Status of the NOvA Experiment

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FOR THE NOVA COLLABORATION

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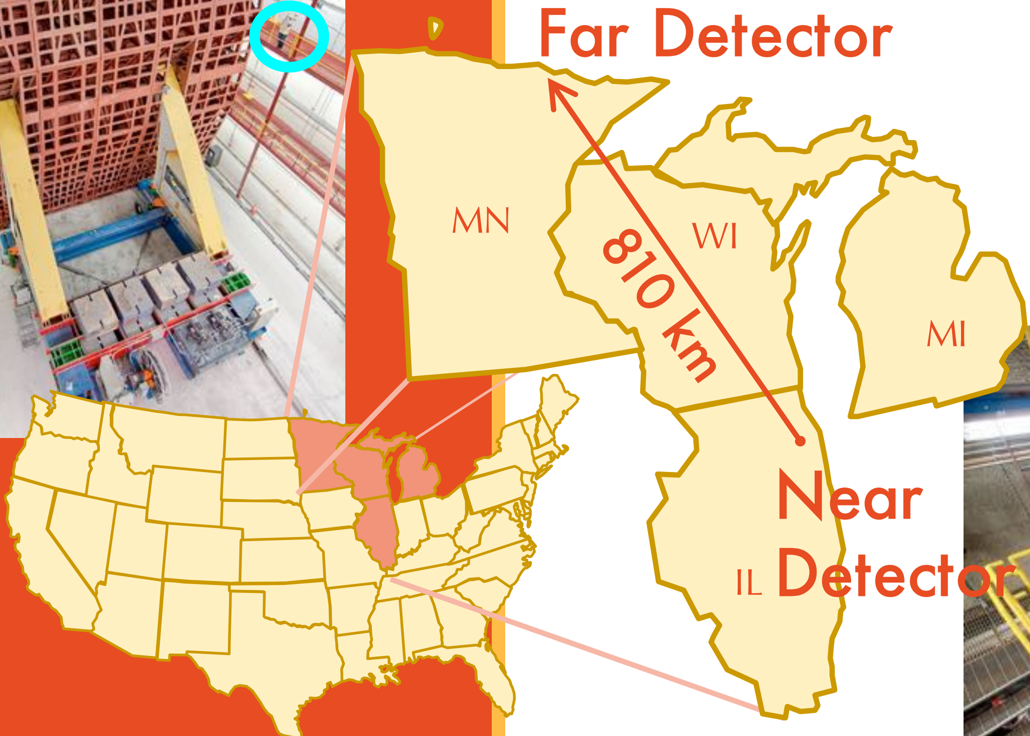
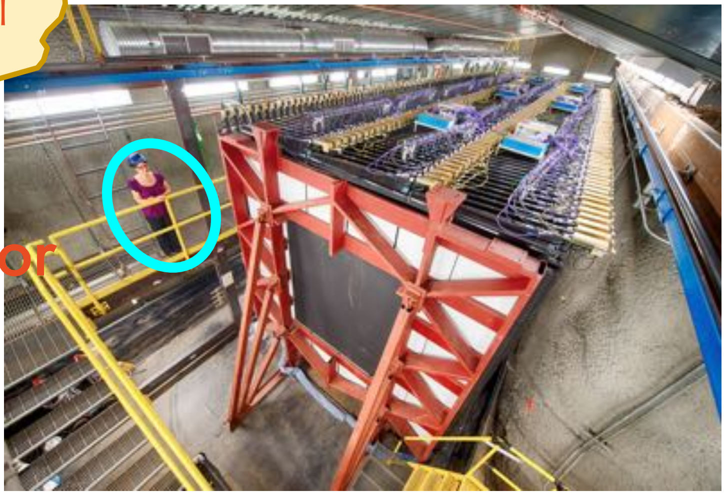
NOvA overview

- NOvA is a **long-baseline neutrino oscillation** experiment
- Study neutrinos from NuMI beam at Fermilab
- 14 mrad off the beam axis
- Two functionally identical liquid scintillator detectors:
  - Far Detector (**FD**) 14 kton; on the surface
  - Near Detector (**ND**) 0.3 kton; underground

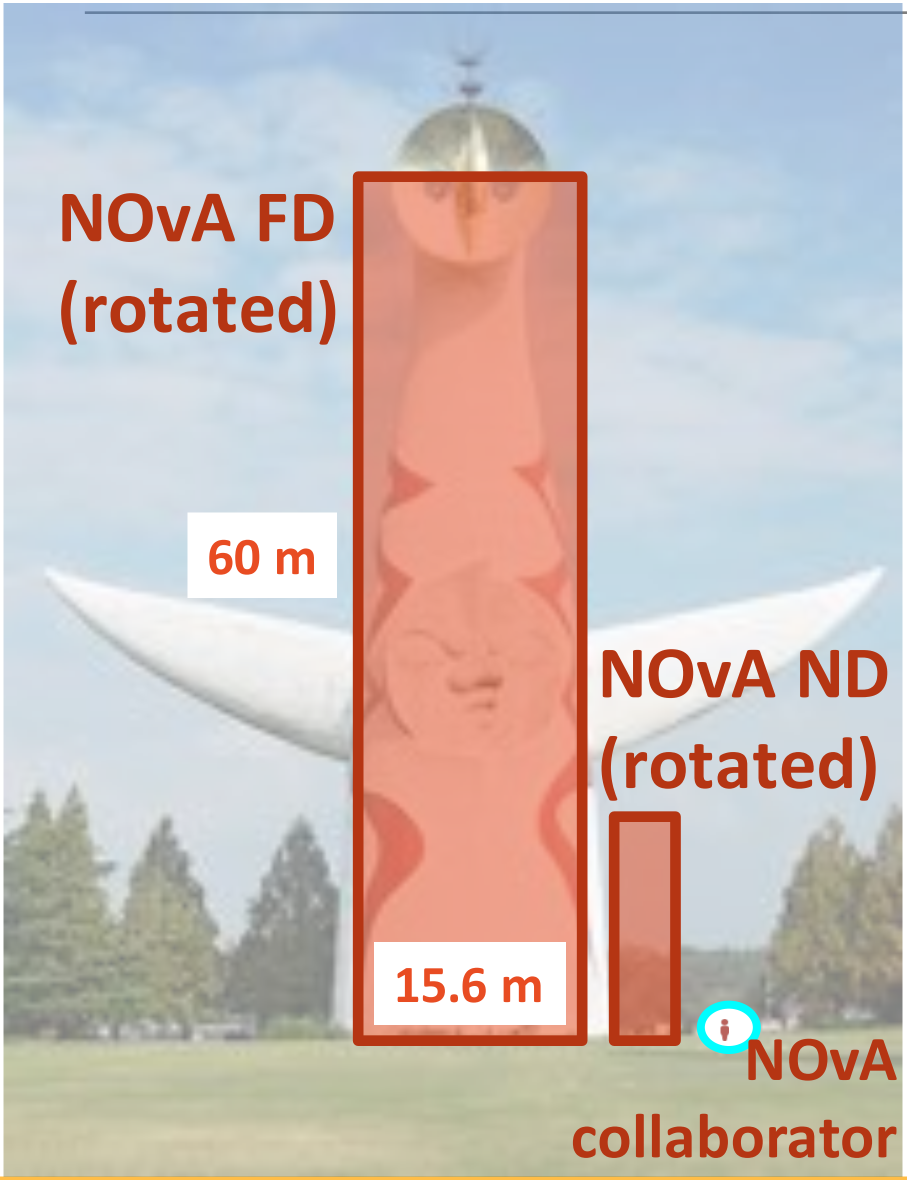




A monumental experiment…

Tower of the Sun

A monumental experiment…



NOvA's physics program

Oscillation channels

$\nu_\mu \rightarrow \nu_e$	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	"appearance"
$\nu_\mu \rightarrow \nu_\mu$	$\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$	"disappearance"

- Neutrino mass hierarchy?
- θ_{23} octant?
- Allowed range of δ_{CP}?
- Precision measurements of $\sin^2 2\theta_{23}$ and Δm^2_{32}

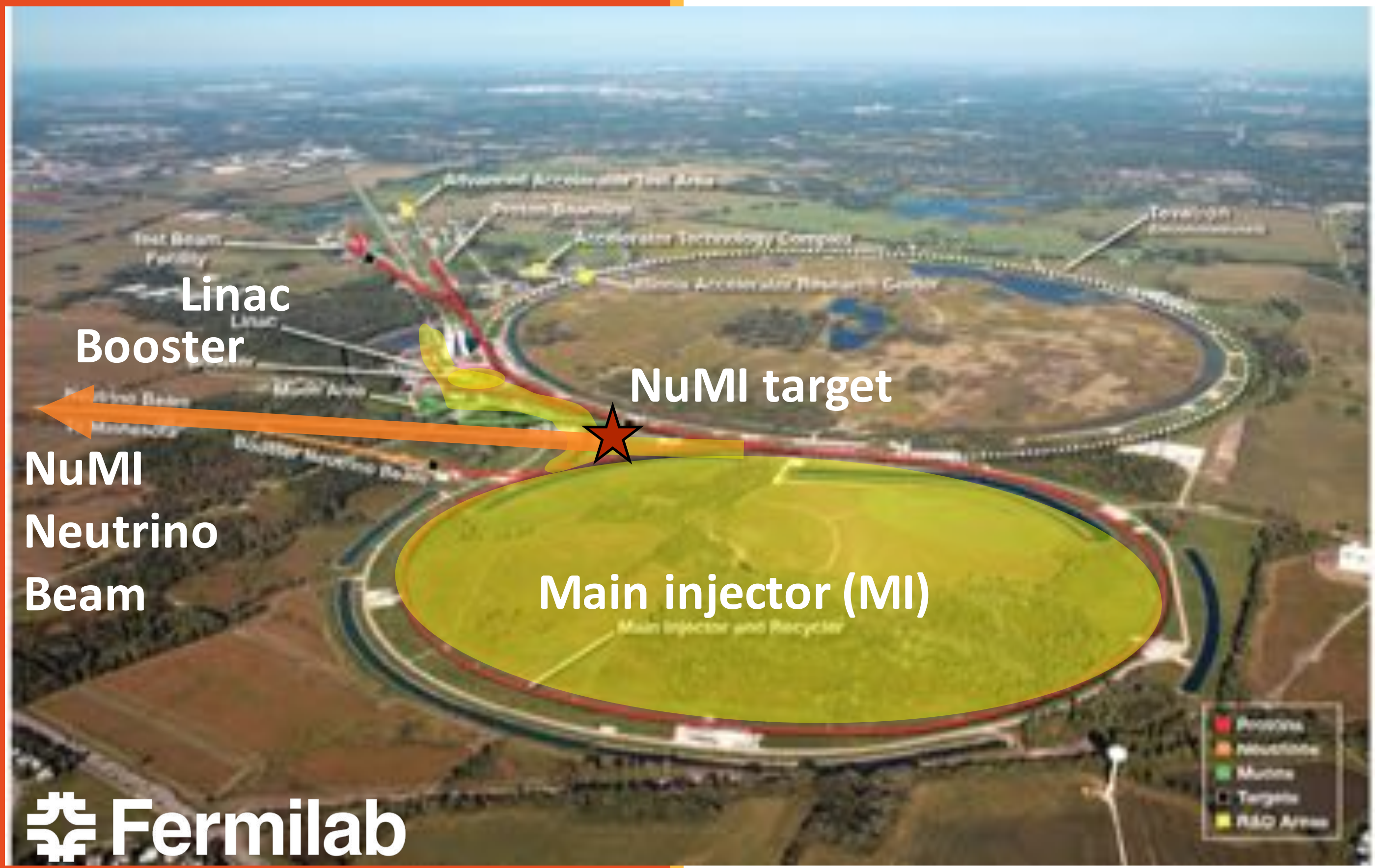
- 2015 ν_e analysis results: PRL.116.151806
- 2015 ν_μ analysis results: Phys.Rev.D93.051104
- 2016 results: to be published

Other analyses:

- Sterile neutrinos
- Cross sections
- Supernovae, monopoles, etc.

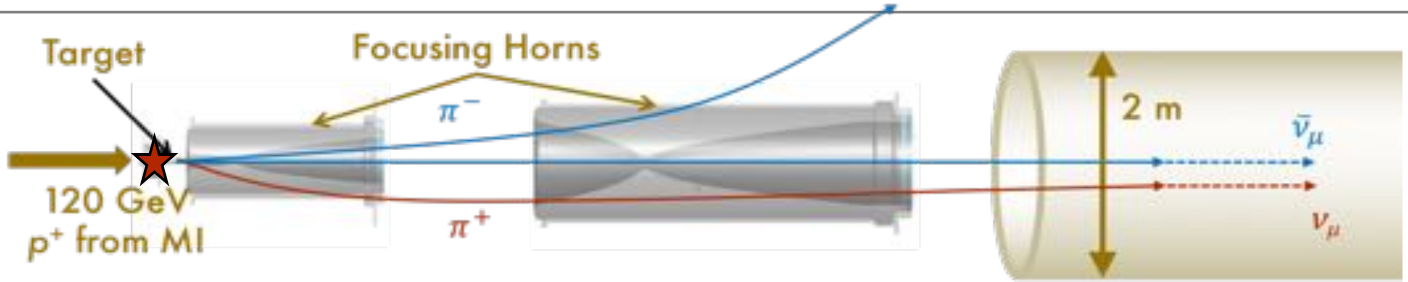
NuMI muon neutrino beam

- **NuMI:** neutrinos from the Main Injector
- Part of Fermilab's accelerator complex

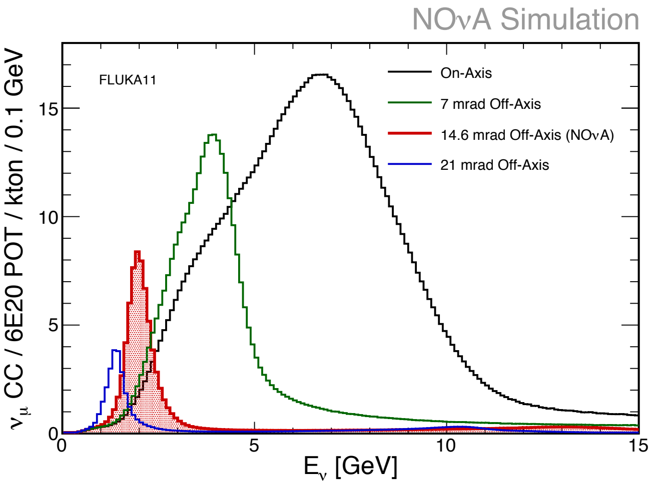


- **Linac:** H- ions, 400 MeV
- **Booster:** protons, 8 GeV
- **Main Injector:** protons, 120 GeV
- These protons are used to make the **NuMI beam**

NuMI off-axis



- MI proton beam is steered onto a narrow **graphite target** approx. 1 m in length
- Produced hadrons are focused in and charge-sign-selected by two **magnetic horns**
- 675 m **decay pipe**
- Predominantly pions and kaons, decay modes $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $K^+ \rightarrow \mu^+ + \nu_\mu$ $\Longrightarrow$ **ν_μ beam**
- Small contamination: $\nu_e, \overline{\nu}$



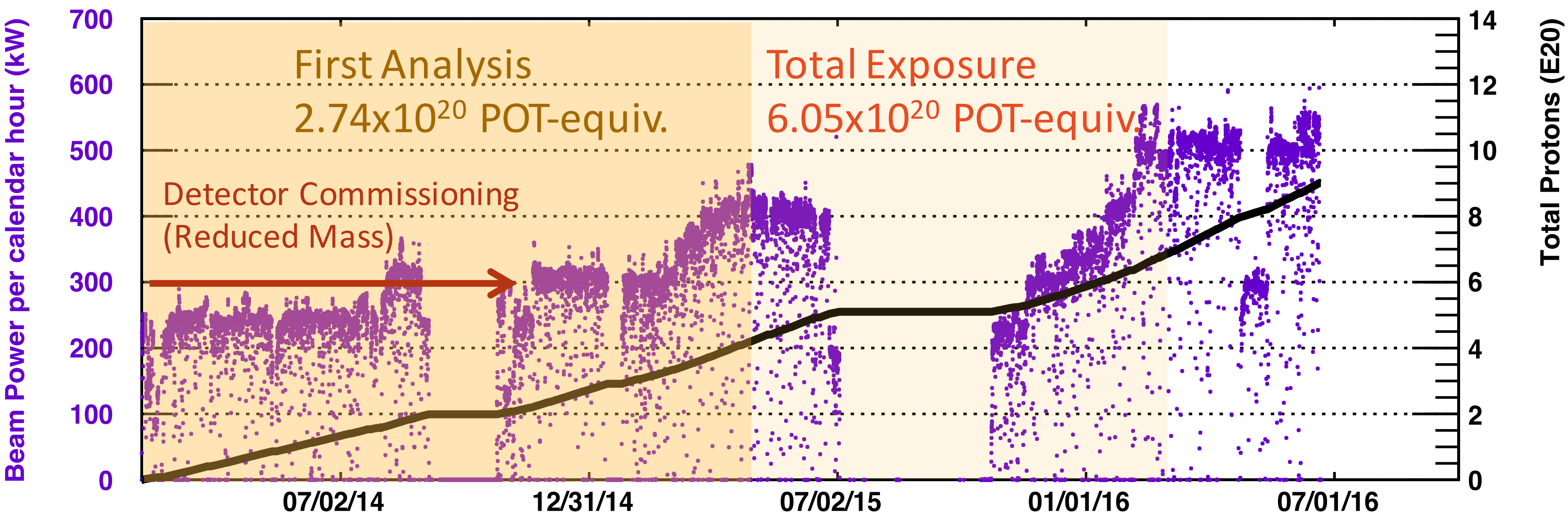
At 14.6 mrad off-axis, NOvA observes a narrow band beam peaked at 2 GeV

- Optimal for $\nu_\mu \rightarrow \nu_e$

Beam Performance

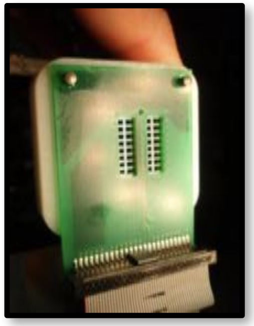
- Accumulated exposure: 6.05×10^{20} POT in 14 kton equivalent detector
- More than double exposure of 2015 analysis
- By July 2016: running at 560 kW (before 3 month shutdown)
- Achieved 700 kW design goal in tests on June 13!
- High intensity beam returns this Friday

POT = Protons On Target

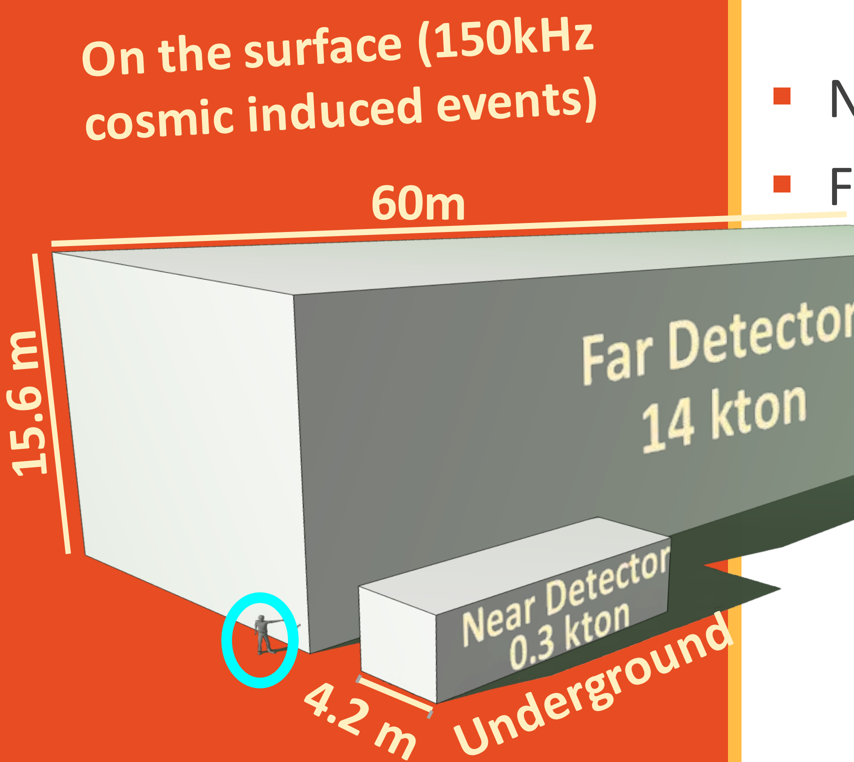


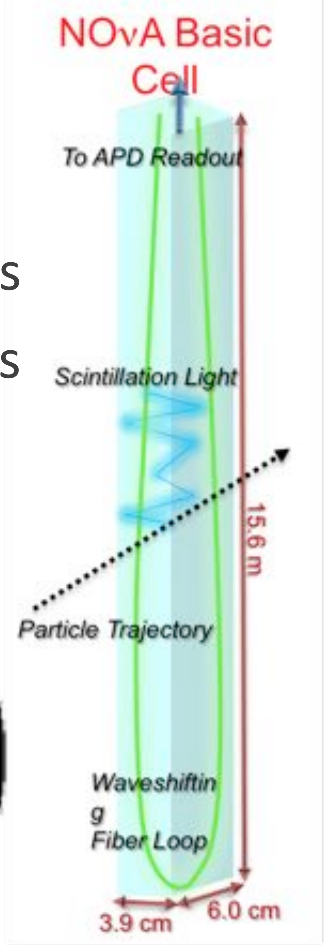
NOvA Detectors

- PVC + Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
- Read out via wavelength shifting fiber to APD
- Layered planes of orthogonal views

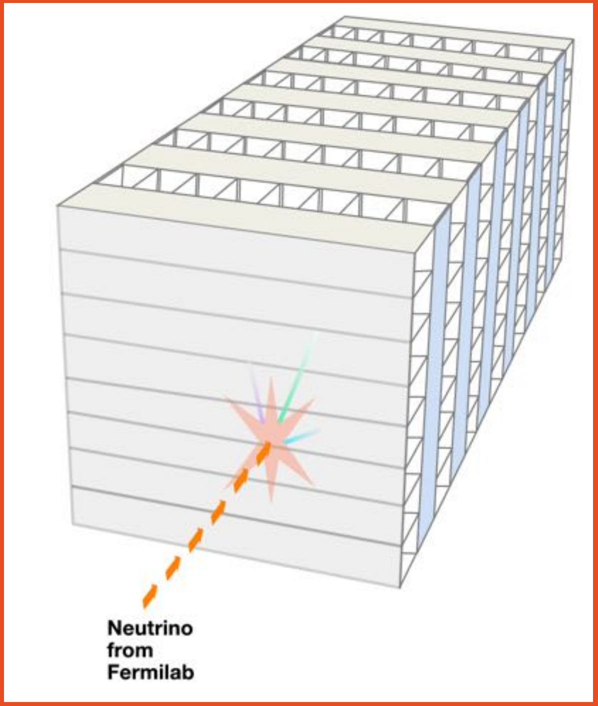


- ND: 214 layers,   18 000 channels
- FD: 896 layers, 344 000 channels

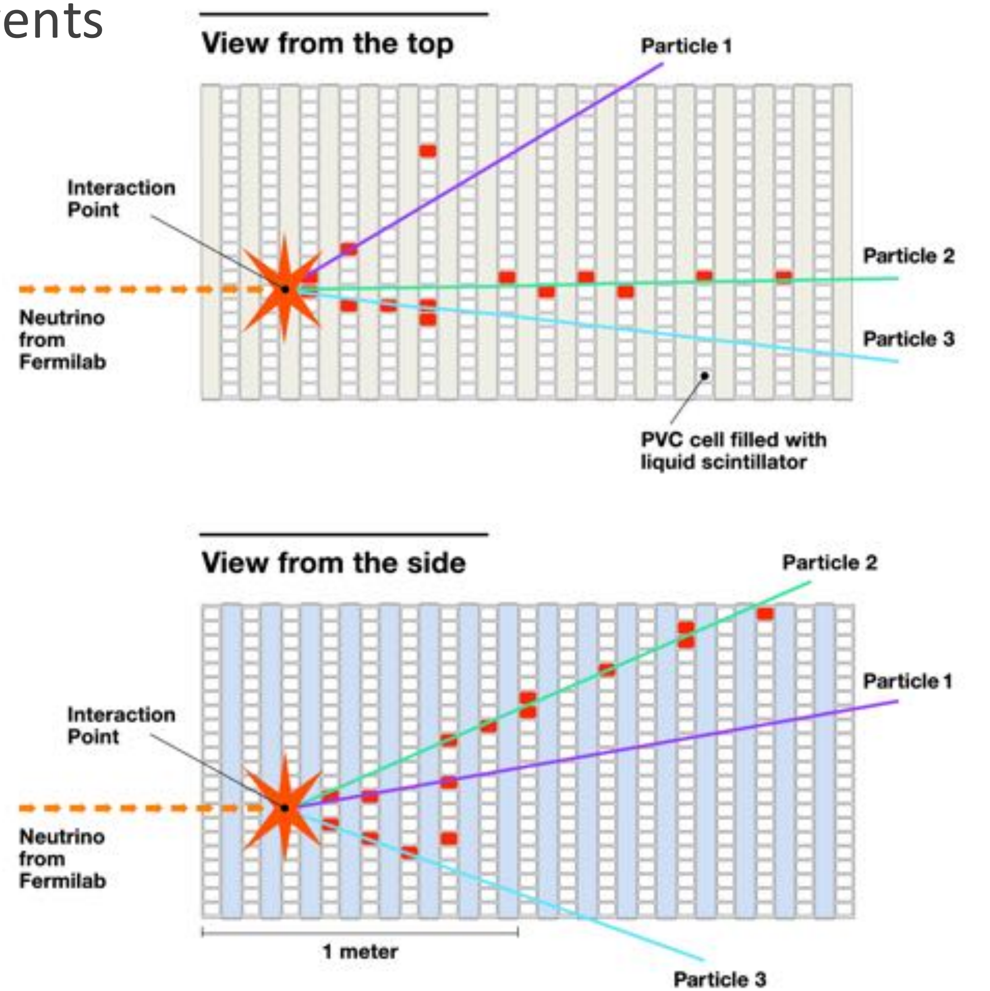




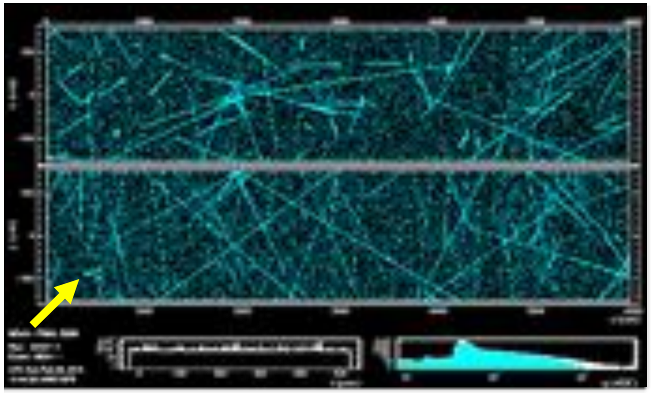
Finding neutrino events



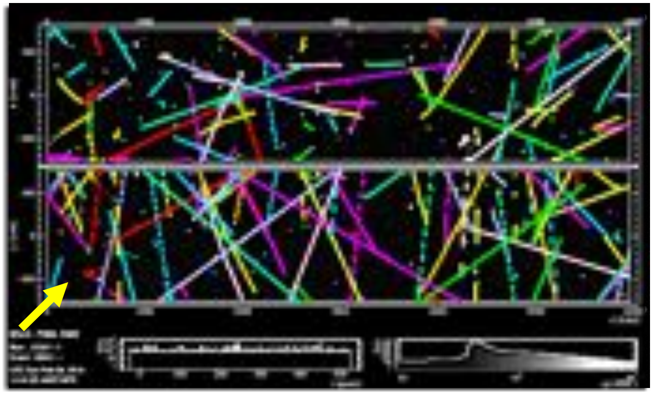
- Detectors are fine-grained, low-*Z*, highly-active tracking calorimeters
- Orthogonal layers → top and side views for each event
- Time and direction help to identify beam events



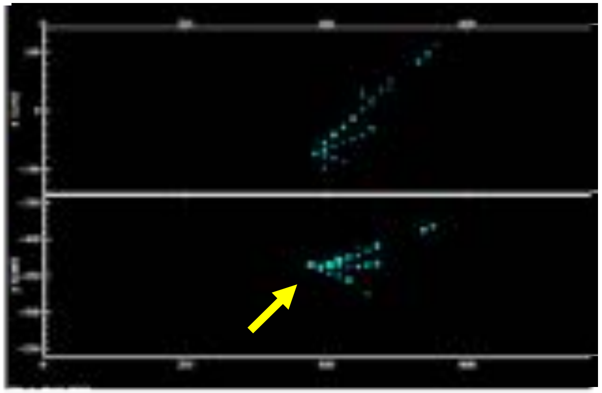
Finding neutrino events



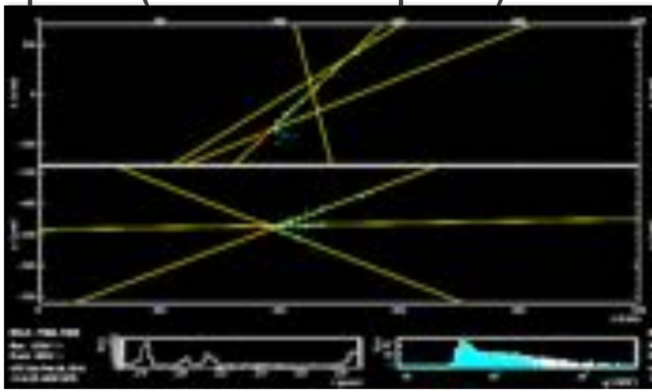
All hits recorded in 550 μsec (beam: ~10 μsec)



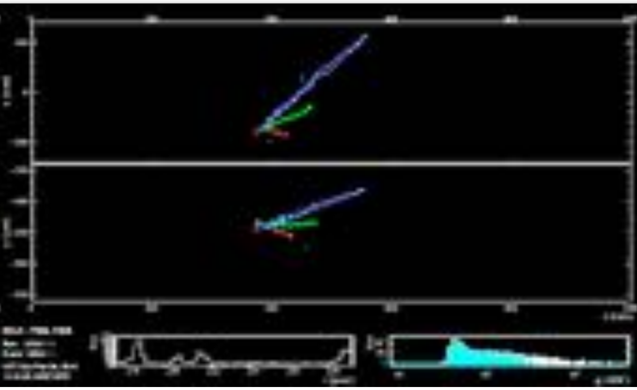
Slicing: Coarse event-level time-space clustering



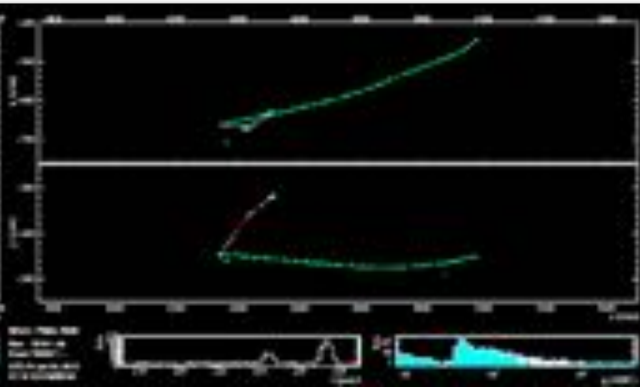
Selected slice with beam candidate



Vertexing: Find lines of energy depositions (CC events: 11 cm resolution)

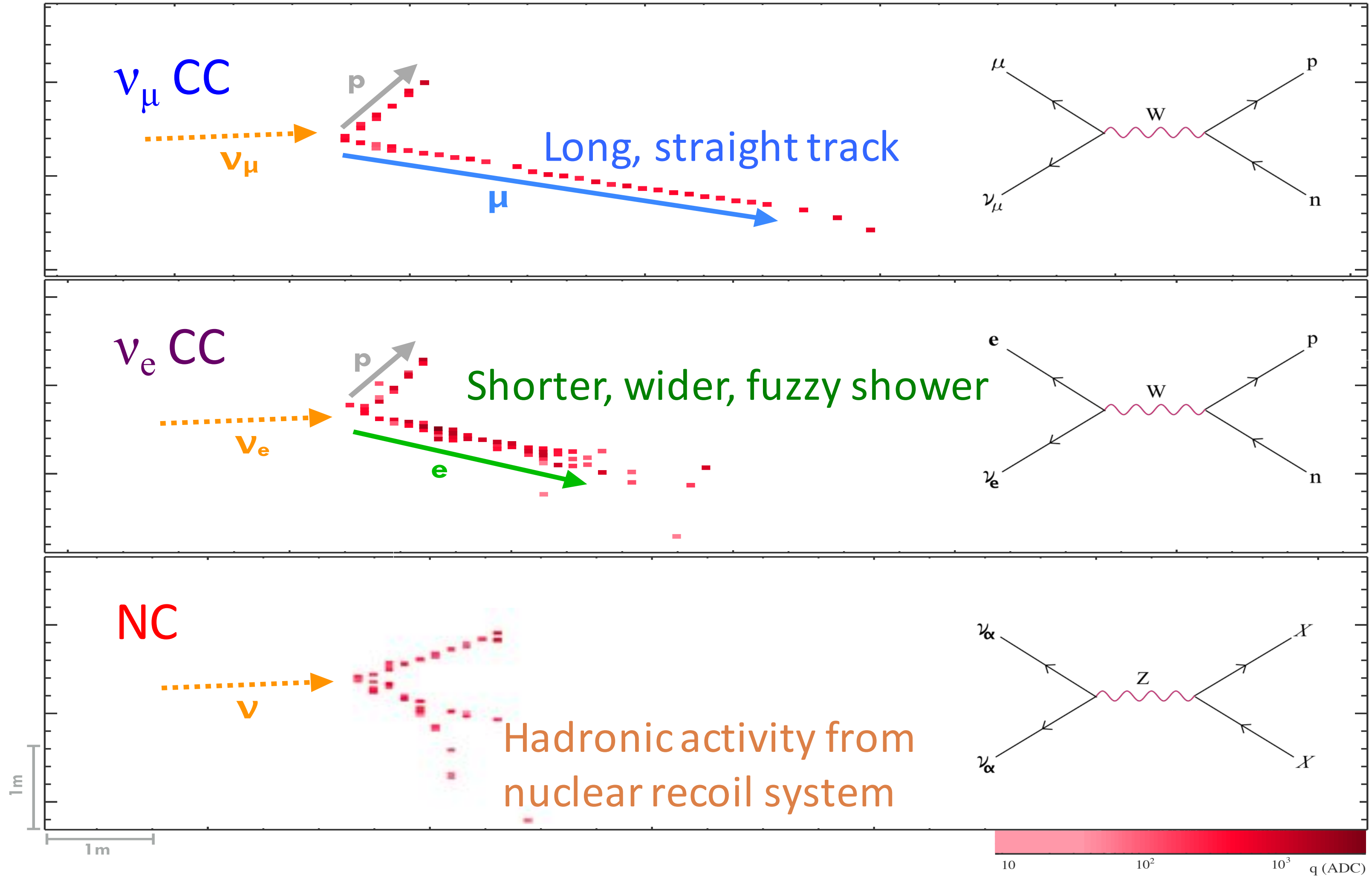


Clustering: Find clusters in angular space around vertex. Merge views via topology and prong dE/dx



Tracking: Trace particle trajectories

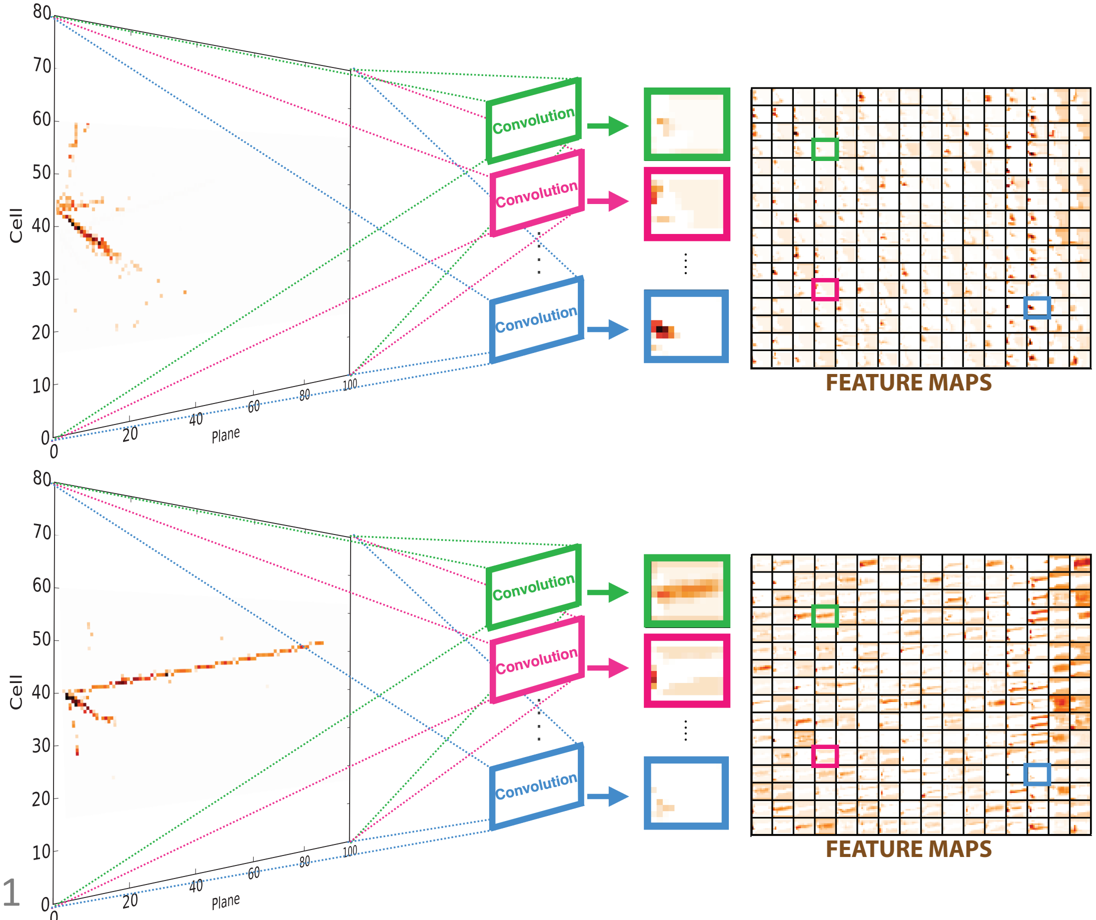
Event topologies



CC = charged current; NC = neutral current

Event selection (particle ID)

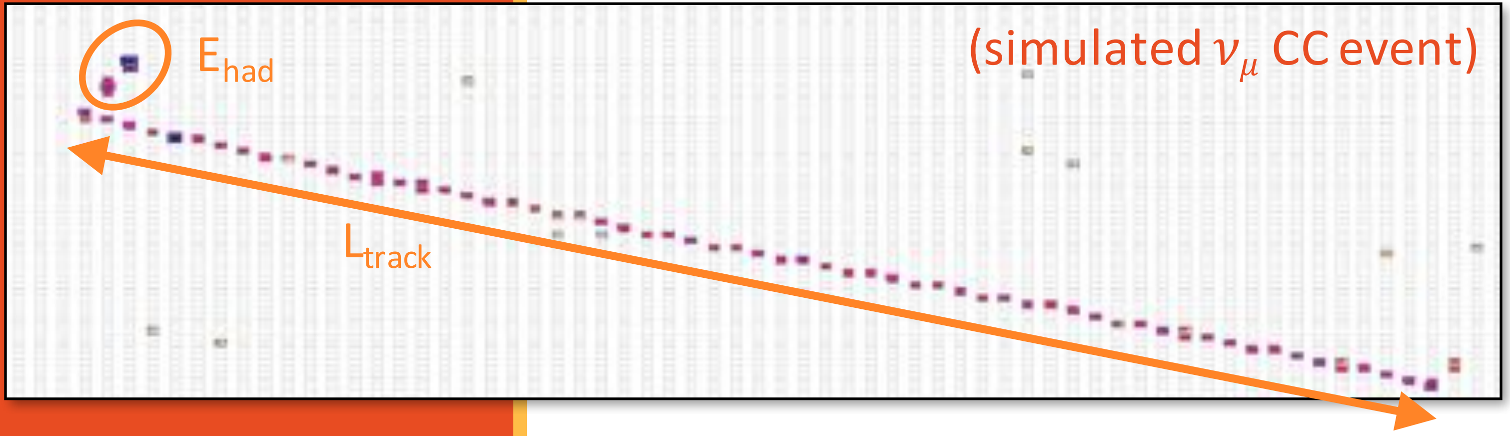
- ν_μ selection: kNN based on muon track length, scattering, plane fraction, dE/dx. Removes most NC background events
- ν_e selection: features a new technique based on ideas from computer vision and deep learning
  - "Convolutional Visual Network" (CVN)
  - Input: Calibrated hit maps
  - Image processing transformations → abstract features
  - Network decides important features + correlations
  - Output: event classifier



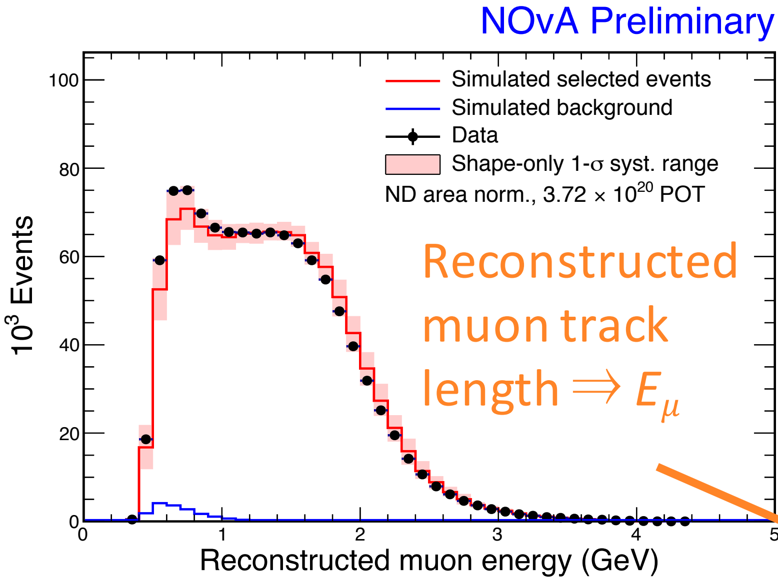
A. Aurisano et al., 2016 JINST 11 P09001

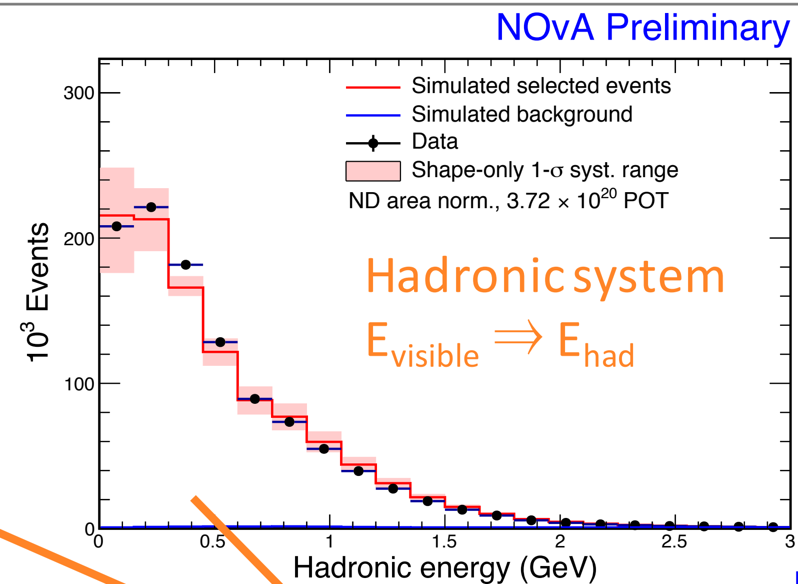
Muon neutrino disappearance

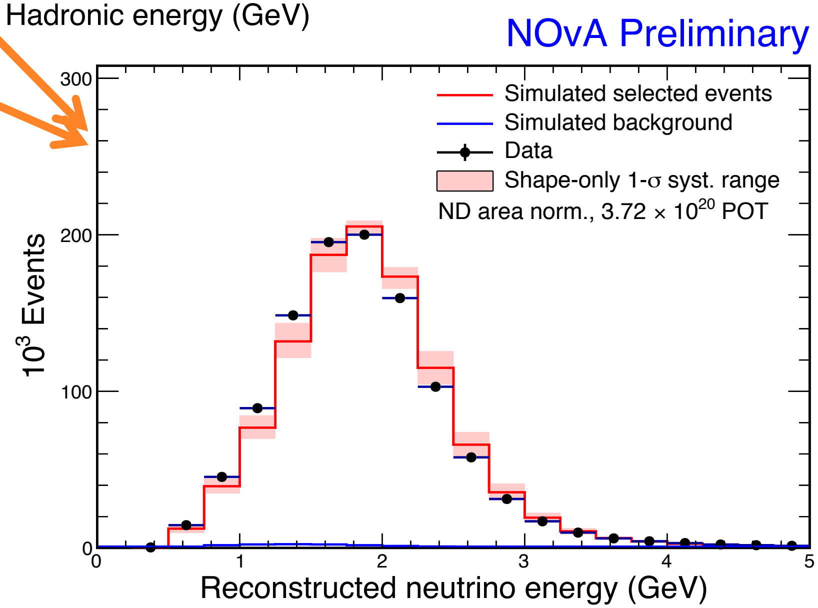
1. Identify contained ν_μ CC events in each detector
2. Measure Near and Far energy spectra
3. Extract oscillation information from differences between both energy spectra



ν_μ selected events in the ND



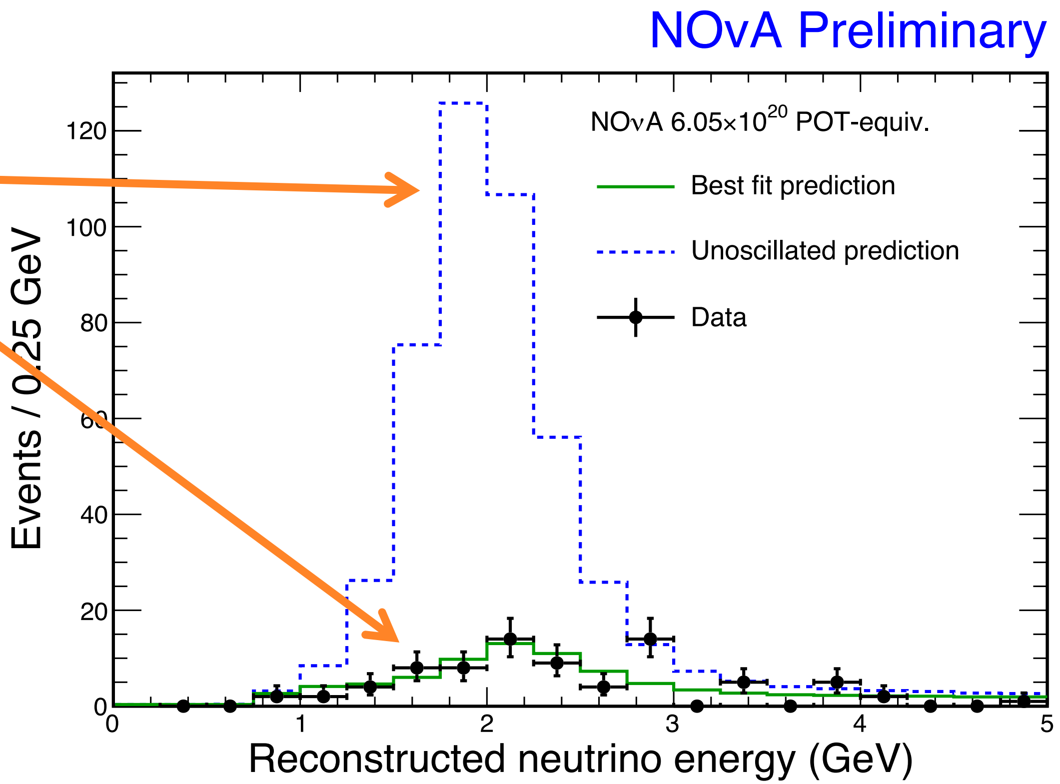


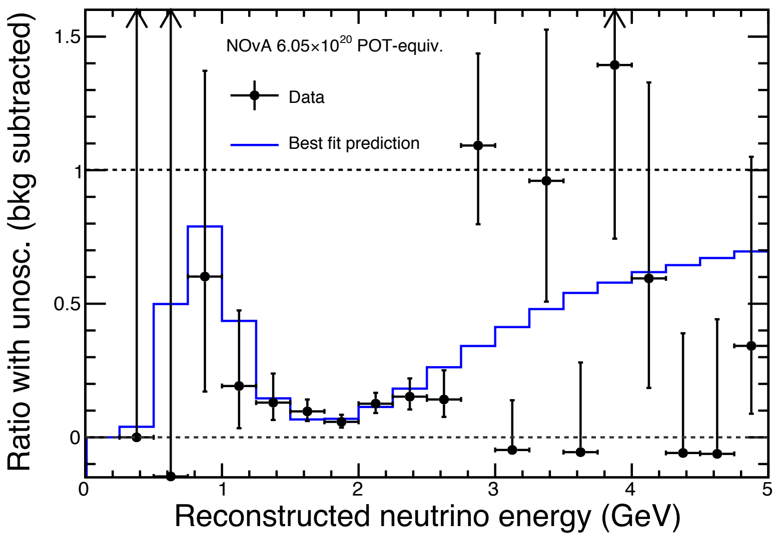


- Reconstructed ν_μ energy is $E_\nu = E_\mu + E_{had}$
- Use ND data to improve the FD prediction: Unfold the reconstructed neutrino energy + use the true Far/Near ratio from the simulation

ν_μ selected events in the FD

- Prediction using ND data: 473±30 with no oscillation
- 78 events observed in FD

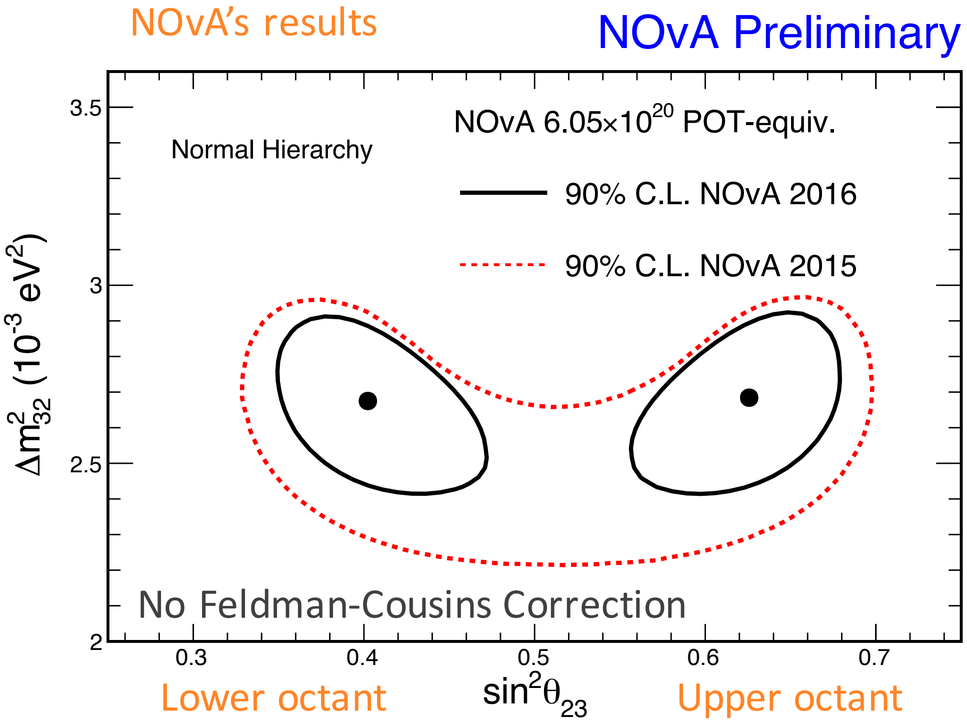




- 82 events at best oscillation fit
- 3.7 beam bkgd. + 2.9 cosmic

Disappearance results

Compared to last year NOvA's results



Best Fit (in NH):

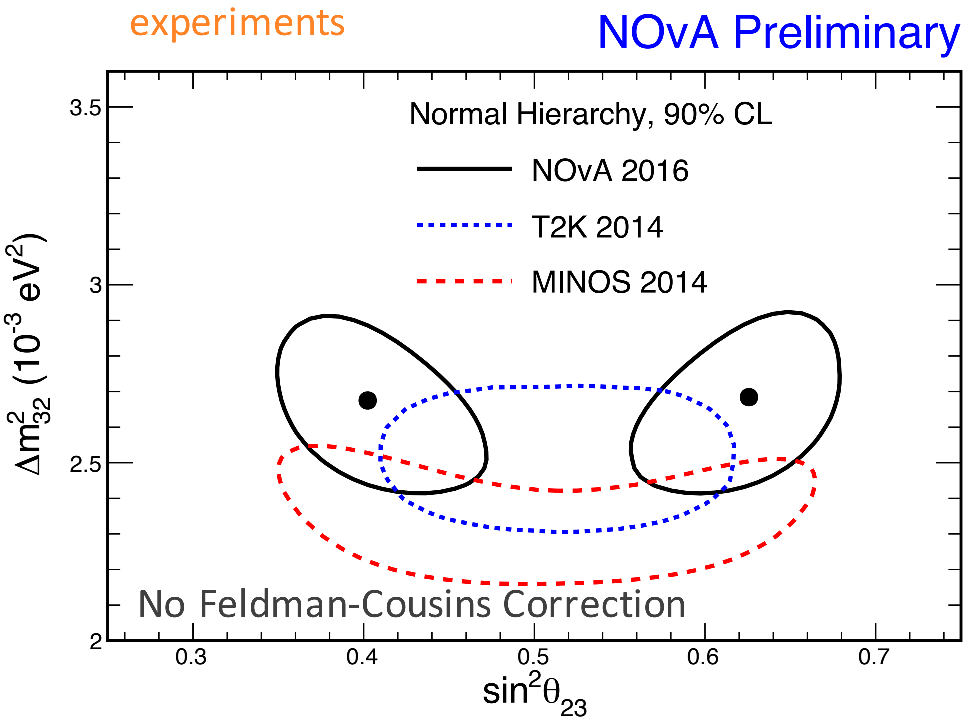
$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

- Fit for Δm^2 and $\sin^2\theta_{23}$
- Using 2D Gaussian C.L. (FC corrected: to be published)
- Maximal mixing excluded at 2.5σ
- Dominant systematic effects included in fit:
  - Normalization
  - NC background
  - Flux
  - Muon and hadronic energy scales
  - Cross section
  - Detector response and noise

Disappearance results

Compared to other experiments



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  - NC background
  - Flux
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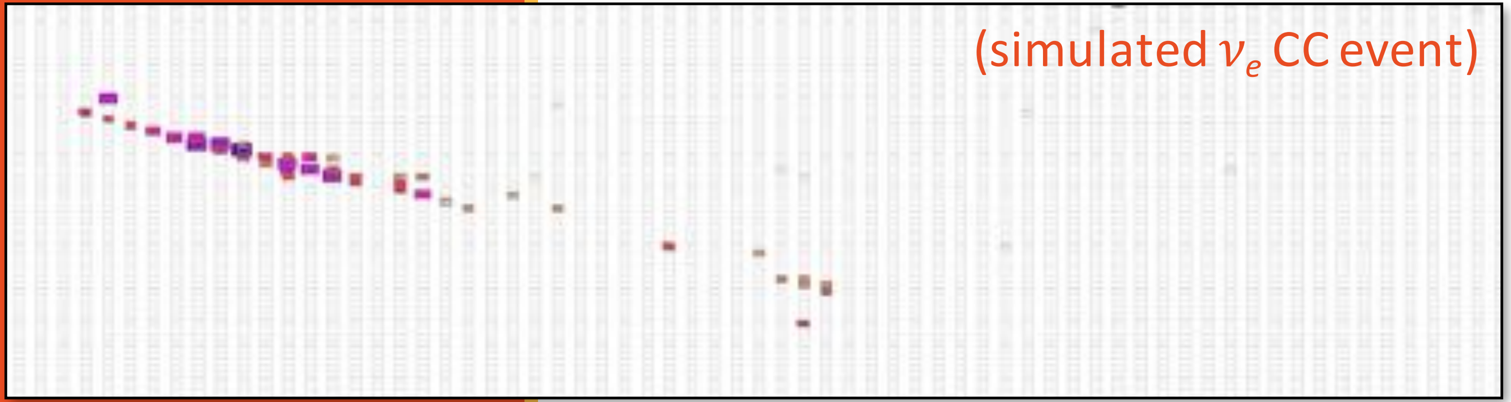
  - Detector response and noise

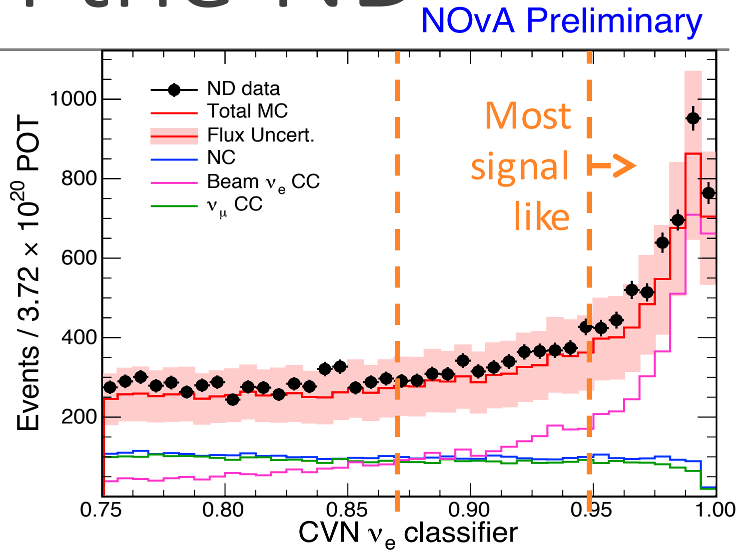
Electron neutrino appearance

1. Identify contained ν_e (ν_μ) CC candidates in each detector.
2. Use data to improve the prediction from the simulation:
   - ND ν_μ candidates → ν_e signal in the FD
   - ND ν_e candidates → FD beam backgrounds
   - FD data outside of the beam time window →FD cosmic ray background
3. Interpret any FD data excess over predicted backgrounds as ν_e appearance

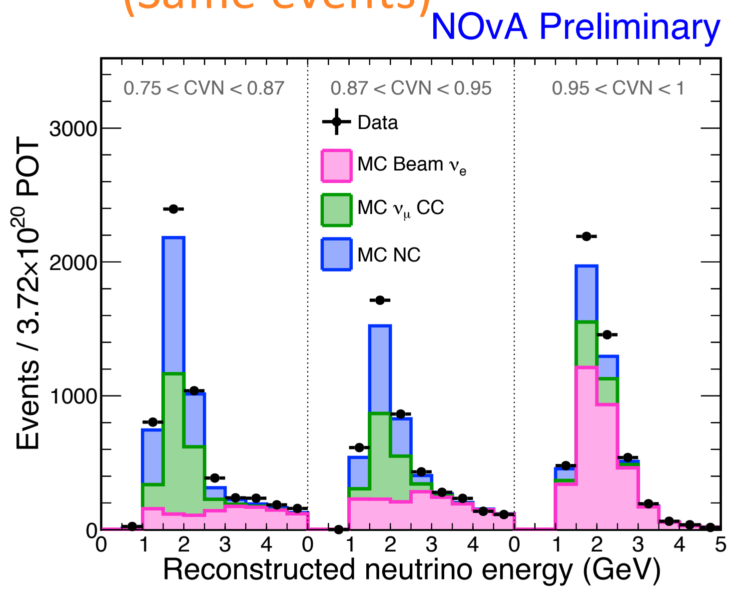


ν_e selected events in the ND

- ND: select 3 components: beam ν_e CC, ν_μ CC, NC
- Correspond to 3 FD backgrounds
  - Beam ν_e CC: intrinsic ν_e component in the beam. In the FD, $\nu_e \rightarrow \nu_e$ is a background to $\nu_\mu \rightarrow \nu_e$.
    Actual ν_e events → score high on classifier
  - ν_μ CC, NC: events that are misidentified as ν_e CC in either detector
- Translate ND data to a FD bkgd. expectation in energy x PID bins using Far/Near ratios from simulation
- ~10% excess of data over MC. How to divide among components?

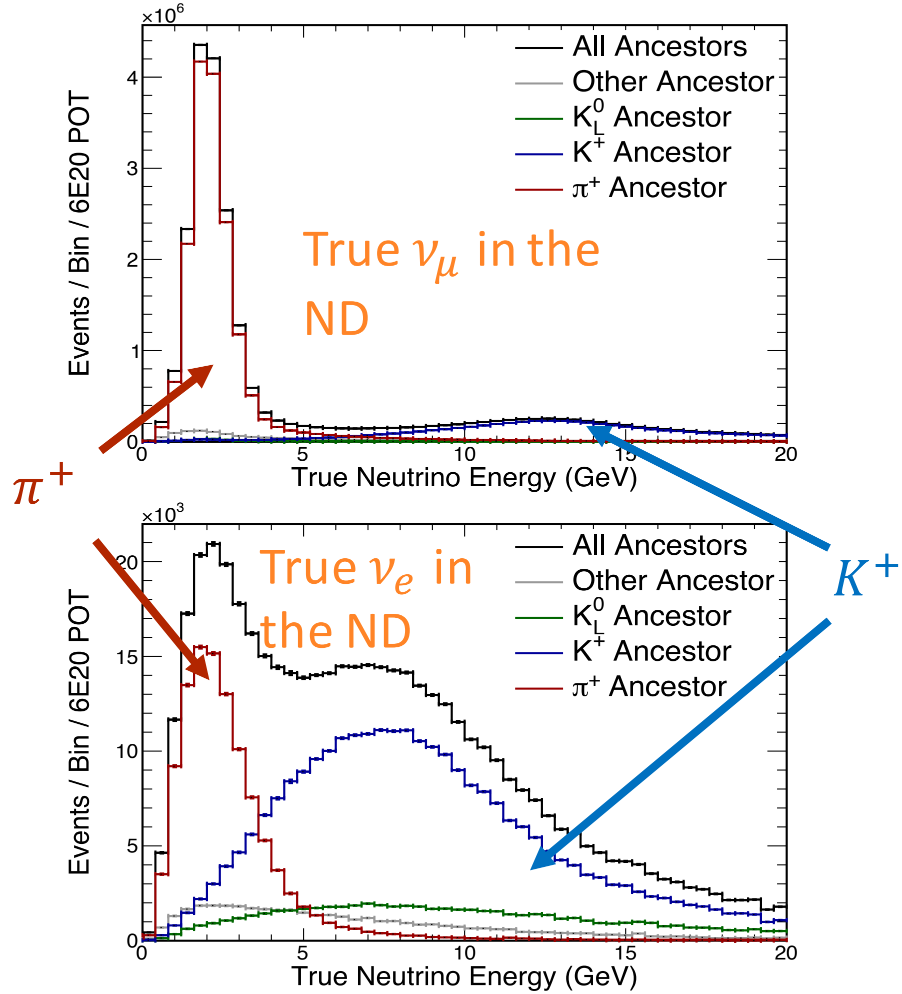


(Same events)



Data-driven background (I)

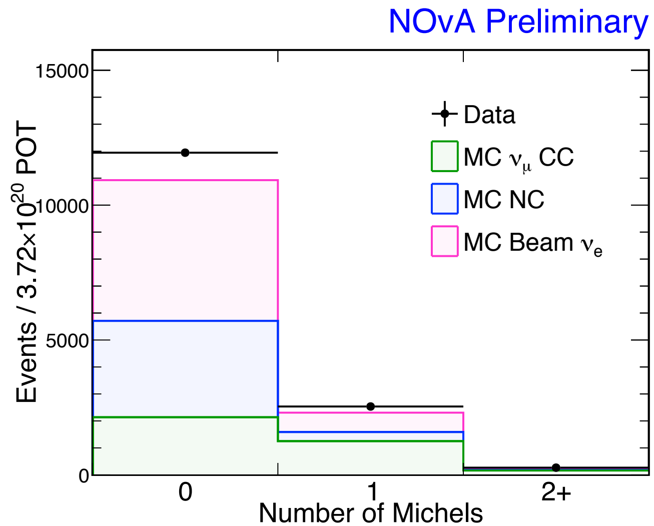
- Recall: dominant decay modes – NuMI beam:
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $K^+ \rightarrow \mu^+ + \nu_\mu$
- Small ν_e contamination "beam ν_e"
  $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$
  $K^+ \rightarrow e^+ + \nu_e$
- We can use ν_μ-selected samples (more statistics, few backgrounds) to correct the numbers of pion and kaon ancestors, and thus constrain the beam ν_e CC
- Using data: we find corrections ~-2% for pions, +17% for kaons

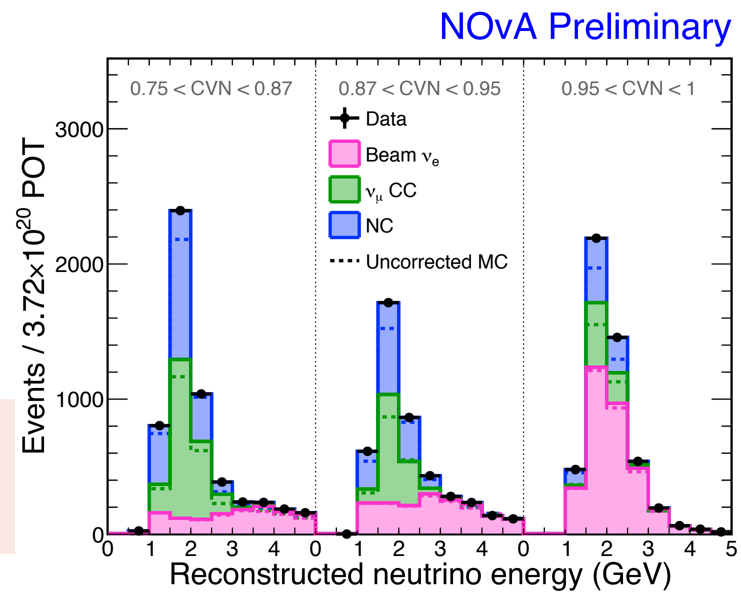


Data-driven background (II)

- ν_μCC backgrounds: CC events that do contain a muon, but its track is not clearly defined and it's mistaken for a ν_e event
- Contained event: the muon decays inside the detector.
  Dominant mode is $\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$
  "Michel" electron
- Looking for Michel-like activity, we can get a handle on the ν_μCC
- Combining the beam ν_e results and a fit to the number of Michels in data → all 3 components are corrected

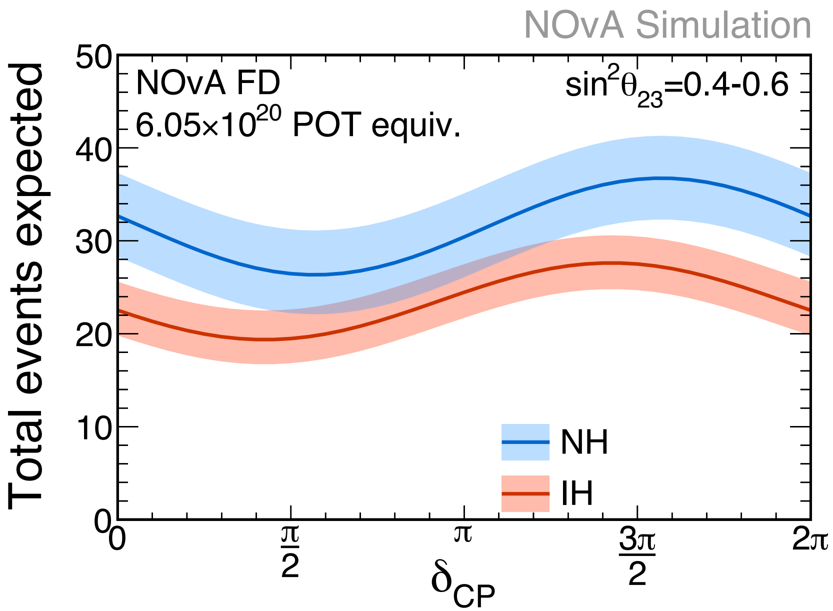
Average corrections: beam ν_e up by 4%, NC up by 10%, ν_μCC up by 17%





Electron neutrino FD prediction

- **FD beam bkgd.** estimated using ND data
- **FD signal expectation** is pinned to the ND-selected ν_μ CC spectrum
- **FD cosmic bkgd.** estimated using ν_e selected FD data outside of the beam time window



- Expected event counts depend on oscillation parameters

Signal events (±5% systematic uncertainty):

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

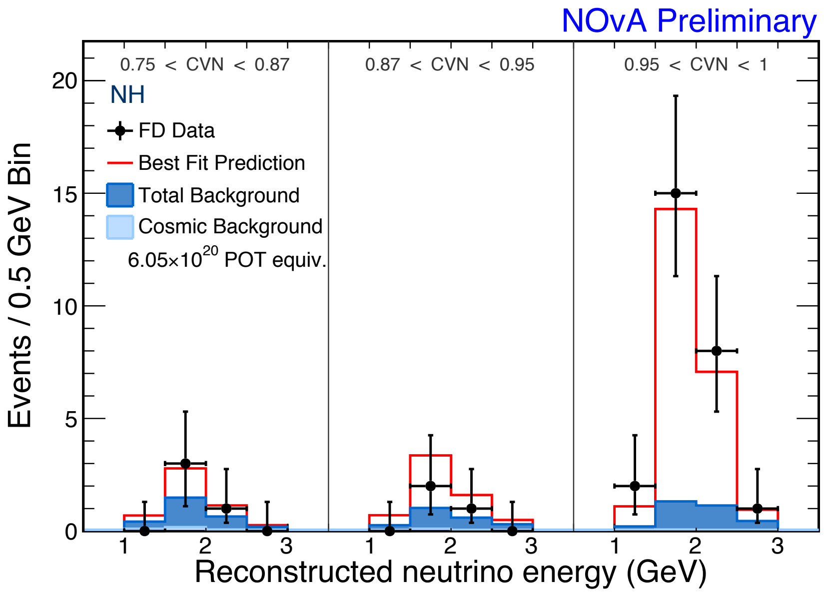
Background by component (±10% systematic uncertainty):

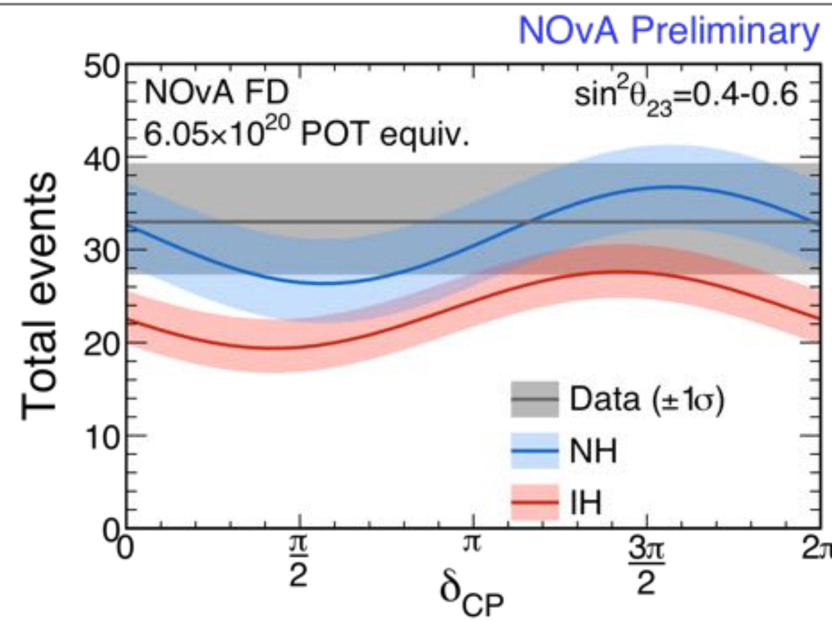
Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5

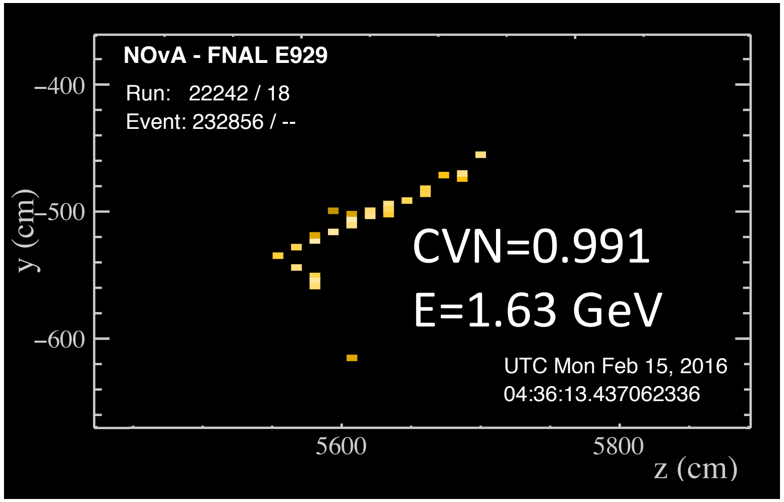
Electron neutrino FD data

Observe **33 events** in FD

- background 8.2±0.8
- >8σ significance of appearance



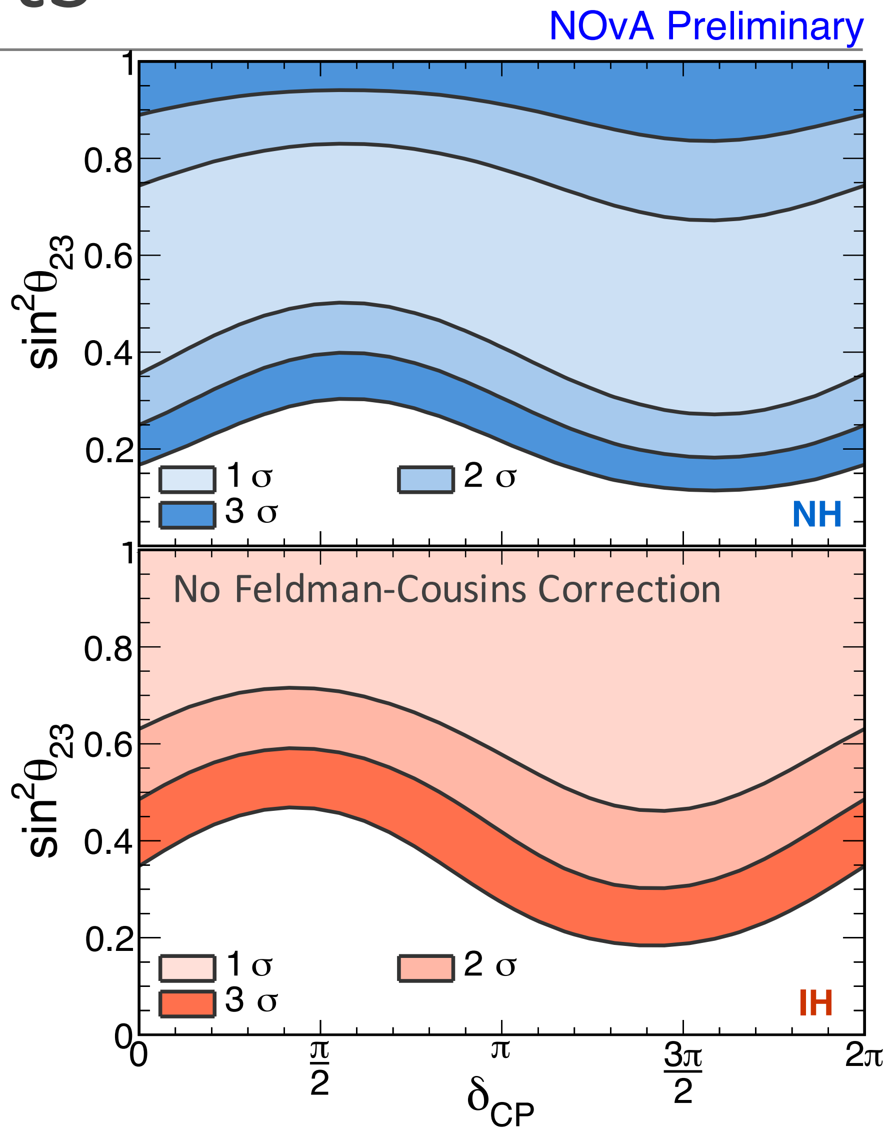




Appearance results

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

- Using 2D Gaussian C.L. (FC corrected: to be published)
- Reactor constraint (PDG 2015) $\sin^2(2\theta_{13})=0.085\pm0.05$
- Δm^2 constraint (PDG 2015) $\Delta m^2=2.44\pm0.06\times10^{-3}\ eV^2$ $(-2.49\pm0.06\times10^{-3}\ eV^2$, IH)
- Systematic effects included as nuisance parameters
  - Normalization
  - Flux
  - Calibration
  - Cross section
  - Detector response



Appearance results

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

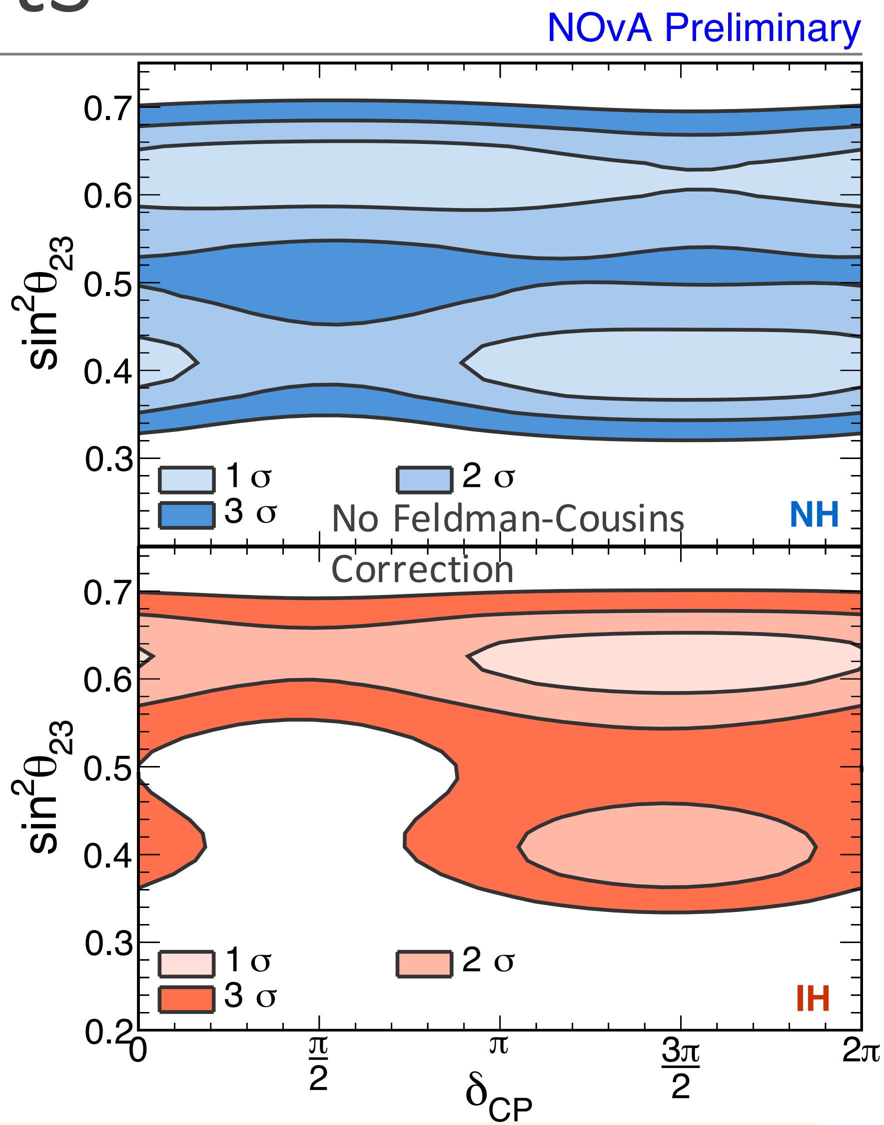
- Reactor constraint (PDG 2015) $\sin^2(2\theta_{13})=0.085\pm0.05$
- Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results

  * Not a full joint fit, systematics and other oscillation parameters not correlated

Global best fit Normal Hierarchy

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

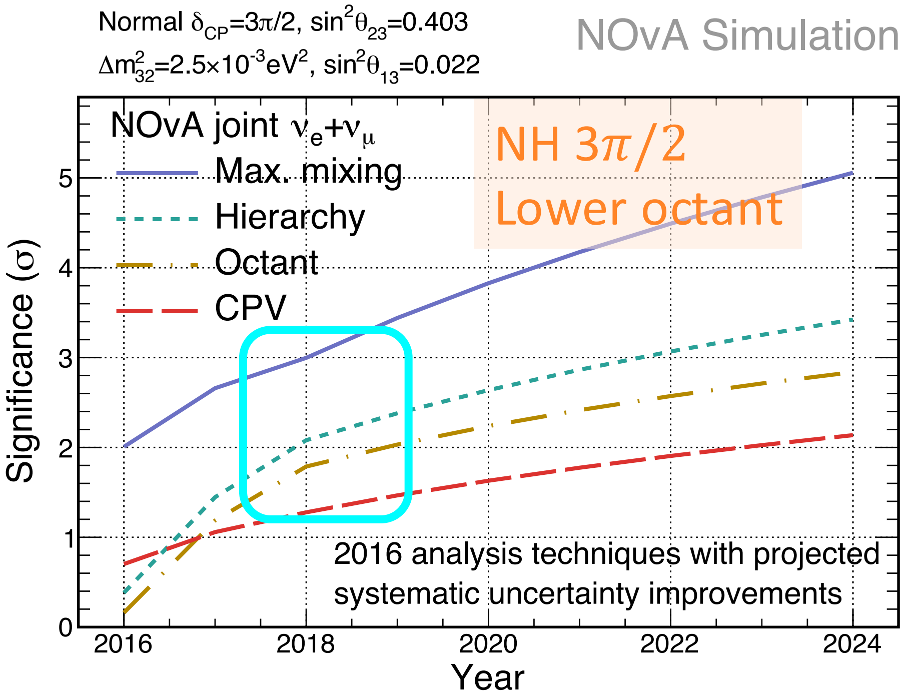
- 3σ exclusion in IH, lower octant around $\boldsymbol{\delta}_{CP}=\pi/2$
- best fit IH-NH, $\Delta\chi^2=0.47$
- both octants and hierarchies allowed at 1σ

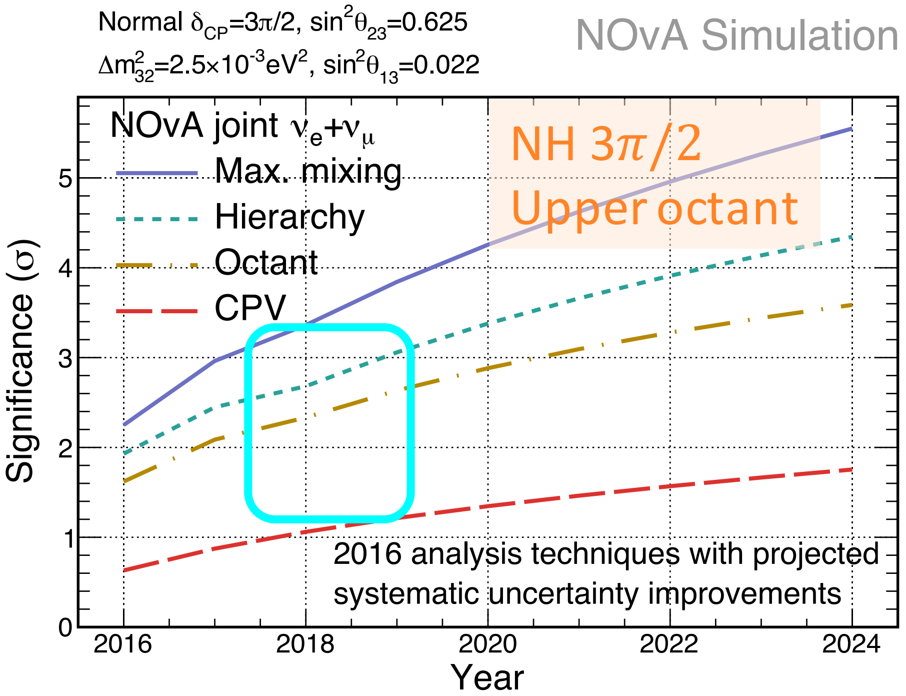


Anti-neutrino running → help remove degeneracies

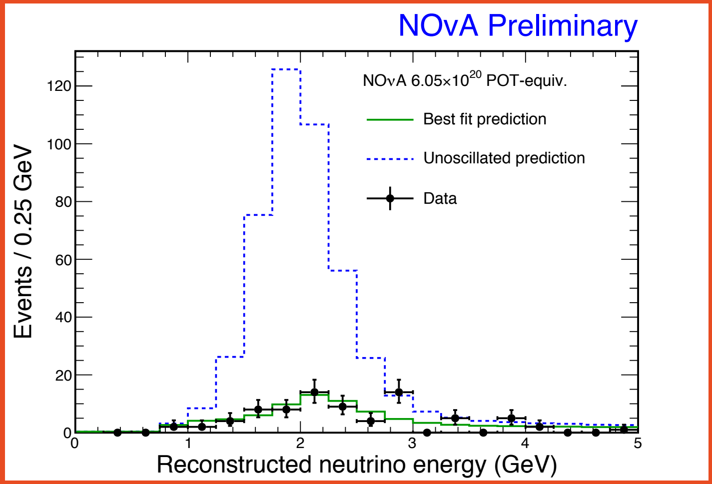
Outlook

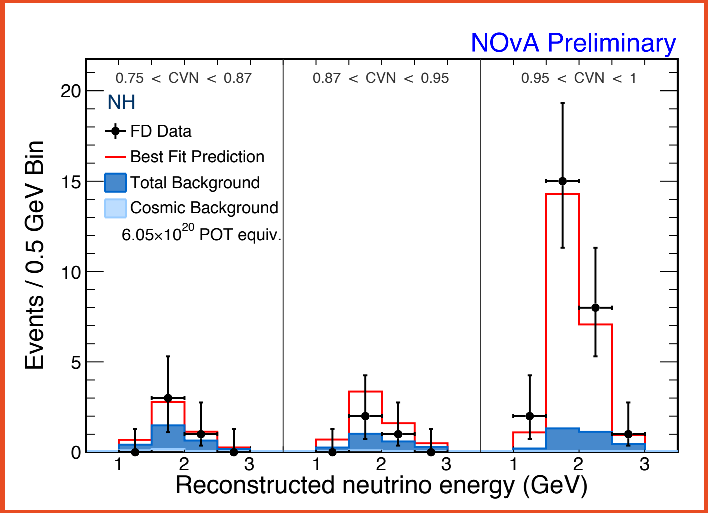
- Below: sensitivities vs time, assuming favored oscillation parameters and modest improvements in the analysis
- Start anti-neutrino running in 2017; run 50% neutrino 50% anti-neutrino after 2018
- In the near term (2018-19) expect to reject
  - Wrong hierarchy at >95% CL
  - Wrong octant at >95% CL
  - Max-mixing at >3 sigma





Summary





- With 6.05×10^{20} POT, NOvA finds:
  - Muon neutrinos disappear: Best fit is non-maximal
  - Electron neutrinos appear: Data prefers NH at low significance
- Excellent detector and beam performance
- Looking forward to more neutrino data + antineutrino running starting in spring 2017!
  - θ_{23} non-maximal? Octant?
  - Mass hierarchy?
- Broad physics program! Sterile neutrinos, cross-section measurements, exotic searches…

Thank you!

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