CHEP-2018 Conference, Sofia, Bulgaria, 9-13 July, 2018

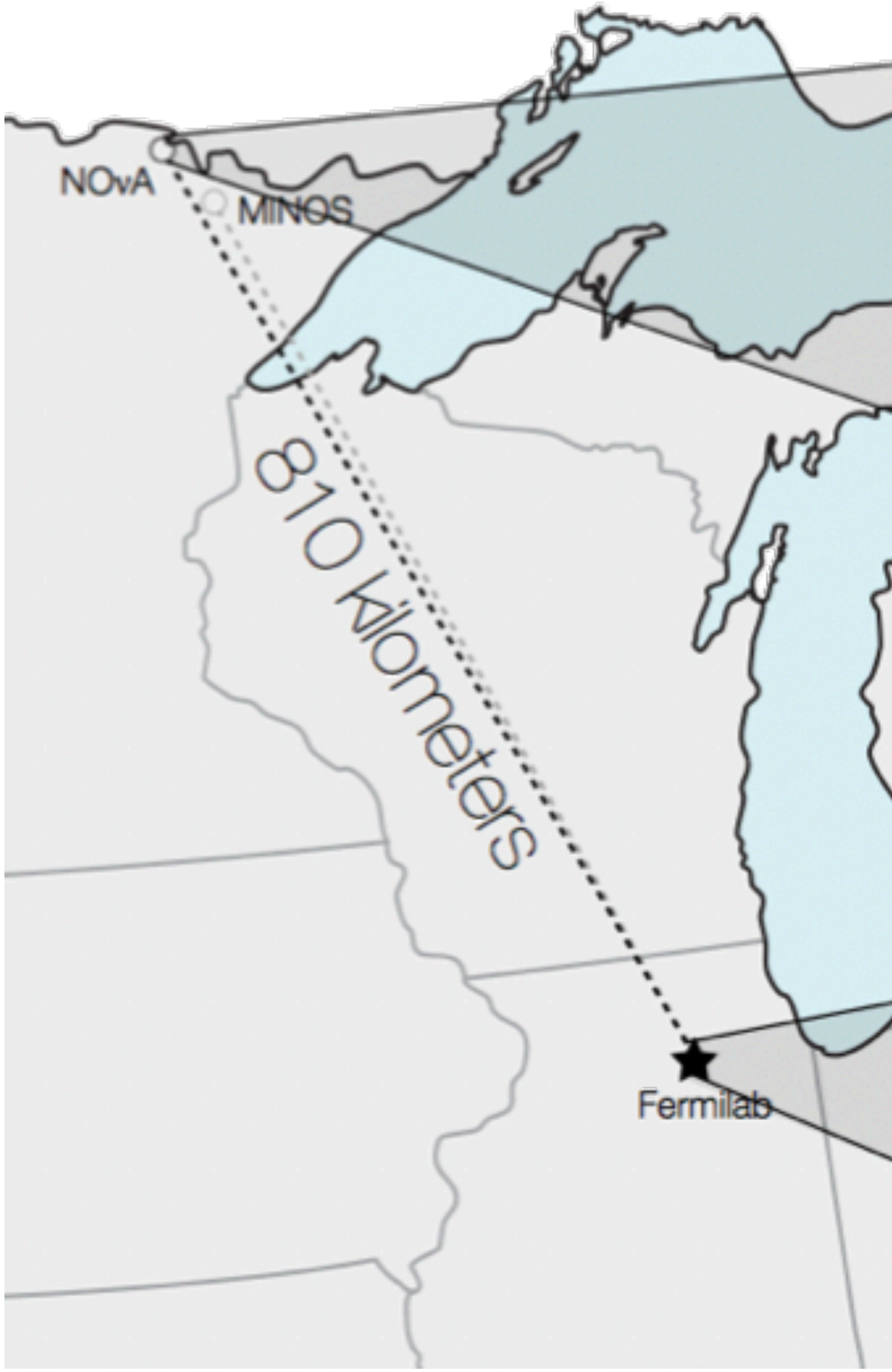
Current status for simulation chain of the neutrino events in the NOvA experiment

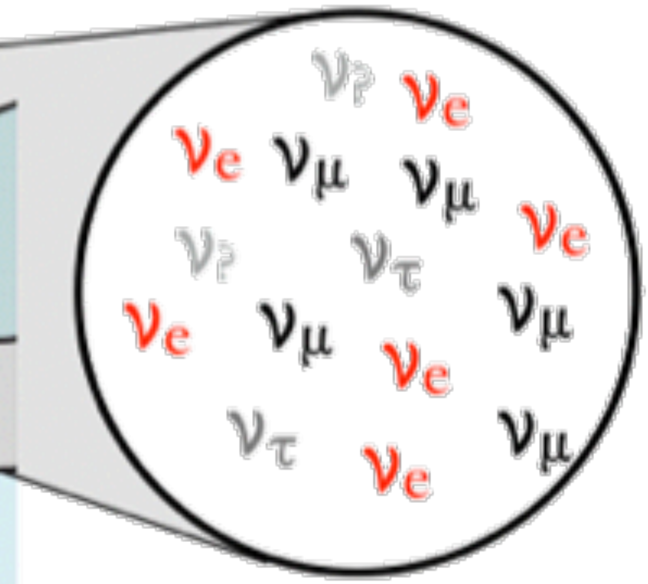
Adam Aurisano[1], Gavin Davies[2], Pengfei Ding[3], Adam Moren[4], Daniel Pershey[5], Oleg Samoylov[6], Matthew Strait[7], Jeremy Wolcott[8]

[1]University of Cincinnati, USA
[2]Indiana University, USA
[3]Fermi National Accelerator Laboratory, USA
[4]University of Minnesota Duluth, USA
[5]California Institute of Technology, USA
[6]Joint Institute for Nuclear Research, Russia
[7]University of Minnesota, USA
[8]Tufts University, USA

(for the NOvA collaboration)

The NOvA experiment





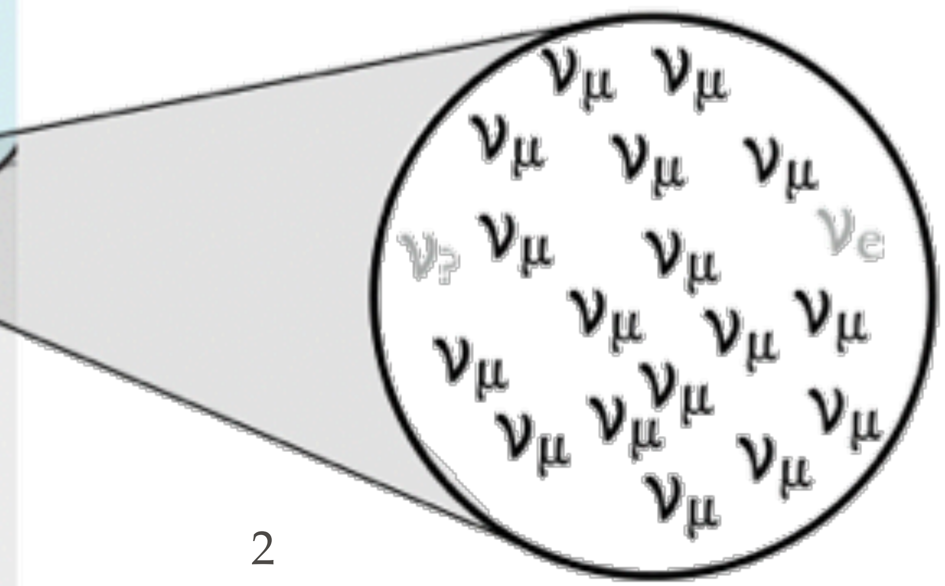
NuMI

Off-Axis

$\boldsymbol{\nu}_e$

Appearance

- is a two-detectors, long-baseline neutrino experiment operating since 2014 at FNAL (USA), sending both muon neutrino and antineutrino beams to detect $\nu_e/\overline{\nu}_e$ appearance and $\nu_\mu/\overline{\nu}_\mu$ disappearance



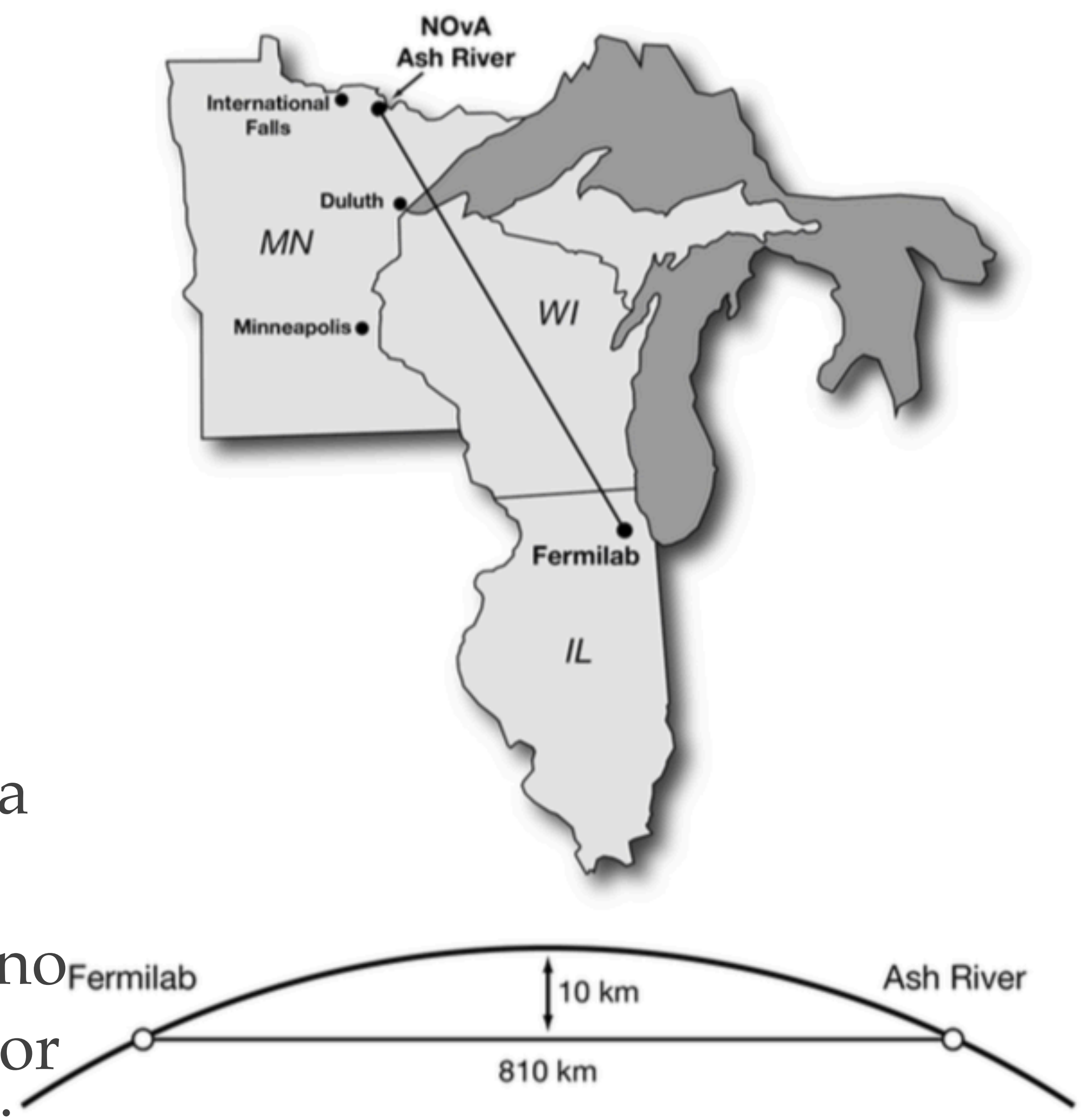
The NOvA Experiment

- NOvA experiment goals:

- Using electron neutrino and antineutrino appearance mode
  - neutrino mass hierarchy
  - CP violating phase

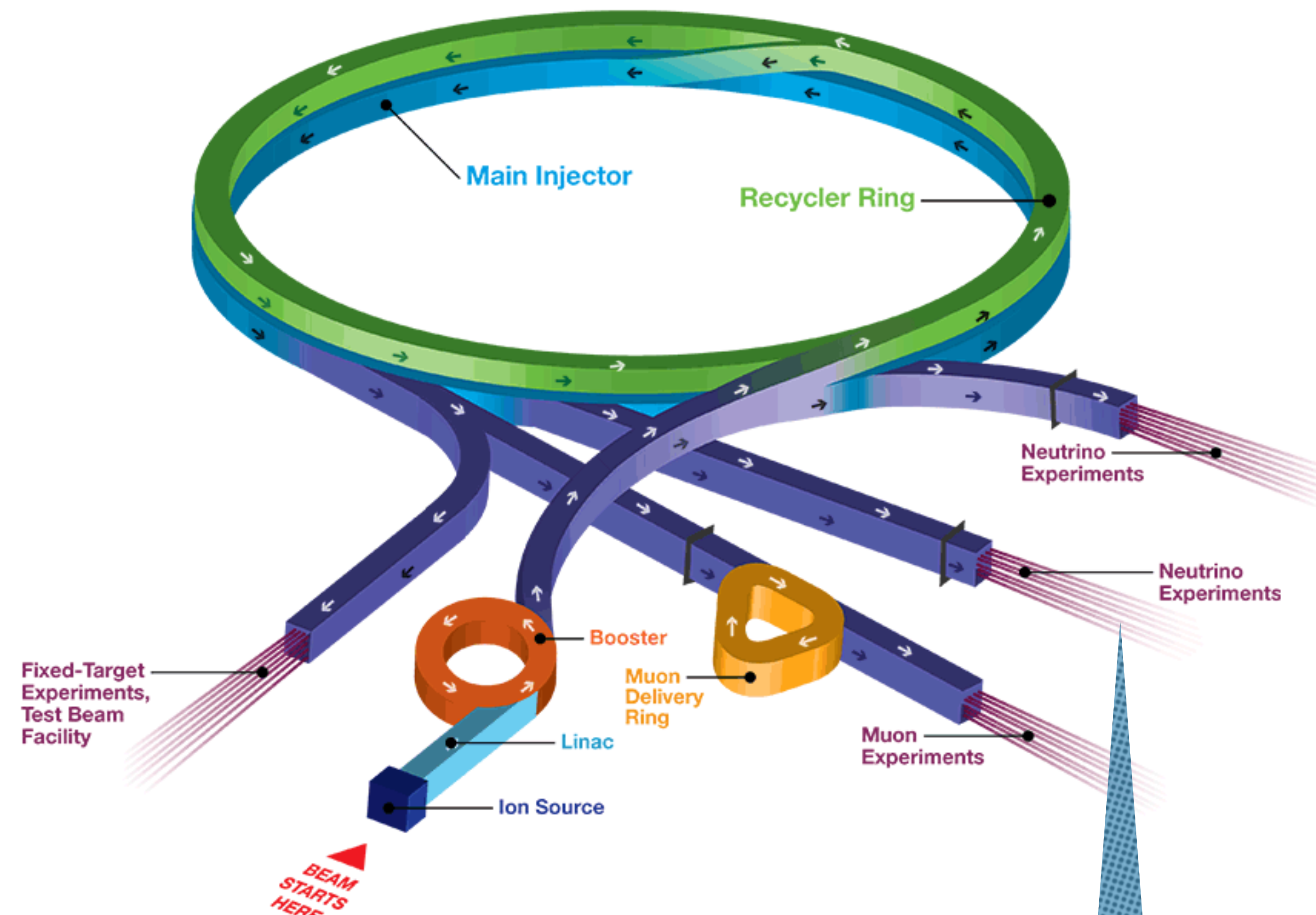
- Using muon neutrino and antineutrino disappearance mode
  - mixing angle θ_{23} octant
  - precision measurement Δm^2_{32}

- Other tasks: search for sterile neutrinos via NC channel, measure neutrino cross-sections in the near detector, detect neutrino signal from supernova explosure, search for monopoles, dark matter, investigate cosmic rays, etc.



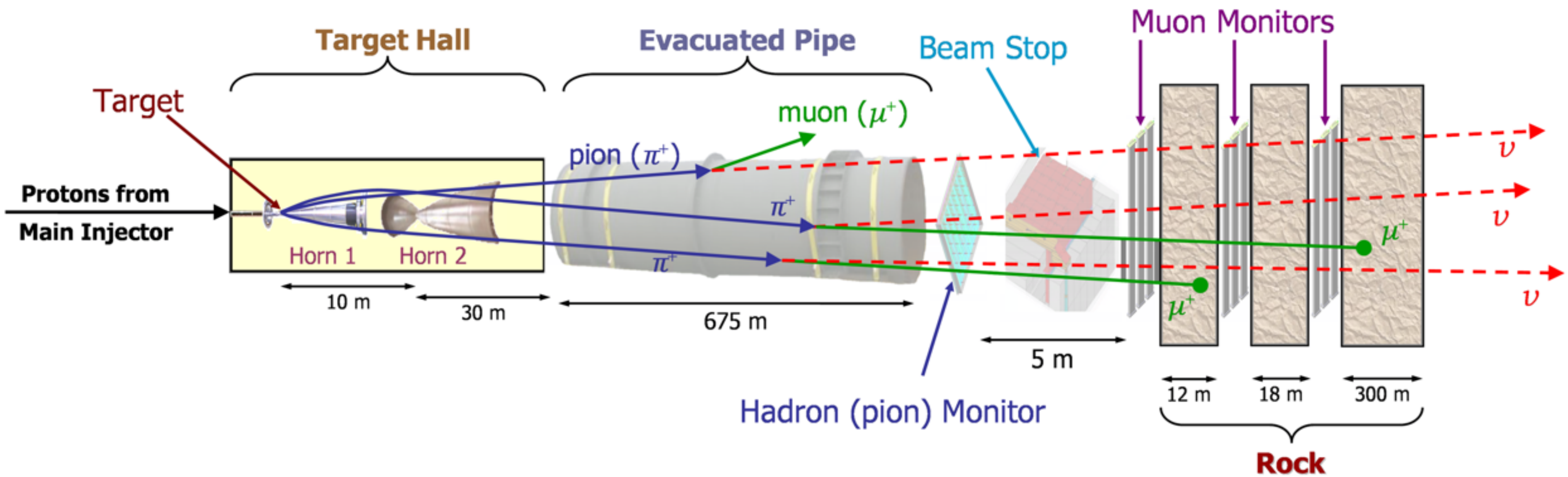
Fermilab accelerator complex

- Neutrinos are produced at Main Injector (NuMI)
- ➡ Linac 750 keV
- ➡ Booster 400 MeV
- ➡ Recycler 8 GeV
- ➡ NuMI 120 GeV
- ➡ to Carbon target



Line to High Energy Neutrino Experiments

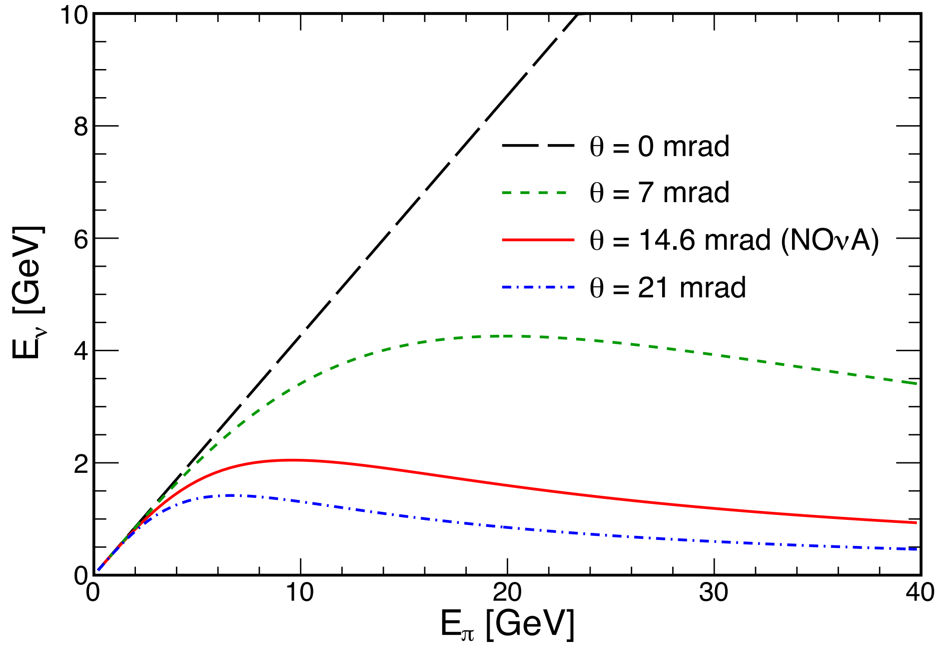
Neutrino flux

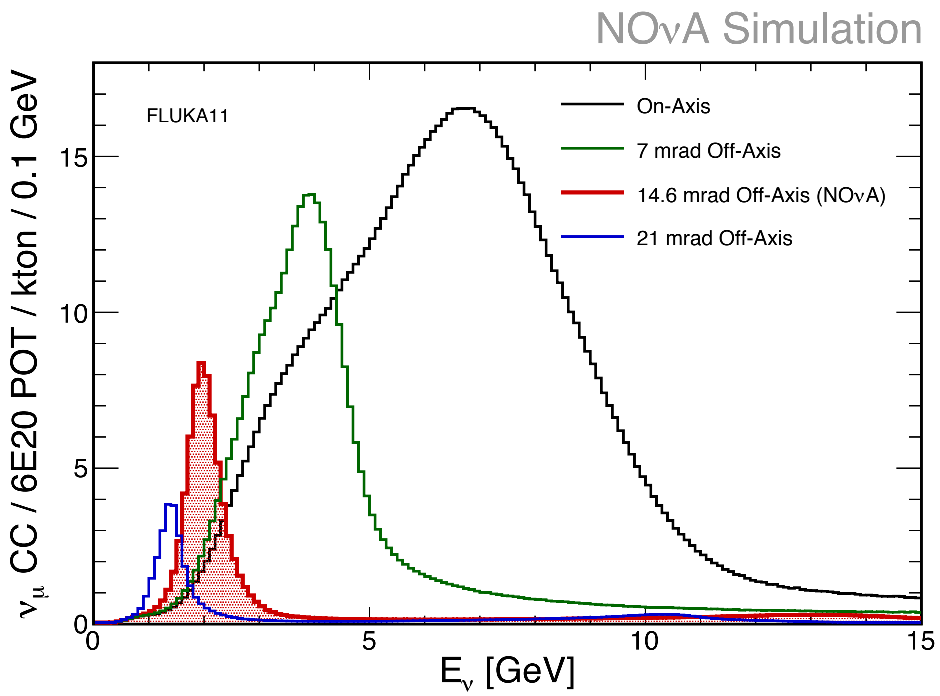


- 120 GeV protons on a carbon target, produce mesons which yield neutrinos (or antineutrinos).
- NOvA is designed for the 700 kW NuMI beam, with 6×10^{20} POT / year. (POT = Proton On Target).
- ➡ We are running in 700 kW now!
- Neutrinos (or antineutrinos) are produced every 1.3 sec in a spill with 6 doubled batches 10 μs time window.

NuMI off-axis beam

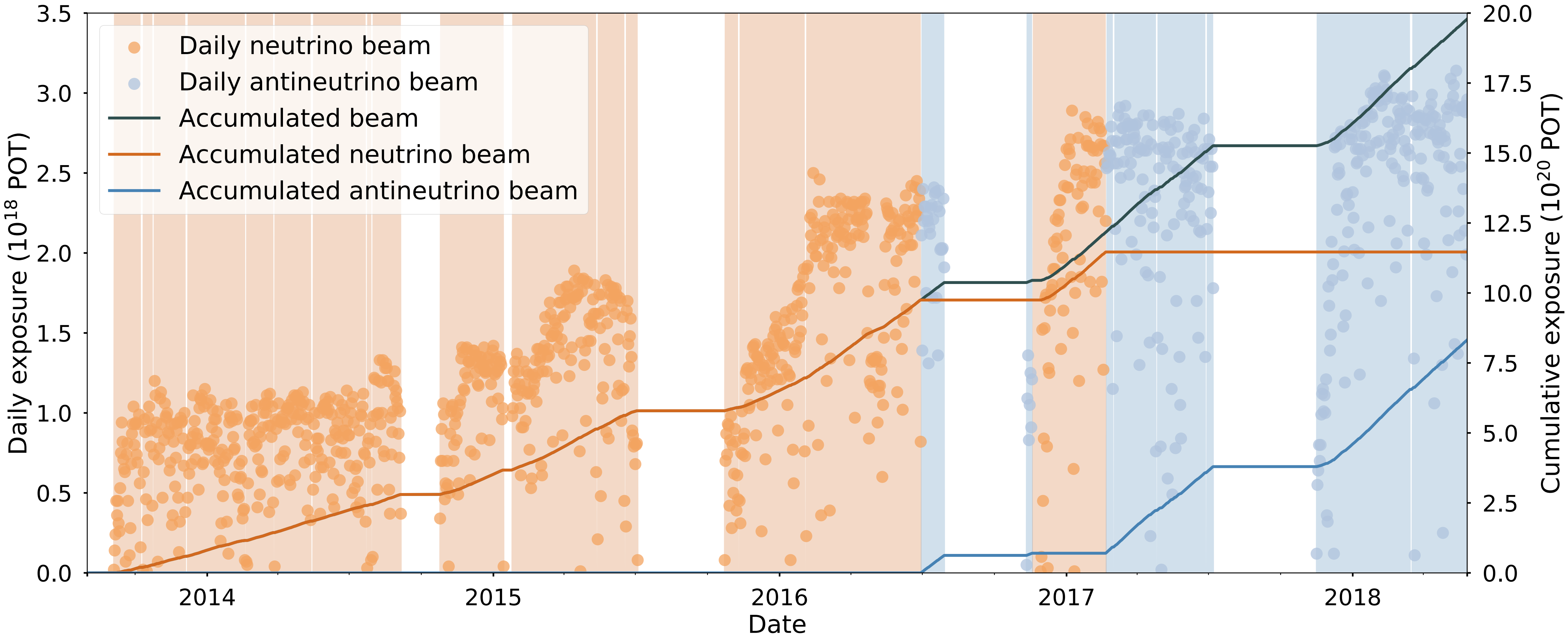
- NOvA detectors are sited 14 mrad off the NuMI beam axis
- With the medium-energy NuMI tune, yields a narrow 2-GeV spectrum at the both NOvA detectors
- Reduces NC and ν_e CC backgrounds in the oscillation analysis while maintaining high ν_μ flux at 2 GeV





Beam exposure

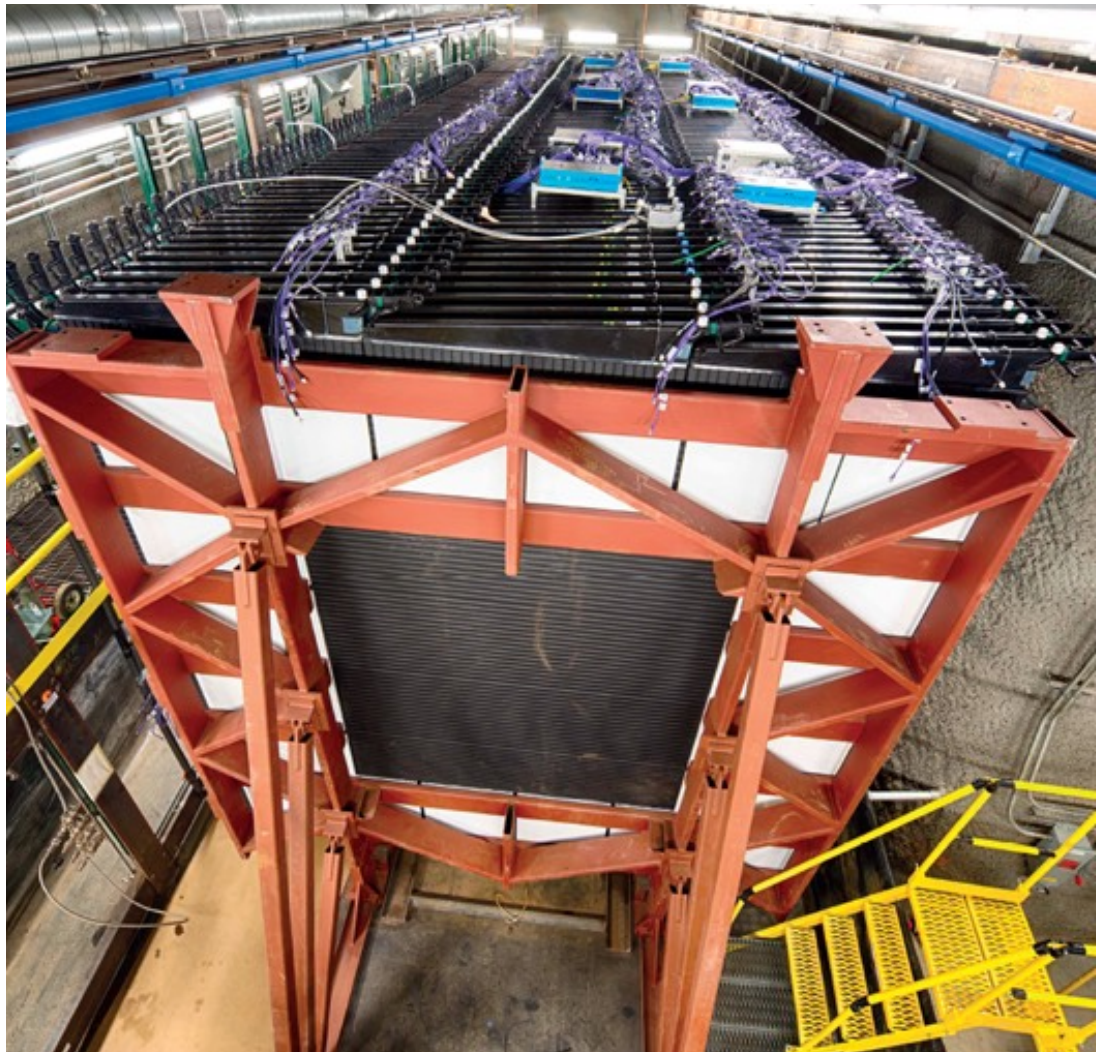
> 700 kW operations

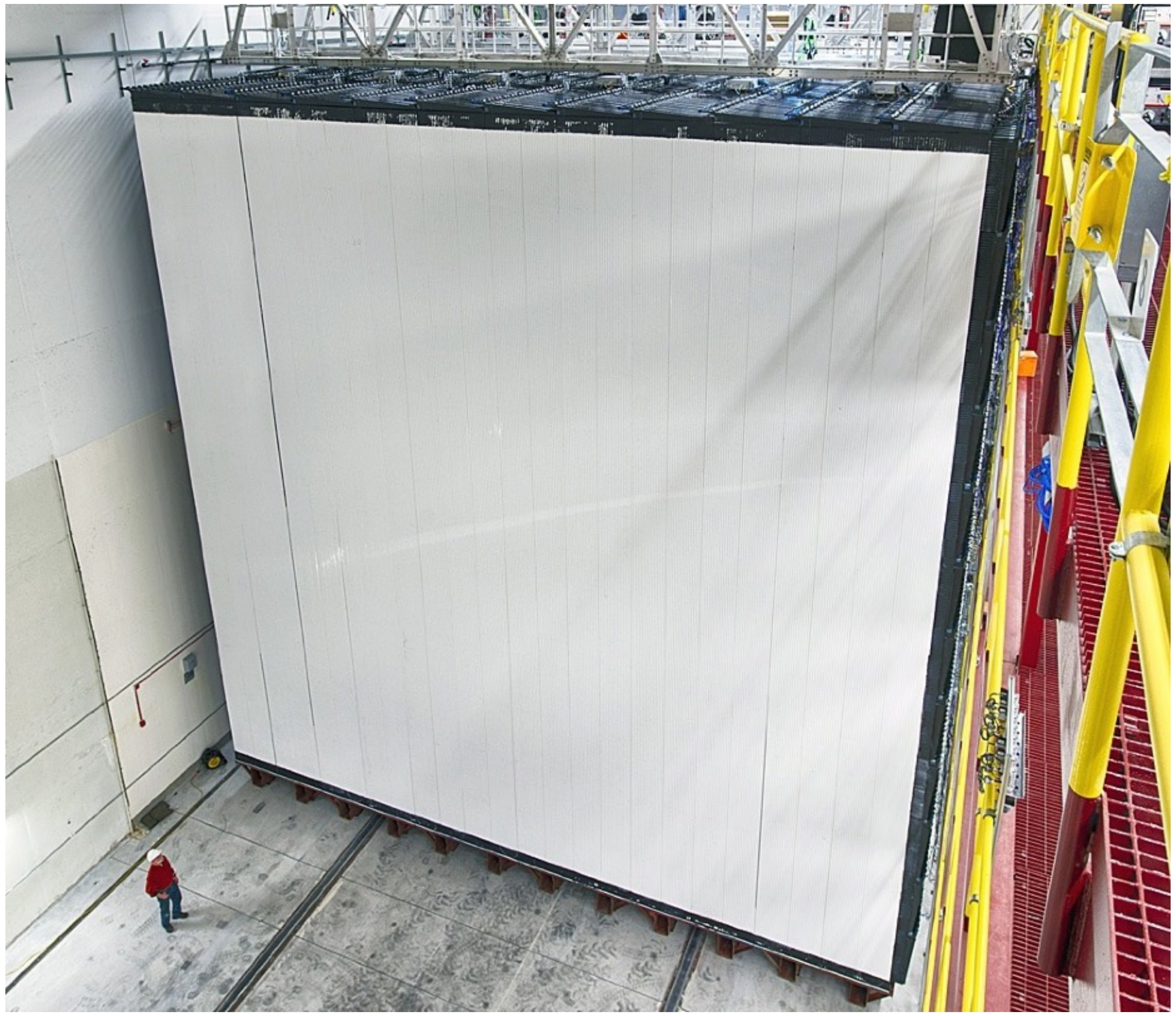


8.9×10^20 POT Neutrino Beam

6.9×10^20 POT Antineutrino Beam

Two-detector scheme

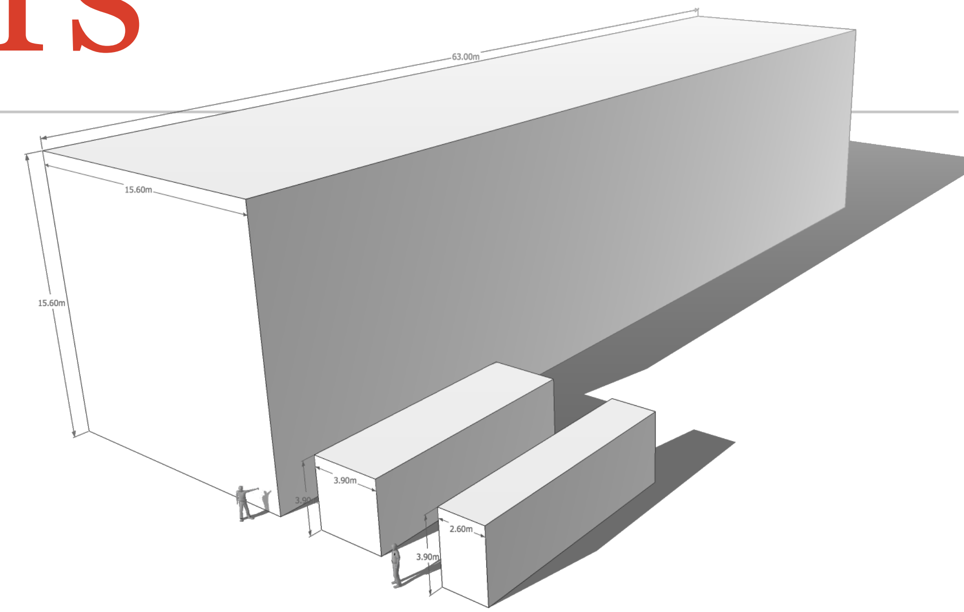




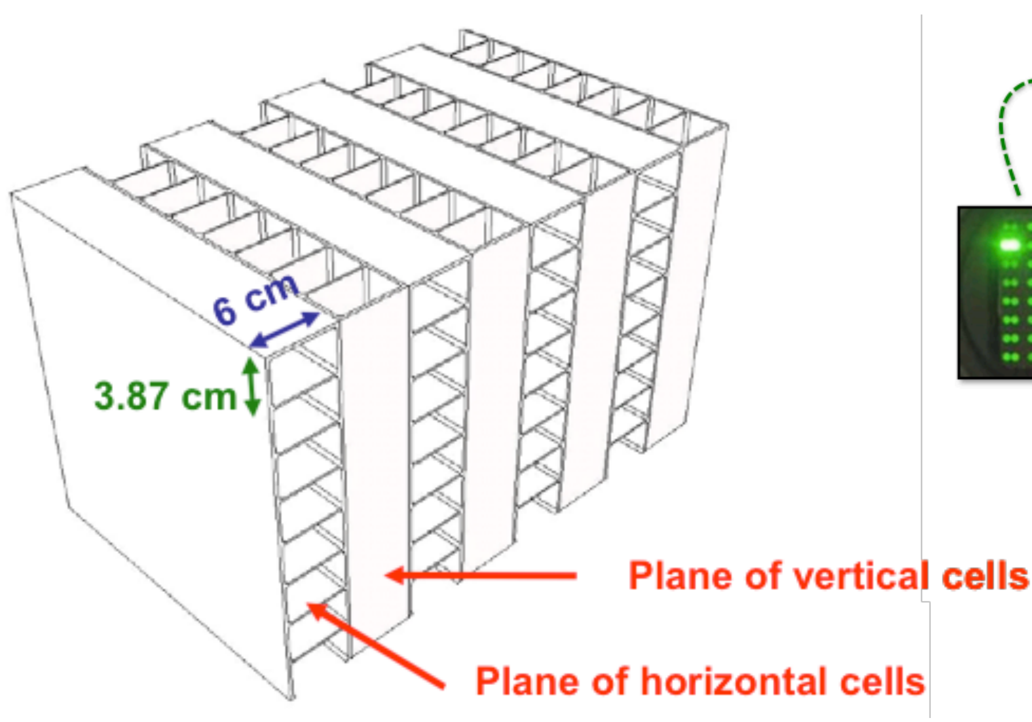
- **Near detector**
  - 1 km after target, weight 300 t
  - measure flux composition before oscillations
  - ND data used for prediction in FD (extrapolation procedure)

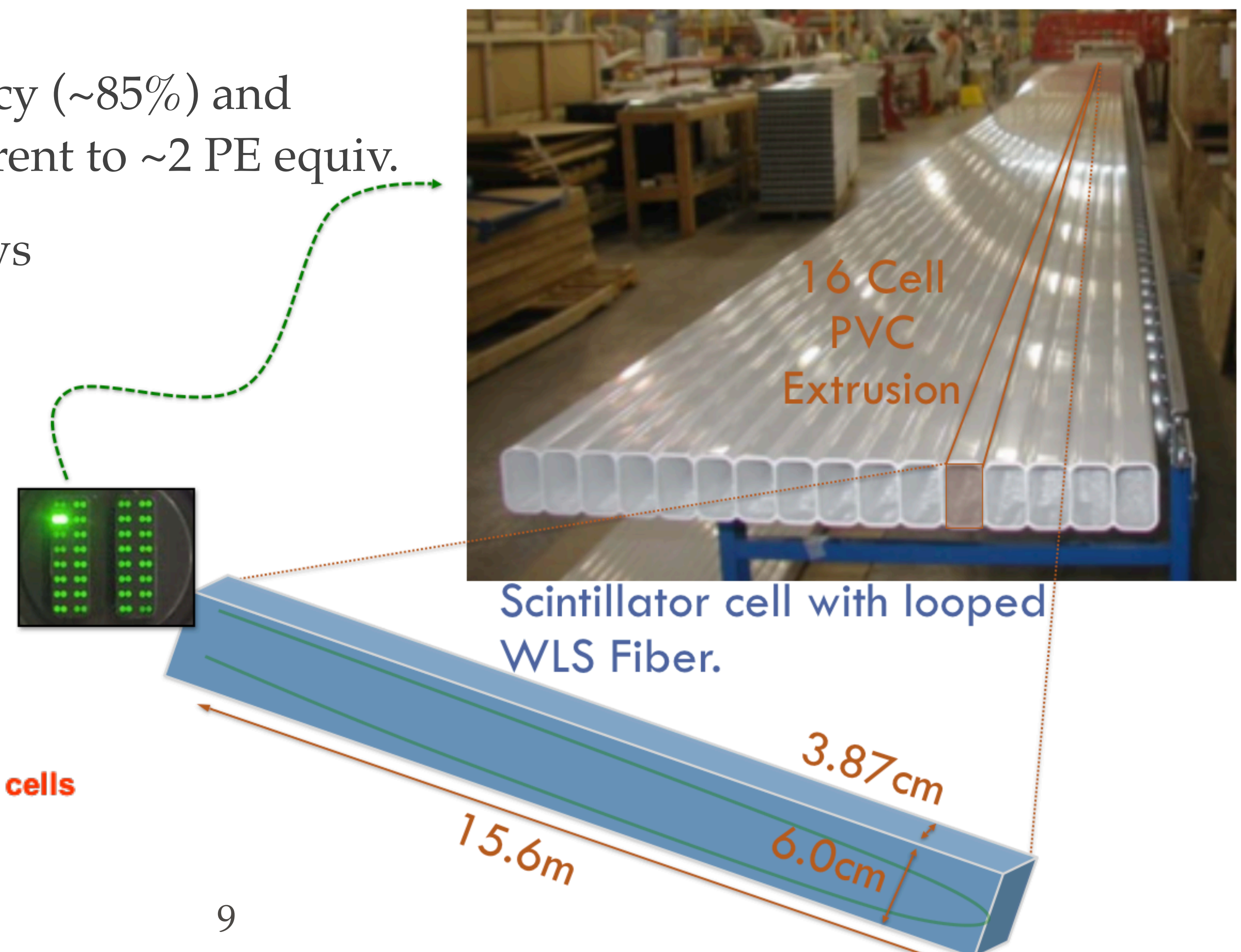
- **Far detector**
  - 810 km after target, weight 14 kt
  - measure neutrino flux after oscillations
  - extrapolation systematics
  - FD identical to ND

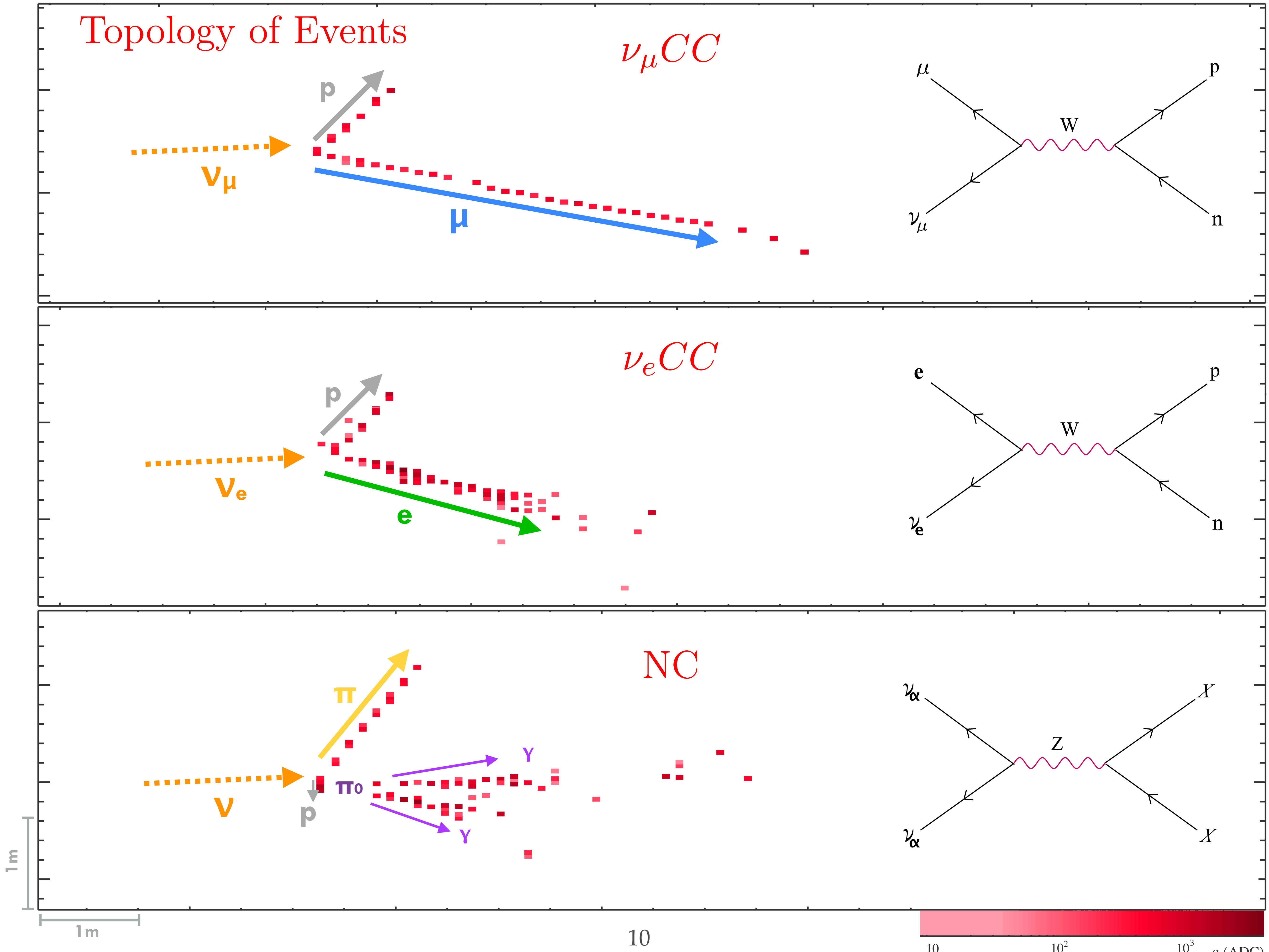
The NOvA Detectors



- PVC extrusion + Liquid Scintillator
  - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
  - FD has ~344,000 channels
  - muon crossing far end ~40 PE
- APDs have high quantum efficiency (~85%) and cooled to -15 C to reduce dark current to ~2 PE equiv.
- Layered planes of orthogonal views







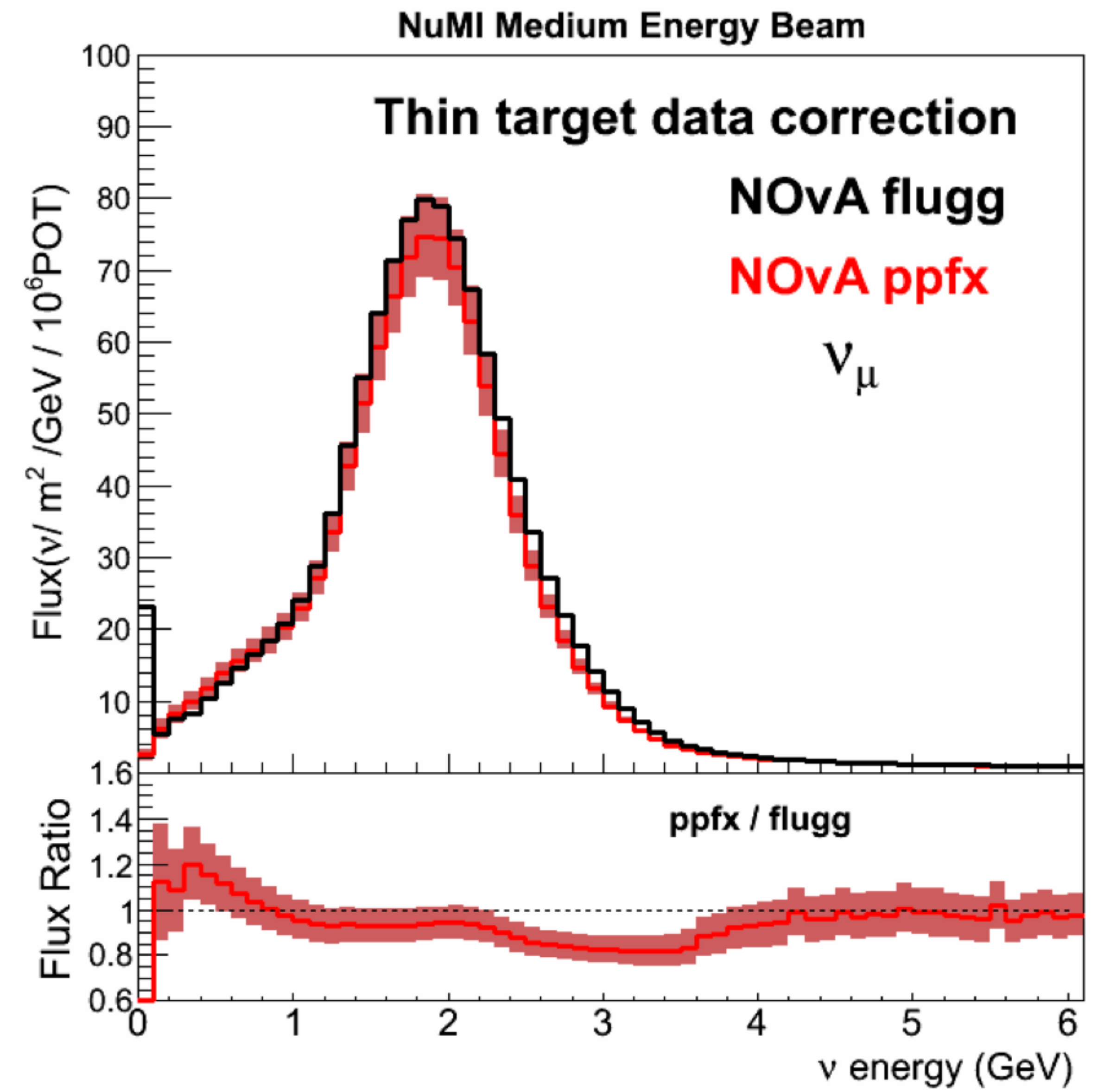
Topology of Events
$\nu_\mu CC$
p
ν_μ
μ
μ
p
W
ν_μ
n
$\nu_e CC$
p
ν_e
e
e
p
W
ν_e
n
NC
π
γ
ν
p
π0
γ
ν_α
X
Z
ν_α
X
1m
1m
10
10^2
10^3
q (ADC)

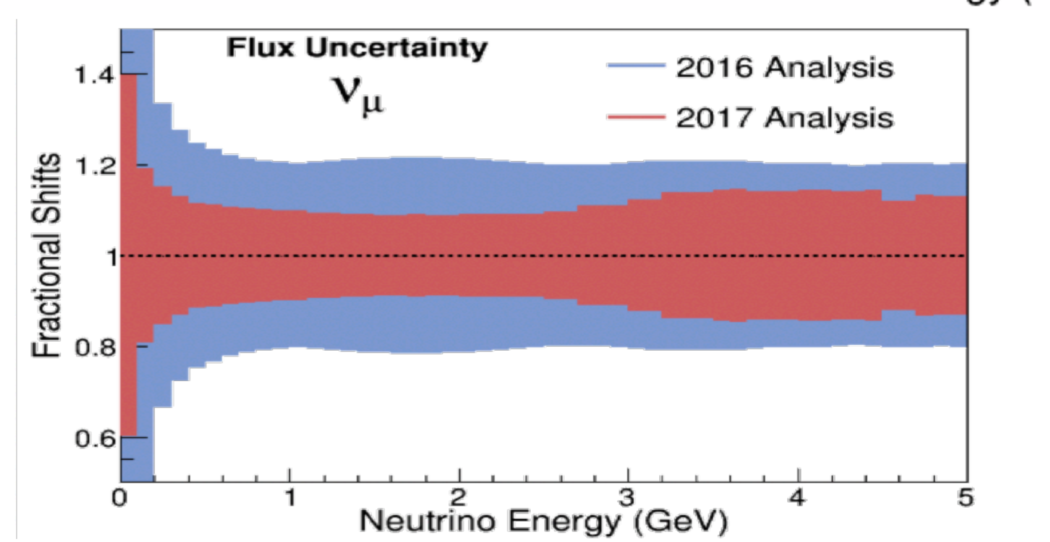
Simulation chain

Step	CHEP-2015	CHEP-2018	Products
Beam simulation	FLUKA / FLUGG	GEANT / External Data (MINERvA)	Simulates the incoming neutrino spices and spectrum from π, K, μ decays
Neutrino interactions	GENIE	GENIE + Cross-section tuning	Produces particle lists and kinematics to be propogated through the detector
Cosmic rays	CRY	Data triggers + Overlay	
Detector simulation	GEANT 4	GEANT 4 upgrade (neutron simulation) + revision in geometry	Propagates particles through the detector and produces energy deposits in active materials
Readout electronics and DAQ	Custom simulation routines	Updates of the light model and electronics setup	Converts energy deposits into scintillation light, its transport to APD and simulates the readout response, produces output like raw data

Neutrino beam simulation

- A new NuMI flux prediction strategy includes G4NuMI package for beamline simulation with GEANT4 base code integrating NuMI geometry and particle propagation in the beamline from incoming protons and ending with decays of secondaries that generates neutrinos.
- Beam flux is tuned then using an external Package to Predict the FluX (PPFX) that calculates the correction for the G4NuMI hadron production mismodel and their uncertainties using dedicated hadron production measurements from hadron-nucleus collisions (input data)*.

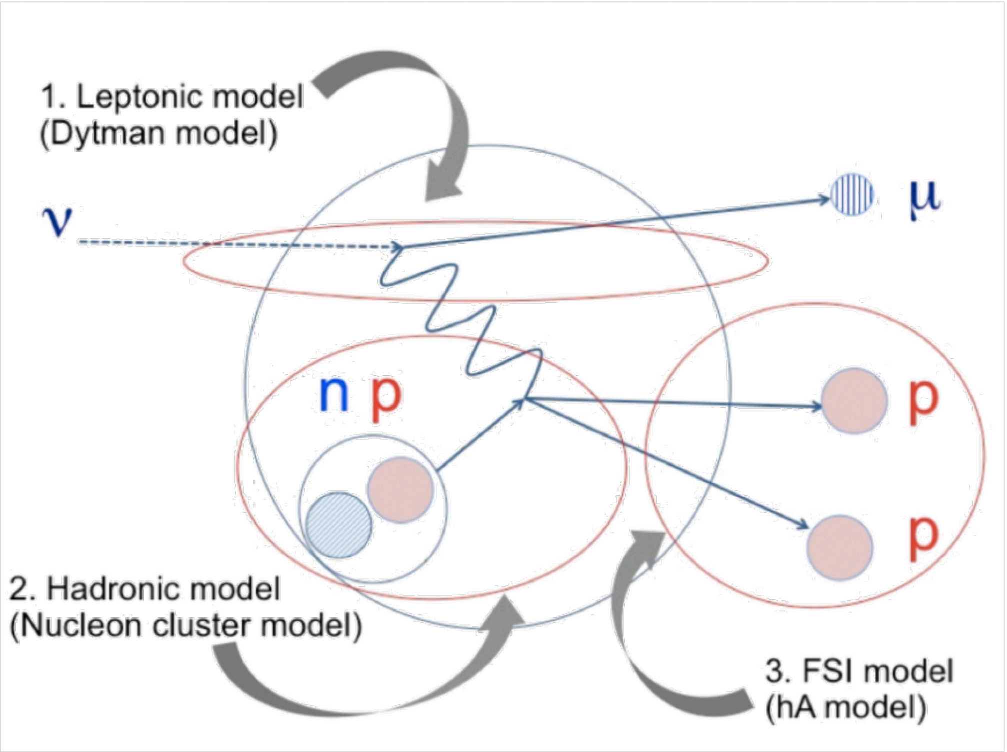




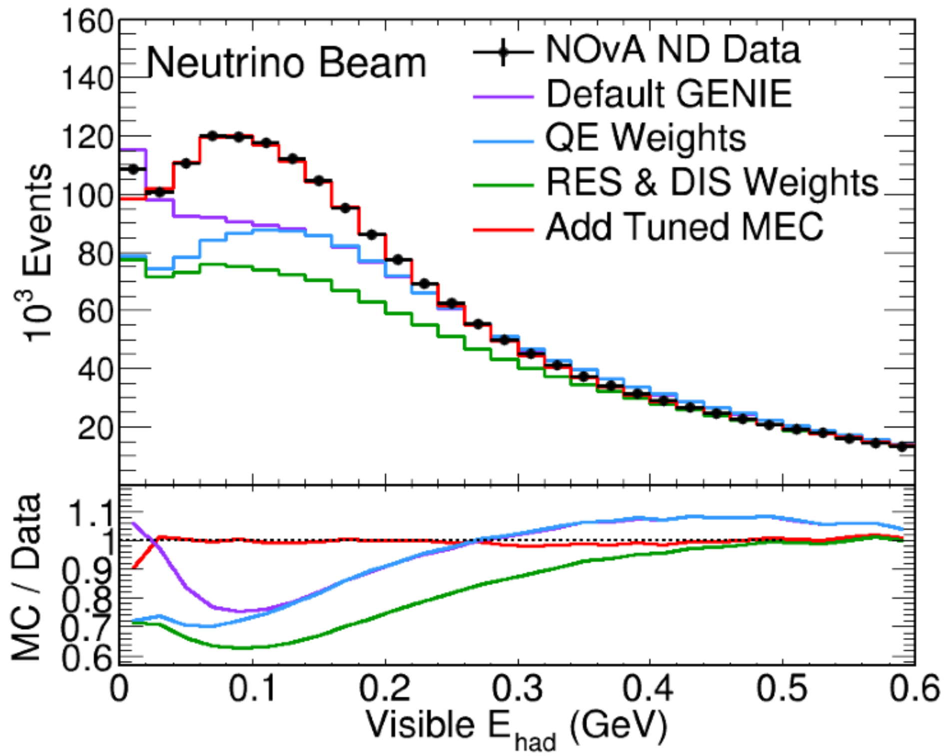
* Phys.Rev. D94 (2016) no.9, 092005 [MINERvA]

Neutrino interactions

- NOvA uses the GENIE neutrino event generator to simulate different neutrino interaction channels:
  - Quasielastic (QE), Baryon resonance (RES), Deep Inelastic (DIS) for "free nucleons" and Coherent on whole nuclei
  - Nuclear effects for a single-nucleon knockout (1 particle, 1 hole – 1p1h) cover by standard "Relativistic Fermi Gas" (RFG) model including also nuclear charge screening, "Random phase approximation" (RPA) effect developed by Valencia theoretical group (QE/RES)
  - GENIE also provides an empirical "Meson Exchange Currents" (MEC) model to simulate two-nucleon knockout (2p2h)
- We finally retune (since we are looking for oscillation in the FD) our ND Monte Carlo simulation to match ND data



- Teppei Katori, MEC models, AIP Conf.Proc. 1663 (2015) 030001

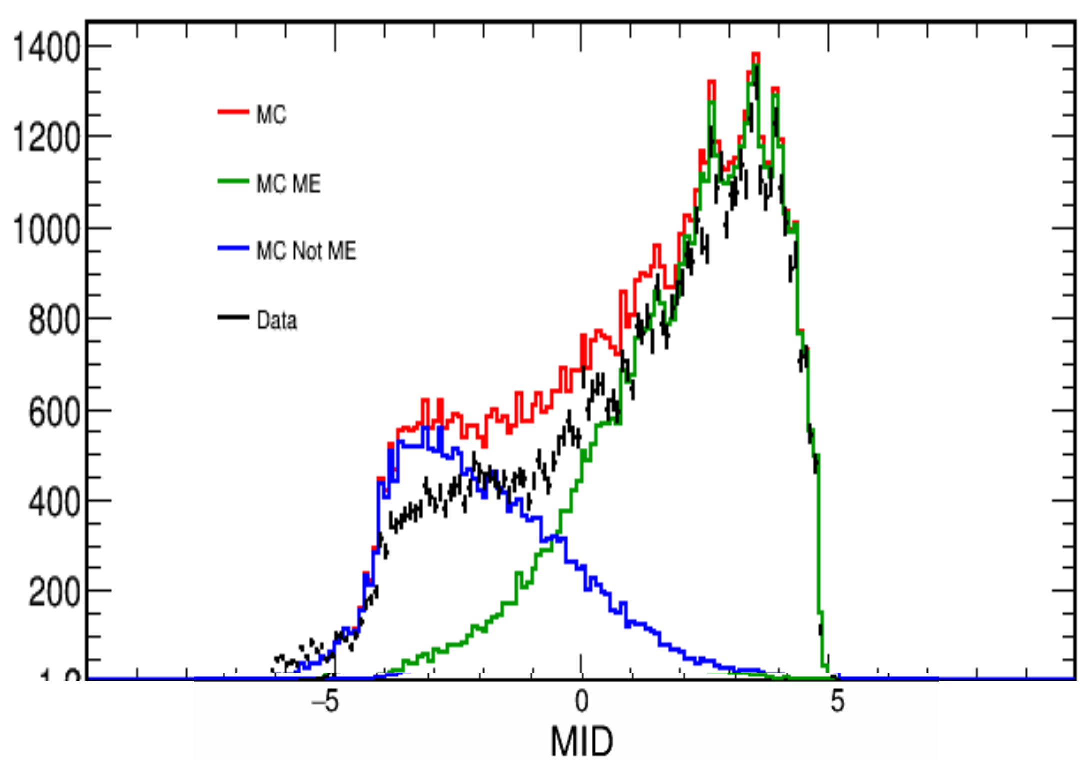


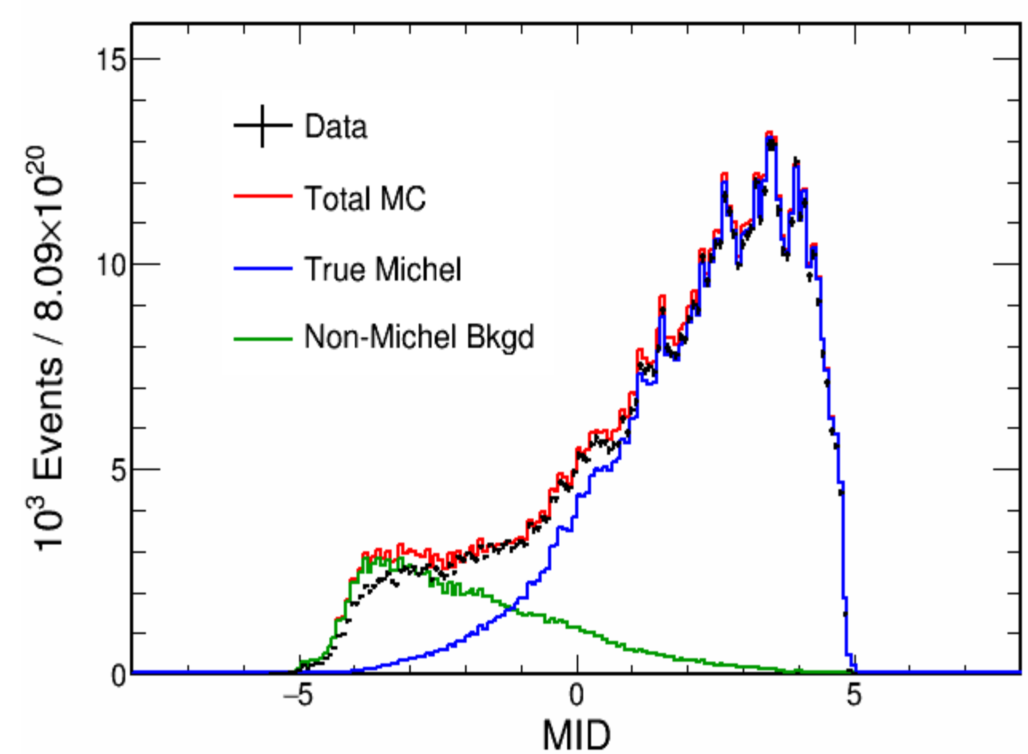
Detector geometries

- Starting with the December 2016, we are using an updated geometry.
- It has more accurate material compositions, dimensions and total masses.
- While separate detector components were changed sensible,
- ➡ Physics changes in dE/dx accidentally remains almost the same (from 1.967 MeV/g/cm^2 to 1.966 MeV/g/cm^2),
- ➡ The radiation length is virtually unchanged also (+0.06 %).
- ➡ However, due to reducing of average density, the tracks are 1.2 % longer, the showers are 1.3 % larger now tending to develop more in the PVC and glue and less in the scintillator.

Geant4 upgrade

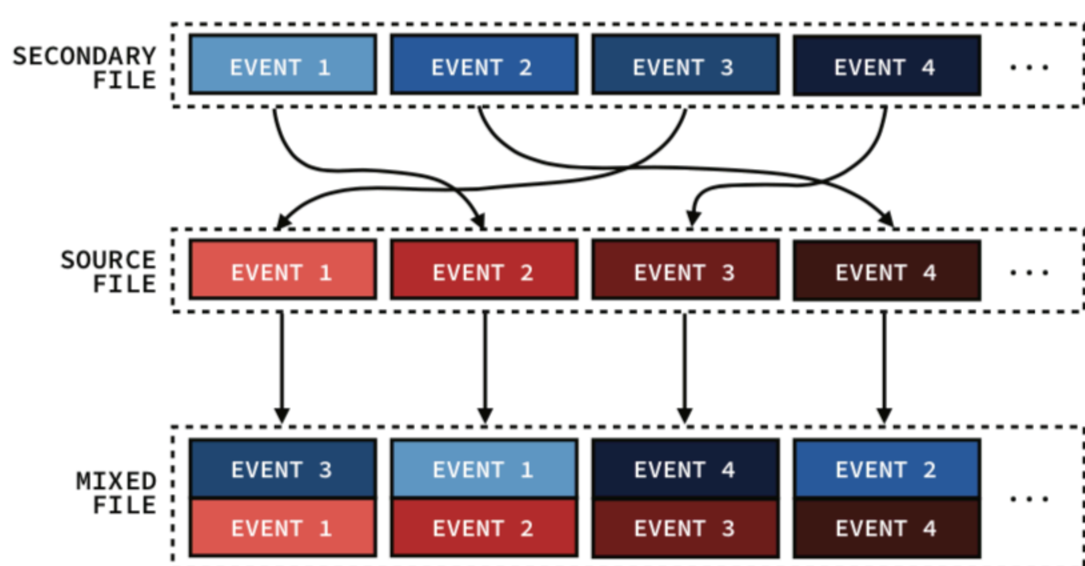
- A primary motivation for the switch to the new GEANT version was the improved tracking model for several MeV neutrons.
- The modeling of these neutrons are particularly important for the Michel decay algorithm developed for the ν_e appearance analysis.

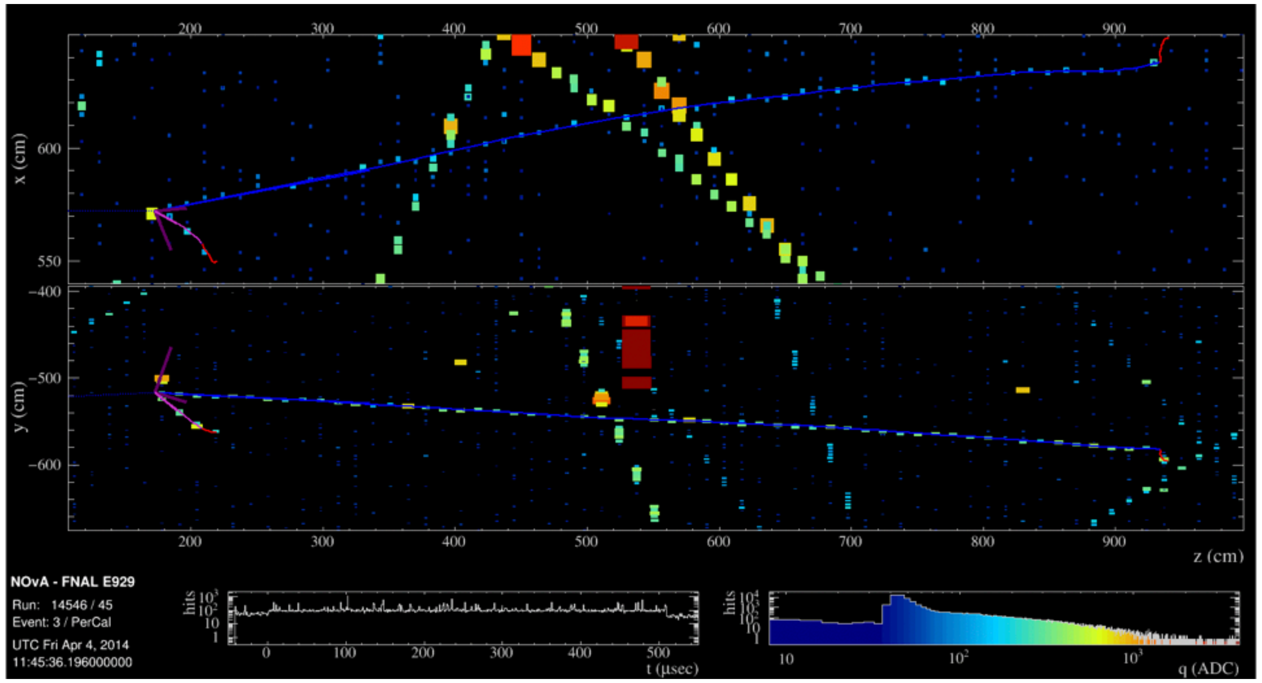




Overlays

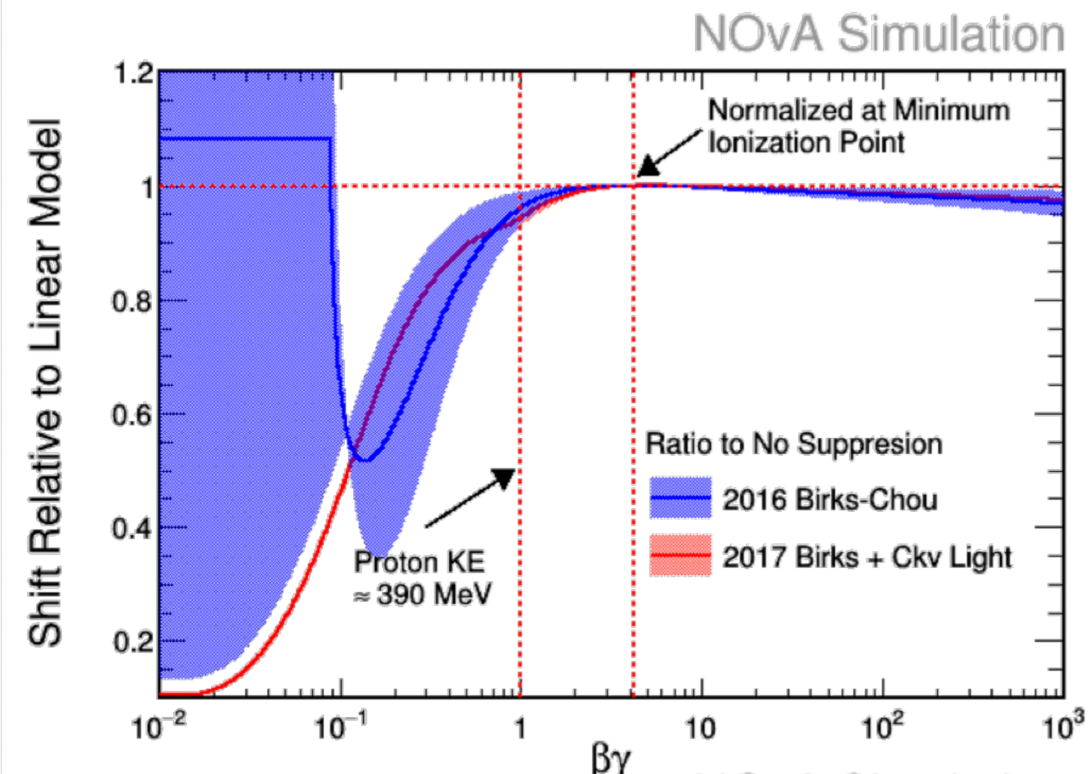
- Since now NOvA collected a large amount of events for the following Monte Carlo samples:
  - Neutrino interactions from the NuMI beam in the detectors
  - Cosmic ray events, mostly muons passing the detectors' volume
  - Rock overlay events, that were simulated in front of the Near Detector and those that released energy in the detector
- While cosmic data can be directly compare with cosmic Monte Carlo to verify our simulations as well as to use these samples for offline calibration and reconstruction, the cosmic data could be also applied to reduce uncertainties associated with modelling cosmic background
- Special machinery procedure developed to reliably mix and merge data products from simulated signal and real minimum-bias data

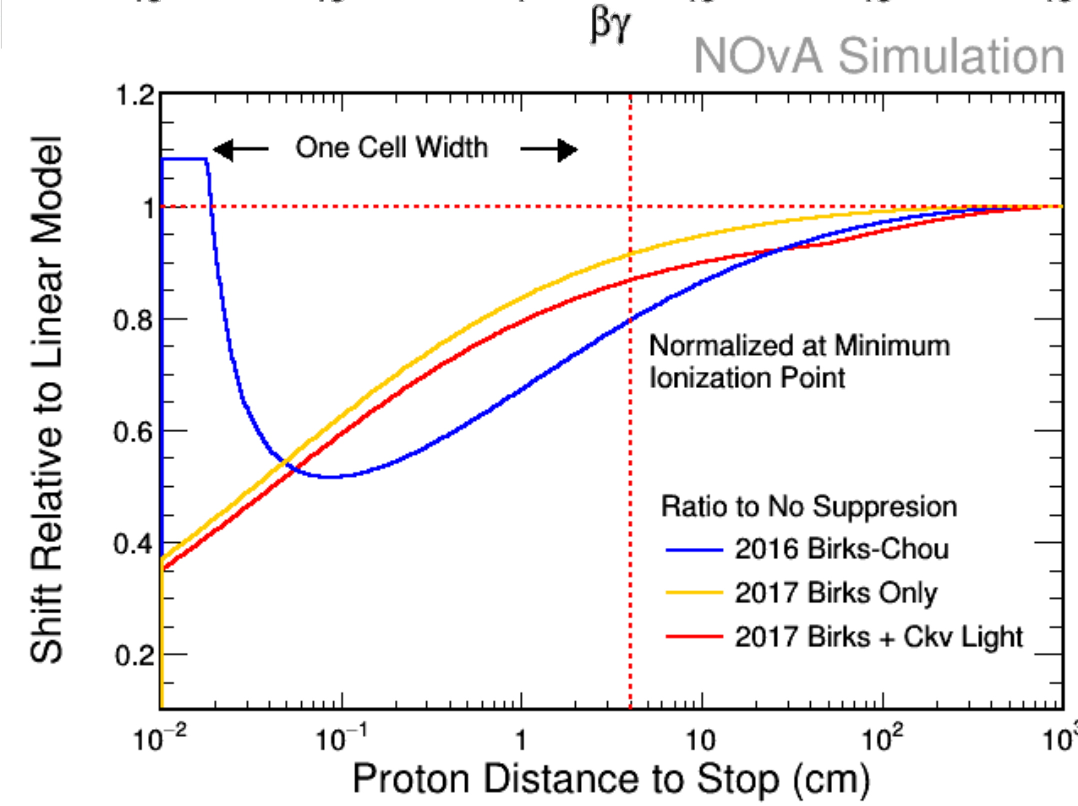




Scintillator light model

- In our Analyses before 2016, minimizing the disagreement between the dE/dx response of protons in data and MC required a much larger Birks constant that reported by experiments using similar scintillators.
- Modeling the Cherenkov light produced in NOvA scintillator significantly improved the modeling of the hadronic system and removed the need for using Chou constants.
- In the old model, light from protons was ~5% too high. For primary protons, this only makes a small change to the apparent overall event energy. However, modeling the response of soft, knock-on protons does produce a large change to the energy of the hadronic system between the Birks-Chou and the Birks+Cherenkov models.





See details in Adam Aurisano's Poster

Future improvements: The test beam

- The test beam program provides us
  - simulation improvements
  - validation of particle ID's
  - reducing systematics
- Installation and commissioning starting this summer
- Beam in the first half of 2019, planning on 2 million particles

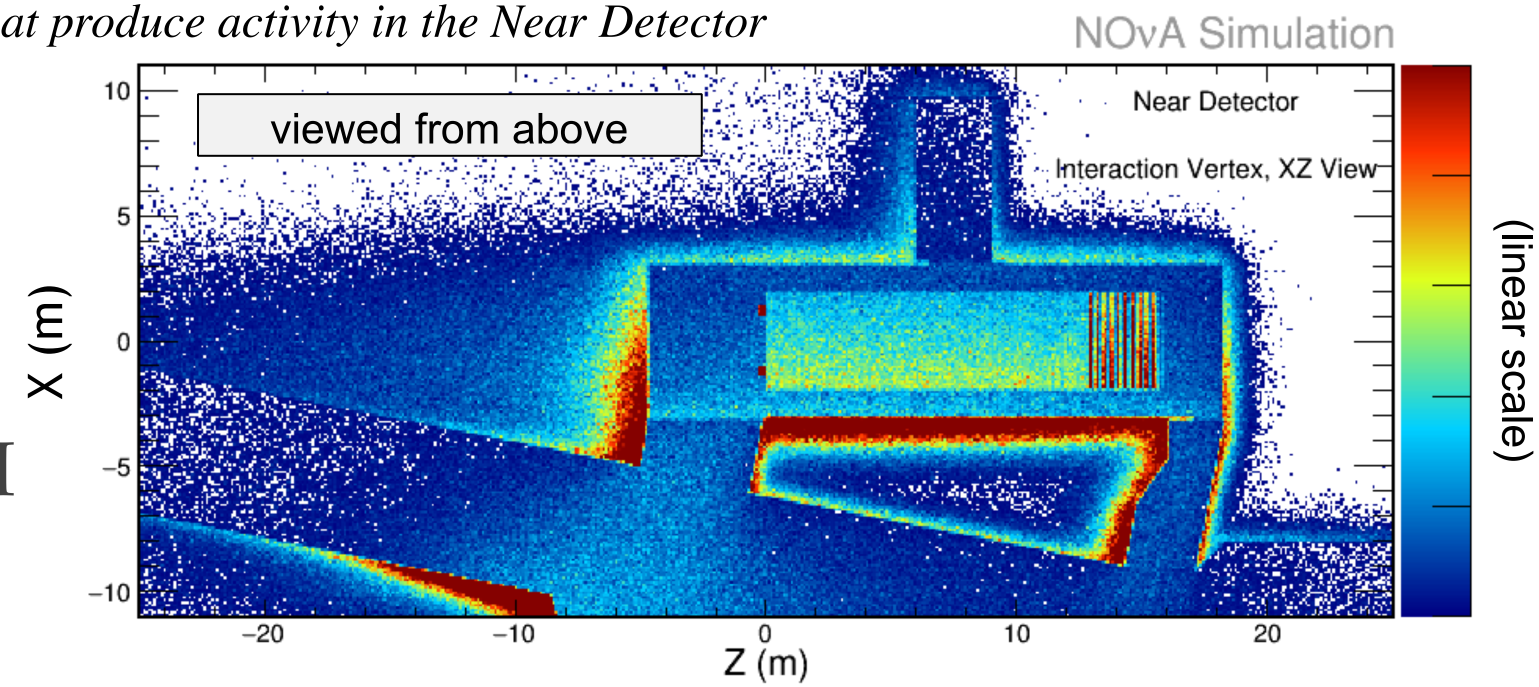
Future improvements: Neutrino generators

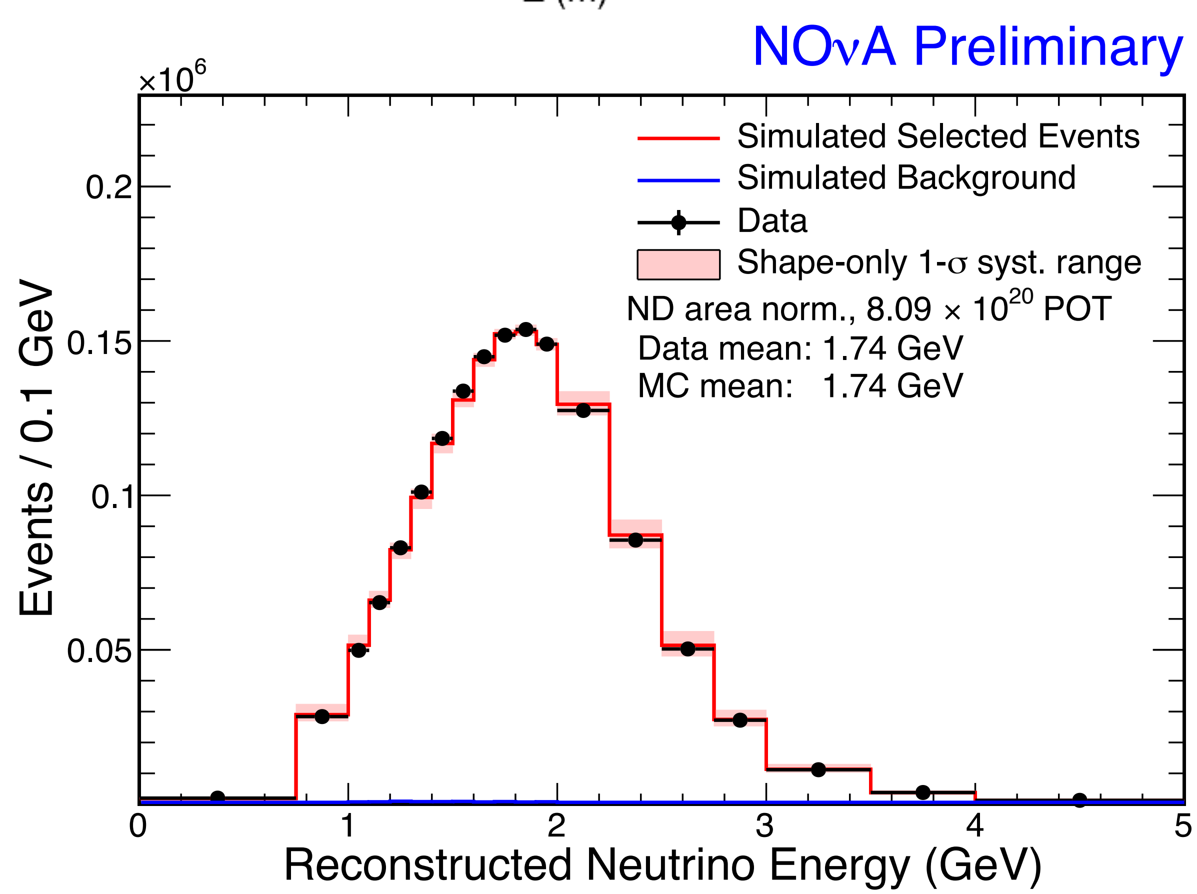
- NOvA is preparing to release GENIE 3.0
- Alternative generators:
  - NOvA is currently able to run standalone executables in both NEUT and GiBUU with the most recent NOvA flux predictions
  - Expect to have full NOvA simulations for both NEUT and GiBUU soon
  - NOvA also has aspirations of implementing NuWro

NOvA simulation summary

- Beam hadron production, propagation, neutrino flux: **GEANT4/External Data**
- Neutrino Interactions and FSI modeling: **GENIE v2.12.2**
- Cosmic ray flux: **Data Triggers**
- Detector Simulation: **GEANT4**
- Readout electronics and DAQ: **Custom simulation routines**
- NOvA is constantly working on improvements of the simulation

Simulation: Locations of neutrino interactions that produce activity in the Near Detector

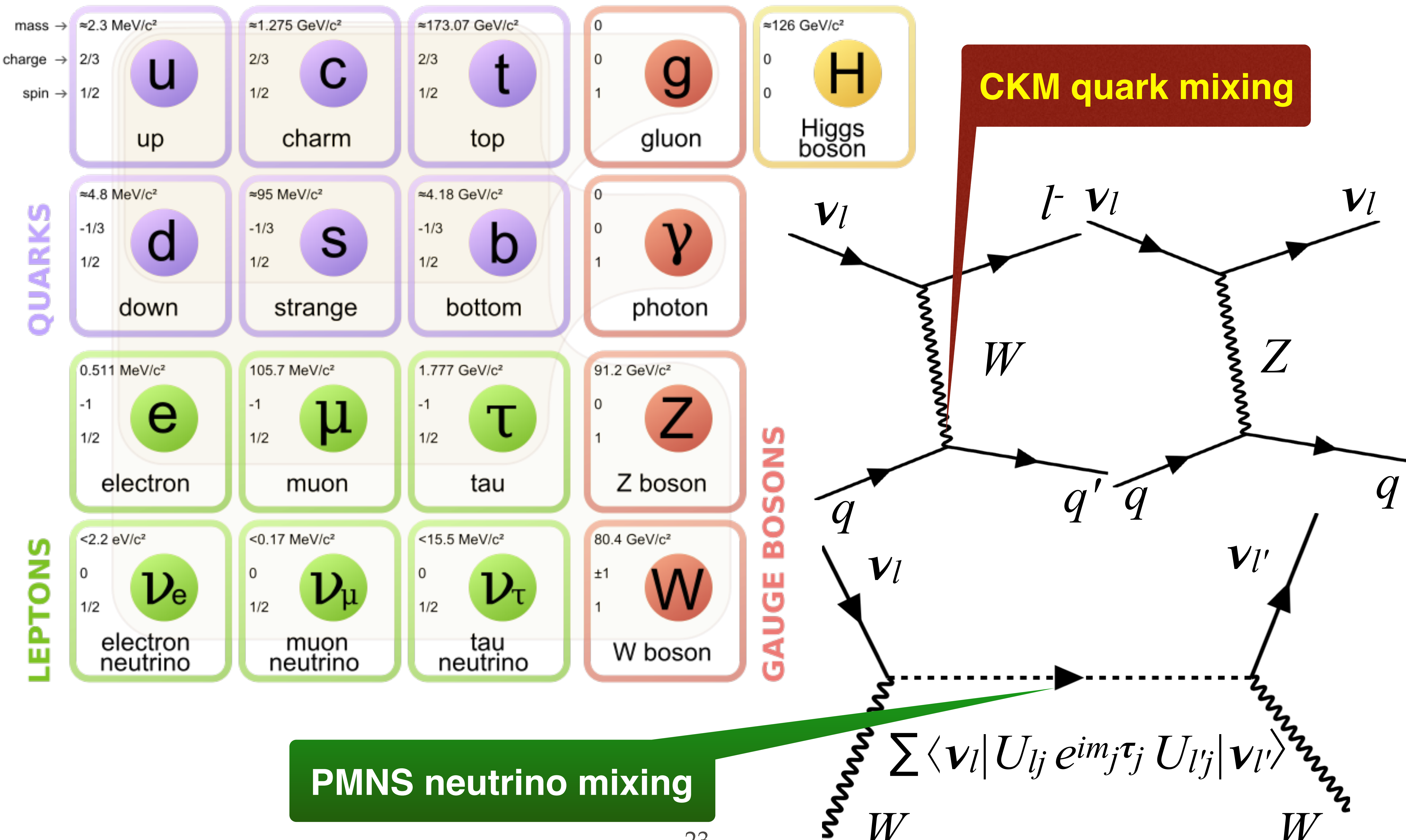




Thank you for your attention

Backup slides

Neutrino



mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
ν_e
electron neutrino
<0.17 MeV/c²
0
1/2
ν_μ
muon neutrino
<15.5 MeV/c²
0
1/2
ν_τ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
CKM quark mixing
ν_l
l^-
ν_l
ν_l
W
Z
q
q'
q
q
ν_l
$\nu_{l'}$
$\sum \langle \nu_l | U_{lj}\, e^{i m_j \tau_j}\, U_{l'j} | \nu_{l'} \rangle$
W
W
PMNS neutrino mixing

Neutrino oscillations

$\theta_{23} \sim 45^\circ$ $\theta_{13} \sim 8.5^\circ$ $\theta_{12} \sim 30^\circ$

$$\left| \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left| \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right\rangle$$

$|\Delta m^2_{32}| = |m^2_3 - m^2_2|$
$\simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$\nu_\mu \to \nu_\mu$
$\nu_\mu \to \nu_\tau$

atmospheric and
long baseline

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

$\nu_e \to \nu_e$
$\nu_\mu \to \nu_e$

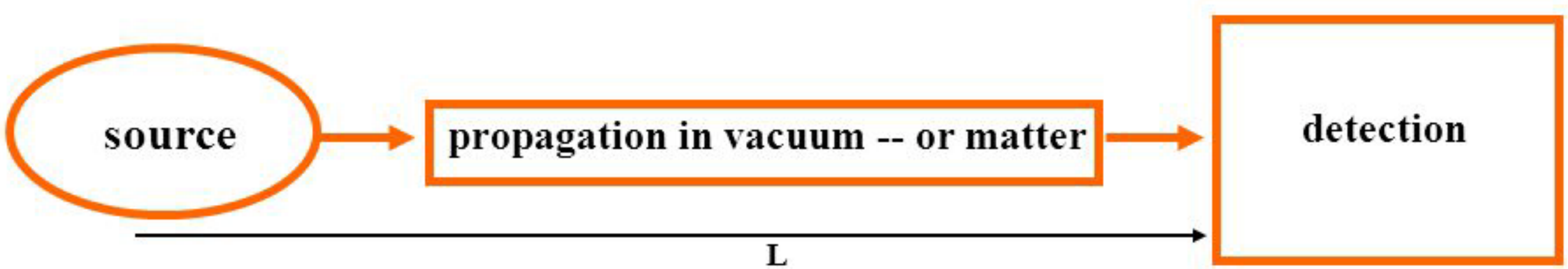
reactor and
long baseline

$\Delta m^2_{21} = |m^2_2 - m^2_1|$
$\simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$

$\nu_e \to \nu_e$
$\nu_e \to \nu_\mu, \nu_\tau$

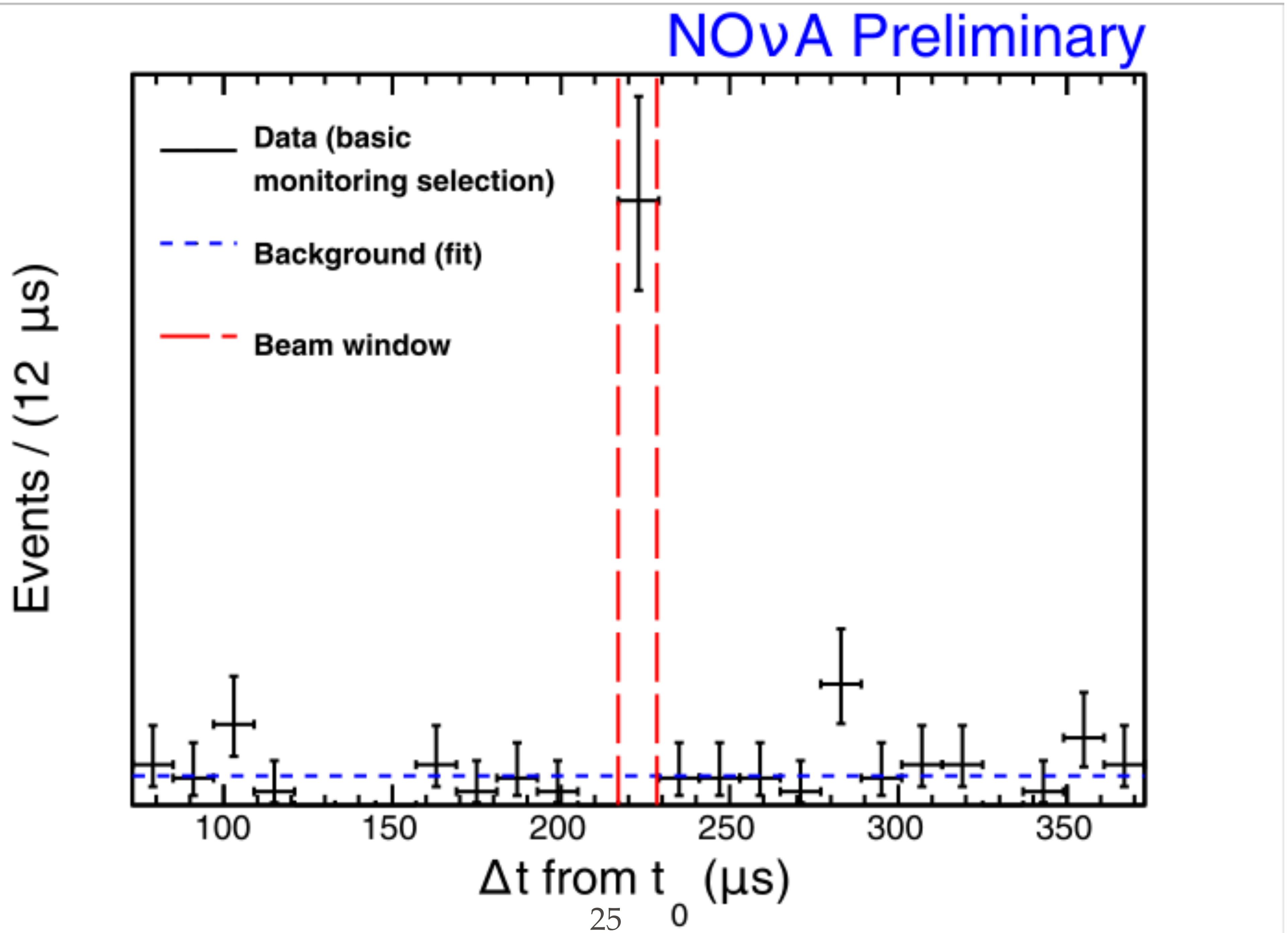
solar and
reactor

Oscillation parameters: $\theta_{12}, \theta_{23}, \theta_{13}$, CP phase δ, $|\Delta m^2_{13}|$, Δm^2_{12}

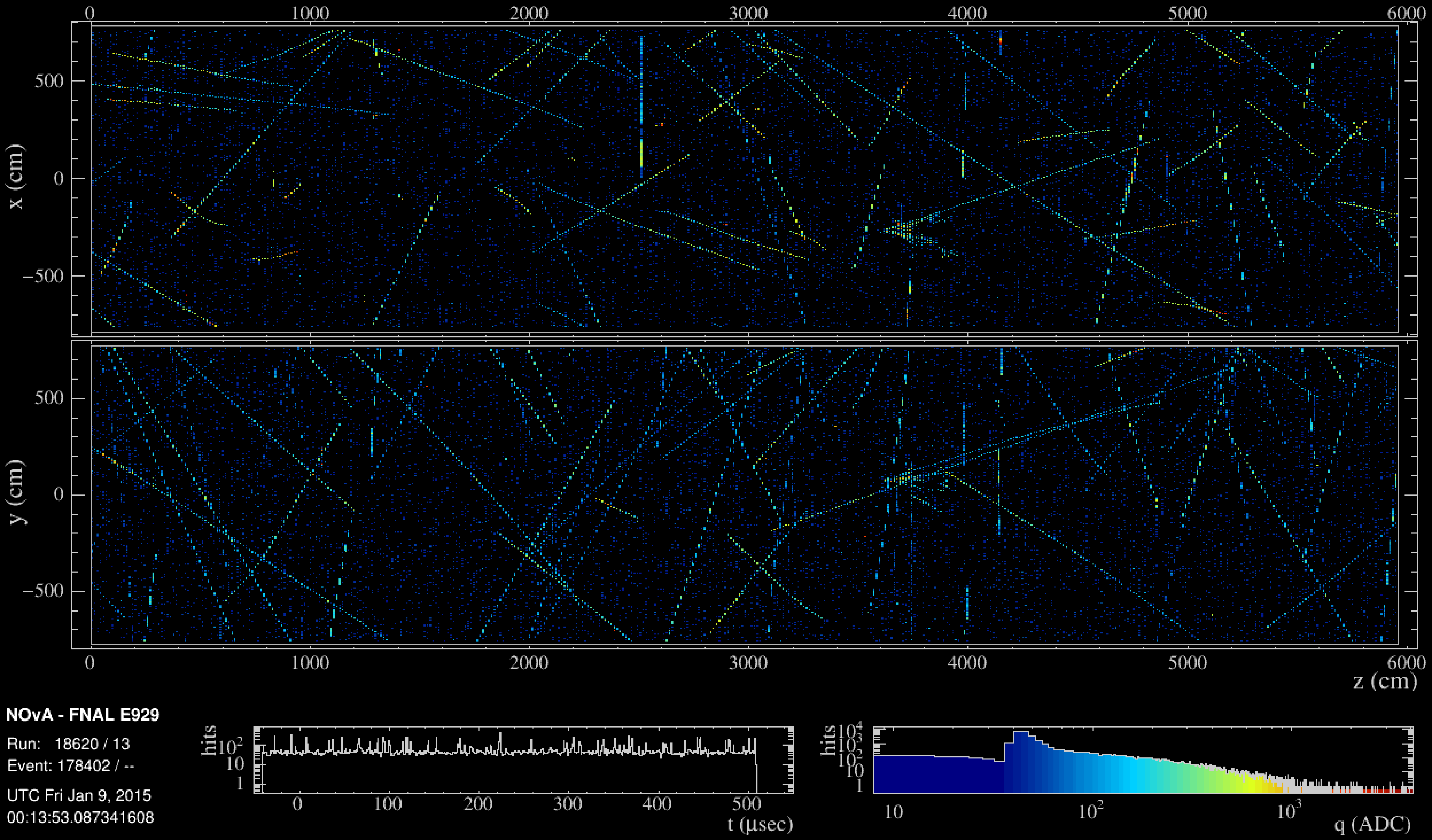


FD Beam Peak

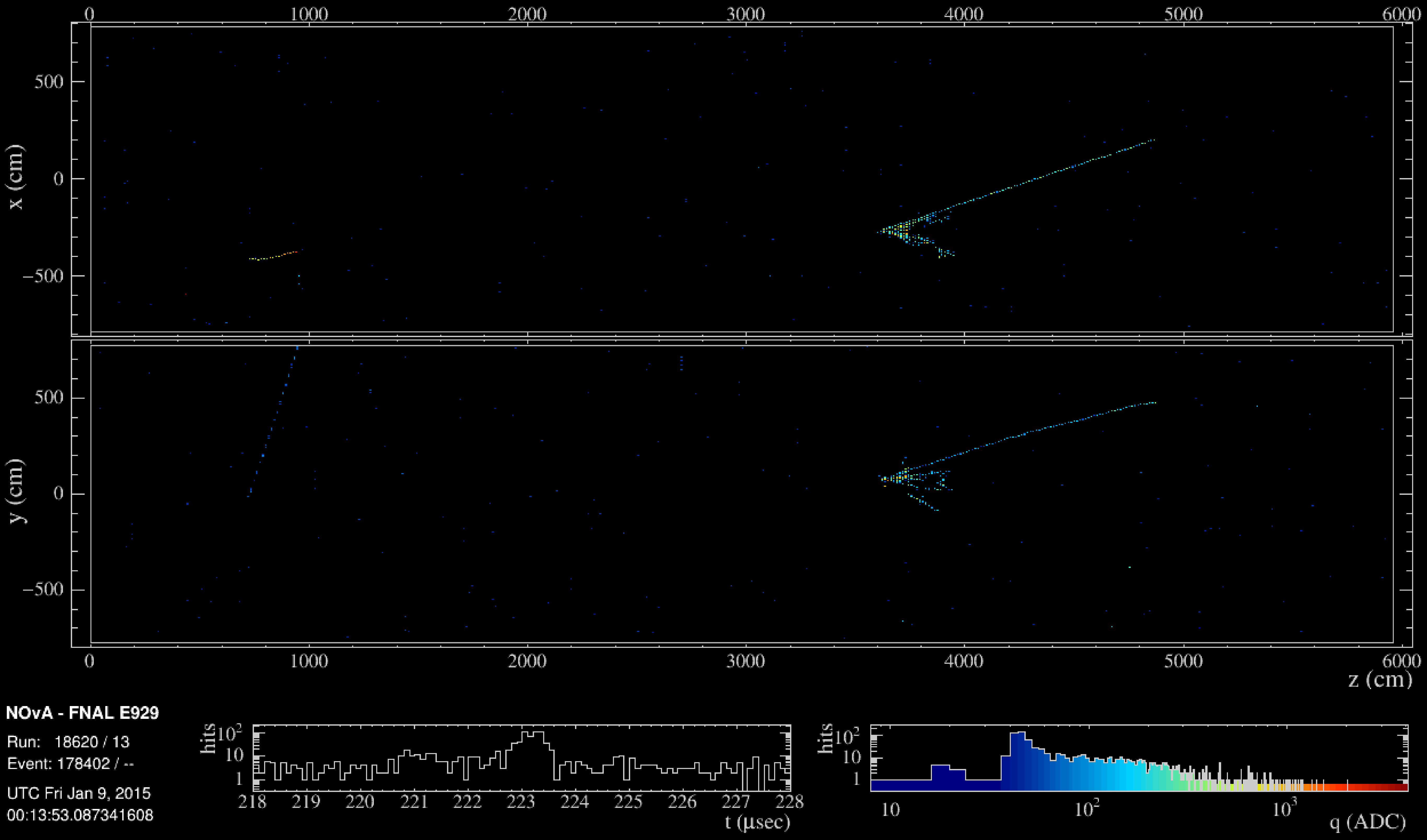
- Trigger structure: 550 μs window, NuMI neutrinos arrive for 10 μs starting at 218 μs



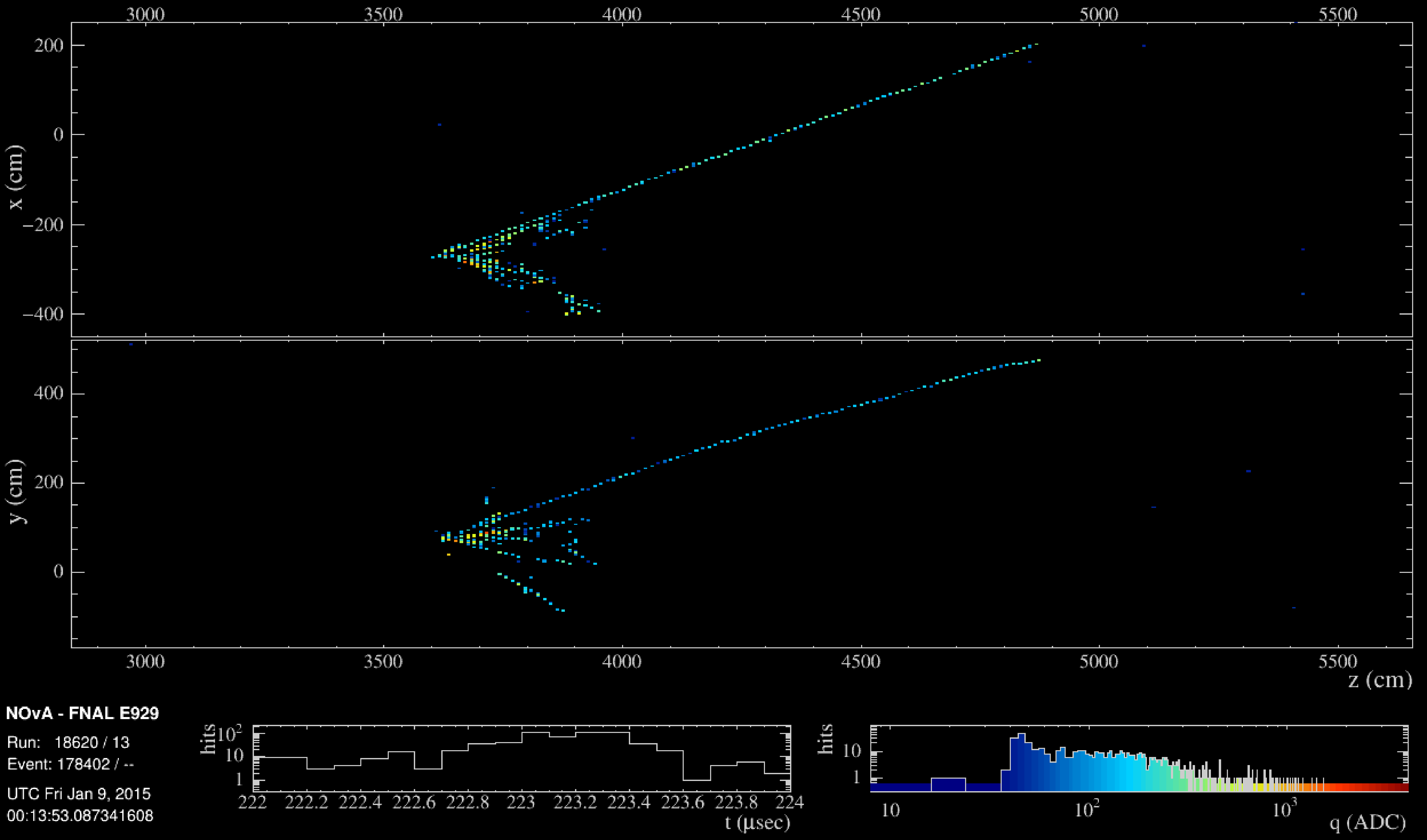
550 μs exposure of the Far Detector



Time-zoom on 10 μs interval during NuMI beam pulse

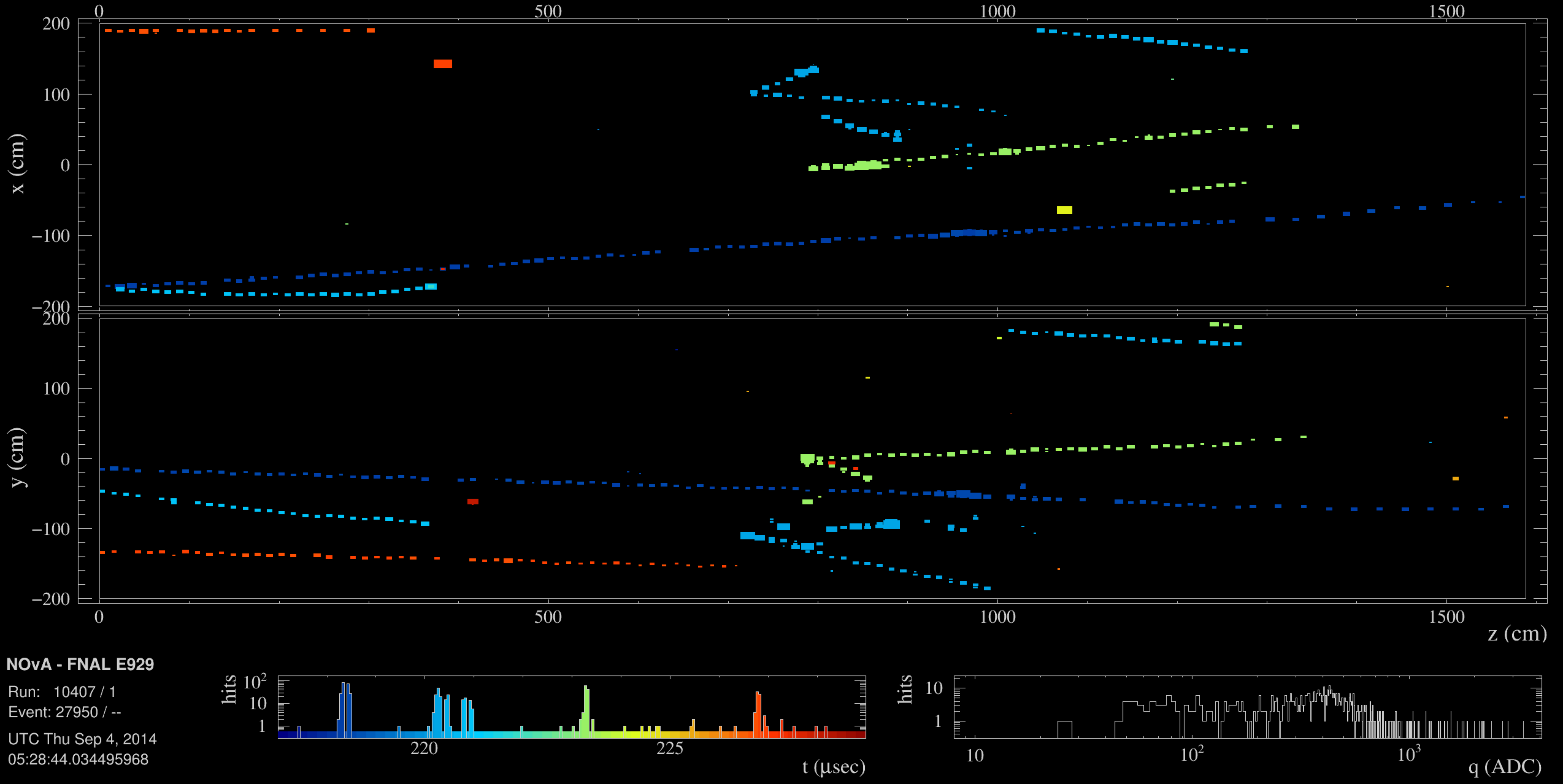


Close-up of neutrino interaction in the Far Detector

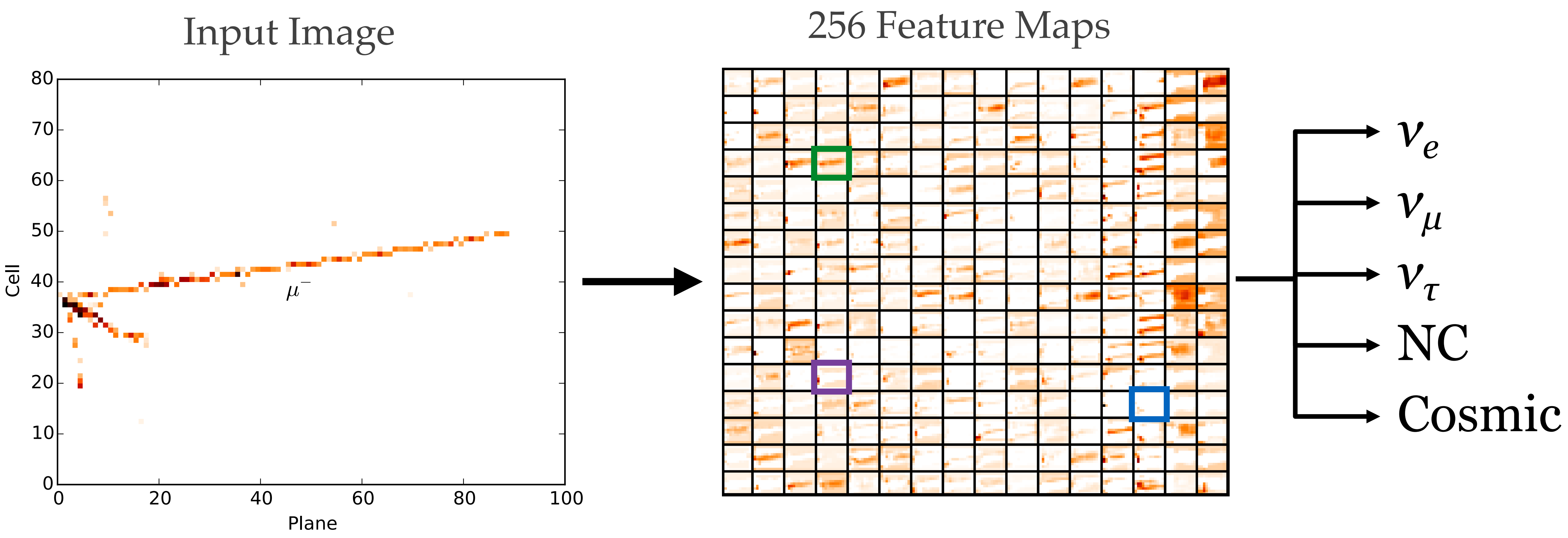


Near Detector: 10 μs of readout during NuMI beam pulse

(color ⇒ time of hit)



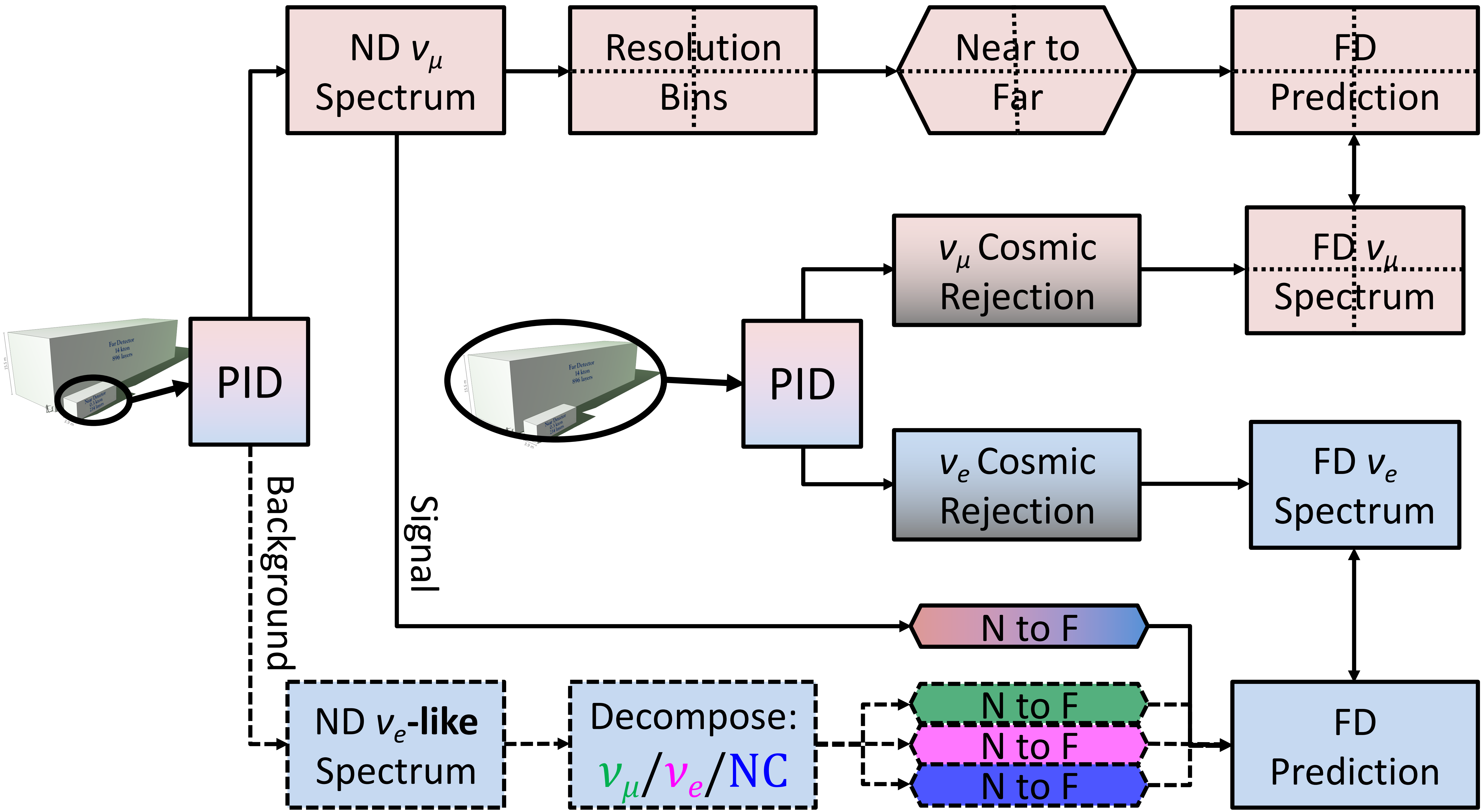
Event selector with Computer vision



- We use a convolutional neural network* based on the GoogLeNet
- Multi-label classifier – the same network used in multiple analyses

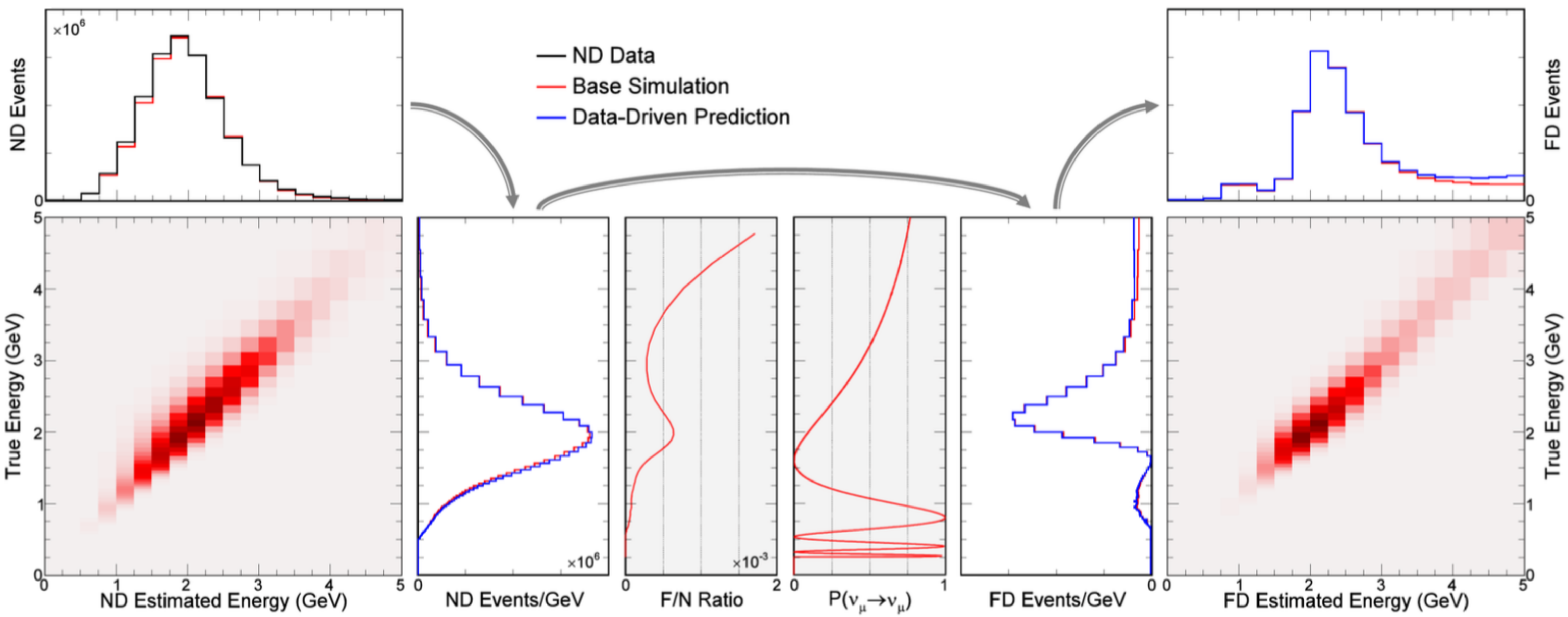
* Adam Aurisano et al., A CNN Neutrino Event Classifier, JINST 11 (2016) no.09, P09001

Analysis strategy

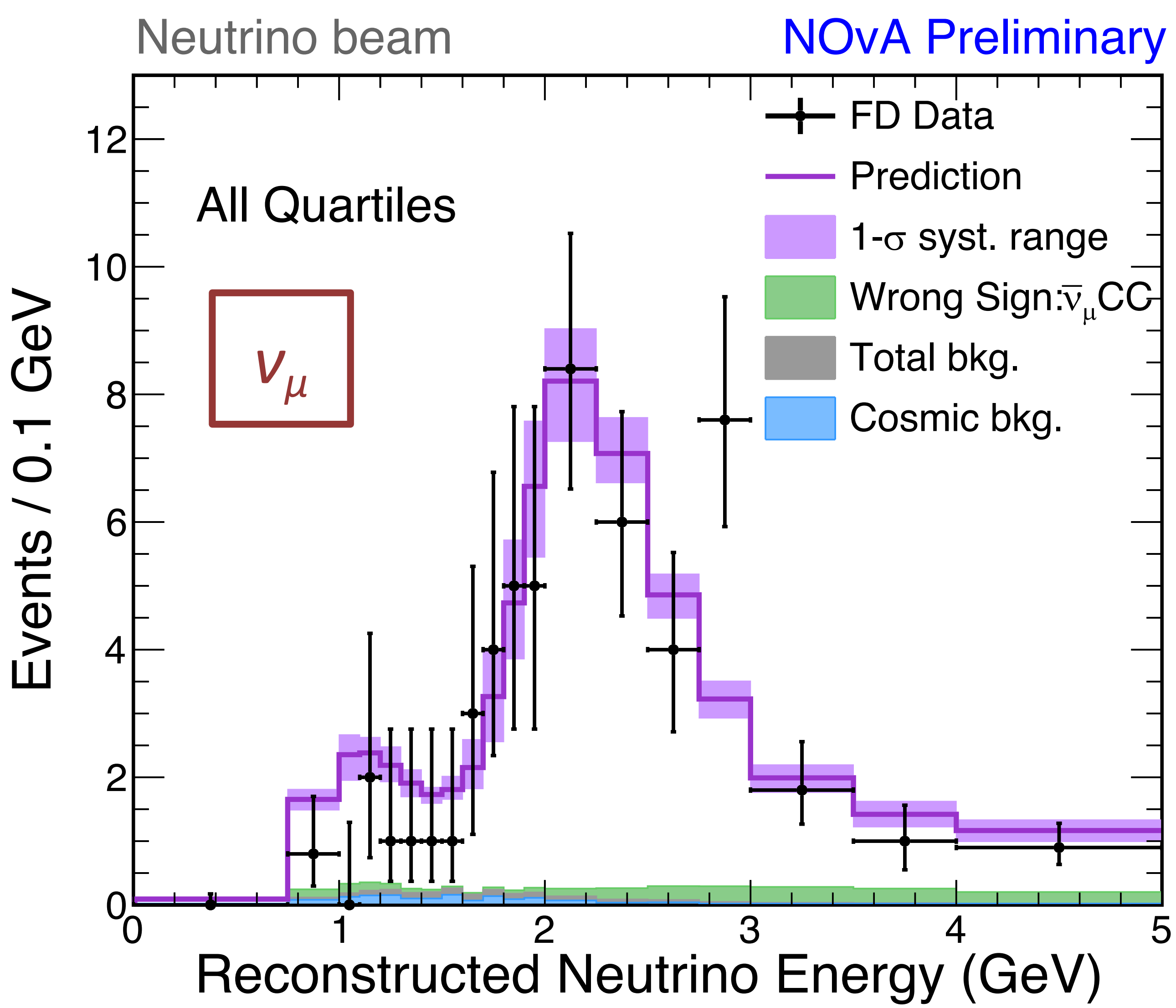


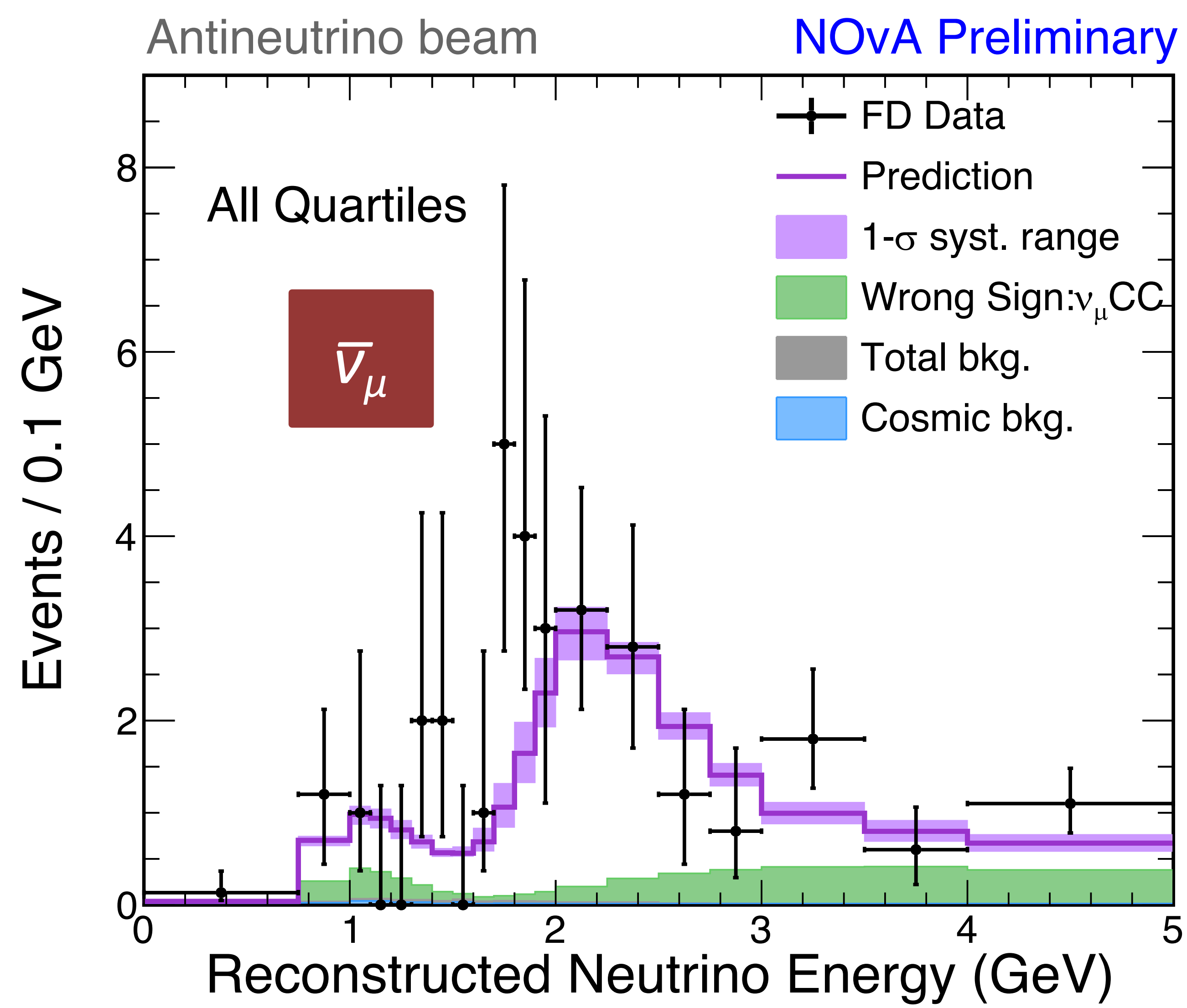
Extrapolation to the Far Detector

- Estimate true energy distribution of selected ND events.
- Multiply by expected Far/Near event ratio and oscillation probability as a function of true energy.
- Convert FD true energy distribution into predicted FD reco energy distribution.
- Systematic uncertainties assessed by varying all MC-based steps.



ν_μ and $\overline{\nu_\mu}$ Data at the Far Detector

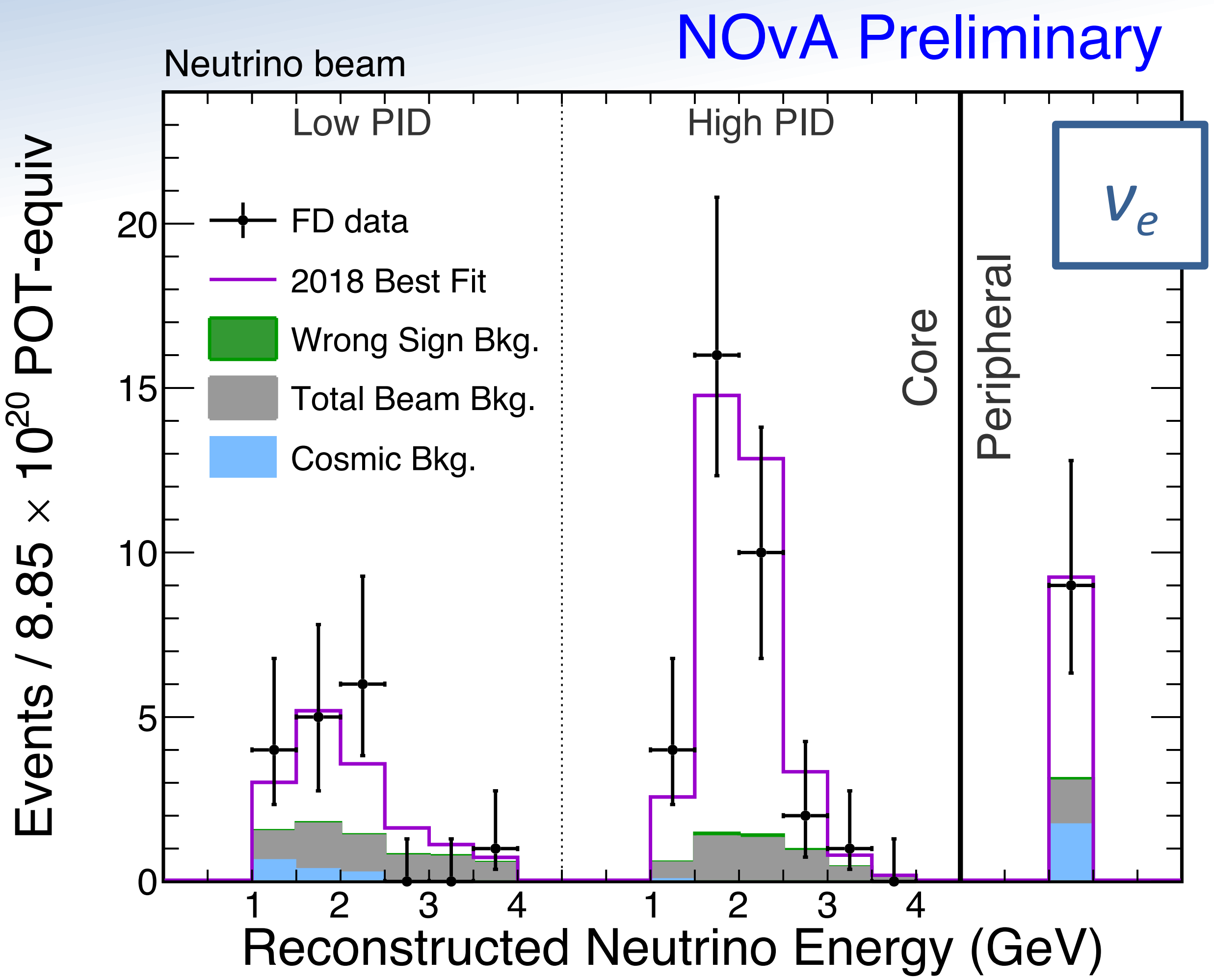


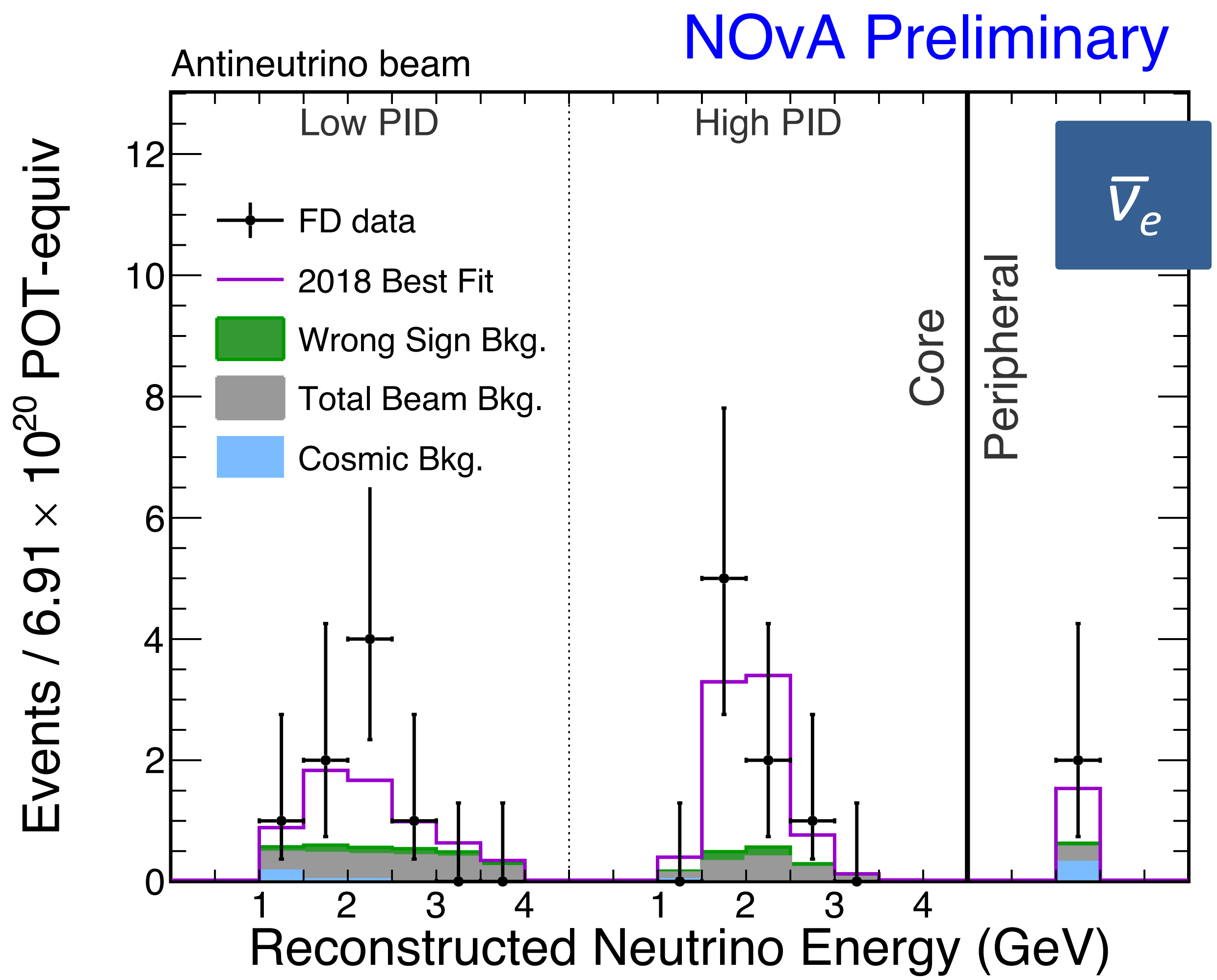


Total Observed	**113**
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

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

ν_e and $\overline{\nu}_e$ Data at the Far Detector





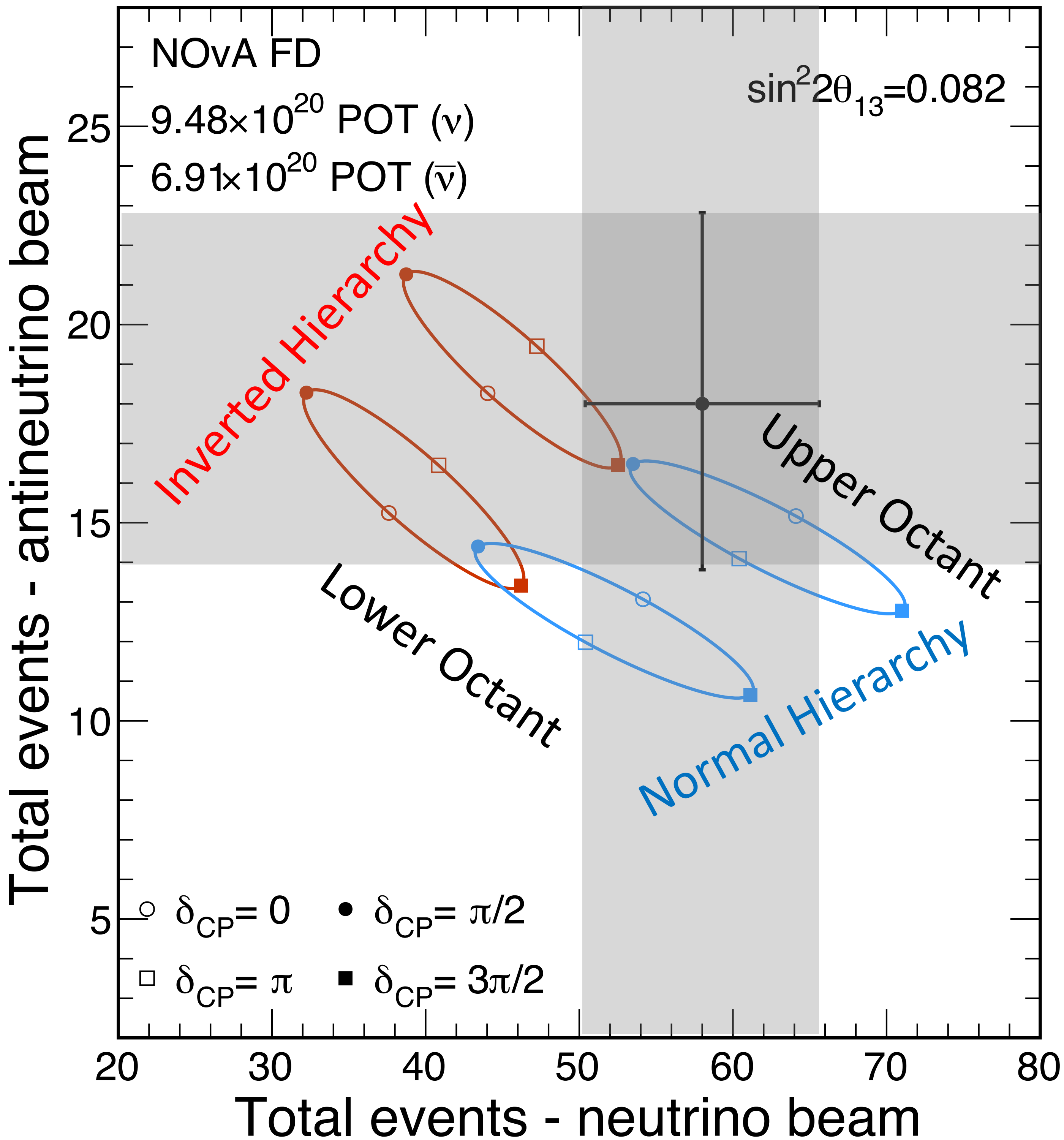
Total Observed	**58**	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

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 $\overline{\nu}_e$ Data at the Far Detector

18 observed $\overline{\nu}_e$

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



58 observed ν_e

30-75 Expected for ν_e