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Decipher the Quantum Behavior of Neutrinos with DUNE-PRISM

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Our understanding of neutrinos faces limitations from neutrino-nucleus interaction uncertainties. Constraining the uncertainties has proven challenging given the absence of a complete model. To bypass most uncertainties, a DUNE physics program named PRISM employs a data-driven approach to measure neutrino oscillations. It involves the near detector (ND) moving off the neutrino beam axis to sample various neutrino energy spectra which are then linearly combined to predict the far detector oscillated spectrum. However, interaction uncertainties still affect the oscillation sensitivity primarily through the Monte Carlo based ND efficiency correction where interaction systematics introduce large variations in the predicted spectrum. We have developed a new data-driven geometric efficiency correction technique that further reduces the interaction model dependence.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

[*] Speaker

PoS(ICHEP2024)111

1. Introduction

DUNE (Deep Underground Neutrino Experiment) [1, 3] stands out as one of the next-generation neutrino experiments, ushering in a high precision era for neutrino oscillation measurements. Our understanding of the quantum behavior of neutrinos will face limitations from neutrino interaction uncertainties. Over the years, constraining these uncertainties has proven challenging, given the absence of a complete model for neutrino-nucleus interactions. To address this, a physics program within DUNE named PRISM (Precision Reaction-Independent Spectrum Measurement) [2] employs a data-driven approach to measure neutrino oscillations, bypassing most theoretical modeling uncertainties. The program involves the DUNE near detector (ND) moving off the neutrino beam axis to sample various neutrino energy spectra. These spectra are then linearly combined to predict the oscillated spectrum at four 17 kt liquid argon far detector (FD) modules 1300 km away.

However, systematics linked to neutrino-nucleus interactions still significantly affect the analysis sensitivity, primarily through ND geometric efficiency correction. The conventional efficiency correction at ND relies on the Monte Carlo sample, where cross-section systematics introduce considerable variations in the predicted spectrum. To address this issue, we have developed a new data-driven geometric efficiency correction technique. The technique further reduces the dependence on the neutrino nucleus interaction model.

2. Data-Driven Geometric Efficiency Correction for Near Detector Events

The objective of the data-driven ND geometric efficiency correction is to determine on an event-by-event basis how probable it is to observe each selected ND event. Then each event is corrected by dividing by this probability. To determine this probability, we randomly rotate the entire event about the neutrino direction, and translate the event in the $\hat{y}$ and $\hat{z}$ directions for a chosen fixed off-axis $\vec{x}$ position. Such operations are defined based on the fact that a priori the raw event vertex position distributions in the $\hat{y}$ and $\hat{z}$ directions should be flat. Meanwhile, the entire event should have a rotation symmetry about the incoming neutrino direction, which means the event's kinematics will not be changed. Such random throw of an event is repeated many times and the fraction of throws that pass the ND selection is calculated as the geometric efficiency for that selection.

The event-level geometric efficiency is factorized into the efficiency associated with the ND hadronic veto selection and the efficiency of the selected muon in ND. The ND hadronic veto requires hadronic energy deposited in the outer 30 cm region of the ND liquid argon (LAr) active volume less than 30 MeV. While the muon can either be fully contained in ND LAr, or matched in the downstream muon spectrometer. A neural network is trained on particle gun muons that can predict the probability of a muon being fully contained in ND LAr or matched to the downstream tracker, given its position and momentum. An illustration of this process is shown in Figure 1.

For each ND event passing the muon and hadronic veto selection, a total of around 5000 random throws are performed. The geometric efficiency is calculated for each event and the reciprocal of the efficiency is used as a geometrical correction factor for the event. The distributions of the raw sample, selected sample, and the data-driven geometric efficiency corrected sample are shown in Figure 2. Some interesting features are shown in the plot. For example, in the muon momentum

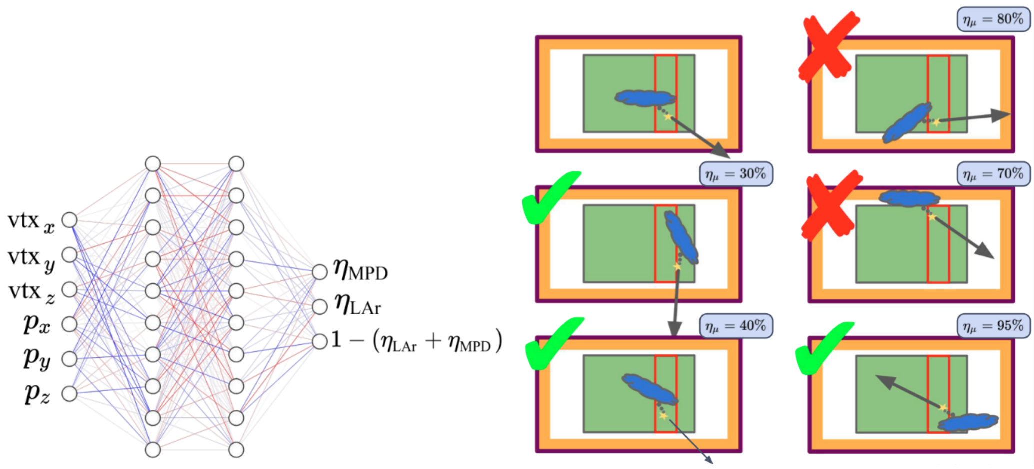

Figure 1: Left: a sketch of the muon neural network. vtx$_i$ and p$_i$ (i = x, y, z) are the vertex positions and momenta of the muon. η_{MPD} and η_{LAr} are the probabilities for accepting the muon in the downstream spectrometer or containing it in the liquid argon detector, respectively. Right: an illustration of five random throws of a selected ND event (top left). The probability of selected muons in the top right box of each throw comes from the neural network. The red cross (green check mark) indicates whether the hadronic deposits fail (pass) the hadronic veto. The event-level geometric efficiency can be derived by multiplying the muon selection probability and hadronic veto result in each throw and average over the total number of throws.

distribution for selected muons in green, a dip is observed at 1.2 GeV. This corresponds to the dead region between the ND LAr and the downstream tracker where fewer muons are selected. For the muon selection, the data-driven technique can perfectly correct the ND geometric acceptance as shown by the overlap of the corrected distribution to the raw distribution. For hadronic veto, the correction is not perfect as shown by the gap between the corrected distribution and the raw distribution. This is due to events with very large hadronic activity that have a vanishing ND selection efficiency. However these events can be selected at the FD because of its much larger volume. One example of such an event from the FD Monte Carlo sample is shown in Figure 3. These events that are very rarely selected at the ND cannot be corrected by the data-driven technique and need to be treated separately. For this, it is necessary to identify the FD events with very small efficiency at the ND.

3. Performance Demonstration with Far Detector Events

One important demonstration of this data-driven technique is that the geometric efficiency corrected ND event distribution should match the targeted unoscillated FD event spectrum when the ND-rarely-selected events are excluded. We use the same ND sample above and the DUNE TDR FD sample. To identify FD events that are rarely selected in ND, each FD event vertex along with its energy deposits is placed randomly in ND LAr in the 3D space with its kinematics preserved and the different local detector coordinate systems taken into account. Throws are performed by randomly placing the FD event in the ND geometry, while rotating the event around the neutrino direction axis. The efficiency for each FD event to be accepted in the ND is estimated from these throws. The ND-rarely-selected FD events are those with close to zero ND geometric efficiency.

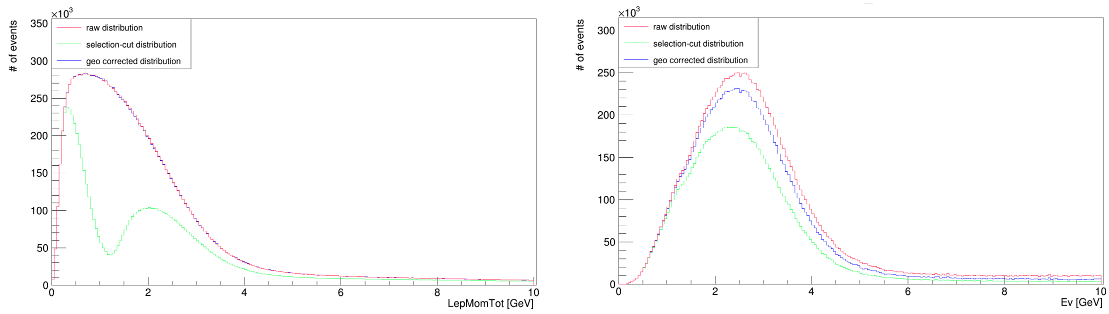

Figure 2: Distribution of the DUNE ND sample for muon (left) and hadronic veto (right) selection. The red, green, and blue curves represent respectively the raw, selected, and data-driven geometric efficiency corrected sample.

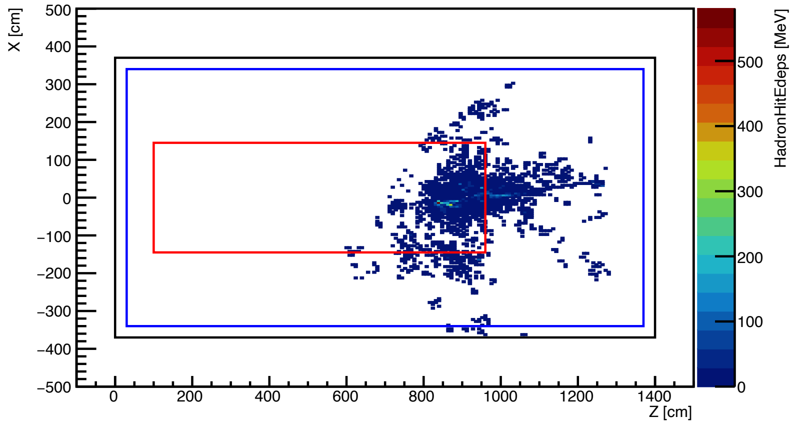

Figure 3: Energy deposits of one FD event with very low probability of being contained in the ND. Black, blue and red boxes represent active, veto and fiducial volume, respectively.

In Figure 4, the fraction of FD events with an ND efficiency larger than 10% is shown as a function of neutrino energy, along with the fraction of selected ND events passing the same criterion, weighted by the efficiency reciprocal. The two ratios track each other within 4%, which indicates the data-driven ND efficiency correction method performs well once the rarely-selected events are discarded from both the ND and FD samples. Strategies for improving the method's precision to below the percent level are discussed in the following section.

3.1 Improved Throw Strategy for FD Events

It has been observed that some FD events can pass the hadron containment criterion while having more than 30 MeV deposited outside of the ND active volume for a given throw. These energy depositions can be brought into the ND active volume for some of the throws. This effect does not occur for ND events, as no energy deposits are recorded outside of the active volume. Therefore, a mismatch is induced between the ND and FD events when applying the minimum ND efficiency criterion to remove rarely-selected events.

An improved throw strategy is thus implemented to take account into these fake pass FD events. In the initial random throws, for each throw when the FD event passed the hadronic veto cut in ND

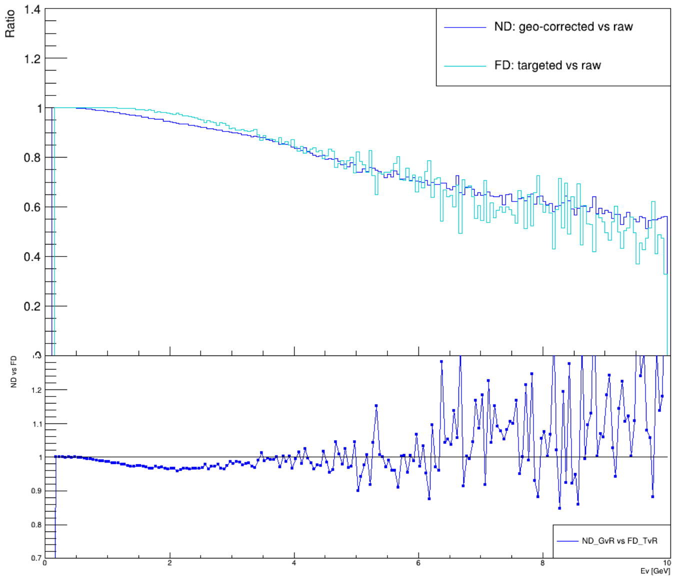

Figure 4: Data-driven ND efficiency correction performance. On the top panel, the fraction of FD events with more than 10% ND efficiency is shown in light blue as a function of true neutrino energy. The fraction of selected events at the ND with efficiencies higher than 10%, weighted by the efficiency reciprocal, is shown in dark blue. The bottom panel shows the ratio between the two fractions on the top panel.

LAr, its energy deposits outside the ND LAr active volume are removed. A second set of random throws is done for the remaining energy deposits along with the FD event vertex inside the ND LAr. Then the FD geometric efficiency is derived from the second set of random throws on those trimmed energy deposits. This treatment removes the bias in the calculated efficiency by treating the FD event as an actual detected event at ND where there is no energy detected outside the active volume. The overall geometric efficiency averaged from both sets of random throws is then used for the geometric efficiency of this FD event. Preliminary results indicate that the discrepancy shown in Figure 4 is reduced with this procedure.

4. Taking into account differences in the readout

In addition to the very different size and muon measurement strategies, the ND and FD LAr time-projection chambers are read out differently. The FD has large drift volumes read out by long wires or traces on printed-circuit boards, while the ND is read out by 2D pixel grids and is segmented into relatively small drift volumes.

In order to directly compare the events recorded at the ND to events recorded at the FD, these differences need to be taken into account.

Machine learning approaches based on image-to-image translation techniques are being developed that take an ND event as the input and produce the same event as if it had instead occurred at the FD: the signals on the pixel detectors are translated to pulses on the wires (or traces) and the dead regions resulting from the ND segmentation are filled in. This approach significantly reduces the impact of interaction model uncertainties on the FD event rate predictions, as shown in Figure 5.

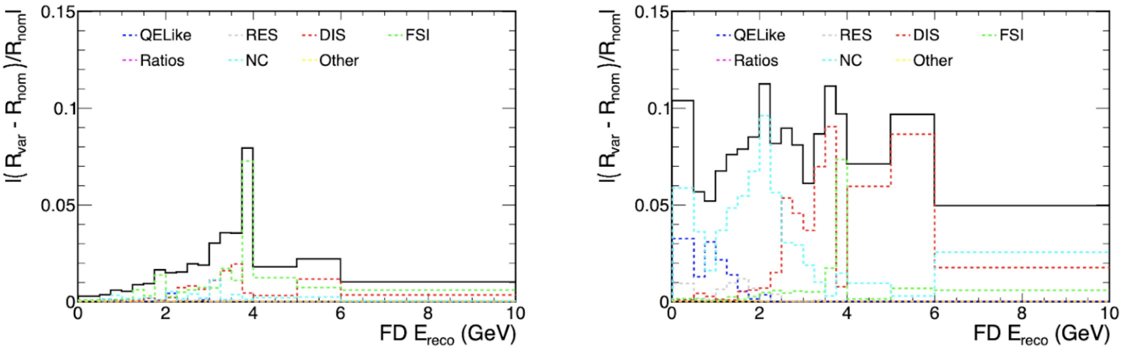

Figure 5: The relative impact of interaction model uncertainties on the FD event rates is shown on the left calculated with the ML ND-to-FD translation approach and on the right with a conventional smearing and unfolding technique.

An alternative method is also being developed that makes use of a neural network to directly translate reconstructed objects at the ND to equivalent reconstructed objects at the FD. A dedicated Monte Carlo sample where the same event is simulated at both the ND and FD has been prepared for training the neural network.

Both methods show promising initial results.

5. Summary

The DUNE-PRISM movable ND allows for a data-driven approach to neutrino oscillation measurements that largely bypasses the use of neutrino interaction models and therefore significantly reduces the main source of systematic uncertainty in these measurements. However a residual uncertainty creeps in through the use of interaction models when correcting for differences in the event selection efficiency between the ND and the FD. We have developed data-driven methods for calculating the ND efficiency for each event, matching the FD efficiency with an accuracy of up to 4%. Enhancements of the method are expected to further improve the accuracy. In parallel, machine learning methods are being developed to account for differences in event reconstruction between the ND and FD that arise from differences in the detectors' read out systems.

References

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