Recent results from the NOvA neutrino experiment

HIGH ENERGY PHYSICS SEMINAR

UNIVERSITY of VIRGINIA

Gavin S. Davies
Indiana University

SEPTEMBER 26TH 2018

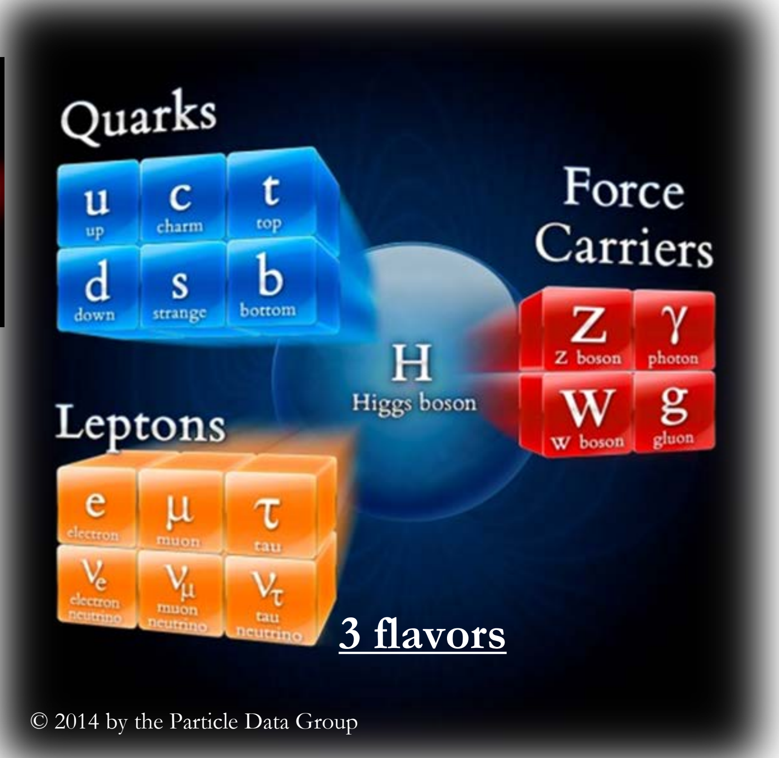
Hello, neutrino

Neutrinos are abundant; 2nd only in the universe to photons

Interact via the weak force carriers

- Enrico Fermi coined the name neutrino (1933): "the little neutral one", spin-1/2

Enrico Fermi



Neutrinos are produced in the sun, supernovae and cosmic rays.

Small cross sections (they rarely interact).
Interactions are flavor conserving

"I have done a terrible thing, I have postulated a particle that cannot be detected"
Wolfgang Ernst Pauli, 1930

Wolfgang Pauli

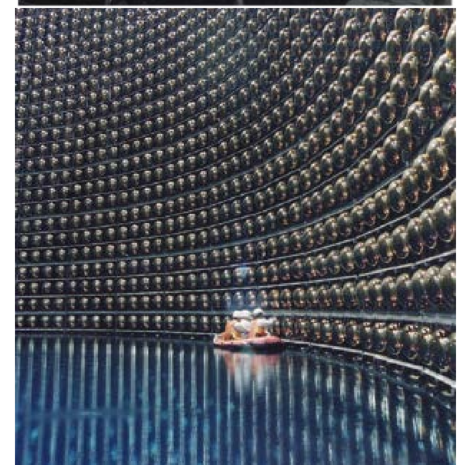
Neutrino Oscillations

1956: F. Reines and C. Cowan report the first evidence for neutrinos

- *Detection of the free neutrino: A Confirmation*
  Science 124:103-104 (1956)
- Nobel Prize in Physics, 1995: F. Reines
  "for the detection of the neutrino"

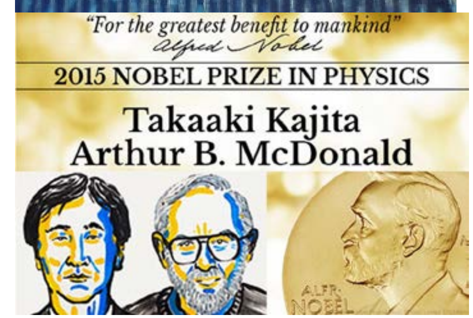
1998: Super-Kamiokande reports first evidence for neutrino oscillations → neutrinos have mass

- *Evidence for oscillation of atmospheric neutrinos*
  Super-Kamiokande Collaboration, Phys. Rev. Lett. 81:1562-1567 (1998)
  5300+ citations to date, #22 of all time



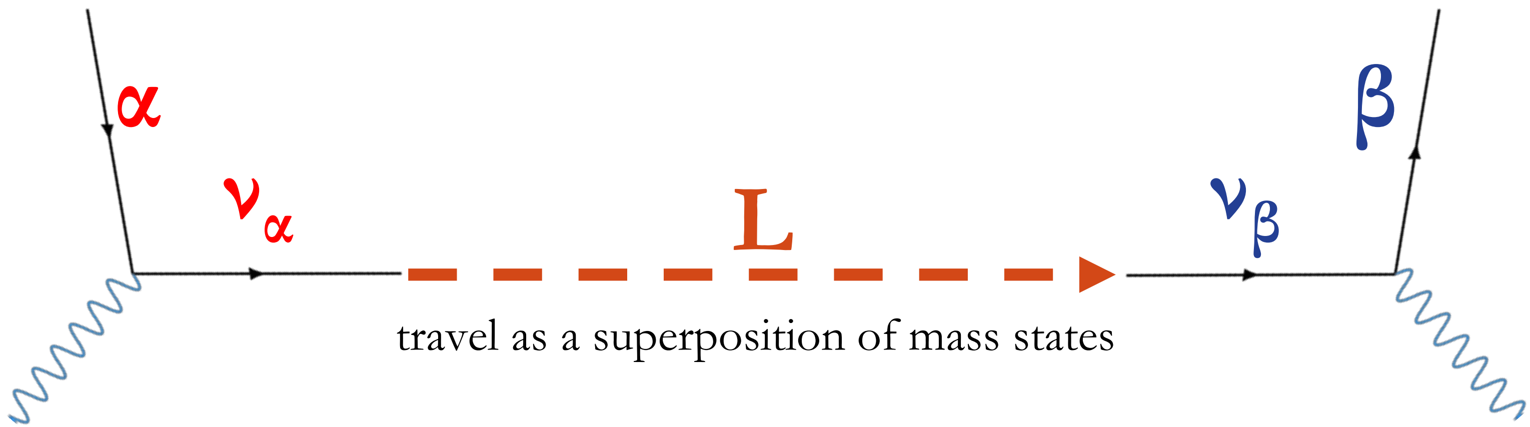
Neutrino oscillation is a well-established, well-described phenomenon over the last 20 years

- Nobel Prize in Physics, 2015
  - *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*
- Fundamental Physics Breakthrough Prize, 2016
  - *"awarded to five experiments investigating neutrino oscillation"*
    - Daya Bay, K2K/T2K, Super-K, KamLAND, SNO



Neutrino Oscillations

Create in one flavour, but detect in another



$$\nu_l = \sum_{m=1}^{3} U_{lm} \nu_m$$

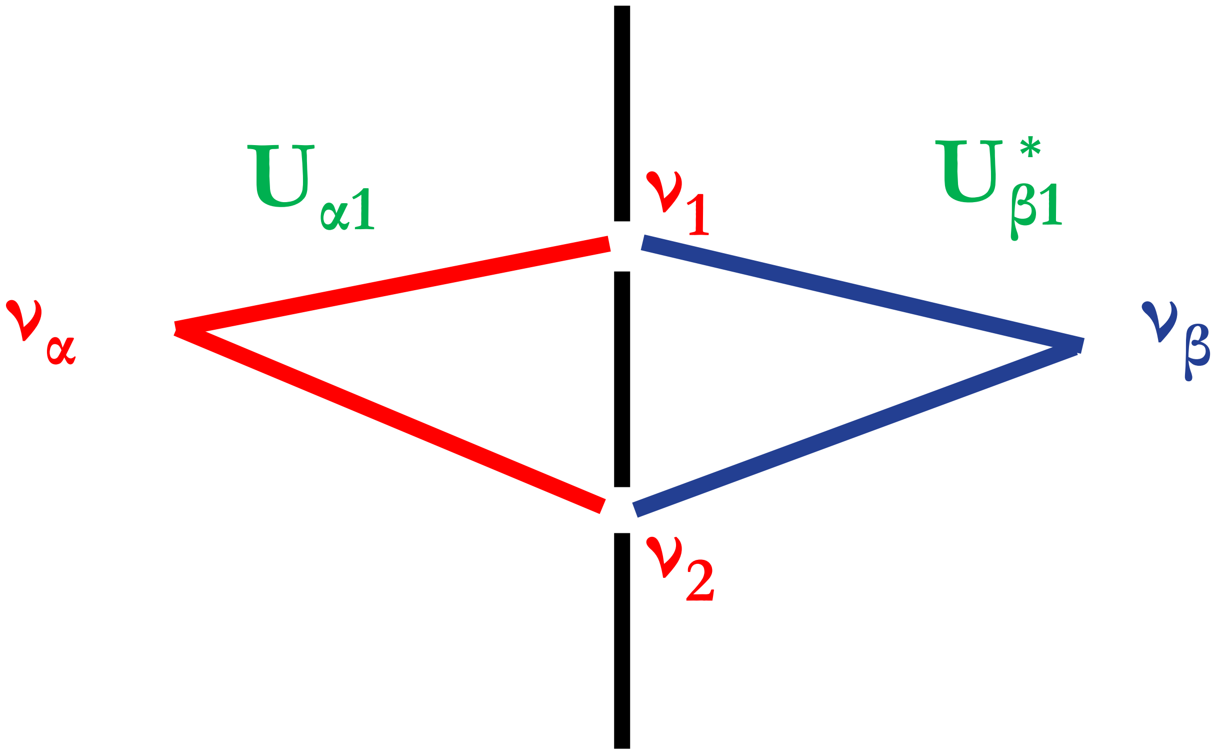
Flavor eigenstates: ν_e, ν_μ, ν_τ
(interactions)

Mass eigenstates: ν_1, ν_2, ν_3
(propagation)

Flavor eigenstate oscillations described by the 3 x 3 PMNS matrix

Neutrino Oscillations

Neutrino oscillation is much like a double slit experiment; the neutrino mass eigenstates propagate differently, and interfere



Given an initial flavor eigenstate of ν_α, observation some time later will yield a combination which:
1) has maximal ν_β (constructive interference)
Or 2) has only ν_α (destructive interference)
The amount of interference is governed by the mixing matrix, U

The PMNS Mixing Matrix

Pontecorvo
Sov. Phys. JETP 6:429 (1957)
Sov. Phys. JETP 26:984-988 (1968)

S. Sakata Z. Maki M. Nakagawa

Maki, **N**akagawa, **S**akata
Prog. Theor. Phys. 28, 870 (1962)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric and long-baseline

reactor and long-baseline

solar and reactor

$\Delta m^2_{32} \sim \pm 2 \times 10^{-3} eV^2$

$\Delta m^2_{31} \approx \Delta m^2_{32}$

$\Delta m^2_{21} \sim 8 \times 10^{-5} eV^2$

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 [eV^2] \frac{L\ [km]}{E\ [GeV]}\right)$$

Sub-dominant term due to small θ_{13}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\sin^2(2\theta_{13})\sin^2(\theta_{23}) + \cos^4(\theta_{13})\boxed{\sin^2(2\theta_{23})}\right)\sin^2\left(\frac{\boxed{\Delta m^2}L}{4E}\right)$$

$$P(\nu_\mu \to \nu_e) \approx \left|\sqrt{P_{\rm atm}}e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\rm sol}}\right|^2$$

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\,(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP})$$

$$\sqrt{P_{\rm atm}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

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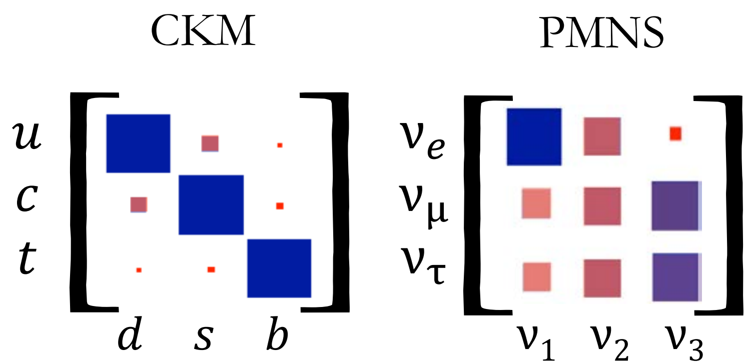
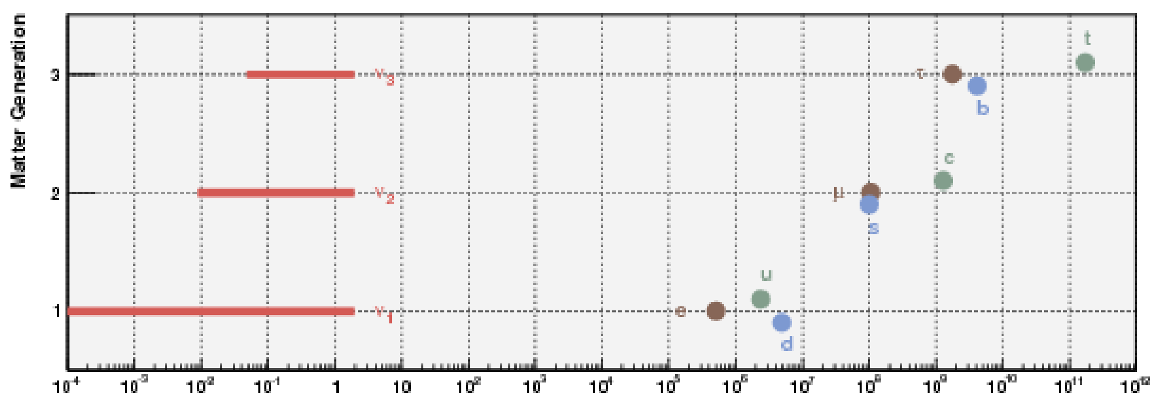
atmospheric and long-baseline	reactor and long-baseline	solar and reactor
$\Delta m^2_{32} \sim \pm 2 \times 10^{-3} eV^2$	$\Delta m^2_{31} \approx \Delta m^2_{32}$	$\Delta m^2_{21} \sim 8 \times 10^{-5} eV^2$

Open Questions

Neutrino mixing very different from quark sector mixing
Masses are really small compared to the rest of the Standard Model (SM)





J. J. Gomez-Cadenas et al., Riv. Nuovo Cim. 35:29-98 (2012)

Open Questions

Neutrino mixing very different from quark sector mixing
Masses are really small compared to the rest of the SM

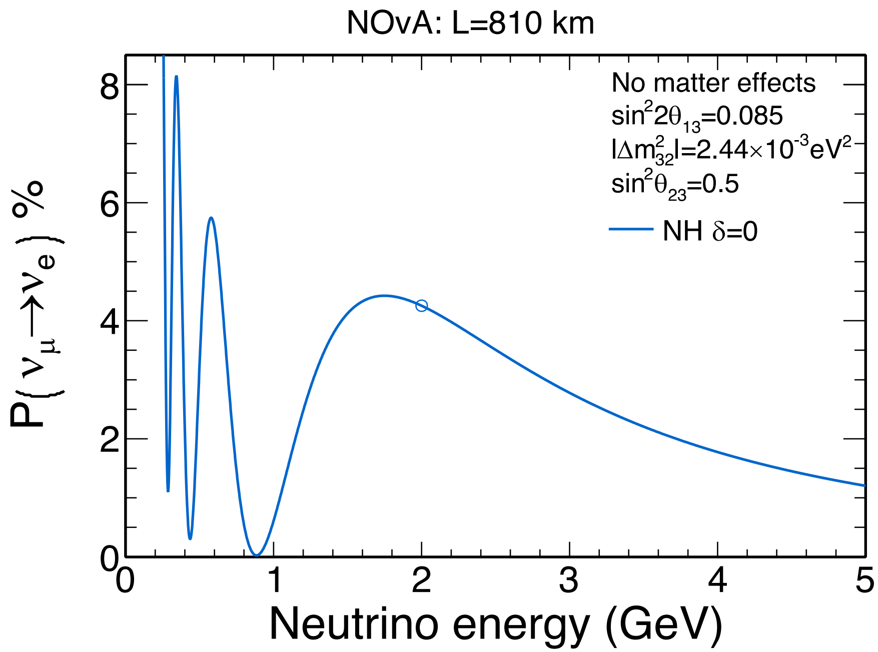
Do neutrino oscillations violate charge-parity (CP) symmetry?

- $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?

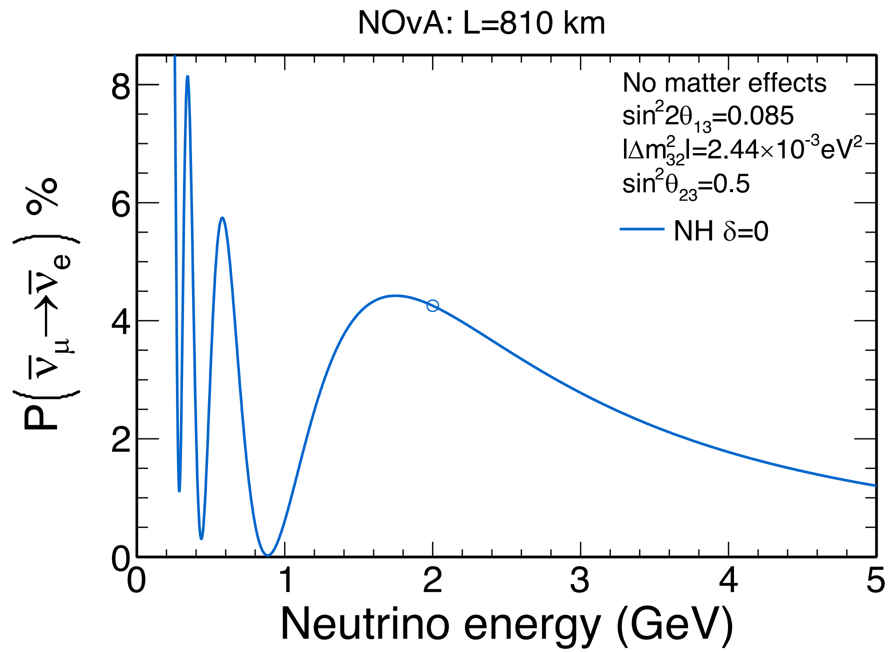
CP Violation

CP conserved

Neutrino



Anti-Neutrino



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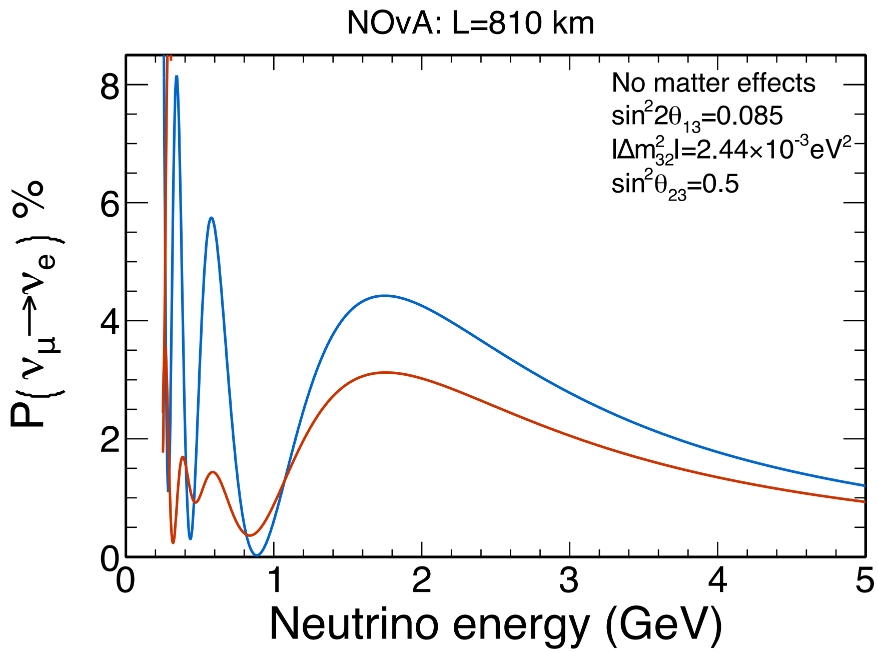
CP conserved

$\delta = \pi/2$

Neutrino



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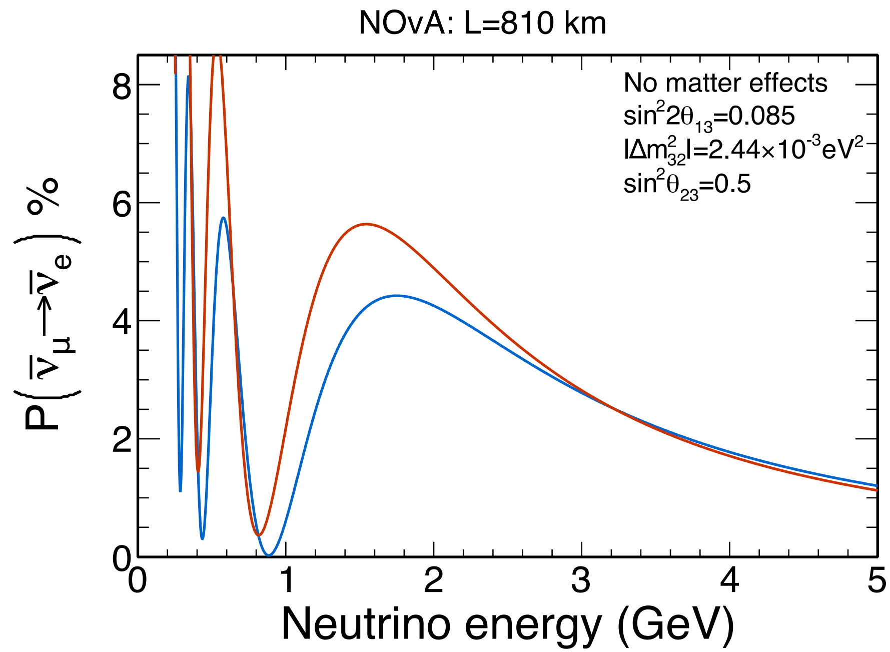

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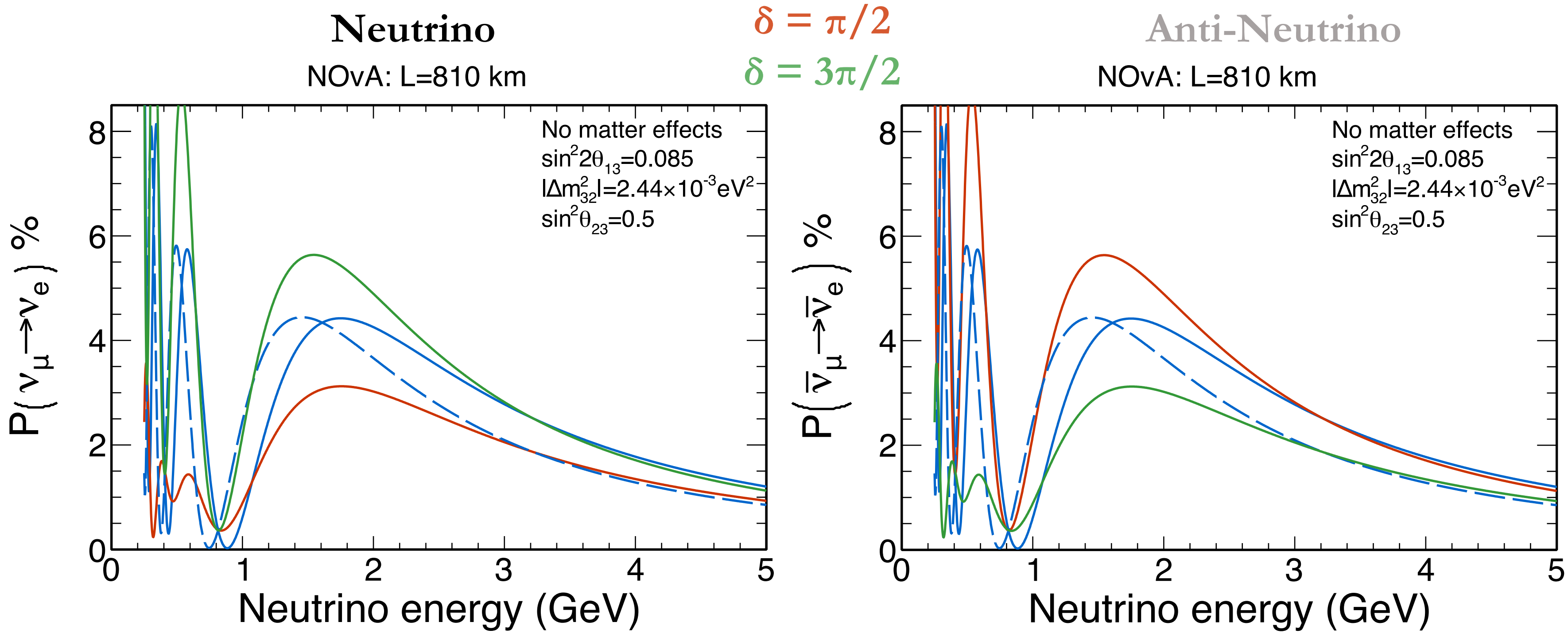
CP Violation

- $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?
- If CP violation is near maximal, δCP can create matter/anti-matter asymmetry via leptogenesis
- "Why are we are here

CP conserved
$\delta = \pi/2$
$\delta = 3\pi/2$



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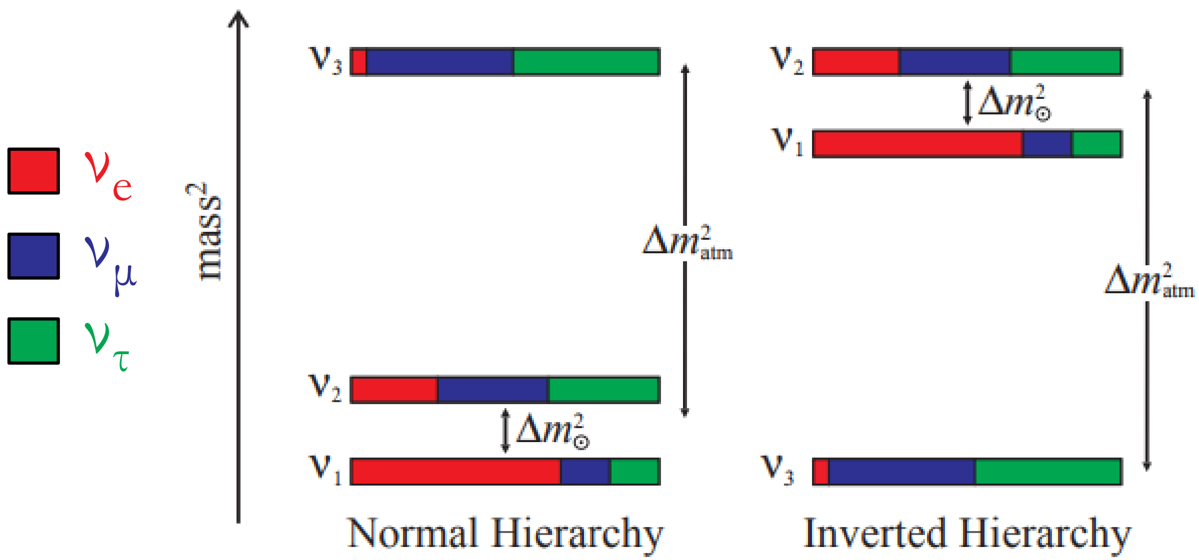
Do neutrino oscillations violate CP symmetry? **CP Violation**

Is the mass hierarchy (ordering) "normal" or "inverted"? **Mass Hierarchy**
i.e. is the most ν_e state the lightest?

- Enhancement or suppression of oscillation probability depending on hierarchy



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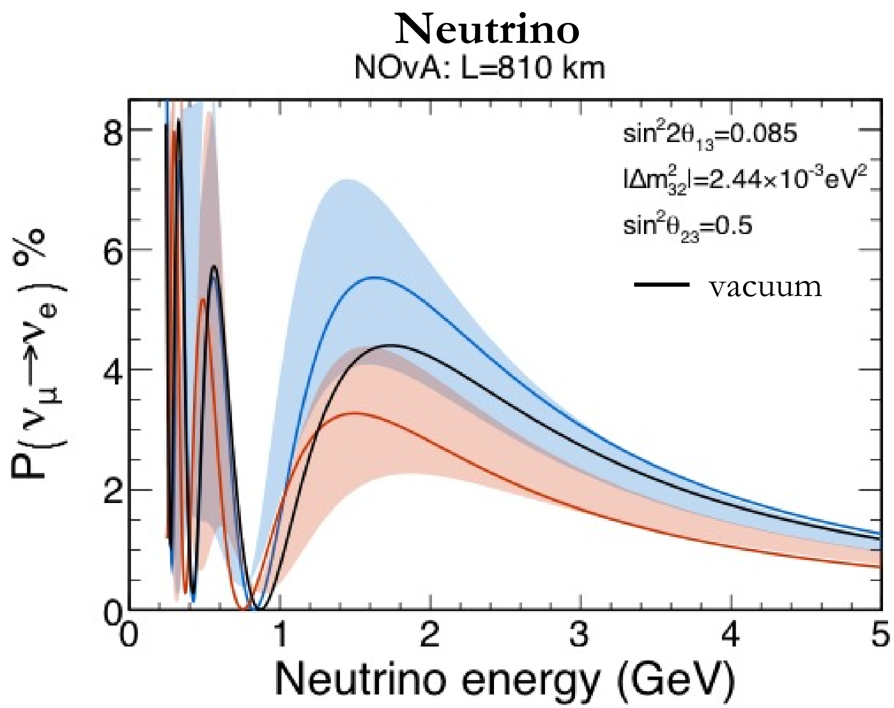
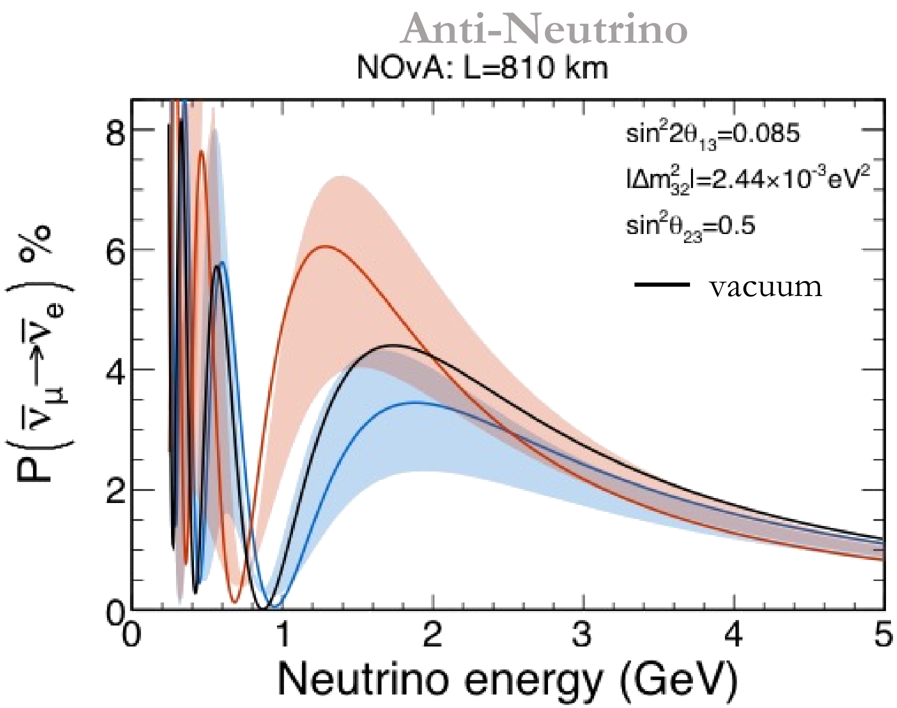
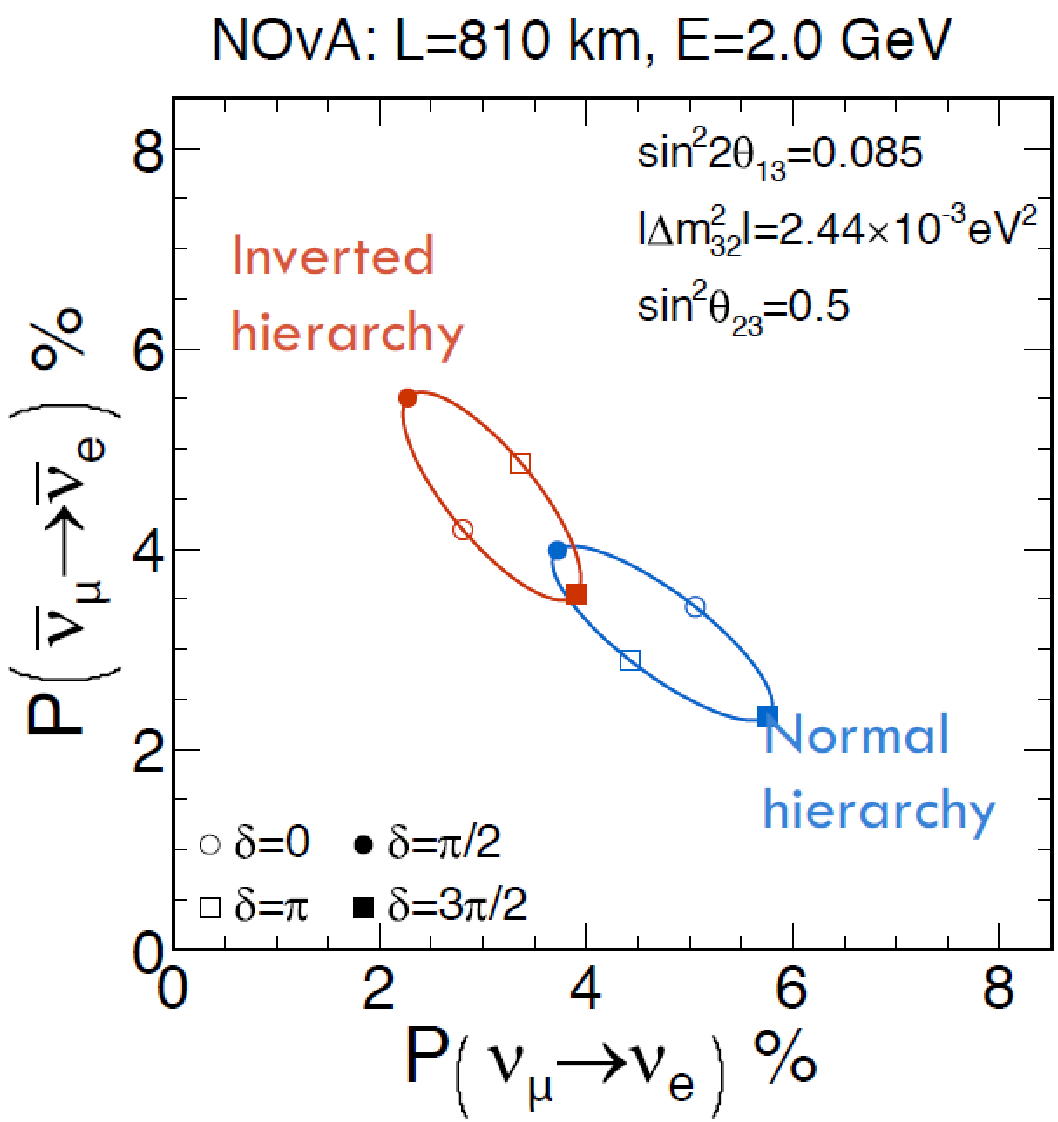




Open Questions: Mass Hierarchy



Open Questions

Neutrino mixing very different from quark sector mixing
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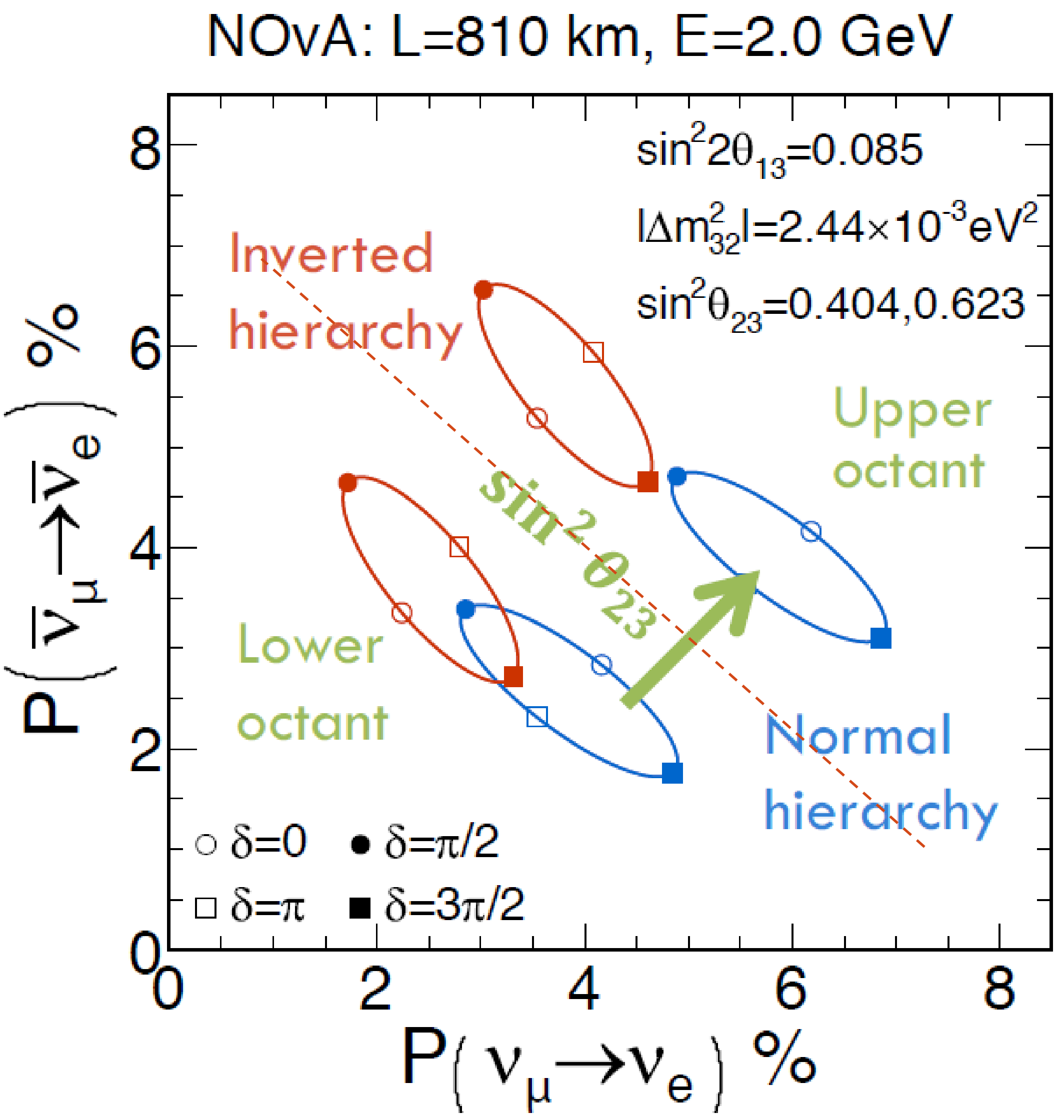
Do neutrino oscillations violate CP symmetry? **CP Violation**

Is the mass hierarchy (ordering) "normal" or "inverted"? **Mass Hierarchy**

What is the octant of θ_{23}? **θ_{23} Octant**

- Governs ν_μ/ν_τ split in ν_3. More muon- or tau-like?
- If equal, imply some underlying symmetry?

Open Questions: θ_{23} Octant



Open Questions

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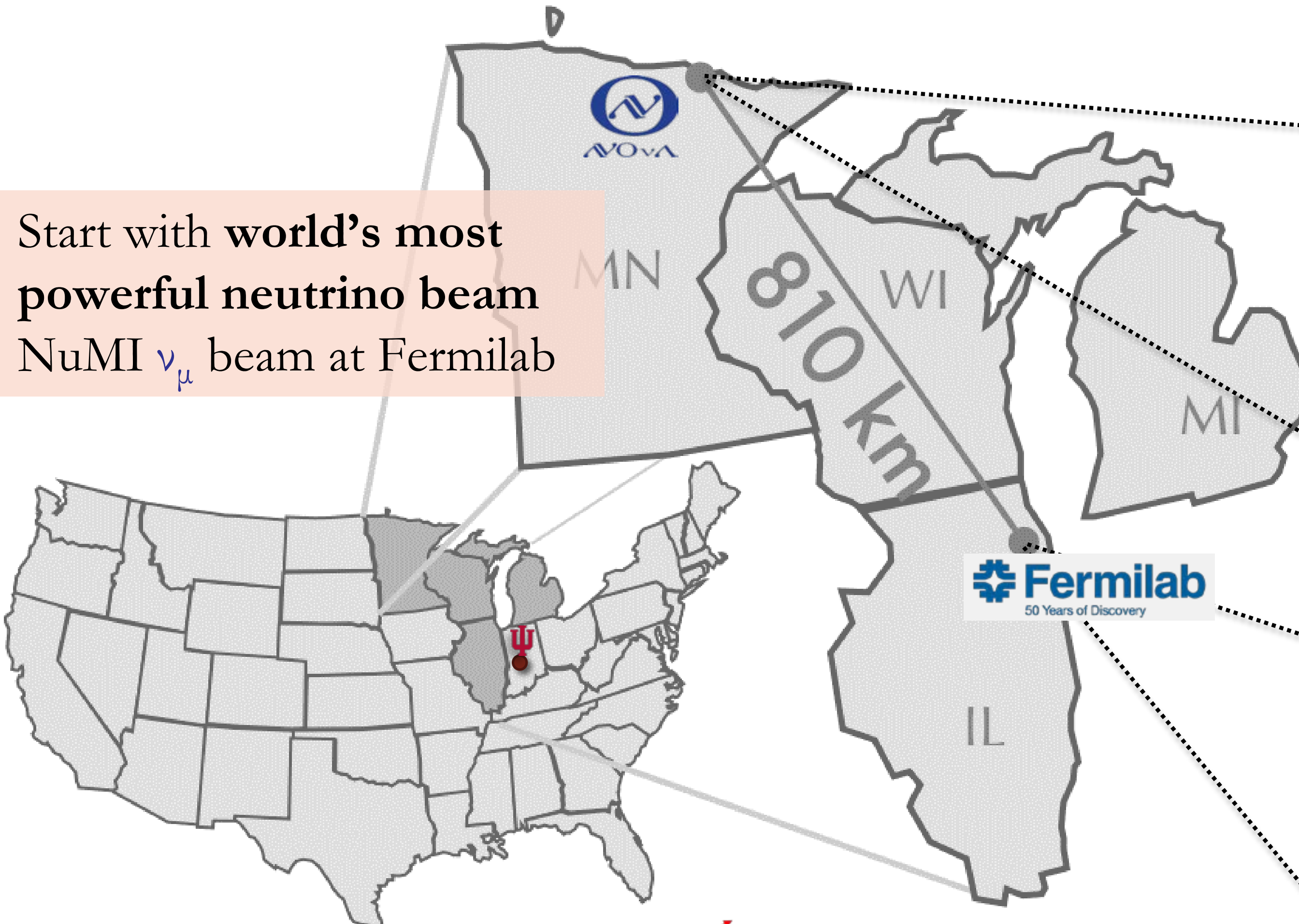
What is the octant of θ_{23}? **θ_{23} Octant**

"The existence of non-zero neutrino masses, inferred from neutrino oscillation experiments, is the only lab-based evidence of physics beyond the standard model."
P.A.N. Machado

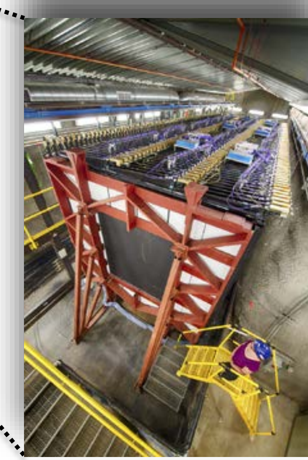
NuMI Off-axis ν_e Appearance

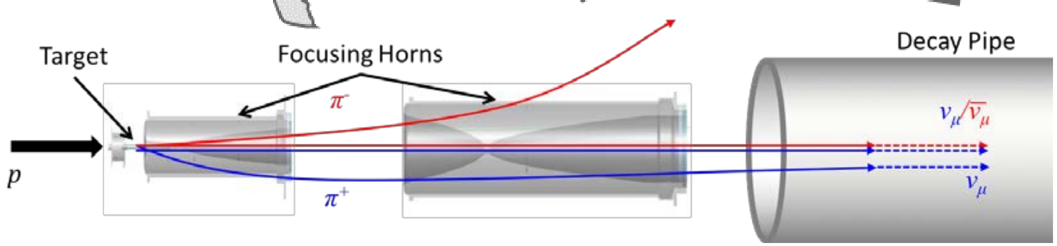
- Start with **world's most powerful neutrino beam**
- NuMI ν_μ beam at Fermilab



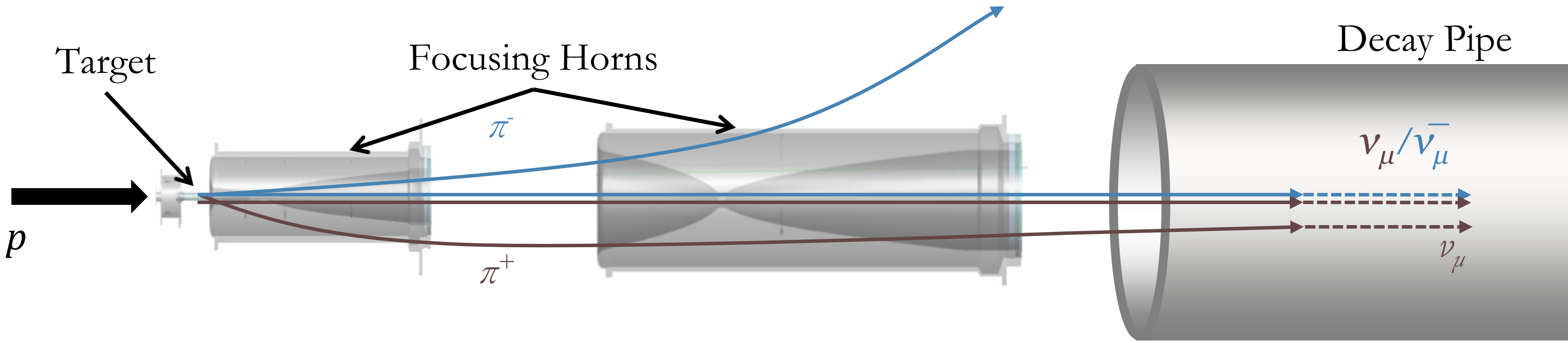
Far Detector

Near Detector

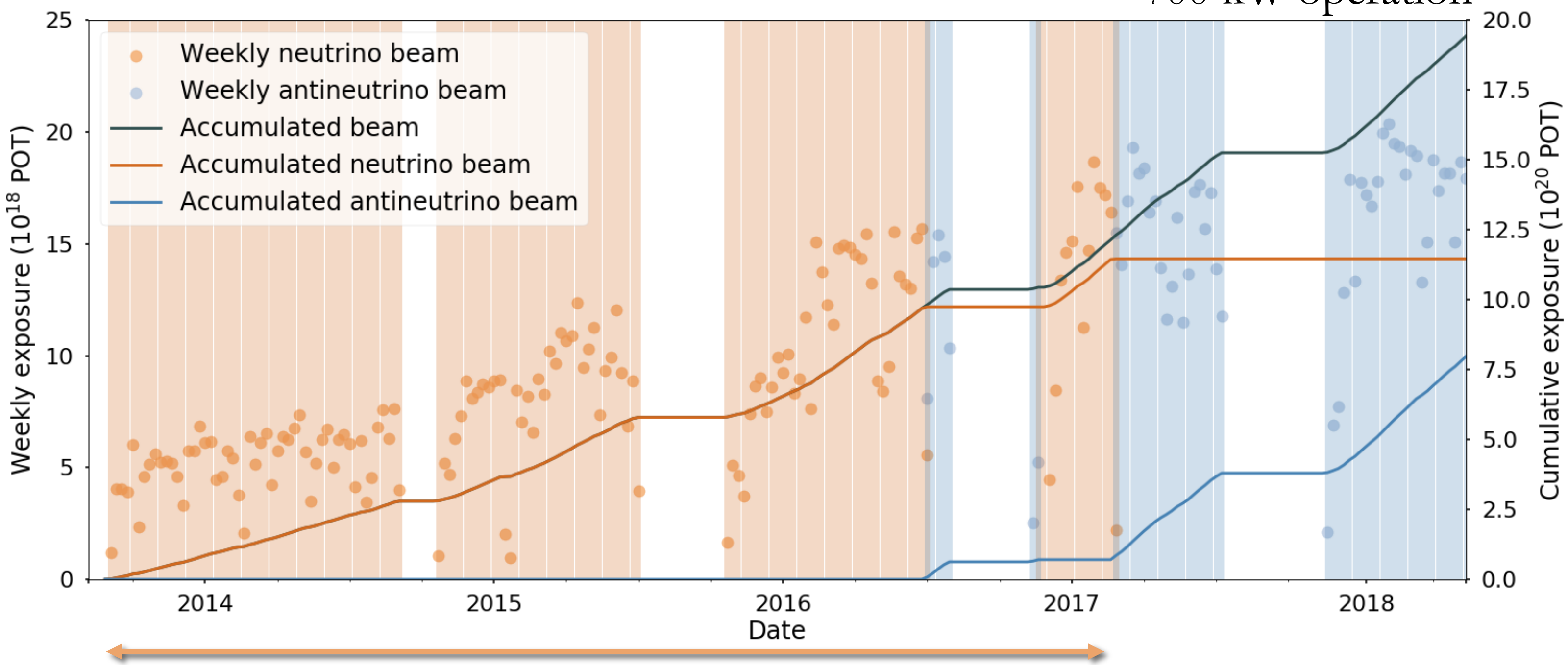




The NuMI Neutrino beam

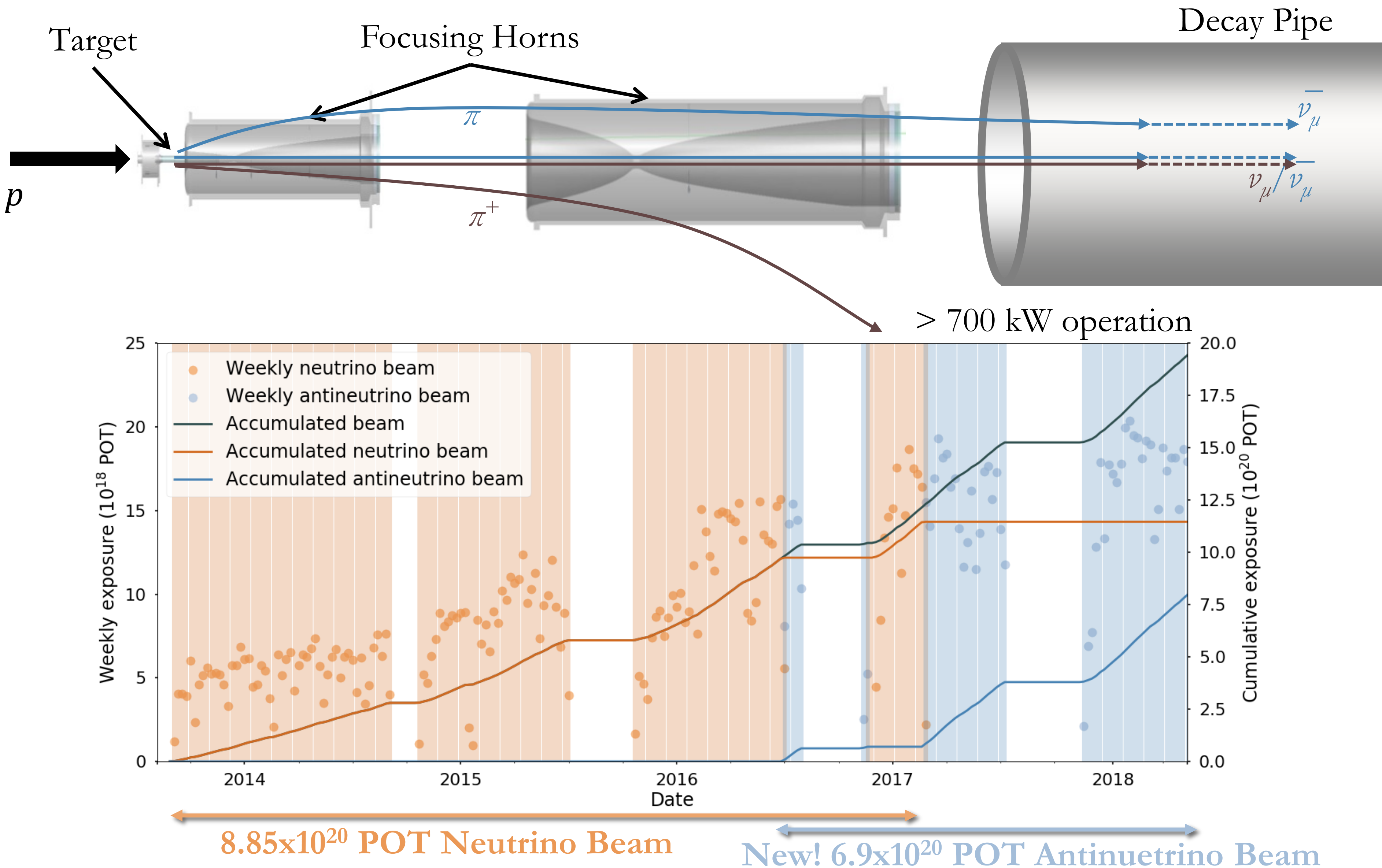


> 700 kW operation

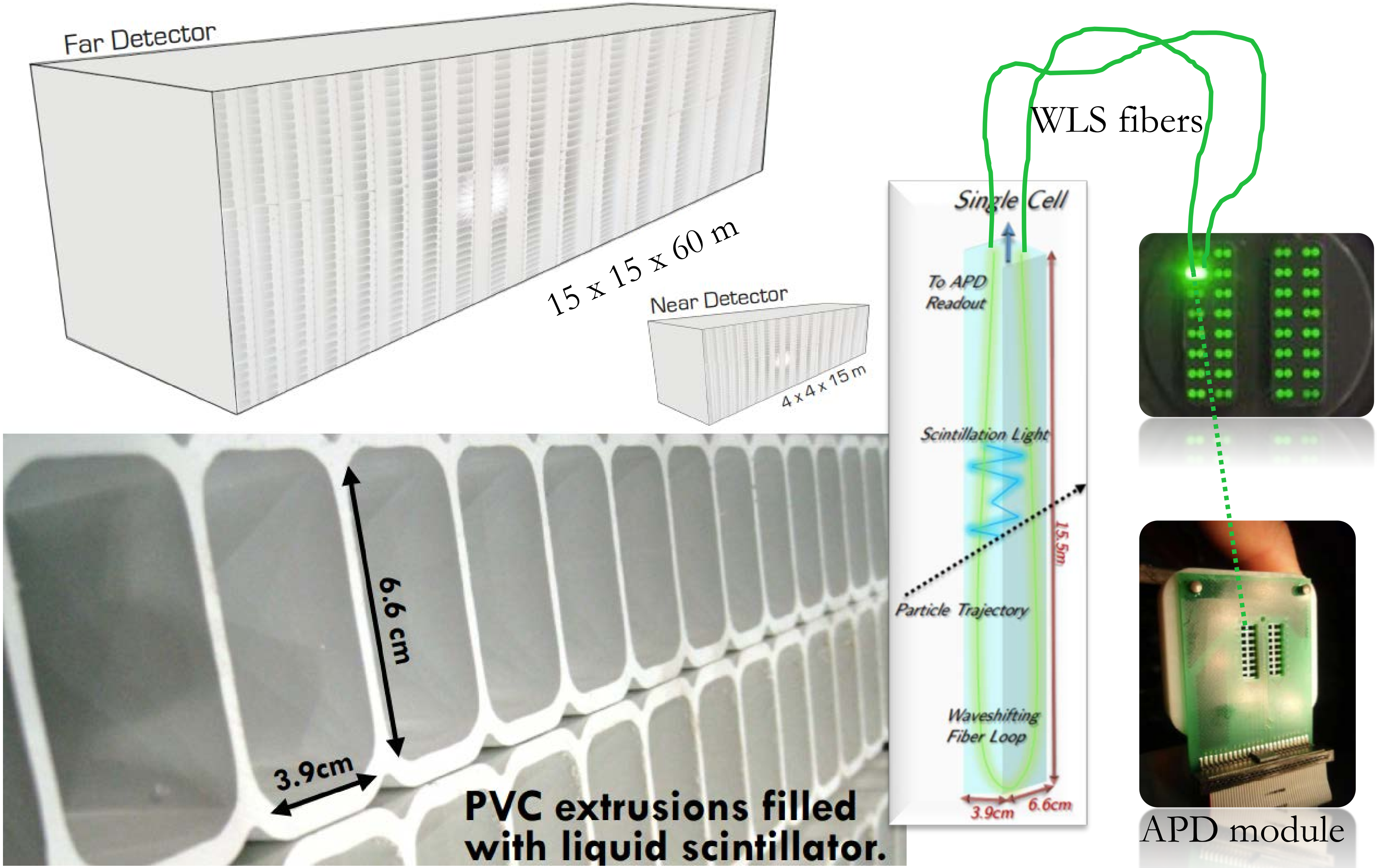


8.85×10^{20} POT Neutrino Beam

The NuMI Antineutrino beam



Detectors


Far Detector
15 x 15 x 60 m
Near Detector
4 x 4 x 15 m
PVC extrusions filled with liquid scintillator.
6.6 cm
3.9cm
Single Cell
To APD Readout
Scintillation Light
Particle Trajectory
Waveshifting Fiber Loop
15.5m
3.9cm
6.6cm
WLS fibers
APD module

NOvA Far Detector

The Rotunda is ~77 feet ~ 23m in diameter and height
NOvA FD is 15m x 15m x 60m
~2/3 height, x 2.5 length

UVA designed and fabricated NOvA Power Distribution System

NOvA Physics Program

Primary Goal:
Measurement of 3-flavour oscillations via:

Disappearance of ν_μ CC events

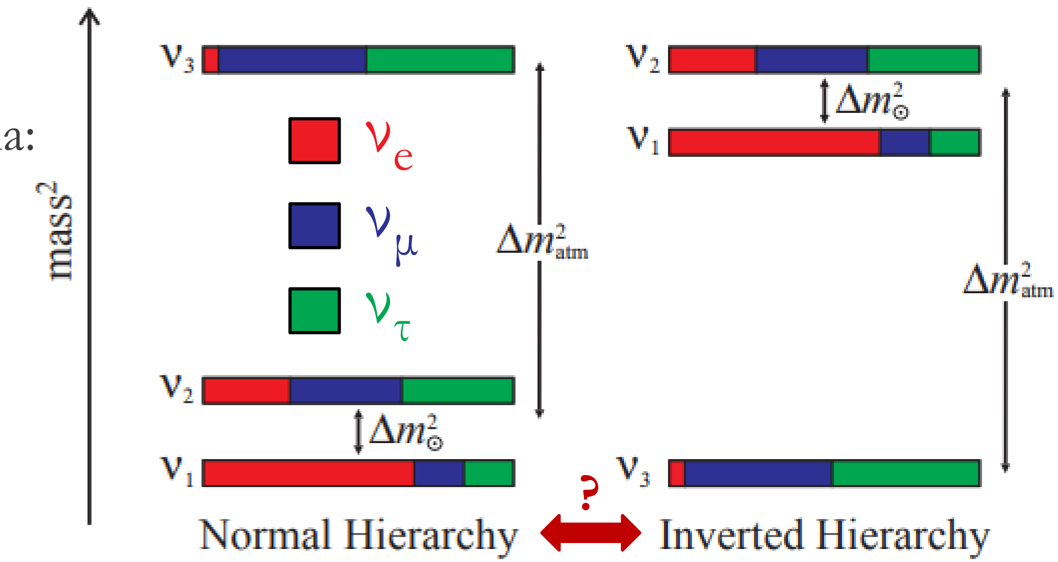
- $\nu_\mu \rightarrow \nu_\mu$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
- Precision measurements of:

  $\sin^2(\theta_{23})$ & $|\Delta m^2_{32}|$

Appearance of ν_e CC events

- $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Determine mass hierarchy
- Search for $\delta_{CP} \neq 0$

  θ_{13} & θ_{23} & δ_{CP}



Other goals include:
Searches for sterile neutrinos
Neutrino cross sections
Supernova neutrinos
Cosmic ray physics
Upwards-going muon (dark matter) analysis (UVA)

New 2018 oscillation analyses including antineutrino oscillations for the first time on NOvA

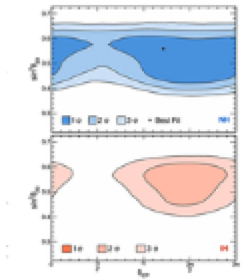
http://novaexperiment.fnal.gov/publications/

Editors' Suggestion

New constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in the NOvA experiment

M. A. Acero *et al.* (NOvA Collaboration)

Phys. Rev. D **98**, 032012 (2018) – Published 24 August 2018



The NOvA Collaboration presents new results on muon- to electron-neutrino oscillations leading to new constraints on neutrino oscillation parameters compatible with other experiments. The inverted mass hierarchy is disfavored by the new results.

Show Abstract +

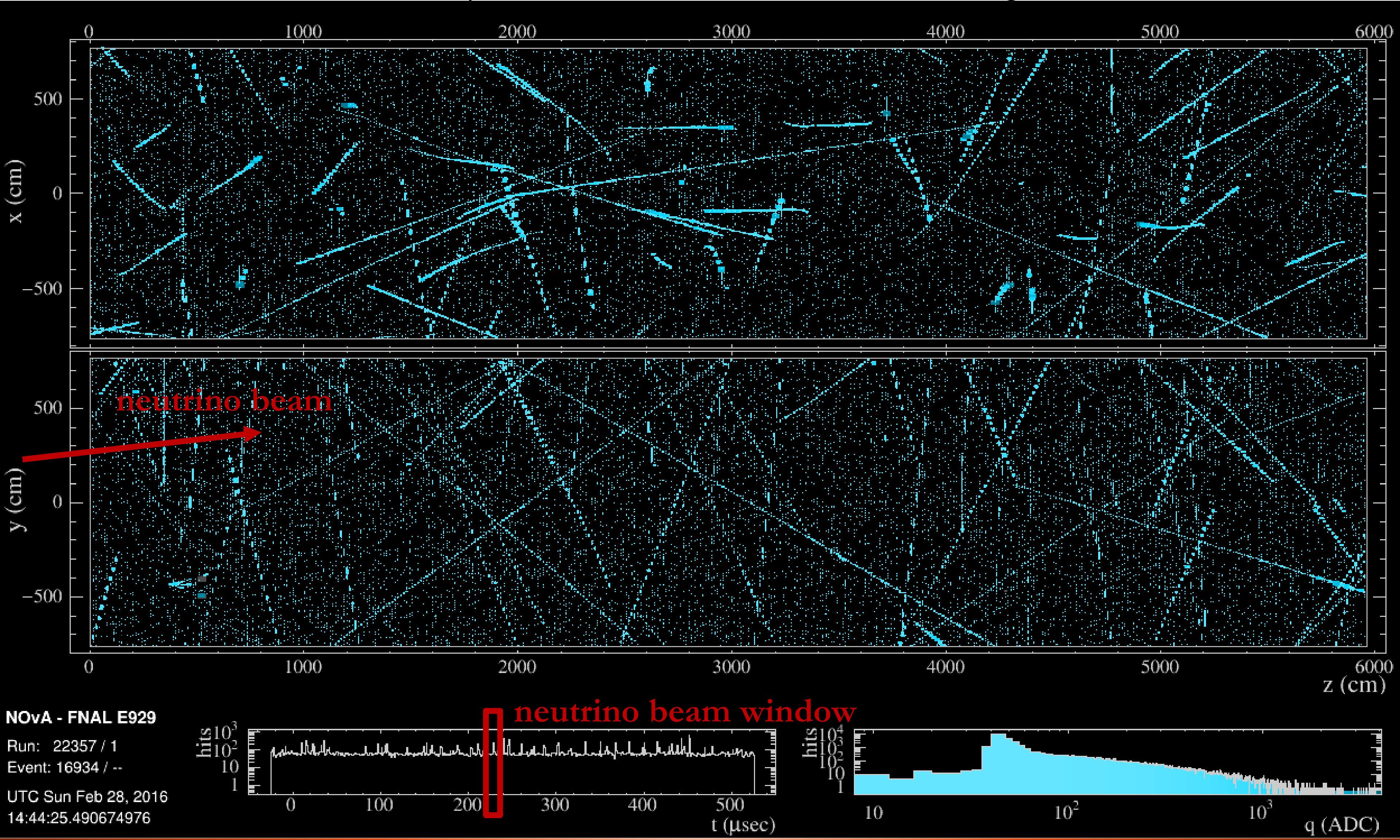
NOvA's last **neutrino-only** oscillation results published in PRD at the weekend
Phys. Rev. D 98, 032012 (2018)

Next frontier is **antineutrino oscillations**

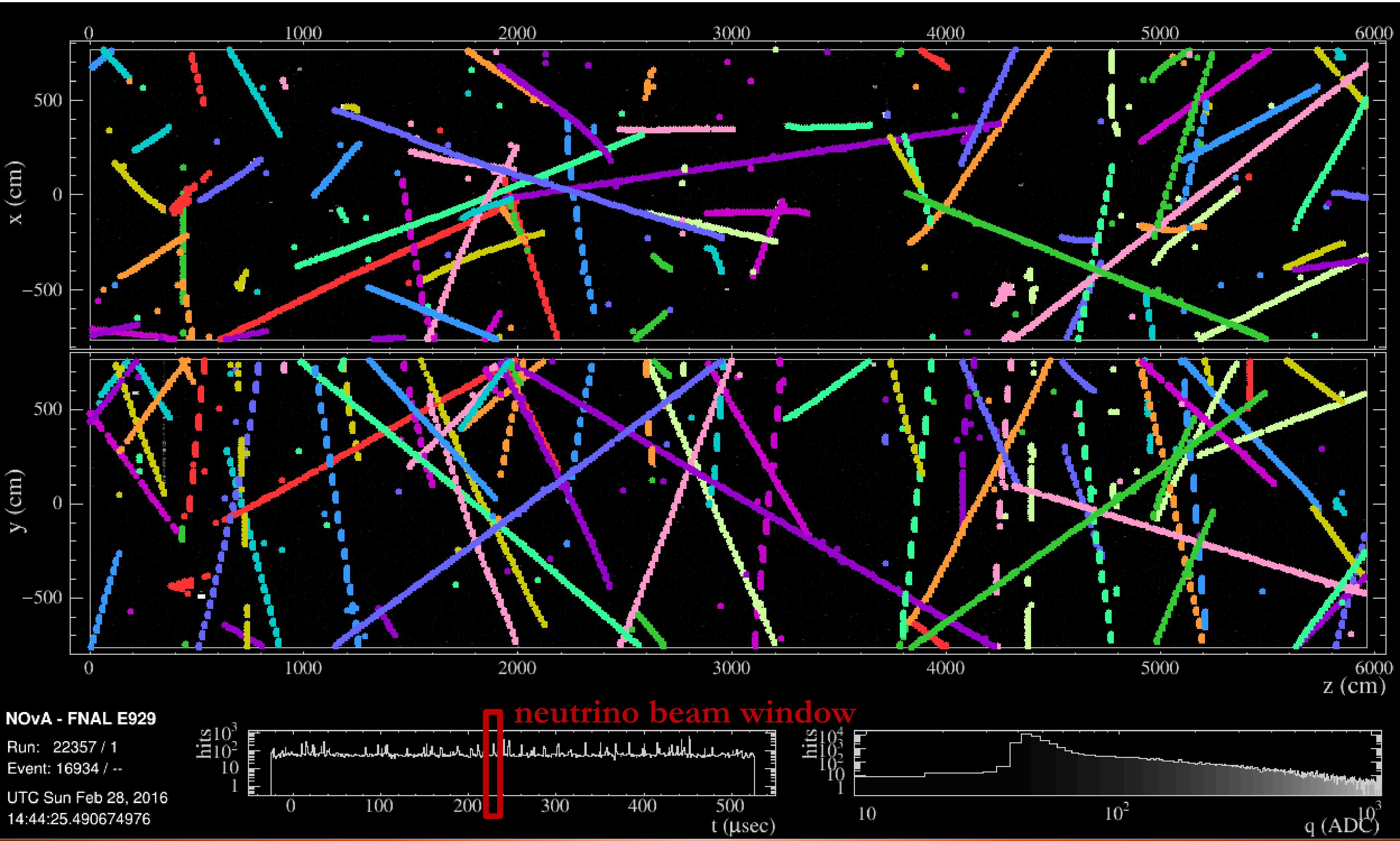
http://novaexperiment.fnal.gov/publications/

NOvA Far Detector readout

Events are 550 μs readouts around the neutrino beam spill

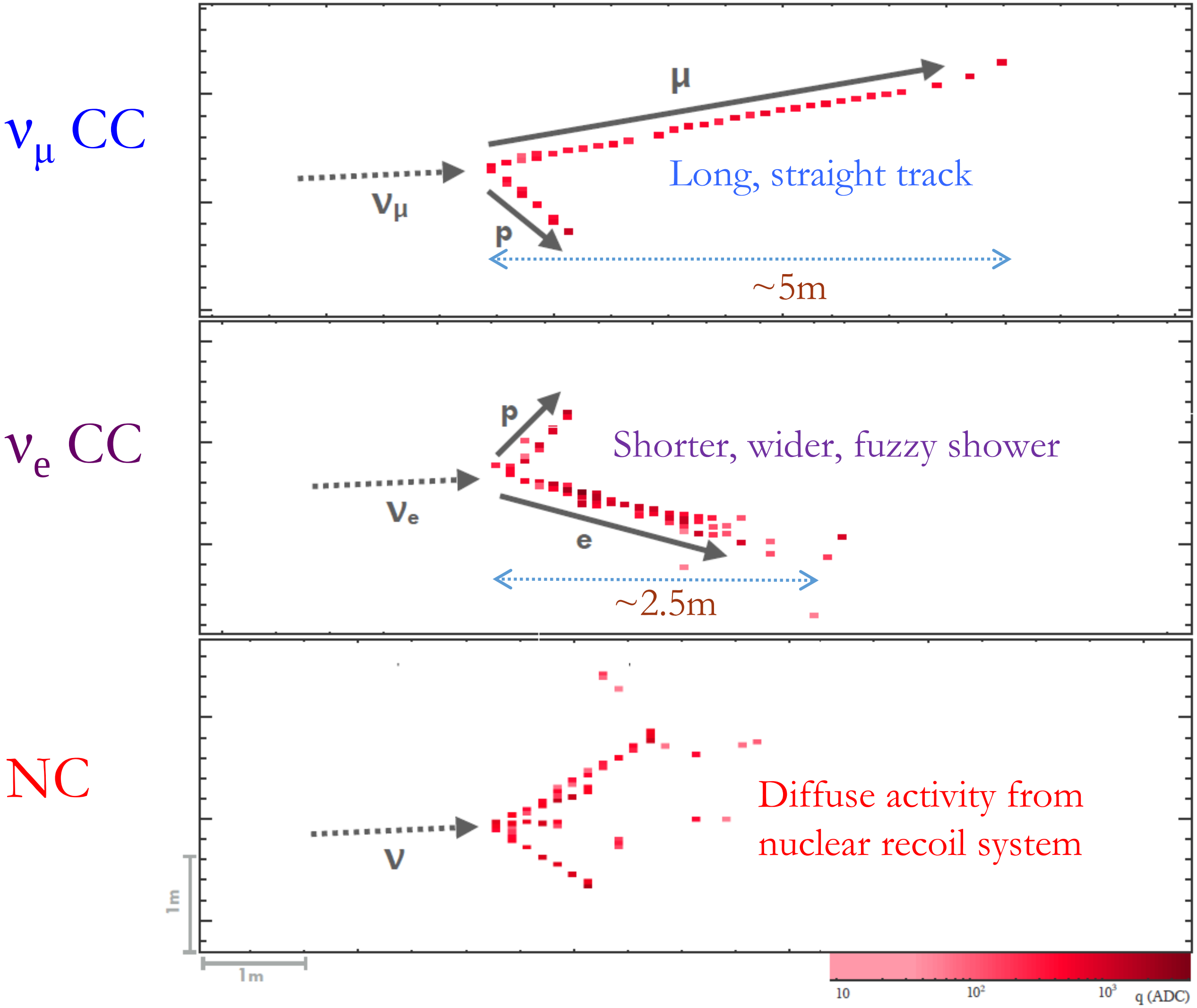


Time-space separation

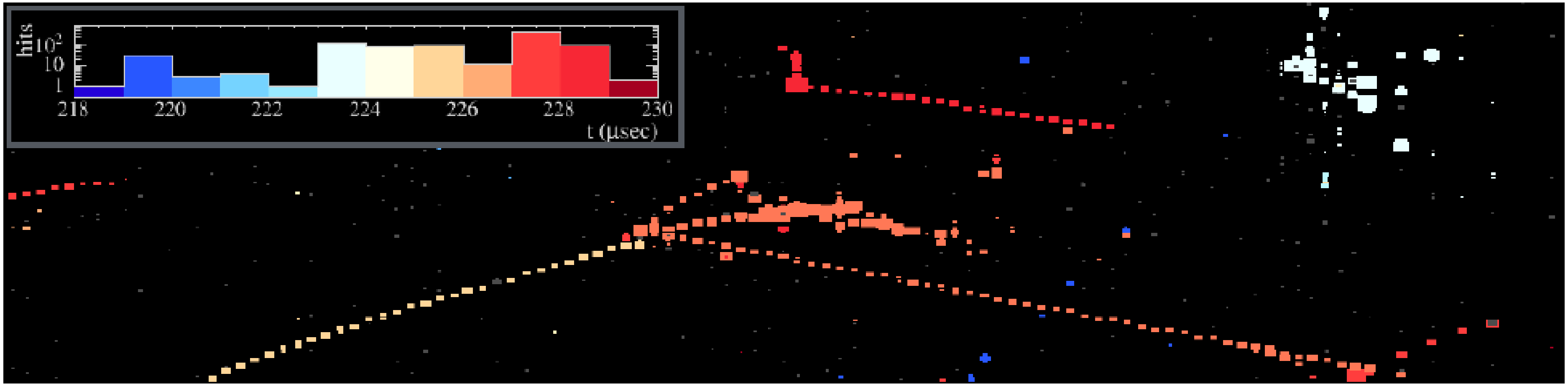


Neutrino Interactions at NOvA

Low-Z to enhance electron photon separation, each plane is ~0.18 X_0
Molière radius is ~10 cm, 2.5 NOvA cells

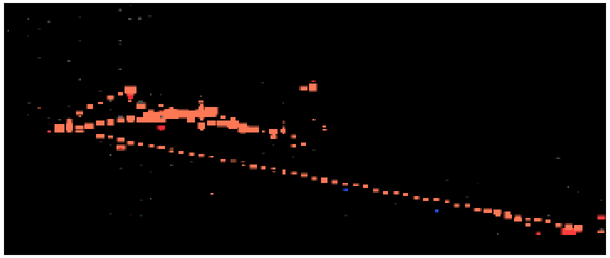


Traditional reconstruction



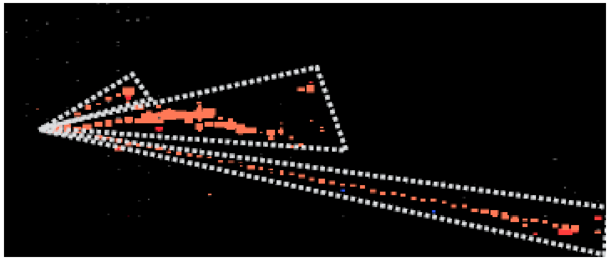
Use the topology and magnitude of the energy depositions.
Takes advantage of the granularity and time resolution of our detectors.

ISOLATE THE EVENT



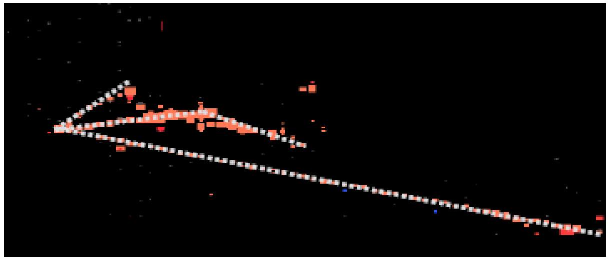
We isolate individual interactions using time and space correlation of the hits

DEFINE CLUSTERS



Groups of hits can be clustered as following the path of same particle starting at the interaction point

FIT TRAJECTORIES

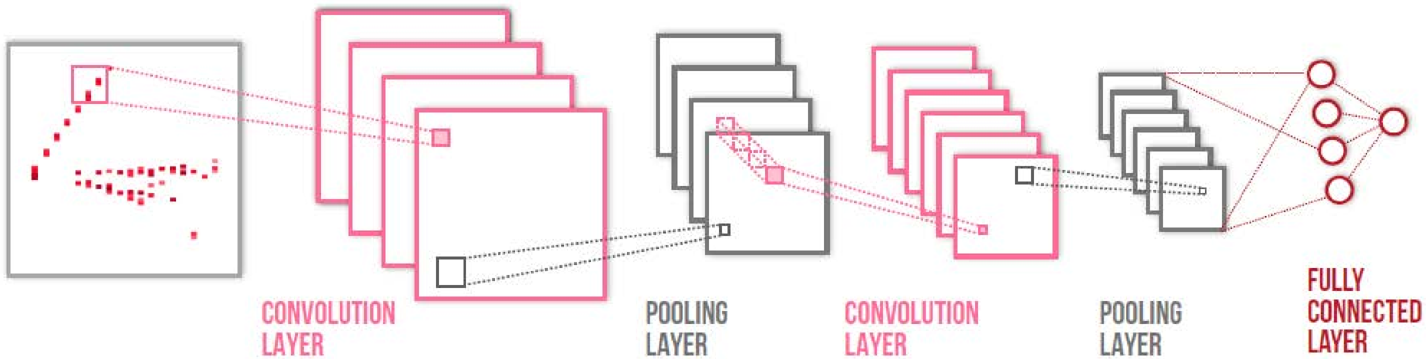


When necessary we can fit an assumed trajectory for each cluster of hits

Reconstruction with deep learning

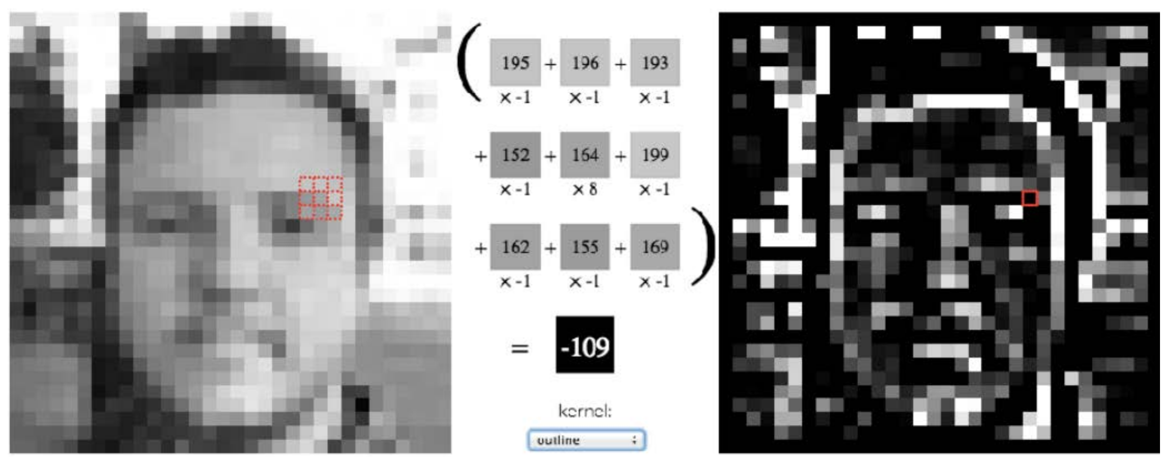
Instead of selecting a set of features a priori, let a deep learning network extract features and draw correlations

Use "images" of our events to train Convolutional Neural Networks (CNNs) to identify neutrino interactions.



Instead of training with a weight for each pixel, convolve kernel operations across the image to extract features

Inspired by the visual cortex



CVN Event Classifier

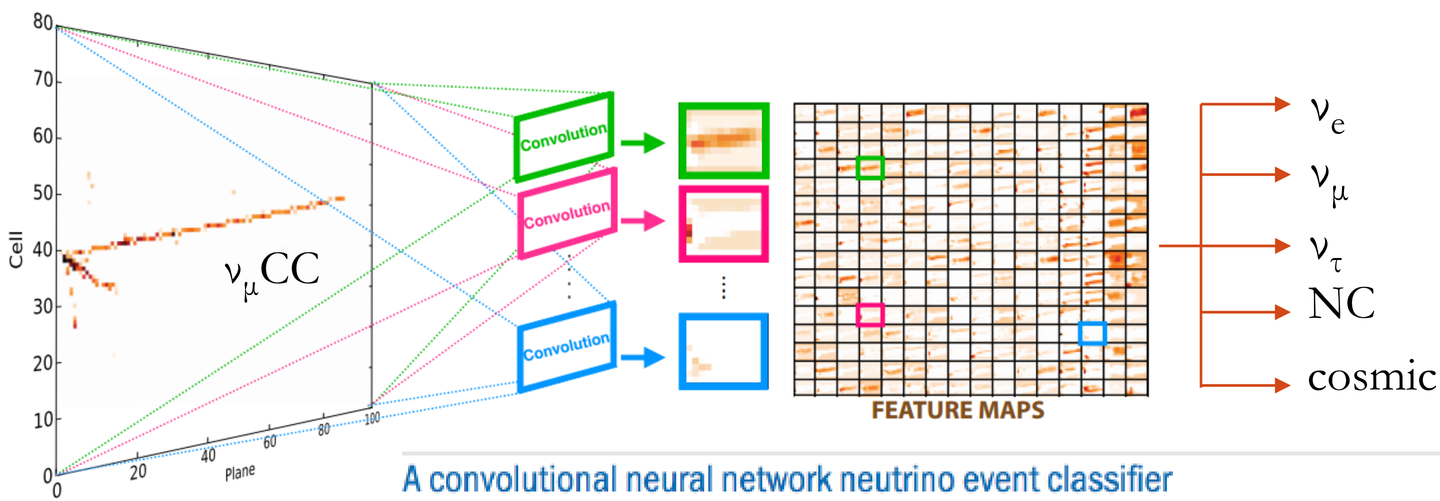
We use a convolutional neural network based on the GoogLeNet.
Calibrated hit maps are inputs to this: Convolutional Visual Network (CVN)

Successive layers of "feature maps" create variants of the original image, which enhance different features at growing levels of abstraction

Extracted features used as inputs to a "feed-forward" neural network to create a multi-label classifier

NOvA's 2016 ν_e appearance analysis was the **first implementation of convolutional neural networks in a HEP result**

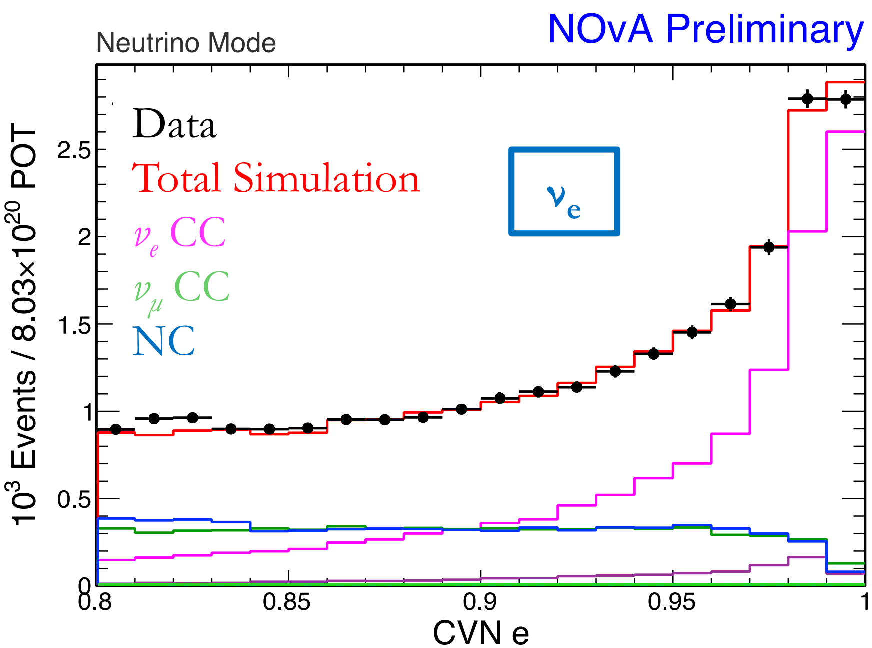
Network produces multi-dimensional classification output, normalized to 1.
Reduces processing time running one network for many analyzes.

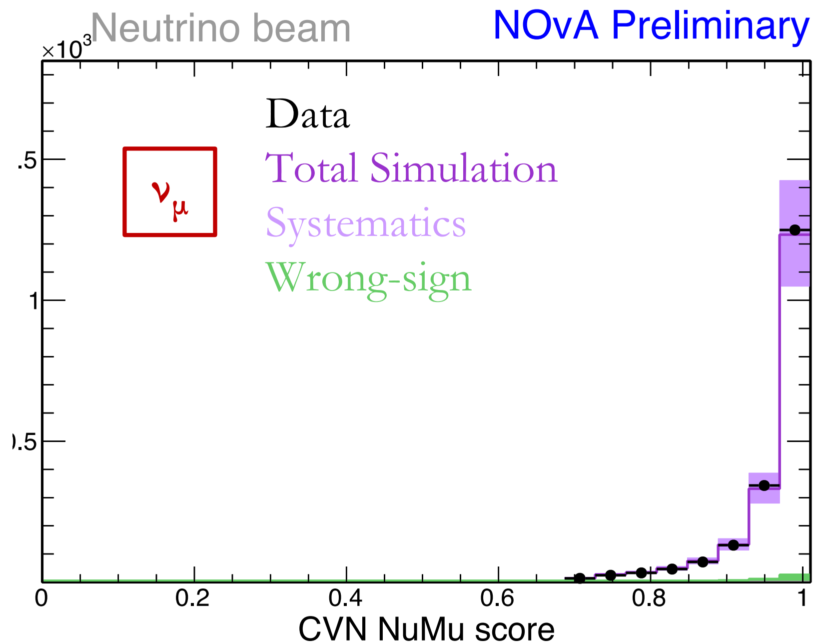


A convolutional neural network neutrino event classifier — 2016 *JINST* **11** P09001

A. Aurisano, A. Radovic, D. Rocco, A. Himmel, M.D. Messier, E. Niner, G. Pawloski, F. Psihas, A. Sousa and P. Vahle

Updated CVN





New for this analysis:

A shorter, simpler architecture trained on updated simulation.

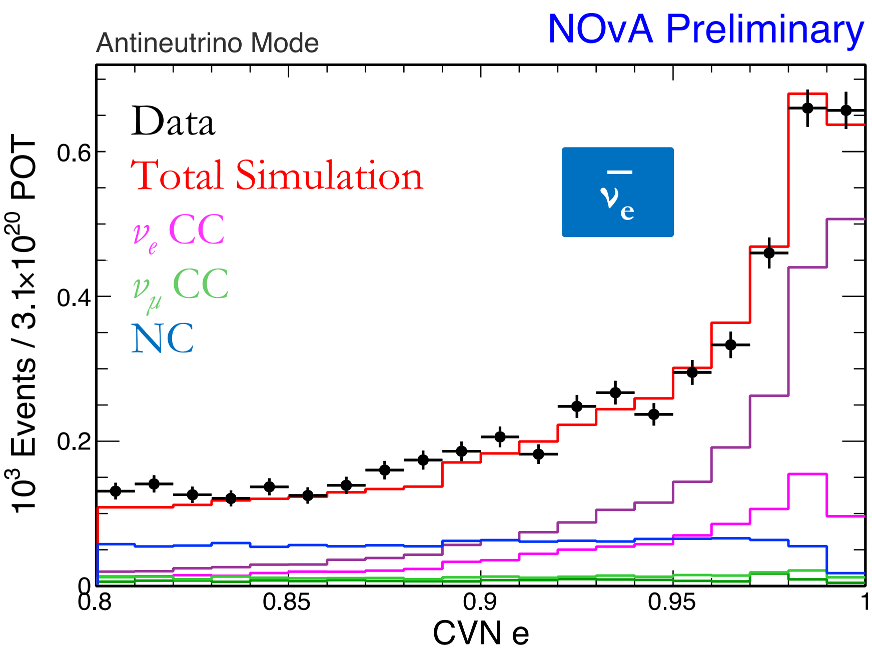
Replaced Genie truth labels with final state labels.

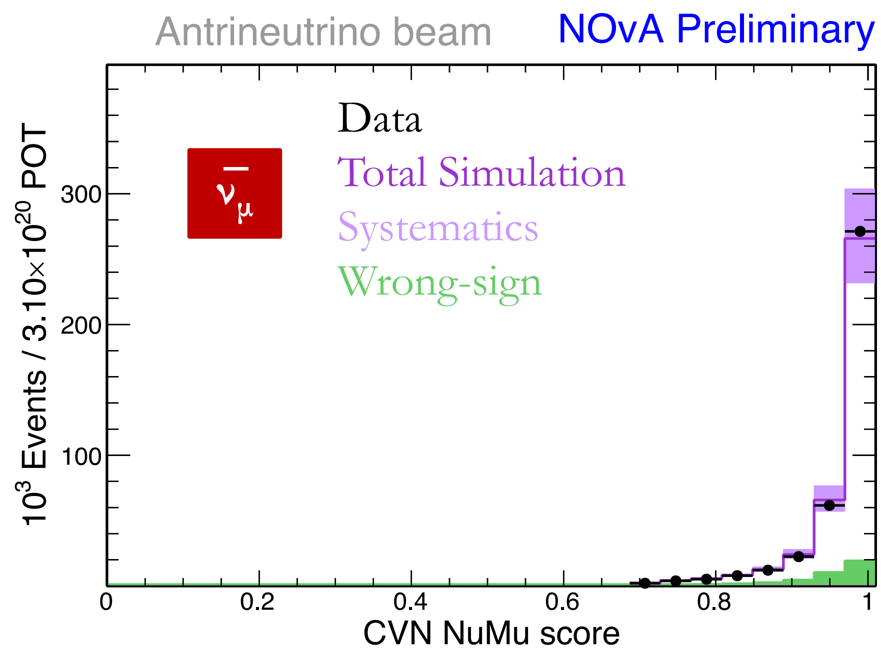
- Exploring using final states with protons to constrain WS backgrounds.

Separate training for the neutrino and antineutrino beams.

- Wrong-sign treated as signal in training.
- 14% better efficiency for $\bar{\nu}_e$ with a dedicated network.

Updated CVN





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Simulation tuning

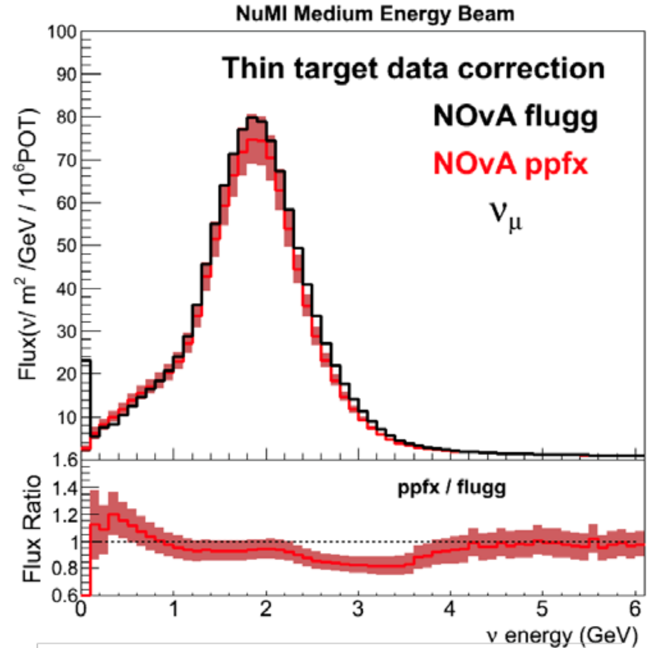
We tune our simulation to get a better central value *and* to set systematic uncertainties.

Beam flux is tuned using the **Package to Predict the FluX** using external data.

- **Minerva**, Phys. Rev. D 94, 092005 (2016)

We tune our cross-section model primarily to account for **nuclear effects**.

- Backstory: disagreements are seen in cross sections as measured on a single nucleons vs. in more complex nuclei.
- Nuclear effects are a likely solution, but the theory for them remains incomplete.
- So, we tune using a combination of **external theory** inputs and our own **ND data**.



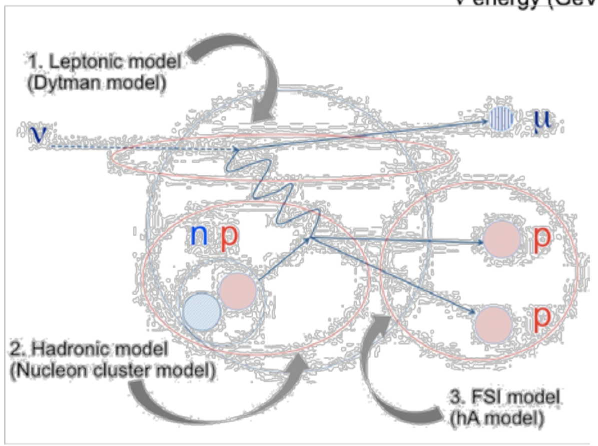
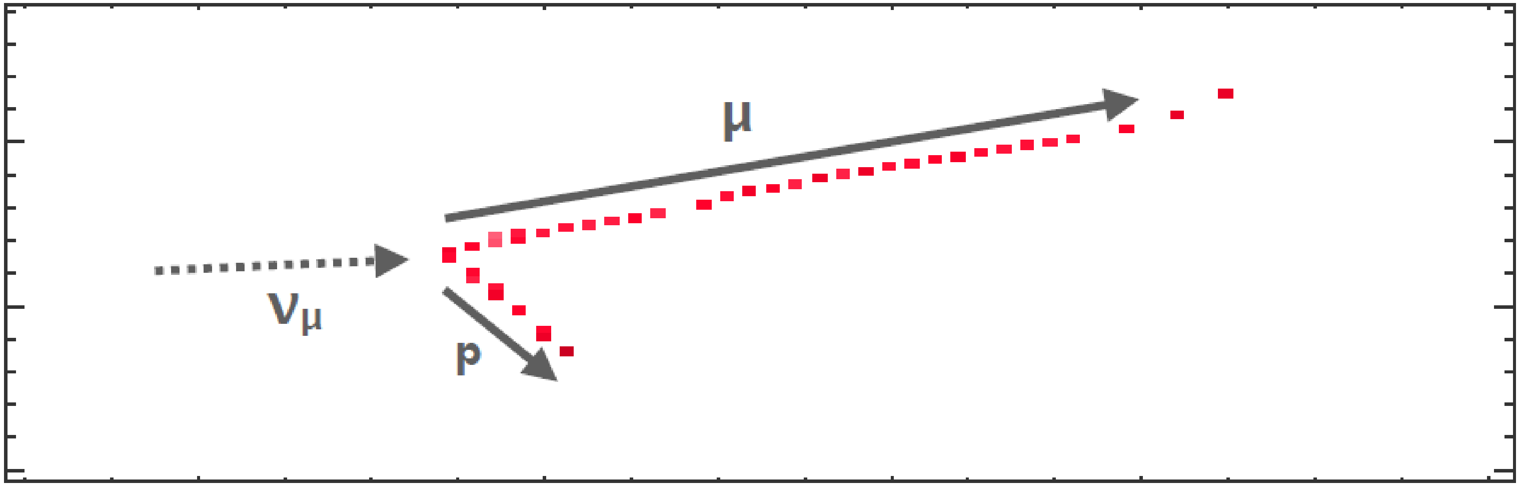


Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001



$\nu_\mu(\overline{\nu_\mu})$ disappearance

ν_μ and $\overline{\nu}_\mu$ at the ND

Select muon neutrino and antineutrino CC events in ND

- Wrong sign contamination ~3% for neutrino (11% antineutrino)

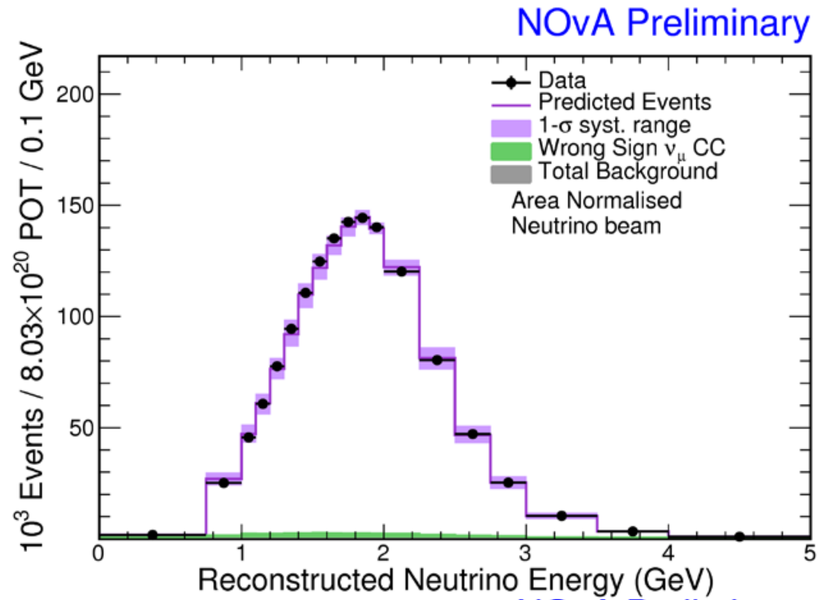
Reconstructed neutrino energy is estimated from muon length and hadronic energy

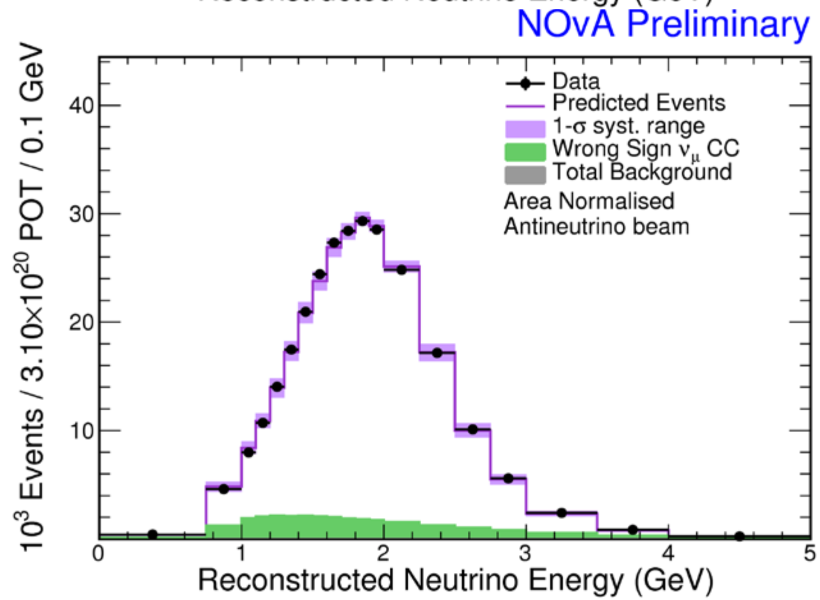
- $E_\nu = E_\mu + E_{had}$

Data is split in 4 equal populations (quartiles) based on hadronic energy fraction as a function of reconstructed neutrino energy

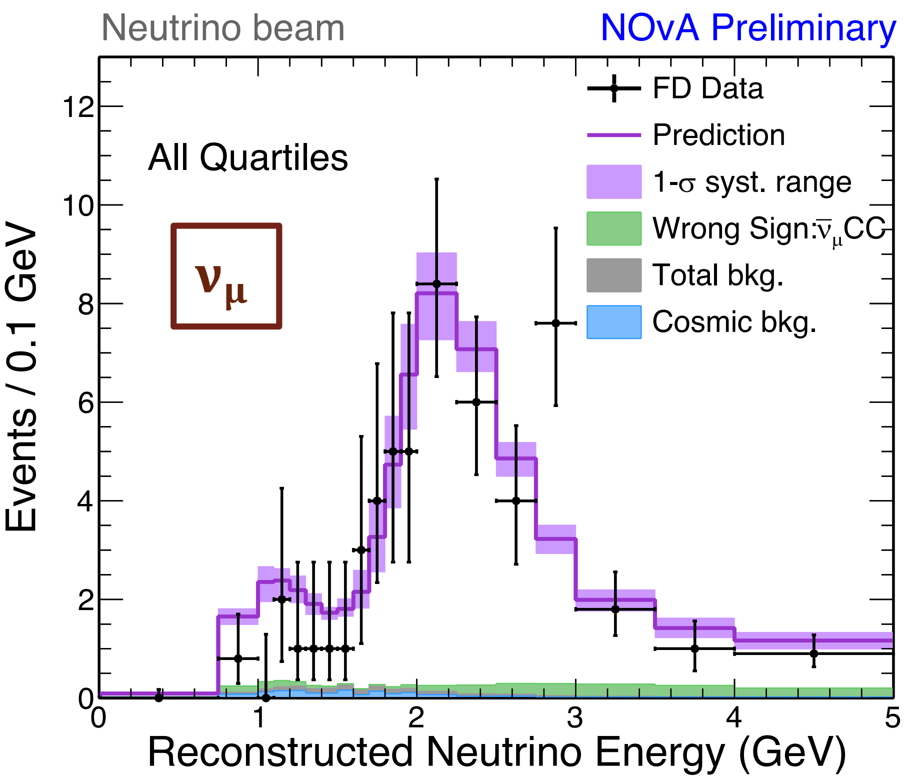
- Energy resolution varies from 5.8% (5.5%) to 11.7% (10.8%) for neutrino (antineutrino) beam

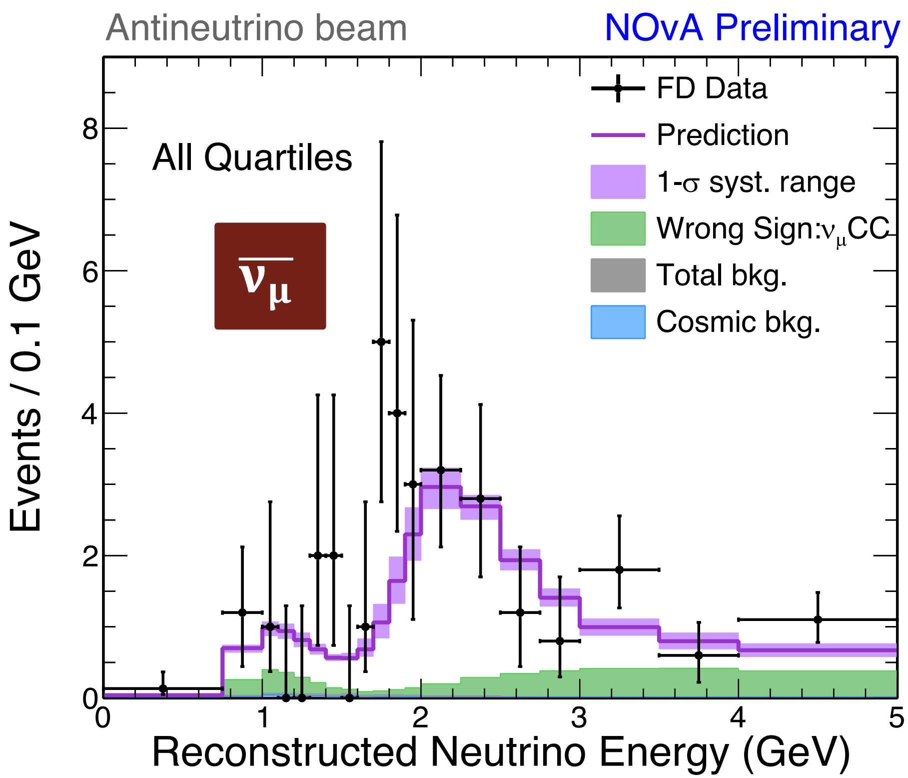
Systematic uncertainties shown are shape only, 1.3% and 0.5% offset for neutrinos and antineutrinos respectively is removed for display purposes





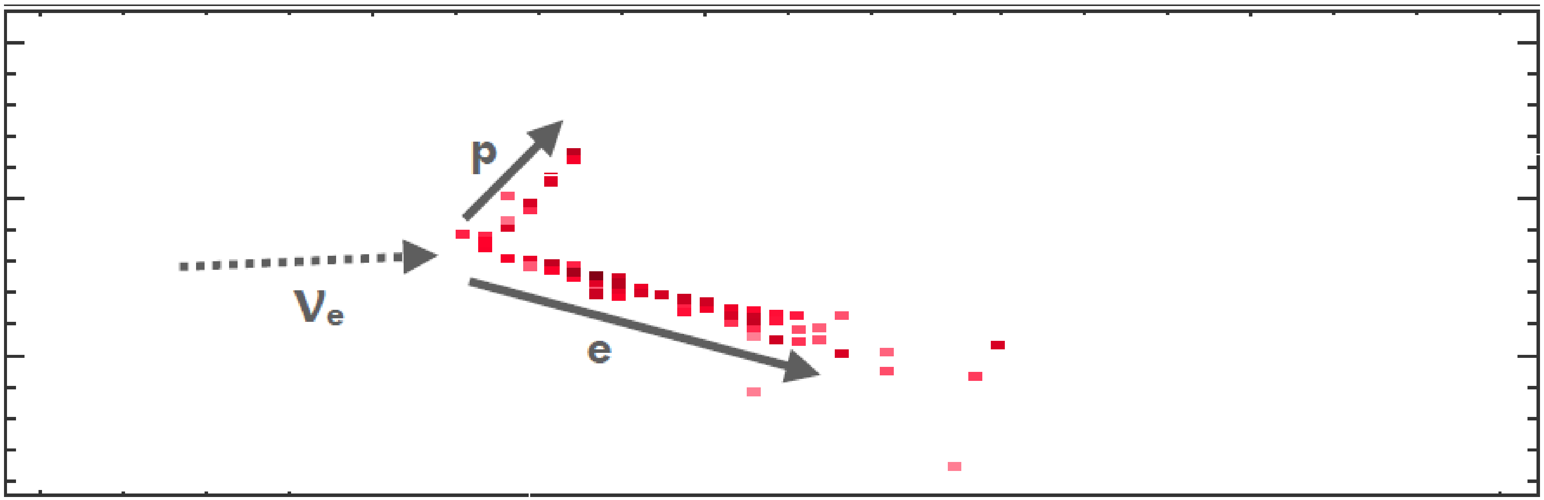
Predict ν_μ and $\overline{\nu_\mu}$ at the FD





Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

Total Observed	65
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266



$\nu_e(\overline{\nu}_e)$ appearance

ν_e and $\bar{\nu}_e$ at the ND

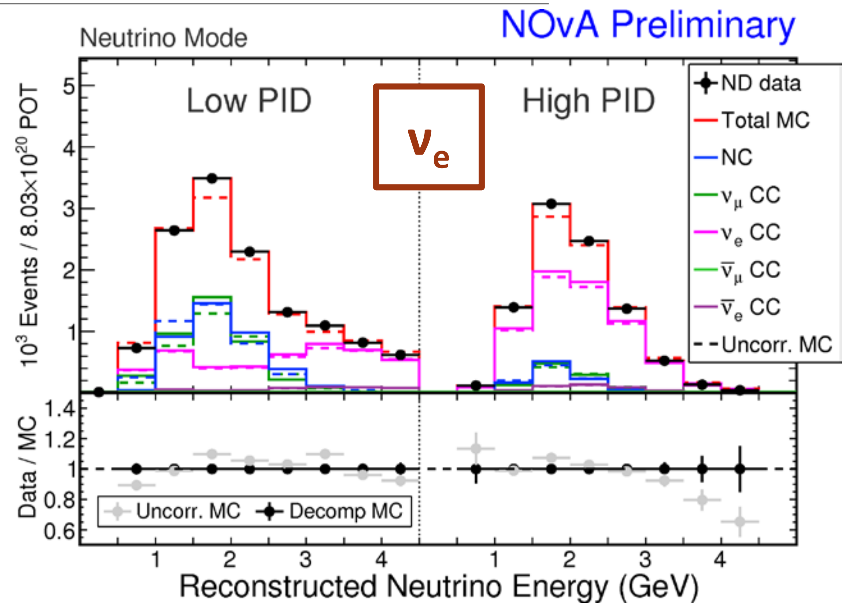
Select electron neutrino and antineutrino CC events using particle ID in the ND for each beam mode

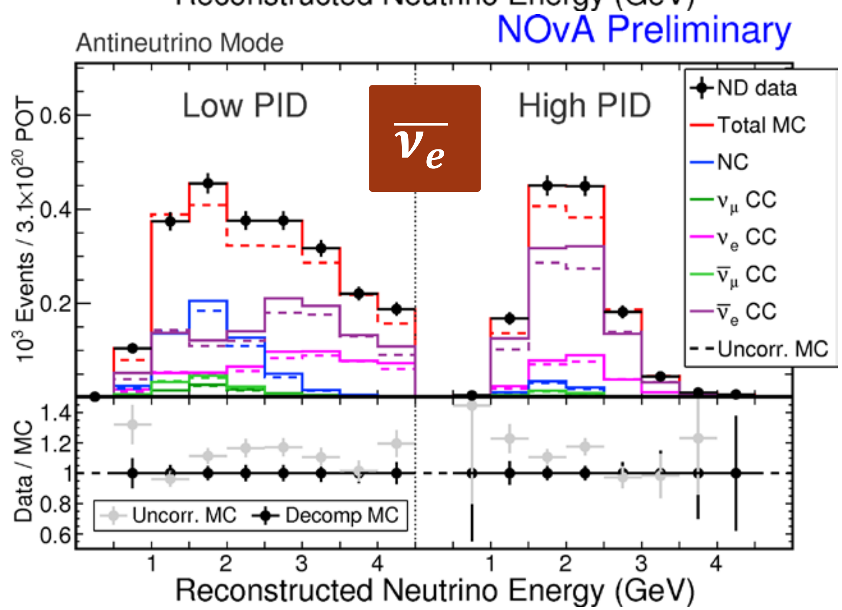
- Separate into low and high particle ID (purity)

For the neutrino beam constrain:

- the beam electron neutrinos using the muon neutrino spectrum
- the muon neutrino background using Michel electrons
- remaining data/MC discrepancy is assigned to the neutral current component

For the antineutrino beam, scale all components evenly to match the data.





Predict ν_e and $\overline{\nu}_e$ at the FD

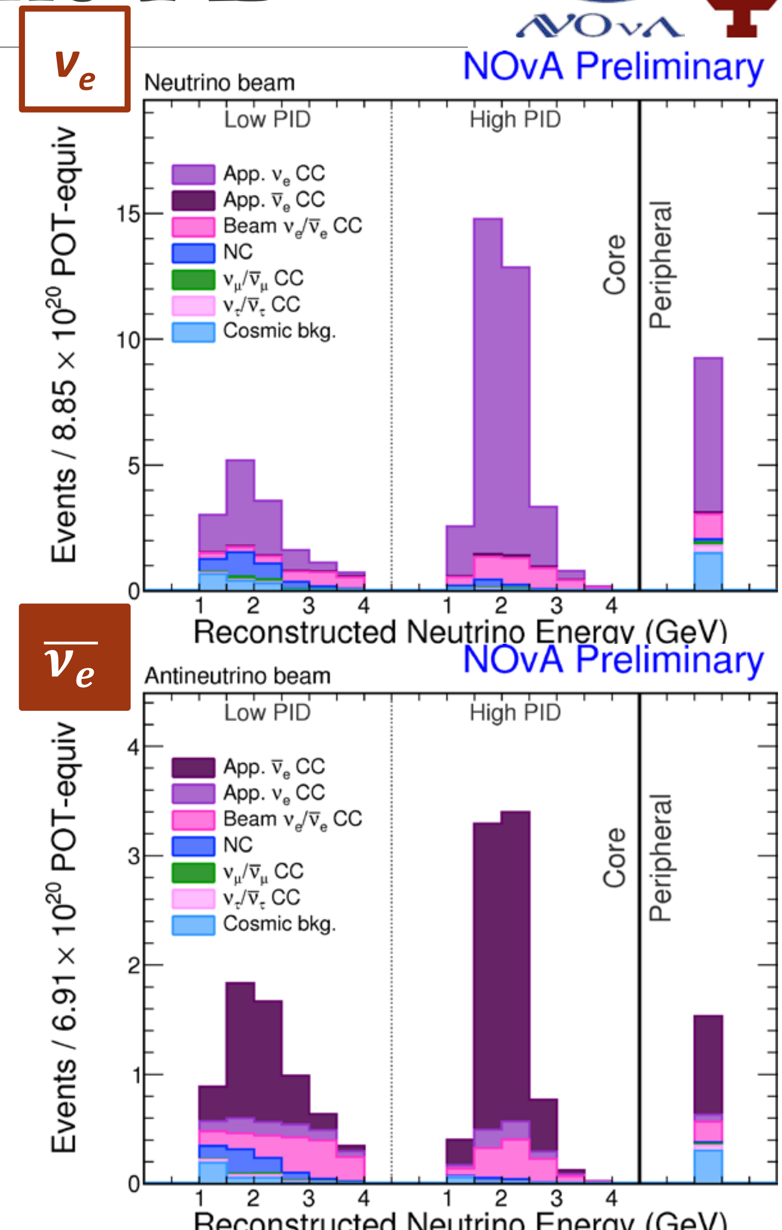
We use the ND data to predict the background in the FD

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 cut

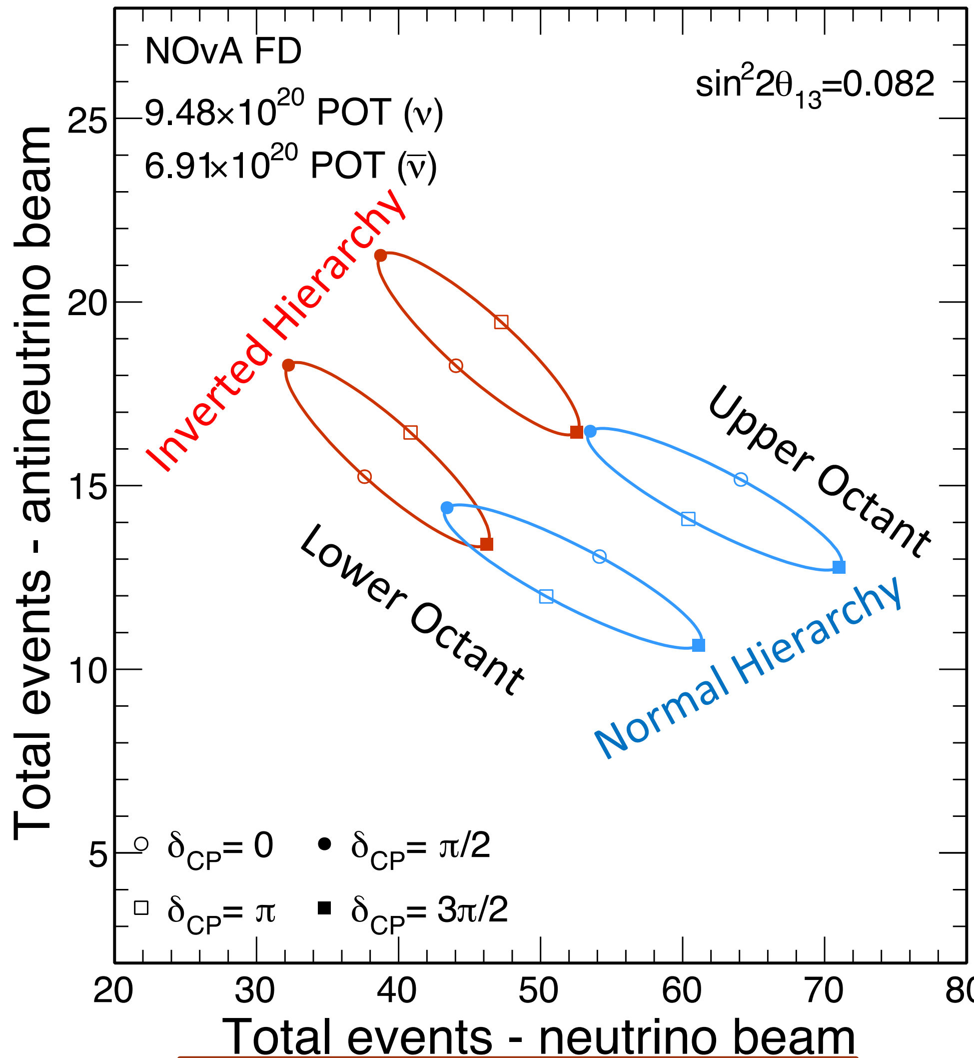
ND wrong sign component is 22% (32%) of the electron neutrino background for the high (low) PID bin

Data-based cross-checks using identified protons and event kinematics within systematic uncertainty.



ν_e and $\bar{\nu}_e$ expectations

NOvA Simulation



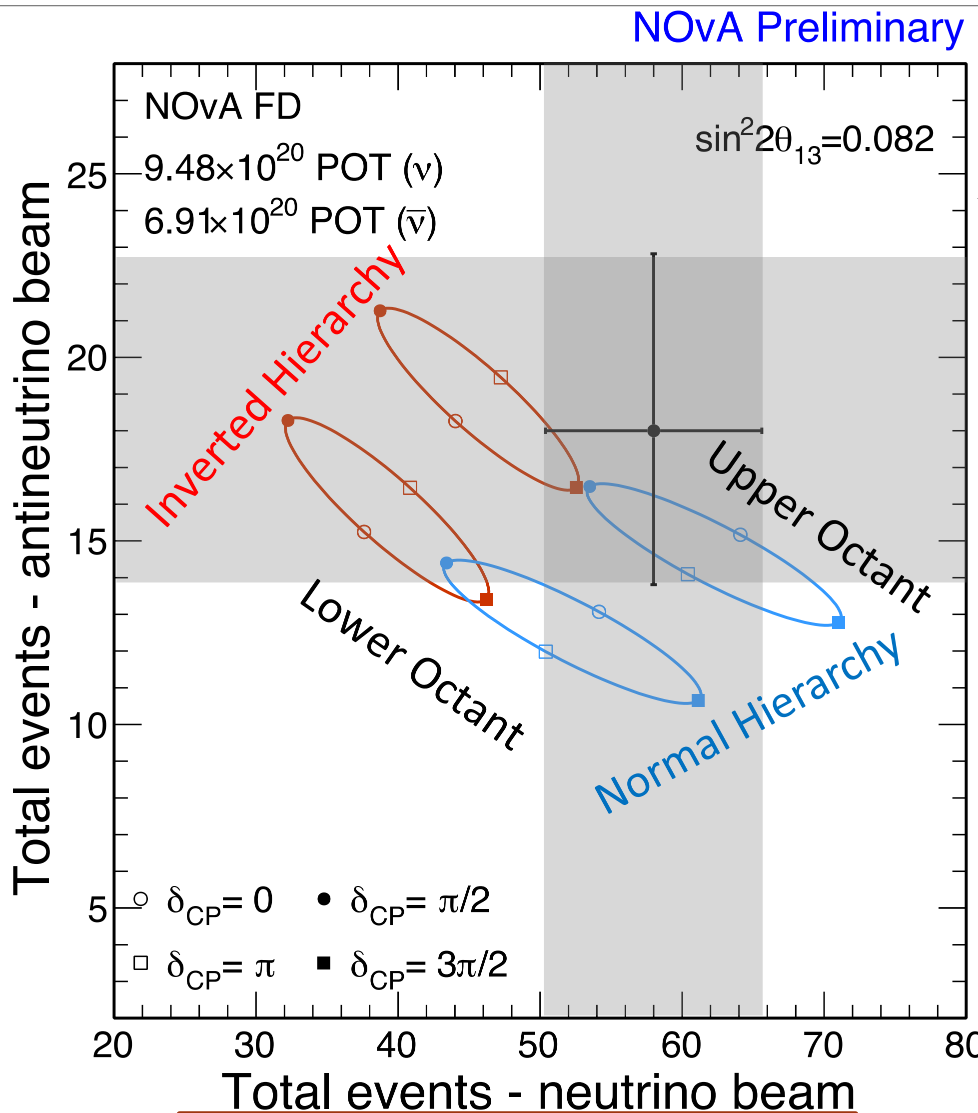
Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.

Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).

10-22 Expected for $\bar{\nu}_e$

30-75 Expected for ν_e

ν_e and $\bar{\nu}_e$ observations



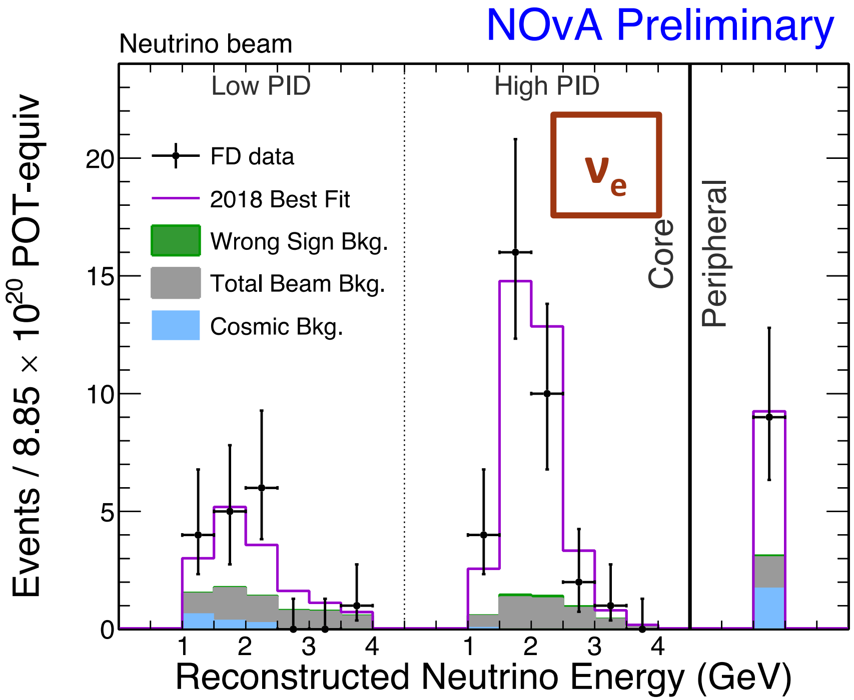
Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.

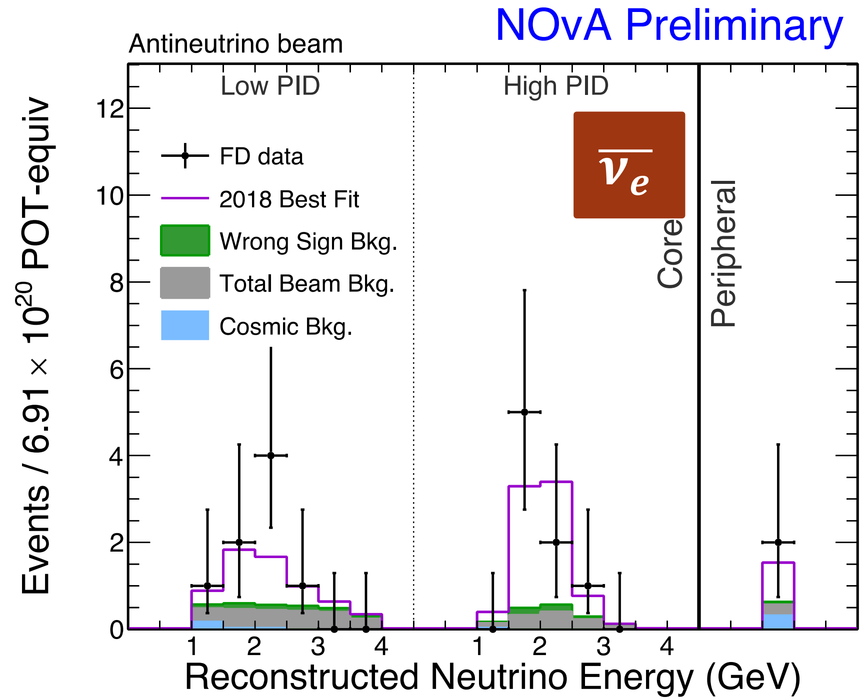
Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).

18 observed $\bar{\nu}_e$

58 observed ν_e

ν_e and $\overline{\nu}_e$ at the FD

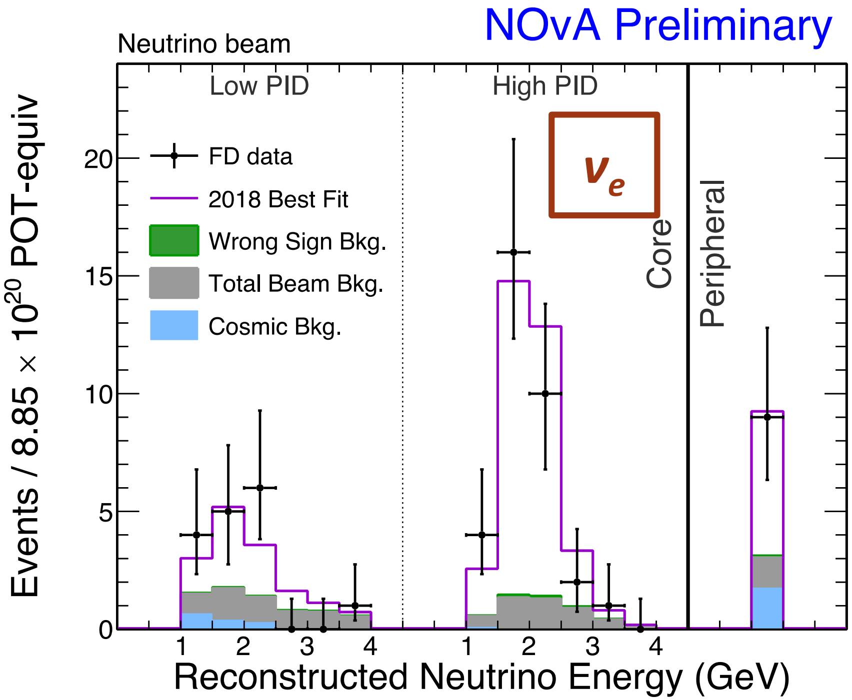


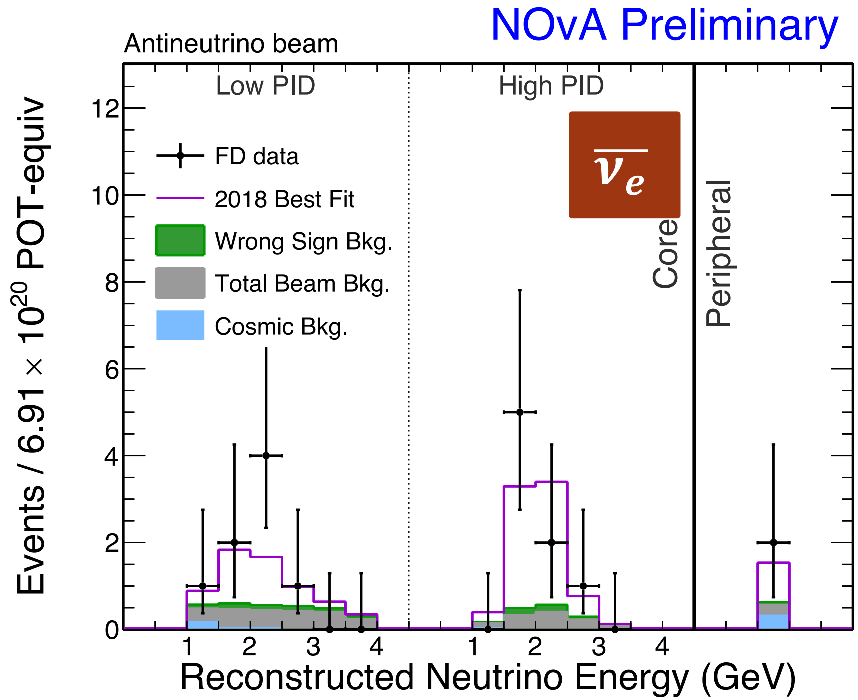


Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

Total Observed	18	Range
Total Prediction	15.9	10-22
Wrong-sign	1.1	0.5-1.5
Beam Bkgd.	3.5	
Cosmic Bkgd.	0.7	
Total Bkgd.	5.3	4.7-5.7

ν_e and $\overline{\nu}_e$ at the FD





Strong (>4σ) evidence of $\overline{\nu}_e$ appearance

Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

Total Observed	18	Range
Total Prediction	15.9	10-22
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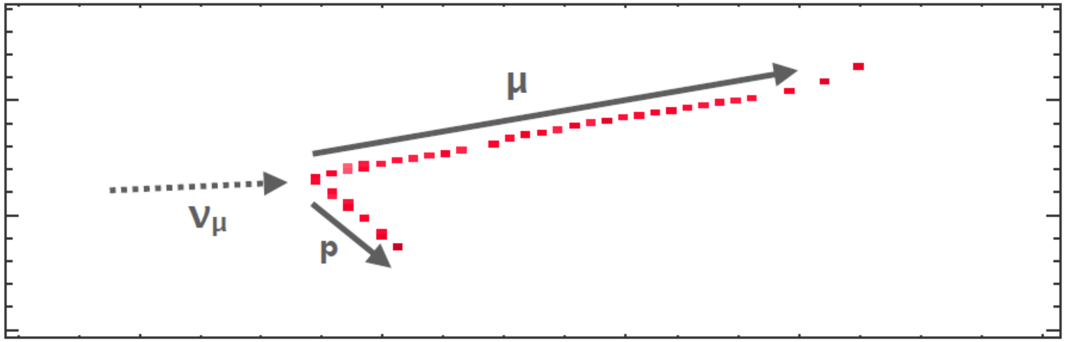
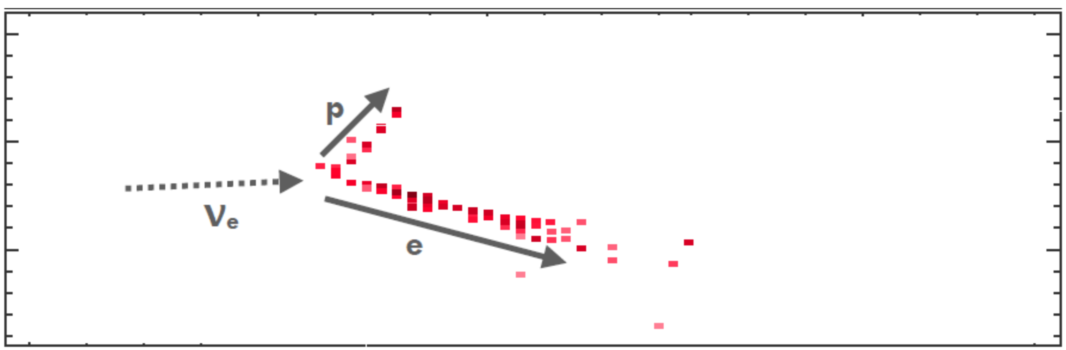
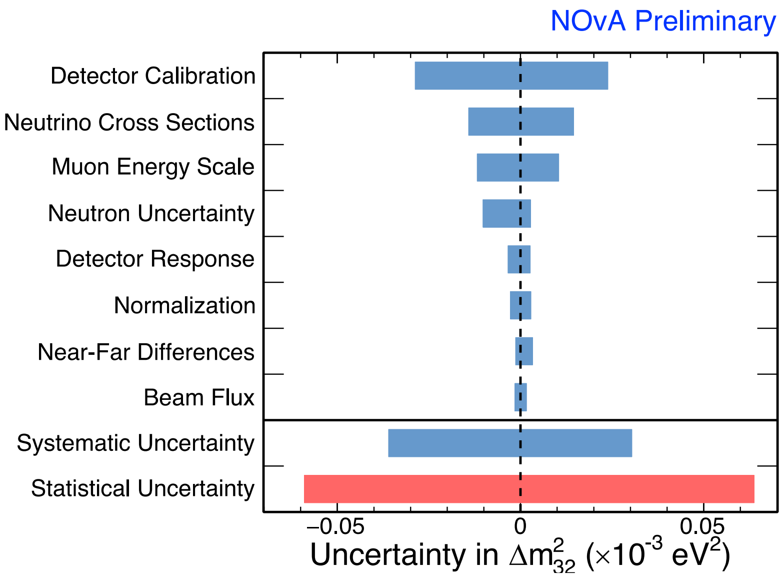


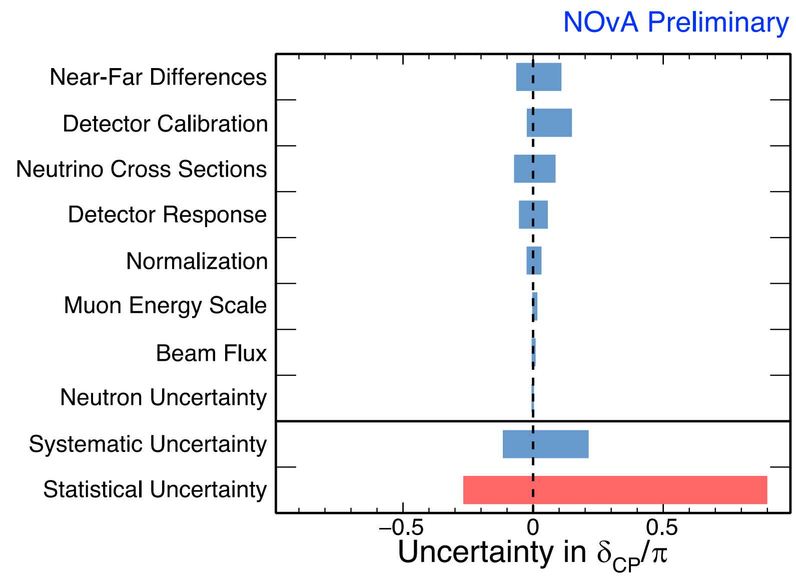
+

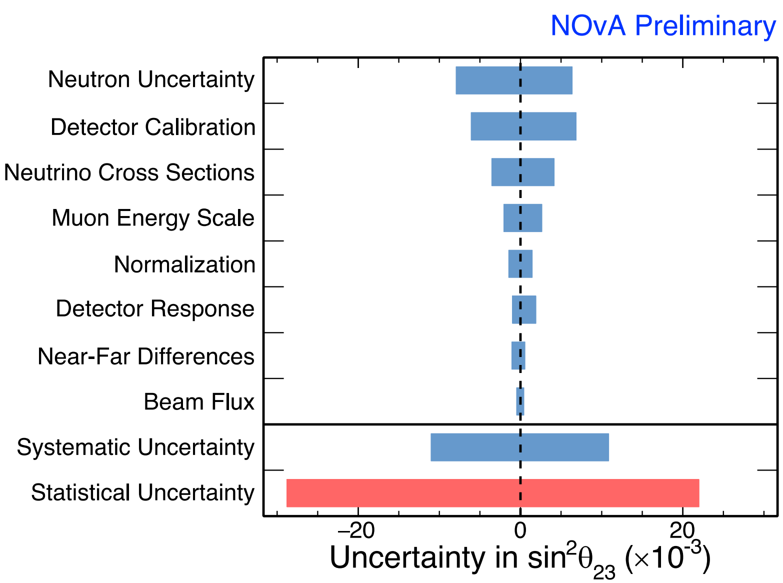


Joint ν_e appearance + ν_μ disappearance

Systematic uncertainties







Most important systematics:

Detector Calibration

- Will be improved by the 2019 test beam program

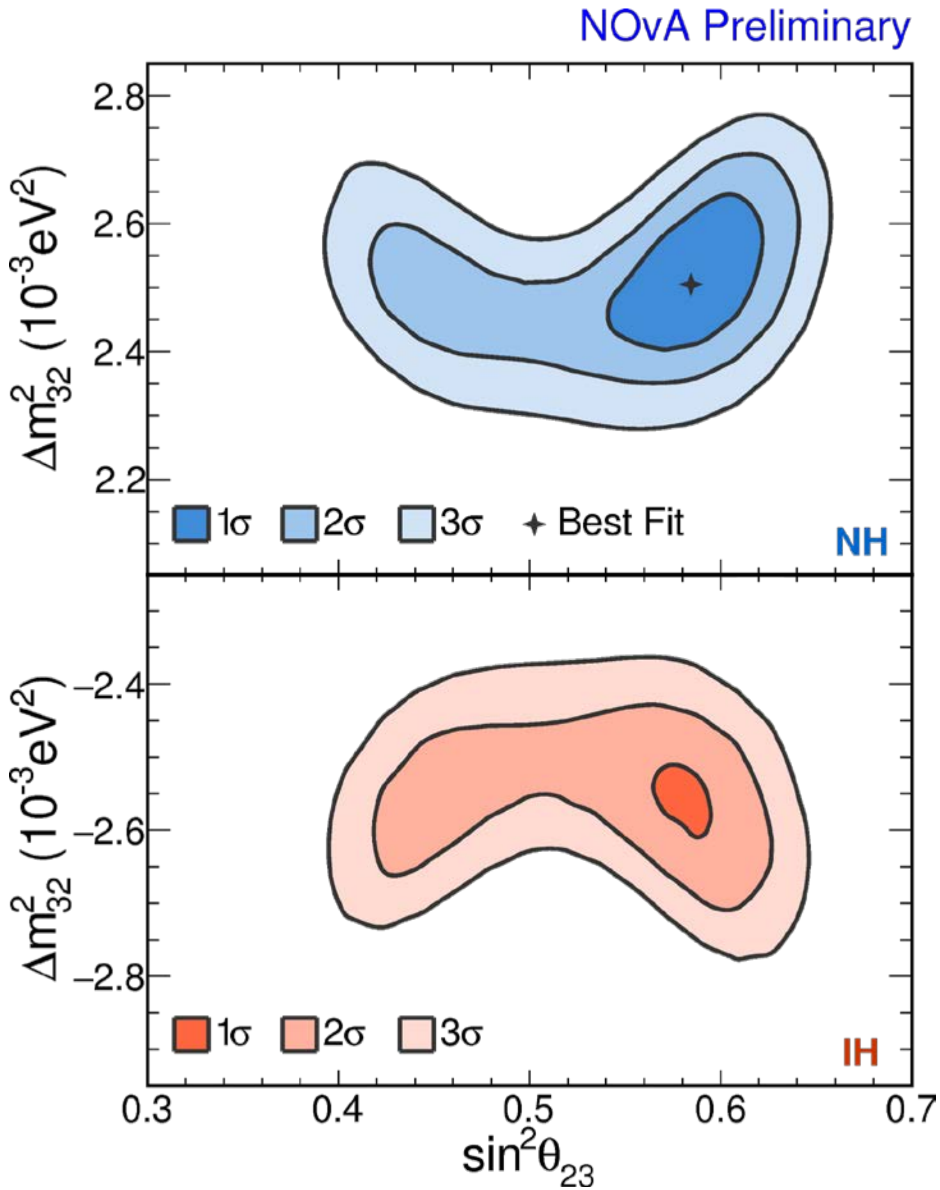
Neutrino cross sections

- Particularly nuclear effects (RPA, MEC)

Muon energy scale

Neutron uncertainty – **new** with $\bar{\nu}$'s

Allowed oscillation parameters



Best Fit

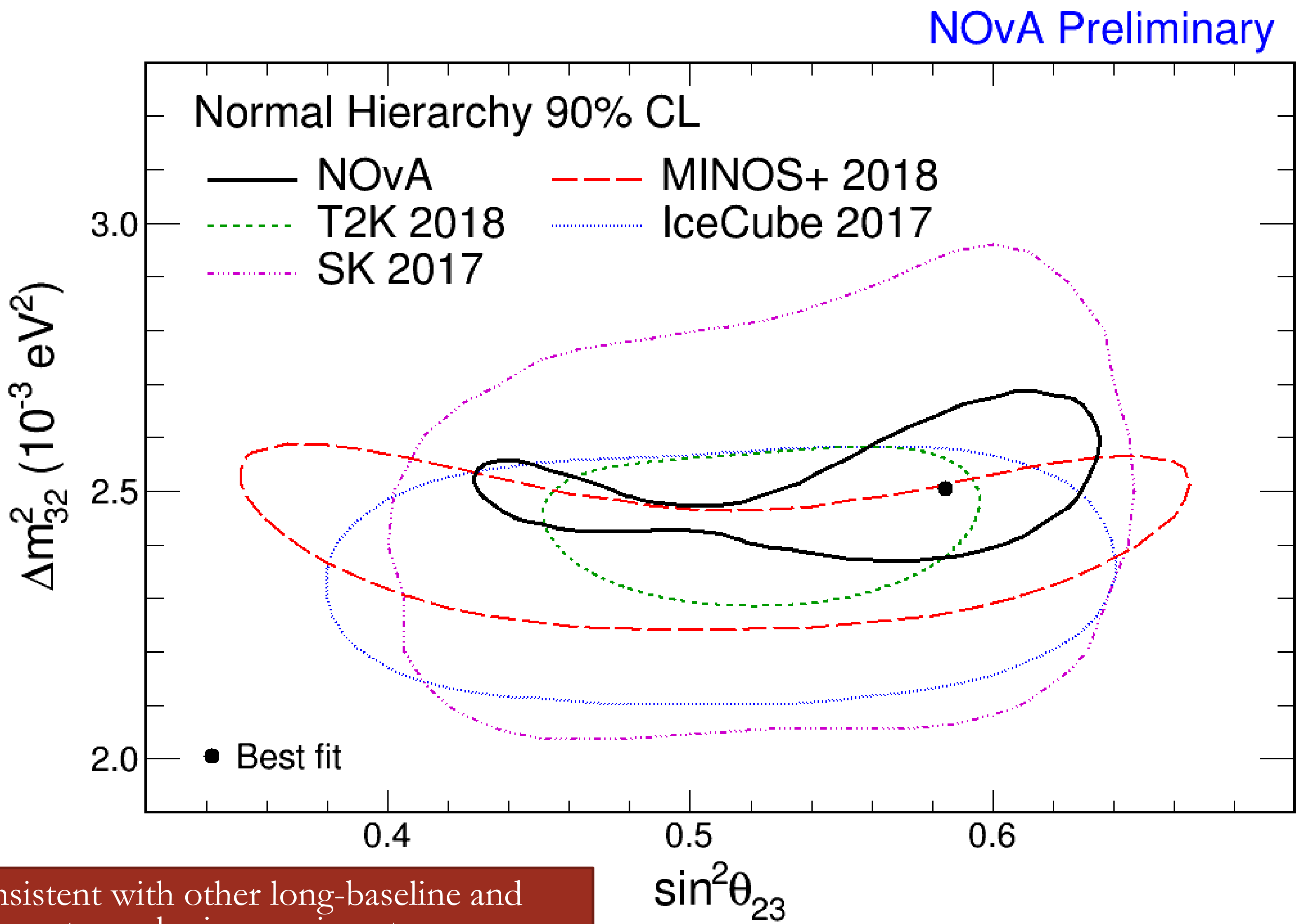
Normal hierarchy

Upper Octant

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

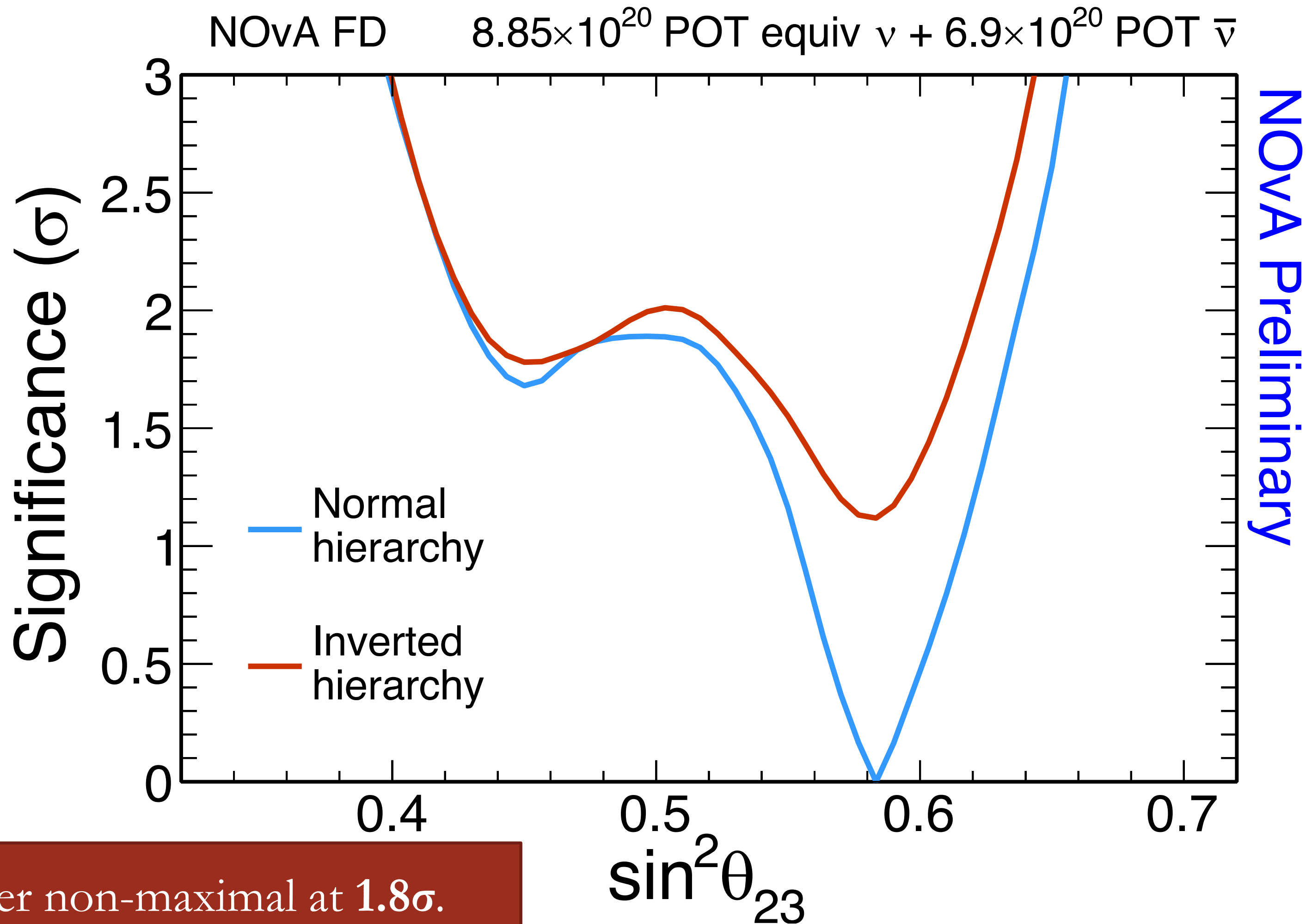
$\sin^2\theta_{23} = 0.58 \pm 0.03$

Allowed oscillation parameters



Consistent with other long-baseline and atmospheric experiments.

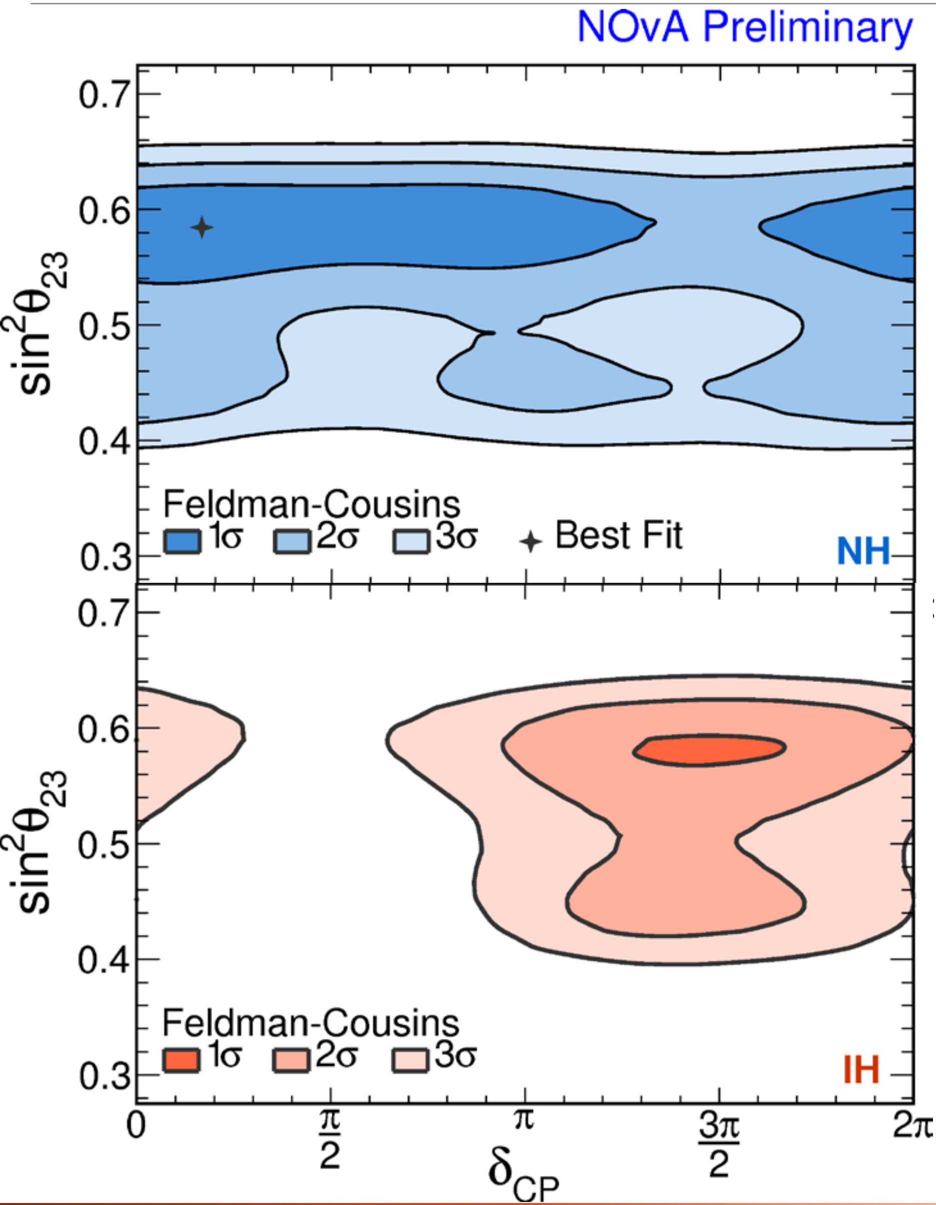
Significance of maximal



Prefer non-maximal at **1.8σ.**

Exclude lower octant at similar level

Allowed oscillation parameters



Best Fit

Normal hierarchy

Upper Octant

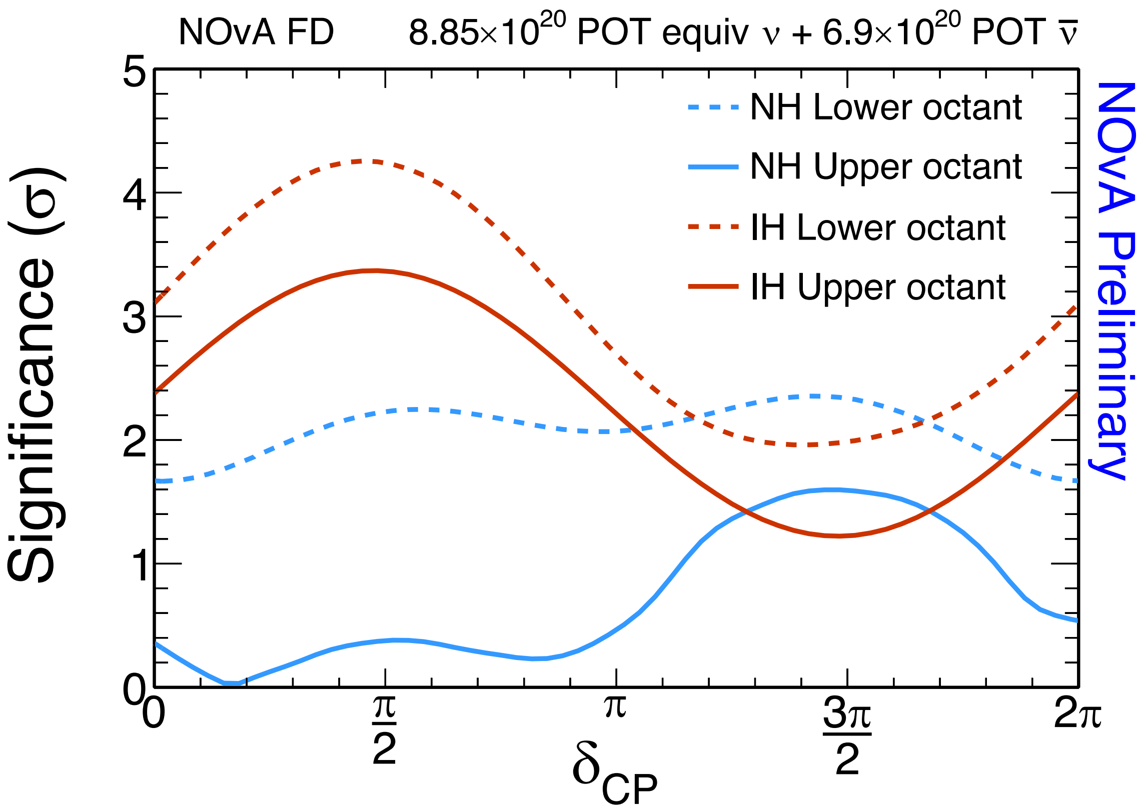
$\Delta m^2 = (2.51^{+0.12}_{-0.08})\times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{23} = 0.58 \pm 0.03$

$\delta_{CP} = 0.17\pi$

Exclude IH, $\delta=\pi/2$ at > 3σ

Allowed oscillation parameters

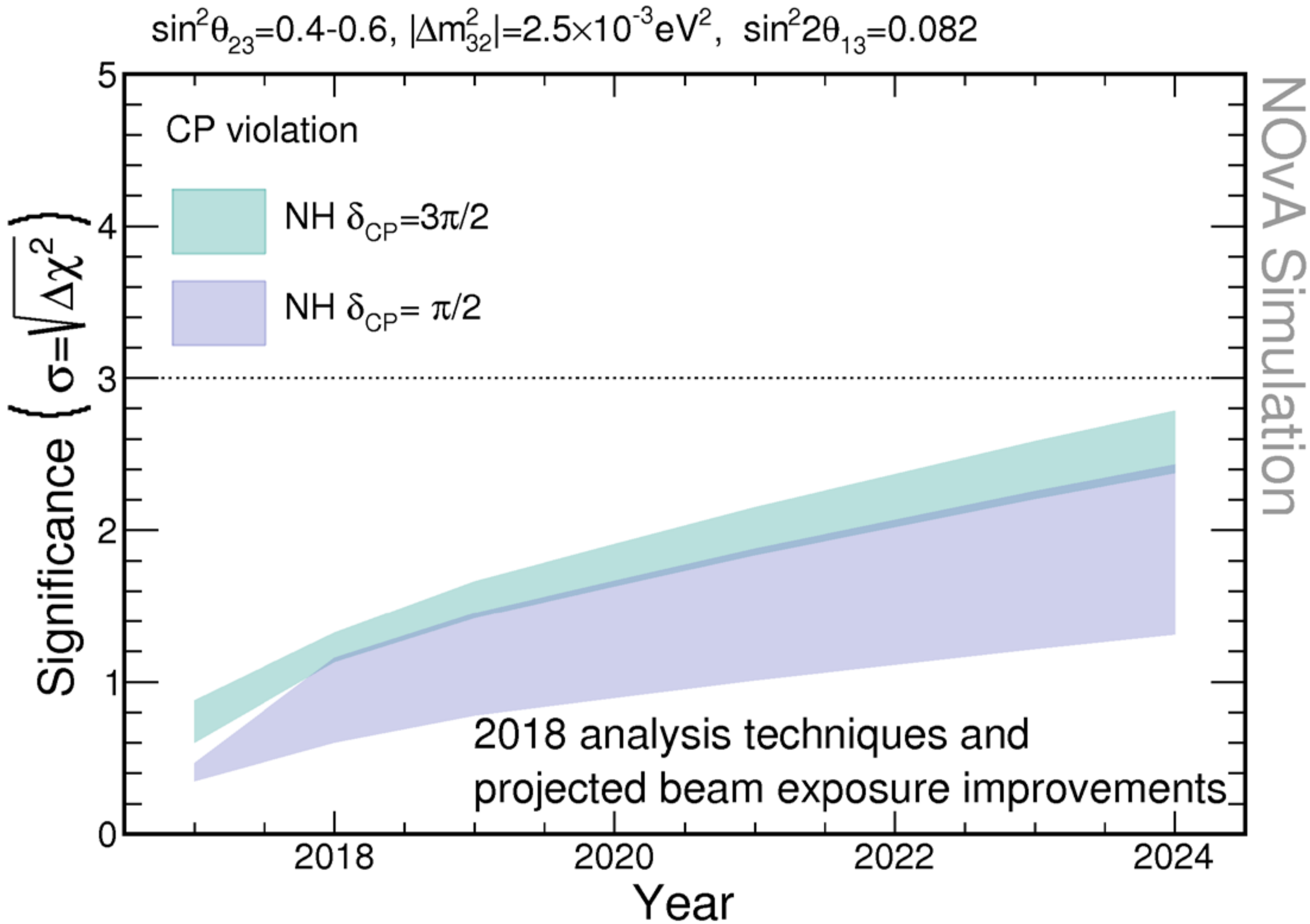


Consistent with all δ_{CP} values in NH at < 1.6σ.

Note: you cannot read the rejection of the MH from this plot.

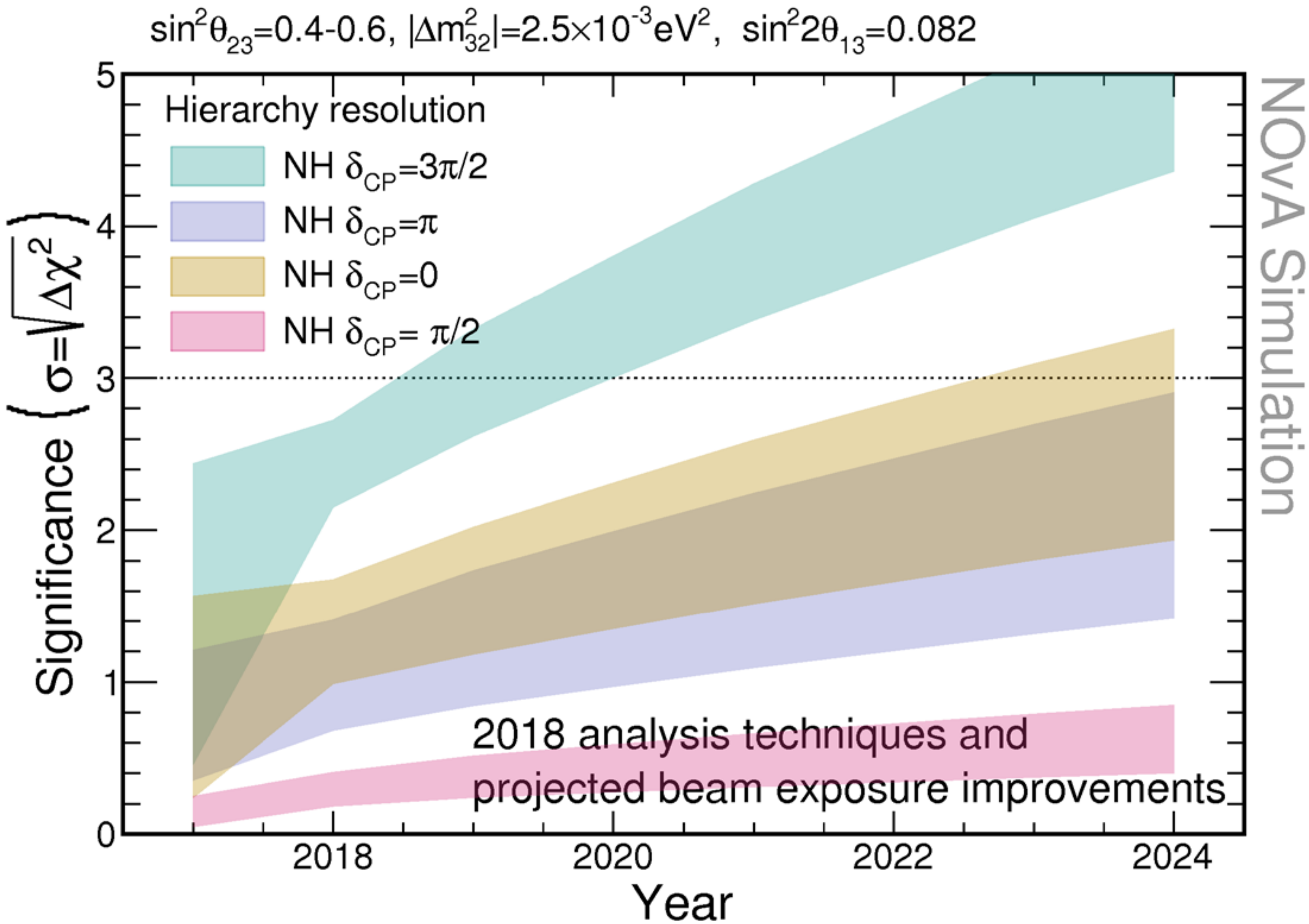
- This is an FC-corrected plot of significance for rejecting particular sets of values: (δ, octant, hierarchy).
- It is *not* a likelihood surface, so it cannot be profiled to remove δ and the octant.

Into the future



2σ sensitivity to CP violation in 2024 for favorable parameters

Into the future



2σ sensitivity to CP violation in 2024 for favorable parameters

3σ sensitivity to the hierarchy possible in 2020 with favorable parameters

Test beam program

The test beam program is how we will realize those analysis improvements

Reduced systematics

Additional validation of DL techniques

Simulation improvements

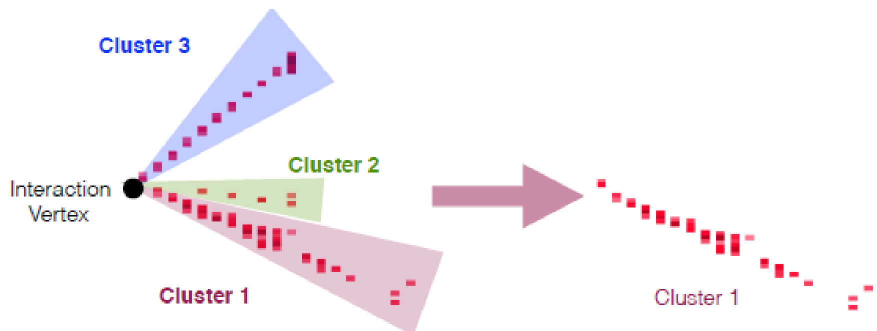
Installation and commissioning starting this summer

Beam in the first half of 2019, planning on 2 million particles

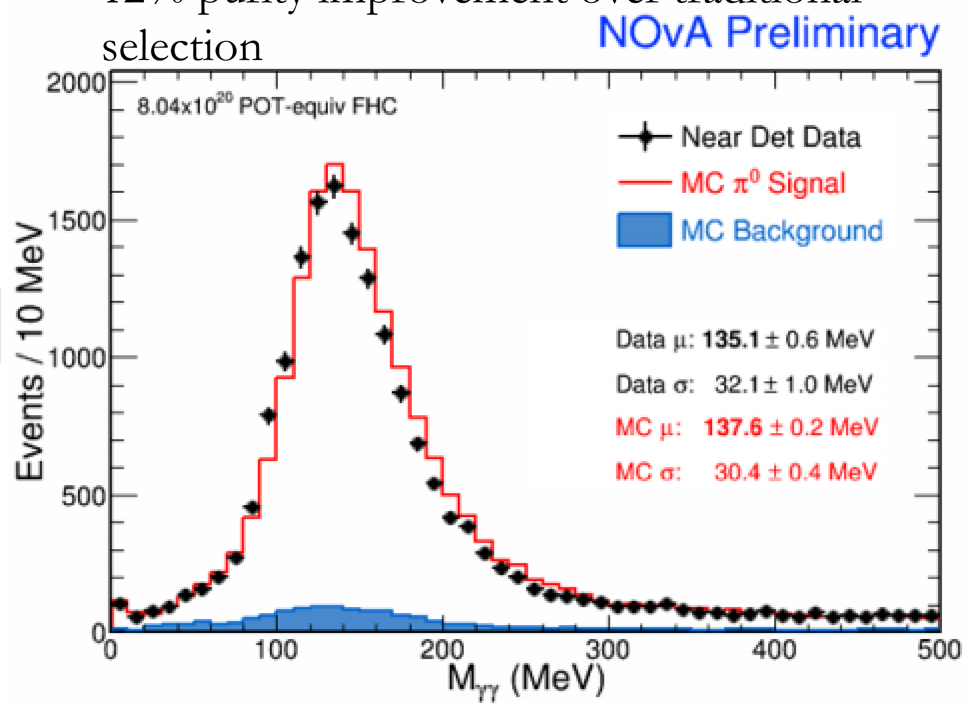
Deep Learning Prospects

Particle classification – thus far shown CVN as an event classifier

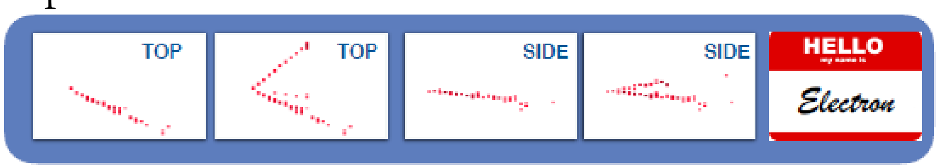
Single particles are separated using geometric reconstruction methods



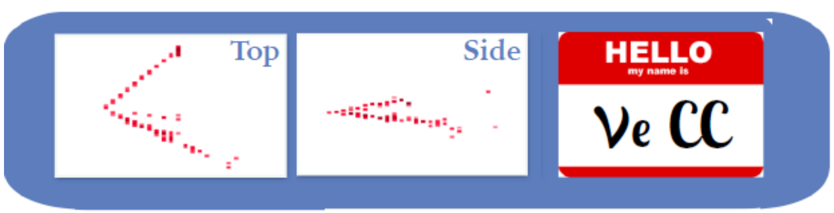
"Prong" CVN: (4-views)
Data check: π^0 mass peak
12% purity improvement over traditional selection



Classify particles using both views of the particle and both views of the event



vs.

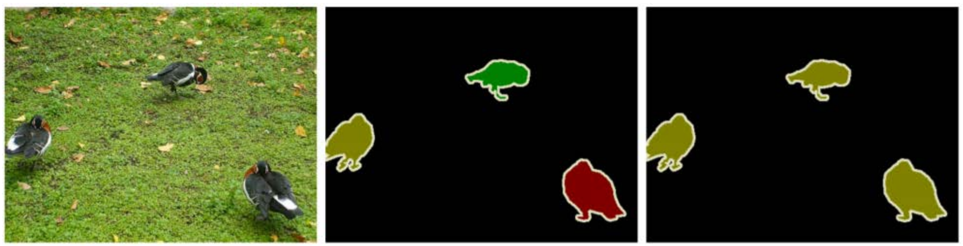


Deep Learning Prospects

Full event reconstruction is the dream

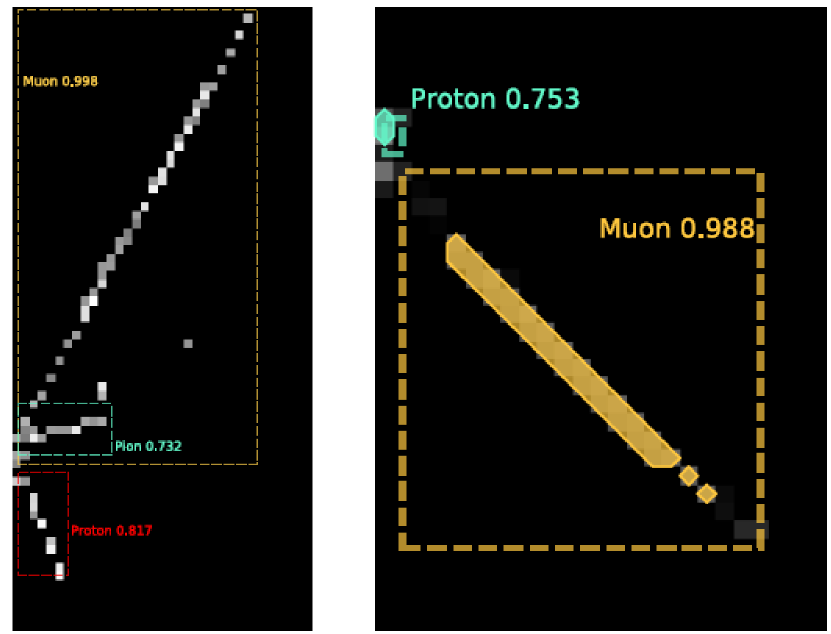
Cluster and **classify** particles simultaneously using **instance aware semantic segmentation**.

A network reconstructs an event **hit by hit**



Classification Object detection Instance segmentation

Bounding Boxes - builds bounding boxes aiming to contain a single particle.
Labels - A softmax function is used to classify the particle in each box.
Clustering - Pixel by pixel clusters are defined to closely contain single particles.



Kaiming He and (2017). Mask R-CNN. CoRR, abs/1703.06870.

A network for full event reconstruction is in development; promising avenue for future improvements

The Next Generation

Many questions will not be firmly established by current LBL experiments

Need new neutrino experiments with larger exposures and better precision

1st Generation

OPERA

K2K

2nd Generation

NOvA

T2K

3rd Generation

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

HYPER K

ESSνSB

HyperK seed funding approved Sept 19th 2018
http://www.hyperk.org/?p=387

DUNE: First particle tracks seen in protoDUNE
http://news.fnal.gov/2018/09/first-tracks-in-prototype-for-neutrino-experiment/

Summary

We have begun the measurement of antineutrino appearance at long baseline

- Analyzed the **first NOvA antineutrino beam** dataset 6.9×10^{20} POT plus 8.9×10^{20} POT of neutrino beam data

We have **strong evidence for $\bar{\nu}_e$ appearance at long baseline**

- $> 4\sigma$ above background, including wrong-sign
- Achieved in our first antineutrino result thanks to outstanding beam performance and support from Fermilab!
- Training on neutrinos and anti-neutrinos separately yields the largest improvement for event classification – several deep learning avenues explored on NOvA

A joint analysis of $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance prefers:

- The Normal Hierarchy at 1.8σ and excludes IH, $\delta CP = \pi/2$ at $> 3\sigma$
- Non-maximal mixing at 1.8σ and similarly prefers the upper-octant

NOvA can reach 3σ sensitivity to the hierarchy by 2020 for the most favorable δ, and >30% of the δ range by 2024

- Thanks to extended running, accelerator improvements, and analysis improvements thanks to the test beam

http://novaexperiment.fnal.gov

Thank you. Questions?

http://novaexperiment.fnal.gov

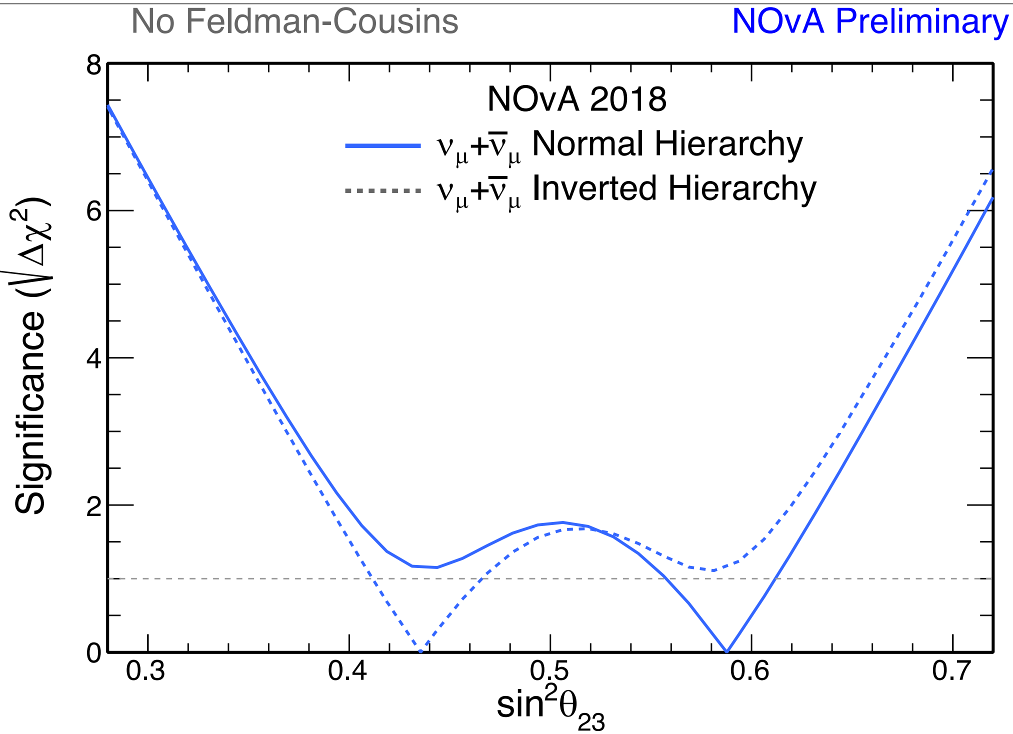
Easter Egg

http://nusoft.fnal.gov/nova/public/nova-events

Can you beat our neural nets?

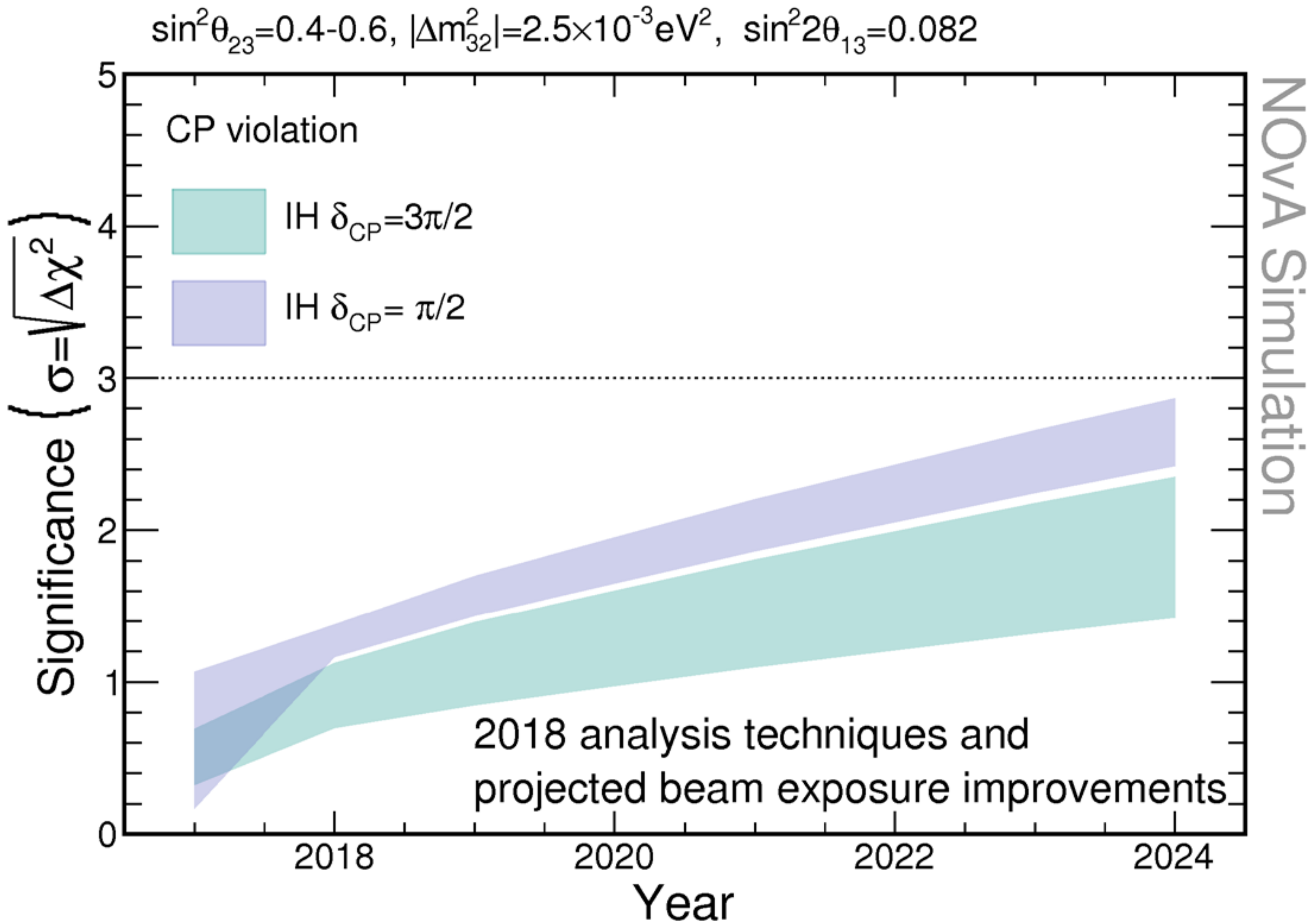
Backup

Significance of maximal



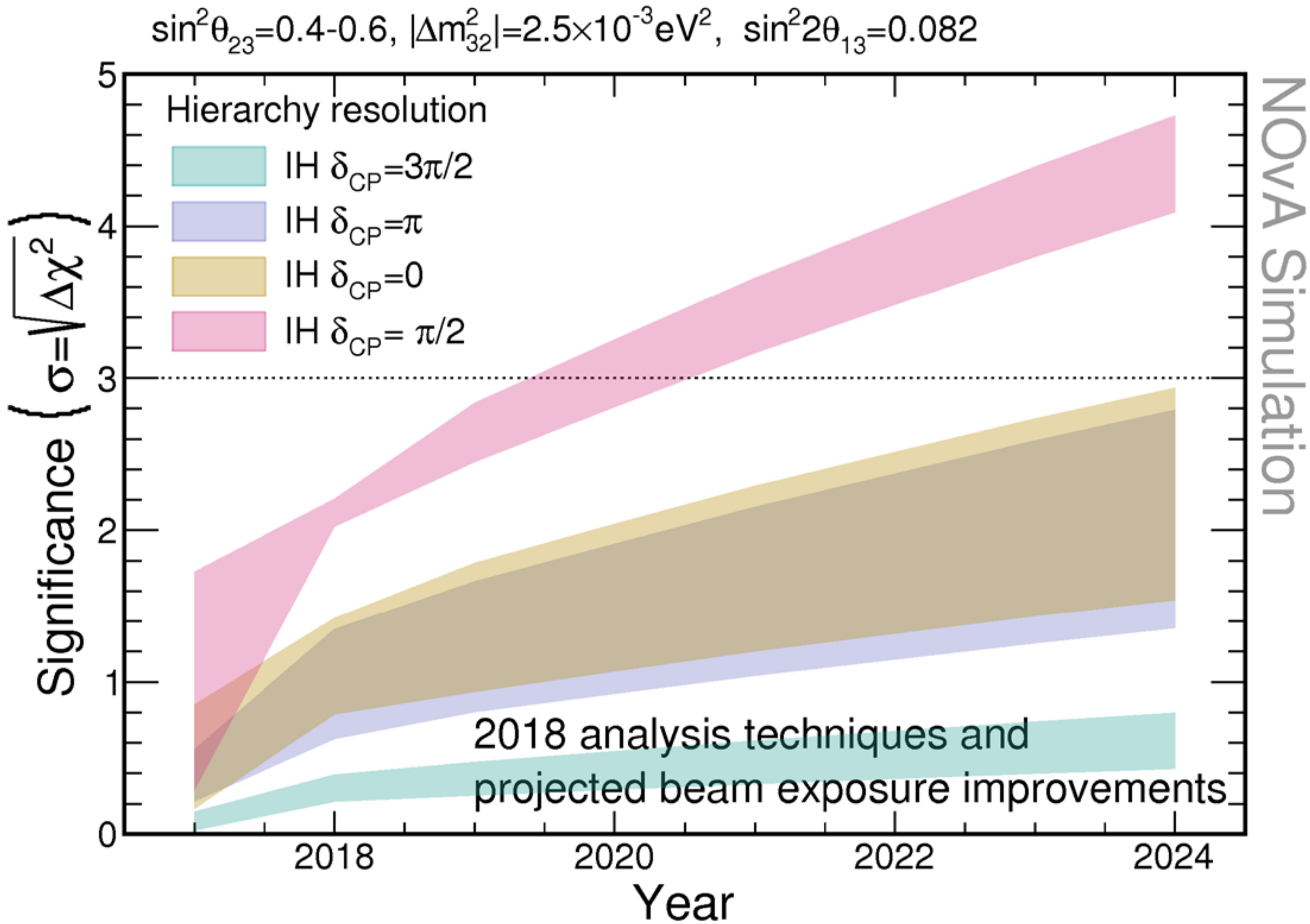
- If fit separately, the $\bar{\nu}_\mu$ data prefers non-maximal while ν_μ prefers maximal.
  - Consistent with joint oscillation parameters to >4%.
- Matter effects introduce a small asymmetry in the point of maximal disappearance.
- Gives a ~1σ preference for the Upper Octant from *just* the $\nu_\mu + \bar{\nu}_\mu$ fit in NH.
  - The asymmetry is flipped in the Inverted Hierarchy, so there is a similar preference for the lower octant there.

Into the future



2σ sensitivity to CP violation in 2024 for favorable parameters

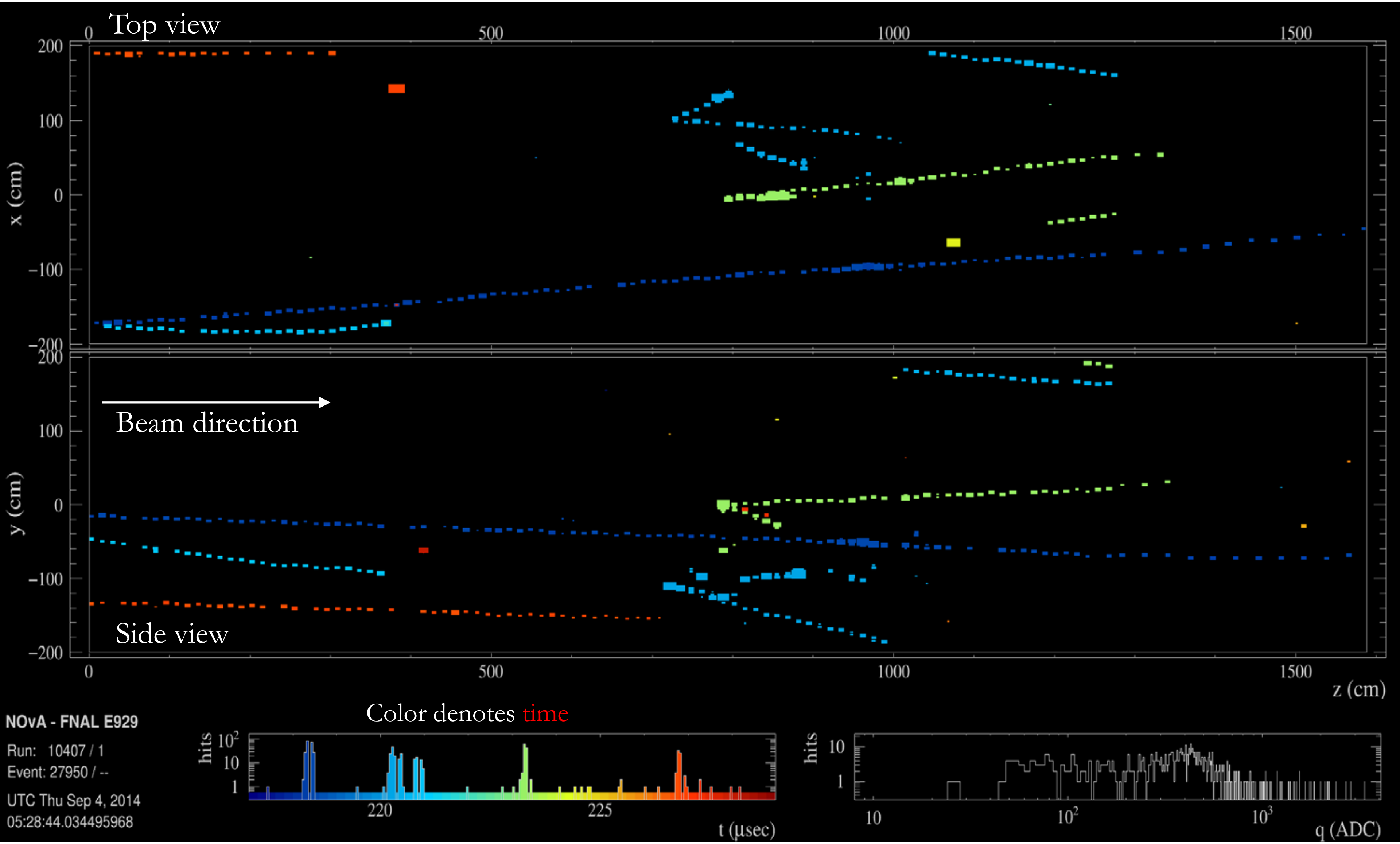
Into the future



2σ sensitivity to CP violation in 2024 for favorable parameters

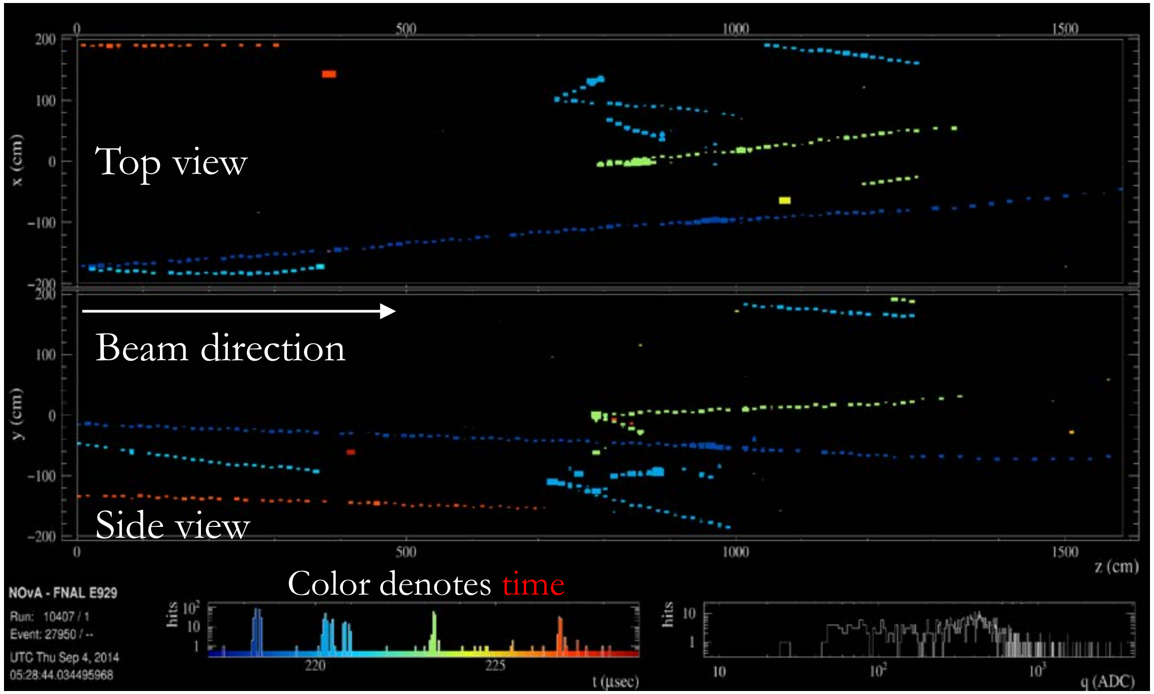
3σ sensitivity to the hierarchy possible in 2020 with favorable parameters

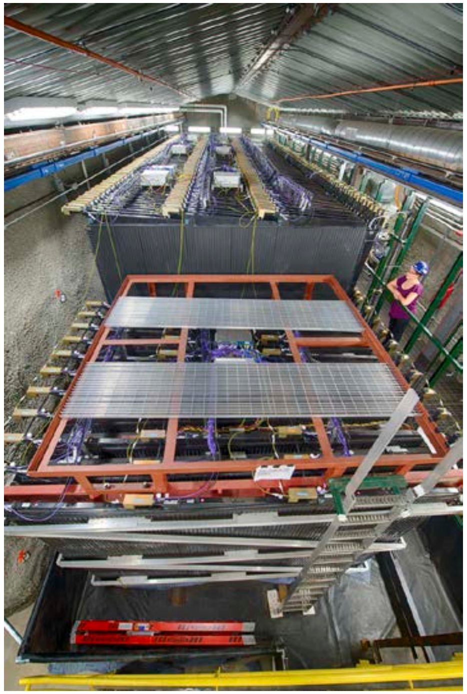
Near detector spills

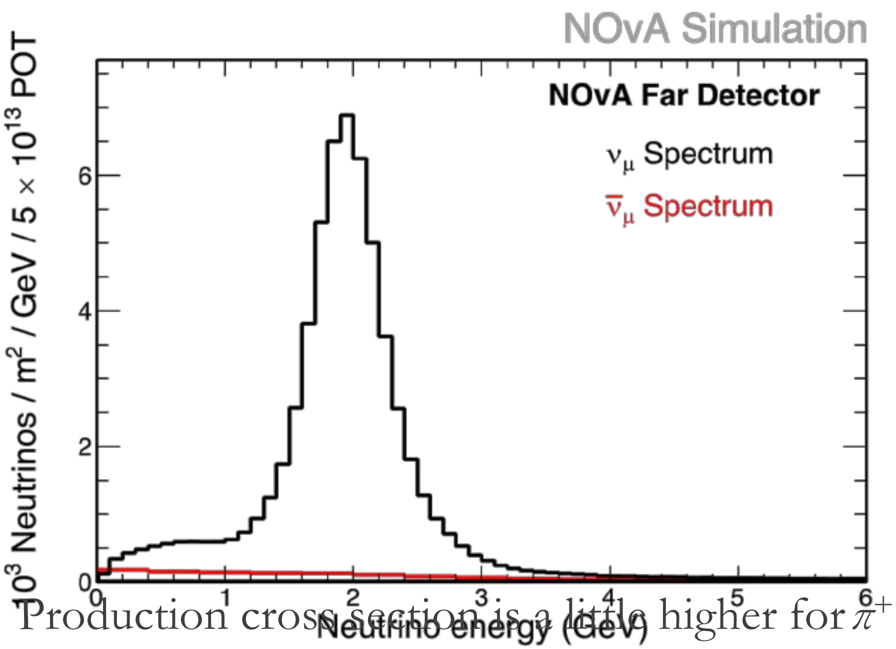


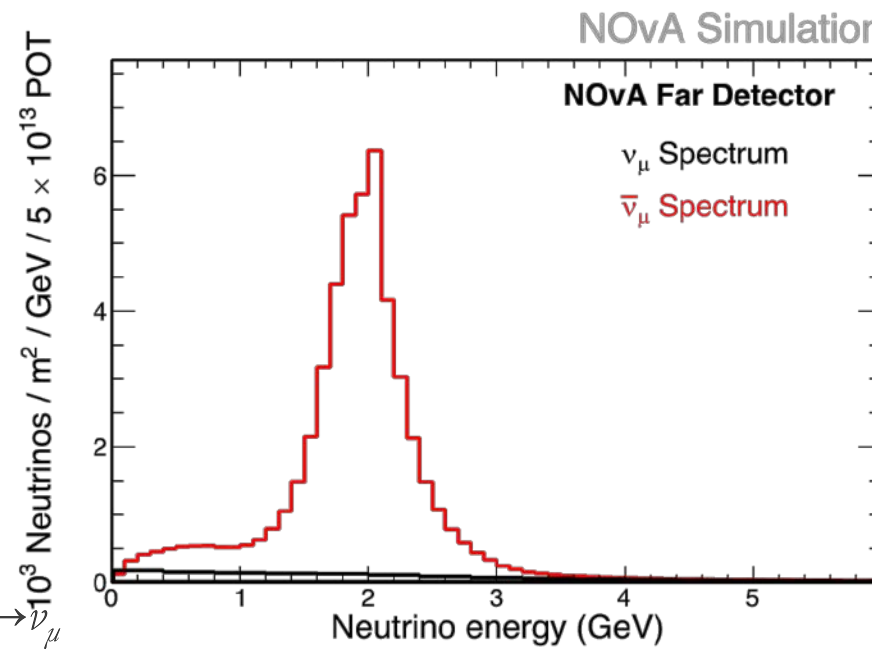
Near detector spills

- Multiple events in ND per NuMI spill
  - Over 2 million/year fiducial events collected
- Events separated using topology and timing
  - Color in display denotes time
  - Blue hits are early in spill, red are late









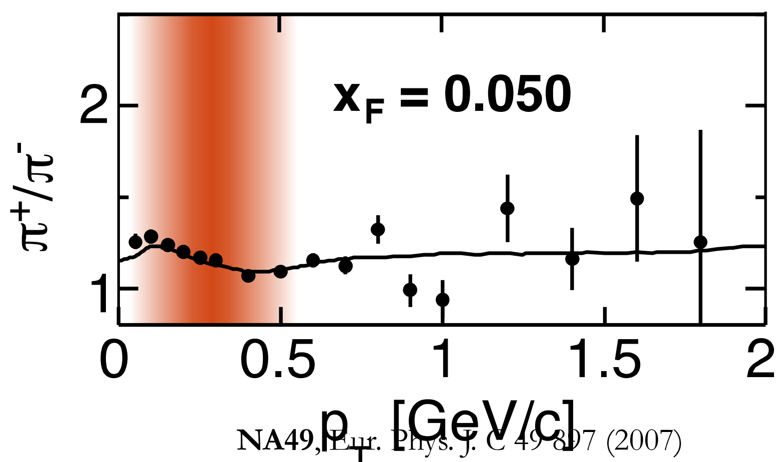
Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$

- p^+ colliding with p^+ and n^0 in the target

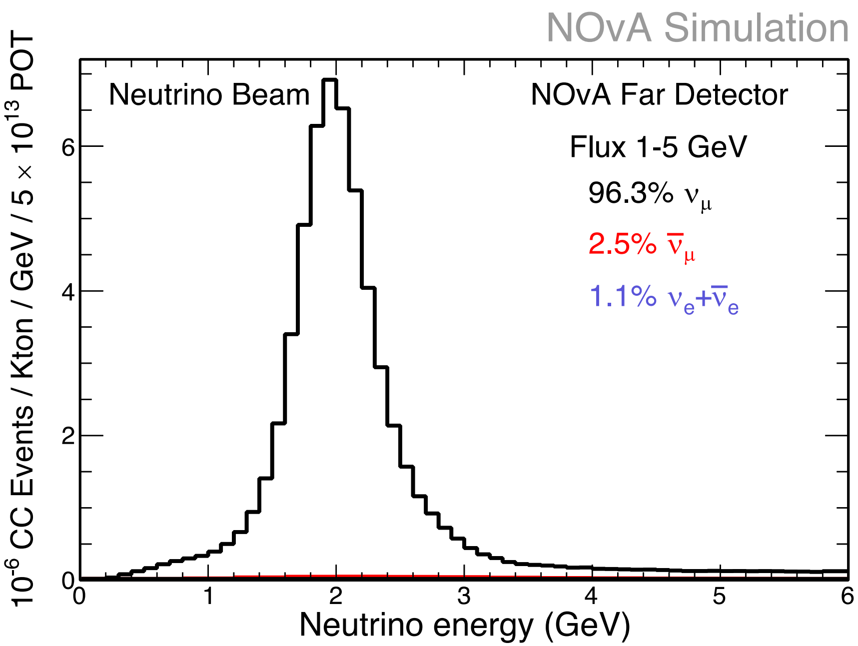
Wrong-sign: ν in the $\bar{\nu}$ beam (or vice versa).

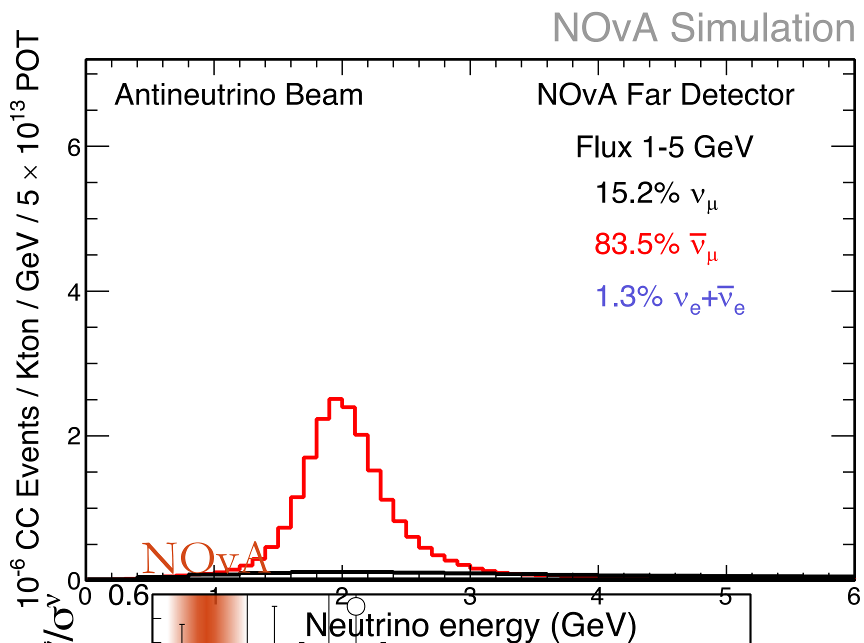
Off-axis beam reduces the wrong-sign.

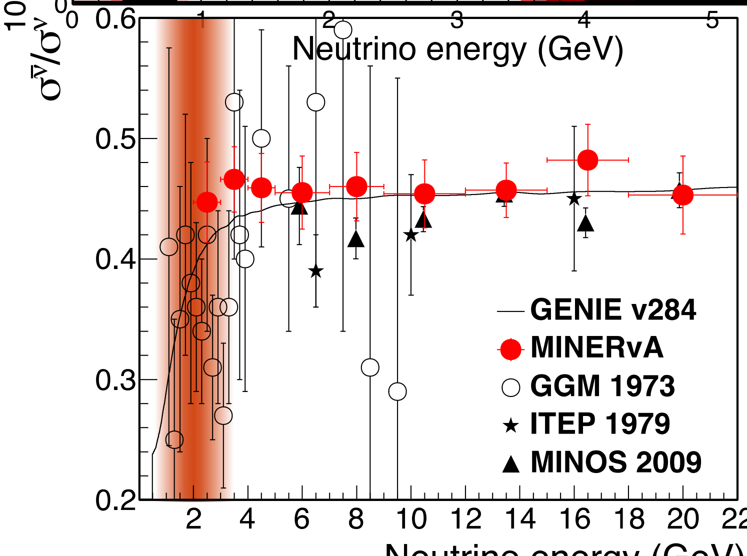
- WS primarily would primarily come from the unfocused high-energy tail.



NA49, Eur. Phys. J. C 49 897 (2007)

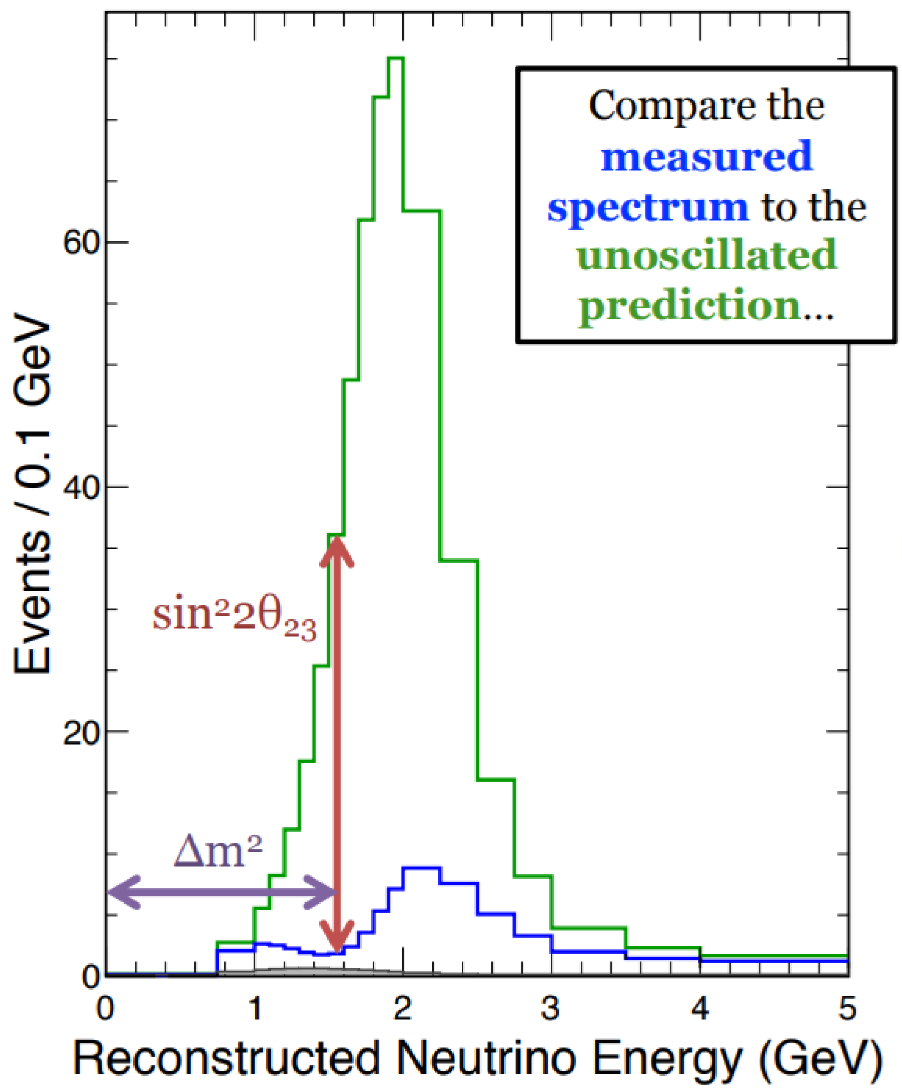


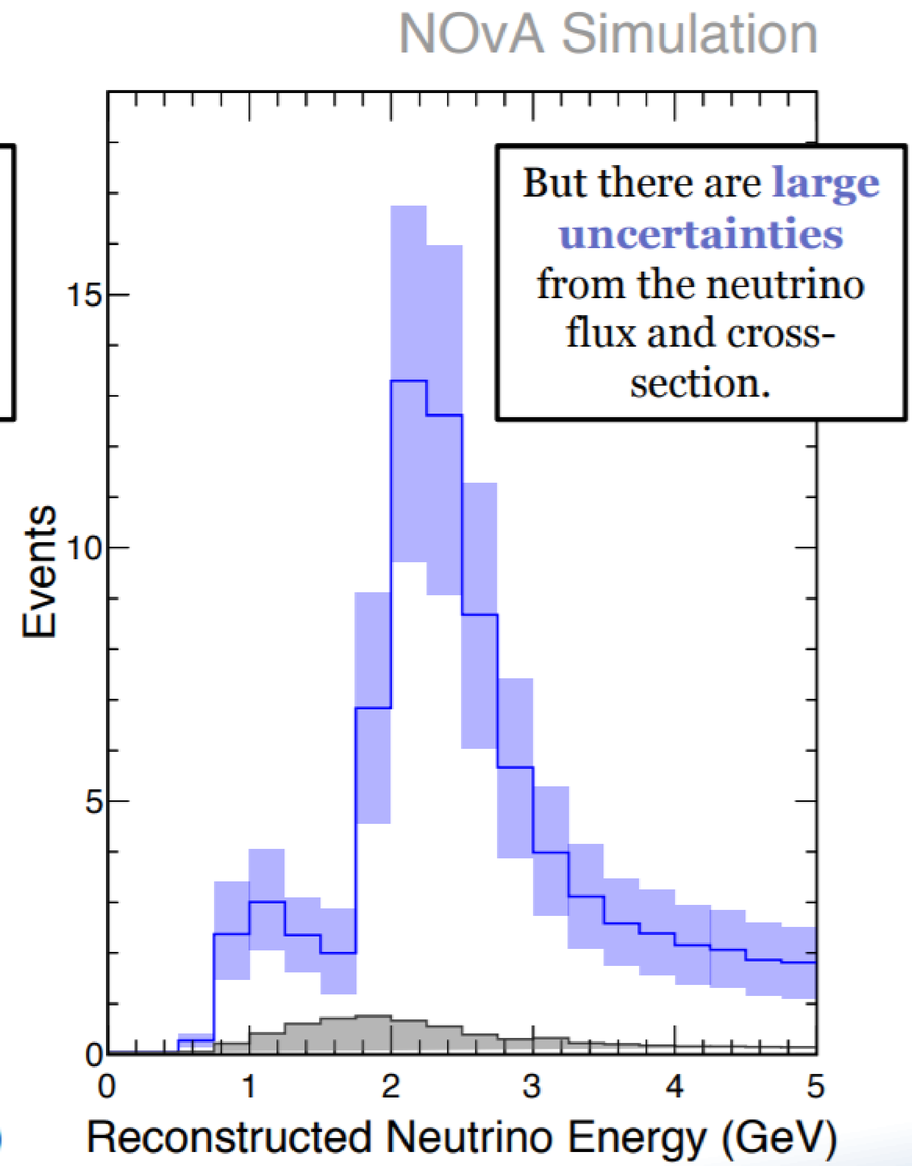




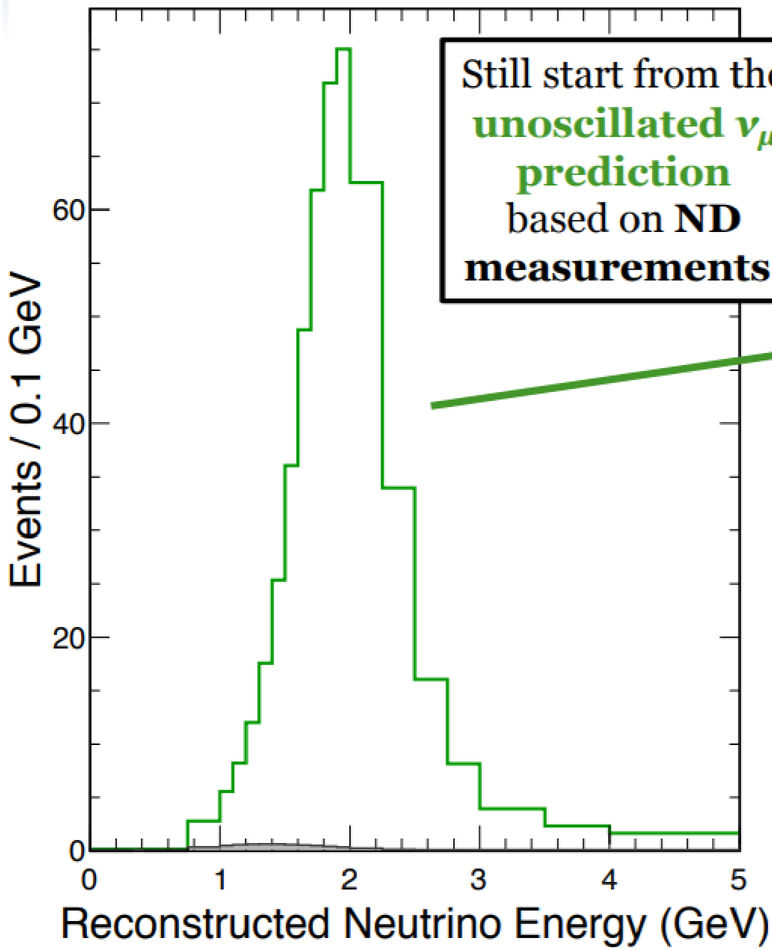
MINERvA, Phys.Rev. D95 (2017) no.7, 072009

How to study disappearance

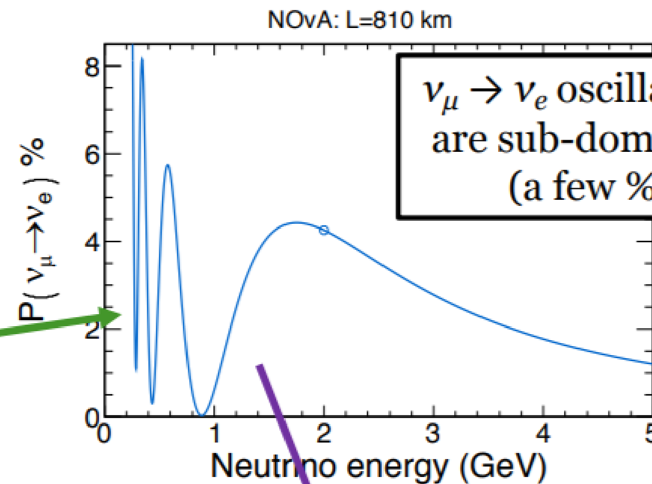




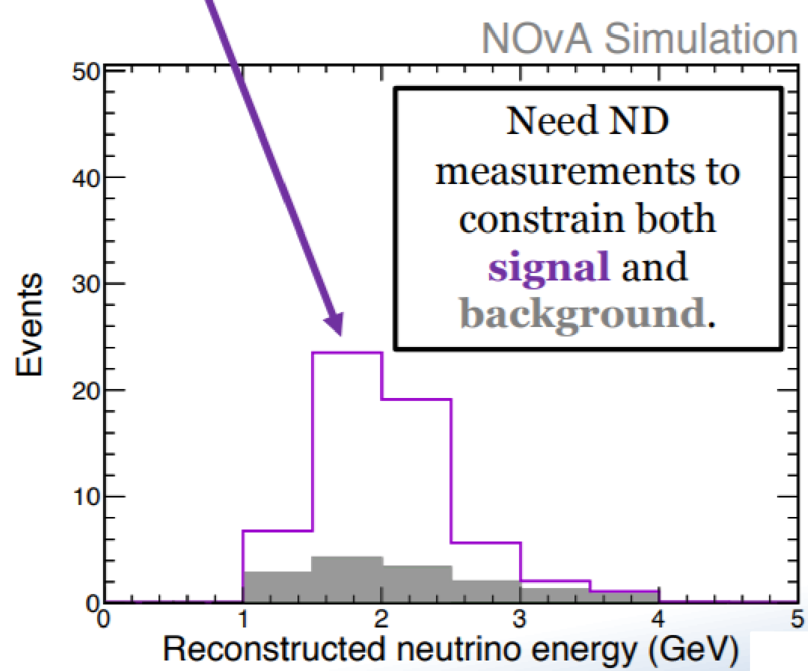
How to study appearance



Still start from the **unoscillated ν_μ prediction** based on **ND measurements.**



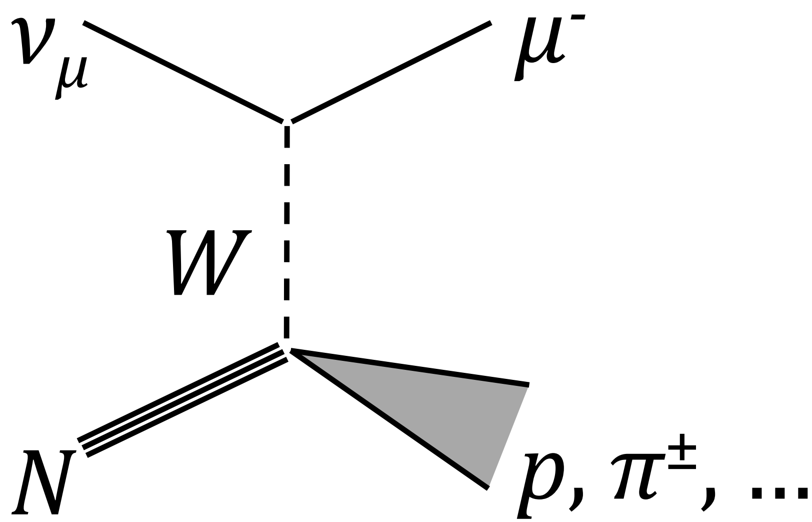
$\nu_\mu \rightarrow \nu_e$ oscillations are sub-dominant (a few %)



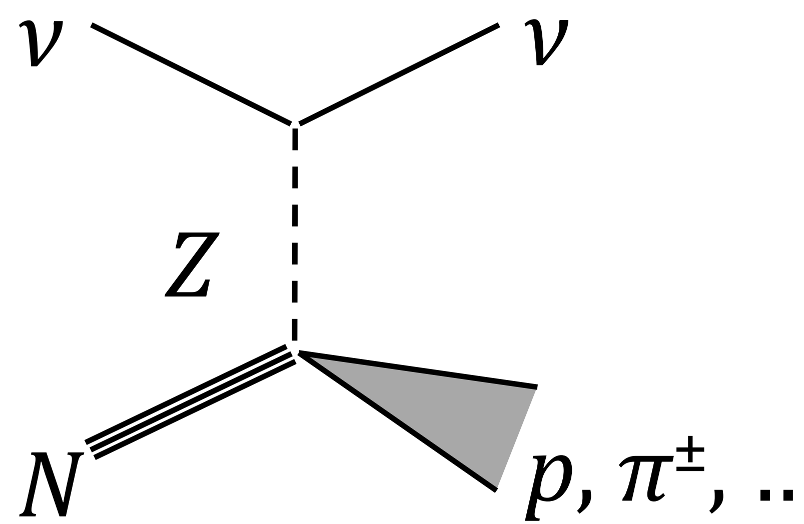
Need ND measurements to constrain both **signal** and **background**.

How to detect a neutrino

Charged Current



Neutral Current

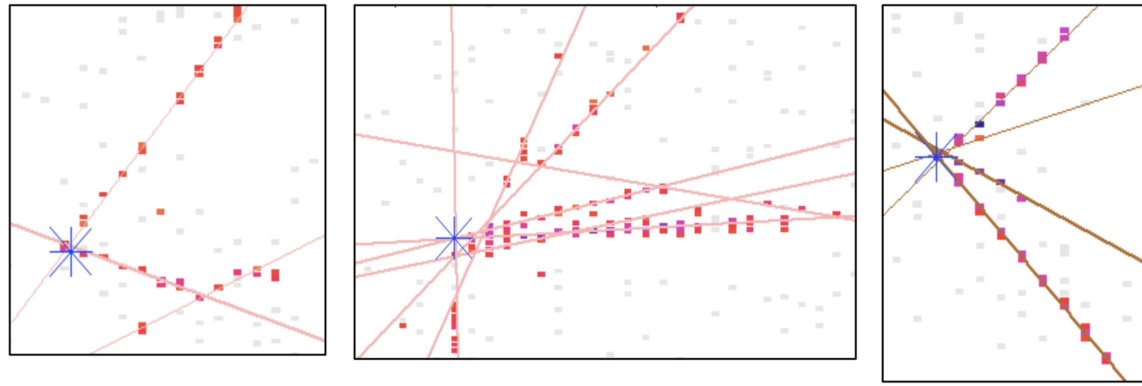


Observe the charged particles after a neutrino interacts with a nucleus:

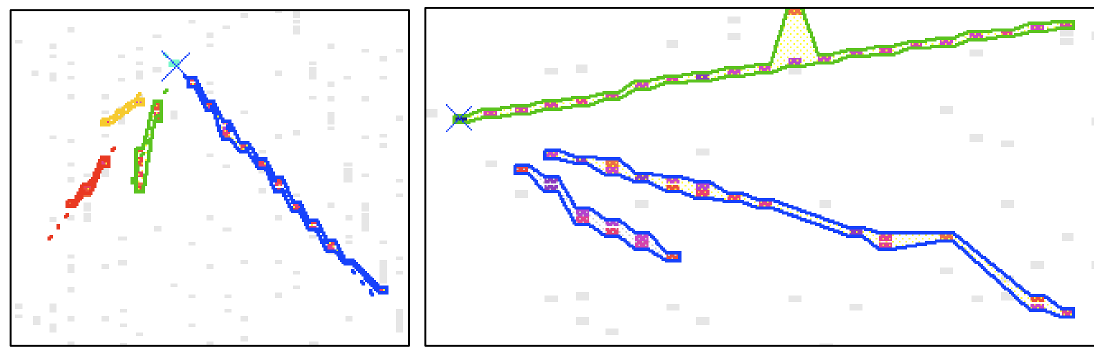
- Lepton
  - CC $\nu_\mu \rightarrow \mu^-$, CC $\nu_e \rightarrow e^-$
  - NC $\rightarrow$ no visible lepton
- Hadronic shower
  - Neutrinos typically produce a proton
  - Antineutrinos typically produce a neutron
  - May one or more $\pi^\pm$, additional p, n, etc.
  - May also contain EM from $\pi^0 \rightarrow \gamma\gamma$

Reconstruction

<u>Vertexing:</u> Find **lines of energy depositions** w/ Hough transform CC events: 11 cm resolution



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

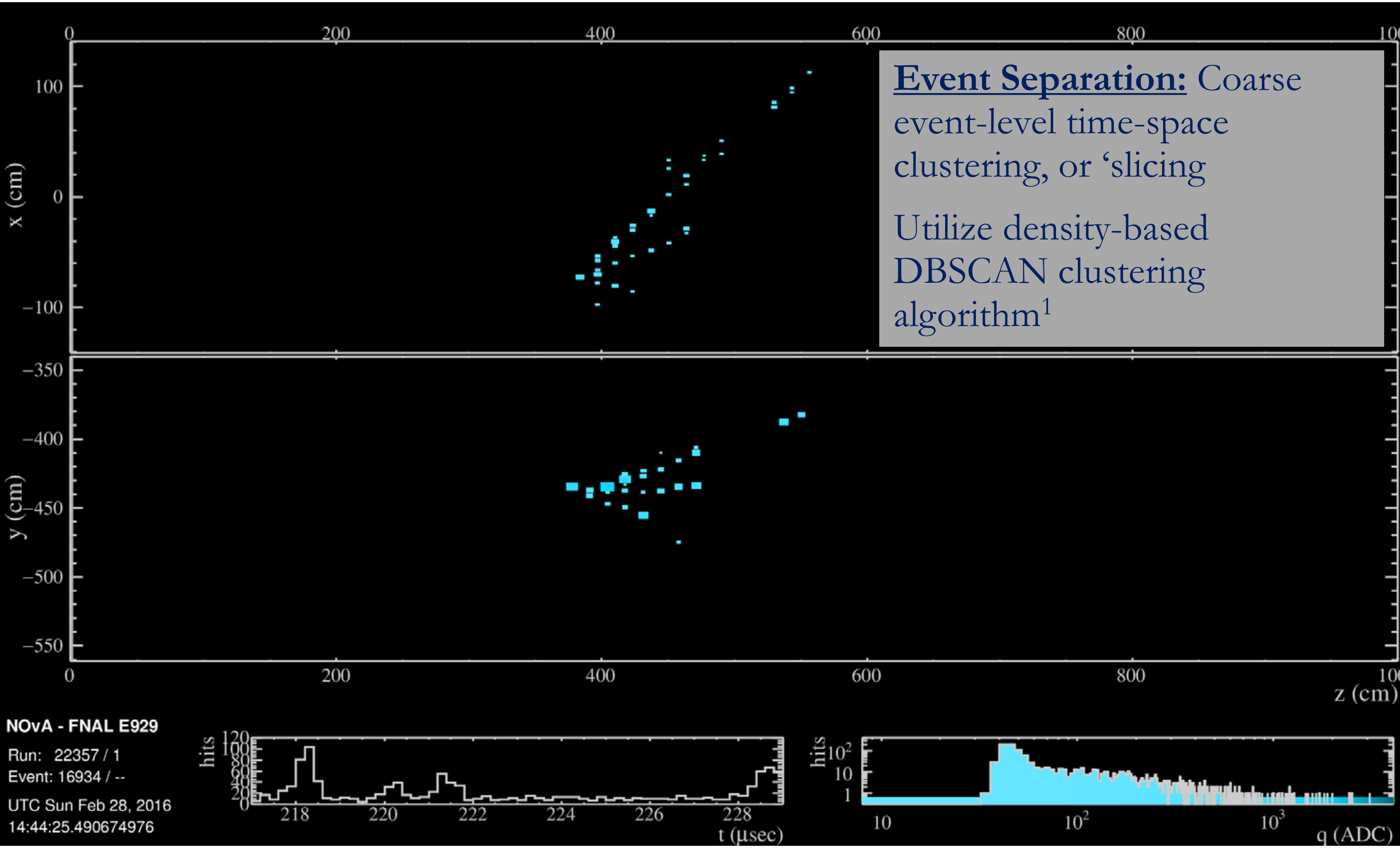


<u>Tracking:</u> Trace particle trajectories with **Kalman filter** tracker.
Also, **cosmic ray tracker**: lightweight, fast, and for large calibration samples, online monitoring.

Reconstruction

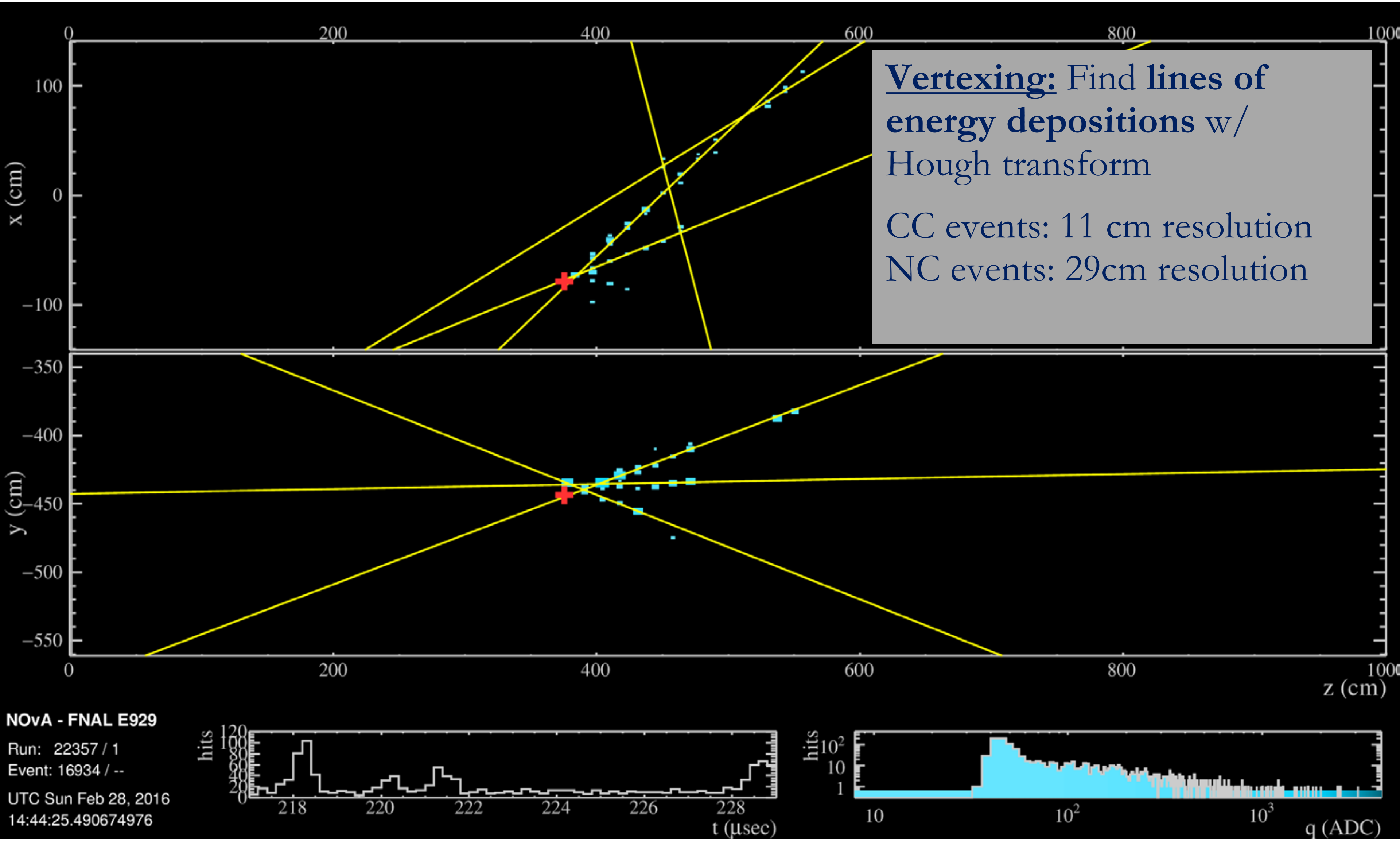
<u>Event Separation:</u> Coarse event-level time-space clustering, or ‘slicing

Utilize density-based DBSCAN clustering algorithm[1]

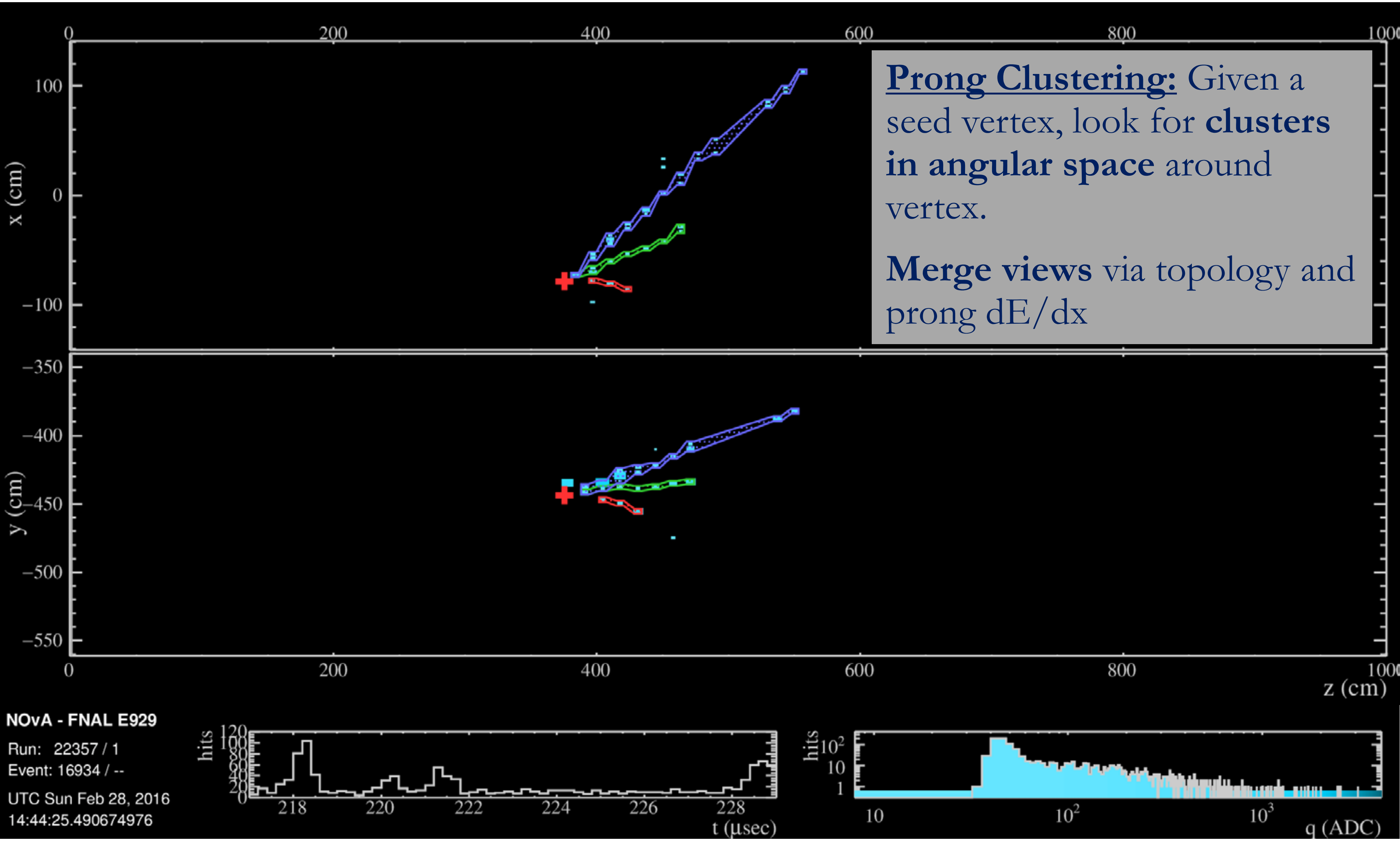


1. M. Ester, et. al., A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise (1996)

Reconstruction



Reconstruction



Prong Clustering: Given a seed vertex, look for **clusters in angular space** around vertex.

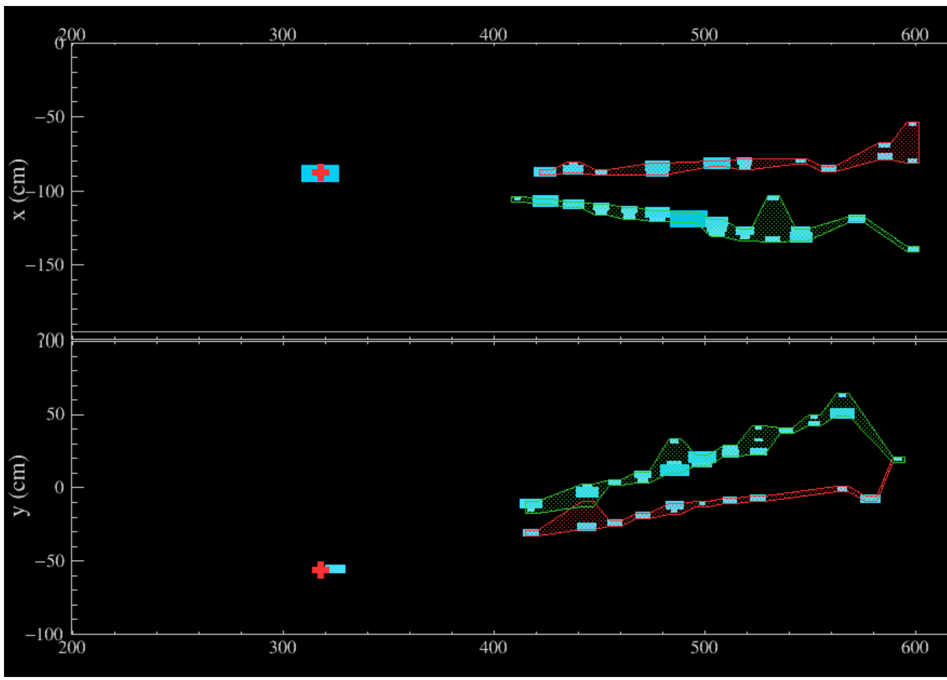
Merge views via topology and prong dE/dx

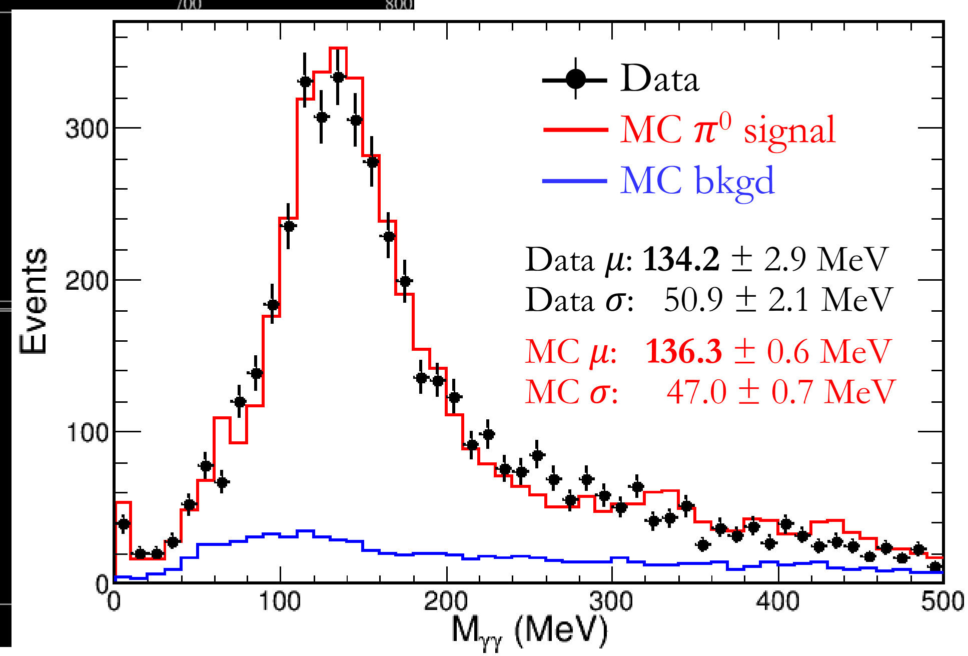
Reconstruction

Excellent reconstruction capabilities

Reconstruct π^0 peak – used as a calibration cross-check

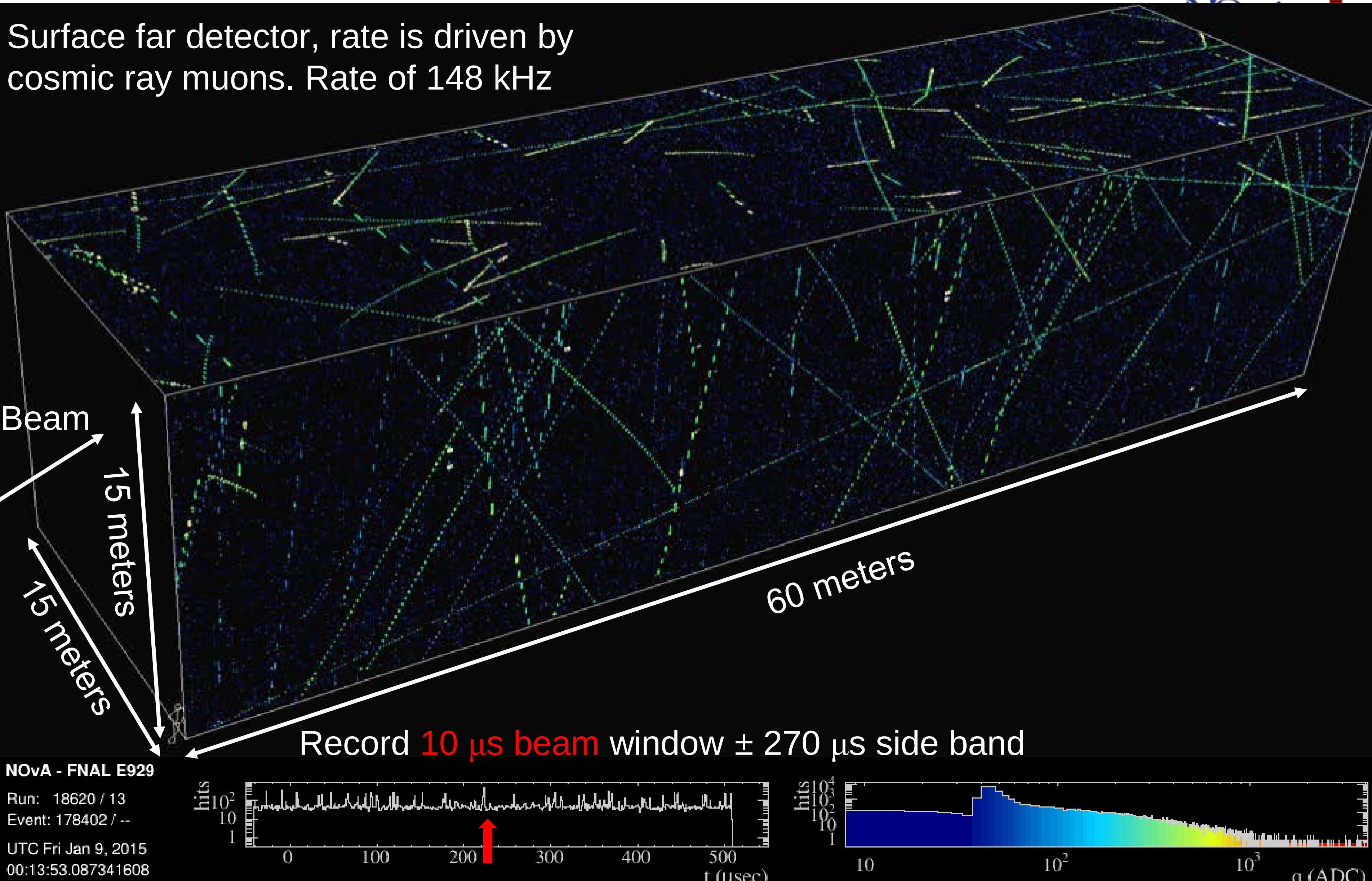
- Demonstrates ability to reconstruct NC events





NOvA FD on the surface

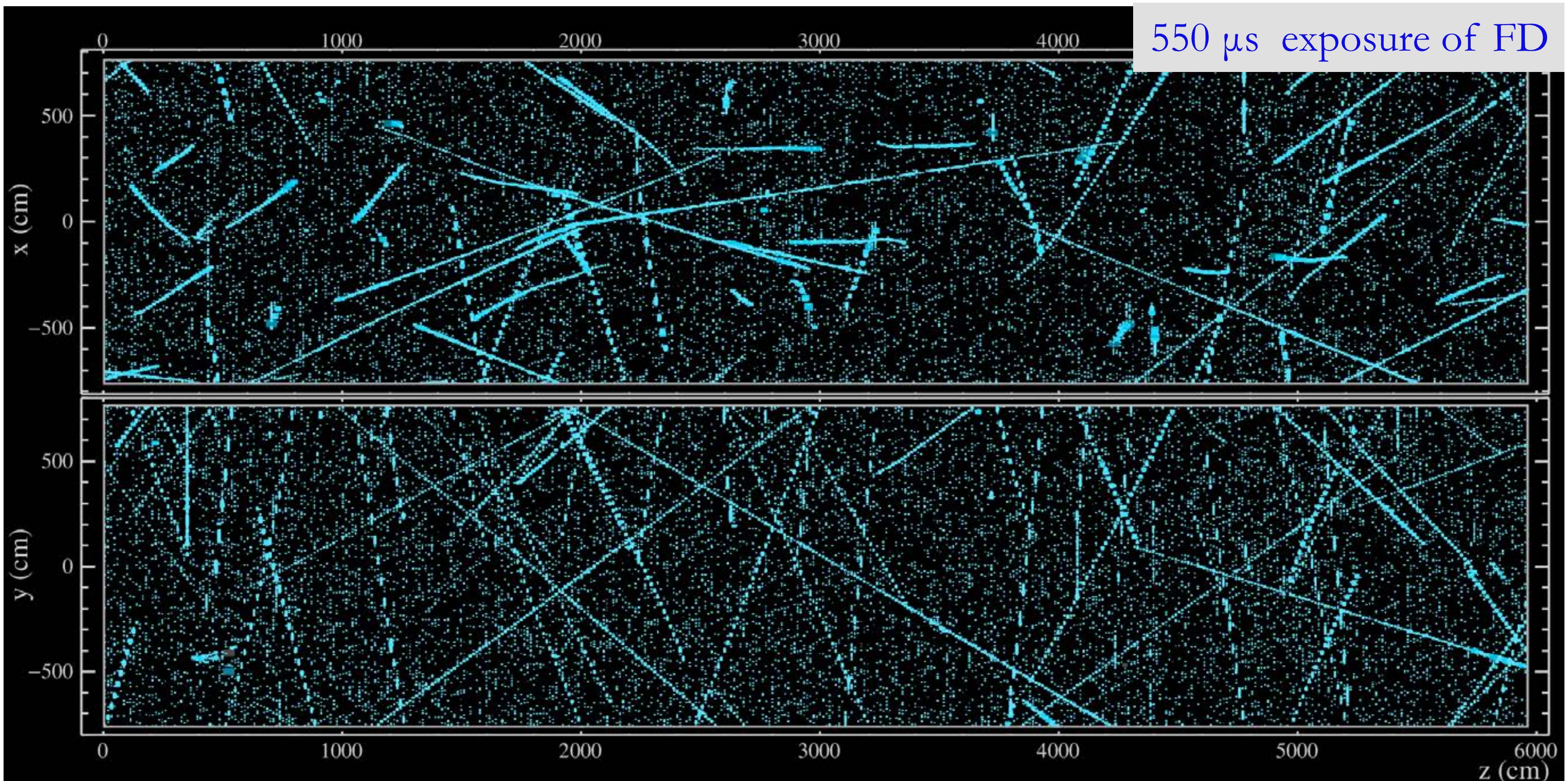
Surface far detector, rate is driven by cosmic ray muons. Rate of 148 kHz



Record 10 µs beam window ± 270 µs side band

Cosmic ray rejection

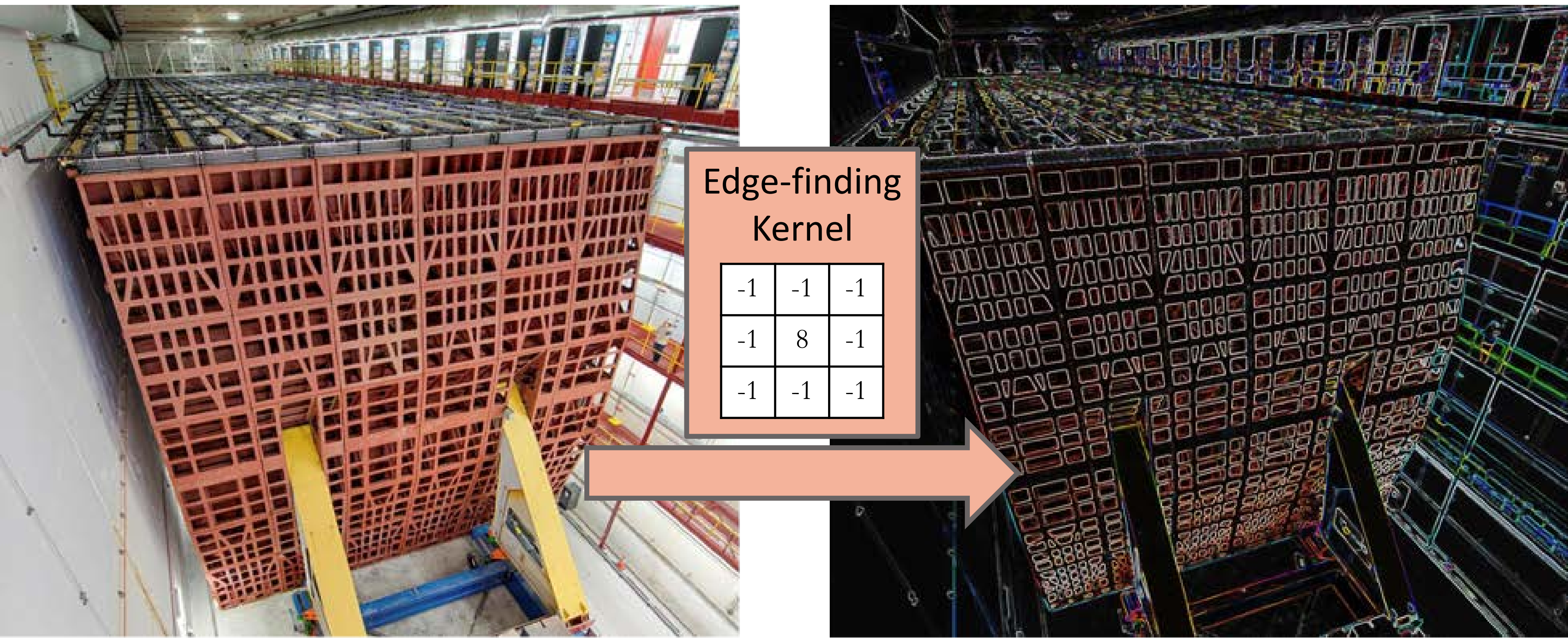
- FD is on the surface; exposed to 150 kHz of cosmic rays
- 10 μs spill window at ~ 1 Hz gives 10^5 rejection
- Cosmic background rate measured from data adjacent in time to the beam spill window



Deep learning on NOvA

The edge-finding kernel below is man-made.

CVN (Convolutional Visual Network), the kernels are learned from the training data.



-1	-1	-1
-1	8	-1
-1	-1	-1

Event Classification

Classify neutrino events using two tower network, **Convolutional Visual Network.**

Each view of the event is examined separately for most of feature extraction.

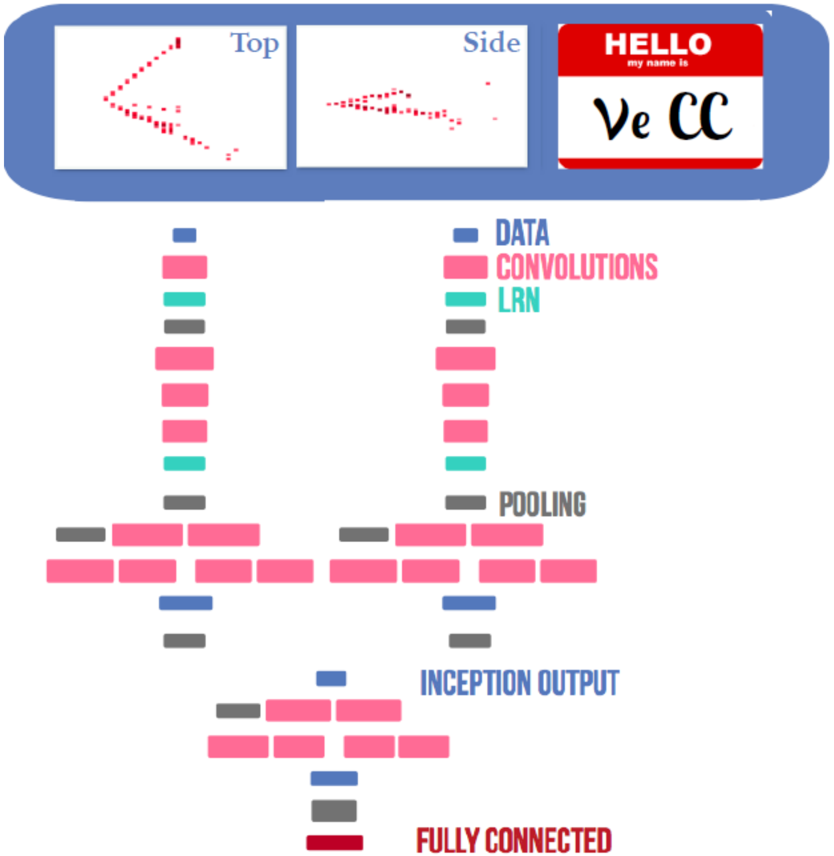
New this analysis:

Updated simulation.

Classification is done using final states.

Network optimizations.

Separate neutrino and antineutrino training.

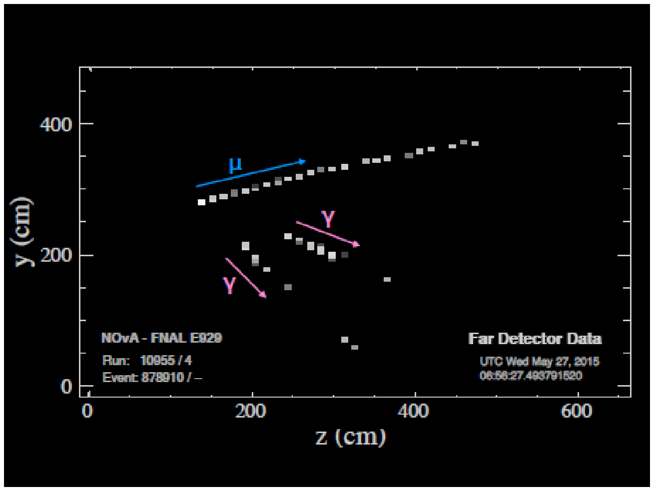


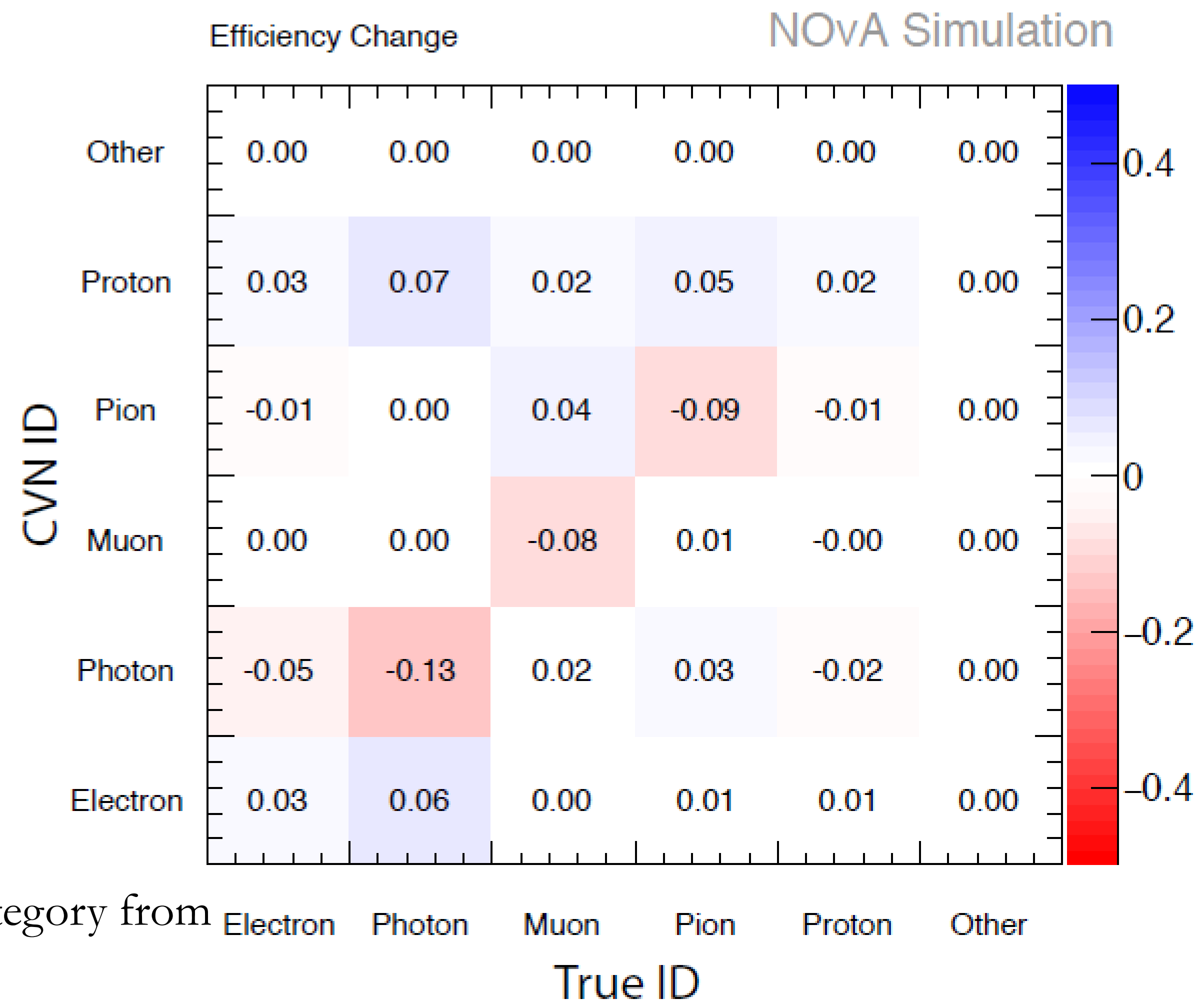
F. Psihas, Ph.D. thesis, Indiana University, 2018, doi:10.2172/1437288.

Particle classification

Showing the network the entire event teaches the network **contextual** information.

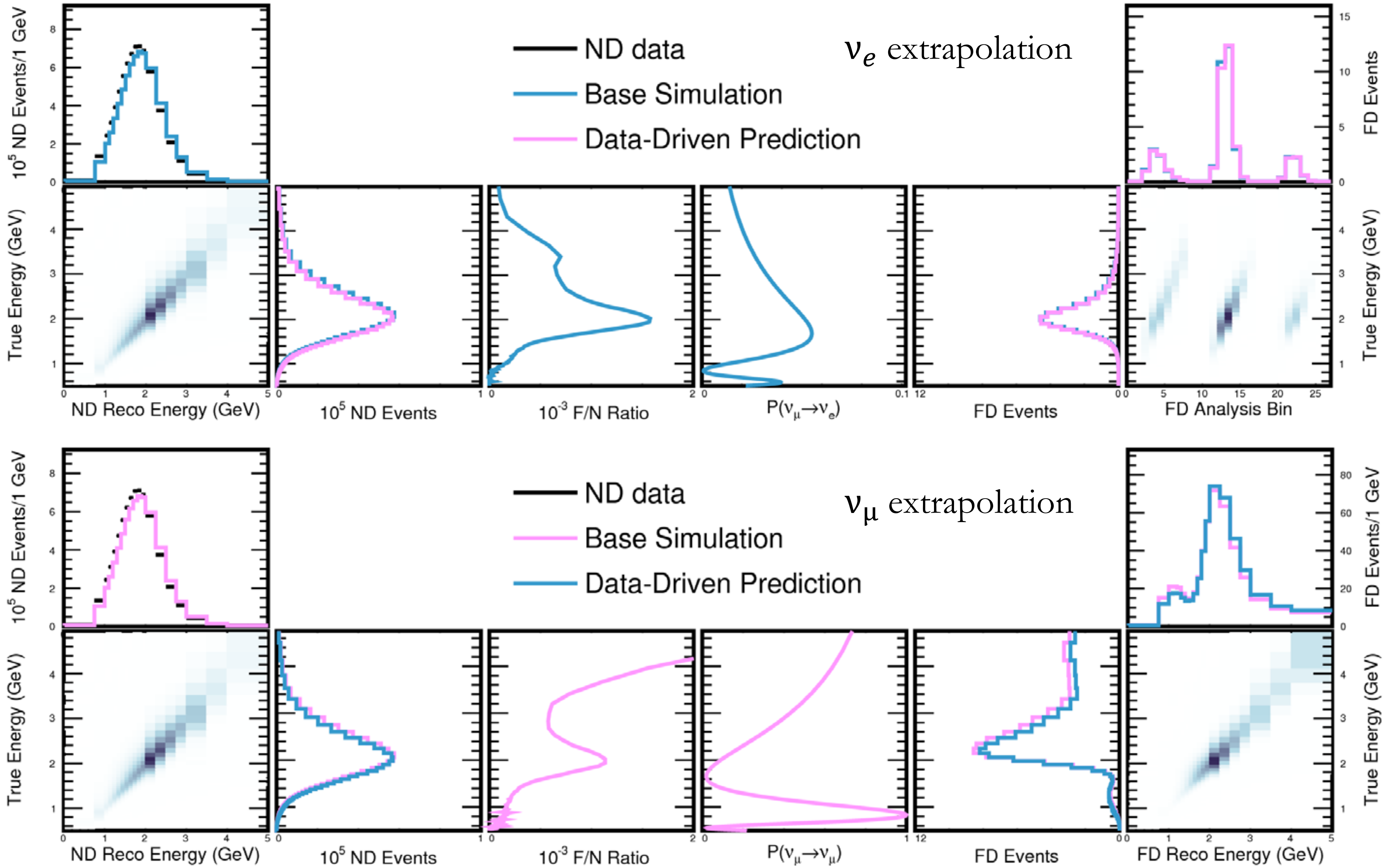
Particularly useful in the classification of photons.





The change in efficiency for each category from removing context information.

Extrapolation



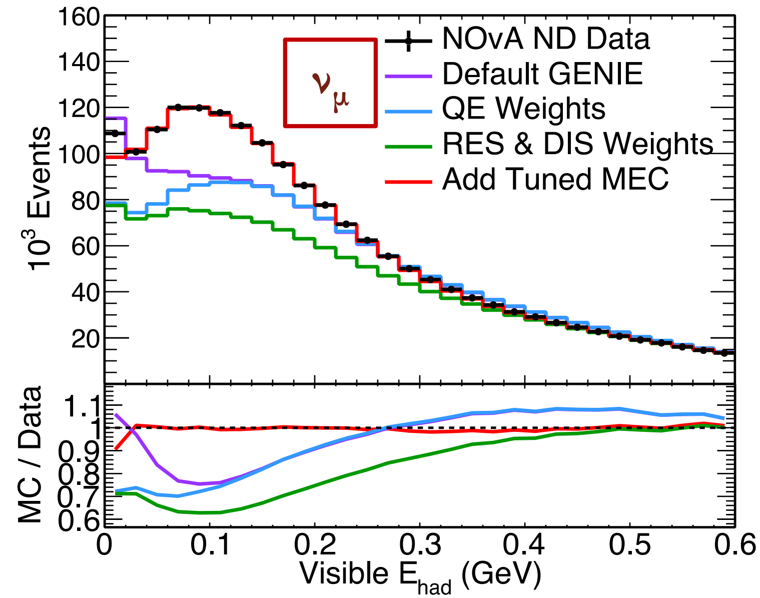
Cross-section tuning

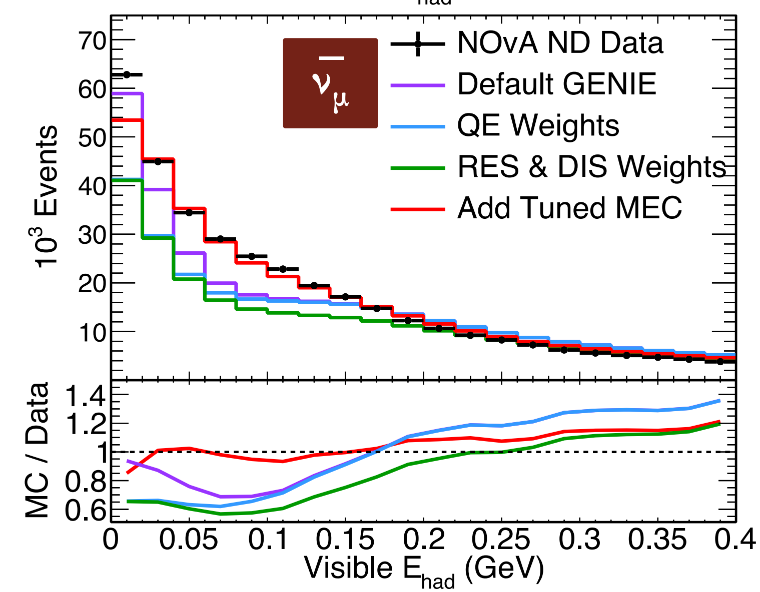
From **external theory:**

- Valencia RPA model† of nuclear charge screening applied to QE.
- Same model applied to resonance.

From **NOvA ND data:**

- 10% increase in non-resonant inelastic scattering (DIS) at high W.
- Add MEC interactions
  - Start from Empirical MEC*
  - Retune in $(q_0, |\boldsymbol{q}|)$ to match ND data
  - Tune separately for $\nu/\bar{\nu}$





† "Model uncertainties for Valencia RPA effect for MINERvA", Richard Gran, FERMILAB-FN-1030-ND, arXiv:1705.02932

* "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators", Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014

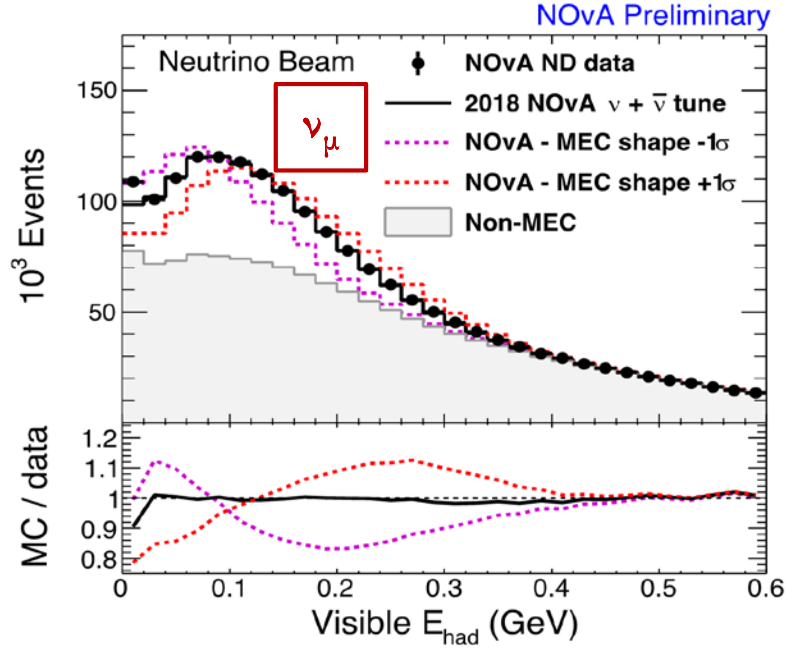
MEC uncertainties

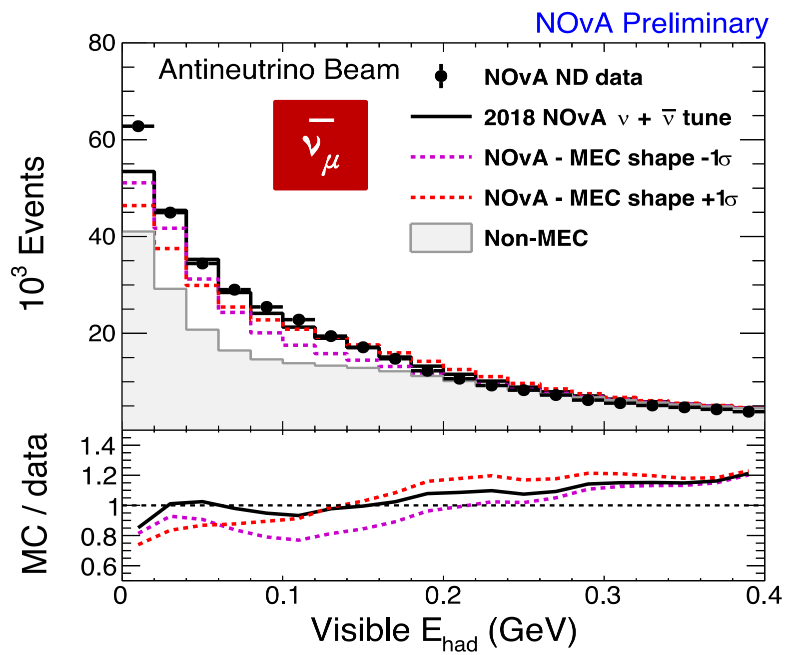
We also determine uncertainties on the MEC component we introduce.

- Both on shape and total rate.

Repeat the tuning procedure with shifts in the Genie model.

- Turn Genie systematic knobs coherently to push the non-MEC
  x-sec more QE-like or more RES-like.





Cross-section tune

We also determine uncertainties on the MEC component we introduce.

- Both on shape and total rate.

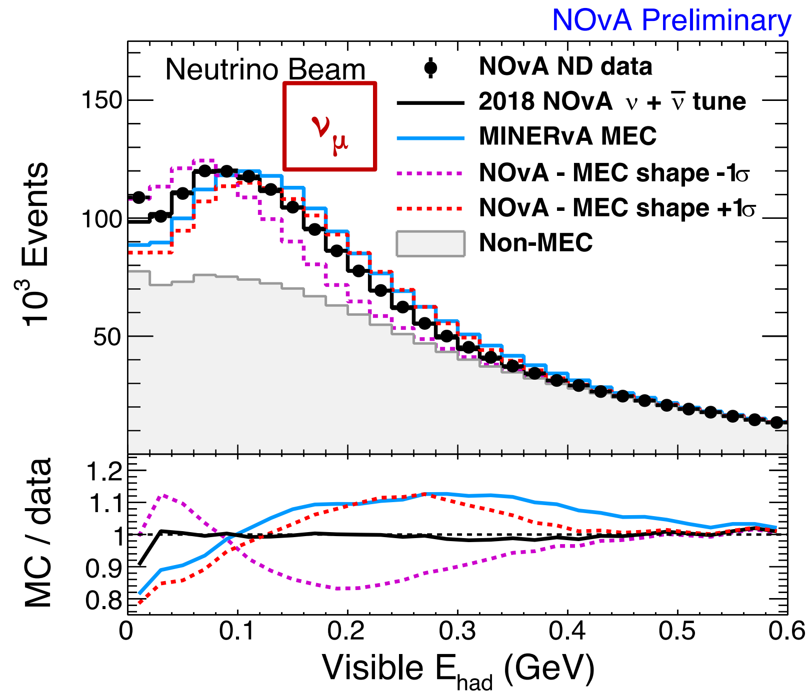
Repeat the tuning procedure with shifts in the Genie model.

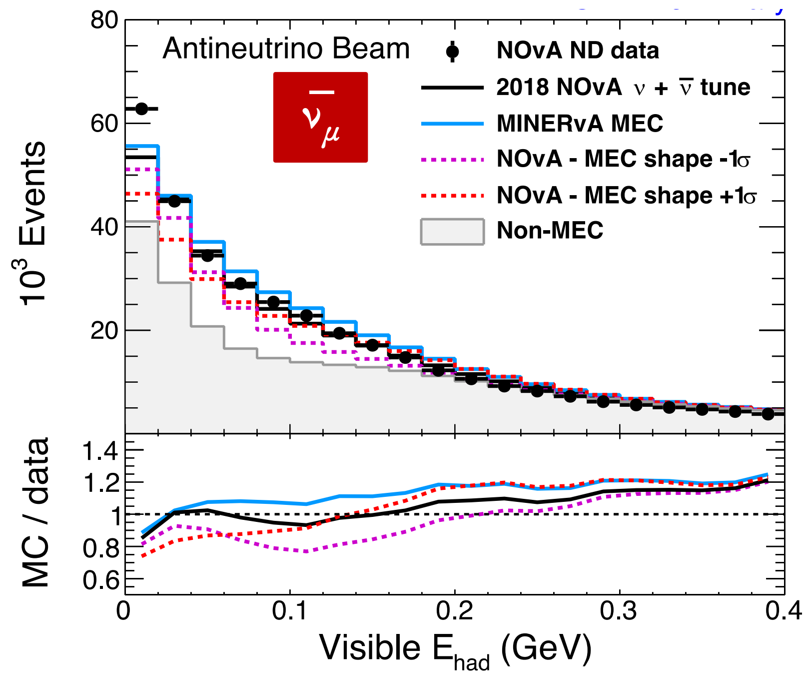
- Turn Genie systematic knobs coherently to push the non-MEC
  x-sec more QE-like or more RES-like.

Independently, **Minerva*** has also tuned a multi-nucleon component to their data.

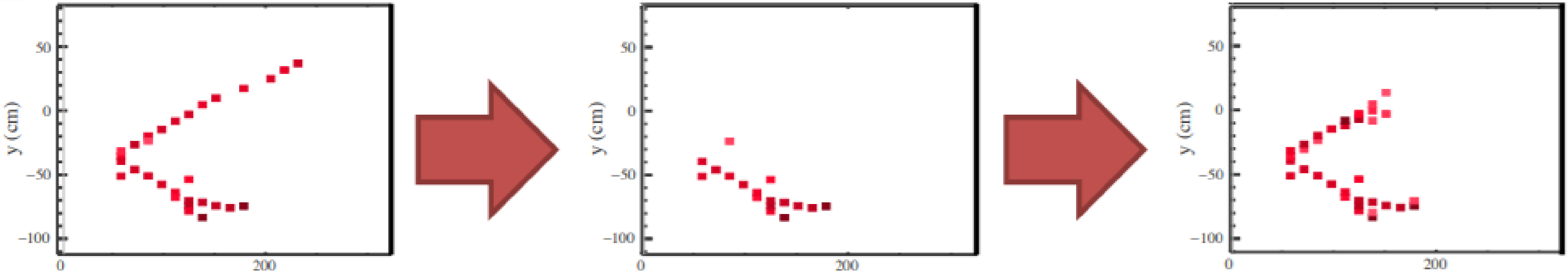
The resulting tune is ~1σ away from the NOvA tune.

* Minerva, Phys. Rev. Lett. 116, 071802 (2016)
Minerva, Phys. Rev. Lett. 120, 221805 (2018)





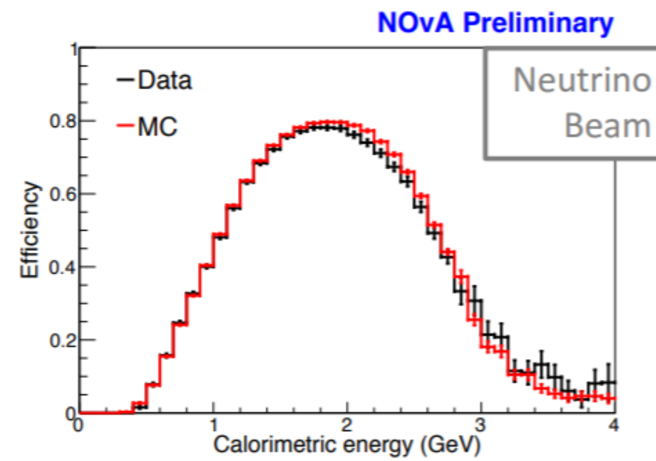
Cross-check: Muon-removed, electron-added

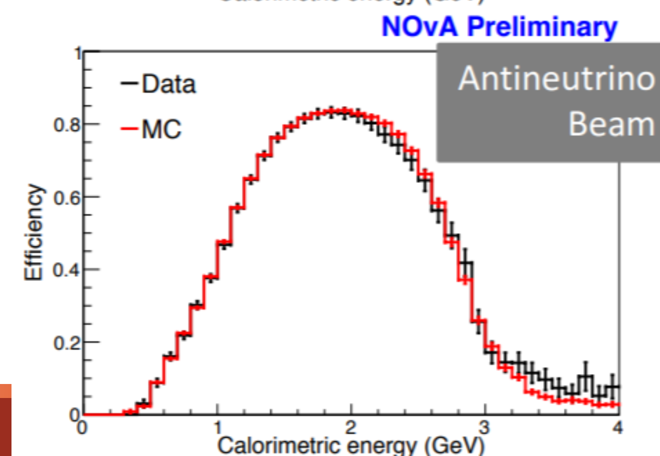


We can create a control sample of “electron neutrino” events by removing the muon and replacing it with a simulated electron.

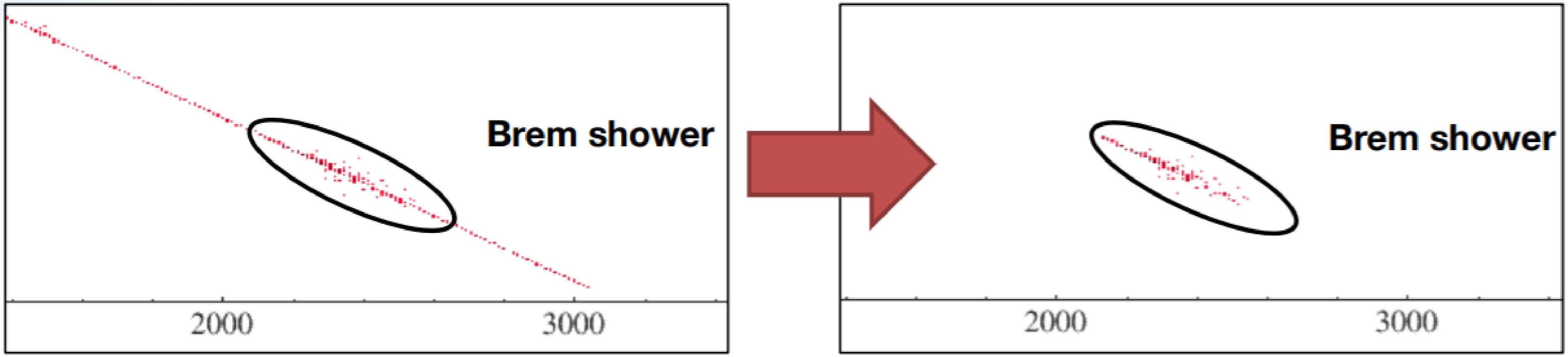
Compare the efficiency between MRE events with real and simulated hadronic showers. – Allows us to focus on the effect of the hadronic shower on efficiency.

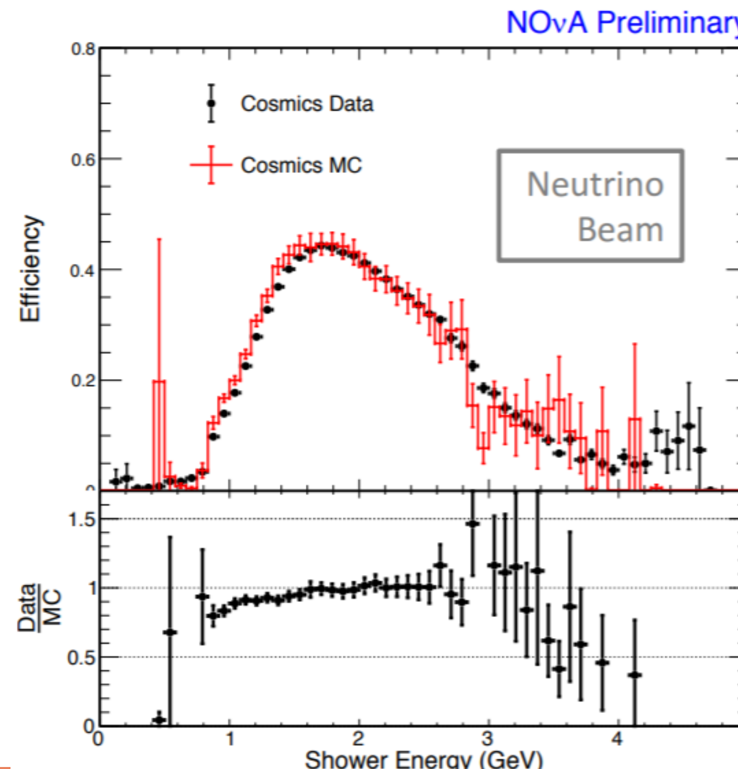
Efficiency agrees between data and MC at the 2% level for both neutrino and antineutrino beams.





Cross-check:
Muon-removed from bremsstrahlung

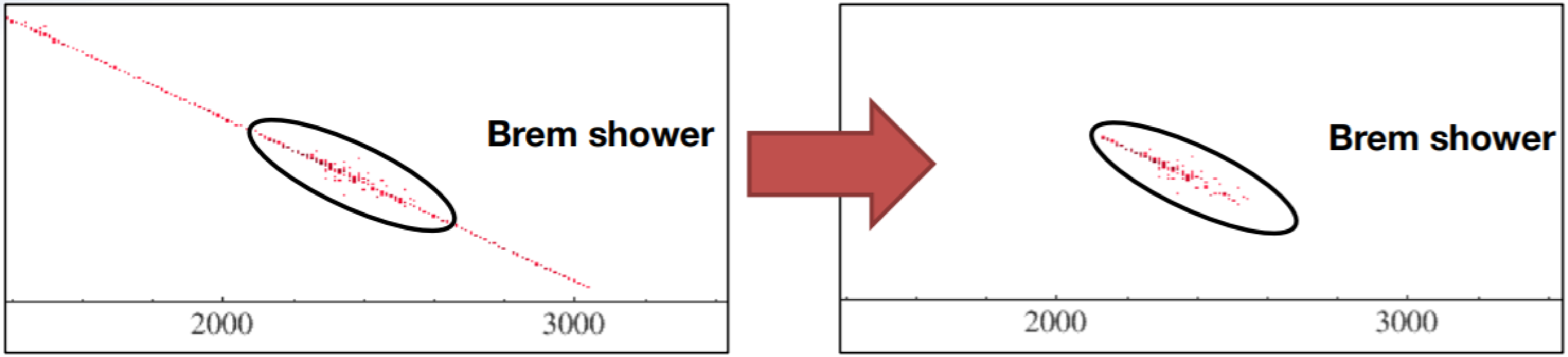




Bremsstrahlung showers in cosmic ray muons provide a sample of known electron showers in data at the Far Detector

Efficiency of data and simulated brem showers agrees within systematics for neutrino and antineutrino CVN.

Cross-check:
Muon-removed from bremsstrahlung



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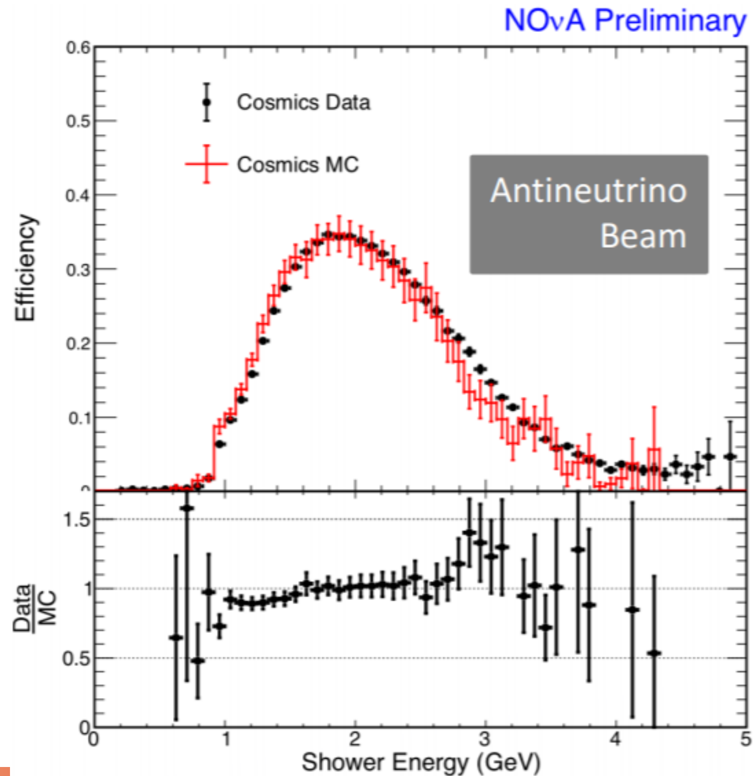


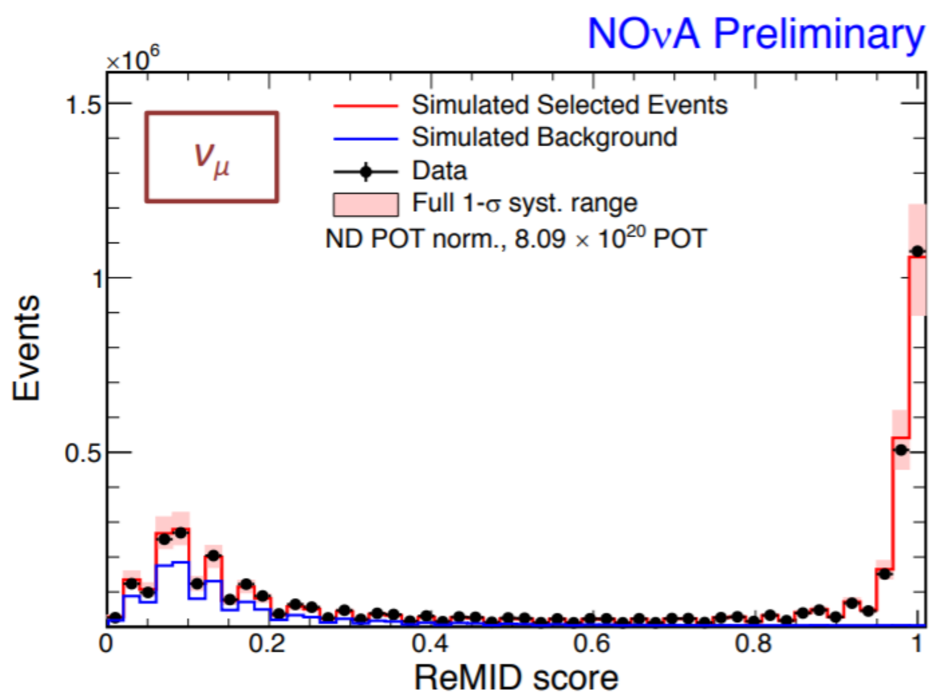
Other analysis selections

Some basic additional cuts: Contained, fiducial events, well-reconstructed, reasonable energy range

An additional νμ requirement: a track identified as a muon

CVN identifies events with a muon, but it does not identify the muon track

Identify muons in reconstructed tracks using a kNN
Track length, dE/dx, scattering, fraction of track-only planes

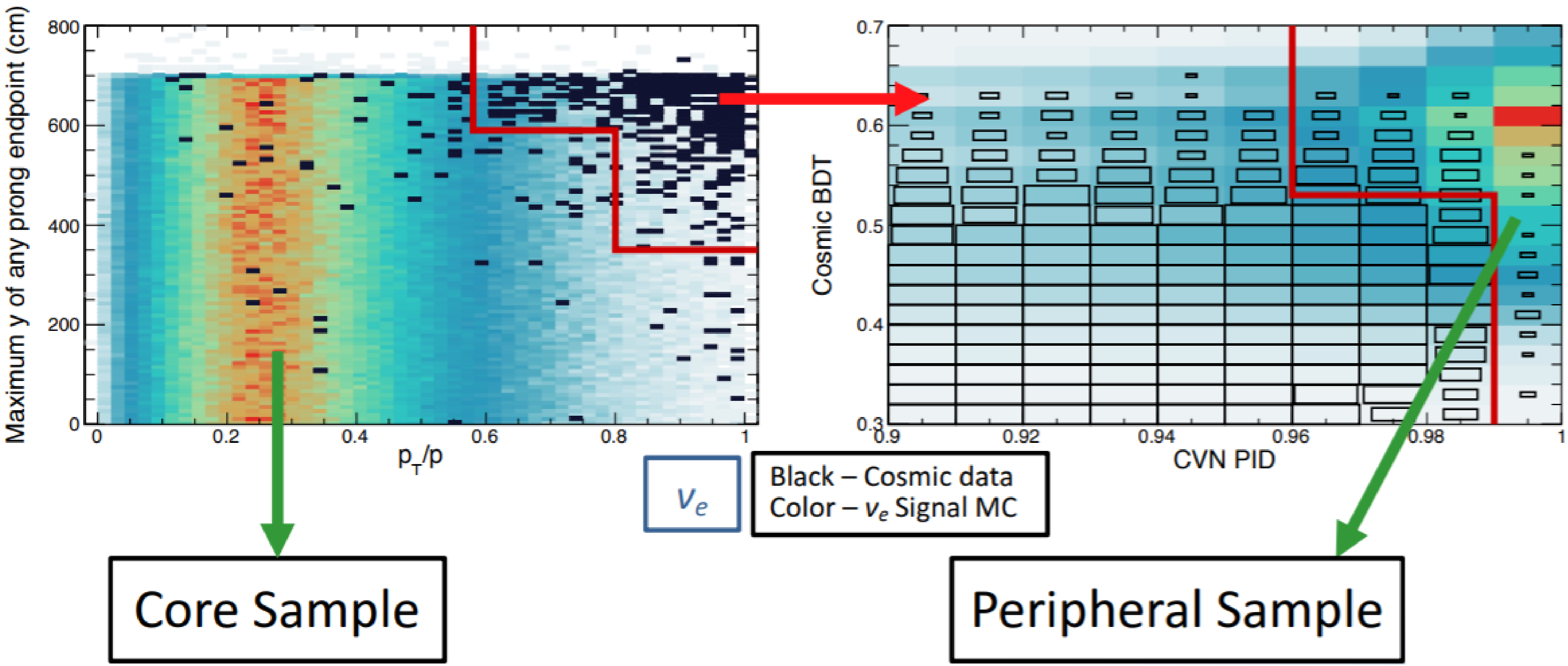


Cosmic rejection at FD

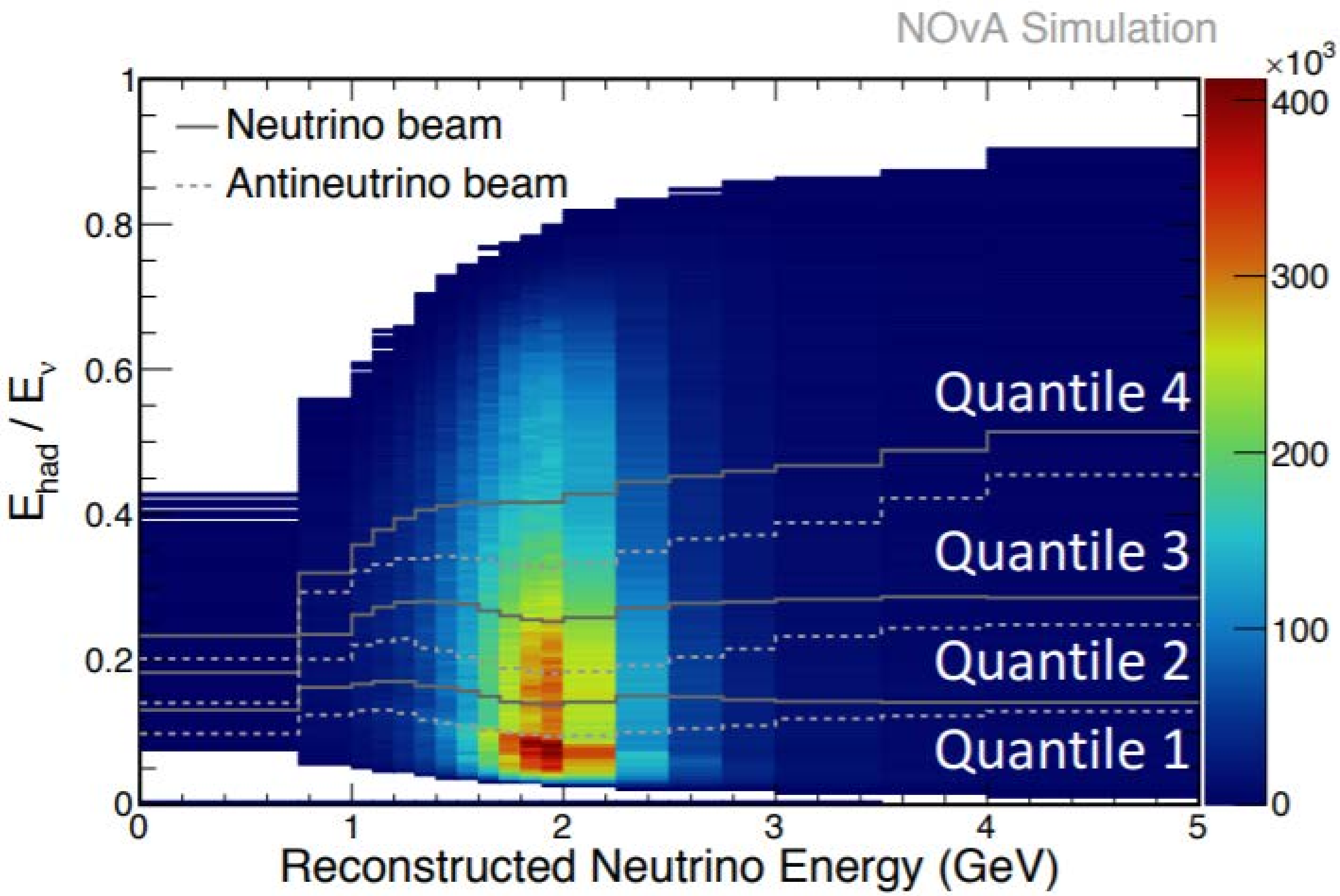
Additional cosmic rejection needed at the Far Detector. – 11 billion cosmic rays/day in the Far Detector on the surface. – 10^7 rejection power required after timing cuts are applied.

The νμ sample uses a BDT based on: – Track length and direction, distance from the top/sides, fraction of hits in the muon, and CVN.

Cosmic rejection for the νe sample is in 2 stages: – Core sample: require contained events, beam-directed events, away from the detector top – Peripheral sample: events failing the core selection can pass a BDT cut plus a tight CVN cut. • Different BDT from νμ



Binning for sensitivity



Oscillation sensitivity depends on spectrum shape

Improve sensitivity by separating high-resolution and low-resolution events.

Split into 4 quantiles by hadronic energy fraction. – Muon energy resolution (3%) is much better than hadronic energy resolution (30%)

Improving energy resolution

Data

Area-normalized MC

Shape-only systematics

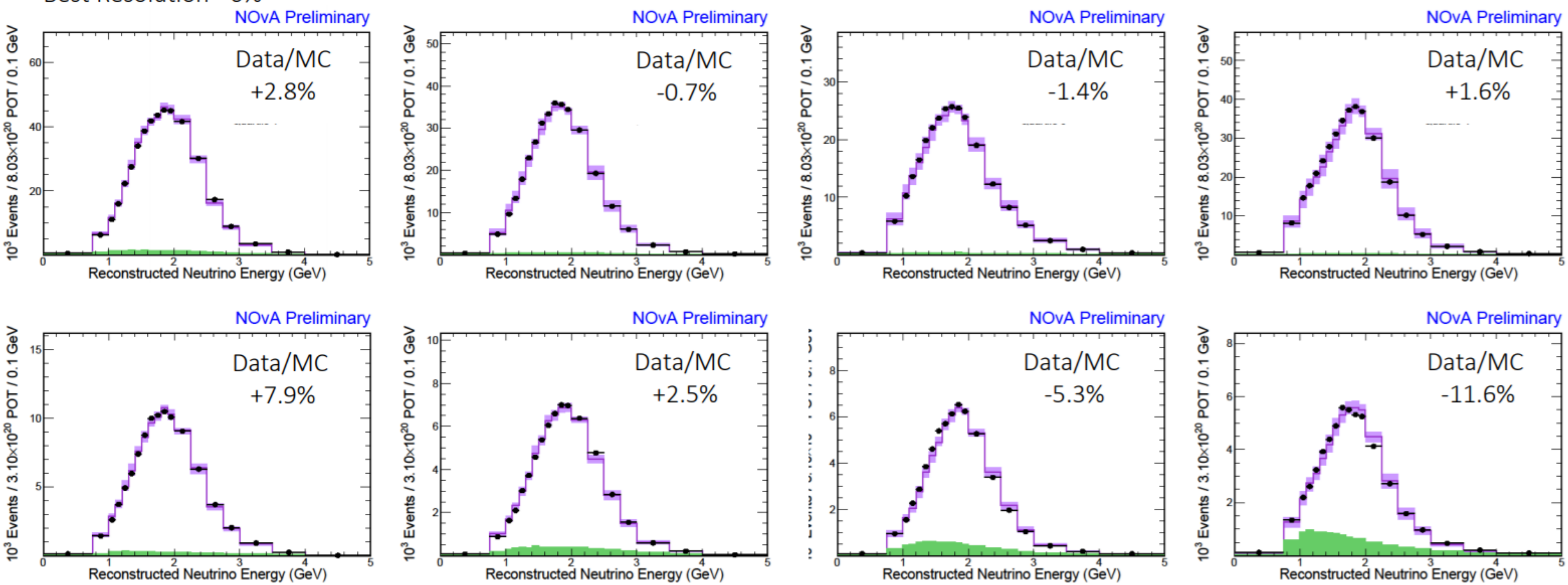
Wrong-sign

Quartile 1

Best Resolution ~6%

Quartile 4

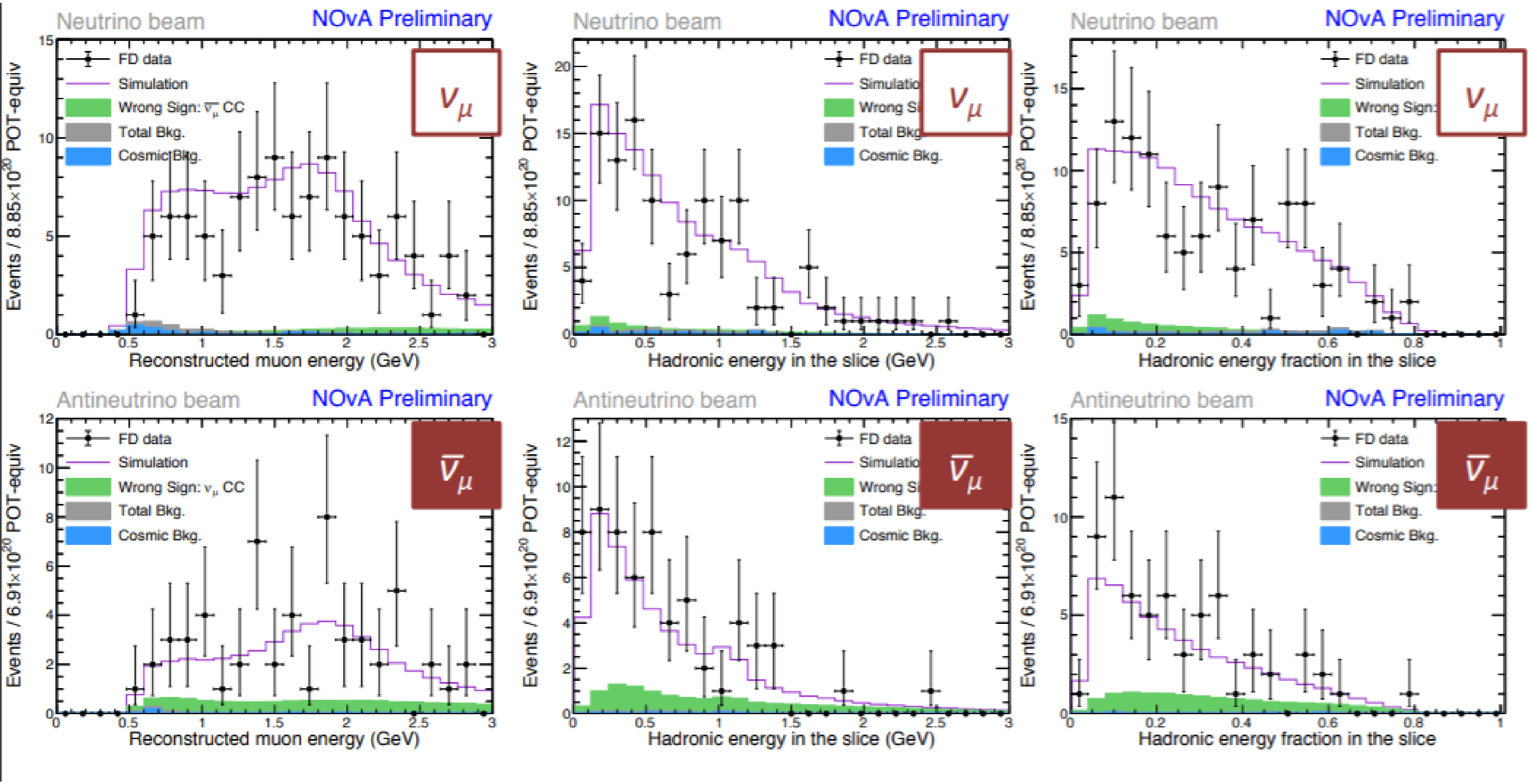
Worst Resolution ~12%



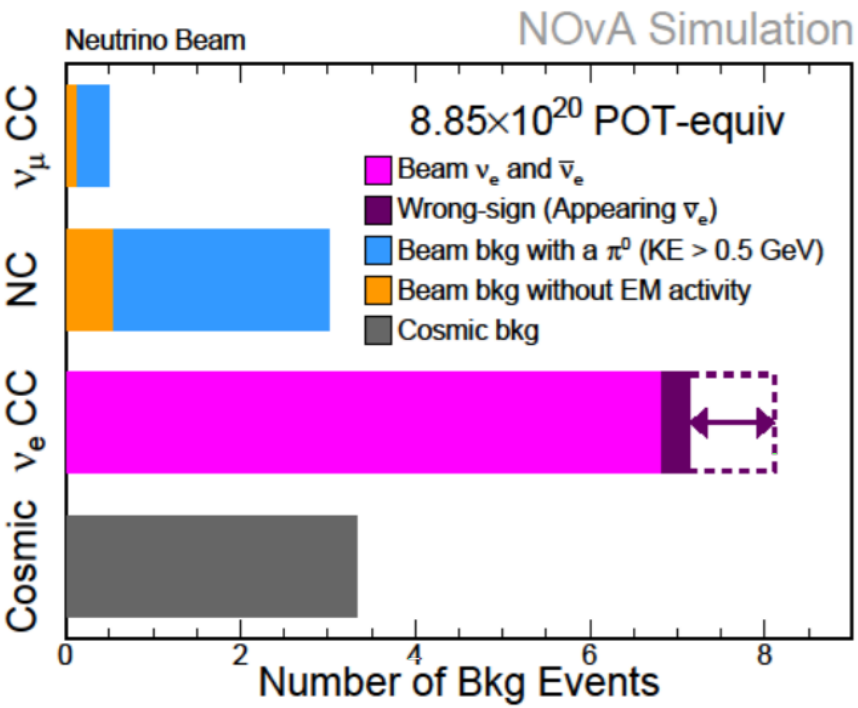
Data/MC shape agrees well per quartile

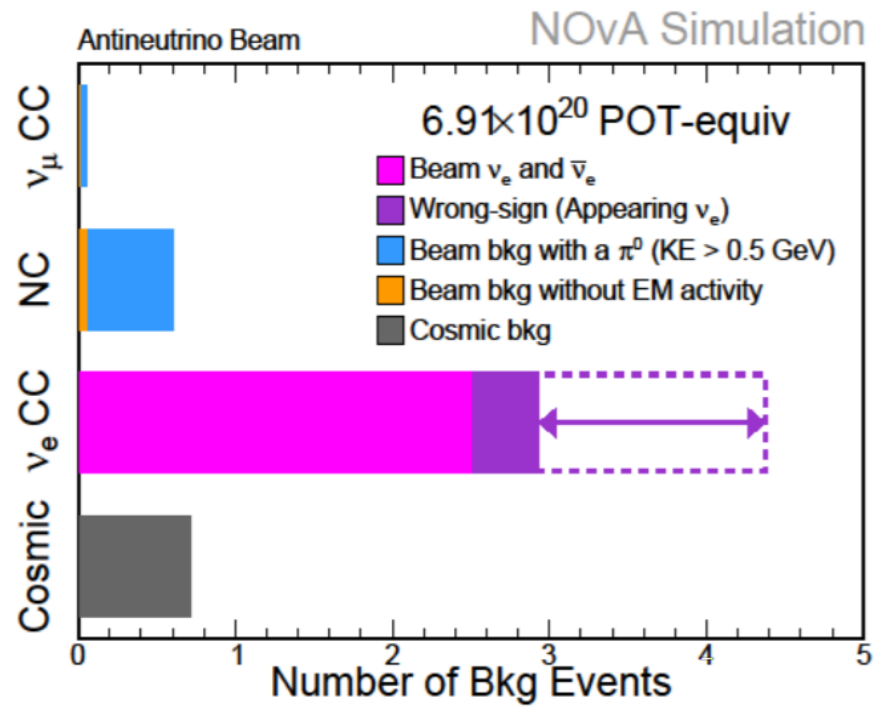
Data vs. MC

Good agreement in FD data distributions of muon and hadronic energy and inelasticity.



Far detector backgrounds to ν_e





14.7 – 15.4 total νe background, 4.7 – 5.7 total $\bar{\nu}_e$ background
Wrong sign depends on oscillation parameters

Didn't you say there are 3 neutrinos?

From LEP, invisible width of Z-boson very strongly measured there are 3 "light" neutrinos

- N_ν = 2.984 +- 0.008

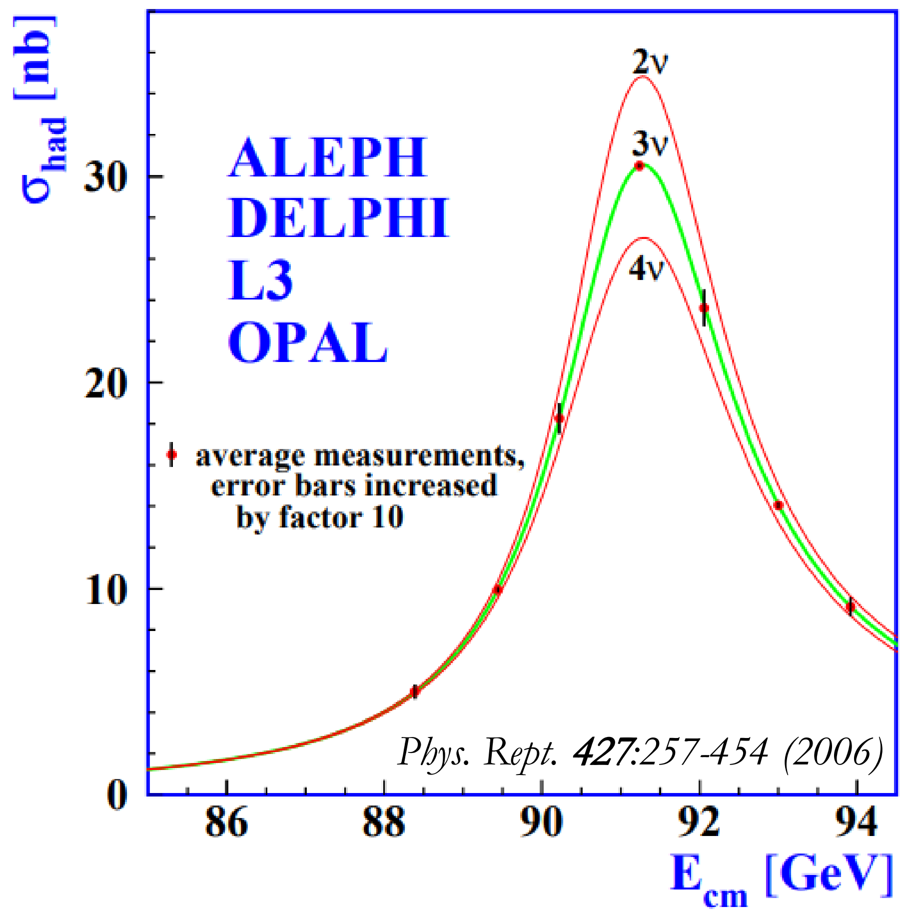
"light" means $m_\nu < ½\ m_Z$ and additional neutrino must not couple to Z

- Hence "sterile" neutrino:
  - no SM charge; no SM interactions

Cosmological constraints:

- $N_{eff} = 3.2 \pm 0.5$
- $\Sigma\ m_\nu < 0.32$ eV
  - *90%, Planck TT+lowP+lensing+BAO*

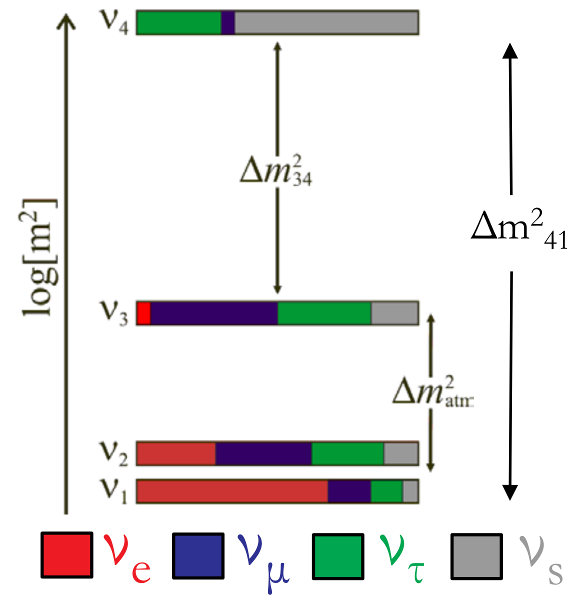
P. A. R. Ade et al. (Planck Collaboration), Astron. Astrophys. ***594*** *A13:63 (2016)*



3+1 formalism

Extend PMNS matrix with an additional sterile neutrino (ν_s), three new mixing angles and two new CP phases
Three new mass-splittings; one is independent Δm^2_{41}

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



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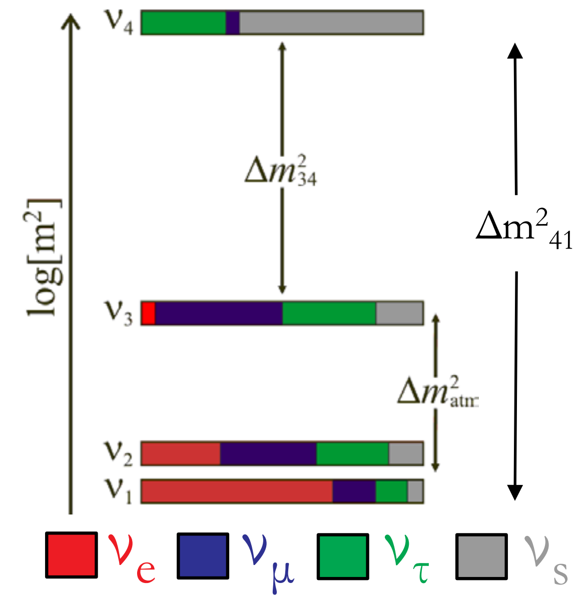


$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \frac{1}{2}\cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24} + \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}$$
$$- \frac{1}{2}\sin\delta_{24}\sin^2\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin^2 2\Delta_{31}$$

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ji} L}{4E}$$

$\nu_e \to \nu_e$ at short baselines (reactor)

$$|U_{e4}|^2 = \sin^2\theta_{14}$$

$\nu_\mu \to \nu_\mu$ at short/long baselines

$$\mathbf{|U_{\mu 4}|^2 = \cos^2\theta_{14}\,\sin^2\theta_{24}}$$

$$4\,|U_{e4}|^2\,|U_{\mu 4}|^2 = \sin^2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$$

$$\mathbf{|U_{\tau 4}|^2 = \cos^2\theta_{14}\,\cos^2\theta_{24}\,\sin^2\theta_{34}}$$

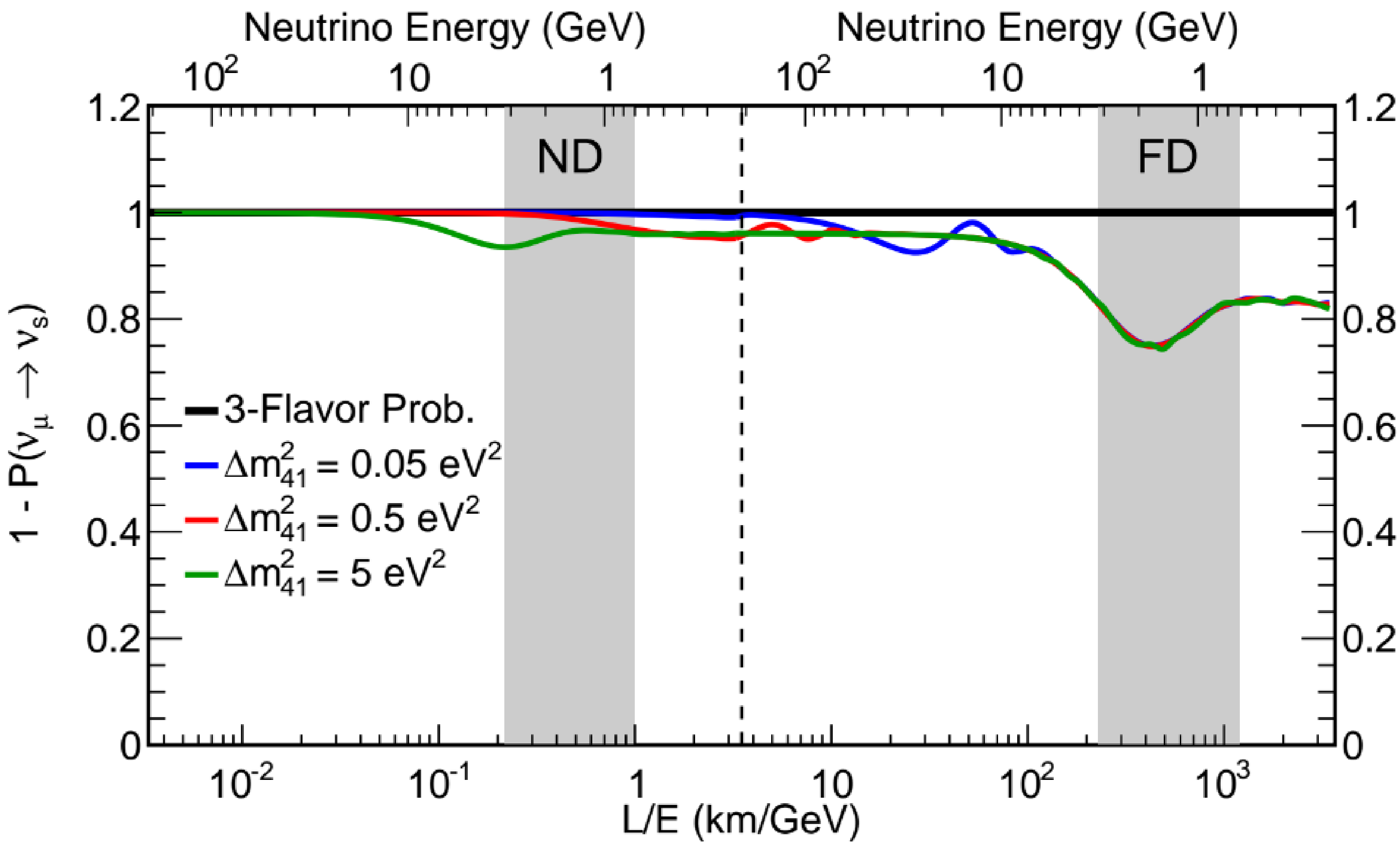
$\nu_\mu \to \nu_e$ at short baselines (LSND)

$\nu_\mu \to \nu_s$ at long baselines (NCs)

Why NC's?

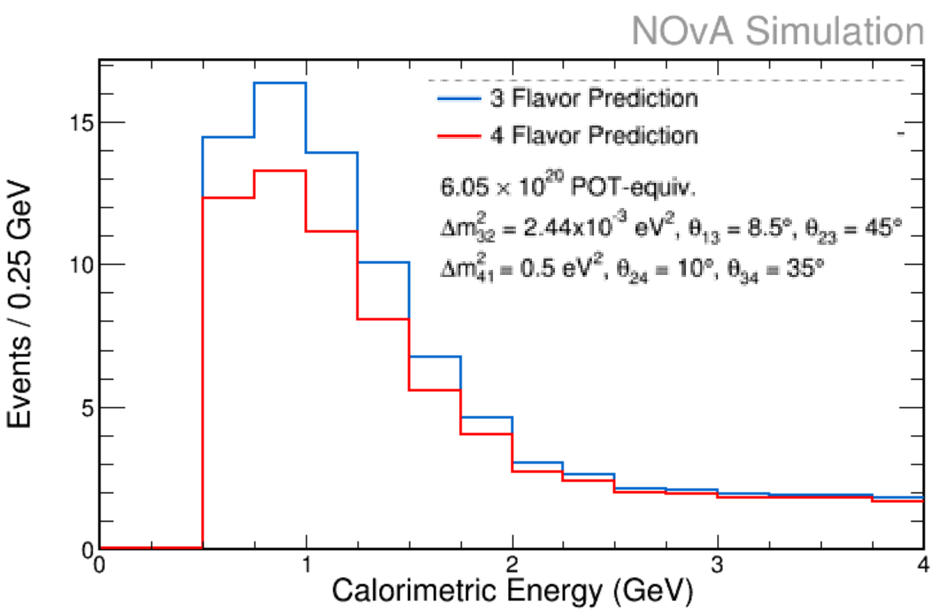
Do any ν_μ oscillate to a sterile state?

- $\nu_\mu \rightarrow \nu_s$ mixing causes energy-dependent depletion of NC



Searching for ν_s in NOvA

- NC interactions unaffected by 3-flavour oscillations but mixing between active and sterile neutrinos reduces the rate of NC events
  - NC rate is the same for all 3 active flavours
- Compare number of Neutral Current events between Near and Far Detectors
  - Select high statistics ND sample to predict expected rate at the FD
  - Select FD events to search for reduced rate due to sterile oscillations
- Null result would allow NOvA to set limits on sterile mixing angles and further increase the exclusion region



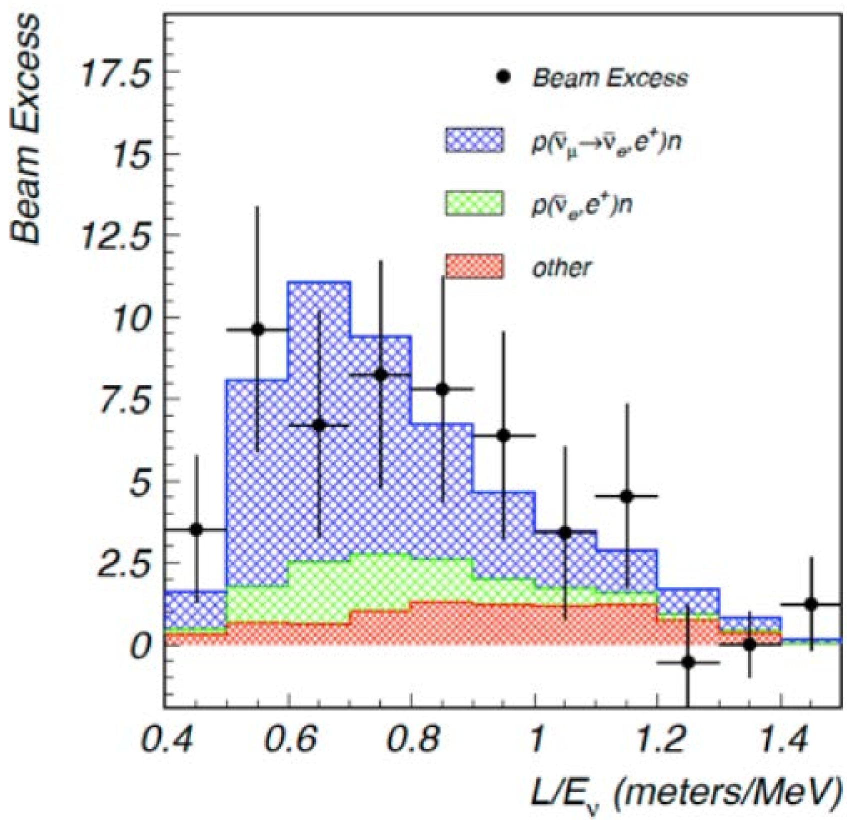
NC disappearance relative to 3-flavour predictions is model independent

Search for a depletion of NC events at the Far Detector

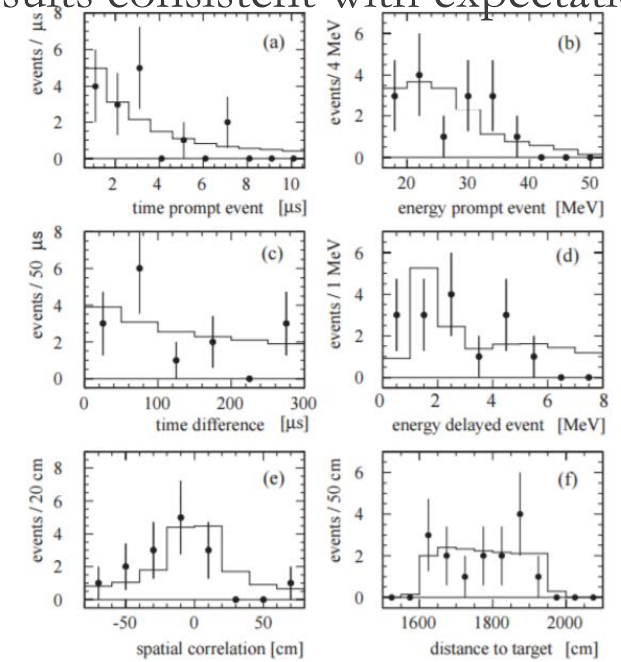
This is a rate-only analysis

Anomaly #1a

LSND (1993 – 1998) observed a 3.8sigma excess of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, could be interpreted as oscillations at high mass-splitting scale ~1eV^2



KARMEN2 experiment, however, saw results consistent with expectation



Church et al. Phys. Rev. D66 (2002), p. 013001

MiniBooNE investigated

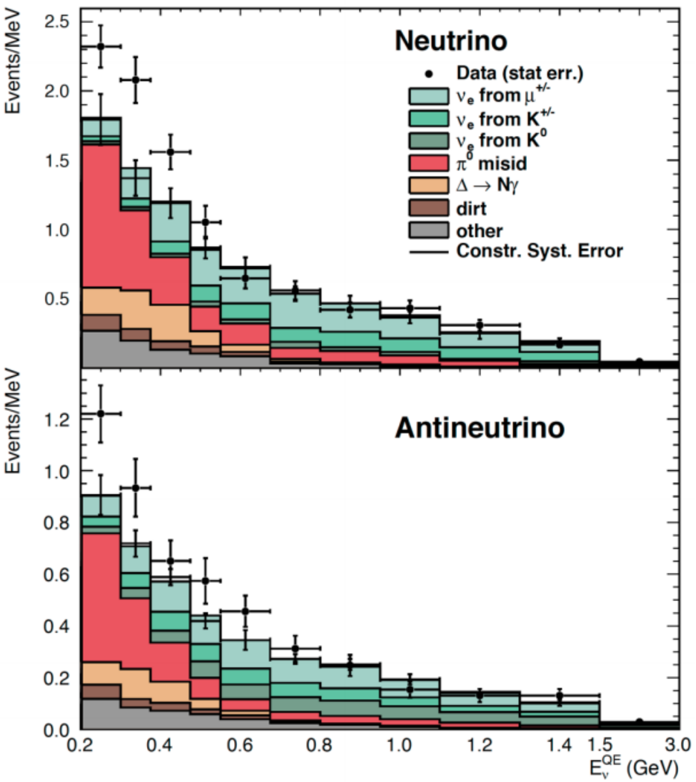
- $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

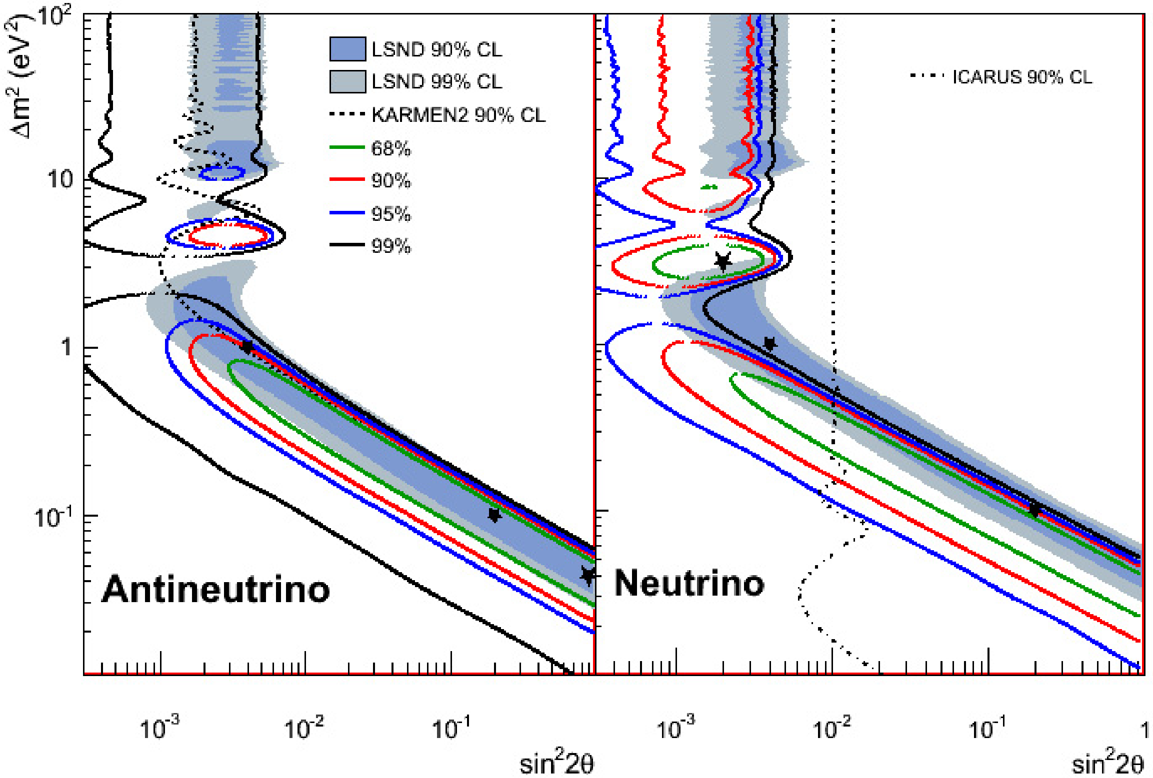
Anomaly #1b

MiniBooNE saw excess appearance in both neutrino and anti-neutrino channels

Data consistent with antineutrino oscillations for $0.01 < \Delta m^2 < 1.0\ \mathrm{eV}^2$

Some overlap with regions of phase-space from LSND





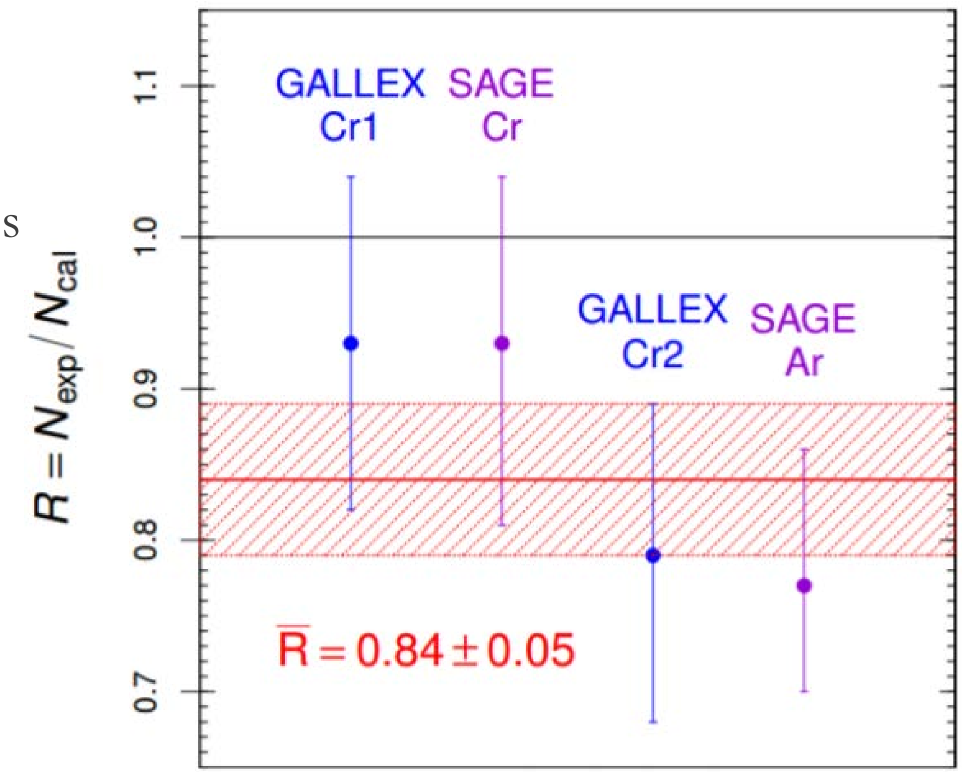
Anomaly #2

Solar neutrino experiments:
GALLEX and SAGE

Calibrated using radioactive sources

Measured rates from the calibration sources displayed consistent deficits

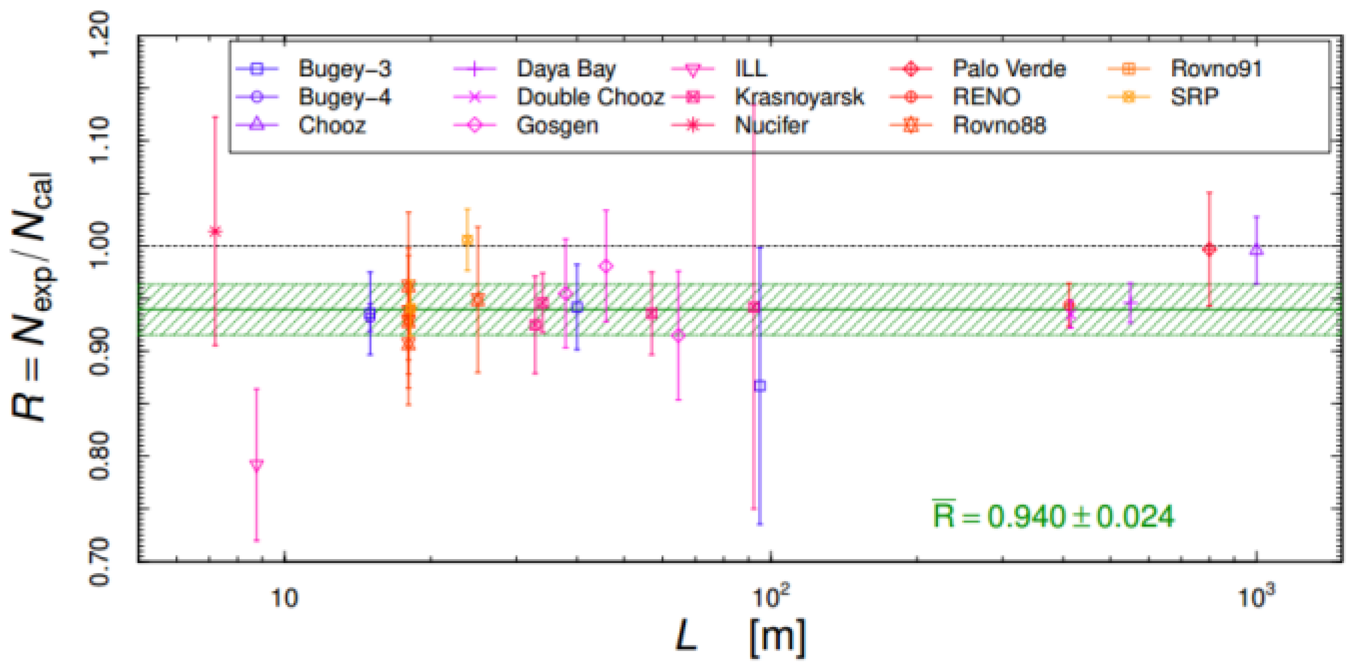
…consistent with a 1 eV^2 mass-splitting



Gariazzo et al. J.Phys. G43 (2016) 033001
DOI:10.1088/0954-3899/43/3/033001

Anomaly #3?

A suite of reactor neutrino experiments have seen a deficit of ν_e



Gariazzo et al. (2017). arXiv: 1703.00860 [hep-ex]

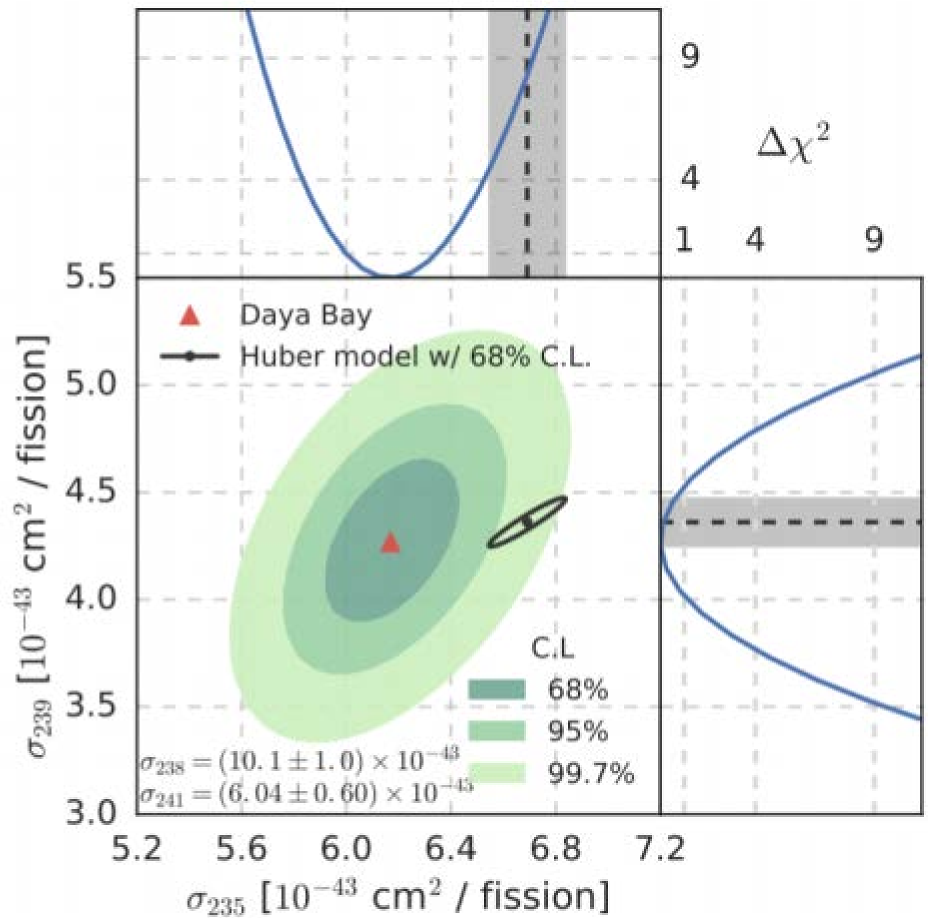
…consistent with a 1 eV^2 mass-splitting. Hang tight, there's more…

So, not an anomaly?

Daya Bay released results in 2017 after studying their flux as a function of reactor fuel cycles to extract information on the uranium (U…) and plutonium component

Flux deficit appears to only come from the uranium flux

Sterile neutrino hypothesis is incompatible with Daya Bay's observation at 2.6 sigma

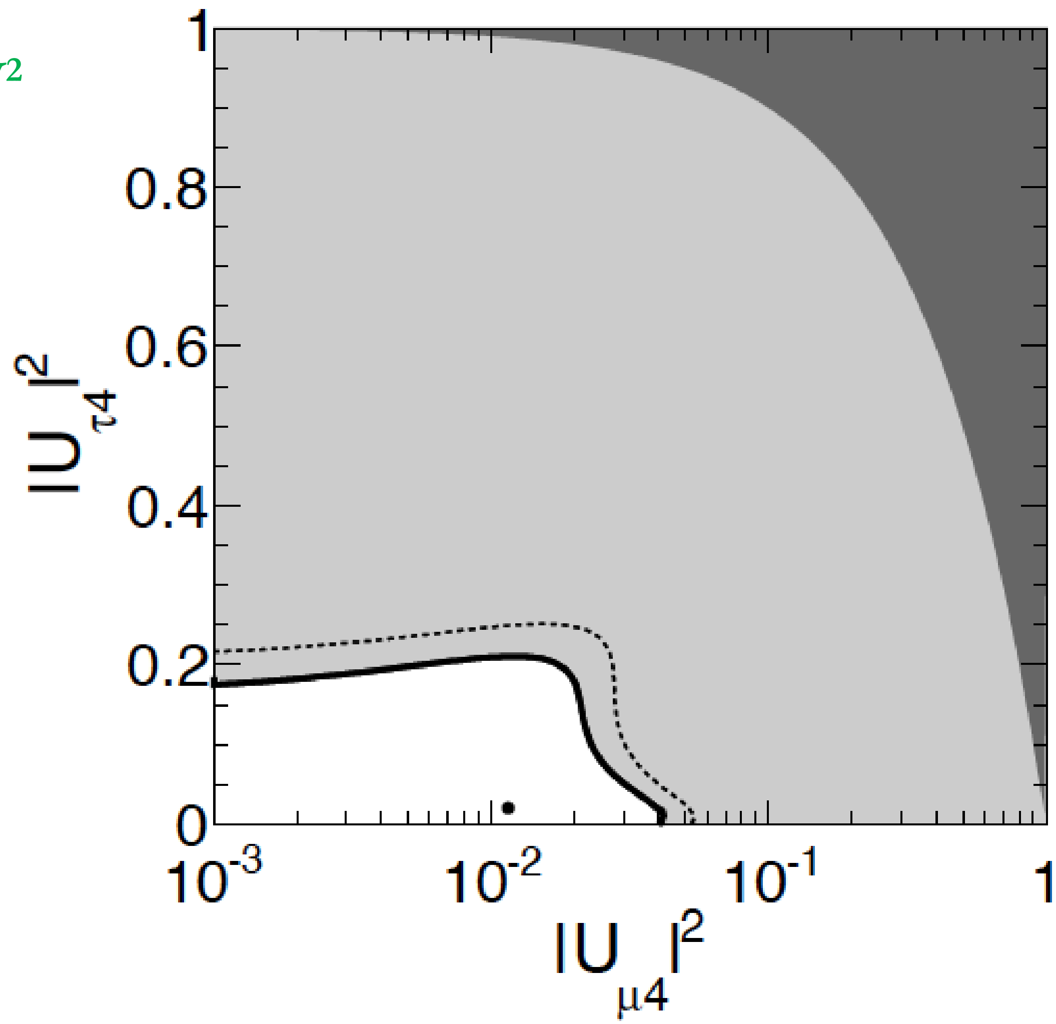


An et al. (2017). arXiv: 1704.01082 [hep-ex]

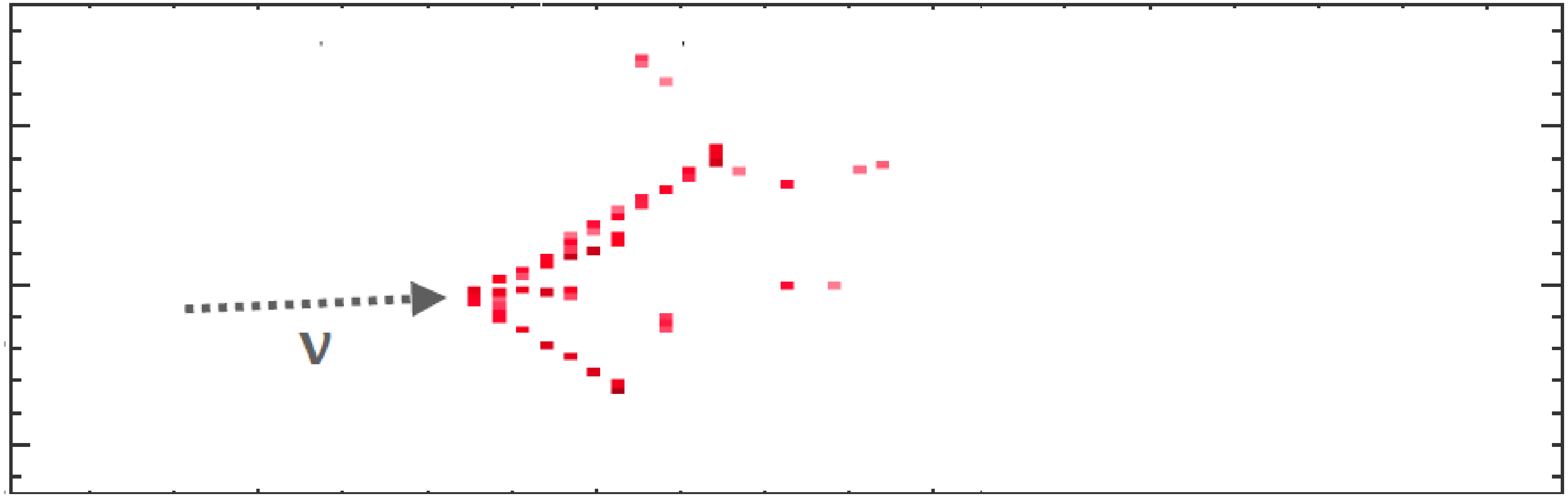
- Super-K exclusion in $|U_{\mu 4}|^2$, $|U_{\tau 4}|^2$ parameter space

  $|U_{\mu 4}|^2 < 0.041$ for $\Delta m^2_{41} > 0.1$ eV^2

  $|U_{\tau 4}|^2 < 0.18$ for $\Delta m^2_{41} > 0.1$ eV^2



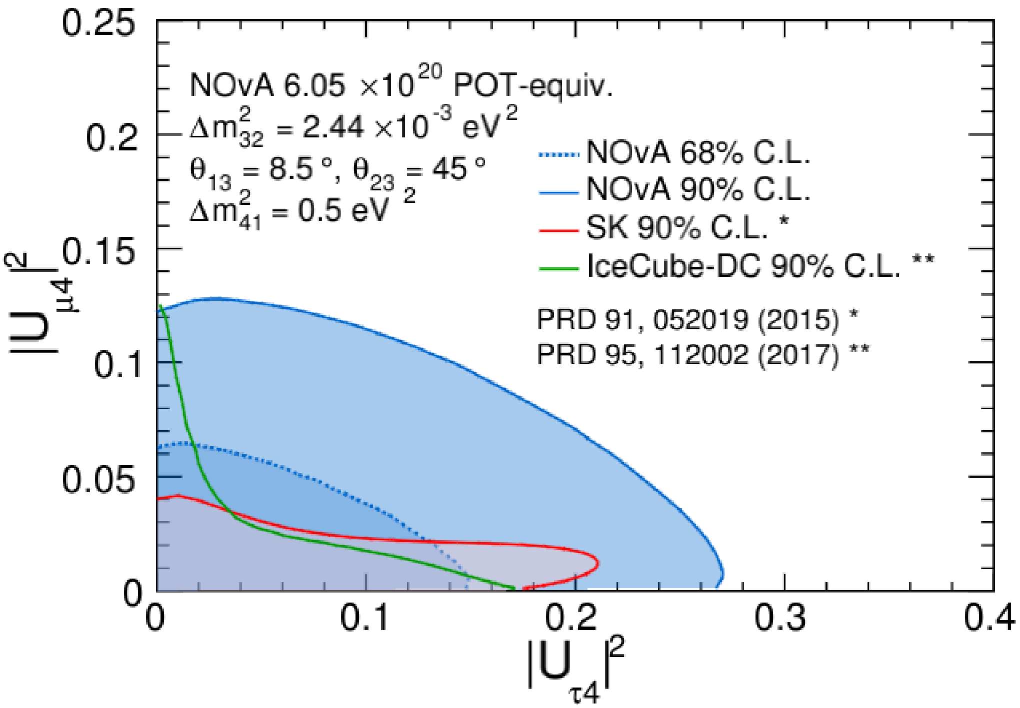
- Super-K only experiment with measurement on $|U_{\tau 4}|^2$ directly comparable to NOvA



NC Disappearance

NOVA'S FIRST PUBLIC 2017 DATASET RESULT

2016 Sterile mixing angle limits



In 3+1 analysis, for $\Delta m^2_{41} = 0.5$ eV^2

$$|U_{e4}|^2 = \sin^2\theta_{14} = 0, \cos^2\theta_{14} = 1$$

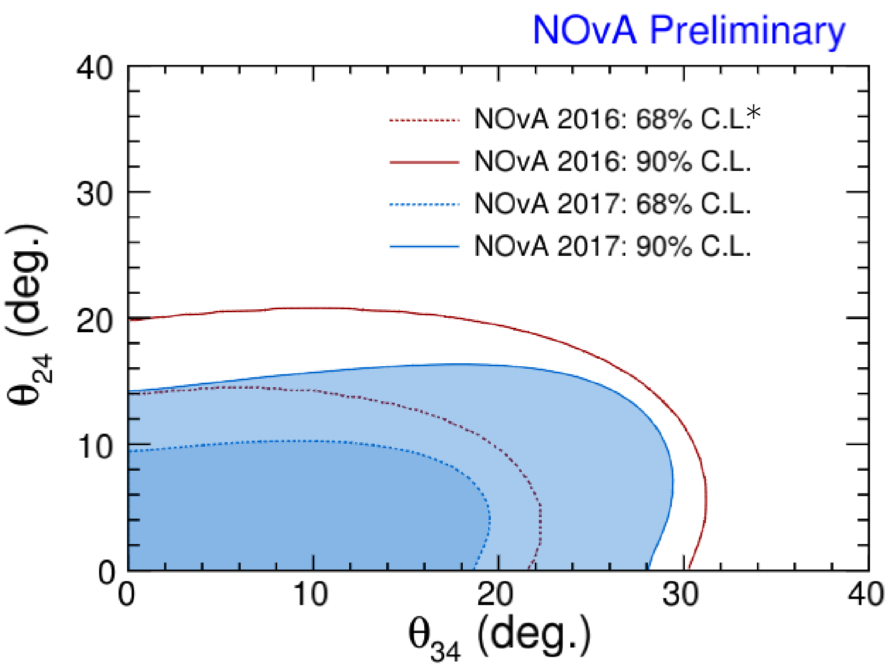
$$|U_{\mu 4}|^2 = \cos^2\theta_{14} \sin^2\theta_{24}$$

$$|U_{\tau 4}|^2 = \cos^2\theta_{14} \cos^2\theta_{24} \sin^2\theta_{34}$$

$|U_{\mu 4}|^2 < 0.126$ at 90% C.L.
$|U_{\tau 4}|^2 < 0.268$ at 90% C.L.

NC Disappearance Results

Constrain **NOvA**'s degenerate best fit points for $\sin^2(\theta_{23})$, $|\Delta m^2_{32}|$, and δ_{CP} (NH)
Profile $\sin^2(\theta_{23})$, δ_{24}
Perform a shape-based fit for θ_{24} and θ_{34}



*: 2016 applies constraints for maximal mixing; rate-only fit

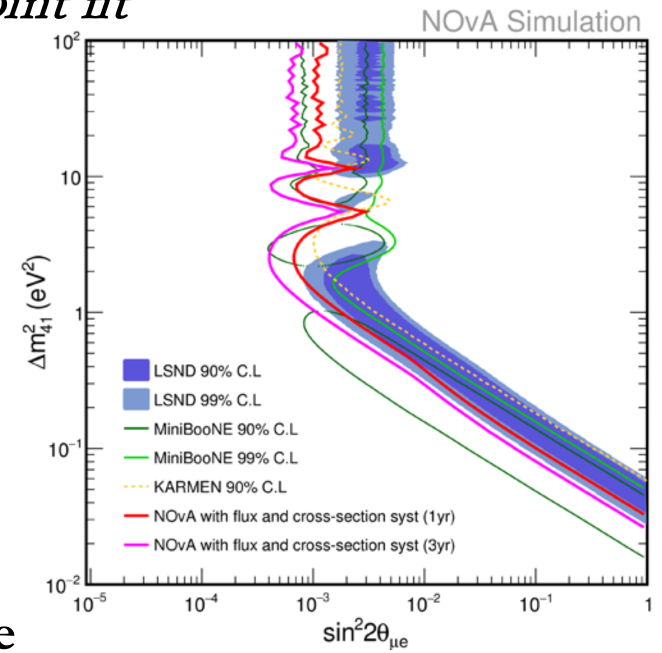
	θ_{24}	θ_{34}	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
NOvA 2016	20.8°	31.2°	0.126	0.268
NOvA 2017	16.2°	29.8°	0.078	0.228
MINOS	7.3°	26.6°	0.016	0.20
SuperK	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

In a 3+1 analysis, for $\Delta m^2_{41} = 0.5$ eV^2:
θ_{24} < 16.2 at 90% C.L.
θ_{34} < 29.8 at 90% C.L.

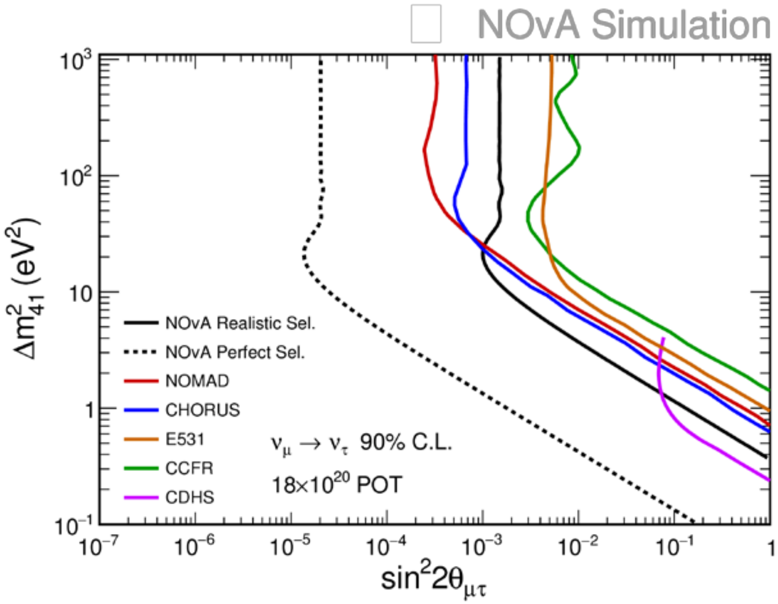
The future for NOvA ν_s searches

NOvA short-baseline ν_e appearance-ν_μ disappearance joint fit

Probe LSND and MiniBooNE allowed regions with one NOvA year



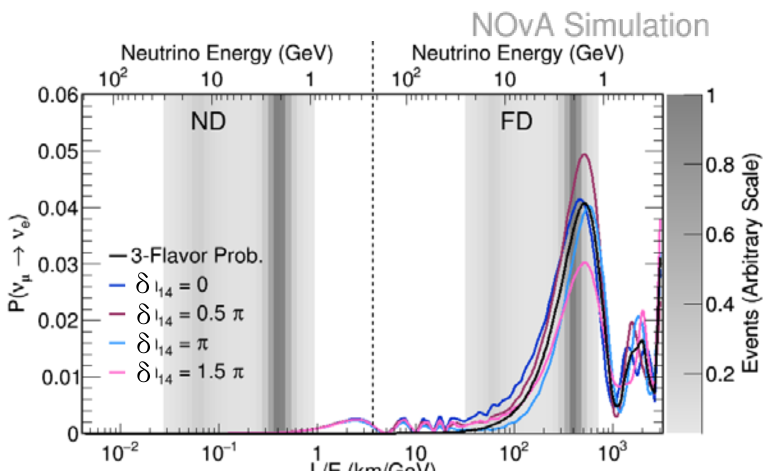
NOvA short-baseline ν_τ appearance



Black line shows NOvA sensitivity to ν_τ appearance; rate-only fit to two flavor model

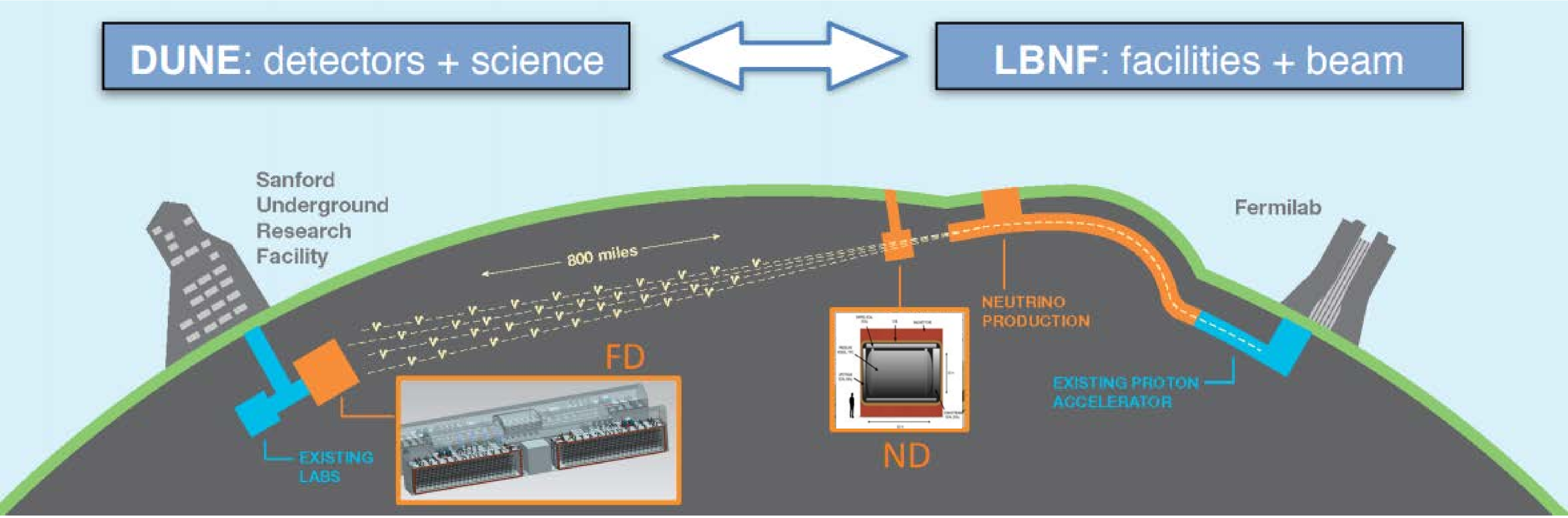
NOvA will be competitive with previous experiments after 3 years of running

Probing δ_{14} & δ_{13} with ν_e long-baseline



DUNE at LBNF

Deep Underground Neutrino Experiment at the Long Baseline Neutrino Facility



DUNE will be the premier long-baseline neutrino experiment

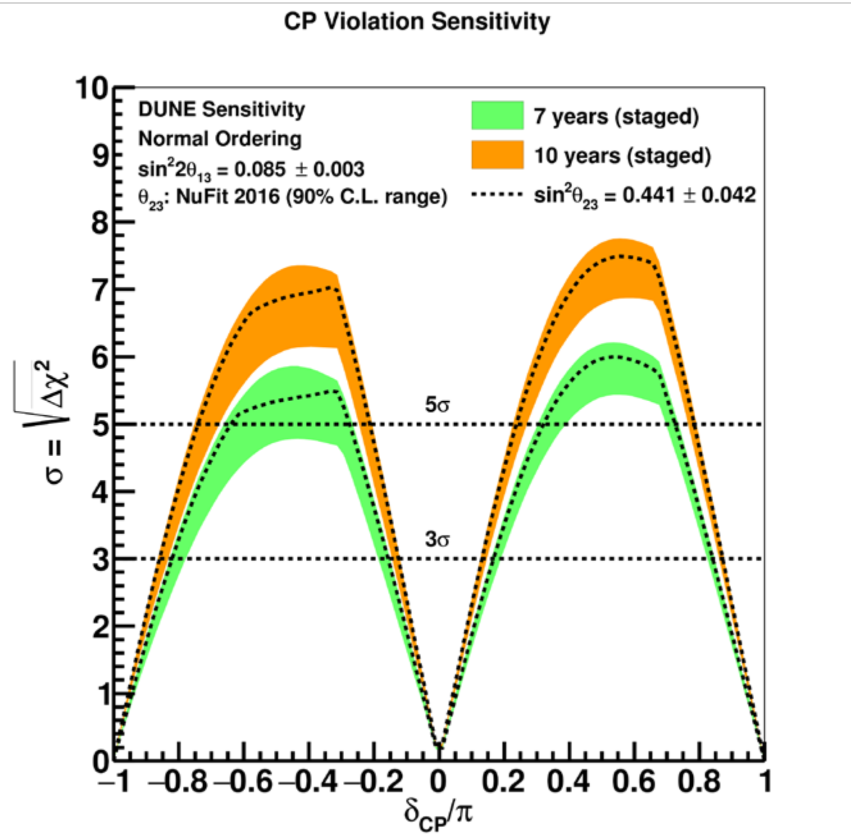
- Multi-megawatt, high intensity, wide band neutrino beam
  - Produced at Fermilab, directed towards the Sanford Underground Research Facility (SURF)
- 40 kT (fiducial mass) Liquid Argon Time Projection Chamber (LArTPC) far detector
  - Four 10kT modules modules located at the 4850 level
- Highly capable neutrino near detector
  - High statistics neutrino cross-section measurements and capability to fully characterize the spectrum and flavor composition of the beam

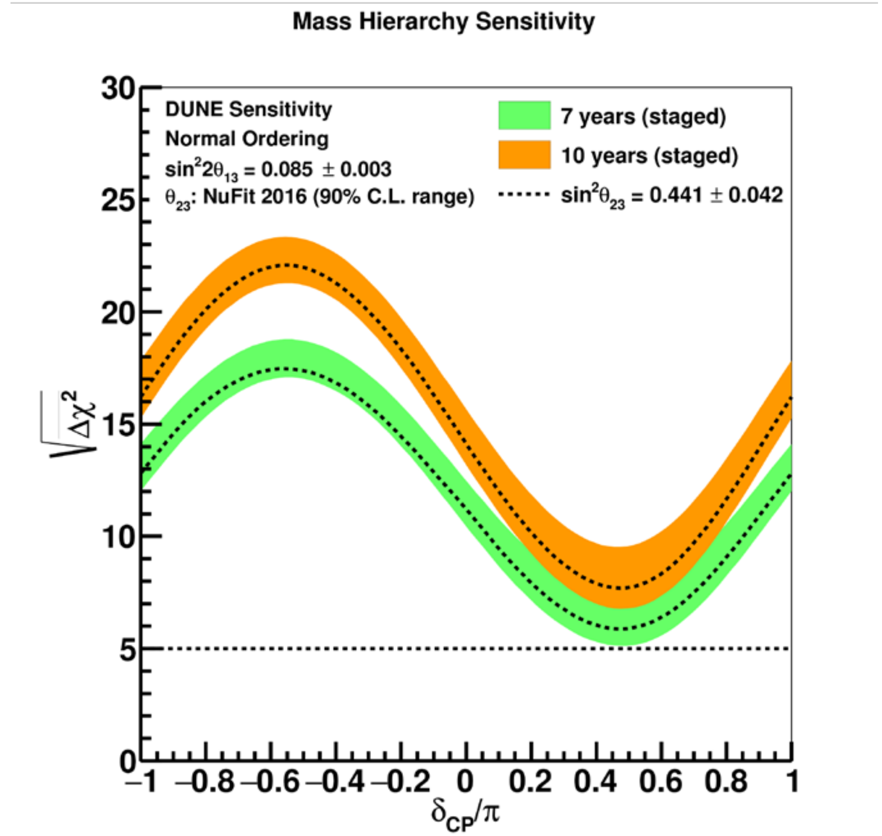
Physics of DUNE

Would like to have > 5σ determination for all 3ν questions

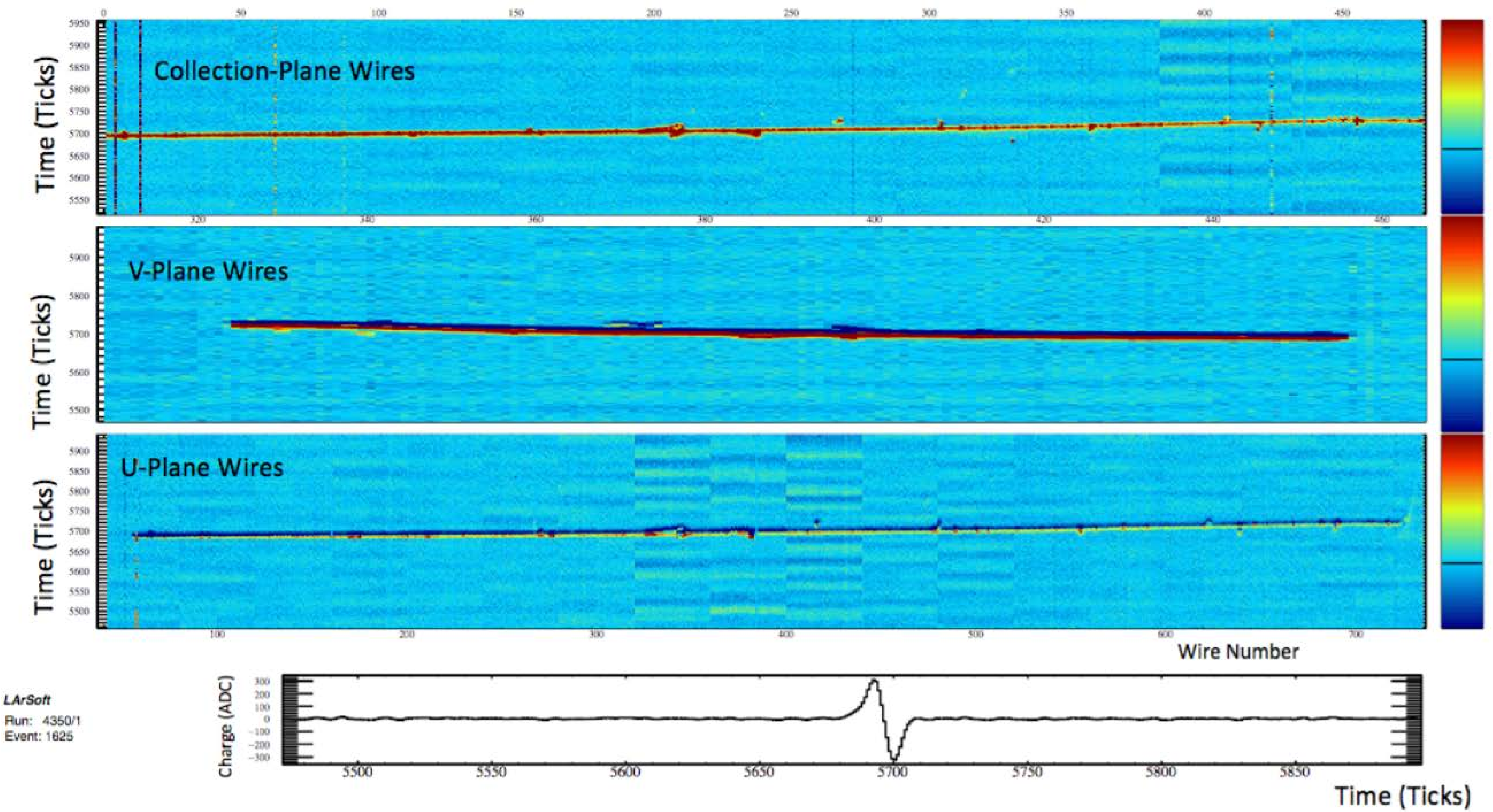
- and sensitive searches beyond 3ν paradigm

Neutrino Oscillations; Proton Decay; Supernova Neutrinos





First ProtoDUNE tracks



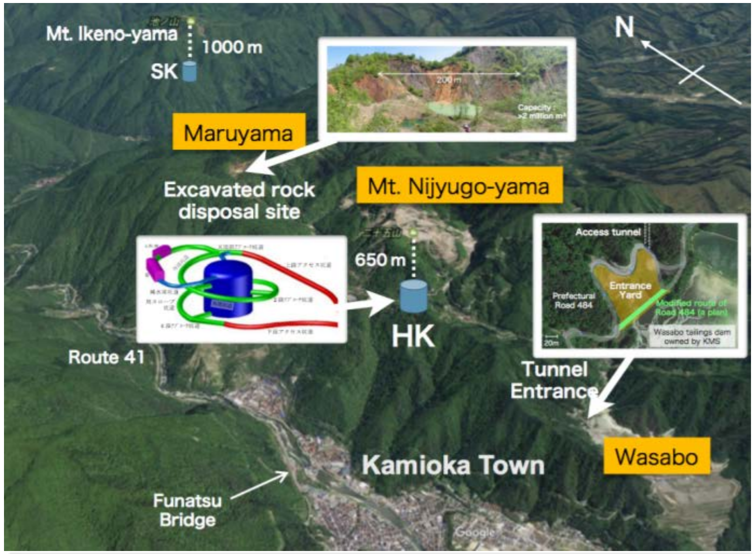
HyperK

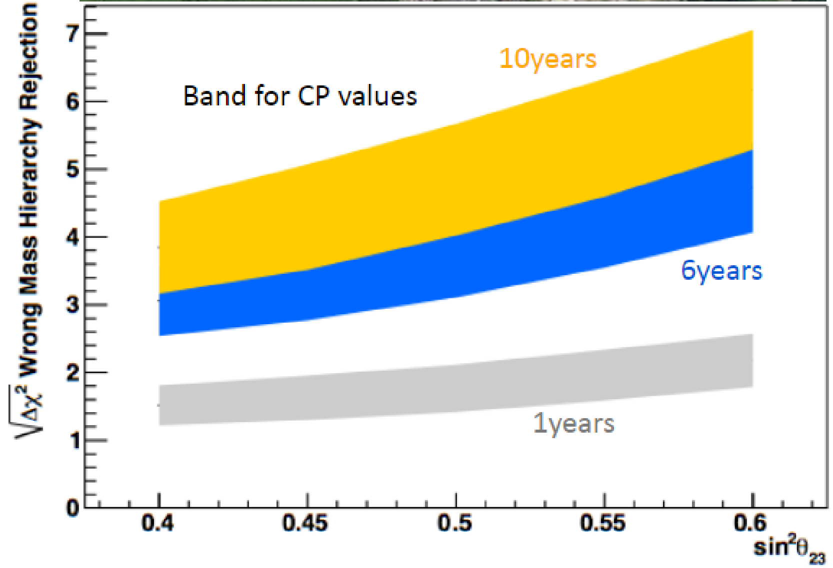
HyperK:
"Seed funding" just approved Sept 19th 2018
Project construction could begin as soon as 2020

Detector(s):
FD – bigger version of SK with better PMTs
~190 kT fiducial mass (10x SK)

ND – continue to use ND280
still uses JPARC beam (upgraded to ~MW level)

Physics:
double proton decay sensitivity (see ~10 if lifetime is at current limits)
could see ~50k SNe events (out to 10 kpc)
expect > 2k appearance events in 10 years
Hierarchy determination "possible" after ~5 yr





M. Shiozawa (Neutrino 2018)