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Using Simulations to Make A Sensitivity Projection of the Electroweak Mixing Angle Measurement in a DUNE Near Detector Environment

Abstract: In the last twenty five years, neutrino experiments have produced conflicting measurements on the electroweak mixing angle. New experiments like the Deep Underground Neutrino Experiment (DUNE) are being proposed that, while designed to be a general purpose neutrino experiment, should allow for an improvement of the measurement. A new charge pixel (QPix) upgrade is being proposed to improve on the performance of DUNE Phase I while also solving some expected complications with the original design. With this improvement, DUNE is in a unique position to weigh in on a widely discussed conflict in measurements of the weak mixing angle ($\sin^2\theta_W$). By simulating neutrino interactions in a hypothetical detector similar to the DUNE Near Detector, this thesis project predicts DUNE will be able to measure $\sin^2\theta_W$ to an uncertainty of XXX after taking YYY years of data. Since this project focuses on phenomenology, it lays the groundwork for a real measurement in the future using a QPix-equipped DUNE ND.

Talk Summary

Background

Neutrinos and the electroweak force

Wolfgang Pauli originally postulated the existence of a new neutral particle that was very light compared to masses of the other particles to explain why neutron decays seemed to violate both energy and momentum conservation and dubbed it the neutrino - meaning little neutral one. We now know the neutrino is the most common particle in the universe. Neutrinos are fundamental particles classified as fermions (having a ½ integer spin), and leptons (not experiencing the strong force), pairing up with the other leptons to make three generations: electron and electron neutrino, muon and muon neutrino, and tau and tau neutrino. Since their discovery, neutrinos have been determined to be massive (but just barely), neutrally charged, colorless, and to travel at slightly under the speed of light. As such, neutrinos primarily interact via the weak nuclear force, as described in electroweak theory.

Electroweak theory describes the unified version of two of the four forces in nature. It combines the nature and behavior of electrically charged particles from electromagnetism with the mass transferring properties of particle decays via the weak force. The electroweak force is propagated by $W^{\pm}$ and Z^0 bosons and transfers mass to and from particles in an interaction and could transfer charge. If an interaction involves the transfer of charge via a $W^{\pm}$ boson (see Figure 1), the interaction is considered a charge current (CC) interaction. Similarly, if no charge is transferred because the propagator was a Z^0 boson (thought of as a heavy photon), the interaction is deemed a neutral current (NC) interaction (See Figure 2).

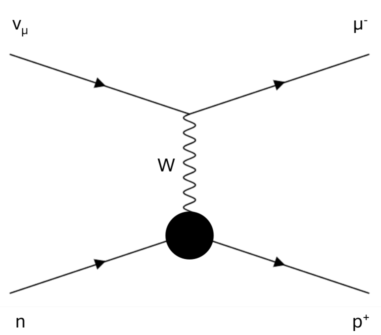

Figure 1: Feynman diagram showing a charge current electroweak interaction propagated by a $W^{\pm}$ boson

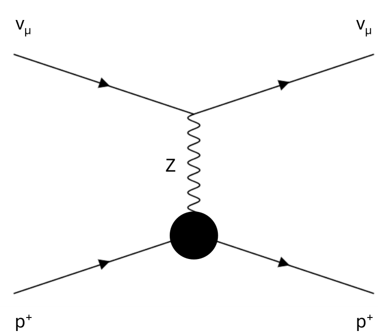

Figure 2: Feynman diagram showing a neutral current electroweak interaction propagated by a Z^0 boson

In any situation where a neutrino interacts with an atom, typically the nucleus, there is a chance that the interaction could proceed as a CC interaction or as a NC interaction. This probability is dictated by a fundamental value in the Standard Model of Particle Physics (SM) called the weak mixing angle. This value in the SM accounts for all known physics that involves the electroweak force. Any deviations from this value in experiment could suggest new physics that is not currently included in the SM.

Deep Underground Neutrino Experiment (DUNE)

The flagship neutrino experiment in the United States is called the Deep Underground Neutrino Experiment (or DUNE for short). It is located in the Long Baseline Neutrino Facility and, as shown in Figure 3, consists of the brightest neutrino beam in the world (PIP-II at FermiLab) and two detectors: a modular liquid argon time projection chamber (LArTPC) detector right at the source (DUNE Near Detector, or DUNE ND for short), and a four-story building sized LArTPC detector 800 miles away and almost a mile underground (DUNE Far Detector, or DUNE FD for short) in South Dakota.

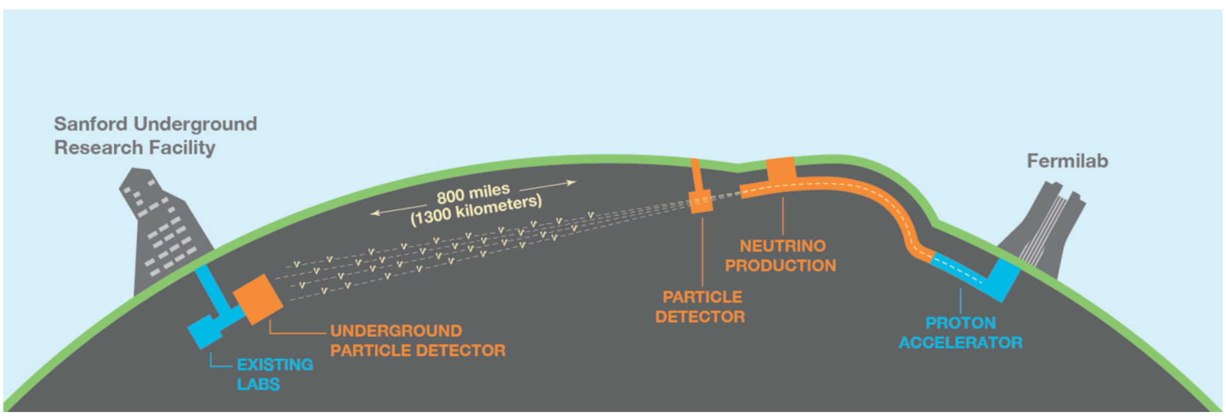

Figure 3: A cartoon of Deep Underground Neutrino Experiment (DUNE). FermiLab (on right) produces the PIP-II beam which serves as the neutrino source for the experiment. In the middle is DUNE Near Detector (DUNE ND), which is a high resolution, modular detector including a liquid argon time projection chamber (LArTPC). Finally on the right, located underground at Sanford Underground Research Facility (SURF) in South Dakota, is DUNE Far Detector (DUNE FD) which is a four-story building size 40kton LArTPC detector.

DUNE is set up to take two types of data. The first is beam data where the detectors try to catch neutrinos produced from the PIP-II beam and record the particle interactions that occur. The second is astronomical data. While serving as parts of complete experiments, DUNE and other neutrino detectors around the world are constantly able to measure neutrinos coming in from space.

LArTPCs are built as tanks of liquid argon in a constant electric field with a detector at one end (see Figure 4). The liquid argon acts as a target for incoming neutrinos. Once the neutrino interacts, the final state particles travel through the liquid argon depositing energy via scintillation (outside the scope of this project) and ionization. The free electrons then drift in the electric field in the direction of the detector wall. The location and time of the arrival of these electrons allows the detector to produce three dimensional reconstructions of the particle event in the detector.

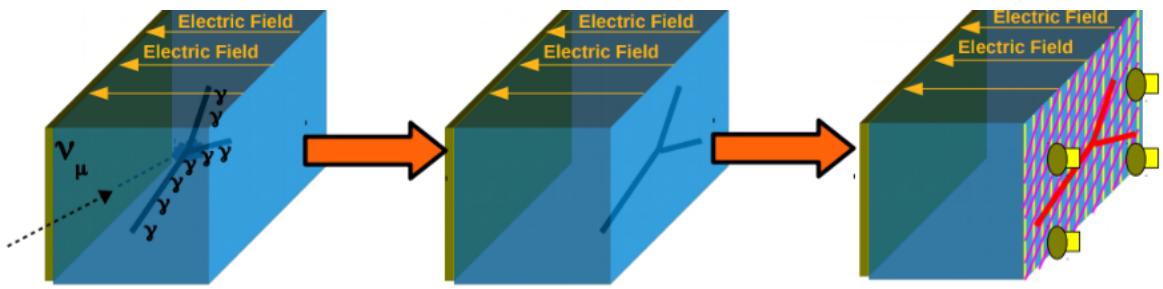

Figure 4: A cartoon of a LArTPC and what happens inside. From the left, a neutrino enters the detector and interacts with an argon atom, producing charged particles that deposit energy through scintillation and ionization along their trajectories. The freed electrons are caught in the electric field and drift towards the detector wall where they are collected by the detector technology (wire planes in DUNE Phase 1) and processed into data.

DUNE Phase 1 is expected to come online in the early 2030s.

Charge Pixel (QPix) Upgrades

The current plans for DUNE Phase 1 includes enormous wire plane detector readout electronics. Each section of the detector will have a frame that holds multiple planes of thousands of perpendicular wires. The full detector is planned to have approximately 1.5 million wires, each reading out with GPS precision (100MHz). At full operation, DUNE is expected to produce exabytes of data per year, most of it being useless and requiring computers (or grad students) to sort through.

The QPix consortium has proposed a charge pixel upgrade as shown in Figures 5 and 6 that is designed based on the principle of least action. These pixels will replace the wire plane readout electronics, and are designed to only report when there is something to report and do nothing in the interim. This drastically reduces the amount of data produced. Pixels are also inherently two dimensional (their position dictates an x and y position), which will improve the ability to record events with complex topologies. Charge collection data will only be time dependent which will allow for a calculation of the z position of the responsible energy deposit.

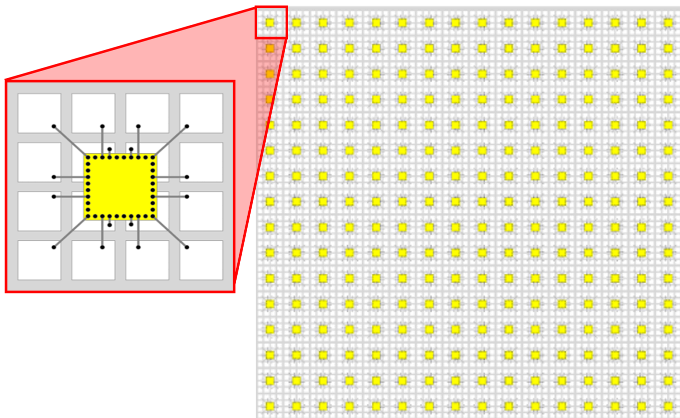

Figure 5: A cartoon of a charge pixel (QPix) assembly. Each white box, seen better in the close up view, is a pixel that collects charge. The back end electronics then connect these pixels together and process the data

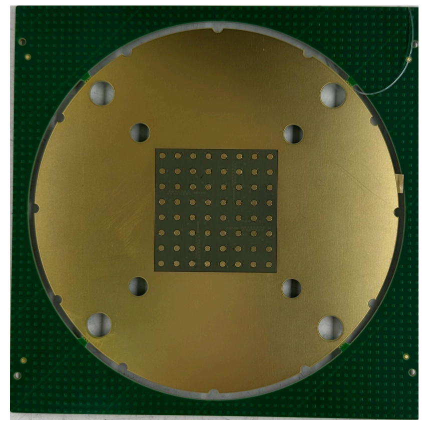

Figure 6: A real life photograph of QPix on a prototype board.

While a QPix is simply an exposed copper plate in a TPC where electric field lines terminate, the electronics behind the pixel integrate charge and send signals once a set charge threshold is reached and reset to start again. This technology allows for slower clocks as data of each individual electron is no longer needed and only the time of the reset.

The goal of the QPix collaboration is to show that QPix will solve the data and topology problems of DUNE Phase 1, while matching or exceeding the performance of the wire plane electronics.

Motivation

There have been many direct and indirect measurements of the weak mixing angle. As mentioned above, the value of the weak mixing angle in the SM takes into account all known physics and should be consistently measured within uncertainties, provided experiments are not measuring something unaccounted for in the SM.

Recently, there has been some controversy over the values of the weak mixing angle when comparing it to the expectations of the SM. Around 2002, the NuTeV experiment produced a measurement that was approximately three standard deviations higher than the SM predicted value (see Figure 7). At similar times, other experiments aligned more closely with theory. Again in 2022, CDF produced a measurement on the mass of the W boson (related to the weak mixing angle) that was 5 sigmas higher than the predicted value (see Figure 8), however other measurements yield values of m_W that agreed with the SM prediction.

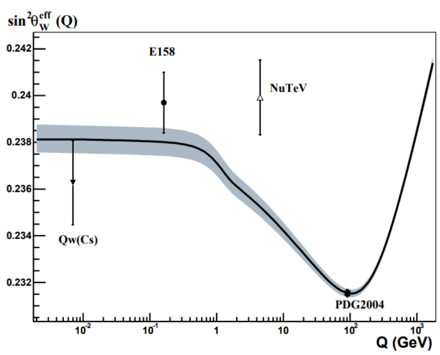

Figure 7: A plot showing experimental measurements of $\sin^2\theta_W$ and comparing them to the standard model (SM) predictions. Note NuTeV exceeds the SM predictions by almost 3 sigma.

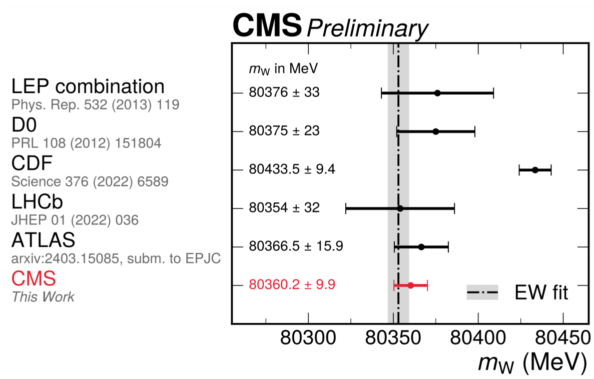

Figure 8: A chart showing experimental measurements of the mass of the W boson, which is related to $\sin^2\theta_W$. Note CDF produced results that exceeded the SM predictions by almost 5 sigma.

It is clear that the value of the weak mixing angle is still a subject for discussion. Are these experiments (NuTeV and CDF) measuring new physics beyond the scope of the SM, or is there something else causing these deviations? Having more data from bigger, more advanced experiments like DUNE will be welcome in the discussion.

Proposal

Since DUNE Phase 1 is not planned to come online until the early 2030s, and DUNE Phase 2 will be years after that, the nature of this project will be phenomenological.

The proposed plan for this project will be to understand and project how incorporating QPix into a DUNE-like detector can affect the sensitivity of a measurement of the weak mixing angle ($\sin^2\theta_W$). This will be done using a series of simulations being developed to simulate the neutrino beam (Genie event generator, hereinafter referred to as “Genie”), the detector response (QPix software packages qpixg4 and qpixrtd), and event reconstruction (qpixrec). Figure 9 shows each part of the experiment that will be simulated. This project will use the simulations to create samples and develop reconstruction techniques to determine the resolution of a QPix equipped detector.

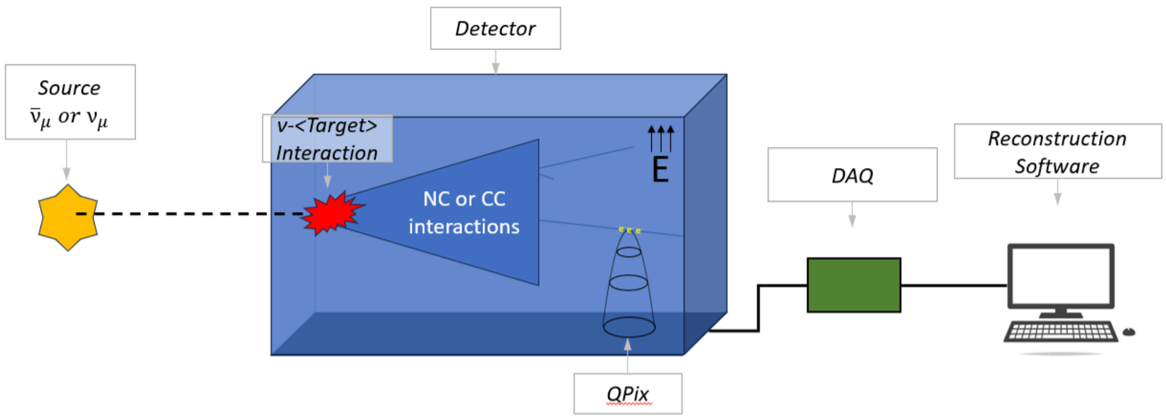

Figure 9: A cartoon showing each “step” in the simulation of particle events in a LArTPC detector. First a neutrino/particle source is simulated. The particles from the source are then simulated interacting with the target, which causes outgoing final state particles. The particles are simulated depositing energy along their trajectory in the form of ionization. The drift and diffusion of the electrons is simulated, as well as the detector response and data acquisition. Finally reconstruction software is developed to turn the data from the detector into a three dimensional model.

The conversion from spatial resolution to vertex resolution to selection efficiency is beyond the scope of this project as DUNE uses a separate study and machine learning to predict the selection efficiencies expected from DUNE Phase 1. An assumption will be made that equipping a detector with QPix instead of the wire plane technology will change the spatial resolution, in turn changing the vertex resolution, and finally changing the selection efficiency.

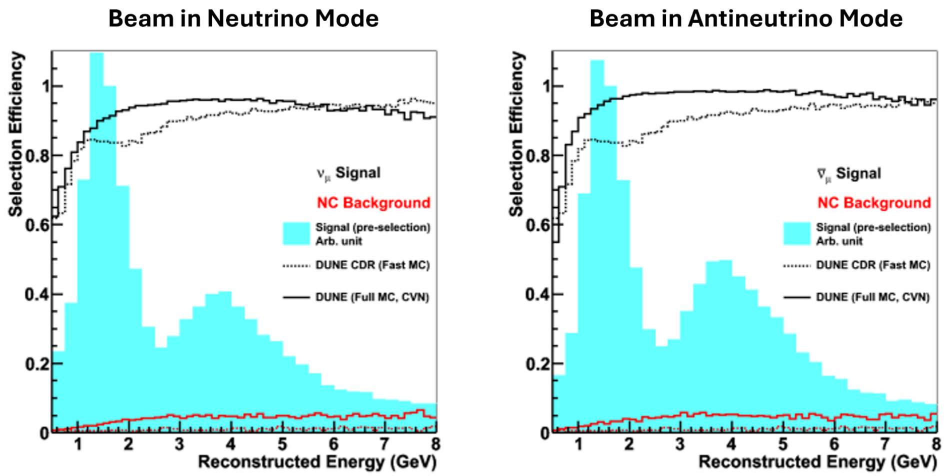

Figure 10: The projected DUNE selection efficiency. In other words, the probability of DUNE correctly selecting a CC event. These can be loosely estimated as 85% across the energy range.

To account for this unknown change in selection efficiency, this project will explore how changing the efficiency of the detector will affect the sensitivity of the $\sin^2\theta_W$ measurement. Multiple efficiencies will be chosen, more densely selected around the predicted 85% (see Figure 10), but spanning the range from 40-100%.

The second half of the project will follow the NuTeV experiment's use of the Paschos-Wolfenstein (PW) relation to use the ratio of neutral current to charge current experimental cross sections to calculate $\sin^2\theta_W$ and then project the dependance of the sensitivity of the measurement on the selection efficiency. Since the PW relation is meant for isoscalar targets, a correction factor will have to be added to correct for argon's non-isoscalar properties. Once a calculation of $\sin^2\theta_W$ has been made, propagation of uncertainties will be used to calculate the uncertainty of the $\sin^2\theta_W$ measurement.

In a measurement like this, statistical uncertainties are expected to dominate, so the systematic errors can be ignored. For each selection efficiency, the uncertainty of the measurement will be projected for varying numbers of neutrino events while holding the number of antineutrino events constant and vice versa. The number of events required to reach the sensitivity levels of the NuTeV experiment will be used to calculate the protons on target (PoT) and the years of data (YoD) required to achieve that sensitivity. The final goal of the project will be to record how the years of data changes with selection efficiency.

Current Status

A set of simulation packages (shown in Figure 11) have been developed that simulate the neutrino beam using Genie. The qpixg4 package uses Geant4 to take the simulated neutrino-nucleon event and simulate the outgoing final state particle tracks through the detector. The qpixrtd package converts the energy deposit data from qpixg4, converts it to electrons, and then uses monte carlo simulations to diffuse the electrons and drift them to the detector wall. It then assigns each electron to a pixel and records time of arrival and produces reset data.

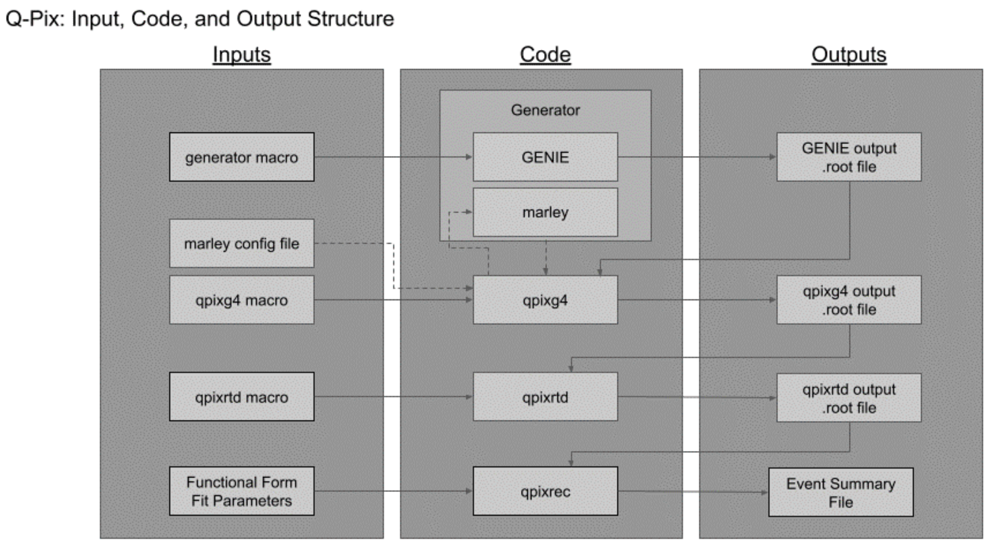

Figure 11: A flow chart showing the input, code, and output of the current QPix simulation packages.

In a separate effort, we have developed an event reconstruction algorithm using the distribution of resets and fitting them to a Gaussian distribution (see Figure 12). The mean and standard deviation of the fitted Gaussian distribution is used to calculate drift time (since diffusion is related to drift time) and comparing the drift time calculation with the mean (time of arrival), we can calculate the t_0 for the pixel. Using the t_0 calculations from all pixels and choosing the mean, this can be used as the t_0 for the event, and can then be used to reconstruct the entire event (see Figure 13). Since the drift velocity is constant and the relation between drift time and time of arrival is linear, the shape of the event (and therefore the physics) is preserved, and the variation in drift time only results in an overall translation in z of the event.

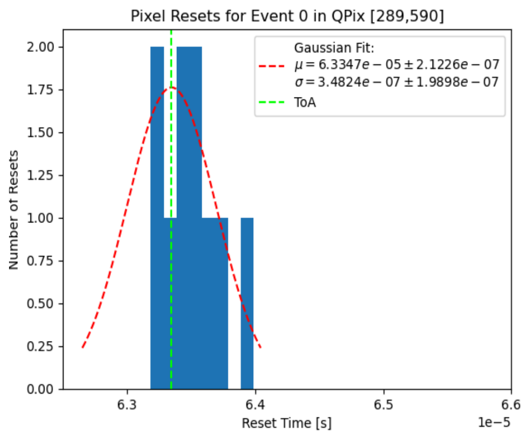

Figure 12: The reset distribution of one pixel during a single particle event. The distribution is fit to a Gaussian and a mean and rms are used for calculations of drift time and time of arrival

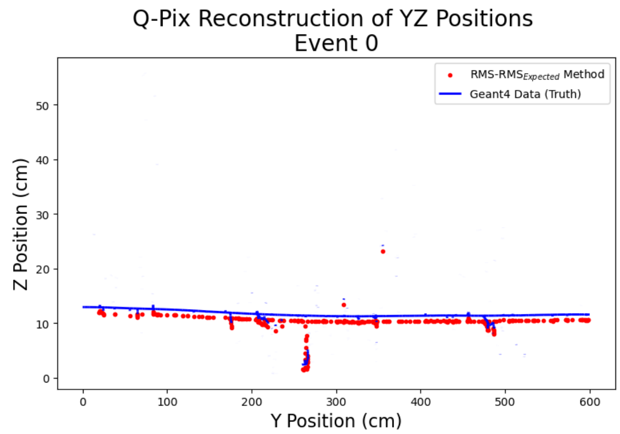

Figure 13: A quick reconstruction of a particle event in 2 dimensions. The red shows the original energy deposition data, while the blue shows the reconstructed particle trajectory.

These simulations have been run and analyzed for resolution using 100 events and a spatial resolution has been calculated. Multiple versions of the reconstruction software has since been developed, with the latest version having a z-dependent accuracy (shown in Figure 14) that asymptotes to 1.32cm at z=0cm and 26.25cm at z=180cm. The precision asymptotes to 0.17mm at z=0 and 0.50mm at z=180cm.

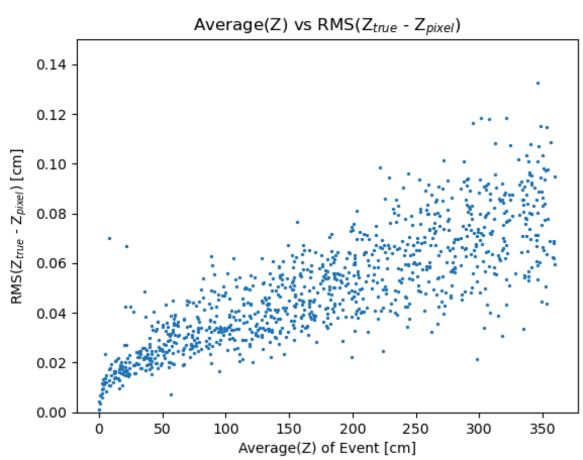

Figure 14: Plot showing the difference in reconstructed z values vs the average z of the event. The relation shows the accuracy and precision is z dependent.

With this data, we make the assumption that this QPix spatial resolution will be different from what is currently expected with DUNE's wire plane spatial resolution.

We have also started using the PW relation to calculate $\sin^2\theta_W$. The PW relation starts by relating the ratio of cross sections of NC interactions to CC interactions. In an experiment like the one we are simulating, since the CC and NC cross sections are being calculated from the same sample, this simply reduces to a ratio of the number of NC interactions to CC interactions.

$$R^{\nu(\bar{\nu})} \equiv \frac{\sigma(\overset{(-)}{\nu} N \to \overset{(-)}{\nu} X)}{\sigma(\overset{(-)}{\nu} N \to \ell^{-(+)} X)} = (g_L^2 + r^{(-1)} g_R^2)$$

This value still takes into account effects of the presence and involvement of heavy quarks in the target and results in large uncertainties. There is a secondary relationship that allows the uncertainties due to heavy quarks to negate each other and utilizes this first ratio

$$R^- = \frac{R^\nu - rR^{\bar{\nu}}}{1-r} = \frac{1}{2} - \sin^2\theta_W$$ where $$r \equiv \frac{\sigma(\bar{\nu}_\mu N \to \mu^+ X)}{\sigma(\nu_\mu N \to \mu^- X)} \sim \frac{1}{2}$$

The PW relation assumes the use of isoscalar targets, and not targets like liquid argon. We assume there will be a correction factor required and will estimate it from our results. Before simulating the full experiment, as a check to make sure we were on the right track, we tested the PW calculation of $\sin^2\theta_W$ in an isoscalar target like hydrogen-2 by changing Genie's target to hydrogen-2 and tracking how many of each type of interaction were simulated using a pure muon neutrino (antineutrino) beam. The measurement of $\sin^2\theta_W$ was plotted by simulating 10^7 neutrino events and varying the number of antineutrino events. The plot (see Figure 15) showed the measurement asymptoting to a value of 0.228 where the value of $\sin^2\theta_W$ hard coded in Genie is 0.231, suggesting that there is still a correction factor needed even in an isoscalar target.

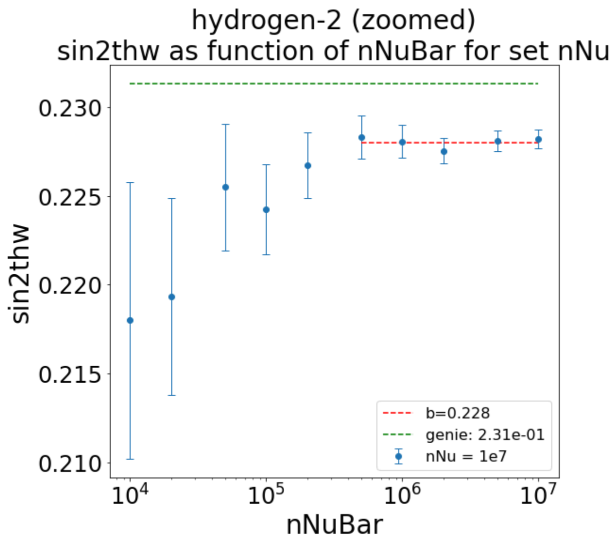

Figure 15: A plot of $\sin^2\theta_W$ as a function of the number of antineutrino events. The value asymptotes a little below the truth value used in the simulation (green dashed line), warranting a correction factor.

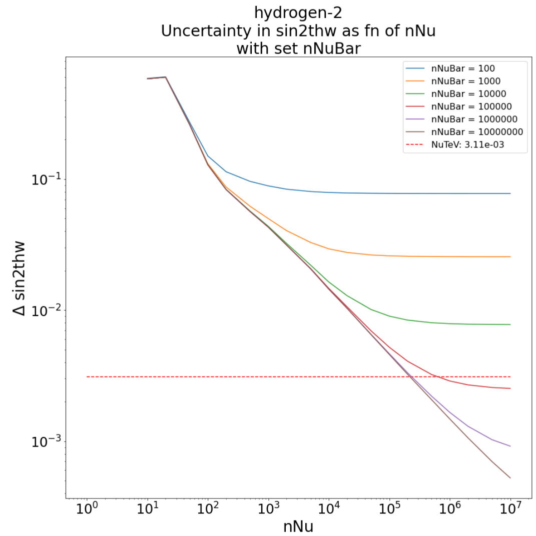

Figure 16: Plots of the uncertainty on $\sin^2\theta_W$ as functions of the number of neutrino events. Each plot represents a different number of antineutrino events. These plots are compared to the uncertainty in the NuTeV experiment (red dashed line)

The statistical uncertainty is shown using this same technique and it was qualitatively observed that for the number of antineutrino (neutrino) events held constant, the uncertainty as a function of the number of neutrino (antineutrino) events would decrease and then asymptote. We compared these plots to the uncertainty in the NuTeV measurements in the plot (see Figure 16).

Background will also be accounted for by simulating the real DUNE beam. Using the fluxes of the different neutrinos published by the DUNE collaboration (see Figure 17), we can create a profile of the background to be used in the uncertainty calculations.

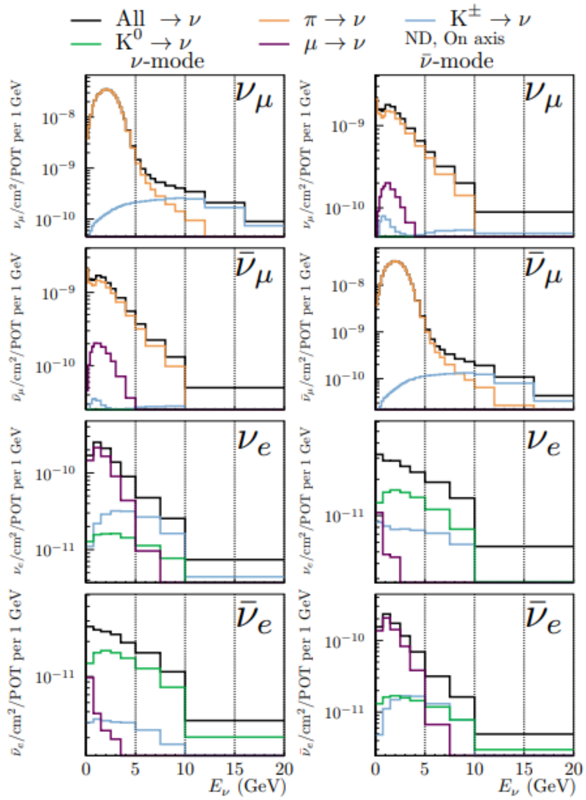

Figure 17: The published fluxes of the neutrino beam by neutrino flavor at DUNE ND.

In order to calculate the PoT, we would use the number of (anti)neutrino events required to reach the desired sensitivity and the cross sections of neutrino interactions to calculate how many neutrinos need to be produced (PoT) to achieve the necessary numbers of interactions. Genie incorporates the cross sections into the simulation and we will use the simulated PoT in the calculations of YoD.

Finally, using the parameters of the PIP-II beam, we can use the luminosity of the beam to calculate the amount of time necessary to produce the PoT needed to achieve the sensitivity of NuTeV.

Next Steps

We will begin to simulate the experiment using liquid argon and calculate the correction factor to have the calculation match with the truth value of $\sin^2\theta_W$ used in the Genie code. The same plots can then be made for liquid argon in a pure muon neutrino beam.

We will then attempt to add background based on the profile of the PIP-II beam and incorporate the background into the uncertainty calculation.

We will then use this calculation for uncertainty to determine the number of neutrino and antineutrino events necessary to reach NuTeV's sensitivity in the liquid argon target, and convert this into PoT and YoD using the neutrino cross sections and beam luminosity.

Selection Efficiency (%)	Years of Data
40	
50	
60	
70	
75	
80	
83	
85	
87	
90	
95	
100	

Figure 18: A blank table relating selection efficiency to Years of Data necessary to achieve NuTeV sensitivity. The completed table is the objective of the project.

Finally, we will repeat this process, inserting different selection efficiencies into the calculation, to project how changing the selection efficiency will impact the YoD necessary to achieve the sensitivity of the NuTeV experiment in a QPix equipped DUNE-like detector (see Figure 18).

Thesis Outline

I. Introduction
   A. A brief introduction to electroweak physics and the necessity for an improved weak mixing angle measurement
   B. Neutrino Detectors and proposed upgrades to improve sensitivity
   C. Simulating the upgraded detectors
   D. Using simulations to make sensitivity projections
   E. Thesis Overview

II. Theory and Experimental Strategy
   A. The Standard Model of particle physics and the Electroweak interaction
      1. The Standard Model
      2. The electroweak interaction, W and Z bosons, neutrinos, and charge and neutral currents
   B. Measuring the weak mixing angle with a beam of neutrinos
      1. The beam and detectors in the ideal neutrino experiment
      2. Converting observations into a measurement of $\sin^2\theta_W$: The Paschos-Wolfenstein relation
      3. Incorporating uncertainties and efficiencies in the best estimate

III. Neutrino Interaction Measurement Methods
   A. Beams and Neutrino detectors
      1. Methods of identifying CC and NC events in the detectors
      2. Liquid Argon Time Projection Chambers (LArTPCs)
      3. DUNE
         a) The beam
         b) The detectors
   B. A hypothetical LArTPC detector
   C. Charge pixels (QPix) to replace wire technology
      1. Measuring the charge arrival time to give 3D tracking
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IV. Simulations of Particle Interactions in the LArTPC Detector and Their Readout with the QPix System
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   B. Simulating the neutrino beam
   C. Simulating the ν-N interactions in the detector volume
   D. Simulating final state particle propagation and their energy deposits in the liquid argon
   E. Simulating electron propagation in liquid argon and QPix response
   F. Simulating event reconstruction

V. Reconstruction Techniques for 3D Position and Resolution Projections
   A. Position reconstruction using qpixrec
   B. Methods for Identifying CC and NC events
      1. Identifiable patterns
      2. Machine learning

   C. Selection efficiency projections based on DUNE resolution and QPix assumptions

VI. Sensitivity Projections for a $\sin^2\theta_W$ Measurement
   A. Overview of Sensitivity Estimation Methods
   B. Description of Samples
   C. Using the Paschos-Wolfenstein relation to calculate $\sin^2\theta_W$
      1. Incorporating correction factors
   D. Using the Paschos Wolfenstein relation to calculate uncertainty on $\sin^2\theta_W$
      1. The limiting factor to the uncertainty in the PW relation
      2. Estimating the uncertainty using different selection efficiencies
   E. Number of years required to achieve NuTeV sensitivity

VII. Next Steps
   A. Using our results to propose making a new measurement using DUNE ND once DUNE is online
   B. Potential future uses for QPix

VIII. Conclusion