The NOνA Simulation Chain

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for the NOνA Collaboration

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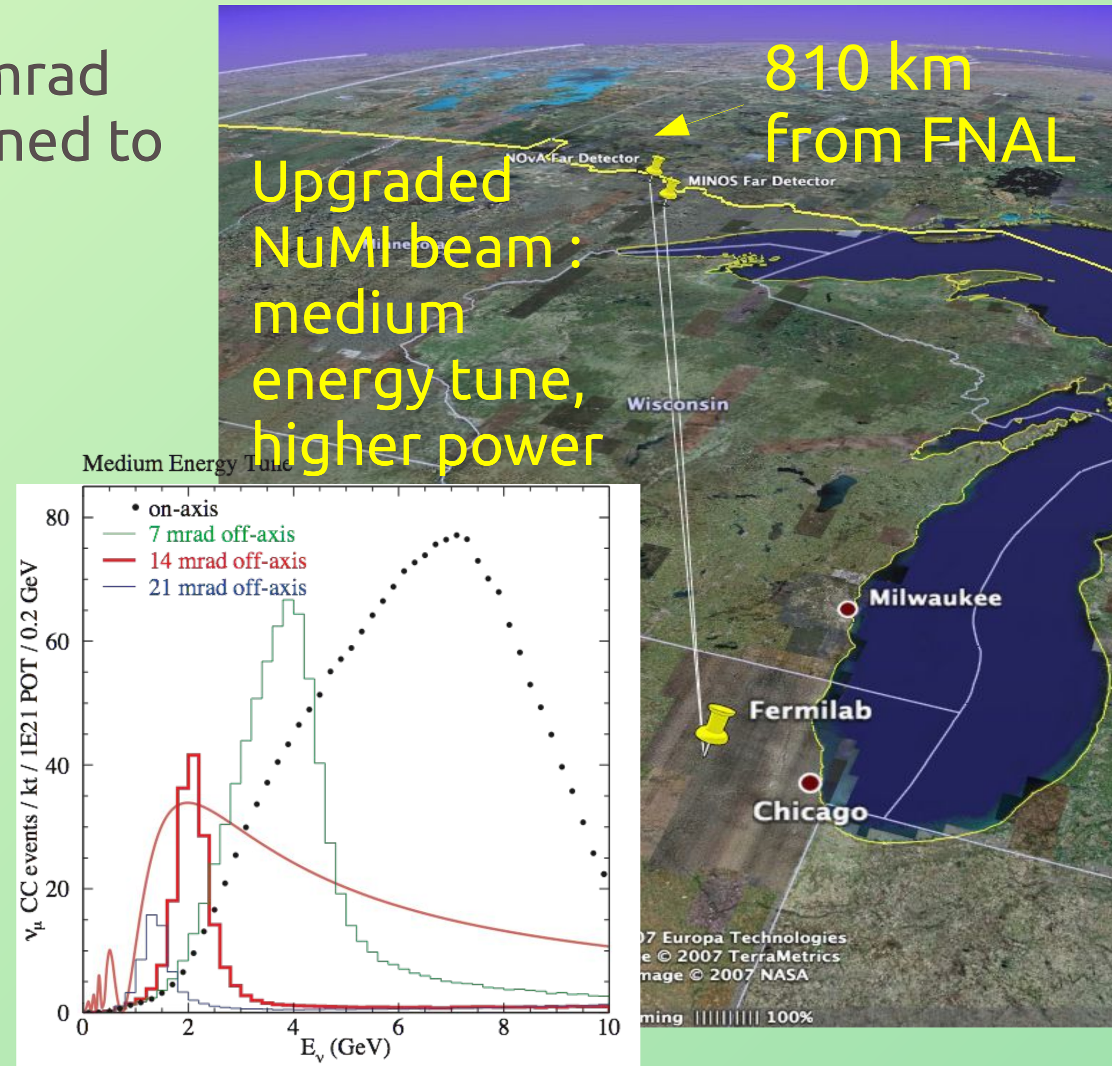
NuMI Off-Axis ν_e Appearance Experiment

NOνA is a long-baseline neutrino oscillation experiment located 14 mrad off-axis from the NuMI beam designed to measure:

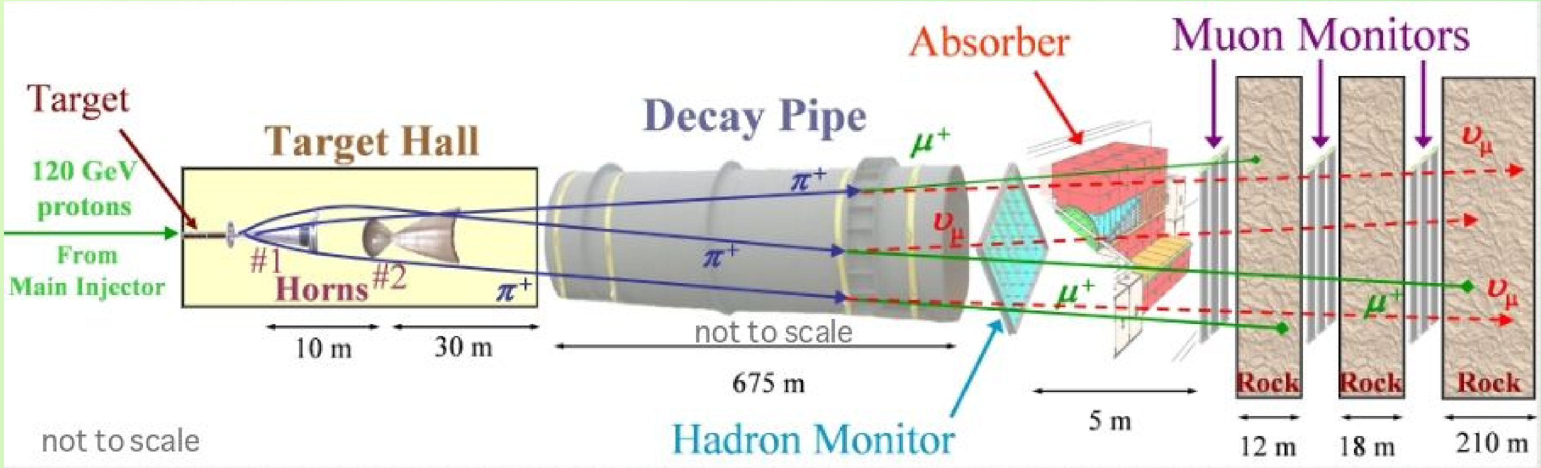
ν_e appearance
- θ_{13}
- Mass hierarchy
- θ_{23} octant
- CP violation

ν_μ disappearance
- Improved precision on $|\Delta m^2_{32}|$ and θ_{23}

Others
- Cross-sections
- Steriles
- Supernovae
- Exotics



NuMI

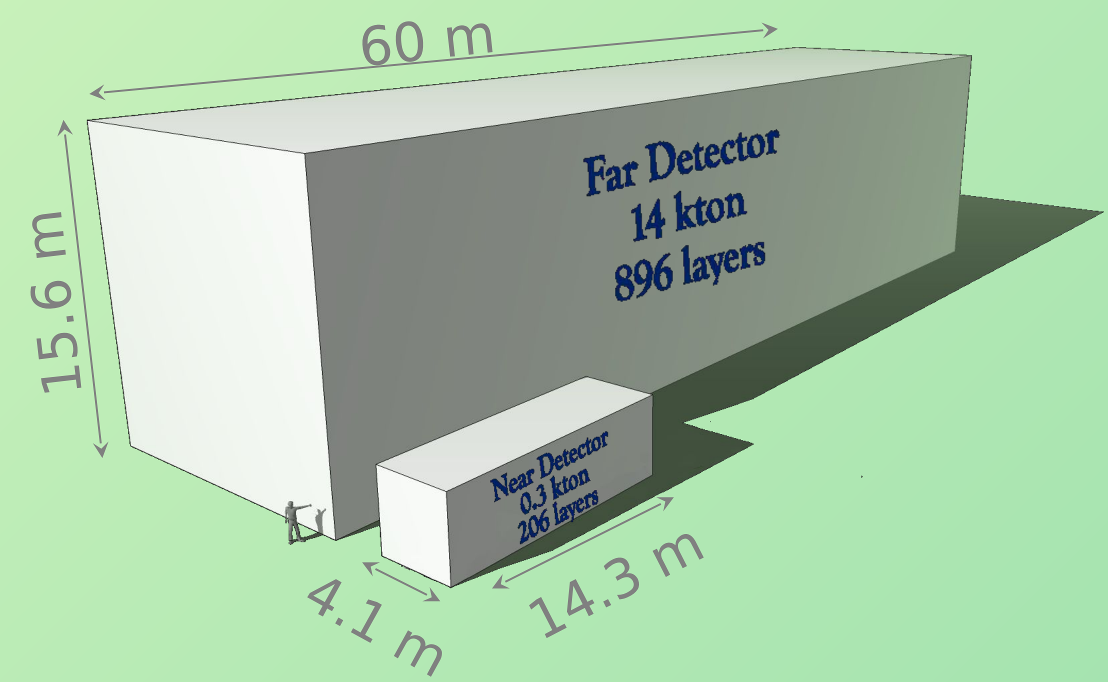


- Protons from the Main Injector at 120 GeV strike a graphite target.
- The resulting debris is focused by two magnetic horns.
- The particles travel down a decay pipe. At the end, only muons and neutrinos are left, and the muons are absorbed by rock.
  - The neutrinos are almost entirely muon neutrinos.

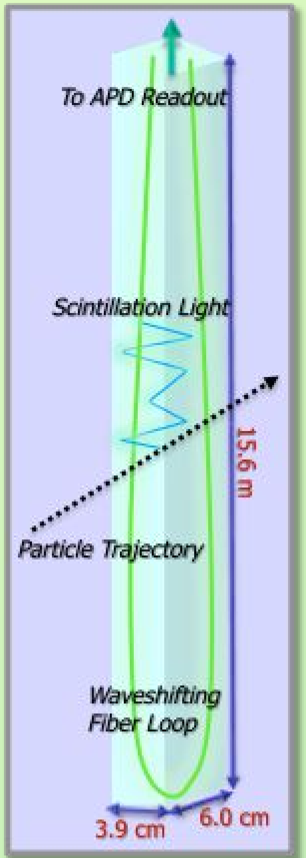
NOνA Design

Far detector:
- 14 kton, low Z tracking calorimeter
- Liquid scintillator filled PVC cells
- ~344,000 channels

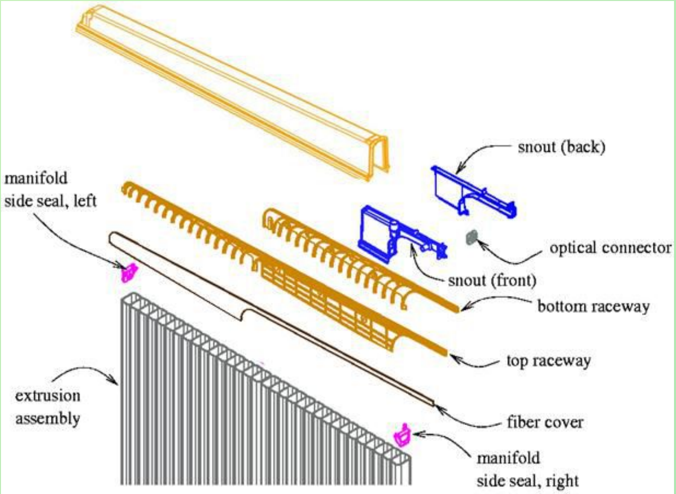
Near detector:
- 0.3 kton
- Functionally equivalent to FD
- 4x faster electronics to handle high rate environment
- ~20,000 channels



Readout Cell



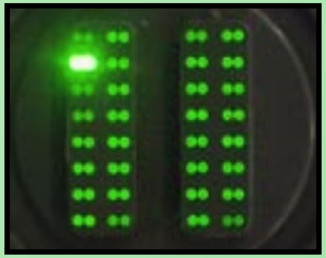
- 16 m x 4 cm x 6 cm PVC cells with 15% TiO_2 for high reflectivity
- Filled with liquid scintillator
- Light transported out by a wavelength shifting fiber loop
- 32 cells in a module read out by a single avalanche photodiode (APD)
  - APD's have high quantum efficiency (~85%) with good uniformity over the WLS fiber spectrum
  - Cooled to -15 °C to reduce dark current to ~2 pe equivalents
  - MIPs produce >30 pe at far end giving better than 10:1 signal to noise ratio

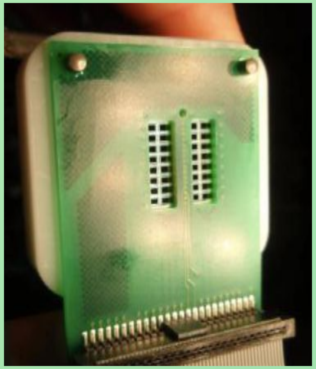


Front end board

32 pixel APD

32 fiber pairs





Simulation Chain

Beam simulation
→ FLUKA/FLUGG

Simulates the incoming neutrino flavor and energy spectrum from π, K, and μ decays

Neutrino interactions
→ GENIE

Cosmic rays
→ CRY

Produces particle lists and kinematics to be propagated through the detector

Detector simulation
→ GEANT4

Propagates particles through the detector and produces energy deposits in active material

Parametrized front-end simulation

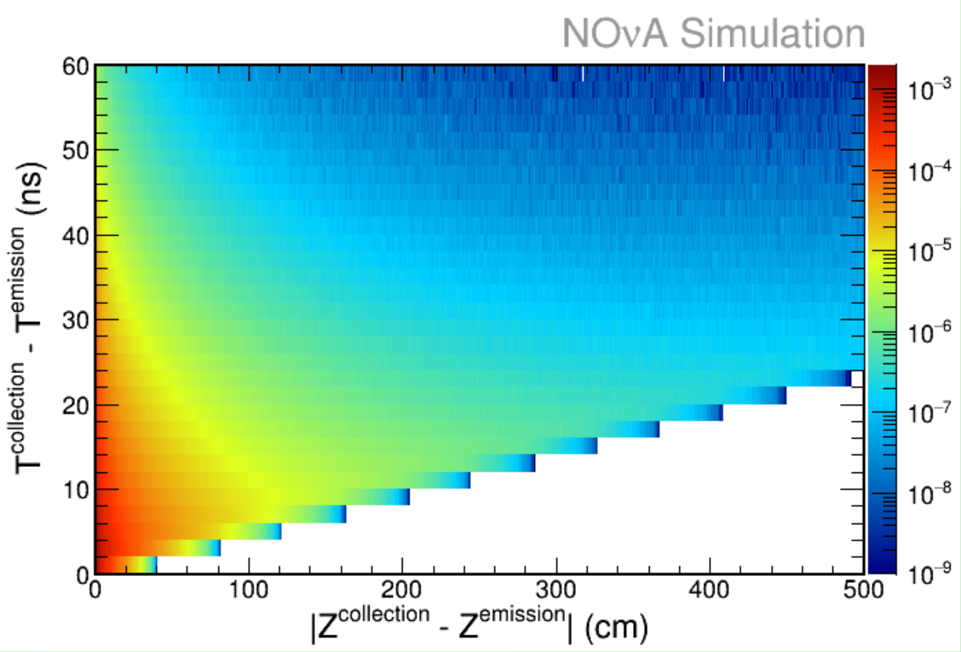
Converts energy deposits into scintillation light, transports scintillation light to the APD, and simulates the readout response.
→ output looks like raw data

Beam Simulation

- To predict the flavor and energy spectrum of the initial beam, we need to simulate:
  - hadron production inside the target
  - downstream tertiary production
  - focusing in the horns
- We use FLUKA/FLUGG to produce flux files as input to the rest of the simulation
- Factorizing the beam simulation:
  - minimizes the number of times this computationally intensive step needs to be run
  - allows for after the fact tuning of hadron production or focusing parameters

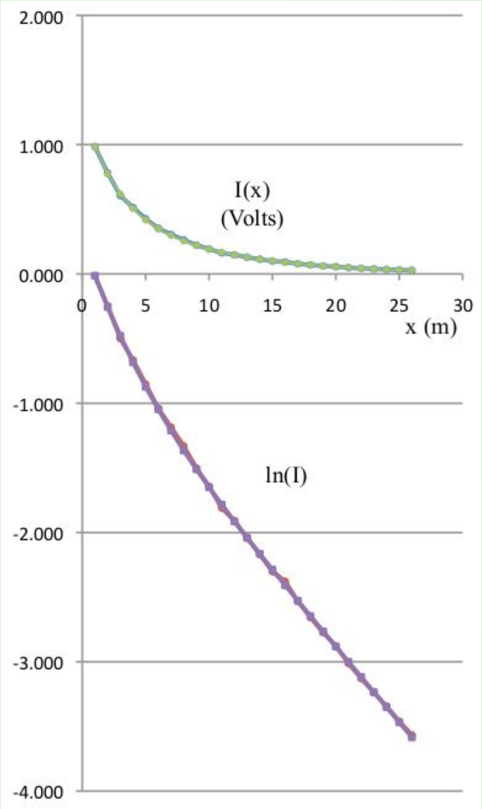
Photon Collection

- The detectors are composed of identical elements repeated many times.
- If we understand how scintillation light is collected by the fibers once, we can apply it everywhere.
- Use a ray tracing simulation to estimate the photon collection rate as a function of distance and time from the scintillation event using the measured properties of the liquid scintillator and the PVC walls.



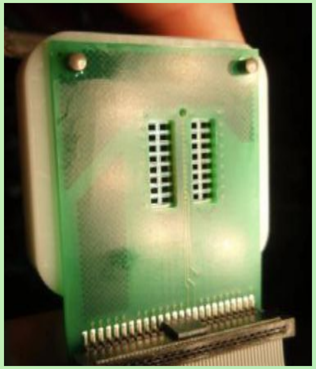
Photon Transport

- Shift the simulated collection rate vs distance from the scintillation event template to where GEANT4 says it happened.
  - Any portion of the template falling outside of the cell is lost light (the bottom and top of the cell are not reflective).
- Use the attenuation curve measured during WLS fiber quality control to transport the captured light to the APD.
- After accounting for the quantum efficiency of the APD, we now have the mean number of photons absorbed by the APD.

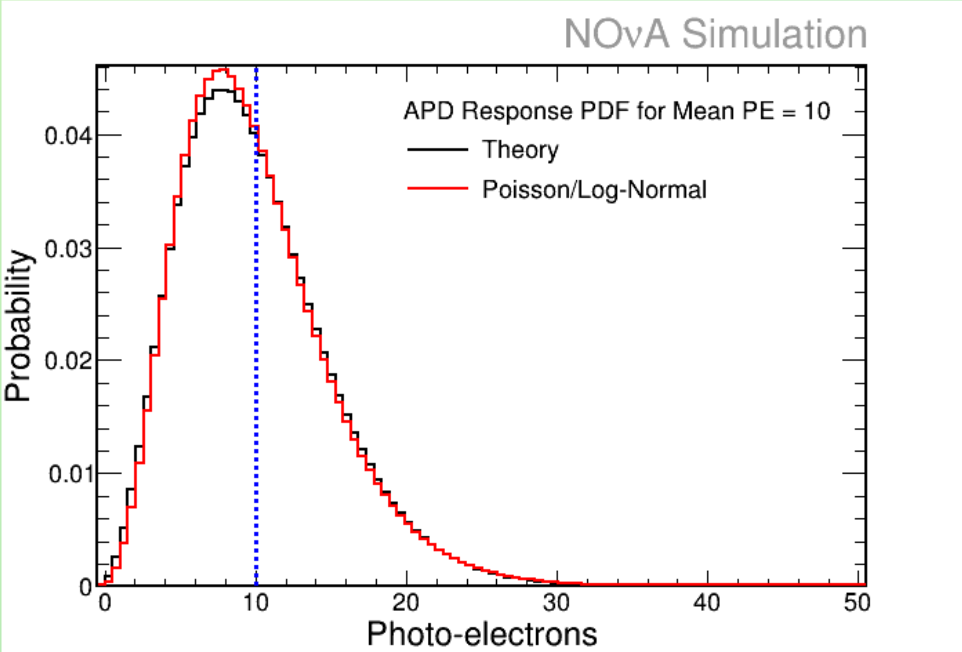


Intensity vs. distance from the APD in WLS fiber quality control tests

APD Response



- In addition to the Poisson variation induced by the number of photo-electrons captured by the APD, APDs have an excess noise factor (F) that expands the variance of the detected signal
- The PDF of the response has been calculated[1], but it is difficult to draw from.
- Try convoluting the Poisson sampled number of photon-electrons with a log-normal distribution with mean = 1 and variance = (F-1)/nPE.

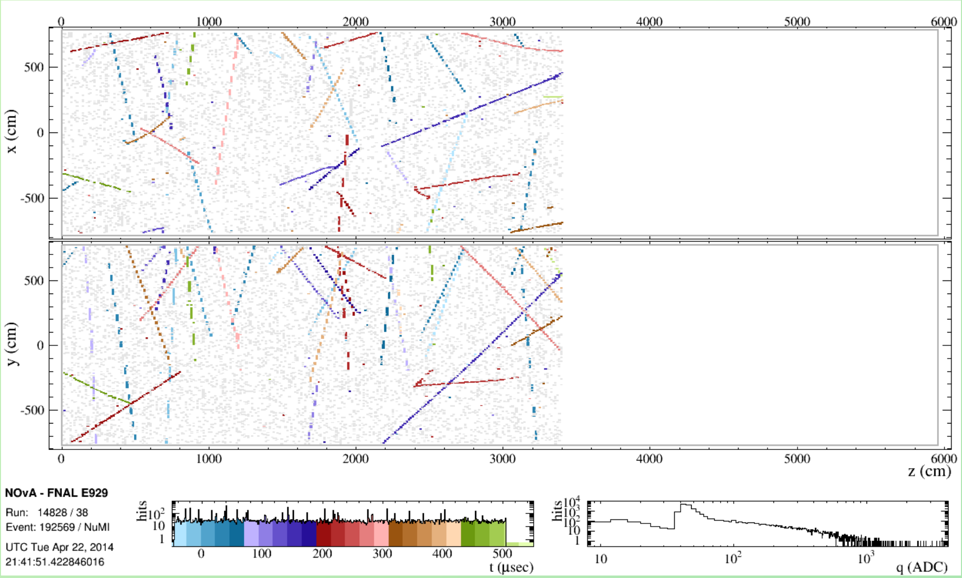


This modified PDF is easy to draw from and matches the theory distribution well.

[1] B. Balaban et al, “Probability Distribution of Gains in Avalanche Photodiodes”, IEEE Trans. Electron Devices, Vol 23, pp. 1189-1190, Oct. 1976

Noise

- Electronics noise is modeled by a the sum of two Gaussian Markov chains representing current and voltage noise sources.
  - Free parameters include the leakage current and the voltage noise density. These are set for each detector by fitting samples taken in pedestal scans.

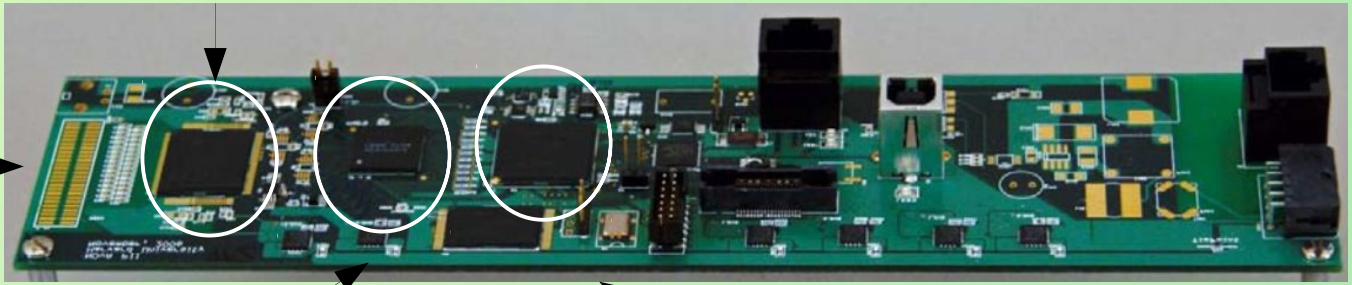


A 550 µs far detector event. All hits uncorrelated in space and time are shown in gray. To save time, hits in this “noise slice” are used to add noise to cells with no physics hits.

Digitization

ASIC:
Shape photo-electrons using CR-RC shaping parameters measured on a test stand. Add in a baseline sampled from the distribution seen in pedestal scans. Also add noise in here.

APD signal in

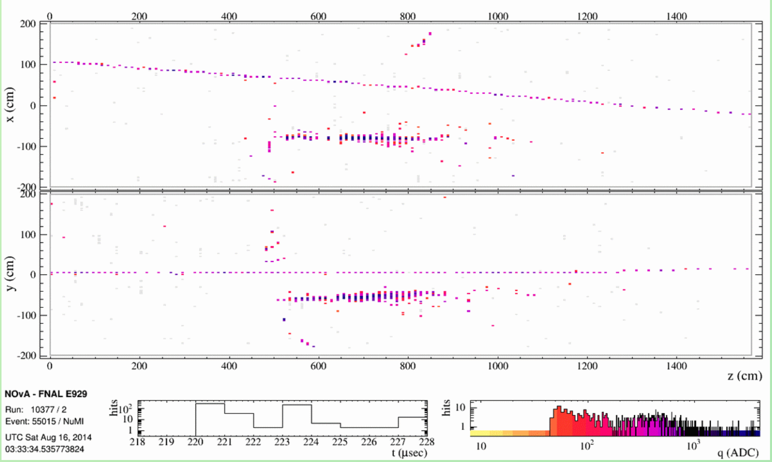


ADC:
Scale to ADC and truncate to integers

FPGA:
Emulate real-time zero suppression. Look for peaks above threshold in dcs[i] = sample[i] - sample[i-3]

Overlays

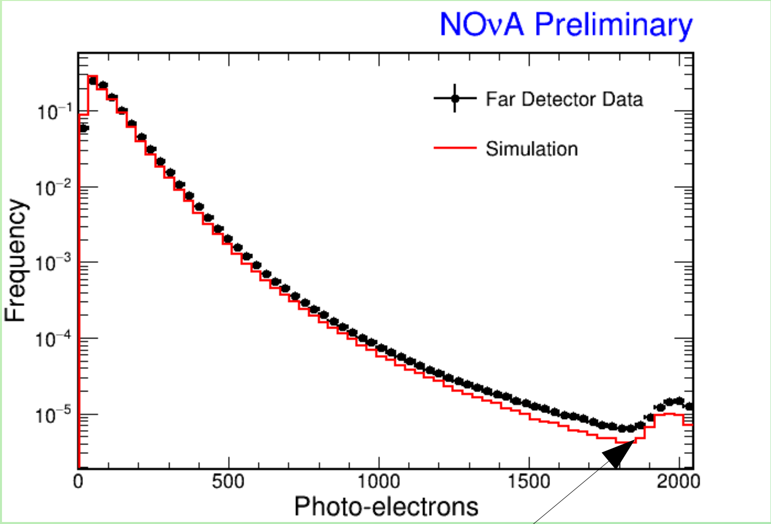
- Due to the high intensity at the near detector, many neutrinos interact in the rock in front of the detector.
  - Simulating these interactions requires allowing GEANT4 to propagate muons through a very large rock volume – and only a few of these muons will make it into our detector.
- Simulate many interactions with the mother volume including a large rock volume in front of the detector, and only keep those that leave energy in the detector.
- During normal simulation, with the mother volume only including the detector and the immediate detector hall, draw from these rock 'singles' at a rate matching the number of rock events expected per POT.

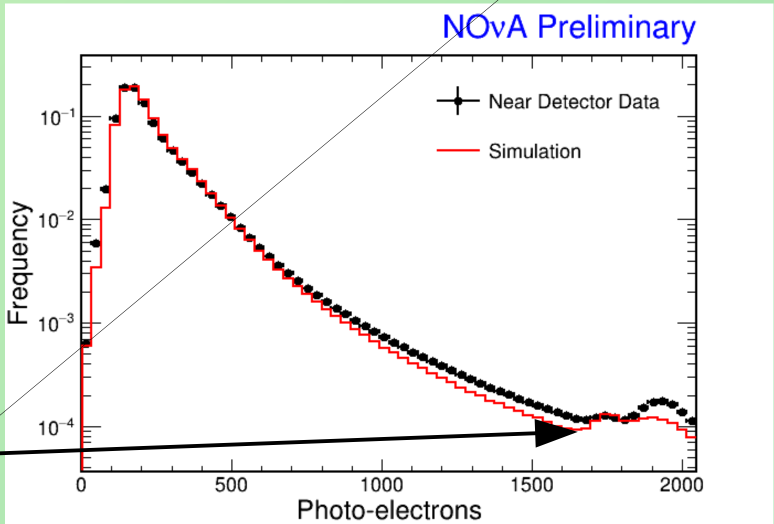


A potential ν_e event seen at the near detector. A rock muon is clearly visible.

Data/MC Comparisons

- The photo-electron spectrum in data and Monte Carlo for cosmic rays agree well.
- No calibrations were used
  - Only light level tuning in the photon transport stage and noise tuning to pedestal scans
- Smearing of saturated hits due to baseline variation is modeled well by distributions taken from pedestal scans.





Conclusions

- Simulation at NOνA is a multi-stage process.
- The modeling of the collection and transport of scintillation light, the response of the APD, and the front-end boards is done by custom, parametrized modules.
- Preliminary results show that low level quantities in cosmic ray data and Monte Carlo match well.

Thank you!