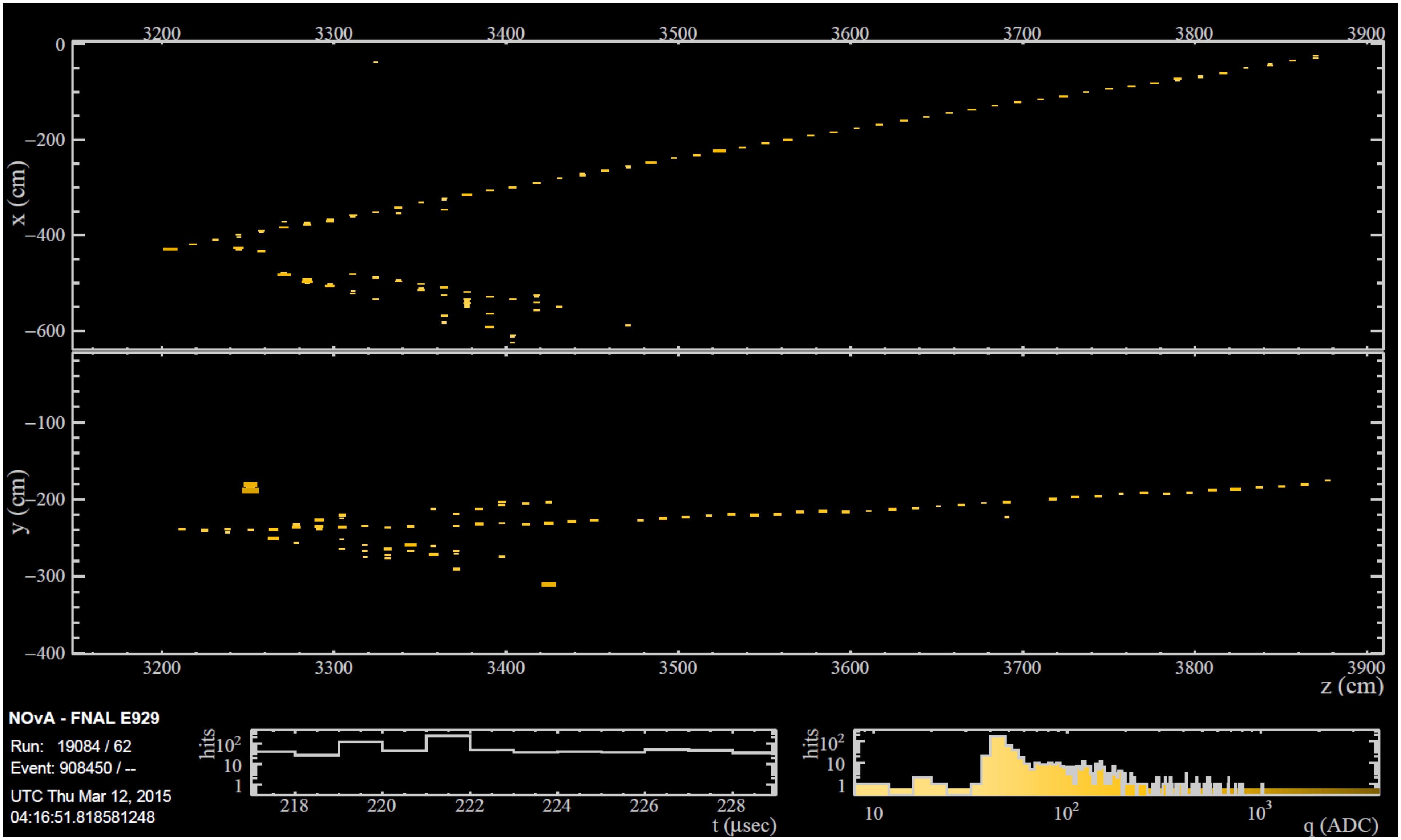
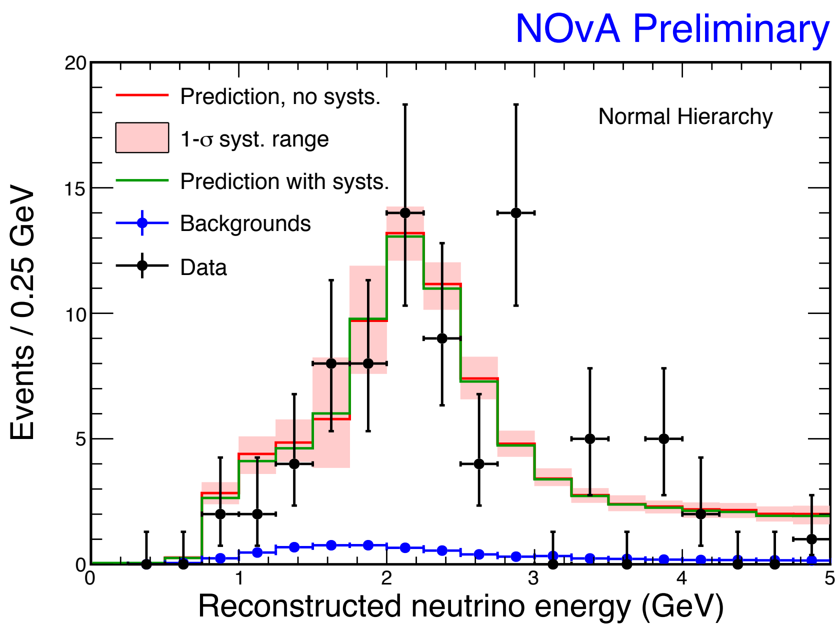
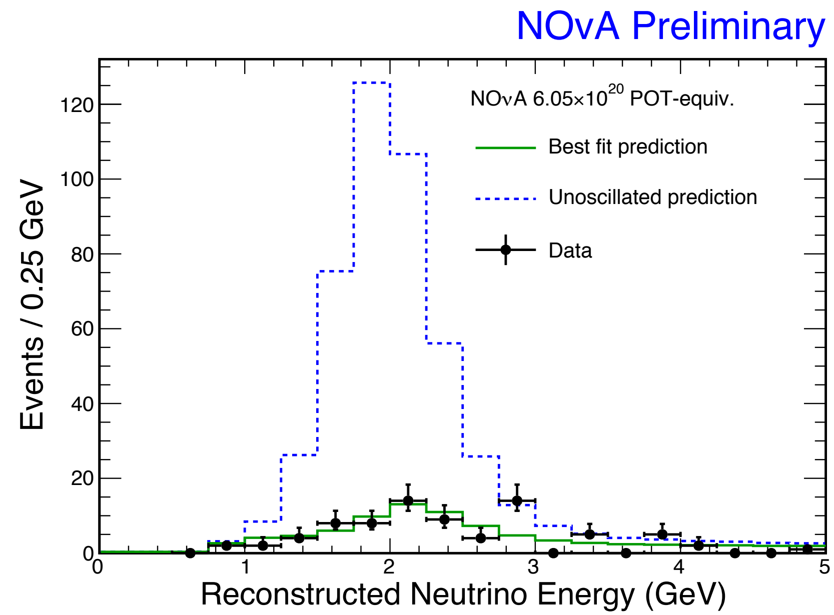
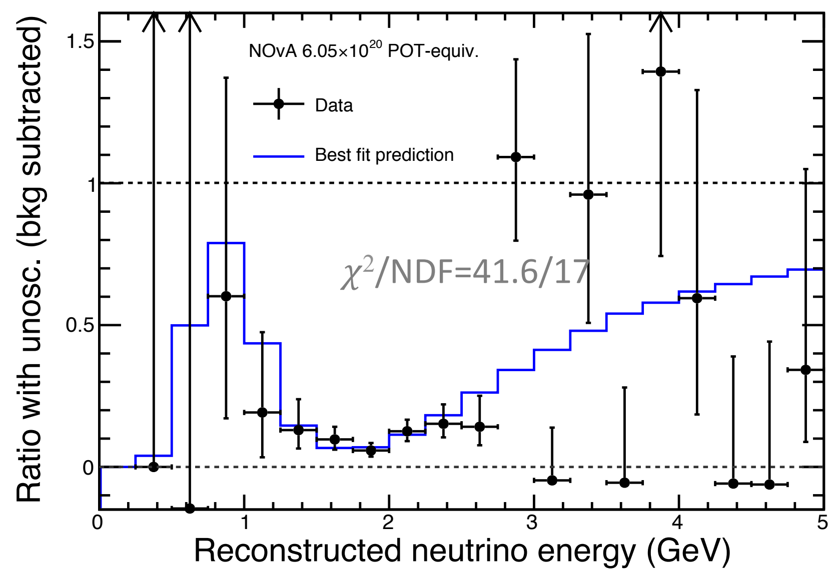


NOvA Far Detector ν_μ Disappearance

- Observed 78 events in 0-5 GeV.







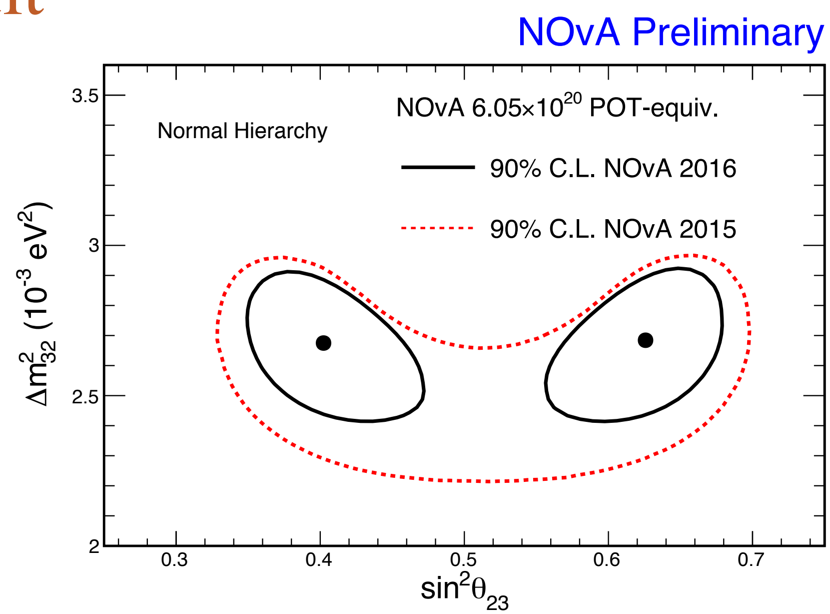
- Spectrum is well matched by oscillation fit for Δm^2 and θ_{23}.
- Systematic uncertainties included in the fit:
  - Normalization
  - NC background
  - Flux
  - Muon and hadronic energy scales
  - Cross section
  - Detector response and noise

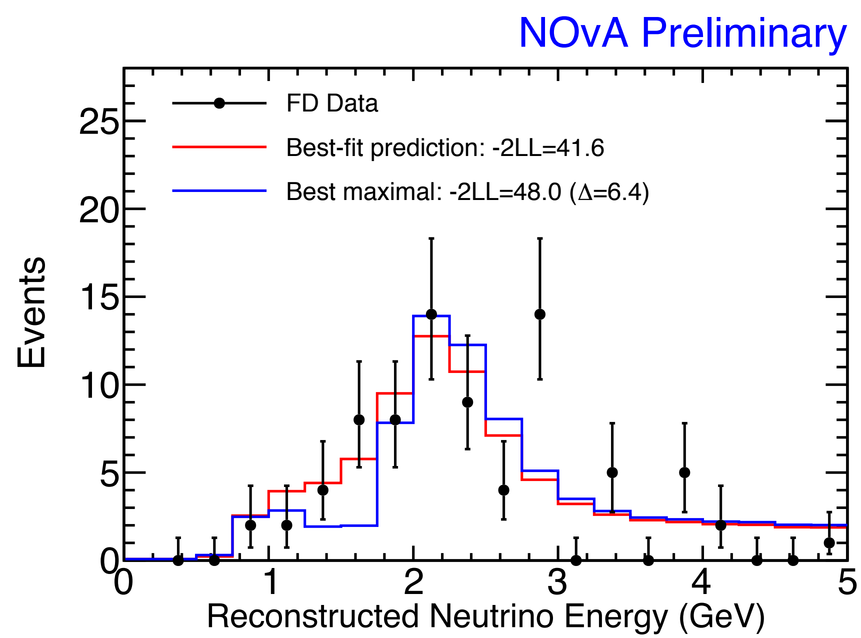
NOvA ν_μ Disappearance Result

- NOvA allowed region in (Δm^2, $\sin^2\theta_{23}$)
- Best Fit Result (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ





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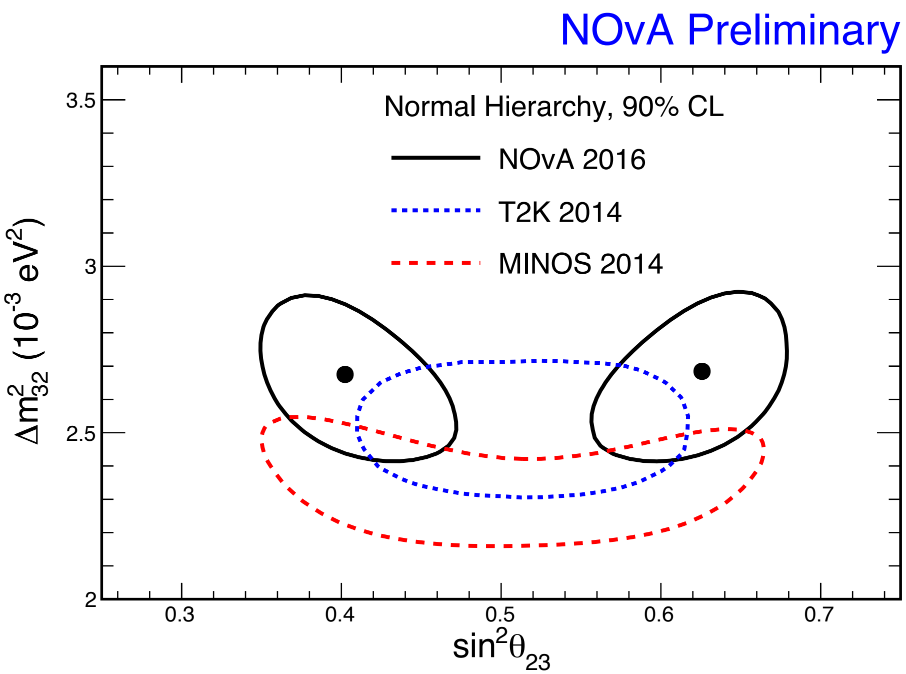
Contours compared



Please see related talks:
-V. Paolone's T2K talk
-T. Yano's Super-K talk
-D. Naumov's Daya Bay talk

ν_e Appearance Search

ν_e Appearance Search

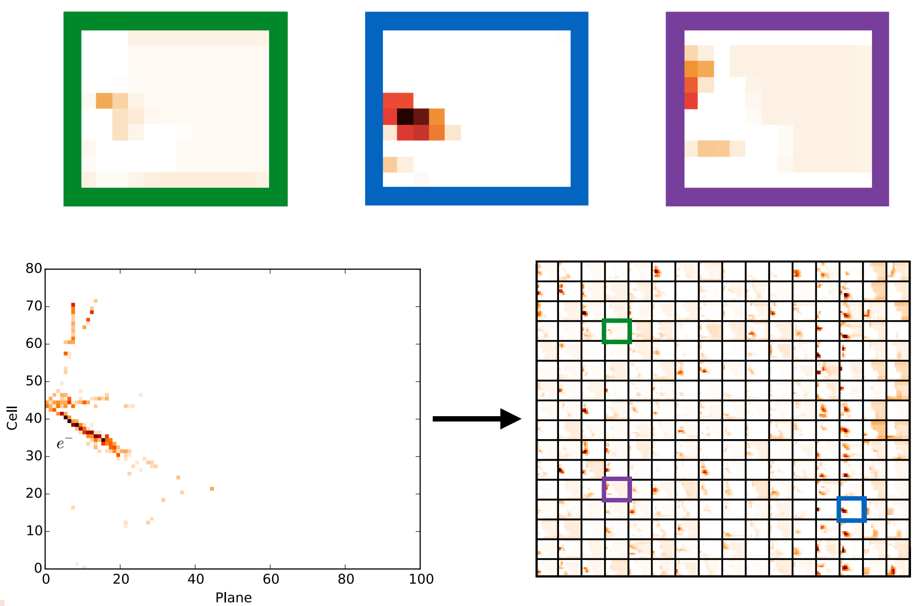
- Identify contained ν_e CC events in both Near and Far Detector
- Use Near Detector Data/MC to predict beam backgrounds in the Far Detector
- Extract oscillation information from Far Detector excess over predicted backgrounds

1st Analysis Published in PRL 116 (2016) no.15, 151806

Improved Event Selection

- A new particle ID techniques used to identify ν_e candidates: A convolutional neural network neutrino event classifier (CVN)
  -event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event



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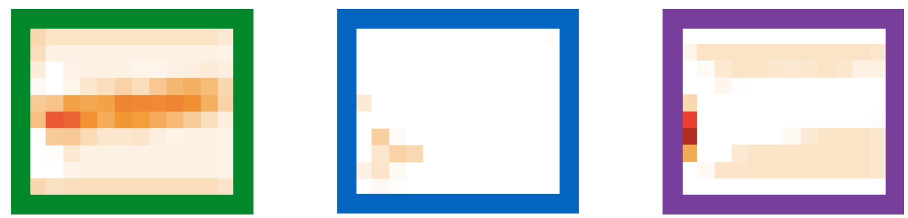

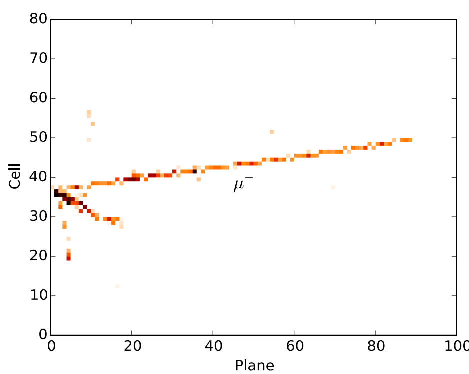

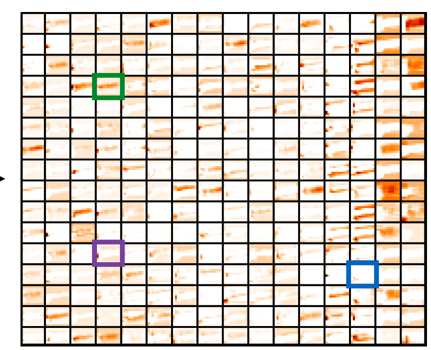

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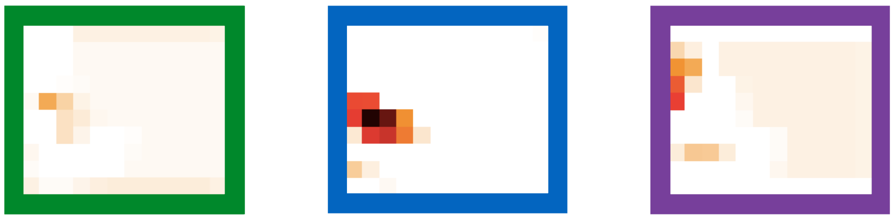
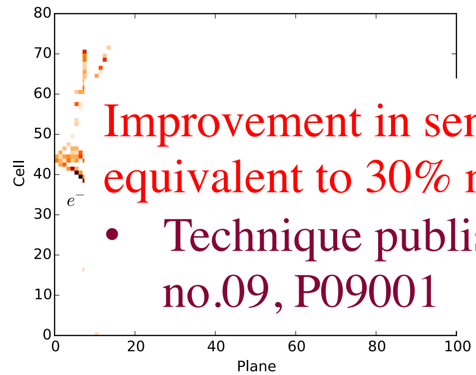
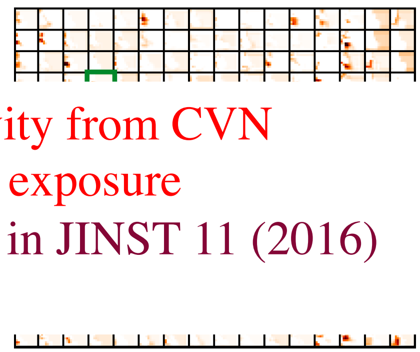






Improvement in sensitivity from CVN equivalent to 30% more exposure

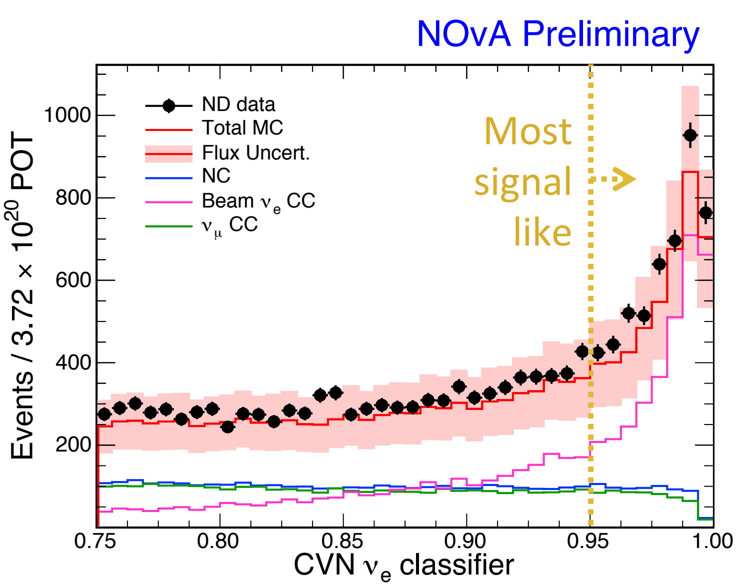
- Technique published in JINST 11 (2016) no.09, P09001

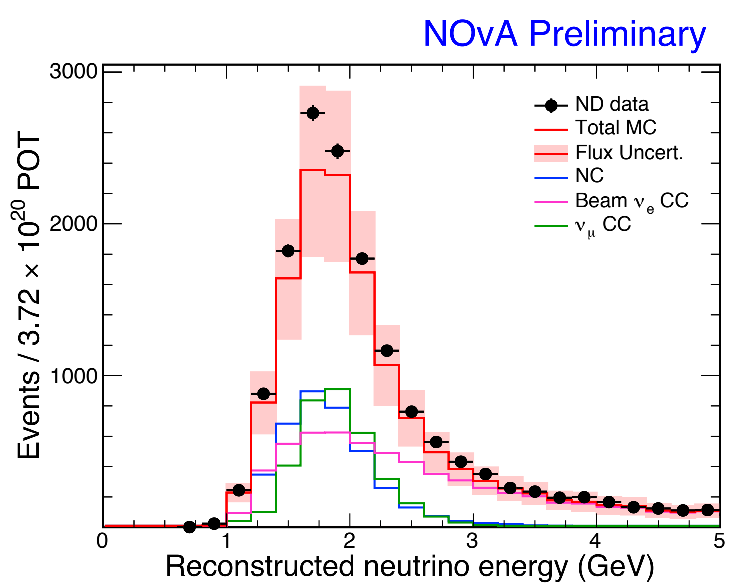
NOvA ν_e Selection and Signal Prediction

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

- Used ND data to predict background in FD
  - NC, CC, beam ν_e each propagate differently
  - constrain beam ν_e using selected ν_μ CC spectrum
  - constrain ν_μ CC using Michel Electron distribution

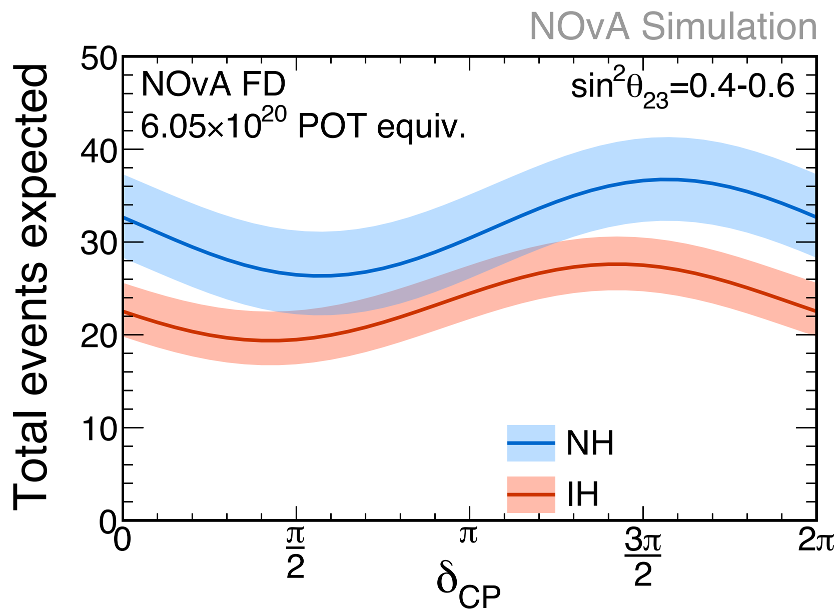
beam ν_e up by 4%
NC up by 10%
ν_μ CC up by 17%

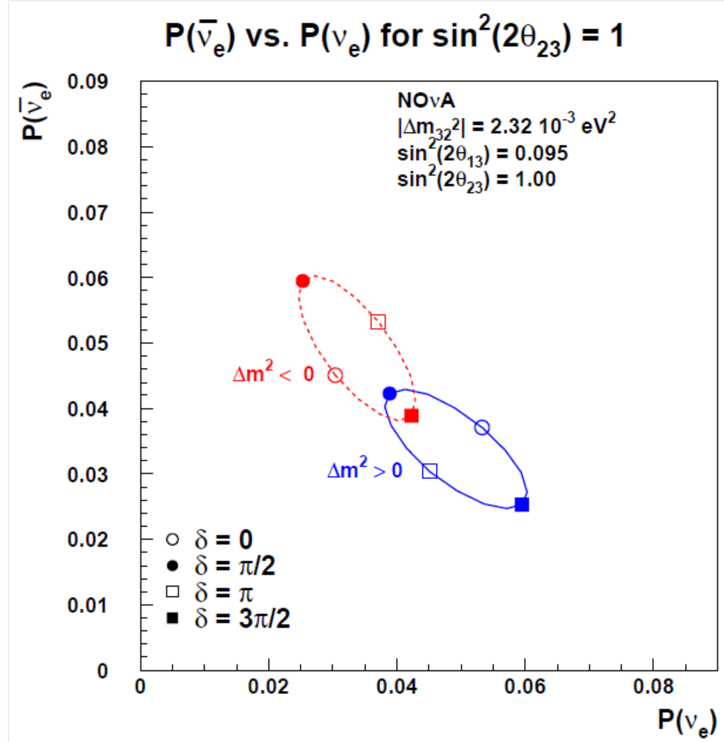




Far Detector ν_e Signal Prediction

- Extrapolate each background component in bins of energy and CVN output
- Expected event counts depend on oscillation parameters





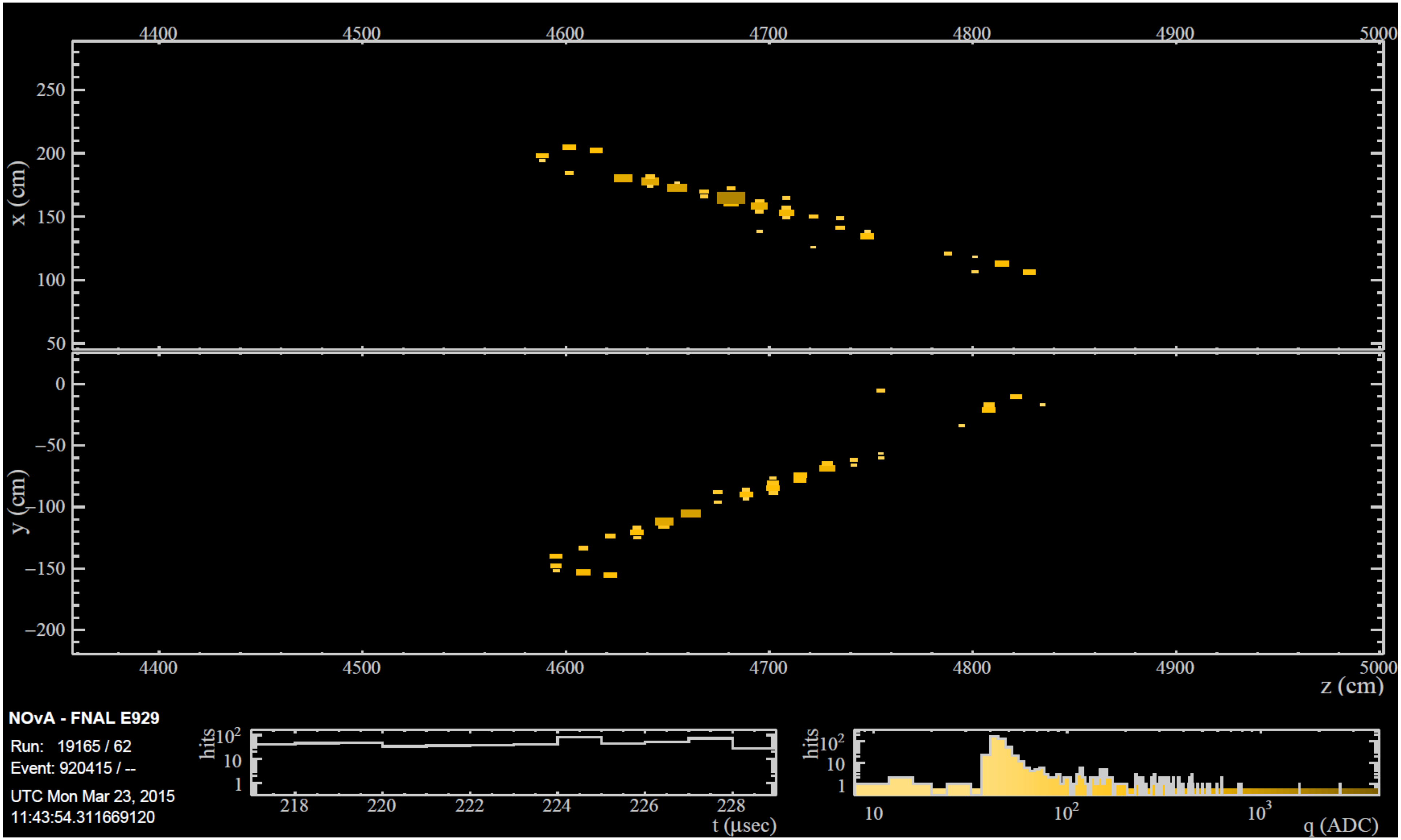
Signal events (±5% systematic uncertainty):

NH, $3\pi/2$,	IH, $\pi/2$,
28.2	11.2

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

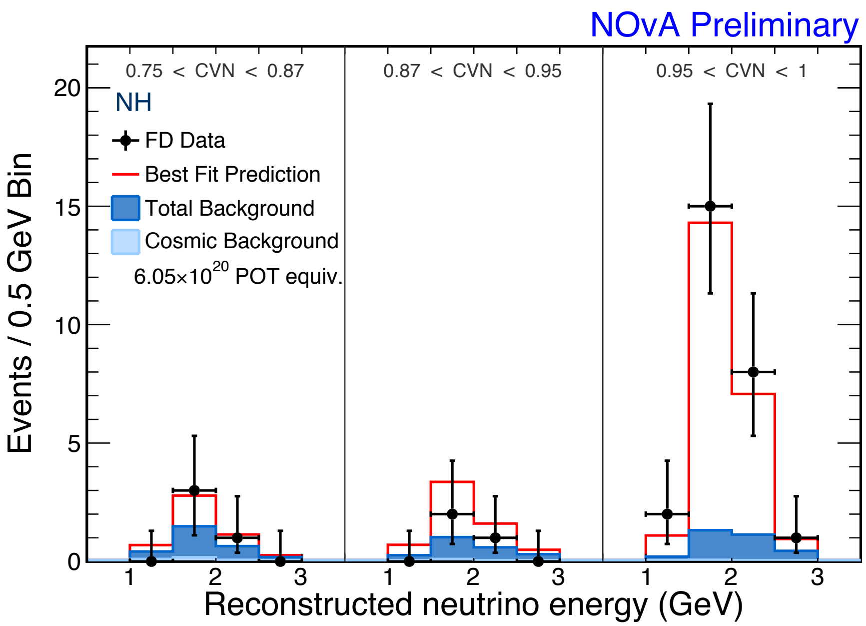
NOvA Far Detector Selected ν_e CC Candidate

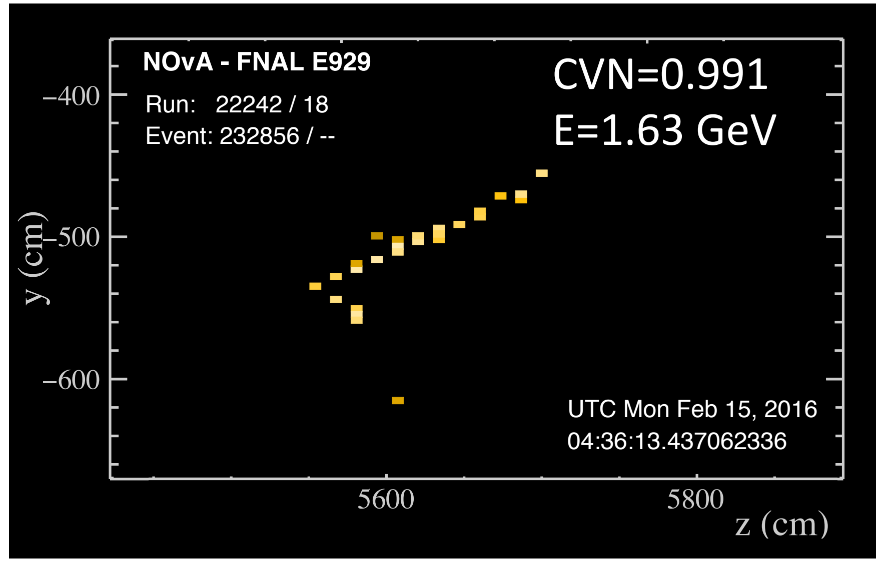


Far Detector ν_e Data vs Prediction

- Observed 33 events in FD
  - Background estimate: 8.2 ± 0.8

>8σ electron neutrino appearance signal





Alternate PID selection based on 2015 analysis show consistent results

- LID: 34 events, 12.2±1.2 BG expected
- LEM: 33 events, 10.3±1.0 BG expected

NOvA ν_e Appearance Results

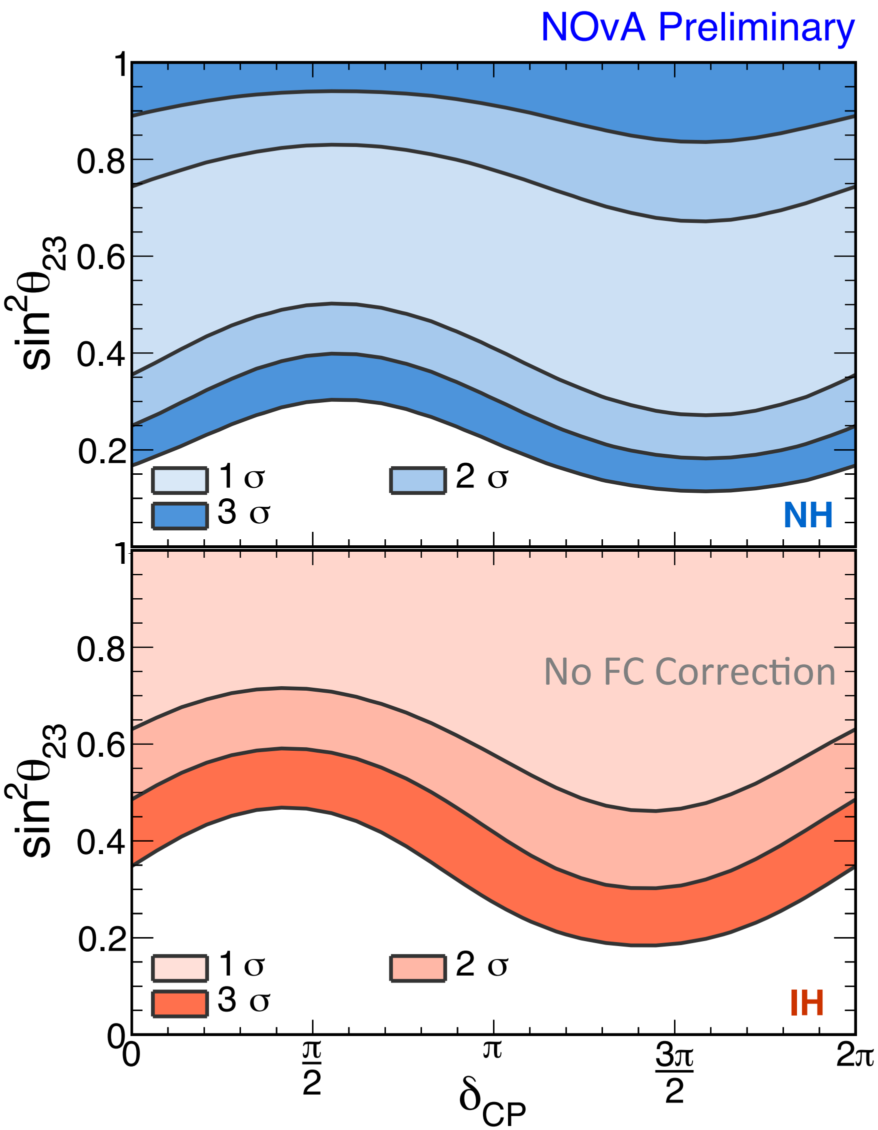
- Fit for hierarchy, $\boldsymbol{\delta}_{CP}$, $\sin^2\theta_{23}$
  - Inputs:

    $\sin^2(2\theta_{13}) = 0.085 \pm 0.05$

    $\Delta m^2 = 2.44 \pm 0.06 \times 10^{-3}$ eV^2, NH

    $\Delta m^2 = -2.49 \pm 0.06 \times 10^{-3}$ eV^2, IH
  - Systematic effects included as nuisance parameters

    (normalization, flux, calibration, cross section, and detector response effects)



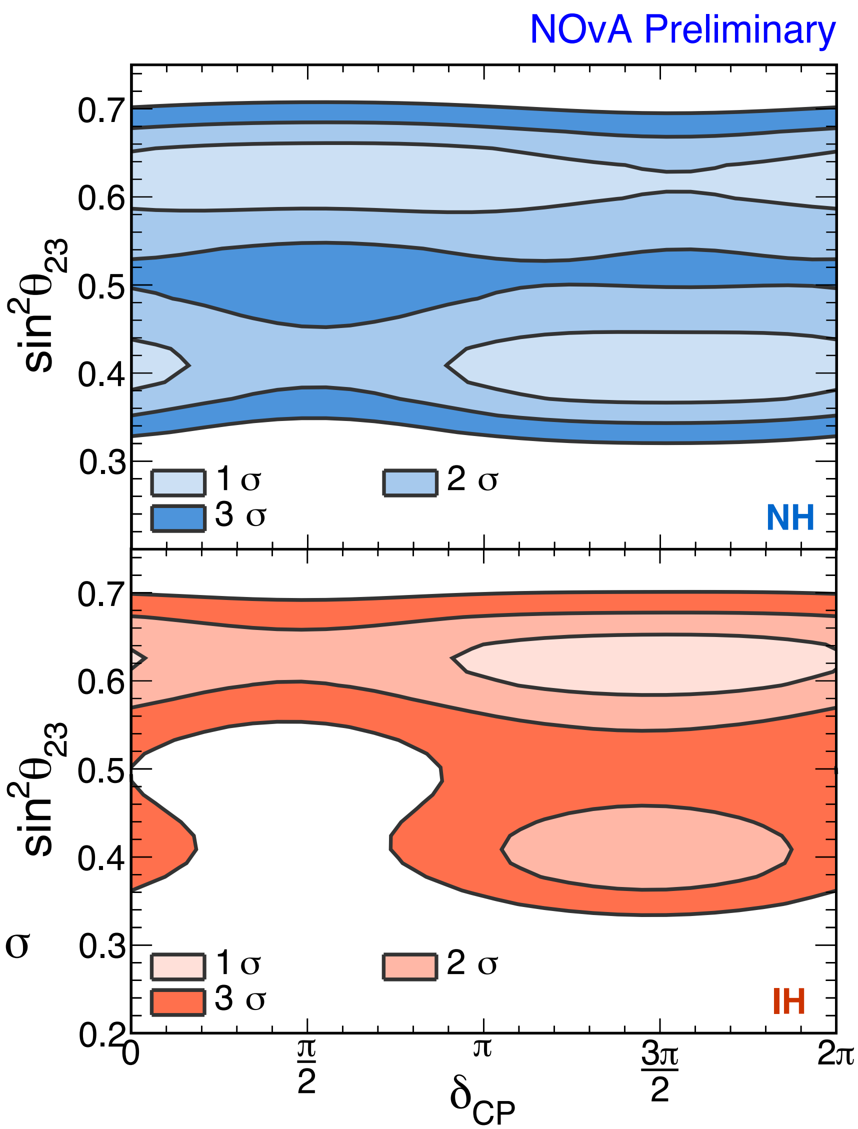
NOvA ν_e Appearance Results

- Fit for hierarchy, $\boldsymbol{\delta}_{CP}$, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated between two samples

- Global best fit Normal Hierarchy

$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

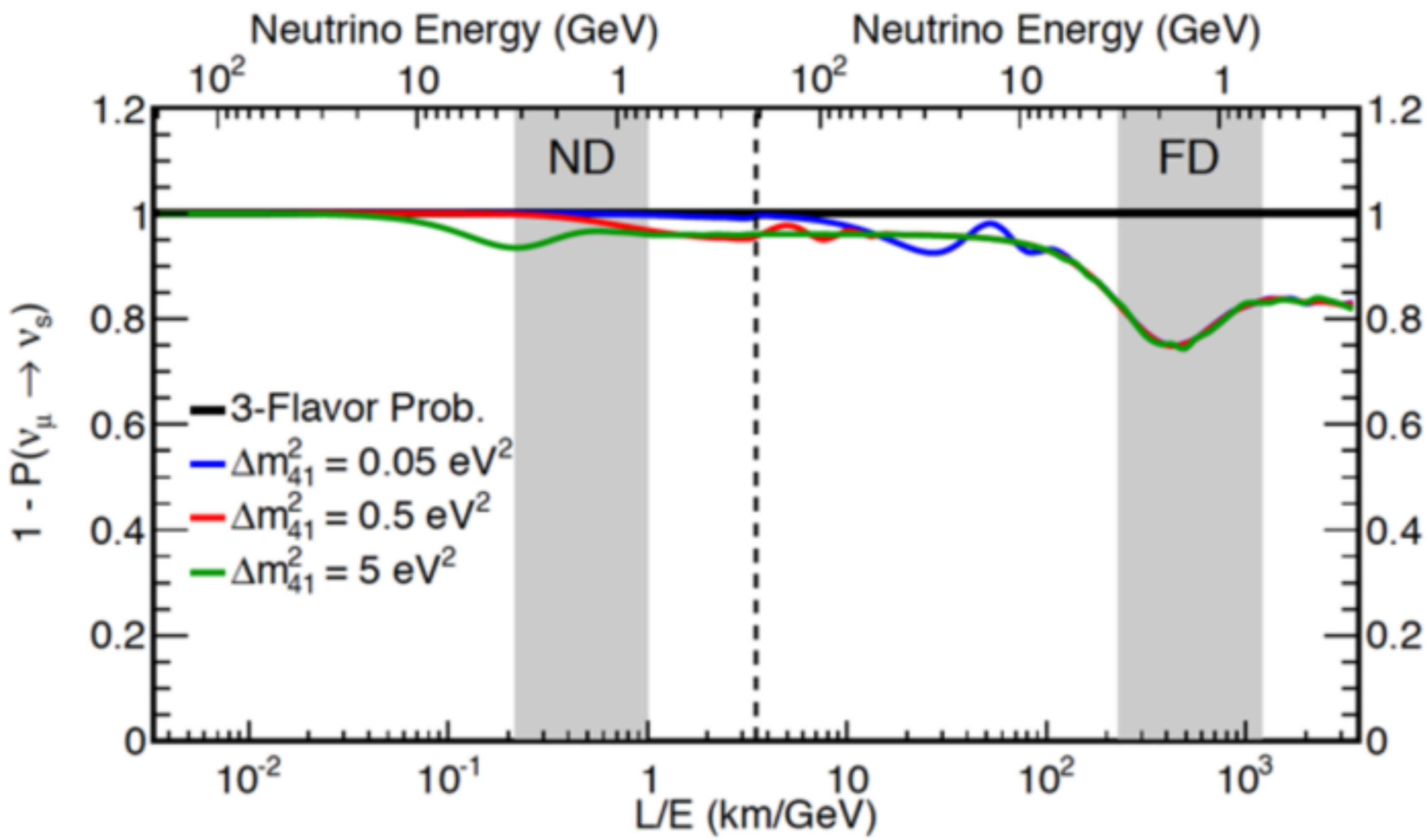
  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\boldsymbol{\delta}_{CP}=\pi/2$



Sterile ν Search

Other Oscillation Results from NOνA

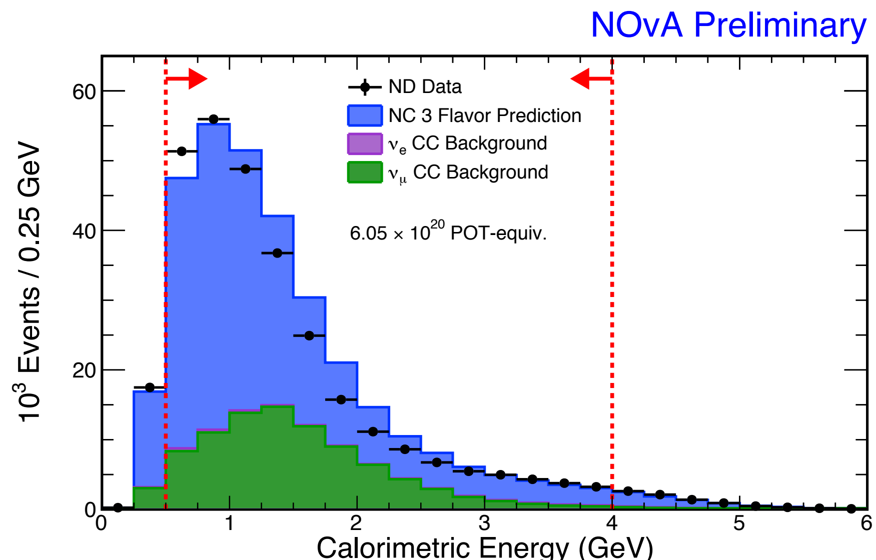
- Sterile Neutrino Search
  - -Deficit of NC events?
  - -NOνA has searched for sterile mediated $\nu_\mu \rightarrow \nu_\mu$ disappearance in NC events



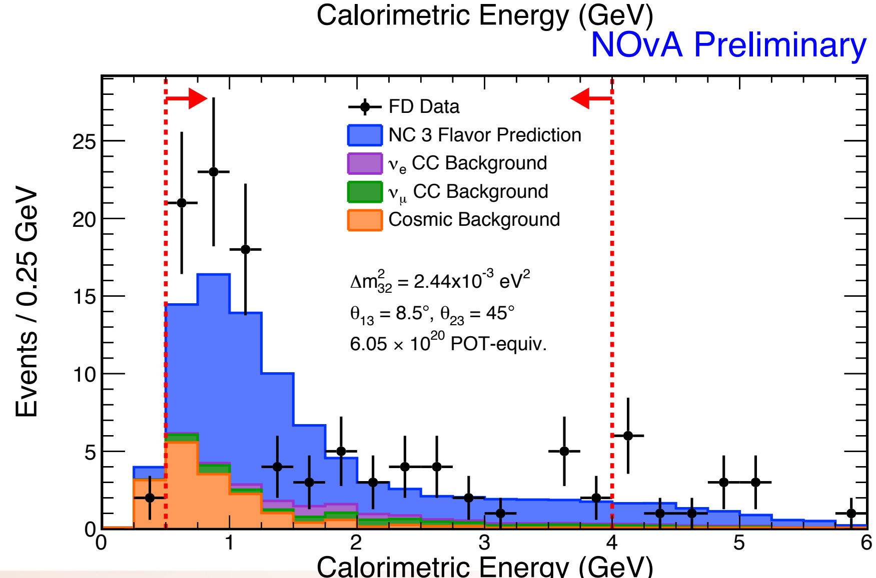
NC Oscillation Search

- Suppression of NCs could be evidence of oscillations involving a sterile neutrino

-Fit to 3+1model $\Delta m^2_{41}, \theta_{34}, \theta_{24}$



- Events classified using CVN
- Normalization agrees well
- Data shifted to lower energy relative to MC
  - No MEC model for NC events
  - Large uncertainties on NC cross section



- Extrapolation of ND data using F/N in reconstructed energy gives a prediction:

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

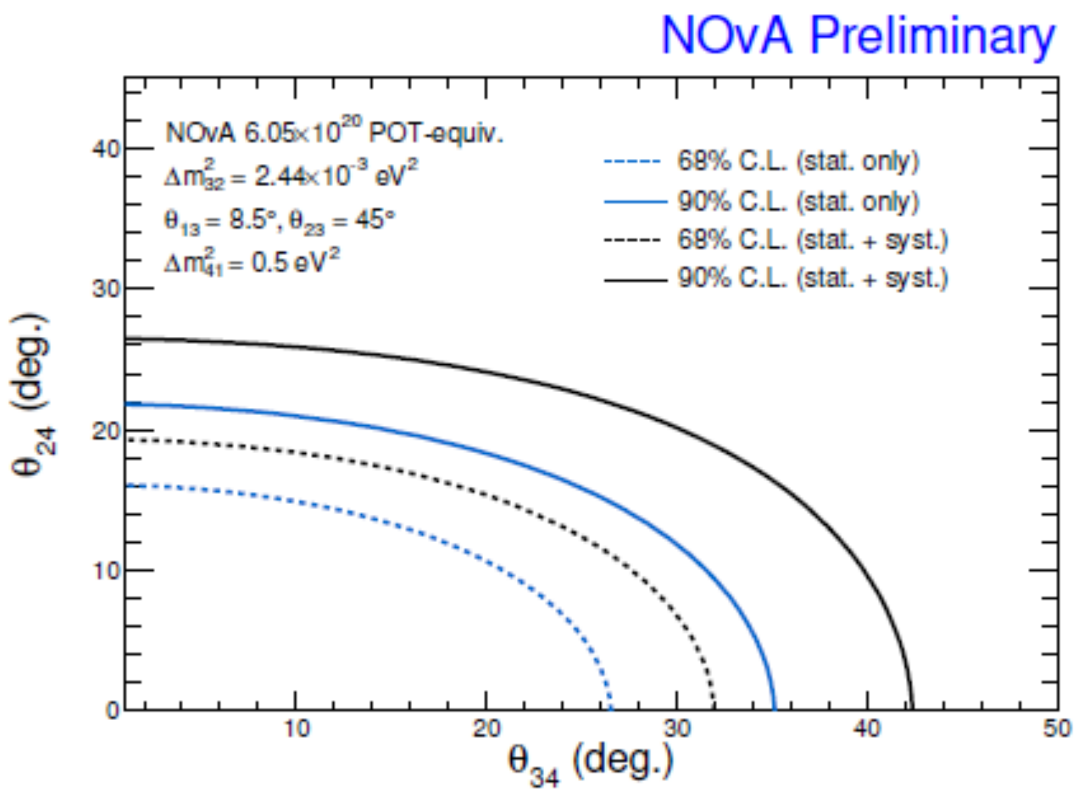
- Observed 95 events
- No evidence of osc. involving sterile ν

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

$\theta_{34} < 35°,\ \theta_{24} < 21°$ (90%C.L.)

NC Oscillation Search

- 2D limits with systematics



- Excellent NC efficiency (50%) and purity (72%) promise strong future limits on θ_{34}

Summary and Prospects

- NOνA delivered new results with 6.05 x 10^{20} POT exposure
- ν_μ Disappearance result
  -Muon neutrinos disappear
  -Best fit is non-maximal: Maximal mixing excluded at 2.5σ
- ν_e Appearance result
  -Electron neutrinos appear at > 8σ
  -Data prefers NH at low significance
  -Region in IH, lower octant around $\boldsymbol{\delta}_{CP} = \pi/2$ is excluded
- Neutral current event rate shows no evidence of sterile neutrinos
  -With more data, expect strong limits on θ_{34}
- NOνA prepares to take anti-neutrino data
  -Short anti-neutrino run taken in Summer 2016
  -Long anti-neutrino run anticipated to start in Spring 2017

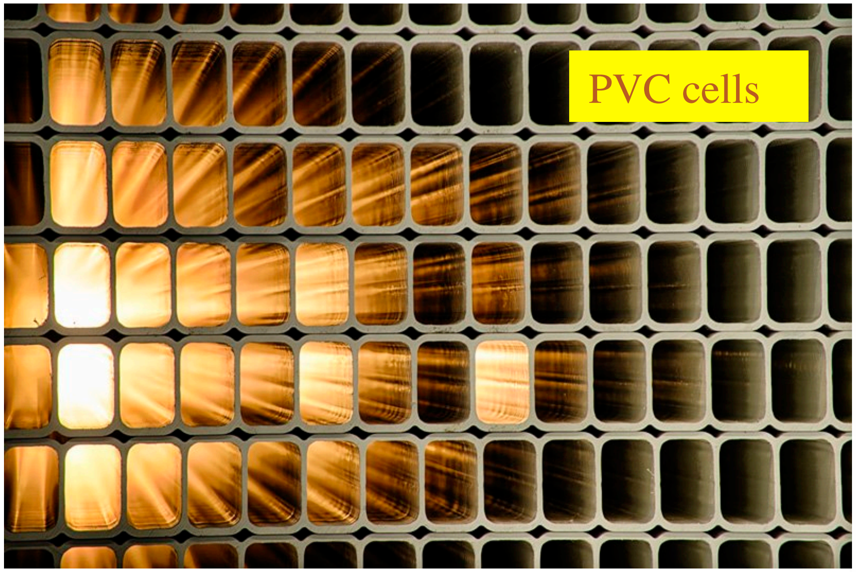
The NOvA Collaboration

Argonne, Atlantico, Banaras Hindu University, Caltech, Cochin, Institute of Physics and Computer science of the Czech Academy of Sciences, Charles University, Cincinnati, Colorado State, Czech Technical University, Delhi, JINR, Fermilab, Goiás, IIT Guwahati, Harvard, IIT Hyderabad, U. Hyderabad, Indiana, Iowa State, Jammu, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Panjab, South Carolina, SD School of Mines, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, UCL,Virginia, Wichita State, William and Mary, Winona State

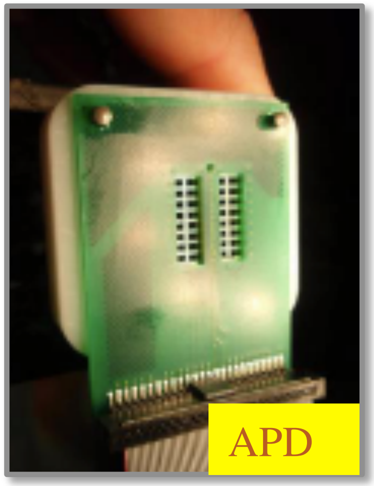
234 Collaborators
41 institutions
7 countries

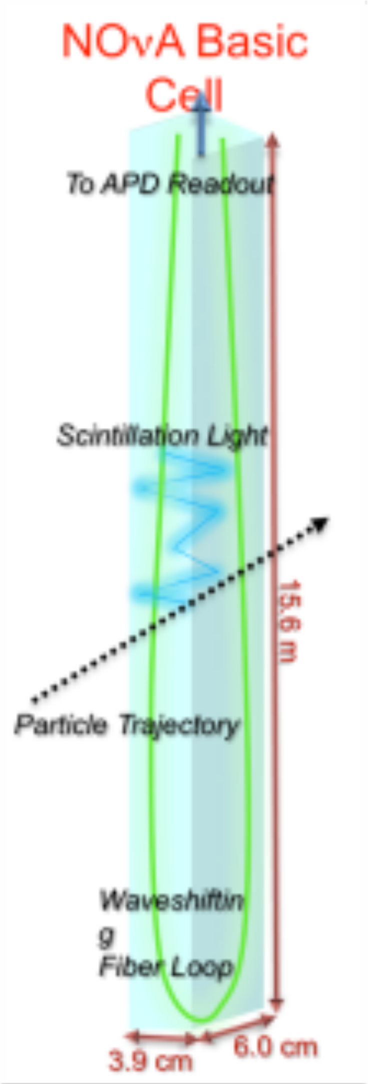
Backups

NOvA Detectors



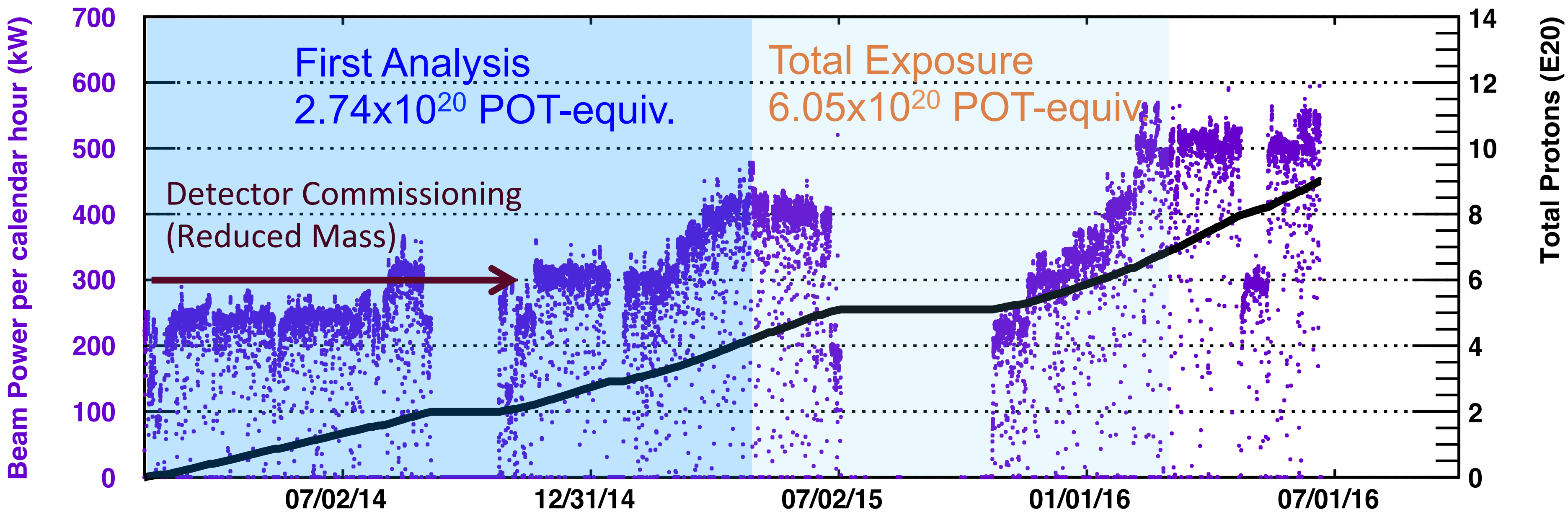
- PVC + Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
- Read out via WLS fiber to APD
- Layered planes of orthogonal views
  - muon crossing far end ~40 PE
  - 0.17 X_0 per layer
- DAQ runs with zero dead-time
  - triggers for beam, SNEWS, cosmic ray calibration samples, exotic searches
  - 150kHz of cosmic induced events





NuMI Beam Performance

- 6.05×10^{20} POT in 14 kton equivalent detector
  - More than double exposure of 2015 analysis
- Averaged 560 kW before present shutdown
- Achieved 700 kW design goal in tests (June13)



Oscillation Probability

- In long-baseline experiment, the ν_μ oscillation probability is given with

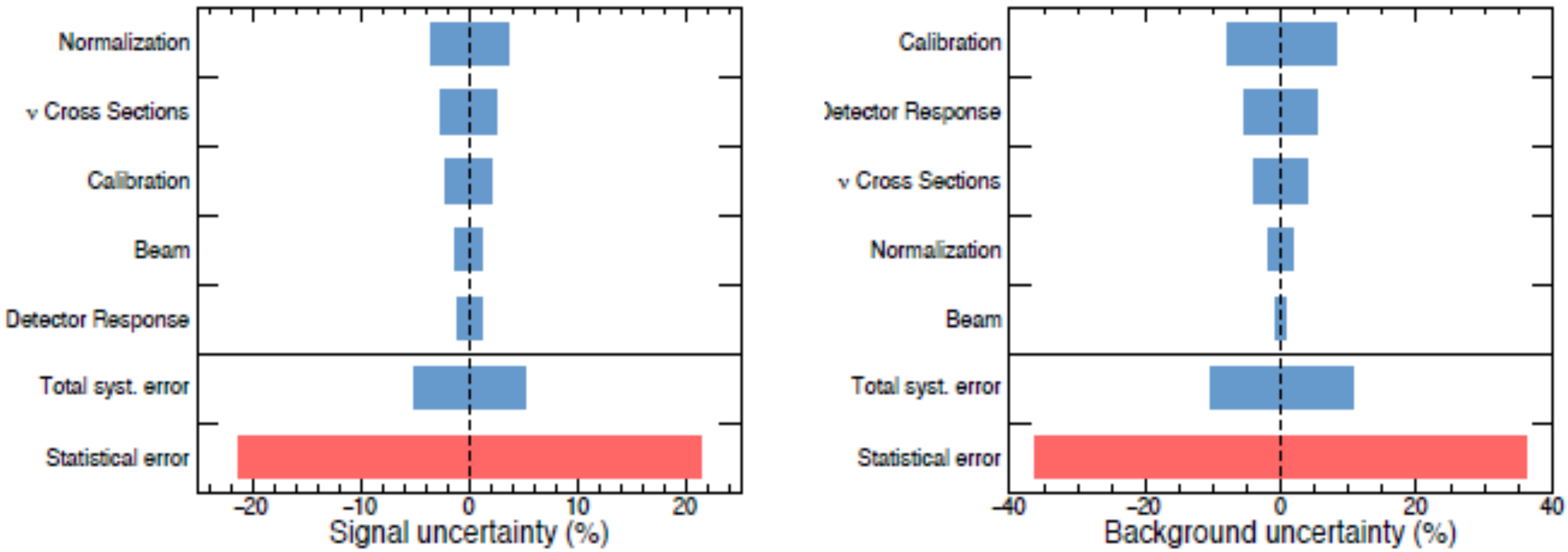
$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E_\upsilon$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\ & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta_{CP}) \\ & + \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2, \end{aligned}$$

$$a = G_F N_e / \sqrt{2}$$

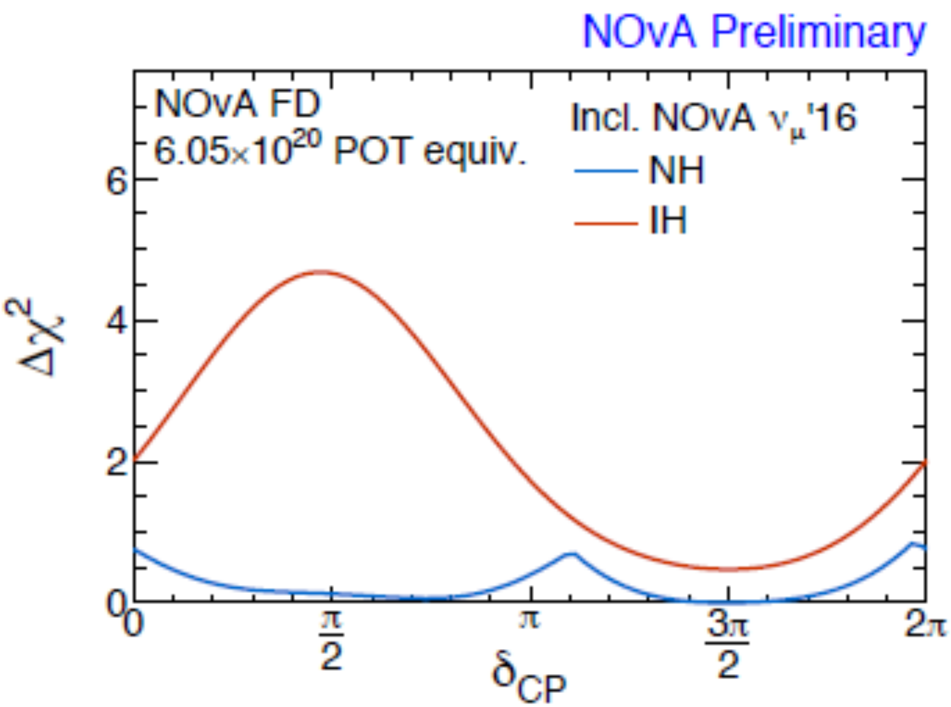
- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and mass hierarchy.
- Large value of $\sin^2 2\theta_{13}$ allows significant ν_e appearance sample.
- δ_{CP} and the term *a* switch signs in going from the $\nu_\mu \to \nu_e$ to the $\bar{\nu}_\mu \to \bar{\nu}_e$

ν_e Appearance Systematics



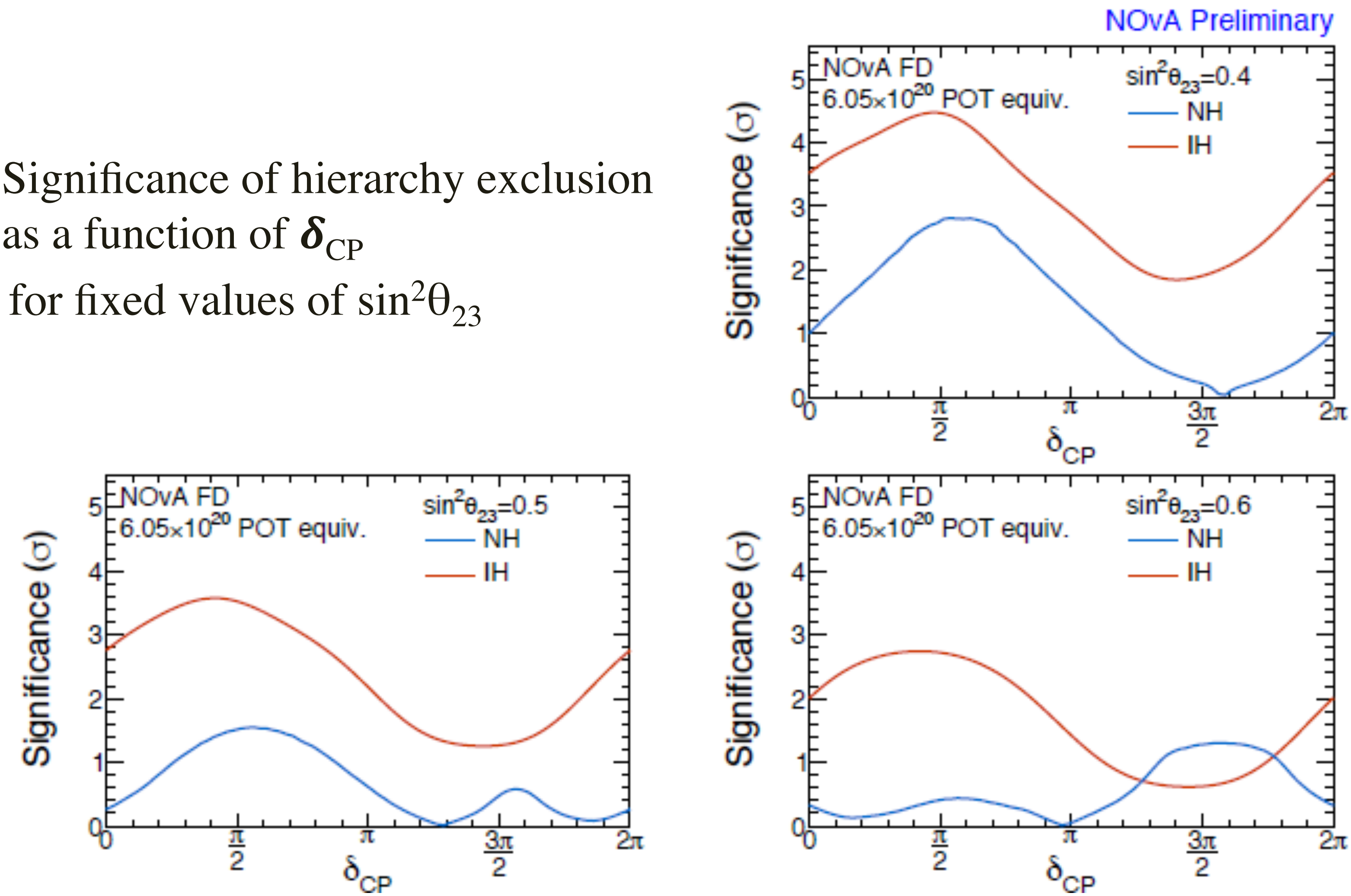
NOvA ν_e Appearance Results: 1D Contours

- Fit for hierarchy, $\boldsymbol{\delta}_{CP}$, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated between two samples
  - No Feldman-Cousins corrections



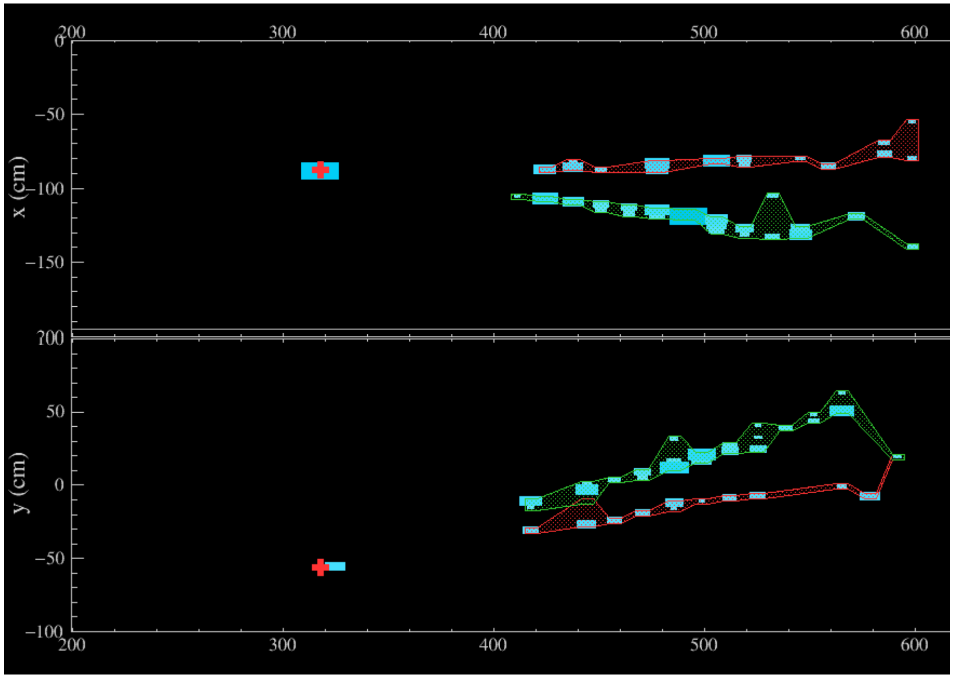
NOvA ν_e Appearance Results: 1D Contours

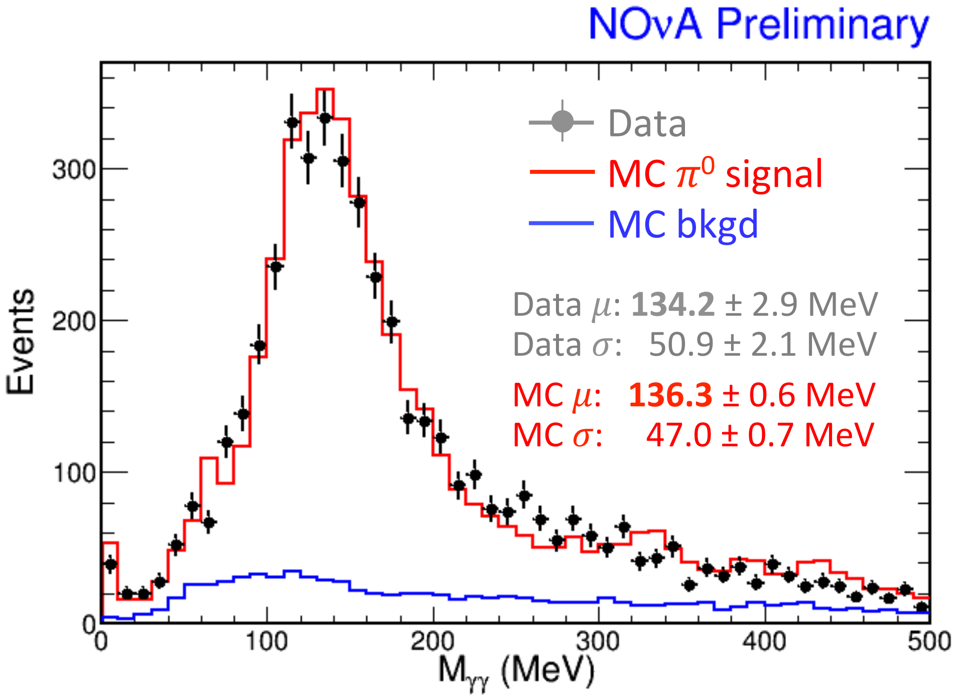
- Significance of hierarchy exclusion as a function of $\boldsymbol{\delta}_{CP}$ for fixed values of $\sin^2\theta_{23}$



NC Event Reconstruction

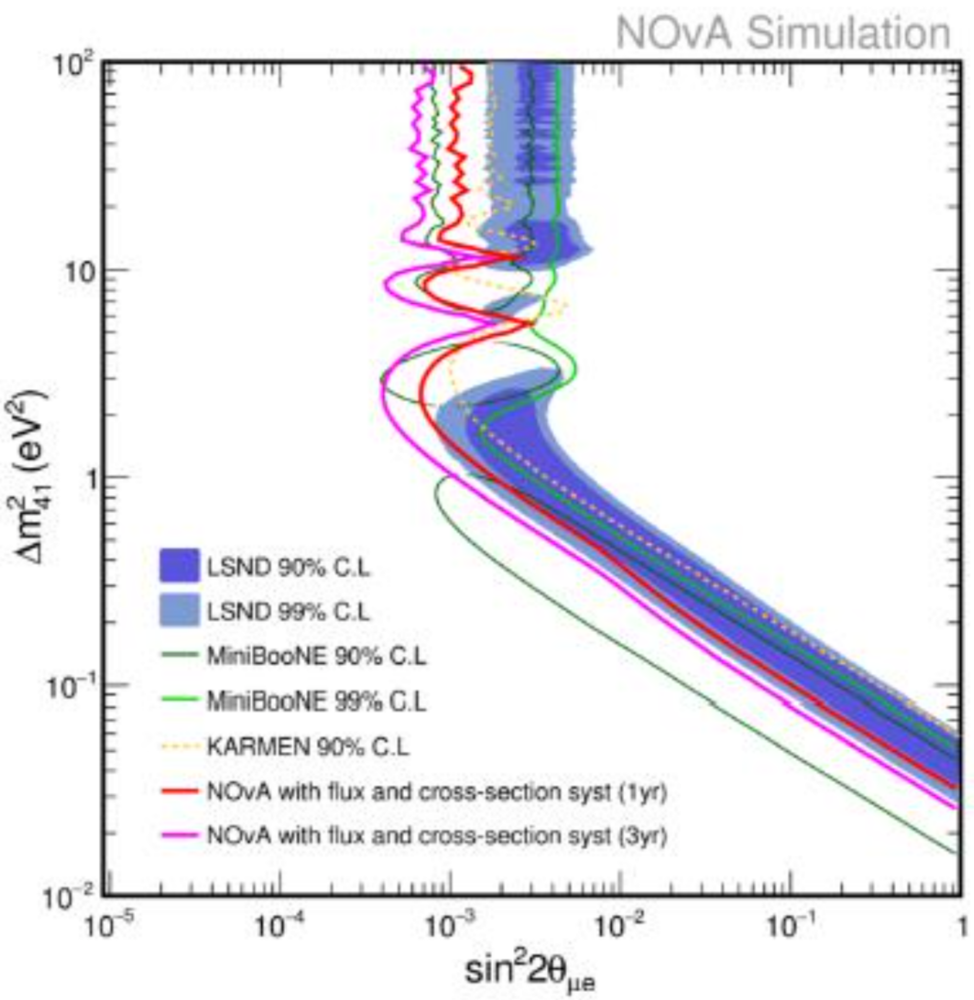
- Reconstruct π^0 peak – used as a calibration cross-check
  -Demonstrates ability to reconstruct NC events





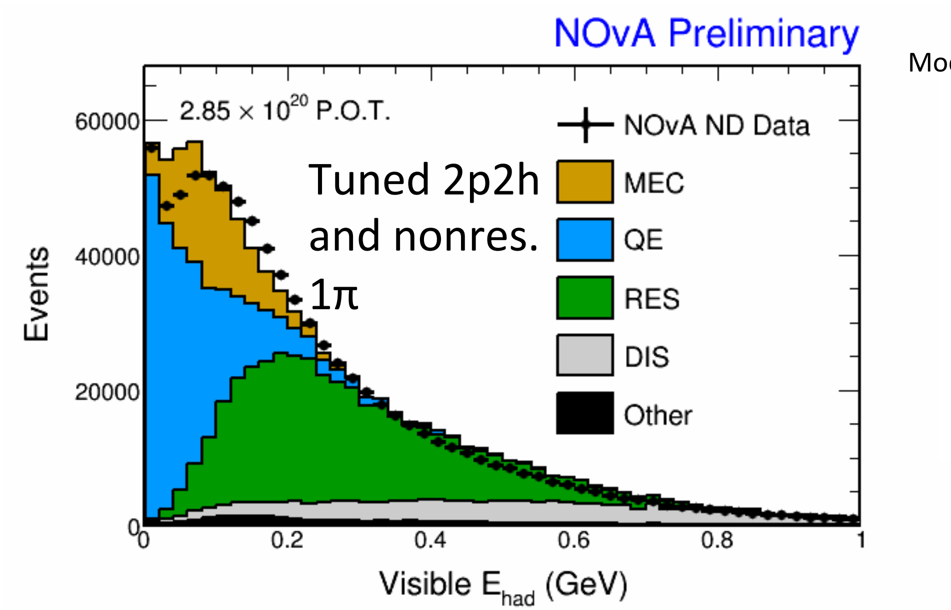
NOvA Sterile Neutrino Search Potential

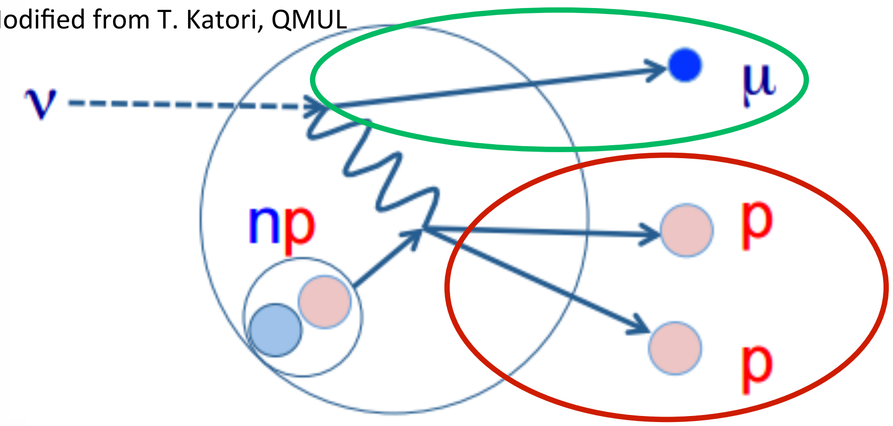
- NOvA is expected to have a future sensitivity that can probe LSND signal at 90% CL



Nuclear Correlations

- ND hadronic energy suggests extra process between QE and Δ production
- MINERνA reported similar excess in their data[1]





$$q_0 = E_{had}$$
$$E_\nu = E_\mu + E_{had}$$
$$Q^2 = 2E_\nu(E_\mu - p_\mu\cos(\theta_\mu) - M^2_\mu)$$
$$|q| = Q^2 + q_0$$

[1]P.A. Rodrigues et al., PRL 116 (2016) 071802 (arXiv:1511.05944)
[2]S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57
[3]P.A. Rodrigues et al., arXiv:1601.01888