The NOvA Neutrino Calorimeter

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Abstract. The NOvA experiment is a long baseline neutrino detector designed to 1) observe oscillations of muon neutrinos to electron neutrinos, 2) determine the ordering of the neutrino mass states, and 3) observe CP violation in neutrinos if it exists. To accomplish this, the NOvA detector is a unique low-Z, high sampling fraction calorimeter capable of precise measurements of the particles produced in a neutrino interaction while also being able to reject particles from background cosmic rays. Some experience has already been obtained with the operation of a prototype near detector on the Fermilab site, and construction of the far detector is just beginning in northern Minnesota. The calorimetric properties of the NOvA detector will be described with emphasis on relevance to the overall experimental goals.

1. The NOvA Long Baseline Neutrino Experiment
The NOvA Collaboration is composed of over 150 Physicists representing more than 26 institutions from 5 countries. It will consist of a Near Detector (ND) on the Fermilab campus and a Far Detector (FD) ~800 km from Fermilab in northern Minnesota. The detectors are situated 14 Mr off-axis of the NUMI neutrino beam which results in a narrow neutrino energy distribution of ~2 GeV on average.

The primary goal of NOvA is to measure the probability of neutrino oscillations from the $\nu_\mu$s produced in the NUMI beam to $\nu_\tau$s detected in the FD. This will allow NOvA to measure the mixing angle $\theta_{13}$, to determine the neutrino mass hierarchy, to study the phase parameter for CP violation in the lepton sector, and to determine the $\theta_{23}$ octant. With $\nu_\tau$s, NOvA can make precision measurements of the parameters $\theta_{23}$ and $\Delta m_{32}^2$. Other topics are searching for sterile neutrinos, measurement of neutrino neutral current cross sections at 2 GeV, and detection of neutrinos from a galactic supernova.

2. Neutrino Oscillation Physics at NOvA
Recent results from reactor neutrino experiments have shown that the mixing angle $\theta_{13}$ is non-zero and large – the world average of all measurements is now $\sin^2(2\theta_{13}) = 0.092 \pm 0.012$ [1]. The $\nu_\mu \rightarrow \nu_\tau$ oscillation probability is therefore large enough for NOvA to be sensitive to the neutrino mass hierarchy in a comparison of the oscillation probabilities of neutrinos and anti-neutrinos. Figure 1 shows possible NOvA measurements of P(anti-$\nu_e$) vs. P($\nu_e$).
Figure 1. (left) Possible NOvA measurements of oscillation probabilities for all $\delta_{CP}$ and both mass hierarchies, and (right) 1- and 2$\sigma$ contours for a measurement example if $\delta_{CP}=3\pi/2$.

The ellipses represent measurements at all possible values of the CP violation parameter $\delta_{CP}$ for each of the mass hierarchies, normal ($\Delta m^2>0$) and inverted ($\Delta m^2<0$). For a possible CP parameter $\delta_{CP}=3\pi/2$, the starred point with 1- and 2$\sigma$ contours represents a NOvA measurement example with 3 years each of $\nu$ and anti-$\nu$ running. At (and near) the example measured point, the inverted mass hierarchy is excluded at $>2\sigma$. Figure 2 shows the significance of mass hierarchy resolution for all possible measurements of both hierarchy possibilities.

Figure 2. Significance of mass hierarchy resolution for both possibilities and for all $\delta_{CP}$.

Since the ellipses overlap, there are 2 points for each hierarchy where there is no hierarchy resolution significance. If, however, NOvA and T2K [2] (shorter baseline than NOvA) results are eventually combined, the difference in sensitivities of the 2 experiments resolves the ambiguity seen in the NOvA-only plot where the normal and inverted hierarchy ellipses overlap. A combined measurement would then result in at least 0.5$\sigma$ sensitivity for both hierarchies over the full range of $\delta_{CP}$.
NOvA can also resolve the current ambiguity in the value of $\theta_{23}$ – whether that mixing angle is less than or greater than 45 degrees. This determines whether the third neutrino mass state, $\nu_3$, is comprised mostly of $\nu_\mu$ or $\nu_\tau$.

3. The NOvA Detectors
The NOvA detectors are made from extruded PVC with cell sizes of 4 cm × 6 cm × 15.6 m long in the FD and × 3.9 m long in the ND. There are 16 cells in each PVC extrusion, 2 of which are glued together to form a 32-cell wide module. Each cell contains a looped WLS fiber, is filled with liquid scintillator, and is read out by an Avalanche Photodiode (APD). Figure 3 shows modules being stacked at the module factory (Univ. of Minn.).

Figure 3. Stack of NOvA modules ready for shipment to the FD.

The WLS fibers are routed through a manifold attached to one end of the module, ending at a connector for the APD. Each layer of the FD has 384 cells in 12 modules, while a ND layer consists of 96 cells in 3 modules. The full 14 kTon FD has 928 layers of PVC cells in alternating vertical and horizontal orientations per layer. The ND is 192 layers of alternating vertical and horizontal cell layers with the addition of a muon catcher block with steel absorber plates between PVC layers at the downstream end. In all, the NOvA detectors are comprised of >370K PVC cells, ~12K 32-pixel APDs, >11 million meters of WLS fiber, and over 3 million gallons of liquid scintillator. When complete, the NOvA FD will be the largest plastic structure in the world.

4. The NOvA Calorimeter
The NOvA detectors are calorimeters designed to detect and identify neutrino interactions. Produced as $\nu_\mu$s in the NUMI beam at Fermilab, the neutrinos propagate towards the NOvA FD as a mixture of neutrino mass states. Due to differences in the propagation speed of the different mass states, the neutrino detected in the FD has a non-negligible probability to be in the $\nu_e$ flavor state – the phenomena known as neutrino oscillations. The length of the baseline – the distance from Fermilab to the NOvA FD site – was chosen such that the magnitude of the oscillation is near its maximum. The flavor of an interacting neutrino is identified by its final state configuration. Figure 4 shows simulated neutrino interaction signatures in the NOvA detector.
Figure 4. Neutrino interaction processes in the NOvA detectors; (top) a $\nu_e$ charged current event with long muon track and a recoil proton, (middle) a $\nu_e$ charged current event with a typical electron shower, and (bottom) a $\nu$ neutral current event with a $\pi^0$ in the final state.

To measure the $\nu_e \rightarrow \nu_\mu$ oscillation probability, identification of an electron in the final state of a neutrino interaction must be made. Backgrounds from $\nu_\mu$ CC events can be relatively easily identified by the presence of a muon in the final state as shown. A NC event containing a $\pi^0$ in which the 2 photons can not be resolved is a particularly difficult background to reject. The design of the NOvA experiment is optimized to detect and characterize electromagnetic showers, distinguishing photon showers (mainly from $\pi^0$s) from electron showers. The NOvA detectors are low Z sampling calorimeters with an active volume of $\sim$77% ($\sim$66% active mass). Some parameters of interest are the critical energy $E_C = 73$ MeV, the radiation length, $X_0 = 38$ g/cm$^2 \rightarrow 37.5$ cm along the axis of the detector, and the Moliere radius of $\sim$10 cm (2.5 cell widths). A single NOvA layer is 6.63 cm thick so electromagnetic showers are sampled at $\sim$0.18 $X_0$ per layer. Due to the relatively high $E_C$ of 73 MeV (compared to $\sim$10 MeV for the ZEUS U/Scintillator calorimeter), electromagnetic showers are short in $X_0$, being almost entirely contained in 10 $X_0$ as opposed to $\sim$25 $X_0$ for ZEUS. However, in spatial dimensions, these showers are $\sim$4 m long in NOvA compared to $\sim$20 cm for ZEUS. Therefore, the high sampling rate per $X_0$ and the large spatial extent of electromagnetic showers will help in distinguishing electrons from photons and $\pi^0$s.

The longitudinal and transverse shower shapes of electromagnetic showers can be calculated using parameters of the detection medium. This is possible since the energy deposits in an electromagnetic shower are highly correlated with each other. The longitudinal profile of electron showers for energies of interest is calculated and shown in Figure 5.
Figure 5. Longitudinal profile plots of electron showers in NOvA for (top row) calculation using detector parameters (lines) compared to simulated data (points), and (bottom row) fits of the longitudinal profile function (lines) compared to the simulated data (points).

At all electron energies, the parameters of the calculation (shown on the top row plots) are very similar to the parameters obtained from fits to the simulated data (shown on the bottom row plots). While the “b” parameter was chosen to be a constant in the calculations (an approximation), in the fits it exhibits a variation with energy which is expected.

Transverse shower distributions can also be calculated – one model being a double Gaussian formula. Figure 6 shows a double gaussian fit to the simulated data and the combined shower shape distribution using both longitudinal and transverse fits.

Figure 6. (left) Transverse profile fit (line) to simulated data shown on linear and log scale with cell boundaries overlaid(dashed lines), and (right) the combined transverse and longitudinal electron shower distribution.

The relative fractions of the narrow and wide Gaussians were allowed to float in the fit and the result yielded ~94% in the narrow term. The full longitudinal extent of the shower is contained in ~10 $X_0$, or ~4 m in the NOvA detector while near longitudinal shower max, ~7 cells contain the shower in the transverse dimension (full width of ~28 cm).
5. Summary
The NOvA detectors are unique low-Z calorimeters optimized for:

1) detection of neutrino oscillations in the NUMI beam at a long baseline $\rightarrow$ 14kTon Far Detector.
2) identification of the detected neutrino flavor by reconstructing final state particles including electromagnetic showers from electrons $\rightarrow$ highly segmented and granular calorimeter with high sampling fraction.

With the recent reactor results indicating a relatively large value for the mixing parameter $\theta_{13}$, NOvA will contribute to understanding of mixing in the lepton sector – in particular towards resolving the hierarchy of neutrino mass states, further constraining the flavor content of the $\nu_3$ mass state, and determining if CP violation in the lepton sector occurs.

References
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