The secrets of oscillating neutrinos at the NOvA experiment

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University of Edinburgh Seminar
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Sandbox Studio, Chicago

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Neutrinos

(Blink 182 “All the small things”)

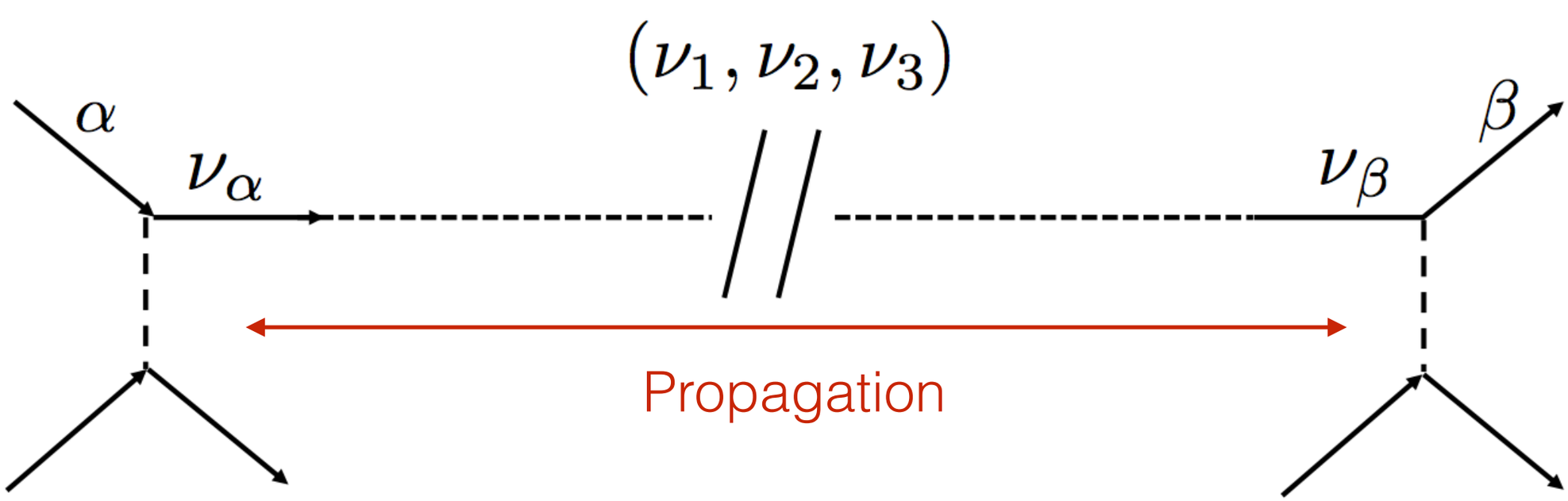
Neutrino oscillations

Flavour eigenstates
ν_e, ν_μ, ν_τ

3x3 unitary matrix
PMNS matrix

Mass eigenstates
ν_1, ν_2, ν_3

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$



The PMNS matrix

- Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

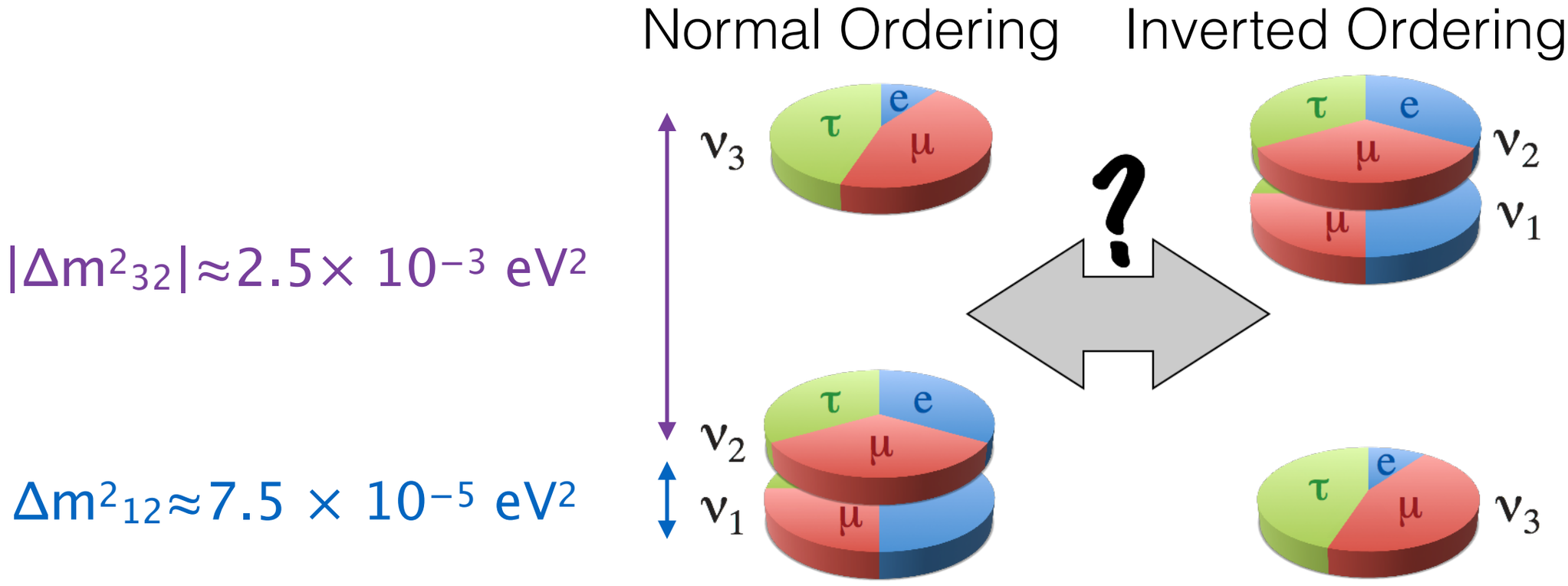
Muon neutrino disappearance
(atmospheric and accelerator)

Electron neutrino appearance (accelerator)
Electron anti-neutrino disappearance (reactor)

Electron (anti-)neutrino disappearance
(reactor and solar)

Some open questions

What's the mass ordering?
Is θ_{23} maximal?
Is there CP violation in the lepton sector?



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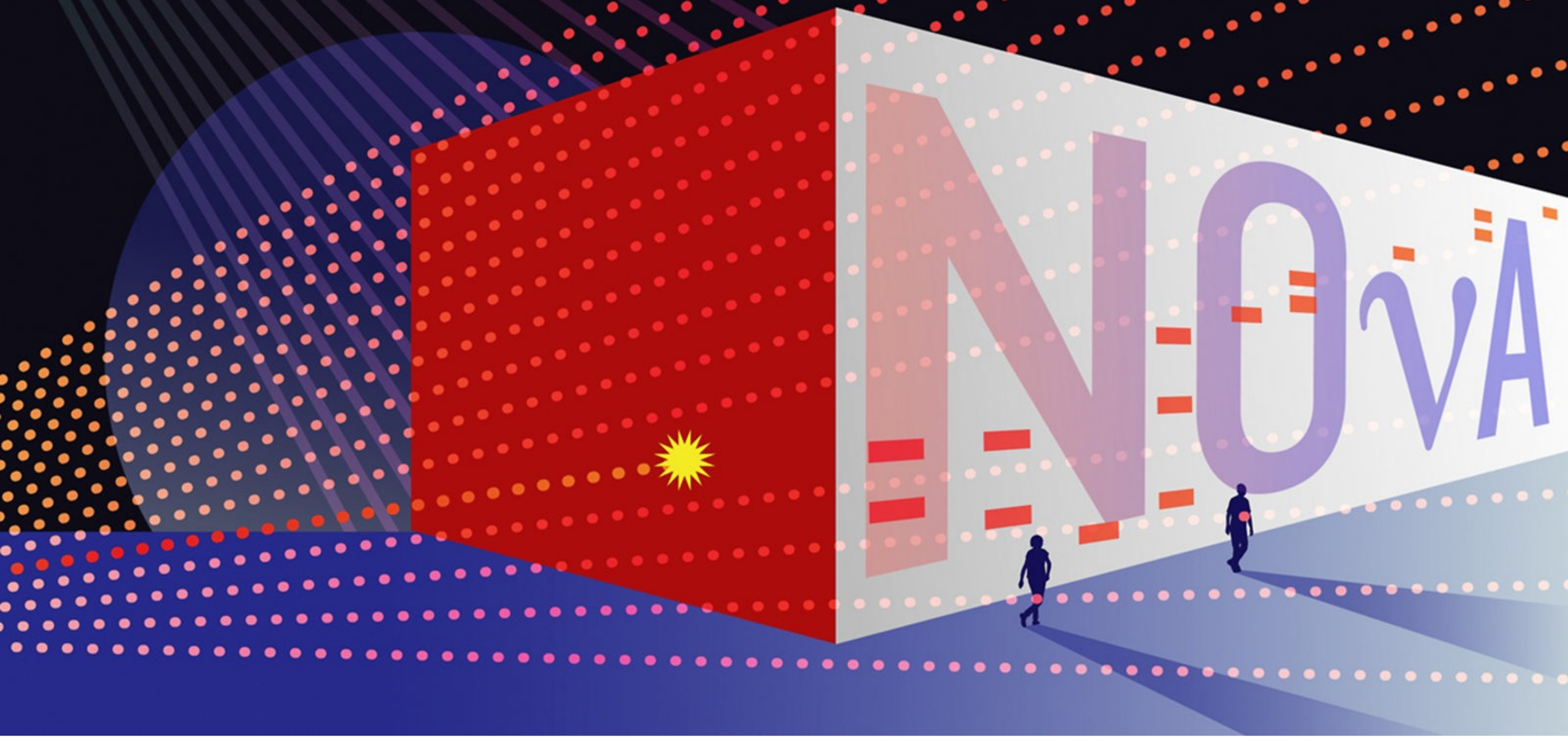


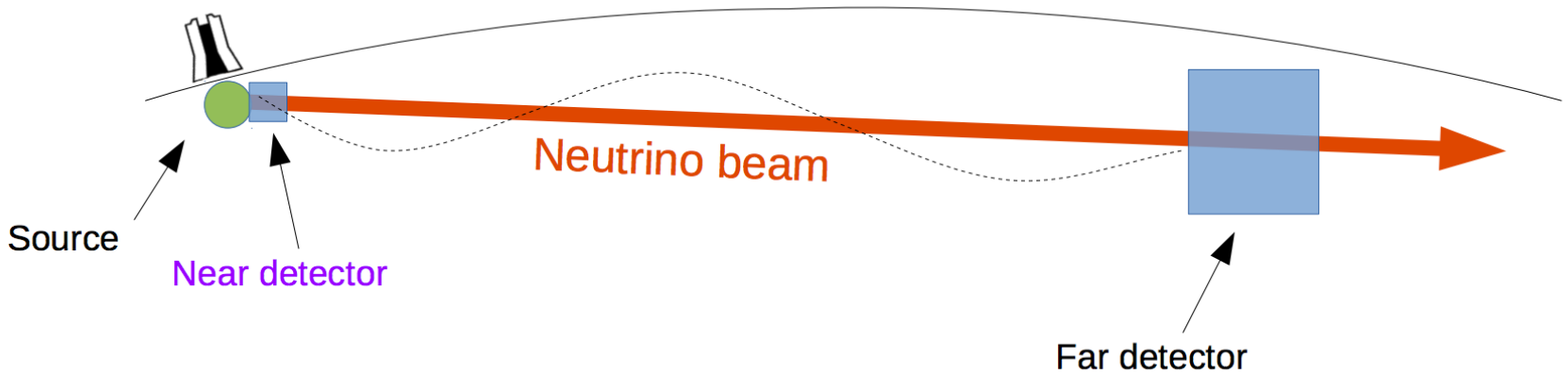
The NOvA experiment

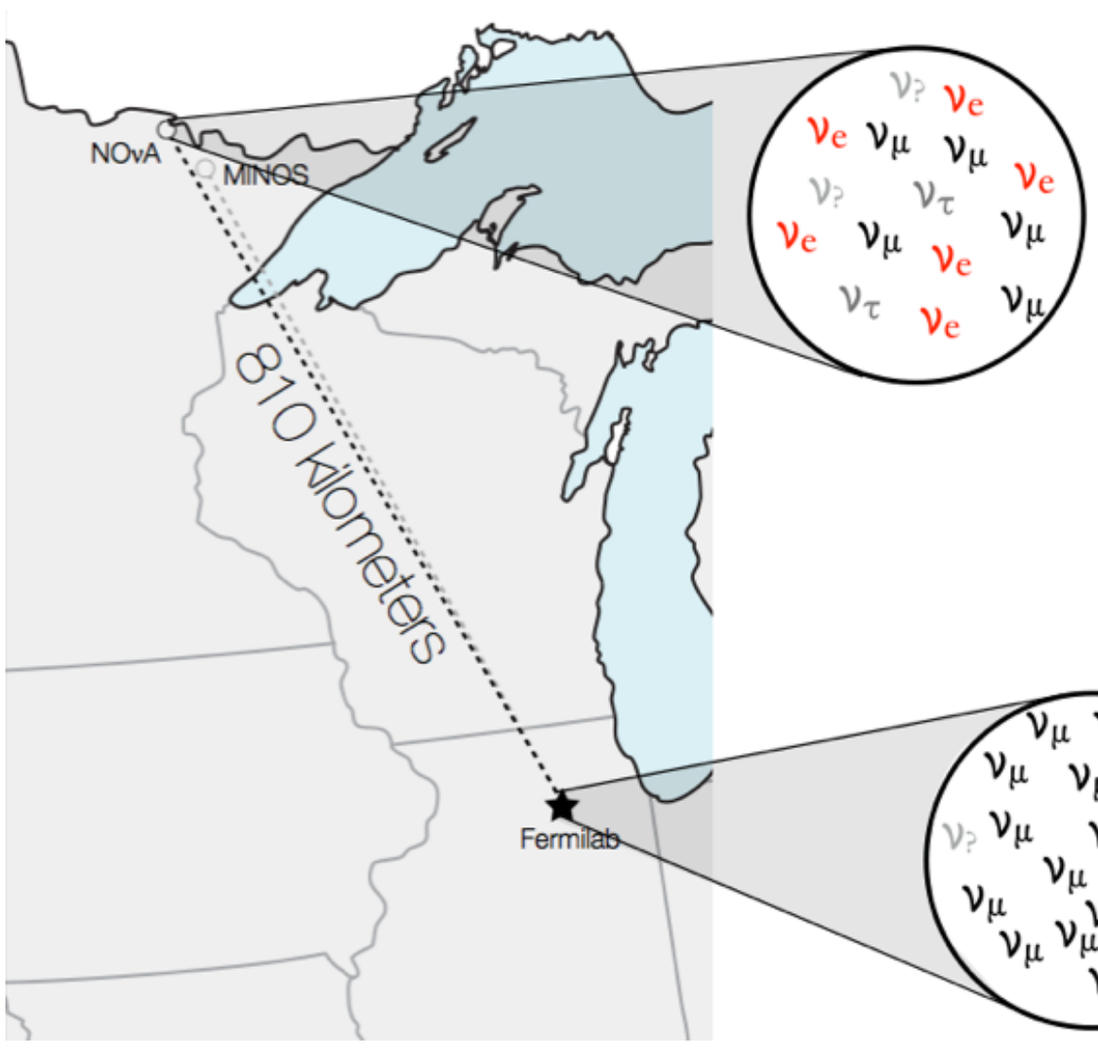
(The Proclaimers “I’m gonna be”)

Who are we?


233 scientists and engineers from 47 institutions
Fermilab

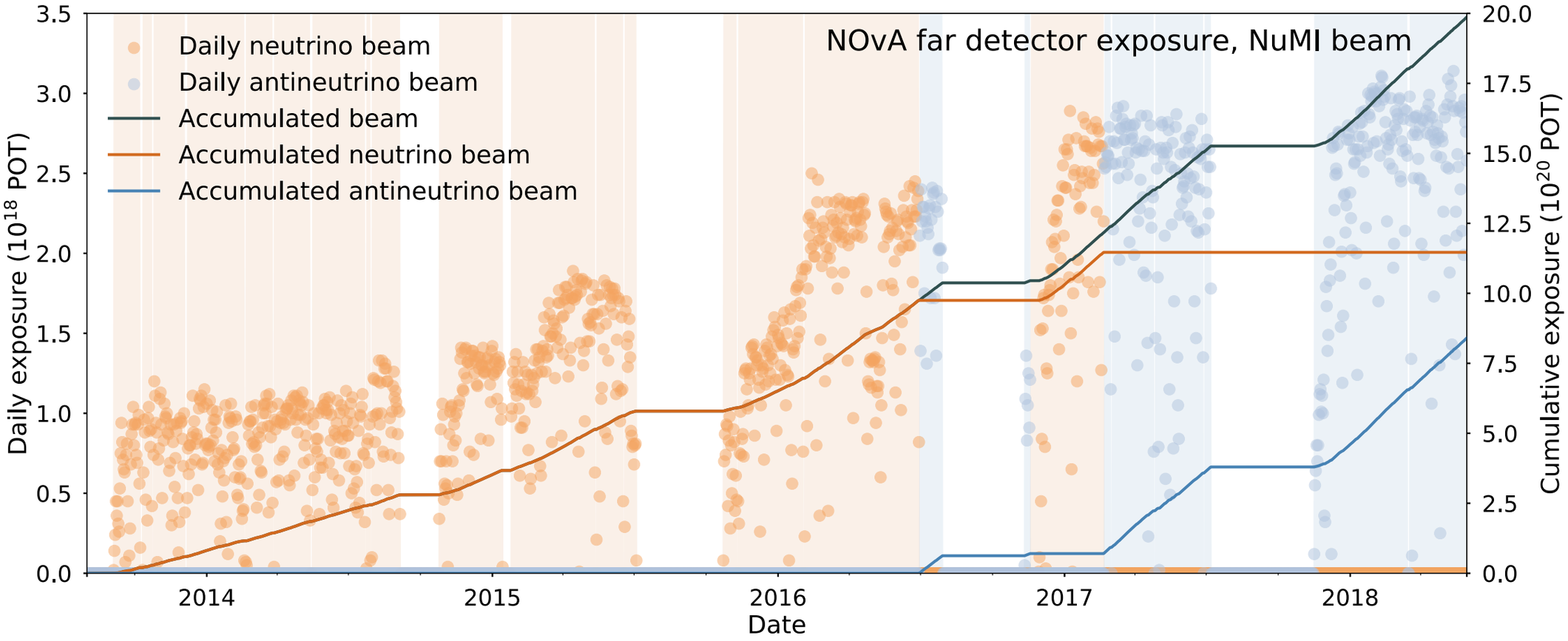
What do we do?





- NOvA is a long-baseline neutrino oscillation experiment
- Observes neutrinos from NuMI beamline at Fermilab
- Two functionally identical detectors, situated 14 mrad off axis, 810 km apart
  - Near Detector is 300 tons (FNAL)
  - Far Detector is 14 ktons (Ash River, MN)

NuMI beam

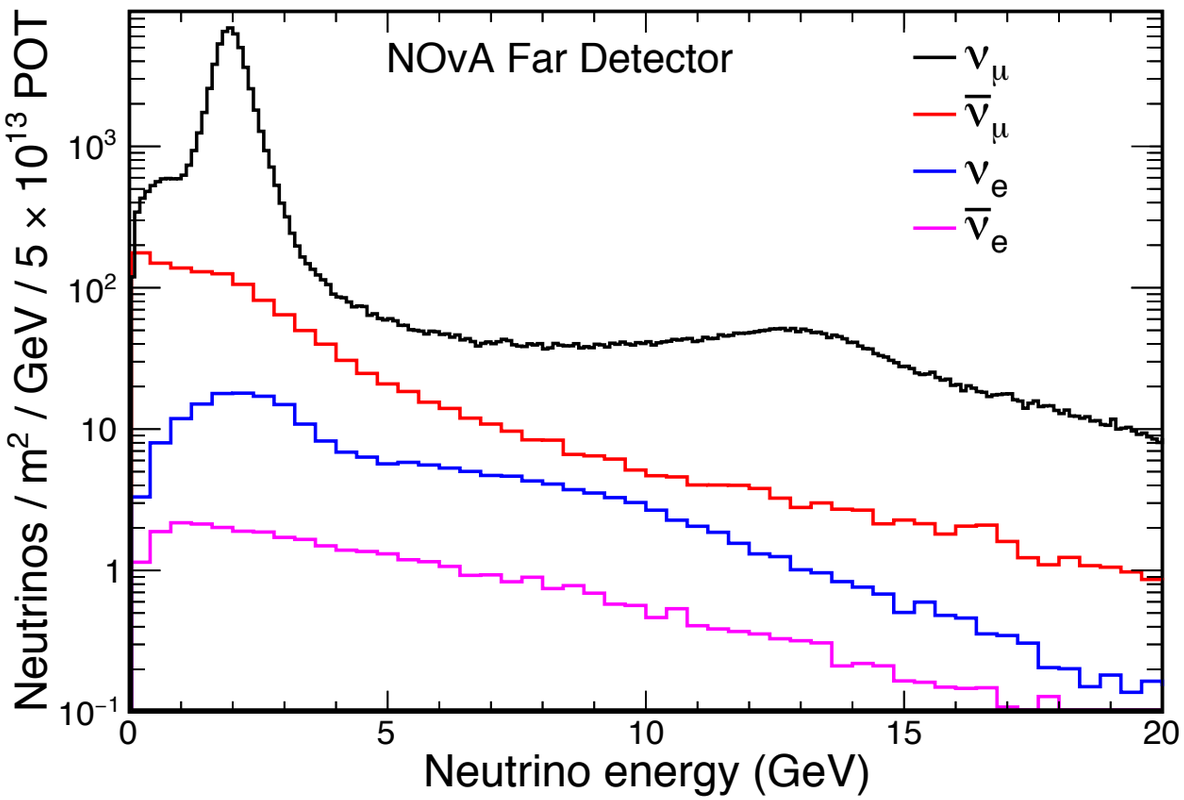


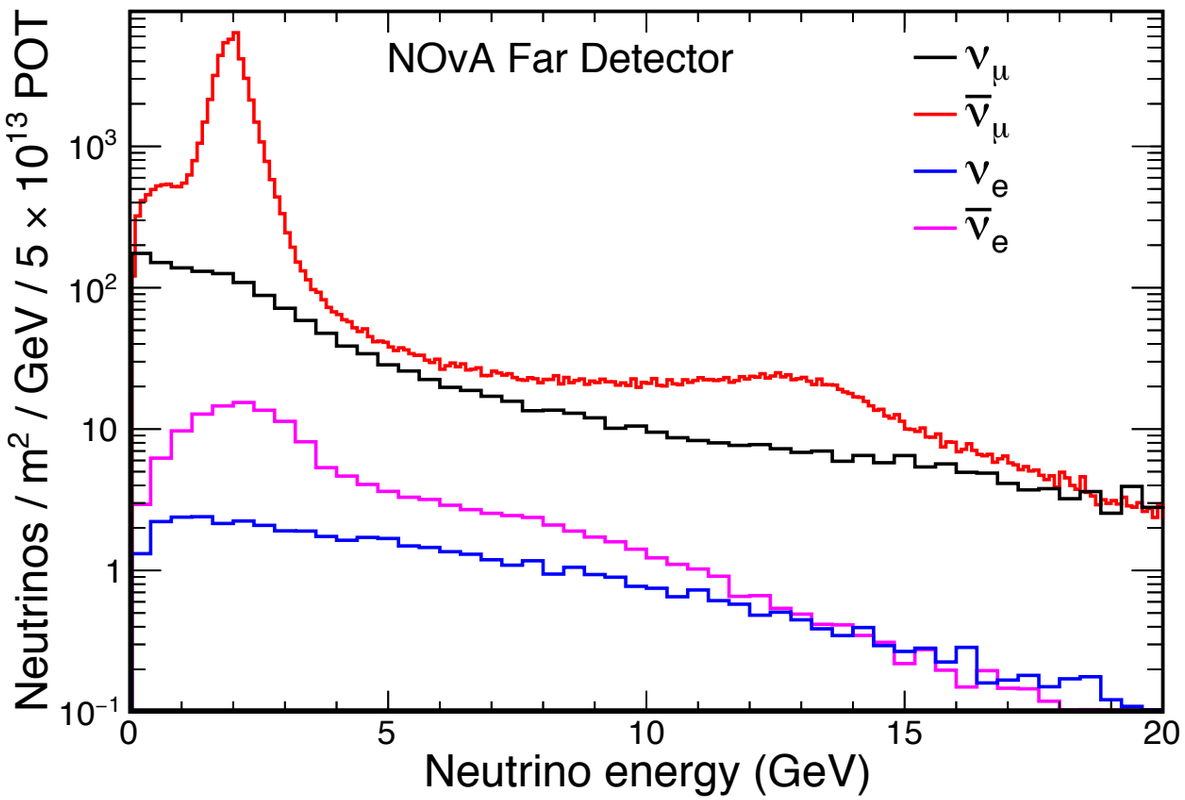
- NuMI beam running at 700 kW design power since January 2017. (> 18 x 10^{18} protons per week). **Highest power beam in the World!**

- Recorded neutrino-mode running 8.85 x 10^{20} protons on target (POT) in 14 kton equivalent detector taken from February 2014 to February 2017.

- **First antineutrino-mode running recorded between February 2017 to April 2018 resulting in 6.9 x 10^{20} POT.**

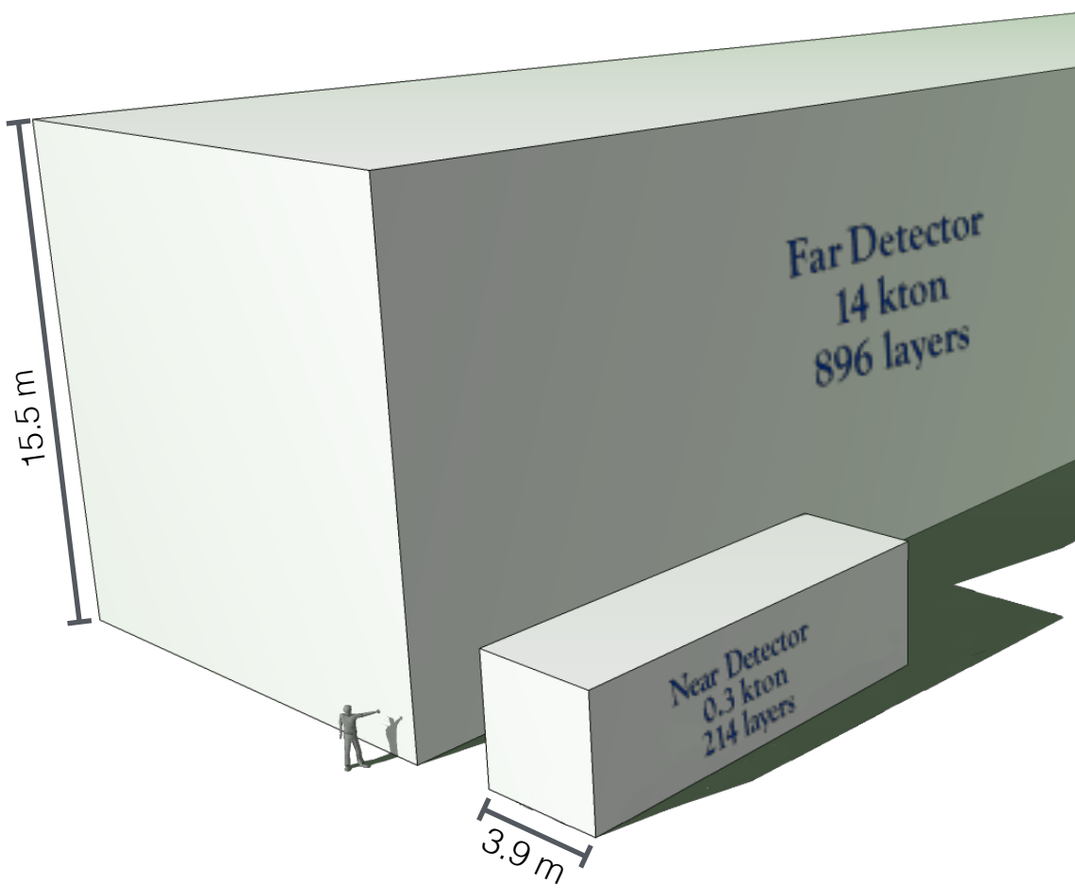
NuMI beam

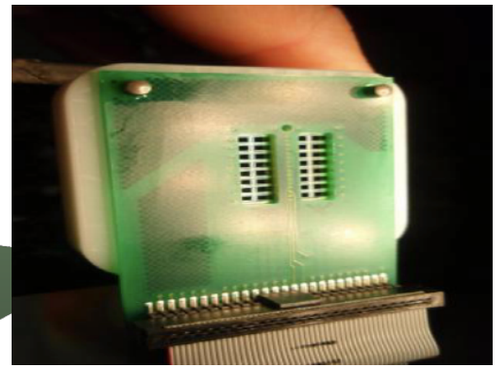


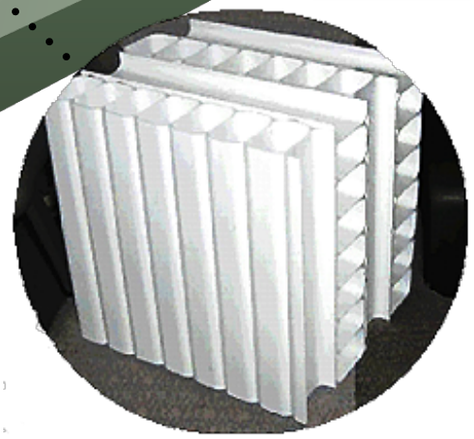


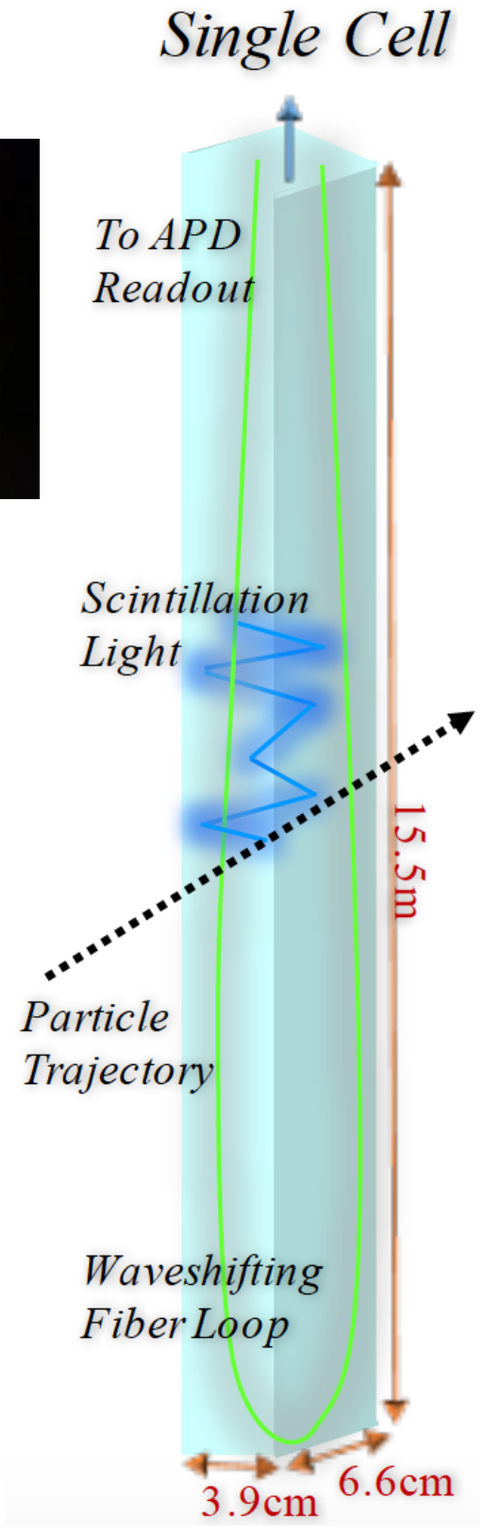
- Off-axis at 14 mrad, peaks just above the oscillation maximum.
- In neutrino mode: 94% muon neutrinos, with 5% wrong sign contamination and 1% electron neutrinos.
- In antineutrino mode: 93% muon antineutrinos, 6% wrong sign contamination and less than 1% electron antineutrinos.

NOvA detectors



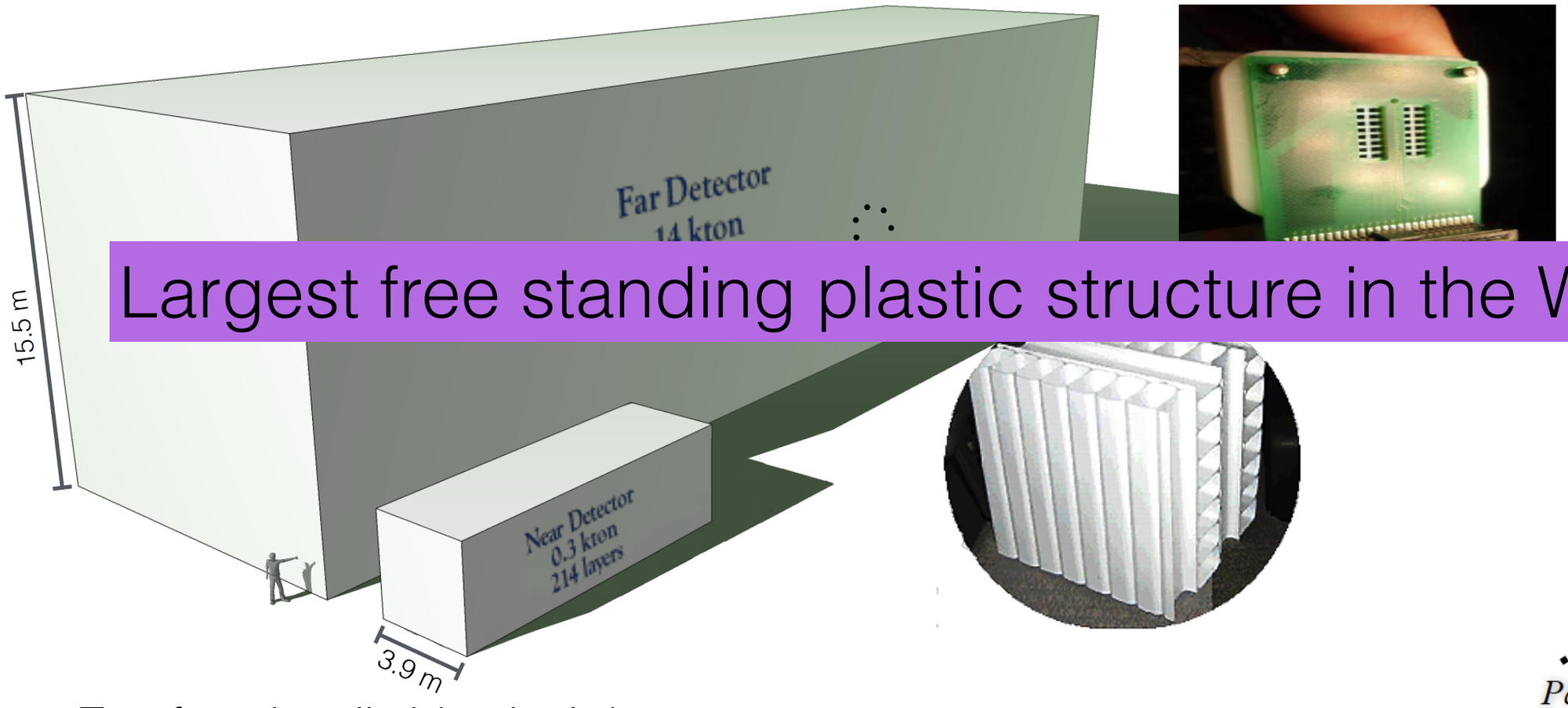




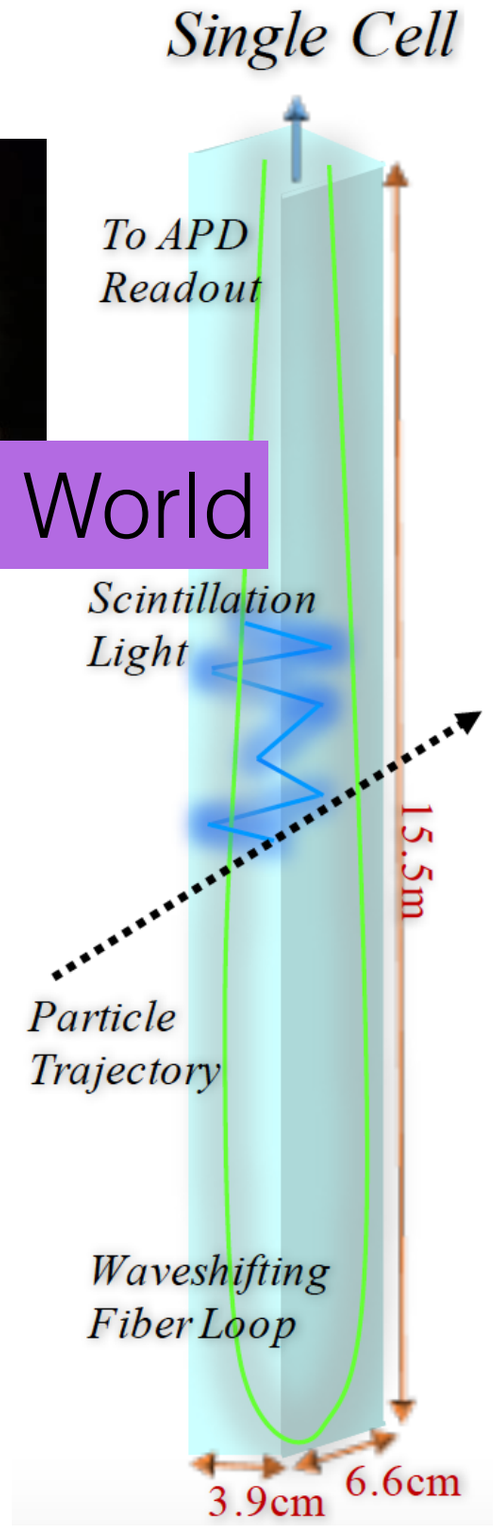


- Two functionally identical detectors
- Extruded plastic cells alternating vertical and horizontal orientation filled with liquid scintillator
- Charged particles passing through cells produce light which is collected.

NOvA detectors



Largest free standing plastic structure in the World



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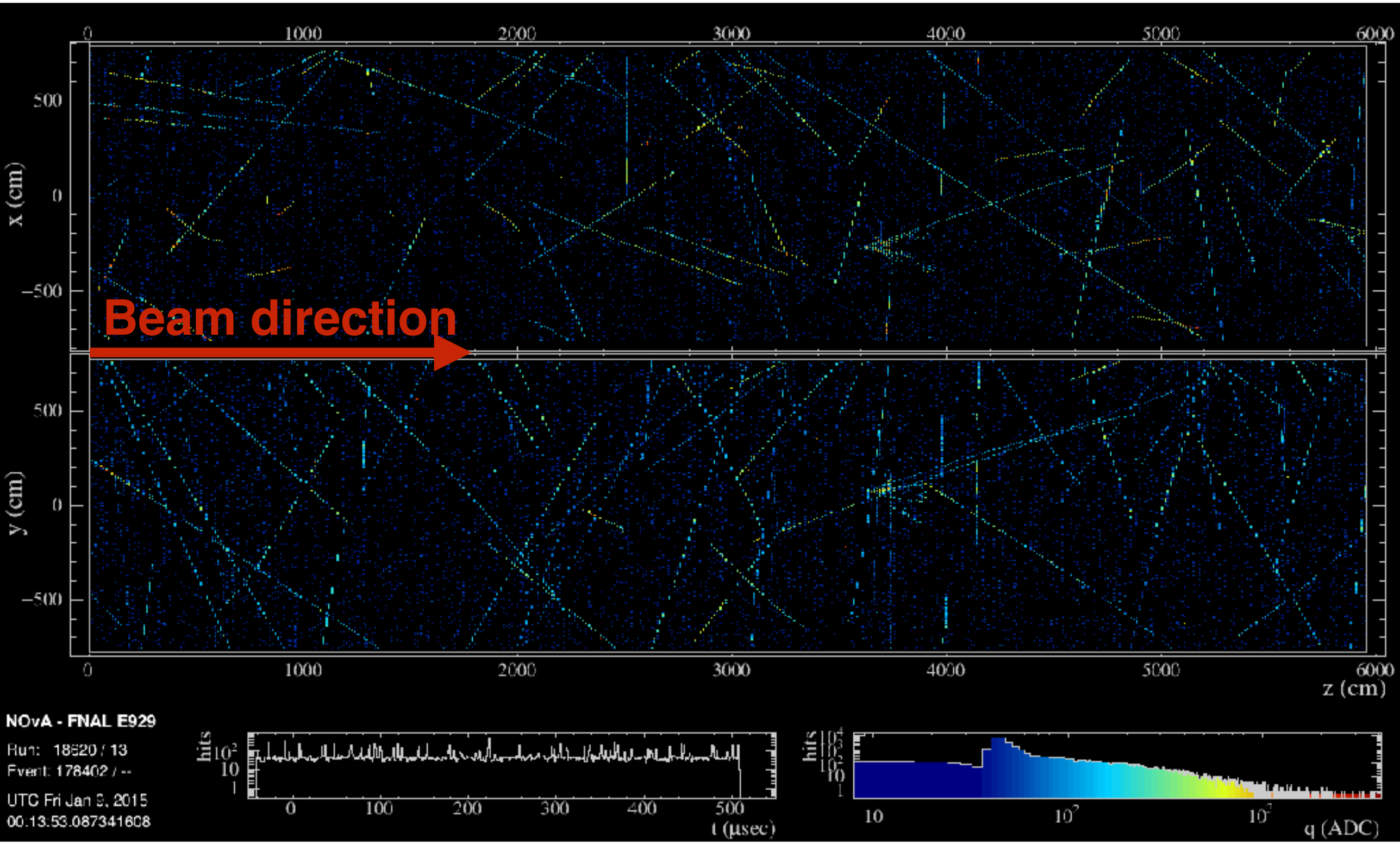
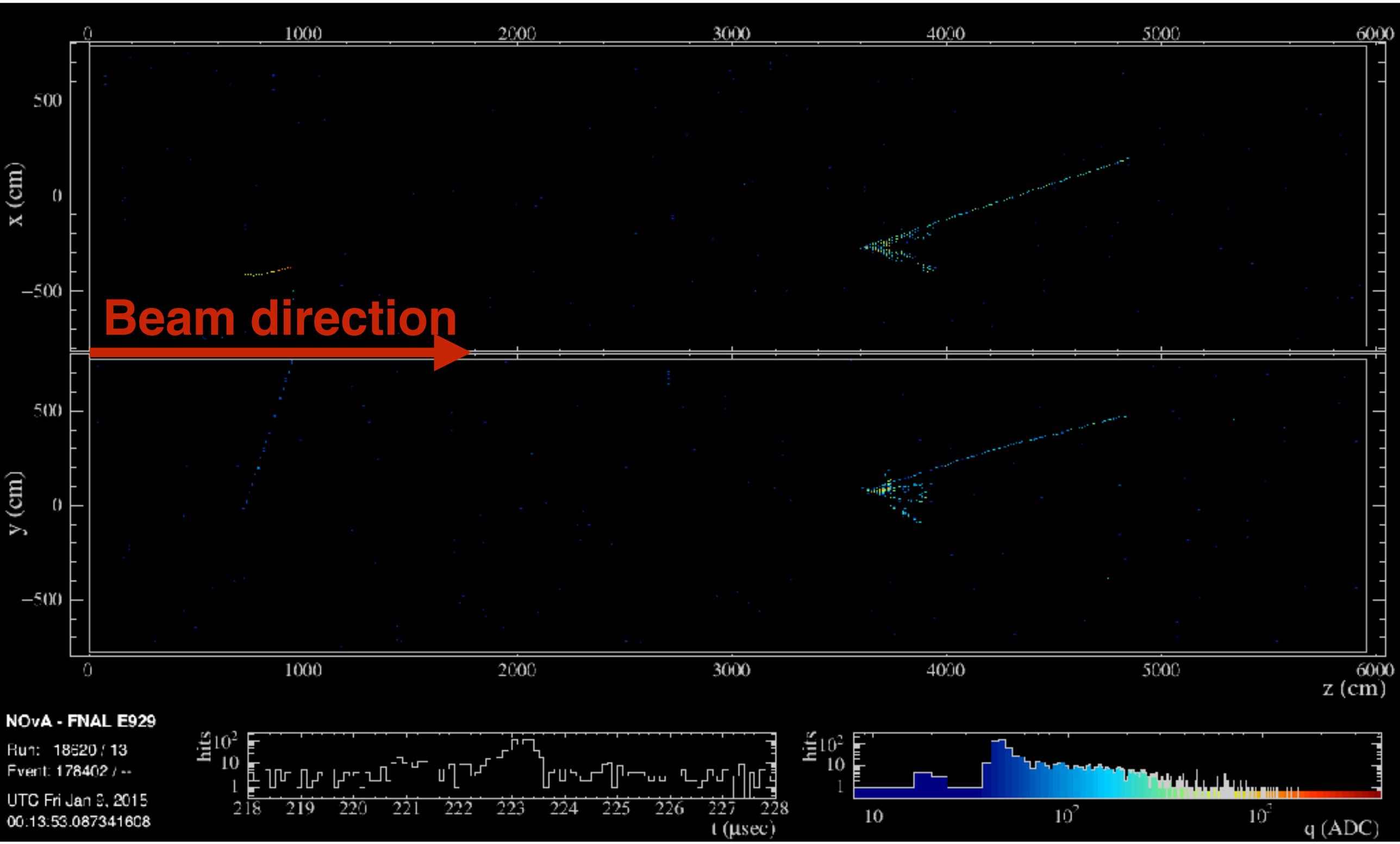
Far Detector 550 μs Readout Window



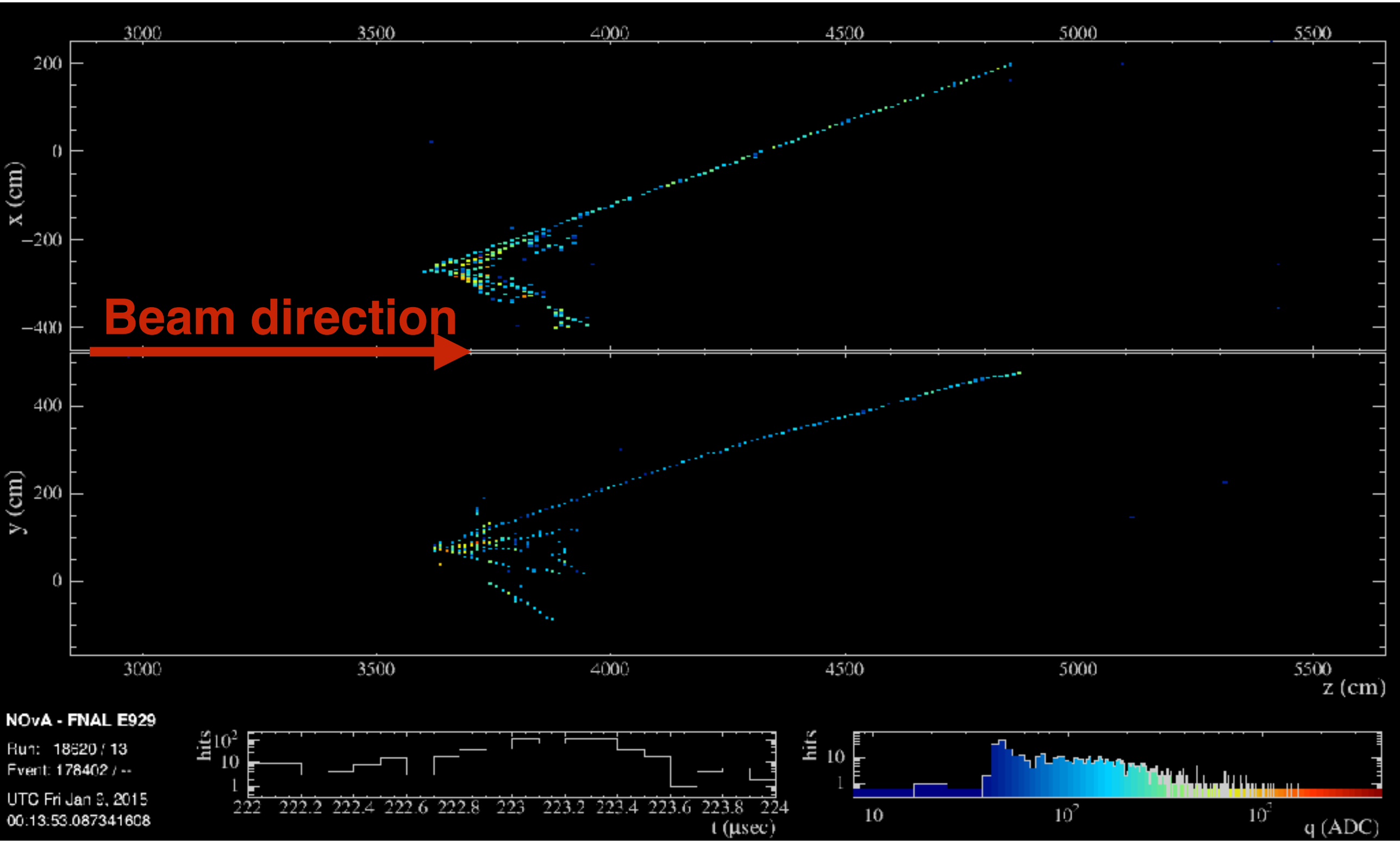
Cell hits coloured by recorded charge (~photoelectrons)

Far Detector 10 μs NuMI Beam Window



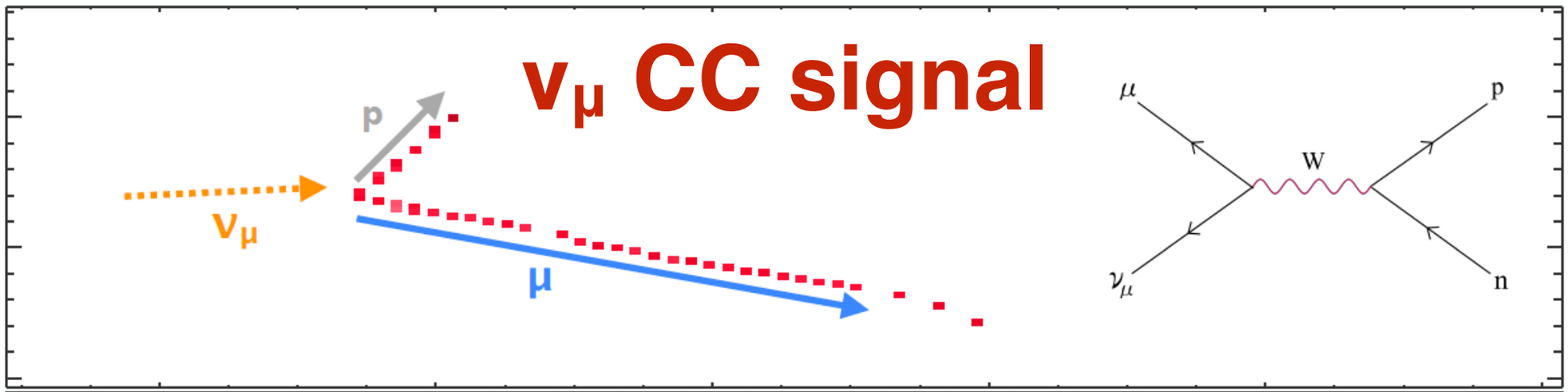
Cell hits coloured by recorded charge (~photoelectrons)

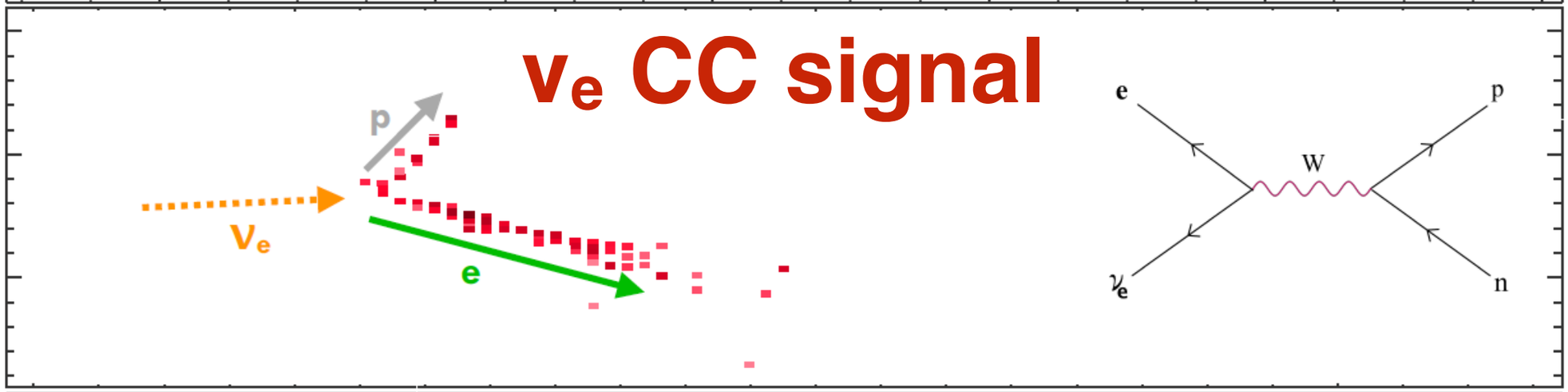
Far Detector Neutrino Interaction

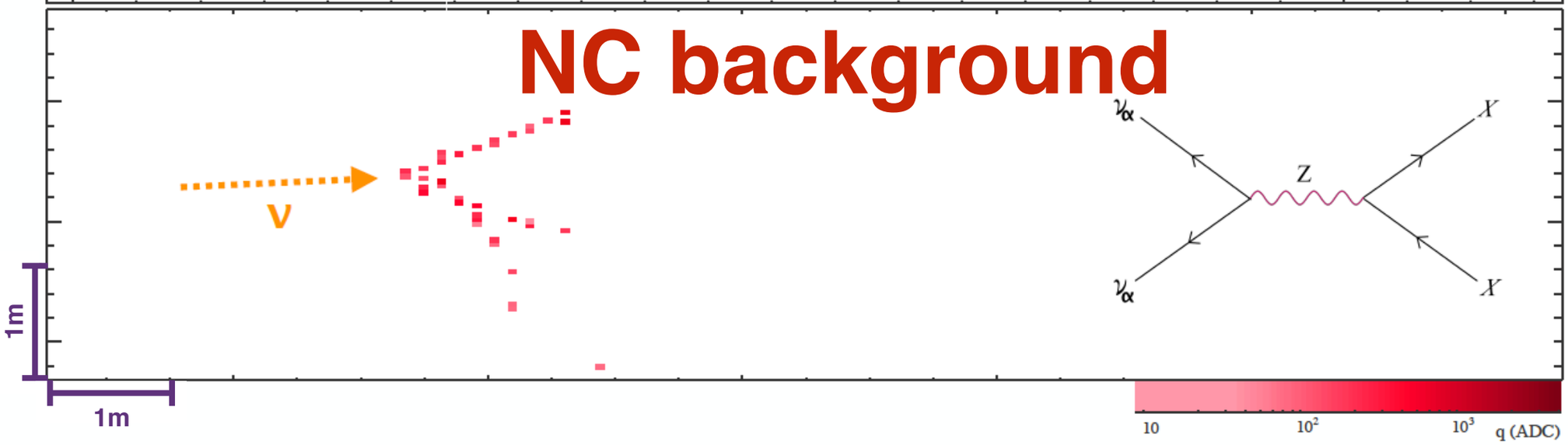


Cell hits coloured by recorded charge (~photoelectrons)

NOvA event topologies







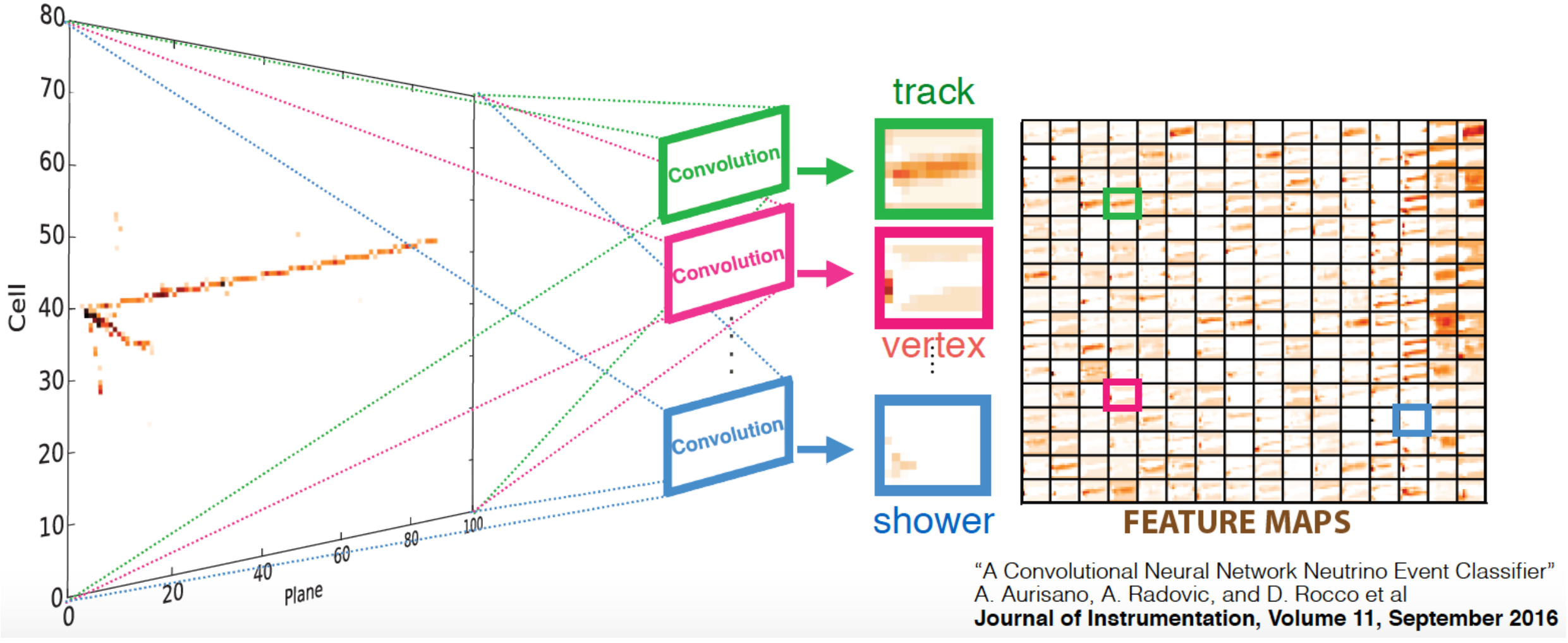
Joint neutrino-antineutrino oscillation analysis

(Lady Gaga“Born this way”)

Neutrino interaction classifier

For all 2018 oscillation analyses:

- Convolutional Visual Network (CVN) based on the GoogLeNet architecture.
- Multi-classifier, assigning an ID : ν_μ, ν_e, 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

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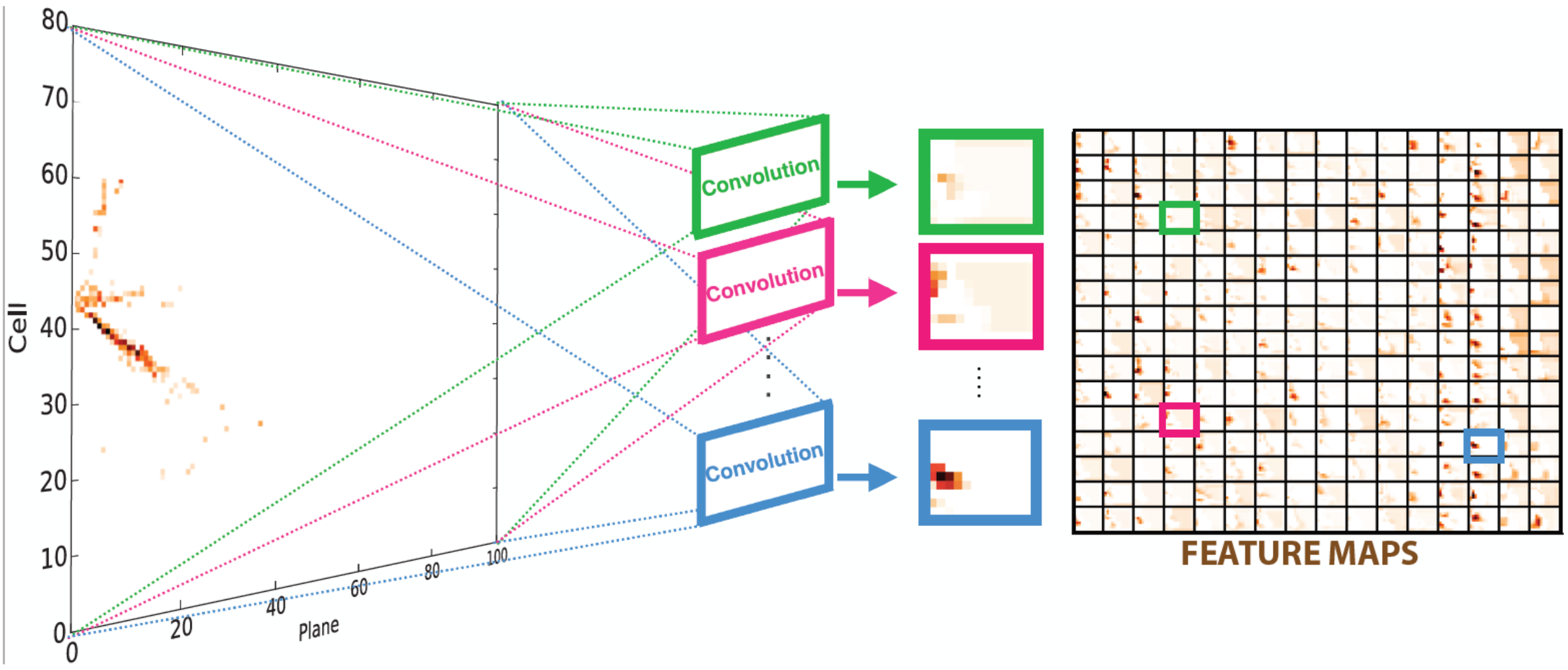
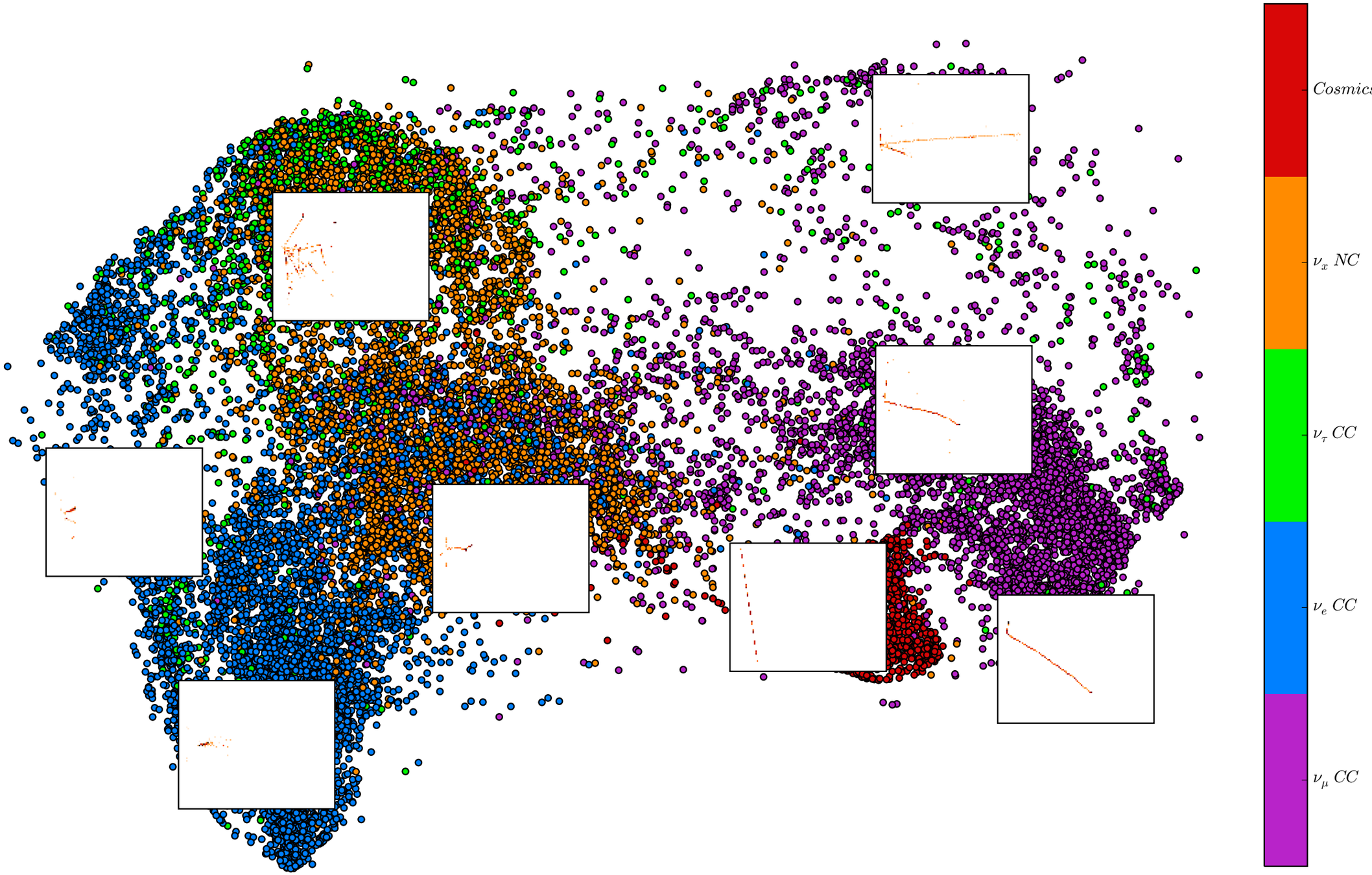


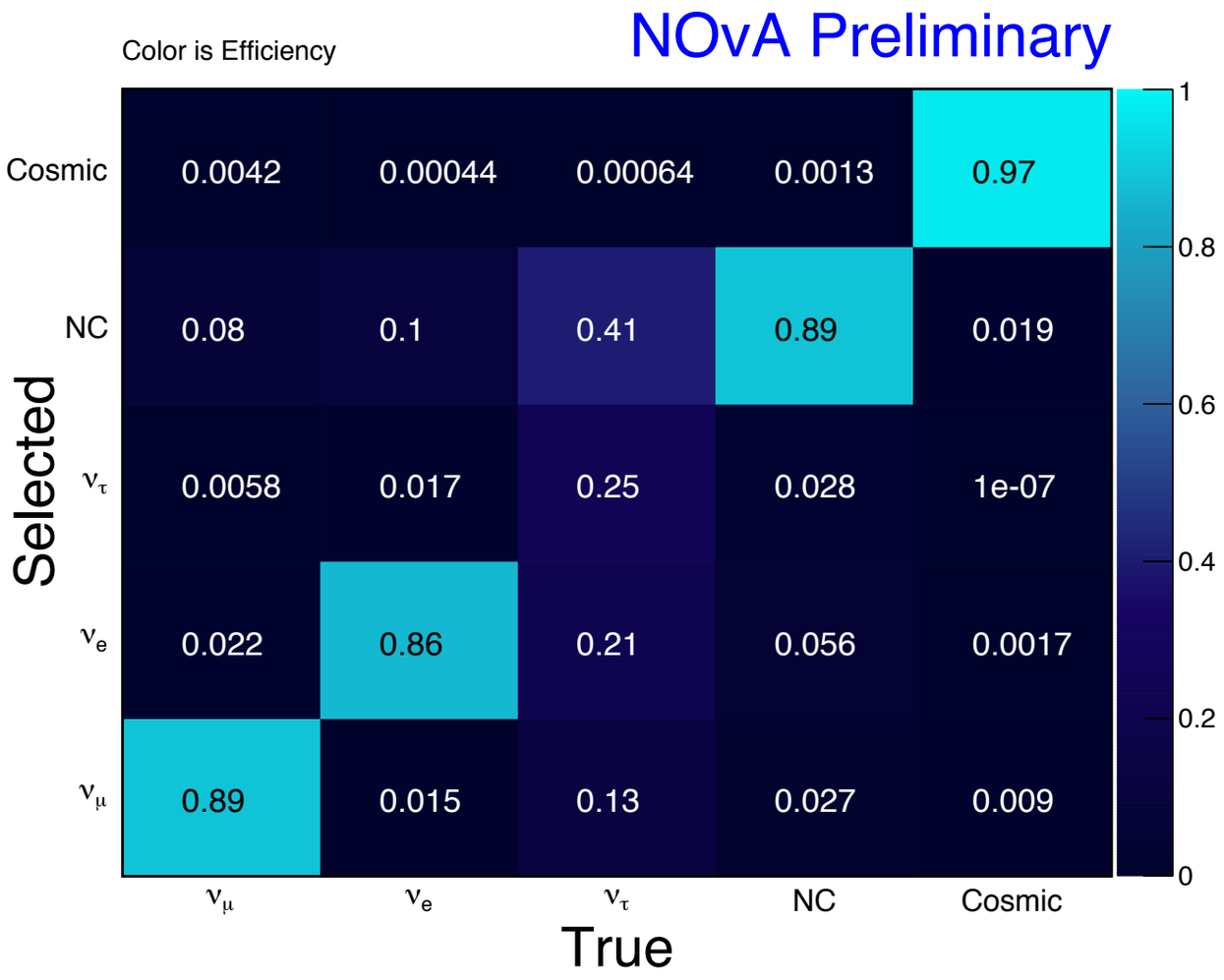
Neutrino interaction classifier

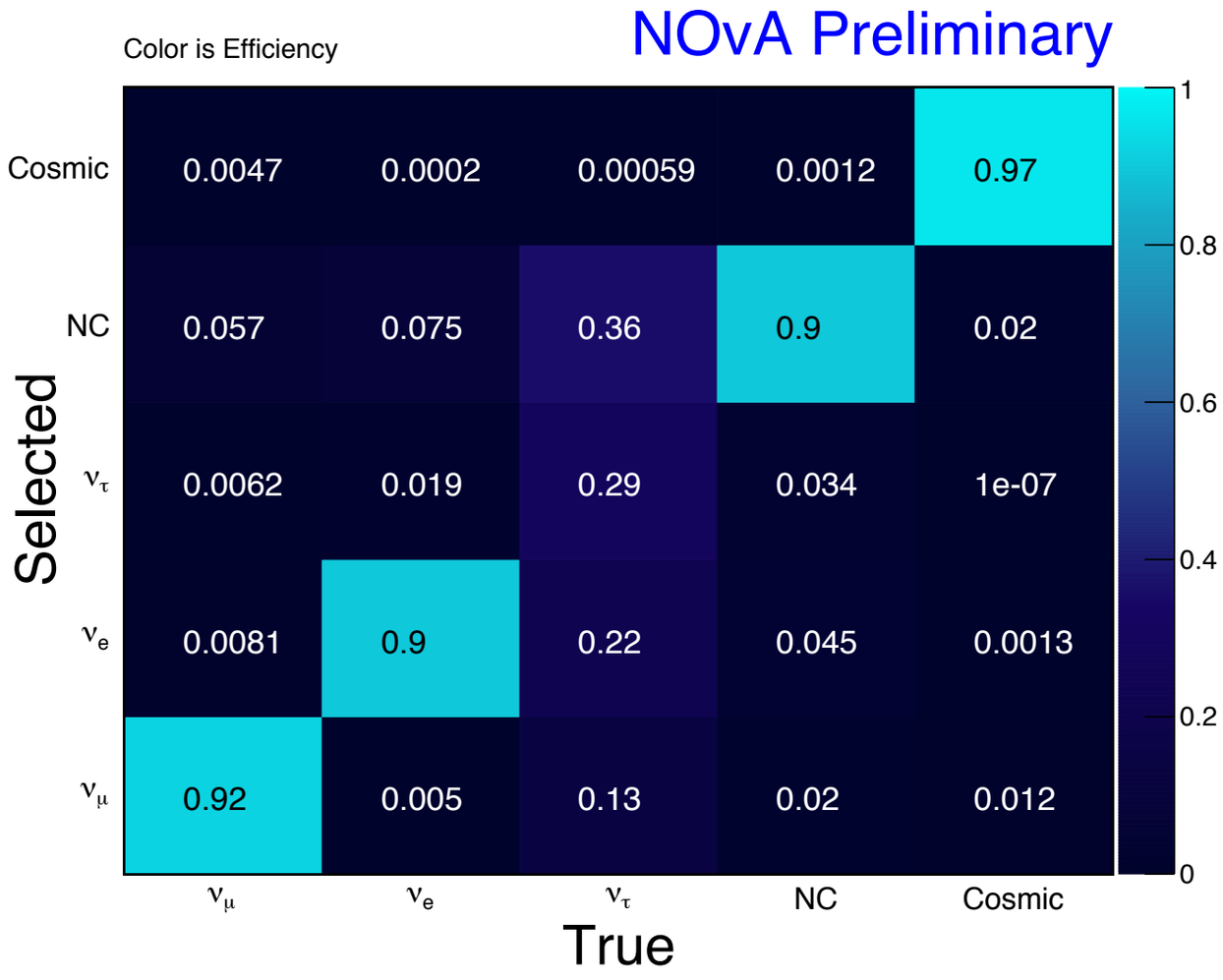


- The extracted features provide good separation among the different types of events. Sample events are shown for each of the areas.

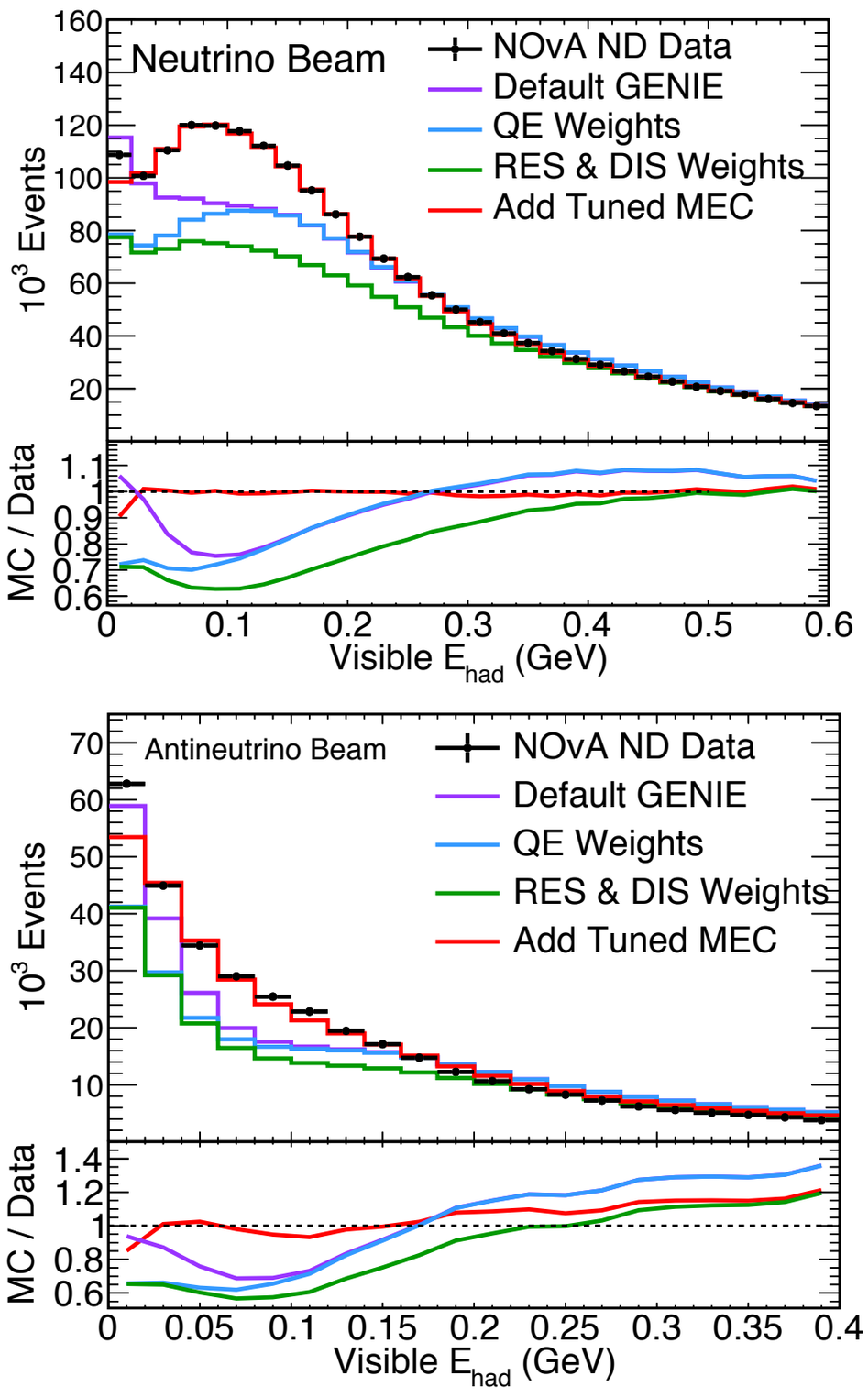
Neutrino interaction classifier

- Trained for neutrino and antineutrino beam separately
- Cosmic data included in training.





Neutrino interaction tuning

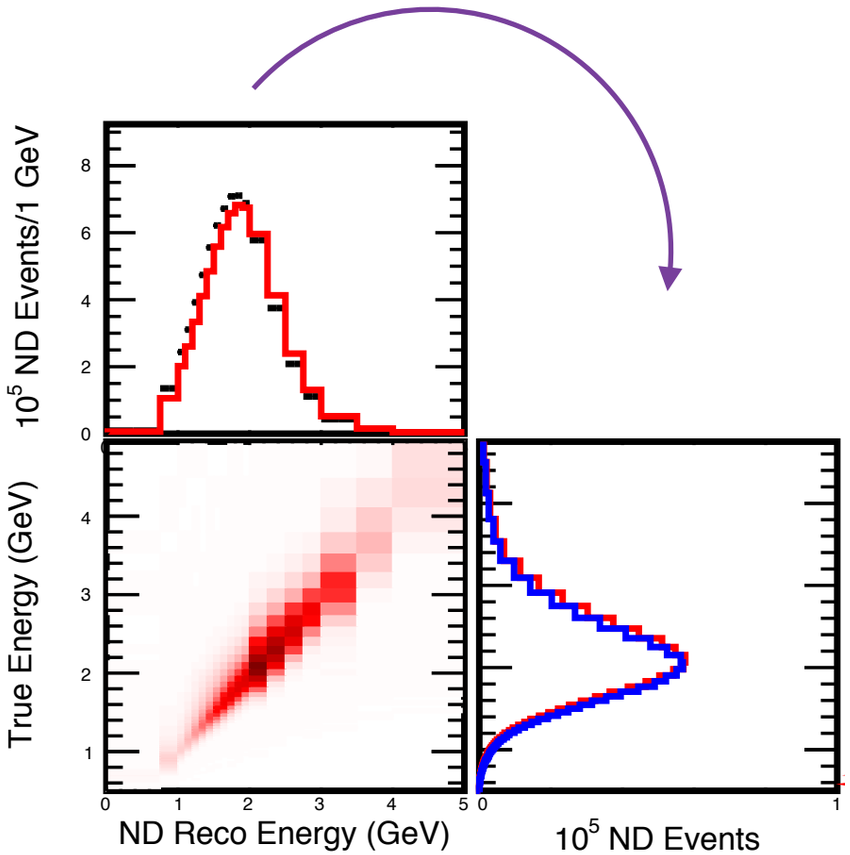


We use NOvA and external data to tune model and get better central values and appropriate uncertainties.

- The tuning is done independently for the neutrino vs antineutrino beam samples.
- Correct quasielastic (QE) component to account for effect of long-range nuclear correlations using model of Valencia group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]
- Apply same long-range effect as for QE to resonant (RES) baryon production.
- Nonresonant inelastic scattering (DIS) at high invariant mass ($W>1.7$ GeV/c^2) weighted up 10% based on NOvA data.
- "Empirical MEC" based on NOvA ND data to account for multinucleon knockout (2p2h).

FD extrapolation

Translate ND data/ MC observation to true energy



ND data

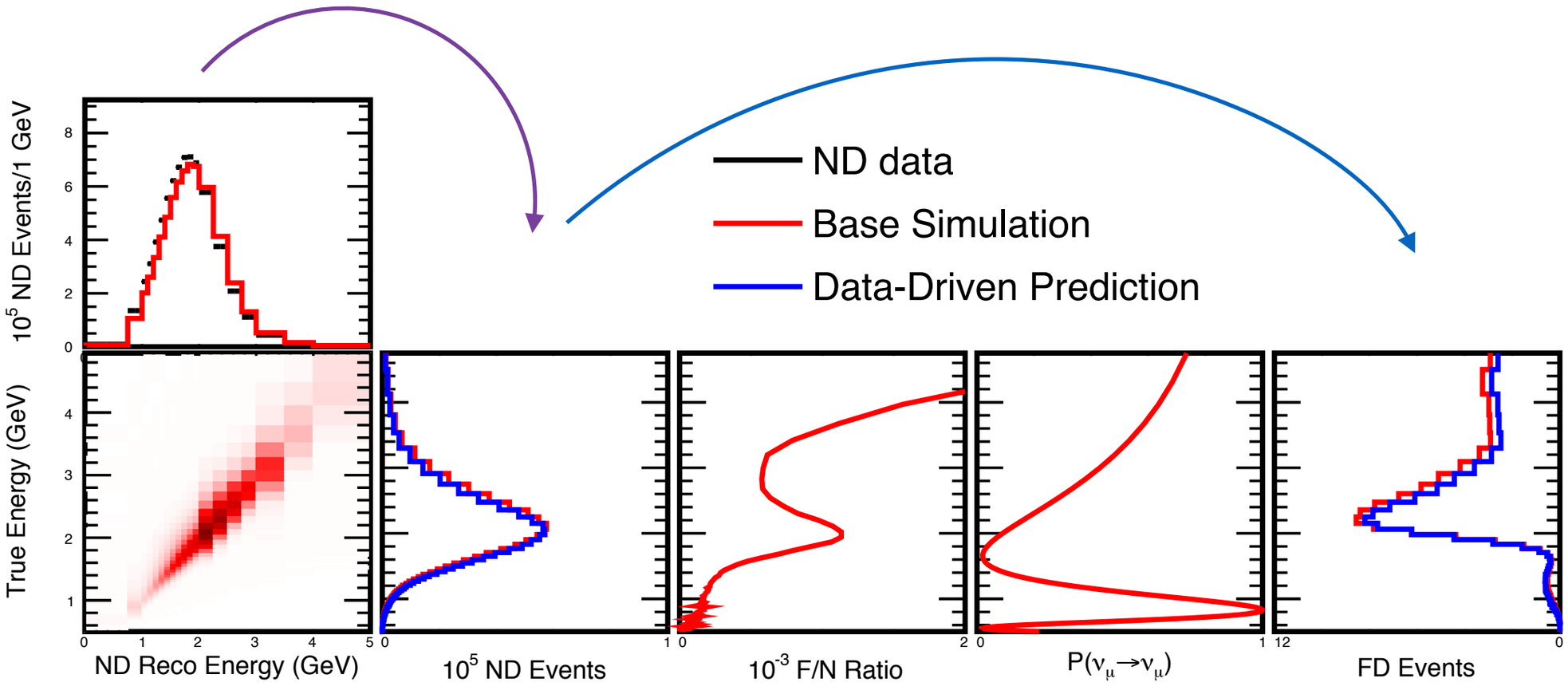
Base Simulation

Data-Driven Prediction

FD extrapolation

Translate ND data/ MC observation to true energy

Oscillate ratio to the FD

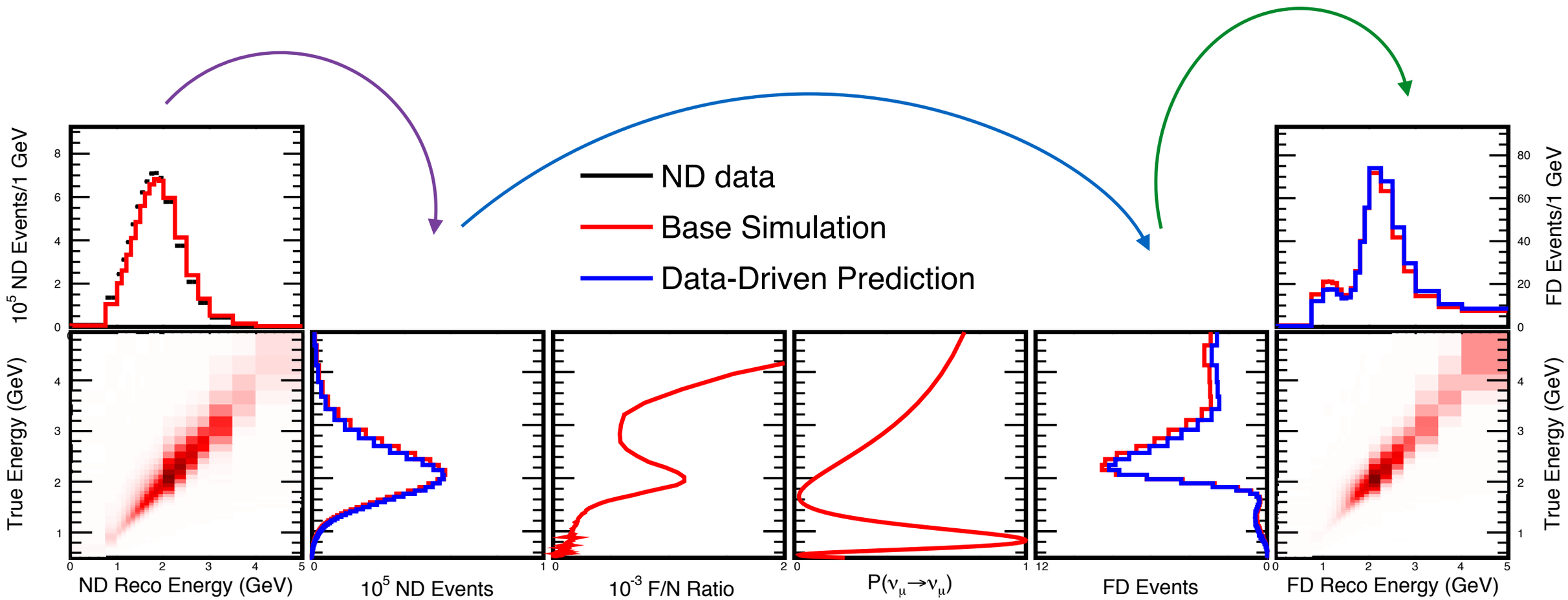


FD extrapolation

Translate ND data/ MC observation to true energy

Oscillate ratio to the FD

Smear back into reconstructed energy



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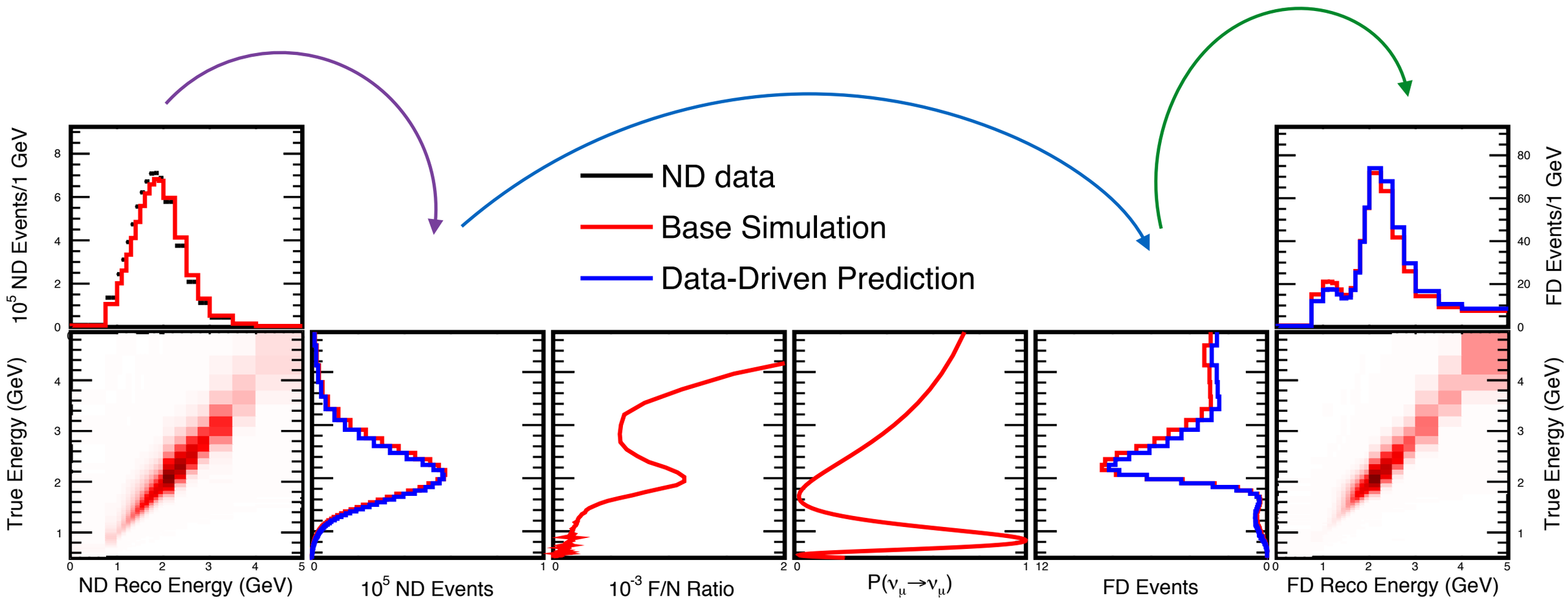
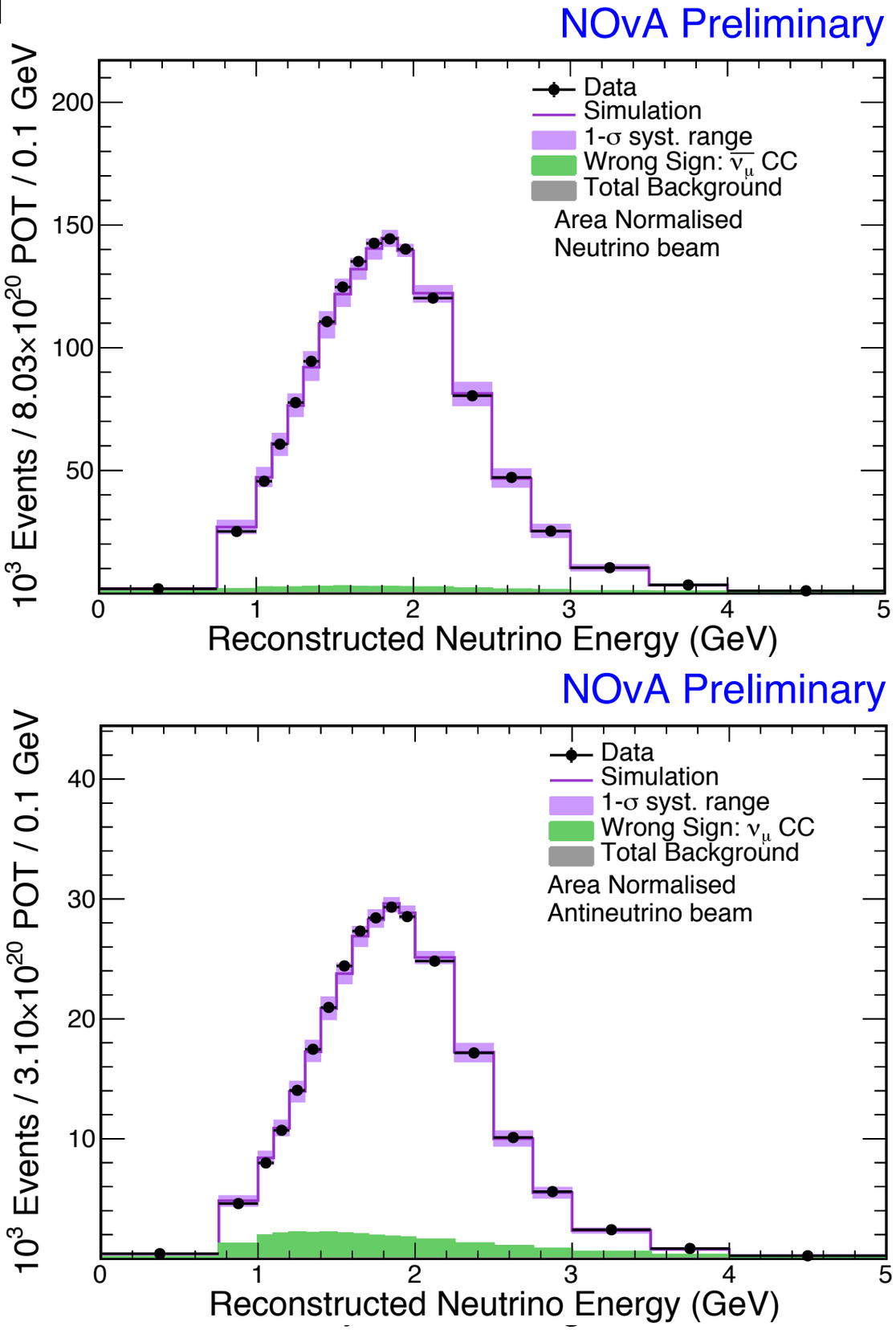


- Since NOvA has functionally similar Near and Far Detectors the flux combined with the cross sections uncertainties largely cancel.

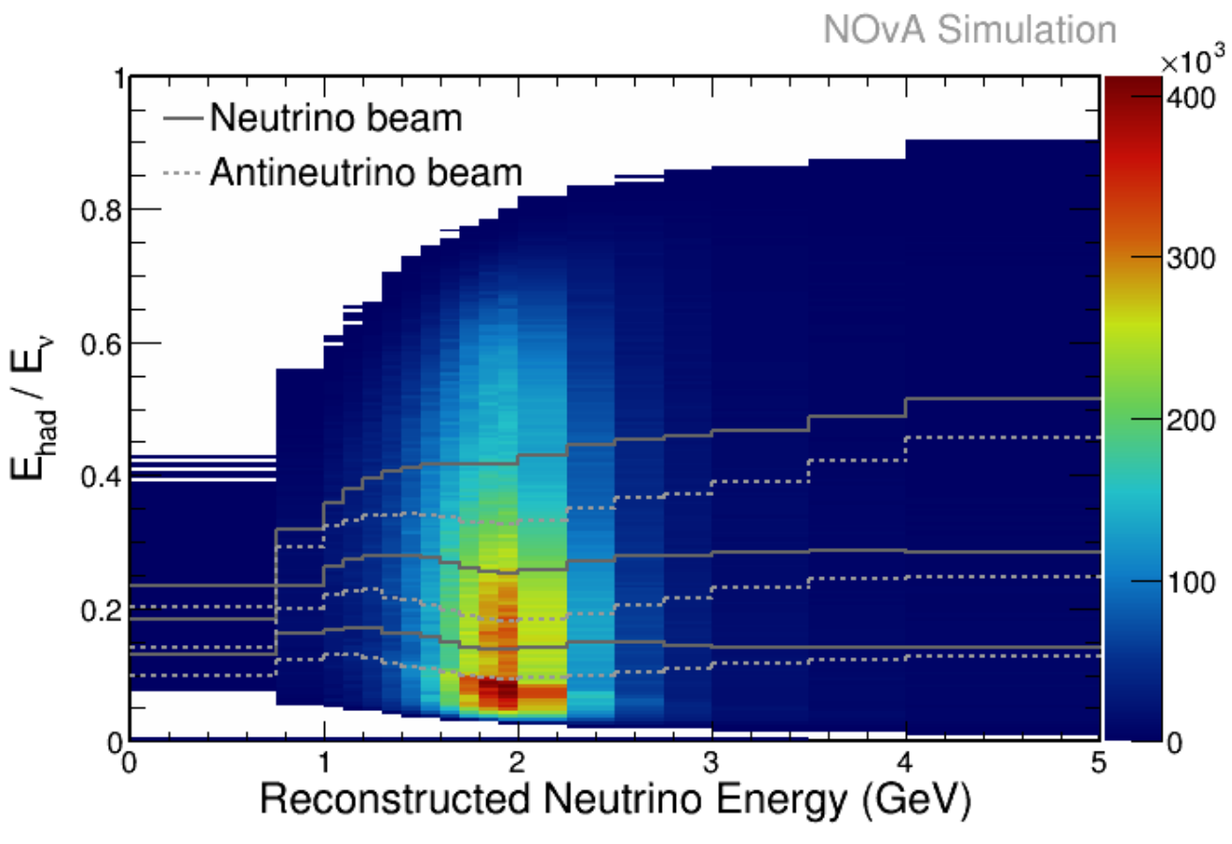
ν_μ ND spectra

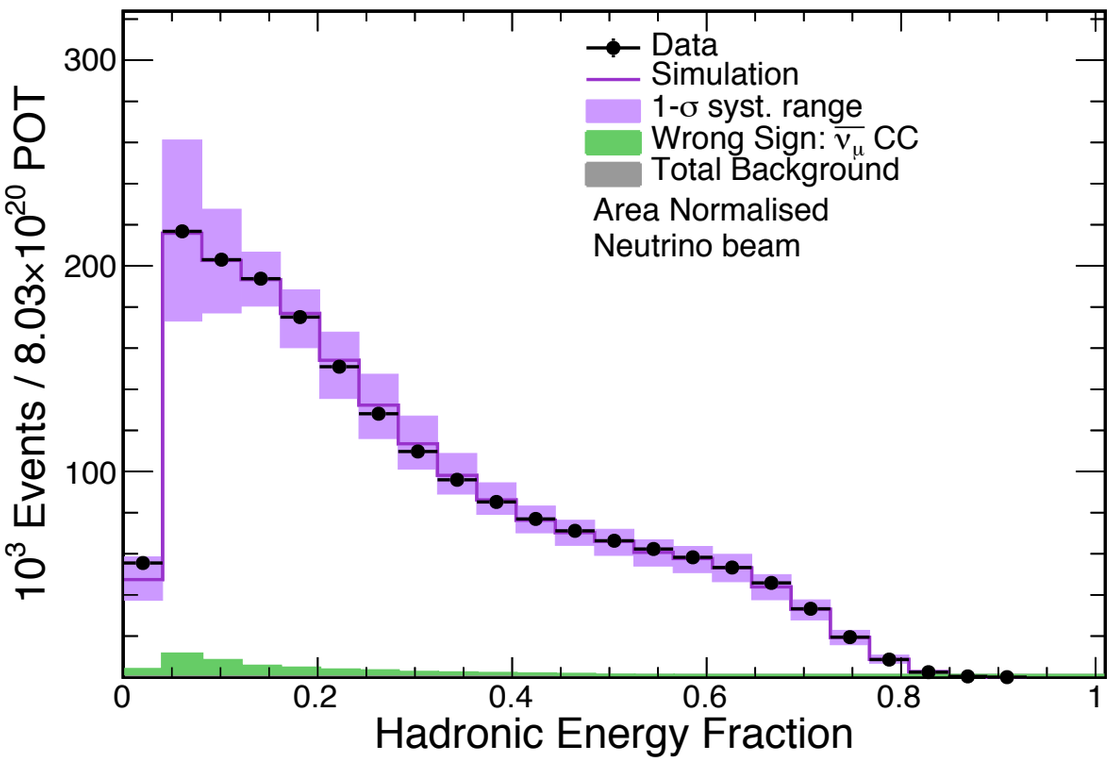
- Selected muon neutrino and antineutrino charged current interactions in ND.
- Reconstructed neutrino energy is estimated from muon length and hadronic energy.
- Wrong sign contamination is estimated to be 3 % for neutrino beam and 11% for antineutrino beam.
- Systematic uncertainties shown are shape only.

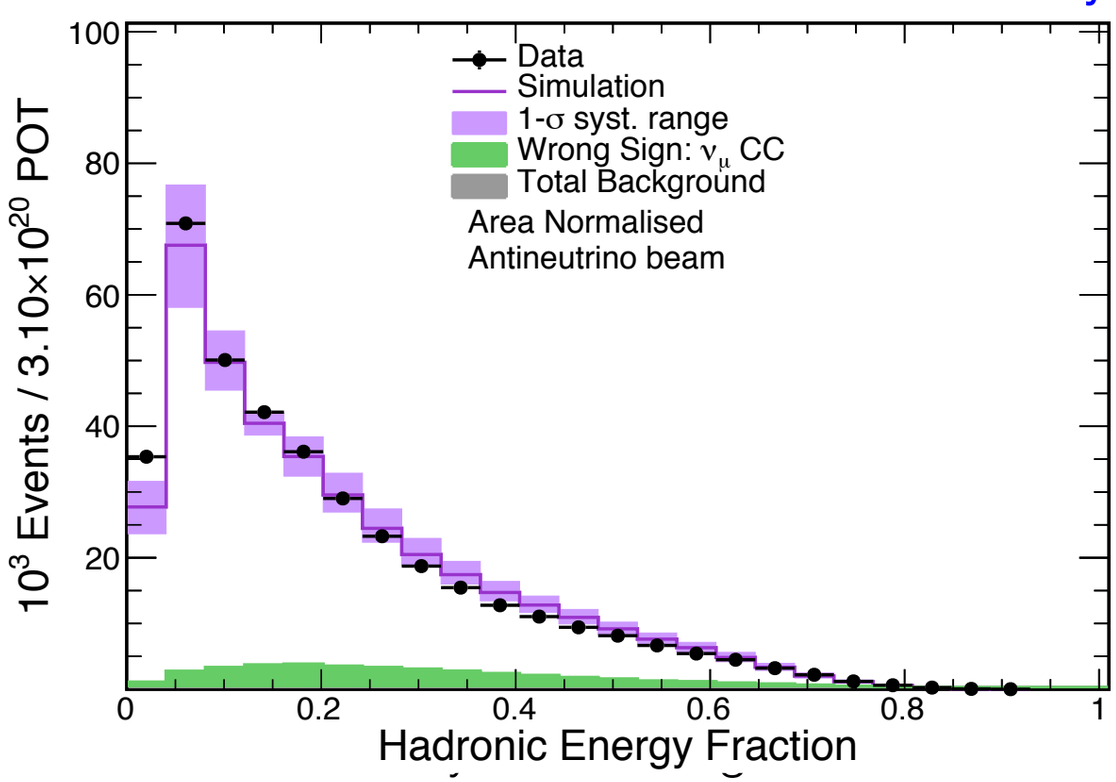


ν_μ Energy resolution quartiles

- The data is split in four equal populations (quartiles) of hadronic energy fraction as a function of reconstructed neutrino energy.
- Done separately for neutrino versus antineutrinos.
- Energy resolution varies from 5.8% (5.5%) to 11.7% (10.8%) for neutrino (antineutrino) beam.

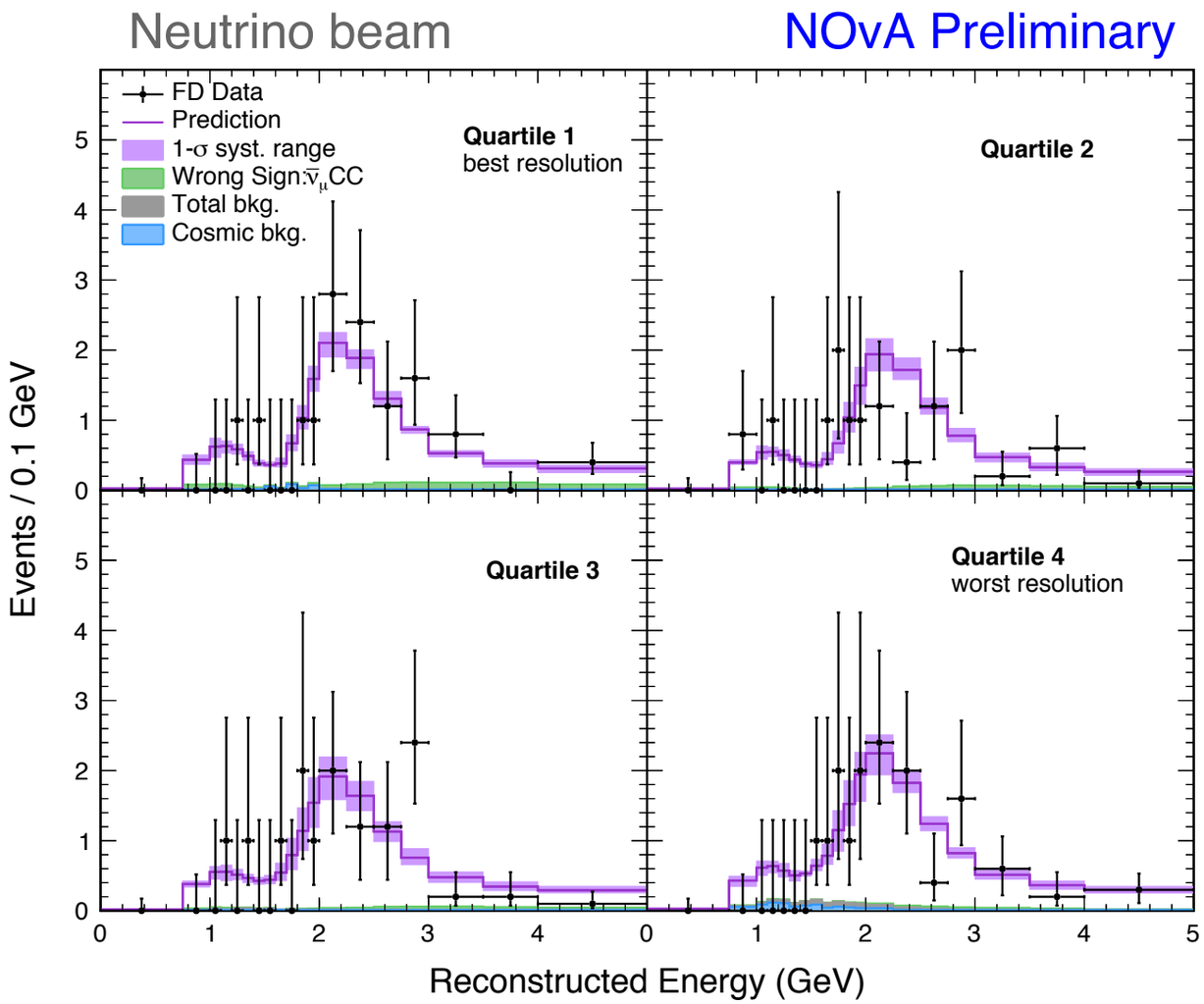


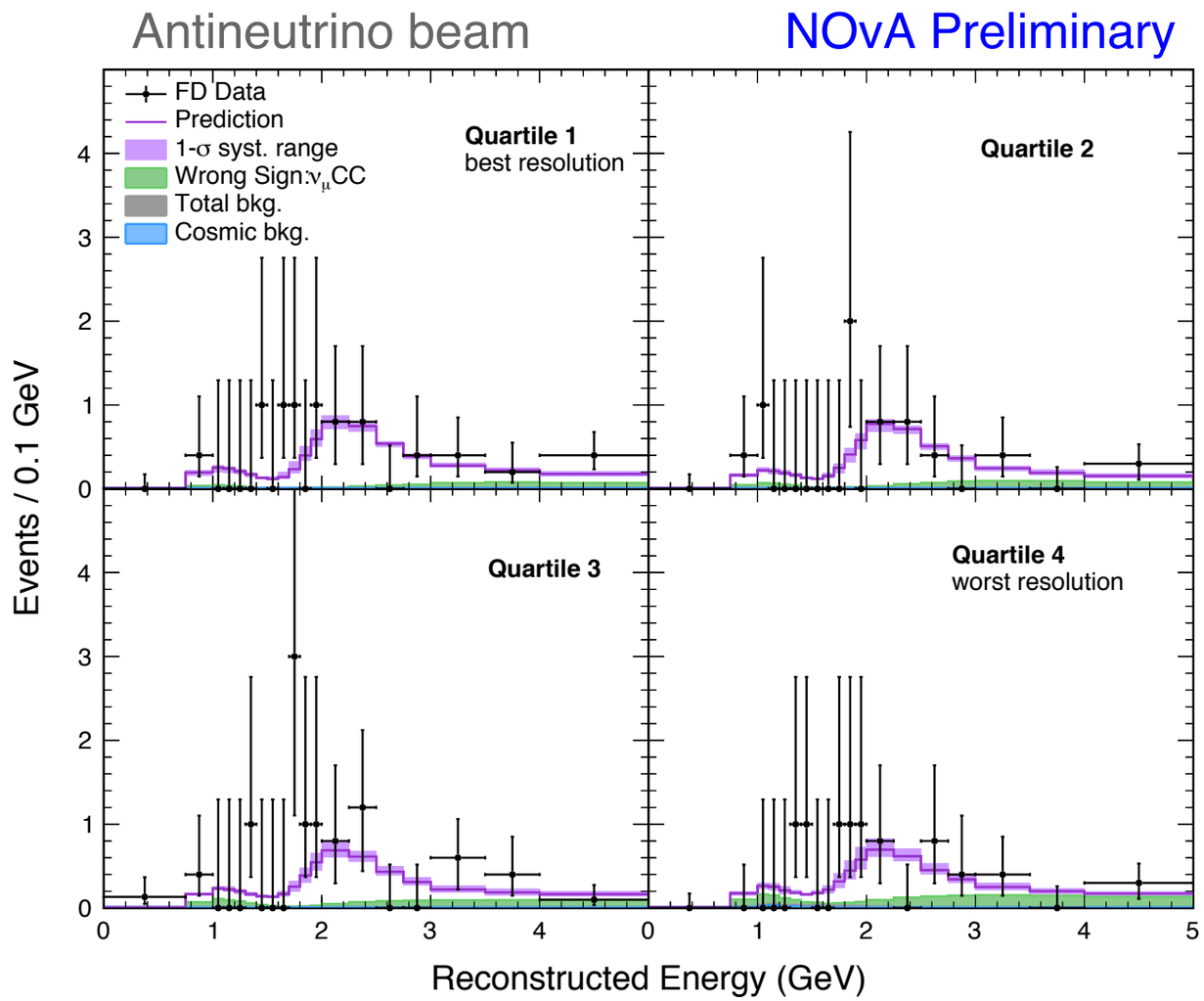




ν_μ FD prediction

- Each quartile for the neutrino and antineutrino beams gets unfolded and the true Far/Near ratio is used to obtain a FD prediction from ND data.
- Cosmic background rate estimates from the timing sidebands of the NuMI beam triggers and cosmic trigger data.
- Observe 113 events in neutrino mode (expect 730 +38/-49(syst.) ± 27(stat.) w/o oscillations), 65 events in antineutrino mode (expect 266 +12/-14(syst.) ± 16(stat.) w/o oscillations).





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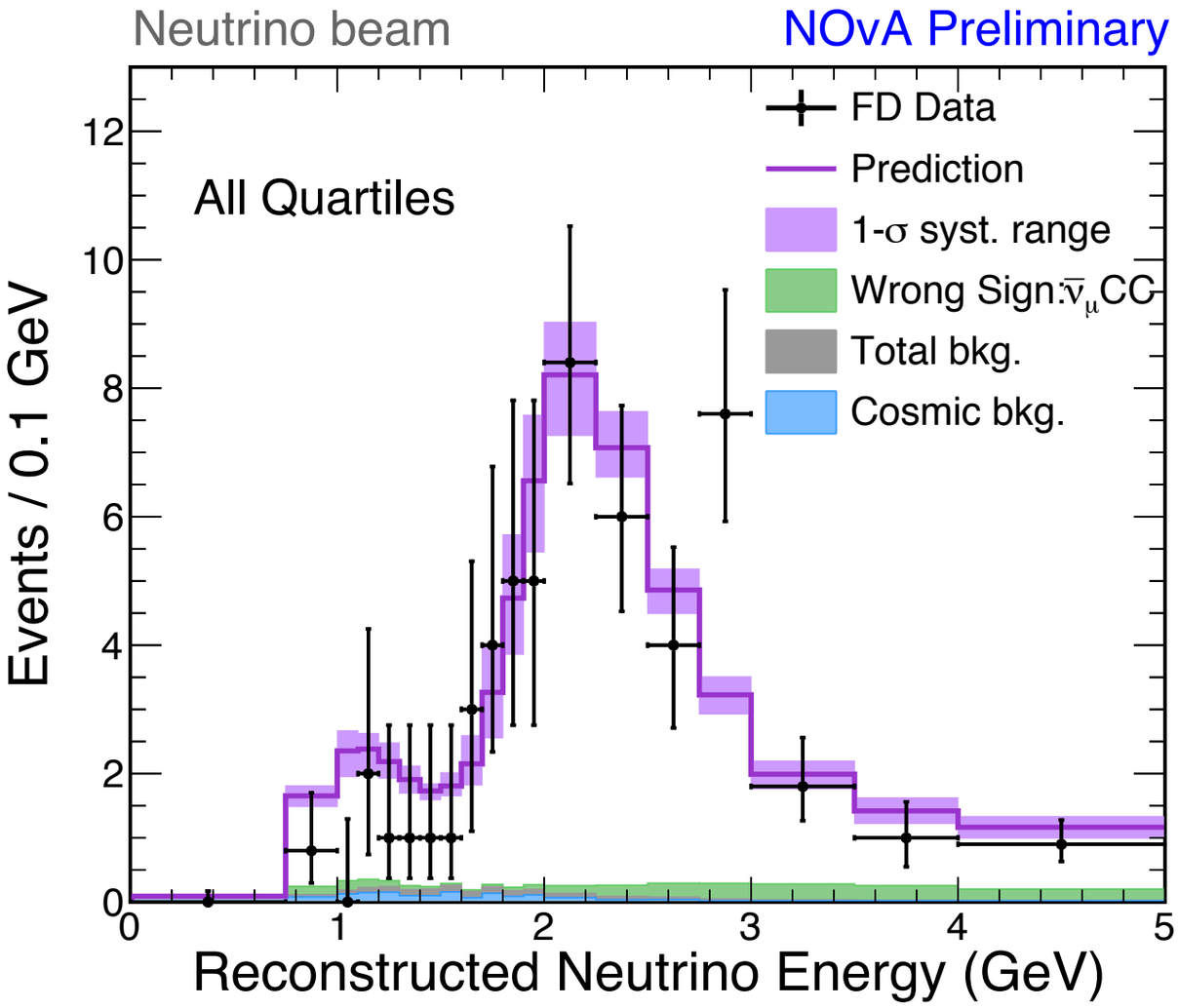
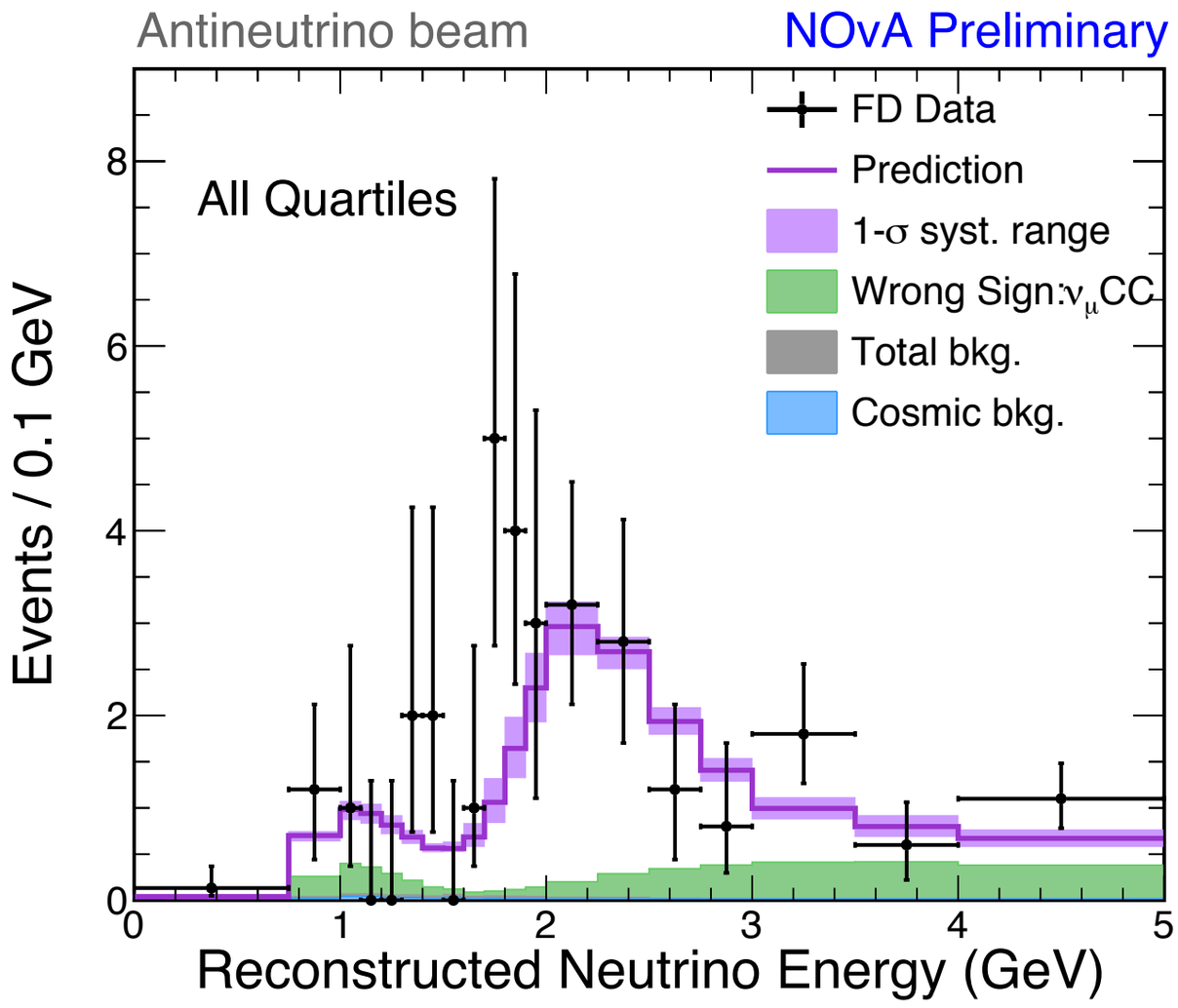
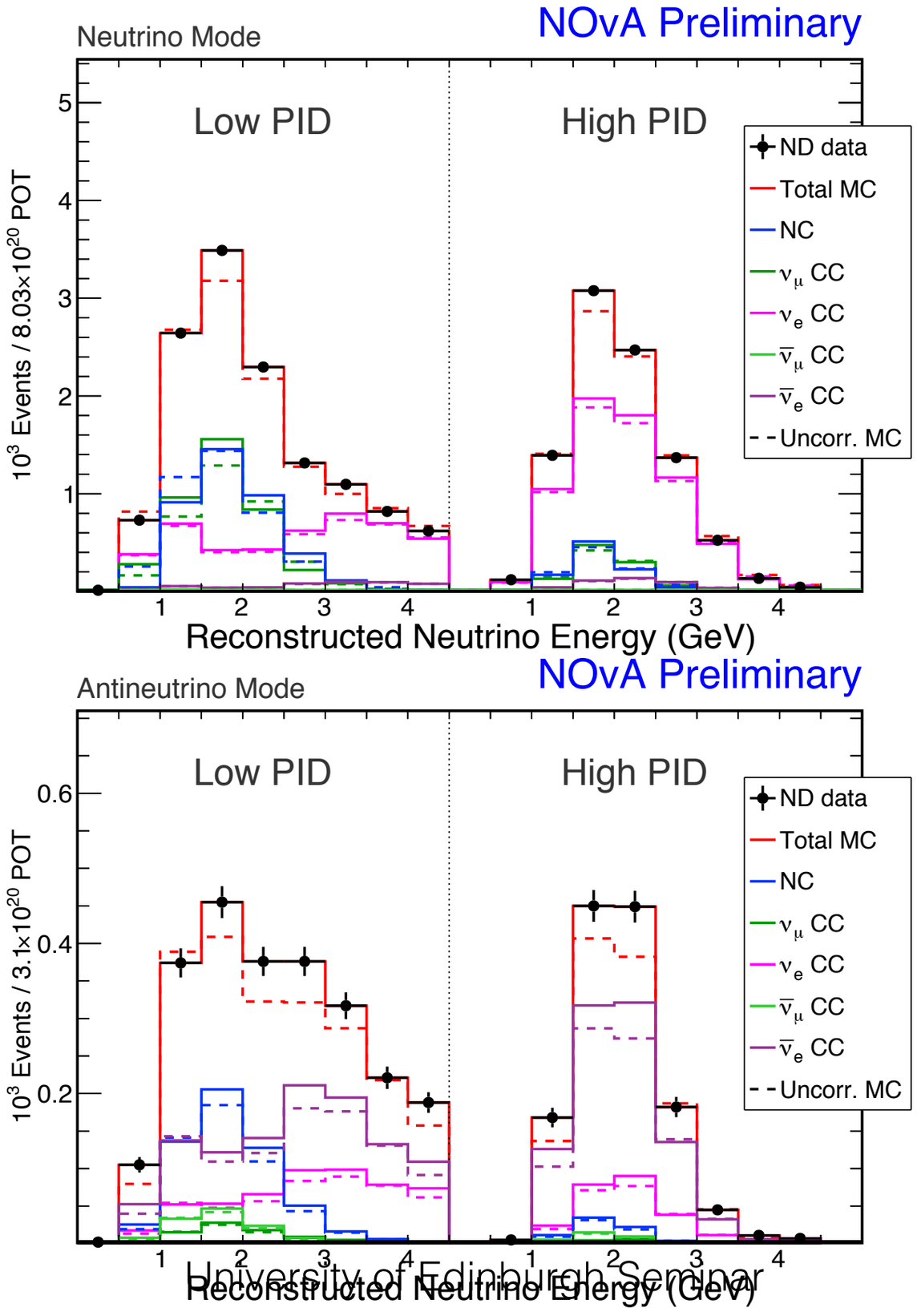




Electron neutrino data

- Select electron neutrino events using particle ID in the ND for each beam mode.
- Separate into low and high particle ID (purity) range.
- For the neutrino beam constrain:
  - the beam electron neutrinos using the muon neutrino spectrum, and
  - the muon neutrino background using Michel electrons,
  - remaining data/MC discrepancy is assigned to the neutral current component.
- For the antineutrino beam, simply scale all components to match the data.



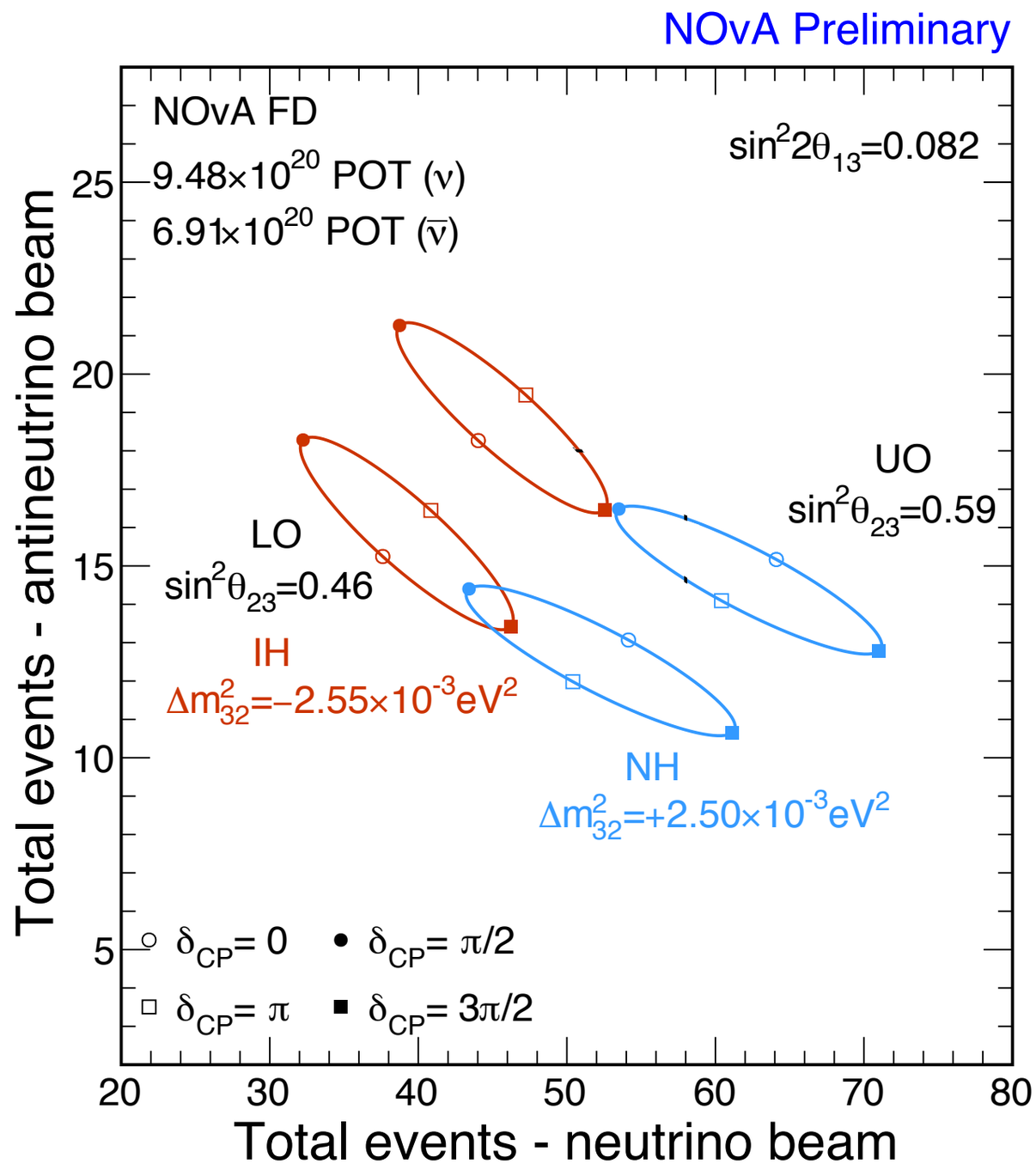
Sandbox Studio, Chicago

Oscillation results

(David Bowie “Changes”)

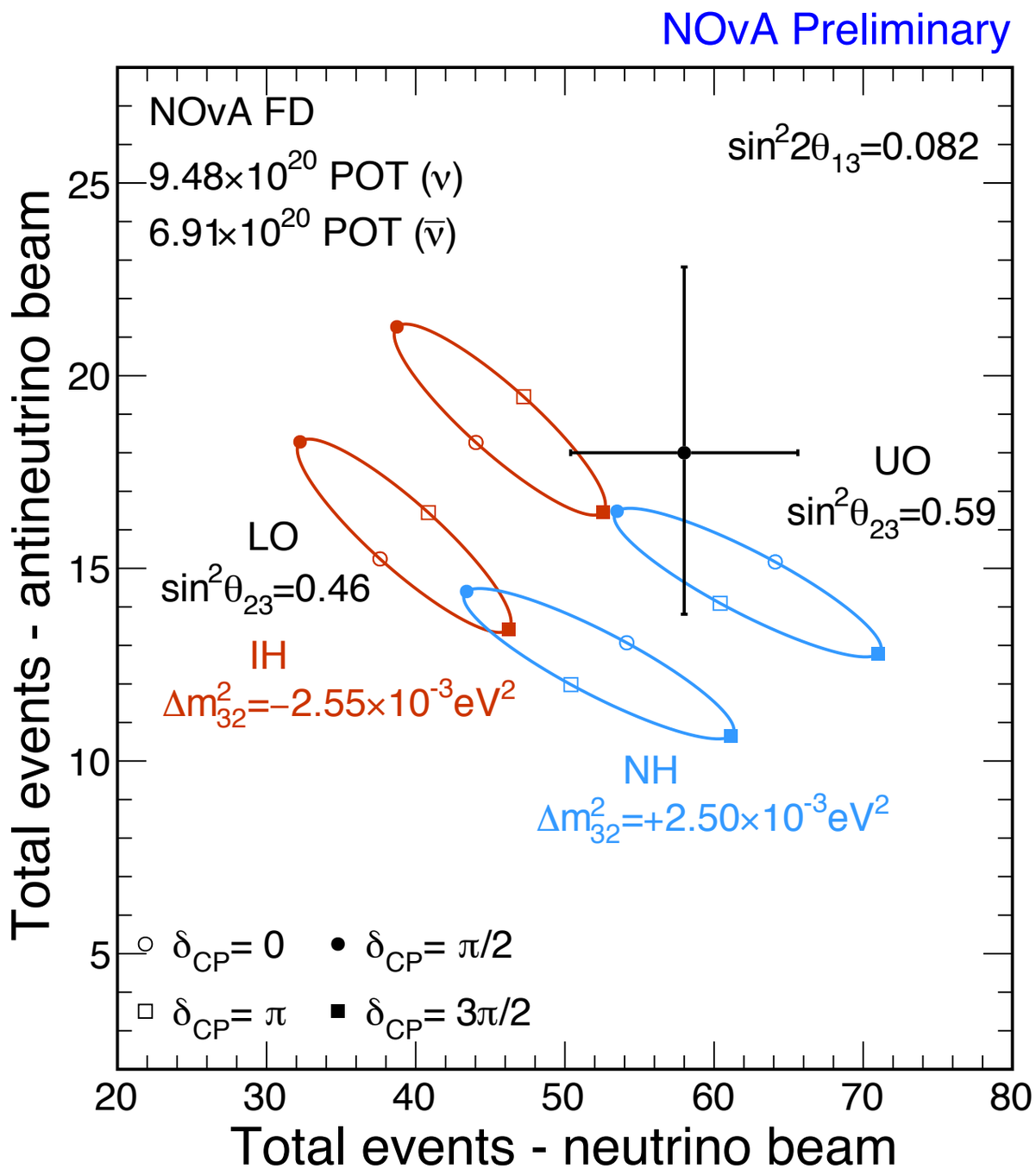
ν_e expectations

- 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 and IH) as well as upper and lower octant (UO and LO).



ν_e expectations

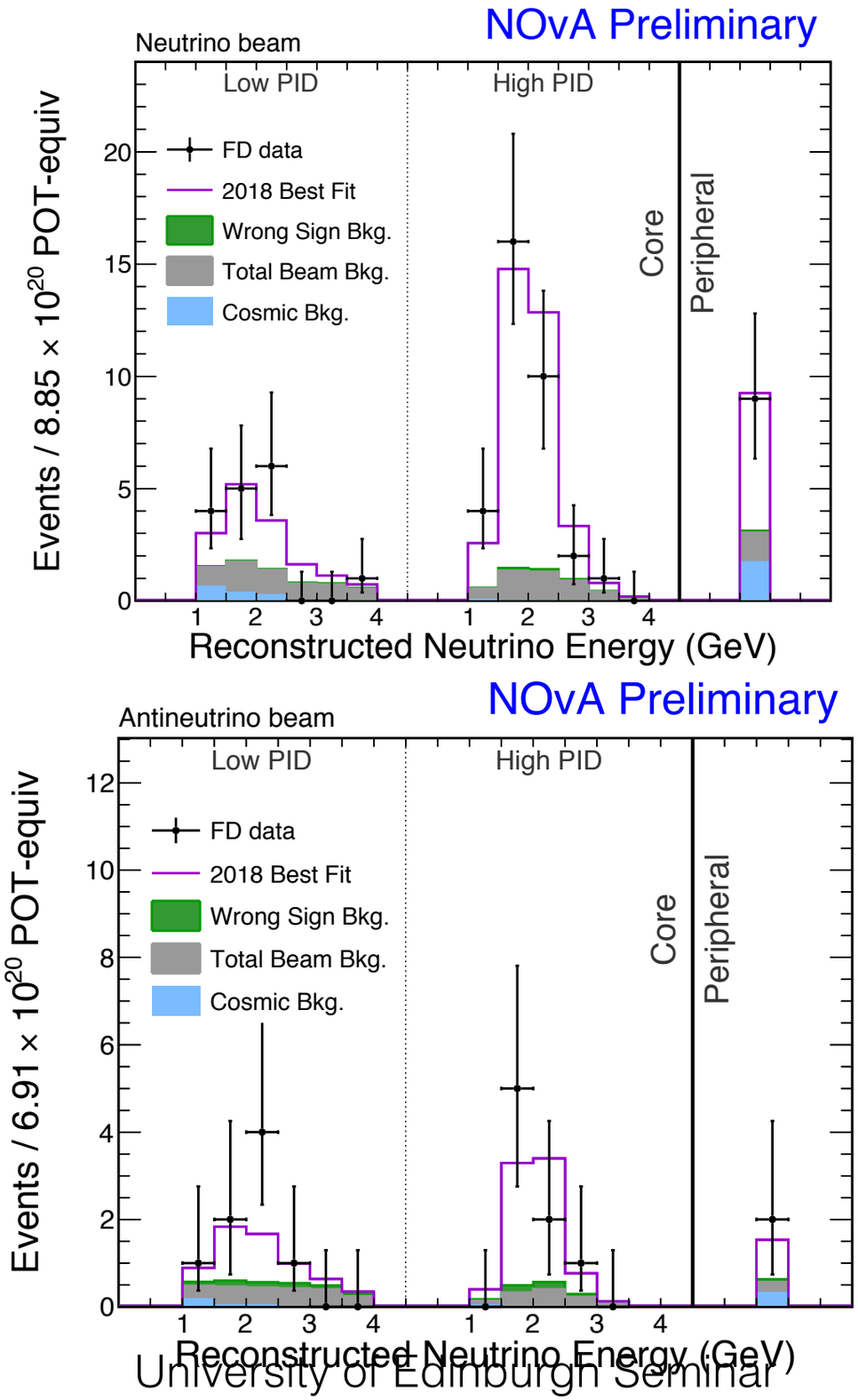
- Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.
- Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).
- NOvA observes 58 events in neutrino, and 18 events in antineutrino mode



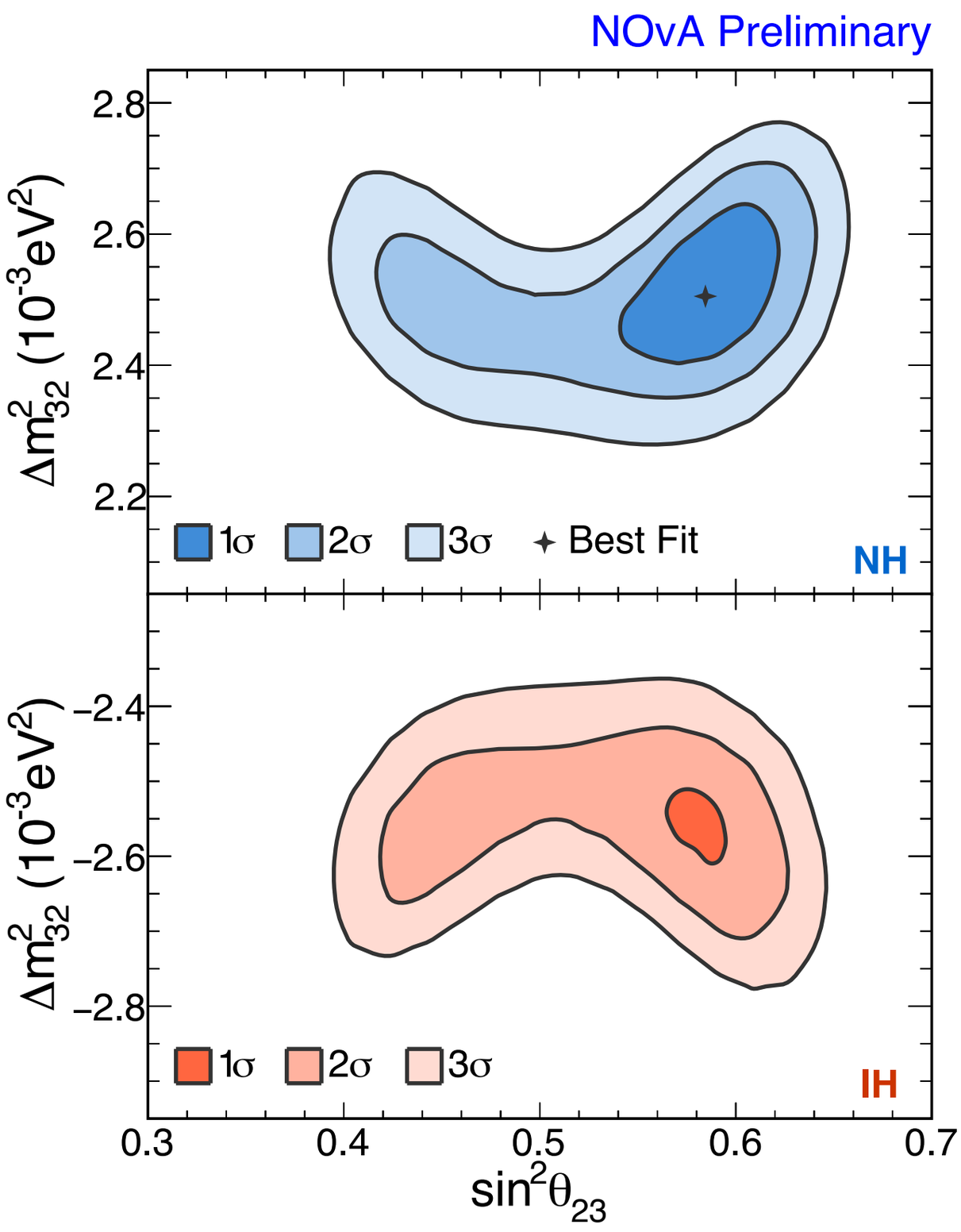
$\nu_e/\bar{\nu}_e$ appearance

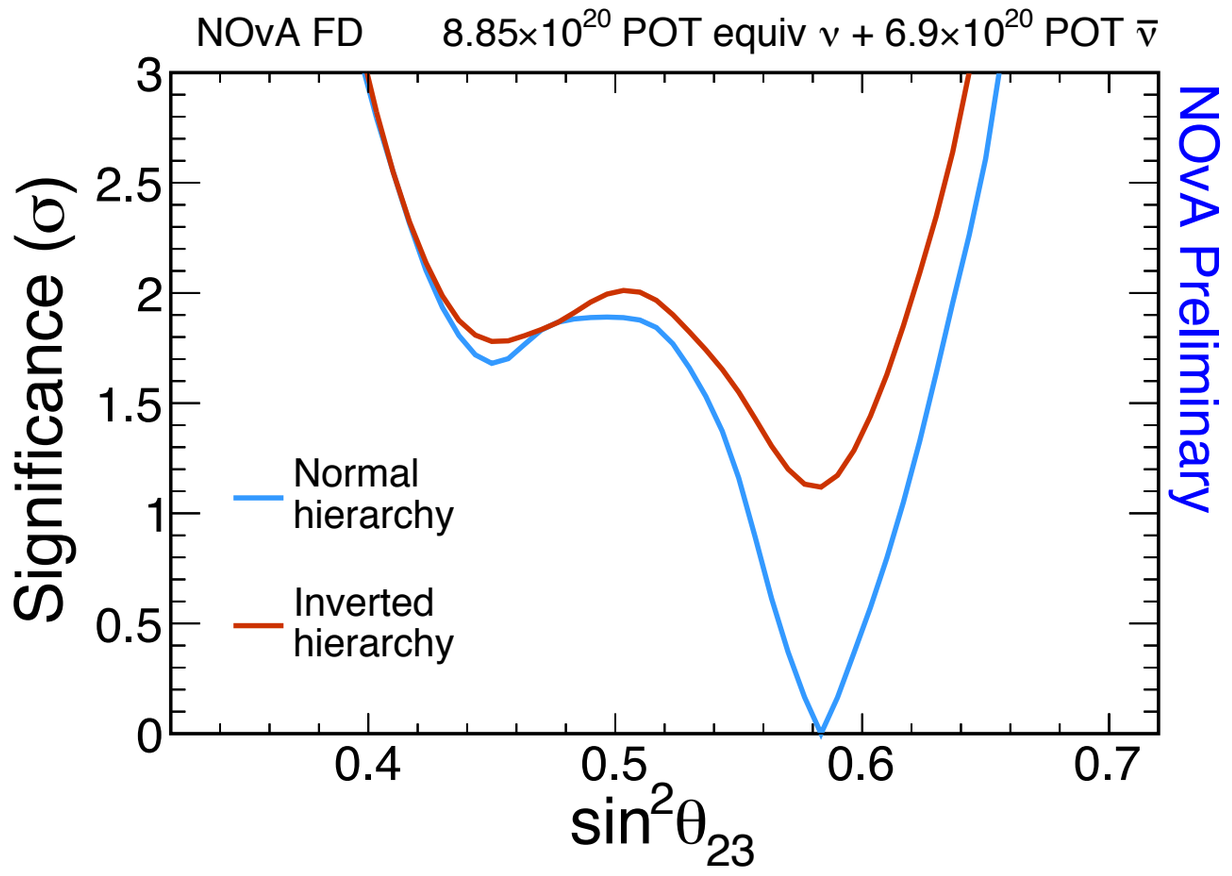
- We use the ND data to predict the background in the FD. Each component is propagated independently in bins of energy and particle ID bins.
- Add peripheral sample as one bin with looser cosmic rejection cut.
- On the neutrino beam we observe 58 events and expect 15 background interactions.
- For the antineutrino beam we observe 18 and expect 5.3 background interactions.

> 4 sigma evidence of electron antineutrino appearance



Allowed oscillation parameters





Best fit: NH

$\delta_{CP} = 0.17\pi$

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

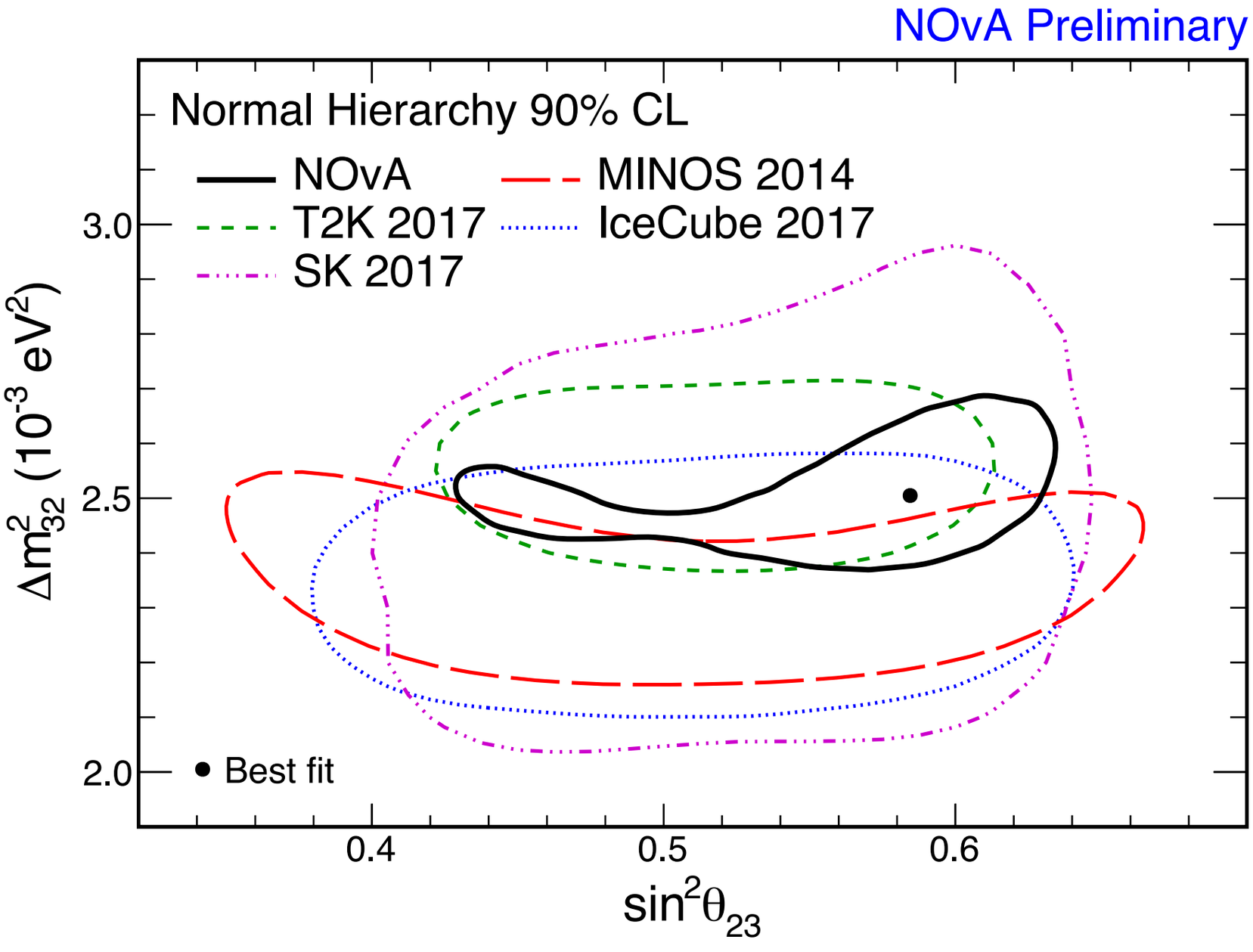
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) 10^{-3}$ eV^2

Prefer non-maximal at 1.8σ

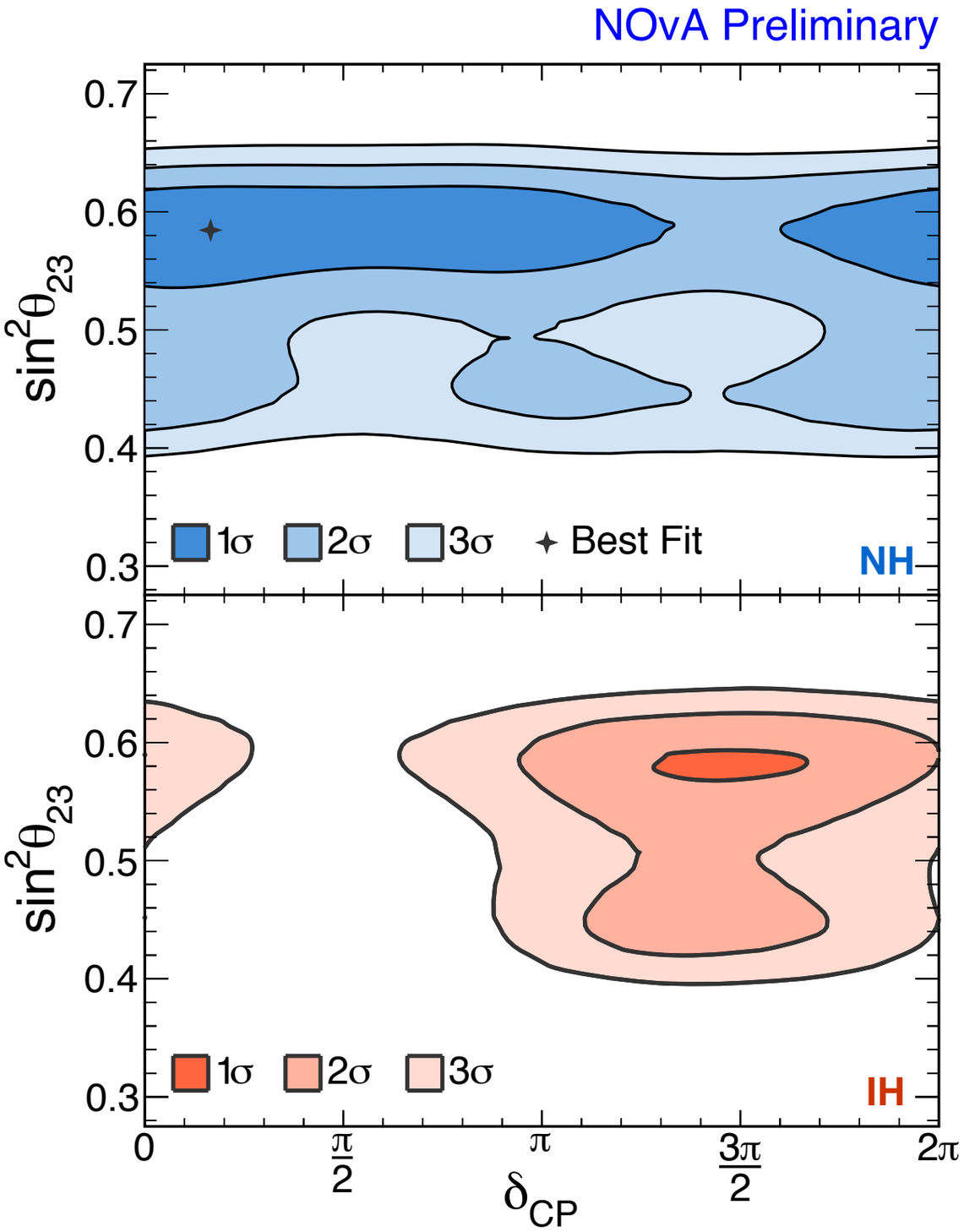
Exclude LO at similar level

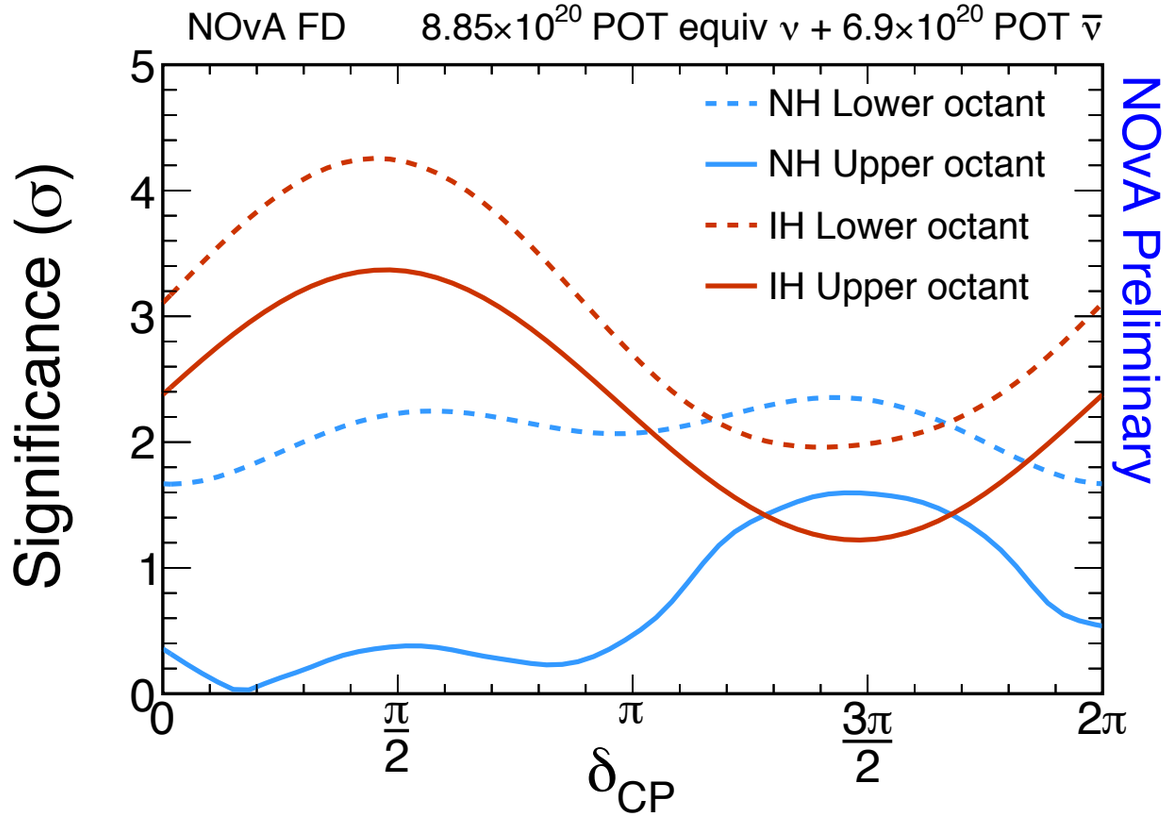
Allowed region comparison

NOvA's results compared to other experiments.
Allowed 90% regions are compatible.



Allowed oscillation parameters





Best fit: NH

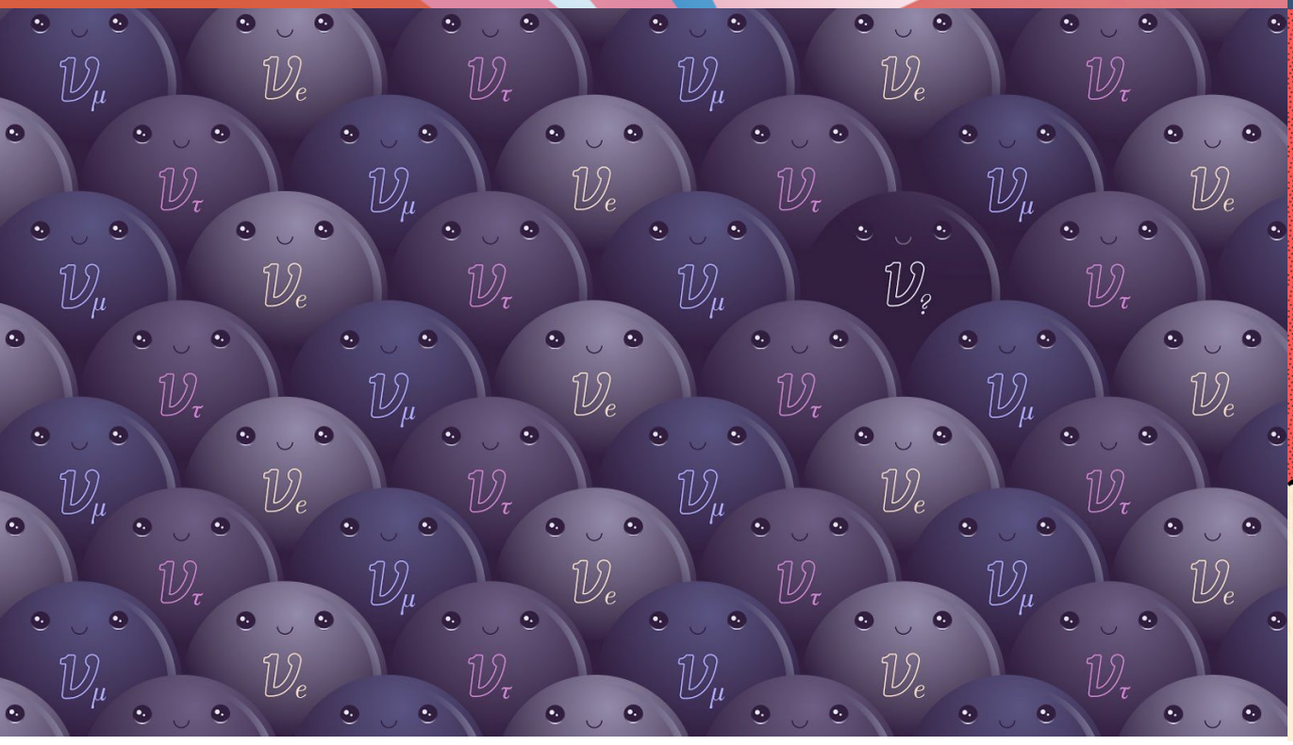
$\delta_{CP} = 0.17\pi$

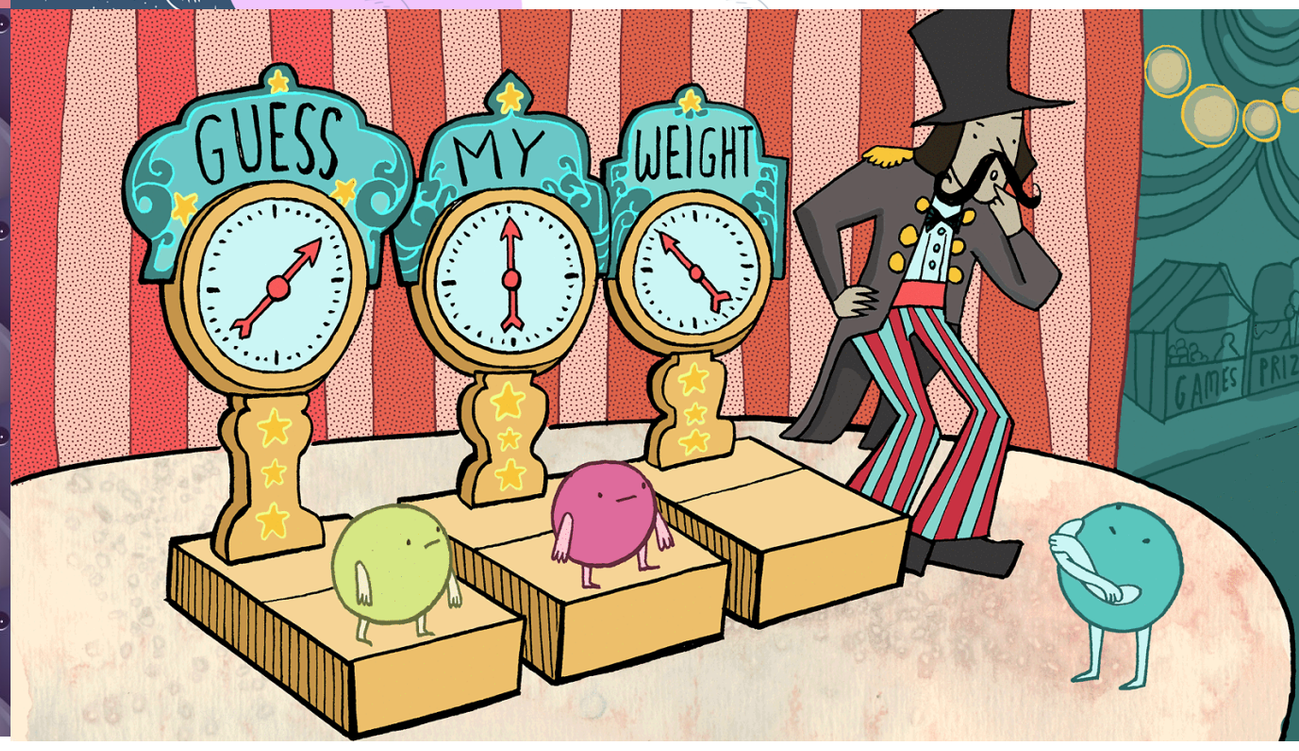
$\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)

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

Prefer NH by 1.8σ

Exclude δ=π/ 2 in the IH at > 3σ



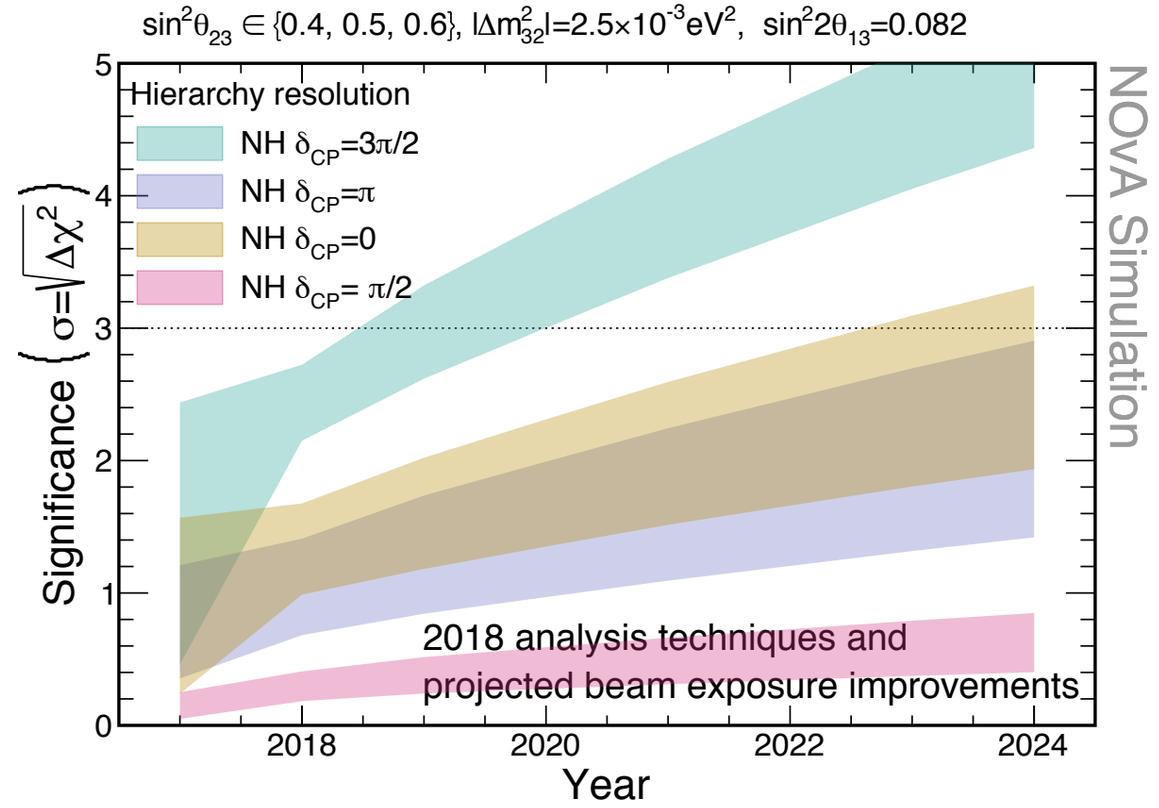


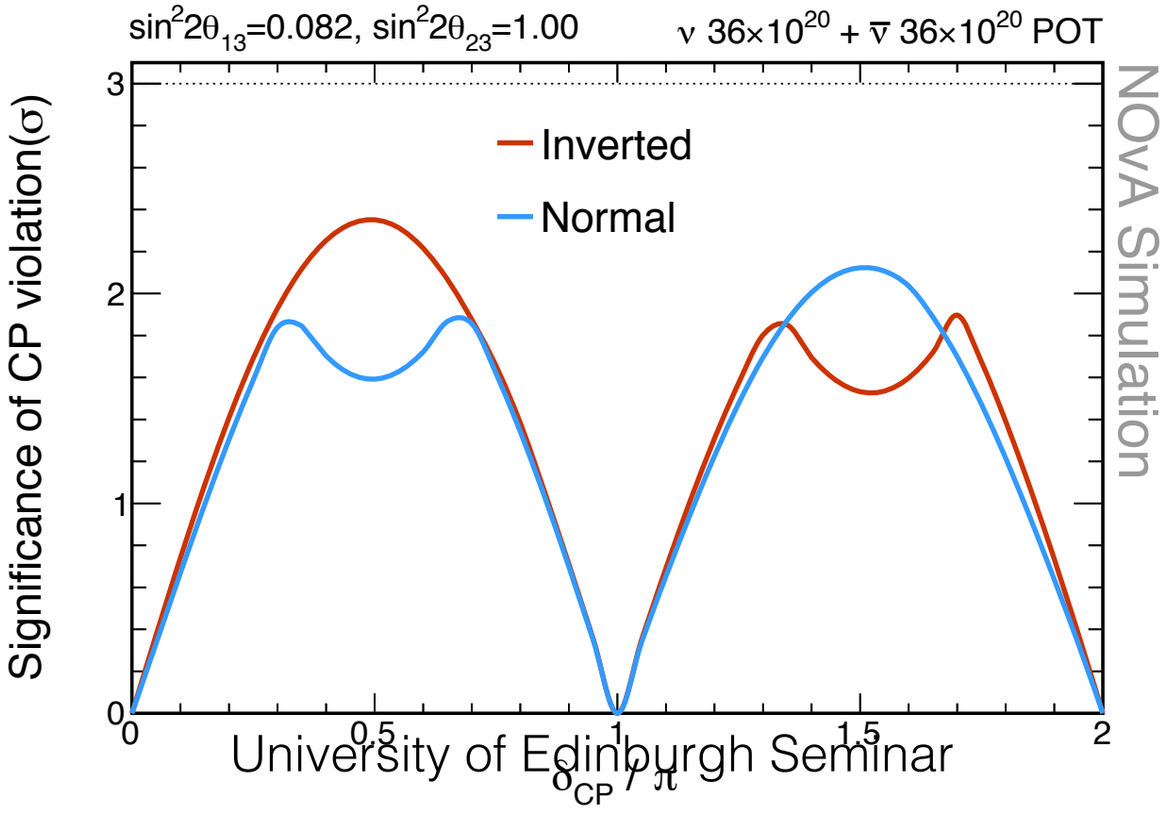
Future

(Journey “Don’t stop believin’”)

NOvA prospects

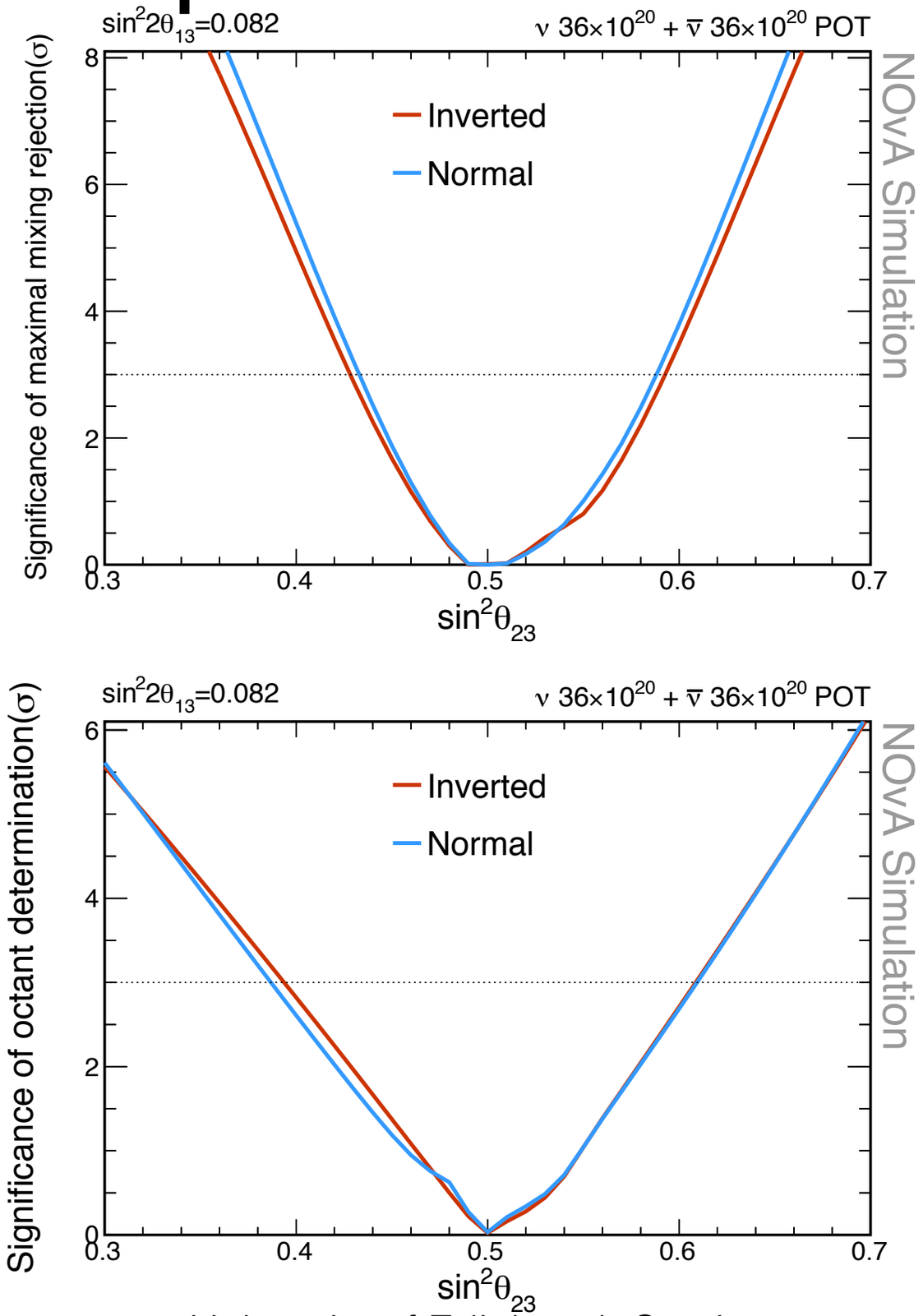
- Currently running anti-neutrino beam. Run 50% neutrino, 50% antineutrino after 2018.
- Extended running and accelerator improvement projects enhance NOvA's ultimate reach.
- 3 σ sensitivity to hierarchy (if NH and 3π/2 CP) for allowed range of θ_{23} by 2020. 3 σ sensitivity for 30-50% (depending on octant) of CP range by 2024.
- 2+ σ sensitivity for CP in both hierarchies at 3π/2 and π/2 CP by 2024.





NOvA prospects

- Currently running anti-neutrino beam. Run 50% neutrino, 50% antineutrino after 2018.
- Extended running and accelerator improvement projects enhance NOvA's ultimate reach.
- 3 σ sensitivity to θ_{23} maximal mixing outside of the 0.42-0.58 range by 2024.
- 3 σ sensitivity for octant determination around 0.4 and 0.6 by 2024.



Things I didn't talk about…

- Sterile neutrino search:
  - Measured the near detector NC spectrum and looking for NC disappearance at the far detector
  - No suppression of NC interactions observed for neutrinos or antineutrinos (Phys. Rev. D 96, 072006)
- Neutrino interaction cross-section measurements:
  - First measurements of neutrino-induced π0 cross-sections in NOvA ND
  - CC inclusive and semi-inclusive analyses presented at NuInt 2018 and will be published soon
- Supernova
- Monopoles

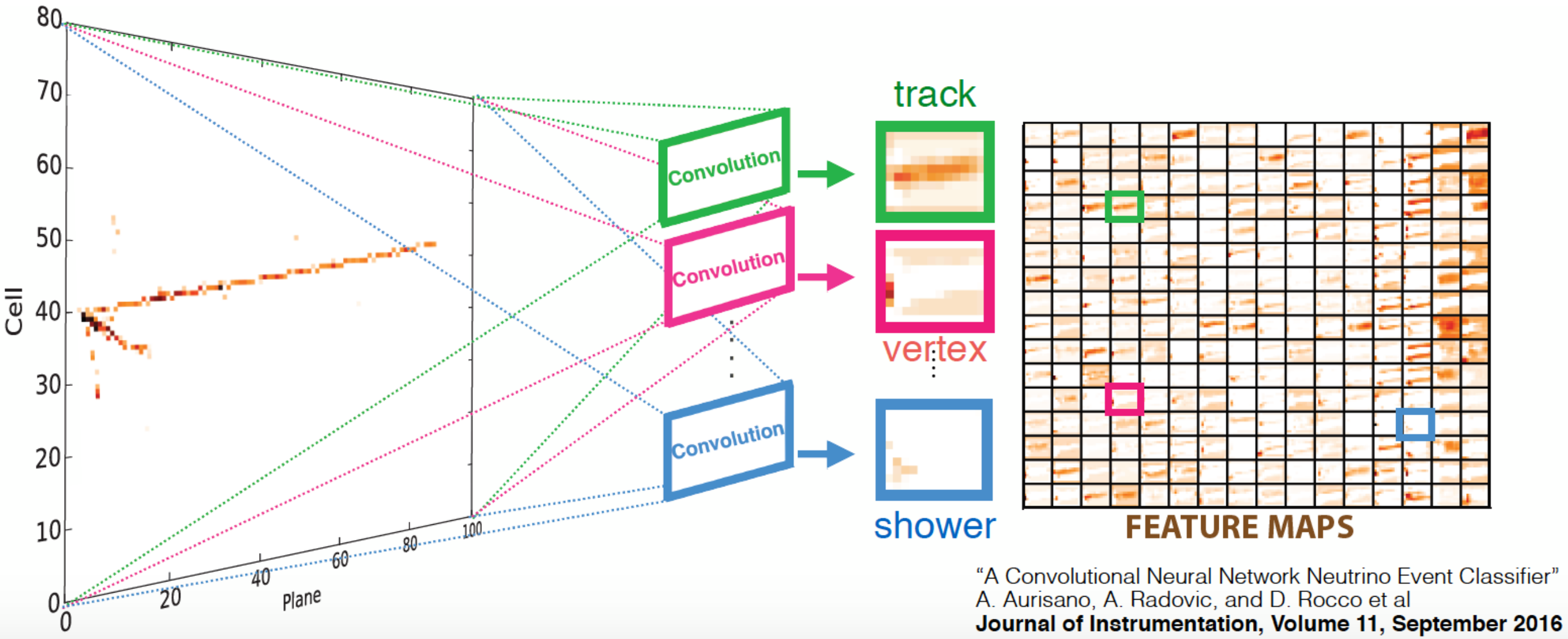
Summary

- First NOvA antineutrino data (6.9 x10^{20} POT) has been analysed together with 8.85 x10^{20} POT of neutrino data.
- We observe >4 σ evidence of antineutrino appearance.
- A joint neutrino and antineutrino combined analysis for these data:
  - Prefers Normal Hierarchy at 1.8 σ and excludes $\delta_{CP}= \pi/2$ at > 3 σ.
  - Rejects maximal mixing at 1.8 σ and the lower octant at a similar level.
- Future NOvA running will reach 3 σ sensitivity for the hierarchy by 2020 (if NH, $\delta_{CP}=3\pi/2$).

Thank you!

Neutrino interaction classifier

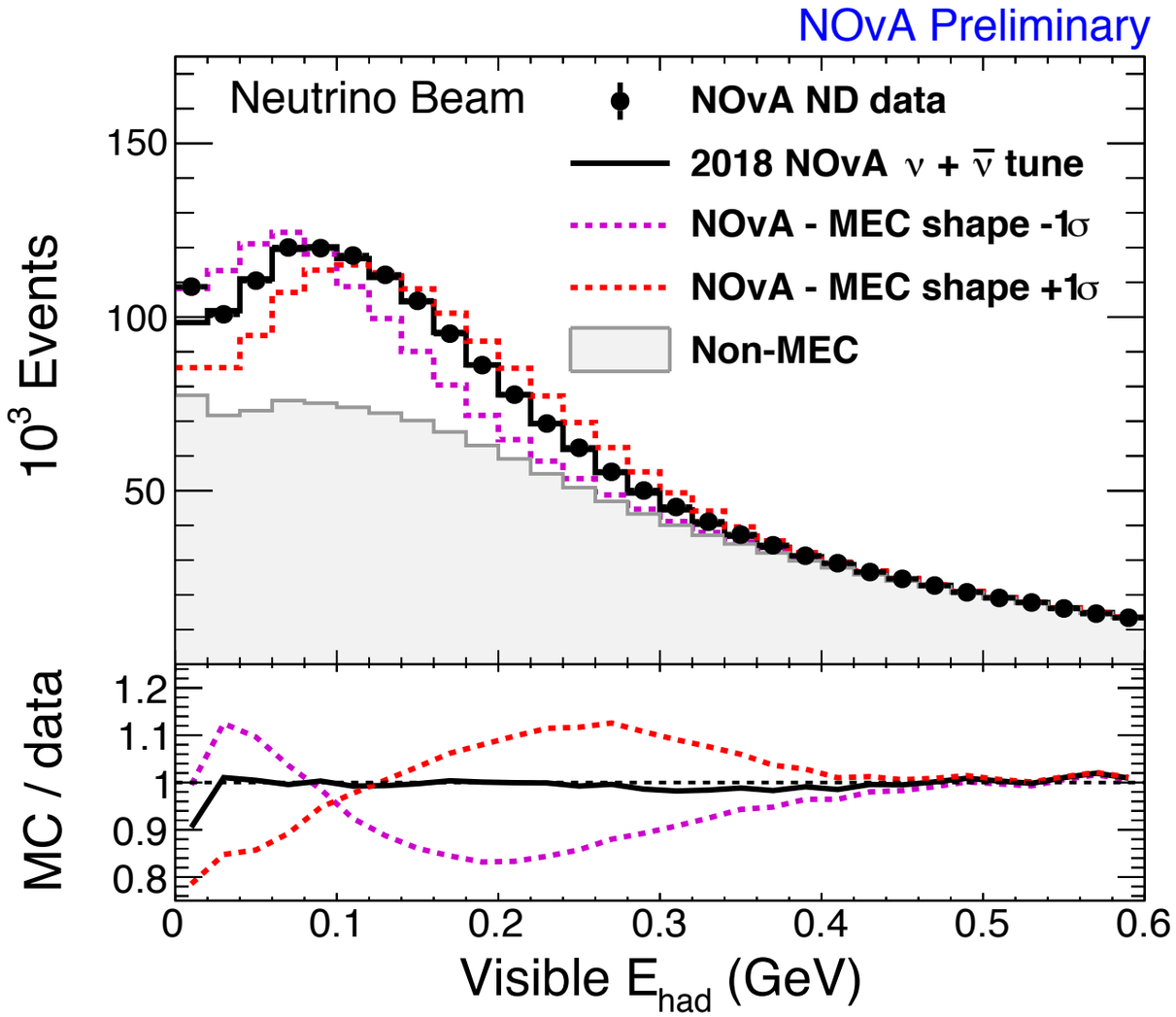
- Use all information in each event with tools from the computer vision community: a Convolutional Visual Network (CVN) based on the GoogLeNet architecture.
- Convolutional layers learn filters to optimally extract features from the data.
- Treats each event as an image with cells as pixels and charge as a colour value
- The architecture is a multi-classifier, assigning an ID : ν_μ, ν_e, NC, cosmic for each interaction.

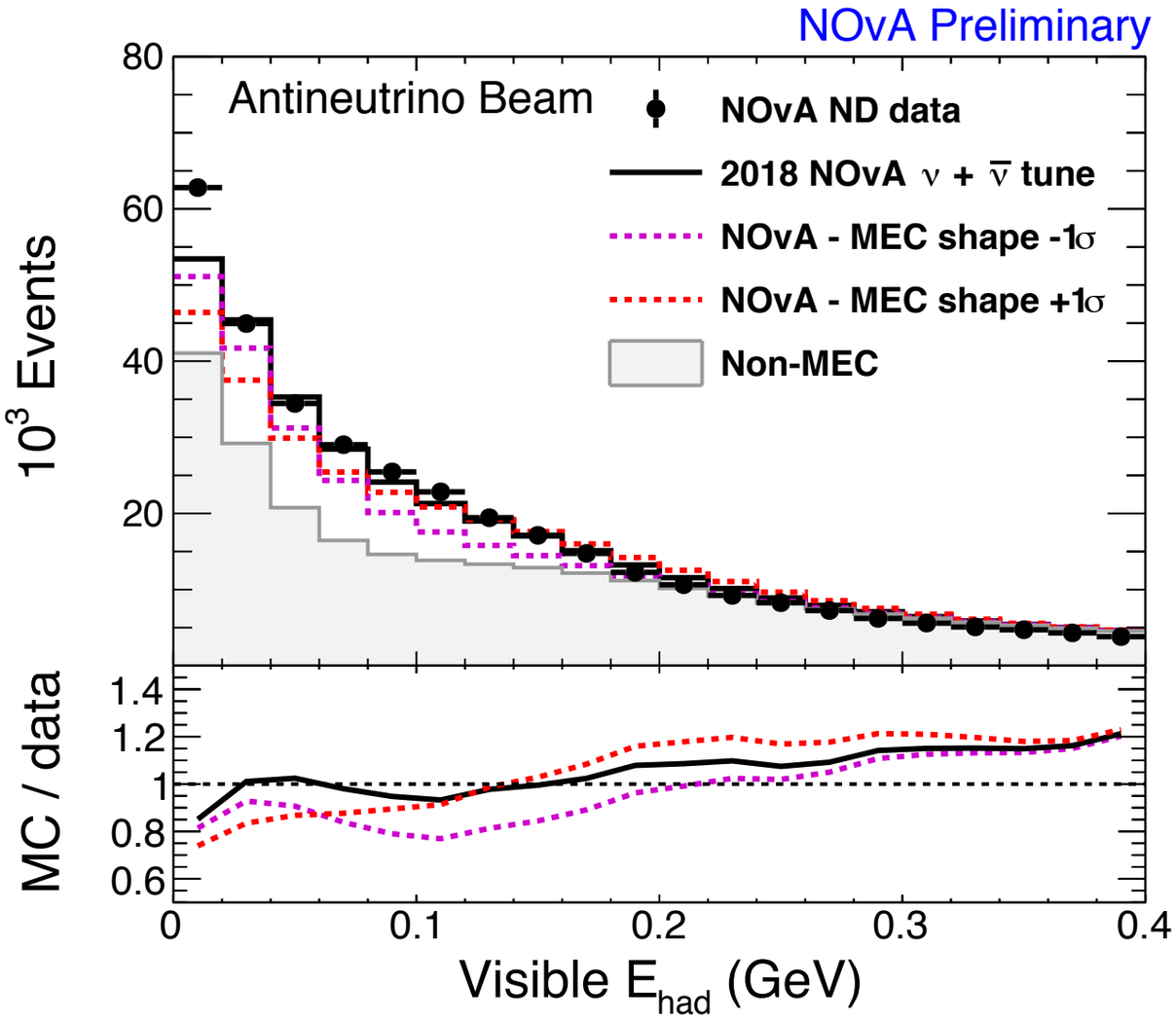


"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

Neutrino interaction tuning

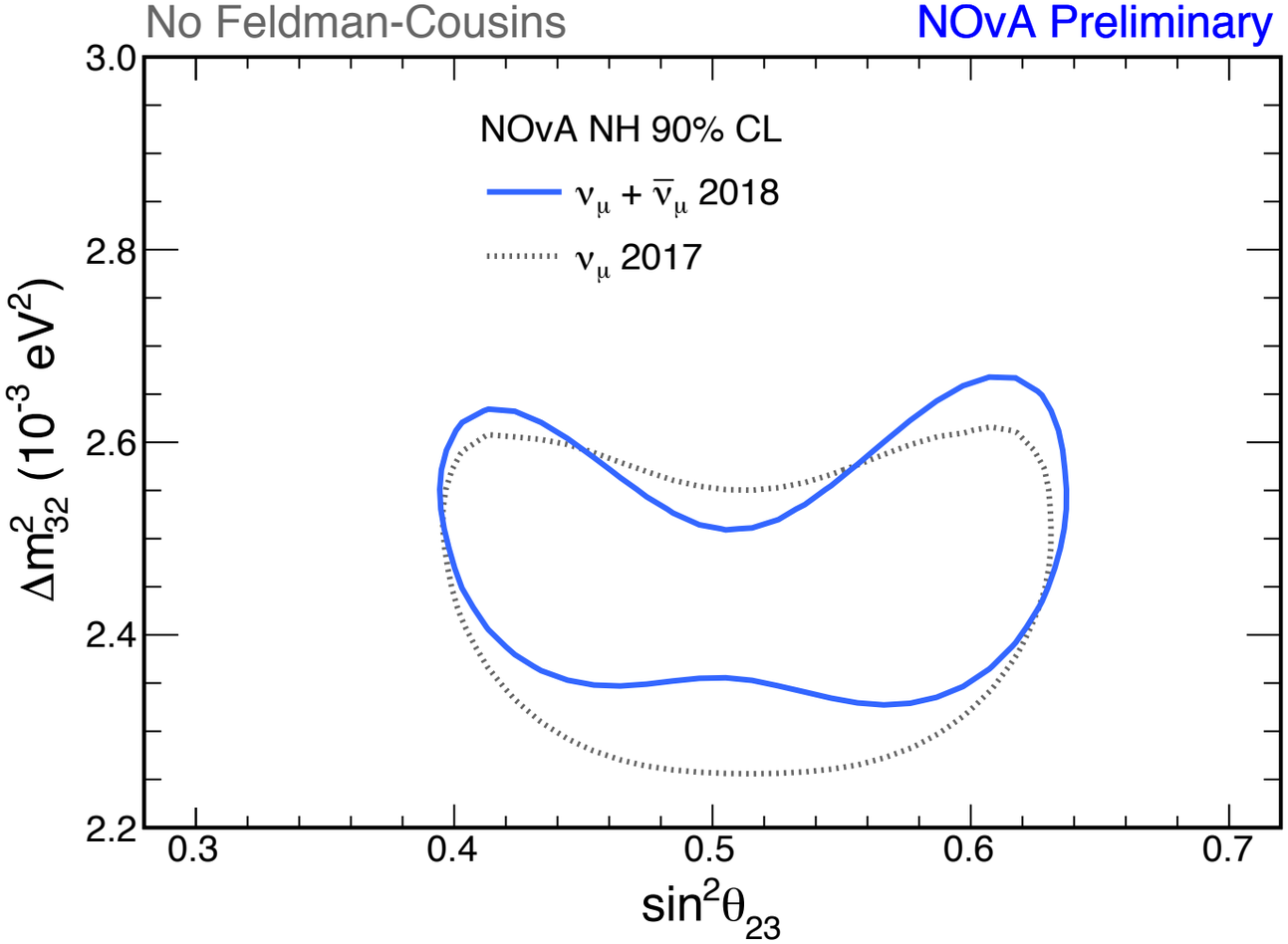
- Tuning of MEC component is done to match the excess in our data, using the empirical MEC model for energy transfer to the hadronic system.
- Tuning is done in bins of momentum transfer using the reconstructed q0 (hadronic energy) distribution.
- Associated uncertainty is shown.





Muon neutrino disappearance

- Combined result of neutrino and antineutrino beam assuming CPT invariance.
- Observe 113 events in neutrino mode (expect 126 at best fit), 65 events in antineutrino mode (expect 52 at best fit).
- Consistency with common oscillation parameters for neutrino and antineutrino datasets better than 4%.



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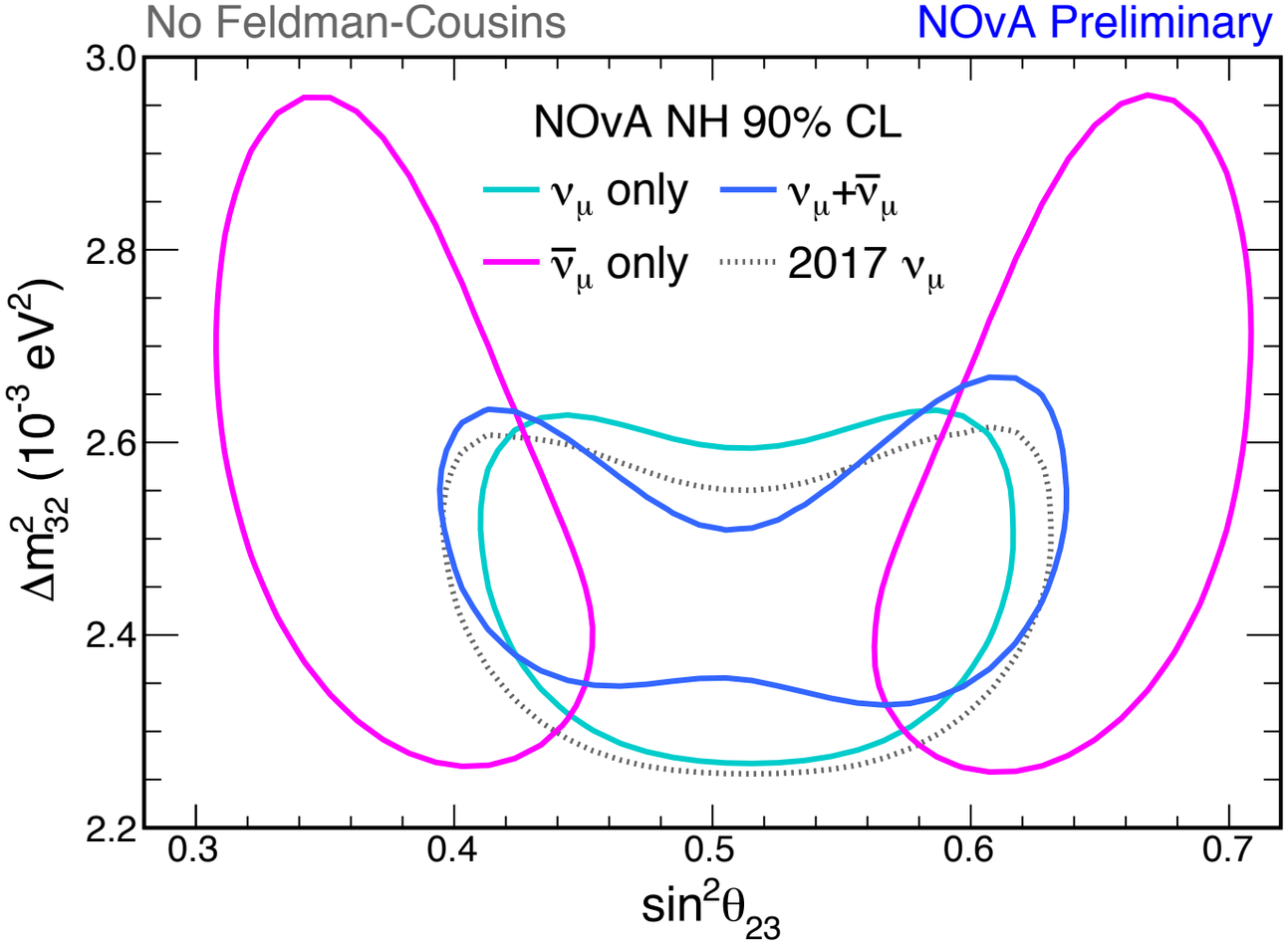
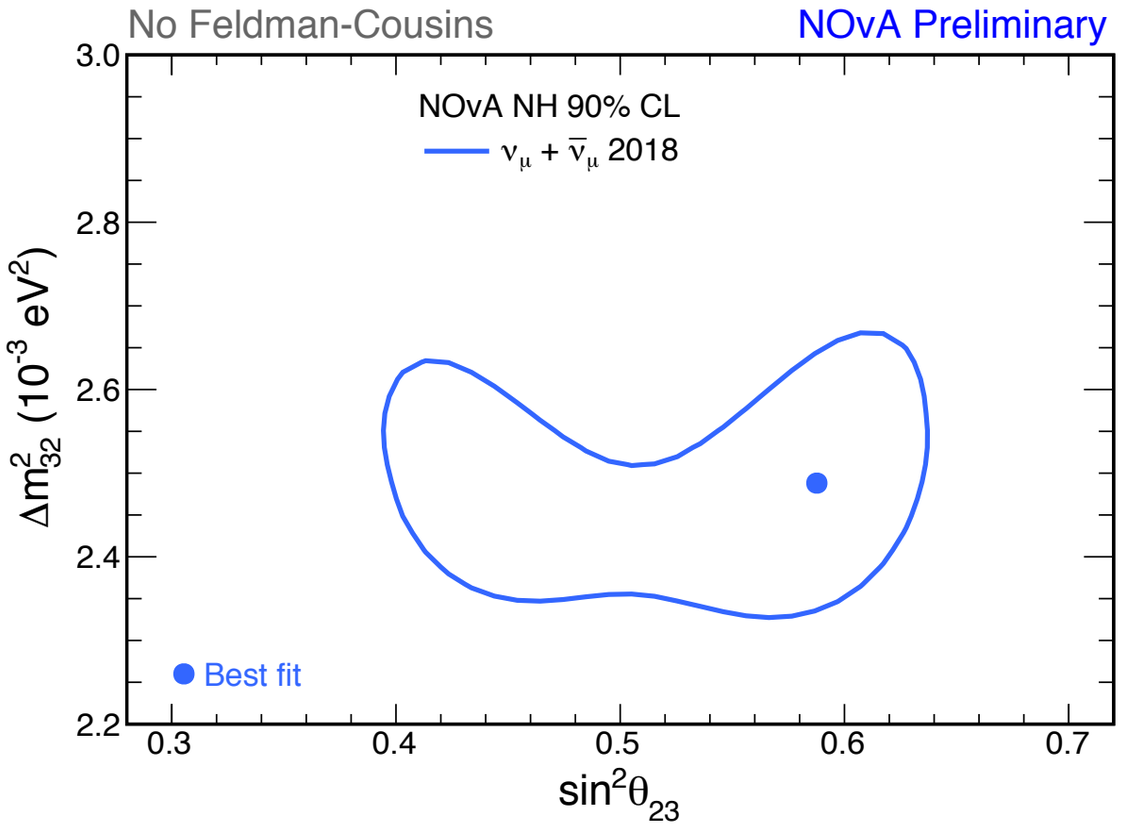
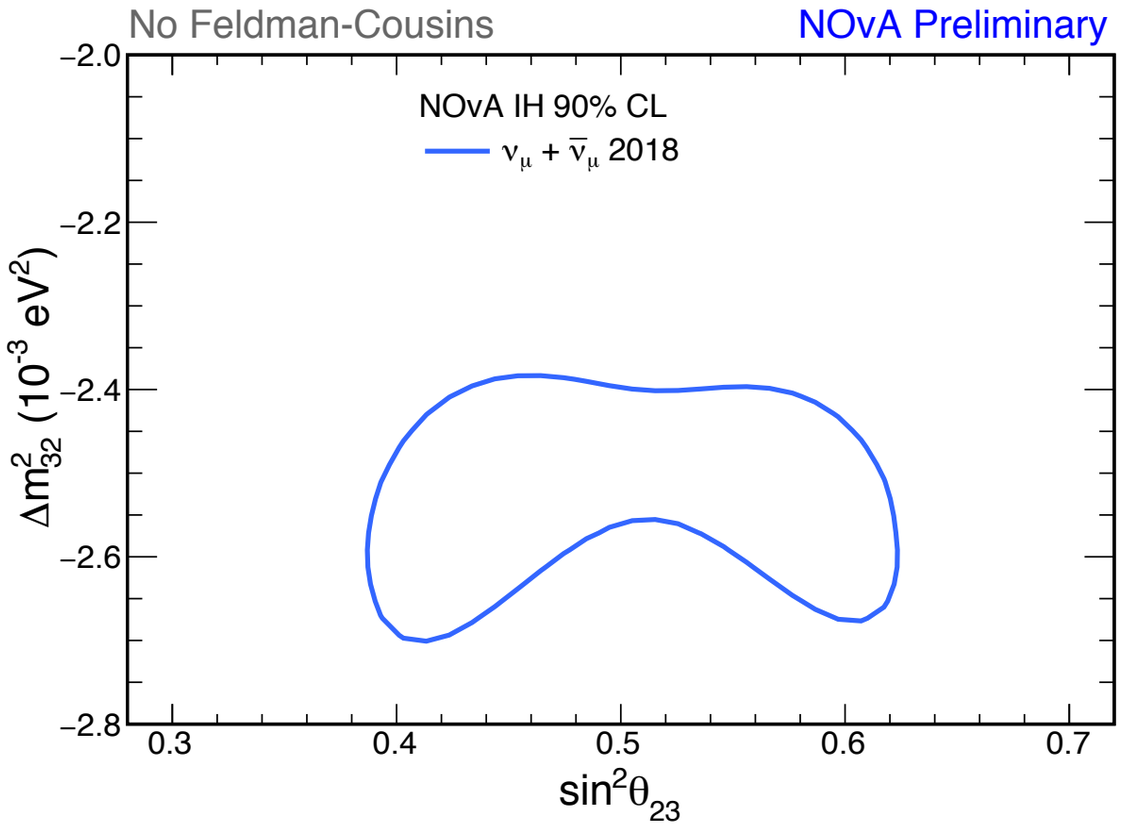


Numu disappearance

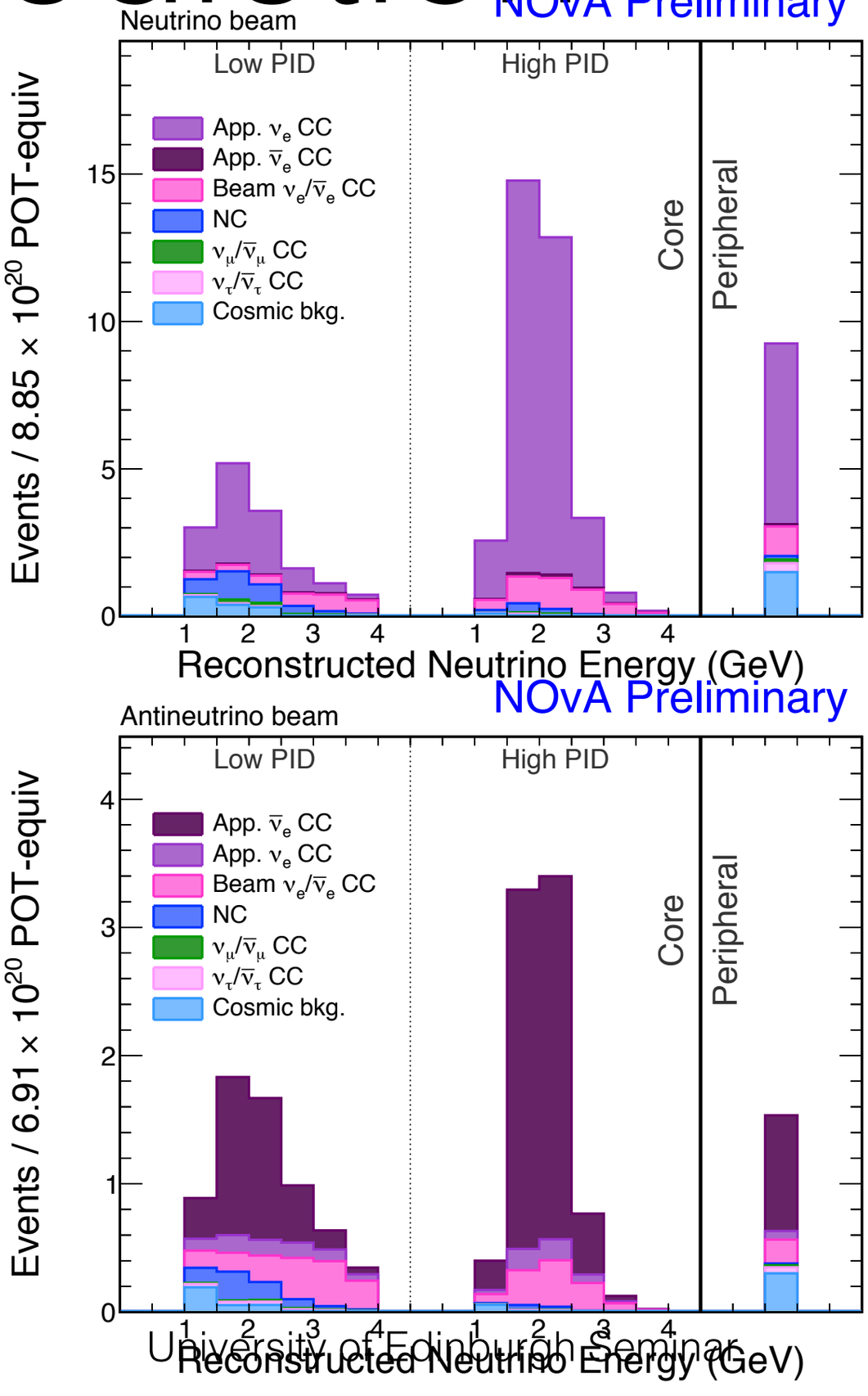
- Matter effects introduce a small asymmetry in the maximal disappearance point between neutrinos and antineutrinos.
- Tension between the muon neutrino and antineutrino datasets favour upper octant (UO) for normal hierarchy (NH) and lower octant (LO) for inverted hierarchy (IH)
- 1.5% probability of this happening for true octant, 0.5 in the false octant.





nue FD prediction

- 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 peripheral sample as one bin that does not pass cosmic rejection cuts with additional cosmic rejection boosted decision tree and high particle ID cut.
- 22% (32%) in the ve background in the high (low) PID bin.



Systematic uncertainties

Improved systematic uncertainties. Most significant uncertainties are coming from calibration, cross sections, and neutron uncertainty. However, we are still statistics dominated.