Estimating the Impact of Neutrino Interaction Mismodeling in DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

With Multivariate Event Reweighting

Neutrino Physics and Machine Learning

July 22 2020

Cristóvão Vilela, for the DUNE Collaboration

Measuring neutrino oscillations

- We measure neutrino oscillation **probabilities** by comparing **event rates** in **near** and **far** detectors as a function of **reconstructed neutrino energy**.
- **Neutrino interaction modeling** is a source of systematic uncertainty even if the near and far detectors are functionally identical. Need to **integrate** over:
  - **Flux**, which is very different **due to oscillations**.
  - **Detector response**, which will also be different.
    - For example, due to very different sizes of near and far detectors.

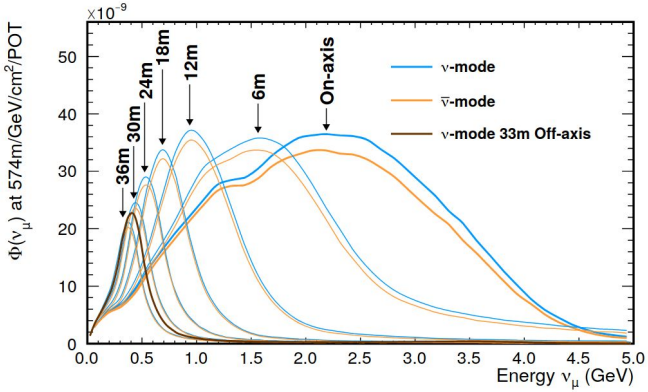
$$\frac{dN_x^{FD}}{dE_{rec}}(E_{rec}) = \int \Phi_{\nu_\mu}^{FD}(E_\nu) P_{\nu_\mu \to x}(E_\nu) \sigma_x^{Ar}(E_\nu) T_x^{FD,Ar}(E_\nu, E_{rec}) dE_\nu$$

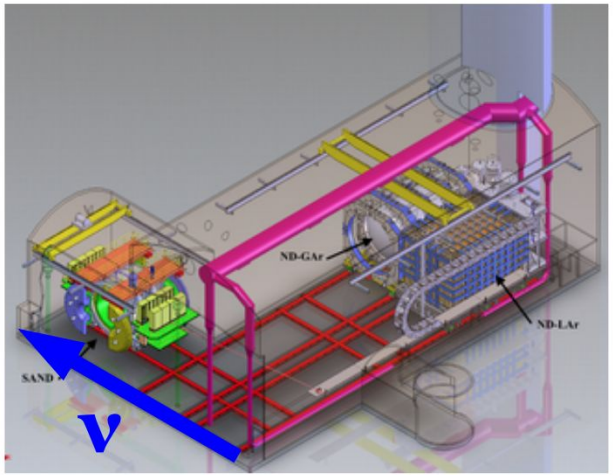
$$\frac{dN_x^{ND}}{dE_{rec}}(E_{rec}) = \int \Phi_x^{ND}(E_\nu) \sigma_x^{m}(E_\nu) T_x^{d,m}(E_\nu, E_{rec}) dE_\nu$$

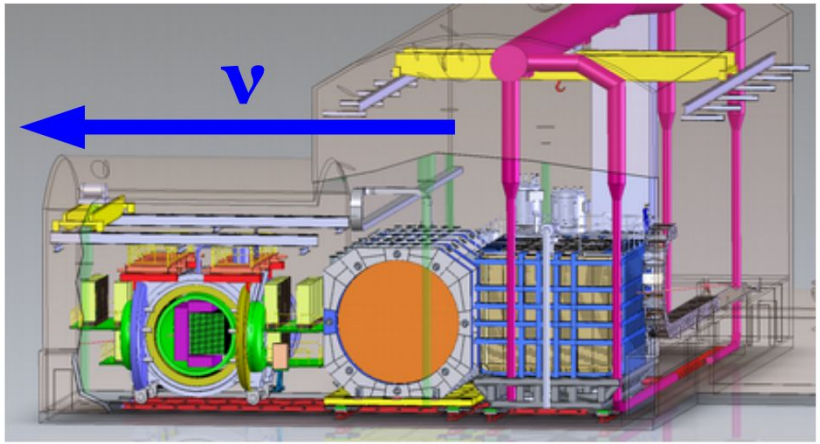
arXiv:2002.02967

The DUNE Near Detector

- Near detector concept explores complementarity between:
  - **Liquid** and **gaseous argon** detectors that move **off-axis**.
    - **High-statistics** in the liquid and **low thresholds** in the gas.
    - Gas detector is **magnetised** - also works as muon spectrometer
  - On-axis fine-grained **carbon** detector.
    - On-axis **flux** monitoring and **neutron** detection capability



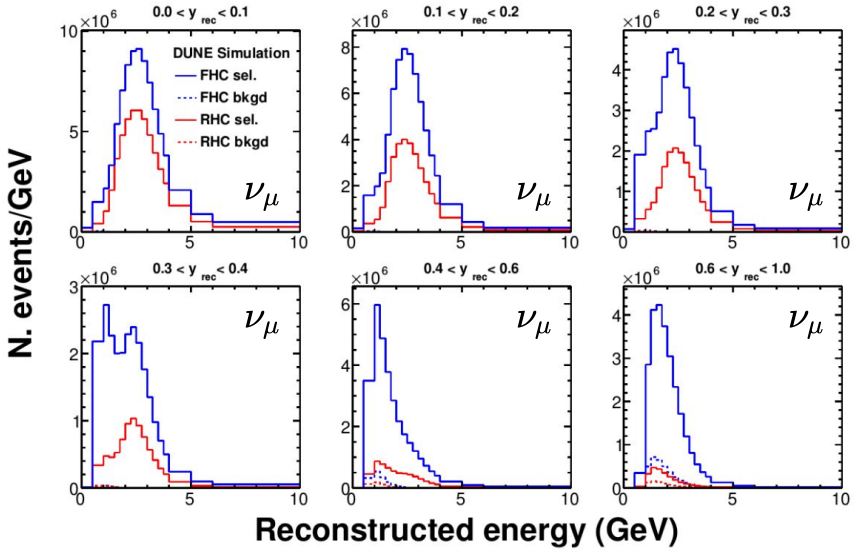




SAND ND-GAr ND-LAr

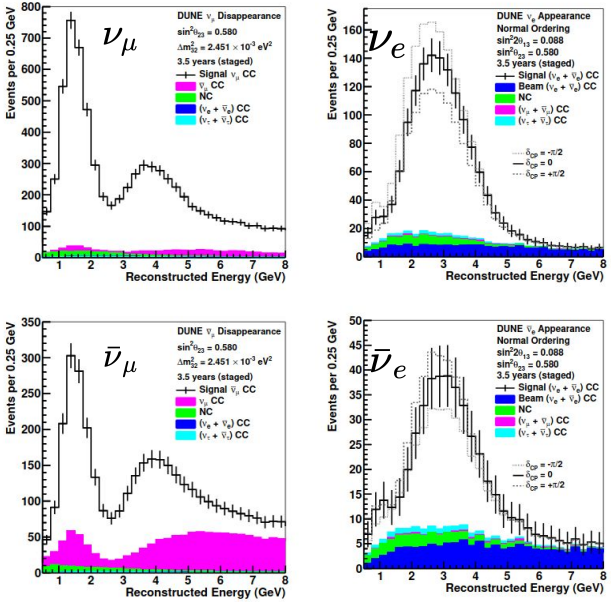
DUNE Simulation

- Near and far detector events are generated using Genie v2.12.10
  - Far detector events selected with convolutional neural network.
  - Parameterized truth-based reconstruction for liquid argon near detector events.
    - Use true Geant4 energy deposits for hadronic energy estimation.
    - Events on gaseous argon and carbon detectors not explicitly used in current iteration of the analysis.



Near

Far

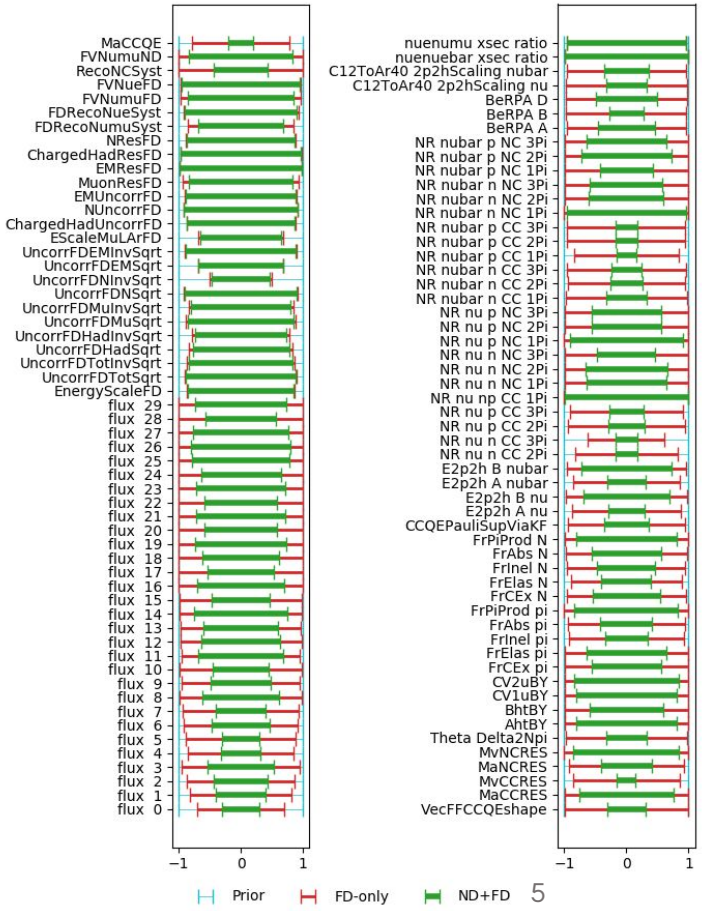


Neutrino mode

Antineutrino mode

DUNE Oscillation Analysis

- **Simultaneous** fit to **near** and **far** detector data using the CAFAna framework.
  - **Near** detector events binned in reconstructed **neutrino energy** and **inelasticity**.
  - **Far** detector events binned in reconstructed **neutrino energy.**
- Sophisticated **flux** and **cross-section** model is constrained by the **near detector** data.
- **Neutrino mixing** parameters get constrained by the **far** detector data.



Reweighting between generators

Multivariate event reweighting

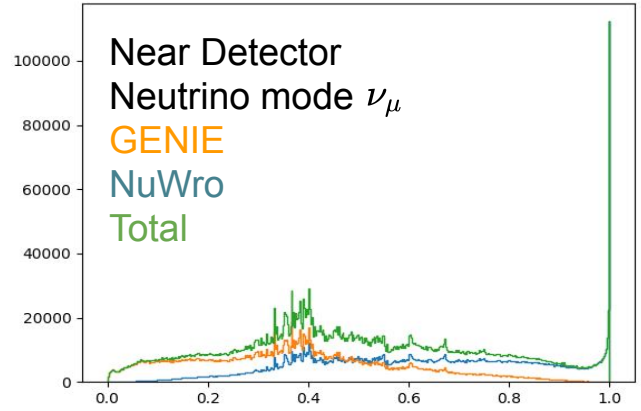
- We have a **detailed** interaction model that allows for varying many important features.
- This doesn't tell us what our results would look like if nature was **substantially different** from Genie v2.12.10.
- One way to probe this is to run the analysis using "data" produced with a **different event generator**.
  - However, **re-generating** the entire data set for each different model we might want to test is **unfeasible**.
- We can **approximate** the alternate generator by **reweighting** our existing data set to a an alternate sample, skipping the time consuming detector simulation and reconstruction steps.
  - Traditional **histogram-based** reweighting schemes only feasible up to ~2 dimensions.
- Use **boosted decision trees** to find reweighting scheme in **many** dimensions.
  - Inspired by: A. Rogozhnikov, J.Phys.Conf.Ser. 762 (2016) no.1, 012036 [arXiv:1608.05806]

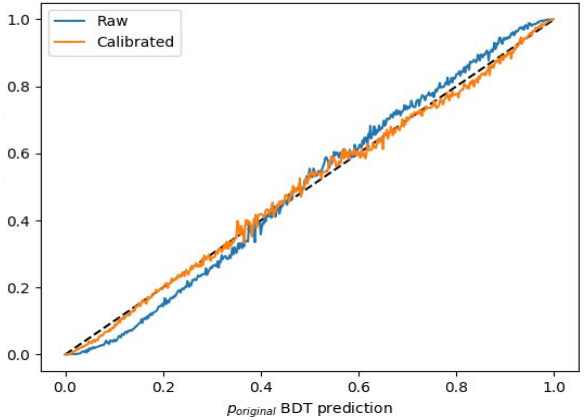
Reweighting Genie to NuWro

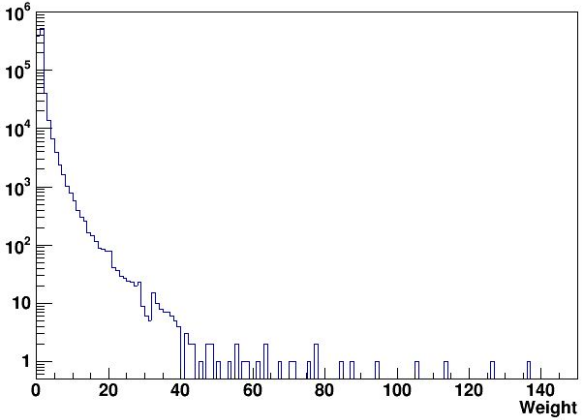
- Generate events using NuWro 18 and DUNE far detector fluxes.
- Choose a set of 18 variables to reweight in.
- Use xgboost to train BST to classify events as being either Genie or NuWro.
  - Train a separate BDT for each flux component.
  - Calibrate BDT output with Platt scaling.
    - Advances in Large Margin Classifiers, 1999, 61 - 64

Variables for reweighting:

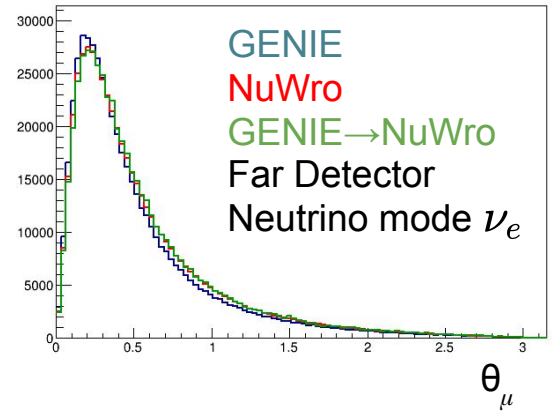
- Neutrino and lepton energies, angle between lepton and neutrino, Q2, W, x and y/
- Number of and total energy carried by:
  - Protons, neutrons, charged and neutral pions.
- Number of EM objects
- Ignore variables that do not have a well defined correspondence between generators:
  - E.g.: interaction mode, “other” and “nucleus” objects.

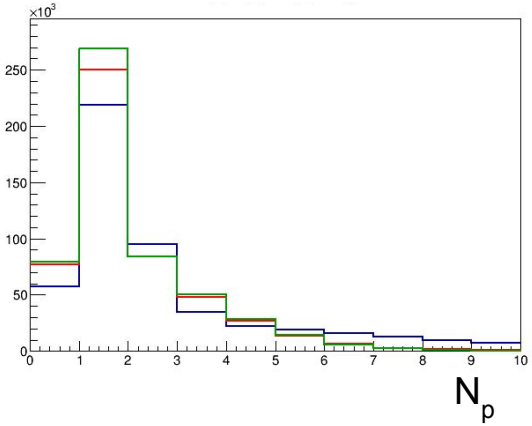


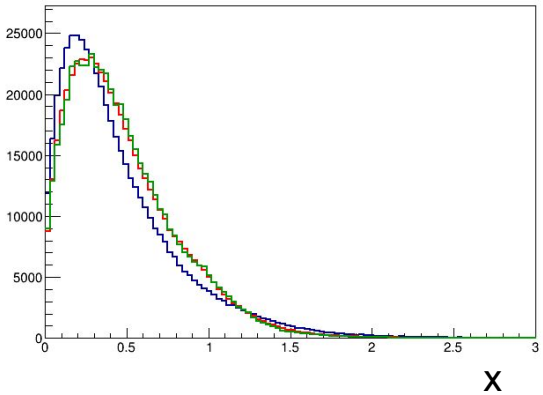


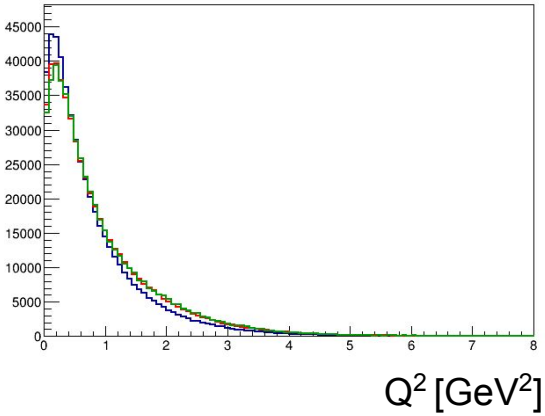


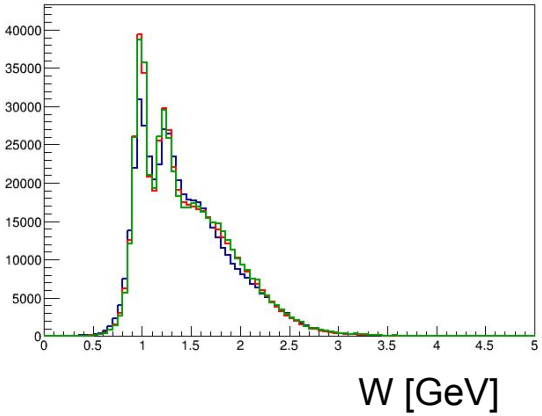
Reweighting examples: neutrinos

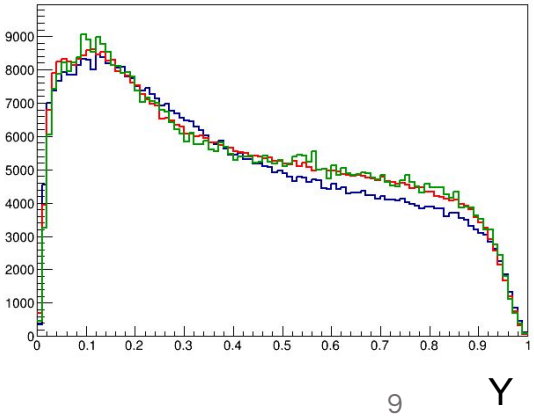




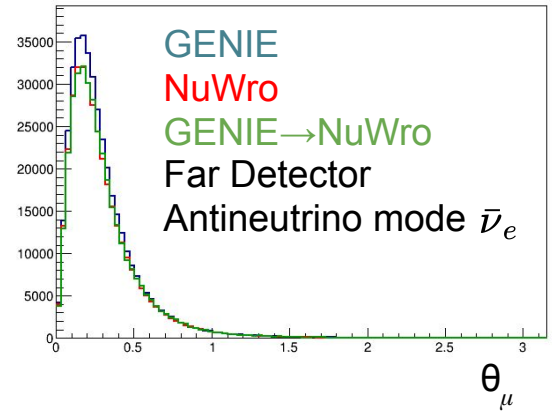


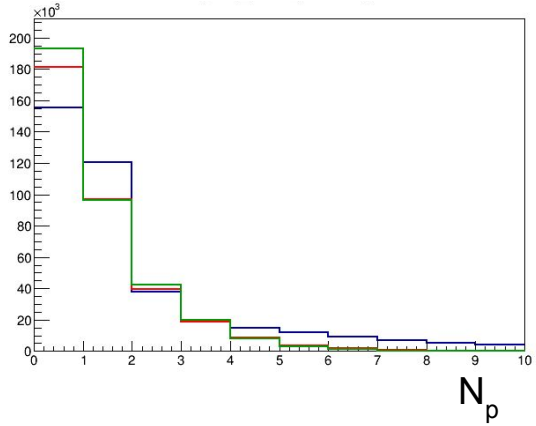


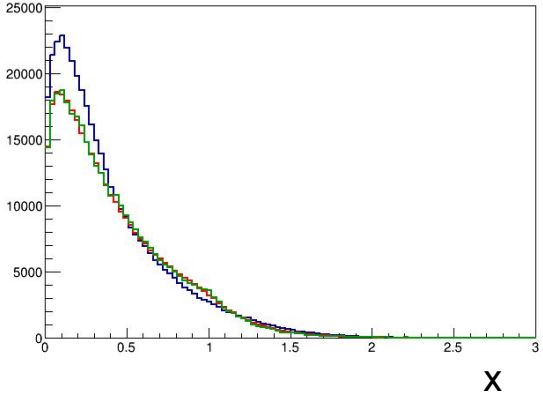


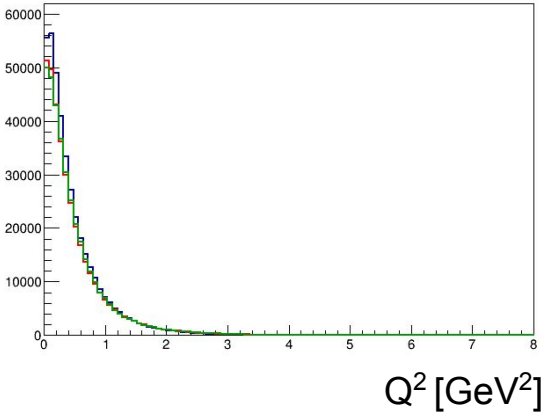


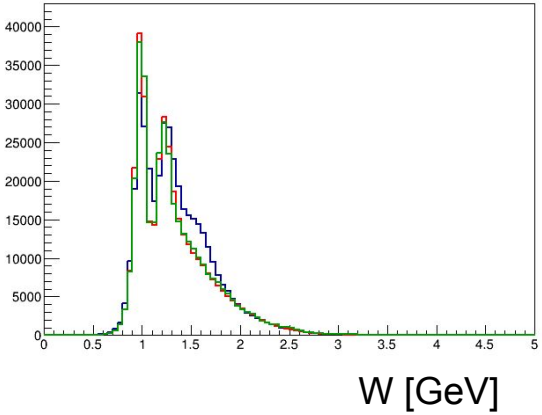
Reweighting examples: antrineutrinos

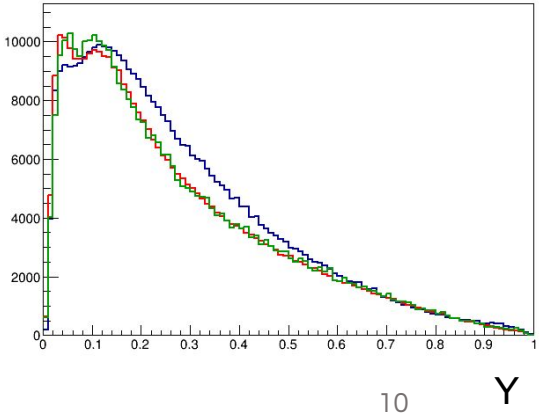






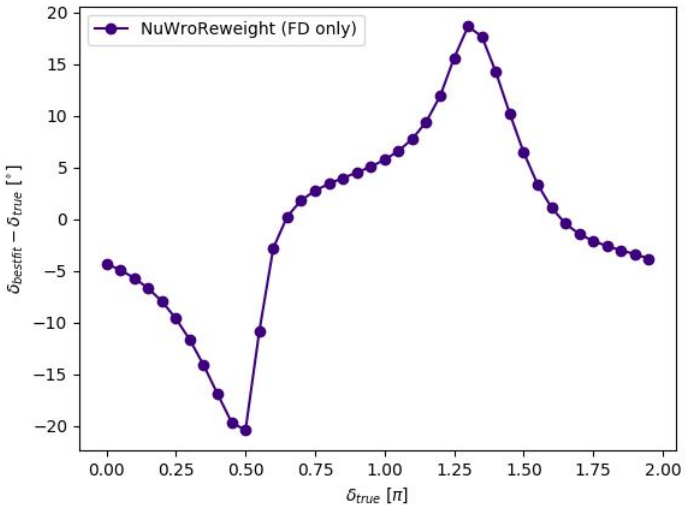


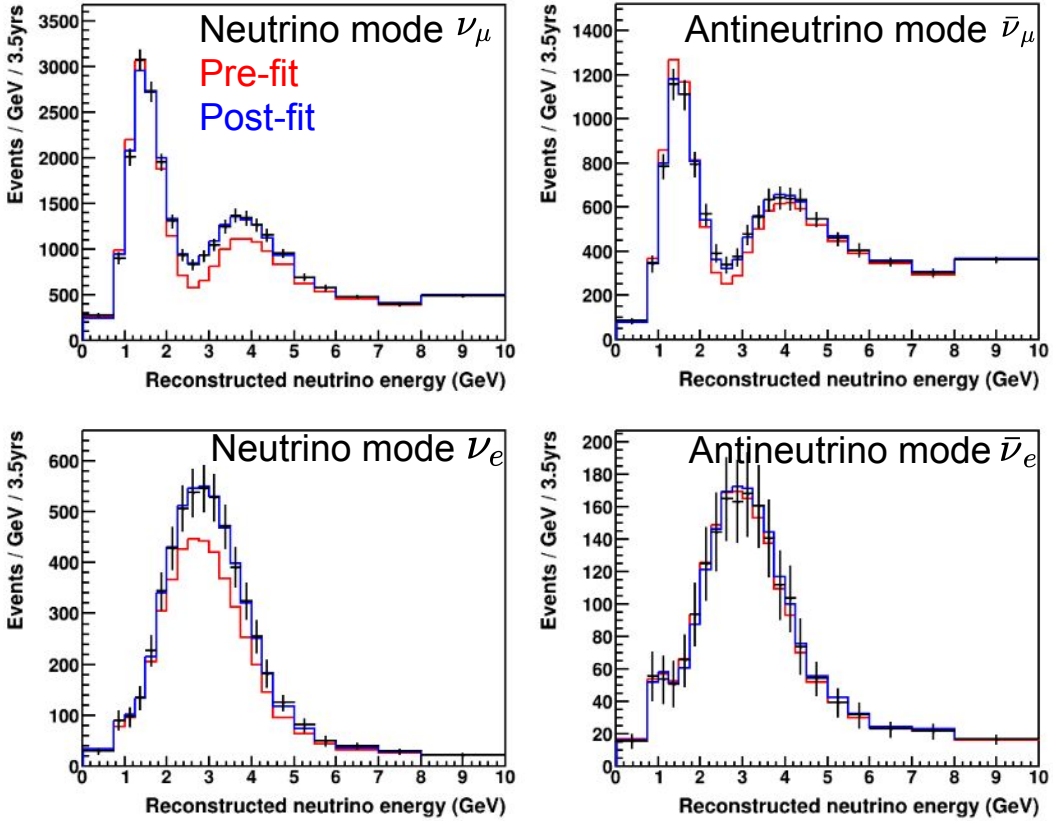




Fit to NuWro-reweighted mock data

- Very bad fit to near detector data.
- Good agreement in far-detector-only fit.
  - χ^2/NDF < 1
- Large **bias** in δ_{CP}:
  - DUNE **needs** a near detector!





Designing a custom model

"Missing proton energy" model

- **Neutrons** can carry a significant fraction of **neutrino energy** and will be very difficult to detect in the argon.
- **Mismodeling** of neutrons can introduce energy **biases** which can be difficult to disentangle from other neutrino cross-section effects.
- Build mock data sample to illustrate this **degeneracy** by moving **20% of proton energy** to (unseen) **neutrons** and **reweight** to **hide** effect in the on-axis near-detector distributions.

$$E_\nu^{cal} = E_\ell + \epsilon_n + \sum_{i=1}^{n} \left(E_{p'_i} - M\right) + \sum_{j=1}^{m} E_{h'_j}$$

Sum over knock-out nucleons:

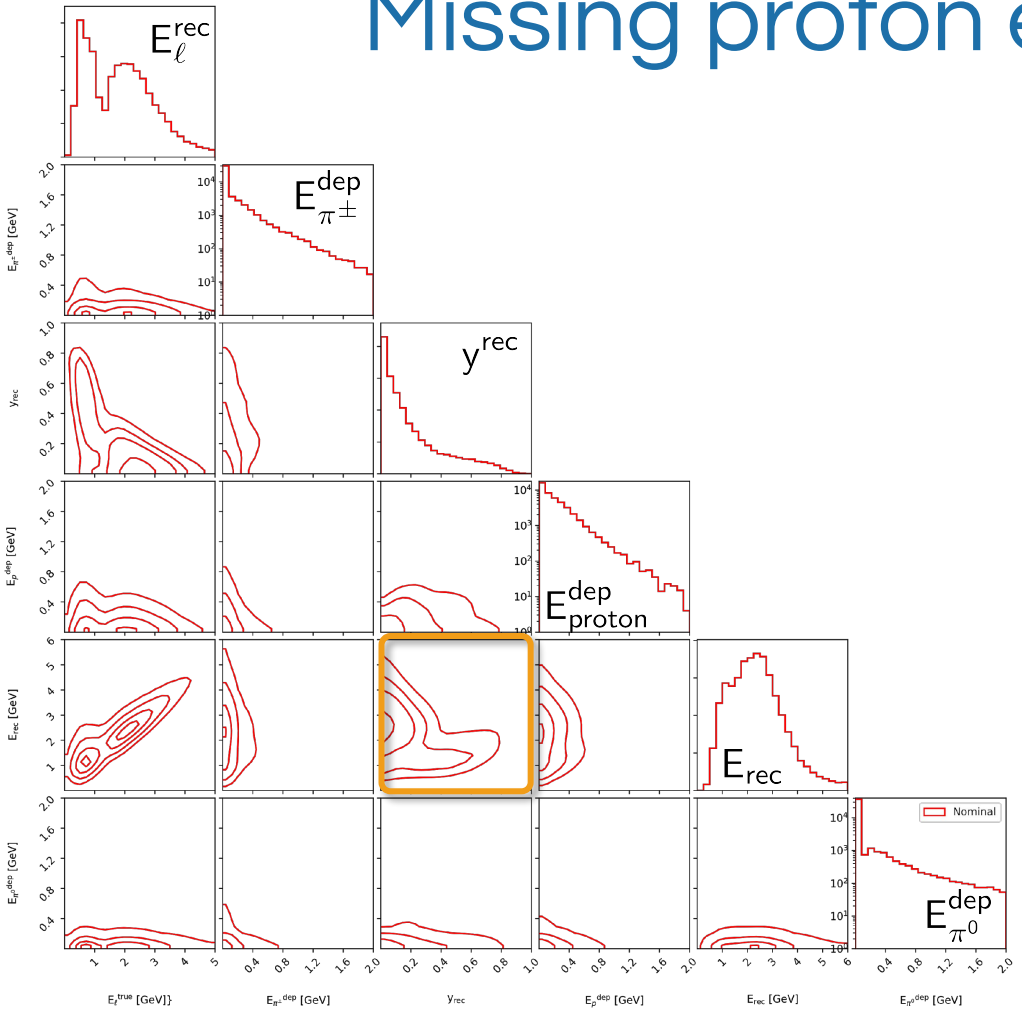
- Neutrons!
- How many?
- How is energy shared?

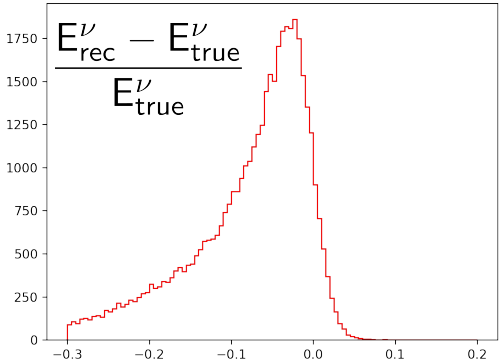
Sum over mesons:

- If undetected, ~m_m bias!
- How many?
- How is energy shared?

Missing proton energy reweighting

NOMINAL

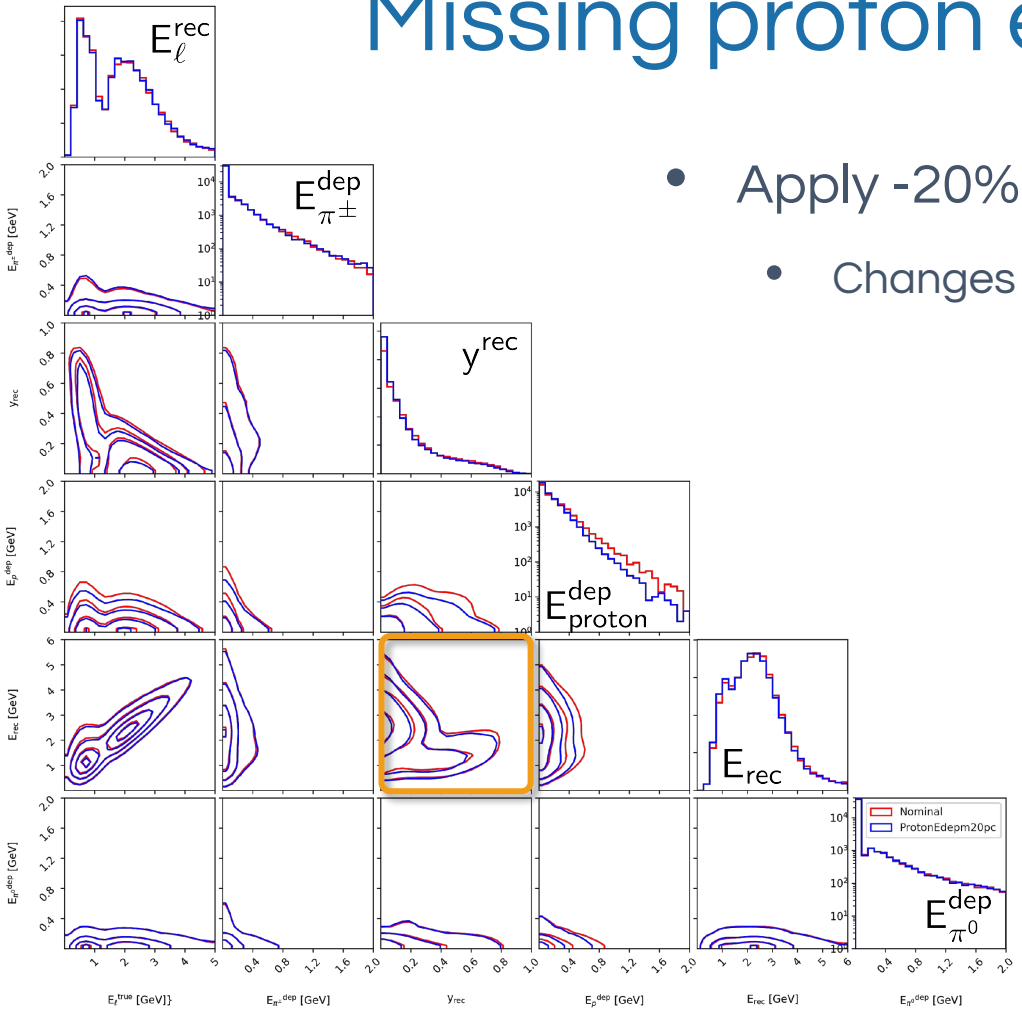


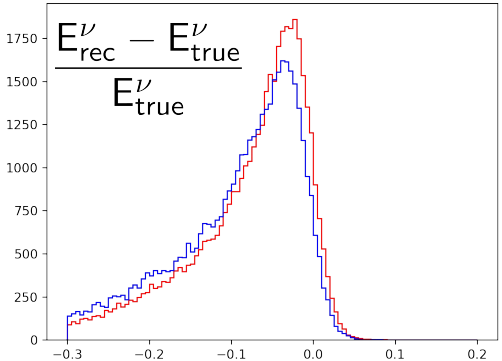


Missing proton energy reweighting

NOMINAL, SHIFTED

- Apply -20% shift to proton energy.
  - Changes reconstructed energy response.

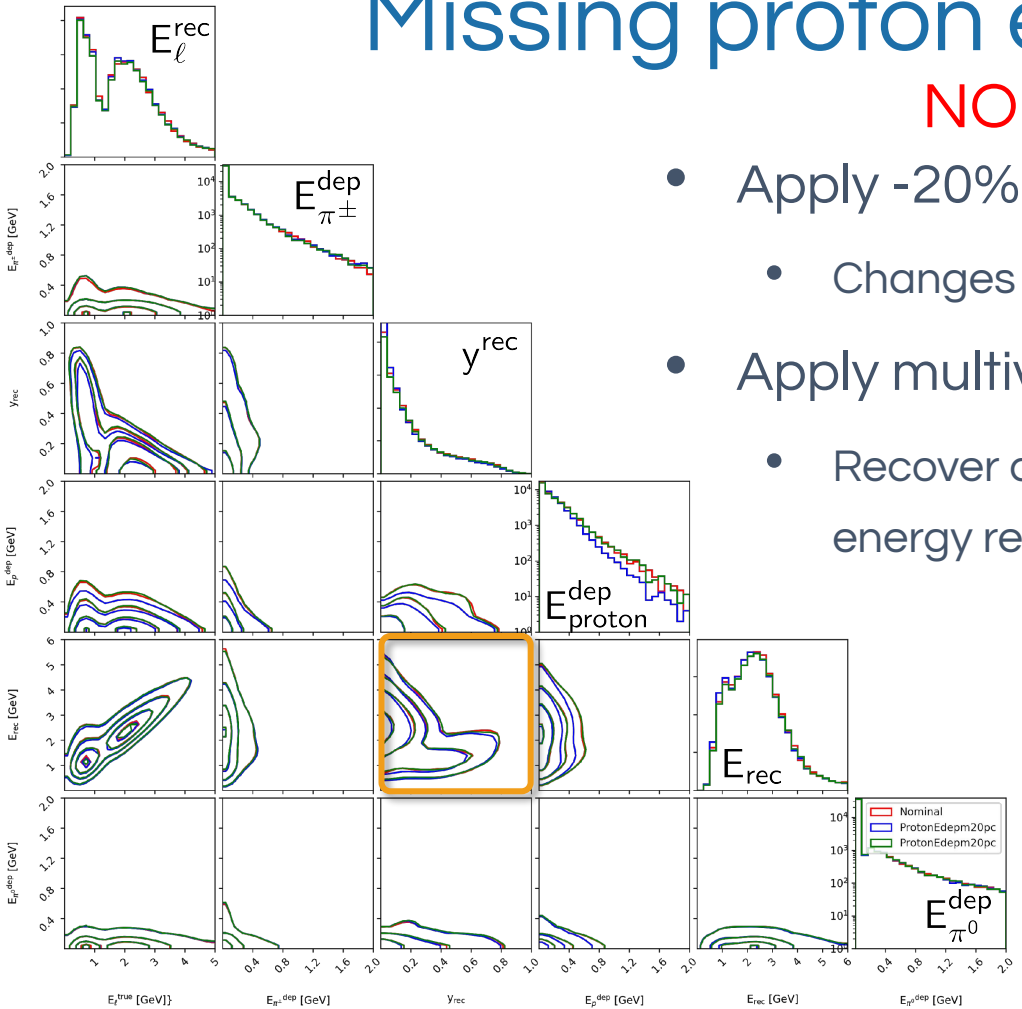


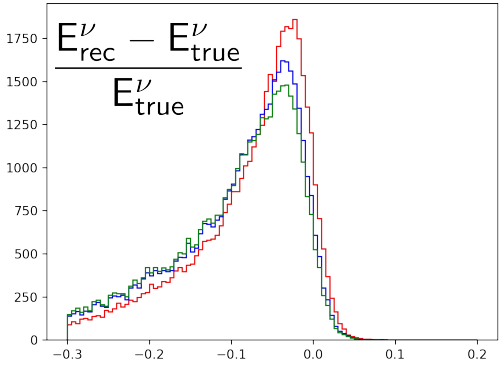


Missing proton energy reweighting

NOMINAL, SHIFTED, MOCK DATA

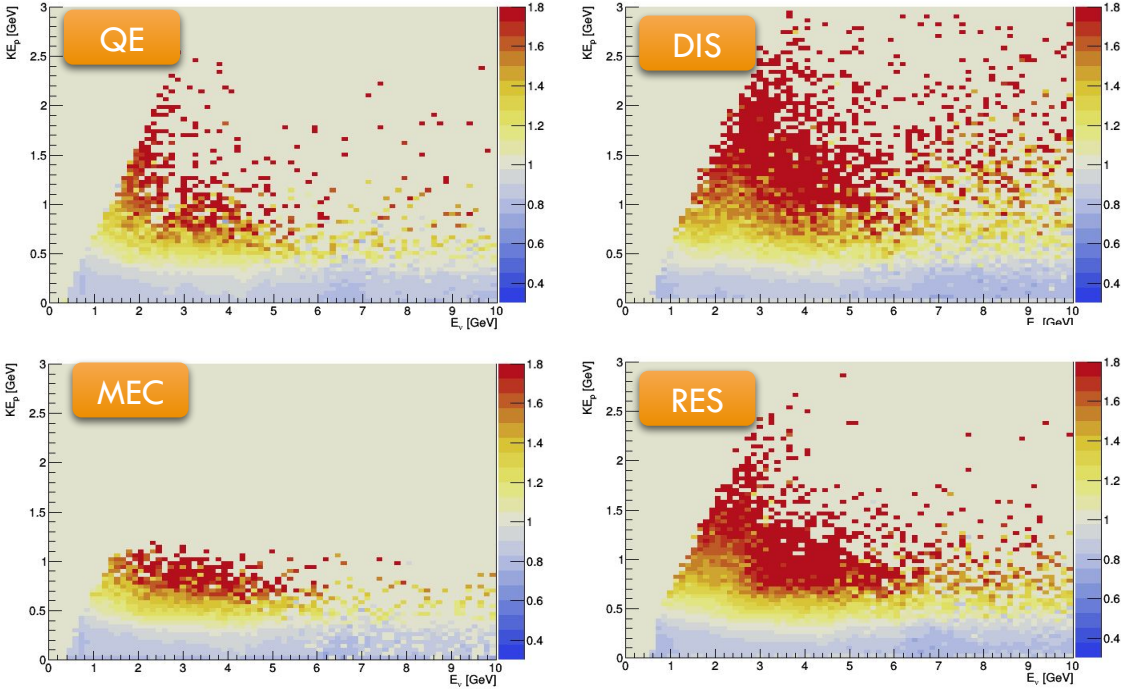
- Apply -20% shift to proton energy.
  - Changes reconstructed energy response.
- Apply multivariate reweighting.
  - Recover distributions, but not the reconstructed energy response!





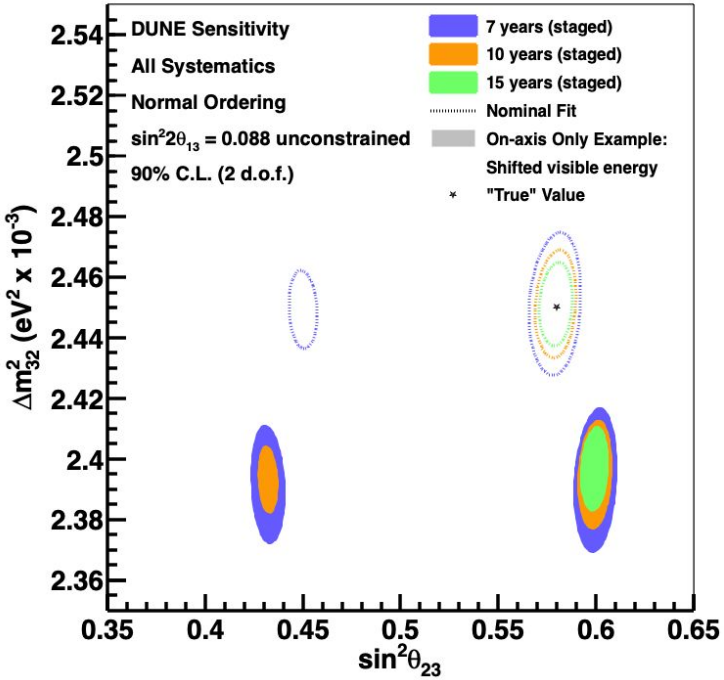
Projecting weights in true variables

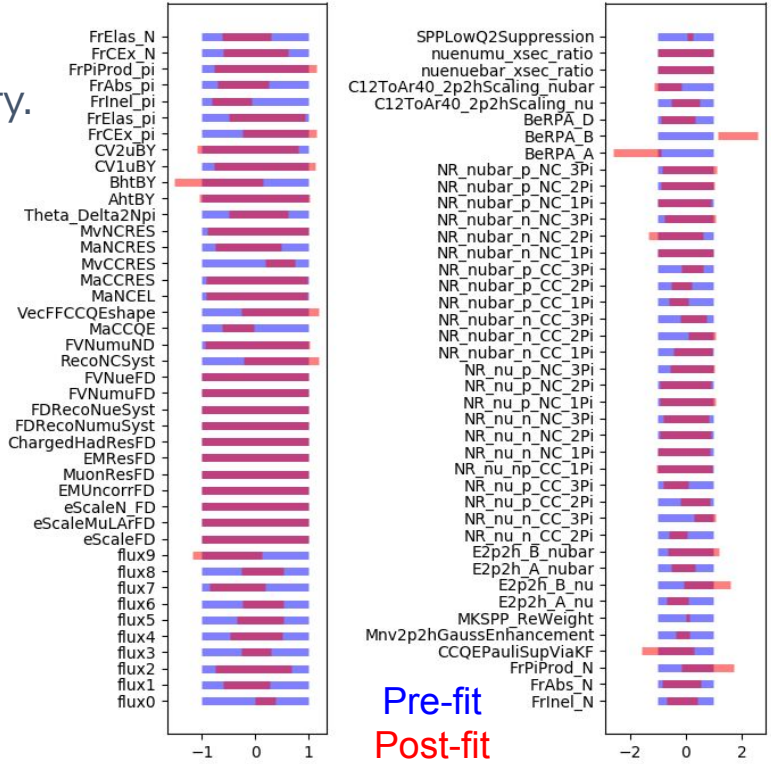
- Weights are **projected** in **true** variables using a **second boosted decision tree** and applied to far detector sample.
  - **Truth-level** BDT is train to predict output of **detector-level** BDT using training sample events.



Fit to missing proton energy mock data

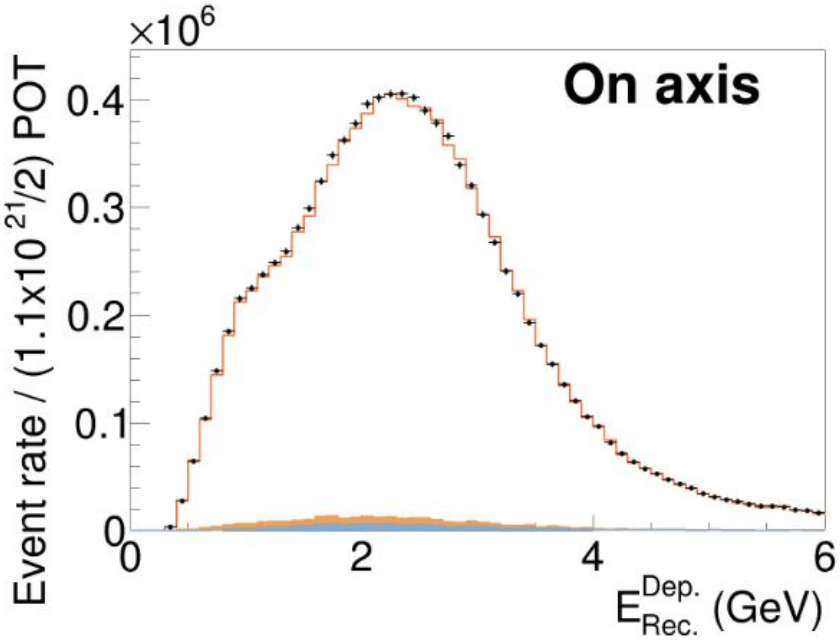
- **Good fit** at the **near detector**, with most flux and cross-section parameters within their prior uncertainty.
- **Biased oscillation measurements** at the far detector!

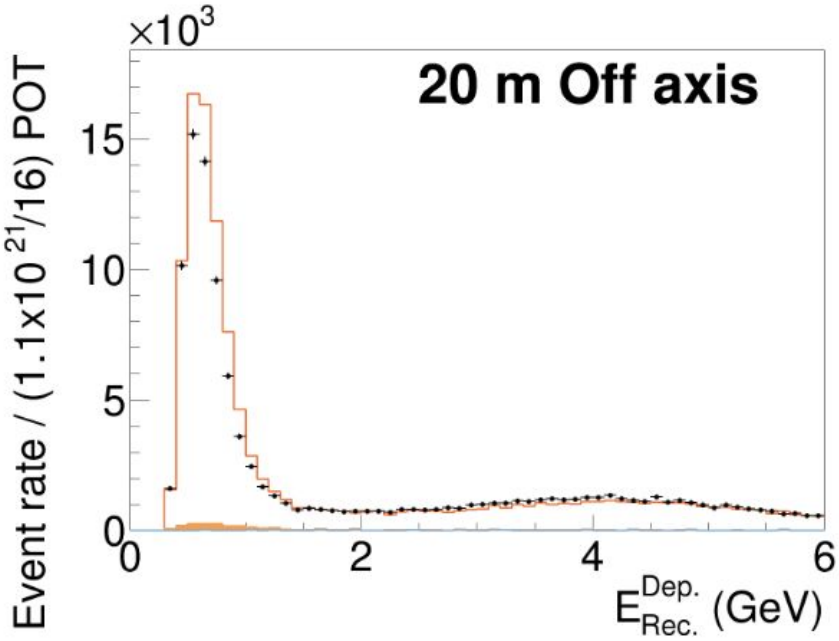




Missing proton energy off-axis

- Broken **energy response** model can be seen in **off-axis** near detector data!





Summary

- A **multivariate** event **reweighting** technique was used to estimate impact of **interaction mismodeling** in DUNE long-baseline neutrino oscillation analysis.
- Show impact of **model choice** (between two event generators) on oscillation analysis **without regeneration** of entire MC sample
- **Designed** interaction model specifically aimed at illustrating **reconstructed energy biases**.
  - Demonstrate **ND** can deal with this by going **off axis**.
- For more details:
  - DUNE TDR Volume II , arXiv:2002.03005

Supplementary slides

Implementation details

- Generator reweight:
  - https://github.com/cvilelasbu/GeneratorReweight/
- Missing proton energy:
  - https://github.com/cvilelasbu/MagicRW

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_{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:
    - se kinematics: δp_T, $\delta\alpha_T$ and $\delta\varphi_T$
    - ctly one pion and one proton:
    - se variable: δp_{TT}

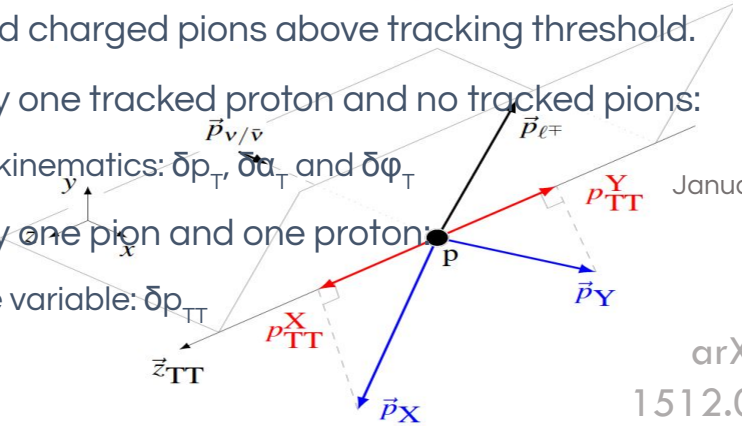
Tracking thresholds:

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

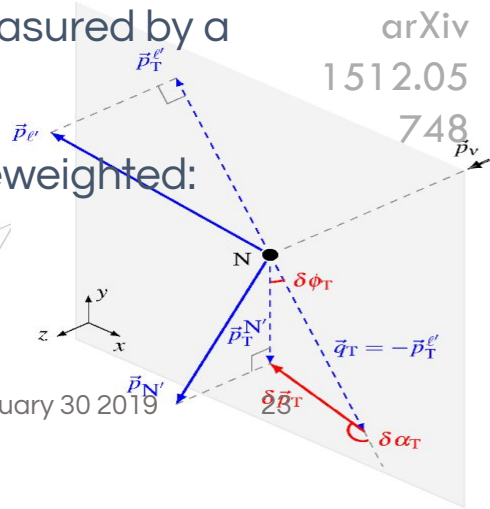
Momentum resolution: 5%

Angular resolution: 2 mrad

From STT document at ND workshop

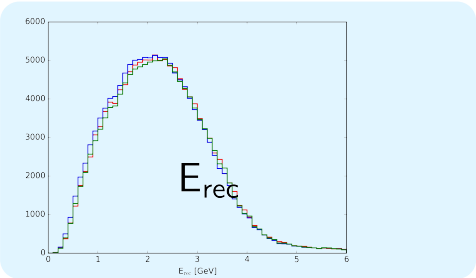


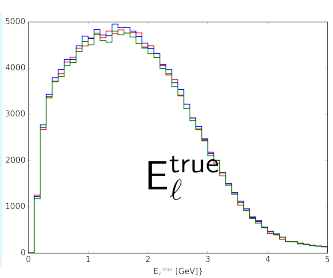
arXiv 1512.09042

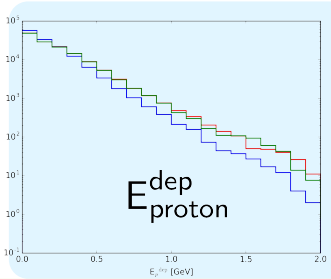


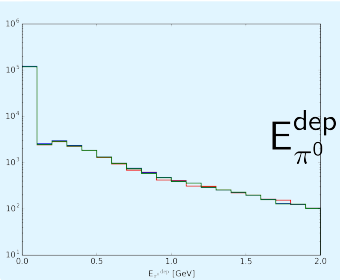
arXiv 1512.05748

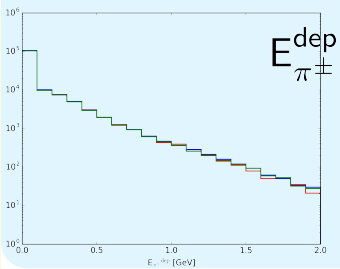
TRANSVERSE VARIABLES, REWEIGHTED

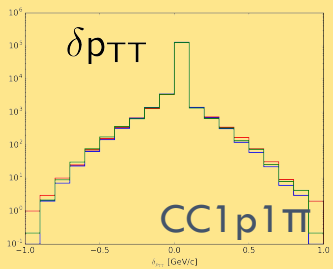


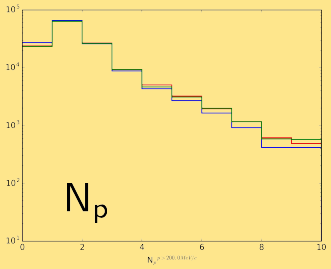


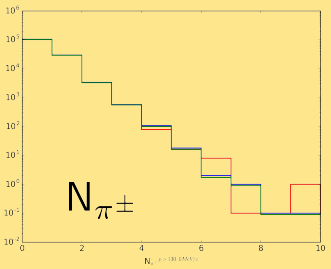


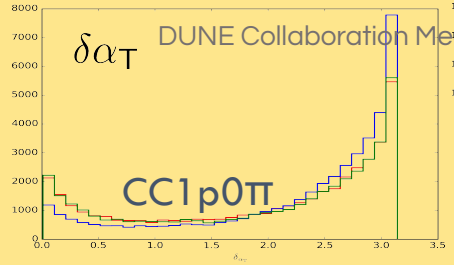


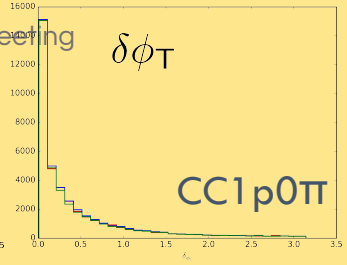


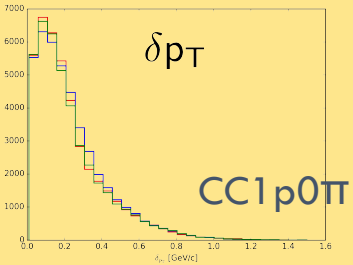








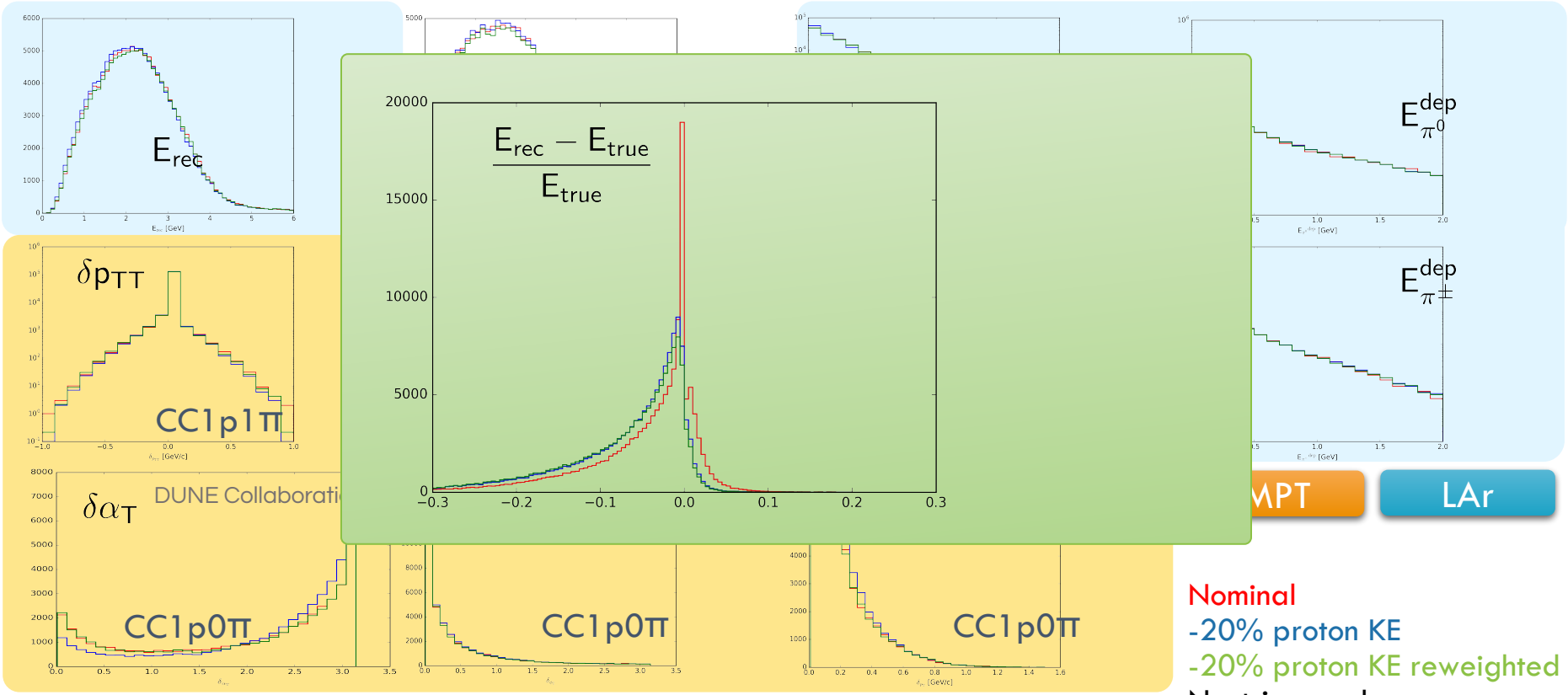




MPT LAr

Nominal
-20% proton KE
-20% proton KE reweighted
Neutrino-mode

TRANSVERSE VARIABLES, REWEIGHTED



Nominal
-20% proton KE
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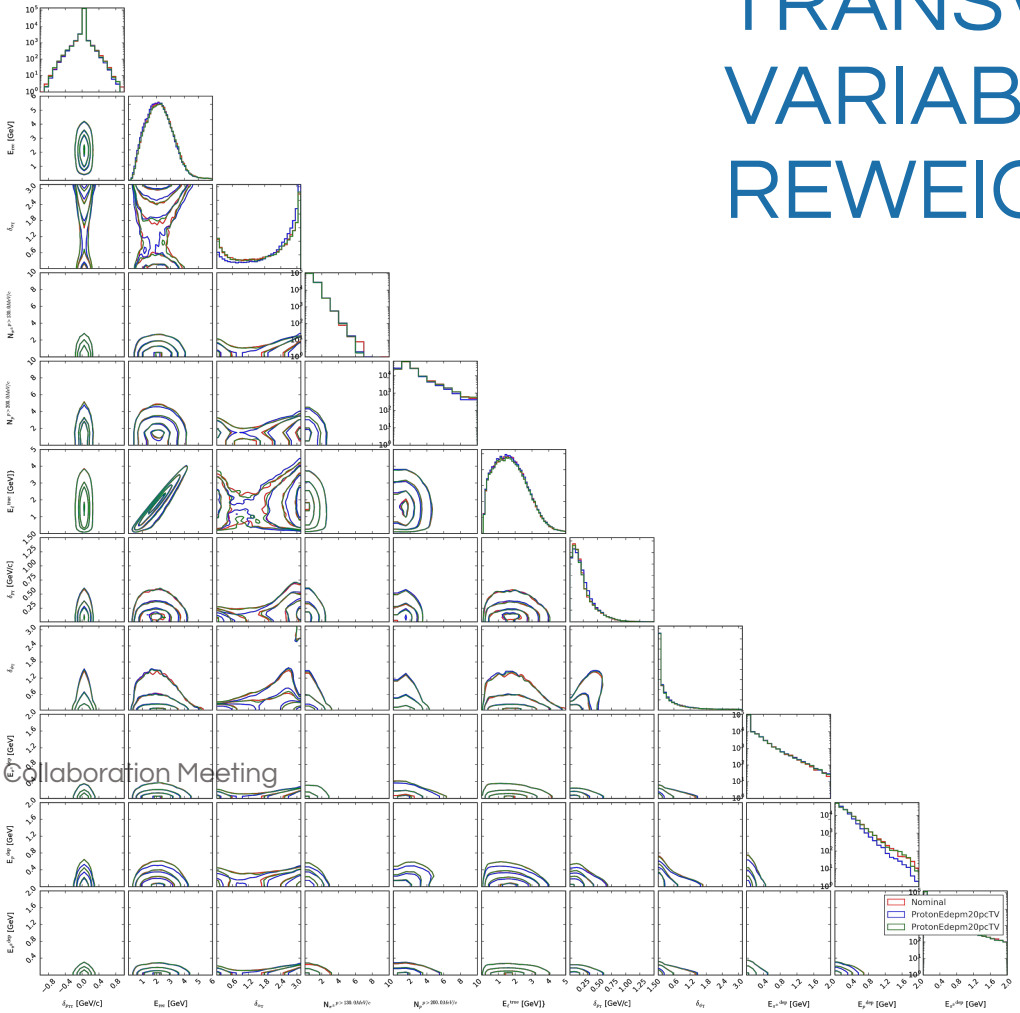
TRANSVERSE VARIABLES, REWEIGHTED

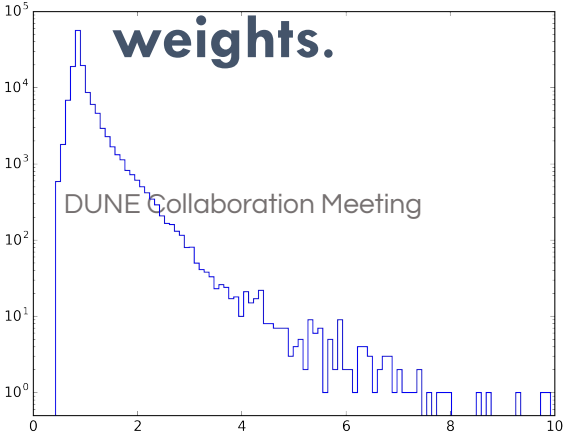


(AN ATTEMPT AT) A SANITY CHECK

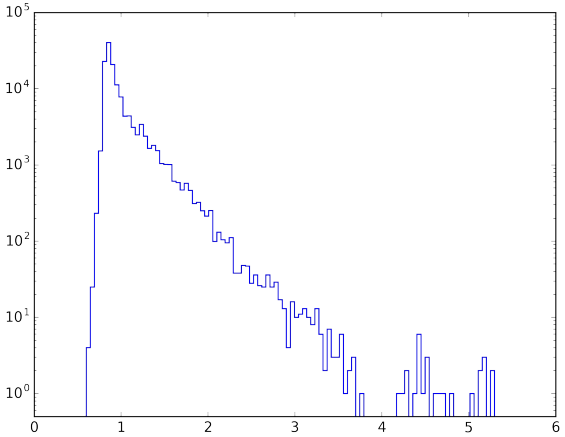
- If we had complete knowledge of the final state for every event we wouldn't expect this type of reweighting to work.
  - Or at least not without somehow "correcting" the E_{rec} response…
- But how would that manifest itself in the distributions we have been looking at?
- Try reweighting initial five "calorimetric" variables **plus** the true neutron kinetic energy, as if we had a 100% efficient neutron detector with perfect

(AN ATTEMPT AT) A SANITY CHECK

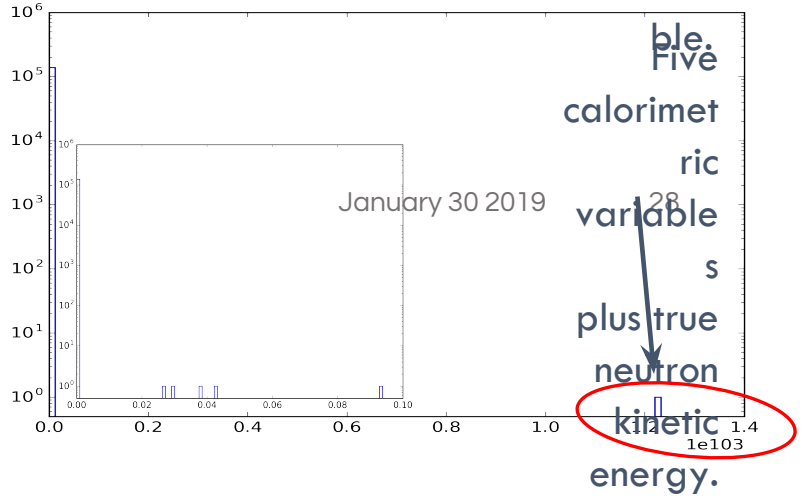
- Distributions of observables don't make a whole lot of sense, so look at distributions of **event weights.**



Five calorimetric variables plus six kinematic variables. Weights look reasonable.



Five calorimetric variables. Weights look reasonable.



Five calorimetric variables plus true neutron kinetic energy.