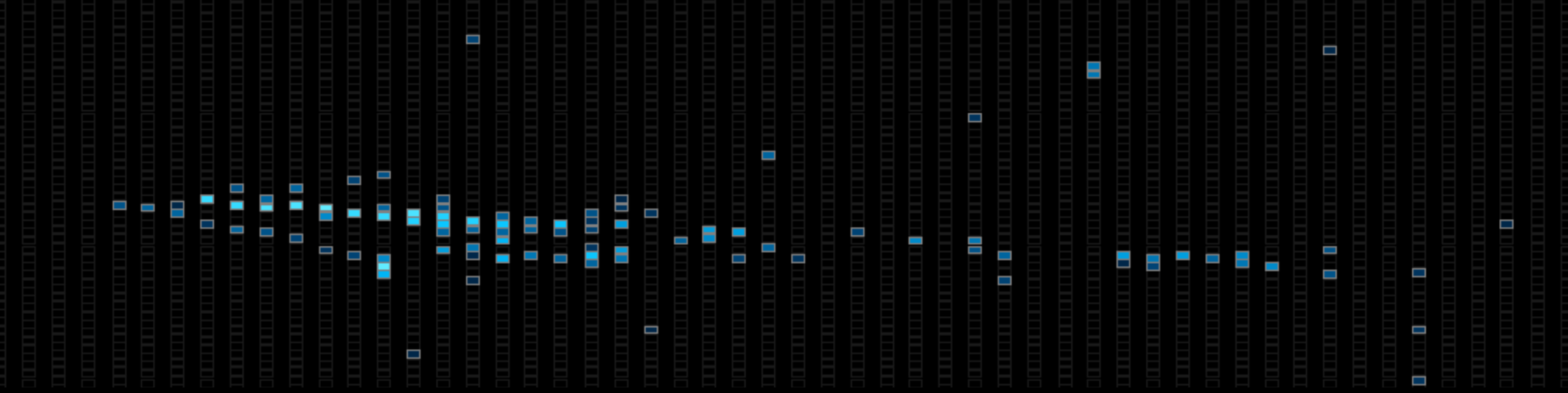


Results from The NOvA Experiment

Mark Messier
Indiana University

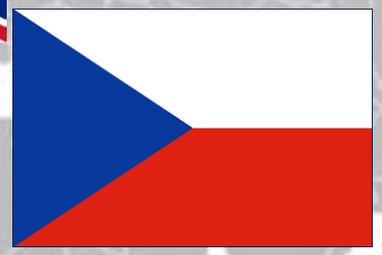
2 November 2017

Colloquium Prague v17

NOvA Collaboration

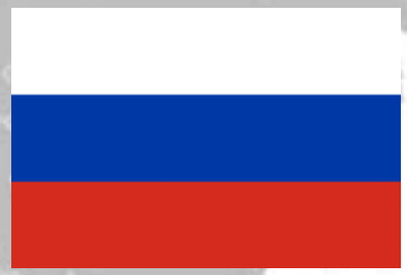
Argonne, CalTech, UC Irvine, Cincinnati, Colorado State, Fermilab, Harvard, Houston, IIT, Indiana, Iowa State, Michigan State,Minnesota Duluth, Minnesota Twin Cities, Pittsburgh, SMU, South Alabama, South Carolina, South Dakota SMT, Stanford, UT Austin, Tennessee, Tufts, Virginia, Wichita State, William & Mary, Winona State

Sussex, University College London



Charles University, Czech Technical University, Institute of Physics, Institute of Computer Science – Czech Academy of Sciences

JINR Dubna, INR Moscow, Lebedev Institute



Banaras Hindu University, Cochin University of S&T, Delhi University, IIT Guwahati, IIT Hyderabad, Jammu University, Panjab University, NISER

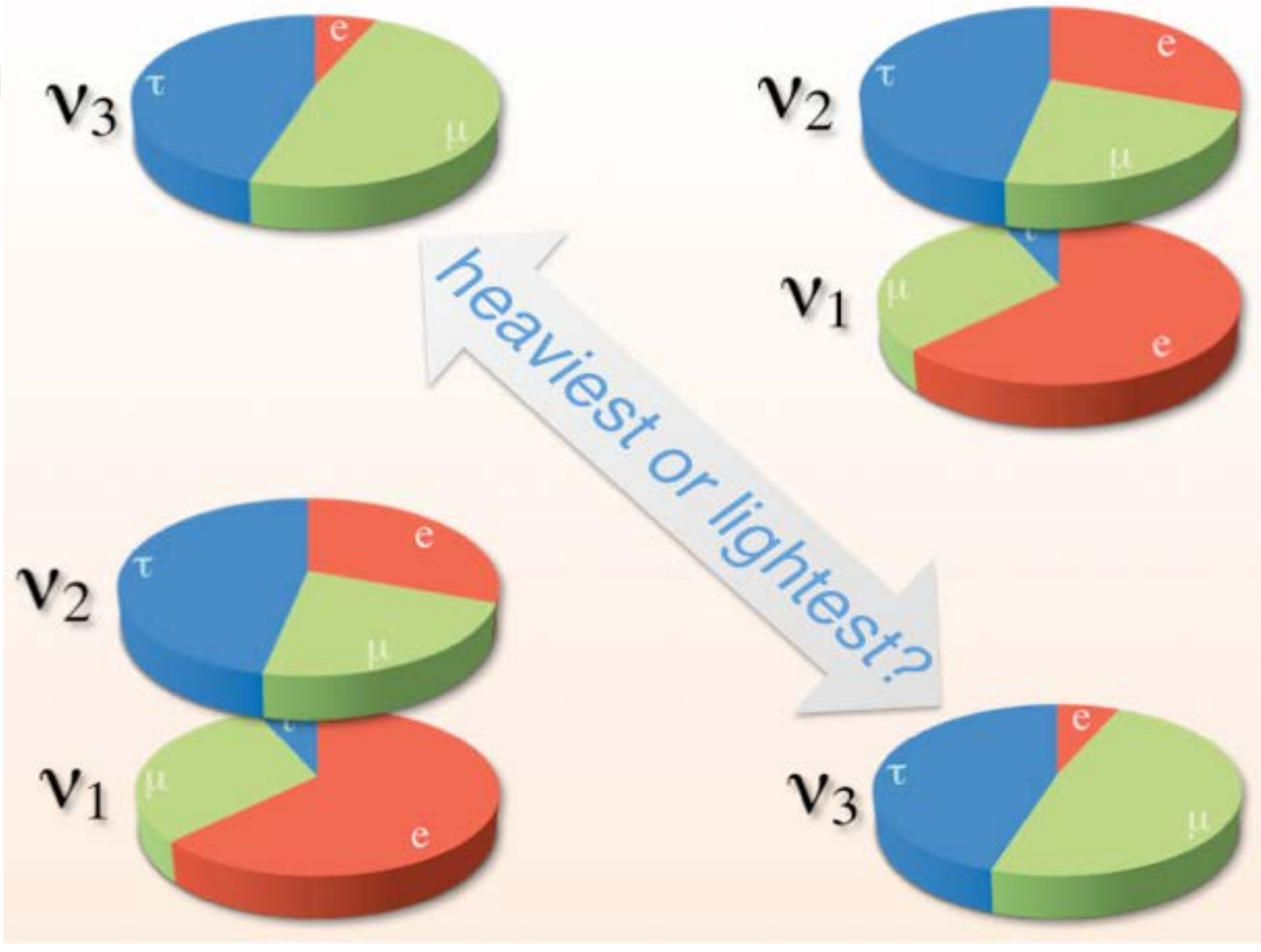
Universidad del Atlantico

Universidade Federal de Goias

- 200 Physicists, Engineers and
- 47 Institutions in 7 Countries

Next Questions In Neutrino Physics

- Mass ordering
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}\left[1 - \cos^2\theta_{13}\sin^2\theta_{23}\right]\sin^2\Delta_{3i}$$
$$\simeq 1 - \sin^2 2\theta_{23}\sin^2\Delta_{3i}$$

$$P(\nu_\mu \to \nu_e) \simeq |\sqrt{P_{\rm atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\rm sol}}|^2$$
$$= P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\left(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta\right)$$

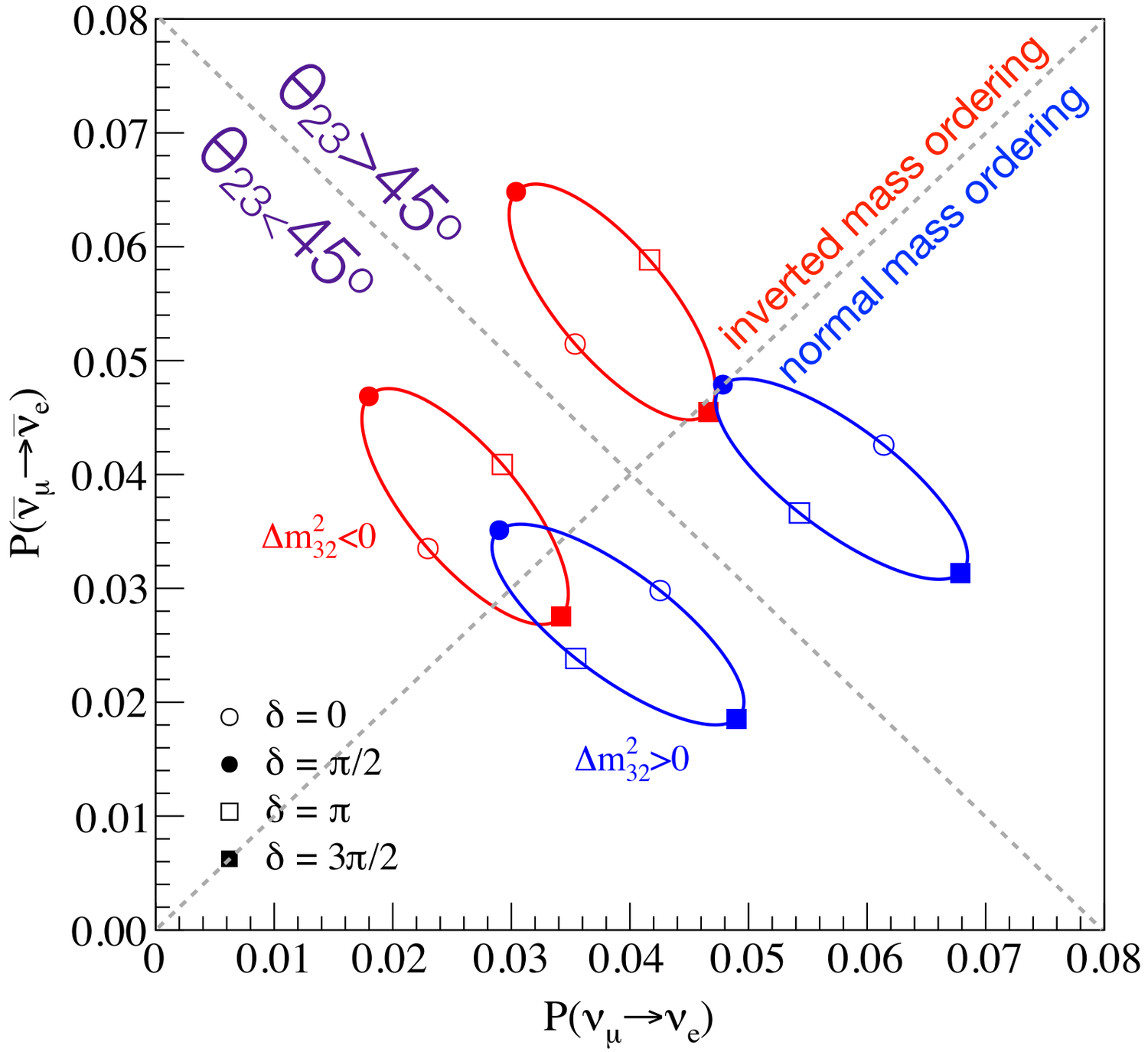
$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL}\Delta_{31}$$

$$\sqrt{P_{\rm sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}$$

$$a = G_F N_e/\sqrt{2} \simeq \frac{1}{3500\ \text{km}}$$

$aL = 0.08$ for $L = 295$ km
$aL = 0.23$ for $L = 810$ km
$aL = 0.37$ for $L = 1300$ km

Parameter	Channels	Question
$\sin^2 2\theta_{23}$:	$\nu_\mu \to \nu_\mu$ and $\bar\nu_\mu \to \bar\nu_\mu$:	Is θ_{23} maximal?
$\sin^2\theta_{23}\sin^2 2\theta_{13}$:	$\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$:	Octant of θ_{23}
$\text{sign}\,[\Delta_{31}]$:	$\nu_\mu \to \nu_e$ vs. $\bar\nu_\mu \to \bar\nu_e$:	Neutrino mass hierarchy
$\delta_{\rm CP}$:	$\nu_\mu \to \nu_e$ vs. $\bar\nu_\mu \to \bar\nu_e$:	Is CP violated?

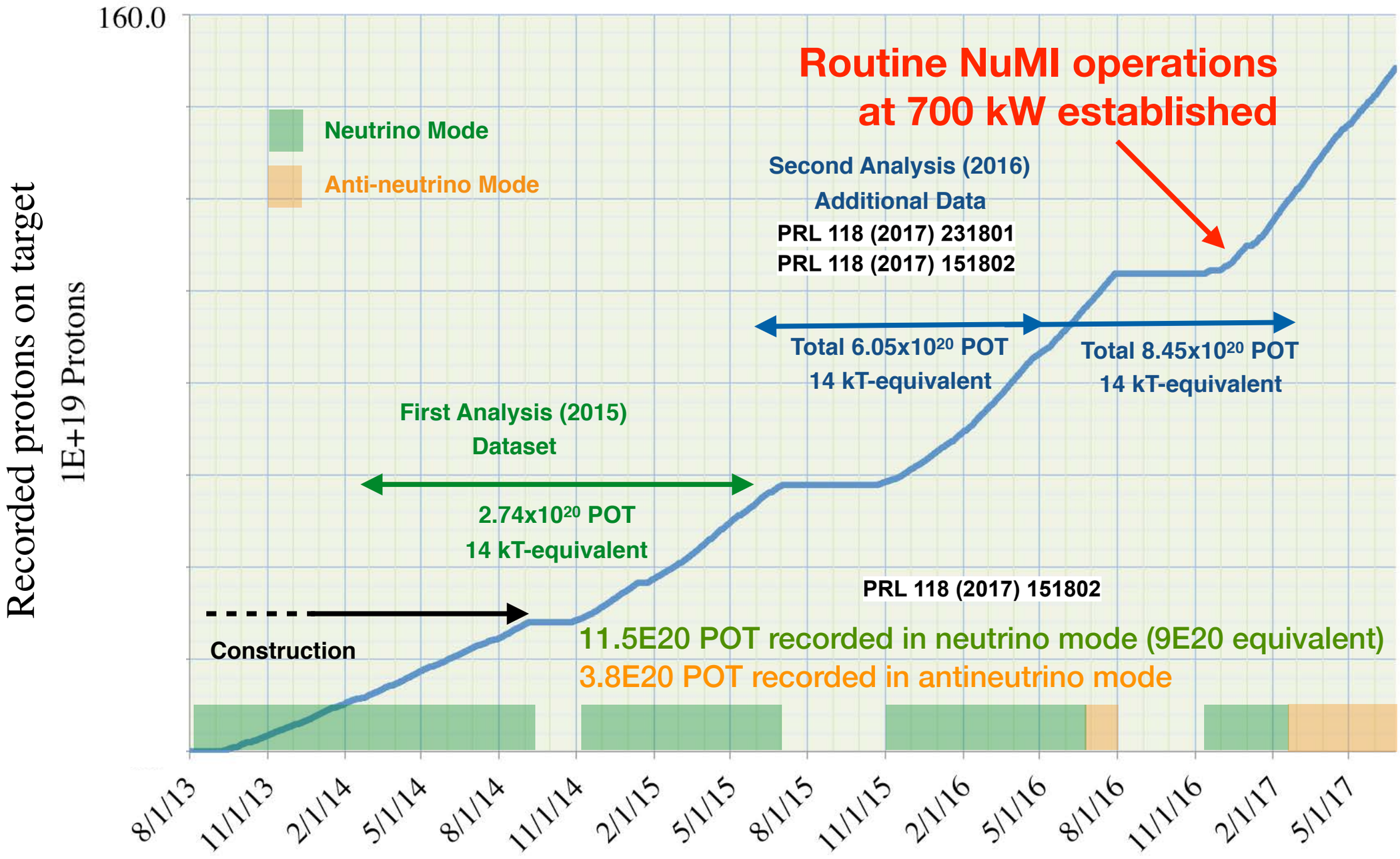


Neutrino Oscillations

Measurements at NOvA using neutrinos and antineutrinos can answer the next questions.

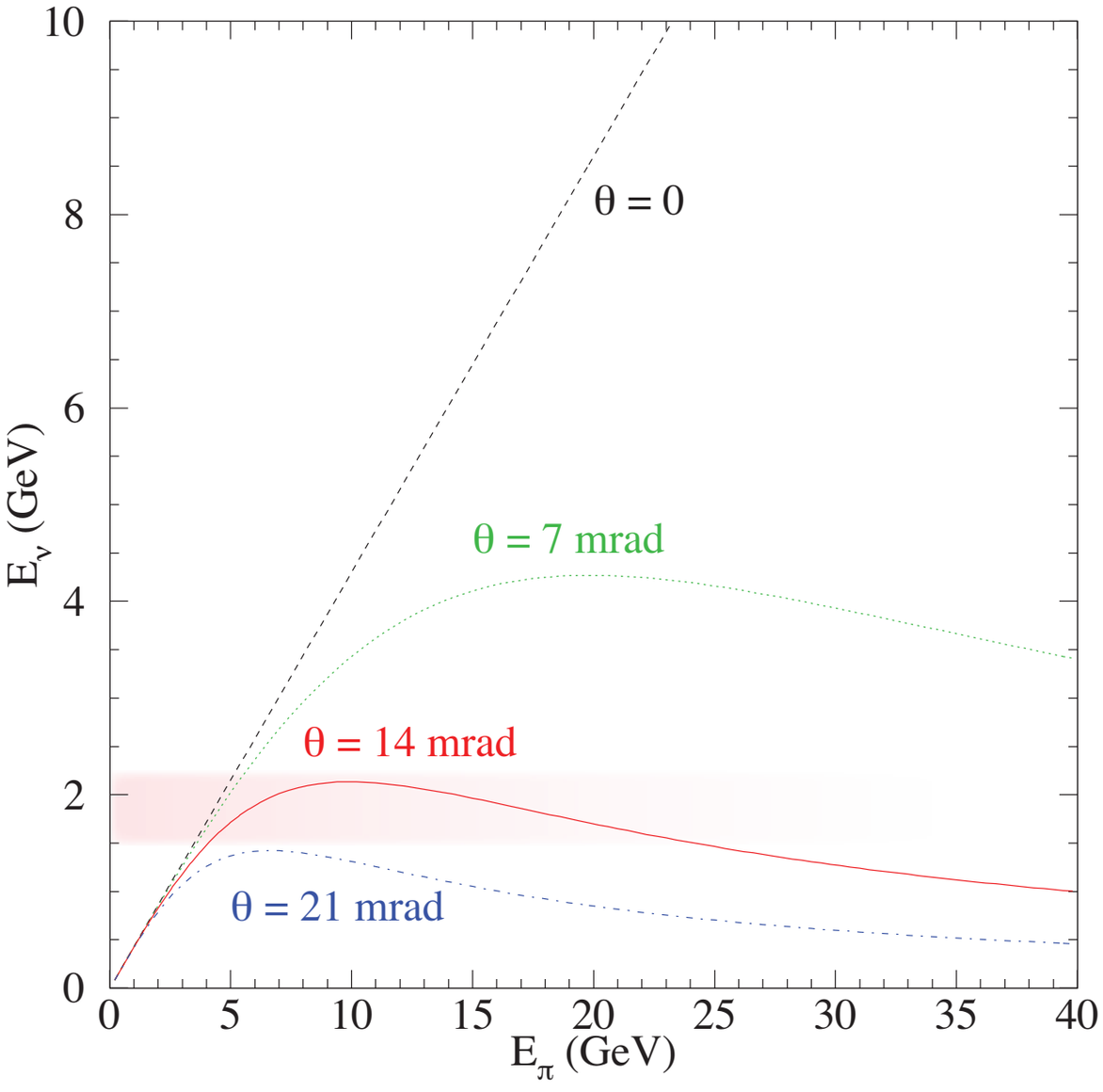
Fermi National Accelerator Laboratory

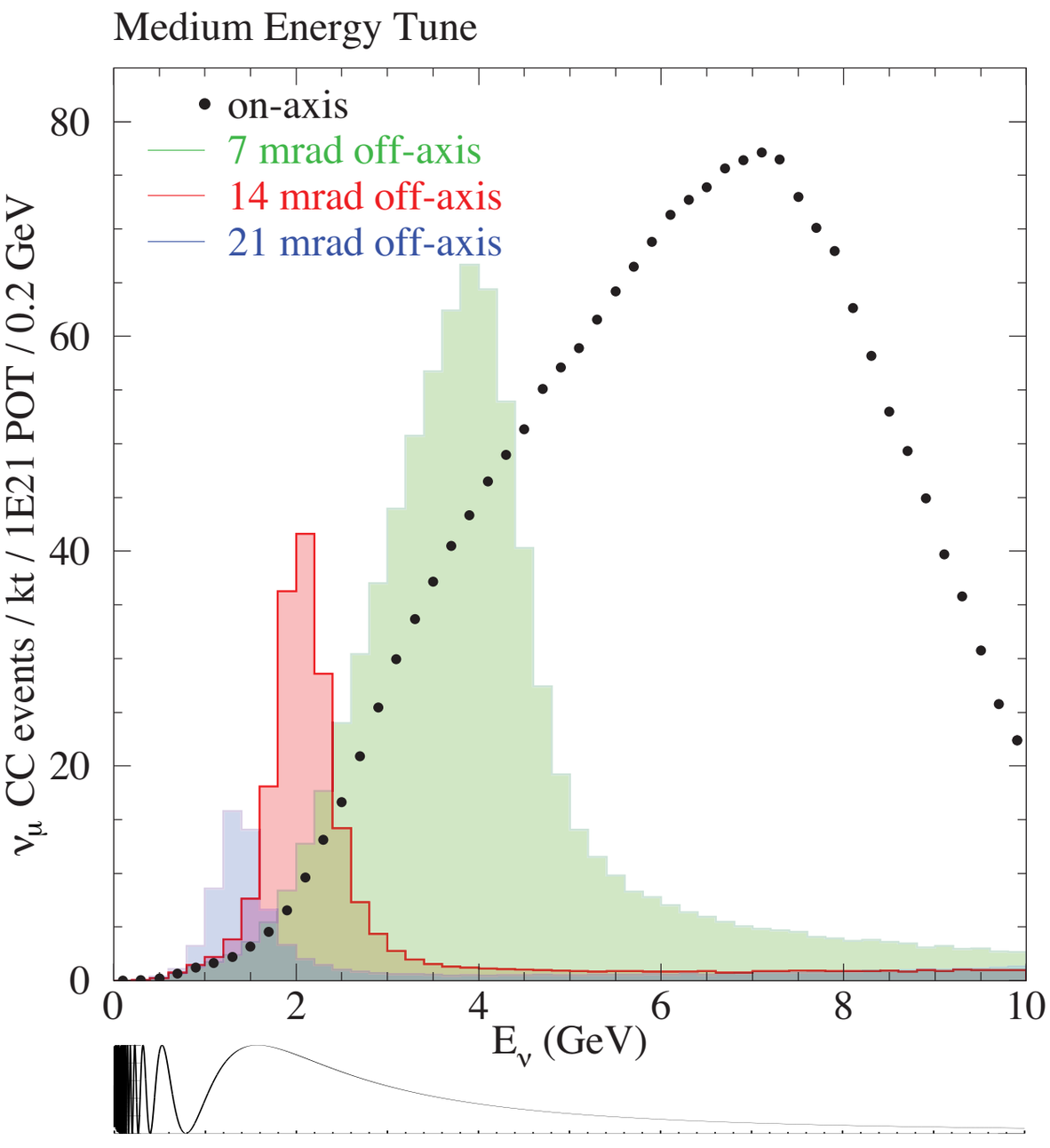
NOvA Data-taking history



Ash River, MN
L = 810 km

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \theta^2_{\mathrm{Lab}}}$$



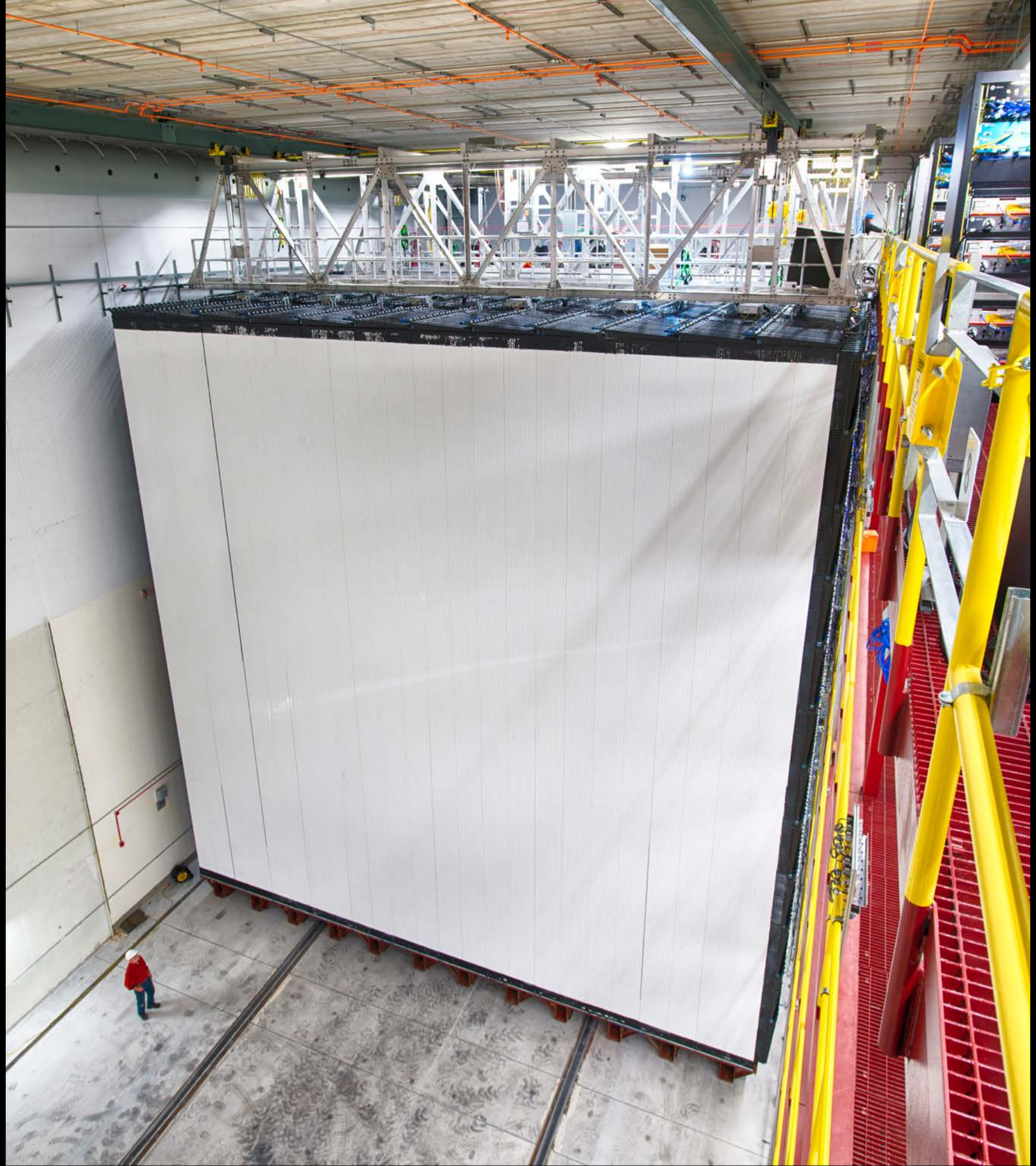


Selecting neutrino energy

Angle is energy

April 2012

344,064 total channels



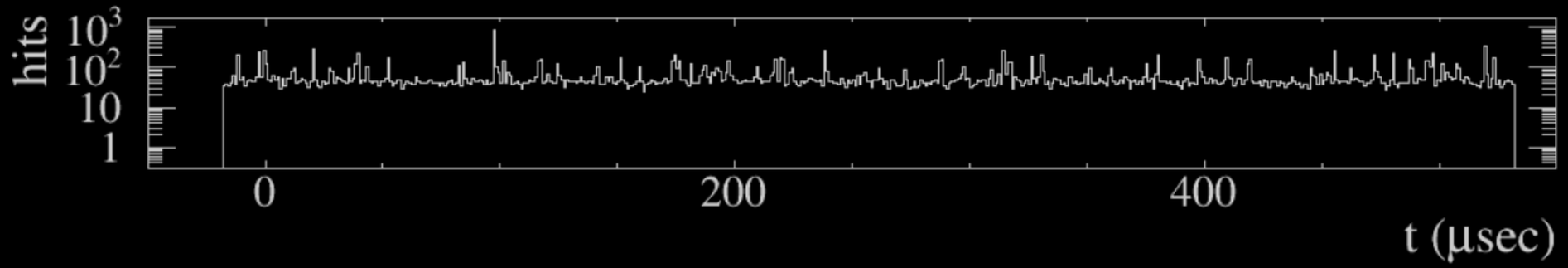
60 m

15.5 m

NOvA - FNAL E929

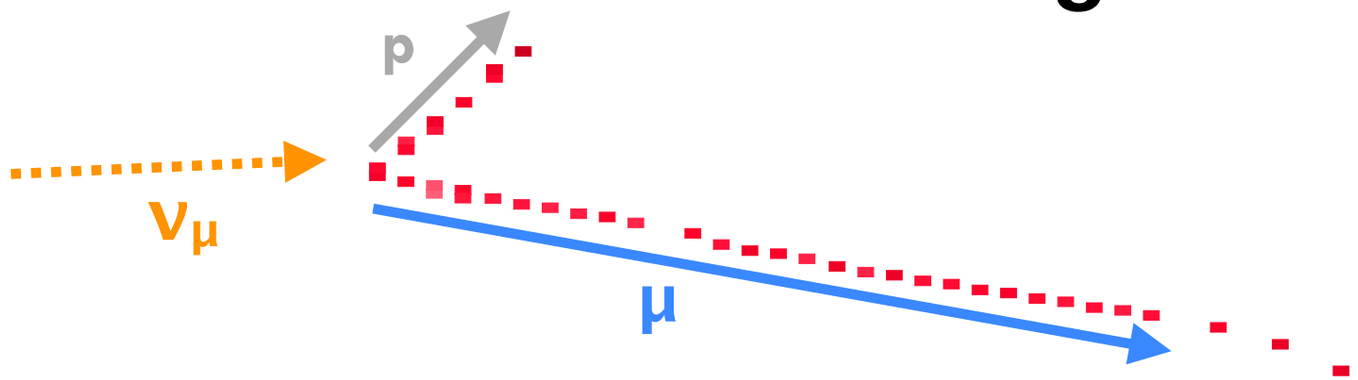
Run: 18605 / 0
Event: 161 / PerCal

UTC Tue Jan 6, 2015
23:25:55.172218000



Charged-current muon neutrino

Is θ_{23} maximal?

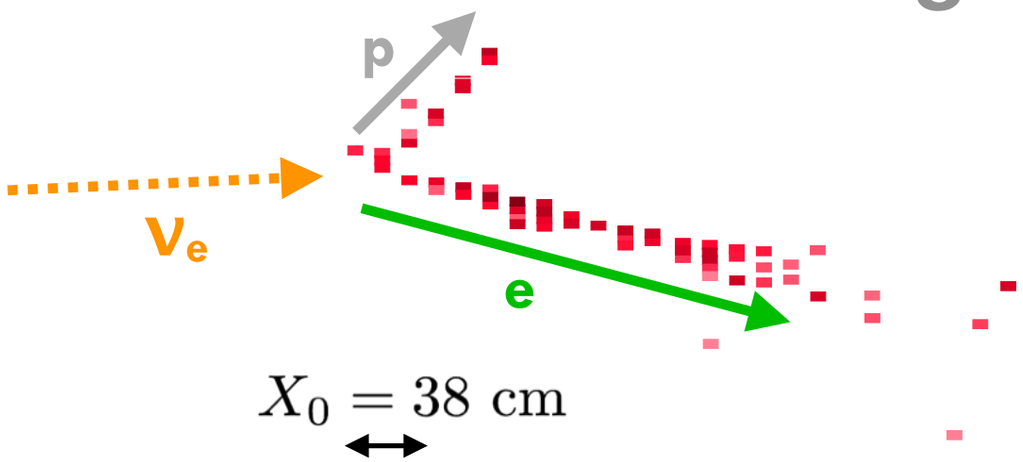


Charged-current electron neutrino

What is the neutrino mass hierarchy?

What octant contains θ_{23}?

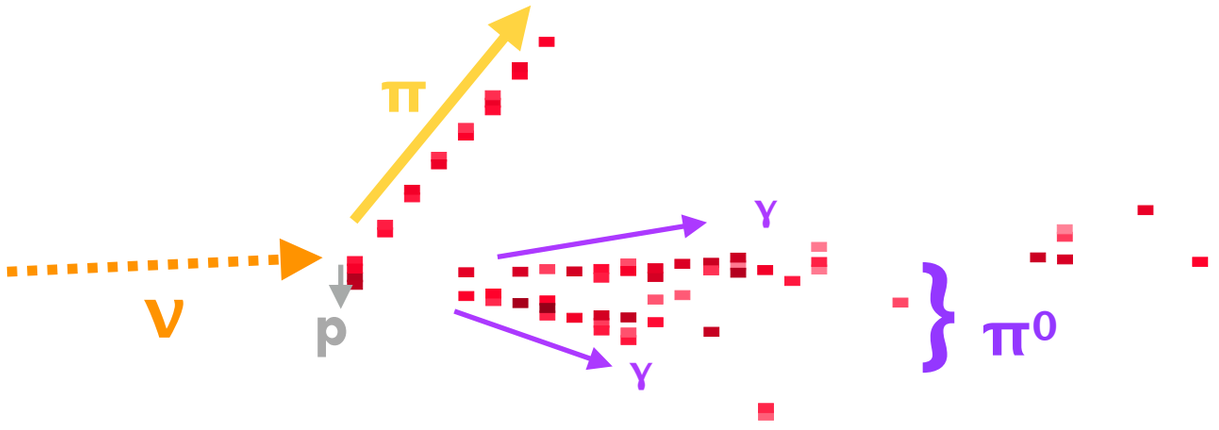
What values of δ_{CP} are allowed?

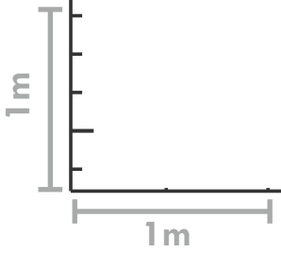


Neutral-current

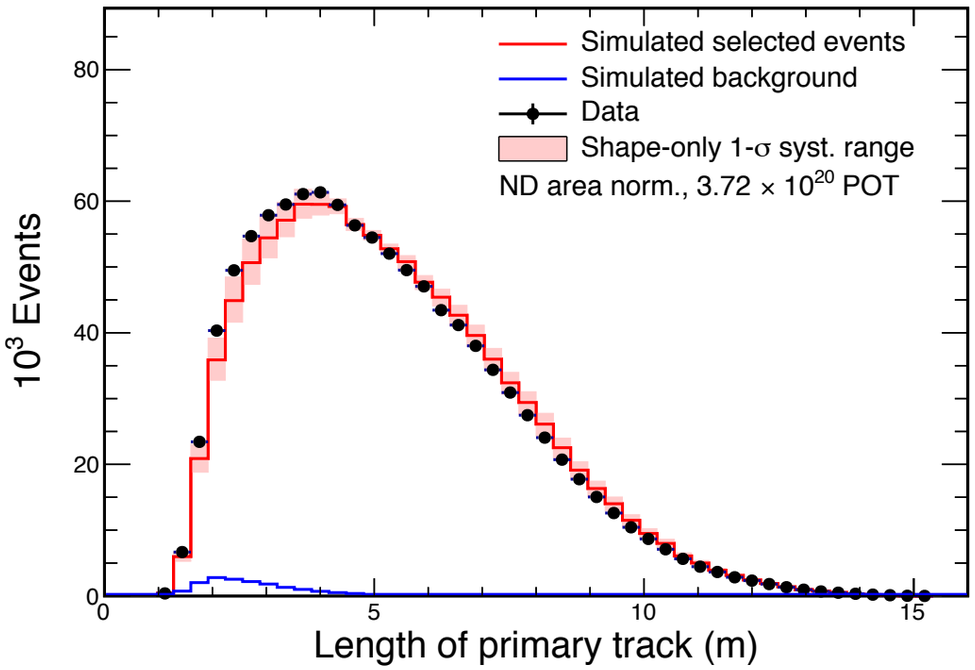
Does the standard picture hold?

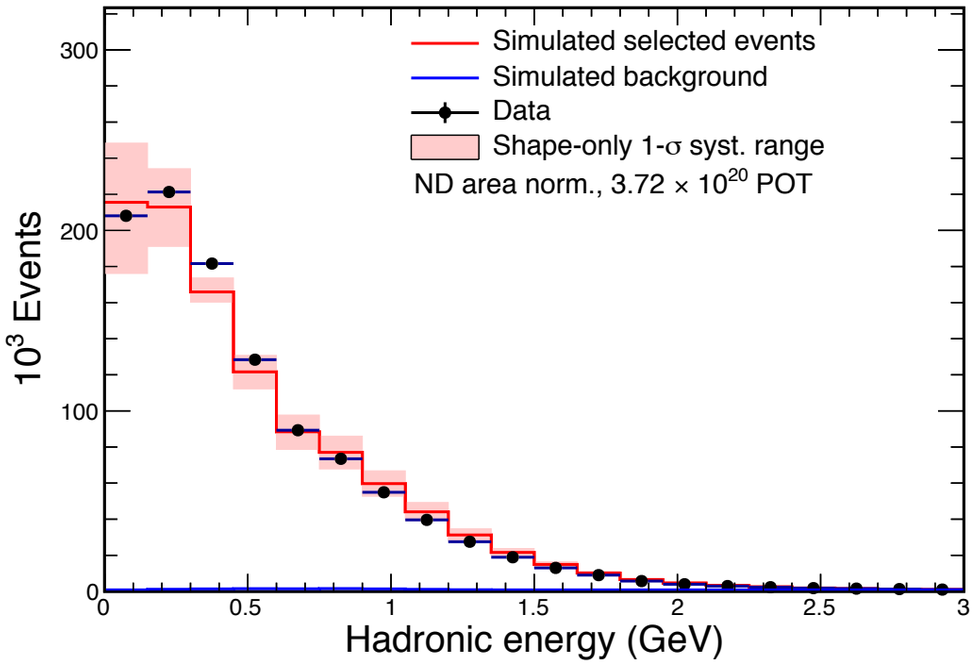
Are there sterile neutrinos?



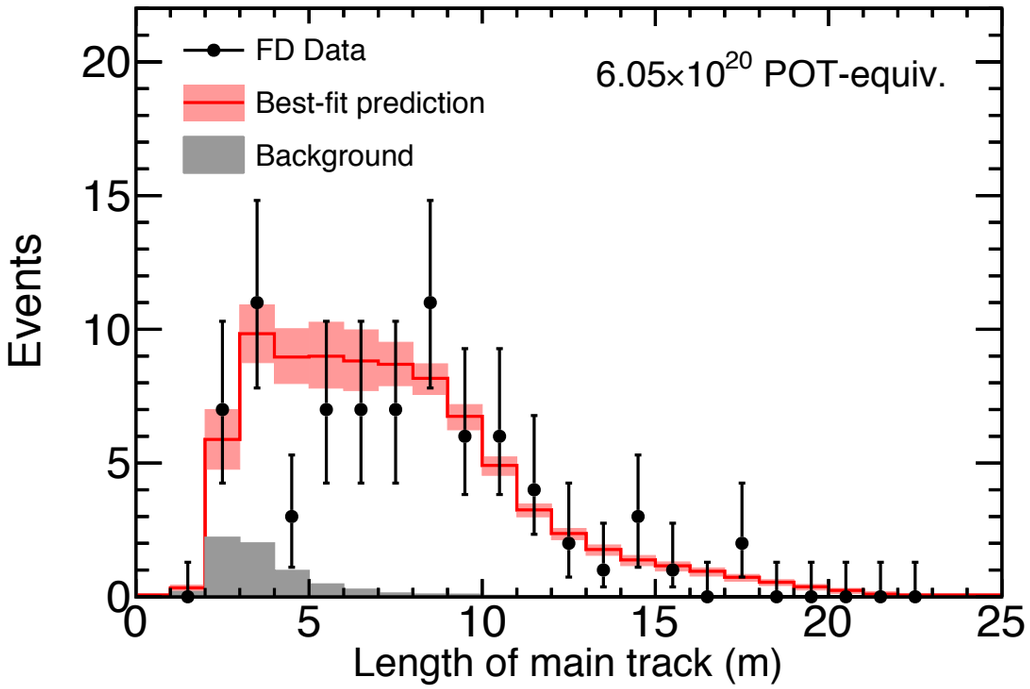


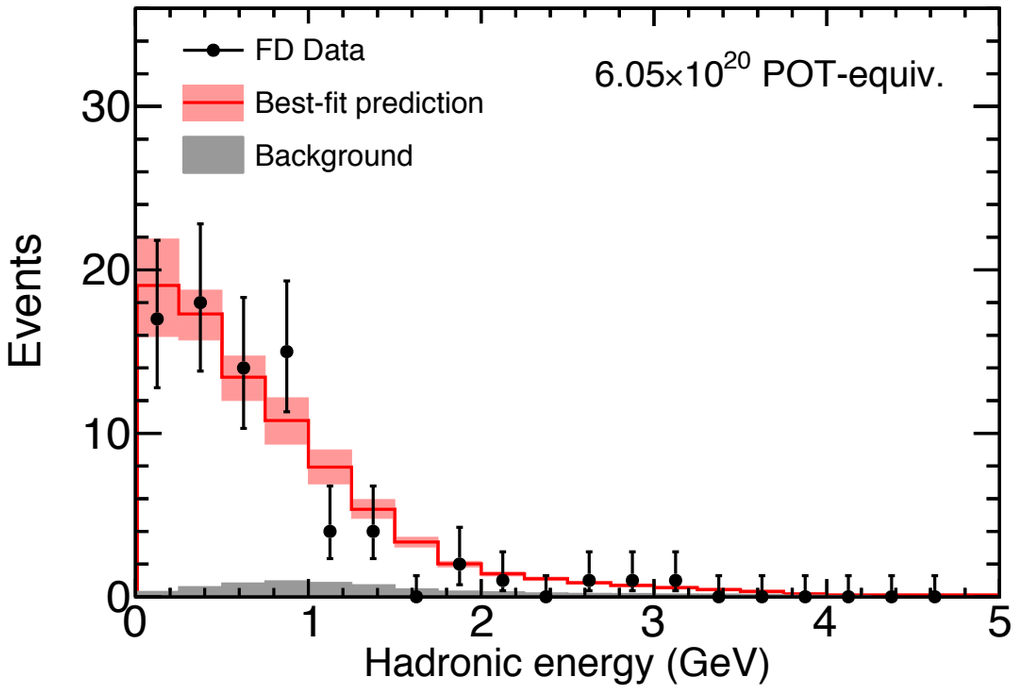
ND:





FD:

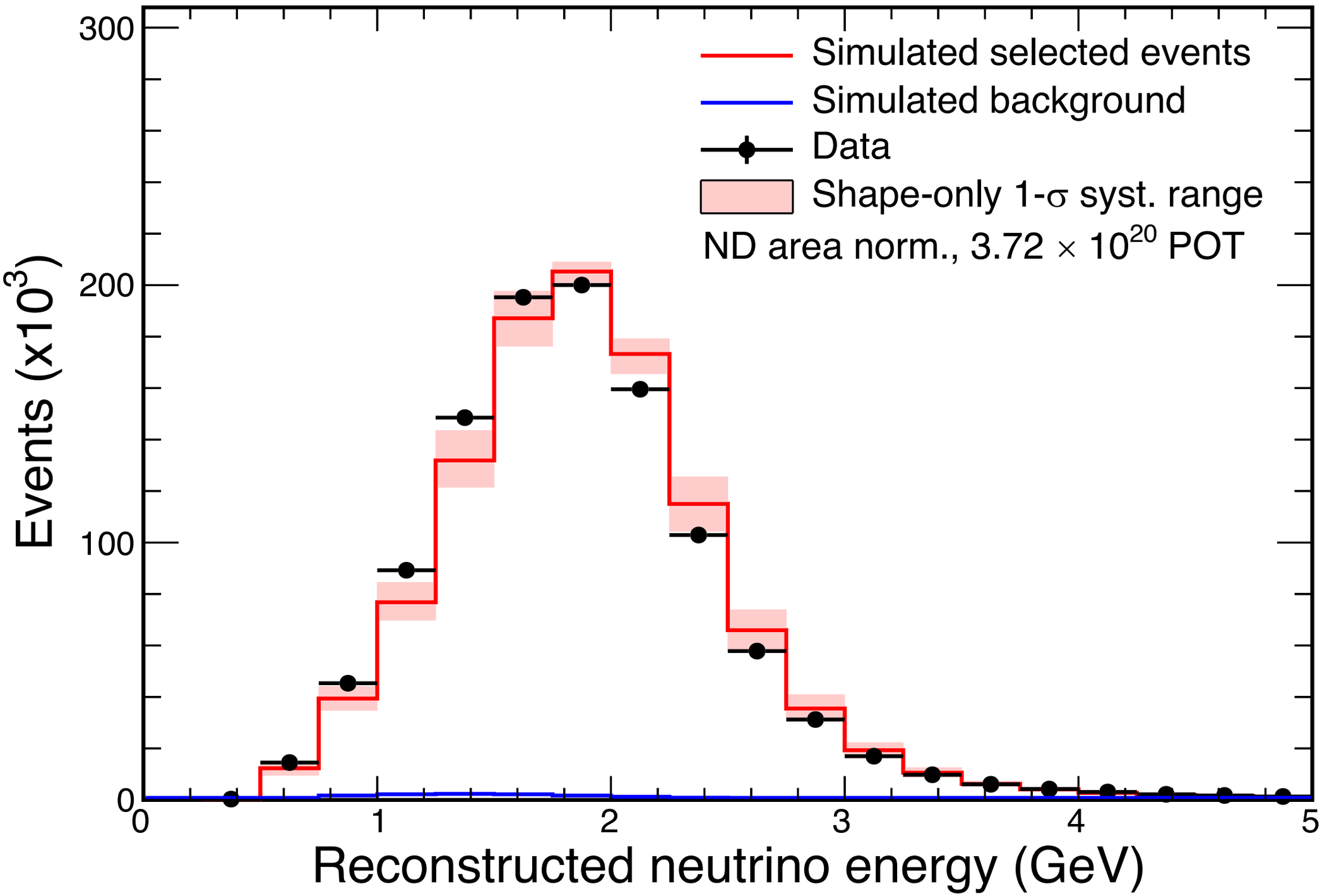




Muon neutrino energy reconstruction

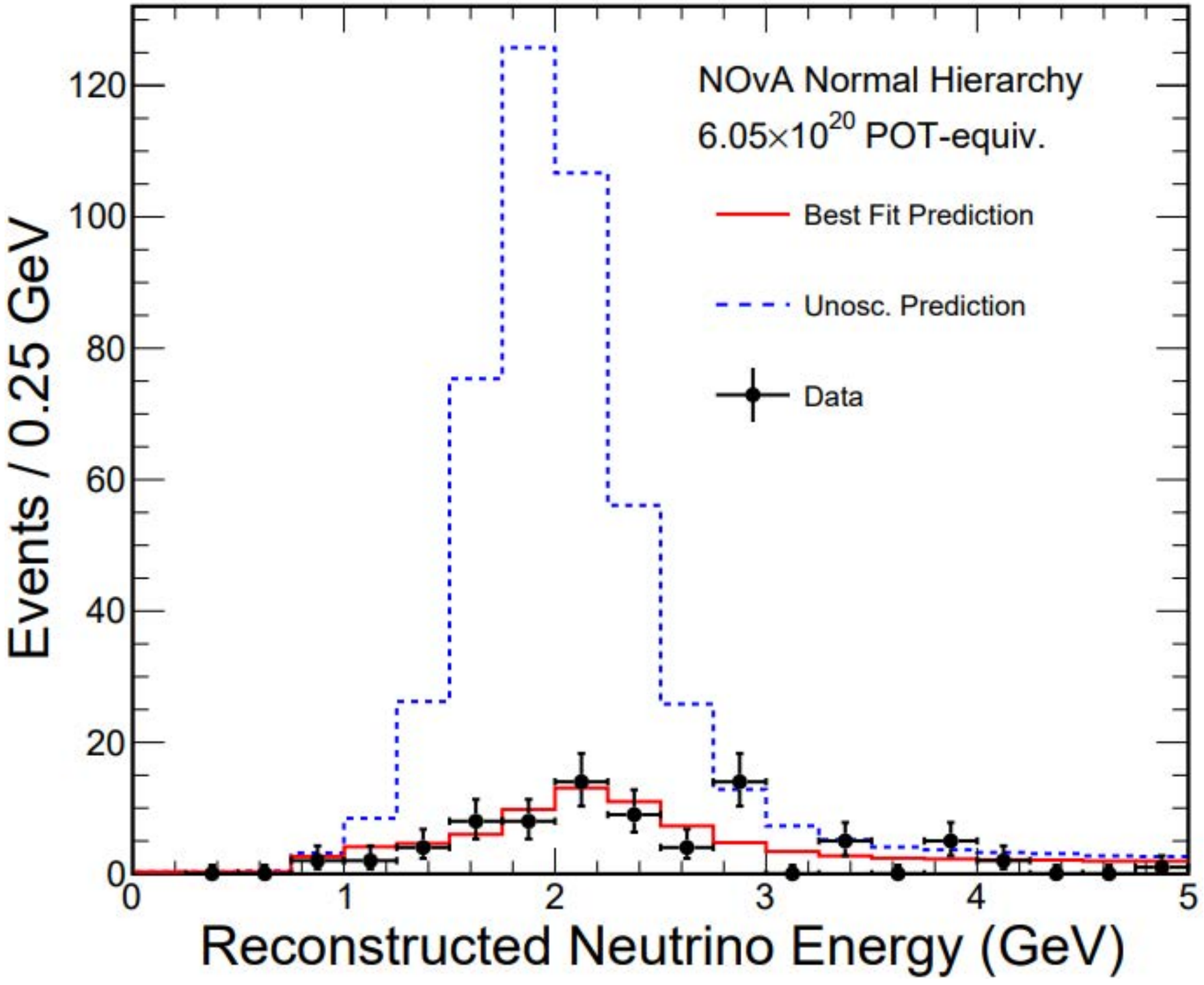
Track length + hadronic energy

3.2% muon energy resolution
28% hadronic energy resolution
7% neutrino energy resolution



NOvA Near detector muon neutrino spectrum

1.1 million contained muon neutrino events



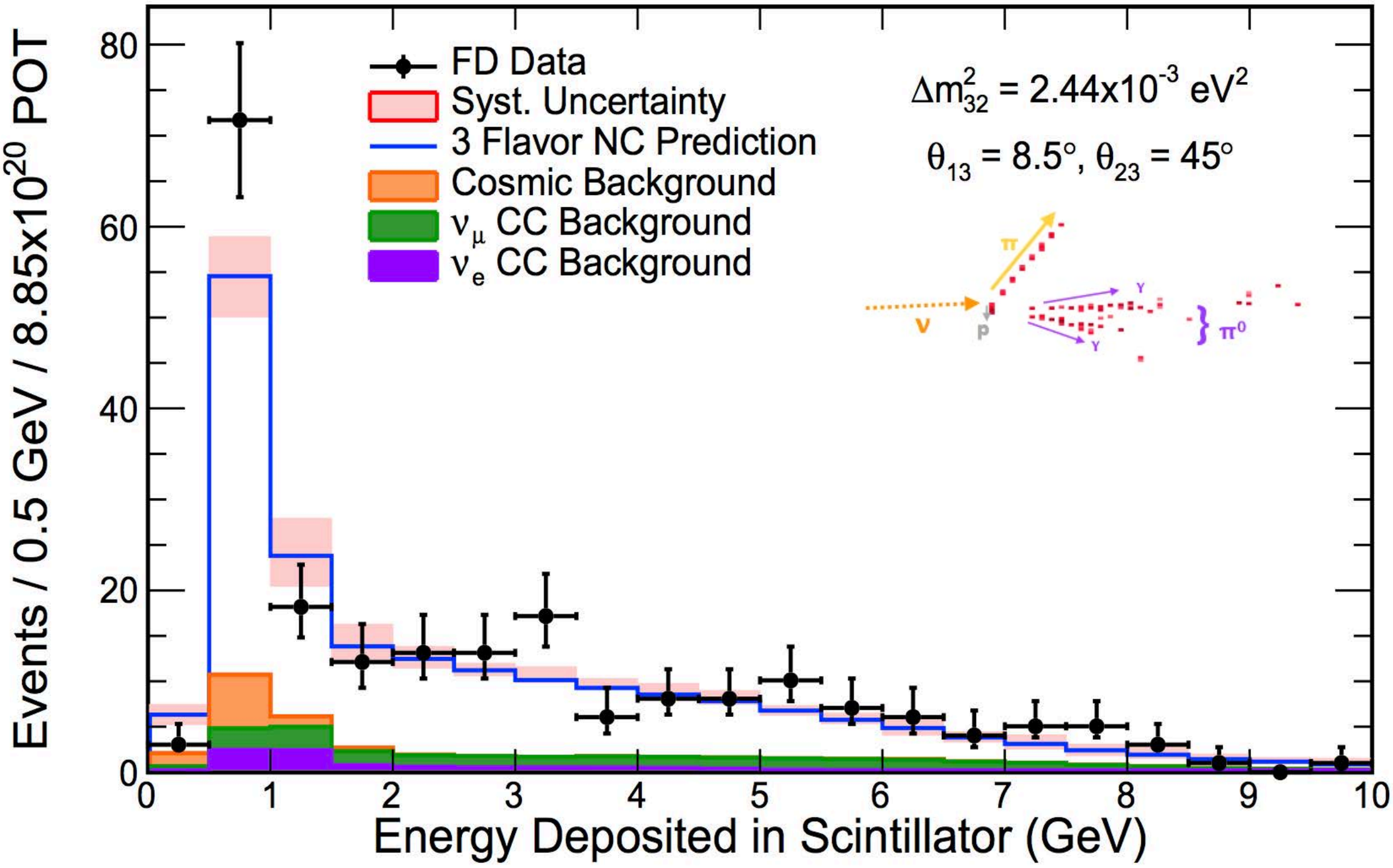
NOvA Far detector muon neutrino spectrum

473 events expected before oscillations

78 events observed

P. Adamson *et al.* (The NOvA Collaboration)
Phys. Rev. D **96**, 072006 – Published 30 October 2017

NOvA Preliminary



Neutral-Current Events at Far Detector

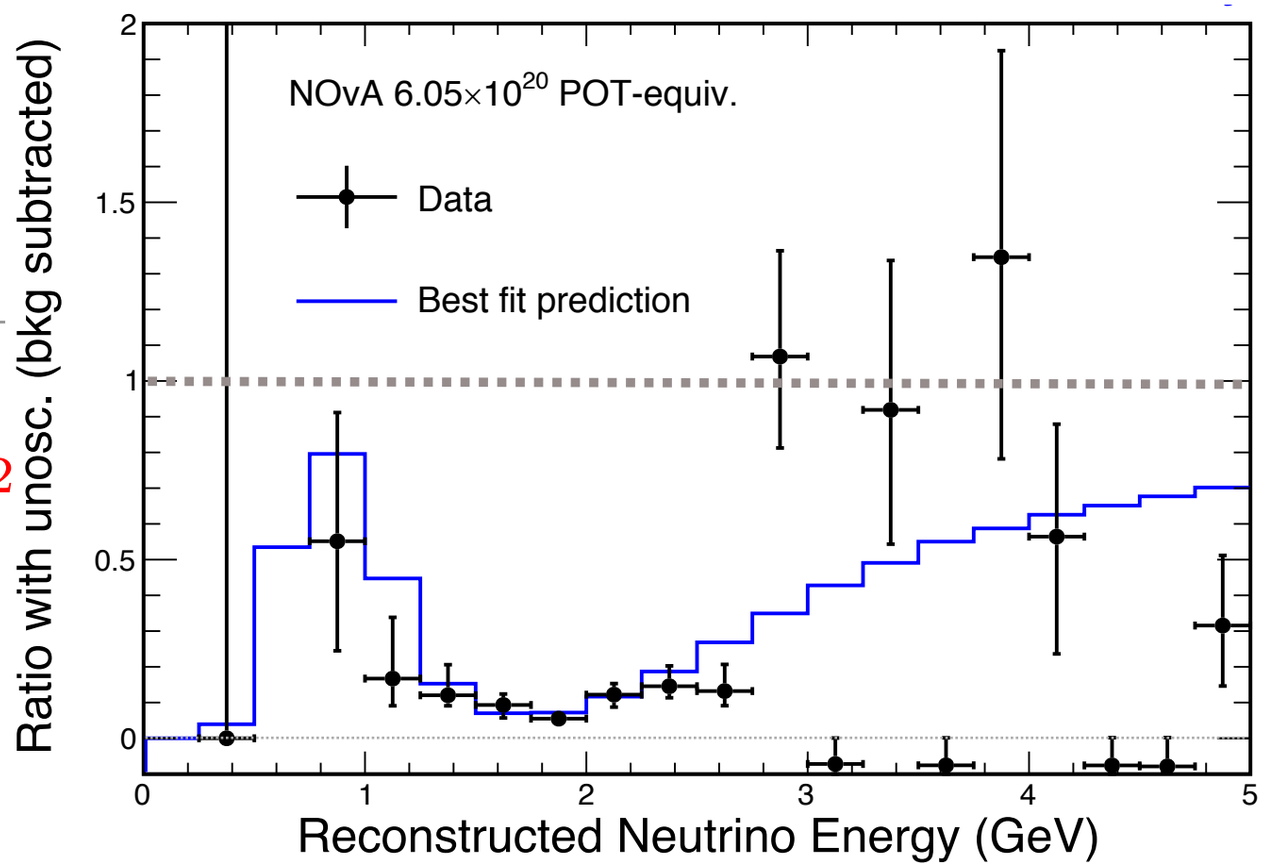
NC events are a way to count the total neutrino flux which should be unaffected by standard oscillations.

Expect: 214 events signal

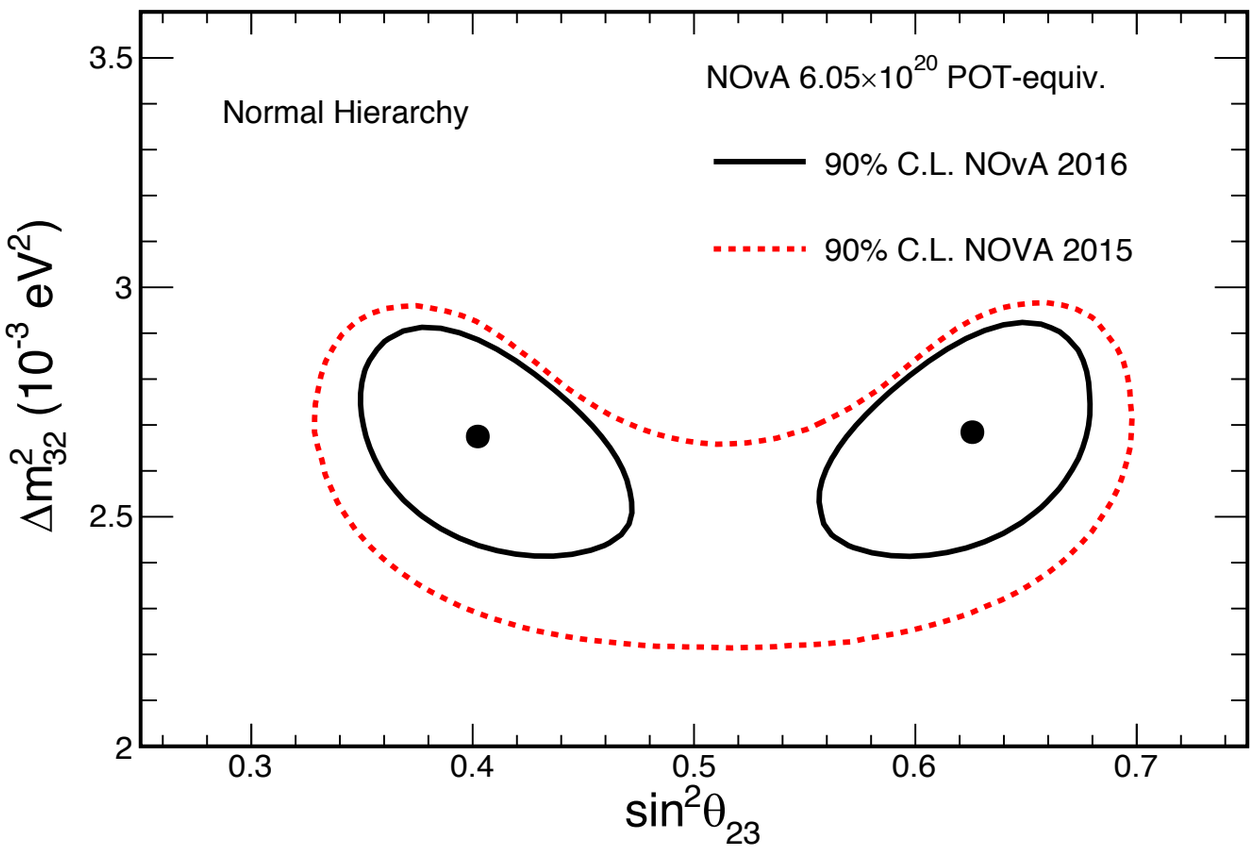
Measure: 191±14 (stat)±22 (syst) events

NOvA
ν_μ Disappearance

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



NOvA Preliminary



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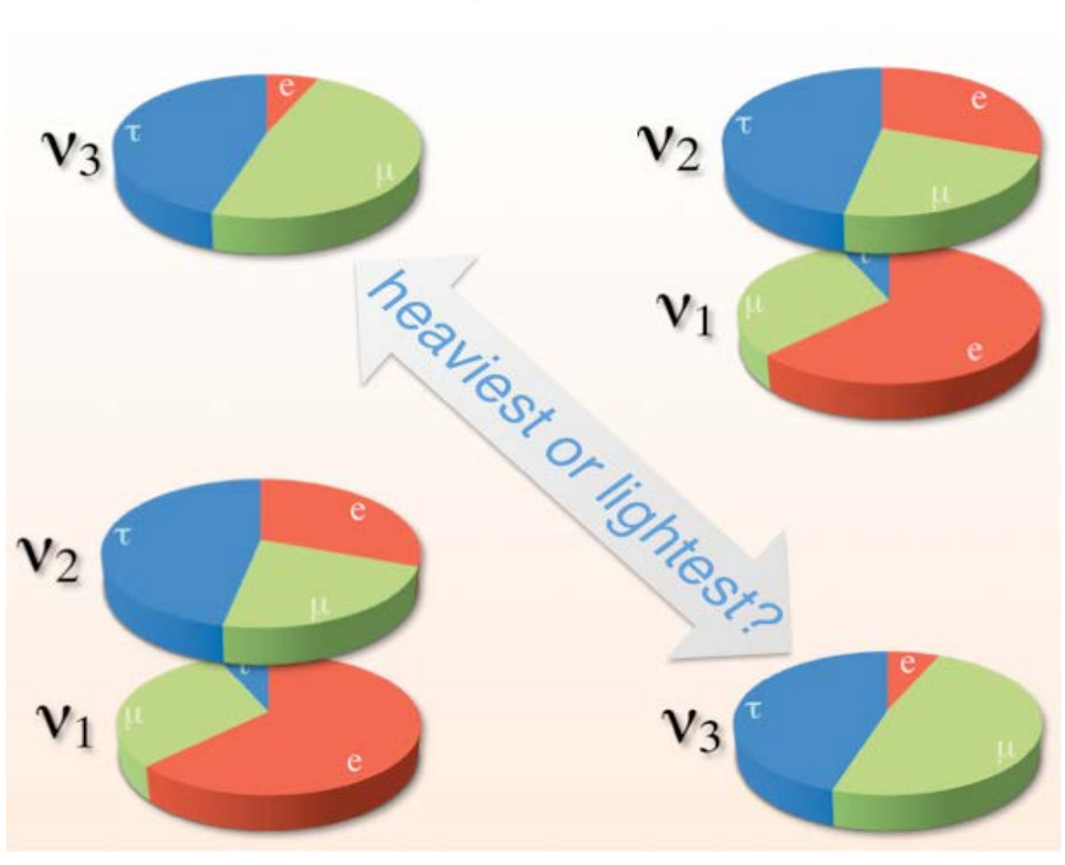
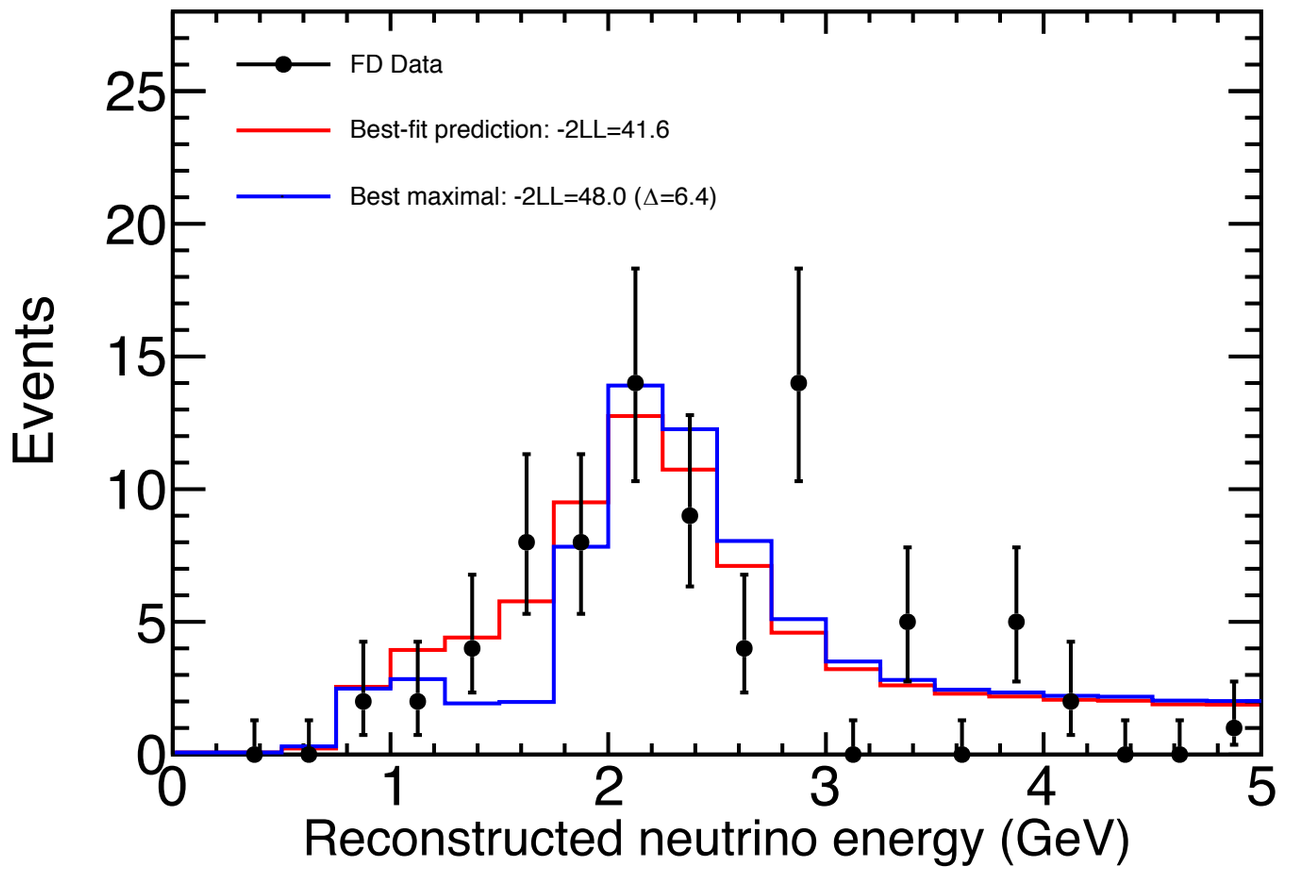
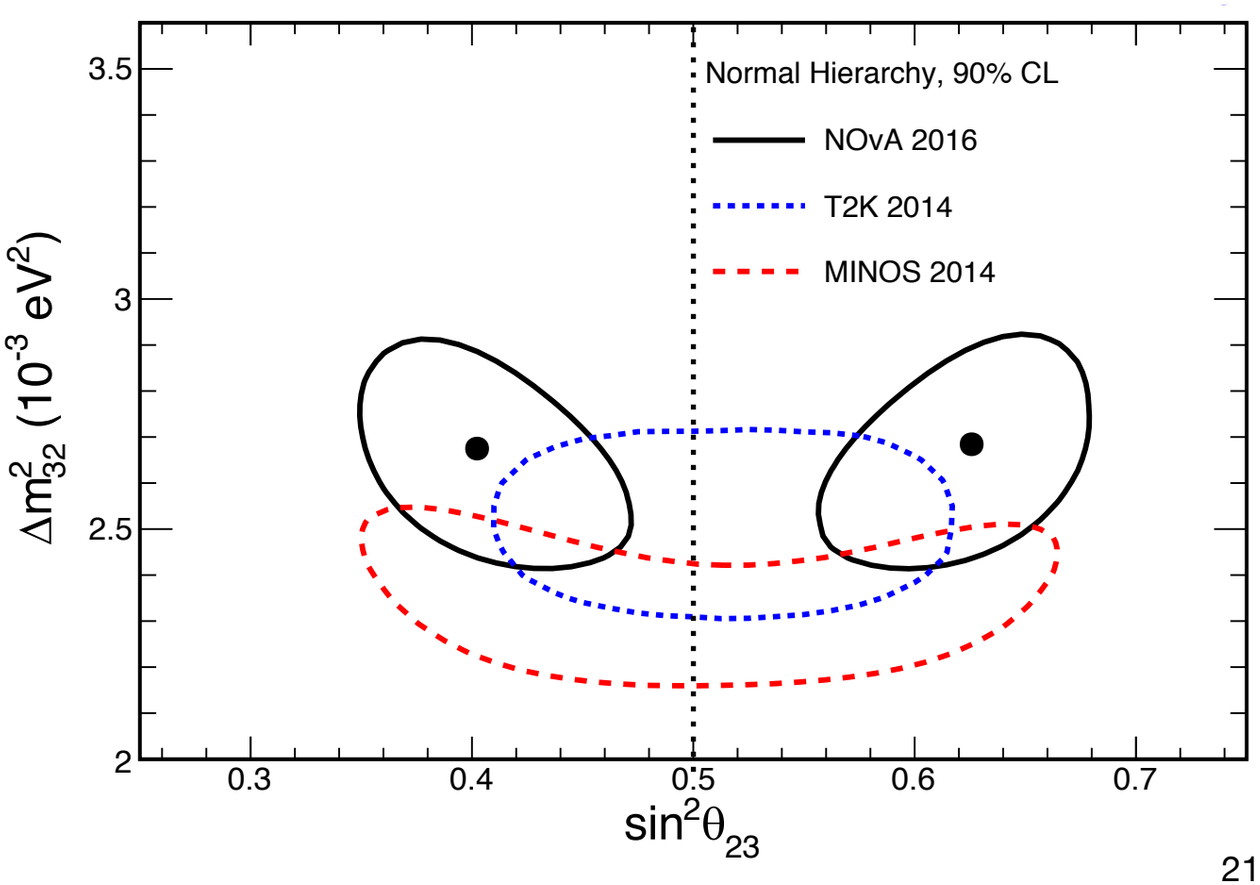
$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\text{eV}$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

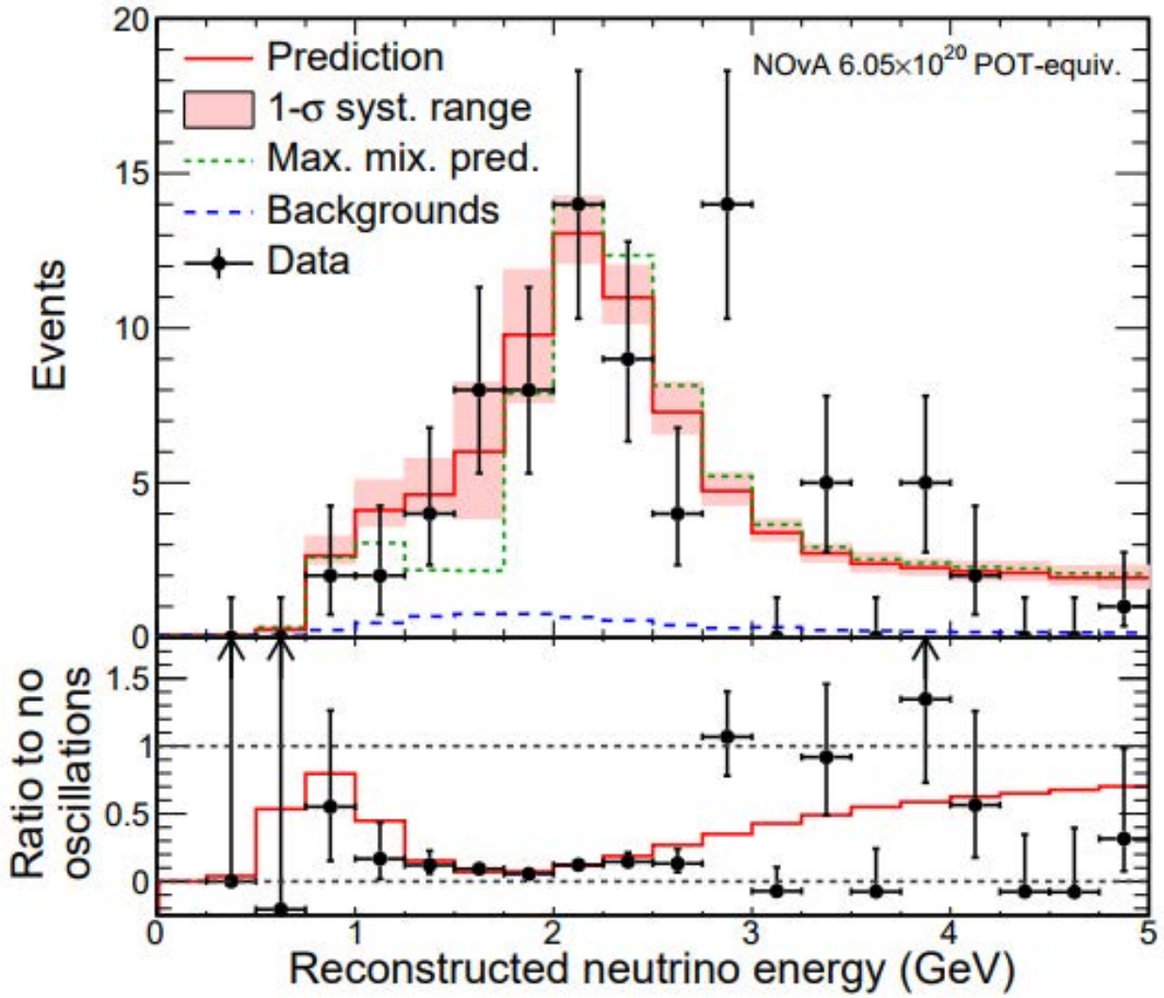
Excludes maximal mixing at 2.6σ



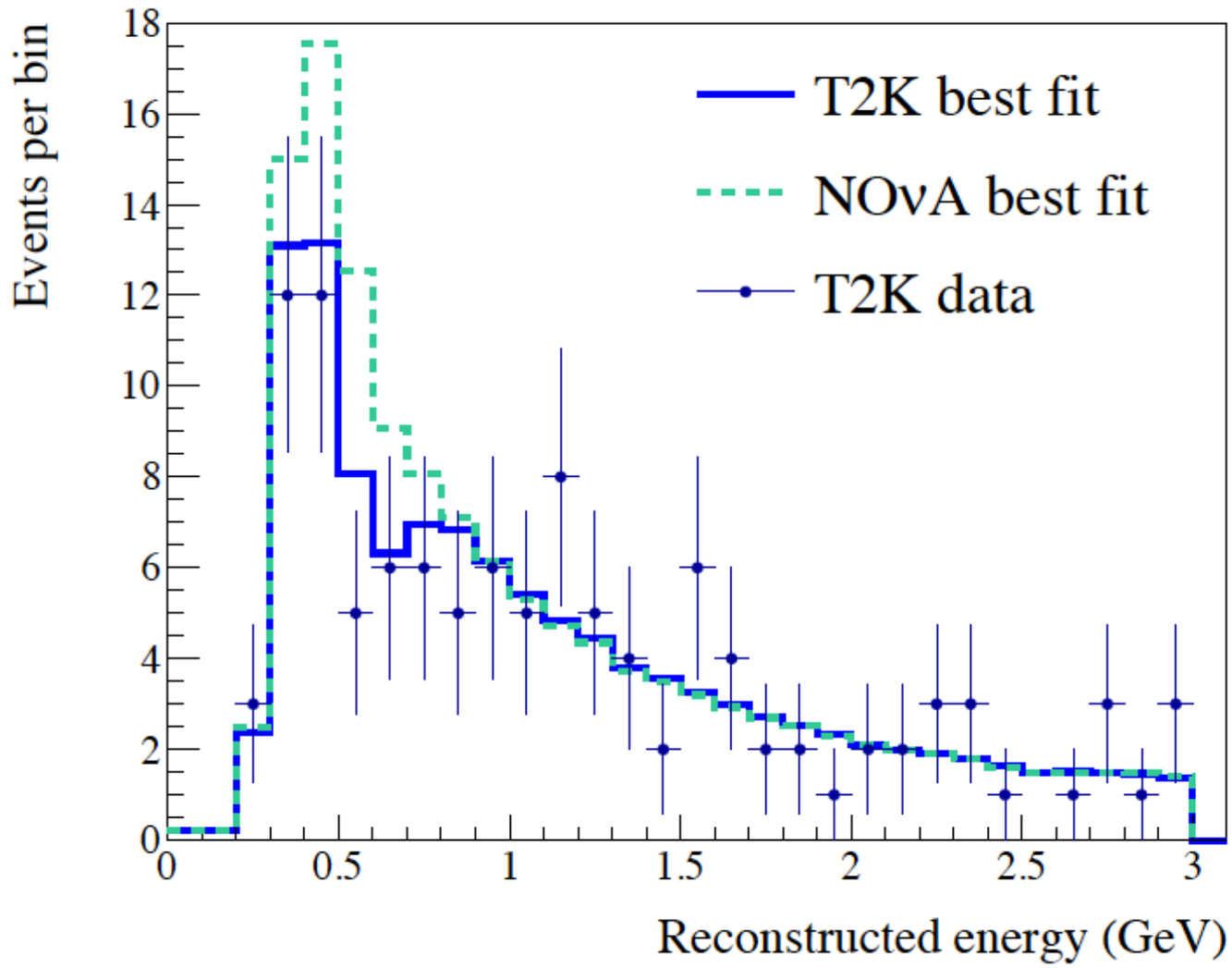




NOvA



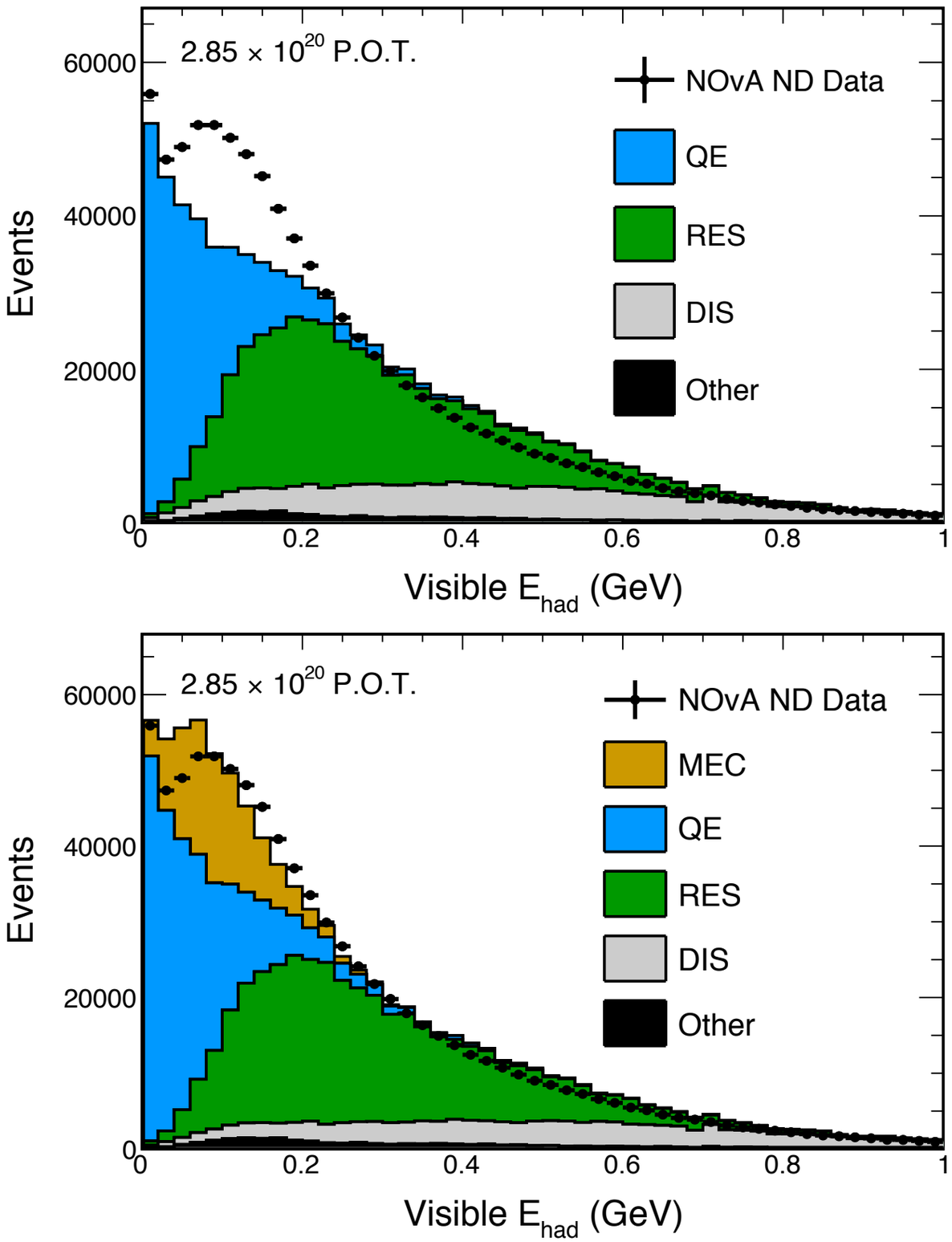
T2K

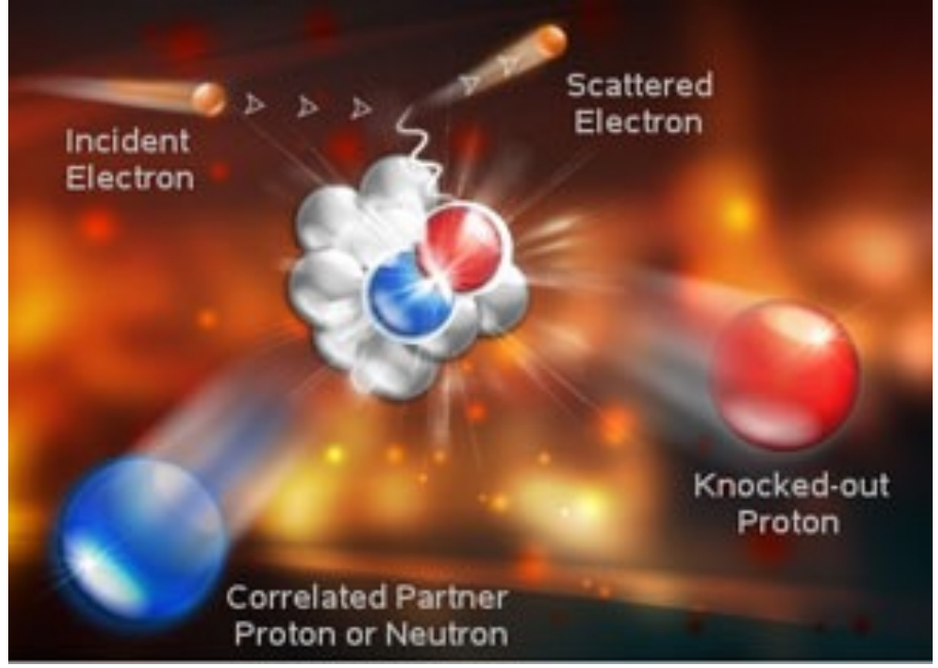


Muon neutrino spectrum side-by-side

Contours overlap at $\sin^2\theta_{23} =$ 0.45 and 0.58 at 90% C.L.

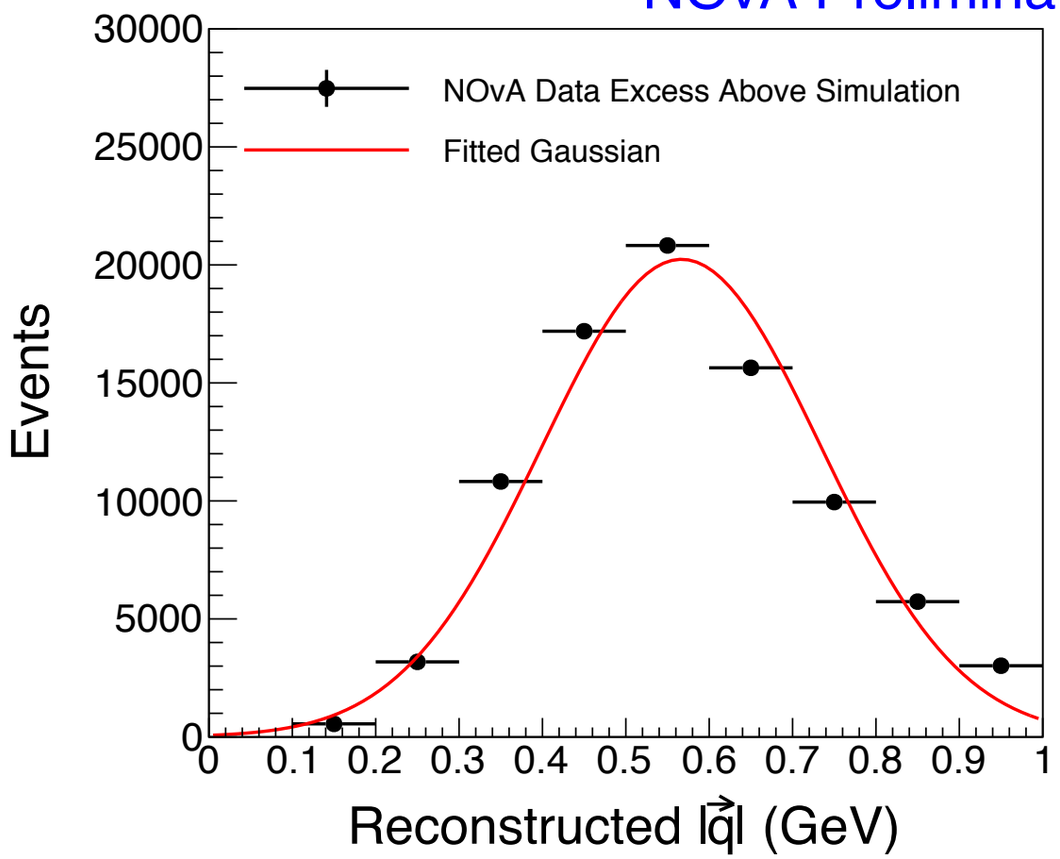
NOvA Preliminary





https://www.jlab.org/highlights/phys.html

NOvA Preliminary



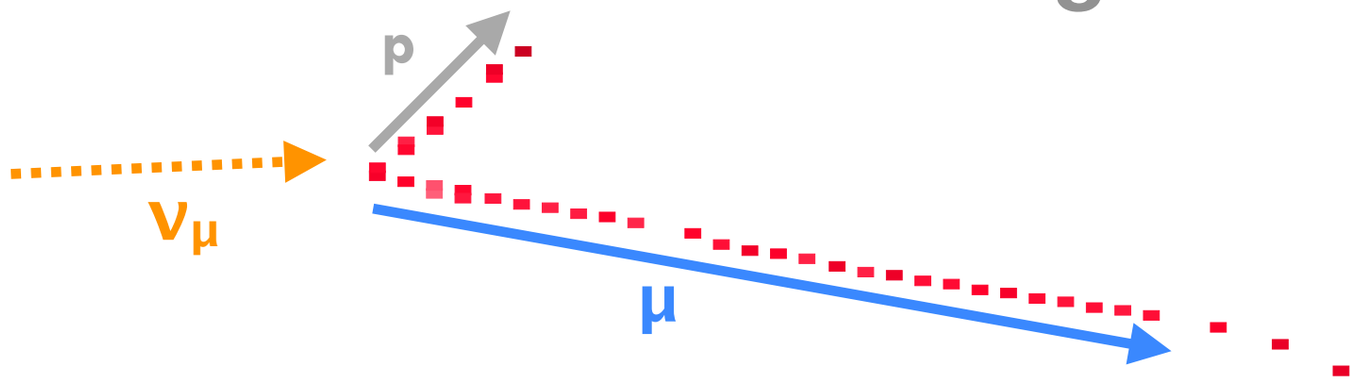
Hadronic energy

First muon neutrino analysis

Absorbed a 14% uncertainty in the hadron energy scale due to mis match at near detector

Charged-current muon neutrino

Is θ_{23} maximal?



Charged-current electron neutrino

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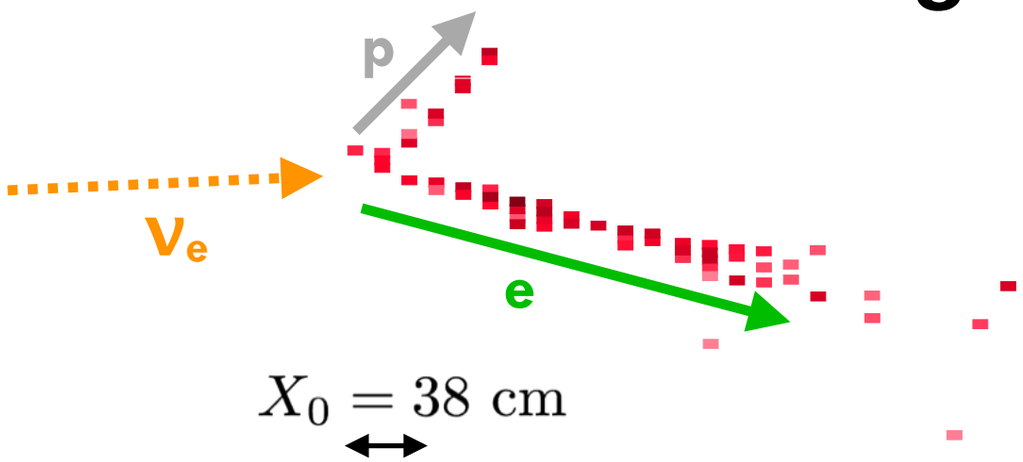
What octant contains θ_{23}?

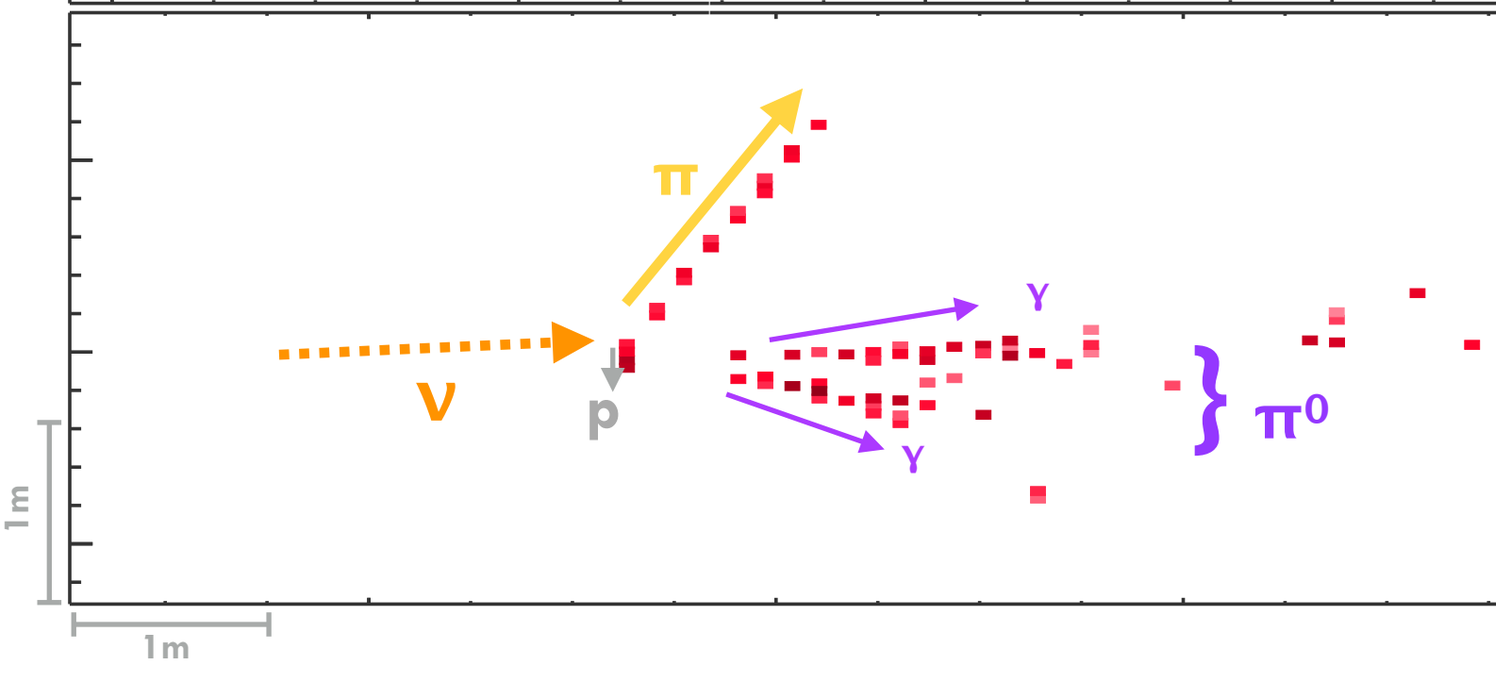
What values of δ_{CP} are allowed?



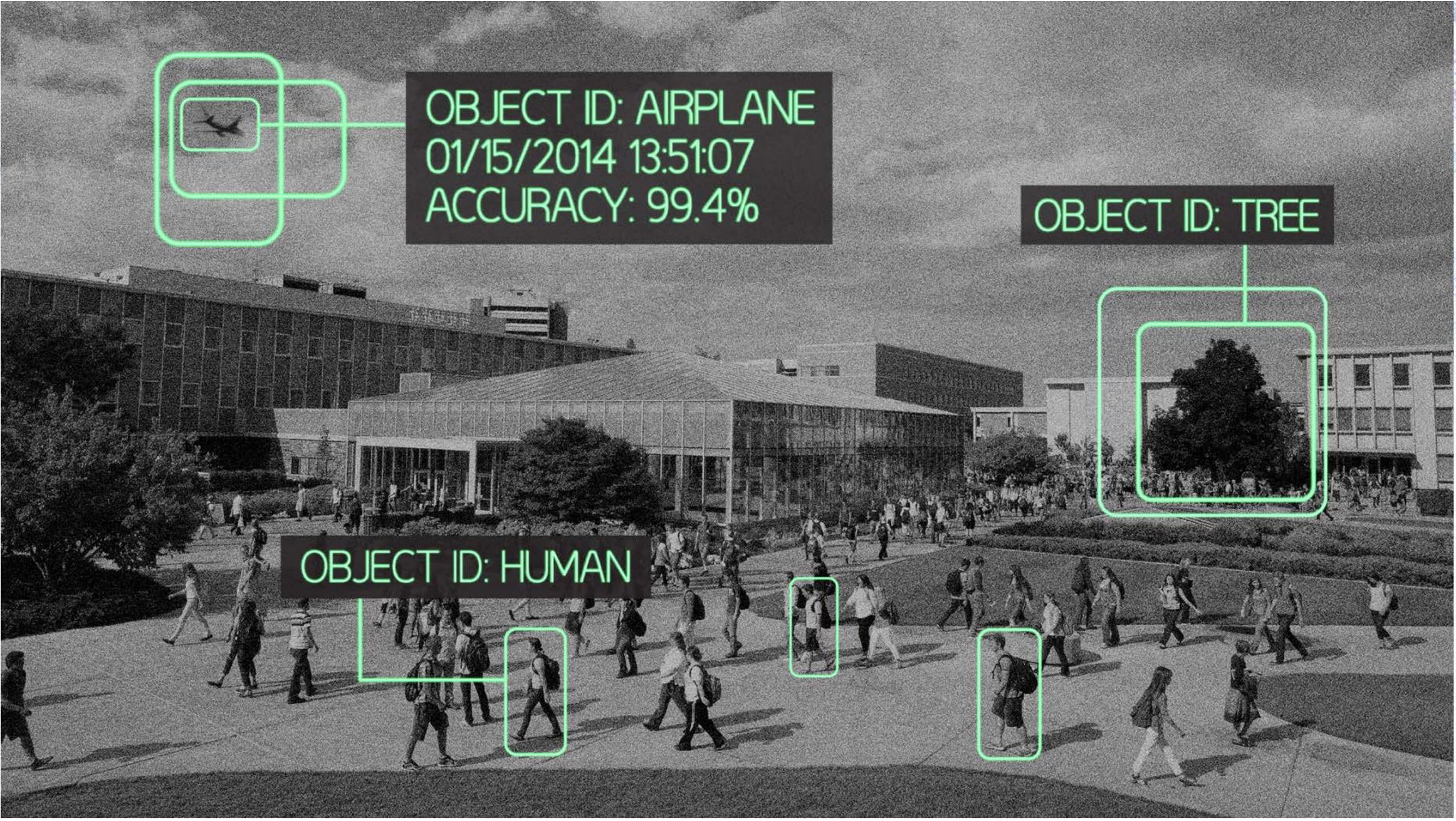
Neutral-current

Does the standard picture hold?

Are there sterile neutrinos?



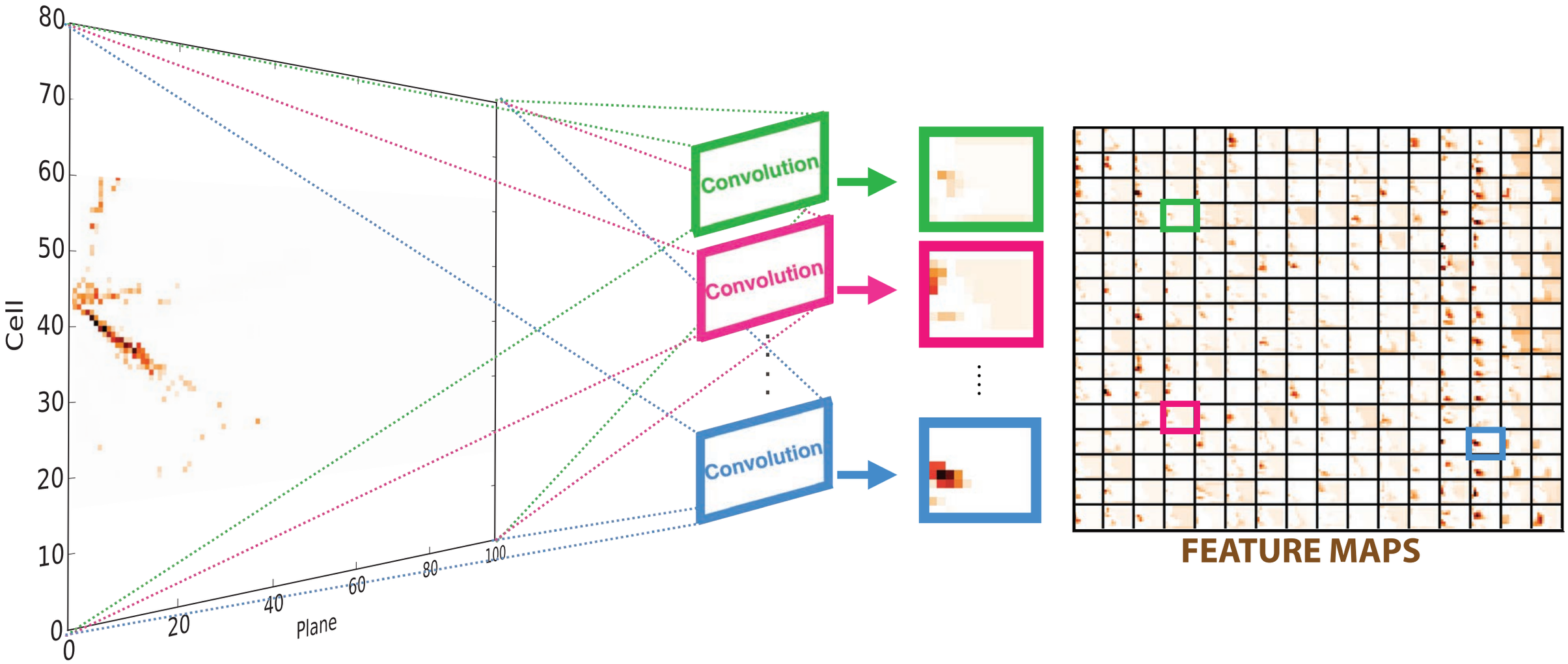
10 10^2 10^3 q (ADC)



ν_e Event Identification in NOvA

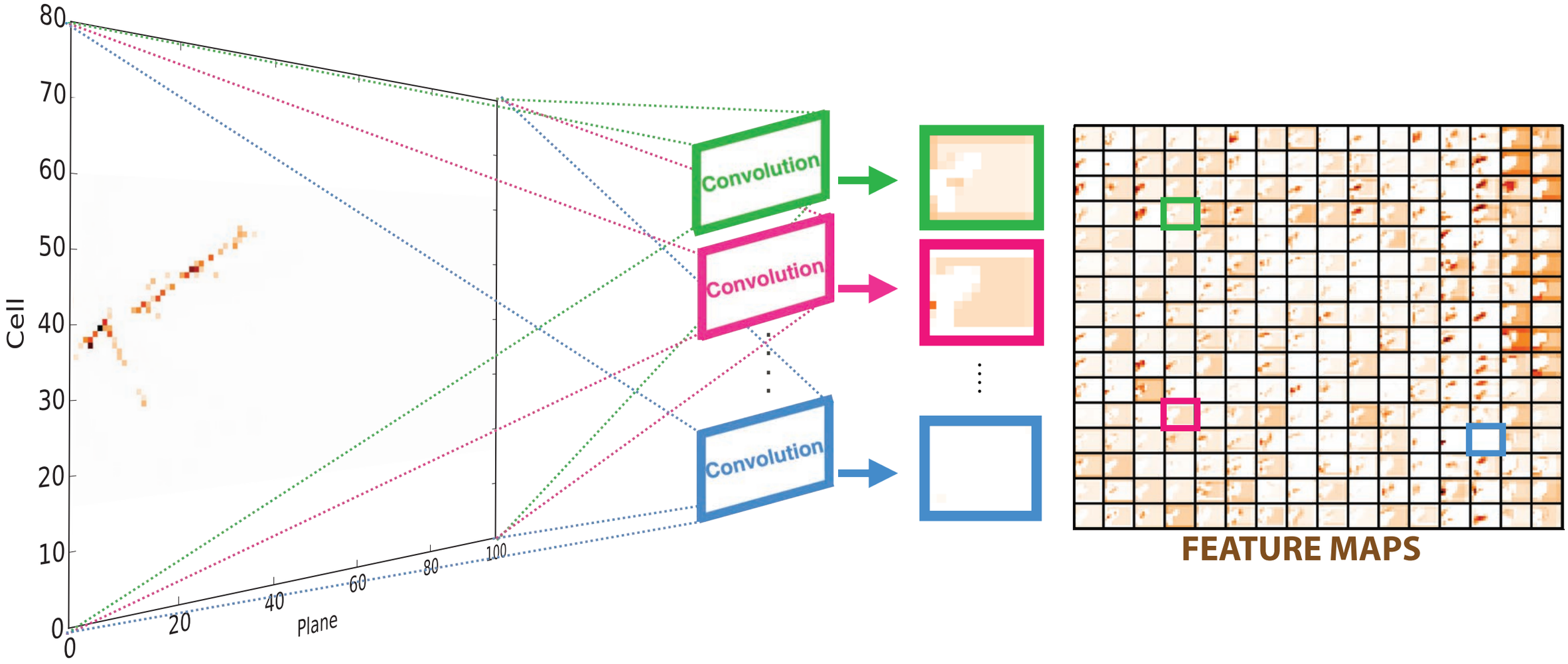
Borrow ideas from Computer Vision: Convolutional Neural Networks and Deep Learning

ν_e Identification in NOvA



ELECTRON NEUTRINO

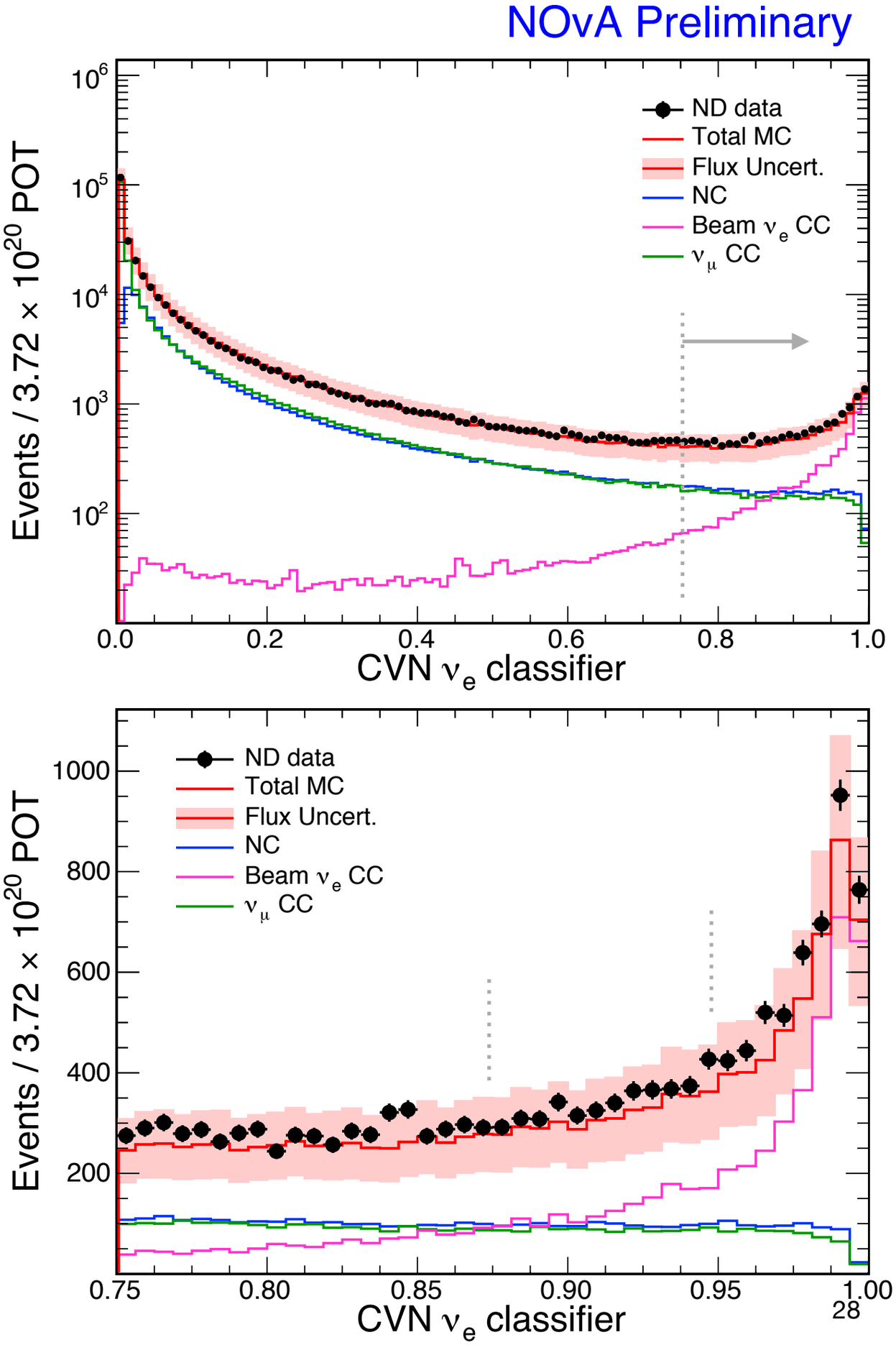
ν_e Identification in NOvA



NEUTRAL CURRENT

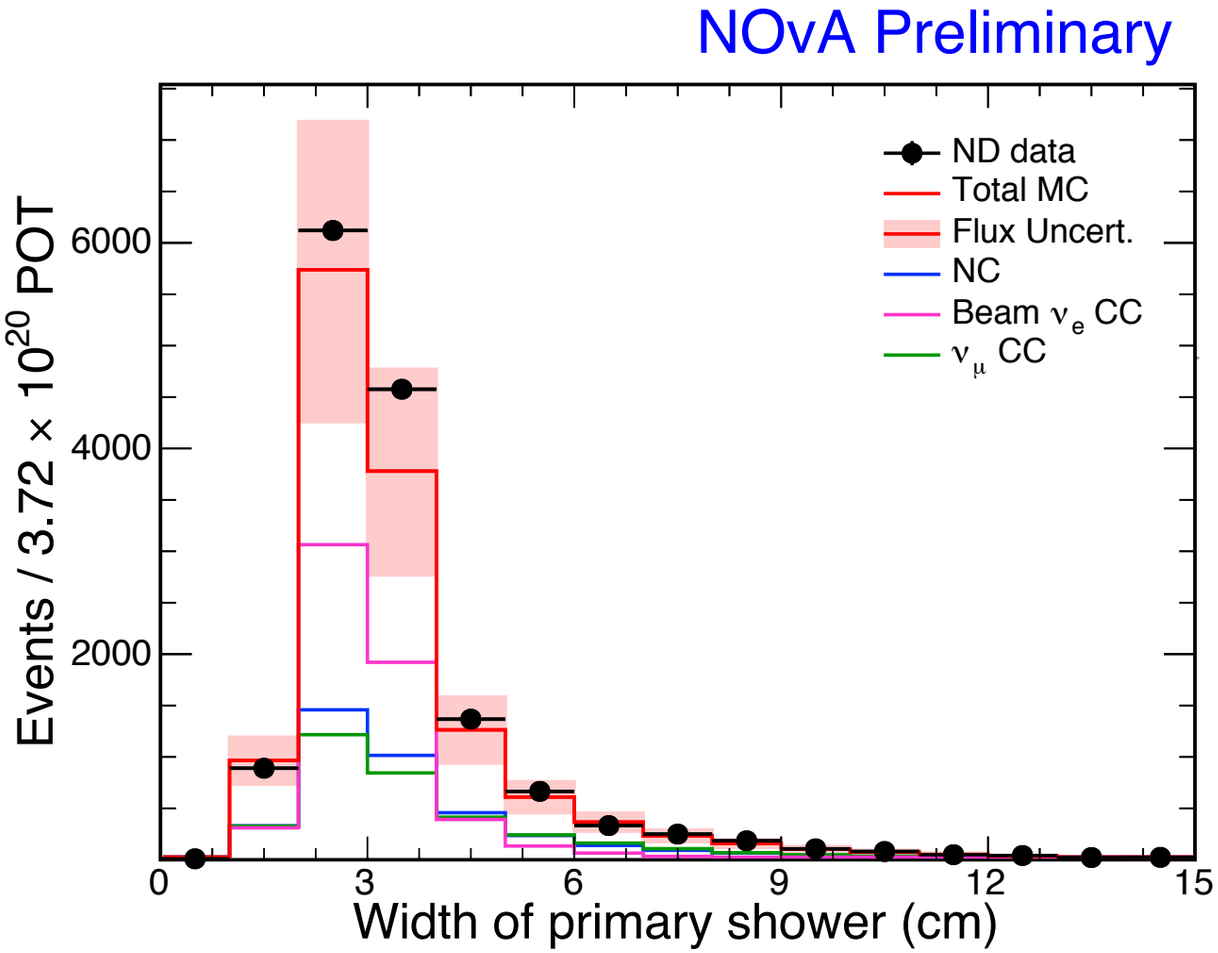
CVN Identifier on Near Detector Data

- CVN selects 73% of pre-selected electron-neutrino charged current events
- Produces a 76% pure sample of electron-neutrino CC events
- Improved S/N worth 30% more exposure over techniques used in our first analysis

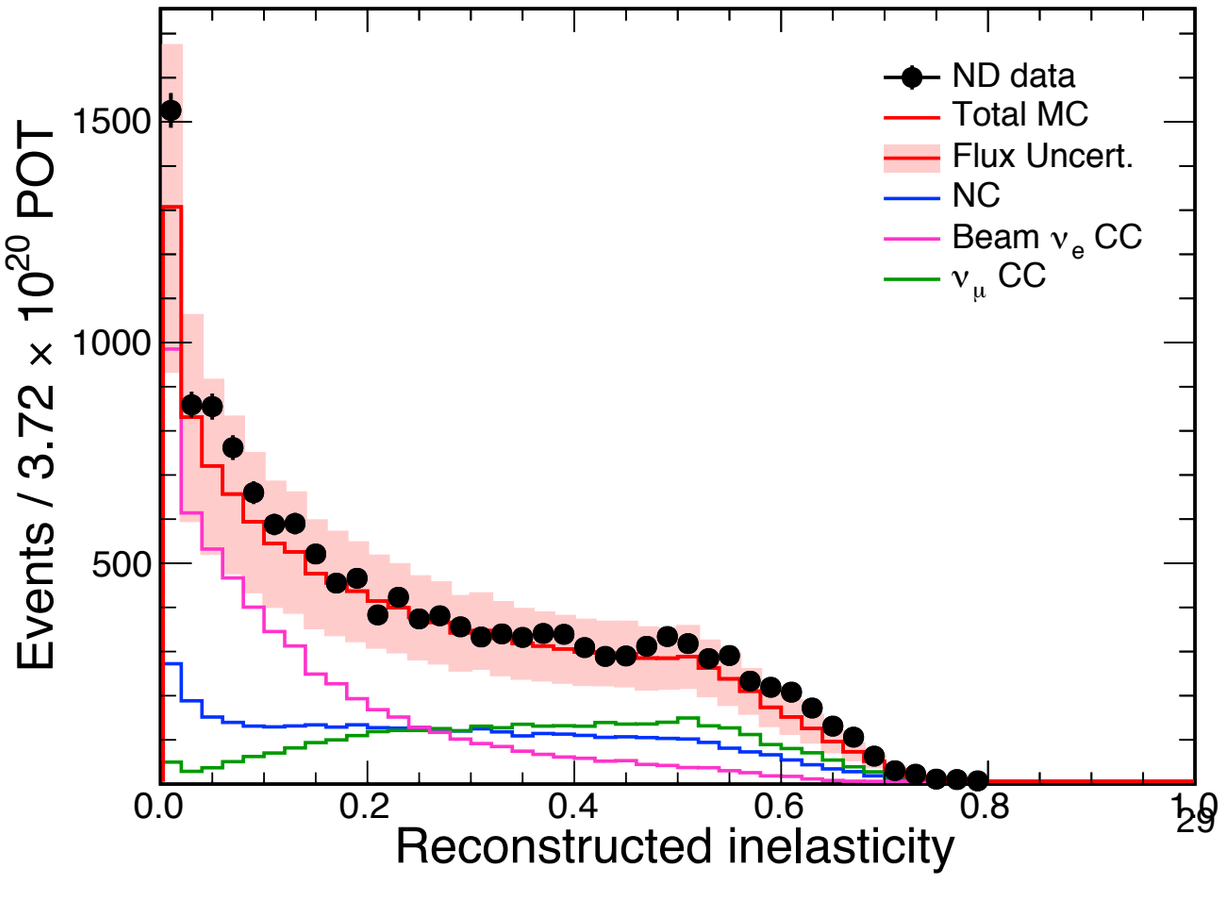


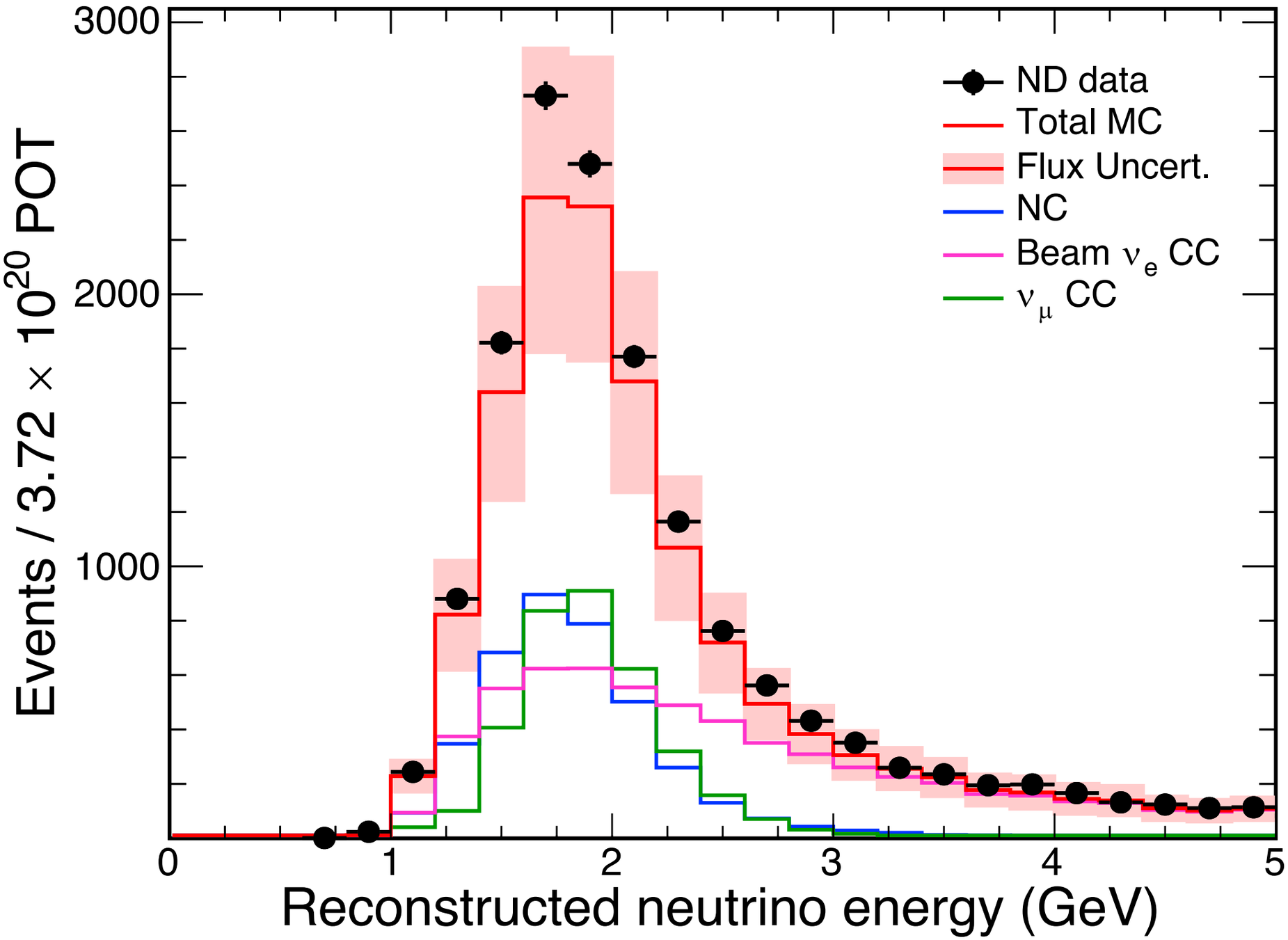
Electron neutrino near detector distributions

- Select events with CVN score of 0.75 and above in the near detector



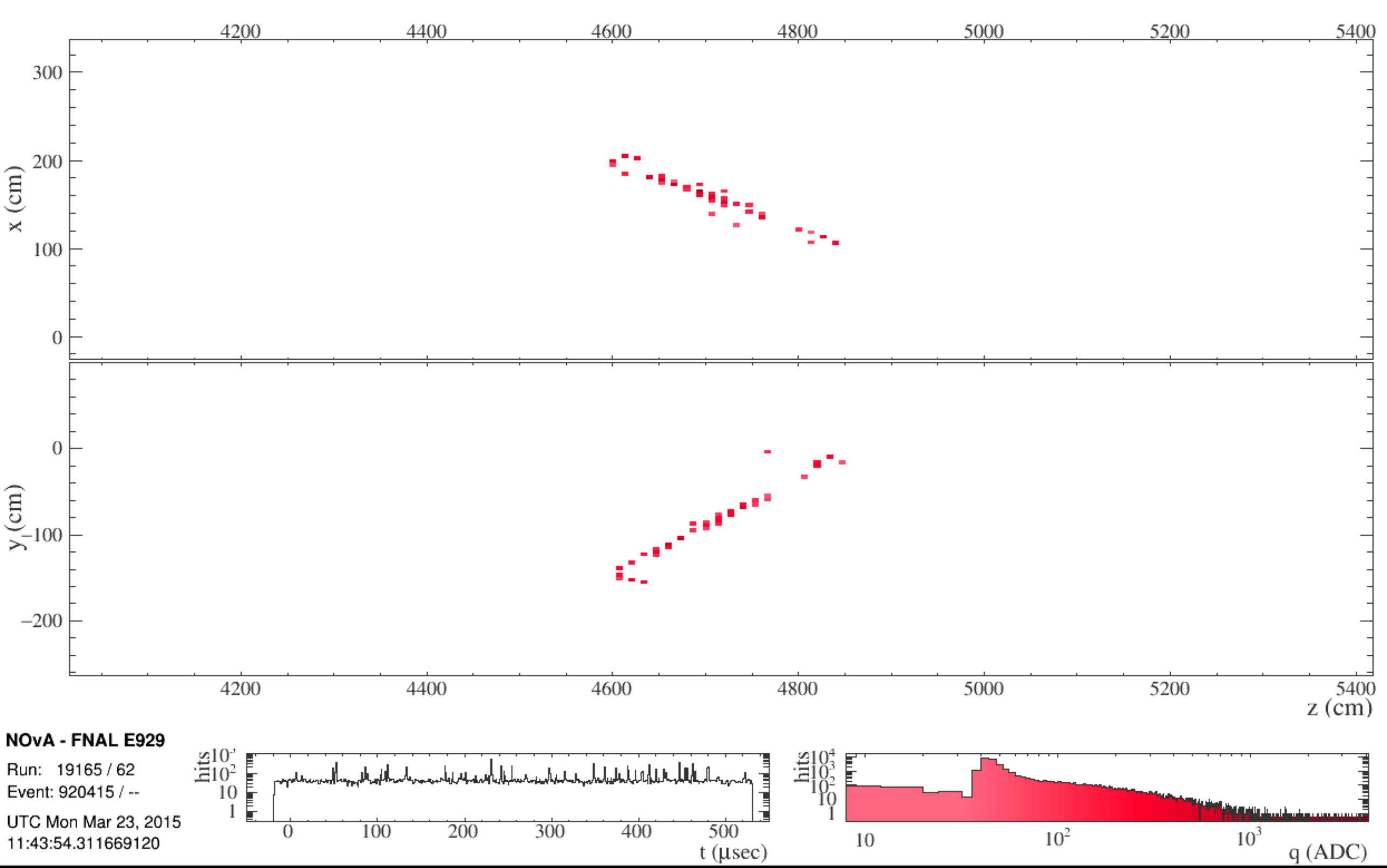
- Top: Transverse shower width.
- Bottom: Inelasticity “y”



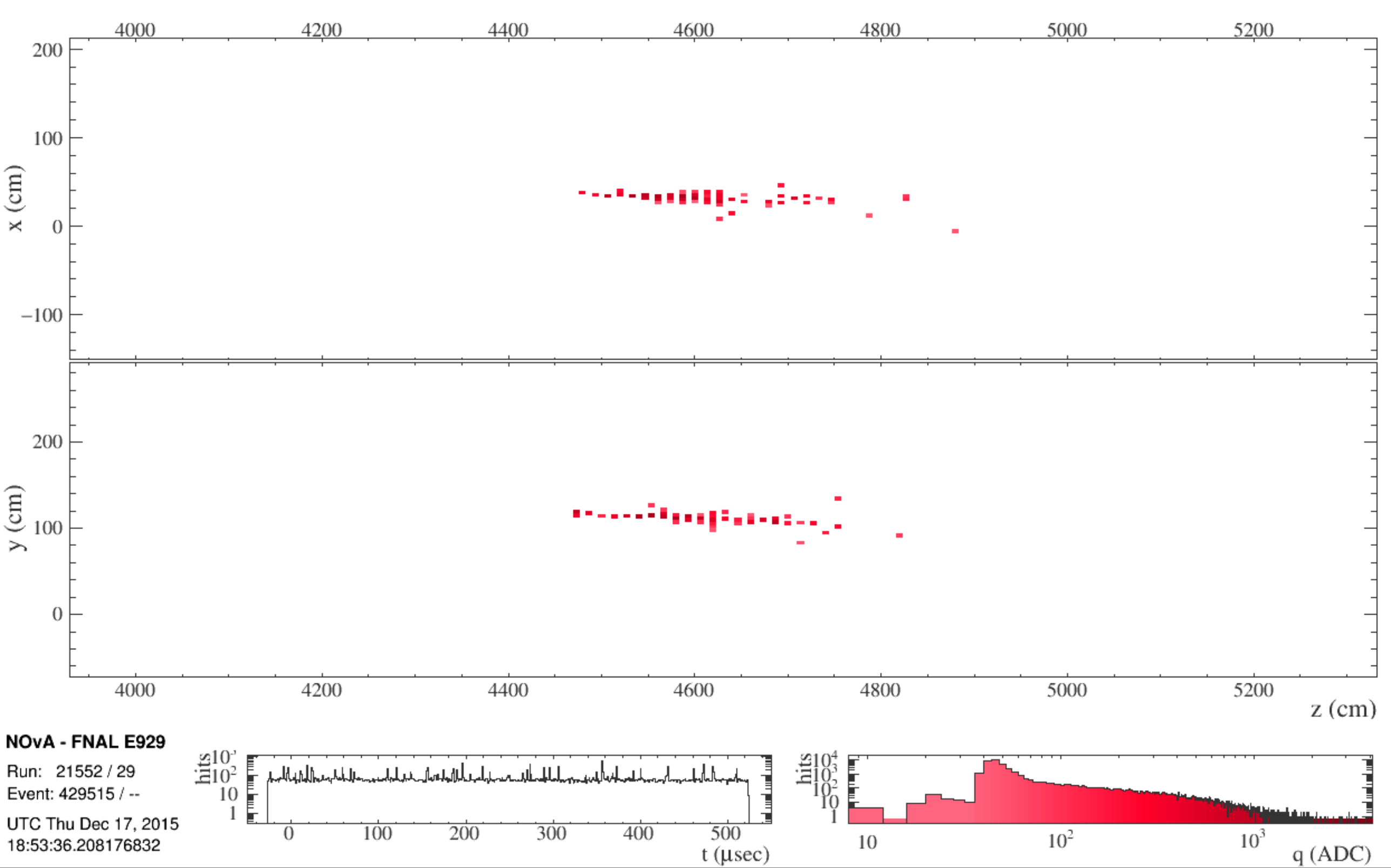


NOvA ν_e Selection Near Detector

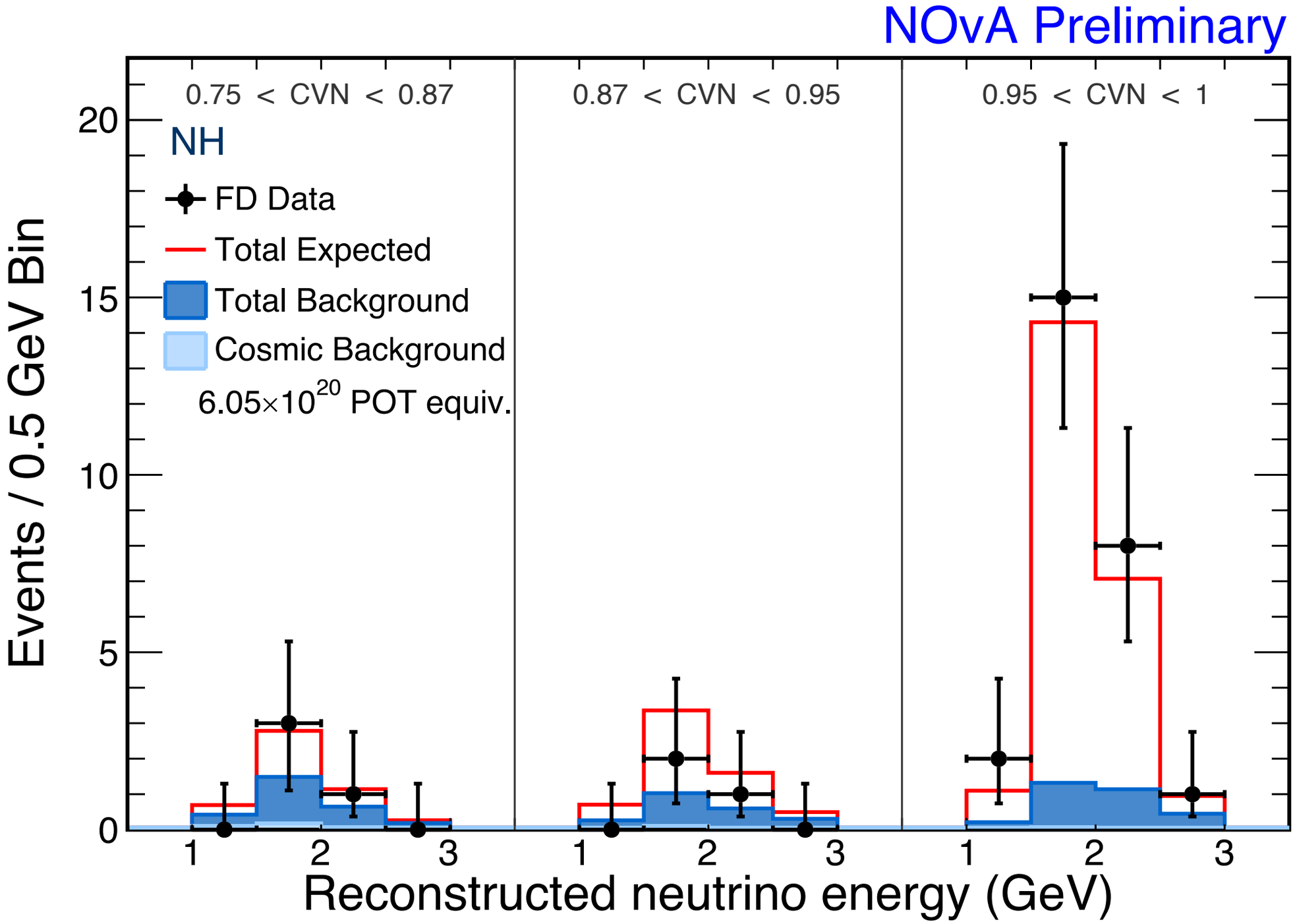
Extrapolate to Far Detector:
8 background events
11 signal [IH $\delta_{CP}=\pi/2$]
28 signal [NH $\delta_{CP}=3\pi/2$]



NOvA ν_e Candidate

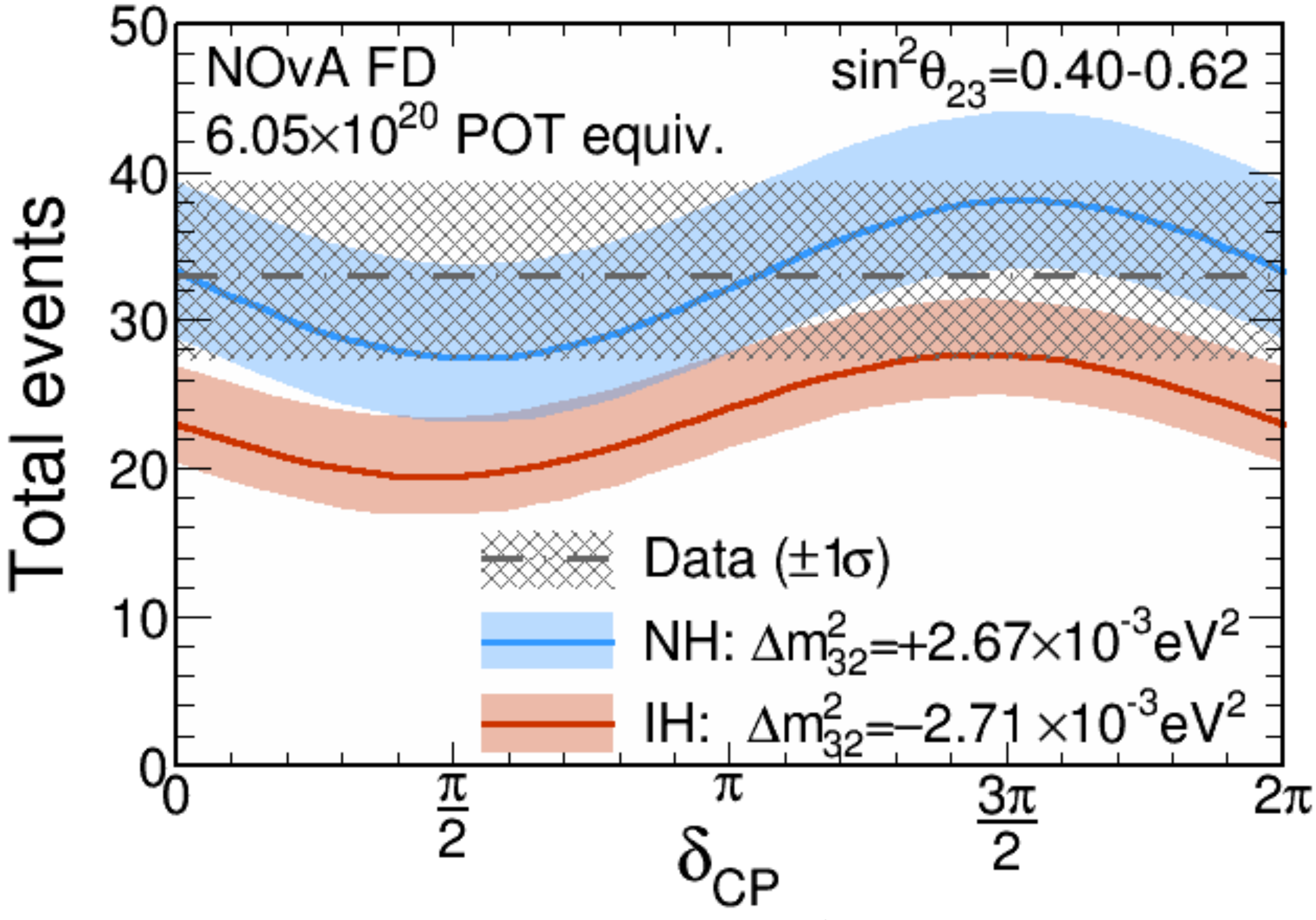


NOvA ν_e Candidate



NOvA Electron Neutrino Appearance

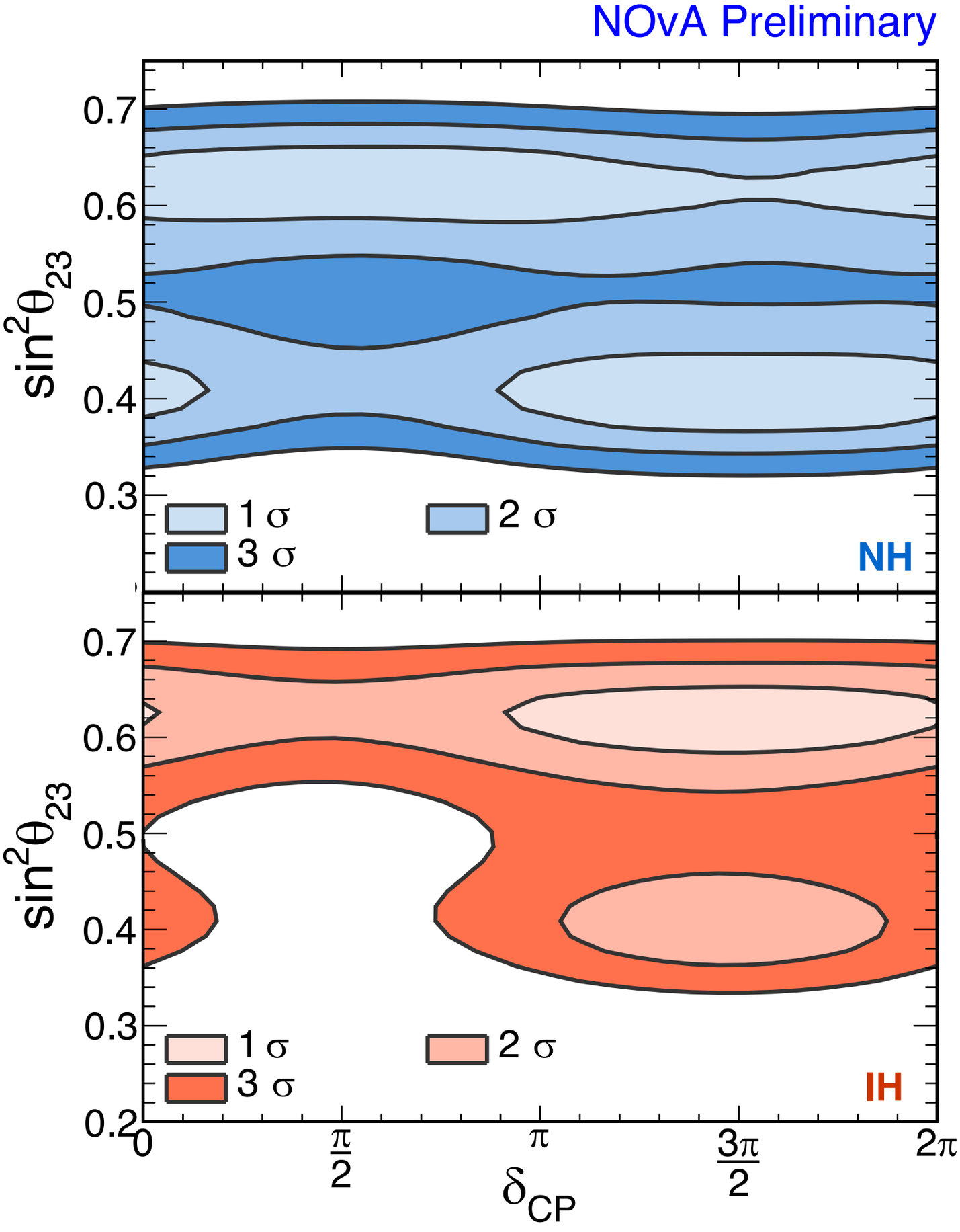
Observe 33 events at far detector

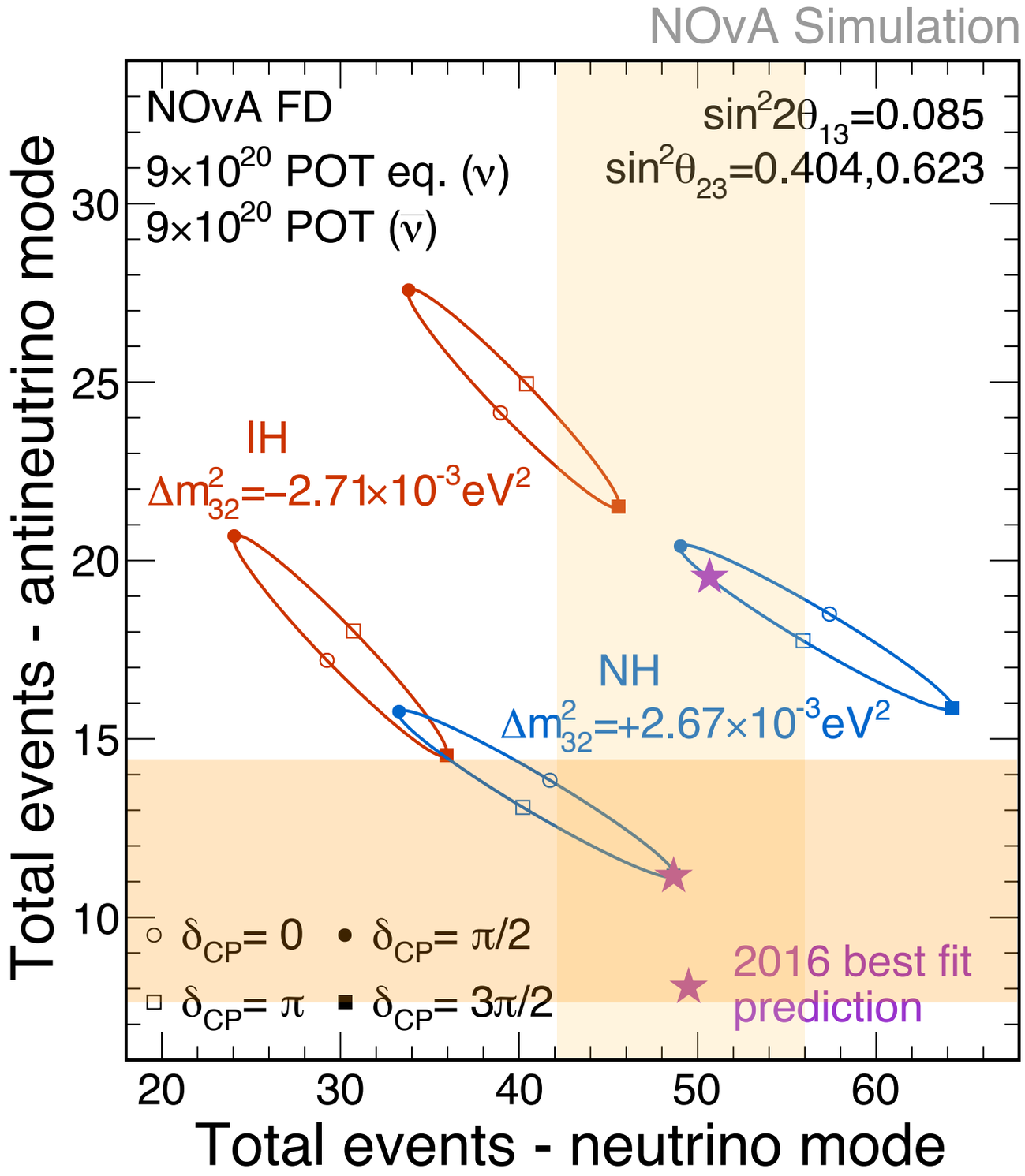


NOvA Electron Neutrino Appearance

Electron Neutrino Appearance

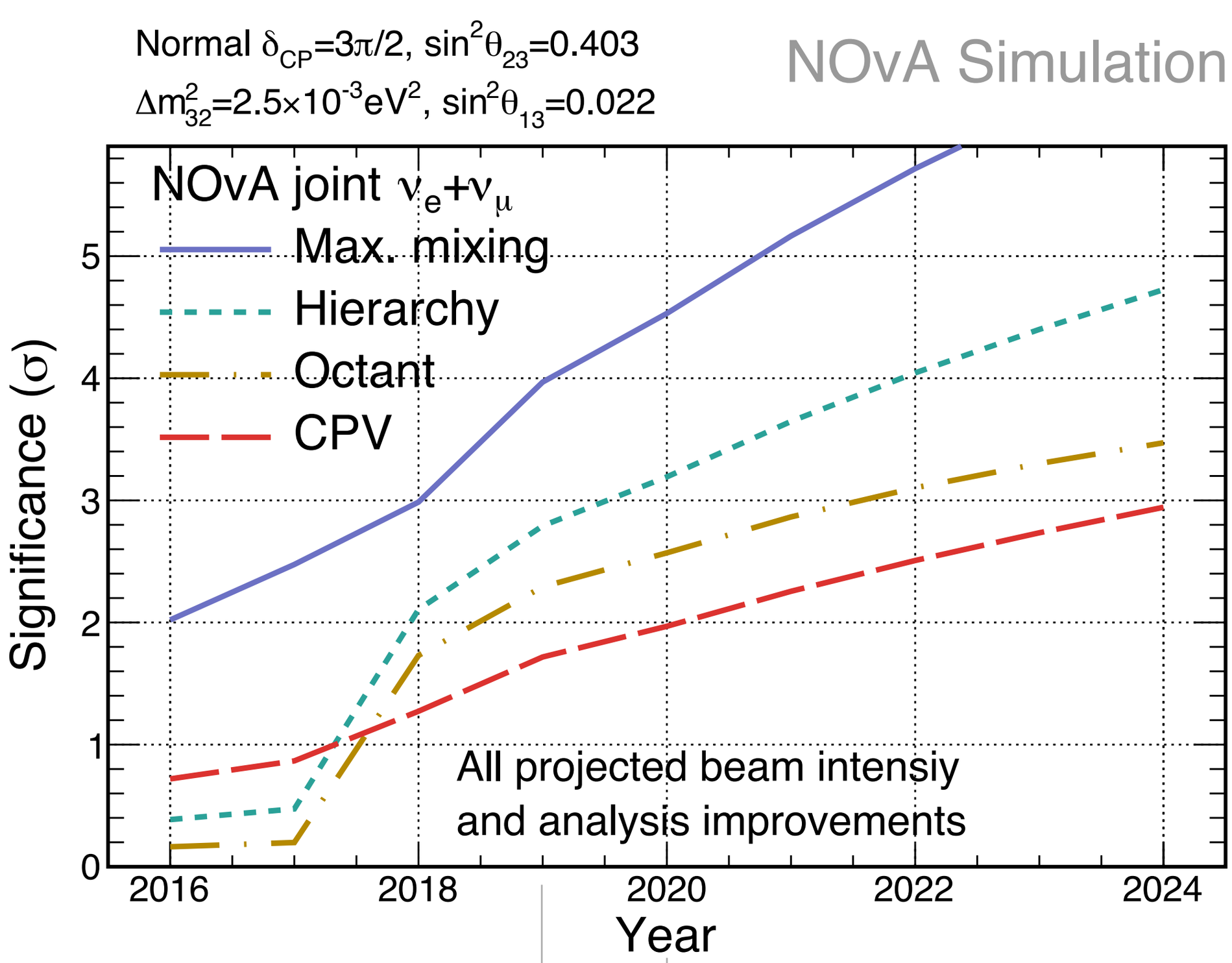
- Rule out lower octant, inverted hierarchy at >3σ
- Resolution of remaining ambiguities requires antineutrino running
- Recorded 0.5E20 POT in antineutrinos at end of run. Will collect 3E20 POT in neutrinos and 3E30 POT in antineutrinos next year
- Current data sample is 1/6th of total planned running.





Near future: NOvA Antineutrino Data

NOvA will run in antineutrino mode until the neutrino and antineutrino data sets have equal exposure.



Opportunities for the NOvA Measurement Program

>5 σ test of μ-τ symmetry

>4 σ resolution of mass hierarchy

>3 σ resolution of θ23 octant

~3 σ measurement of CP violation