NOvA Results & Future Prospects

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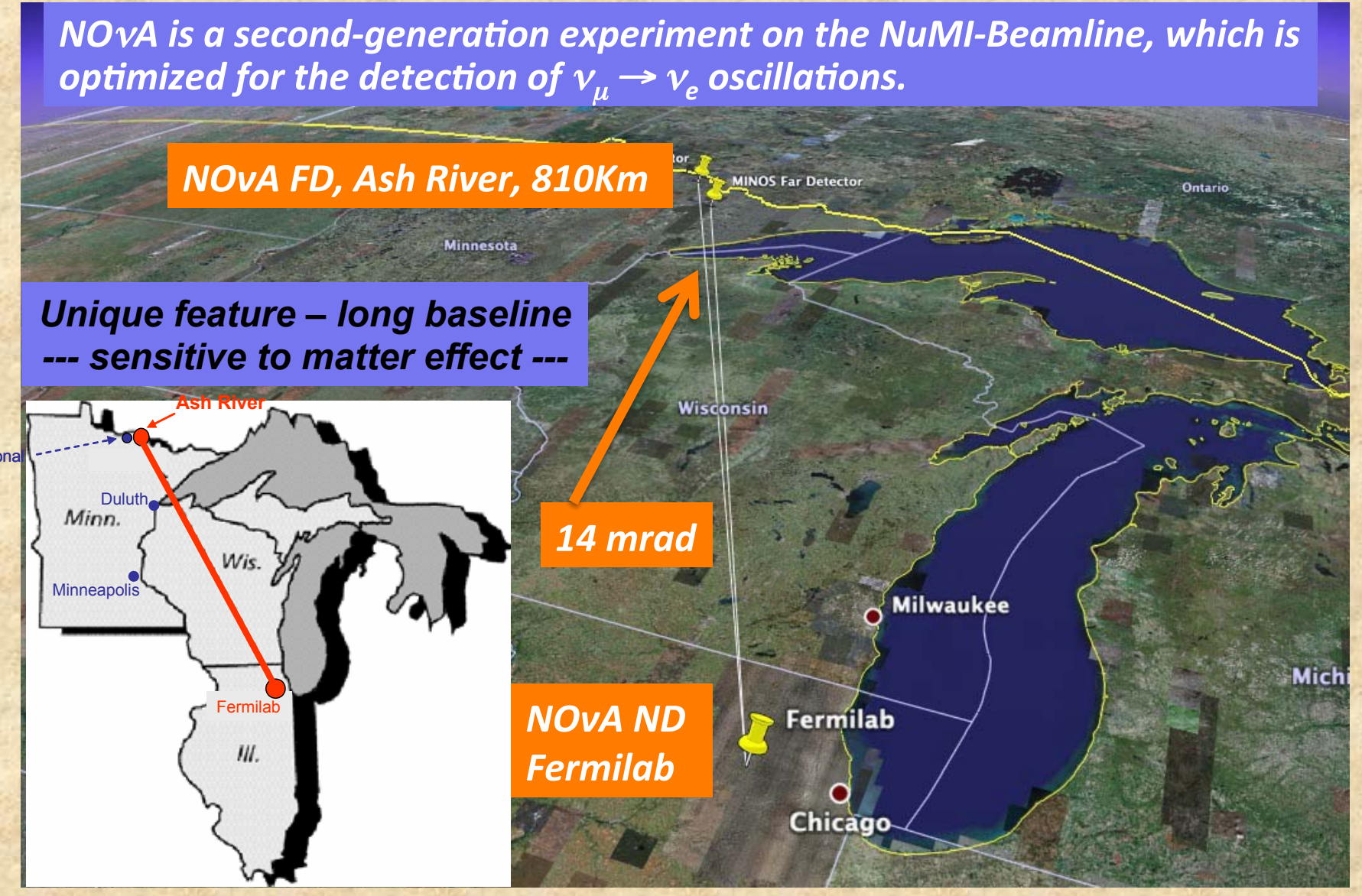
On behalf of the NOvA Collaboration

9 August 2018

Fermilab

NOνA Experiment

NOνA is a second-generation experiment on the NuMI-Beamline, which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ oscillations.



NOνA Collaboration

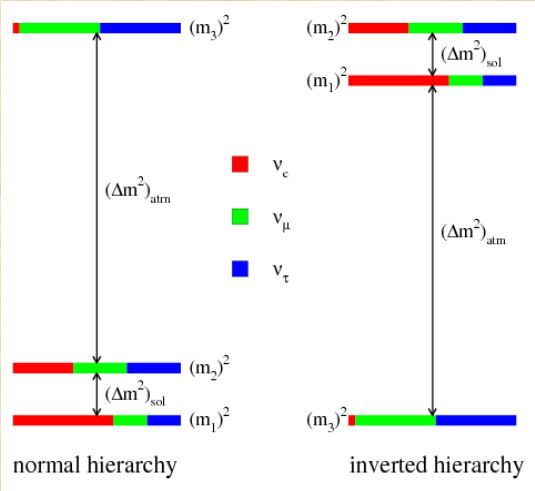
Argonne, Atlantico, BHU, Caltech, CUSAT, Institute of Physics and Computer science of the Czech Academy of Sciences, Charles University, Cincinnati, Colorado State, Czech Technical University, Delhi, JINR, Fermilab, Goiás, IIT Guwahati, Harvard, IIT Hyderabad, UOH, Indiana, Iowa State, Jammu, Lebedev, 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

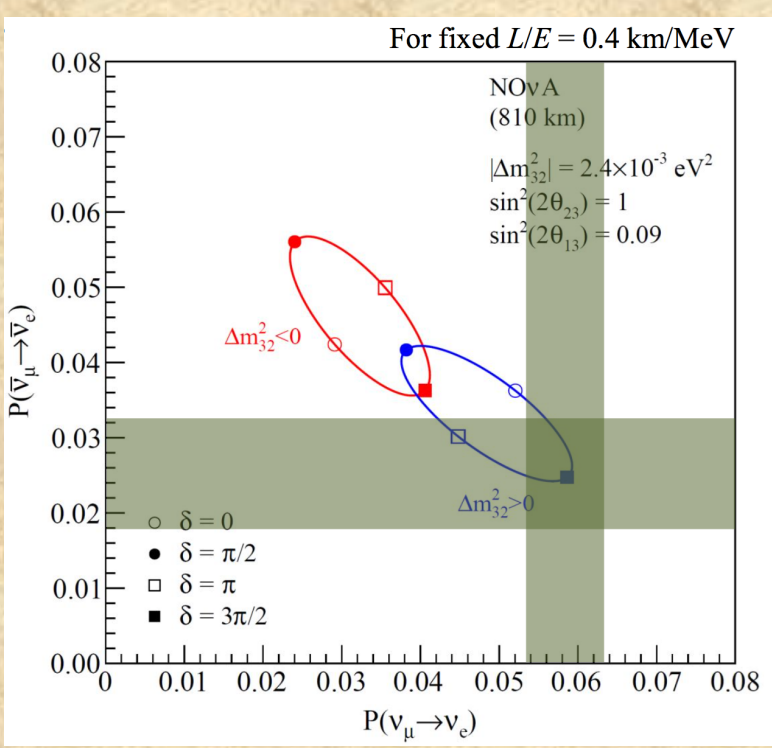
Goals of NOvA Experiment

- 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 Mass Hierarchy
- Study the CP violation parameter δ



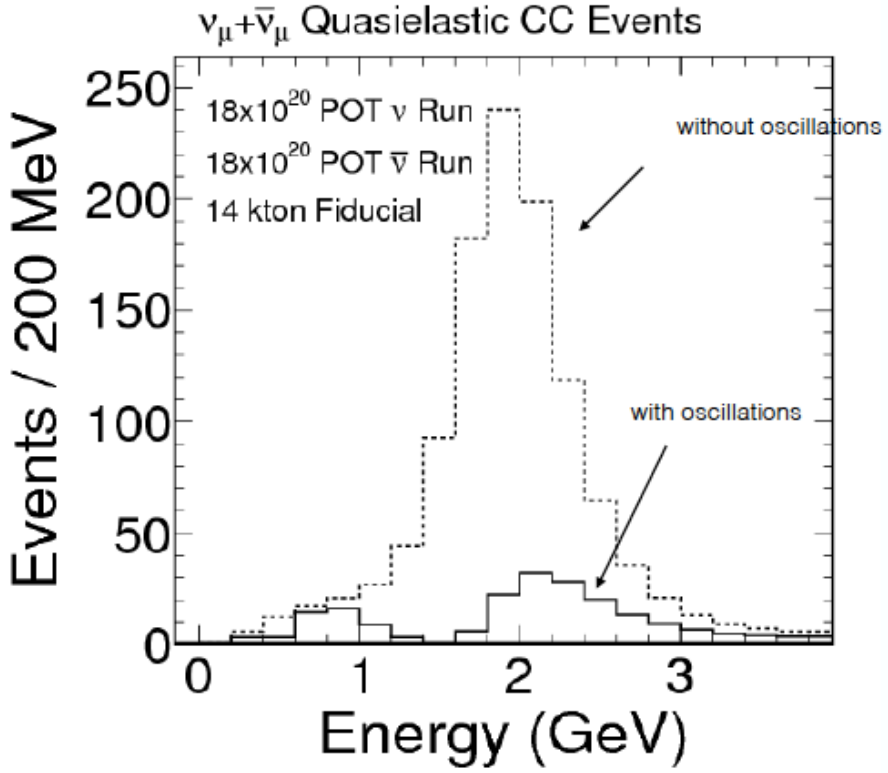


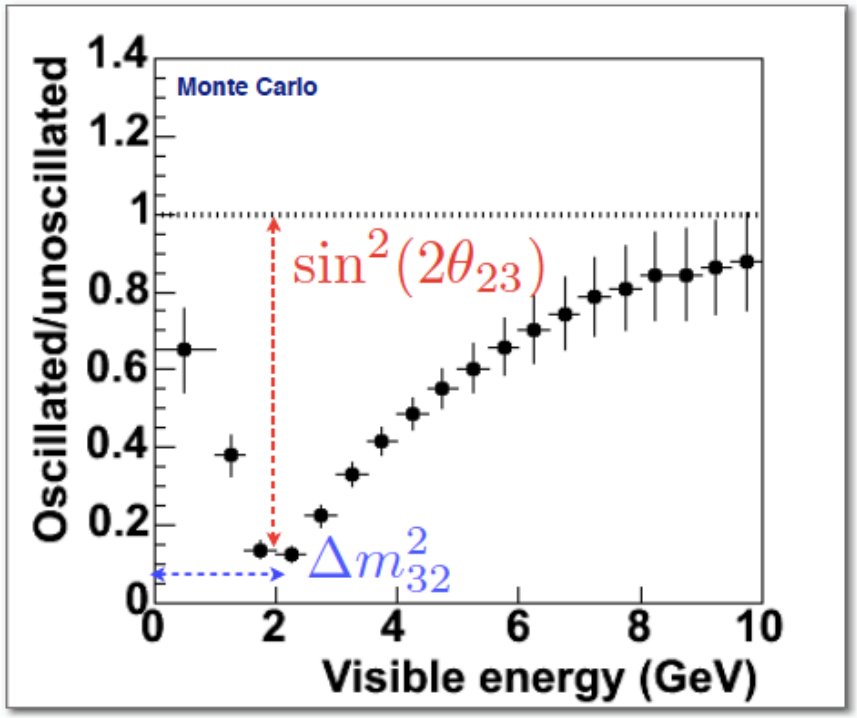
- Additional Physics Goals:
  -Neutrino cross-sections and interaction physics
  -Sterile Neutrinos
  -Supernovae and Exotic Searches

Goals of NOvA Experiment

ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{atm} L}{E}\right)$$





Goals of NOvA Experiment

ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

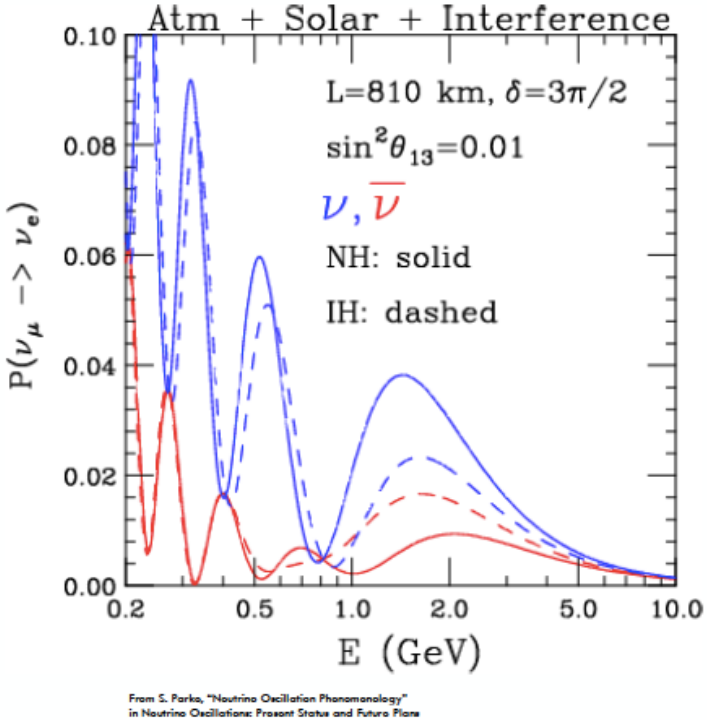
$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

Solar term contributes <1% at ~400 L/E

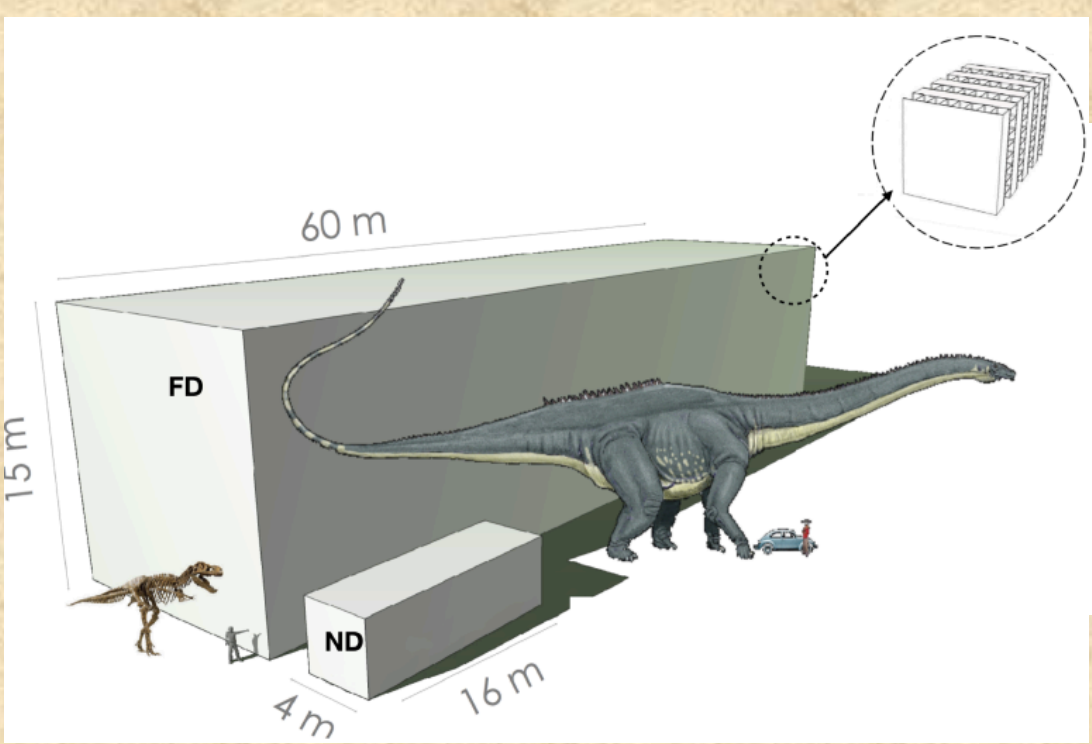
Precision with which this appearance can measure δ_{CP} and MH depends on the precision of the measurement of ϑ_{23}

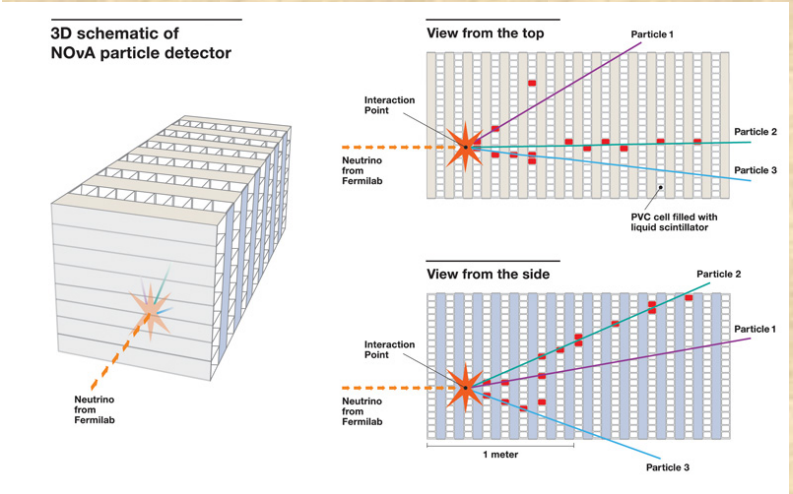
Electron neutrinos experiences an extra interaction as they pass through matter, modifying the oscillation probabilities, thus giving us an extra handle on MH

Additional measurements of Δm^2_{21}, θ_{12} and θ_{13}



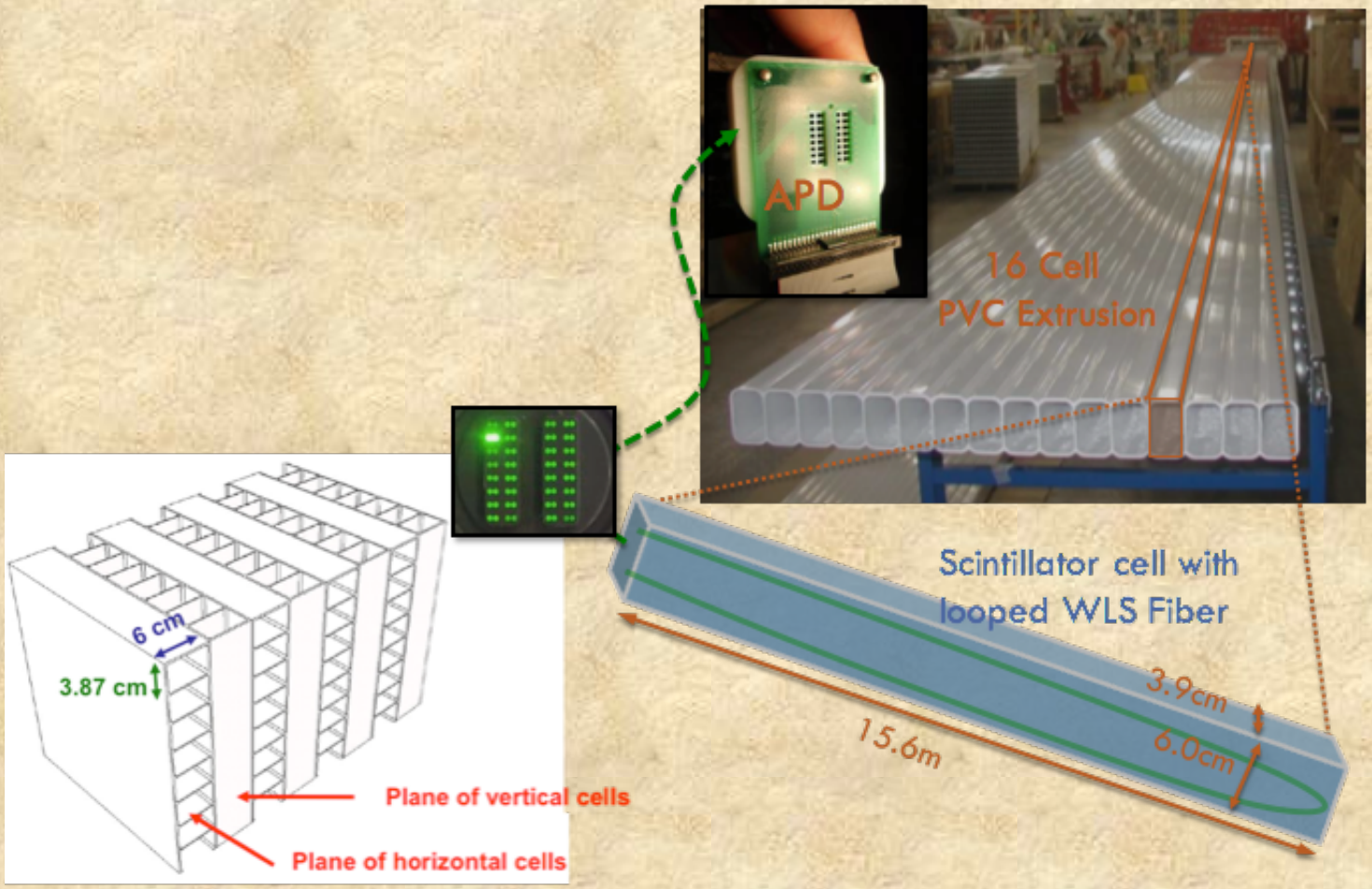
NOvA Detectors





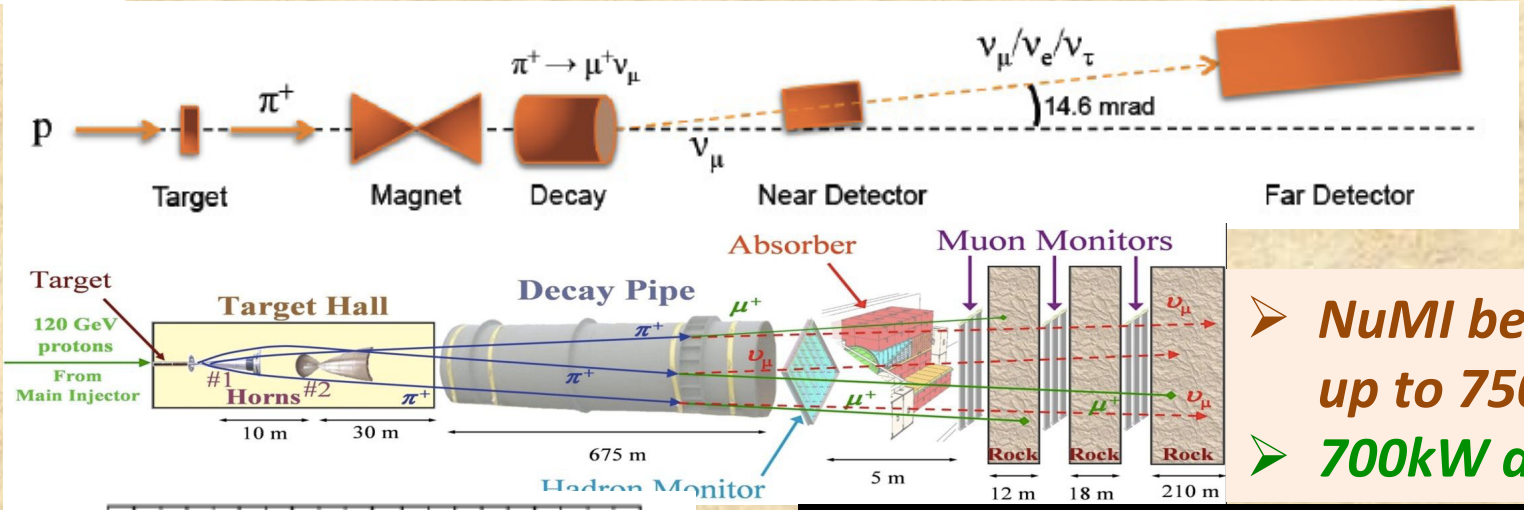
- ✓ ***14 kton Far Detector, low-Z tracking calorimeter, 810 km from the source, on the surface, 3 m.w.e overburden, 65% active detector mass***
- ✓ ***0.3 kton Near Detector at 1 km from source, at a depth of 100m***
- ✓ ***Detector response simulation significantly improved with the addition of Cherenov light reducing larger uncertainties of the previous results***

NOνA Detectors

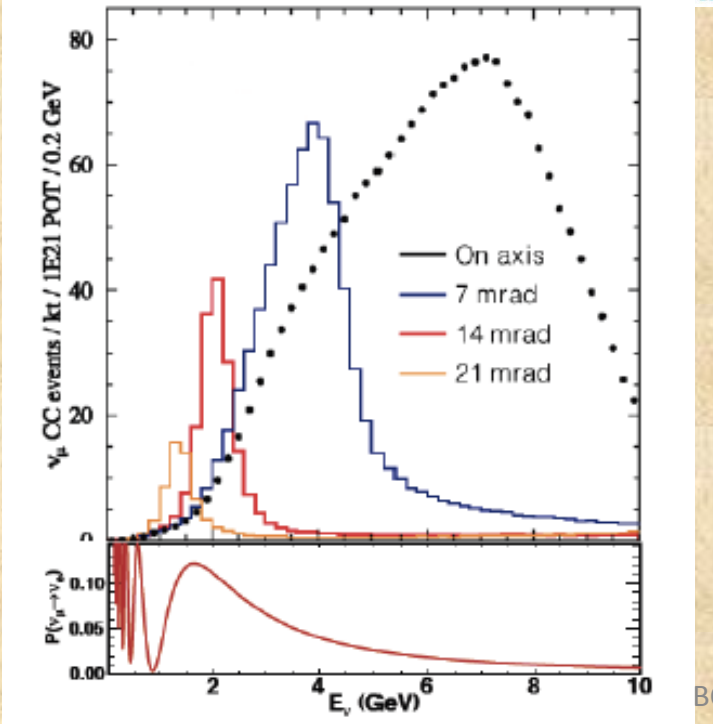


- ***PVC extrusion + Liquid Scintillator, 11M liters of mineral oil + 5% pseudocumene***
- ***Read out via WLS fiber to 32-pixel APD, FD has 344,064 channels, ND has 18,000 channels, muon crossing far end at FD~25 PE***
- ***Layered planes of orthogonal views, 0.15 X_0/layer, excellent for e identification.***

NOvA Off-Axis Beam



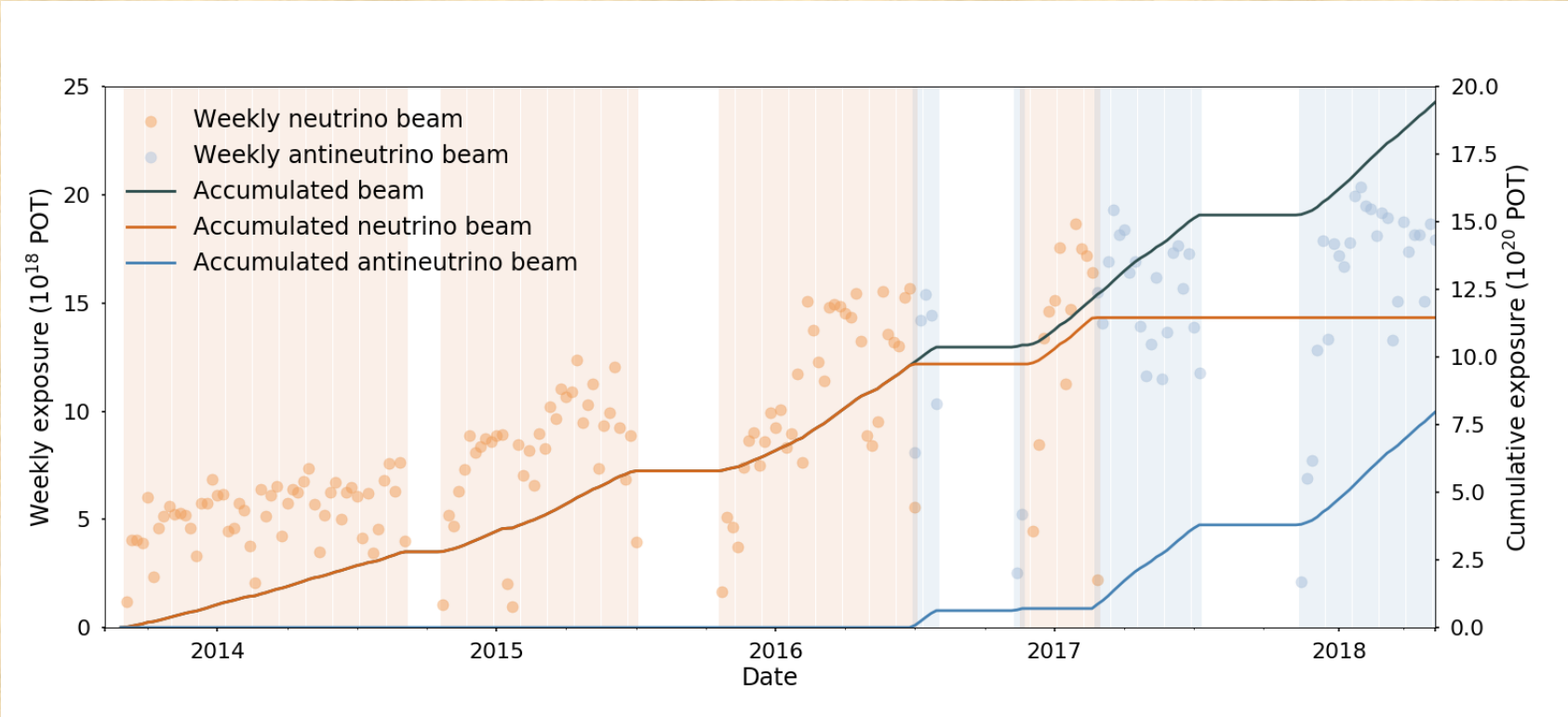
- NuMI beam operated up to 750 kW
- 700kW achieved



Detectors placed at 14.6 mrad off-axis from the beam direction

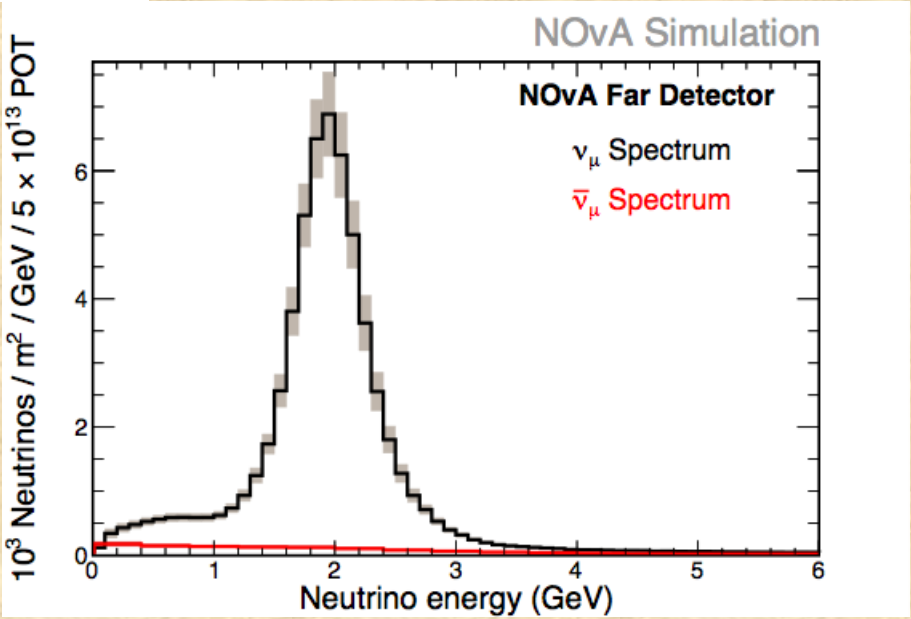
- ✓ This leads to a narrow band beam peaked at ~2GeV energy
- ✓ This happens near the maximum oscillation
- ✓ Leads to reduced high energy Neutral Current (NC) events

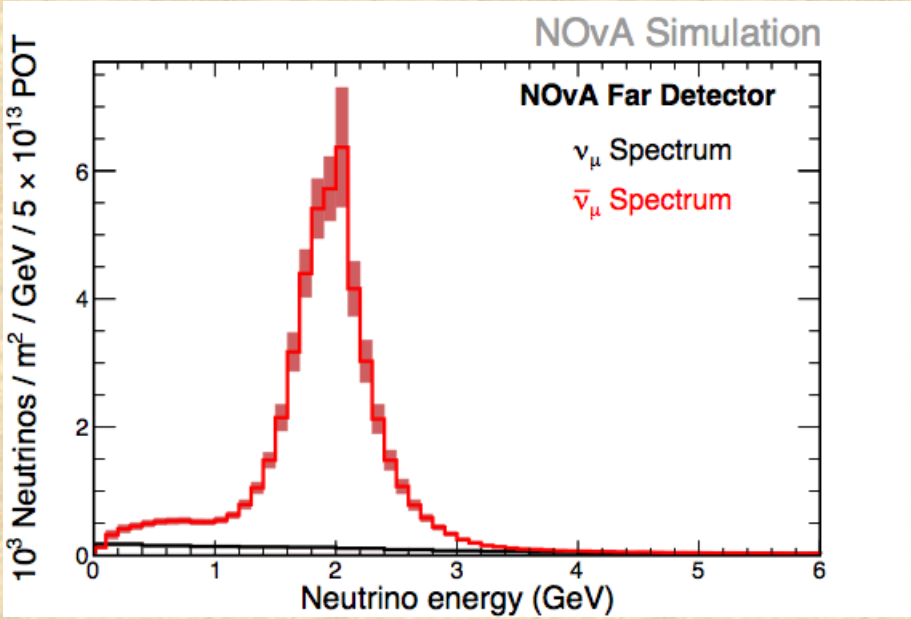
NOνA Beam Performance and Exposure



1. NuMI beam operating at 700kW power since January 2017.
2. >18 X 10^{18} protons/week.
3. Highest power neutrino beam in the world.
4. Neutrino Data: 8.85X10^{20} POT, from 2/2014 – 2/2017.
5. Anti-neutrino Data: 6.9X10^{20} POT, from 2/2014 – 4/2018.

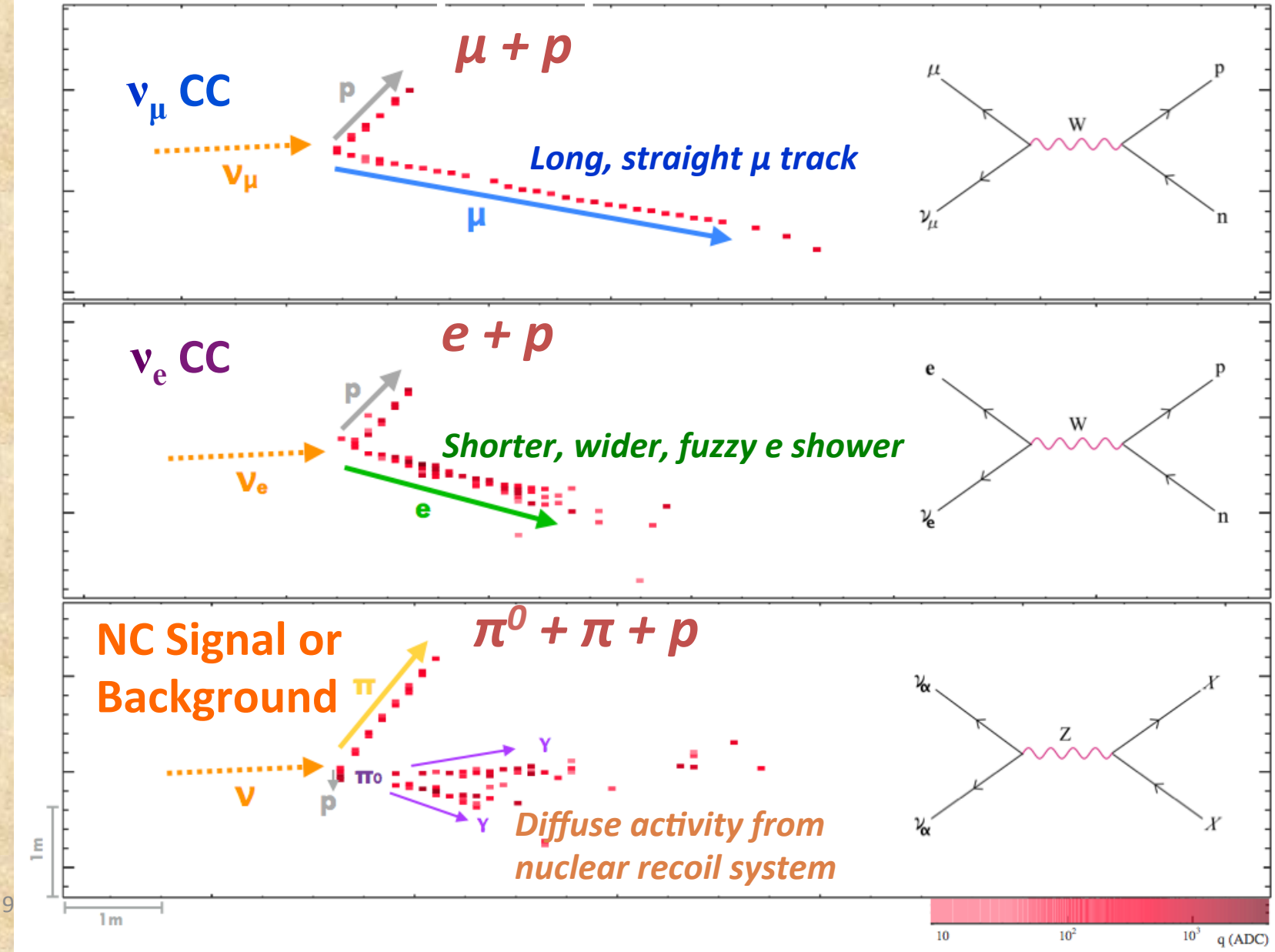
NOvA Beam Performance and Exposure



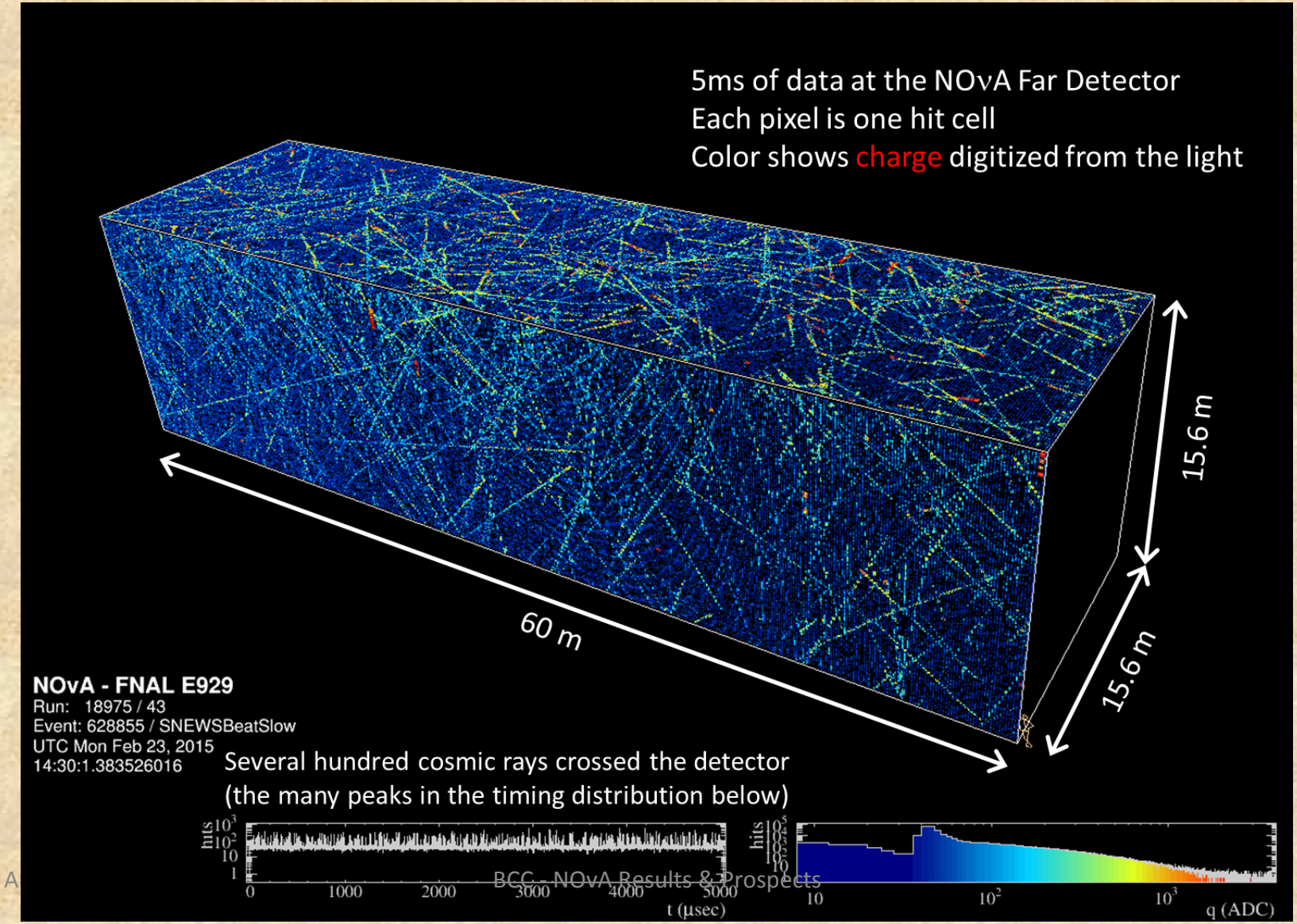


- *Off-axis at 14 mrad, peaks just above the oscillation maximum. Small wrong sign component for both beams.*
- *The prediction of the NuMI beam at the NOvA detectors is made using the package to predict the FluX (PPFX), a method developed by MINERvA (Phys. Rev. D 94, 092005. 2016).*
- *The beam optics uncertainties are also incorporated by propagating the errors in the alignment of the beam-line elements such as the horn and NuMI target geometries, magnetic fields, etc.*

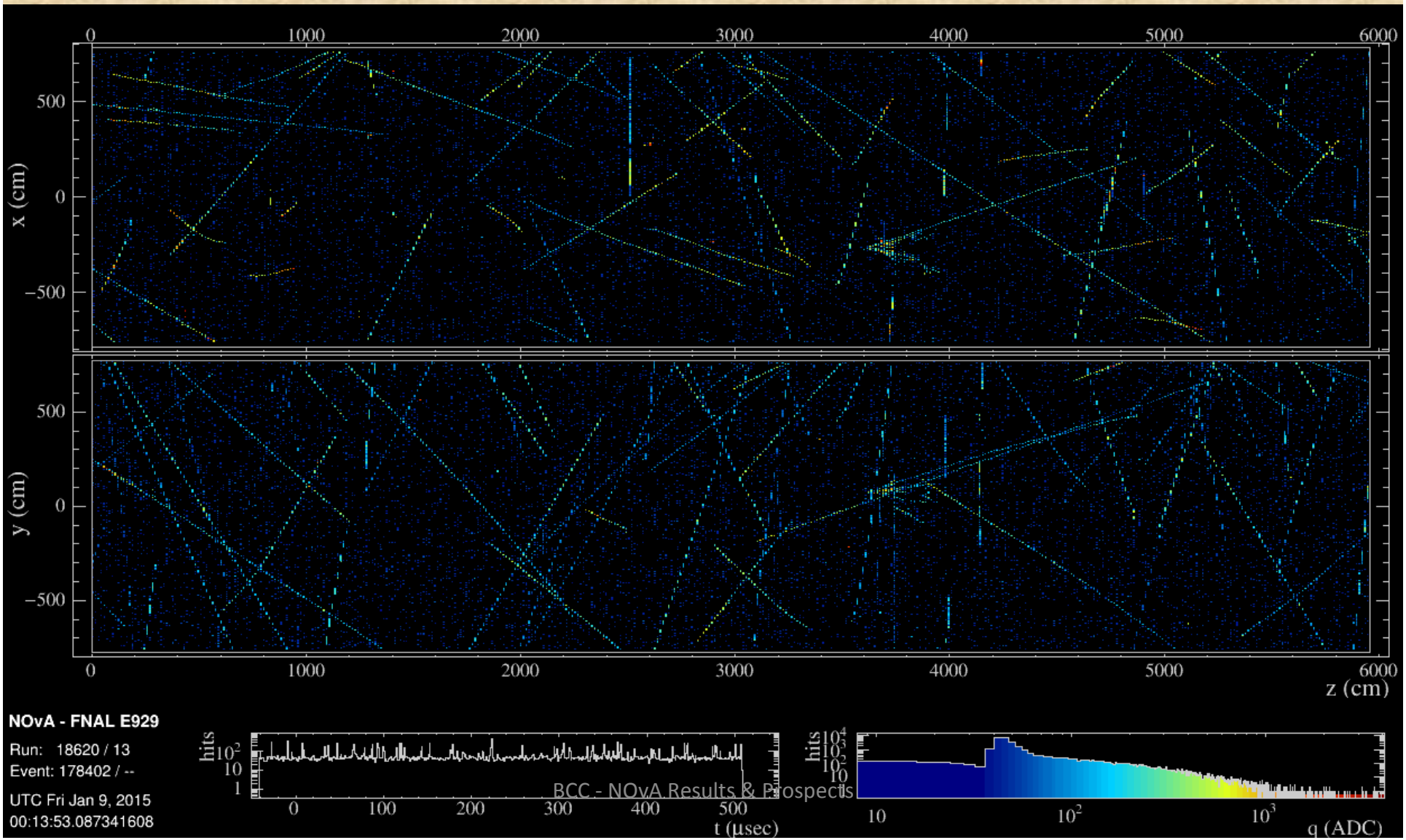
NOνA Event Topologies



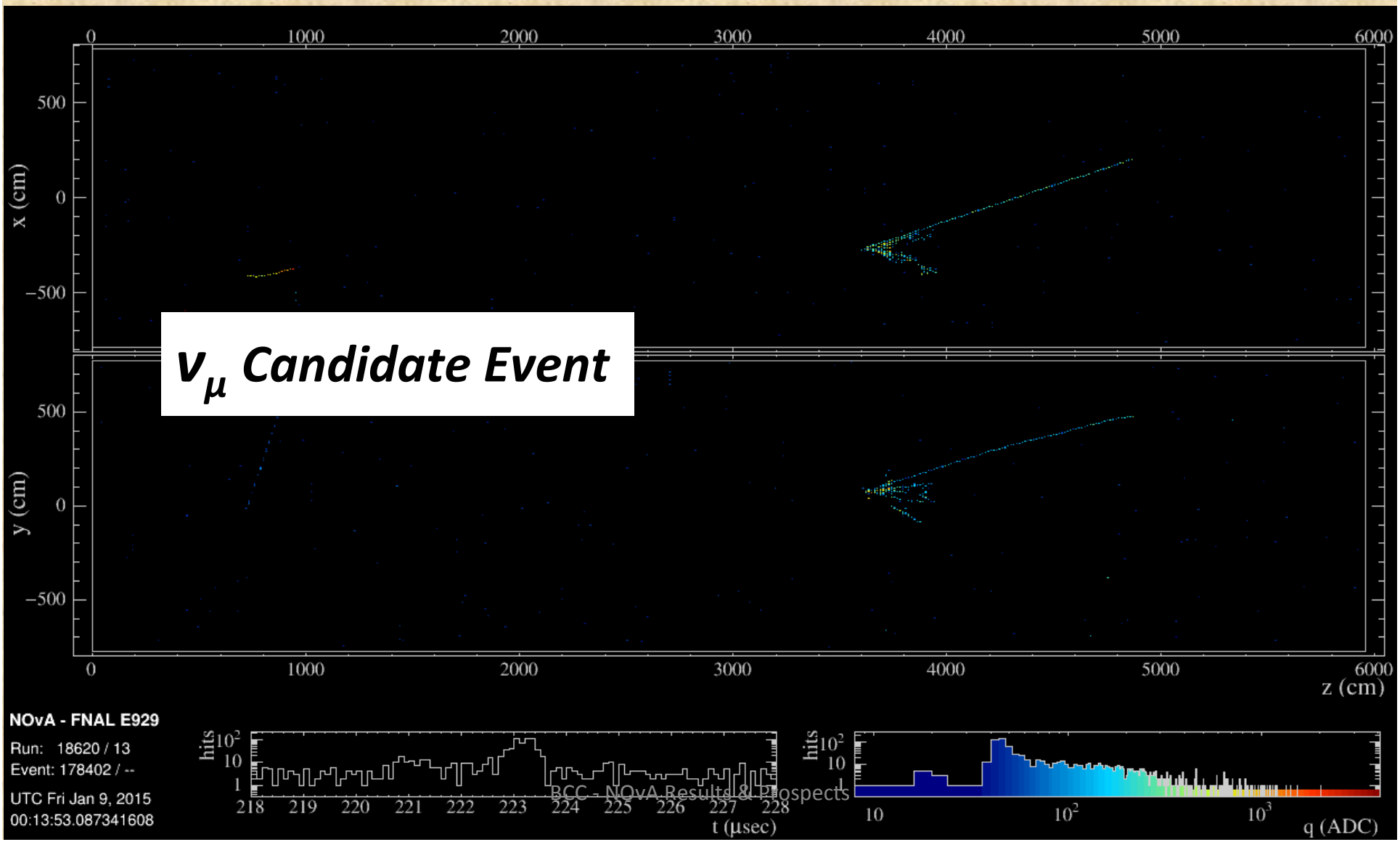
NOνA FD ~ 5 ms Block



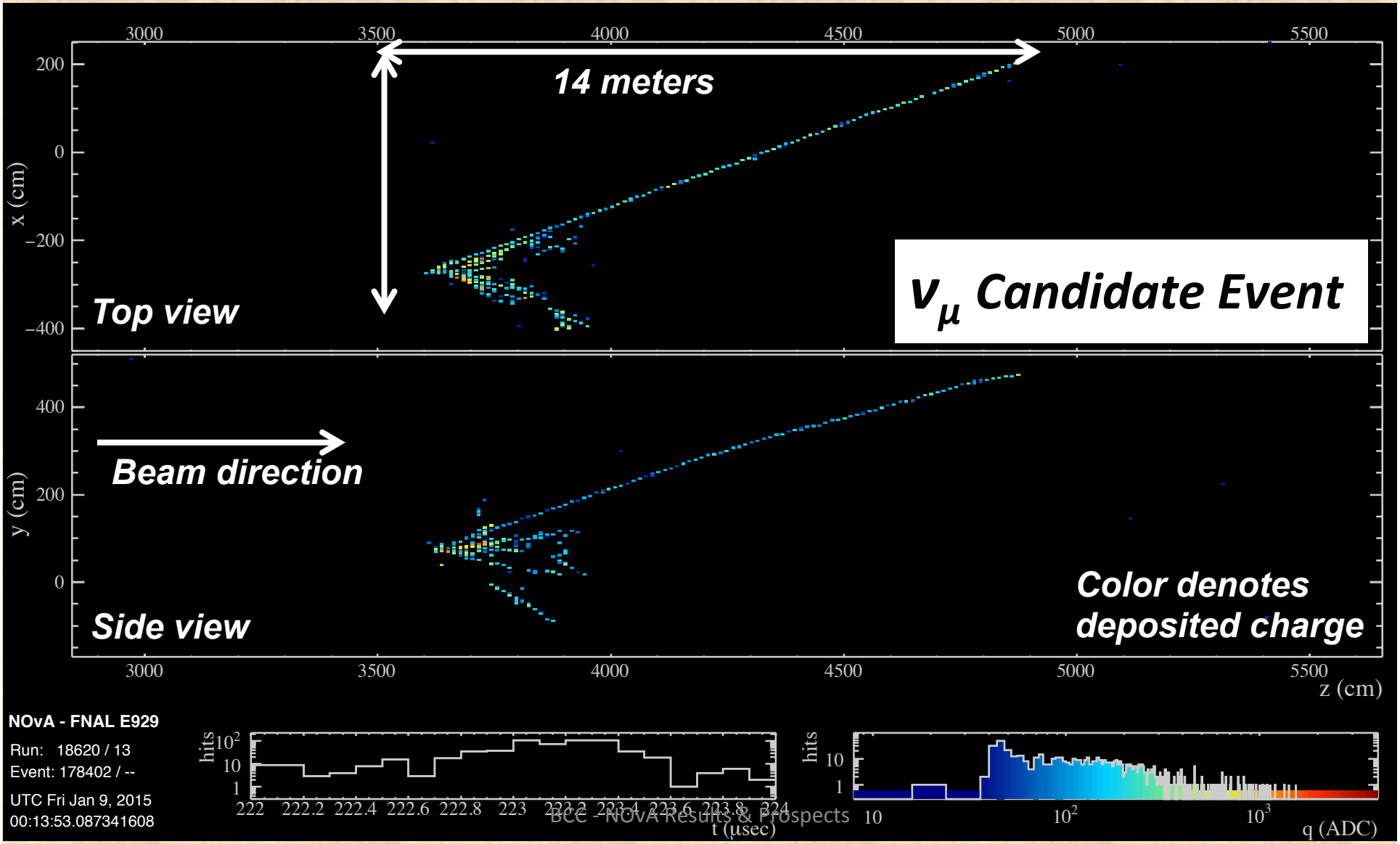
NOvA FD ~ 500 μs around a NuMI Spill



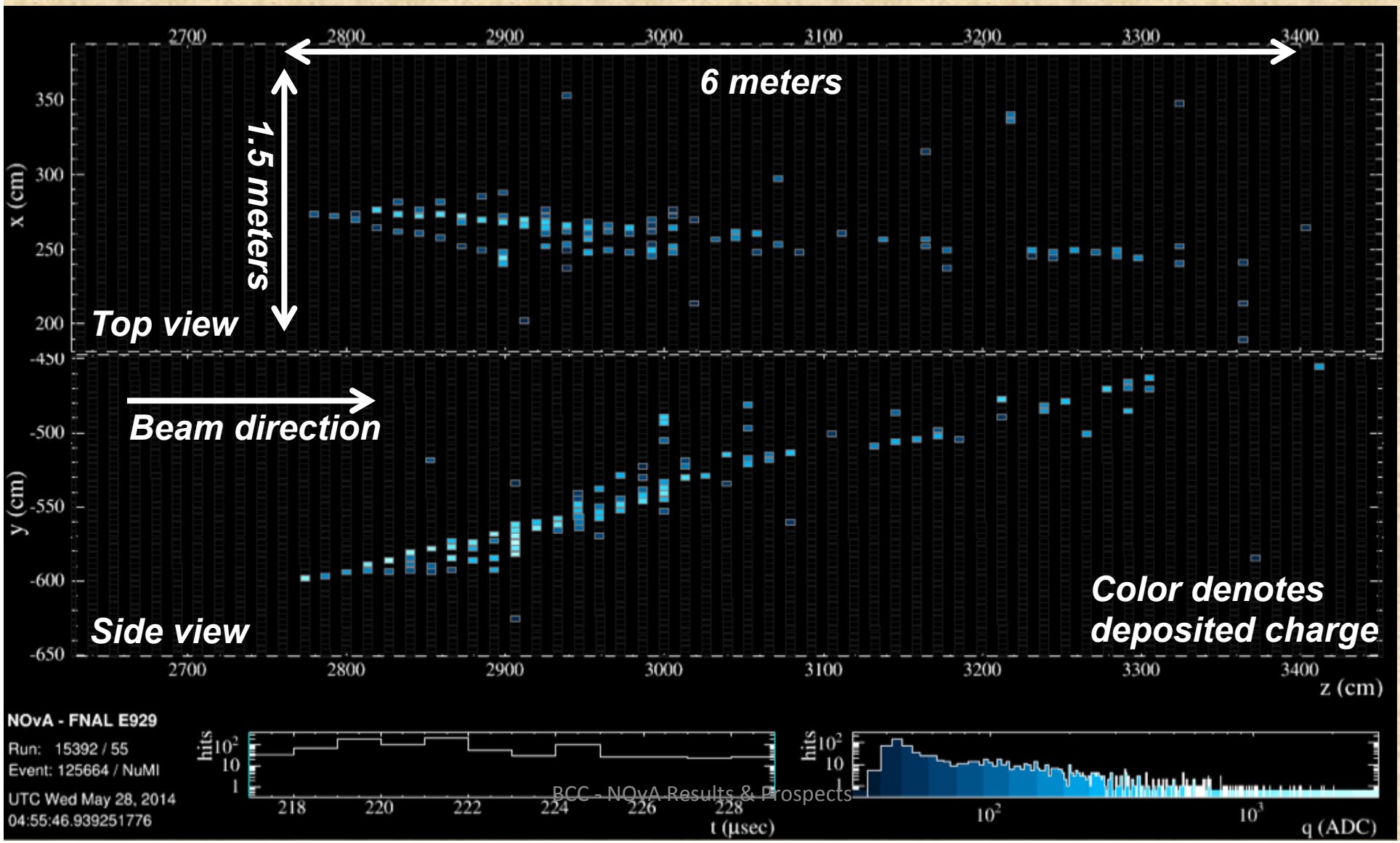
NOνA FD ~ 12 μs Beam Window



NOνA FD - ν_μ Candidate Event

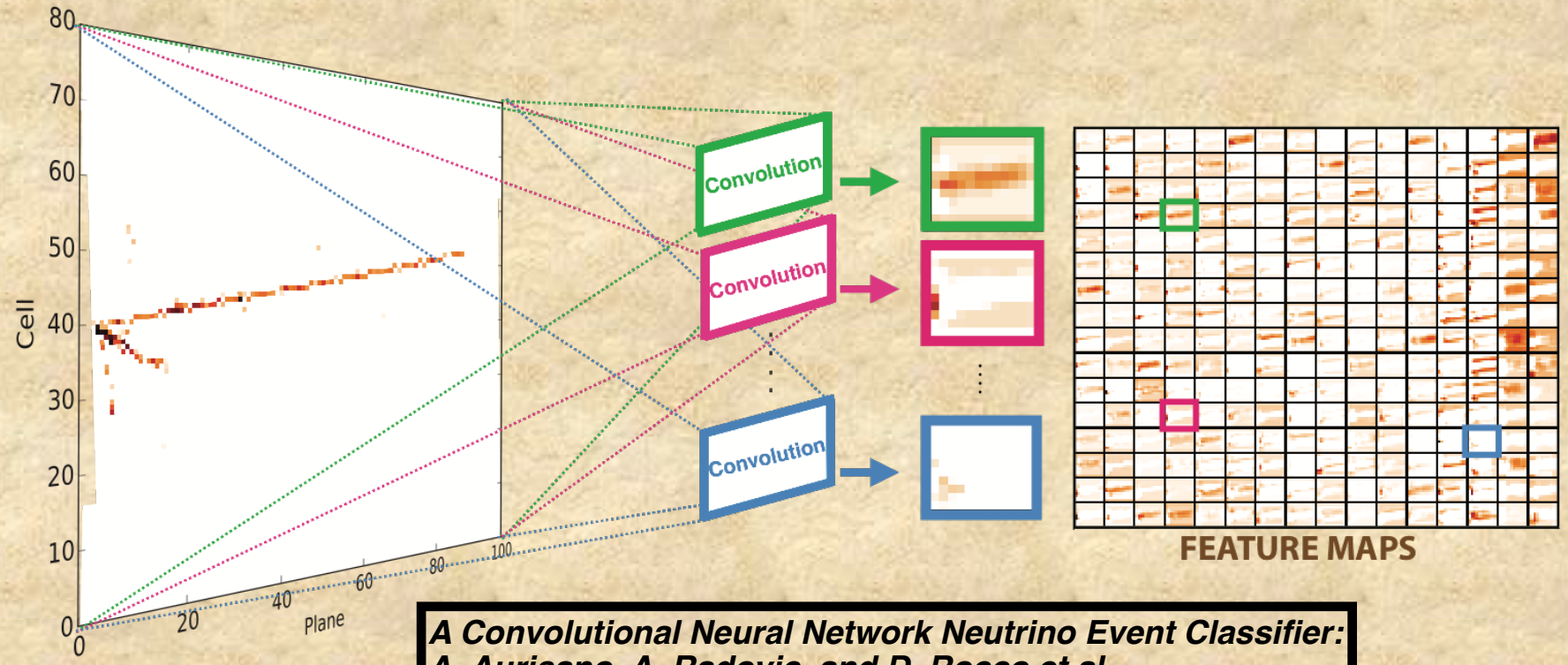


NOνA FD - ν_e Candidate Event



Neutrino Interaction Classifier

- *NOvA has pioneered the use of Convolutional Visual Networks (CVN) based on Convolutional Neutral Network for particle classification in neutrino physics*
- *Using this technique we treat each interaction as an image with cells as pixels and charge as color value. The convolutional layers optimally extract features from the data.*
- *The NOvA architecture is a multi-classifier, assigning an output ID: ν_μ CC, ν_e CC, NC, cosmic for each interaction.*

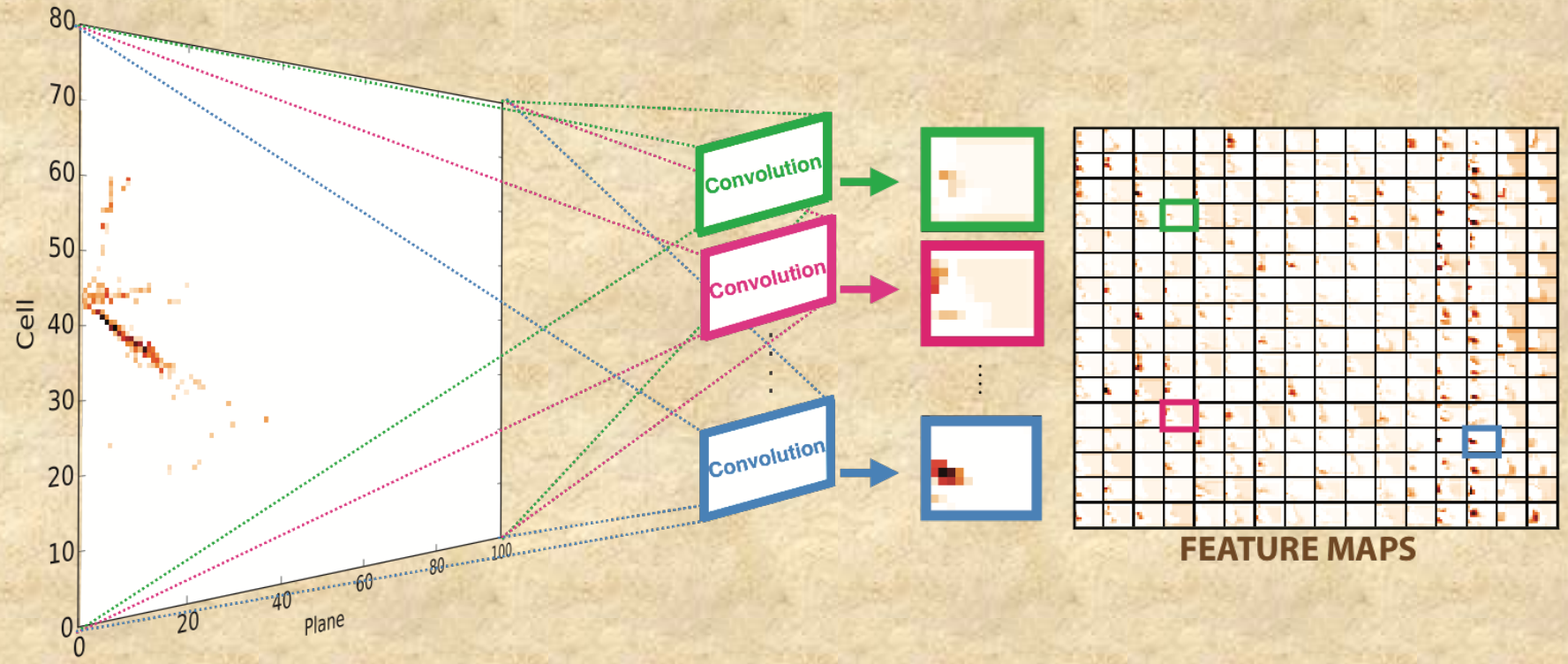


A Convolutional Neural Network Neutrino Event Classifier:
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

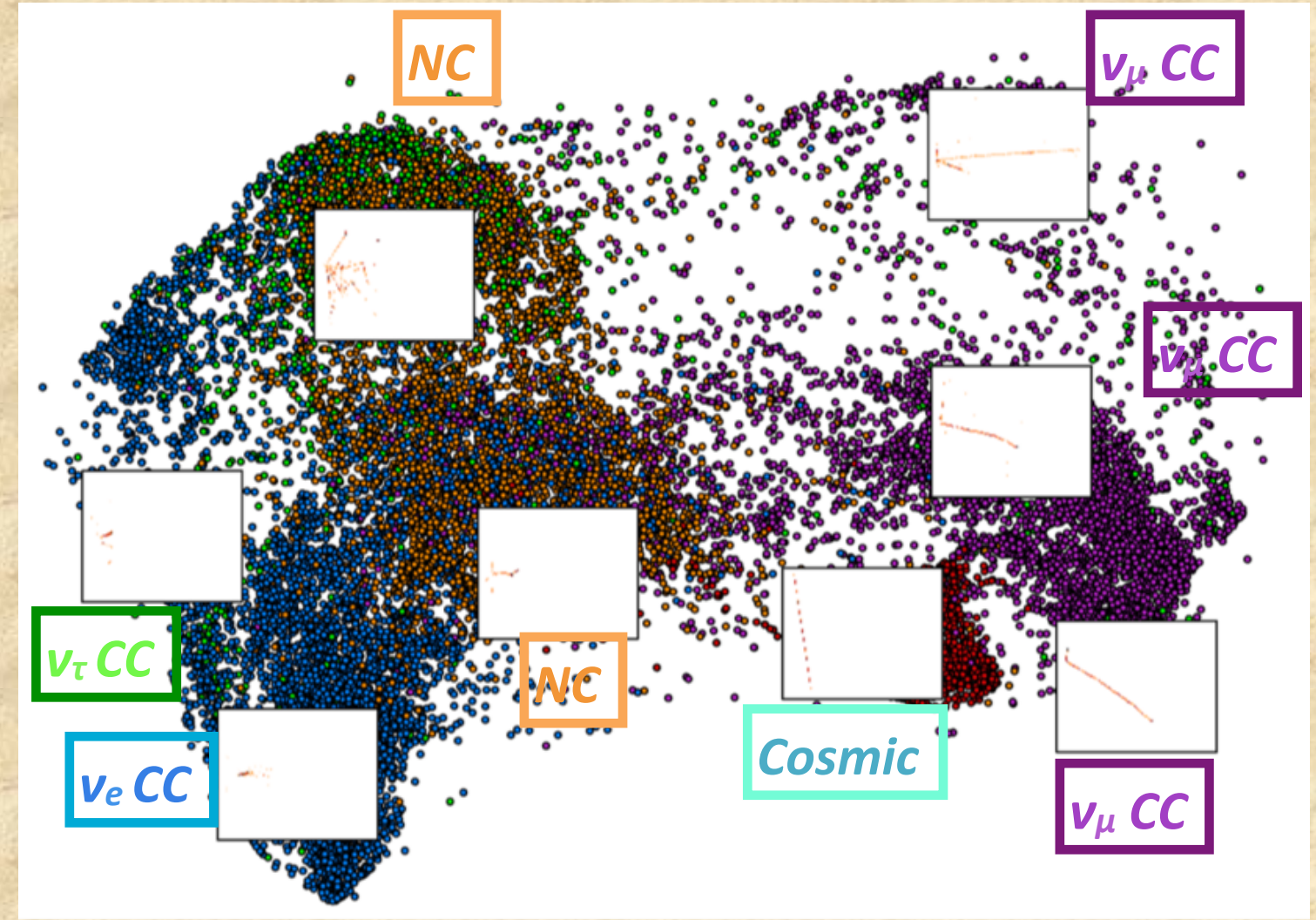
Neutrino Interaction Classifier

Showing an electron neutrino interaction and the first layer of feature maps extracted from the convolutional kernels.

The strong features extracted are the shower as opposed to a muon track.

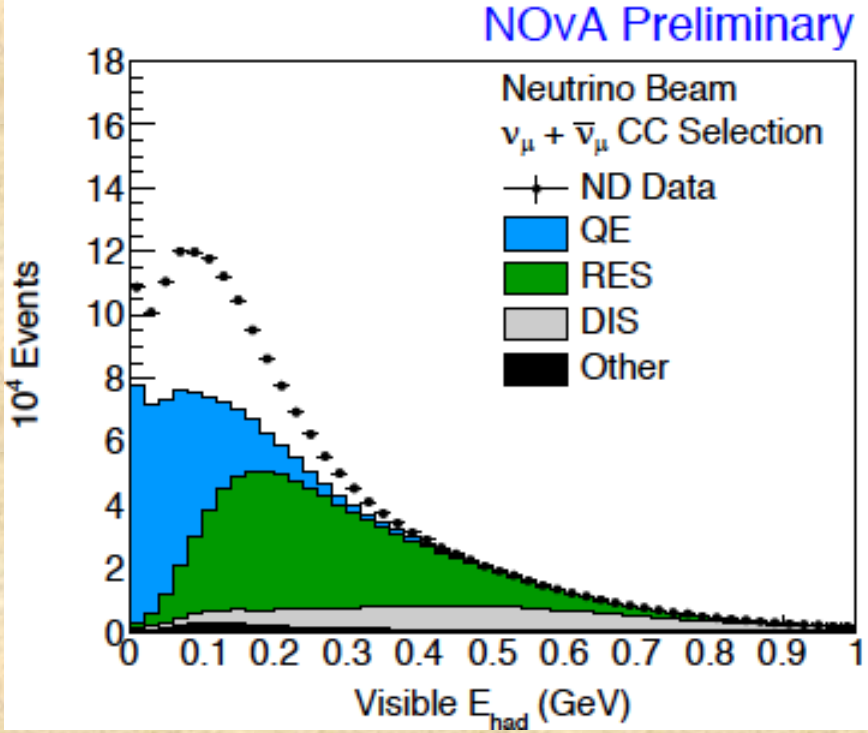


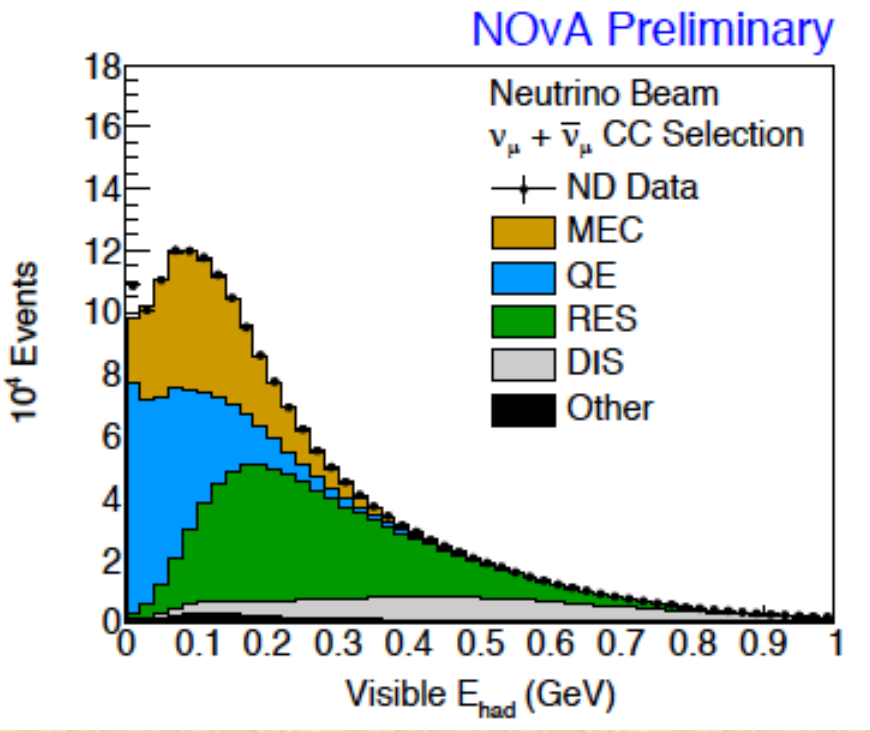
Neutrino Interaction Classifier



The extracted features provide good separation (as shown in this projected 2-dimensional space) among the different types of events. Typical events are shown for each of the areas.

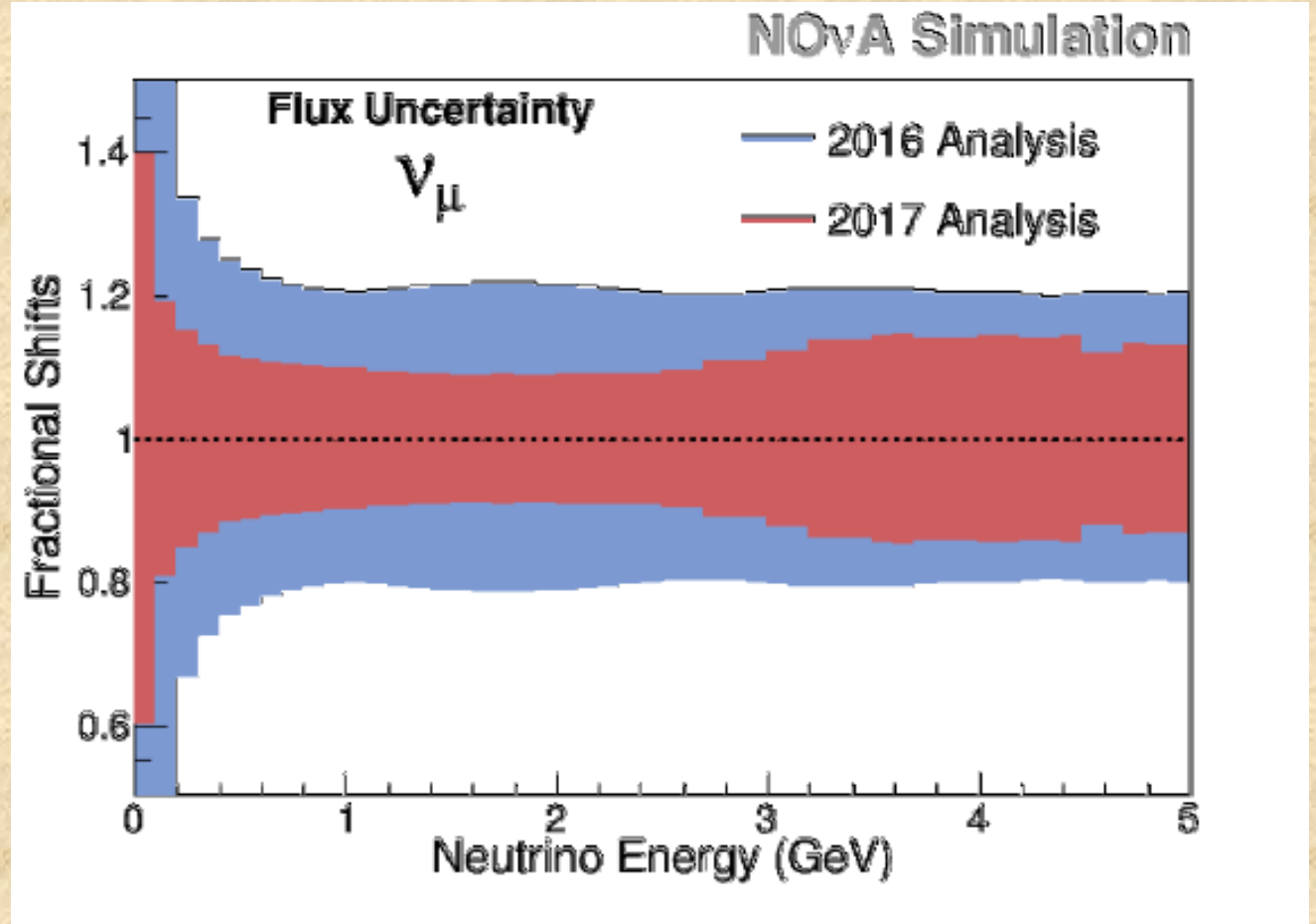
Neutrino Interaction Tuning





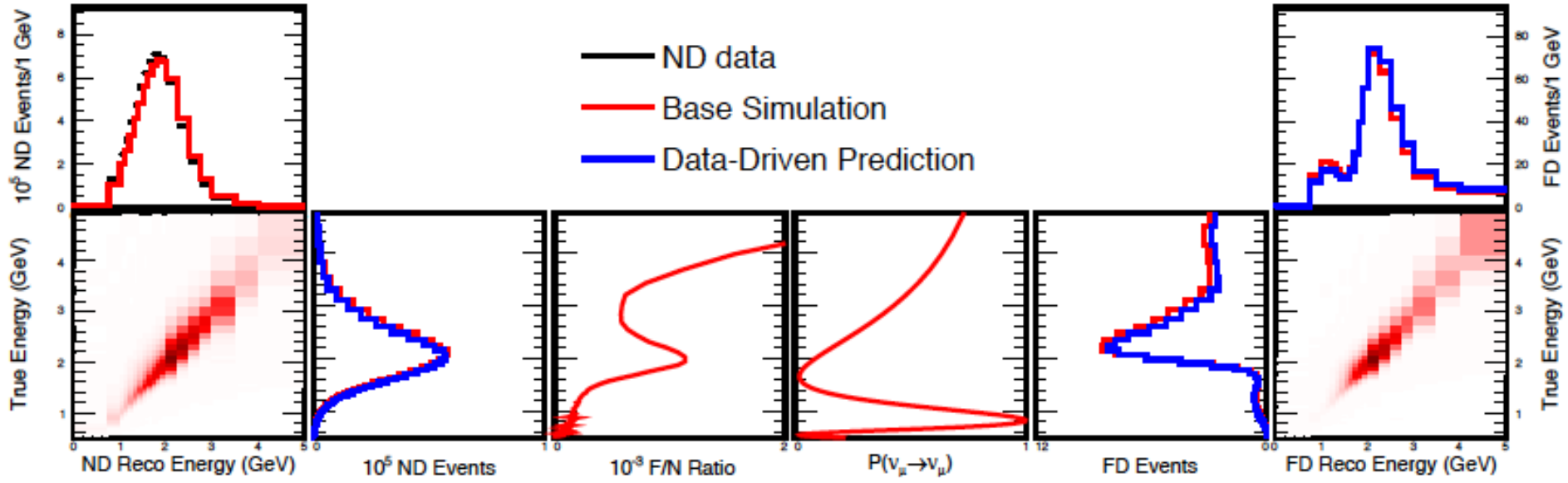
- ✓ *The default GENIE prediction is insufficient to describe the NOvA ND data, i.e, the hadronic energy in ν_μ CC interactions show disagreement with the default simulation*
- ✓ *QE, RES tunes to consider long-range nuclear correlations using Valenia model via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]*
- ✓ *DIS at high invariant mass (W>1.7 GeV/c^2) weighted upto 10% based on NOvA data*
- ✓ *Empirical MEC (Meson Exchange Current) model for multi-nucleon ejection (2p2h) amount tuned in 2D 3-momentum and energy transfers space to match ND data [T. katori, AIP Conf. Proc. 1663, 030001 (2015)]*

Improved Flux Model



Package to predict the flux (PPFX) taken from MINERvA PRD 94, 092005 (2016). Based on thin target hadron production data of NA49 & MIPP. Significantly reduces systematic uncertainties. Central values also changed within prior systematics but not shown here.

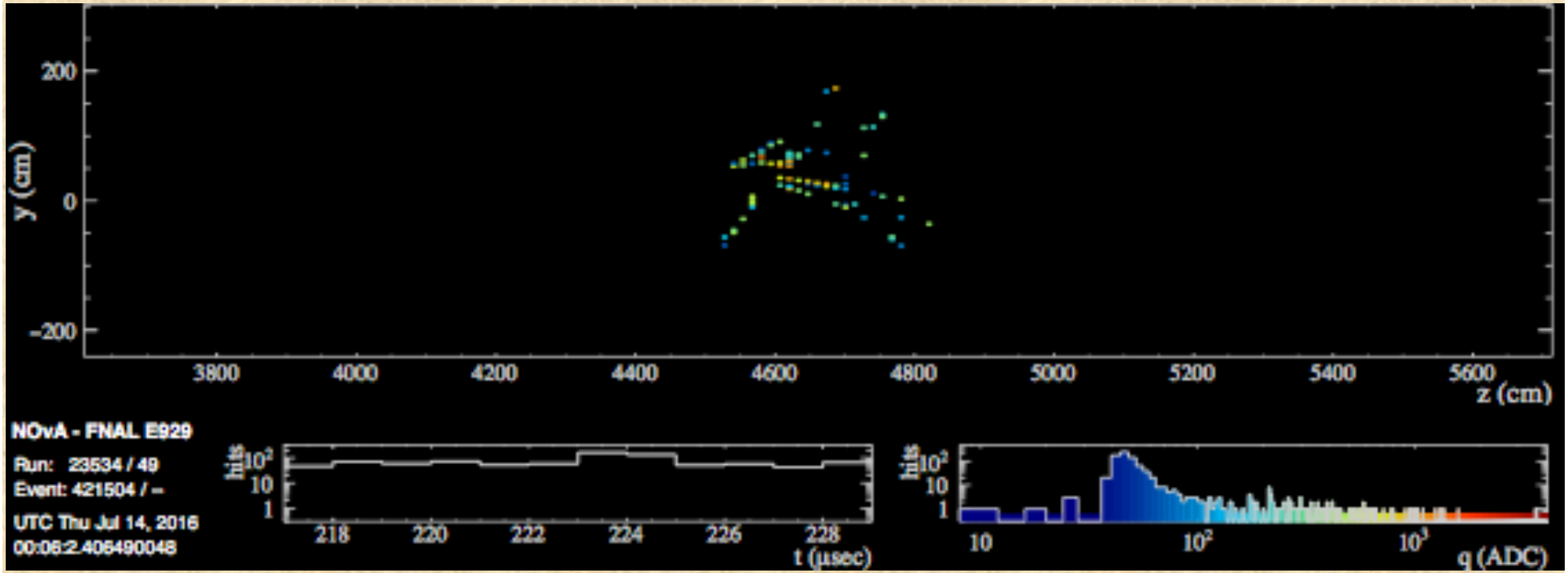
Near Detector to Far Detector Extrapolation



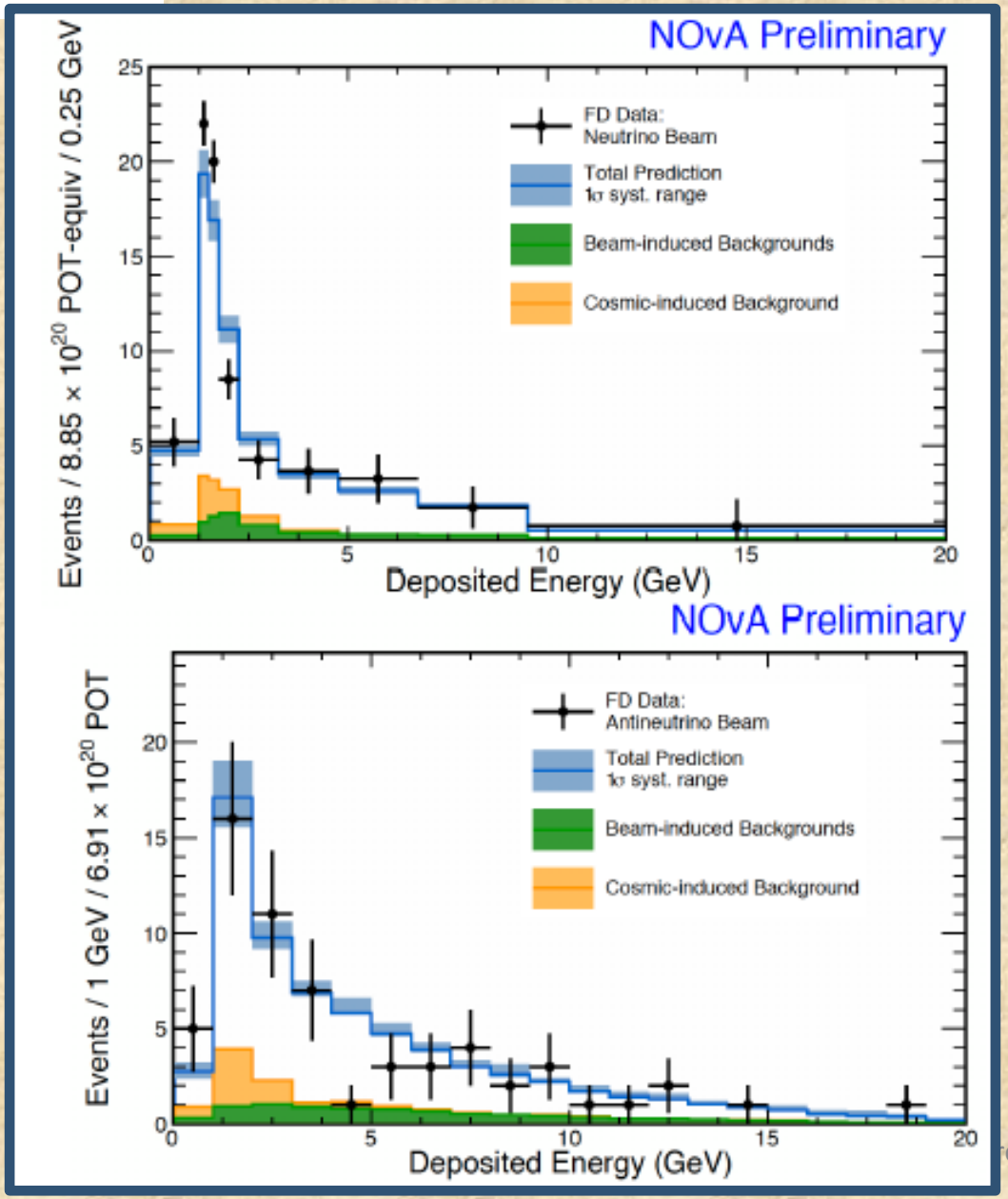
- *The neutrino spectrum is measured at the ND (before oscillation). This is a combination of neutrino flux times cross-section times efficiency.*
- *Use the measured ND spectrum to predict the FD spectrum*
  - *Translate ND data/MC observation to true energy*
  - *Oscillate ratio to the FD*
  - *Smear back into reconstructed energy*
- *Reduces systematic uncertainties due to largely cancellation of flux combined with cross-section uncertainties*

Neutrino and Anti-Neutrino NC Event Disappearance

Are there other neutrinos beyond the three known active flavors?



Observer NC Spectra in the Far Detector



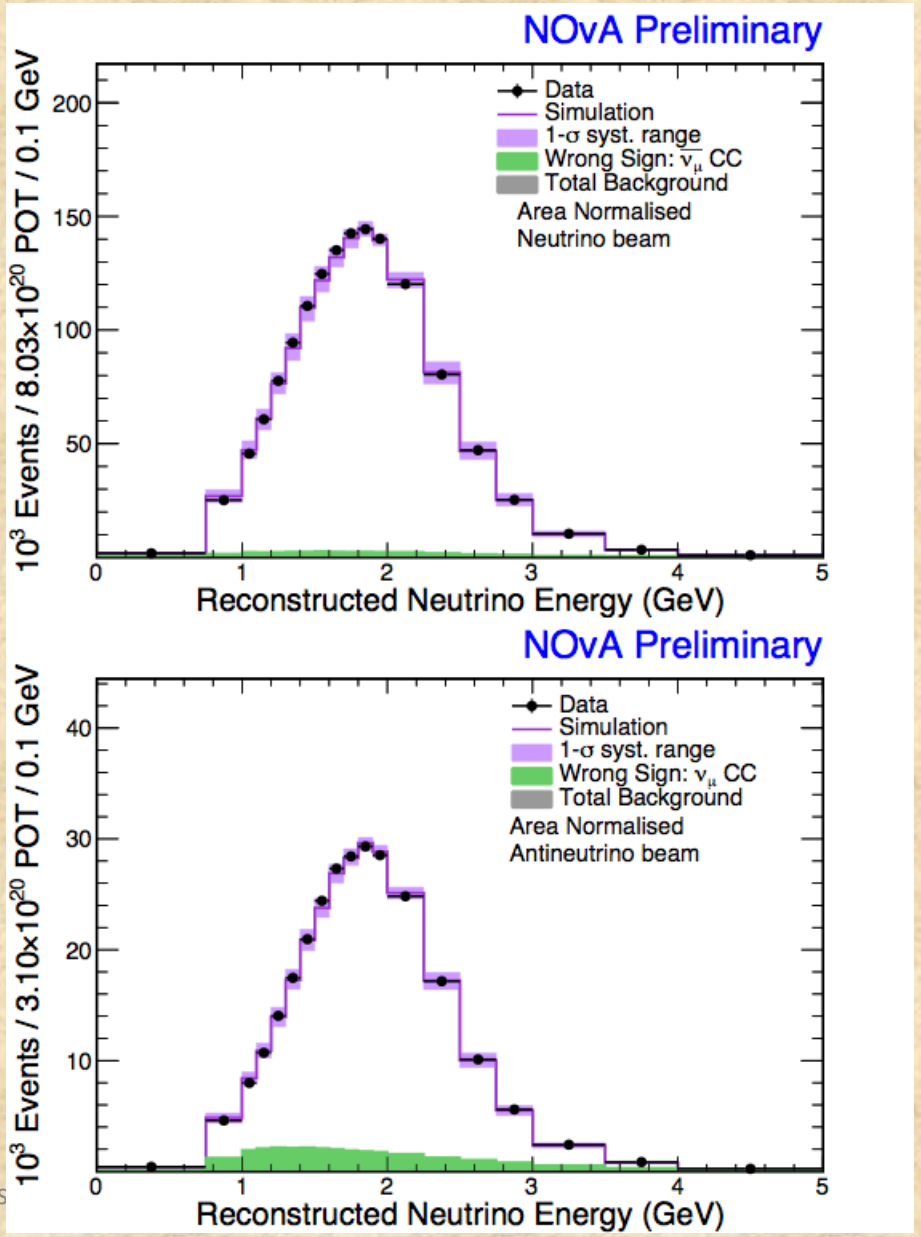
For the neutrino beam:
Observe: 201 events
Predict: 188 ± 13 (syst.)
events (38 background)

For anti-neutrino beam:
Observe: 61 events
Predict: 69 ± 8 (syst.)
interactions (16 background)

No significant suppression of Neutral Current events observed either for neutrino or anti-neutrino beams.

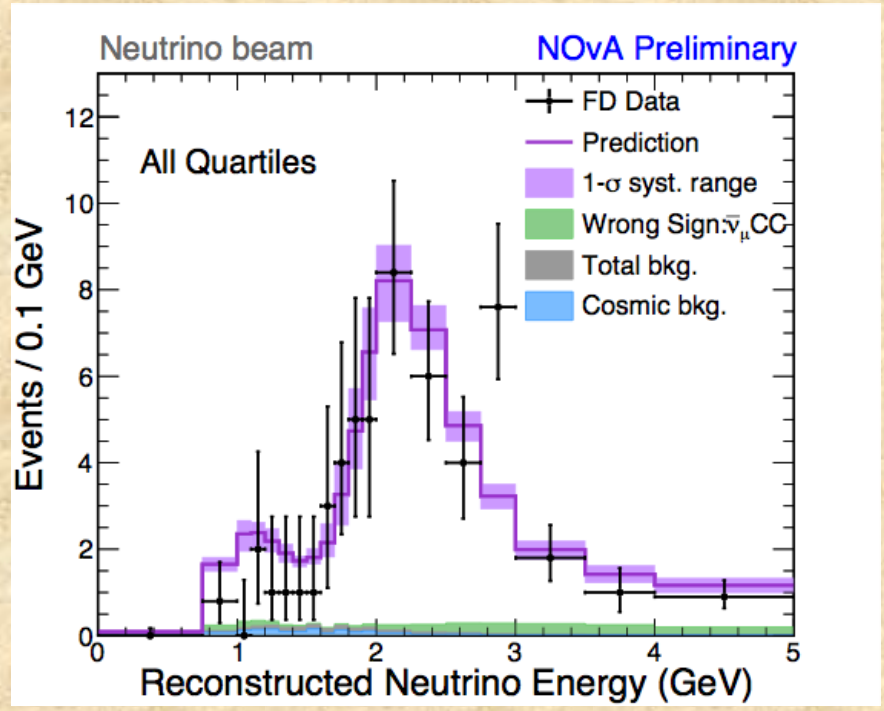
Near Detector Beam Spectra

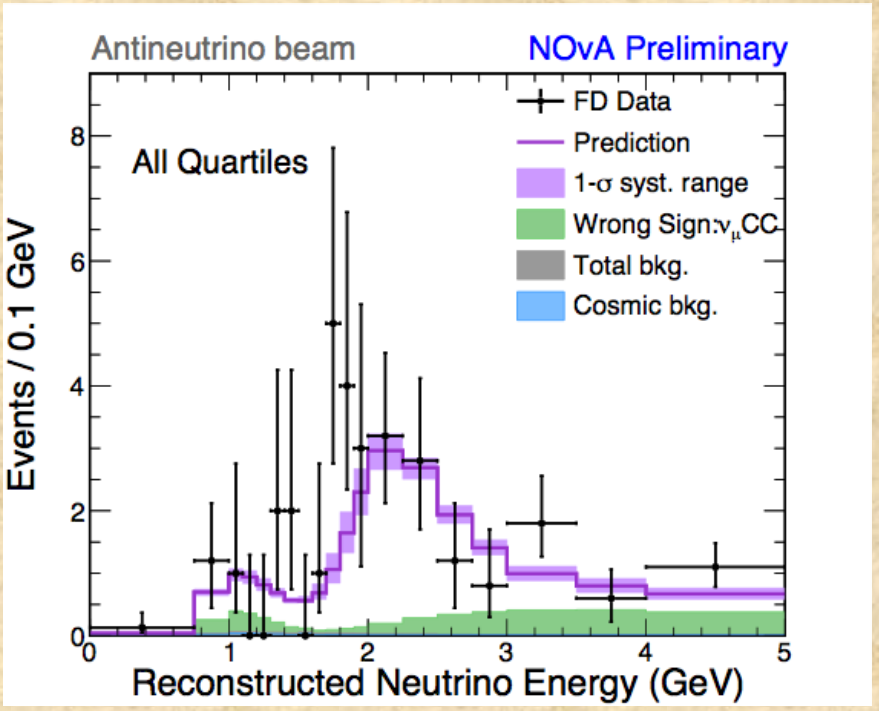
- *Select muon neutrino & antineutrino CC interactions in ND. Reconstructed neutrino energy estimated from muon length & hadronic energy.*
- *Wrong sign contamination in ND estimated to be 3% for neutrino beam and 11% for antineutrino beam.*
- *Systematic uncertainties shown are shape only. 1.3% and 0.5% offset for neutrinos & antineutrinos respectively is removed for display purposes.*
- *The data is split in four equal populations (quartiles) of hadronic energy fraction as a function of reconstructed neutrino energy. Energy resolution varies from 5.8% (5.5%) to 11.7% (10.8%) for neutrino (antineutrino) beam.*



Prediction of the FD Spectra

- *Each quartile for the neutrino & antineutrino beams gets unfolded independently & the true F/N ratio is used to obtain a FD prediction from the ND data.*
- *We estimate cosmic background rate from the timing sidebands of the NuMI beam triggers and cosmic trigger data.*

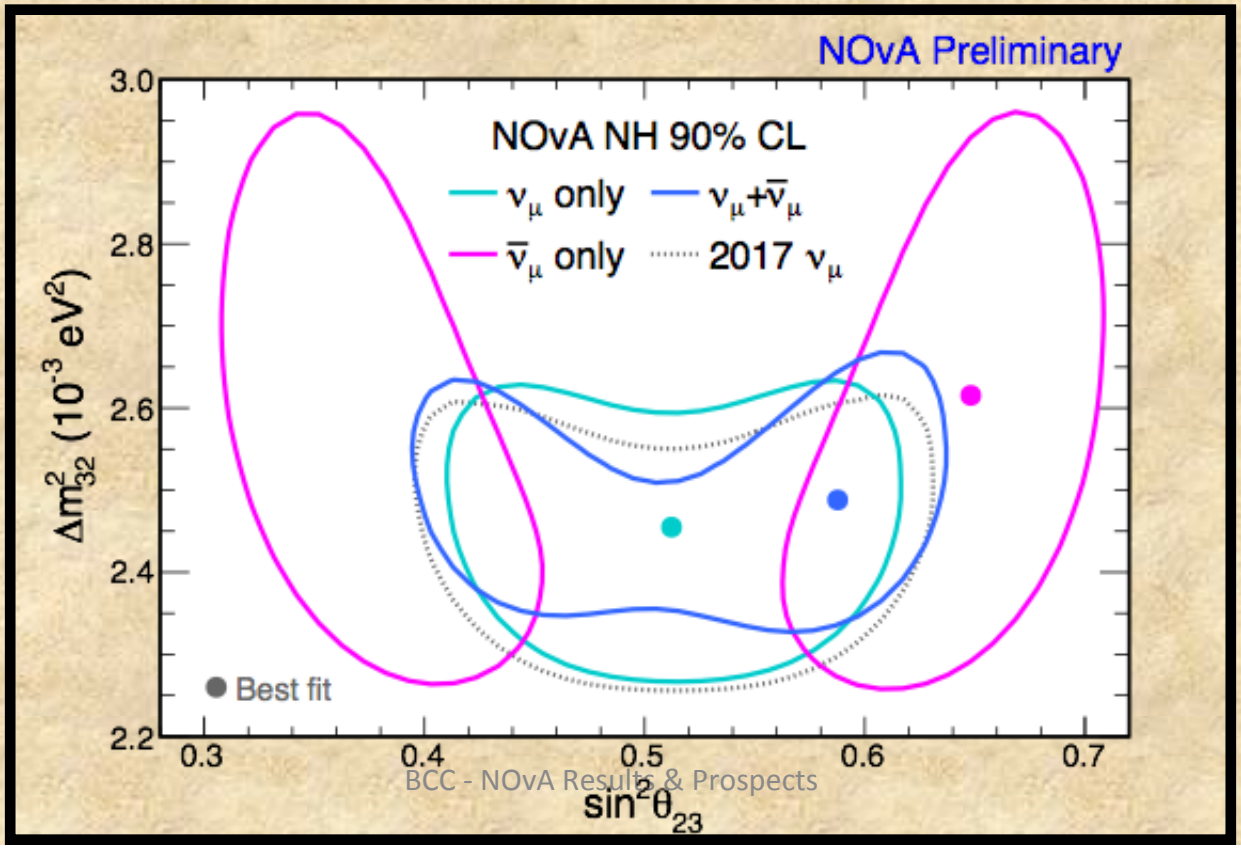




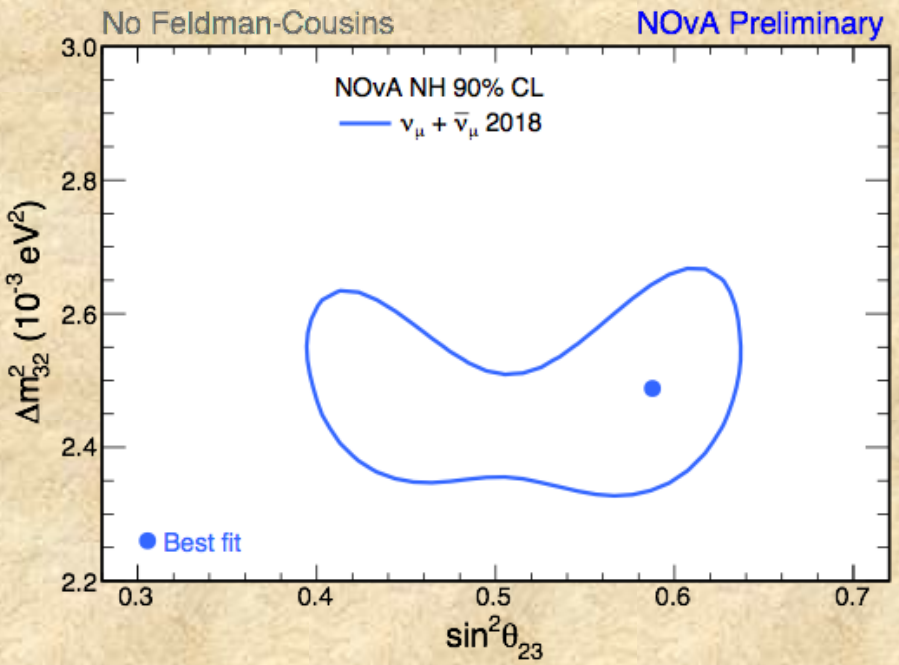
Neutrino Mode: Observe: 113 events; Expect: 730 +38/-49 (syst.) events w/o oscillation
Anti-Neutrino Mode: Observe: 65 events; Expect: 266 +12/-14 (syst.) events w/o oscillation

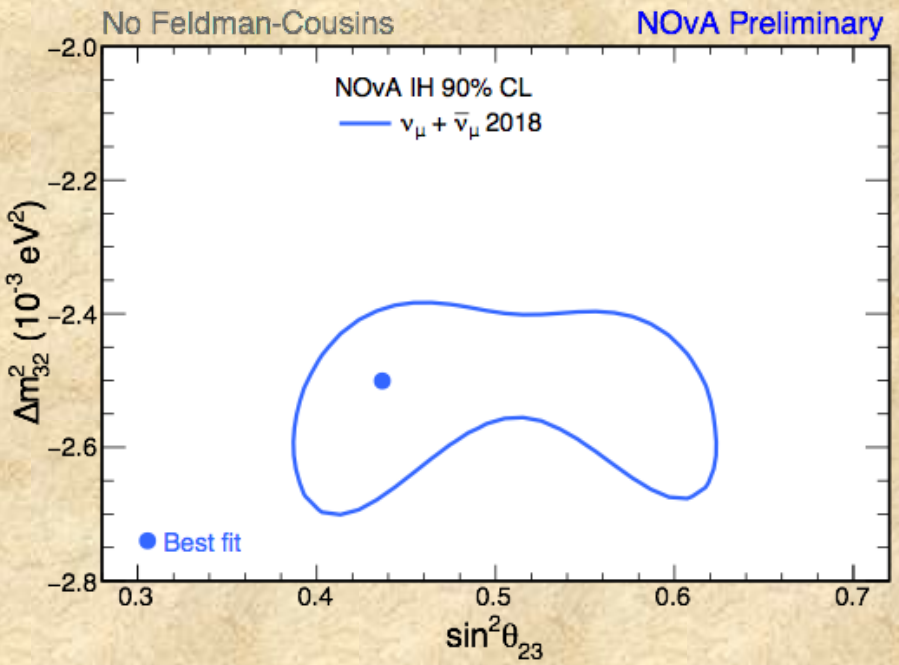
ν_μ Disappearance Results

- ✓ *The combined data of neutrino & antineutrino beams are fit assuming CPT invariance*
- ✓ *Neutrino beam mode: Observe: 113 events, Best fit expectation:126 events*
- ✓ *Anti-neutrino beam mode, Observe: 65 events, Best fit expectation: 52 events*
- ✓ *If fit separately, the anti-neutrino beam mode prefers a more non-maximal solution.*
- ✓ *Consistency with the combined fit oscillation parameters for the neutrino and antineutrino datasets is better than 4% (32% for neutrino-only compatibility and 14% for antineutrino-only). Combined data is consistent with the previous results.*



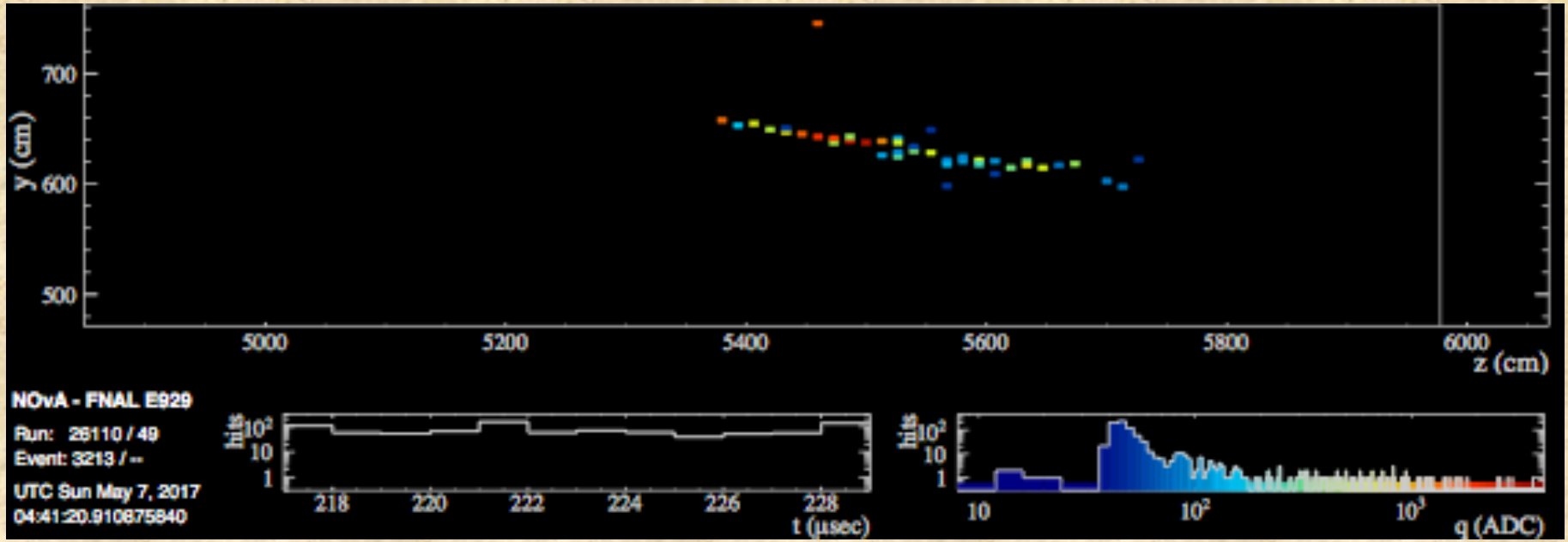
ν_μ Disappearance Results





- ✓ *Matter effect introduces a small asymmetry in the maximal disappearance point between neutrinos and anti-neutrinos*
- ✓ *Tension between the muon neutrino and antineutrino dataset (at the 1σ level) favors upper octant for normal hierarchy and lower octant for the inverted hierarchy*

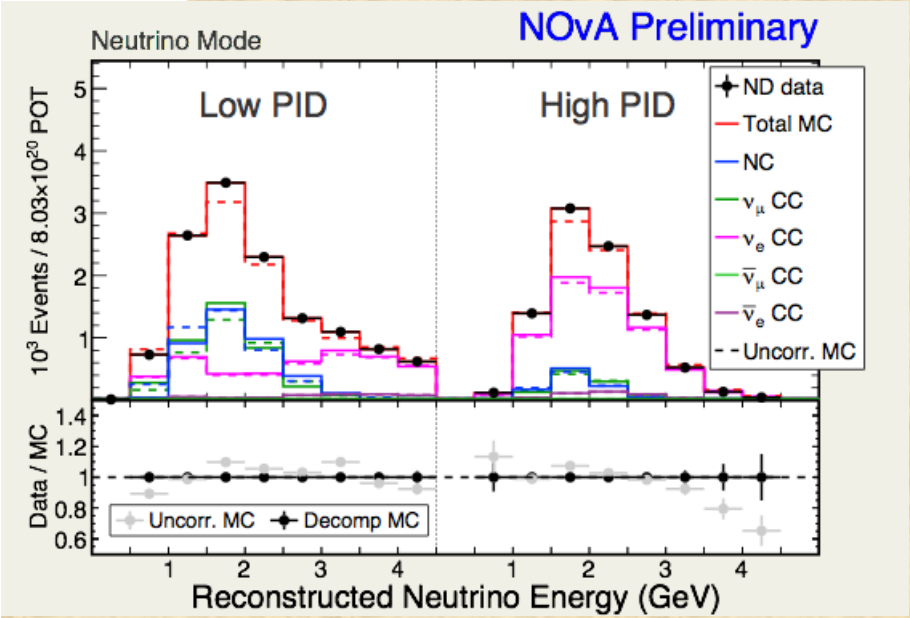
ν_e and ν_{ebar} Appearance

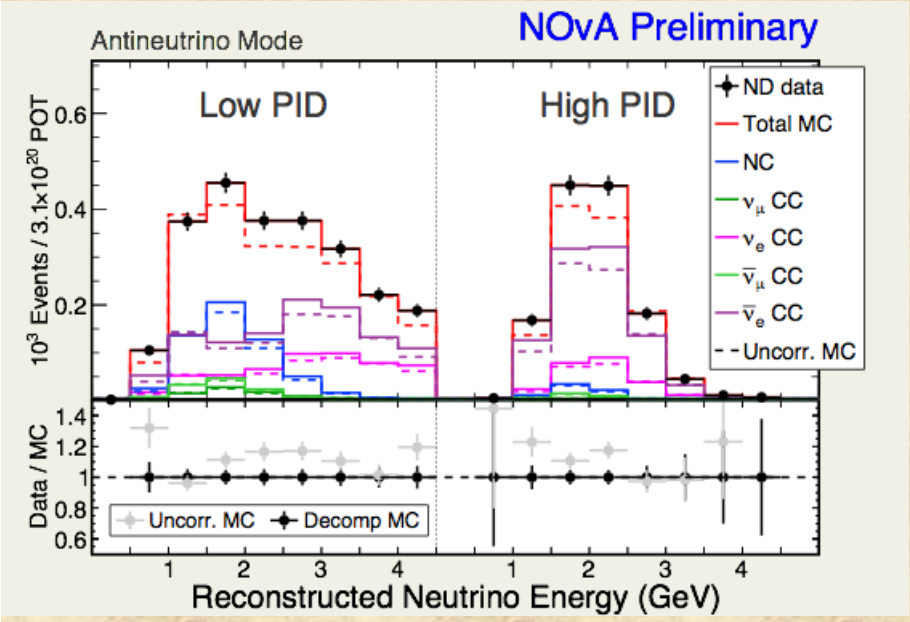


What is the Mass Hierarchy or Ordering?

Is CP violated in the lepton sector?

Near Detector ν_e Data

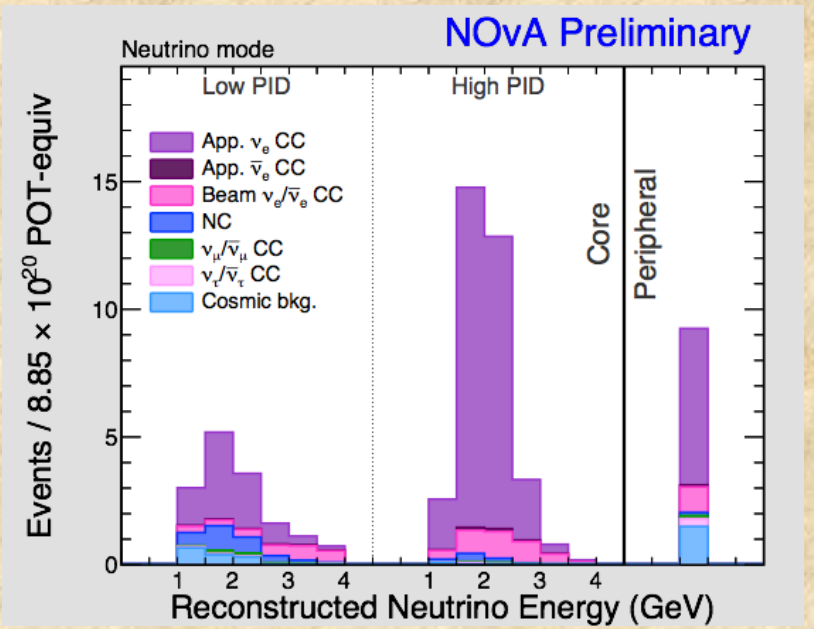


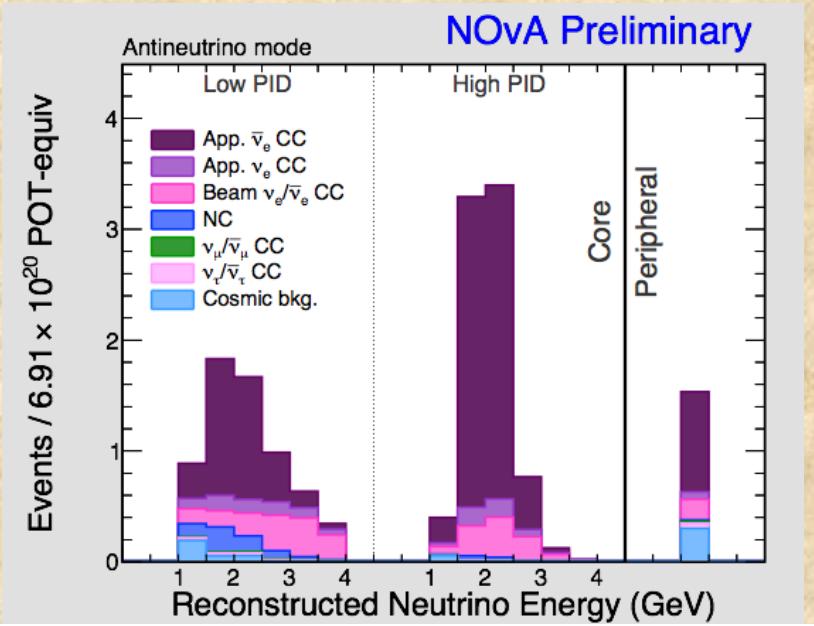


- *Select ve events using particle ID in the ND for each beam type.*
  - *Separate into low and high (ID) purity range*
- *For neutrino beam constrain:*
  - *The beam ν_e using the ν_μ spectrum, &*
  - *The ν_μ background using Michele electrons,*
  - *Remaining data/MC discrepancy is assigned to the NC component*
- *For the antineutrino beam, scale all components evenly to match the data.*

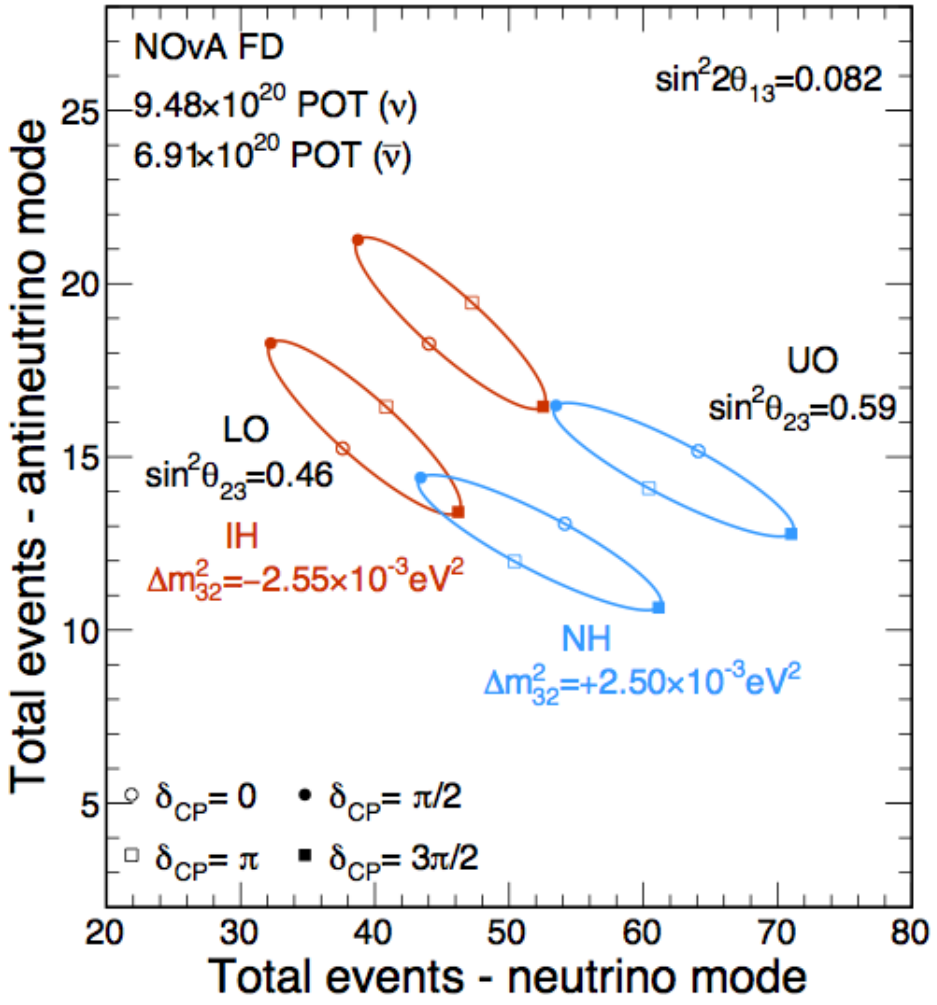
Far Detector Prediction

- ✓ *Use the ND data to predict the background in the FD. Each component is propagated independently in bins of energy and particle ID bins.*
- ✓ *Add a one-bin peripheral signal sample. This sample has a less stringent containment selection, adds a different cosmic rejection boosted decision tree and high particle-ID*
- ✓ *ND wrong sign component is 22% (32%) of the ν_e background for the high (low) PID bin.*
- ✓ *Data-based cross-checks using identified protons and event kinematics within systematic uncertainty.*





ν_e Appearance Expectations

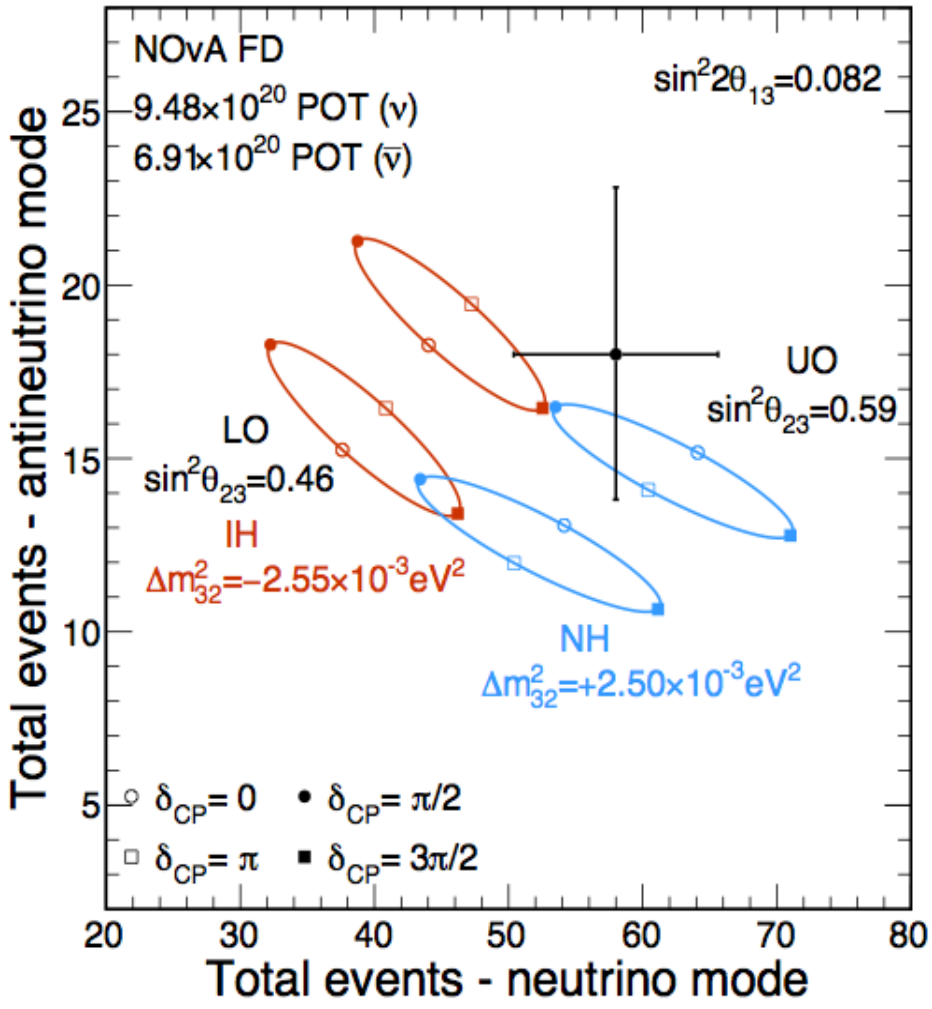


Event counts in neutrino and antineutrino mode vary according to the oscillation parameters

Ellipses as a function of CP are drawn for Normal and Inverted hierarchy (NH & IH) as well as Upper Octant (UO) and Lower Octant (LO)

Expect 30 to 72 events in neutrino mode & 10 to 22 events in antineutrino mode

ν_e Appearance Expectations



Event counts in neutrino and antineutrino mode vary according to the oscillation parameters

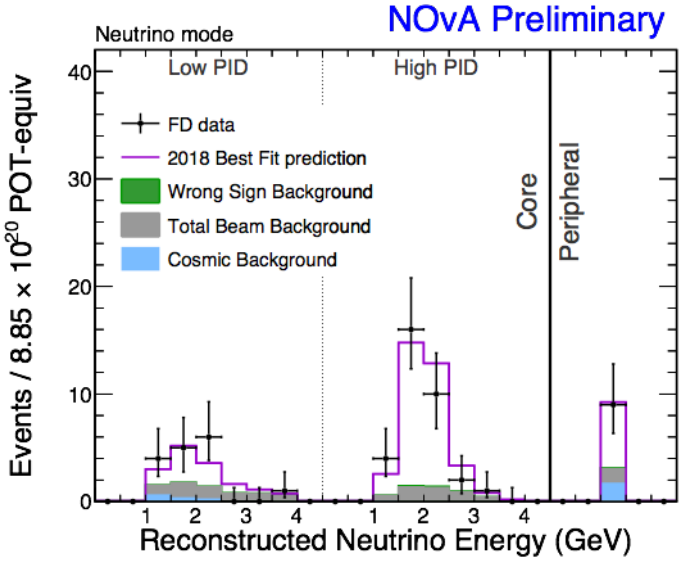
Ellipses as a function of CP are drawn for Normal and Inverted hierarchy (NH & IH) as well as Upper Octant (UO) and Lower Octant (LO)

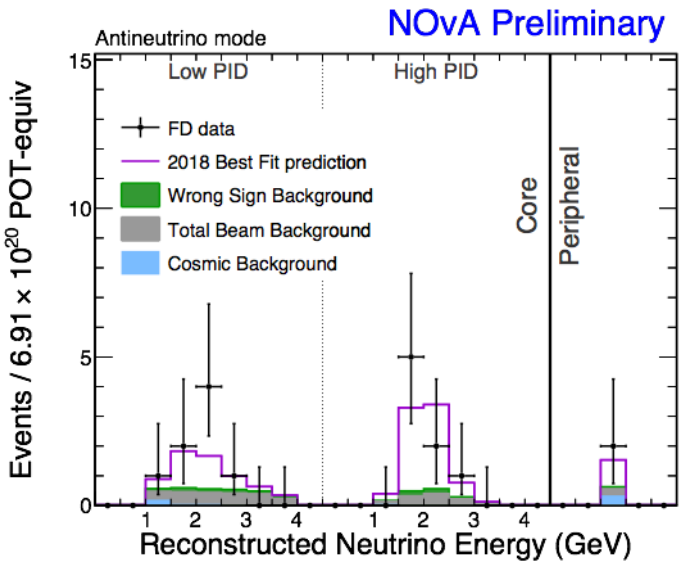
NOvA observes 58 events in neutrino mode & 18 events in antineutrino mode

ν_e and ν_{ebar} Appearance

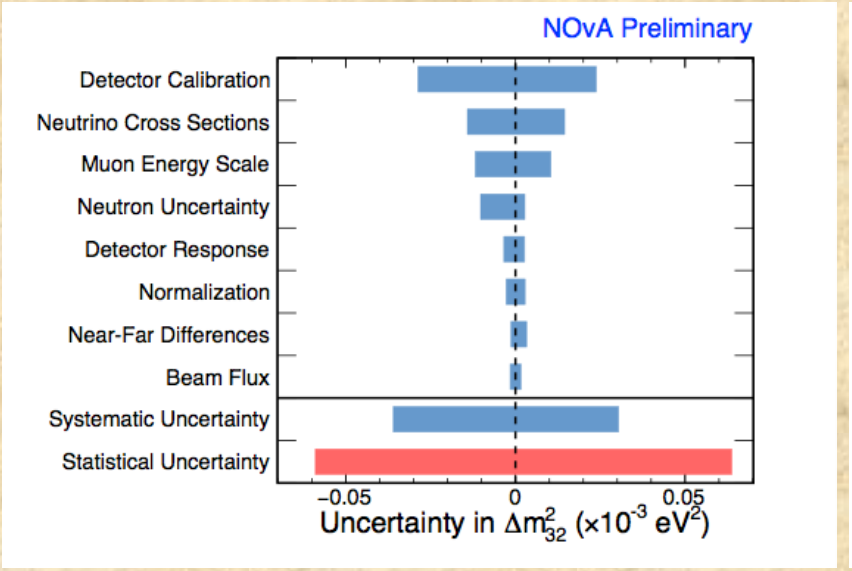
- ✓ *In the neutrino beam we observe 58 events and expect 15 background events*
  - ➢ *11 from beam*
  - ➢ *3 cosmic background, &*
  - ➢ *< 1 wrong sign one*
- ✓ *For the antineutrino beam we observe 18 events and expect 5.3 background evnts*
  - ➢ *3.5 beam background*
  - ➢ *< 1 cosmic, &*
  - ➢ *1 wrong sign event*

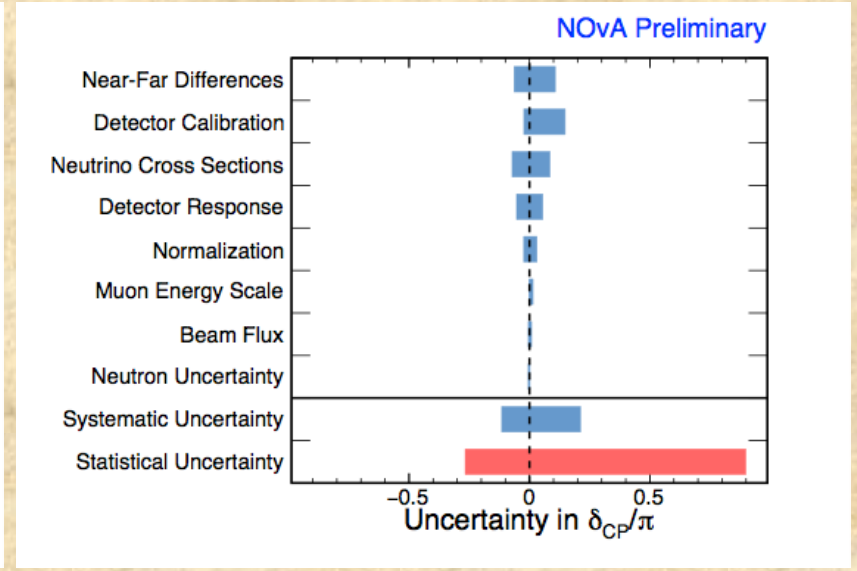
> 4σ evidence for electron anti-neutrino appearance

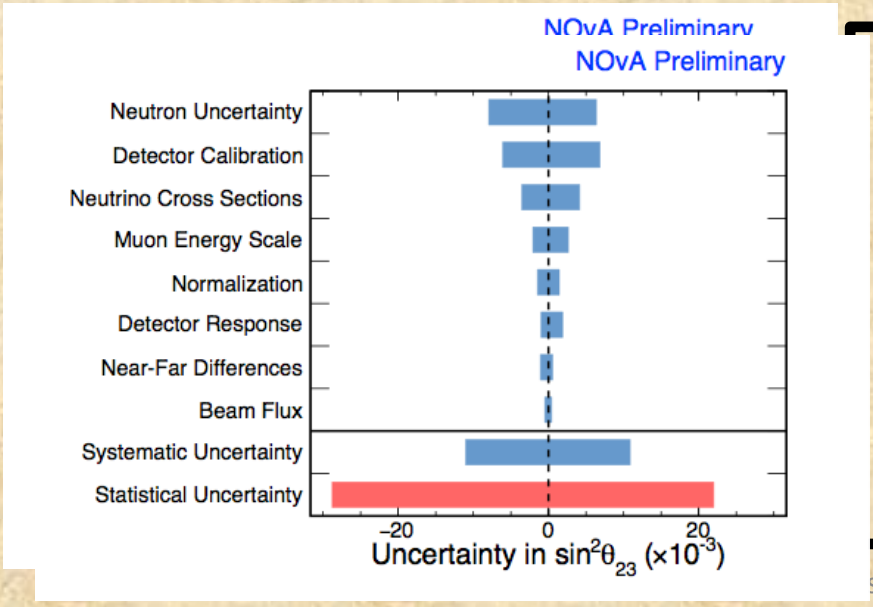




Systematic Uncertainties

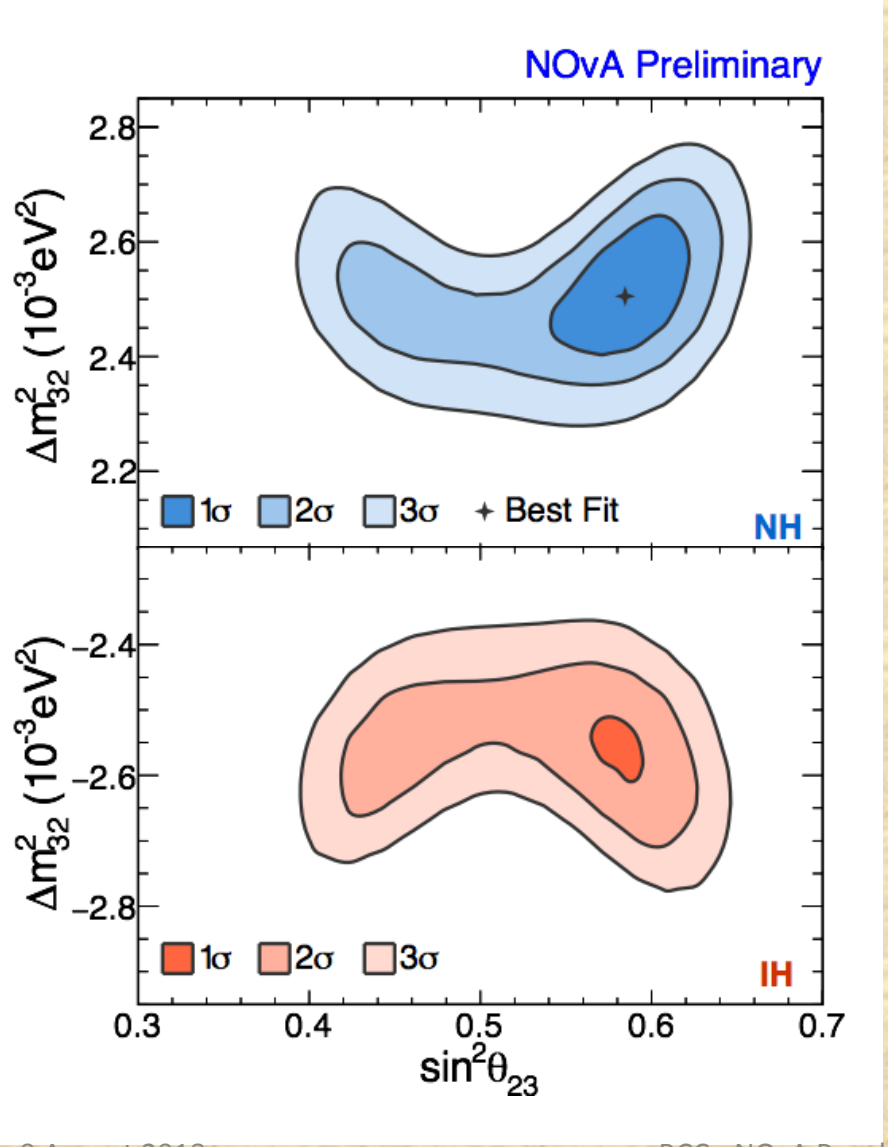


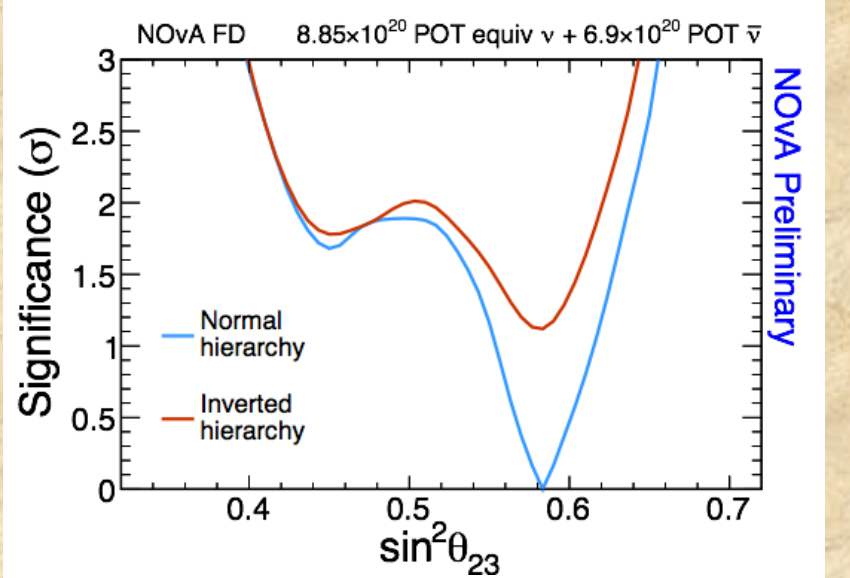




- ✓ *Improved systematic uncertainties, though still statistics limited.*
- ✓ *Calibration and cross-sections are the largest uncertainties.*
- ✓ *A test beam program will address the calibration and detector response uncertainties.*

Allowed Oscillation Parameters

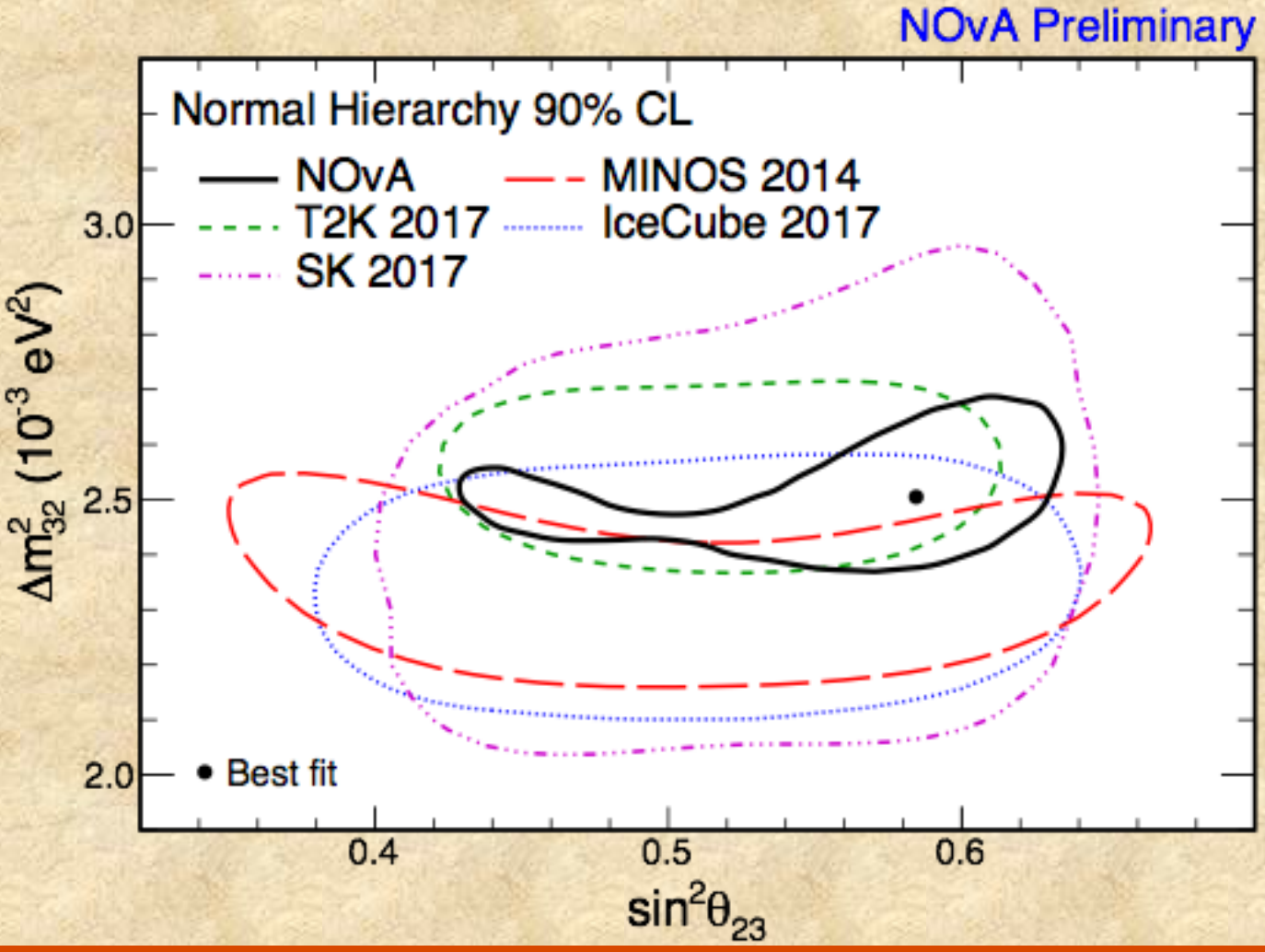




Best Fit:
Normal Ordering
$Sin^2\vartheta_{23}$ = 0.58 ± 0.03 (UO)
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2

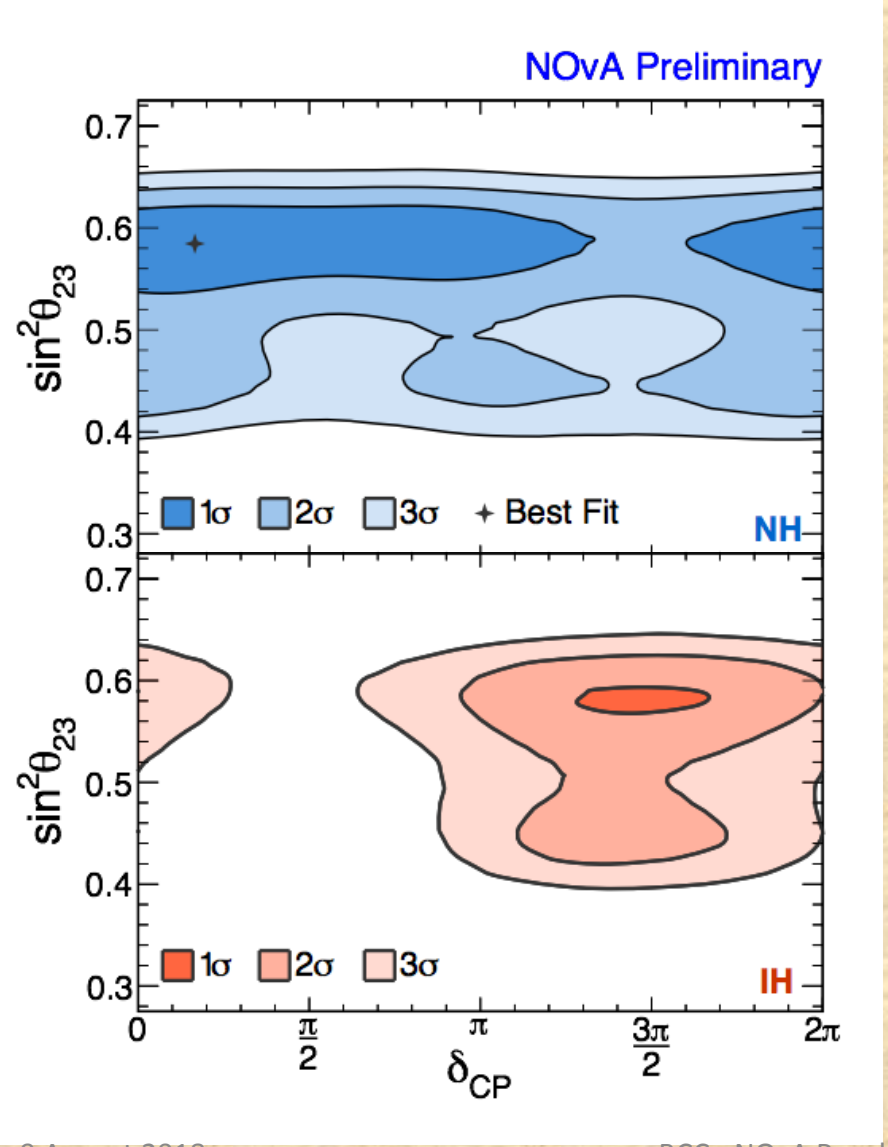
Prefer nan-maximal ϑ_{23} at 1.8σ.
Exclude LO at a similar value.

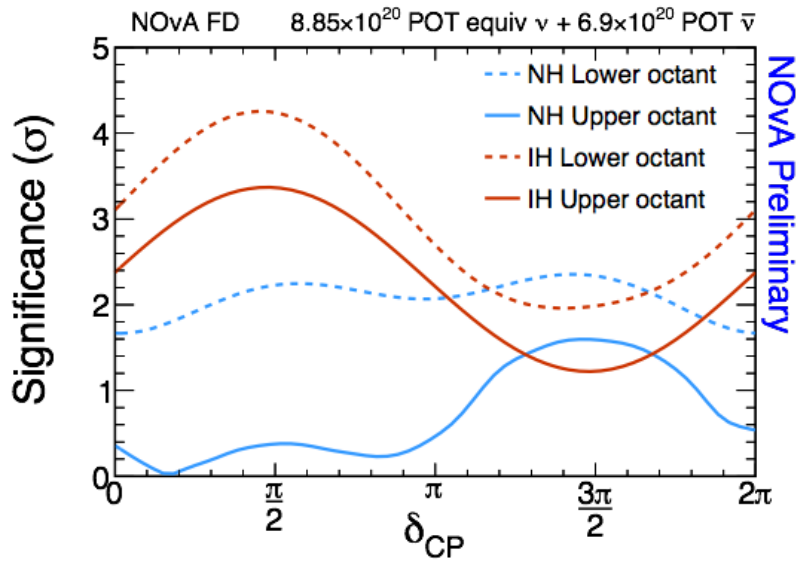
Allowed region from appearance and disappearance



Allowed 90% CL are compatible with other experiments.

Allowed Oscillation Parameter





Best Fit:

$\delta_{CP} = 0.17\pi$

$\sin^2\vartheta_{23} = 0.58 \pm 0.03$ (UO)

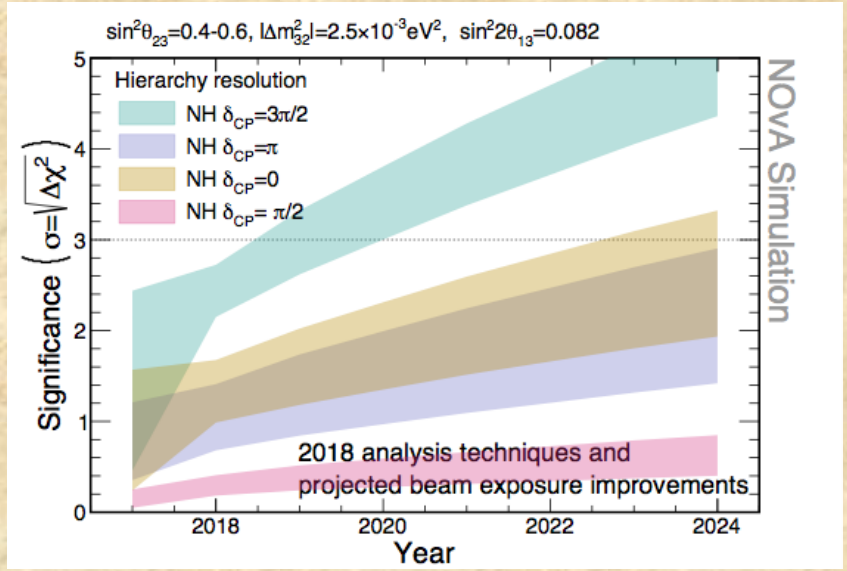
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2

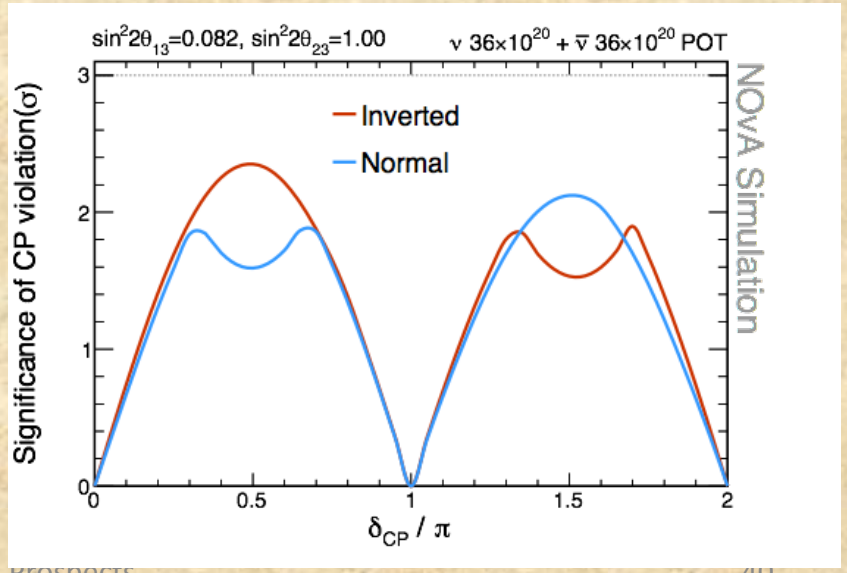
Prefer NH by 1.8σ.

Excludes $\delta_{CP} = \pi/2$ in the IH at > 3σ

NOvA Prospects

- ✓ *Currently data collection with anti-neutrino beam. After 2018, run 50% with neutrino & 50% with anti-neutrino beam.*
- ✓ *Extended running through 2024, proposed accelerator improvement projects & test beam program will enhance NOvA's ultimate reach.*
- ✓ *3σ sensitivity to hierarchy (if NH and $\delta_{CP} = 3\pi/2$) for allowed range of ϑ_{23} by 2020. 3σ sensitivity for 30-50% (depending on octant) of δ_{CP} range by 2024.*
- ✓ *>2σ+ sensitivity for CP phase in both hierarchies at $\delta_{CP} = 3\pi/2$ or $\delta_{CP} = \pi/2$ (assuming unknown hierarchy) by 2024.*





Summary and Outlook

- ✓ *First NOvA antineutrino data with $6.9X10^{20}$ POT has been analyzed together with $8.85X10^{20}$ POT of neutrino data.*
- ✓ *We observe > 4σ evidence of electron-antineutrino appearance. At this level, this is first such result from any experiment.*
- ✓ *Publication on analysis of $8.85X10^{20}$ POT neutrino data is on the arXiv: 1806.00096v2 [hep-ex] 6Aug2018 & accepted for publication in PRD.*
- ✓ *No evidence of mixing with sterile neutrinos or antineutrinos from Neutral Current channel.*
- ✓ *A joint appearance and disappearance analysis for these data:*
  - ✓ *Prefers NH at 1.8σ and excludes $\delta_{CP}= \pi/2$ at > 3σ in IH.*
  - ✓ *Rejects maximal mixing at 1.8σ and the lower octant at a similar level.*
- ✓ *Future NOvA running can reach 3σ sensitivity for the mass hierarchy by 2020 and will cover significant range of CP by 2024.*

धन्यवाद

Cam On

Thank you