Cosmic Ray Induced High Energy Extensive Air Showers: Exploring Exotics with NOνA

Mehreen Sultana
Department of Physics and Astronomy, University of Georgia.
(Fermilab SIST)

Dr.Martin Frank
University of Virginia
(NOνA Collaboration)
(Dated: August 12, 2014)

Although NOνA's primary experimental goal is to study neutrinos, there are other physics that it can be used for. One such example is to use the NOνA detectors to study cosmic ray induced high energy extensive air showers. While most of the electromagnetic radiation is absorbed or scattered in the atmosphere and the matter above the detector (overburden), muons are easily detected in the NOνA surface detectors, Far Detector (FD) and Near Detector On Surface (NDOS). Multiple parallel long tracks in a single event are characteristic of these muon showers. Thus, this project investigates methods to first identifying and then analyzing these events. By applying cuts to the parameters available from the raw data file, bad and uninteresting events are filtered out to obtain a sample of data primarily composed of muon shower events. Hough Transform and Kalman Track reconstruction methods are used to reconstruct the geometry of these tracks to obtain information regarding multiplicity and directionality of each track. The reconstructed objects provide access to angular distribution of each tracks. Although the final goal of retracing the primary cosmic ray could not be attained given the limited scope of time, the results portray the potential of the NOνA detectors and the possible evolution of this project.

I. INTRODUCTION

The NOνA (NuMI Off-Axis Electron-Neutrino (ν_e) Appearance) experiment's primary goal is to understand neutrinos. However, the large detectors provide the potential of observing other phenomenon outside of the primary physics goal. Cosmic ray induced high energy extensive air showers are one such phenomenon easily observed through the NOνA detectors. Can these detectors be used to extract any useful information about these showers? Can the primary cosmic ray be traced back to a position in the sky depending on the time and day of the event recorded in the detector? This project investigates such questions, presenting results obtained over the summer and possible future extensions of this project.

A. Background

Cosmic Rays are highly energetic charged particles and nuclei from some extraterrestrial source. When cosmic rays collide with matter in the atmosphere, it induces a cascade of collisions that shower down on earth. The term "primary" refers to the particles and nuclei that are accelerated at astrophysical sources and have life time of at least 10^6 years. The term "secondary" is used to refer to particles produced from those first interactions of the primaries with interstellar gas or atmospheric matter (in the context of this investigation). Cosmic rays at the surface level are detected through the products of atmospheric collisions: muons, electromagnetic radiation, and protons. At sea level, muons are the most numerous. These are produced at about 10-20 km high in the atmosphere depending on the energy of the primary. Typical altitude of muon production is about 15 km. Muons are minimum ionizing particles that deposit the same amount of energy per unit of matter traversed, i.e. g cm^{-2}. As a result, they travel through a lot of matter without much deflection. These airshower muons are seen as long seemingly parallel tracks in the NOνA detectors and can be observed the moment they happen.

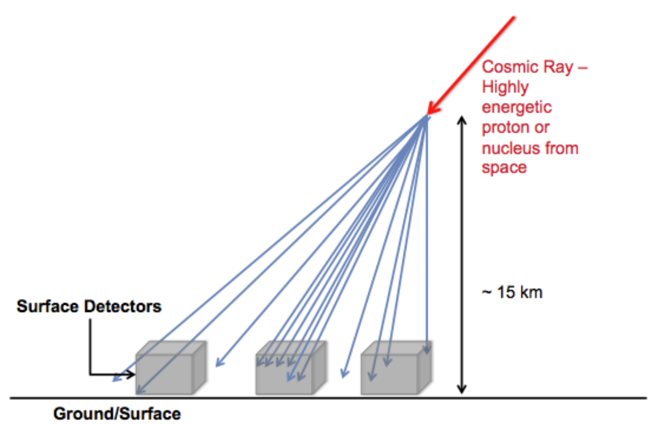

FIG. 1. A simple conceptualization of an cosmic ray collision and the resulting muon tracks

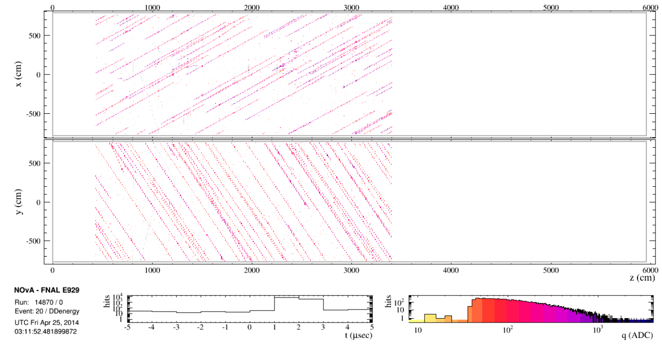

FIG. 2. An example of an ideal muon air shower seen through the NOνA Far Detector (FD)

Fig. 1 displays a simplified schematic of an air shower and the muons tracks that would be detected by surface detectors. Fig. 2 displays an actual air shower event recorded by FD on April 25th, 2014. NOνA surface detectors, FD and NDOS, can provide visuals of the event the moment it happens. Simply from looking at the Event Display[1] it is apparent that the parameters that can easily be extracted are the multiplicity of the tracks and the directionality relative to the axis[2]. Given just the raw data, tracking modules, Hough Transform and Kalman Track (Merge), were used to reconstruct the tracks to access multiplicity and directionality relative to an axis for the tracks in each event.

1. *Hough Transform*

The Hough Transform is a tracking method that parametrizes a set of points (x_i, y_i, z_i), $i = 1, ..., N$ in the image space (x-y-z plane) and produces a new space based on the parametrized variables. For example lines are often written, in x-y Cartensian coordinates, in the form of

$$y_i = mx_i + b \tag{1}$$

where m is the slope and b is the intercept. Eq. 1 can also be written as $b = -x_i m + y_i$. Where the latter equation is transforming the line into a parameter space. Now, given two lines in the parameter space,

$$b = -x_i m + y_i \tag{2}$$

$$b = -x_j m + y_j \tag{3}$$

the point of intersection for these two lines is given by

$$m = \frac{y_j - y_i}{x_j - x_i} \tag{4}$$

$$b = \frac{y_i x_j - x_i y_j}{x_j - x_i} \tag{5}$$

Points on the same line would have the same slope m and intercept b. While points that are parallel would have the same slope m but not the same intercept b. If lines are collinear, they would correspond to the peaks of a local minmum or a maximum in the parameter space.

The Hough Transform used to reconstruct the tracks parametrizes lines into a polar coordinate space.

$$\rho = x_i cos\theta + y_i sin\theta \tag{6}$$

where ρ is the perpendicular distance from the origin to the line and θ is the angle between ρ and the x-axis in this case (but could be defined for any particular axis depending on what's needed to be calculated).

The Hough Transform module used to reconstruct the tracks in this project takes the positions of individual cells in XZ and YZ views individually and plots out these lines by mapping out the Hough spaces for the tracks in each view separately. Again individual tracks would correspond to peaks in the Hough Space. The reconstructed line is projected beyond the recorded cell hits, independent of start and end position.

2. *Kalman Track (Merge)*

Kalman Track is a tracking method that looks at a point or a cell hit and pairs it with subsequent points around it within a radius to create a "seed." As it moves down the subsequent points and their subsequent surrounding points within proximity of each seed, it performs a regression test. Any lines created that deviate too far, increase the χ_2 value and are discarded if the value doesn't fall within a predefined threshold. Kalman Track Merge takes the 2-D constructed lines in XZ and YZ views and matches them according to their Z coordinates to create 3-D Tracks. Thus it reconstructs well matched tracks in both XZ and YZ views. The reconstructed lines are dependant on the start and end cell hits of each track. However, since this algorithm loops over individual hits multiples times to create these lines, it is time and computational resource intensive for events with large number of cell hits and/or tracks.

II. EXPERIMENT AND RESULTS

The events are recorded live based on a high energy data-driven trigger (DDT). For these particular events, the trigger records events with Total ADC value of $>$ 40,000 ADC (Analog-Digital (Converter) Counts) for NDOS and $>$ 275,000 ADC for FD. ADC is a value related to the energy deposited within a cell by the particles, but a measurement of energy itself. After visually and manually scanning the data files, it was found that the air shower events happen relatively sparsely over a large span of events. In order to easily filter out electronics noise events and other uninteresting events and obtain a smaller sample of events containing the ideal showers, a Z Extent cut was applied to the data. As seen in Fig. 2, these air shower events would have tracks that would essentially pass through the length of the whole detector depending on the angle of their trajectory. The event itself would contain tracks recorded over a large z span of the detector. The following plots are of events recorded by NDOS since they are recorded over a smaller scope, contain less hits, and are faster to process.

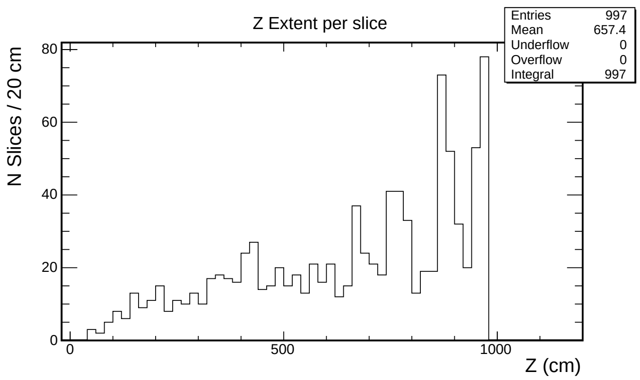

FIG. 3. Distribution of Z extent (z_{max} - z_{min}) per slice of 1000 NDOS events (including the ideal muon shower events). A slice is defined as a cluster of cell hits associated by time, position, and energy.

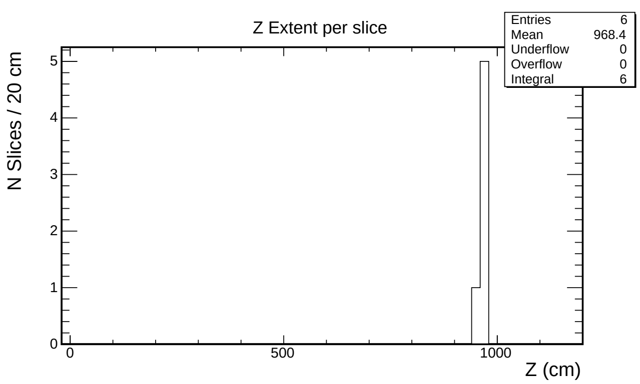

FIG. 4. Distribution of Z extent (z_{max} - z_{min}) per slice of 1000 NDOS ideal muon shower event. A slice is defined as a cluster of cell hits associated by time, position, and energy.

It is apparent from Fig. 3 and Fig. 4 that this simple cut can easily remove most of the unwanted events. However the value of the cut or the z extent is dependant on which part of the detector is taking data and which detector is being looked at.

A sample of golden events obtained were then analyzed through the aforementioned reconstruction modules, Hough Transform and Kalman Track (Merge). Fig.

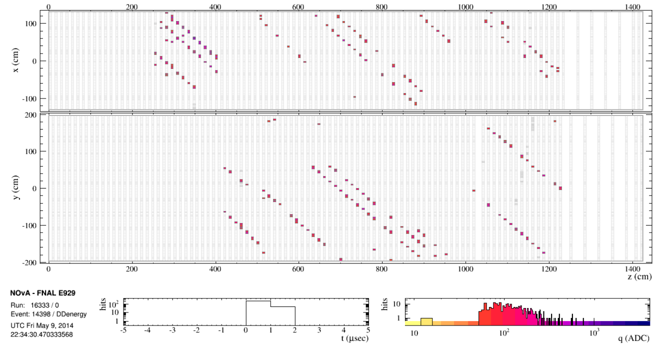

FIG. 5. Ideal muon shower event recorded in NDOS. Note the parallel tracks.

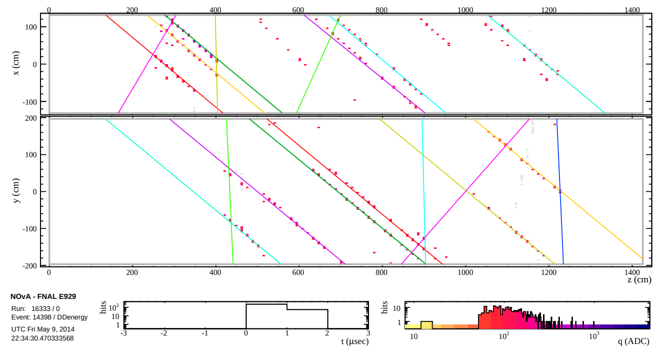

FIG. 6. Ideal muon shower event recorded in NDOS with reconstructed tracks from Hough Transform. Note that the tracks are projected beyond the recorded cell hits.

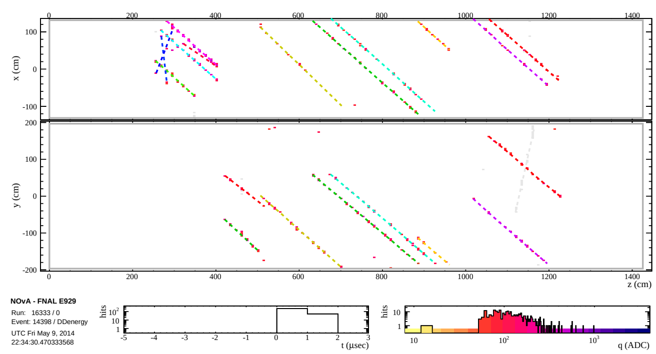

FIG. 7. Ideal muon shower event recorded in NDOS with reconstructed tracks from Kalman Track. Note that the tracks are projected beyond the recorded cell hits.

5 shows a raw display of an ideal muon shower event recorded in NDOS. With the Hough Transform applied, reconstructed tracks are displayed in Fig. 6. The random lines crossing the parallel tracks are due the defined parameters in the code that allow for certain points to be associated with a ”false” track. This can also be seen in the Kalman Track (Merge) reconstruction in Fig. 7.

Fig. 8 shows a low multiplicity muon shower event (compared to the high multiplicity event in Fig. 2)

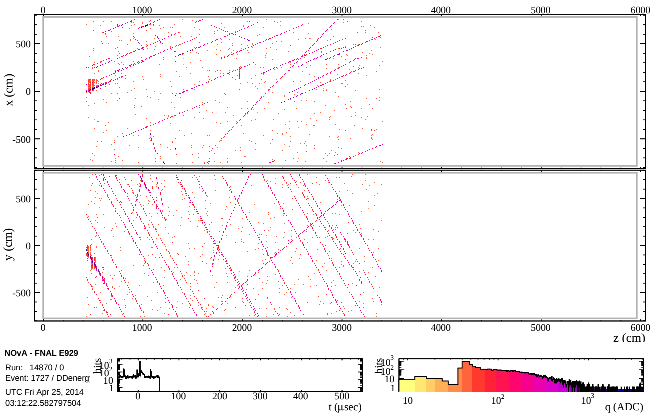

FIG. 8. Muon tracks from an air shower recorded in Far Detector (FD). Notice the range of the axes and the larger number of tracks and hits recorded within the event.

recorded in the Far Detector. Events with relatively low number of parallel muon tracks are easier to analysis and run reconstruction modules over as they use less time and computational resources. Fig. 9 shows the Hough Transform reconstructed tracks for the same event. Notice how efficient the module is in tracking every single track in the event. However, it does not match. The coloring is arbitrarily assigned by the module.

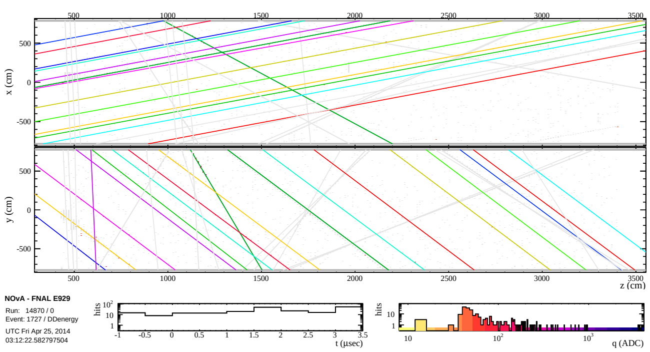

FIG. 9. Muon tracks from an air shower recorded in Far Detector (FD) reconstructed by Kalman Track

Fig. 10 displays the reconstructed Kalman Tracks. The greyed out tracks in both events are noisy (or uninteresting) slices and hits that were filtered out by applying a time cut to the event. Note in the time distribution at the bottom left of the plots that the muon shower events peak over about 2 seconds since the moment the event was triggered (0 μs). This is another characteristic of these muon tracks. They travel at nearly the speed of light and peak over a range of $2\mu s$ since the moment the event was triggered.

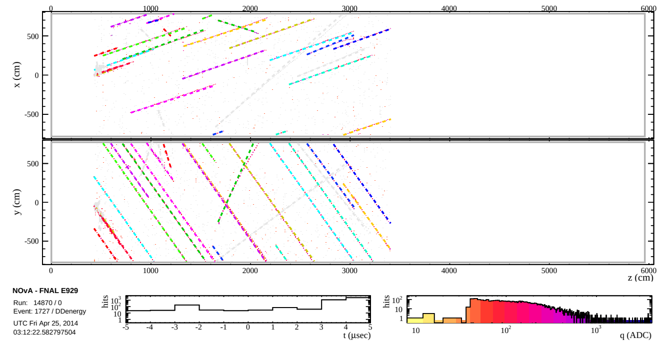

FIG. 10. Muon tracks from an air shower recorded in Far Detector (FD) reconstructed by Kalman Track

A. Angular Distrubution

From the tracks reconstructed by Kalman Track (Merge), angular distribution of the plots relative the y-axis can be extracted. Fig. 11 displays the angle of interest and a single muon track's conceptualization through the detector.

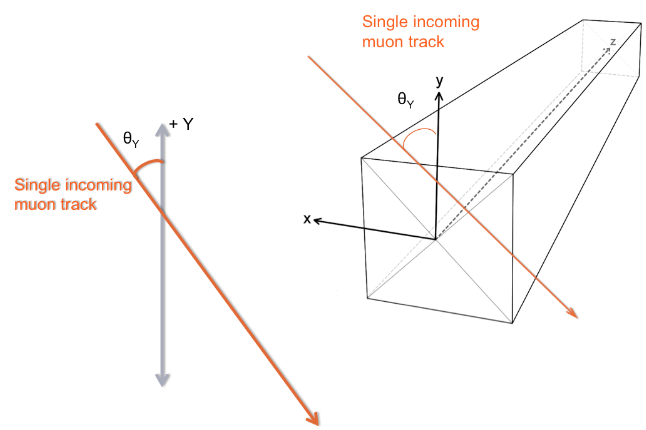

FIG. 11. Simplified conceptualization of a single cosmic ray moving through the detector.

The angular distribution of the tracks in Fig. 10 are plotted out in Fig. 12 and 13. Fig. 13 is the re-binned plot, zoomed at the location of peak of 18 tracks. The peak at 30^o can be checked visually in the event display. Fig. 14 shows the y-axis drawn over the track and a visual confirmation of the angle calculated.

III. DISCUSSION

The angular distribution in Fig. 13 is only first step in trying to reconstruct as much information as possible

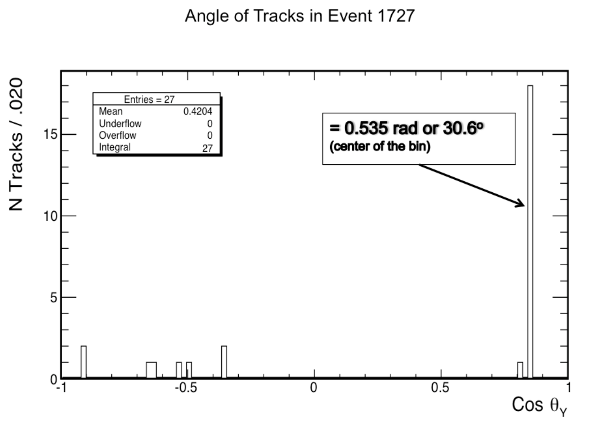

FIG. 12. Cosθ distribution of the tracks relative to the y-axis. Notice the peak of 18 tracks at the bin center of 30.6 degrees. This correlates with the number of seemingly parallel tracks seen in Fig. 10.

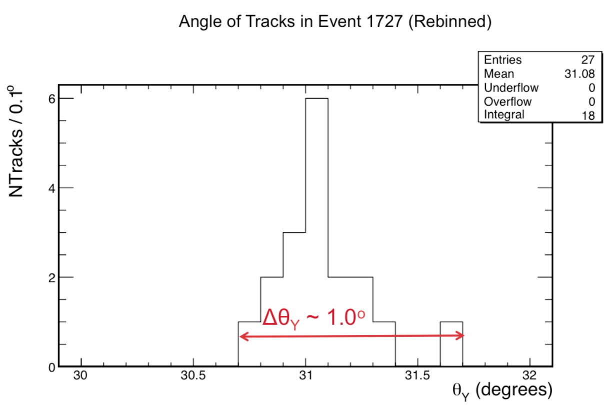

FIG. 13. Cosθ distribution of the tracks relative to the y-axis. Rebinned and zoomed in at the location of the 18 track peak seen in Fig. 12.

from the given raw data. The next steps would have involved obtaining the RMS values of each parallel track peak and plotting them against histograms. However, with the limited amount of time that is 12 weeks, it not likely to be completed by this author due to amount of time it takes to process a single Far Detector event. A further extension of the project would involve calculation of the statistical error in the directionality of the tracks and estimating their trajectory relative to the stars instead of a local axis. A proposal would be to set up smaller surface detectors around the Far Detector to obtain information on the spread of the showers. With enough statistics, it may be possible to pin point the source of the cosmic ray to some point in the sky.

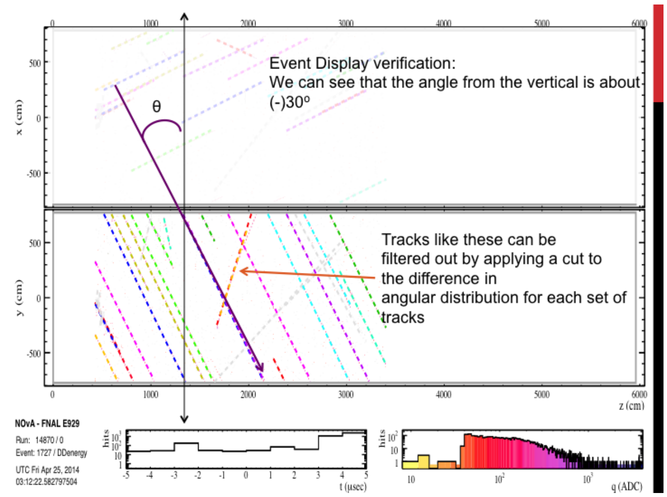

FIG. 14. Trajectory angle "loosely" drawn to visually relate θ_y to the event display. Notice that θ_y is approximately a third of the second quadrant from the y-axis.

IV. APPENDIX A: NOνA DETECTOR SET UP

In order to understand event displays, it is necessary to understand how the NOνA detector is set up. A conceptualization of the detectors is shown in Fig. 15. The image at the top right shows how individual modules are set up within the detector. These modules consist of $4cmx6cm$ cells extruded along the height and width of the detector alternatively. Each cell is filled with scintillating oil, wave-shifting die, and an optical fiber loop where the ends connect to a single pixel on an APD (Avalanche Photo Diode). When a particle deposits energy in one of these cells, it is called a "cell hit." The APDs pick up the electromagnetic signal and the subsequently connected Front End Boards (FEBs) convert it to a digital signal, ADC (Analog-Digital Converter) count. The data is then recorded in terms of ADC counts in cells as the particle interacts with the scintillating oil and travels through the detector. The Event Displays show the location of these hits in XZ and YZ views separately. They also present a time and ADC distribution of the number of hits and ADC counts.

V. REFERENCES

1. J. Beringer *et al.* (Particle Data Group), Phys. Rev. D86, 010001 (2012) and 2013 partial update for the 2014 edition.

2. Rao, M. V. S, Sreekantan, B. V. (1998). Extensive air showers. Singapore: World Scientific.

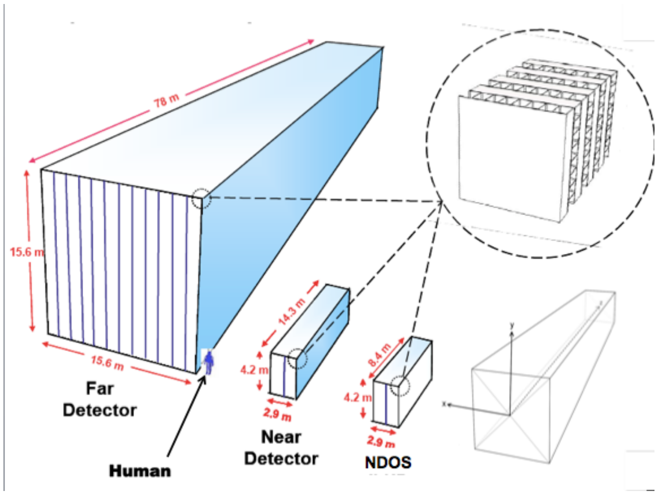

FIG. 15. Comparison of Far Detector (FD), Near Detector (ND), and Near Detector on Surface (NDOS). The bottom left figure portrays the orientation of the axes relative to each of the detectors.

---

[1] The module that is used to present the visualization of the NOνA data.

[2] See Appendix A for a brief description of the detector set up and the axes.