Fermilab
U.S. DEPARTMENT OF ENERGY | Office of Science

Neutrino Oscillation Results from NOvA

Peter Shanahan *on behalf of the NOvA collaboration*

Neutrinos in Cosmology, in Astro-, Particle-, and Nuclear Physics

Erice

19 September 2017

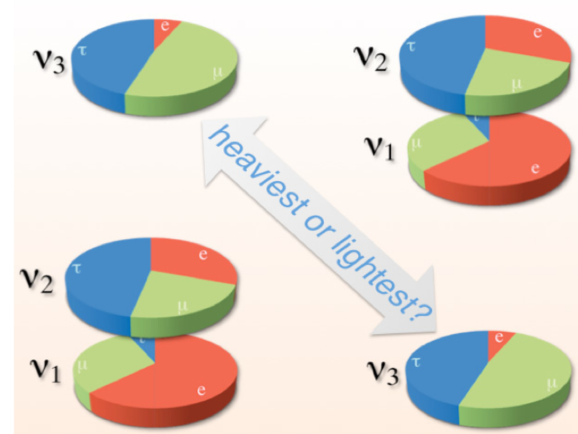
In partnership with:

NOvA

Physics with Long Baseline Neutrino Oscillations

- Structure of mixing
  - Is there a new symmetry driving equal ν_μ - ν_τ contributions to ν_3?
    - Maximal mixing, $\theta_{23}=45^o$, $\sin^2(\theta_{23})=0.5$
  - If not, does ν_3 have more ν_τ, or more ν_μ
    - Lower octant vs upper octant of θ_{23}

- Mass Hierarchy
  - Is ν_3 heaviest (normal) or lightest (inverted)?



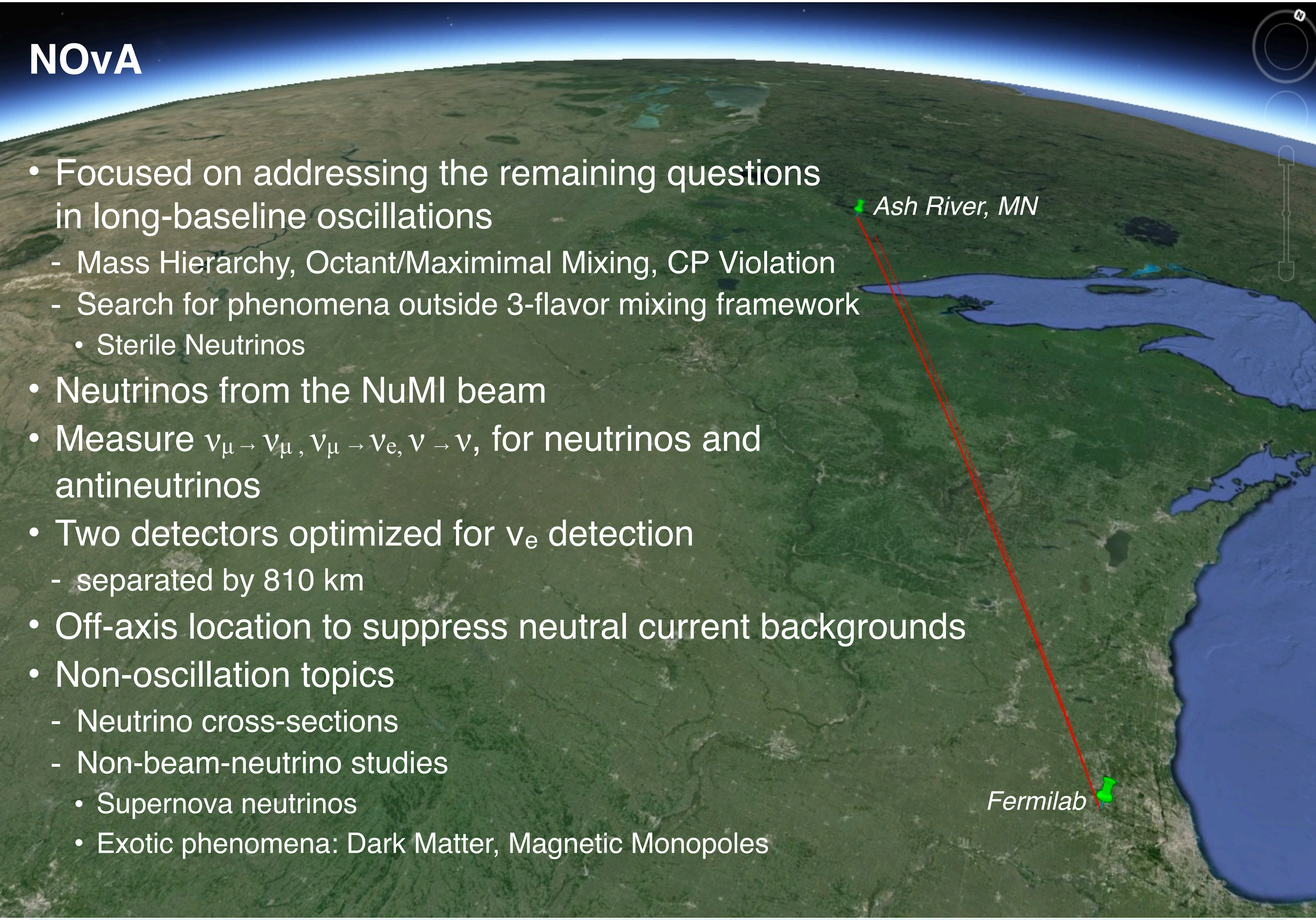
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- CP Violation
  - $P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ differ depending on value of CP violating phase of PMNS matrix, δ

- Is there more to the picture?
  - Is there evidence of oscillations to flavors not participating in Neutral Current interaction?
    - Sterile Neutrinos

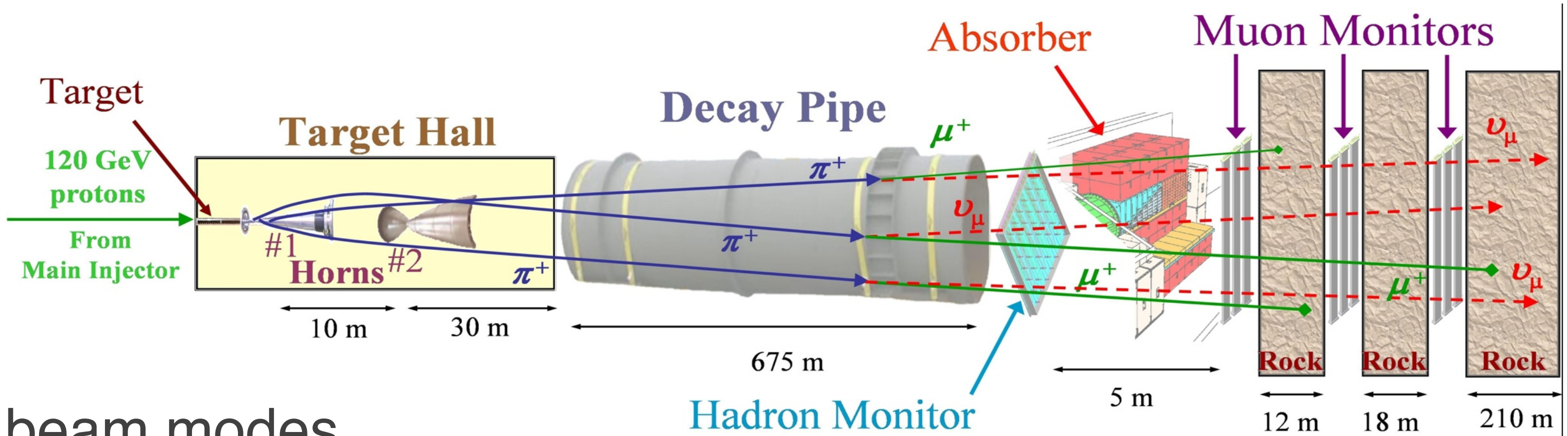
NOvA

- Focused on addressing the remaining questions in long-baseline oscillations
  - Mass Hierarchy, Octant/Maximimal Mixing, CP Violation
  - Search for phenomena outside 3-flavor mixing framework
    - Sterile Neutrinos
- Neutrinos from the NuMI beam
- Measure $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\nu \to \nu$, for neutrinos and antineutrinos
- Two detectors optimized for ν_e detection
  - separated by 810 km
- Off-axis location to suppress neutral current backgrounds
- Non-oscillation topics
  - Neutrino cross-sections
  - Non-beam-neutrino studies
    - Supernova neutrinos
    - Exotic phenomena: Dark Matter, Magnetic Monopoles

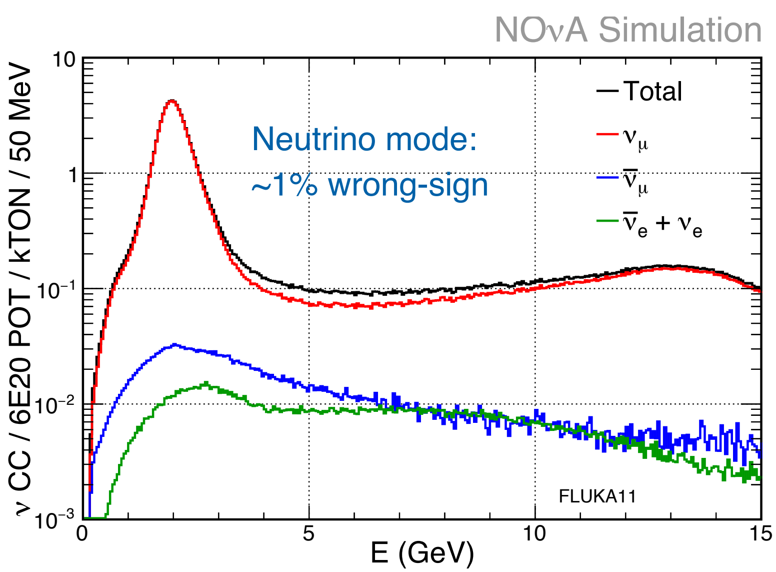


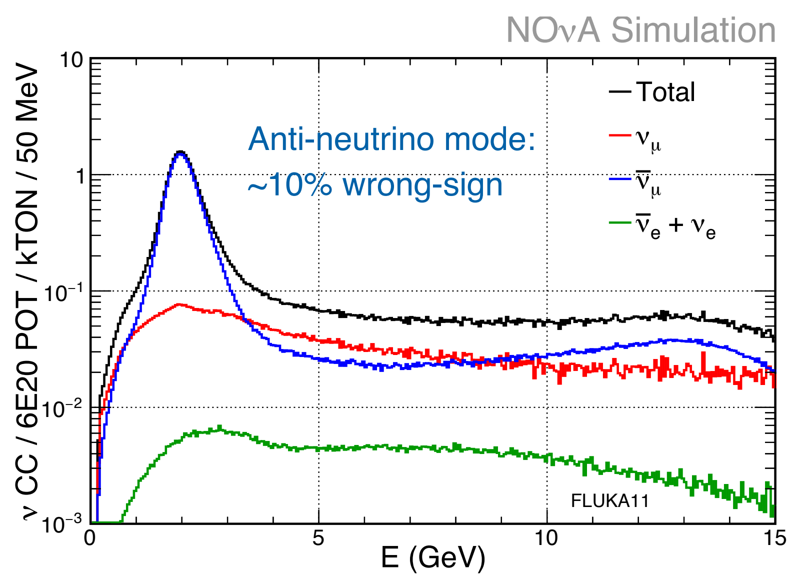
NuMI Beam

- Highest power neutrino beam in the world - 700 kW



- ν and $\bar{\nu}$ beam modes
  - Direction of focusing horn current





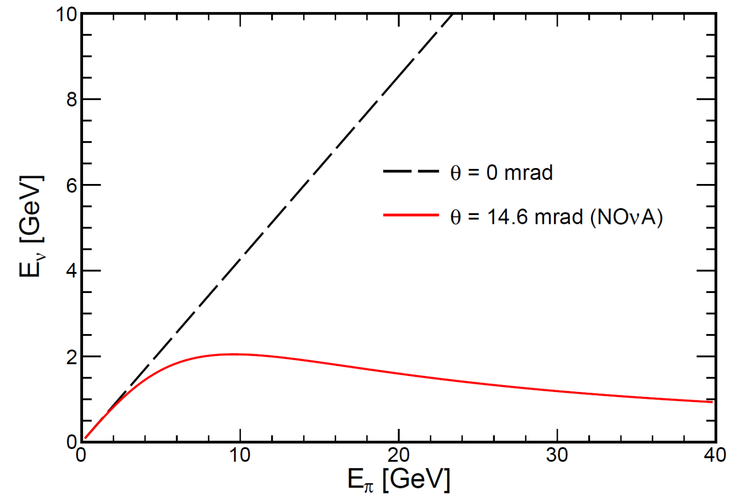
Location

- 14 mad (11km) off the NuMI beam axis
  - Pion 2-body decay kinematics

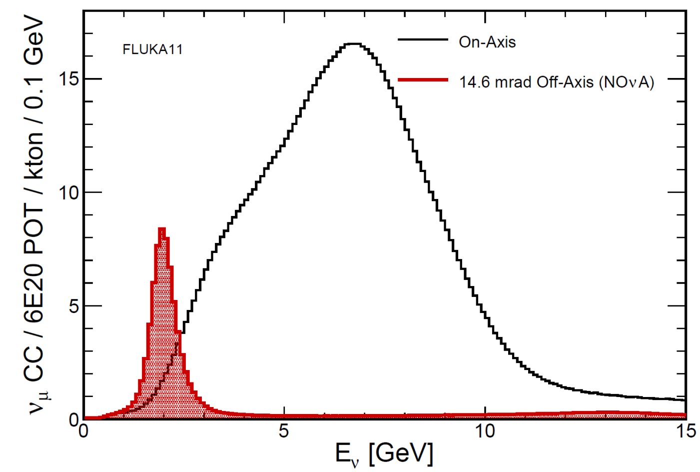
$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

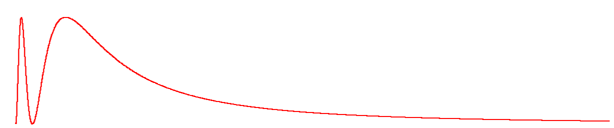
  - Neutrino spectrum peaks near 1st oscillation maximum
  - High energy tail is suppressed: reduced Neutral Current π^0 background

- As far as possible from Fermilab for maximum matter effect → Sensitivity to Mass Hierarchy



NOνA Simulation

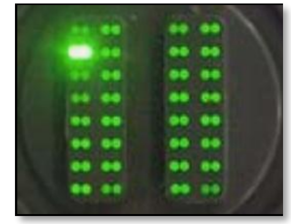


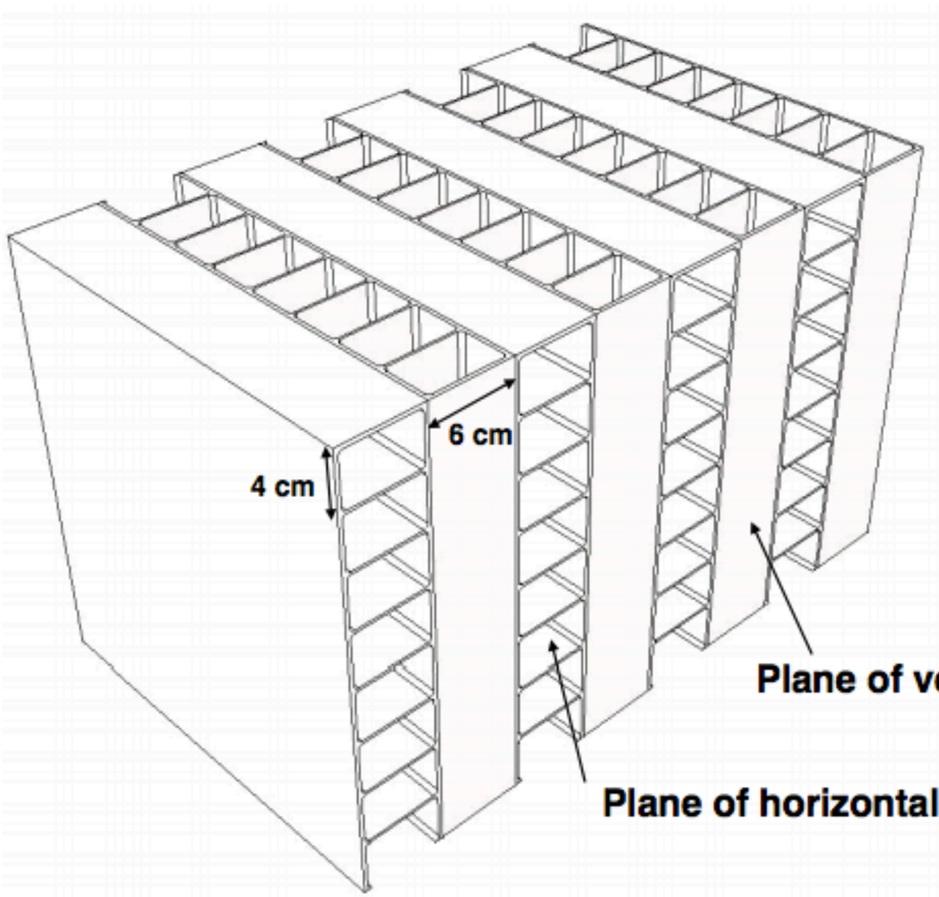


NOvA Detector Technology

- Low-Z Tracking Calorimeters
  - PVC Cell Structure
  - Filled with Mineral Oil + 5% pseudocumene

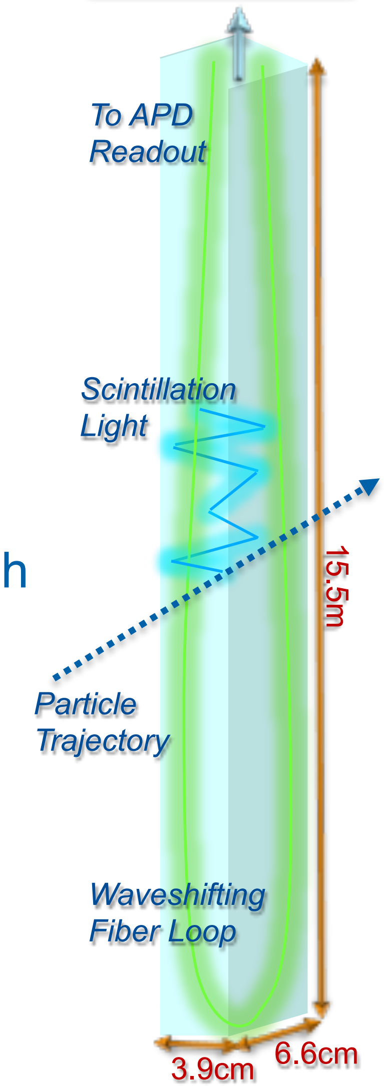
32 cells read out into 1 Avalanche PhotoDiode



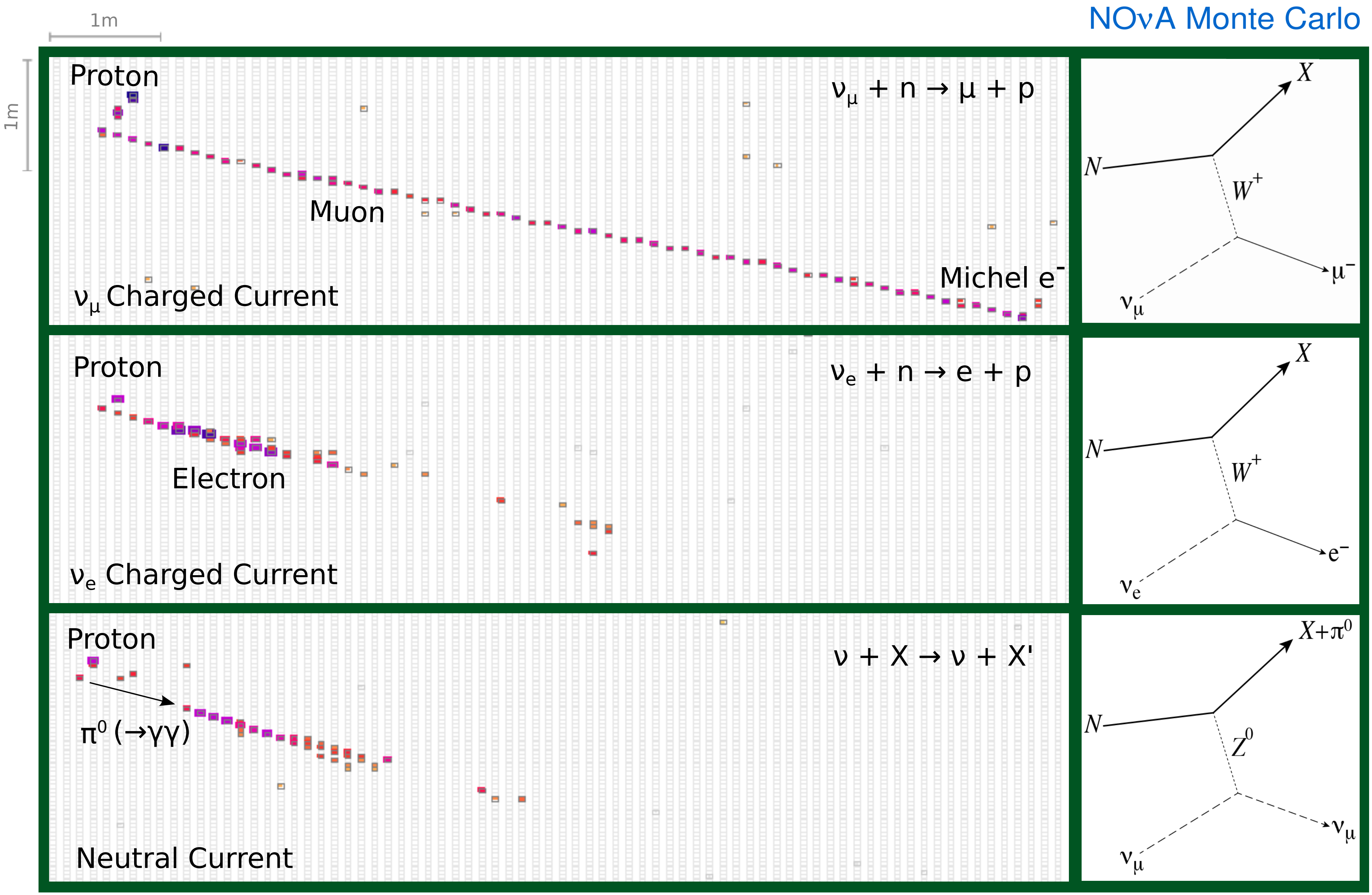


Excellent electromagnetic shower characterization with 6 samples per radiation length

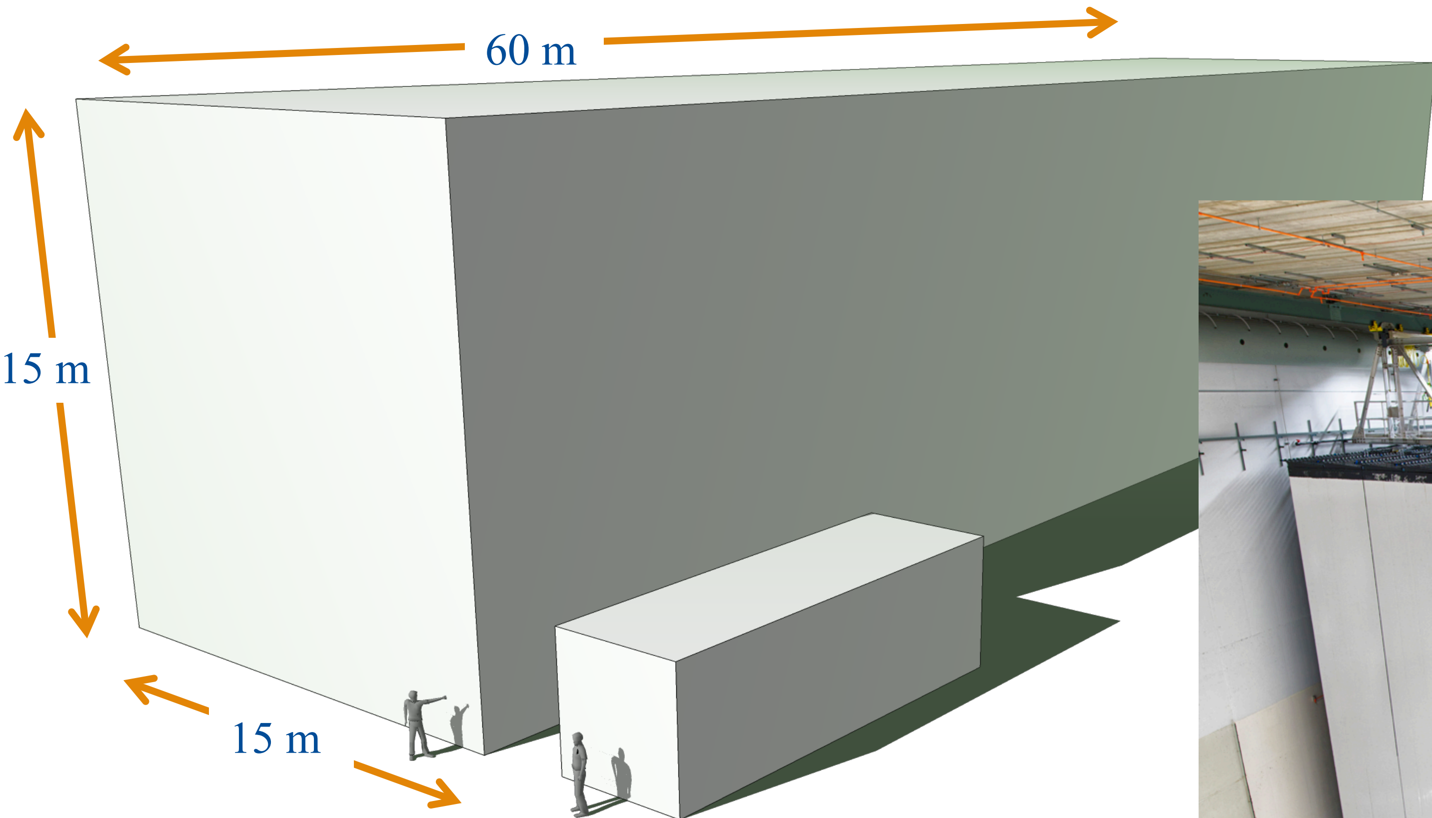
Single Cell



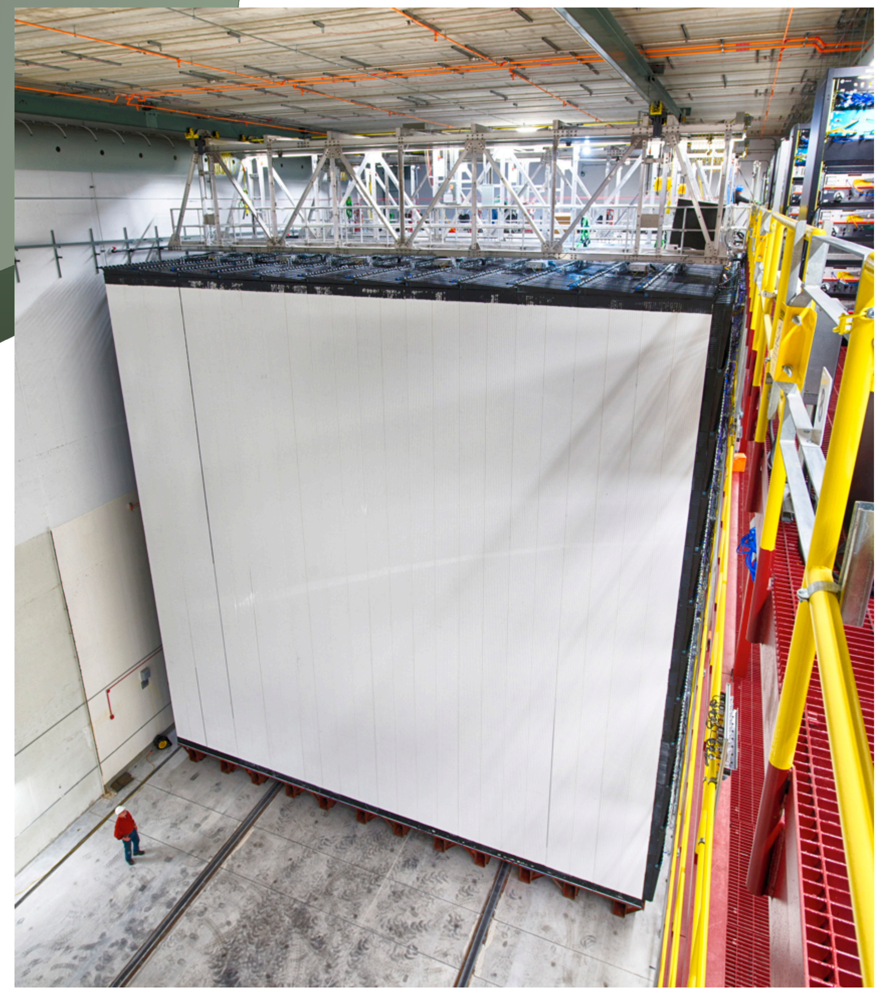
Detector Design



NOvA Detectors

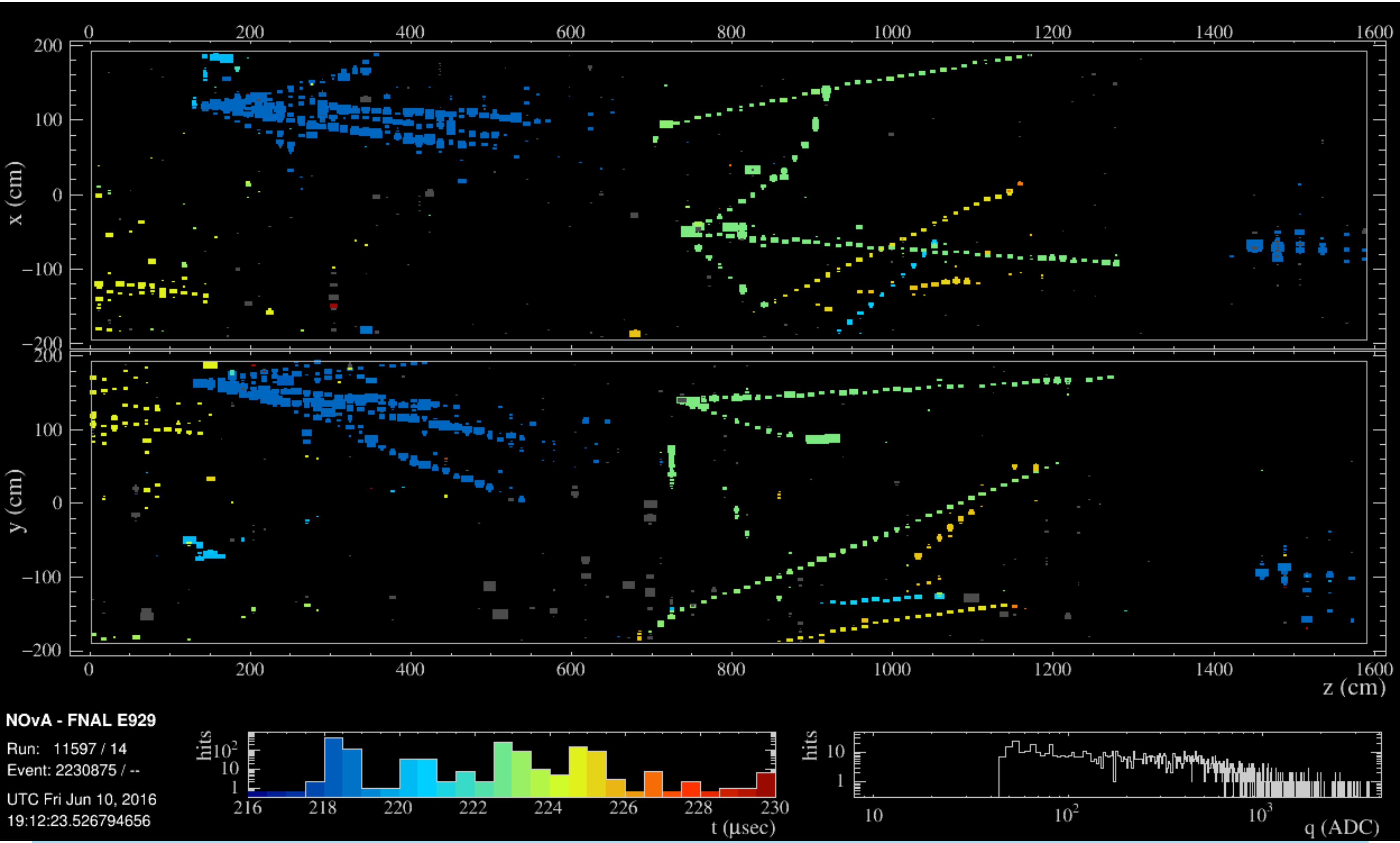


- Far Detector
  - 14 kt, 896 planes



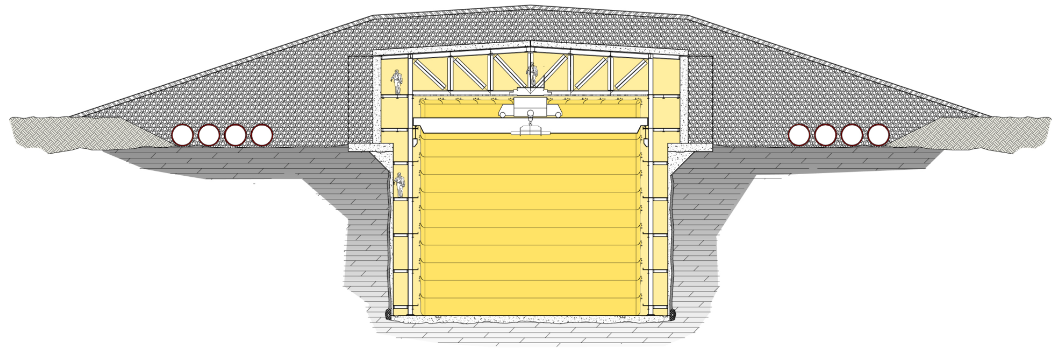
- Near Detector
  - 293 tons, including muon catcher
  - used to measure neutrino beam flavor and energy spectrum before oscillations

NOvA Near Detector - a typical beam spill

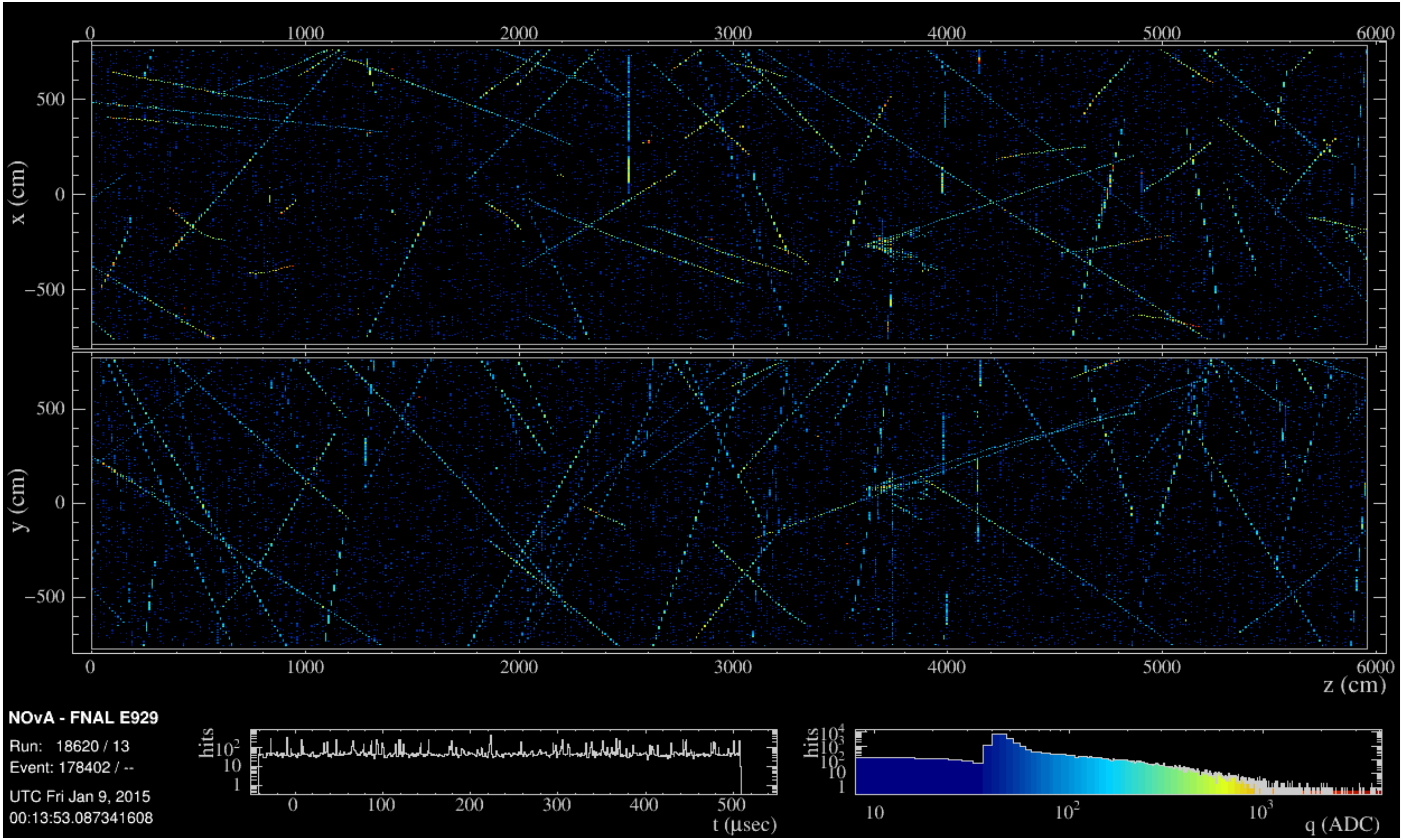


NOvA Far Detector

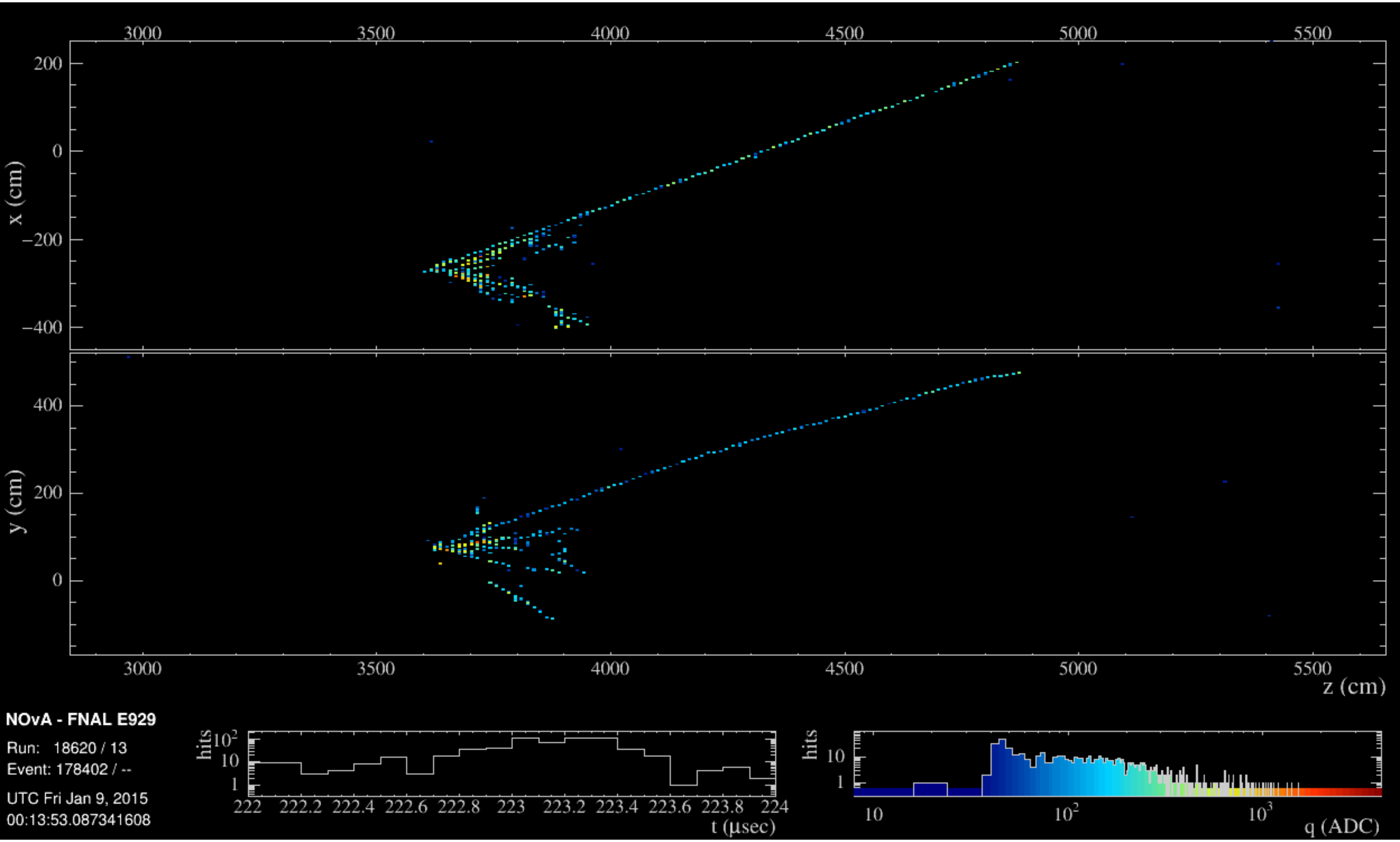
- Detector is mostly below-grade
- Overburden of 1.37m concrete & 0.15 Barite ($BaSO_4$) for cosmic background reduction



Far Detector - 550 μs NuMI Beam Spill Window

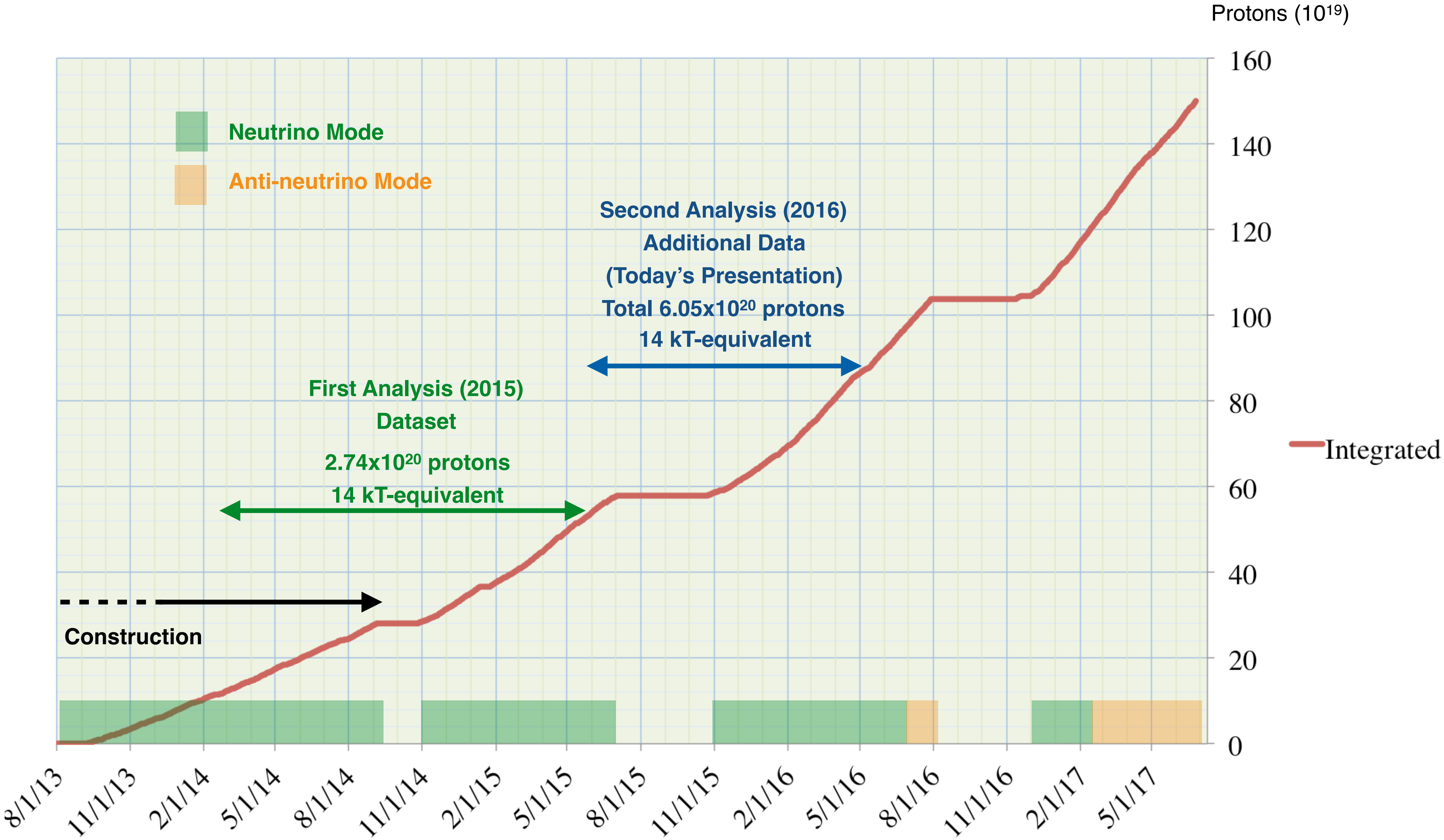


Zoom-in: ν_μ candidate event



NOvA Oscillation Analyses

- Analyses Presented today from first 15 months of neutrino-mode data



ν_μ Disappearance Analysis: Sensitive primarily to $|\Delta m^2_{32}|$, $\sin^2(2\theta_{23})$

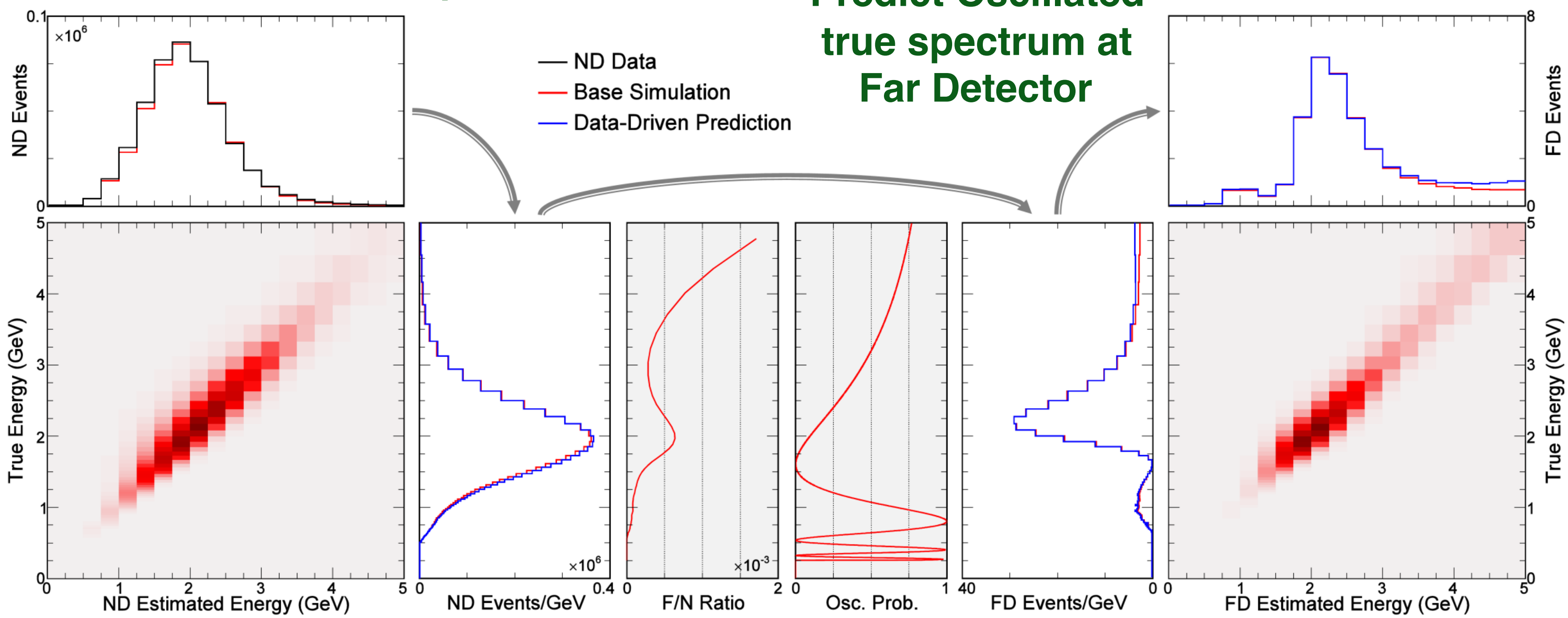
Compare observed and simulated Near Detector ν_μ Charged Current Interaction Spectrum

Compare observed and predicted selected ν_μ CC spectra in Far Detector to extract oscillation parameters

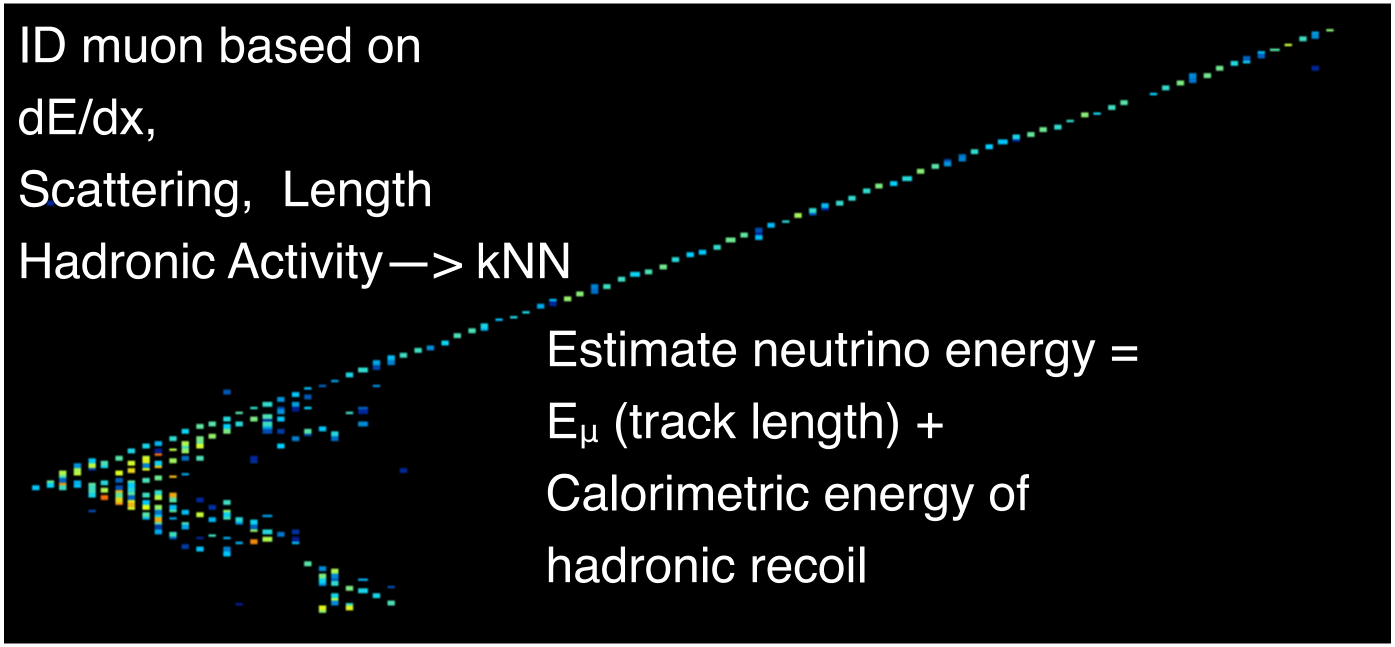
Blind Analysis: examine Far Detector Data only after all systematic studies are complete

Scale simulation for adjusted true ν_μ spectrum

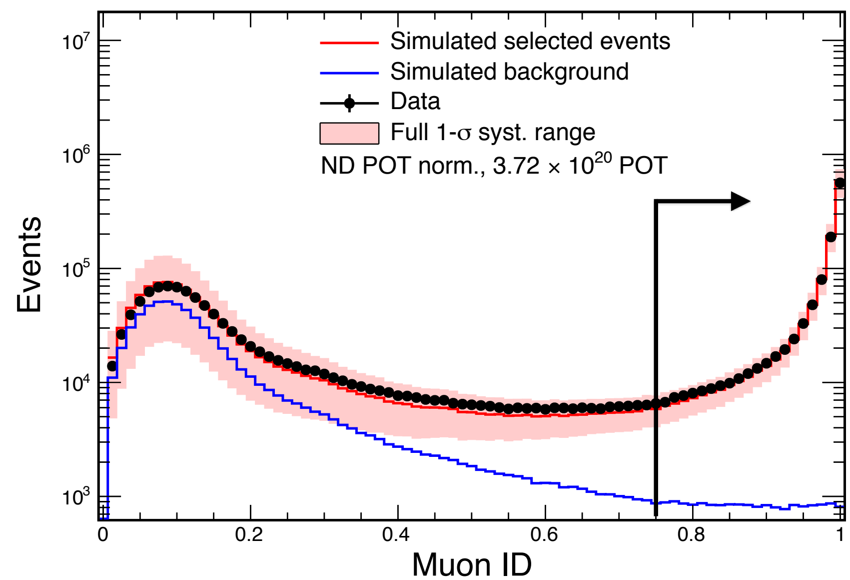
Predict Oscillated true spectrum at Far Detector



ν_μ Charged Current Event Selection

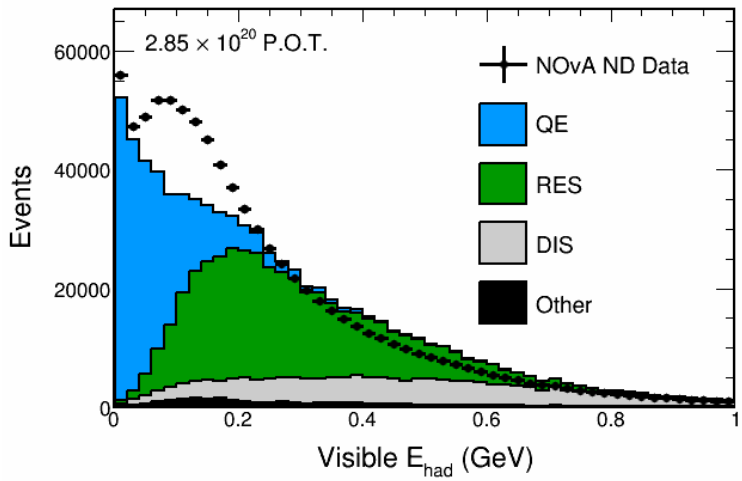


Resulting kNN output in Near Detector

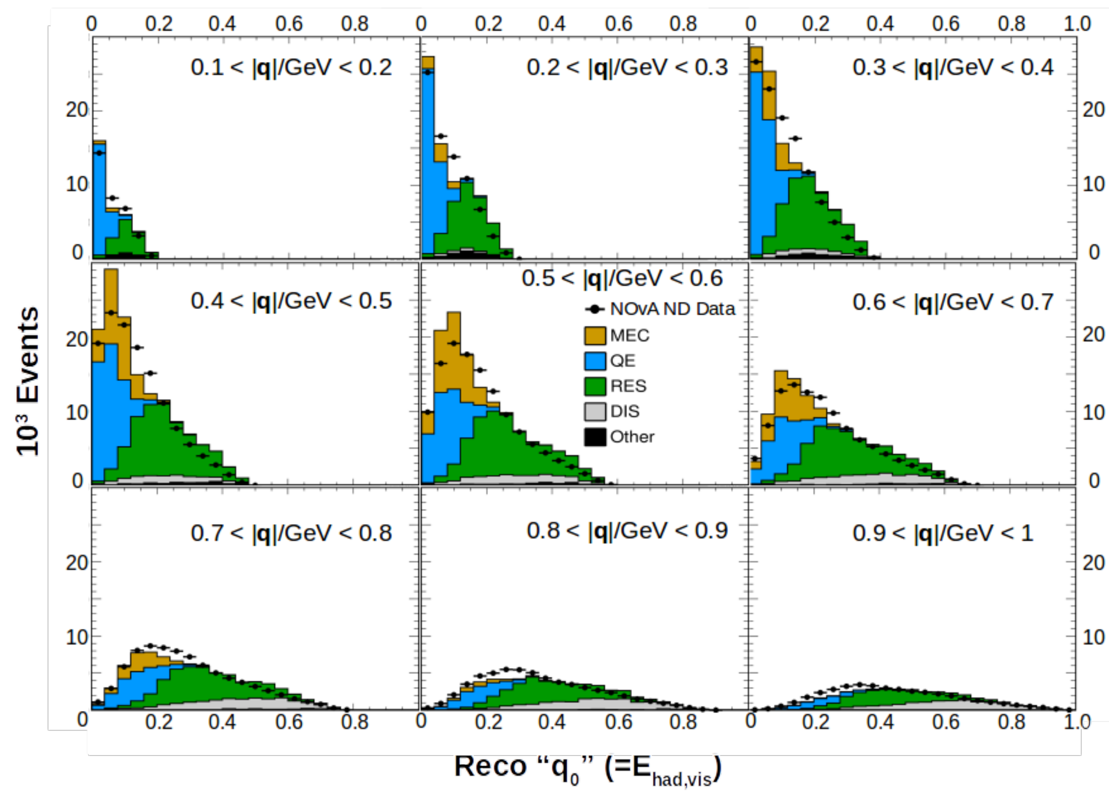


Tuning the GENIE Simulation

Hadronic energy distribution using the previous default GENIE configuration had significant mismatch with data



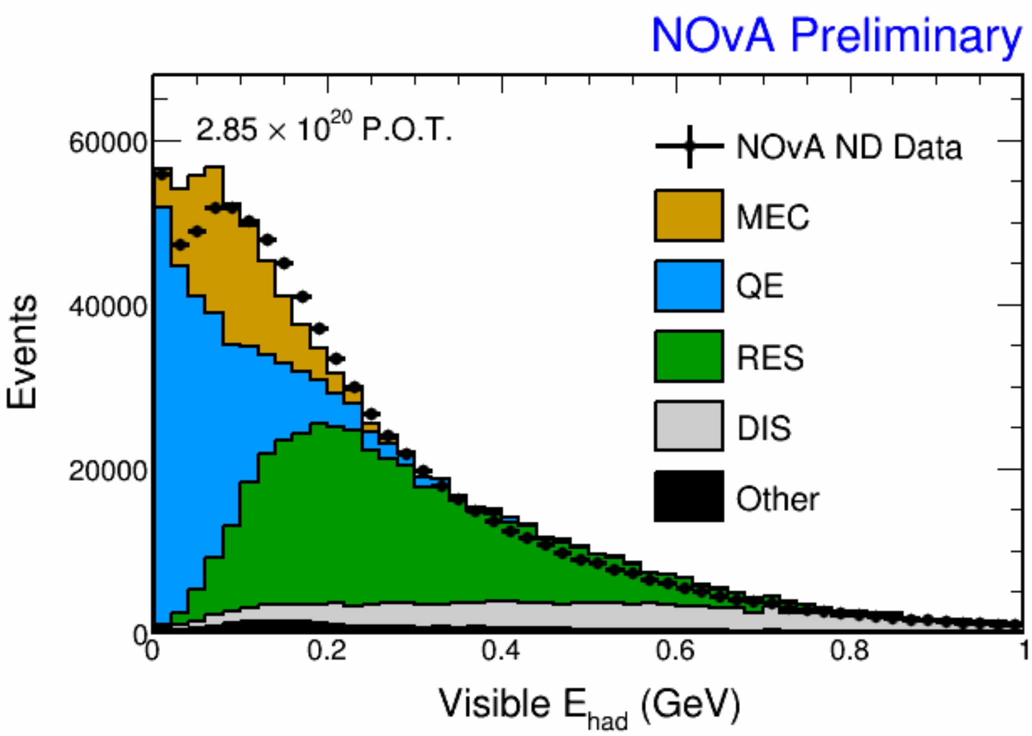
Weight multinuclear scattering to match observed excess in bins of $|q_3|$ and $|q_0|$

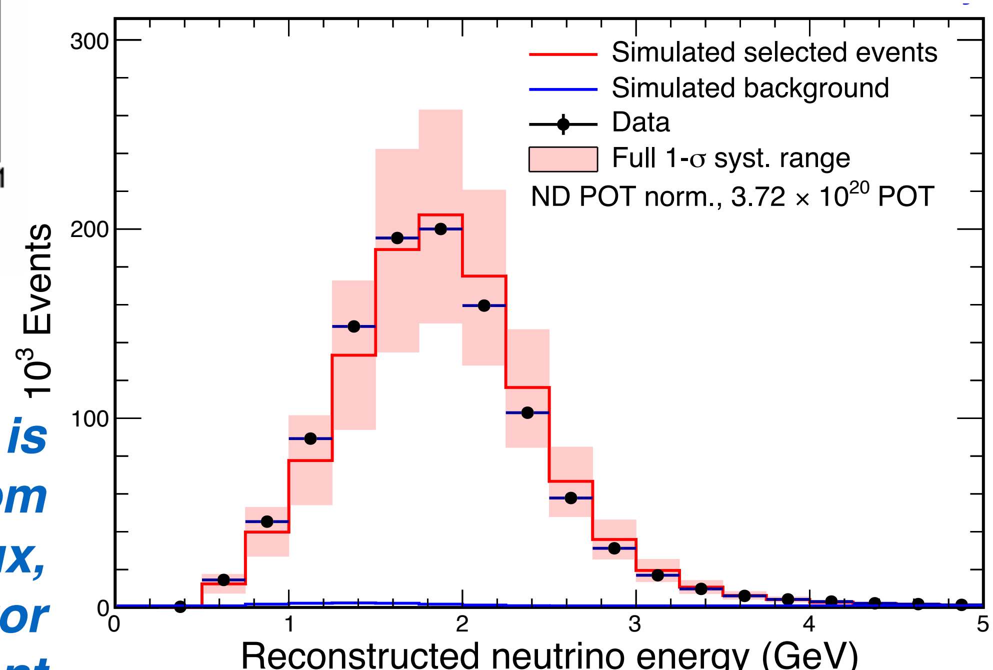


Motivated by recent observations*, we include optional empirical model in GENIE for scattering off correlated nucleon pairs, and rescale other components.

* Rodrigues *et al.* (MINERvA): Phys. Rev. Lett. **116**, 071802, etc.
Rodrigues, Wilkinson, McFarland: Eur Phys J C (2016) **76:** 474

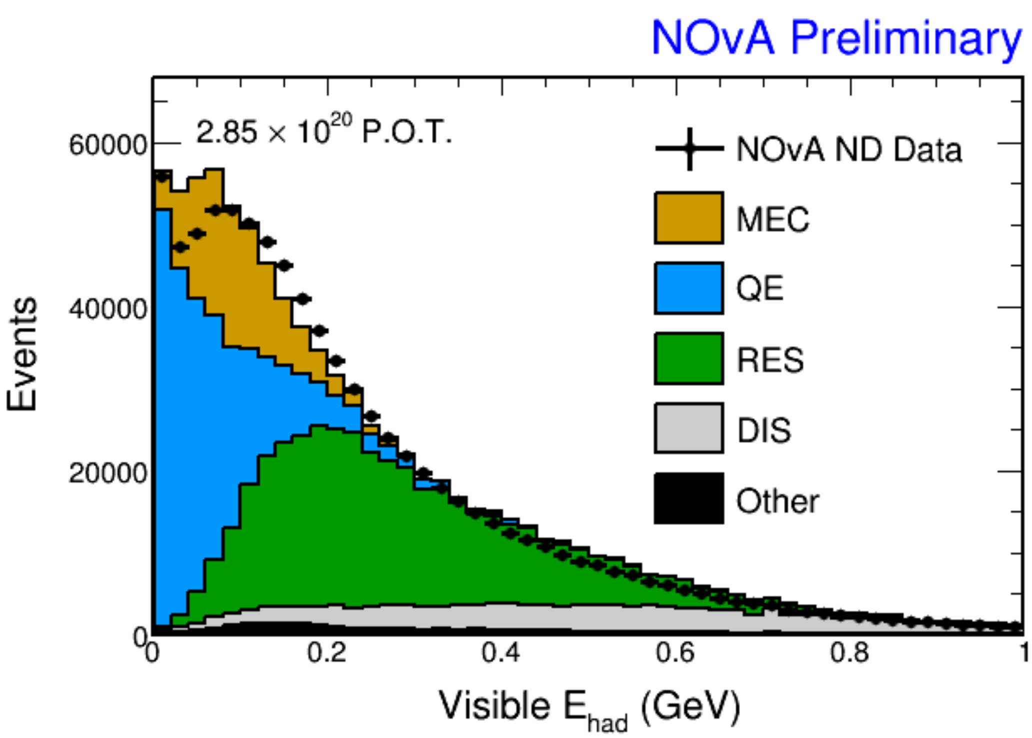
Tuned Simulation Compared to Near Detector Data

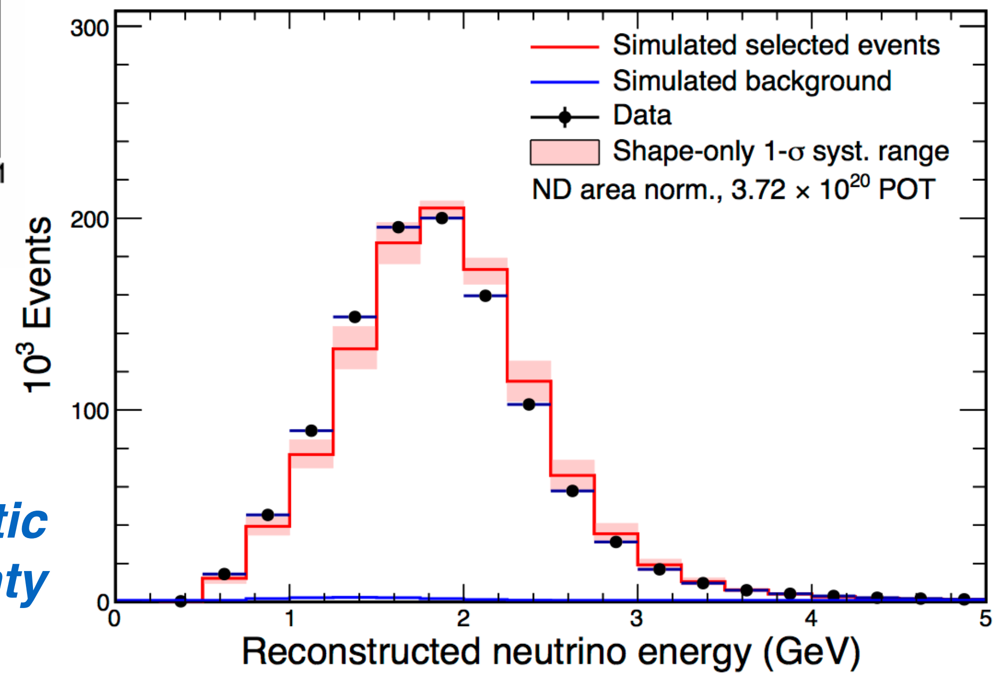




Most of the error band is normalization uncertainty from cross sections and beam flux, and cancels in two-detector measurement

Tuned Simulation Compared to Near Detector Data



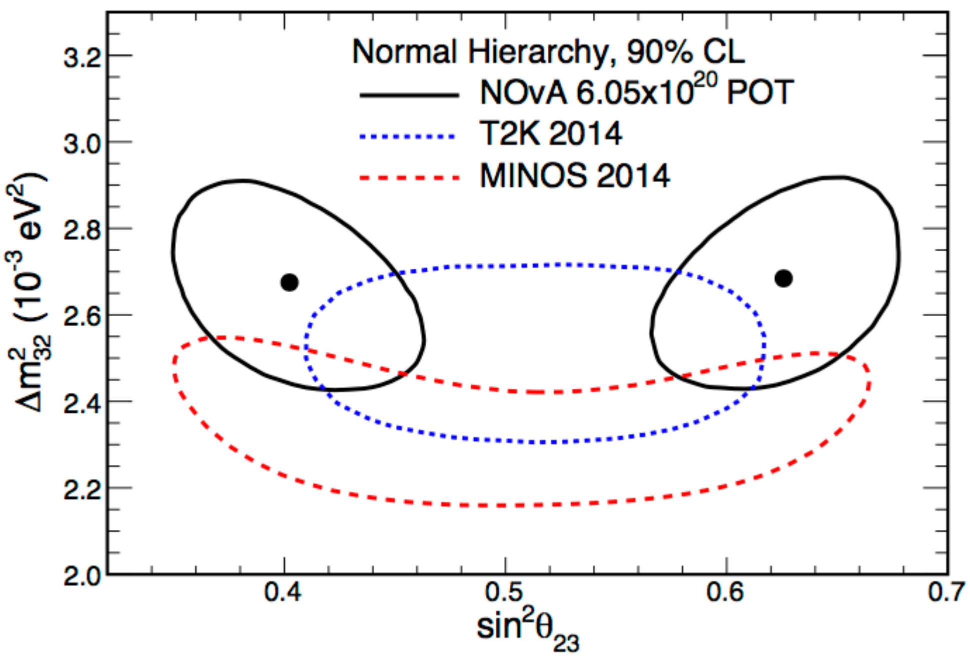


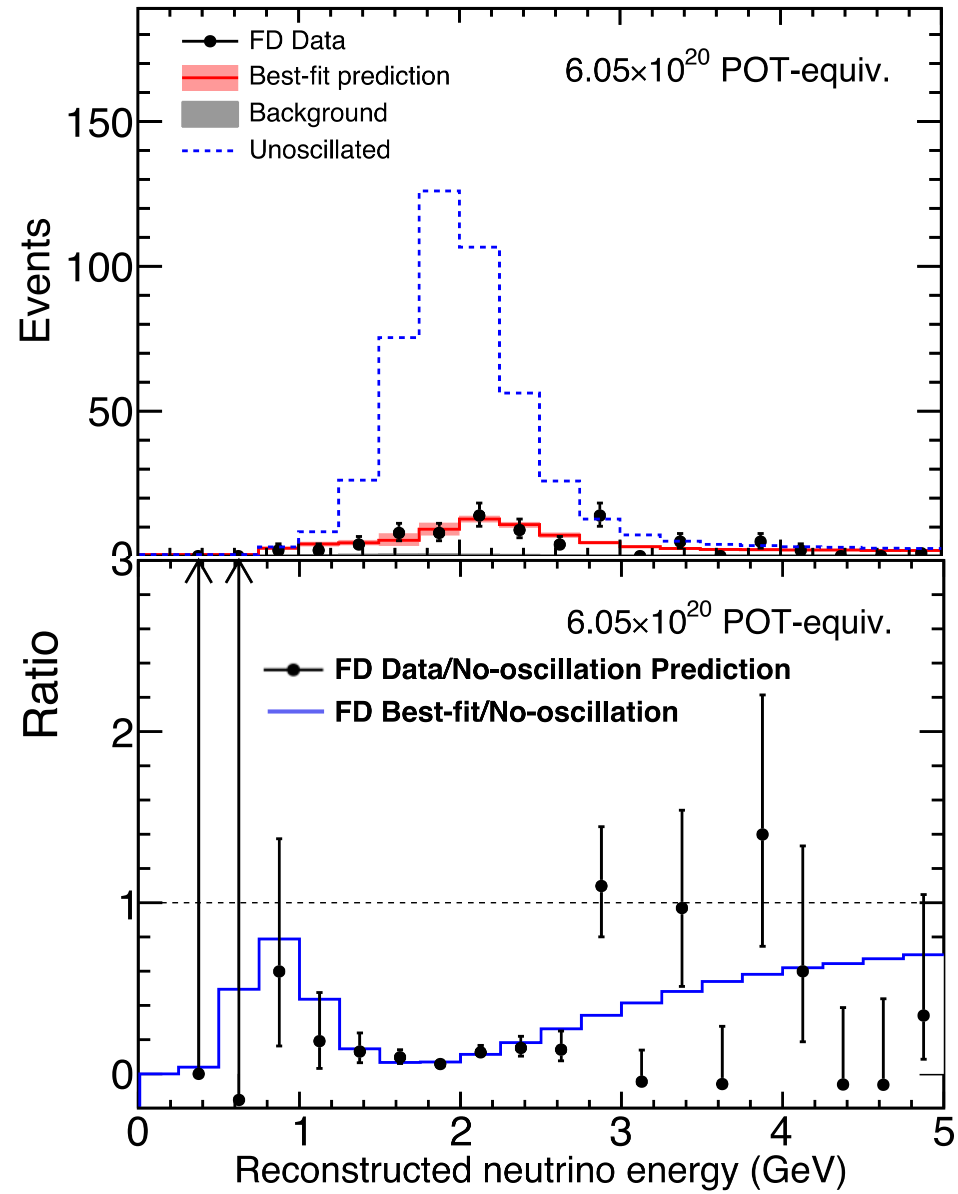
Shape-only systematic uncertainty

ν_μ Disappearance Result

- Most of the muon neutrino flux is absent at the Far Detector
  - Expect 473 ± 30 in absence of oscillations
  - Observe 78 events on background of 6.6
- However, the effect is not maximal
  - Maximal mixing (θ_{23}=45°) is disfavored at 2.6 σ

Best fit and contours assuming Normal Hierarchy





Systematic uncertainties on sin²(θ_{23}) (Δm^2) are currently ~80% (~50%) of statistical. Improvements are in progress.

Long Baseline $\nu_\mu \rightarrow \nu_e$ Appearance Probability

- $P(\nu_\mu \rightarrow \nu_e) \cong P_{Atm} + P_{\sin\delta} + P_{\cos\delta} + P_{Sol}$

DUNE Science Report and References

$$P_{Atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(A-1)\Delta]}{(A-1)^2}$$

$$P_{Sol} = \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2}$$

$$P_{\sin\delta} = \alpha 8 J_{CP} \sin\Delta \sin(A\Delta) \frac{\sin[(1-A)\Delta]}{A(1-A)}$$

$$P_{\cos\delta} = \alpha 8 J_{CP} \cot\delta_{CP} \cos\Delta \sin(A\Delta) \frac{\sin[(1-A)\Delta]}{A(1-A)}$$

Interference Terms

δ_{CP} and A change sign for $\bar{\nu}$
A depends explicitly on (sign of) Δm^2_{31}

$\Delta = \Delta m^2_{31} L/4E$

$A = \sqrt{2} G_F N_e 2E/\Delta m^2_{31}$

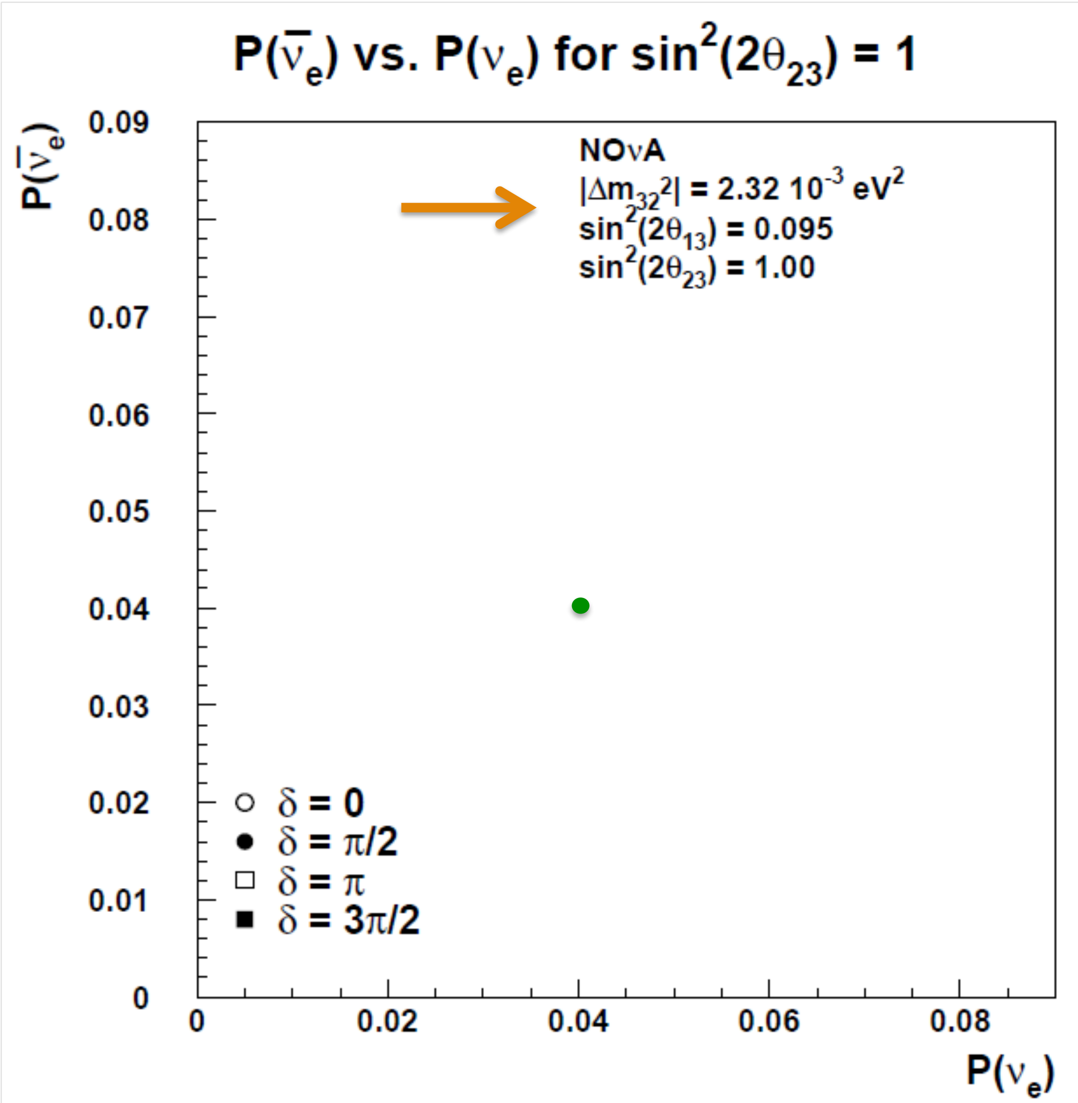
Matter Effect

$\alpha = |\Delta m^2_{21}|/|\Delta m^2_{31}|$

Jarlskog Invariant

$J_{CP} = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta_{CP}/8 \approx 0.03 \sin(\delta_{CP})$ - up to 1000x J(CKM)

ν_e and $\bar{\nu}_e$ Appearance Probabilities

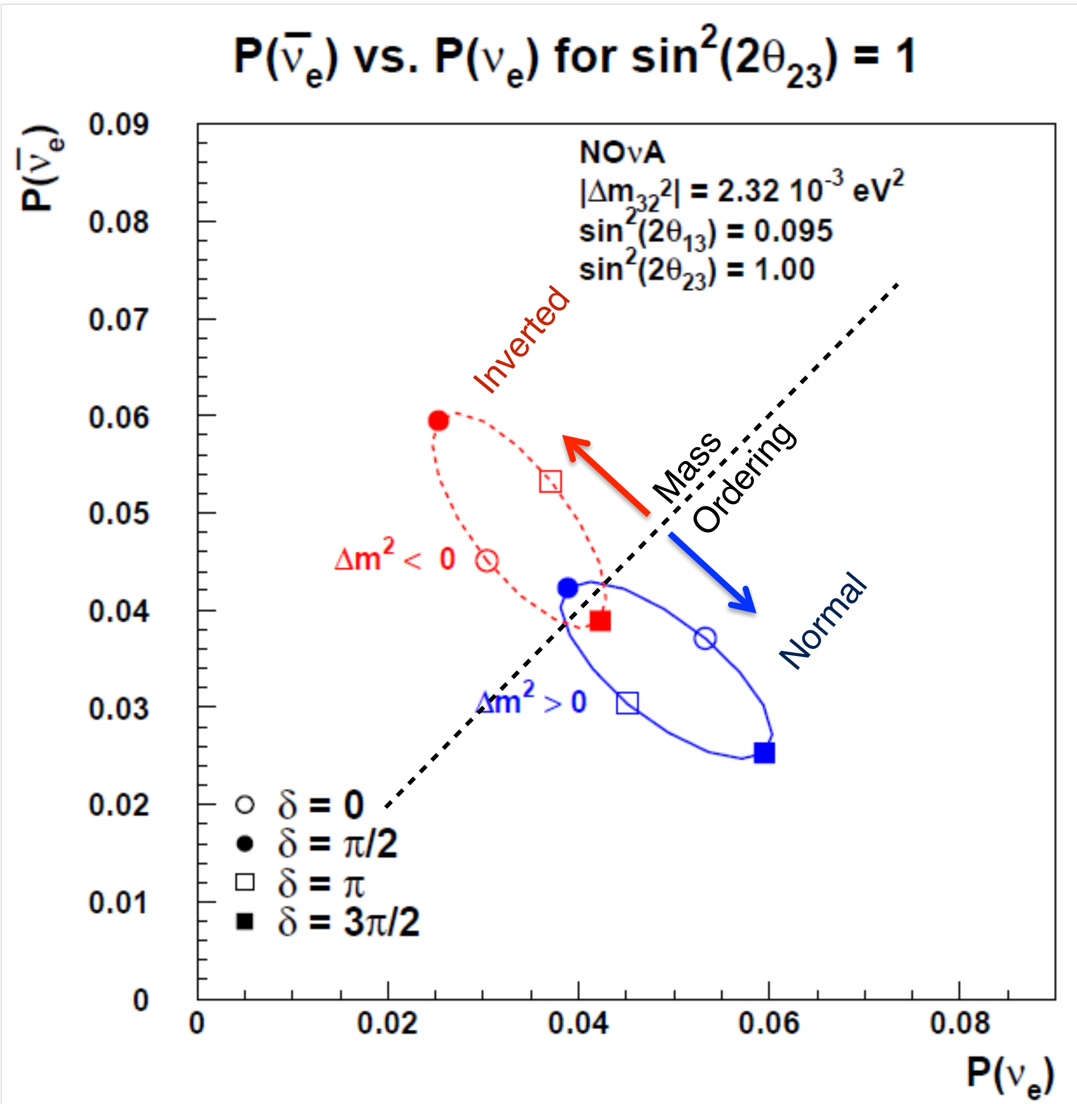


Comparison of neutrino and antineutrino appearance for a specific baseline and energy

Assuming

- **No Matter Effect**
- **No CP Violation**
- **Maximal μ-τ mixing**

CP Violation and Neutrino Mass Ordering

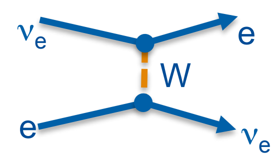


CP Violation

- *CPT theorem requires ν_μ and $\overline{\nu_\mu}$ disappearance to be equal in vacuum*
- ν_e appearance probabilities vary on an ellipse with δ_{CP}

Mass Ordering

- *ν_μ disappearance largely sensitive to $|\Delta m^2|$*
- ν_e appearance is sensitive to sign(Δm^2) via matter effect
  - due to presence of electrons in matter

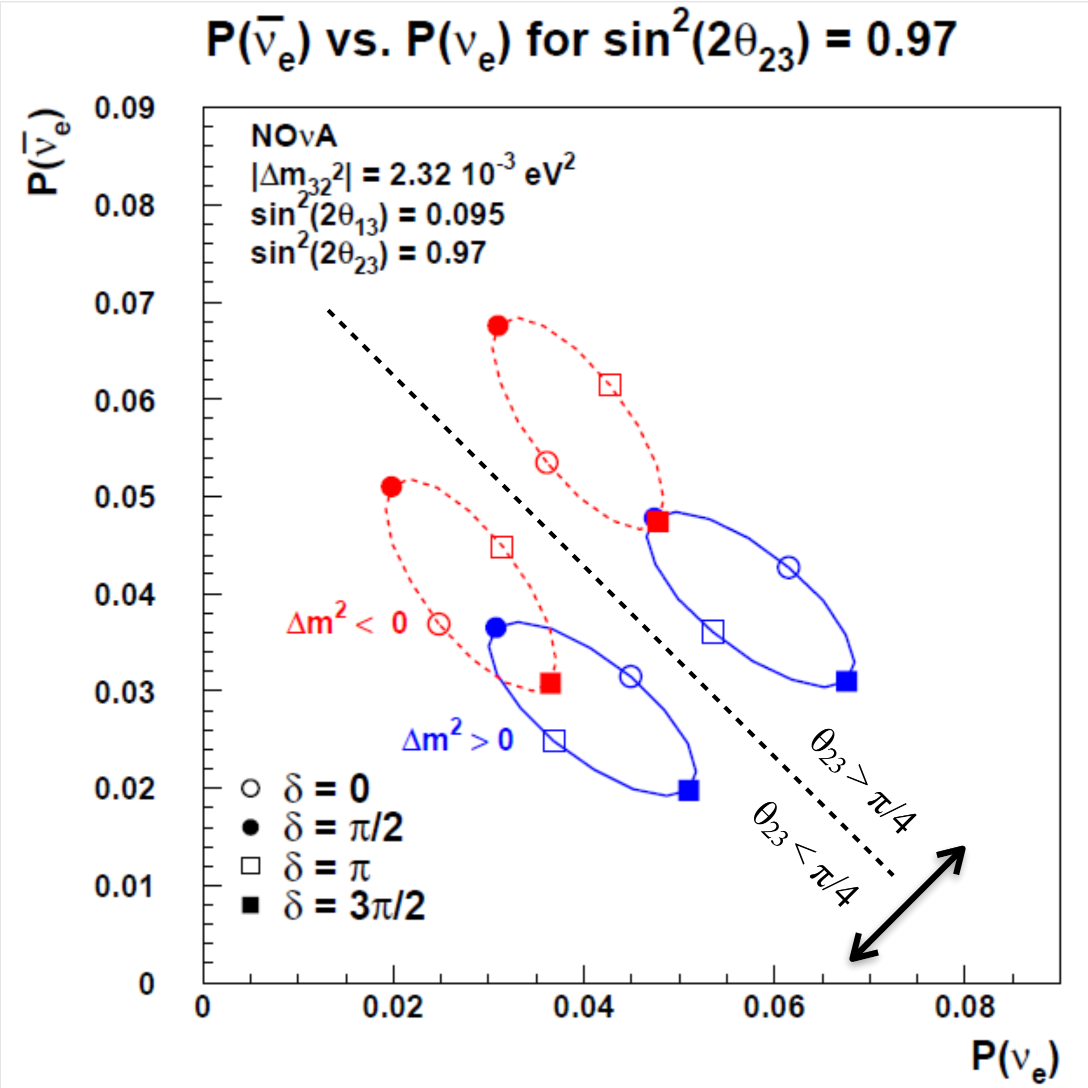


$\sqrt{2} G_F N_e 2E/\Delta m^2_{31}$

- ~30% effect for NOvA baseline, 11% for T2K

Shown for maximal θ_{23}

θ_{23} Octant

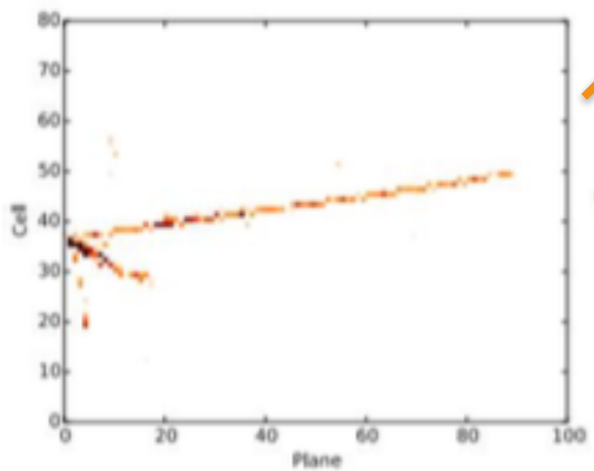


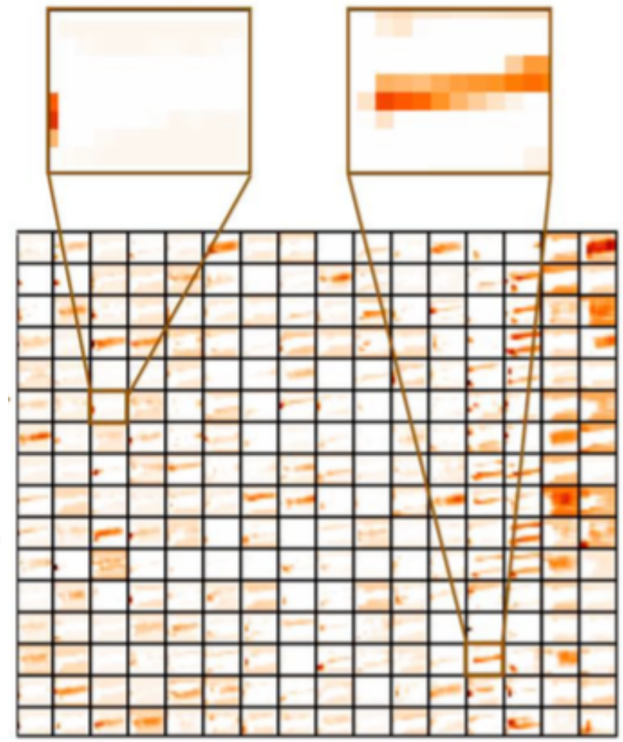
ν_μ disappearance measures $\sin^2(2\theta_{23})$

ν_e appearance depends in leading order on $\sin^2(\theta_{23})$

ν_e Appearance Analysis - Event Selection

- Computer vision-based deep learning algorithm for identification of ν_e charged-current events
  - Convolutional Neural Net - CNN
  - Development of “Feature Maps” is part of the training





Feature Maps at an early convolutional layer

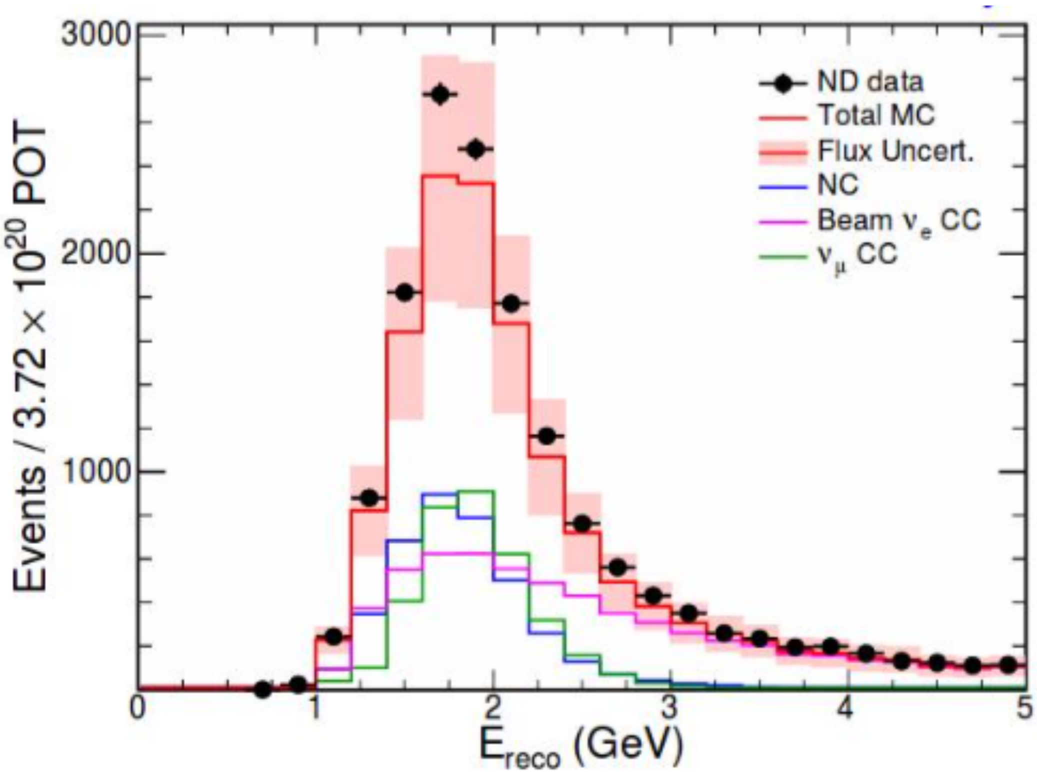
- NOvA version - CVN
  - Based on GoogLeNet
  - Led to improvement for NOvA 2016 analysis equivalent to 30% increase in exposure

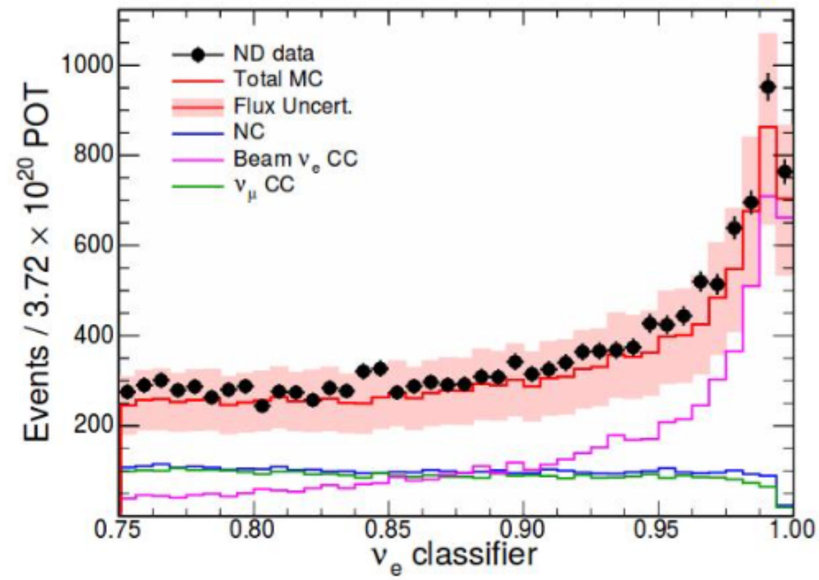
“A Convolutional Neural Network Neutrino Event Classifier”

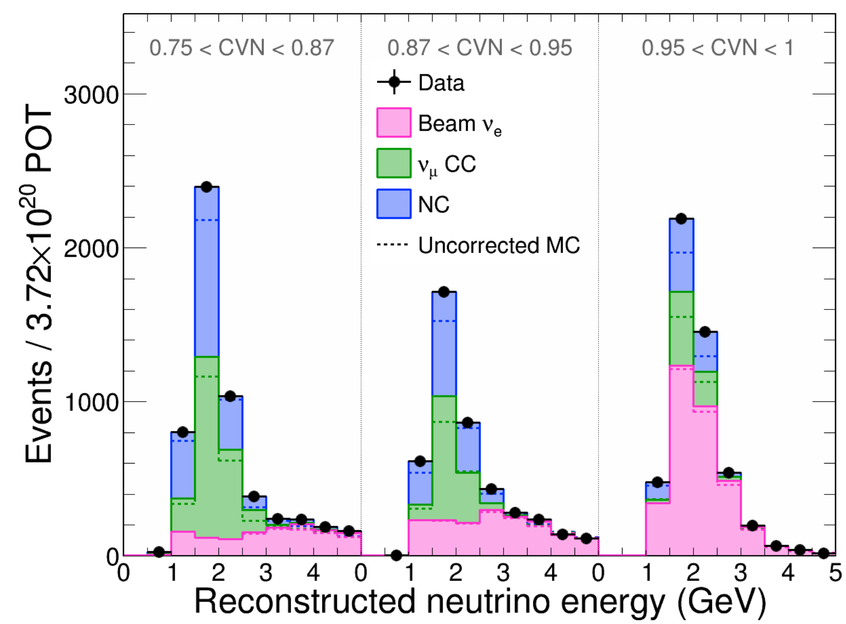
2016 JINST 11 P09001

ν_e in the Near Detector

- Comparison of simulated and observed ν_e CC candidate spectra in Near Detector

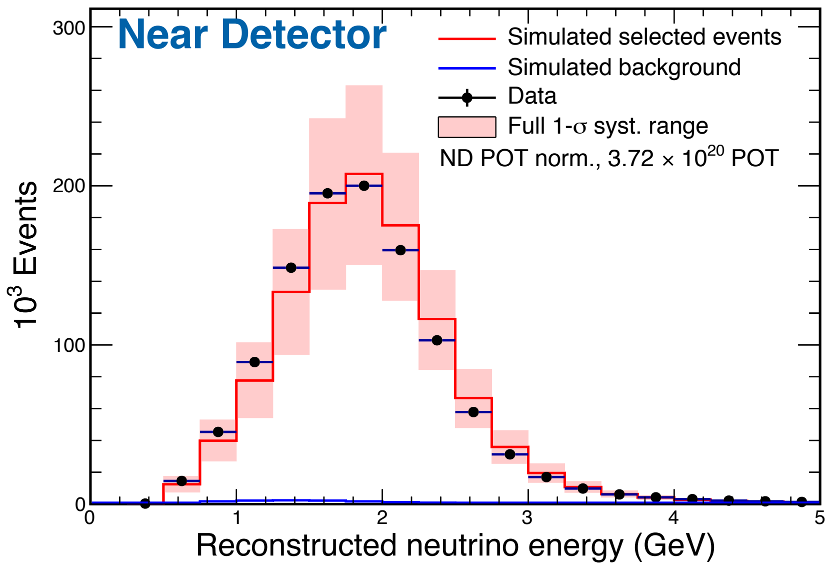




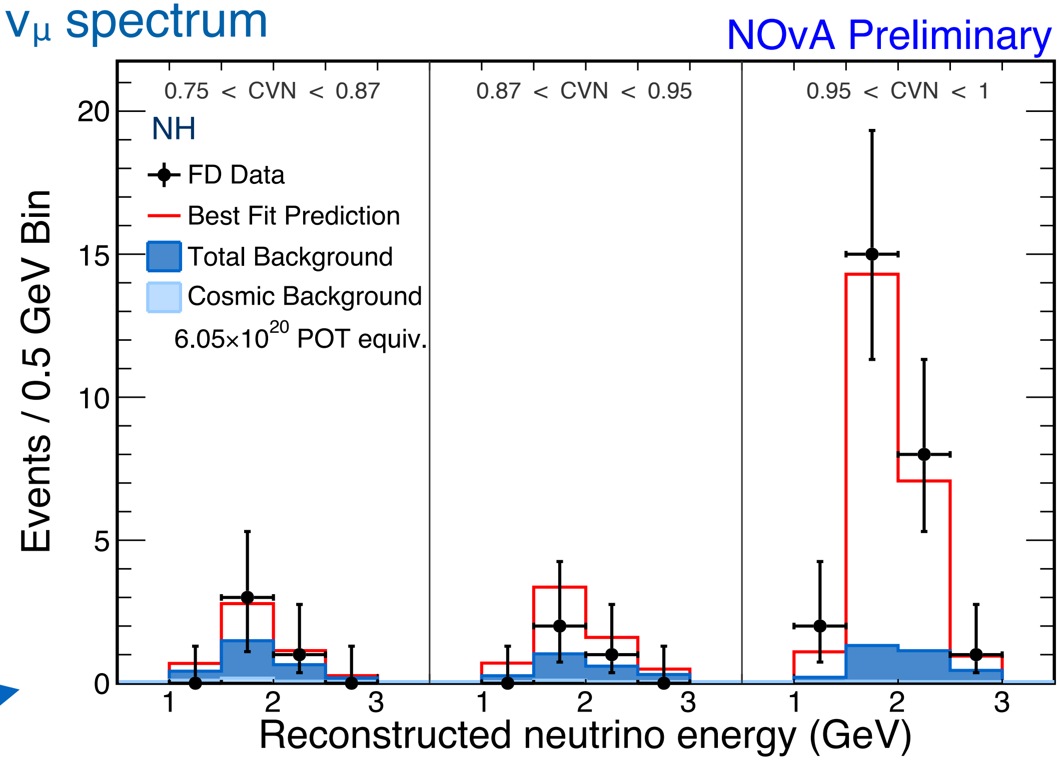


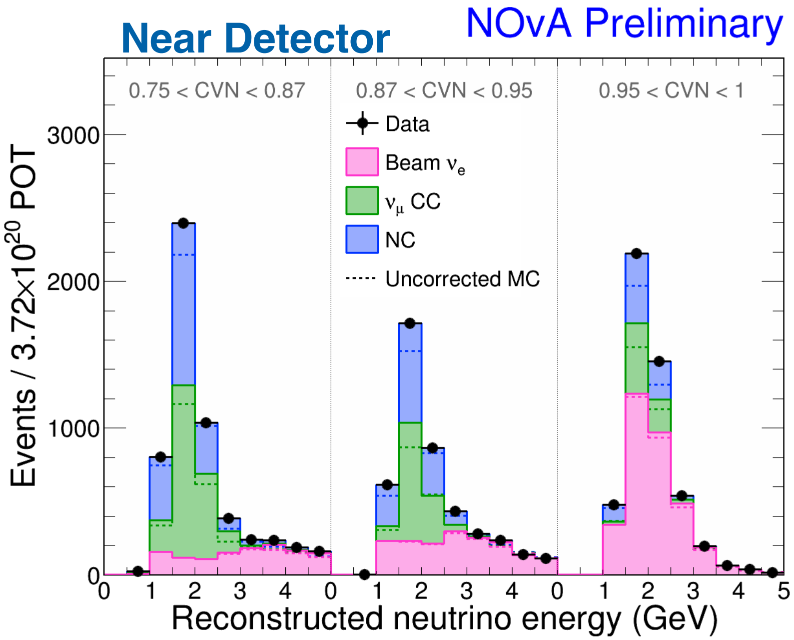
- Adjust simulation for Near Detector based on
  - GENIE tune used for ν_μ CC analysis
  - ν_μ CC - based tune of pions and kaons for ν_e
  - Michel electron templates for ν_μ, NC

Predicting ν_e at the Far Detector



Signal:
Oscillate ν_μ spectrum

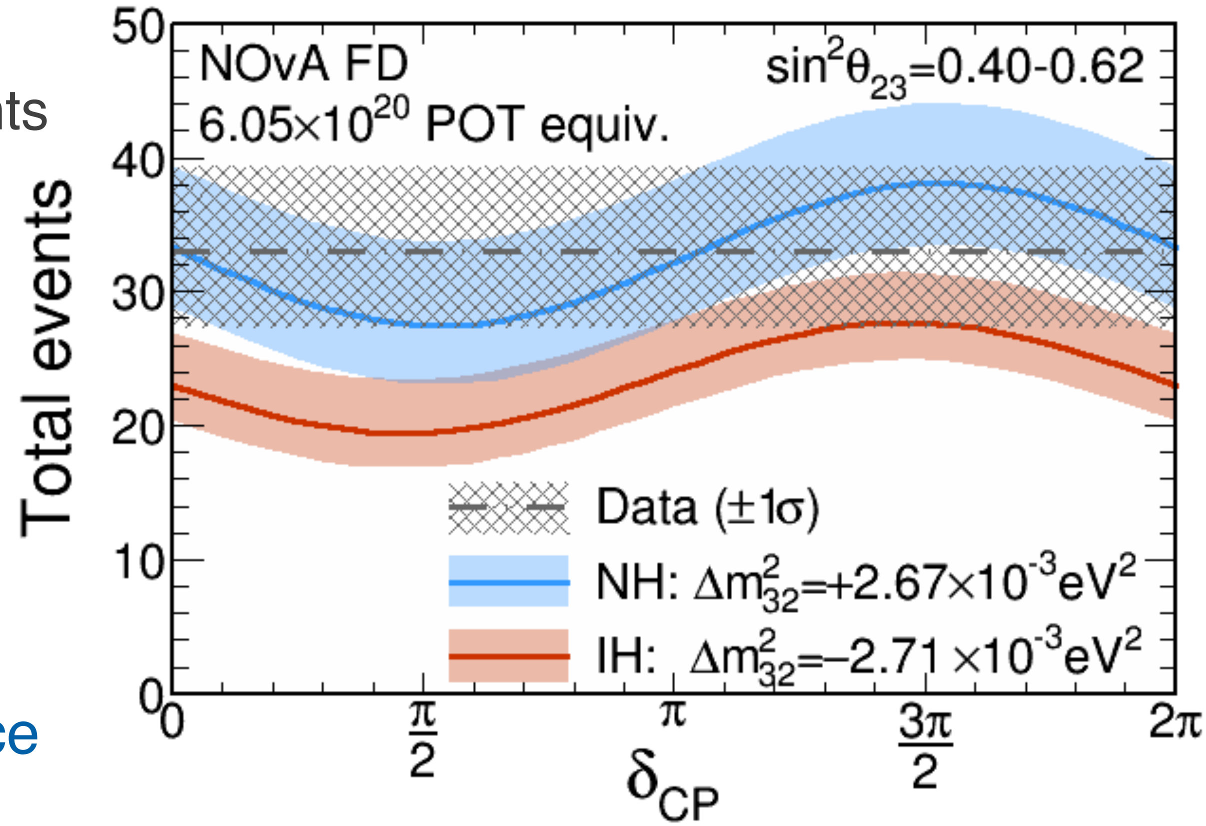




Background:
Oscillate ν_μ & beam ν_e
background spectra
Propagate NC background

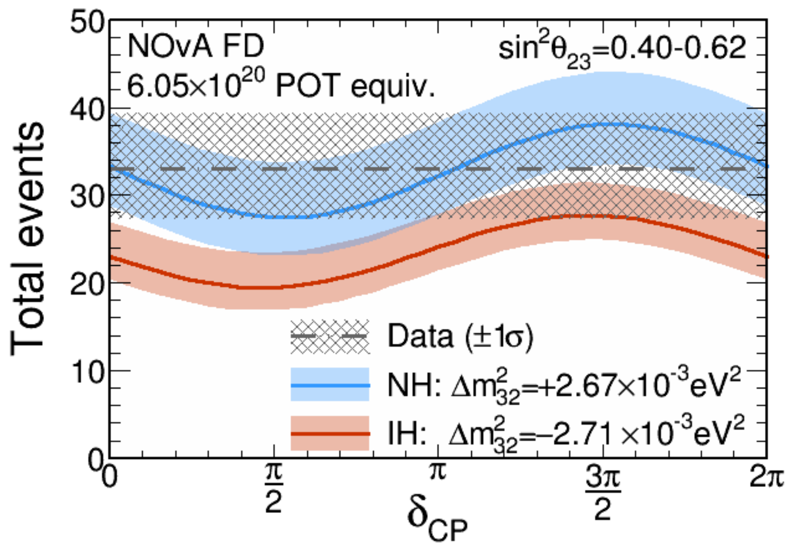
ν_e Appearance Results

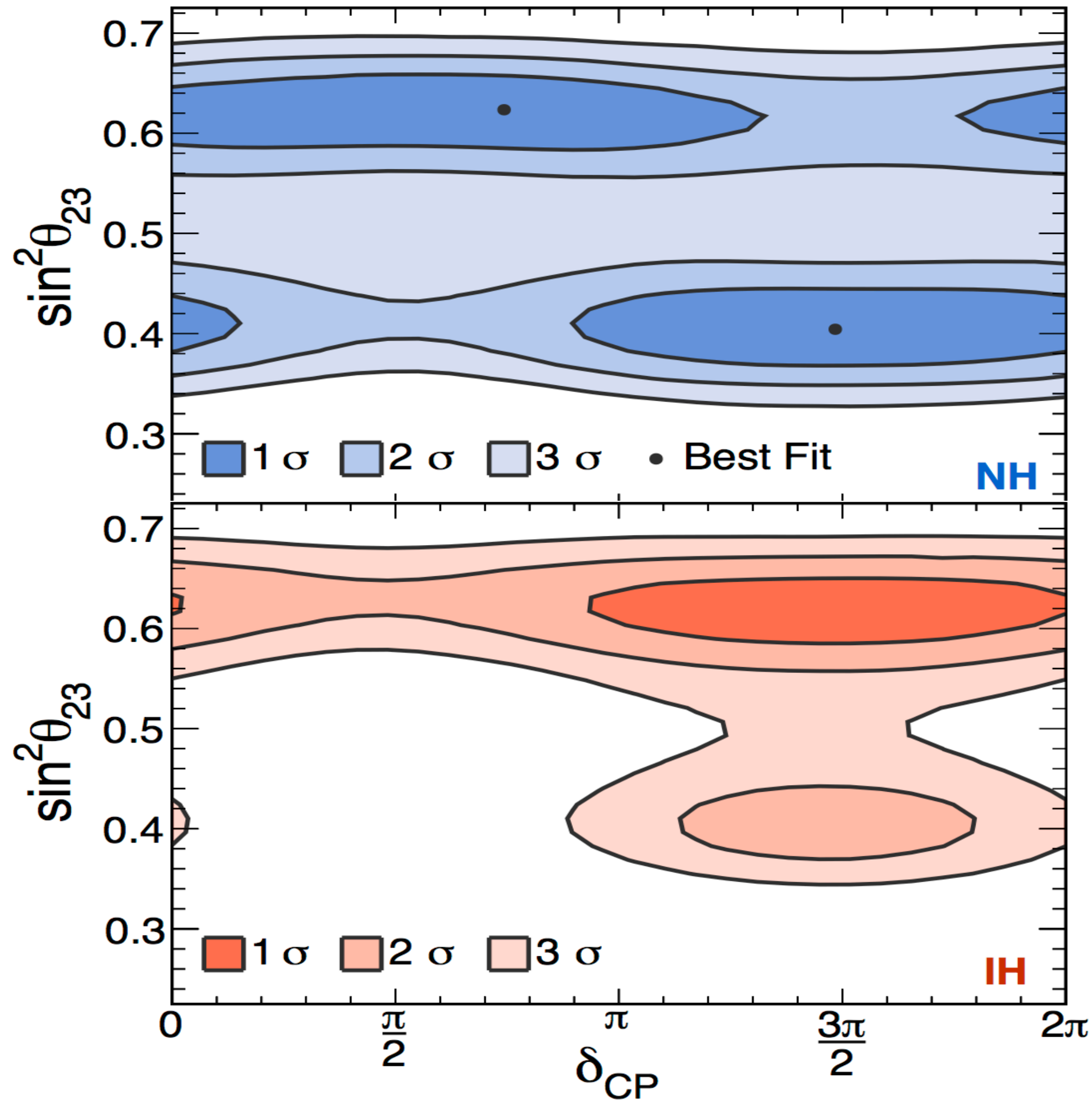
- 33 ν_e candidate events observed at Far Detector
  - expected background of 8 events
  - Systematic uncertainties are small compared to statistical
- Far Detector ν_e prediction
  - In addition to Mass Hierarchy, phase δ_{CP}, and value of θ_{23}, appearance probability depends strongly on θ_{13}
    - Use reactor ν_e disappearance measurements for θ_{13}



ν_e Appearance Results

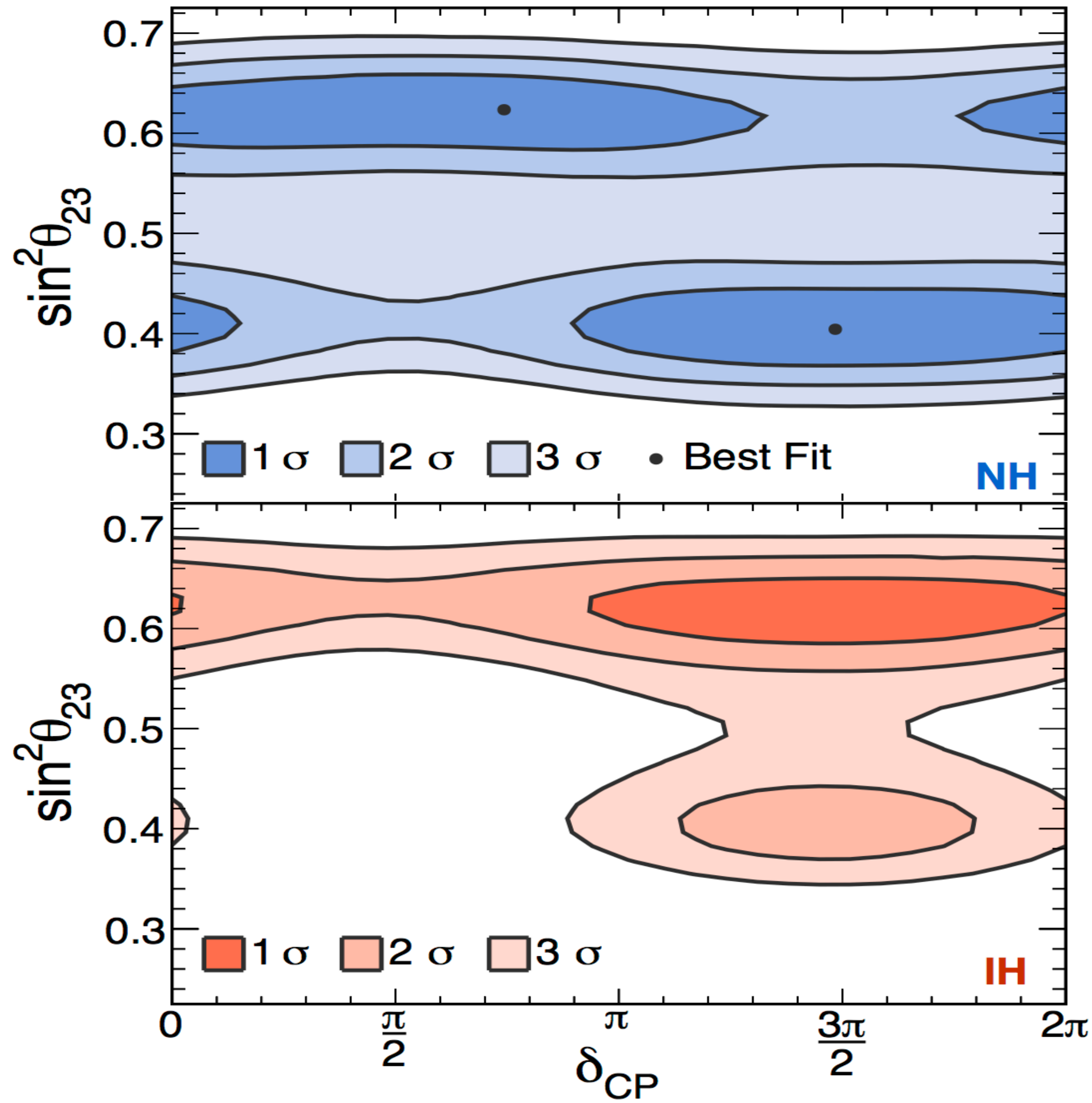
- Combine with ν_μ disappearance result to better constraint Mass Hierarchy, δ_{CP}, θ_{23}
  - Fit ν_e in bins of E_ν and selection parameter
  - Two effectively degenerate best fits, Normal Hierarchy





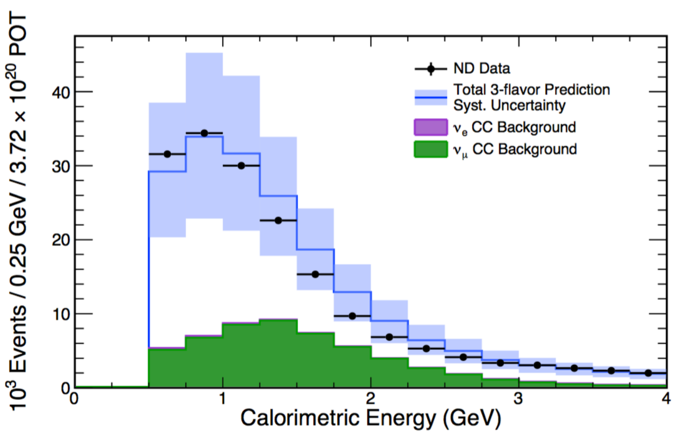
ν_e Appearance Results

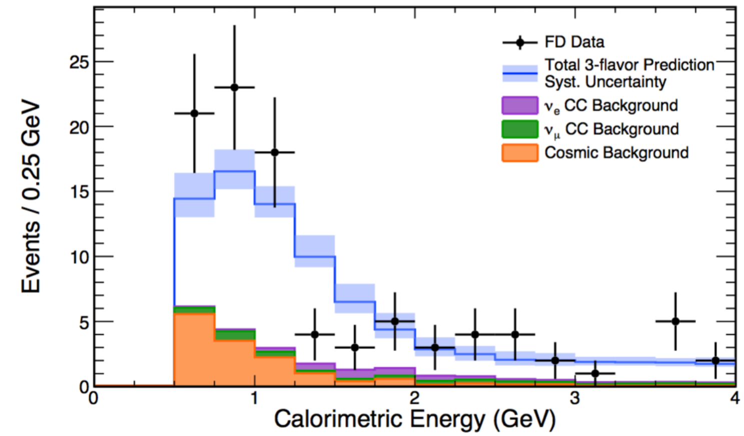
- Combine with ν_μ disappearance result to better constraint Mass Hierarchy, δ_{CP}, θ_{23}
  - Fit ν_e in bins of E_ν and selection parameter
  - Two effectively degenerate best fits, Normal Hierarchy
  - Lower octant in Inverted Hierarchy disfavored at 93% CL for all δ_{CP}
  - Large region of parameter space disfavored at 3 σ for Inverted Hierarchy



Sterile Neutrino Searches

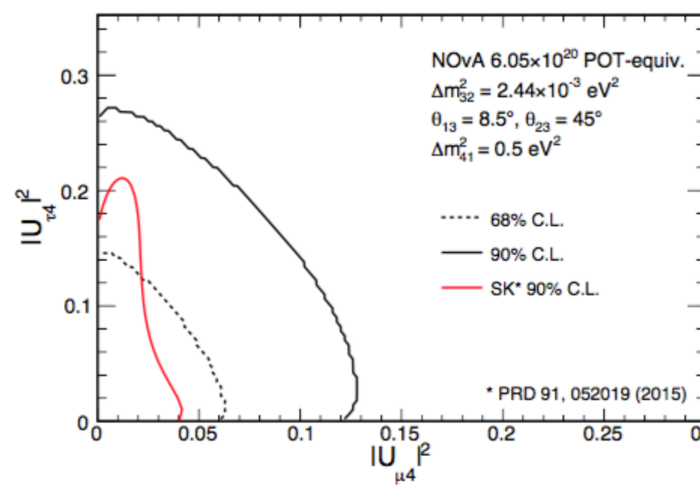
- Short-baseline
  - combined ν_μ disappearance and ν_e appearance in Near Detector
  - ν_τ appearance in Near Detector
- Long-baseline Neutral-Current Disappearance
  - Flavor-independent - 3-flavor oscillations are not in play
  - CVN NC classifier to select NC sample
    - main feature is lack of prominent lepton
  - Simple counting analysis
    - Predict Far Detector NC rate based on Near Detector observation





Predict 83.5 events (23 background)

Observe 95

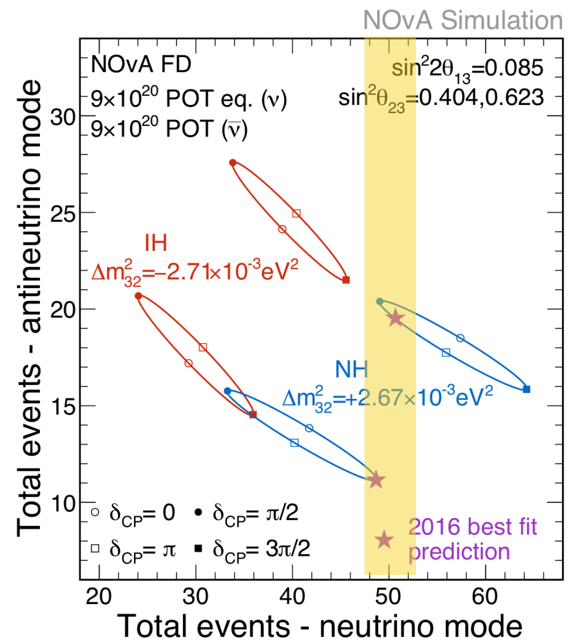


  - Constrain 3+1 mixing parameters based on rate
    - Valid for 0.05 eV^2 < Δm^2_{41} < 0.5 eV^2

Antineutrinos

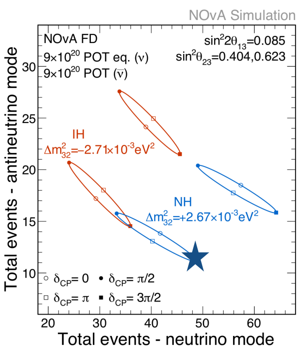
- NOvA expects 18x10[20] protons-on-target by summer 2018
- NuMI beam switched to antineutrino mode in February, and will continue with antineutrinos to summer 2018
  - NOvA will maintain ~50/50 split henceforth on yearly basis
- At our current best fit, continued neutrino-mode running alone will not be sufficient to resolve remaining degeneracies
- Antineutrinos will be key to resolving this ambiguities

Projected ν_e event counts by summer 2018



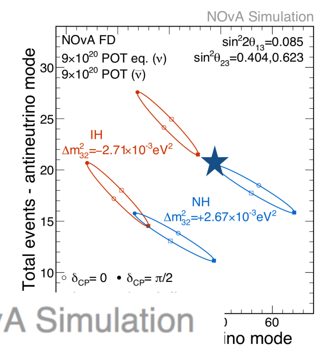
NOvA Physics Reach

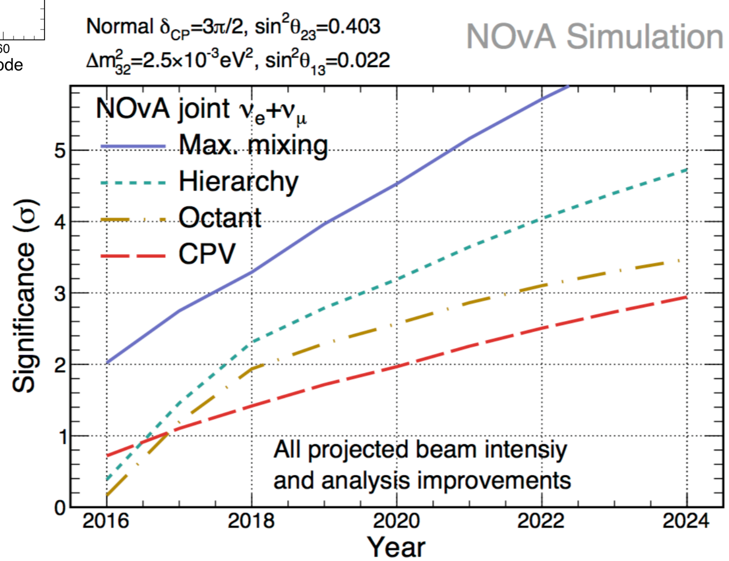
- NOVA expects to be able to run until 2024 - typically 40 weeks/year
- Fermilab is investigating increasing NuMI beam power to 900 - 1000 kW
  - PIP-1+ - 800 kW in 2019, 900 kW in 2021
- We are investigating redesign of the NuMI target to increase neutrino flux per proton delivered
- We anticipate efficiency improvements to our analysis

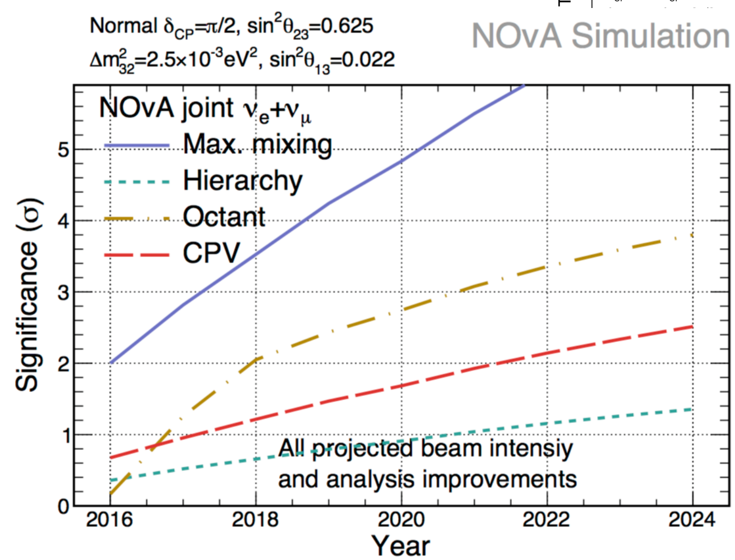


NOvA Reach with the above improvements

equivalent to 16 times exposure of results presented today







Summary

- NOvA has been designed and built to study most of the key remaining questions in the physics of neutrino masses and mixing
- NuMI beam recently reached full design power of 700 kW
- First major anti-neutrino run is now in progress
- Current results based on 6×10^{20} protons-on-target (neutrino-mode only)
  - In muon neutrino disappearance, maximal θ_{23} disfavored at 2.6 σ
  - In electron neutrino appearance, significant part of θ_{23} - δ_{CP} space disfavored at 3 σ in Inverted Hierarchy
- We expect updates with 50% more neutrino-mode data soon
- We are aiming for first antineutrino results in summer 2018

- NOvA is aiming at improvements to extend its original planned reach by a more than a factor of two in effective exposure

- **Much more data to come**

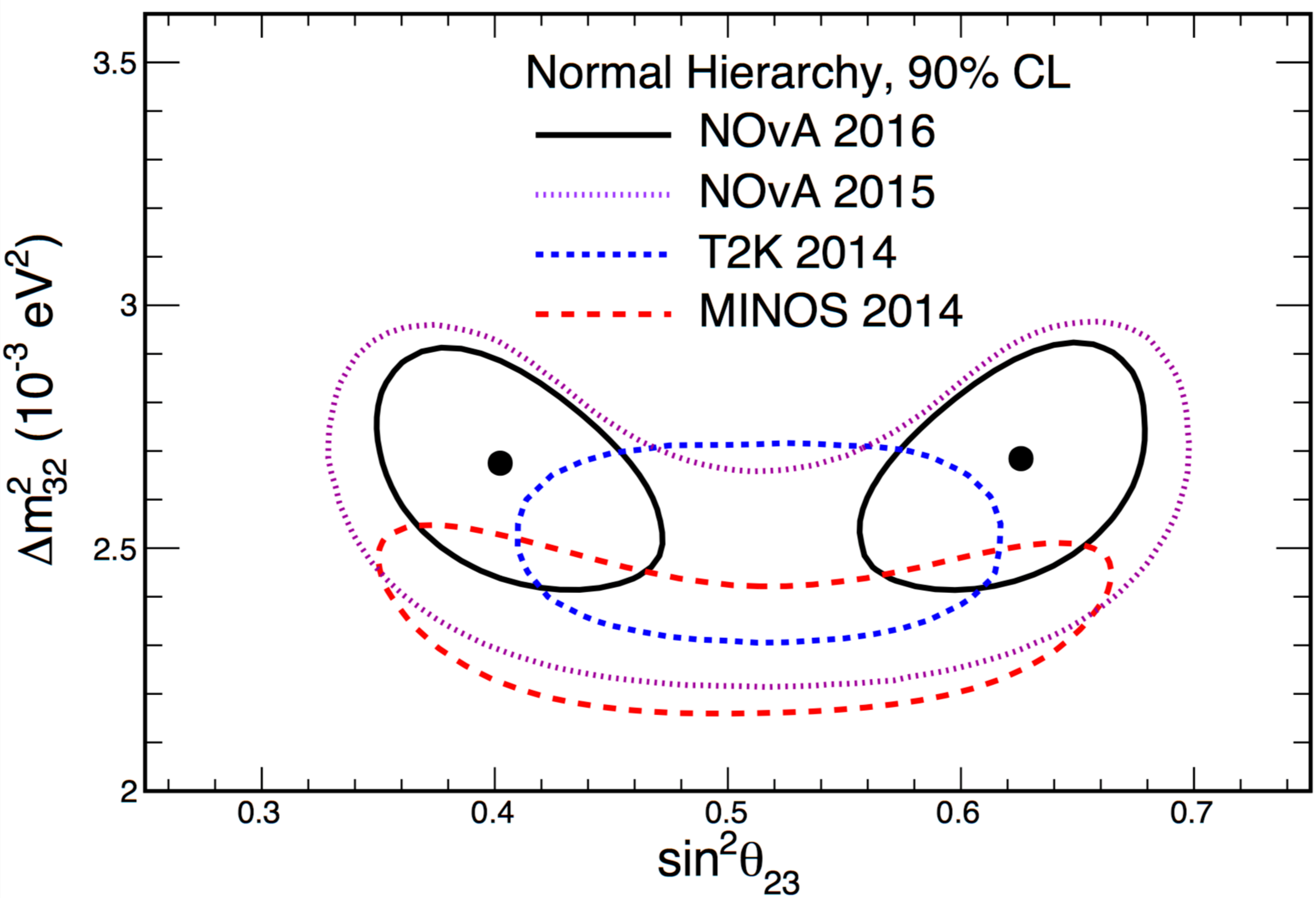

Fermilab

Supplemental Material

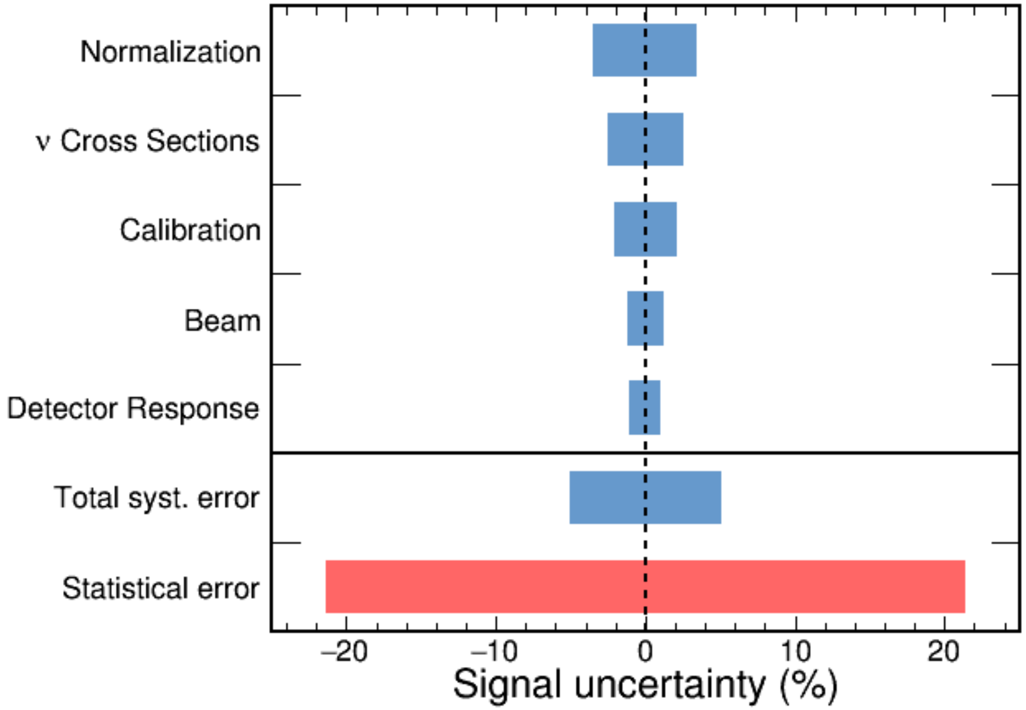
ν_μ Systematic Uncertainties

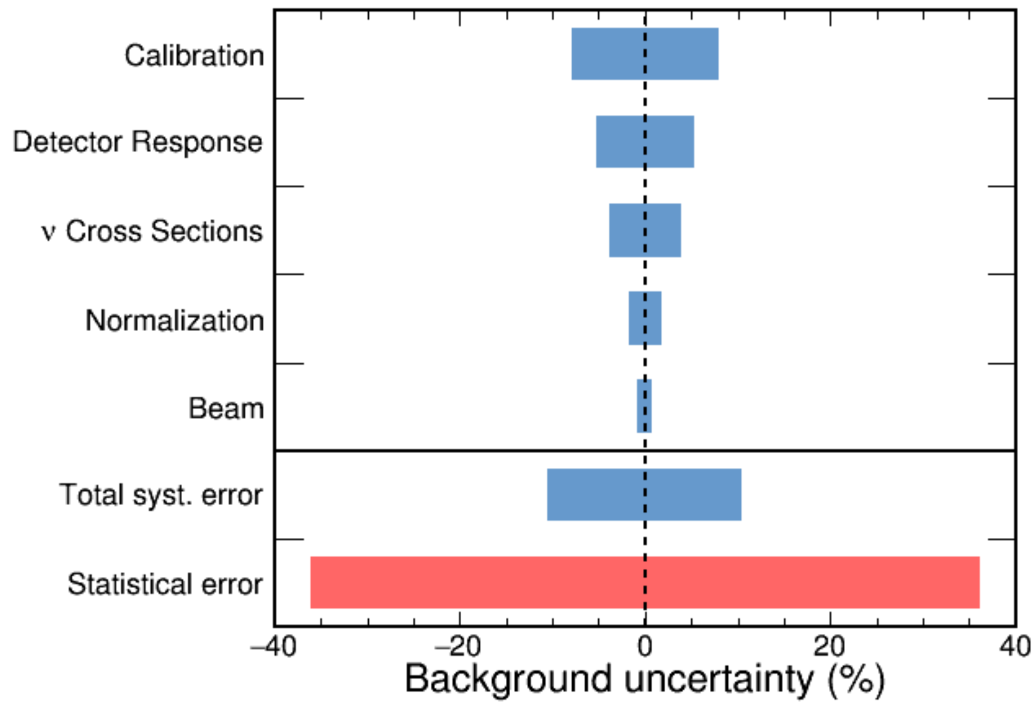
Source of uncertainty	Uncertainty in $\sin^2\theta_{23} (\times 10^{-3})$	Uncertainty in Δm^2_{32} $(\times 10^{-6}\ \mathrm{eV}^2)$
Absolute muon energy scale [±2%]	+9 / -8	+3 / -10
Relative muon energy scale [±2%]	+9 / -9	+23 / -14
Absolute hadronic energy scale [±5%]	+5 / -5	+7 / -3
Relative hadronic energy scale [±5%]	+10 / -11	+29 / -19
Normalization [±5%]	+5 / -5	+4 / -8
Cross sections and final-state interactions	+3 / -3	+12 / -15
Neutrino flux	+1 / -2	+4 / -7
Beam background normalization [±100%]	+3 / -6	+10 / -16
Scintillation model	+4 / -3	+2 / -5
δ_{CP} $(0 - 2\pi)$	+0.2 / -0.3	+10 / -9
Total systematic uncertainty	+17 / -19	+50 / -47
Statistical uncertainty	+21 / -23	+93 / -99

Comparison to First NOvA Result



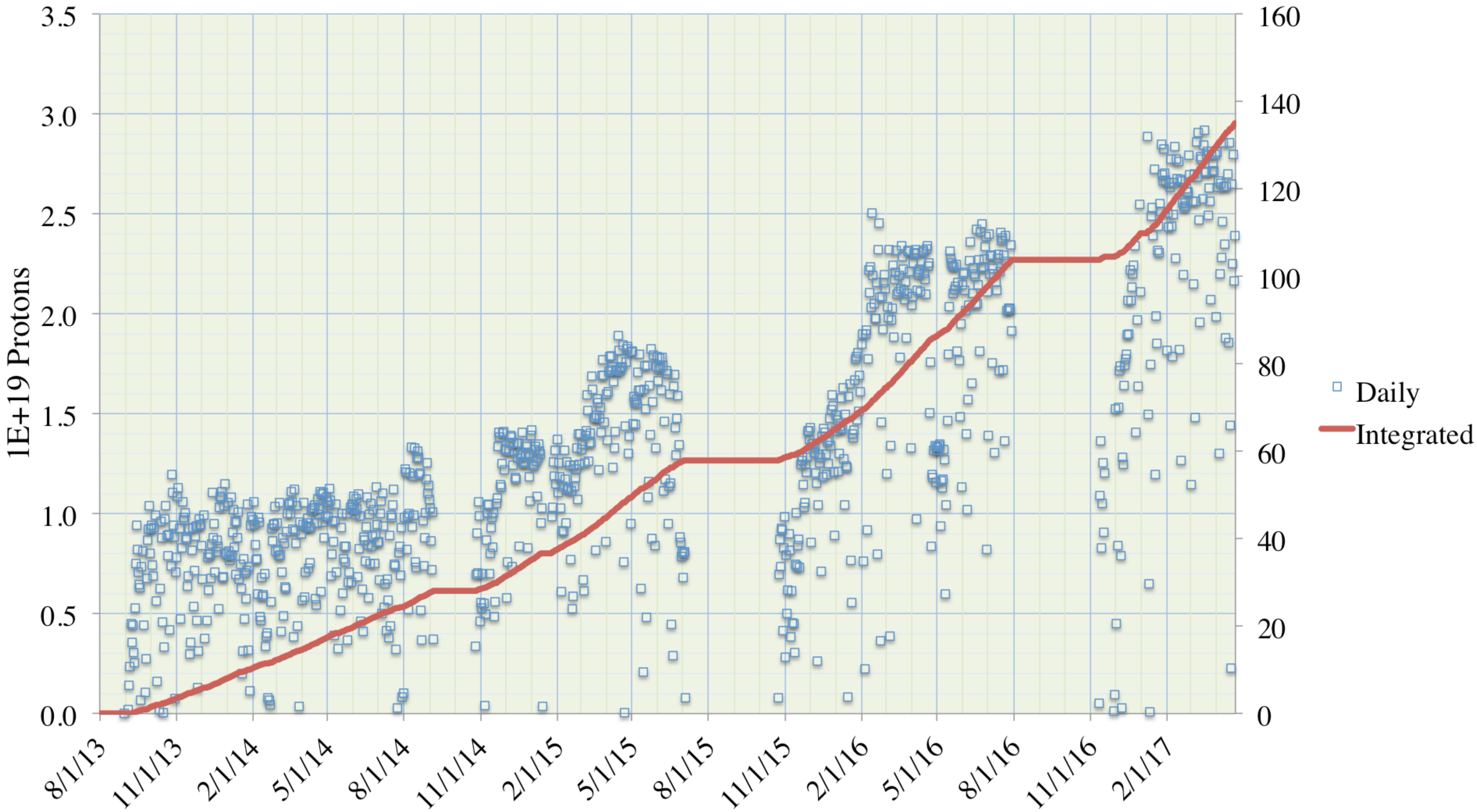
ν_e Systematic Uncertainties





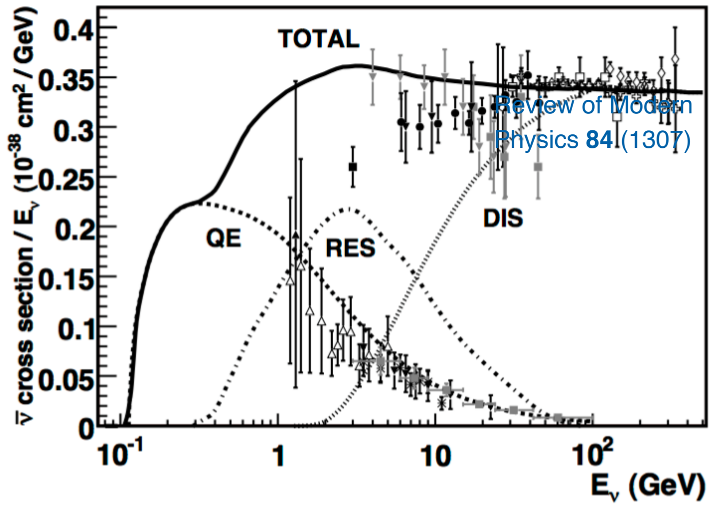
NuMI Performance

- Protons delivered to the NuMI target when Far Detector live
  - Routine 700+kW (minus 10% tax for other experiments) running achieved in January 2017

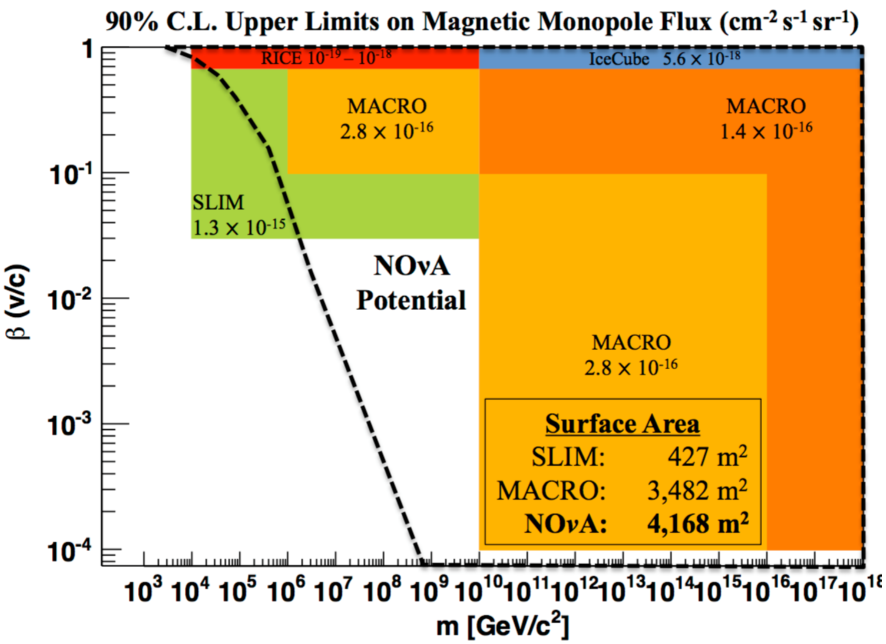


Other NOvA Physics Topics

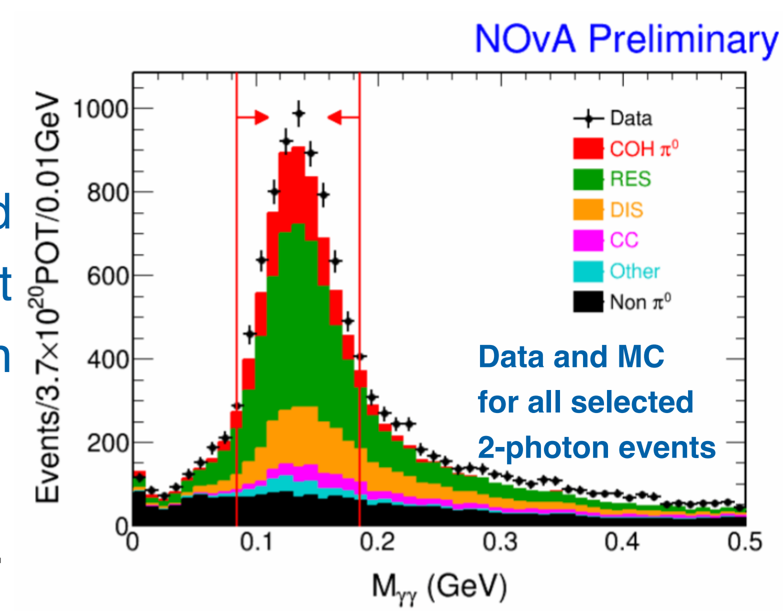
- Neutrino interaction physics in the Near Detector - Advantages for NOvA
  - Intense NuMI beam - high statistics
  - Narrow-band beam due to off-axis location
  - Interesting 1-3 GeV energy region not well covered by other experiments, especially in $\bar{\nu}$



- Fast magnetic monopoles
  - Substantial β-m range accessible to NOvA



ν-induced coherent π⁰ production



- Other topics: Supernova Neutrinos, Dark Matter