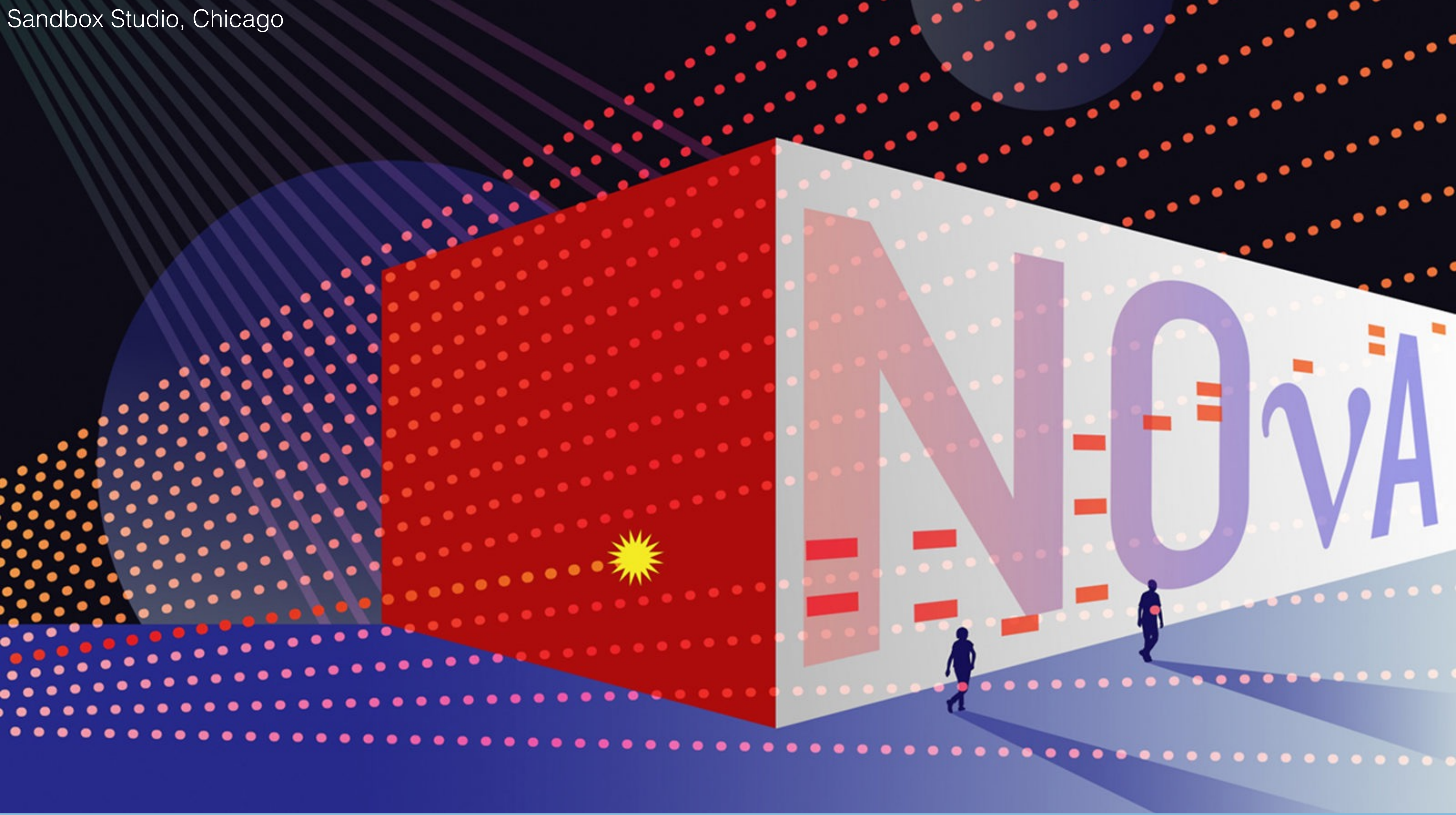
Sandbox Studio, Chicago



Details of the NOvA ν_μ disappearance analysis

Linda Cremonesi
for the NOvA collaboration

Outline

- The NOvA experiment
- The Far Detector Extrapolation
- Uncertainties
- Results
- Improvements for future analyses

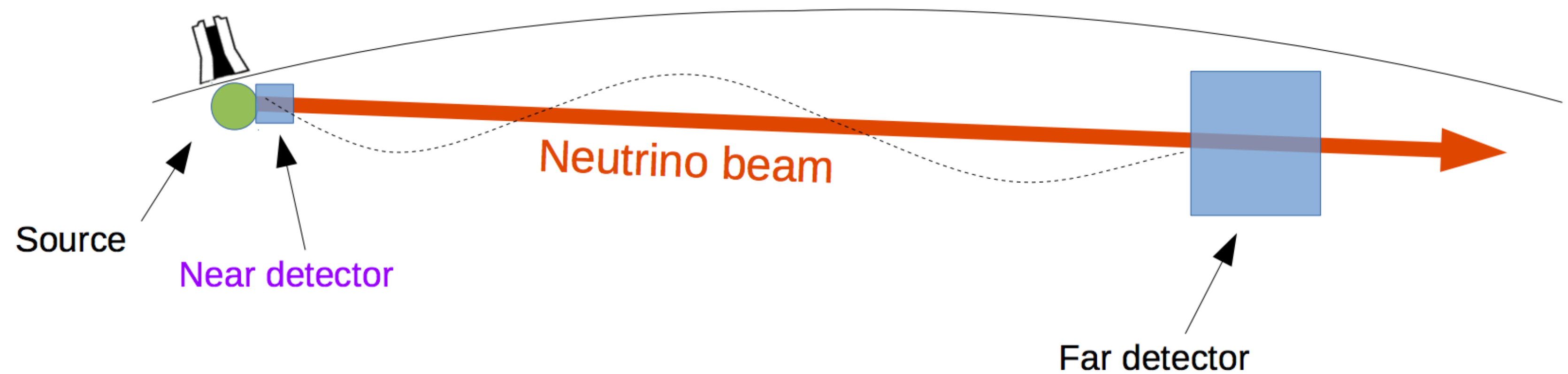
Motivation

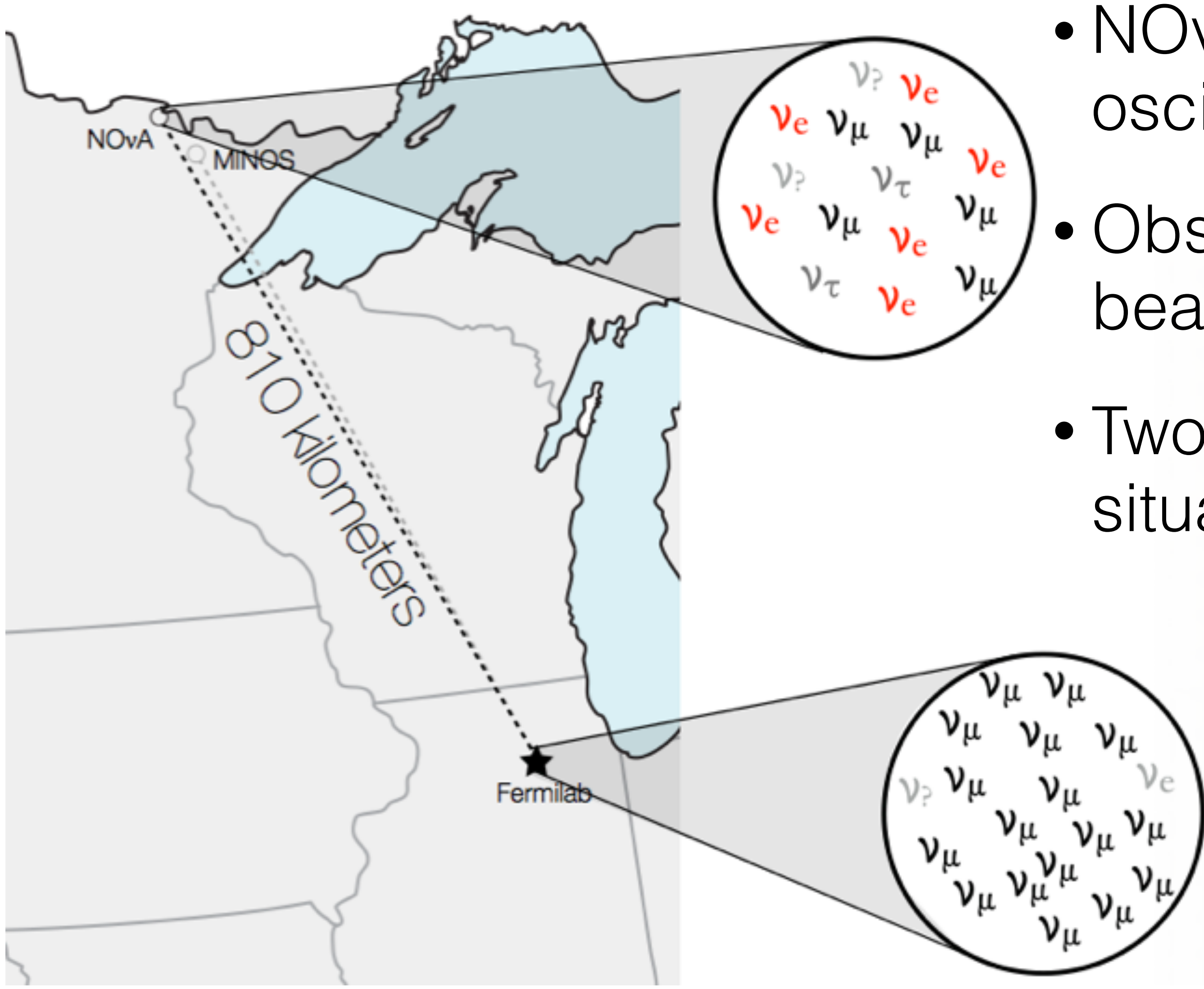
1. θ_{23} was the first angle to be measured but (prior to NOvA and T2K) was the one known to the least precision.

2. A precision measurement of θ_{23} can help determine the correct texture for the PMNS matrix.

3. An accurate measurement of θ_{23} improves the NOvA appearance measurement (and if it is non-maximal, could allow us to resolve the octant.)

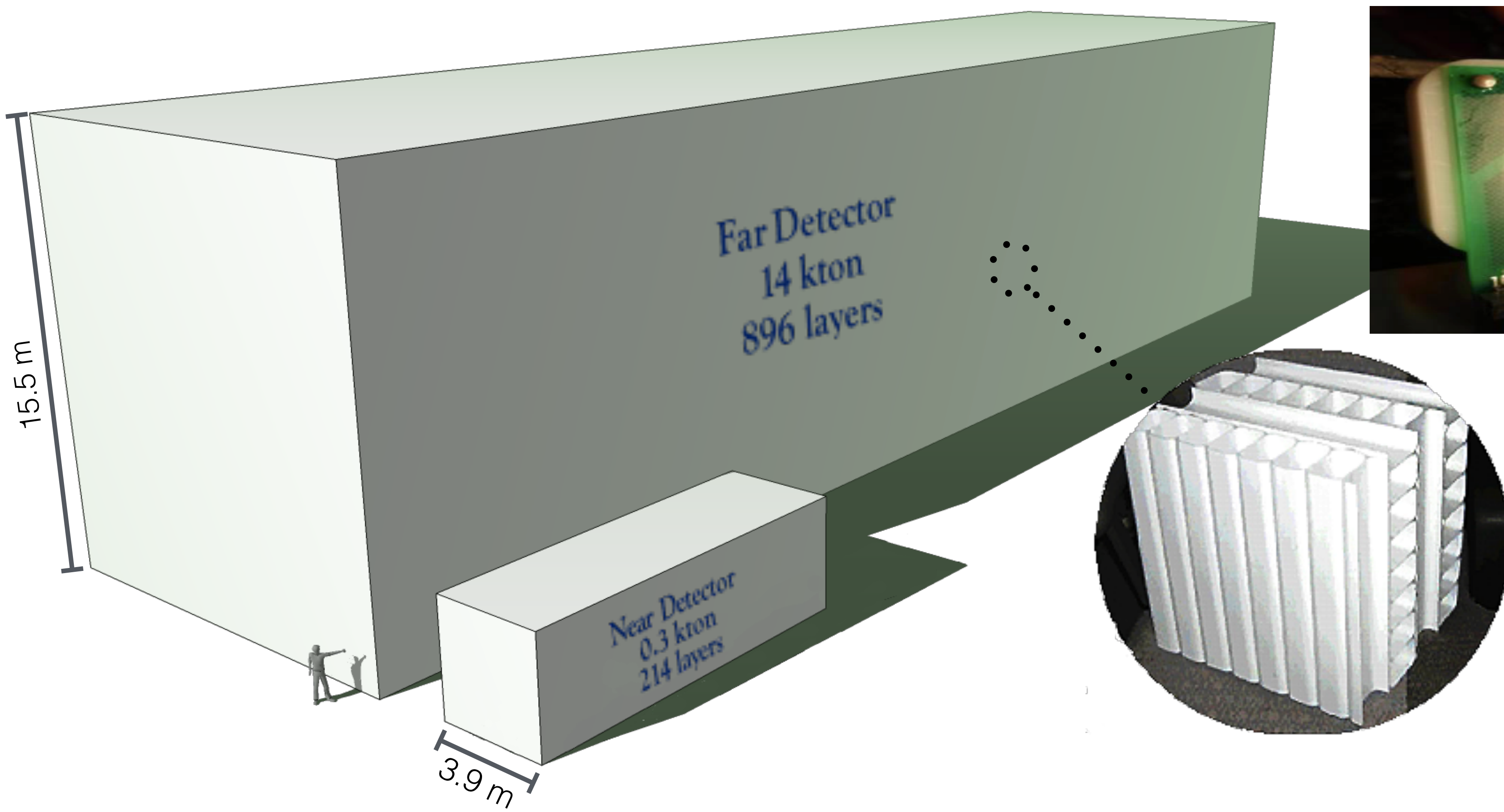
The NOvA experiment

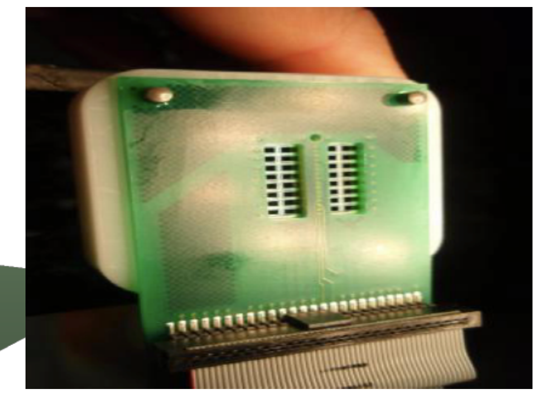


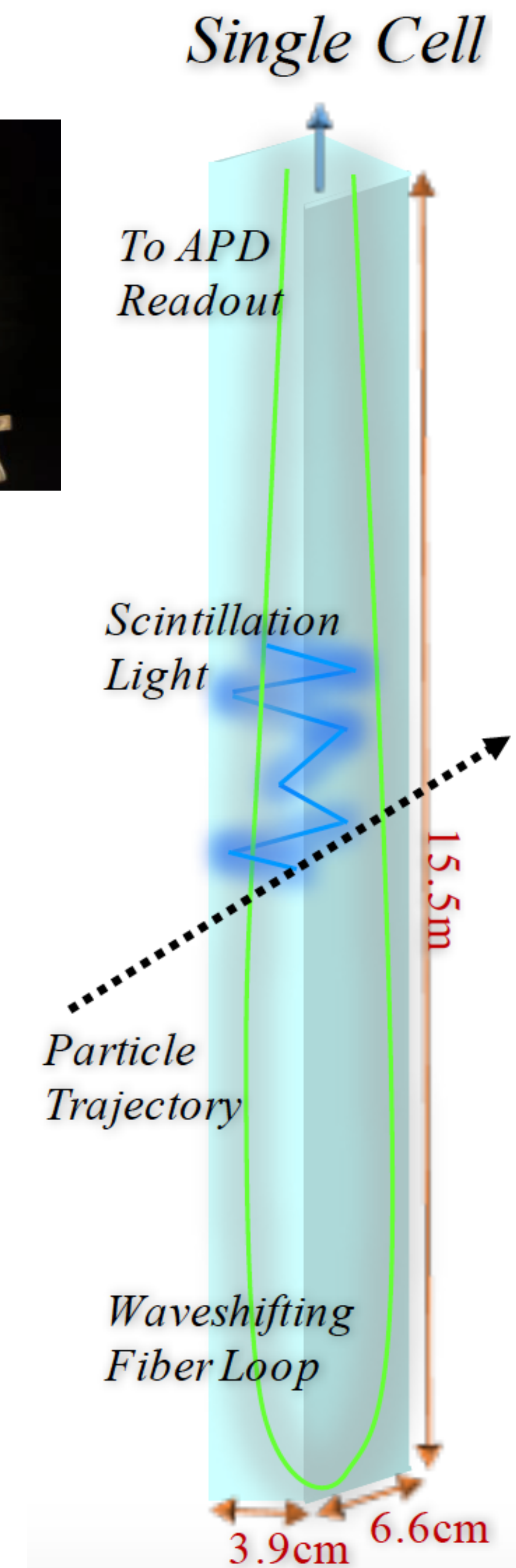


- NOvA is a long-baseline neutrino oscillation experiment
- Observes neutrinos from NuMI beamline at Fermilab
- Two functionally identical detectors, situated 14 mrad off axis, 810 km apart
  - Near Detector is 300 tons (FNAL)
  - Far Detector is 14 ktons (Ash River, MN)

NOvA detectors

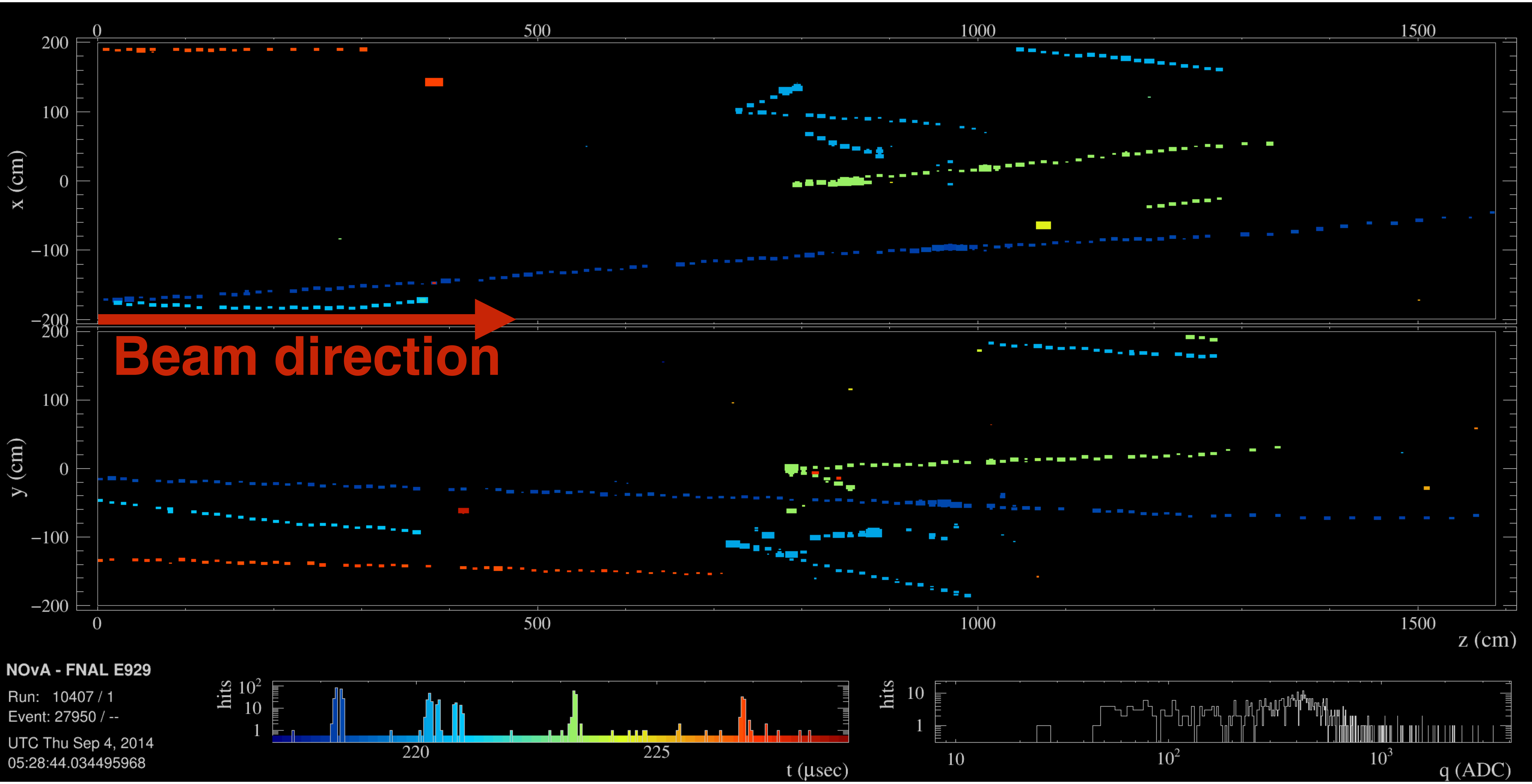






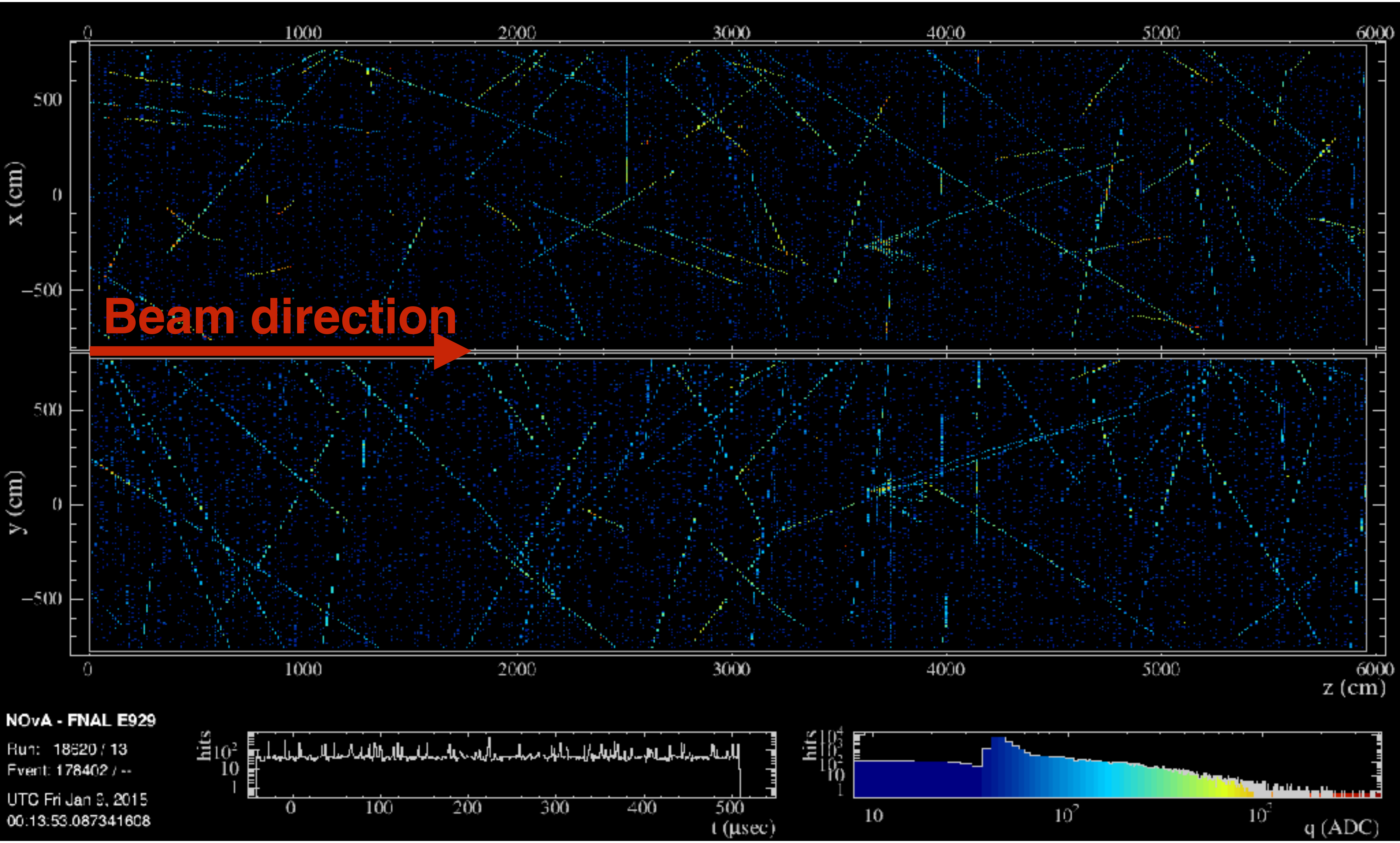
- Two functionally identical detectors
- Extruded plastic cells alternating vertical and horizontal orientation filled with liquid scintillator
- Charged particles passing through cells produce light which is collected.

Near Detector Event Display



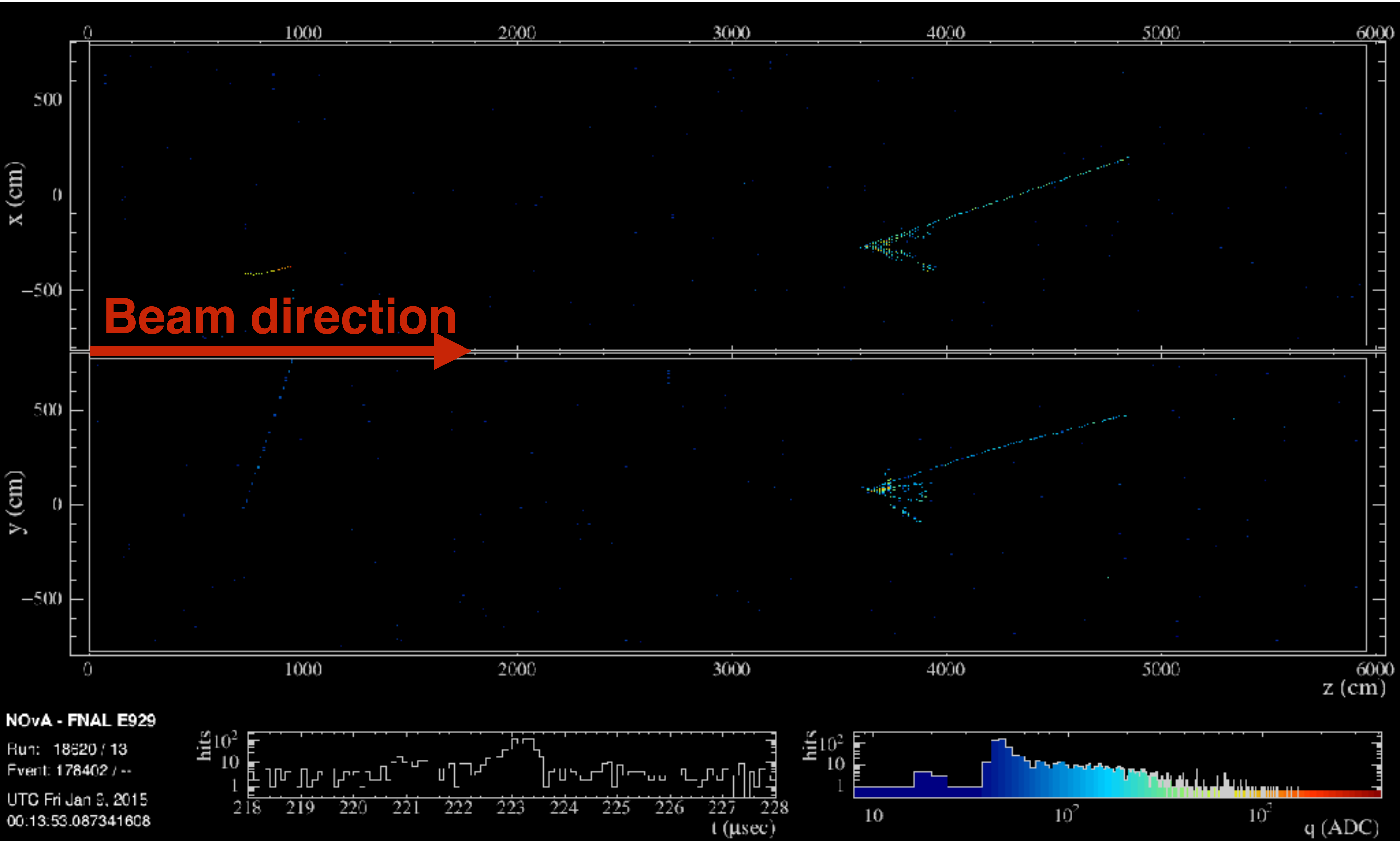
Colours show hit times

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)

Muon neutrino disappearance

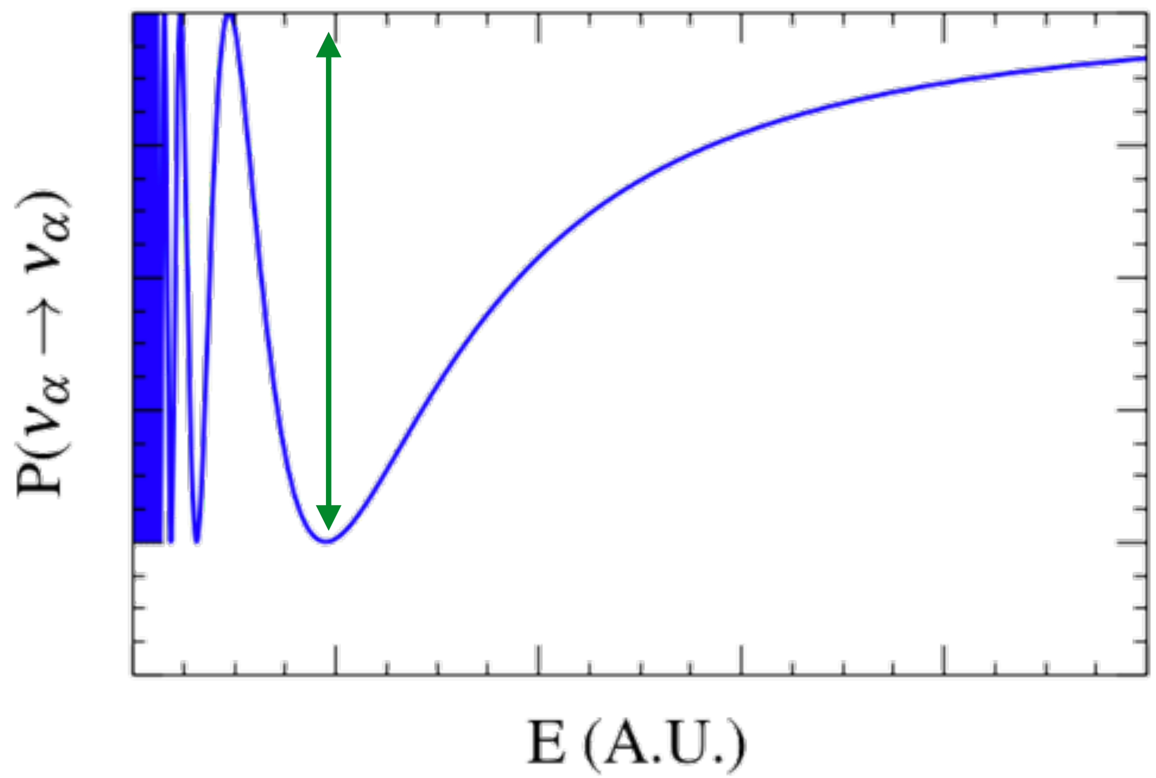
Small

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

1. Measure neutrinos at ND

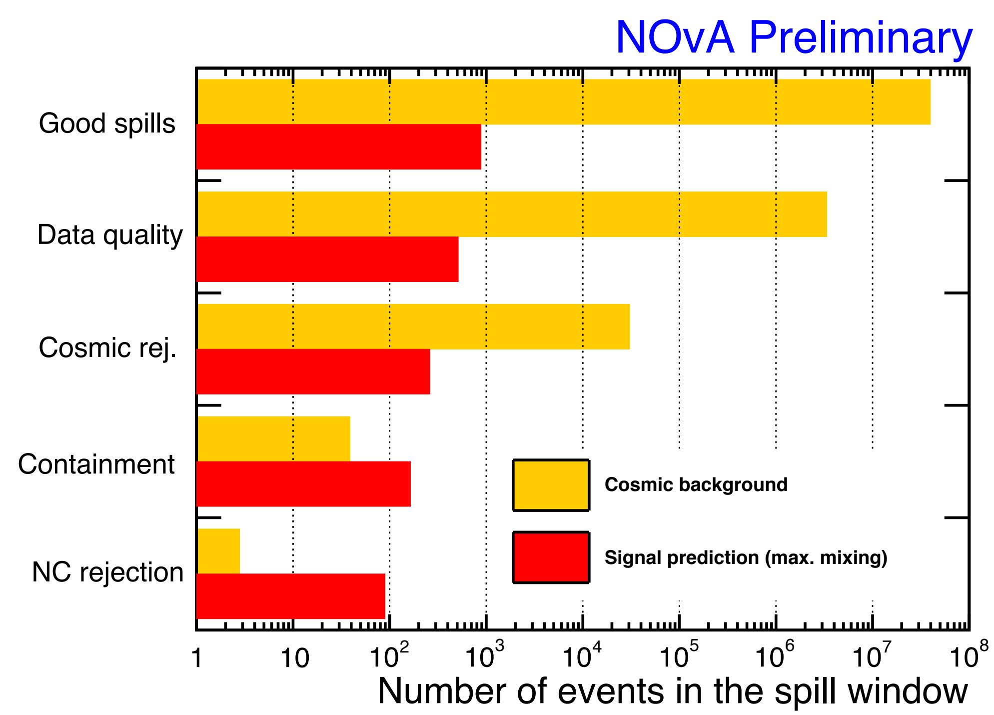
2. Extrapolate measurements to make FD prediction

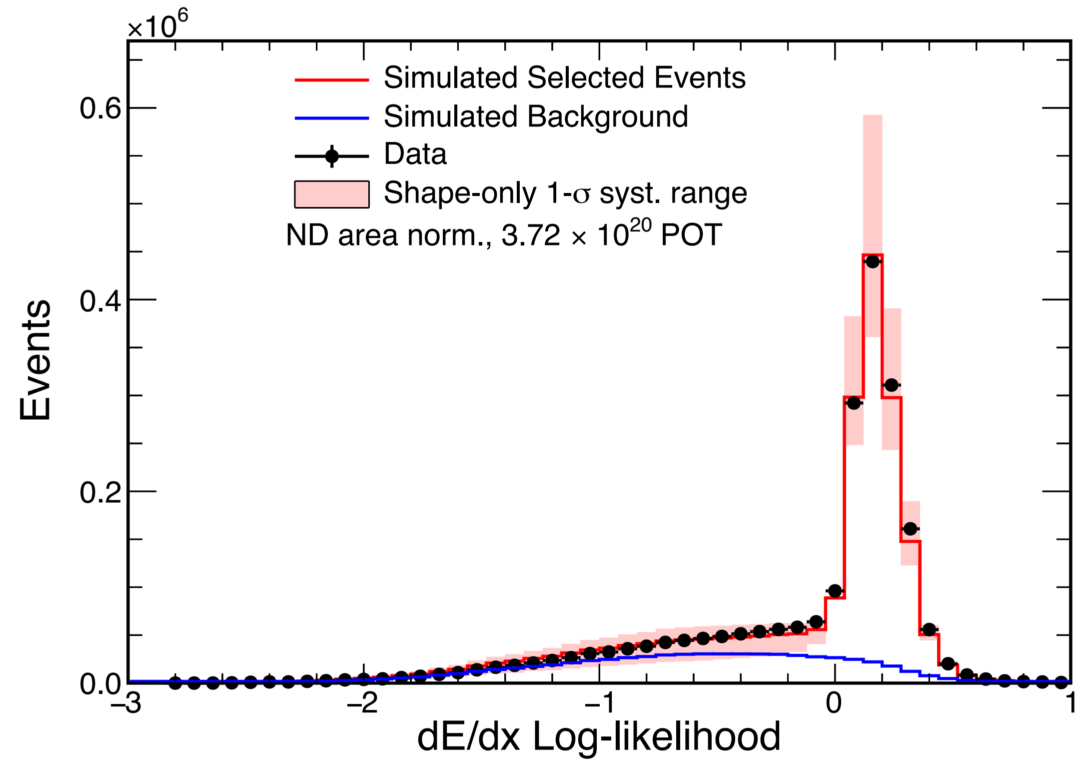
3. Compare FD data to prediction to find best fit of oscillation parameters

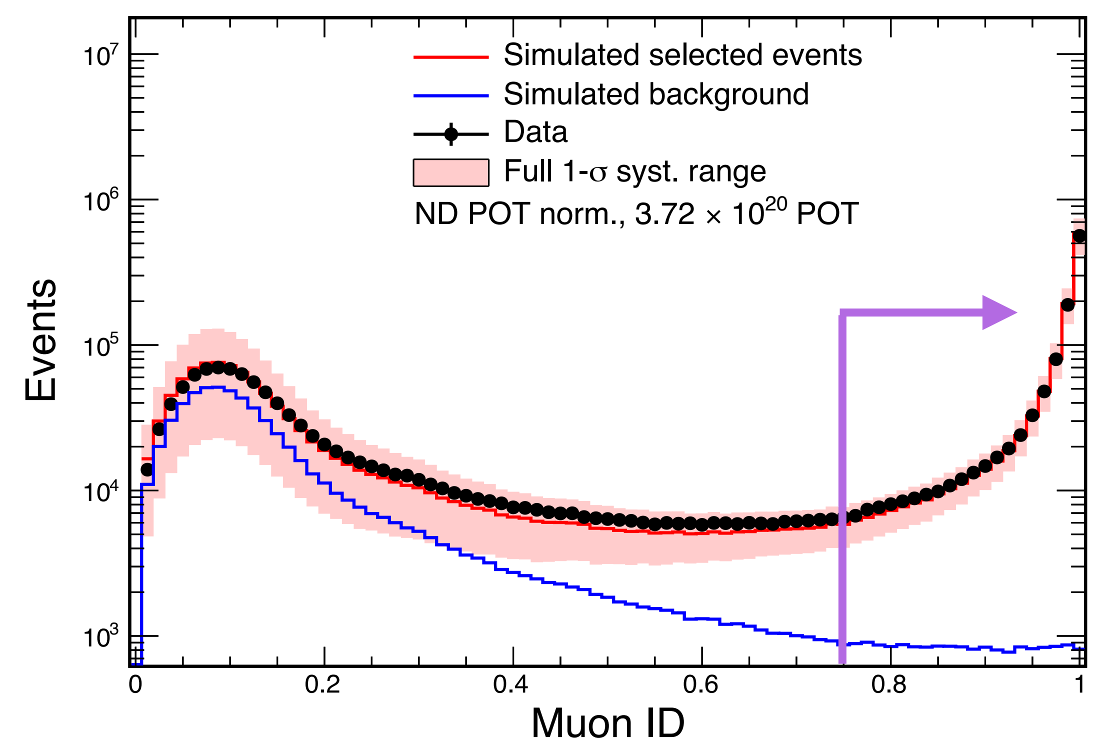


Muon neutrino selection

- Containment cuts remove activity near walls
- Use 4 variable k-Nearest Neighbour to select μ
- Separate νμ CC interactions from NC and cosmic-ray backgrounds
- At FD additional Cosmic rejection from event topology and Boosted Decision Tree
- Selection is 81% efficient and 91% pure

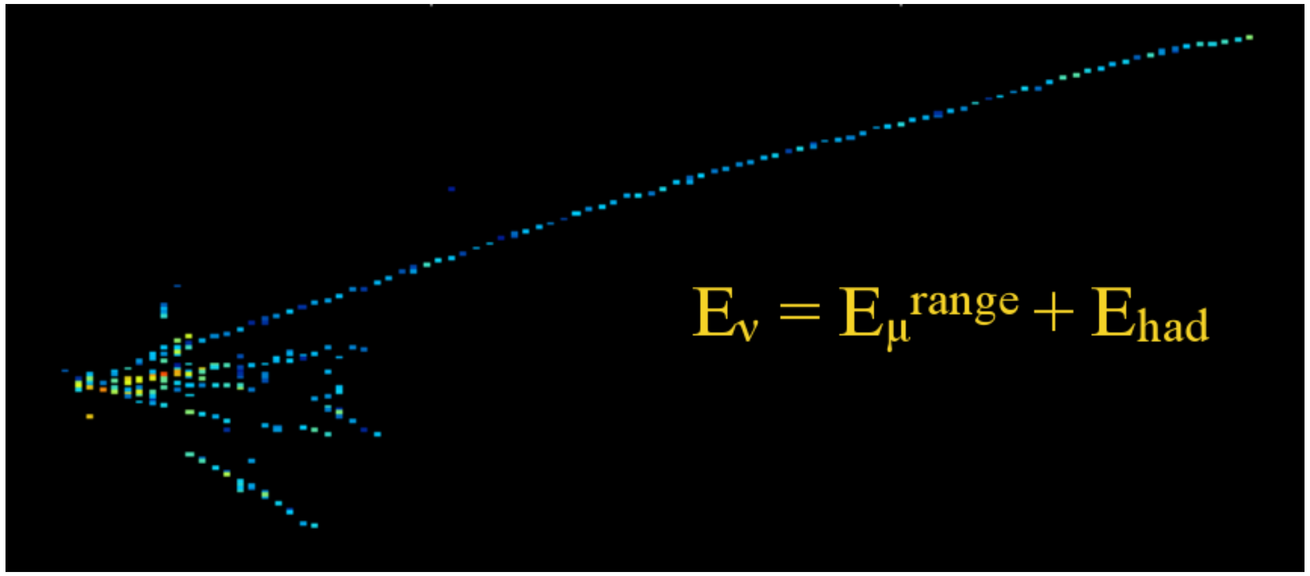


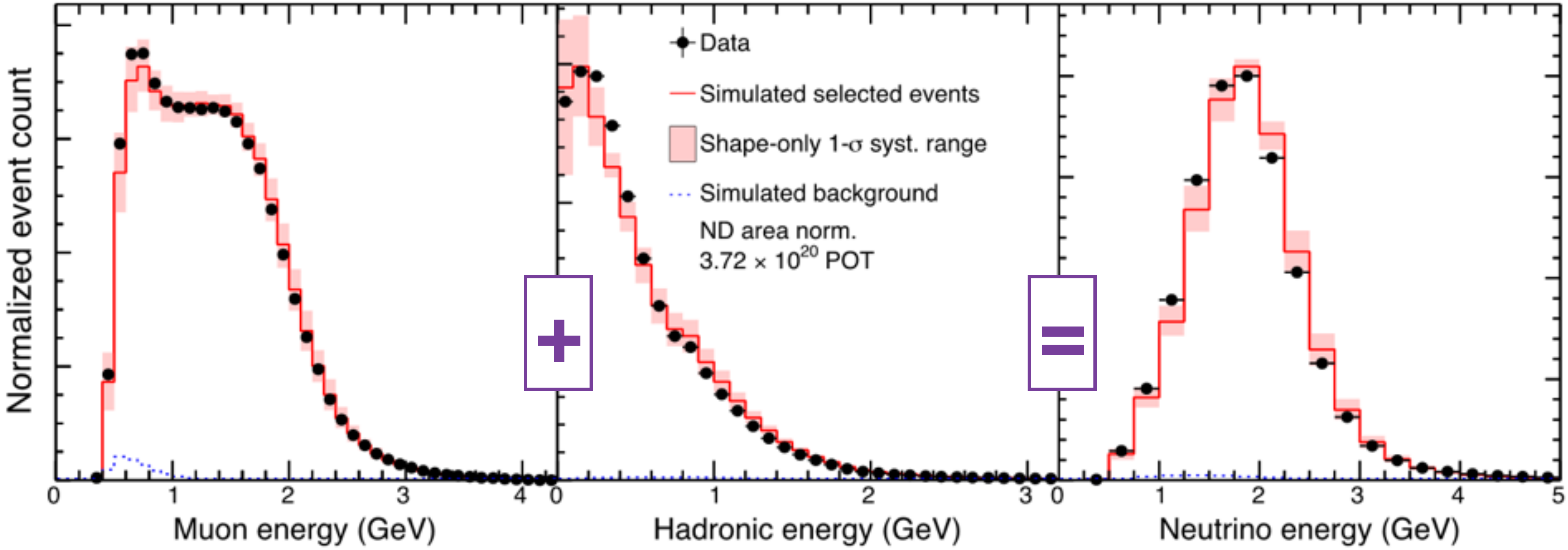




Neutrino energy estimation

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



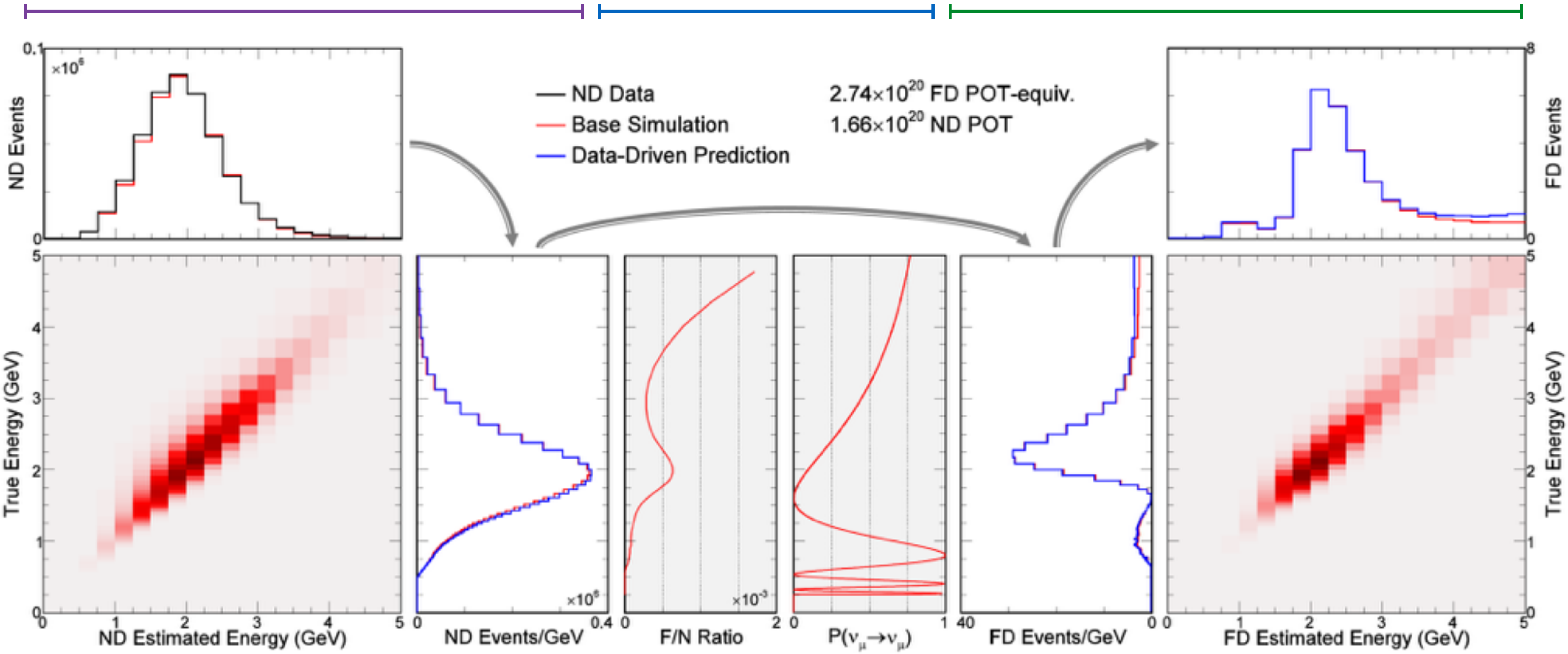


Far detector prediction

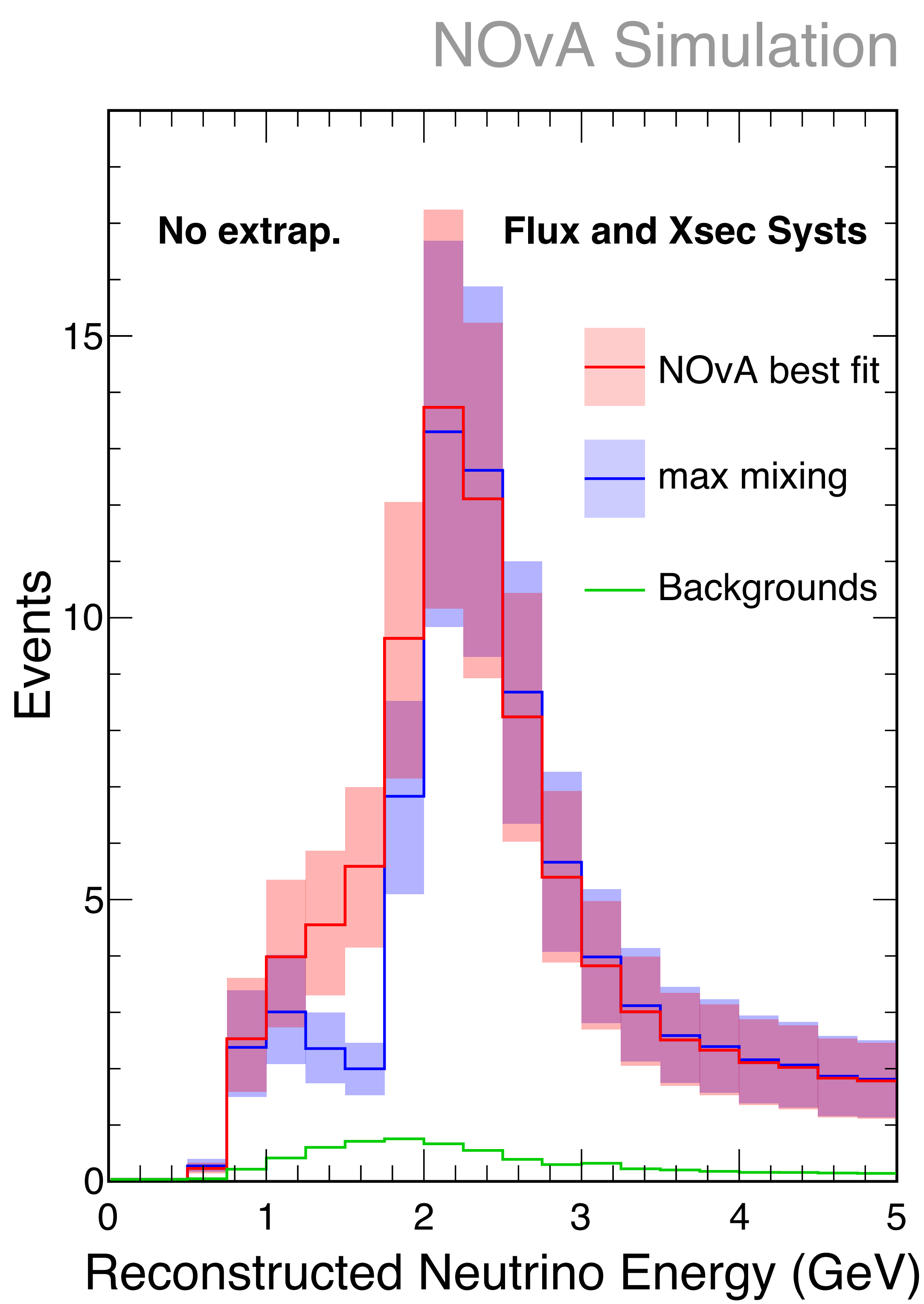
Translate ND data/ MC observation to true energy

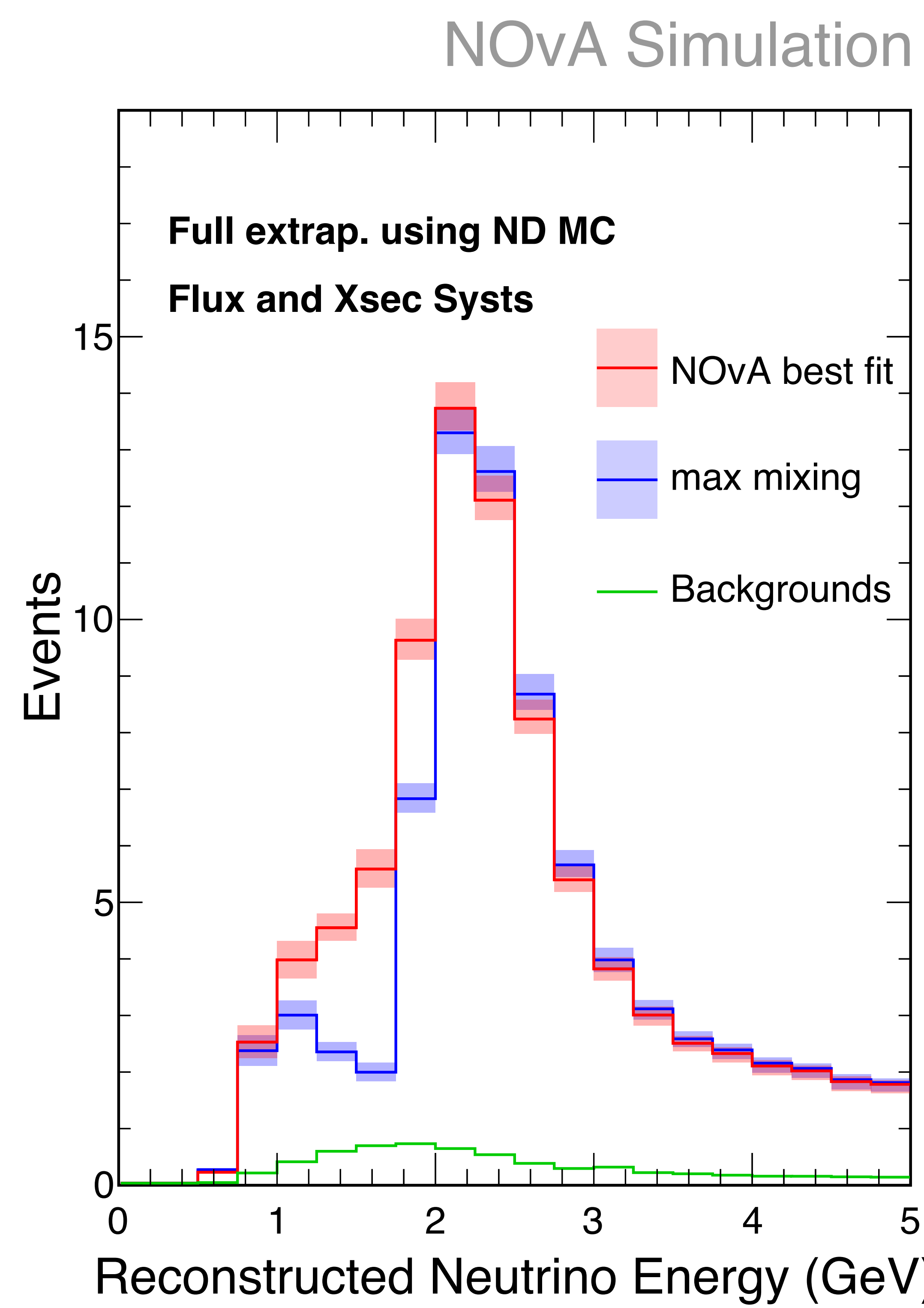
Oscillate ratio to the FD

Smear back into reconstructed energy



Far Detector Prediction





Systematic uncertainties

- The effect of many large uncertainties is reduced by the near-to-far extrapolation technique (cross sections, beam flux, etc.)

Systematic (*)	Effect on $\sin^2(\theta_{23})$	Effect on Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model	± 0.7 %	± 0.1 %
All systematics	**± 3.4 %**	**± 2.4 %**
Stat. Uncertainty	**± 4.1 %**	**± 3.5 %**

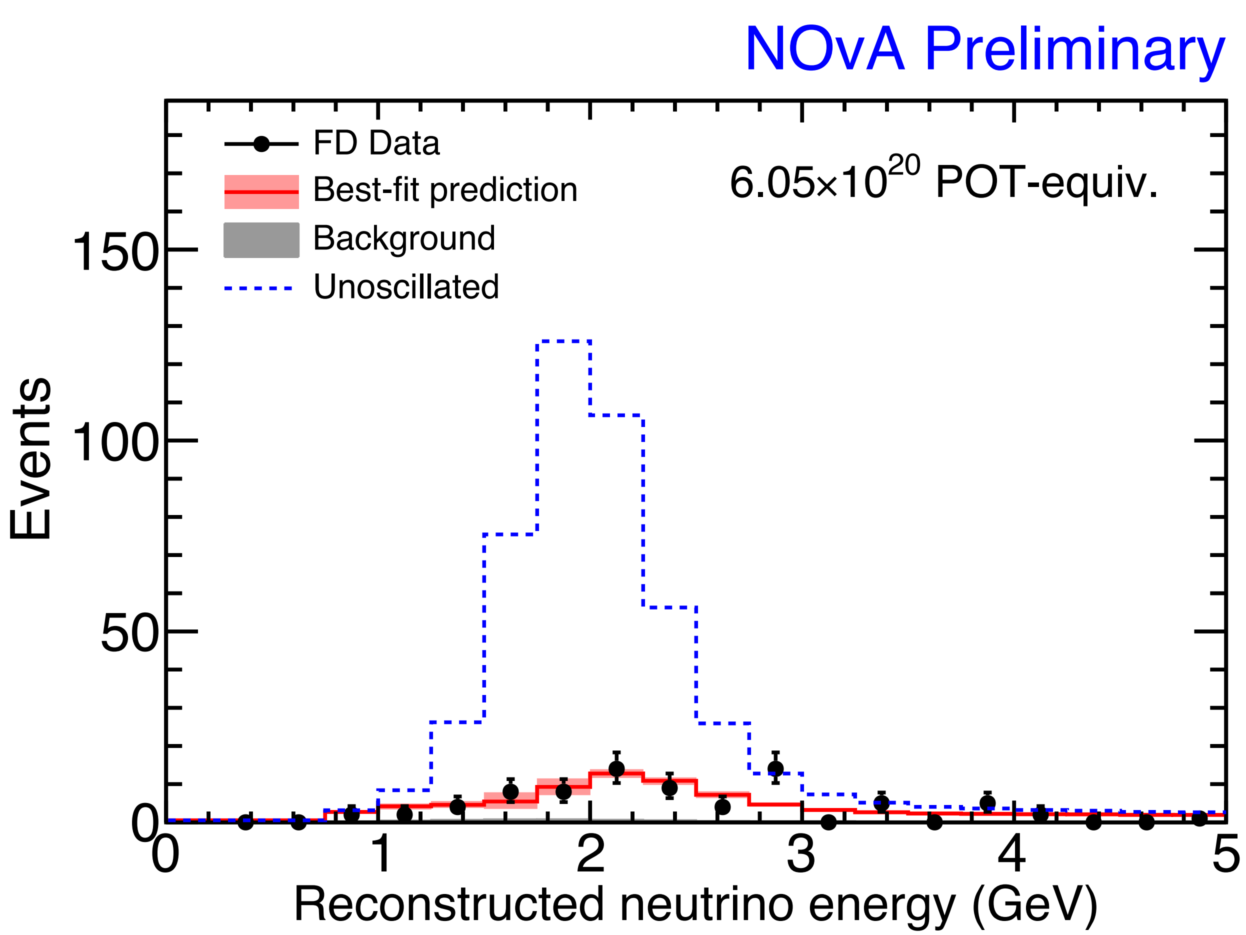
(*) Relative contribution evaluated at $\sin^2(\theta_{23}) = 0.514$ and $\Delta m^2_{32} = 2.52 \times 10^{-3}$ eV^2

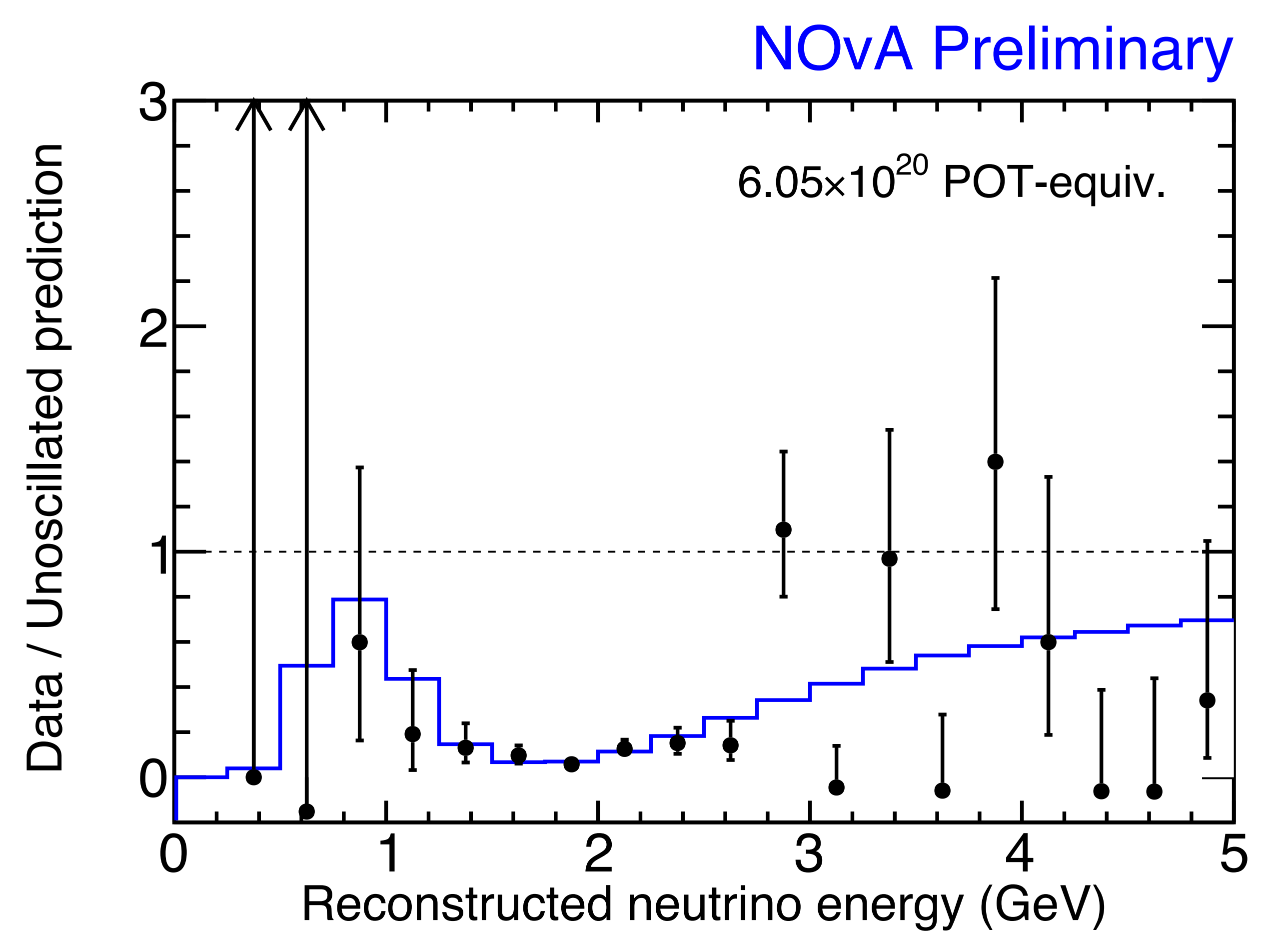
- The 2015 analysis was dominated by a large systematic uncertainty placed on the hadronic energy component (which has since been significantly reduced.)

- All systematics were evaluated by varying the MC based steps in the extrapolation.

NuMu FD spectrum

- Observed: 78 events
- Predicted with NO oscillation: 473 ± 30 events
- Predicted at the best fit point 82 events
- 3.7 from beam background
- 2.9 cosmic induced events





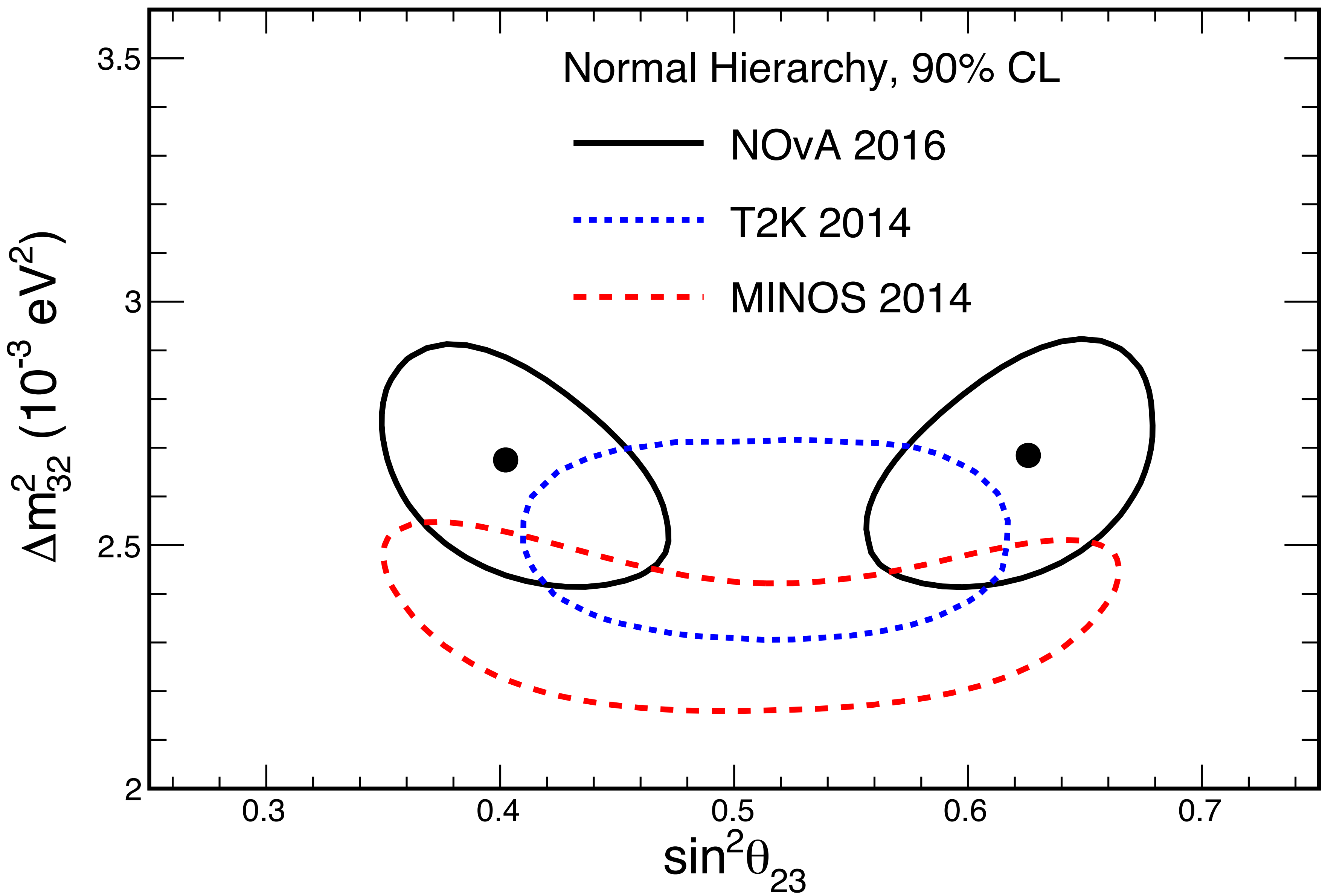
Oscillation measurement

Maximal Mixing
Disfavoured
at 2.56 σ

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

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

Best Fit in NO:



Improvement 1: Energy Resolution

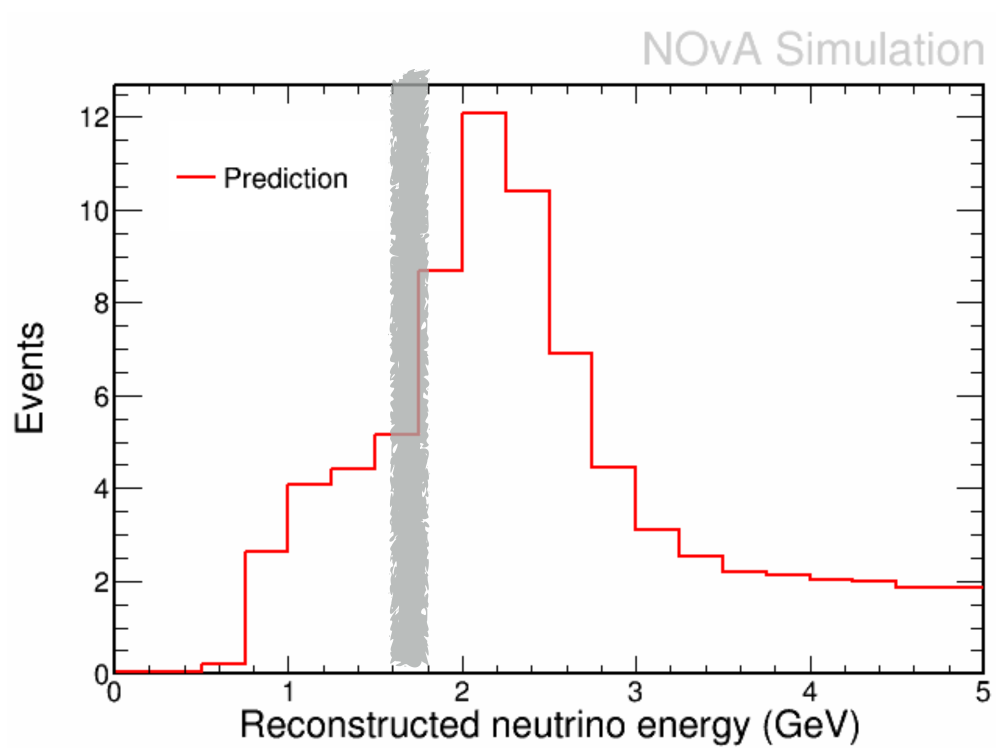
$E_\nu = E_\mu + E_{had}$

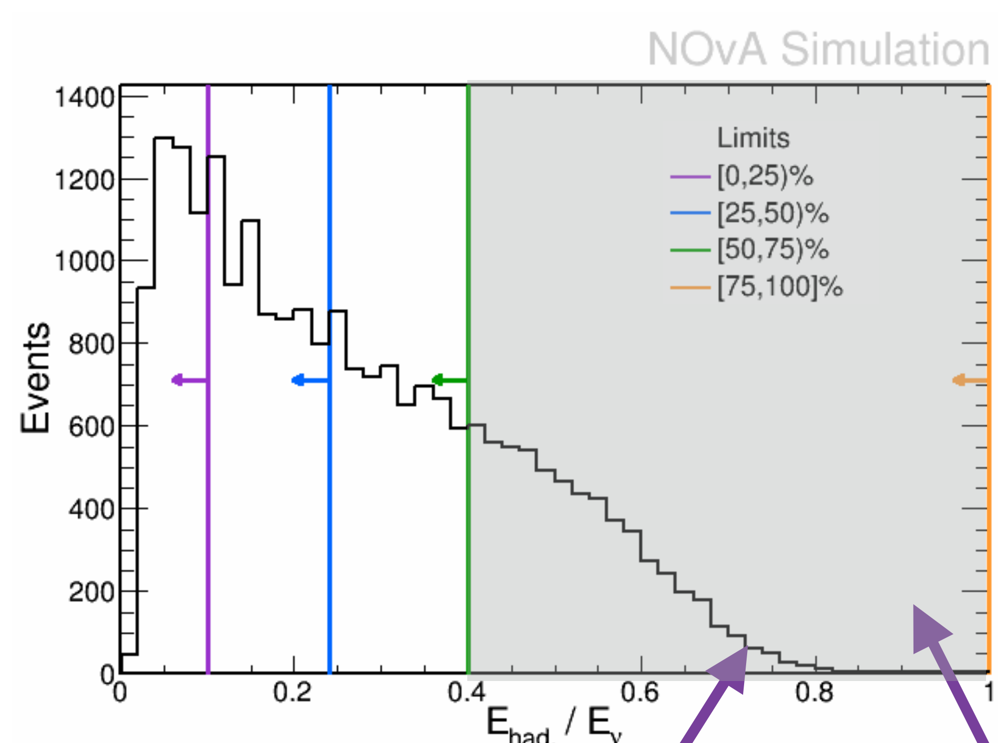
Mean resolution:

- E_μ = 3.5 %
- E_{had} = 25%
- E_ν = 7%

Neutrino energy resolution **E_{had} / E_ν**

Separate well resolved energies by quantiles of hadronic energy fraction





Cosmics

NC

Improvement 1: Energy Resolution

$E_\nu = E_\mu + E_{had}$ → Mean resolution:

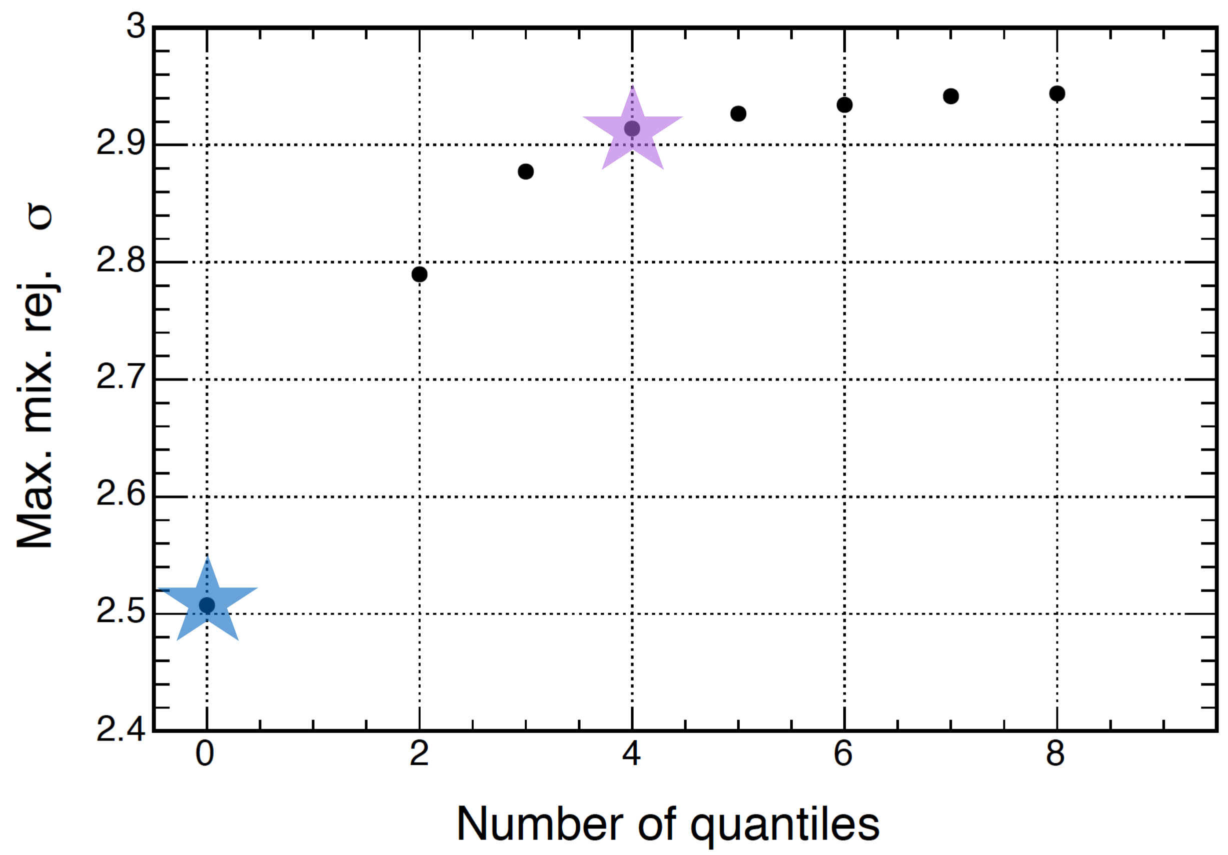
- E_μ = 3.5 %
- E_{had} = 25%
- E_ν = 7%

→ Neutrino energy resolution **E_{had} / E_ν**

Neutral current systematic impact improves by a factor of 2-4:

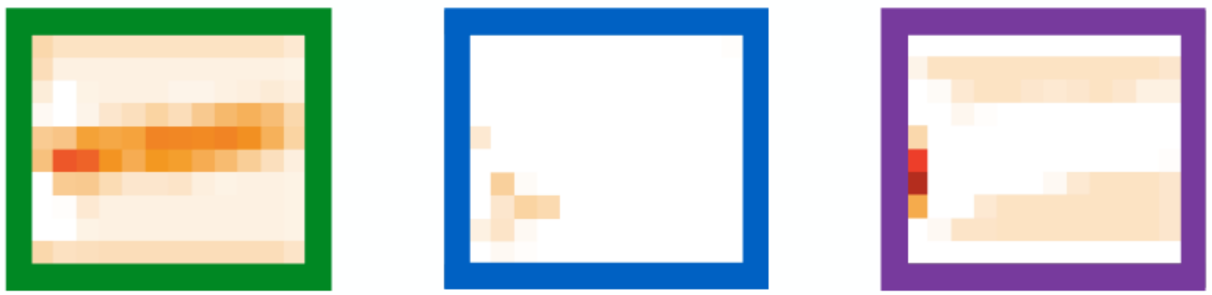
$\sin^2\theta_{23}$ +3.3/-6.6% —> +1.4/-2.3%

Δm^2_{32} +9.2/-17% —> +3.3/-4.6%

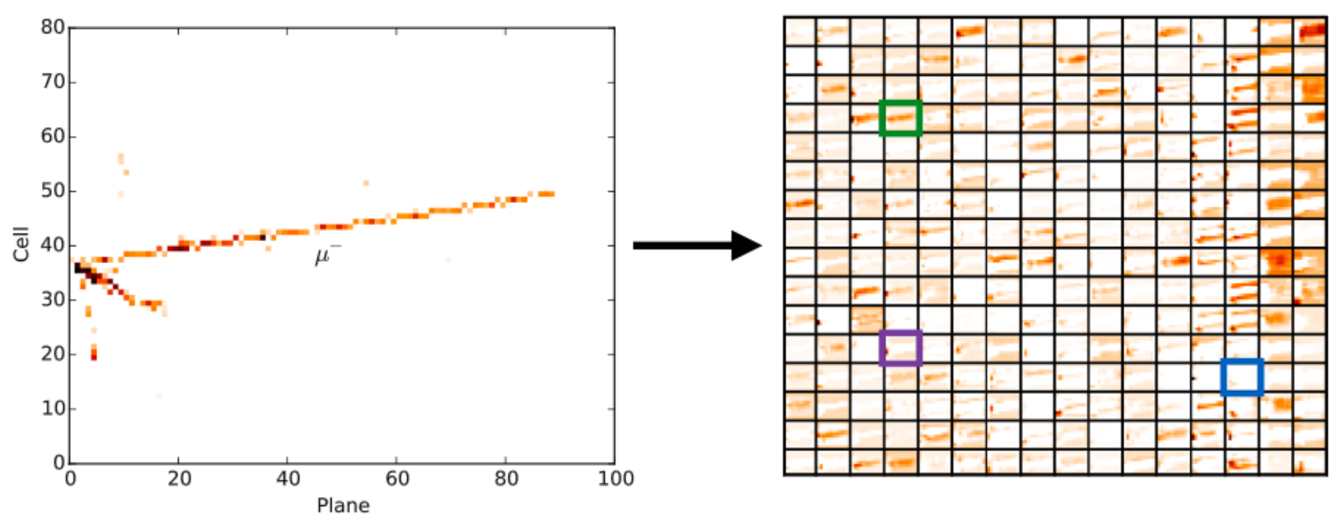


Improvement 2: PID

- CVN (Convolutional Visual Network) used by the electron neutrino appearance analysis already
- Based on CNN (Convolutional Neural Networks)
- Hit maps are read as images with filters applied to them to extract features



Including CVN in our selections improves efficiency by ~10% while reducing background by nearly 50%

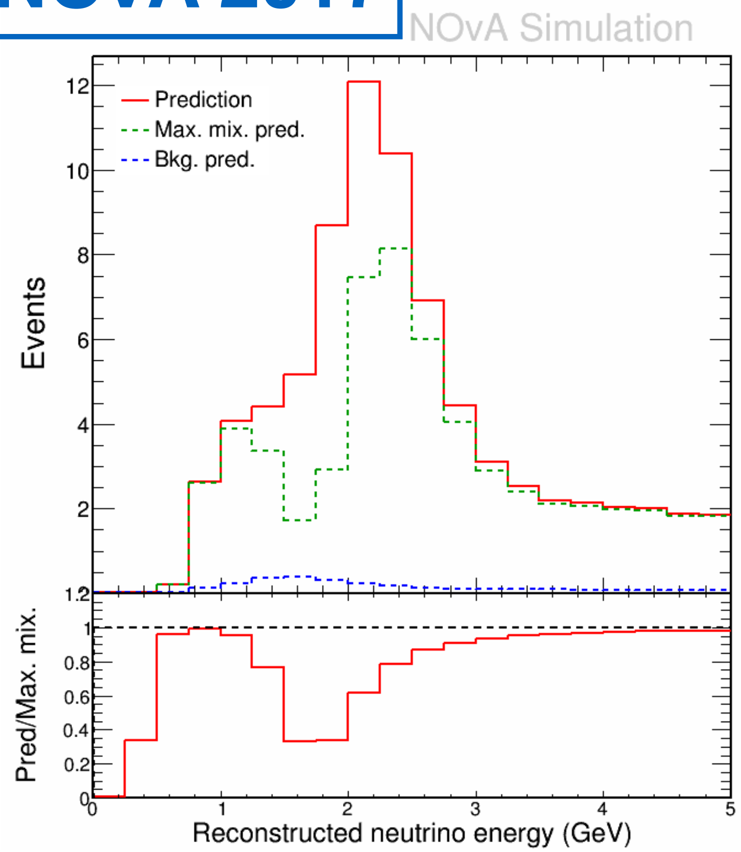


Improvement 3: Binning

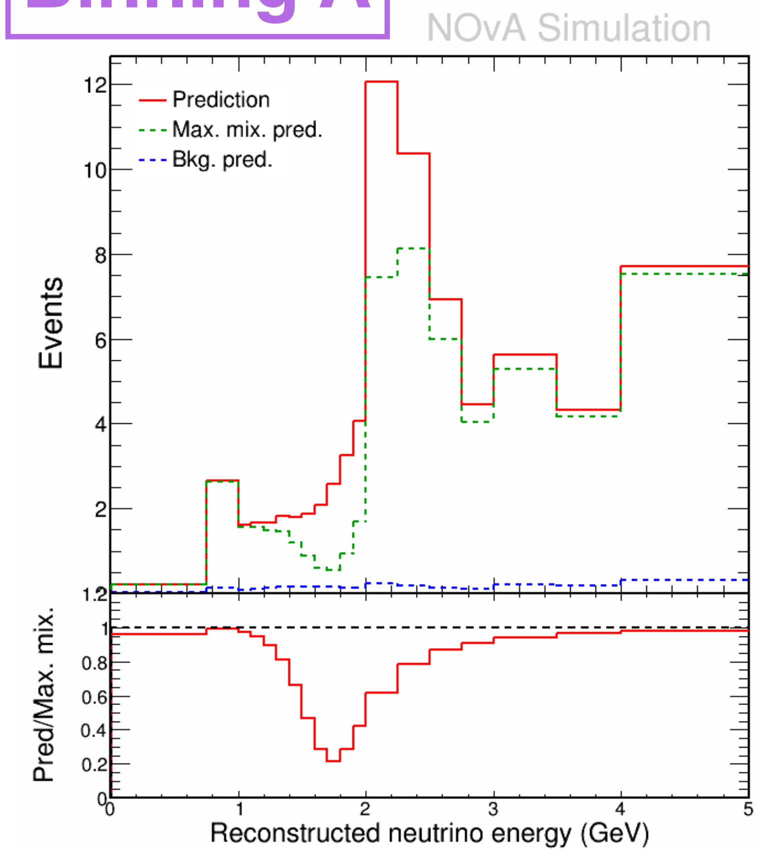
Finer binning around the maximum oscillation region could enhance the sensitivity of the analysis

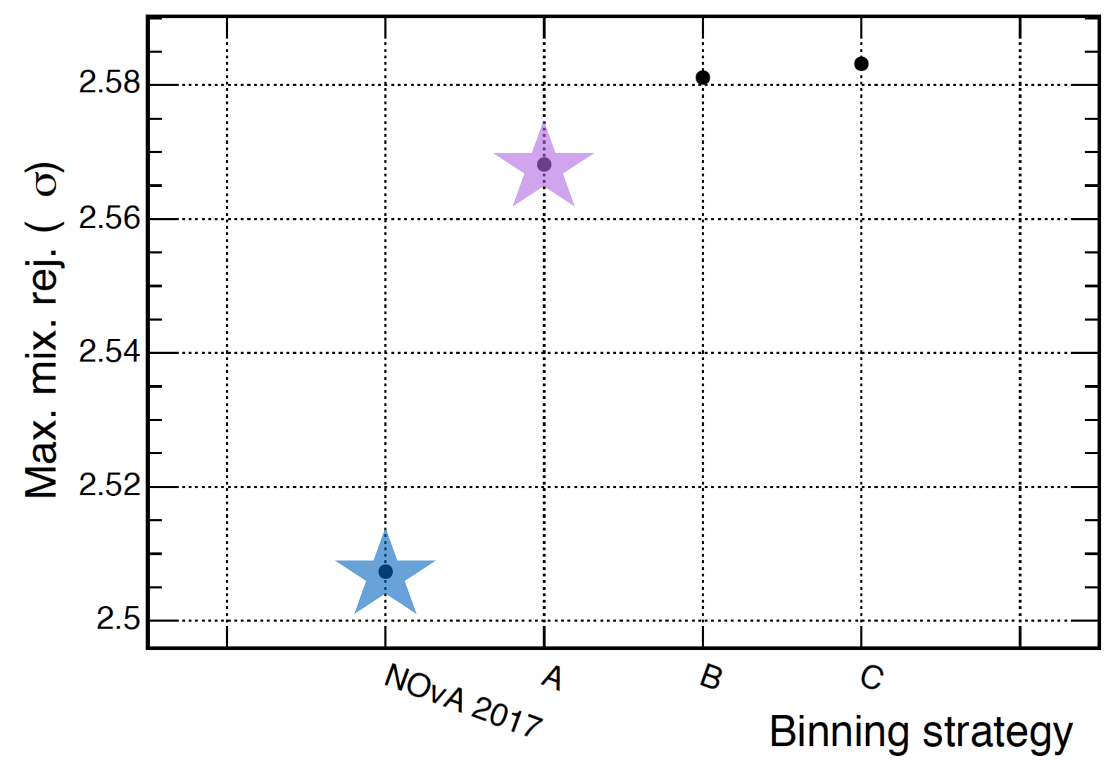
- NOvA's standard energy binning: 20 bins of 0.25 GeV each
- Optimum binning: increased number of bins between 1 and 2 GeV

NOvA 2017

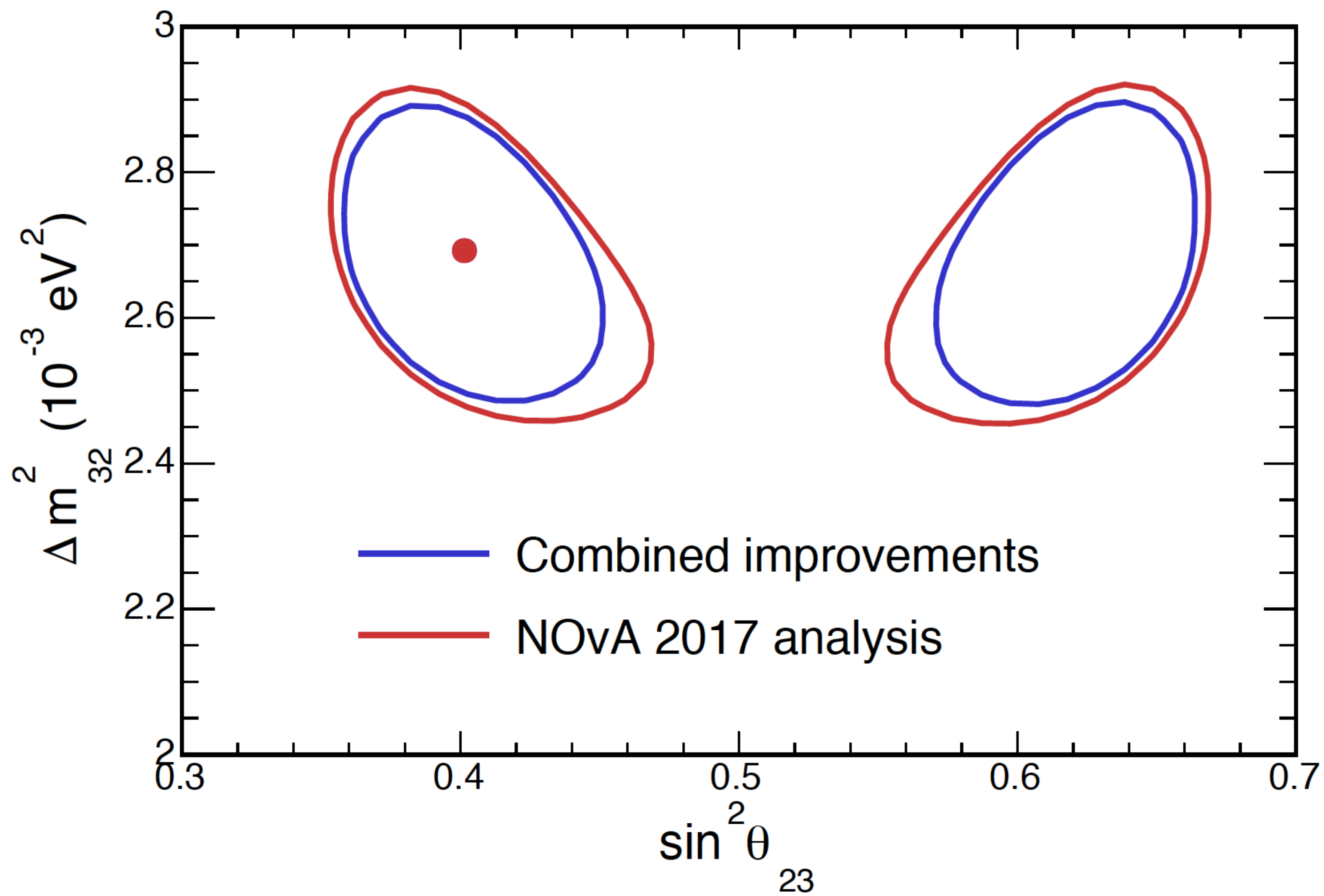


Binning A





Combined improvements



Combination of the improvements reduces uncertainties and significantly increases our sensitivity:

- Systematic uncertainties reduced from 2.2% to 2.0% on Δm^2_{32} and from a 2.1% to 1.5% on $\sin^2\theta_{23}$
- Maximal mixing rejection from 2.51 to 3.25σ equivalent to 75% more data

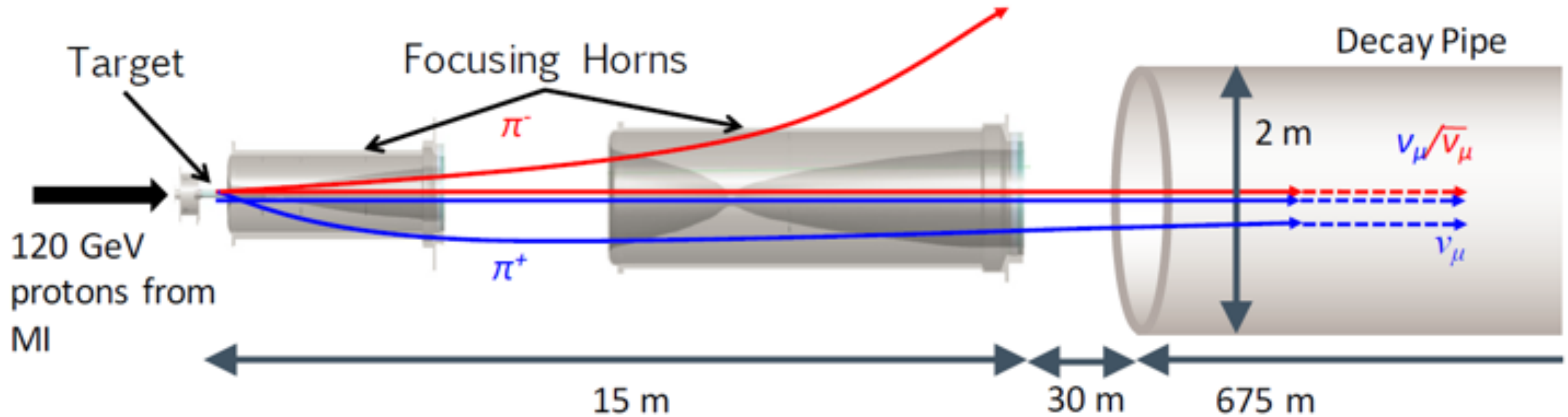
Outlook

- Analysis of 6.05×10^{20} POT of NOvA data (1 nominal year)
- Muon-neutrino disappearance (Phys. Rev. Lett. 118, 151802 (2017))
  - Best fit to muon-neutrino disappearance data is a non-maximal value of θ_{23}, maximal mixing disfavoured at 2.56σ
- Current analysis improvement will result maximal mixing rejection from 2.56 to 3.25σ (equivalent to 75% more data) for 2017 oscillation analysis parameters.
- Didn't mention here our electron neutrino appearance, sterile neutrino search, neutrino interaction, supernova, monopoles, and a lot more
- Switched to anti-neutrino running in February and already have 3e20 POT - Stay tuned!

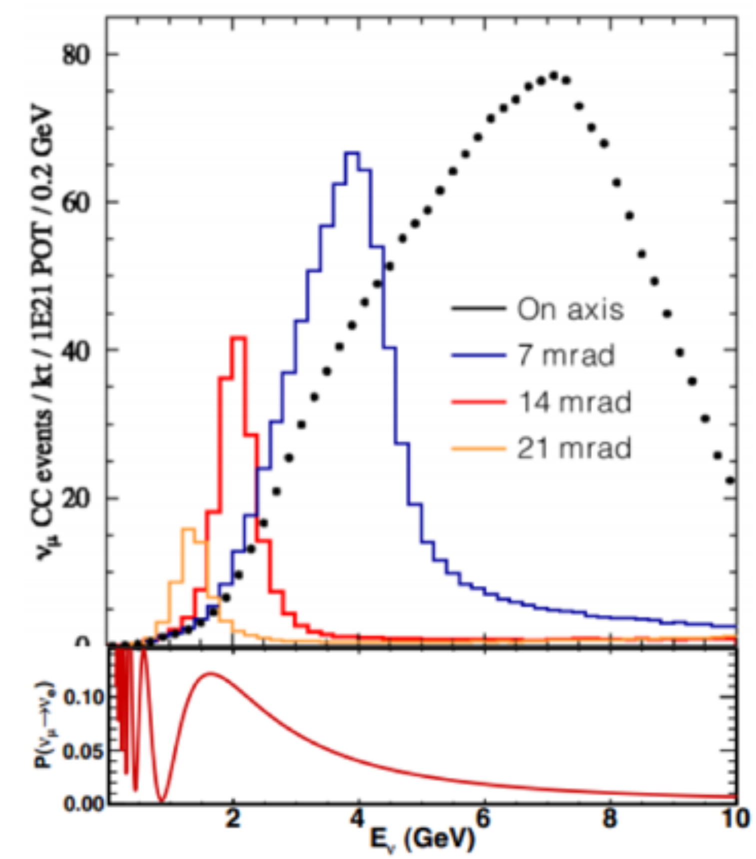
Thank you!

Neutrino beam

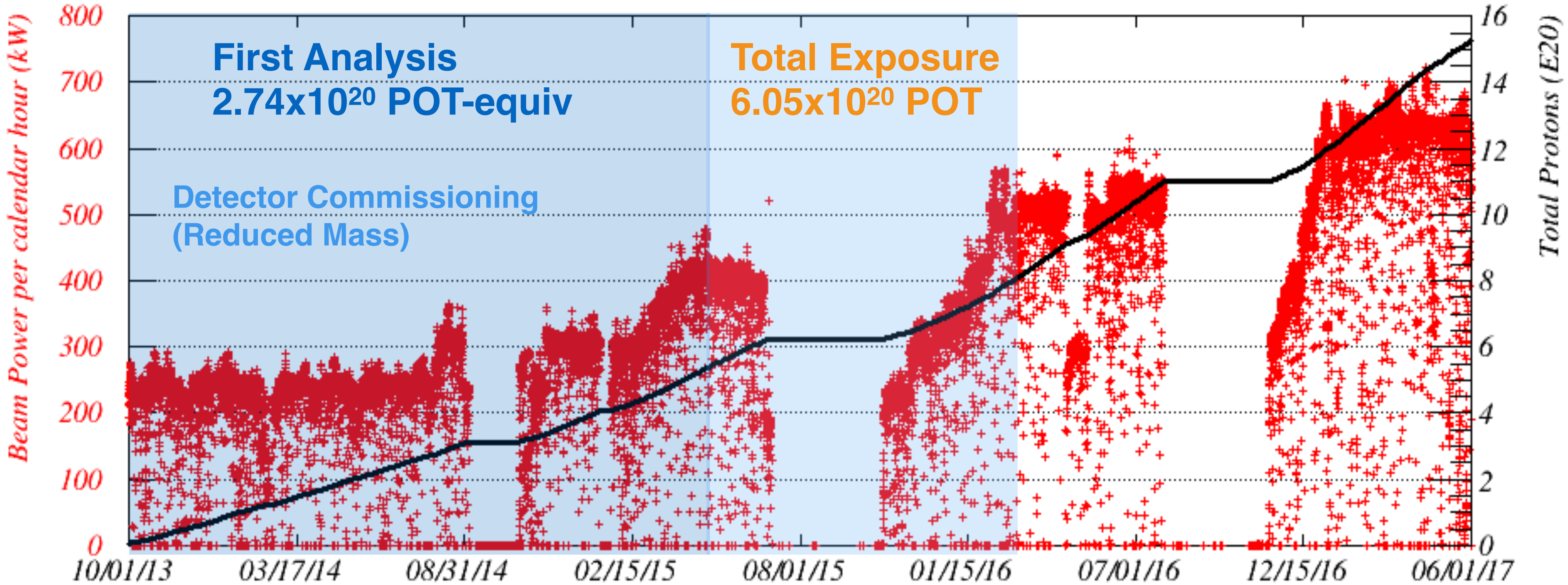
NuMI Beam



- 120 GeV protons extracted from the Main Injector at Fermilab in 10 μs spills
- Focus secondary pions using magnetic horns
  - Positive hadrons for neutrino beam
  - Negative hadrons for antineutrino beam
- Decay kinematics mean a detector at 14.6 mrad sees a narrowly peaked energy spectrum
- Beam 97.5% ν_μ with 0.7% ν_e and 1.8% wrong-sign



NuMI beam performance



Switched to antineutrinos on Feb 20th 2017

- Present results data collected between February 6, 2014 and May 2, 2016
- Equivalent to 6.05×10^{20} protons-on-target in a full 14 kT detector
- Beam had been running at 560 kW
- **Achieved 700 kW design goal, most powerful neutrino beam in the world**

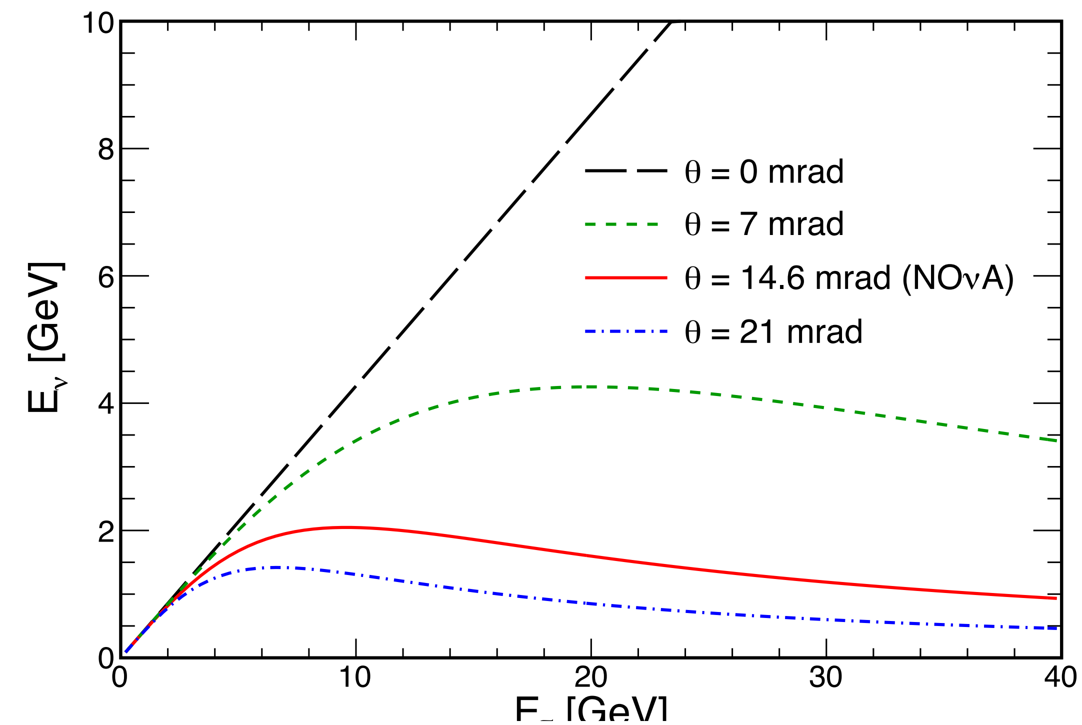
Why off-axis?

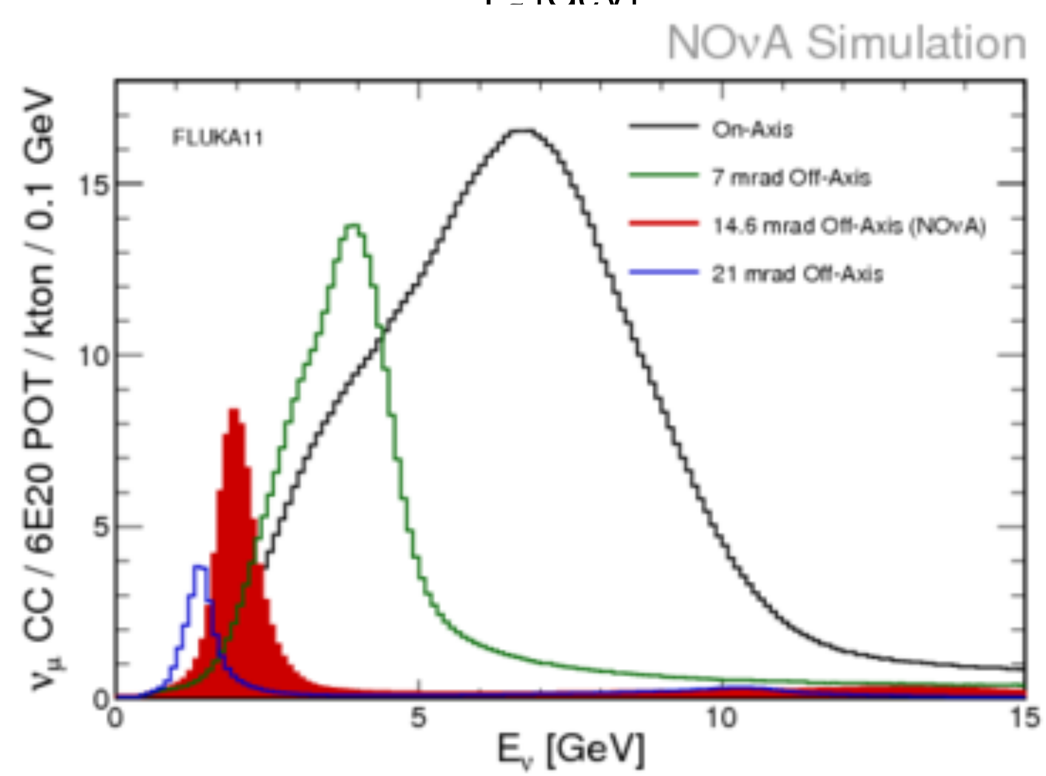
- NOvA detectors are located 14 mrad off the NuMI beam axis.

- With the medium-energy NuMI configuration, it yields a narrow 2-GeV spectrum at the NOvA detectors due to meson decay kinematics:

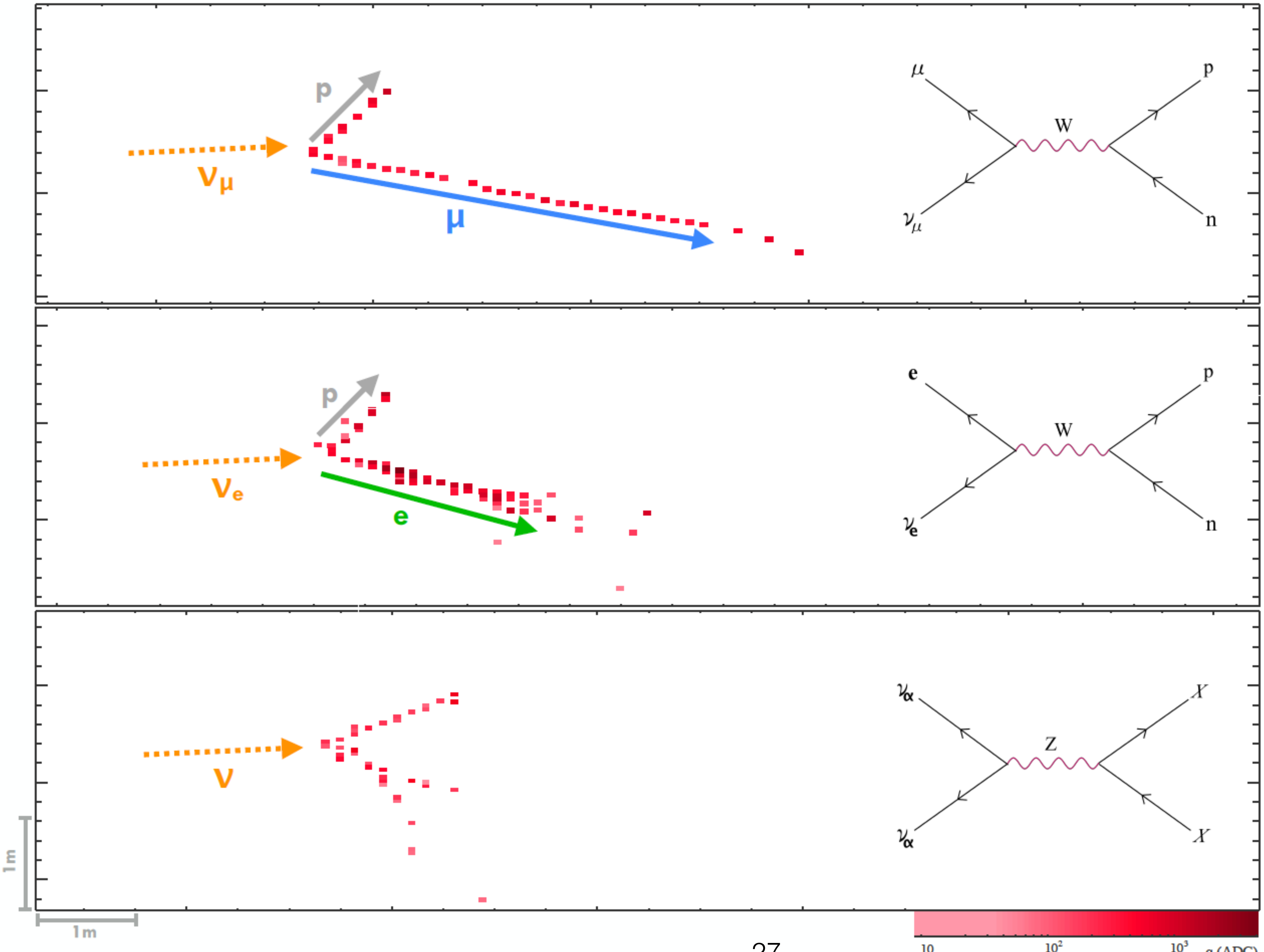
$$E_\nu = \frac{1-(m_\mu/m_\pi)^2}{1+\gamma^2\tan^2\theta}E_\pi$$

- Location reduces NC and ν_e CC backgrounds in the oscillation analyses while maintaining high ν_μ flux at 2 GeV.





Event topologies

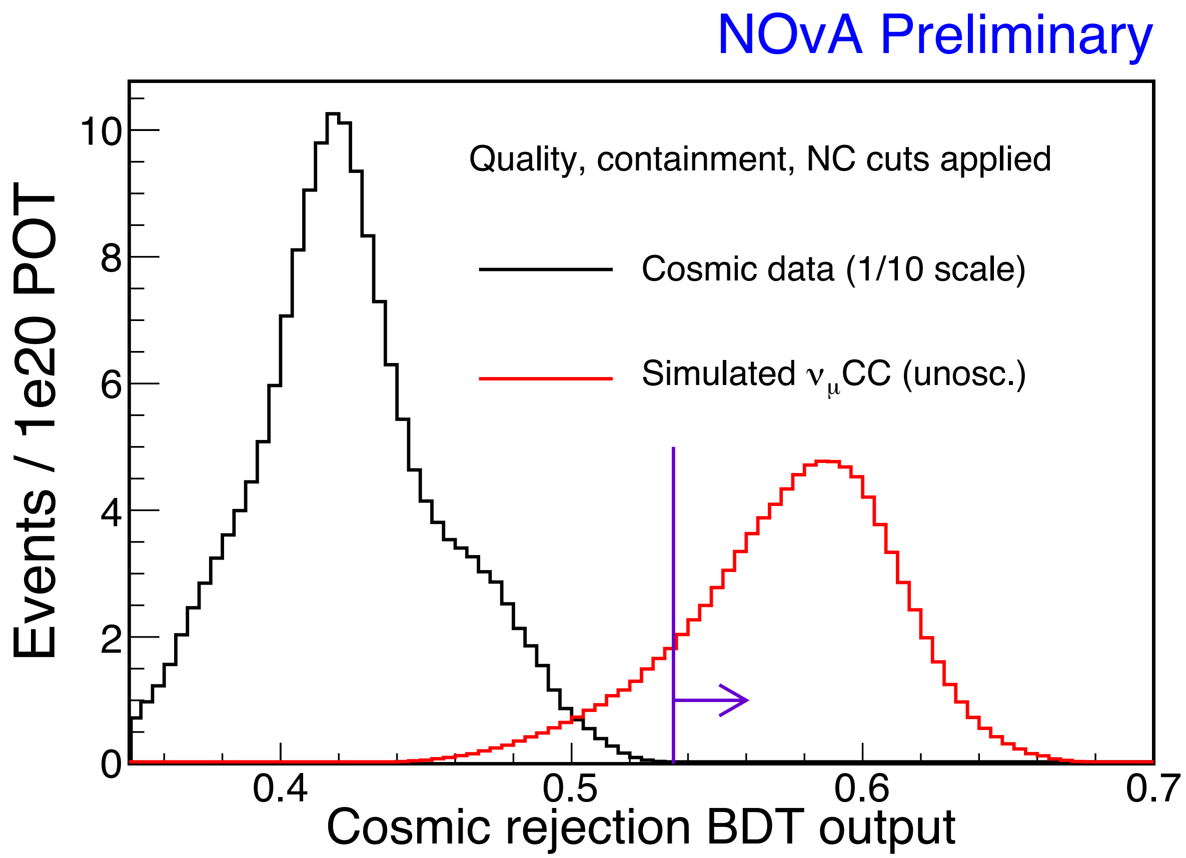


ν_μ CC

ν_e CC

NC

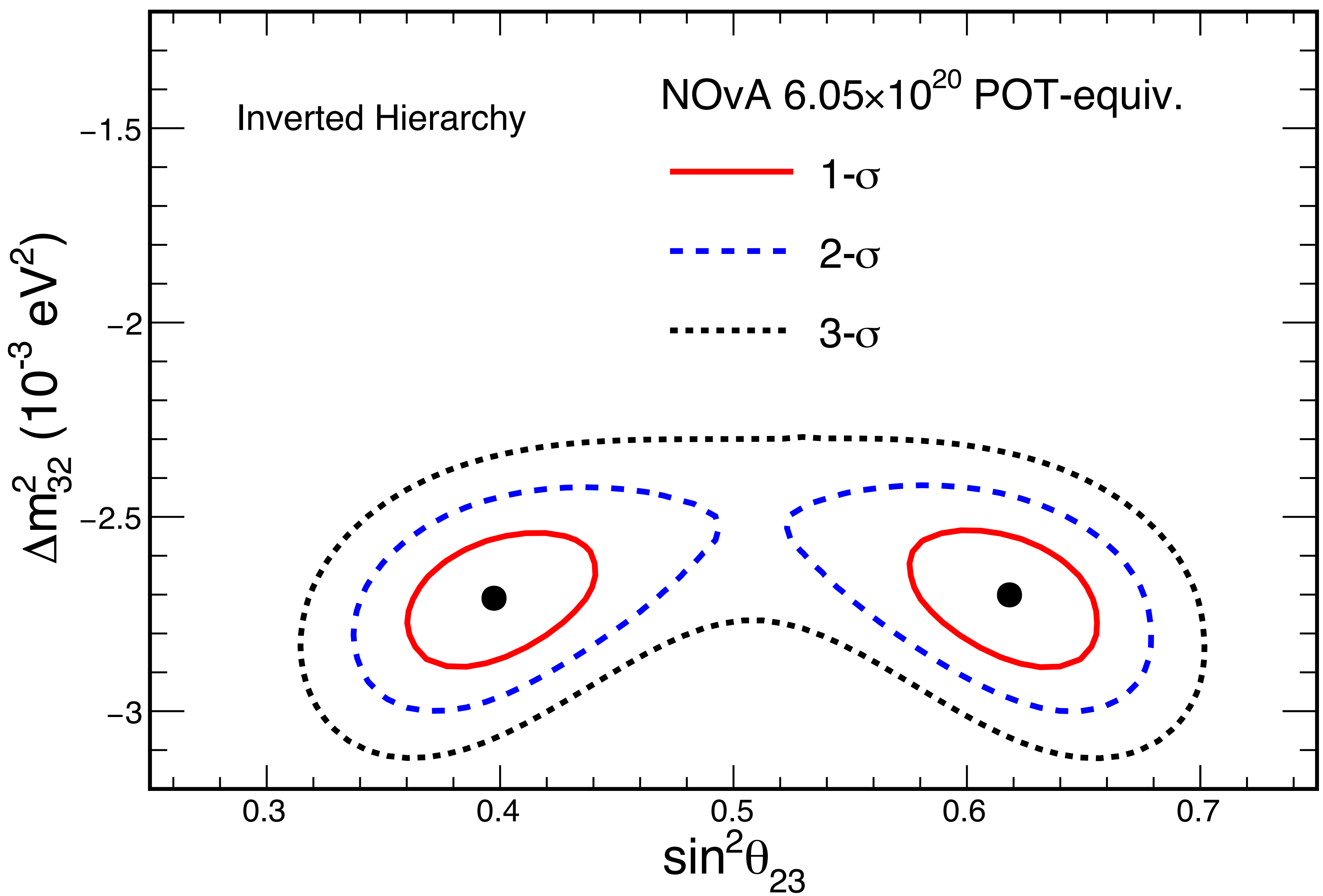
FD Cosmic Rejection



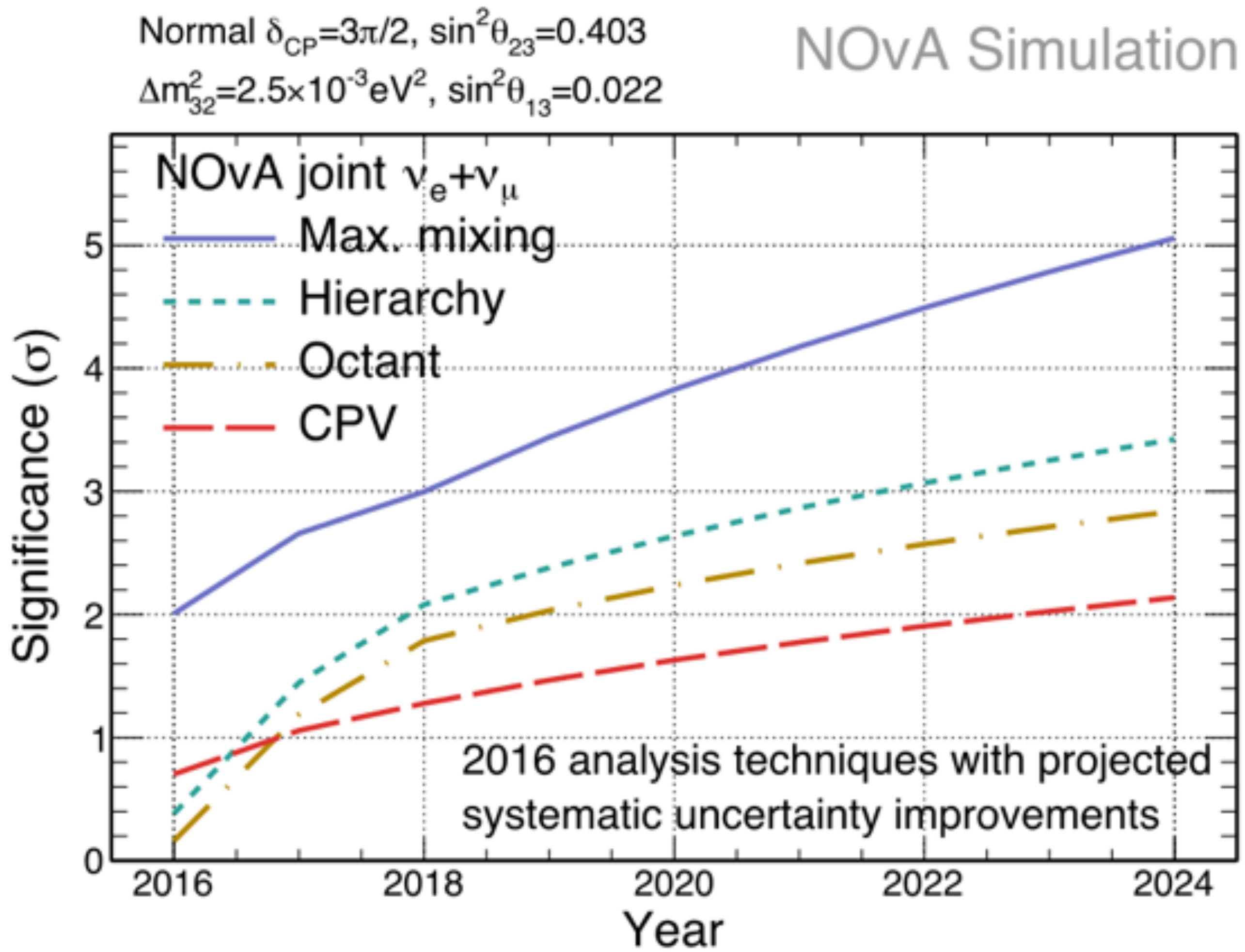
- We expect ~65,000 cosmic rays in-time with the NuMI beam spills per day. The expected number of contained $\nu\mu$ CC events per day is only a few.
- Containment cuts will remove 99% of the cosmics.

- We use a boosted-decision-tree (BDT) algorithm that takes input from reconstruction variables to reject the remaining cosmics.
- All cuts together give us > 15:1 s:b. **Cosmics are reduced by 10^7!**

NuMu disappearance IO



Looking forward



- Switched to anti-neutrino running in February 2017 (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