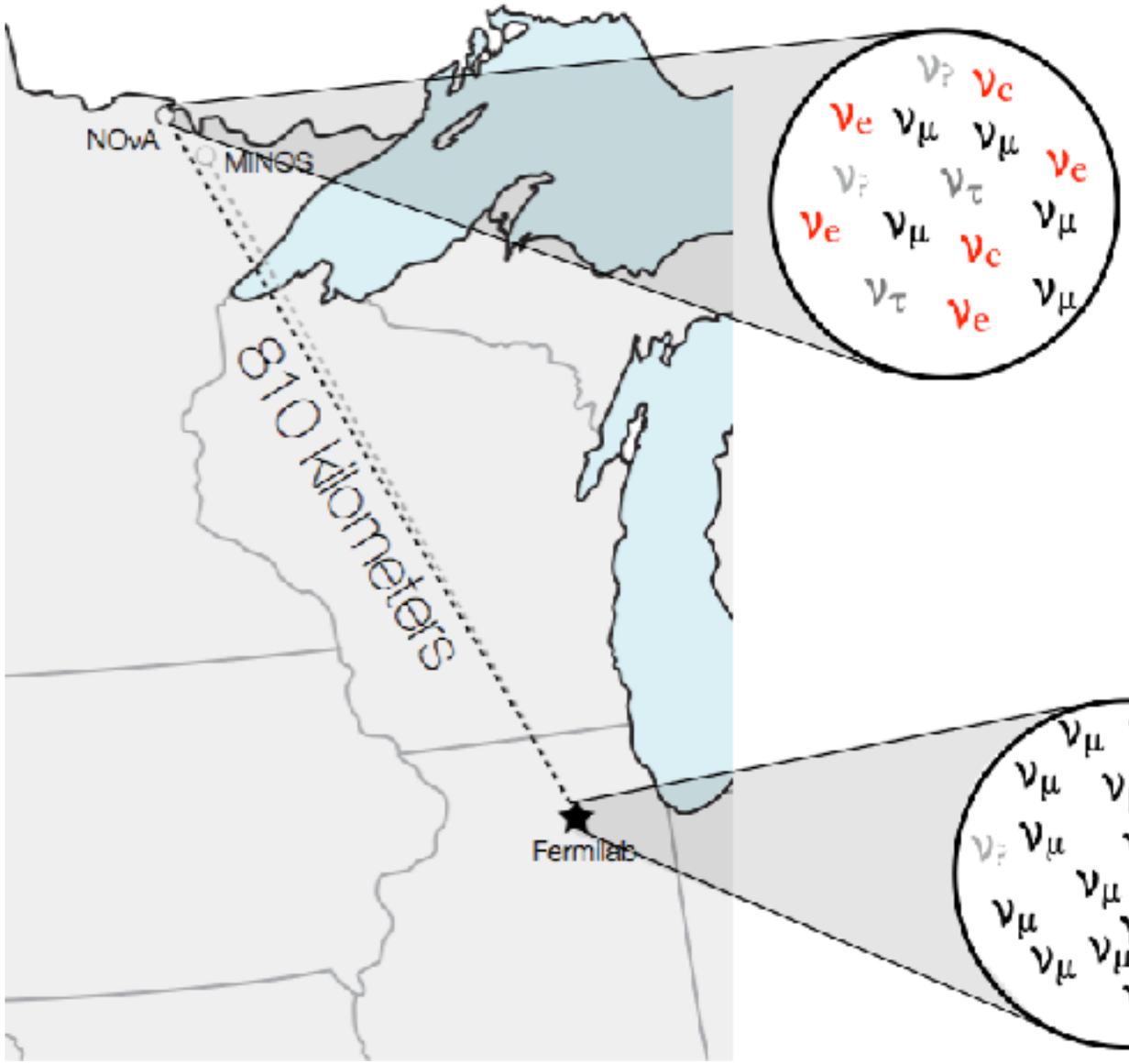
Results from NOvA

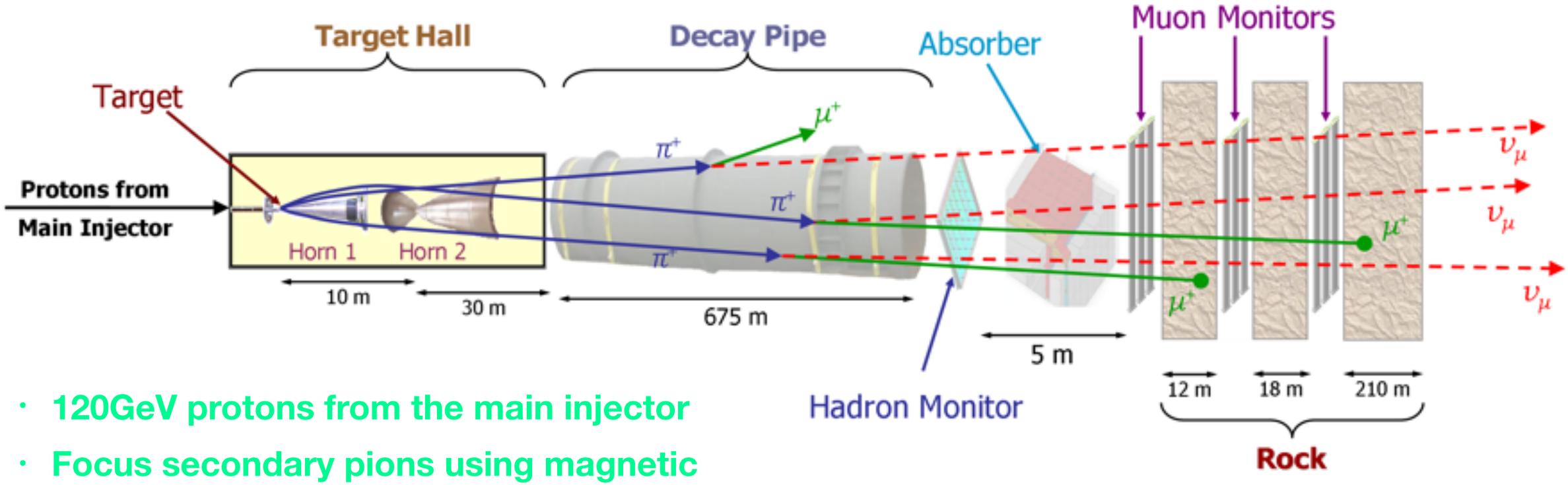
Jenny Thomas

NOvA Experiment

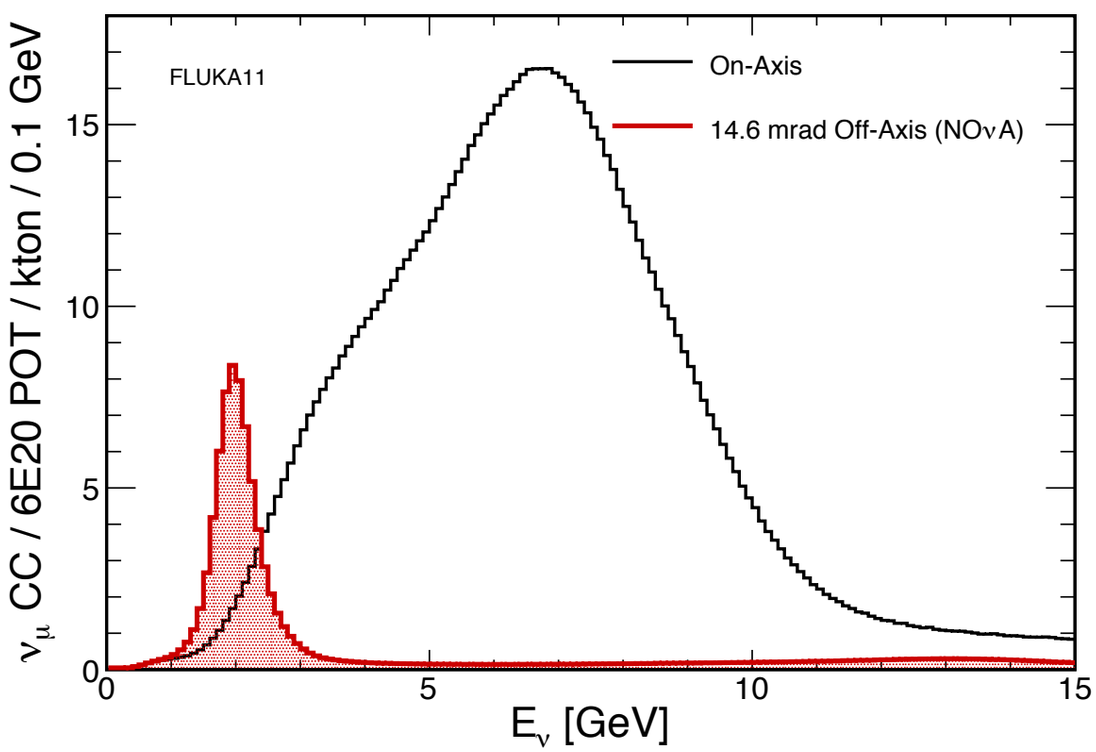
- Longest baseline accelerator neutrino search (810 km)
  - **NuMI is a beam of mainly muon-neutrinos created at Fermilab**
  - **Two functionally identical detectors at 14.6 mrad (FD) and 14.6 mrad (equivalent) for smaller ND**
- Measures muon-neutrino disappearance and electron-neutrino appearance
  - **starting to do the same with anti-neutrinos**
- Sensitive to PMNS matrix, mass hierarchy, CP violation



How to make a neutrino beam

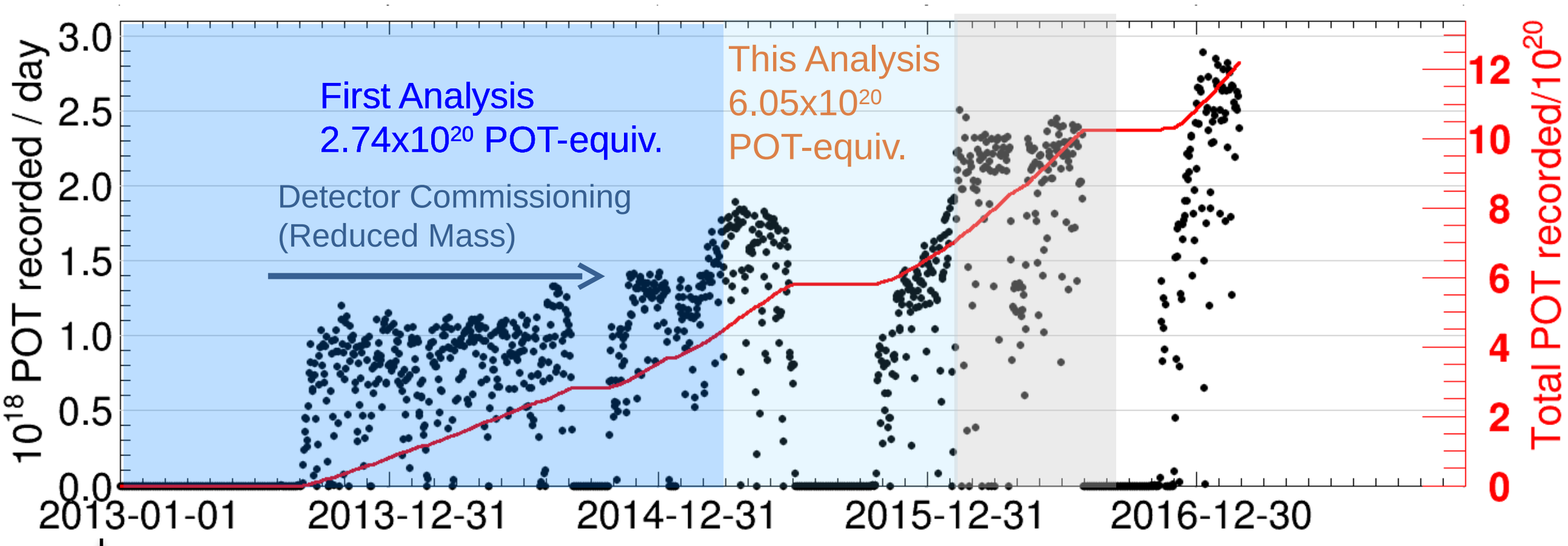


- **120GeV protons from the main injector**
- **Focus secondary pions using magnetic horns**
  - Focus positive hadrons for neutrino beam, negative for antineutrino
- **Pions decay to produce muon neutrinos**
  - Decay kinematics mean a detector at 14.6mrad sees a narrowly peaked energy spectrum
- **97.5% muon-neutrino, only 0.7% beam electron-neutrino (remainder wrong-sign)**



NuMI Beam Performance

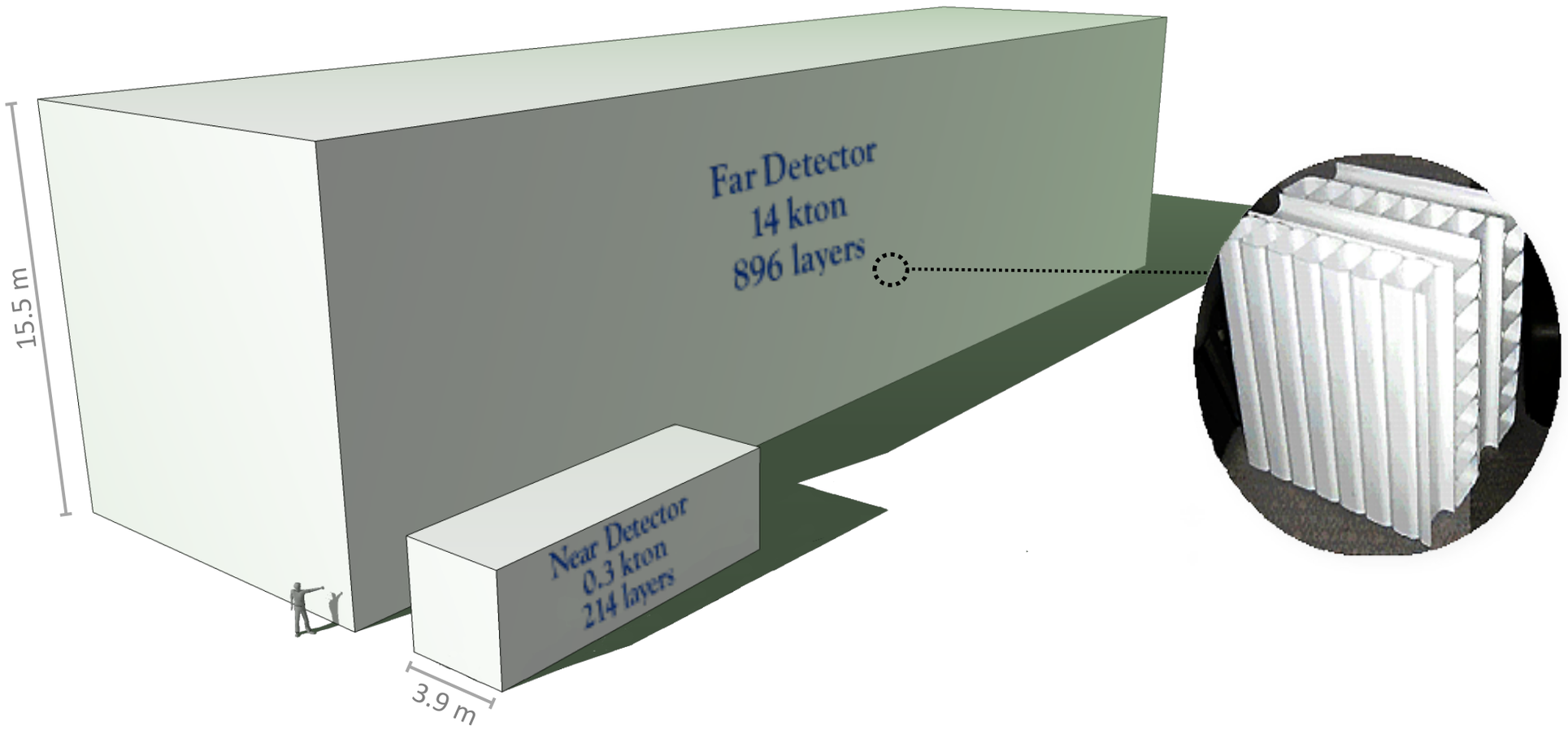
- Results today from data collected between February 6, 2014 and May 2, 2016
- Data equivalent to 6.05×10^{20} protons-on-target in a full 14 kT detector
- Achieved 700 kW design goal, most powerful neutrino beam in the world
- Switched to antineutrino beam, shut down first week of July

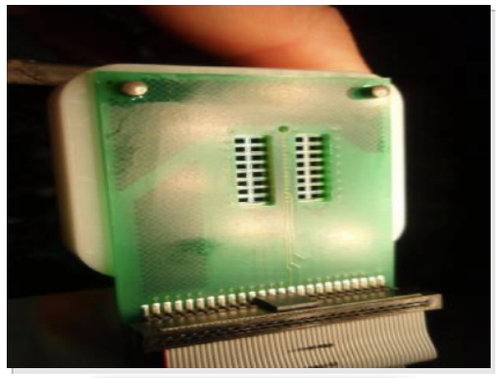


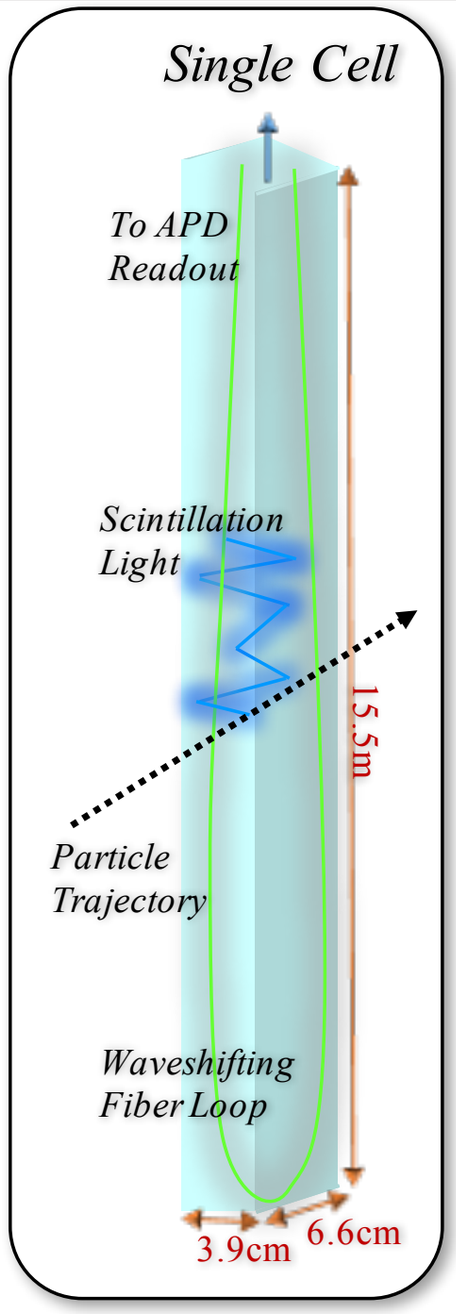
$\nu_\mu \rightarrow \nu_\mu$: Phys.Rev.D93.051104

$\nu_\mu \rightarrow \nu_e$: PRL.116.151806

NOvA Detectors

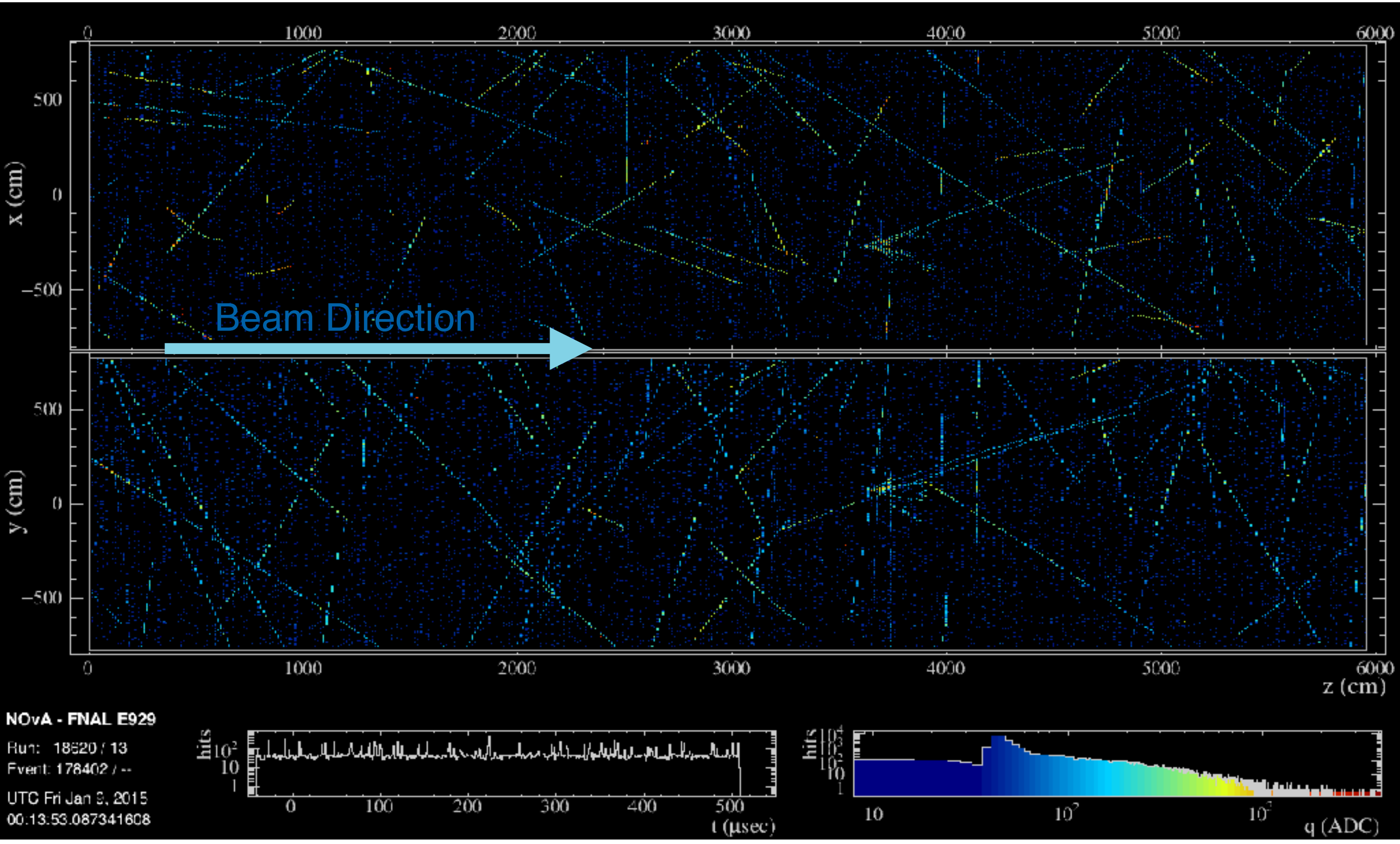






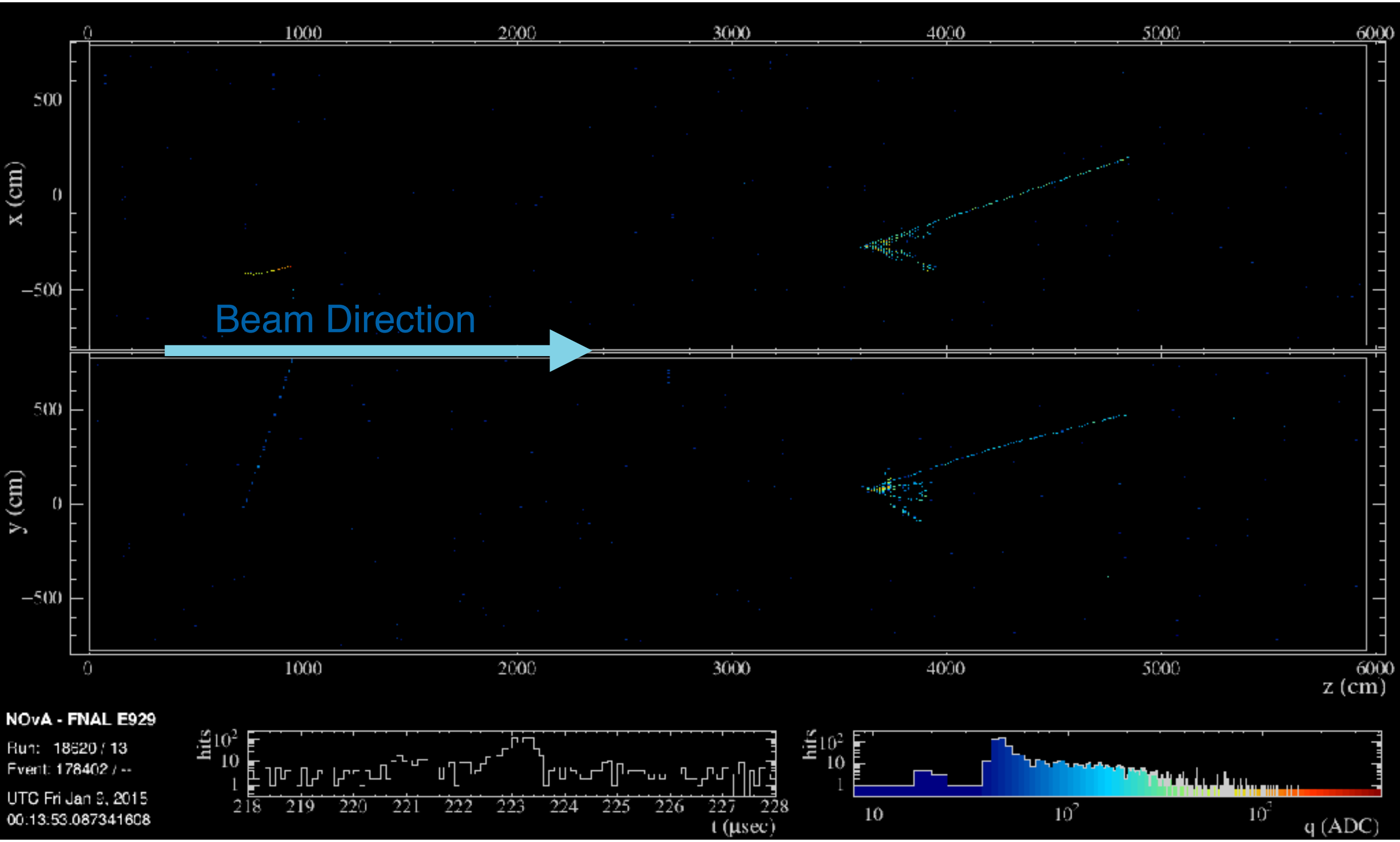
- Two functionally identical detectors
- Extruded plastic cells alternating vertical and horizontal orientation filled with liquid scintillator
- Charged particles passing through cells produce light which is collected by a wavelength shifting fibre and read out with an APD

Far Detector 550 μs Readout Window



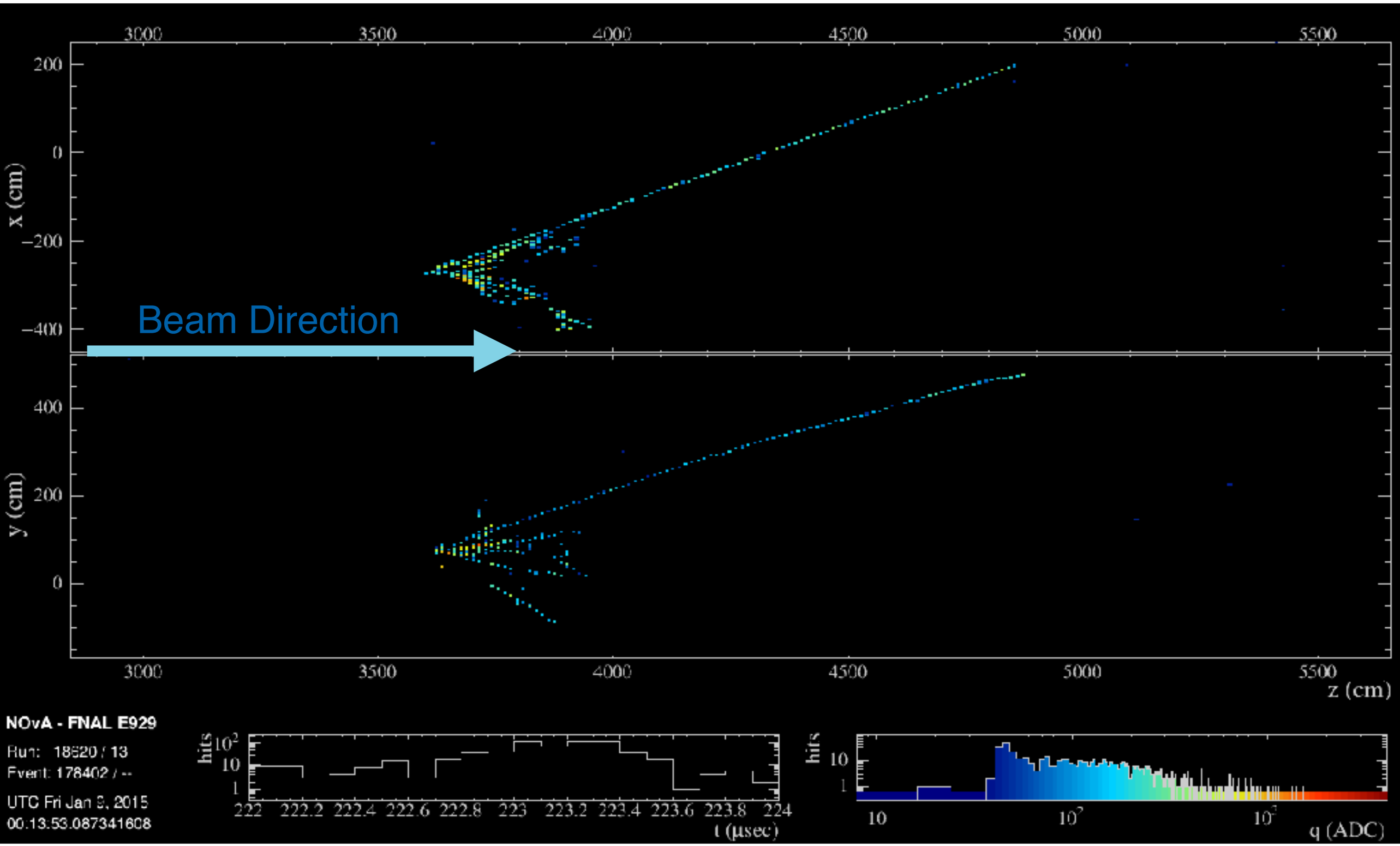
Cell hits coloured by recorded charge (~photoelectrons)

Far Detector 10 μs NuMI Beam Window



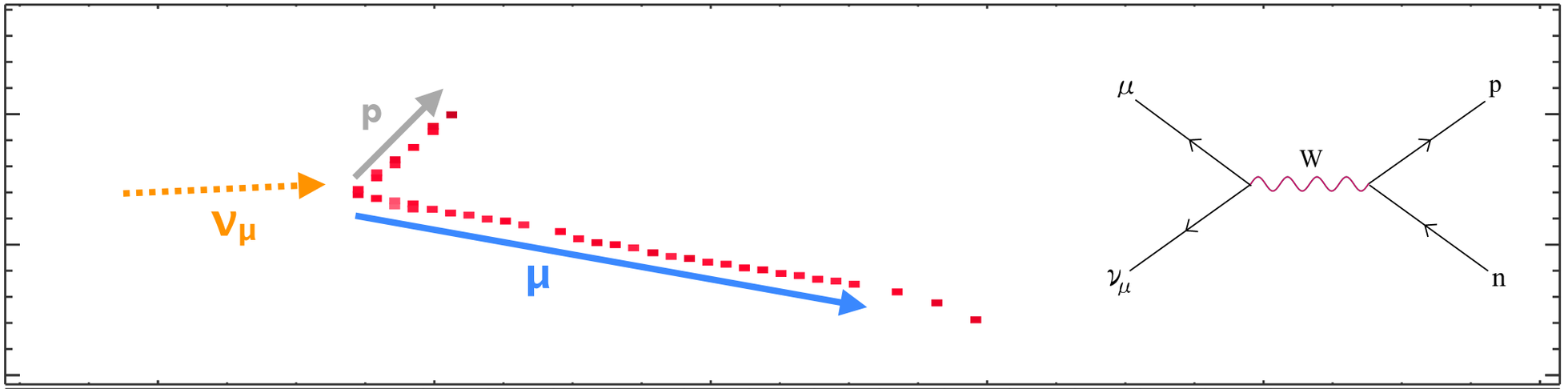
Cell hits coloured by recorded charge (~photoelectrons)

Far Detector Neutrino Interaction

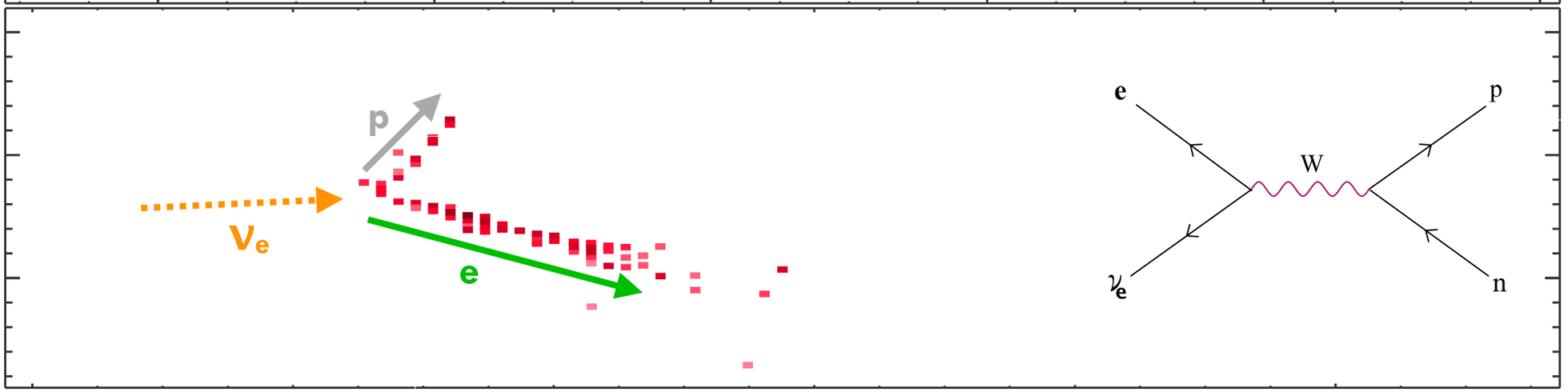


Cell hits coloured by recorded charge (~photoelectrons)

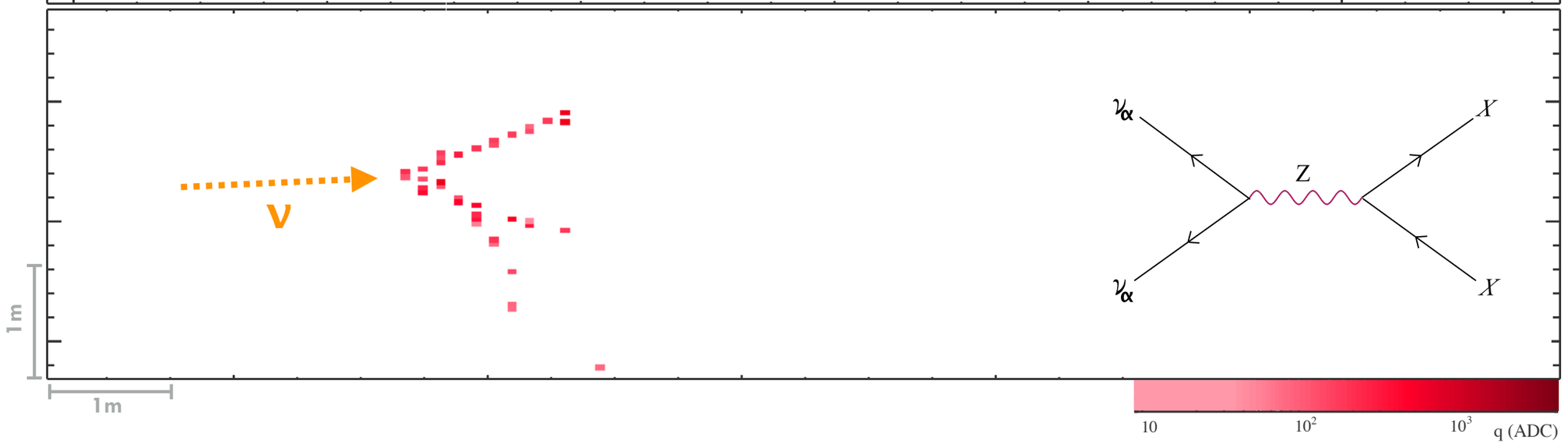
Event Topologies



νμ-CC



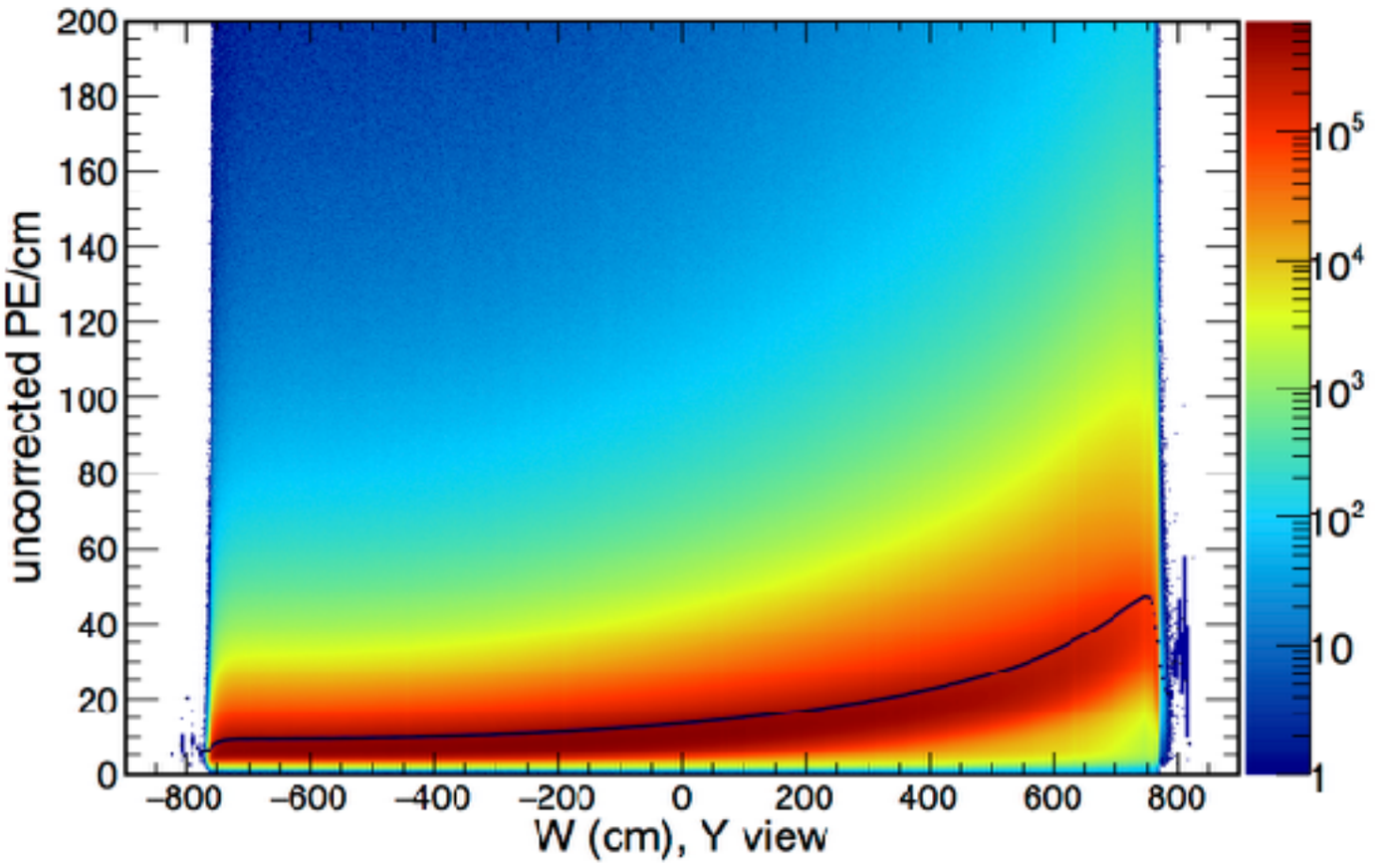
νe-CC

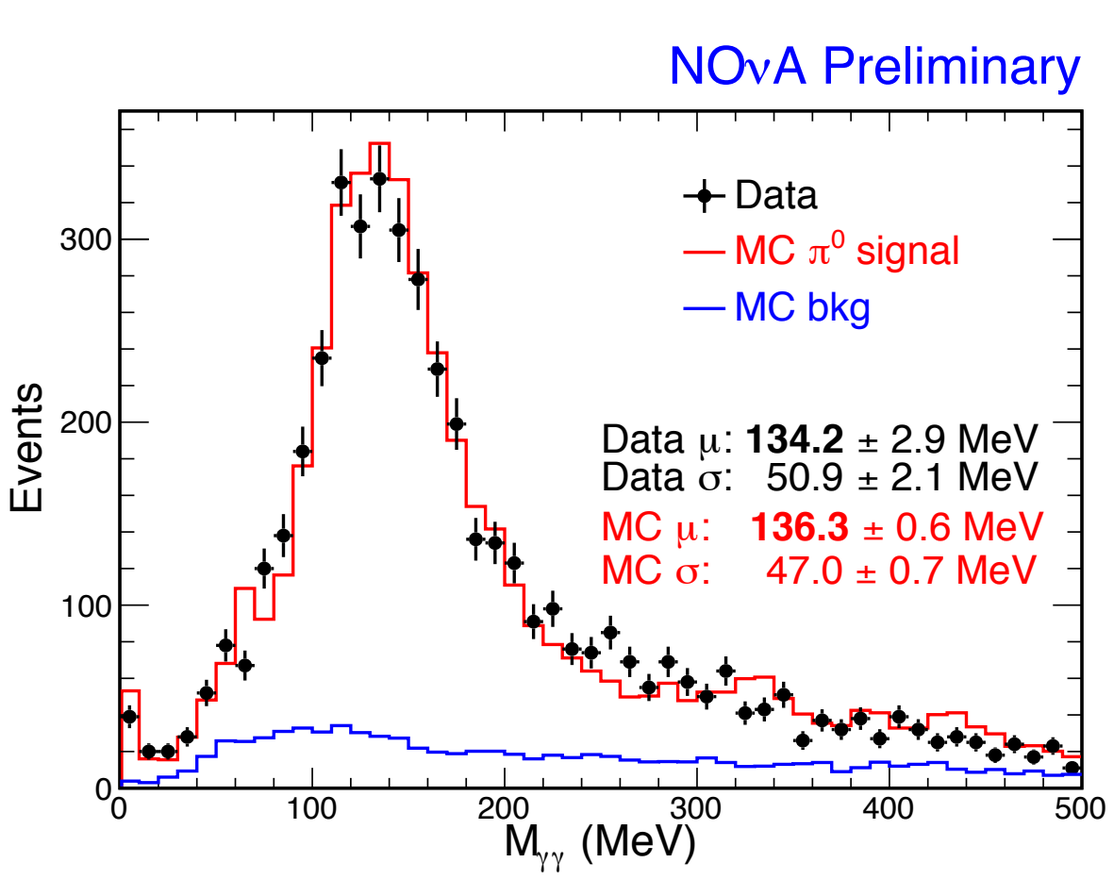


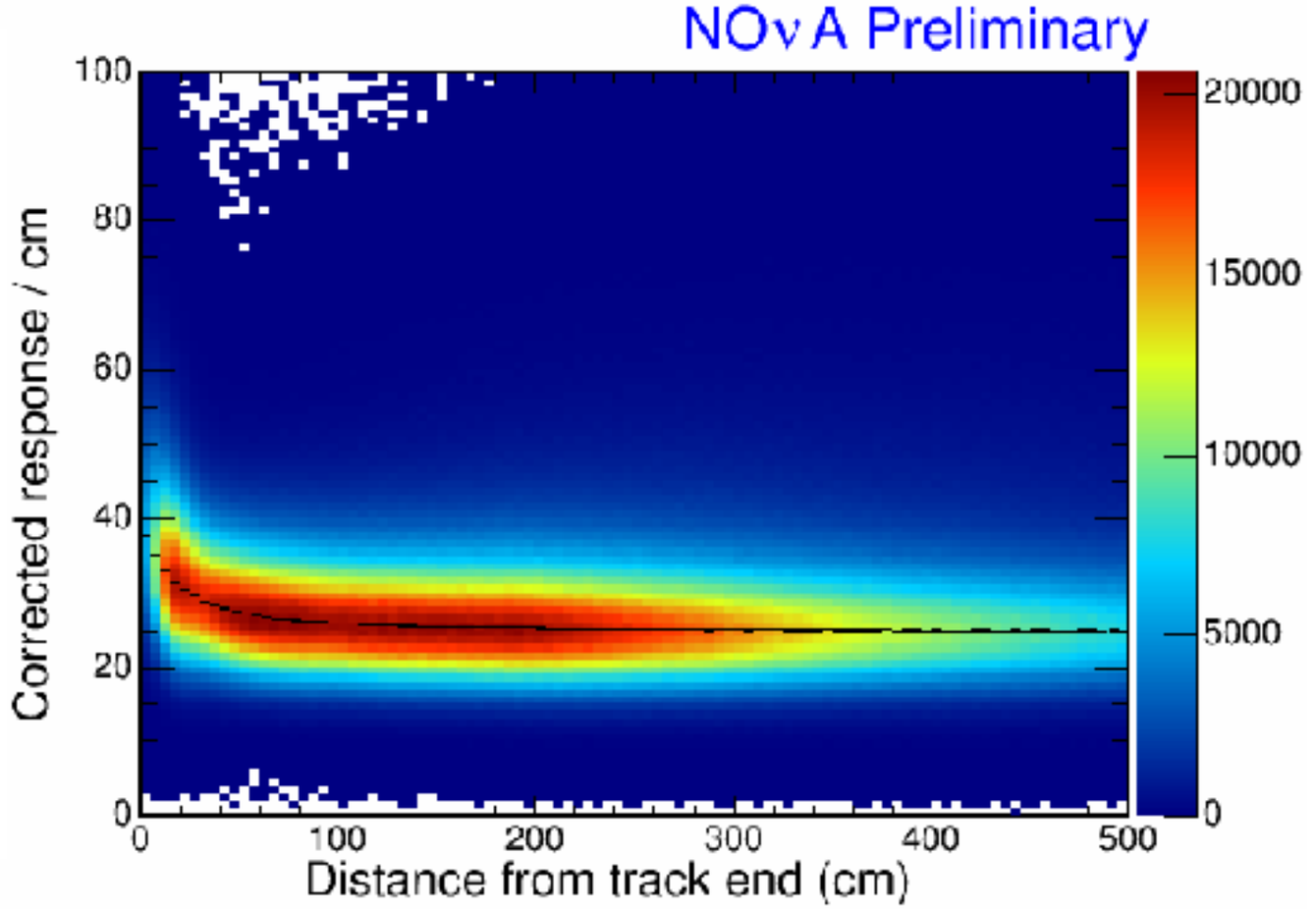
NC

Detector Calibration

- Cosmic ray muons used to correct attenuation
- Stopping muons used as a standard candle



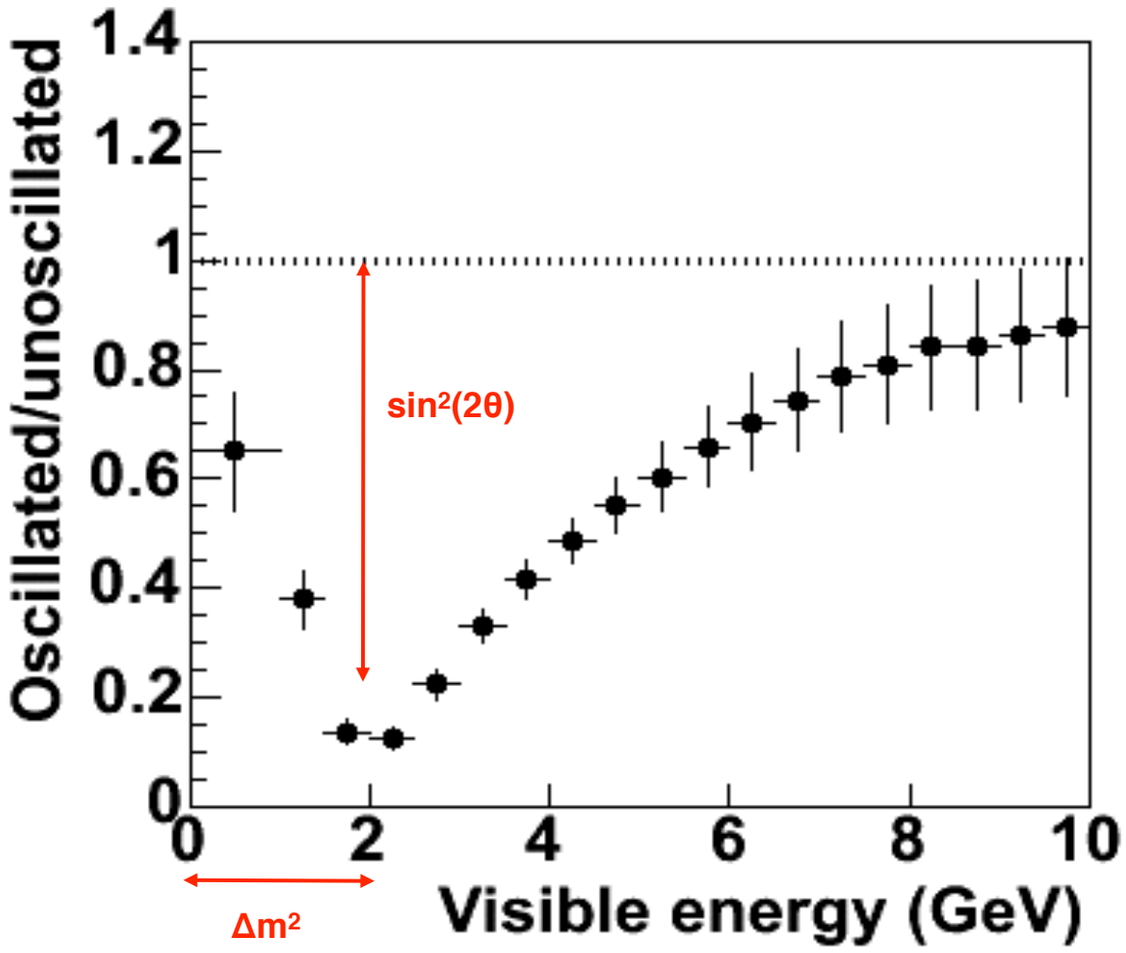




Muon-neutrino disappearance

Muon-Neutrino Disappearance

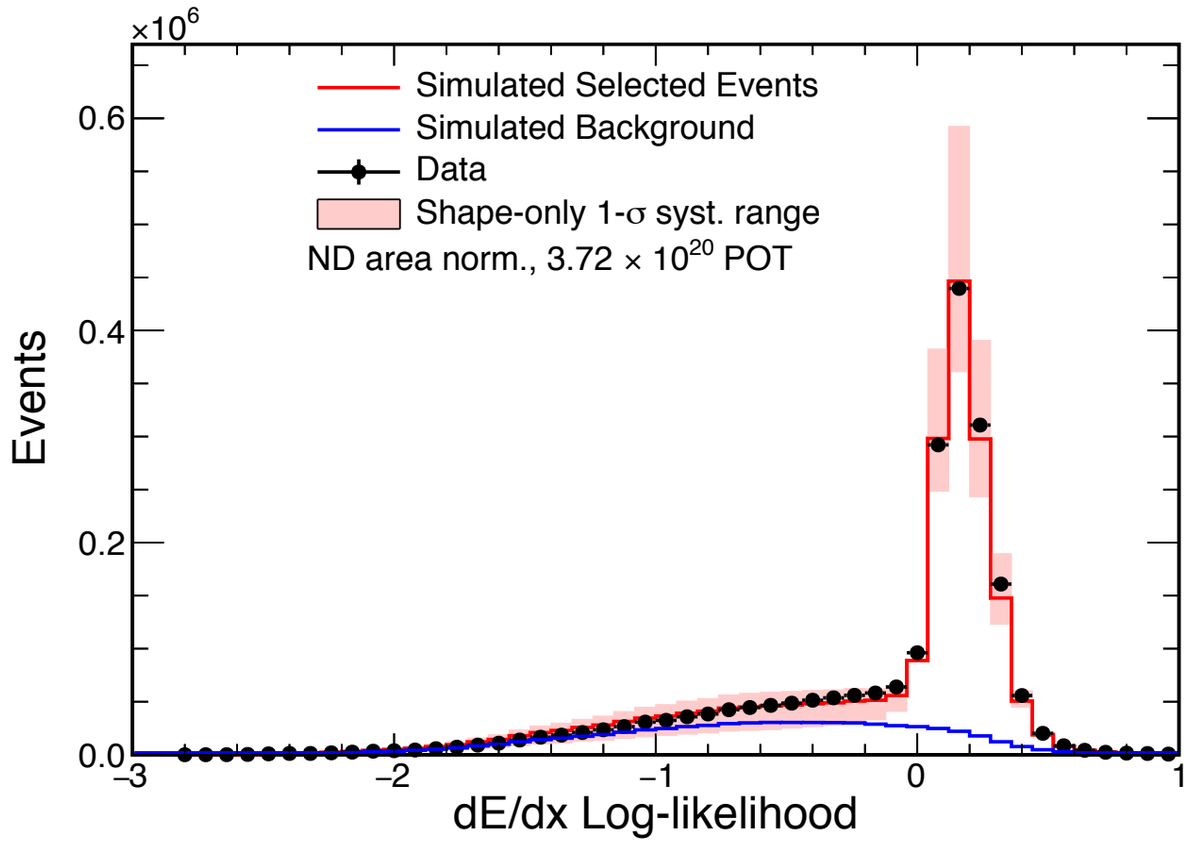
- Two-flavour approximation still basically valid (although analysis uses full three-flavour formalism)
- Measure neutrinos in the ND
- ‘Extrapolate’ measurements to form FD prediction
  - **Taking into account decay kinematics, geometry, efficiencies, purities, energy resolutions, etc.**
- Compare FD data to predictions to find the best fit oscillation parameters

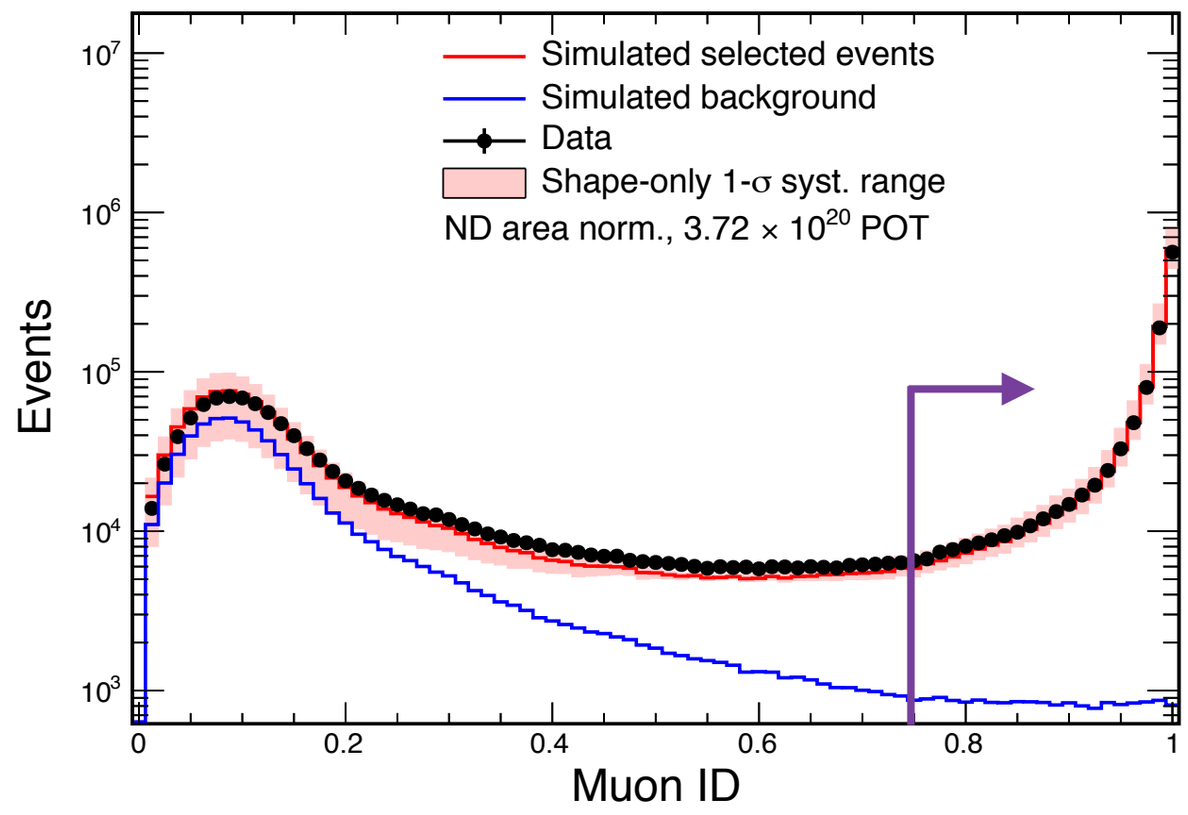


$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$

Muon-Neutrino Selection

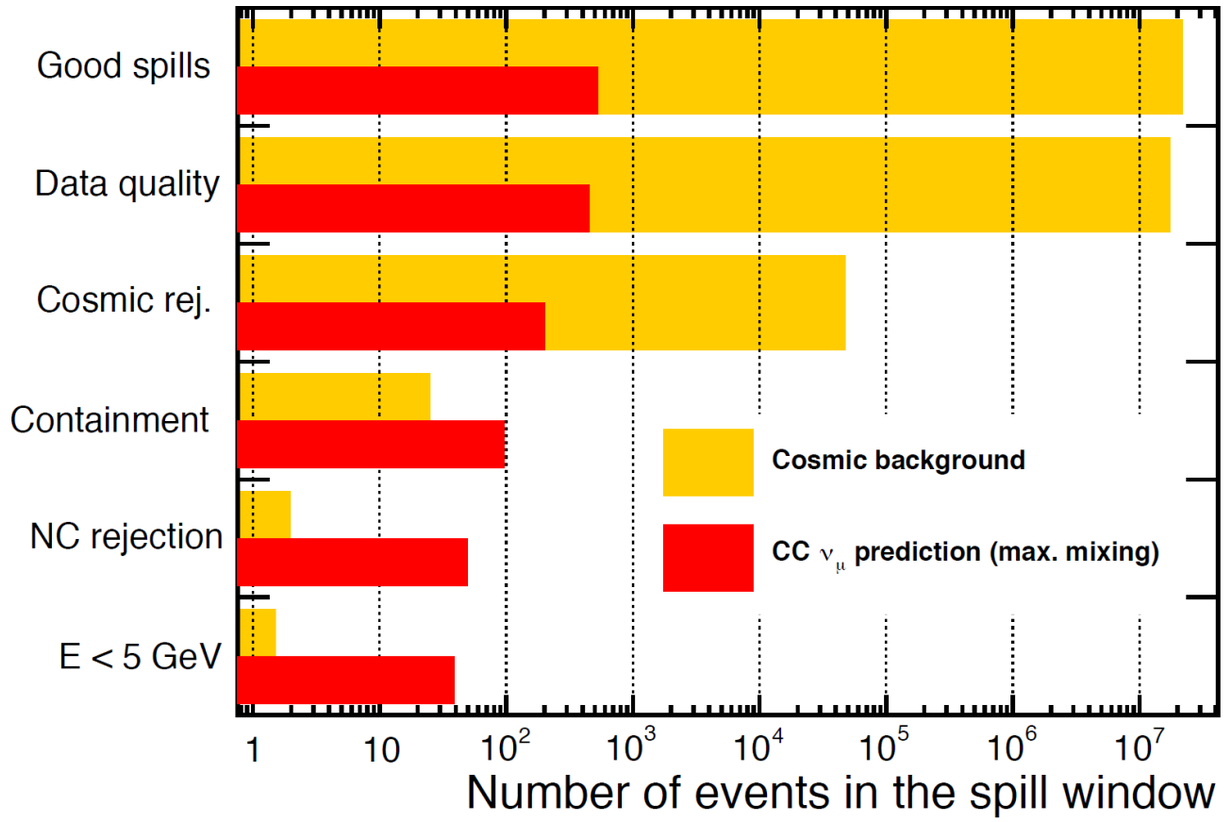
- Separate ν_μ-CC interactions from NC and cosmic-ray backgrounds
- Containment cuts remove activity near walls
- Four variable k-Nearest Neighbour to select muons
  - **Track length**
  - **dE/dx along track**
  - **Scattering along track**
  - **Track-only plane fraction**
- Selection is 81% efficient and 91% pure



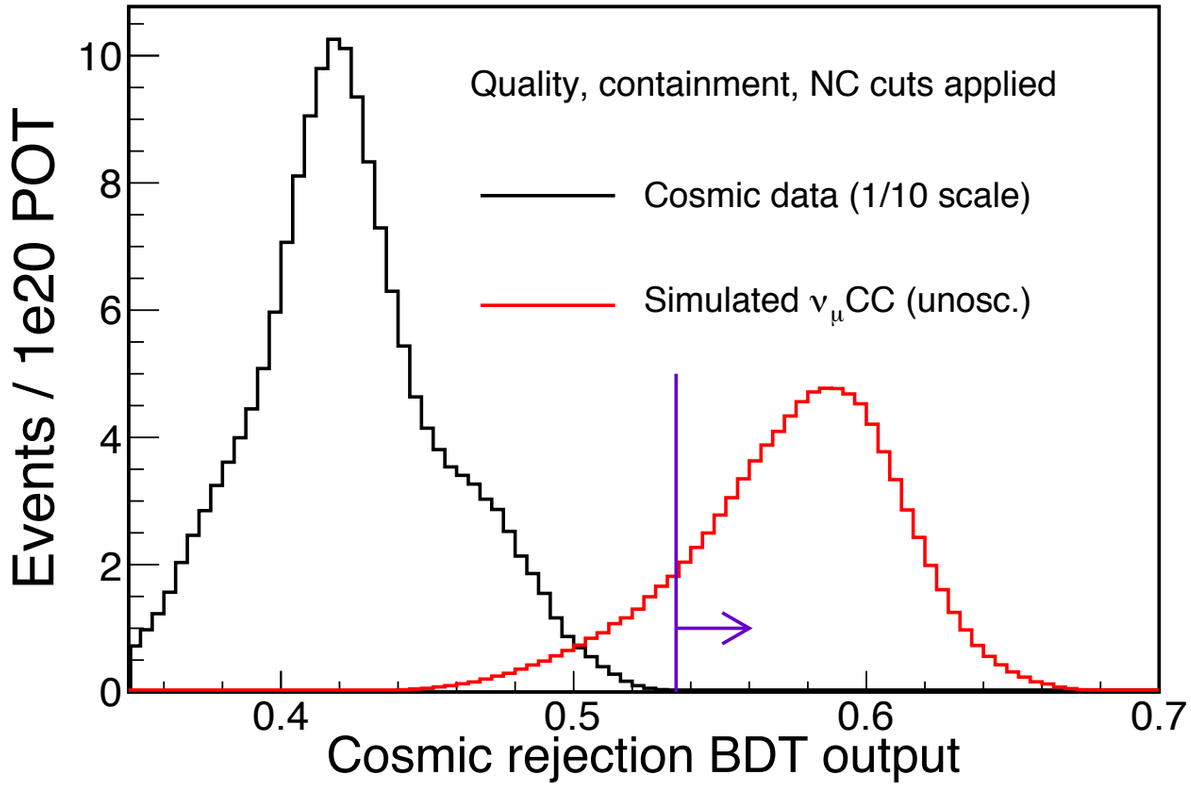


Cosmic Rejection

- Far Detector is on the surface and sees 150 kHz of cosmic induced events
- 10 μs beam window every 1.3s reduces background by 10^5
- Additional factor of 10^7 rejection achieved from event topology and a boosted decision tree (BDT) based on:
  - **track direction**
  - **start/end points of track**
  - **track length**
  - **energy**
  - **number of hits**
- Predict 2.7 cosmic background events

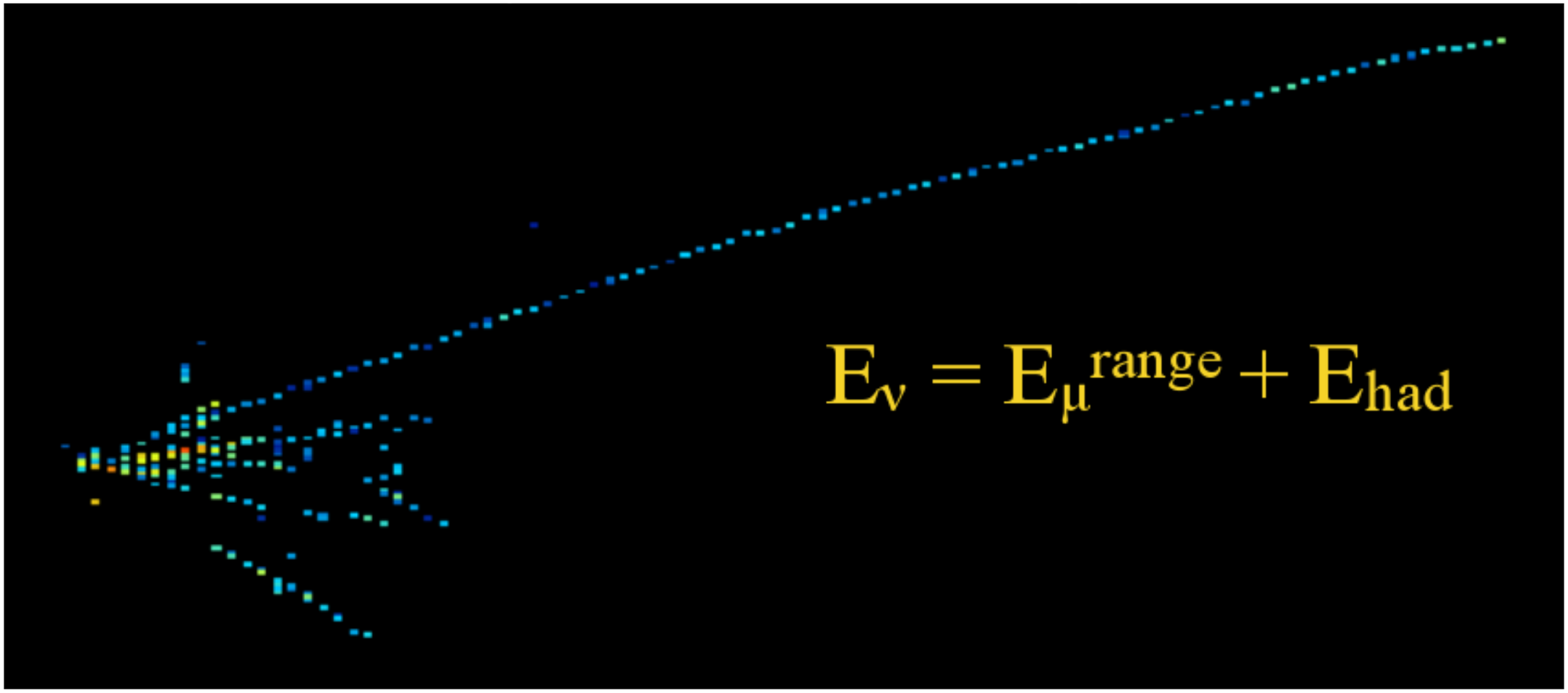


NOvA Preliminary



Energy Estimation

- Muon dE/dx used in length-to-energy conversion
- Hadronic energy estimated from calorimetric sum of non-muon hits
- ~7% resolution on neutrino energy



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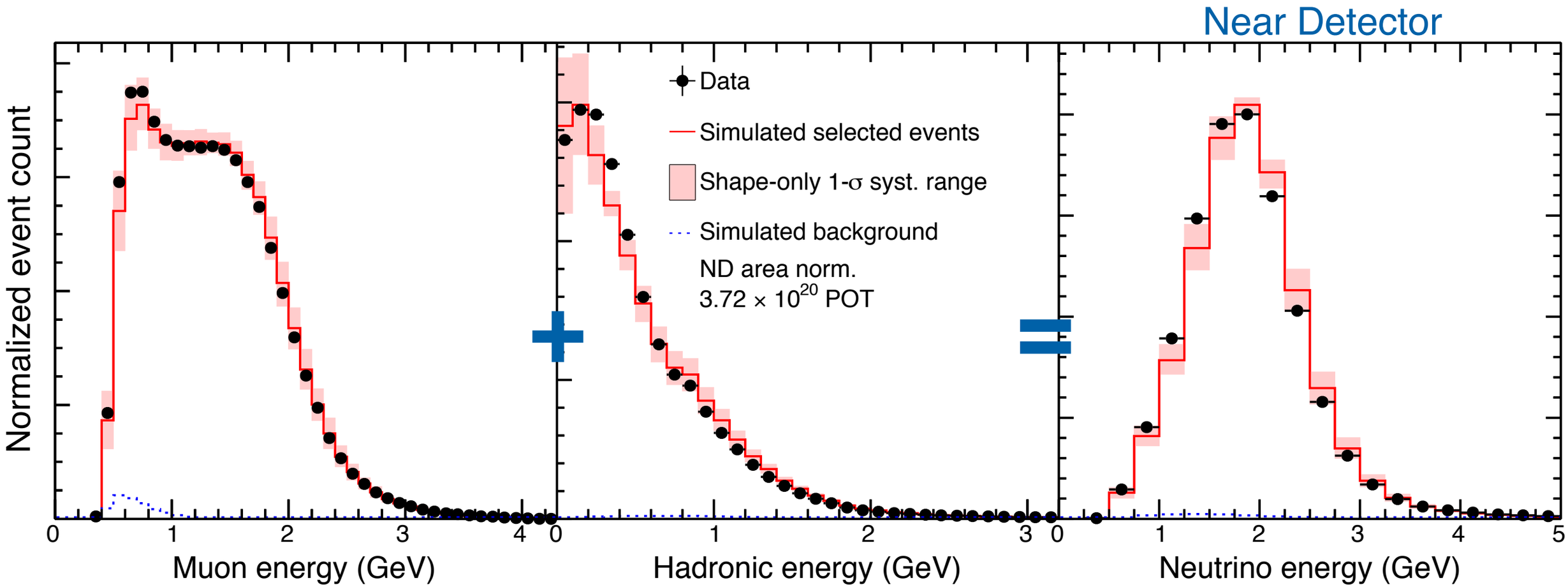
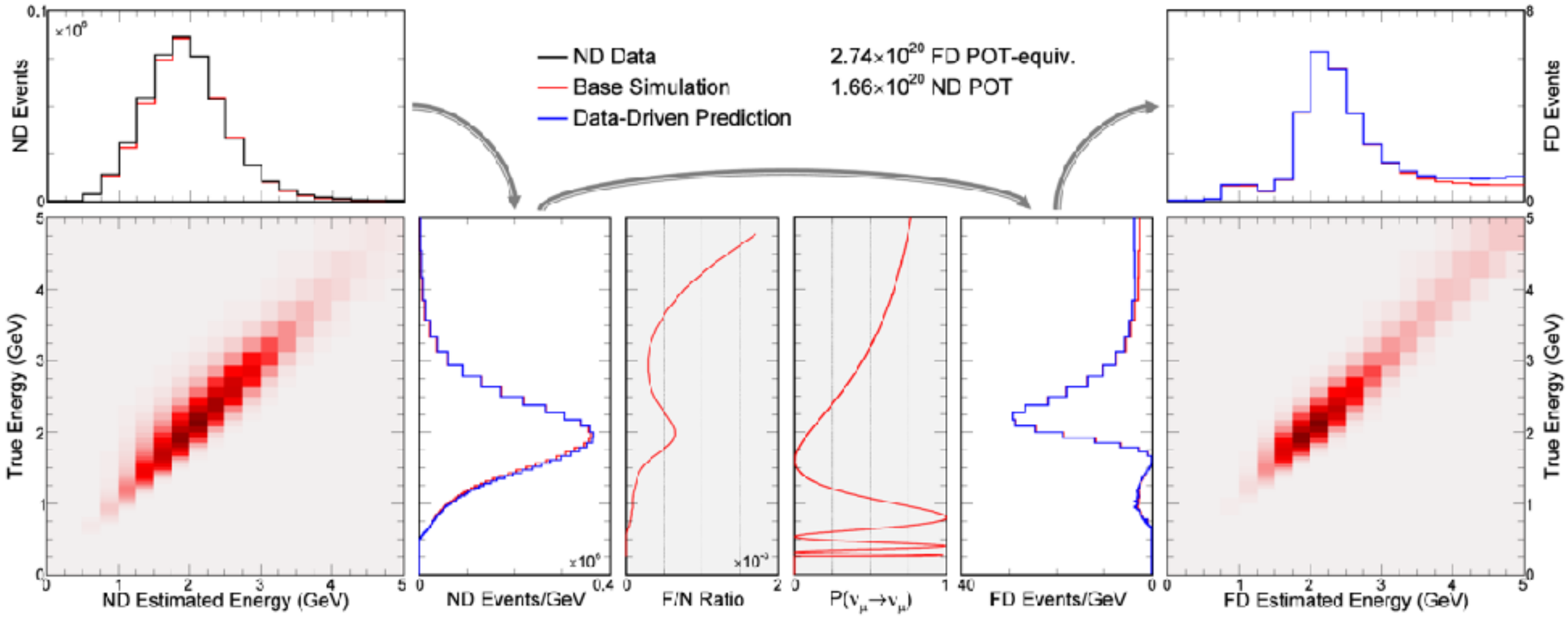


$$E_\nu = E_\mu(L_\mu) + E_h$$

Extrapolation

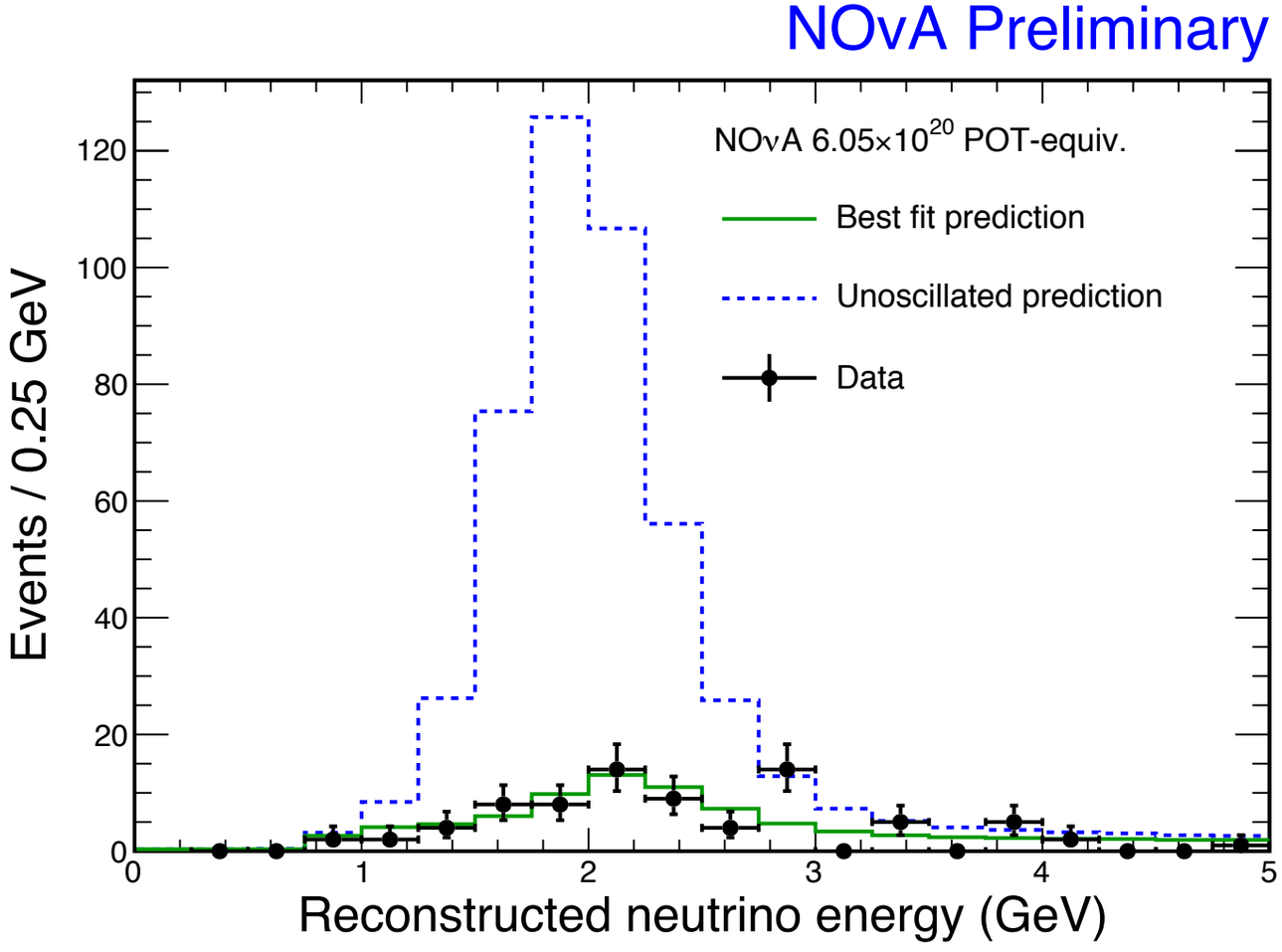
- Use high statistics ND data/MC to adjust prediction at FD
  - **Translate ND data/MC observation to true energy**
  - **Oscillate ratio to the FD**
  - **Smear back into reconstructed energy**



Muon-Neutrino Disappearance

10.1103/PhysRevLett.118.151802

- Using 6.05x10^{20} POT equivalent
- 473 +/- 30 events predicted in the absence of oscillations
- Observed 78 events
- 82 events predicted at the best fit point including 3.7 beam background and 2.9 cosmic induced events



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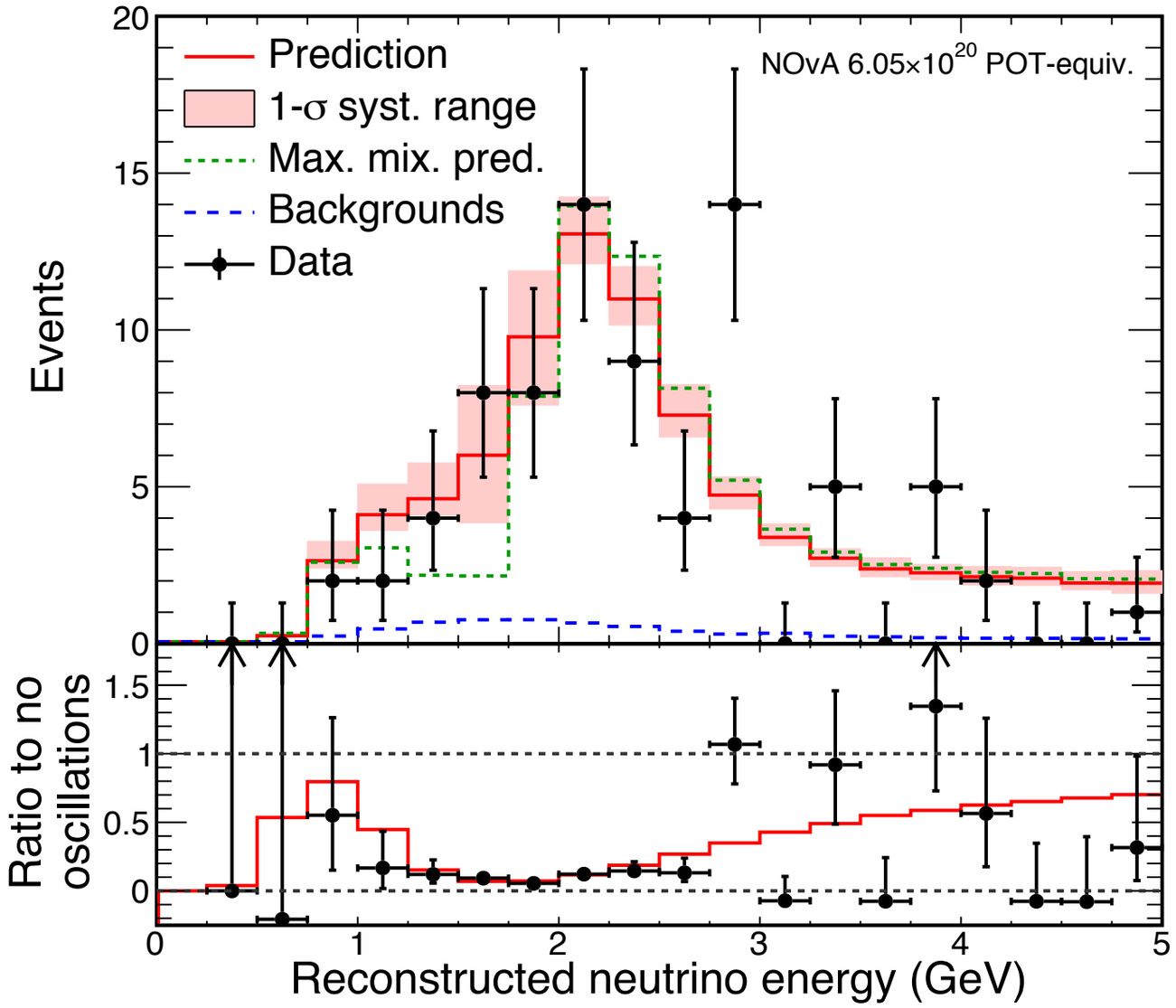
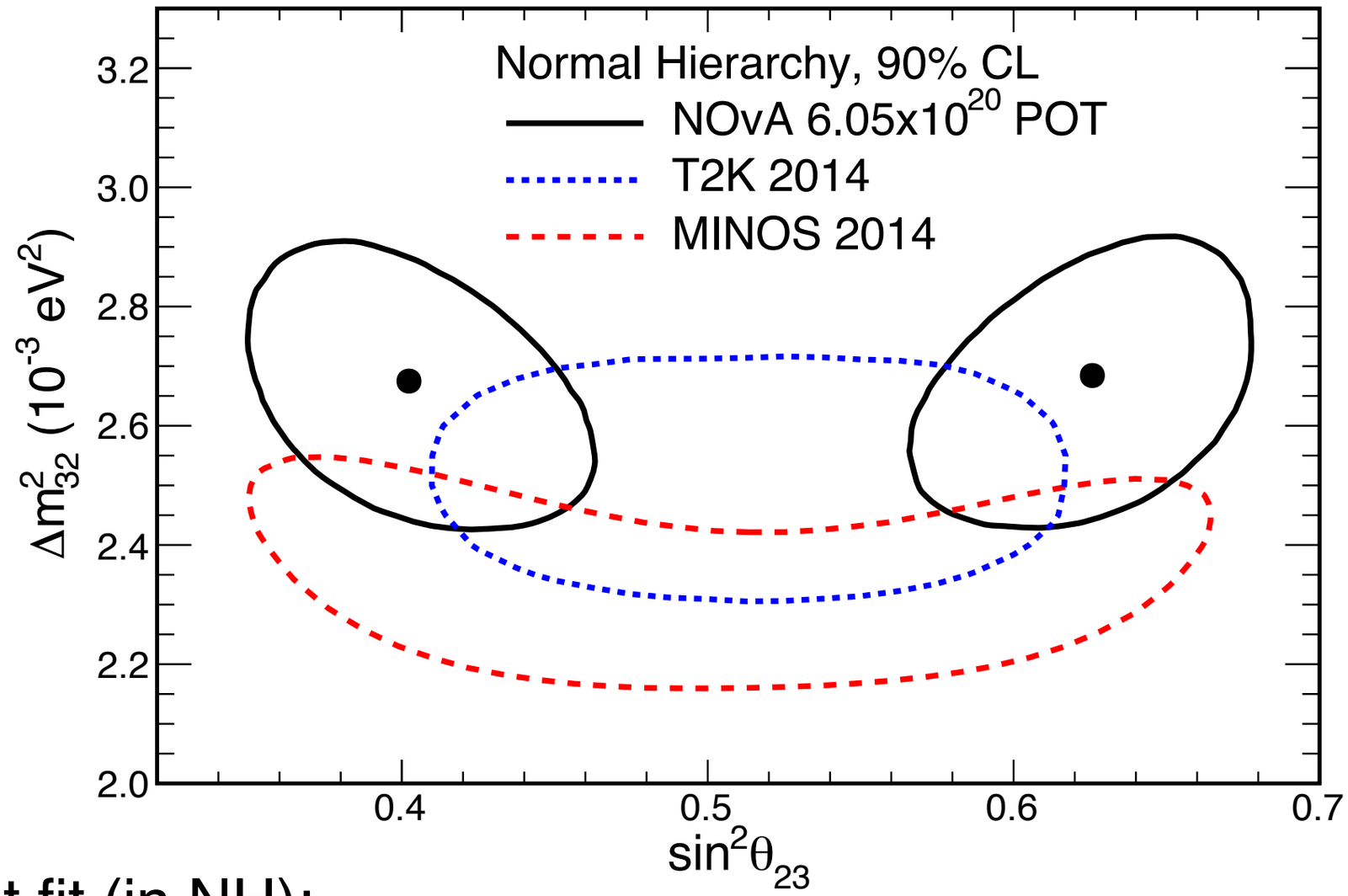


Muon-Neutrino Disappearance

arXiv:1701.05891



Best fit (in NH):

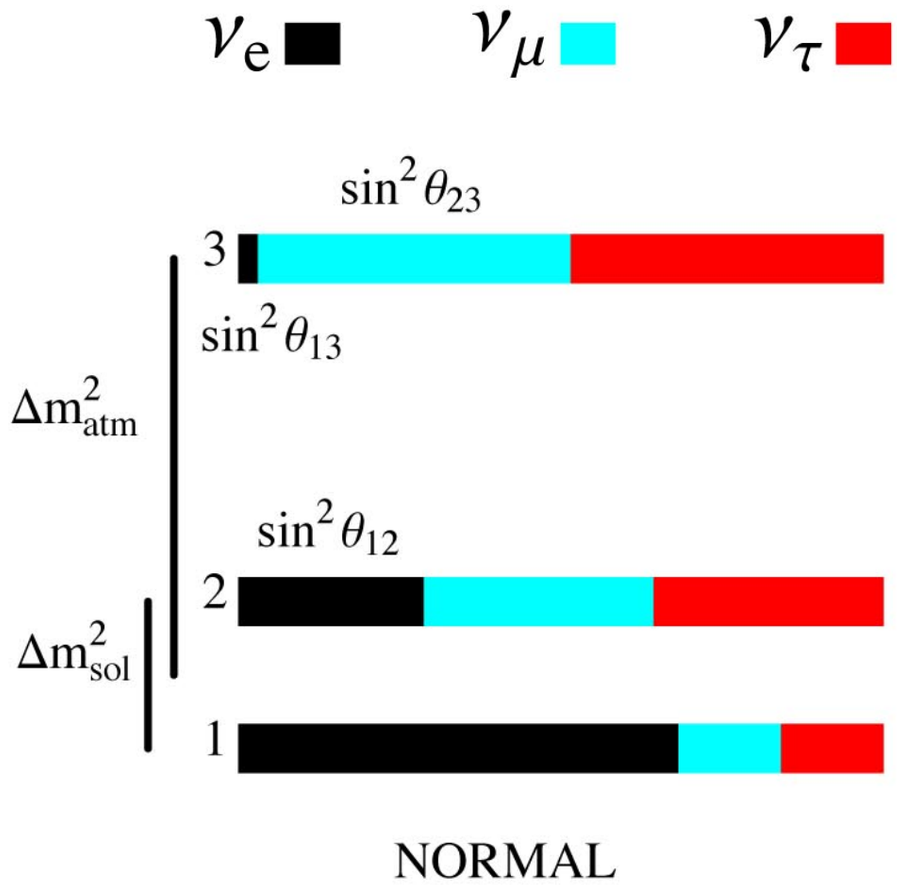
$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3}\mathrm{eV}^2$$

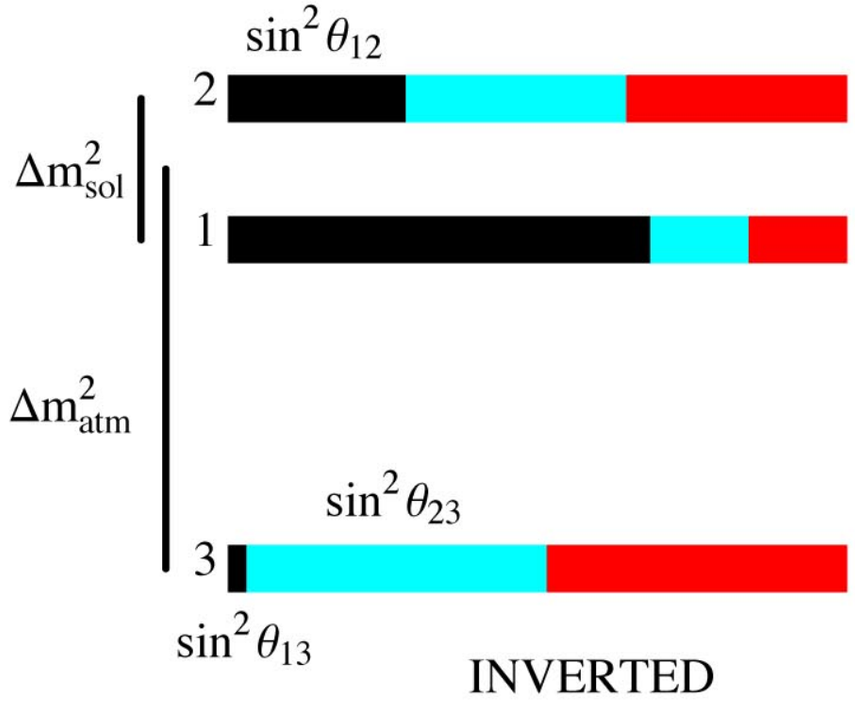
$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022} (0.624^{+0.022}_{-0.030})$$

- Maximal-mixing disfavoured at 2.6 sigma
- Interesting tension between NOvA and T2K, new results eagerly anticipated

Electron-Neutrino Appearance

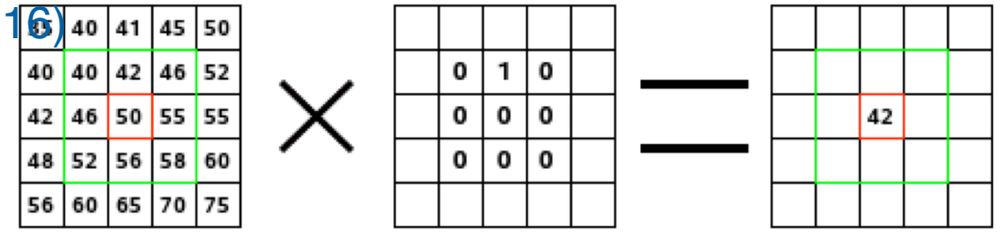
- Electron-neutrino appearance is a sub-dominant oscillation mode at the NOvA L/E
- Matter effects matter (almost 3 times longer baseline than T2K)
- Sensitive to
  - **Mass hierarchy**
  - **CP violating phase**
  - **Octant of θ_{23}**

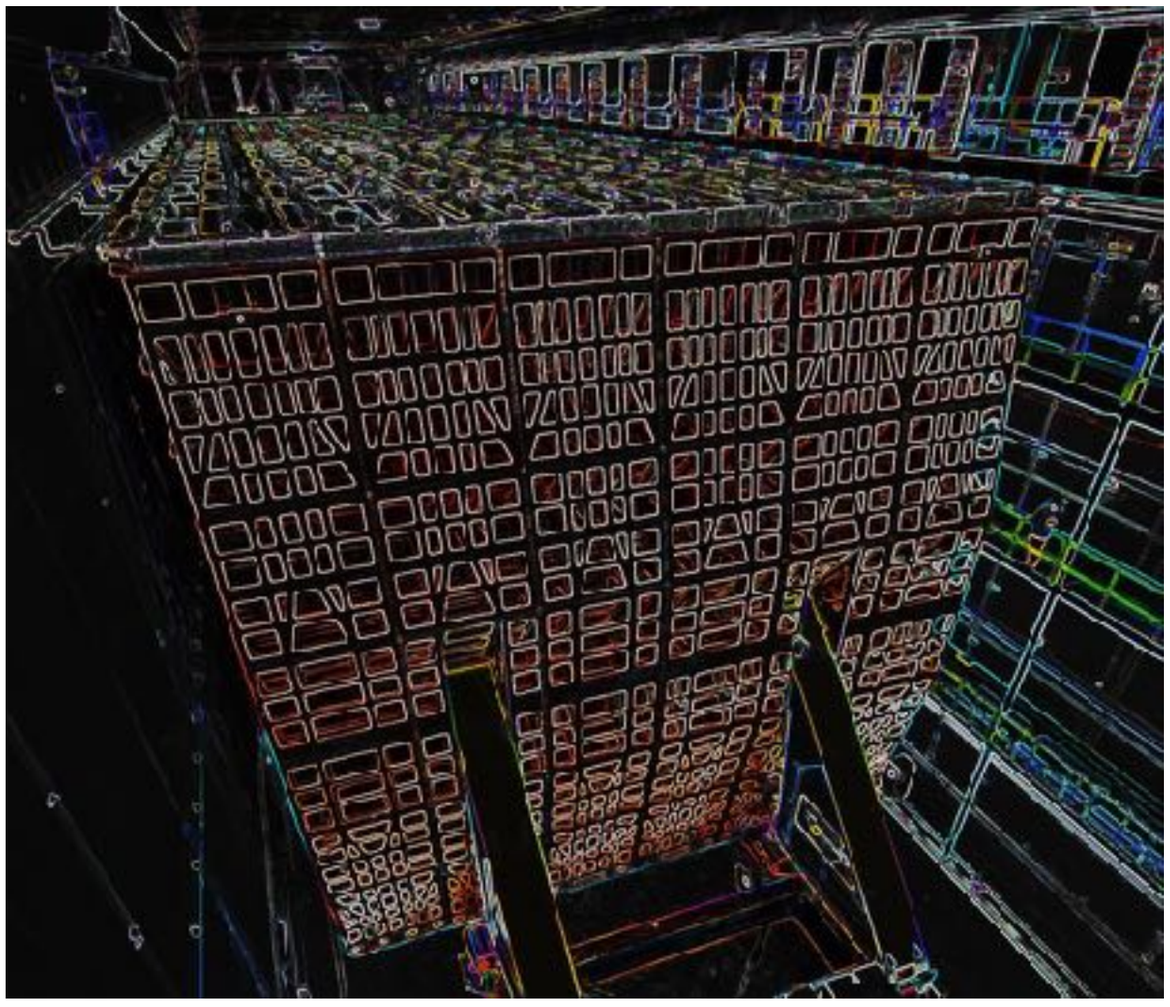




A. Aurisano and A. Radovic and D. Rocco et. al, JINST **11** P09001 (2016)

New Classification Algorithm

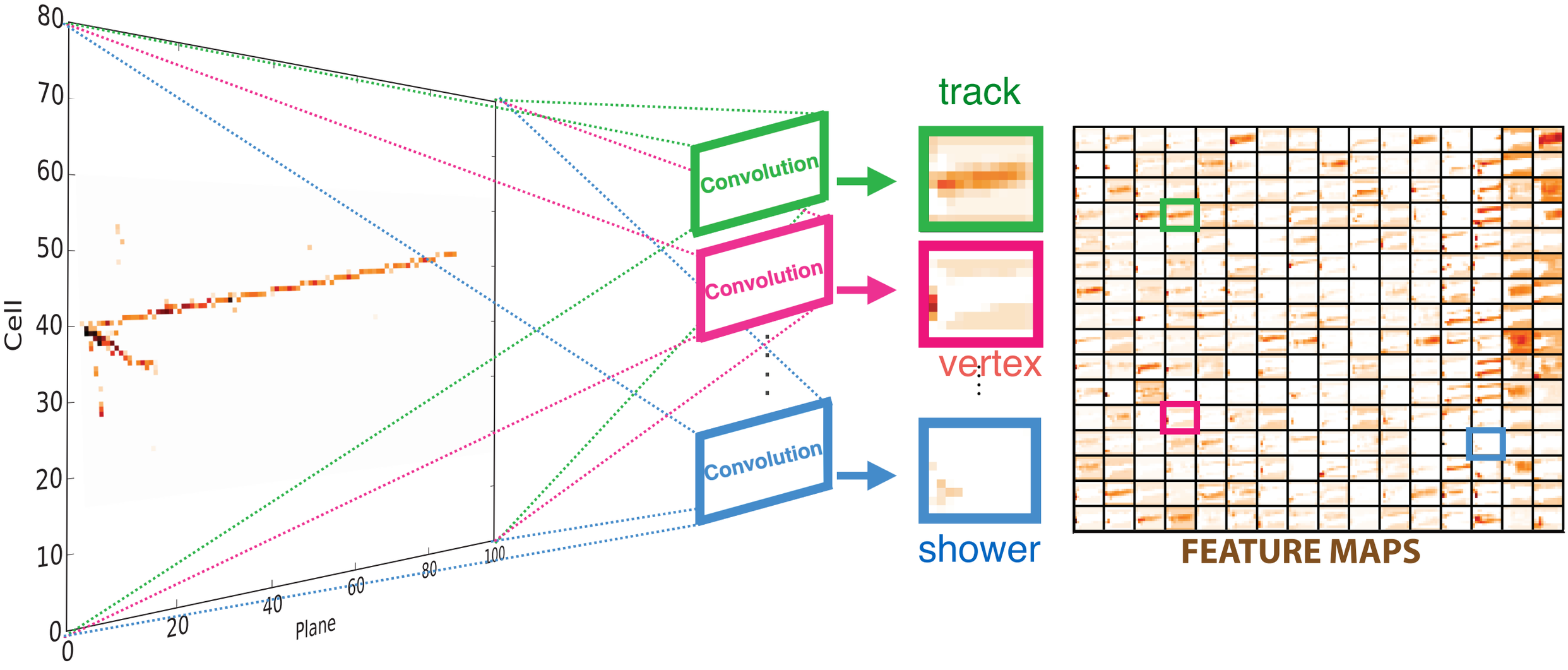




- Take advantage of recent advances in machine learning/computer vision
- Deep networks extract complex features from input data, GPUs greatly improve training time
- Inputs to the network are pixels in image
- Apply convolutional kernels to pull out event features
  - **Image on right has gone through a convolutional kernel looking for edges**

Convolutional Visual Network (CVN) Selection

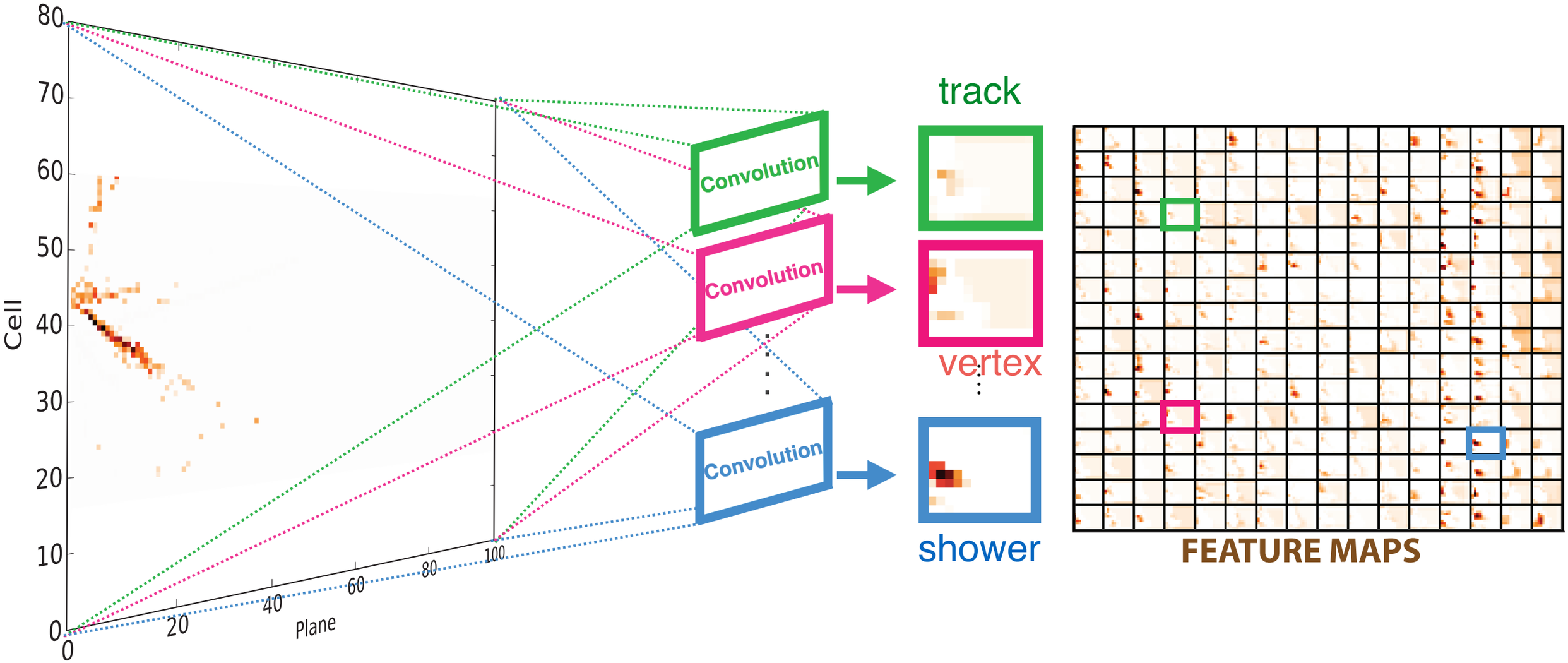
- Showing a muon neutrino interaction and the first layer of feature maps extracted from the convolutional kernels
- Strong feature here is the track



Convolutional Neural Networks

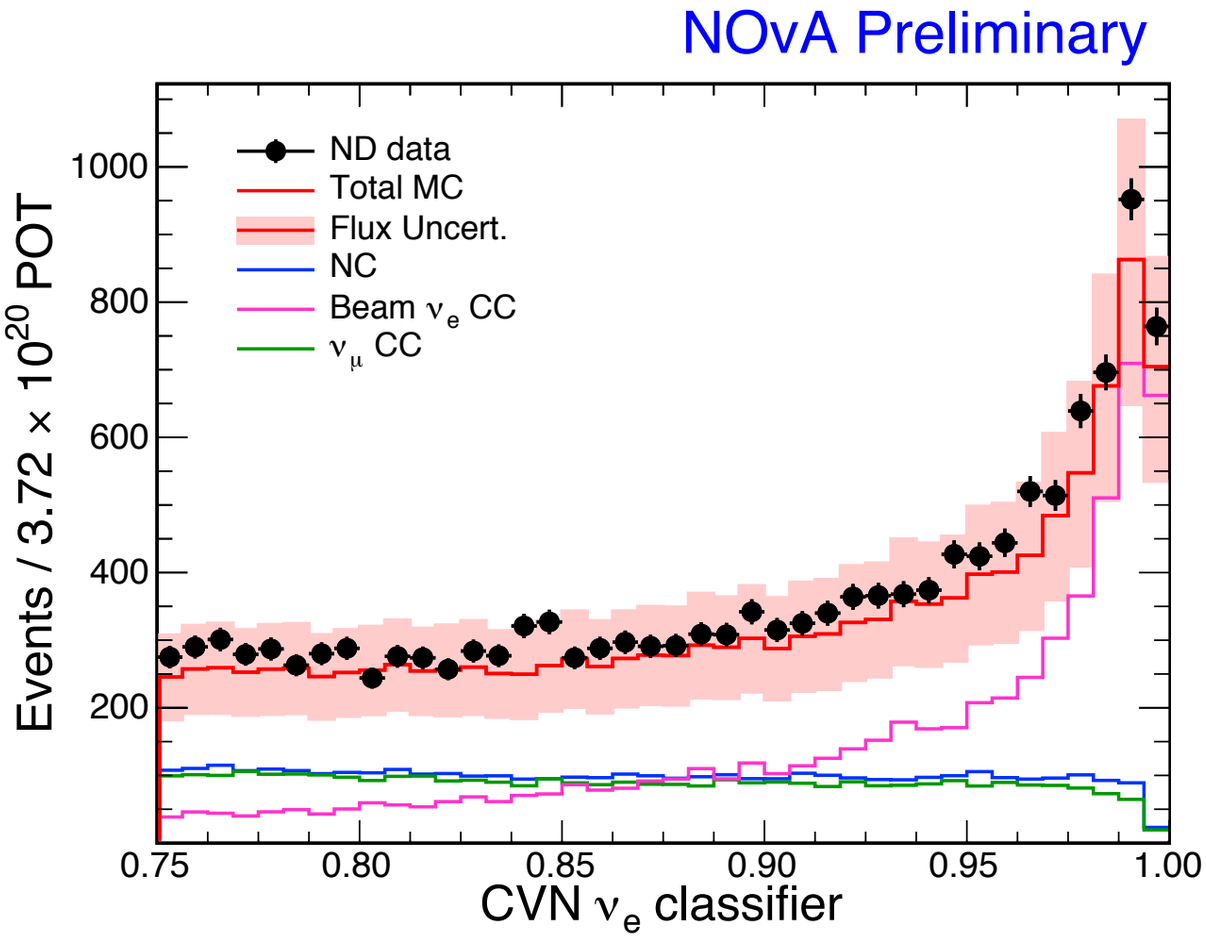
- Showing an electron neutrino interaction and the first layer of feature maps extracted from the convolutional kernels

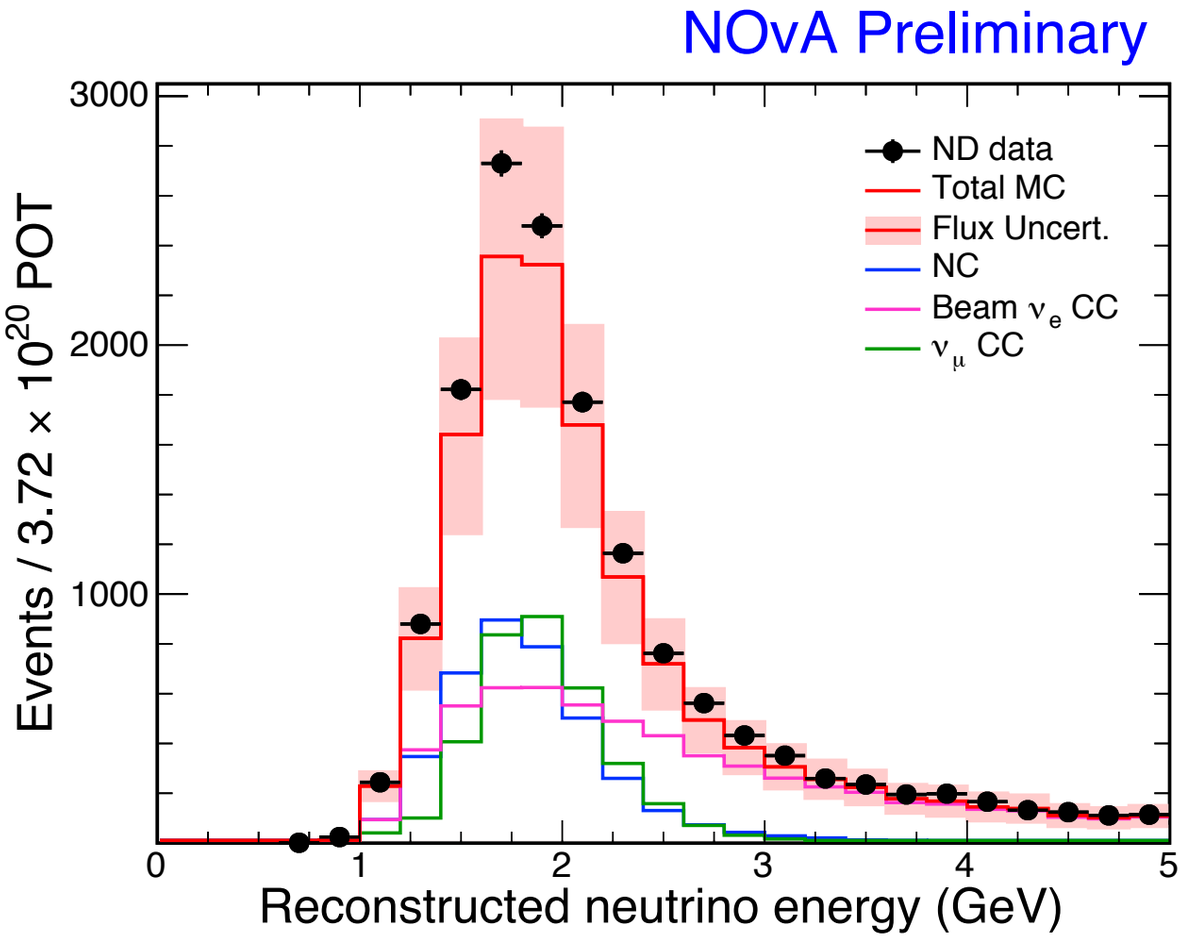
- The strong features extracted are the shower as opposed to the track



Electron Neutrino Selection ND

arXiv:1703.03328

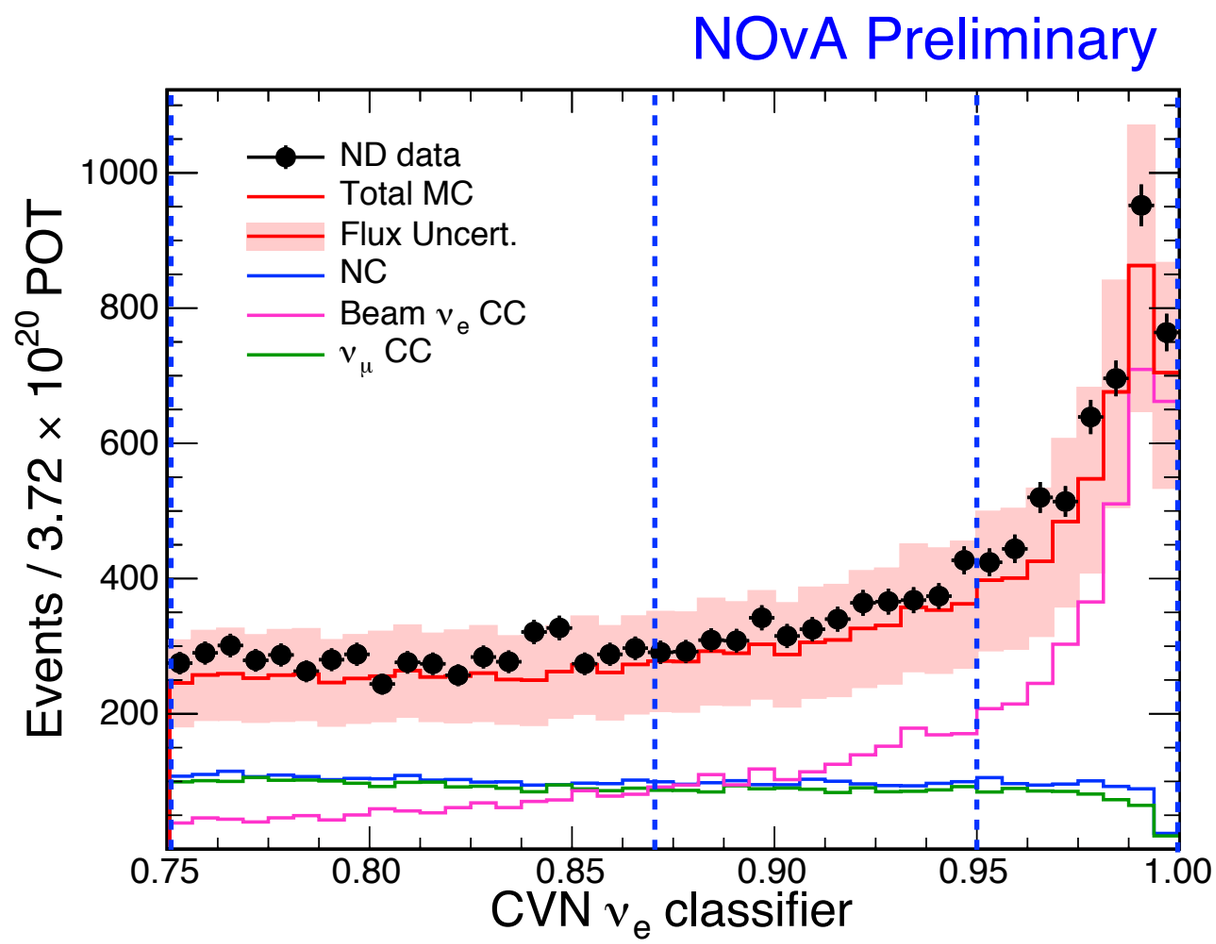


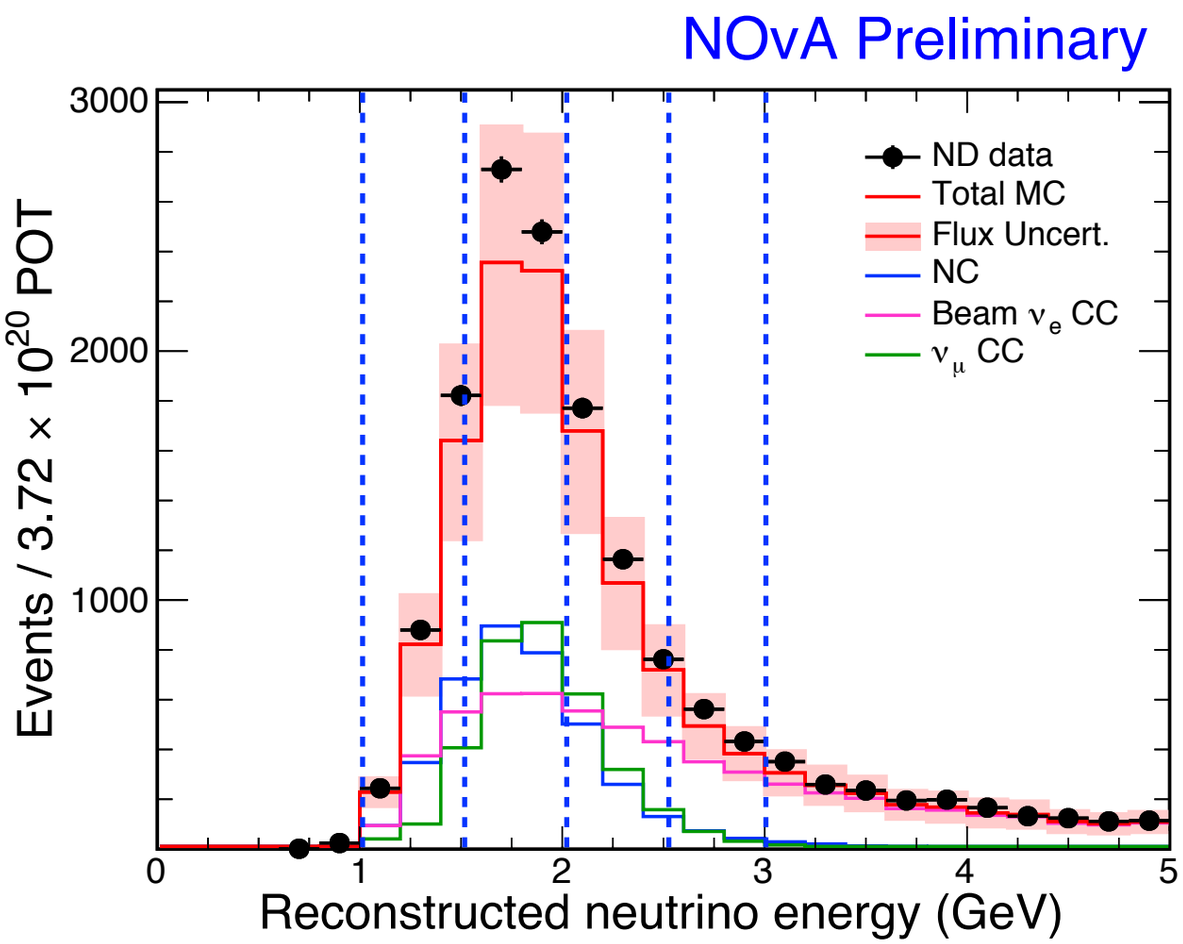


- 73% ν_e CC selection efficiency, 76% purity with CVN classifier
- Good ND Data/MC agreement
- CVN provides better cosmic rejection and similar systematics to 2015 classifiers

Electron Neutrino Selection ND

10.1103/PhysRevLett.118.231801



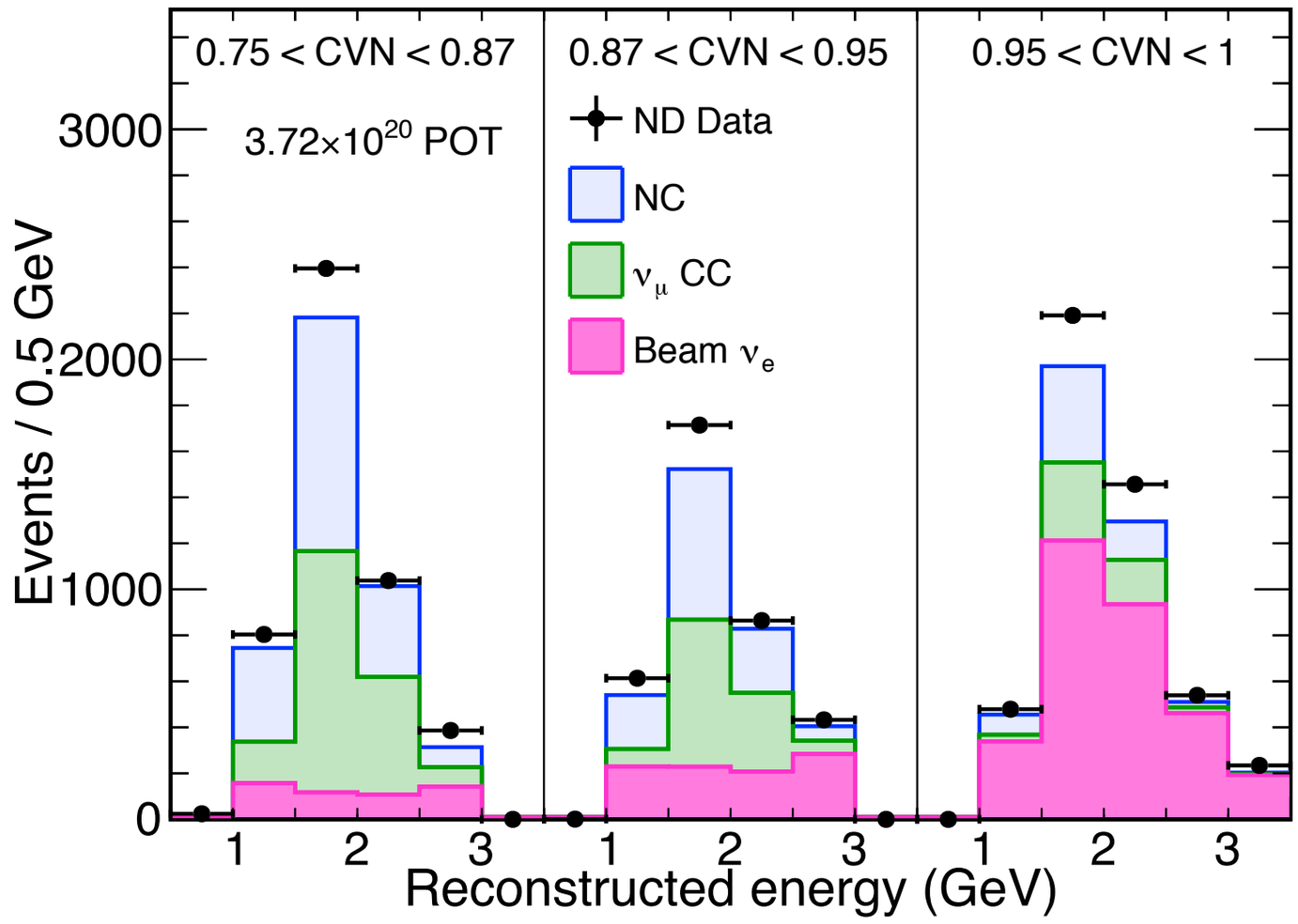


- Bin analysis in four bins of energy and three of CVN

Data Driven Background Corrections

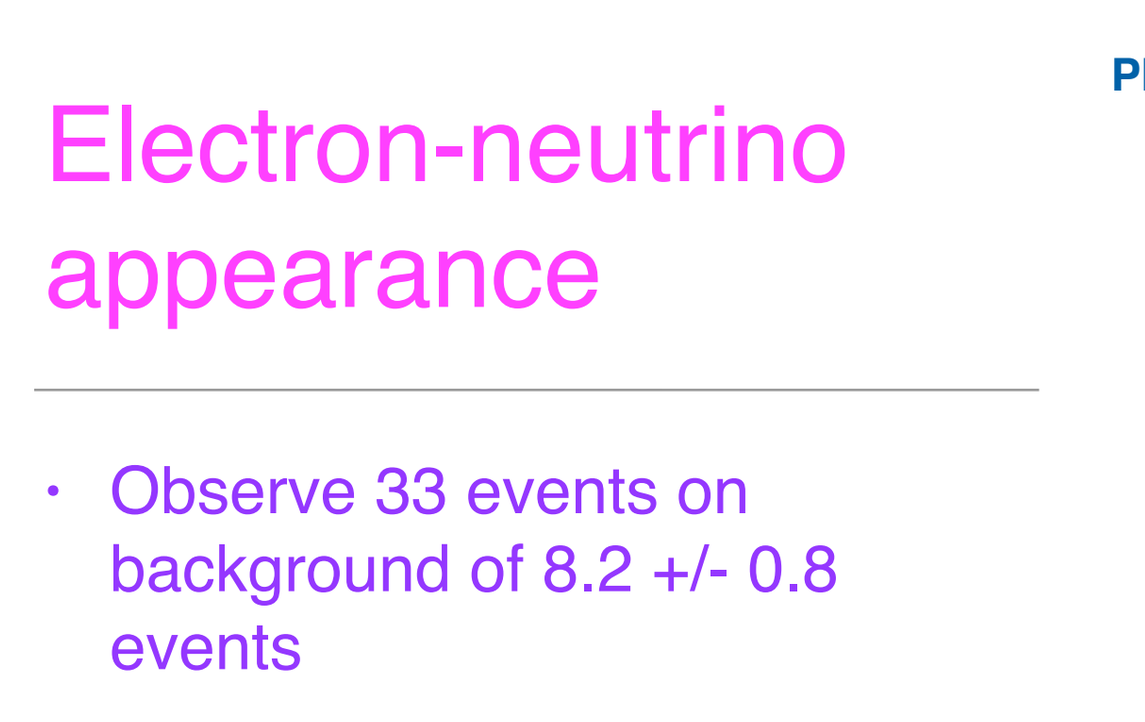
arXiv:1703.03328

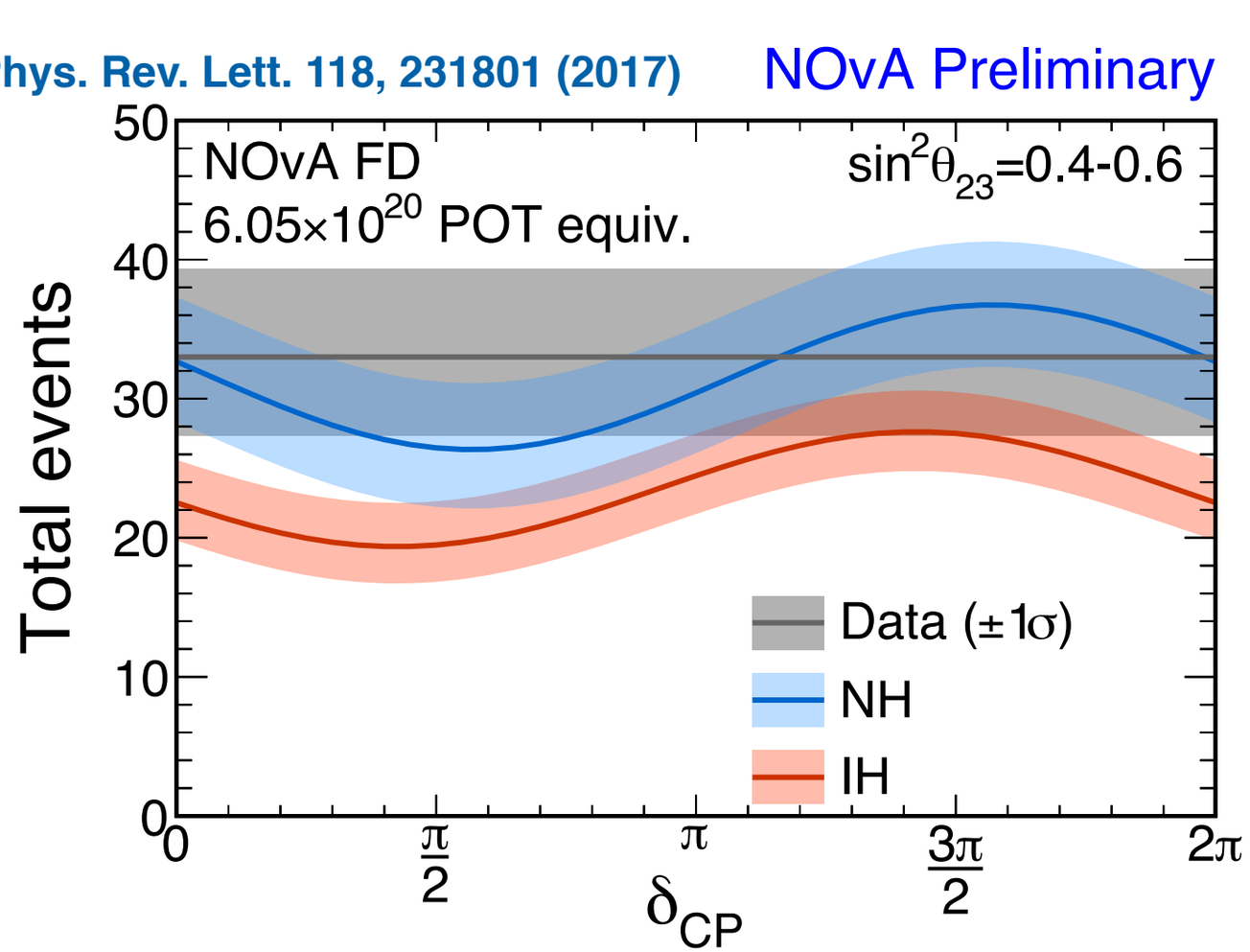
- ν_e-CC selection in the ND picks out FD backgrounds
  - **Beam ν_e-CC**
  - **ν_μ-CC**
  - **Neutral current**
- ~10% excess of data over MC in the ND
- Extrapolate data/MC differences to adjust FD prediction
- Each component oscillates differently
- Must decompose the data into constituent components

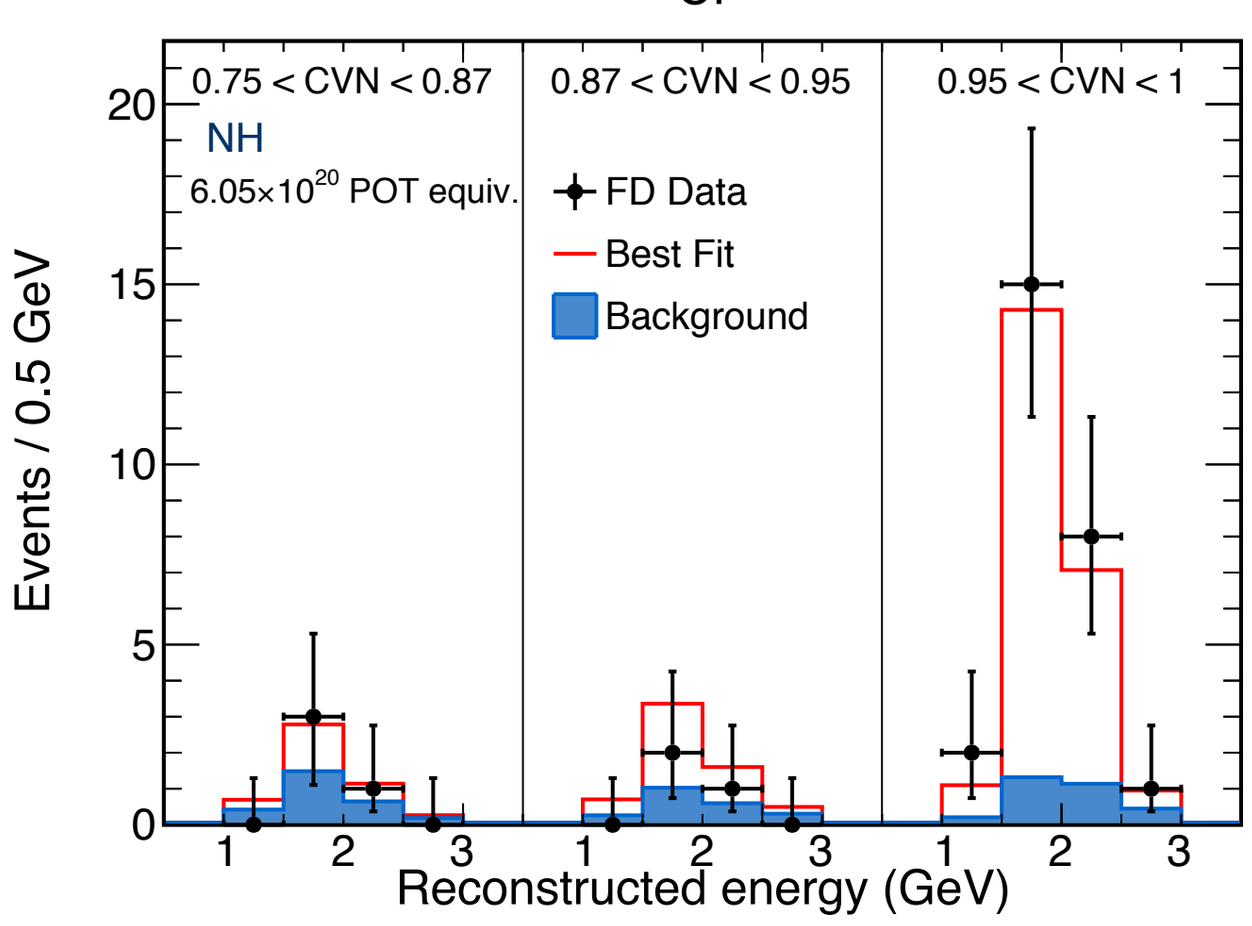


Electron-neutrino appearance

- Observe 33 events on background of 8.2 +/- 0.8 events
- Confirmation that electron neutrinos are appearing (8 σ)

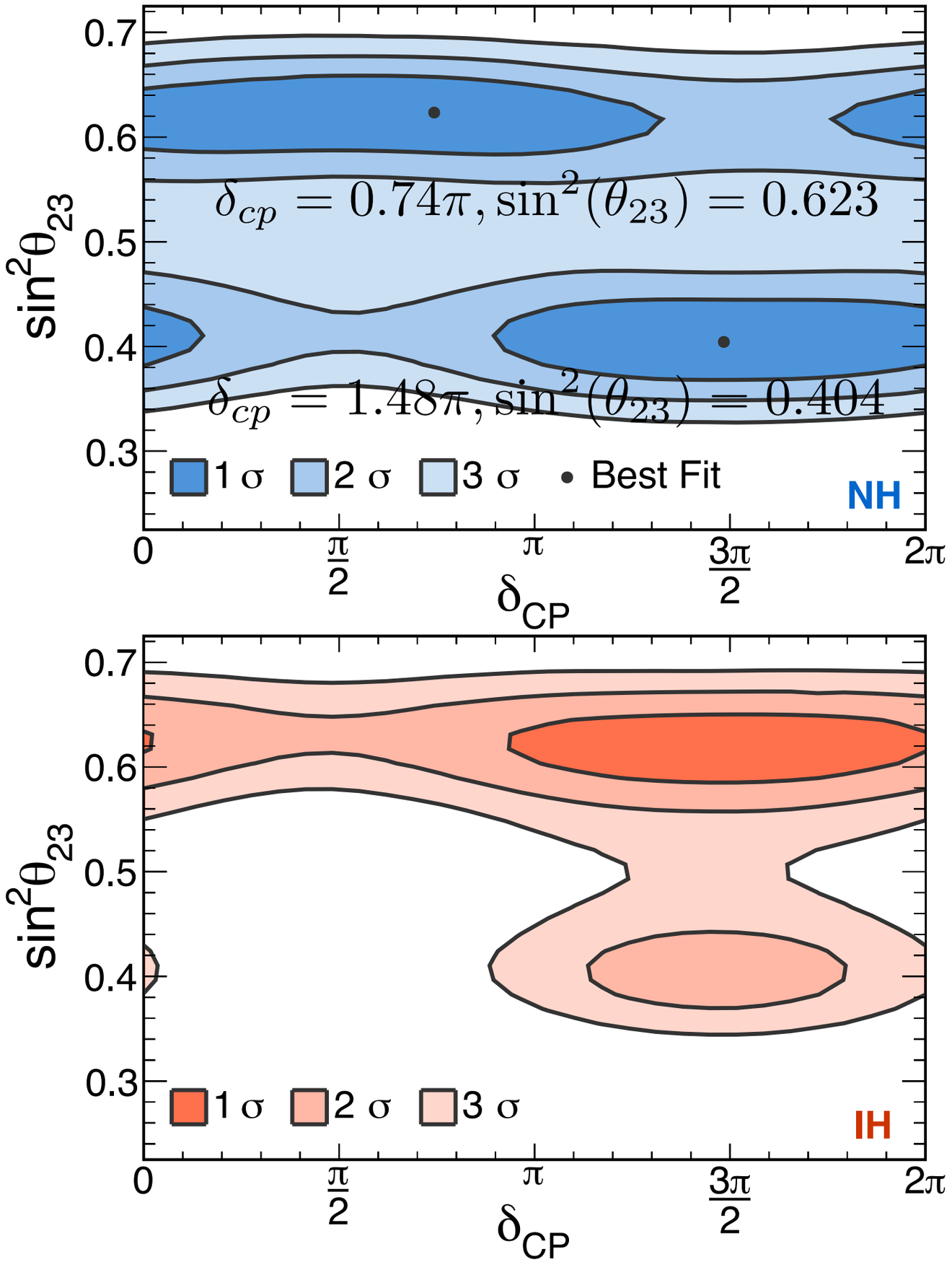






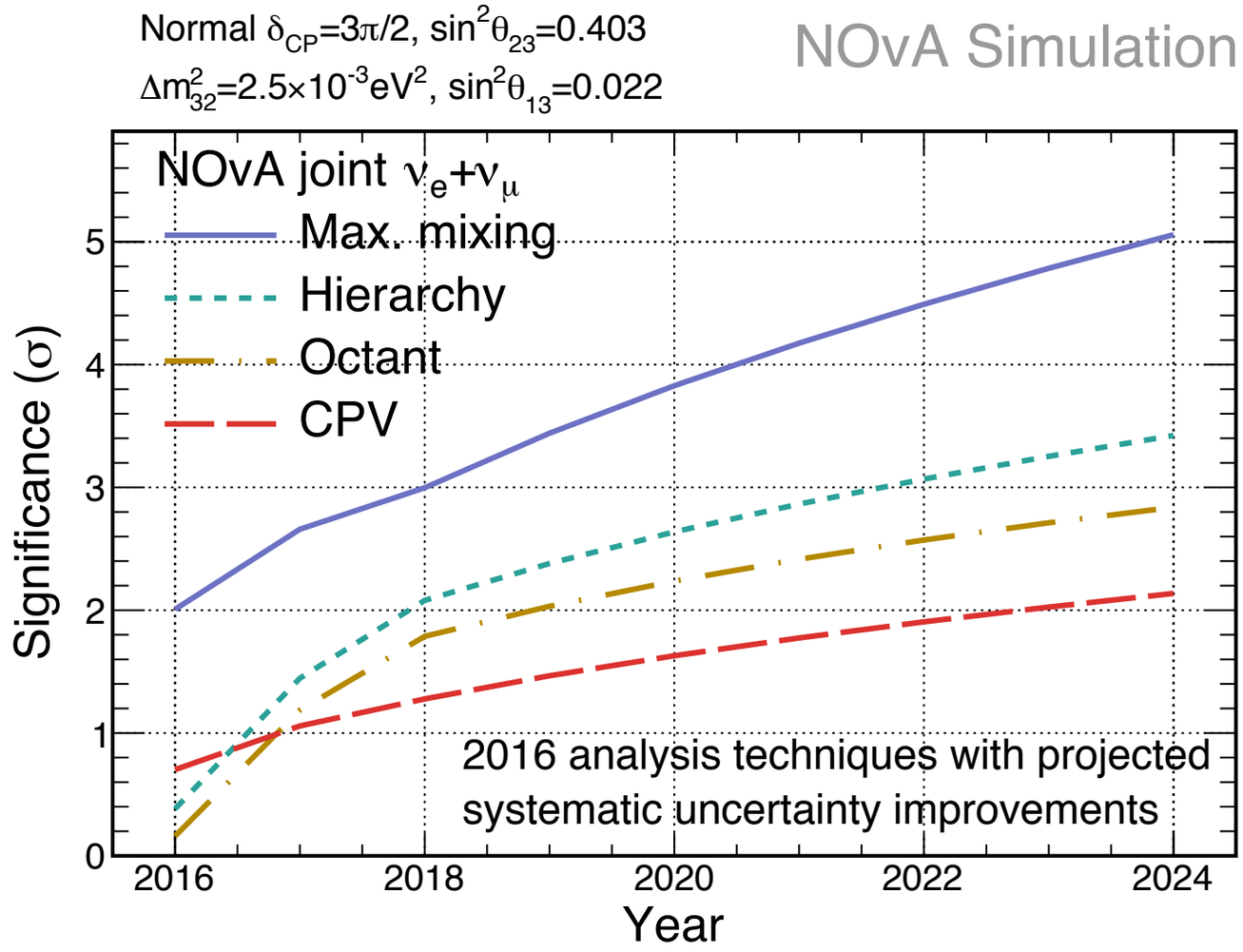
ν_μ -> ν_e Oscillation Results

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - **Constrain $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ from reactor experiments**
  - **Simultaneously fit NOvA disappearance and electron appearance data**
- Global best fit, two degenerate points in Normal Hierarchy
  - **best fit IH-NH, $\Delta\chi^2=0.47$**
  - **Lower octant, IH is disfavoured at greater than 93% C.L for all values of δ_{CP}**



Phys. Rev. Lett. 118, 231801 (2017)

Looking Forward



- NOVA Switched to anti-neutrino running in February 2017
- Plan to run 50% neutrino, 50% anti-neutrino after 2018
  - **3 σ sensitivity to maximal mixing of θ_{23} in 2018**
  - **2 σ sensitivity to mass hierarchy and θ_{23} octant in 2018-2019**

Conclusions

- Analysis of 6.05x10^{20} POT of NOvA data (1 nominal year)
- Muon-neutrino disappearance (arXiv:1701.05891)
  - **Best fit is non-maximal value of θ_{23}, maximal mixing disfavoured at 2.6σ**
- Electron-neutrino appearance (arXiv:1703.03328)
  - **First joint fit of NOvA appearance and disappearance data**
  - **Weak preference for normal hierarchy**
  - **Inverted hierarchy, lower octant is disfavoured at > 93% C.L.**
- Anti-neutrino run 2017 completed last week
- Watch out for new results at next years Neutrino Conference