WHY DO WE NEED A DUNE-PRISM?

• In reality

\[
\frac{dN_{\nu}^{\text{det}}}{dE_{\text{rec}}} = \int \phi_{\nu}^{\text{det}}(E_{\nu}) \cdot \sigma_{\nu}^{\text{target}}(E_{\nu}) \cdot T_{\nu\mu}^{\text{det}}(E_{\nu}, E_{\text{rec}}) \ dE_{\nu}
\]

Alan Bross, this morning

• We cannot factorize flux, cross-section and detector effects – “no easy cancellations”.

• The goal of DUNE-PRISM is to use the flux model to predict far detector event rates with minimal cross-section model dependence.

• Achieve this by collecting data at several off-axis angles, exposing the detector to different fluxes.
  • A movable near detector!

• This concept was initially developed in the context of T2K and Hyper-K (NuPRISM/J-PARC E61).
MEASURING NEUTRINO ENERGY
THE CALORIMETRIC CASE

• Calorimetric neutrino energy estimation is model dependent.

• Part of the neutrino energy will be carried by particles that will go undetected.

• This will introduce model-dependent feed-down effects.

• Expect differences between neutrinos and antineutrinos.

\[ E_{\nu}^{cal} = E_\ell + \epsilon_n + \sum_{i=1}^{n} (E_{p_i} - M) + \sum_{j=1}^{m} E_{h_j} \]

Sum over knock-out nucleons:
• Neutrons!
• How many?
• How is energy shared?

Sum over mesons:
• If undetected, \( \sim m_m \) bias!
• How many?
• How is energy shared?
Near Detector Constraints

An Example from Water Cherenkov

- Neutrino flux is different in far detector compared to near detector: neutrinos oscillate!

- This presents an additional difficulty in constraining neutrino interaction models.
  - We only ever measure a combination of flux and cross-section.

- Multi-nucleon effects, for example, can smear reconstructed neutrino energy into oscillation dip at far detector, biasing the measurement.
  - But this is obscured by the flux peak at the near detector!
CALORIMETRIC FEED-DOWN

- Significant feed-down effects due to “missing energy” in calorimetric neutrino energy reconstruction.
  - Mis-modelling will lead to bias!

- Look at fake data to study the impact of nucleon kinematics mis-modelling on oscillation analyses.
20% MISSING PROTON ENERGY

- For each event generated with a nominal interaction model, scale proton energy deposits in the LAr detector by 80%.
  - Difference is given to neutrons.

- Difference in reconstructed energy spectra at on-axis LAr ND clearly seen.
  - If we saw this in our data, we would tune our cross-section model to remove the discrepancy. But would this “fix” the true to reconstructed energy relation?
MULTIVARIATE REWEIGHTING

- Start with nominal MC.
- Look at multidimensional distribution of observables.
MULTIVARIATE REWEIGHTING

- Apply -20% shift in proton deposited energy.
- Changes $E_{\text{true}} \rightarrow E_{\text{rec}}$ relation.
MULTIVARIATE REWEIGHTING

- Reweight the distribution as a function of the observables.
- Recover multidimensional nominal distribution.
- $E_{\text{rec}}$ bias still present!
MULTIVARIATE REWEIGHTING

• Repeat for \textbf{antineutrino} mode.
• Effect on $E_{\nu} \rightarrow E_{\text{rec}}$ is much smaller.
• To study the effect on oscillation fits, we need to propagate this model to far detector.
  • Also to off-axis near detector stops, to demonstrate the PRISM technique.
• Bin event weights in true variables useful for describing interaction models.
  • Get smoothly varying functions!
  • MVA treats interaction modes differently.
  • Even though it doesn’t “know” about them!
• For this data set, use $E_{\nu}$ vs true proton kinetic energy.
• Extract weights separately for $\nu$ and anti-$\nu$ using FHC and RHC on-axis near detector data.
  • Assume perfect charge separation.
• Do not reweight regions of the space that fall outside of the ND acceptance.
  • These events get weight = 1, but 20% proton deposited energy removed.
IMPACT ON OSCILLATION ANALYSIS

• Use CAFAna framework to fit fake data at near and far detector.
  • Fitter assumes the nominal model: get bias!
• Flux systematic parameters fixed at nominal value.
  • Get same results if allowed to vary in the fit.
• No large pulls on cross-section parameters.

$$\chi^2/NDF = 81.6/202$$
IMPACT ON OSCILLATION ANALYSIS

• A good fit is achieved at the on-axis near and far detectors, but significant biases are seen in the estimation of oscillation parameters.
DUNE-PRISM

• What if we could use the same detector to measure interactions in a (very) different flux?

• Move the detector to an off-axis position and take data!

• Get true to reconstructed energy maps for a wide range of true* energies.

  * As given by the flux model.
LOOK AT THE FAKE DATA THROUGH A PRISM

• Narrow fluxes at off-axis near detector positions give away the $E_{\text{true}} \rightarrow E_{\text{rec}}$ mismodelling.

• Cross-section parameters in the model fitted to on-axis data didn’t move much from nominal values, as intended.

• Near detector best-fit prediction is significantly different from “observed” fake data at 20 m off-axis.

![Graph showing nominal and fake data comparison](image)
• Moving the LAr near detector horizontally (e.g., on rails) in a direction transverse to the neutrino beam would result in a **PRISM**.

• At 574 m from the target, a lateral travel of around 33 m would cover the range of fluxes necessary to get down to 2\textsuperscript{nd} oscillation maximum energies.
  * Beyond 33 m flux shape doesn’t change much and flux drops rapidly.
Several engineering questions under study.

- Hall size optimization.
- Drive mechanism.
- What moves? Cryo system, other detectors...

- Several engineering questions under study.
- Hall size optimization.
- Drive mechanism.
- What moves? Cryo system, other detectors...

- MOVING THE DETECTOR
  - C. Vilela - POND
  - M. Wilking

- MOVING THE DETECTOR
  - C. Vilela - POND
  - M. Wilking
The first step in producing a data-driven prediction for the far detector is to mock-up a far detector oscillated flux using linear combinations of flux predictions at different off axis positions.

Can be written as a linear algebra problem:

\[ \Phi_{ij}^{ND} c_j = \Phi_i^{FD} \]

• Solve for \( c_i \)
DATA DRIVEN OSCILLATION ANALYSIS

LINEAR COMBINATIONS

• Solution given by \( \tilde{c} = \left( (\phi_{ND})^T \phi_{ND} + \Gamma^T \Gamma \right)^{-1} (\phi_{ND})^T \phi_i^{FD} \)

• With Tikhonov regularization using a difference matrix \( \Gamma \)

- Coefficients can be applied to data taken at the corresponding off-axis position to form a prediction for event rate at the far detector.

- Need to correct for differences in acceptance between near and far detector as well as shortcomings in the linear combinations.
DATA DRIVEN OSCILLATION ANALYSIS
LINEAR COMBINATIONS

- Can reproduce both disappearance dips with linear combinations for a wide range of oscillation parameters.
- Beam uncertainties have a small effect on the linear combinations.
- Difficult to fit high energy bump completely.
  - Region close to the dip is well reproduced – most important to control feed-down effects.
HADRONIC CONTAINMENT

• A cut on activity on a veto region on the sides of the LAr near detector is used to remove events where the hadronic system escapes the detector.

• This introduces model-dependent loss of efficiency for events at with vertices close to the veto region.

• Mitigate the effect by fiducializing the volume, events outside the “vertex desert” are removed from analysis samples.
  • Geometric, data-driven, efficiency correction method in early stages of development.

• This presents additional motivation for a wider (7 m) LAr volume.
DUNE-PRISM OSCILLATION ANALYSIS

• Put all of this together for a far detector event rate prediction.

• Linear combinations perform poorly at high energies (> 4 GeV) given that we can’t access fluxes peaked at higher-than-on-axis energies.

• Use traditional MC prediction to account for the flux difference.
  • Most of the prediction comes from near detector data – cross-section model independent.

• Implementation of this technique in oscillation analysis framework ongoing.
  • Stay tuned!

C. Vilela - PONDD

December 3, 2018
SUMMARY AND PROSPECTS

• Understanding true to reconstructed energy relation is crucial for precision long baseline oscillation measurements.

• Given the wide flux at the near detector (much wider than oscillation features) and undetected components in the final states, energy reconstruction bias can go unnoticed in an on-axis near detector.

• Taking near detector data at off-axis positions reveals reconstructed energy mis-modelling and allows for a largely data-driven oscillation analysis.
SUPPLEMENTARY SLIDES
DUNE-PRISM SIMULATION

- Simulate GENIE events in a large liquid argon volume
  - 39 x 3 x 5 m.
- Divide large volume into 13 detector-sized (3 x 2 x 4 m) chunks, mimicking “stops” of a moveable detector.
- Define a veto region 50 cm from the detector edges in all directions.
  - Use this region to require hadronic system containment in active volume: non-primary-lepton energy deposits in veto region < 50 MeV.
LOOK AT THE FAKE DATA THROUGH A PRISM

• Narrow fluxes at off-axis near detector positions give away the $E_{\text{true}} \rightarrow E_{\text{rec}}$ mismodelling.

• Cross-section parameters in the model fitted to on-axis data didn’t move much from nominal values, as intended.

• Near detector best-fit prediction is significantly different from “observed” fake data at 30 m off-axis.
# EVENT RATES

<table>
<thead>
<tr>
<th>Offset</th>
<th>(10^{19})POT</th>
<th>(\mu) contained</th>
<th>CCInc</th>
<th>(\mu) exit, (T_{\mu}^{\text{exit}} &gt; 50\text{MeV})</th>
<th>NCInc</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>(\nu_\mu)</td>
<td>(\epsilon_{\nu_\mu,\text{CC}})</td>
<td>(\bar{\nu}<em>\mu/\nu</em>\mu)</td>
<td>(\nu_\mu)</td>
<td>(\epsilon_{\nu_\mu,\text{CC}})</td>
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<tr>
<td>0 m</td>
<td>55</td>
<td>6.6E5</td>
<td>3%</td>
<td>1%</td>
<td>5.3E6</td>
</tr>
<tr>
<td>3 m</td>
<td>4.58</td>
<td>5.5E4</td>
<td>3%</td>
<td>1%</td>
<td>4.1E5</td>
</tr>
<tr>
<td>6 m</td>
<td>4.58</td>
<td>5.8E4</td>
<td>4%</td>
<td>1%</td>
<td>3.0E5</td>
</tr>
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<td>9 m</td>
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<td>6.0E4</td>
<td>7%</td>
<td>2%</td>
<td>1.9E5</td>
</tr>
<tr>
<td>12 m</td>
<td>4.58</td>
<td>5.9E4</td>
<td>12%</td>
<td>3%</td>
<td>1.1E5</td>
</tr>
<tr>
<td>15 m</td>
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<td>5.4E4</td>
<td>18%</td>
<td>3%</td>
<td>6.2E4</td>
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<tr>
<td>18 m</td>
<td>4.58</td>
<td>4.6E4</td>
<td>22%</td>
<td>4%</td>
<td>3.8E4</td>
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<td>24 m</td>
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<td>6%</td>
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<td>27 m</td>
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<td>2.6E4</td>
<td>32%</td>
<td>7%</td>
<td>1.2E4</td>
</tr>
<tr>
<td>30 m</td>
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<td>33%</td>
<td>7%</td>
<td>9.6E3</td>
</tr>
<tr>
<td>33 m</td>
<td>4.58</td>
<td>1.7E4</td>
<td>35%</td>
<td>8%</td>
<td>7.5E3</td>
</tr>
<tr>
<td>36 m</td>
<td>4.58</td>
<td>1.2E4</td>
<td>35%</td>
<td>8%</td>
<td>6.1E3</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>(\nu_\mu)</th>
<th>---</th>
<th>(\bar{\nu}_\mu)</th>
<th>(\nu_\mu)</th>
<th>---</th>
<th>(\bar{\nu}_\mu)</th>
<th>(\nu_e)</th>
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<tbody>
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<td>All</td>
<td>110</td>
<td>---</td>
<td>1.6E4</td>
<td>6.5E6</td>
<td>---</td>
<td>2.2E5</td>
<td>8.7E4</td>
<td>2.3E6</td>
</tr>
</tbody>
</table>
ON-AXIS NEAR DETECTOR

• Very little difference between nominal and fake data sets at on-axis near detector.
FAR DETECTOR

- Different $E_\nu \rightarrow E_{\text{rec}}$ significantly distorts far detector oscillated spectrum.
  - This will induce bias in estimation of oscillation parameters!

![Graph showing oscillated spectra for different detector conditions]

- Nominal
- Fake
- Far detector

- $E_{\text{rec}}$ [GeV]
- Arbitrary units
MULTIVARIATE REWEIGHTING

• Use multivariate method* to reweight distributions of observables back to nominal.
  • Train BDT to learn differences between shifted and nominal MC, and produce event weights from output.
  • Five observables considered, assume energy deposits can be unambiguously assigned to particle species:
    • $E_{\text{rec}}$
      • Defined as sum of non-lepton energy deposits in LAr detector plus true lepton energy.
        • No attempt to reconstruct Michel electrons and correct for energy taken by neutrinos…
    • Primary lepton energy
    • Proton deposited energy
    • Charged pion deposited energy
    • Neutral pion deposited energy
  
• This is a proxy for tuning a sufficiently flexible cross-section model.

MULTIVARIATE REWEIGHTING

• Use Gradient Boosted Decision Tree event reweighting technique*.

• Hyperparameters:
  • Tree splitting criterion: mean squared error
  • Number of estimators: 200
  • Maximum tree depth: 3
  • Minimum samples per leaf: 1000
  • Learning rate: 0.1
  • Loss regularization: 1

• Split MC sample in two: one half will be “Nominal” and the other “Fake”.

• For training, use 75% of the Nominal and Fake samples, and check result on the rest.

*arXiv:1608.05806
IS AN ON-AXIS MPT SENSITIVE TO THIS TYPE OF MISMODELLING?

- The proposed multi-purpose tracker will be able to measure tracks precisely down to low thresholds.

- Are we able to reweight kinematic-balance distributions measured by a MPT and still get a biased $E_{\text{rec}}$ model?

- Add the following variables to the list of observables to be reweighted:
  - Number of protons and charged pions above tracking threshold.
  - For events with exactly one tracked proton and no tracked pions:
    - Single transverse kinematics: $\delta p_T$, $\delta \alpha_T$ and $\delta \phi_T$
  - For events with exactly one pion and one proton:
    - Double transverse variable: $\delta p_{TT}$

Tracking thresholds:
- Protons: 200 MeV/c
- Pions: 130 MeV/c

Momentum resolution: 5%
Angular resolution: 2 mrad

From STT document at ND workshop
TRANSVERSE VARIABLES, REWEIGHTED

Nominal
-20% proton KE
-20% proton KE reweighted
Neutrino-mode
TRANSVERSE VARIABLES, REWEIGHTED

Nominal
-20% proton KE
-20% proton KE reweighted Neutrino-mode
TRANSVERSE VARIABLES, REWEIGHTED
(AN ATTEMPT AT) A SANITY CHECK

• If we had complete knowledge of the final state for every event we wouldn’t expect this type of reweighting to work.
  • Or at least not without somehow “correcting” the $E_{\text{rec}}$ response…

• But how would that manifest itself in the distributions we have been looking at?

• Try reweighting initial five “calorimetric” variables plus the true neutron kinetic energy, as if we had a 100% efficient neutron detector with perfect resolution and acceptance.
  • That should constrain the final state quite tightly…
(AN ATTEMPT AT) A SANITY CHECK

- Distributions of observables don’t make a whole lot of sense, so look at distributions of event weights.

- Five calorimetric variables. Weights look reasonable.

- Five calorimetric variables plus six kinematic variables. Weights look reasonable, but clearly more of an effort for the BDT...

- Five calorimetric variables plus true neutron kinetic energy. One event to rule them all?! BDT FAIL!
DUNE-PRISM 20 METRES OFF-AXIS

- Fake and nominal data look different when looking at a narrow flux at off-axis positions.
Geometric efficiency correction

- Want to know: For an event of a given ‘shape’, if I selected X, how many did I veto because of my detector geometry and selection conditions.

- Might imagine an efficiency determination procedure like:
  - For a selected event, with full 3D deposit mapped out by ArgonCube.
  - Make throws of translations and rotations around the beam axis.
  - How often would that event have still been selected?
\[ \sin^2 \theta_{23} = 0.5 \]
\[ \Delta m^2_{32} = 2.5 \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2 \theta_{23} = 0.5 \]
\[ \Delta m^2_{32} = 2.8 \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2 \theta_{23} = 0.65 \]
\[ \Delta m^2_{32} = 2.2 \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2 \theta_{23} = 0.65 \]
\[ \Delta m^2_{32} = 2.8 \times 10^{-3} \text{ eV}^2 \]

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\[ \Delta m^2_{32} = 2.5 \times 10^{-3} \text{ eV}^2 \]