DUNE-PRISM

PHYSICS OPPORTUNITIES AT THE NEAR DUNE DETECTOR HALL

FERMILAB

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Stony Brook University

Cristóvão Vilela

WHY DO WE NEED A DUNE-PRISM?

- In reality

Alan Bross, this morning

$$\frac{dN_{\nu}^{det}}{dE_{rec}} = \int \phi_{\nu}^{det}(E_{\nu}) * \sigma_{\nu}^{target}(E_{\nu}) * T_{\nu_{\mu}}^{det}(E_{\nu}, E_{rec})\ dE_{\nu}$$

- 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.

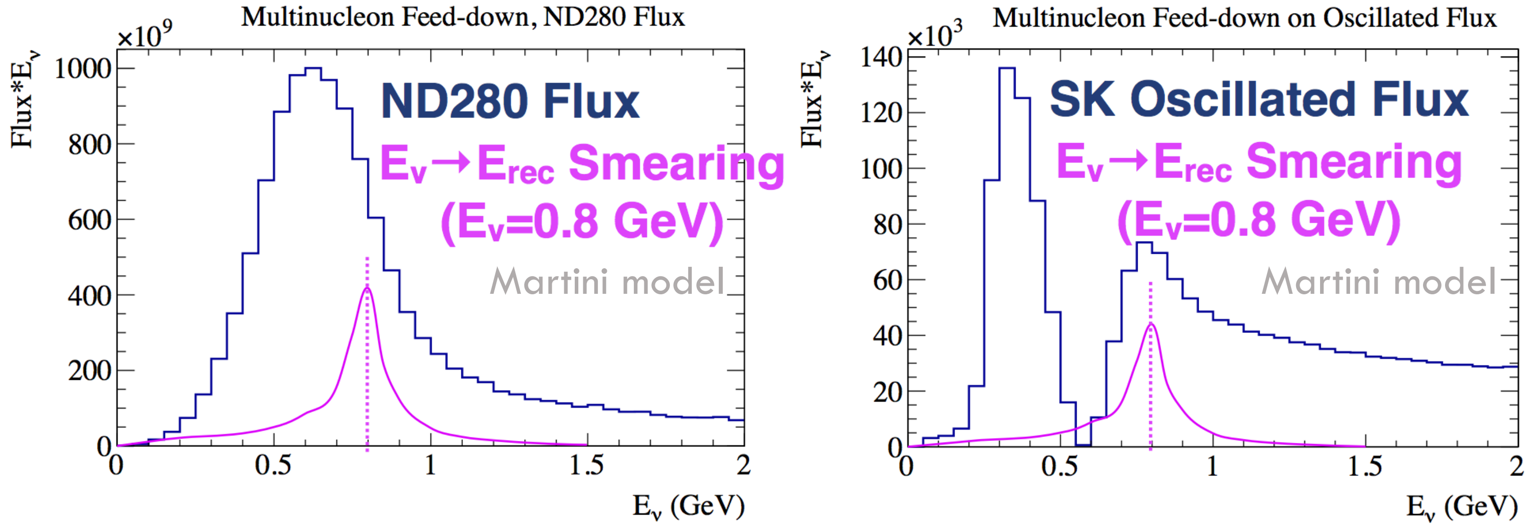
$$E_\nu^{cal} = E_\ell + \epsilon_n + \sum_{i=1}^{n} (E_{p'_i} - M) + \sum_{j=1}^{m} E_{h'_j}$$

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

Sum over mesons:
- If undetected, ~m_m bias!
- How many?
- How is energy shared?

NEAR DETECTOR CONSTRAINTS
AN EXAMPLE FROM WATER CHERENKOV

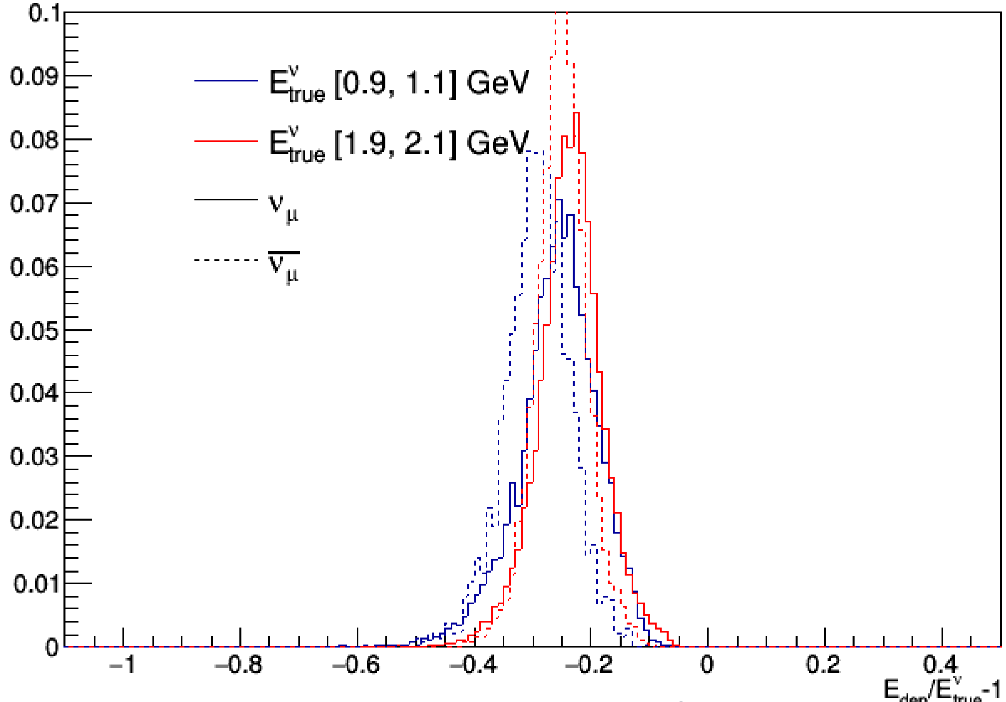
- Neutrino flux is different in far detector compared to near detector: neutrinos oscillate!



- 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

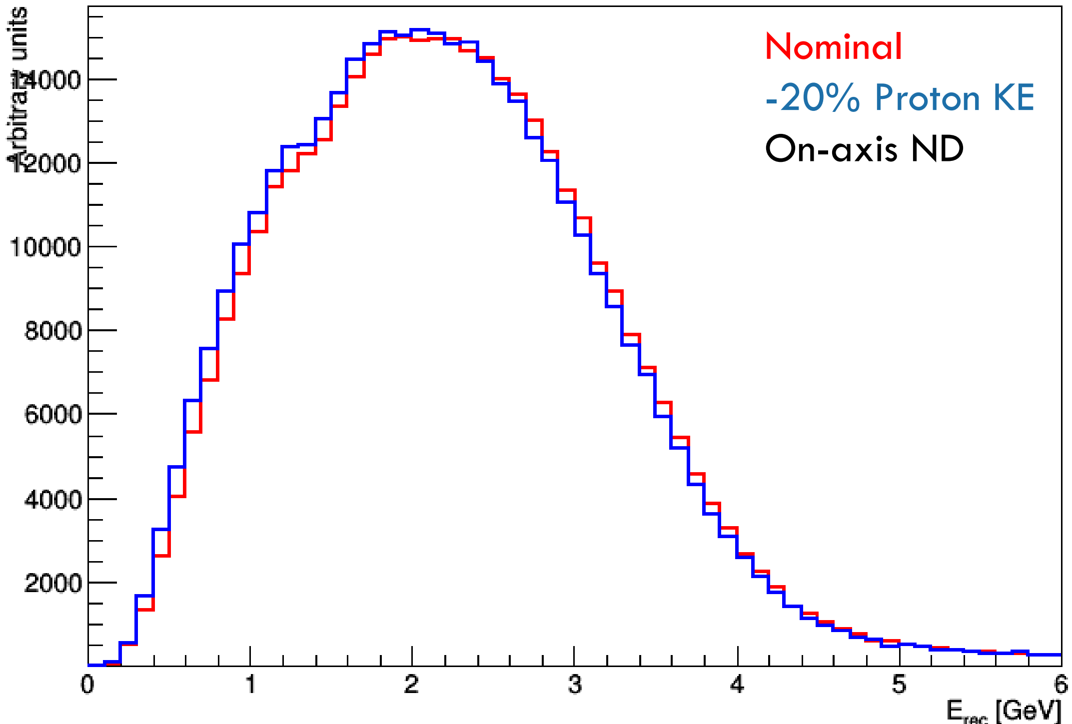
- Significant feed-down effects due to "missing energy" in calorimetric neutrino energy reconstruction.
  - Mis-modelling will lead to bias!



- Look at fake data to study the impact of nucleon kinematics mis-modelling on oscillation analyses.

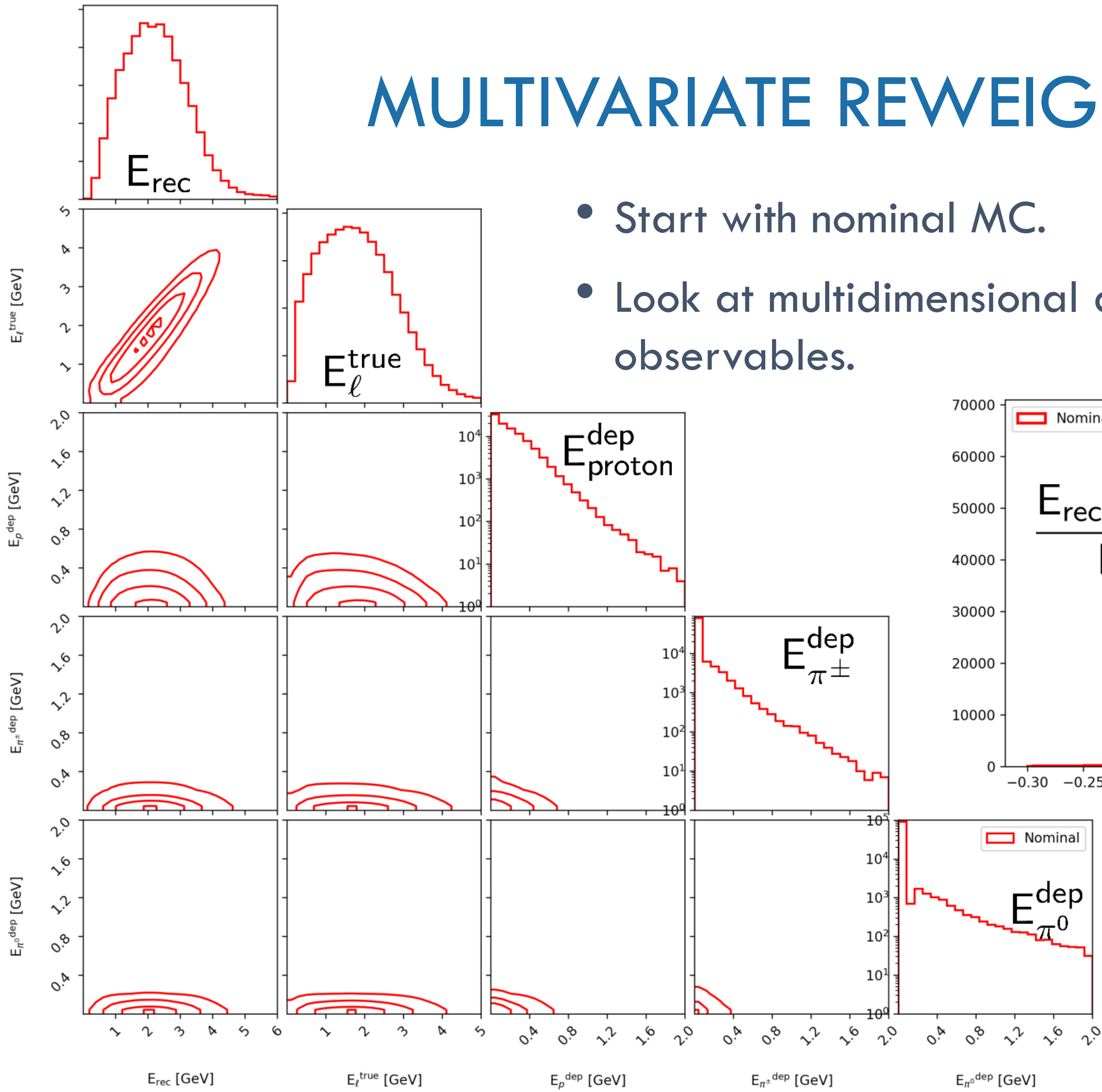
20% MISSING PROTON ENERGY

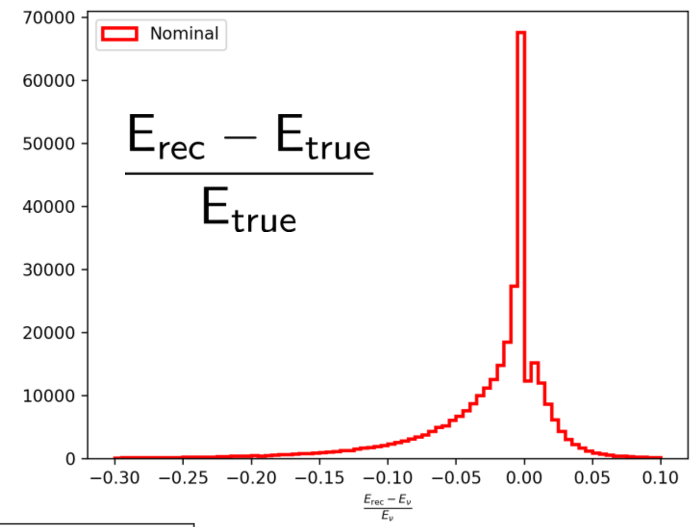
- For each event generated with a nominal interaction model, scale proton energy deposits in the LAr detector by 80%.
  - Difference is given to neutrons.
- Difference in reconstructed energy spectra at on-axis LAr ND clearly seen.
  - If we saw this in our data, we would tune our cross-section model to remove the discrepancy. But would this "fix" the true to reconstructed energy relation?



MULTIVARIATE REWEIGHTING

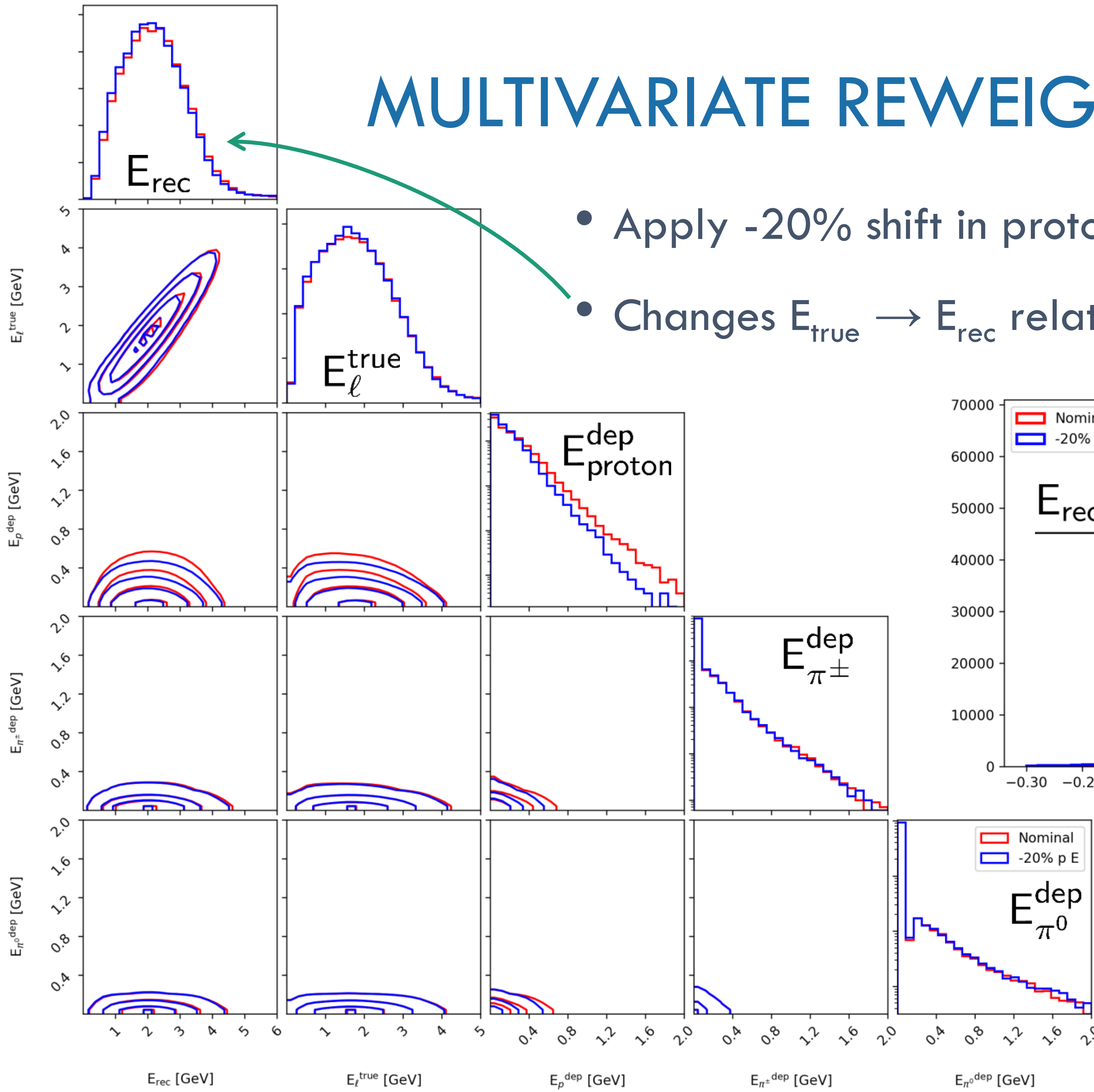
- Start with nominal MC.
- Look at multidimensional distribution of observables.

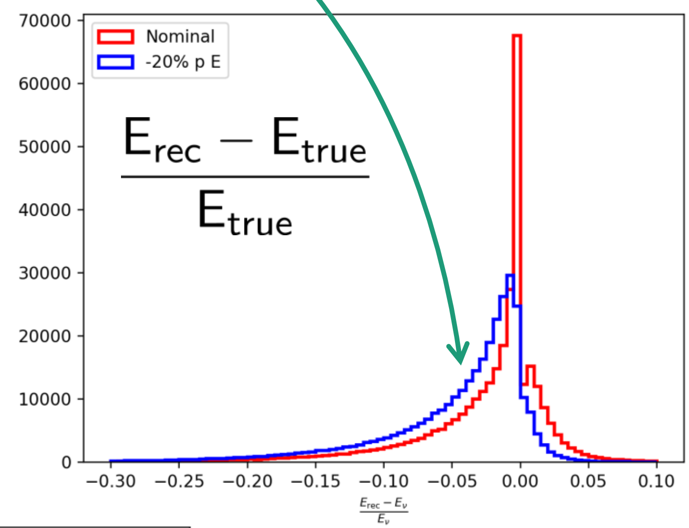




MULTIVARIATE REWEIGHTING

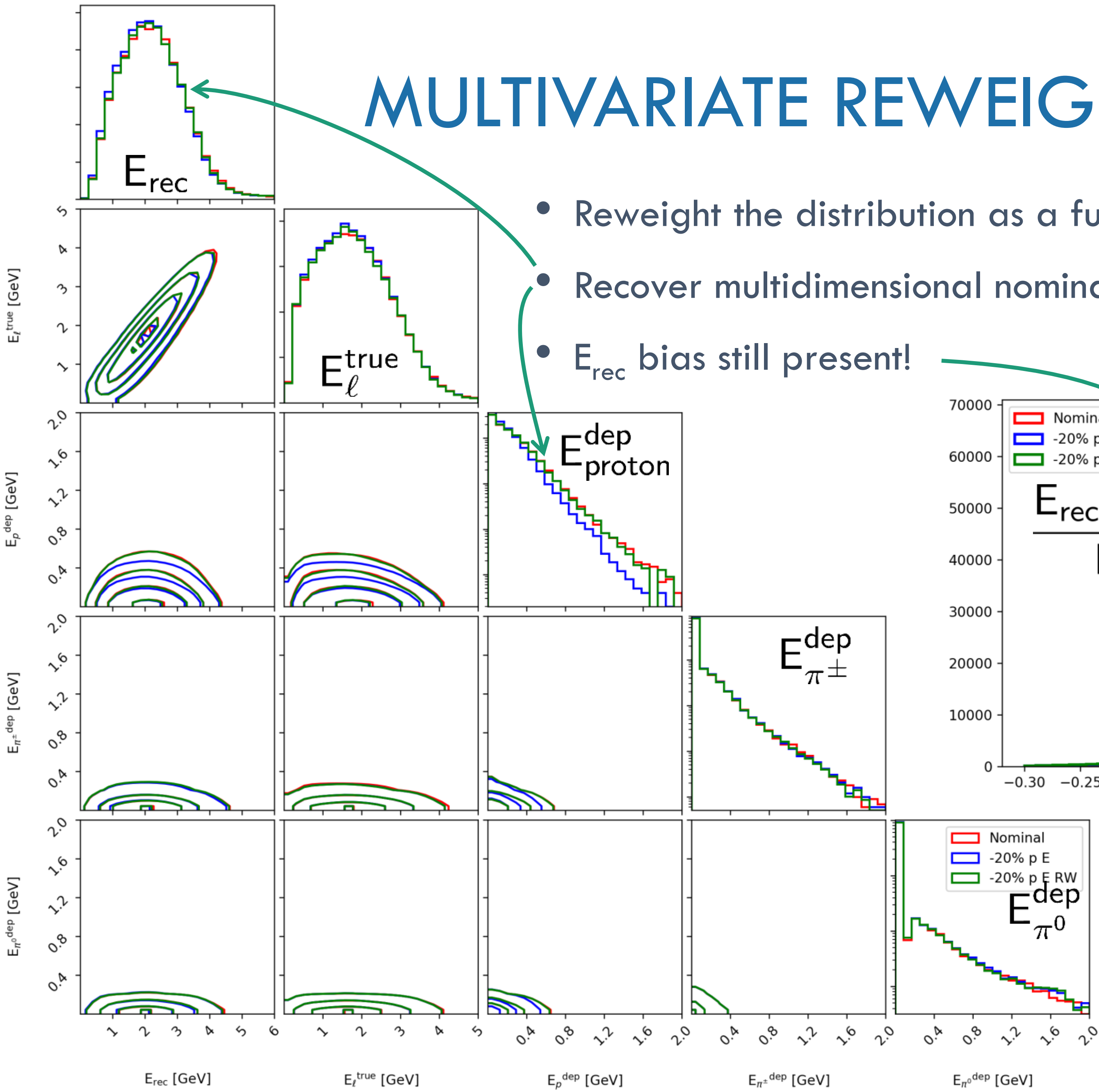
- Apply -20% shift in proton deposited energy.
- Changes $E_{true} \rightarrow E_{rec}$ relation.

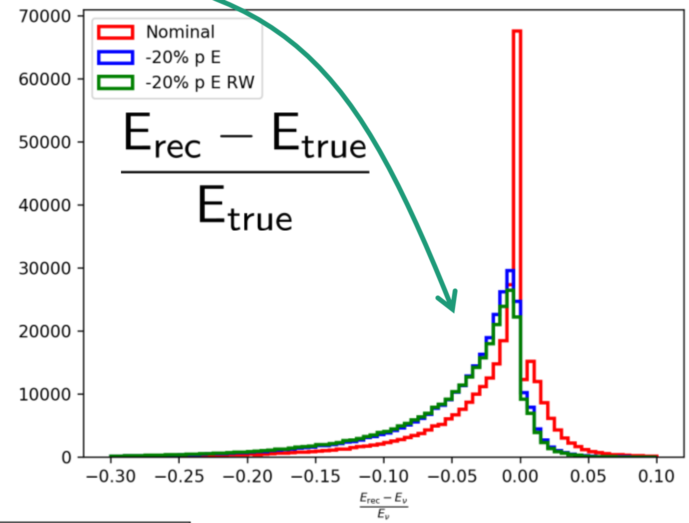




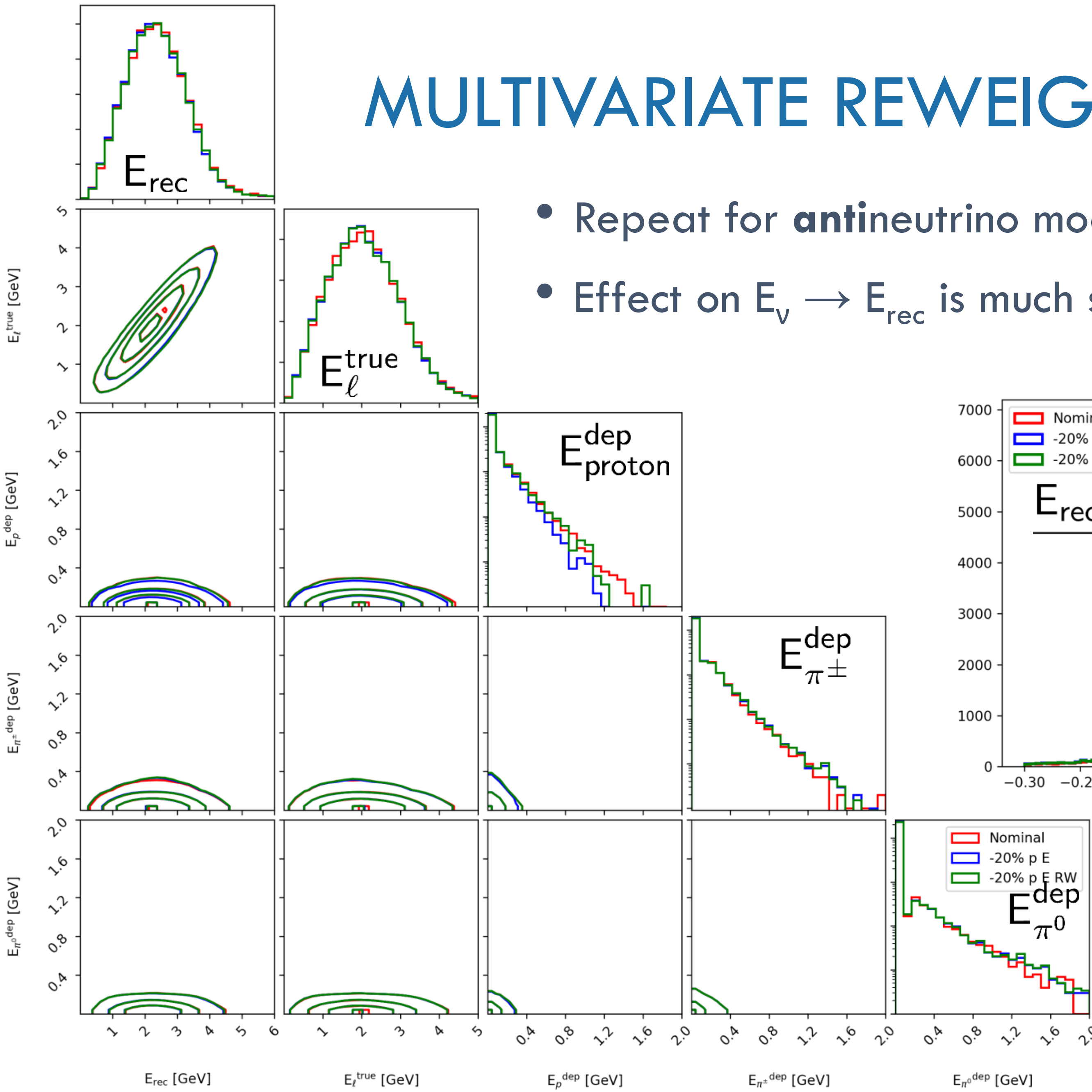
MULTIVARIATE REWEIGHTING

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

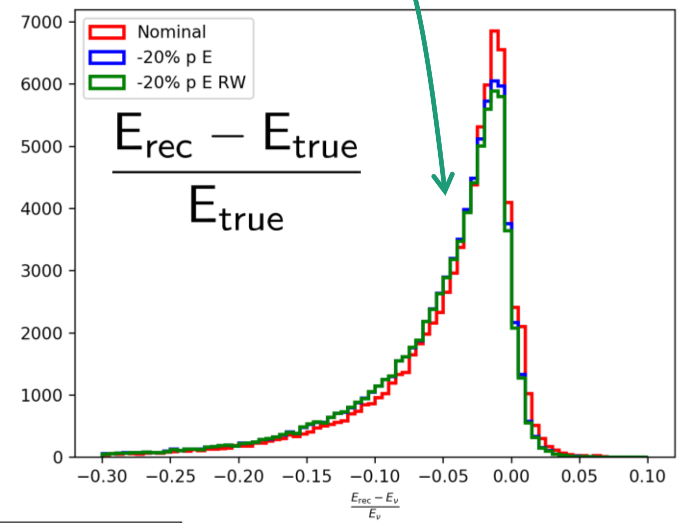




MULTIVARIATE REWEIGHTING

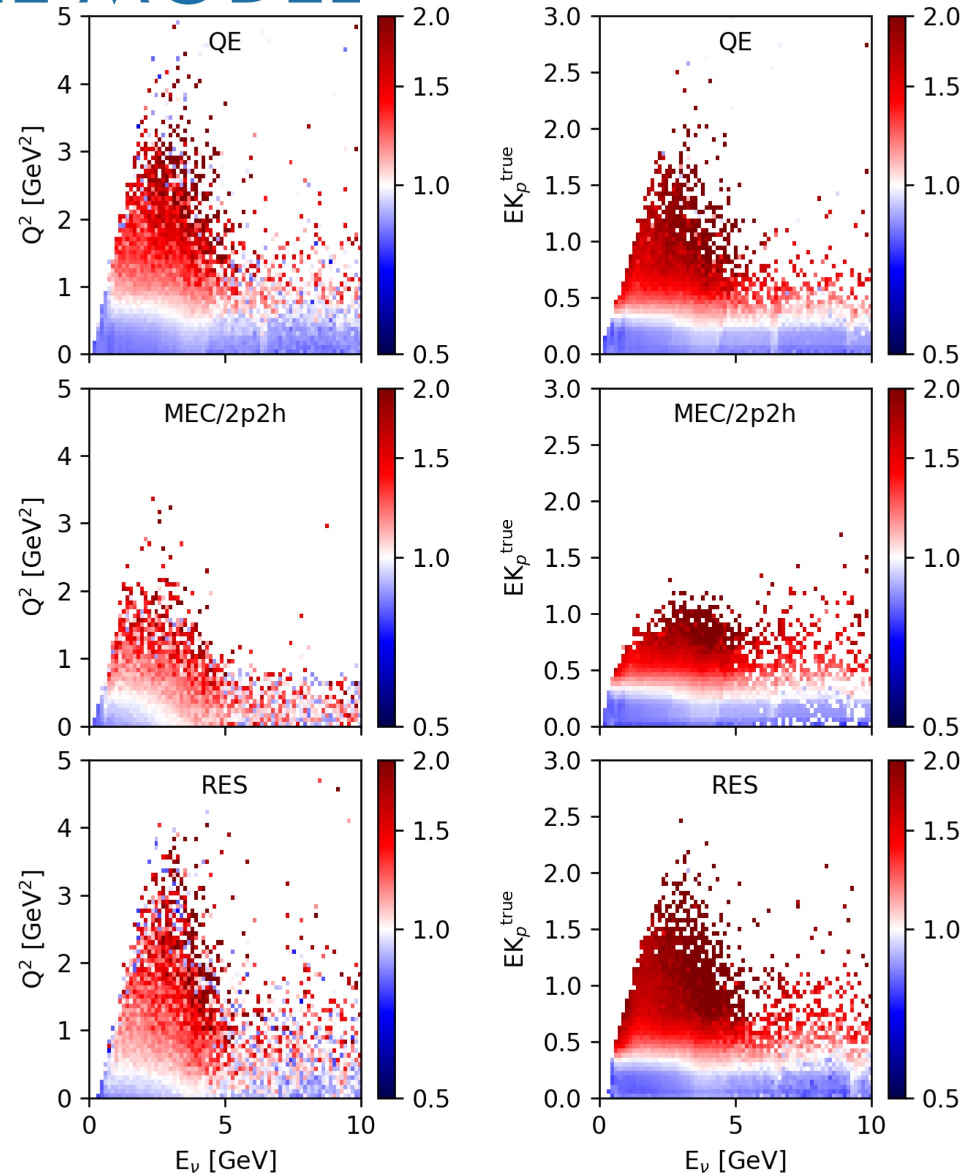


- Repeat for **anti**neutrino mode.
- Effect on $E_\nu \longrightarrow E_{rec}$ is much smaller.



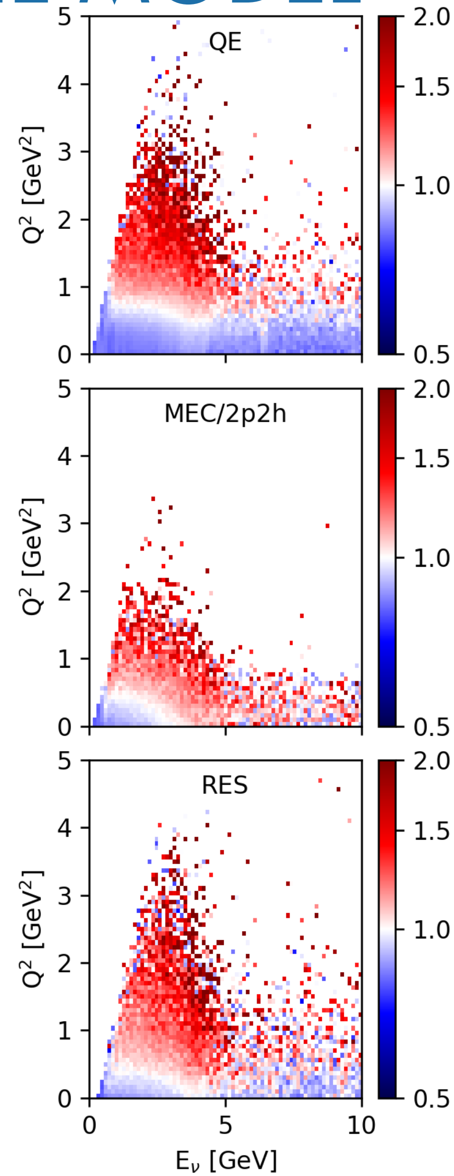
PROPAGATING THE MODEL

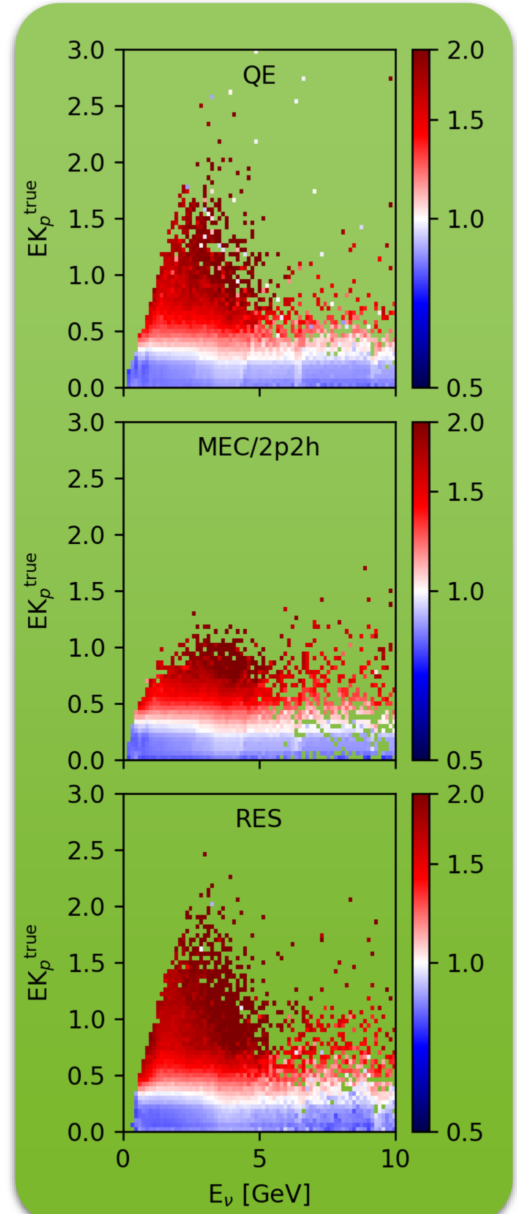
- To study the effect on oscillation fits, we need to propagate this model to far detector.
  - Also to off-axis near detector stops, to demonstrate the PRISM technique.
- Bin event weights in true variables useful for describing interaction models.
  - Get smoothly varying functions!
  - MVA treats interaction modes differently.
    - Even though it doesn't "know" about them!



PROPAGATING THE MODEL

- For this data set, use E_ν vs true proton kinetic energy.
- Extract weights separately for ν and anti-ν 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.

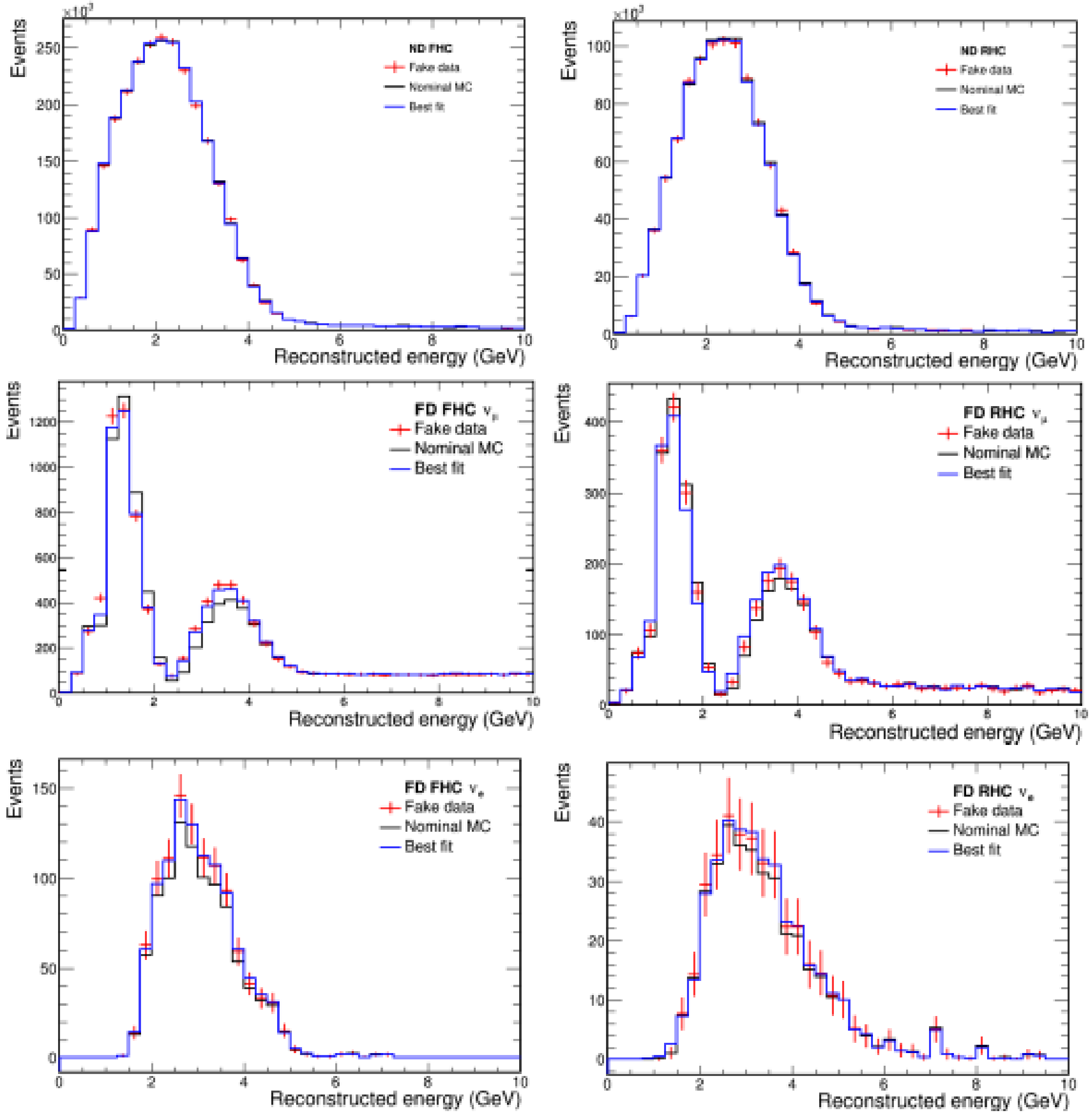




IMPACT ON OSCILLATION ANALYSIS

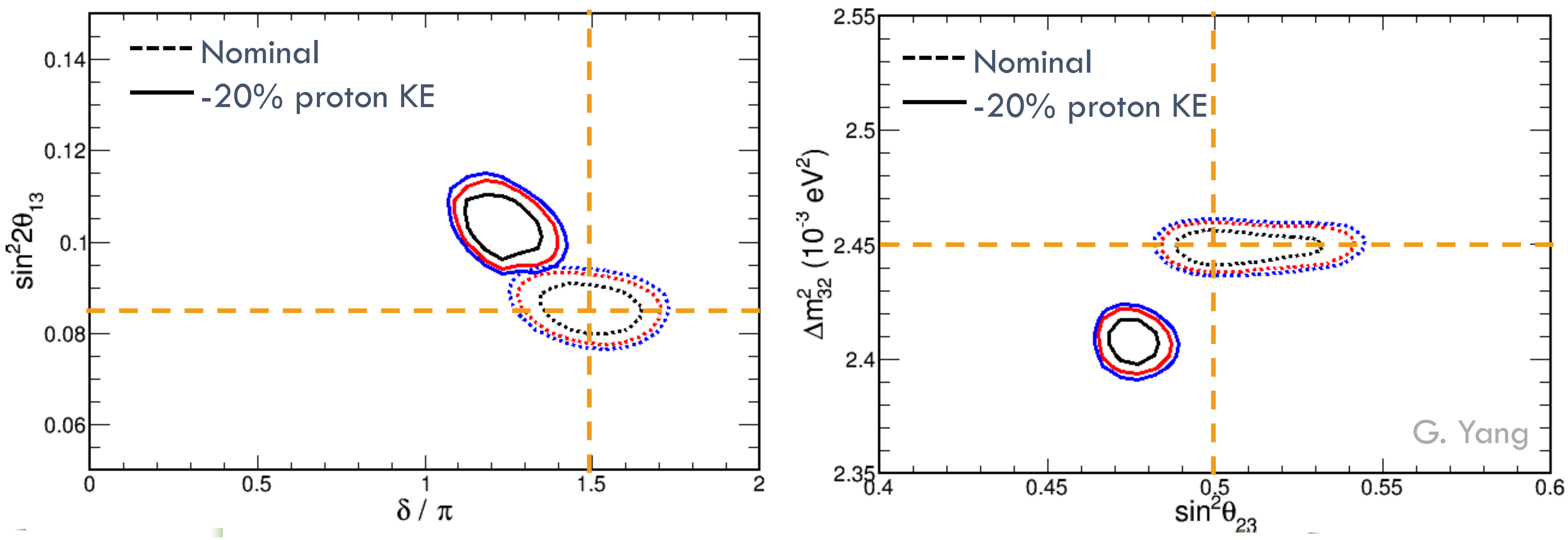
- Use CAFAna framework to fit fake data at near and far detector.
  - Fitter assumes the nominal model: get bias!
- Flux systematic parameters fixed at nominal value.
  - Get same results if allowed to vary in the fit.
- No large pulls on cross-section parameters.

$\chi^2/NDF = 81.6/202$



IMPACT ON OSCILLATION ANALYSIS

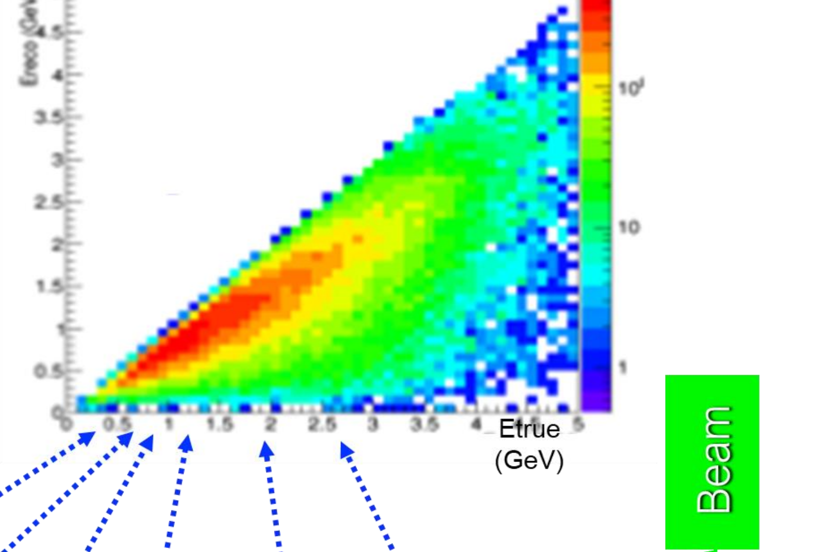
- A good fit is achieved at the on-axis near and far detectors, but significant biases are seen in the estimation of oscillation parameters.

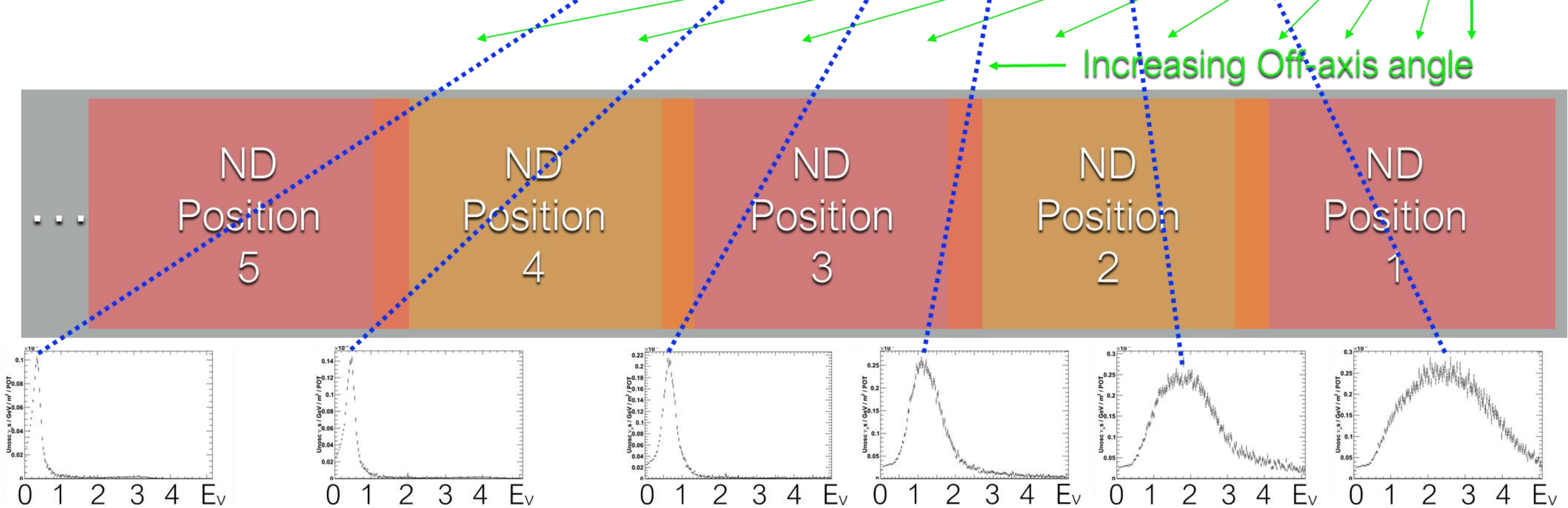


DUNE-PRISM

- 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.

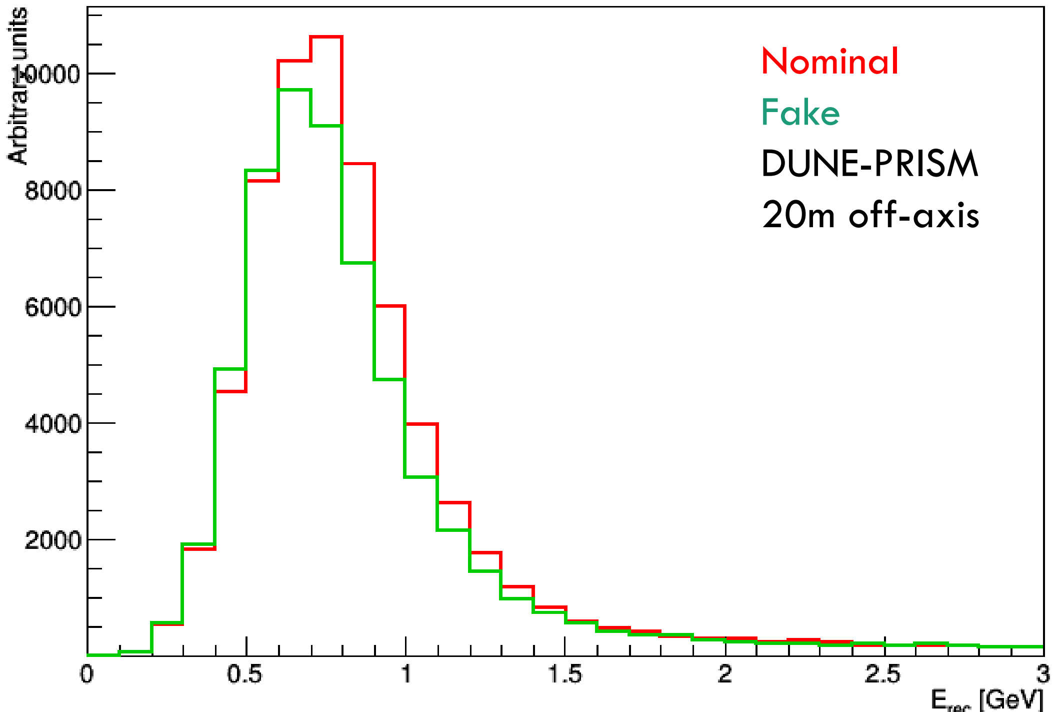
  * As given by the flux model.





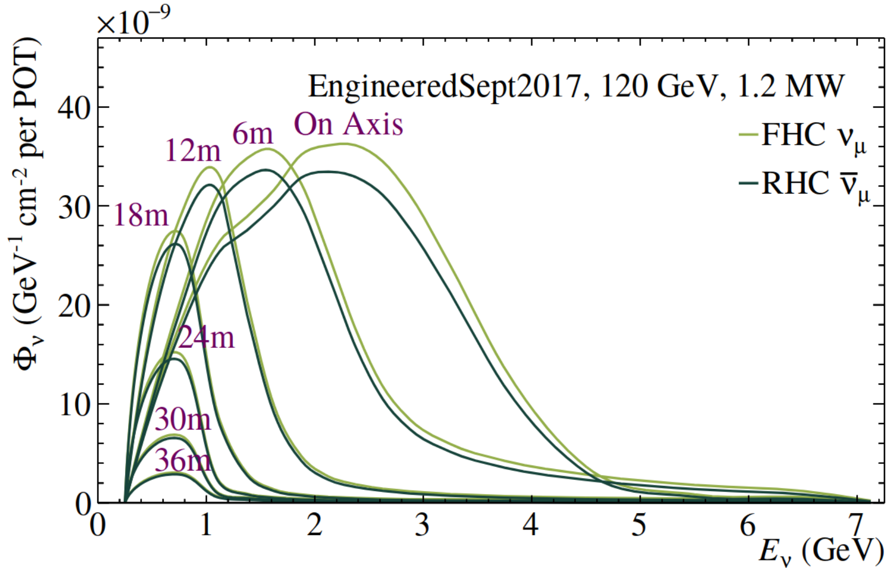
LOOK AT THE FAKE DATA THROUGH A PRISM

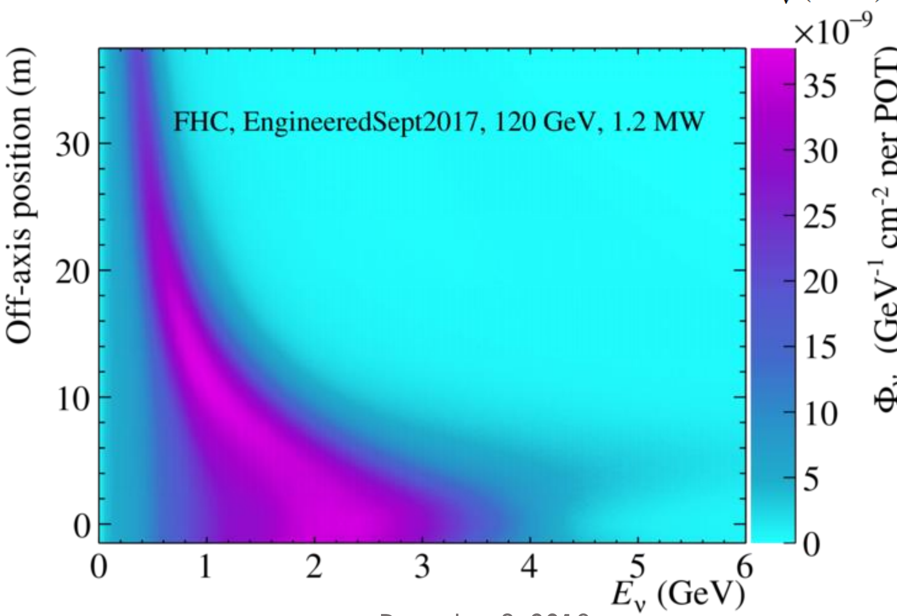
- Narrow fluxes at off-axis near detector positions give away the $E_{true} \rightarrow E_{rec}$ mismodelling.
- Cross-section parameters in the model fitted to on-axis data didn't move much from nominal values, as intended.
- Near detector best-fit prediction is significantly different from "observed" fake data at 20 m off-axis.



OFF-AXIS ANGLE SPANNING DETECTOR

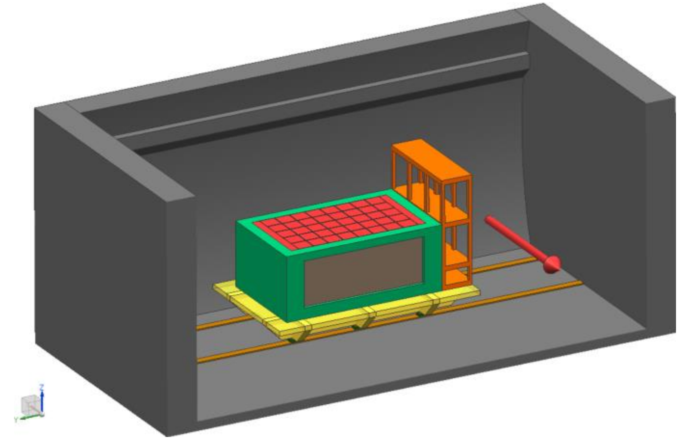
- Moving the LAr near detector horizontally (e.g., on rails) in a direction transverse to the neutrino beam would result in a **PRISM**.
- At 574 m from the target, a lateral travel of around 33 m would cover the range of fluxes necessary to get down to 2nd oscillation maximum energies.
  - Beyond 33 m flux shape doesn't change much and flux drops rapidly.

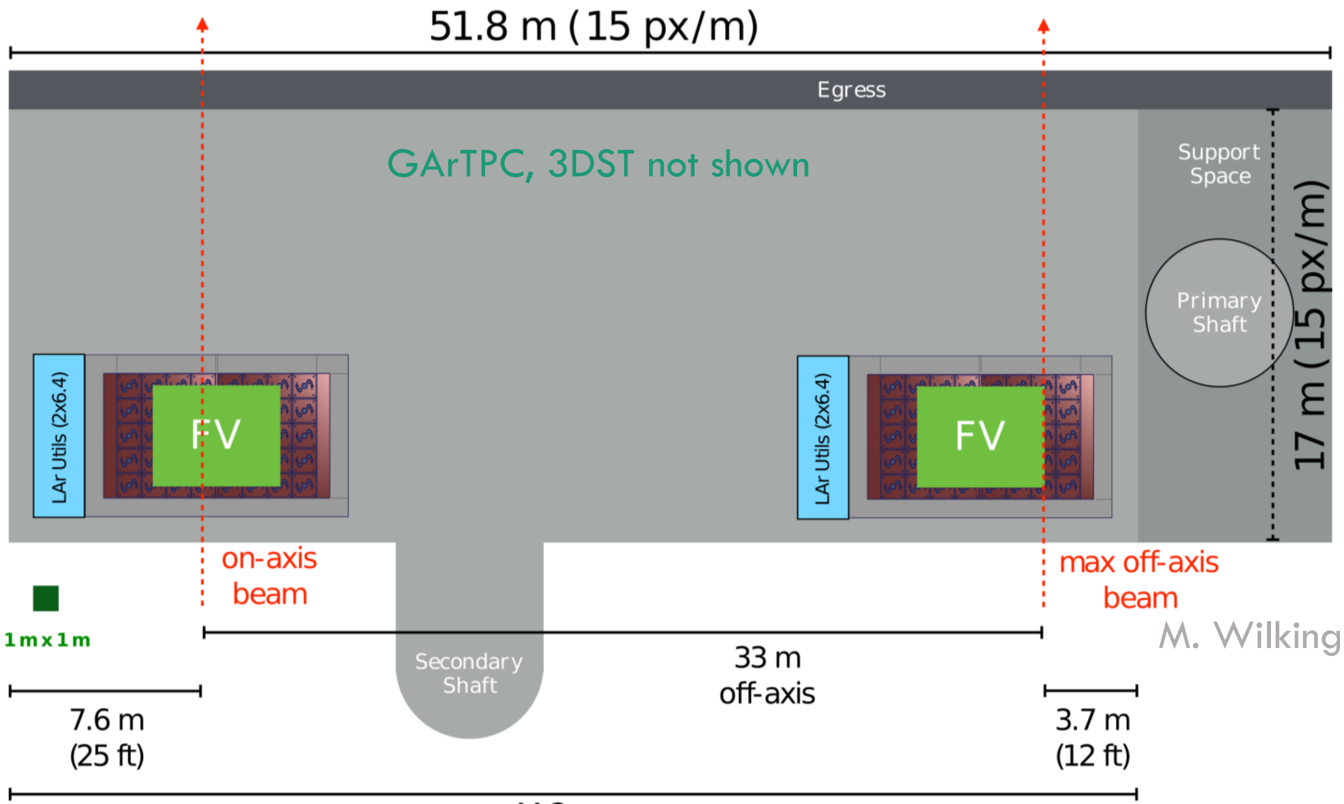




MOVING THE DETECTOR

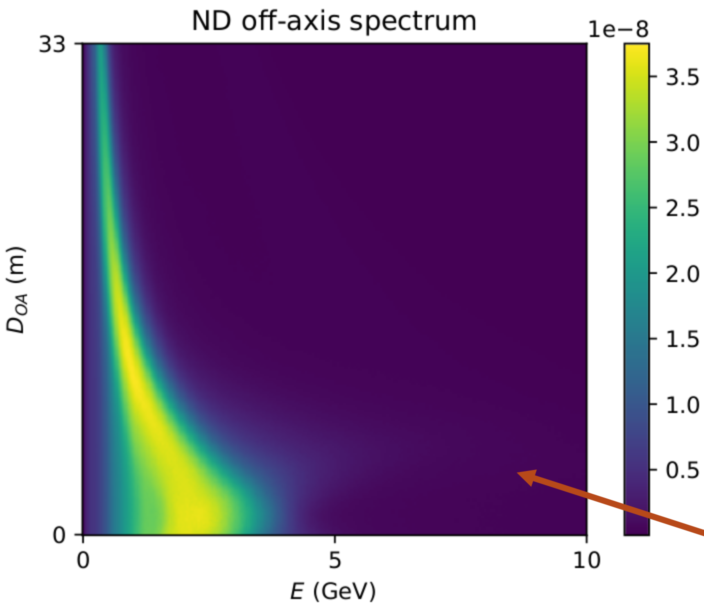
- Several engineering questions under study.
  - Hall size optimization.
  - Drive mechanism.
  - What moves? Cryo system, other detectors…

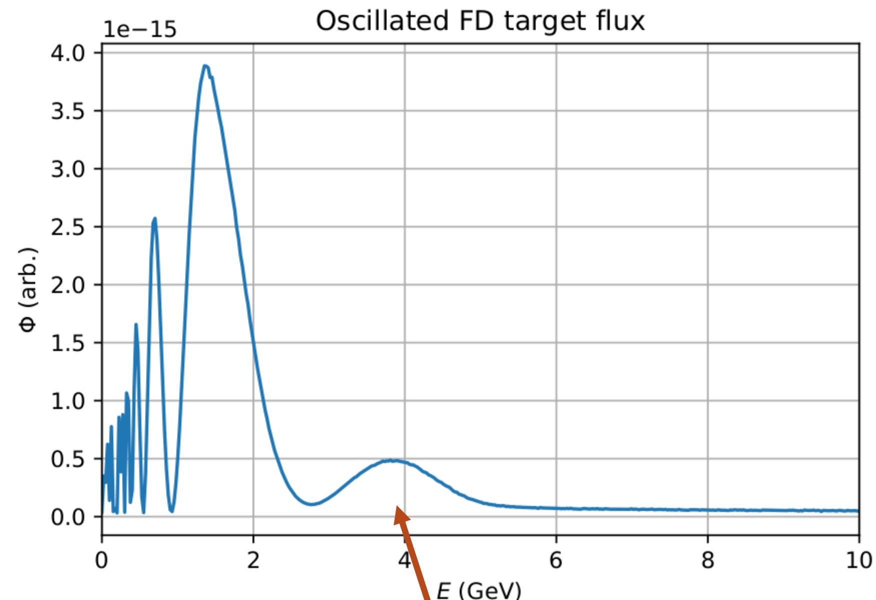




DATA DRIVEN OSCILLATION ANALYSIS
LINEAR COMBINATIONS

- 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.



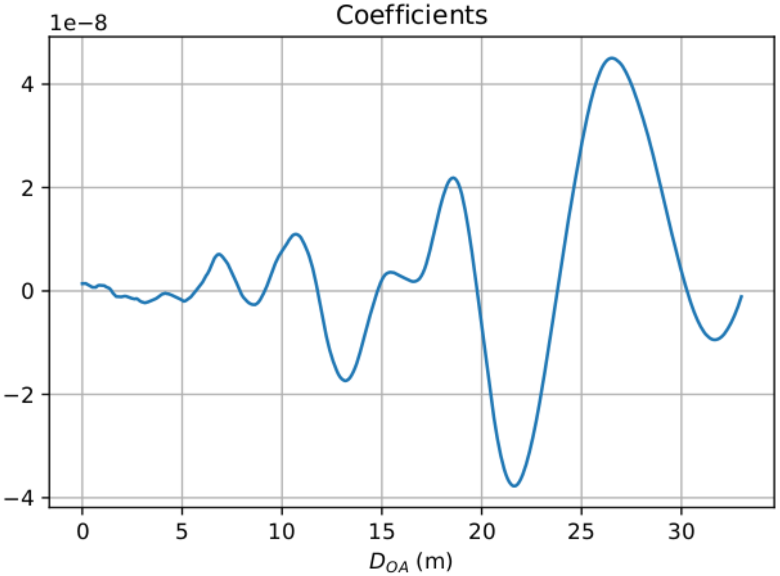


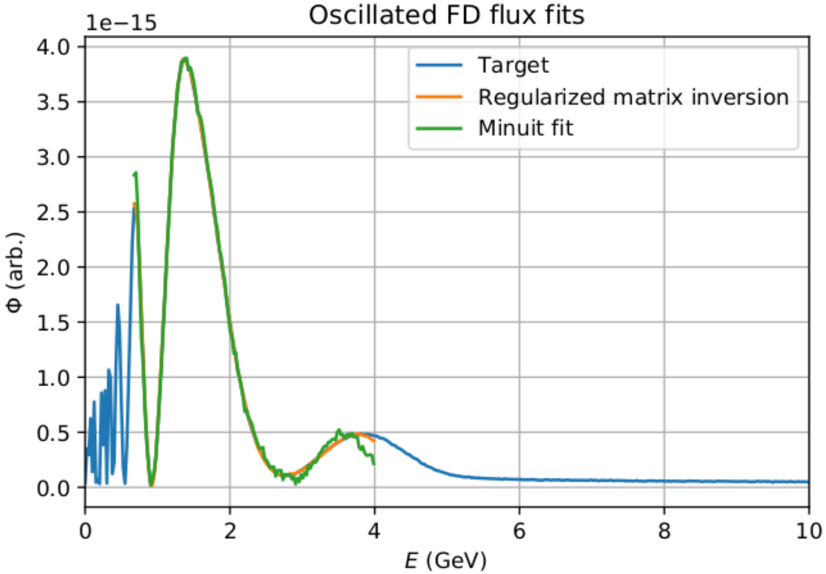
D. Douglas

- Can be written as a linear algebra problem: $\Phi^{ND}_{ij} c_j = \Phi^{FD}_i$
  - Solve for c_j

DATA DRIVEN OSCILLATION ANALYSIS
LINEAR COMBINATIONS

- Solution given by $\vec{c} = \left[\left(\Phi^{ND} \right)^T \Phi^{ND} + \Gamma^T \Gamma \right]^{-1} \left(\Phi^{ND} \right)^T \Phi_i^{FD}$
  - With Tikhonov regularization using a difference matrix Γ



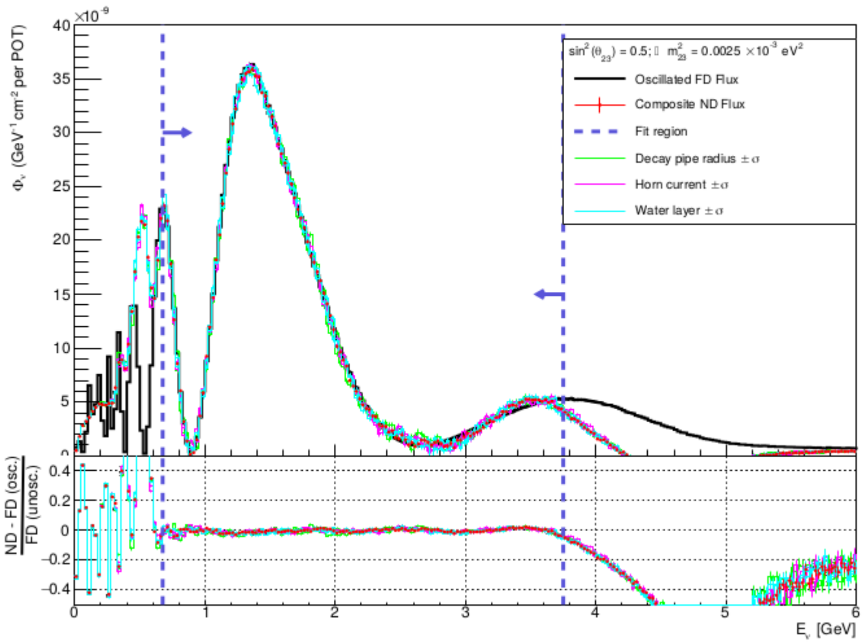


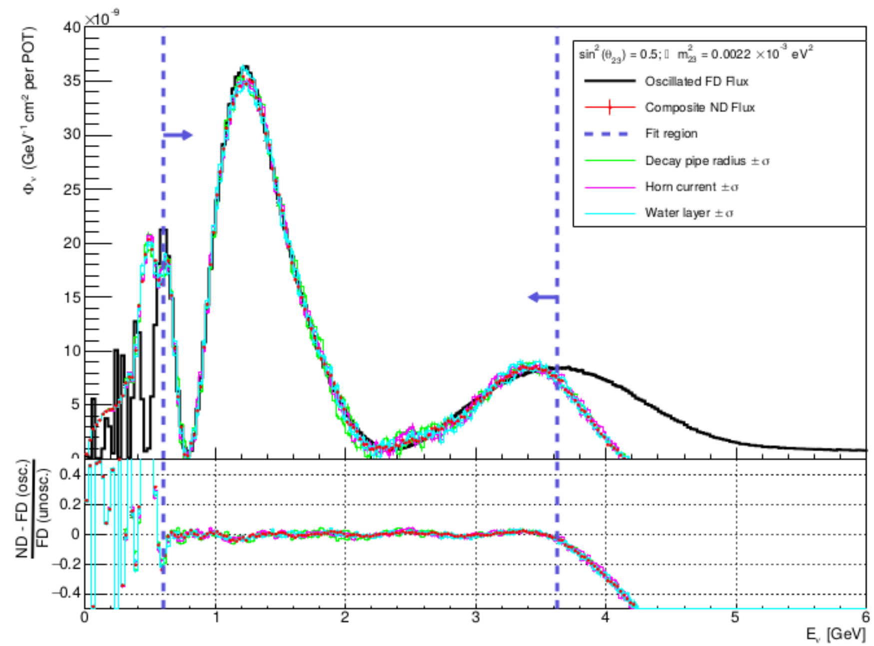
D. Douglas

- 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

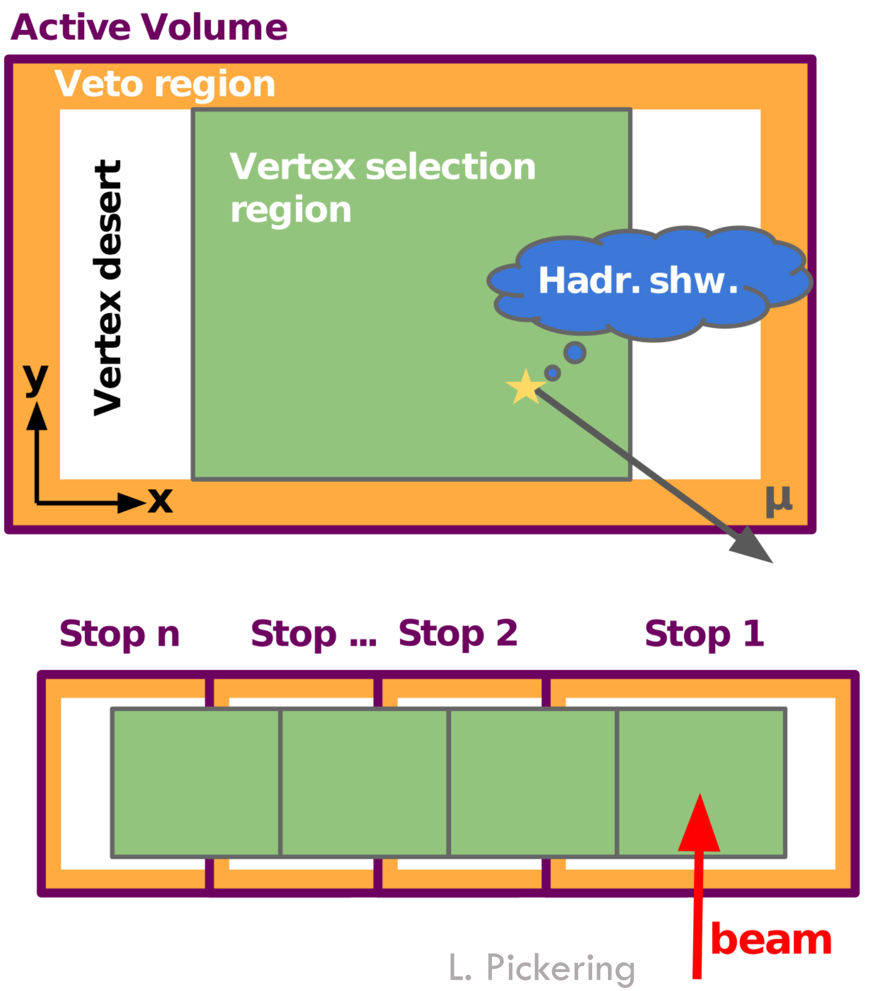
- Can reproduce both disappearance dips with linear combinations for a wide range of oscillation parameters.
- Beam uncertainties have a small effect on the linear combinations.
- Difficult to fit high energy bump completely.
  - Region close to the dip is well reproduced – most important to control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





HADRONIC CONTAINMENT

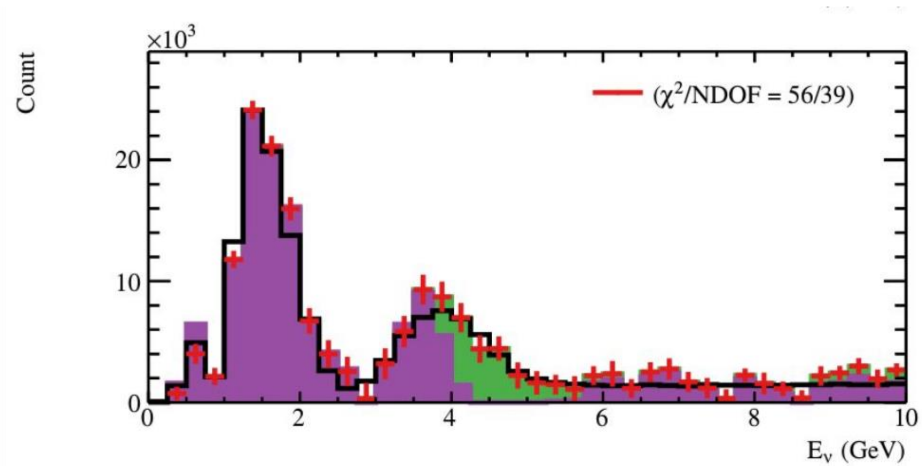
- A cut on activity on a veto region on the sides of the LAr near detector is used to remove events where the hadronic system escapes the detector.
- This introduces model-dependent loss of efficiency for events at with vertices close to the veto region.
- Mitigate the effect by fiducializing the volume, 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.

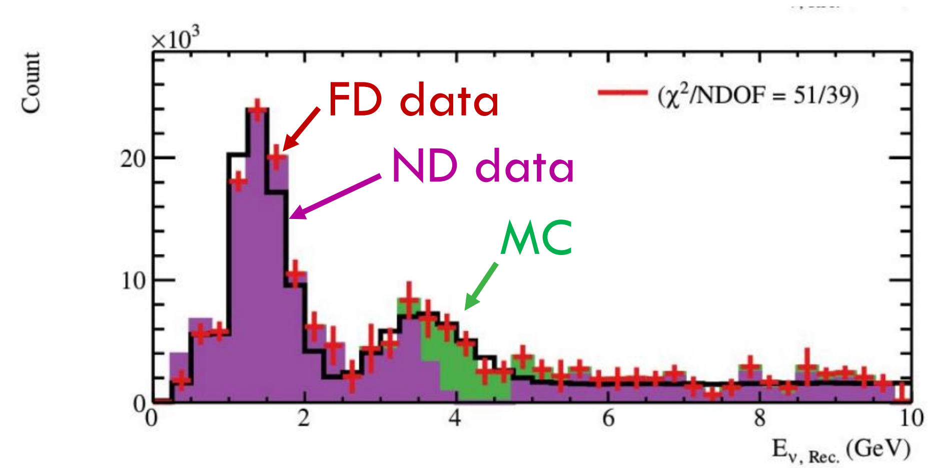


L. Pickering

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!





L. Pickering

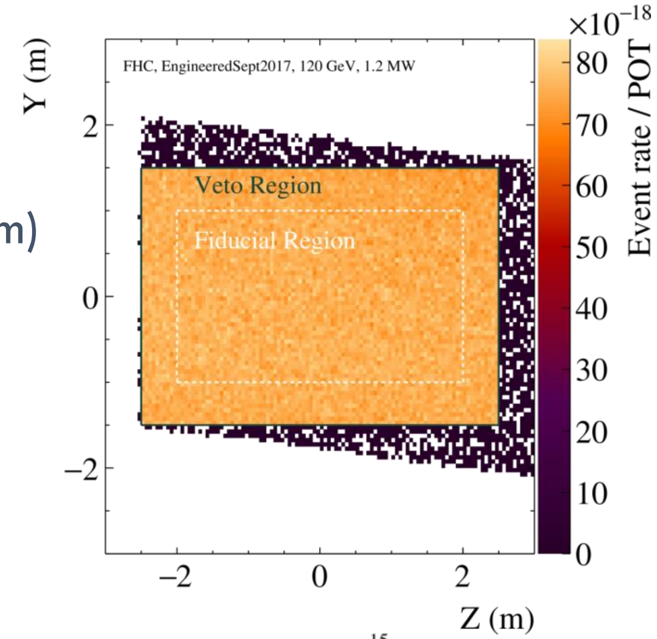
SUMMARY AND PROSPECTS

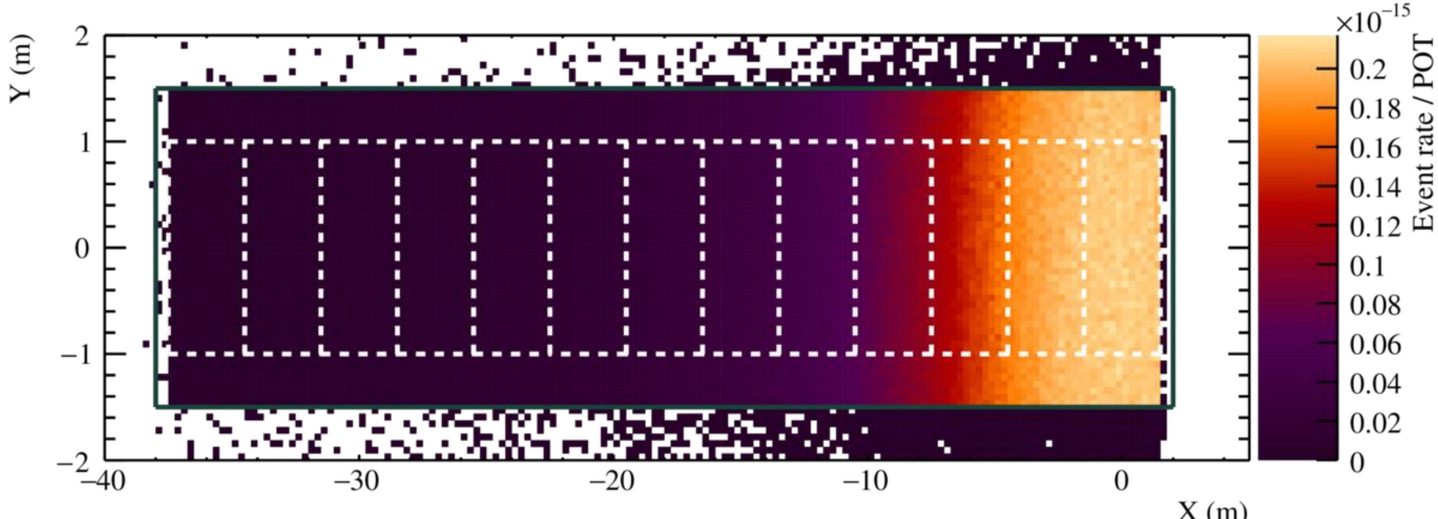
- Understanding true to reconstructed energy relation is crucial for precision long baseline oscillation measurements.
- Given the wide flux at the near detector (much wider than oscillation features) and undetected components in the final states, energy reconstruction bias can go unnoticed in an on-axis 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

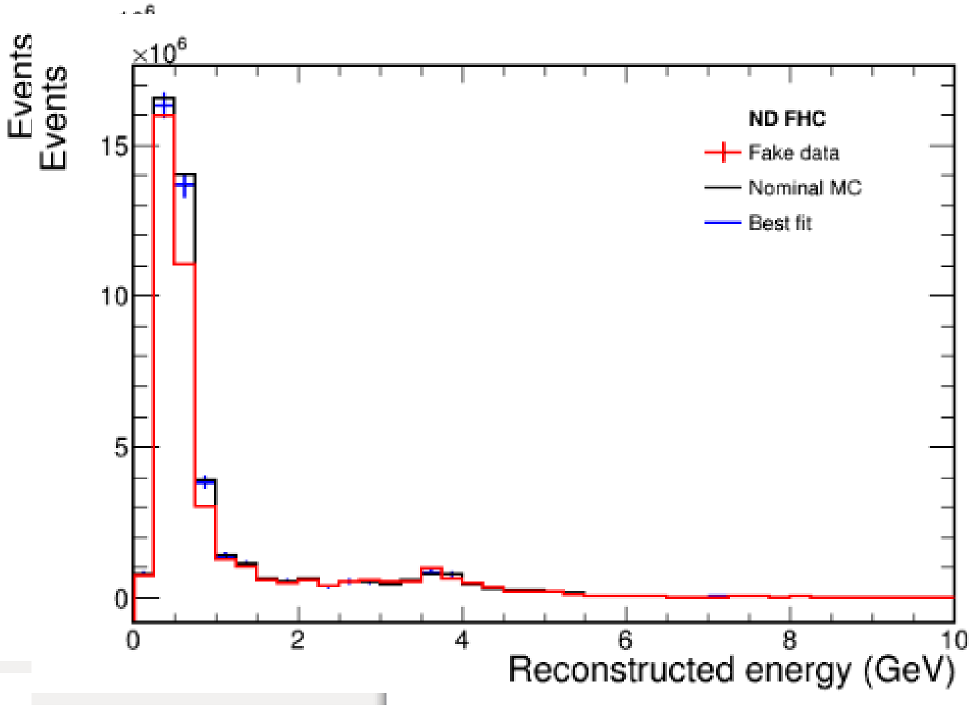
- Simulate GENIE events in a large liquid argon volume
  - 39 x 3 x 5 m.
- Divide large volume into 13 detector-sized (3 x 2 x 4 m) chunks, mimicking "stops" of a moveable detector.
- Define a veto region 50 cm from the detector edges in all directions.
  - Use this region to require hadronic system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

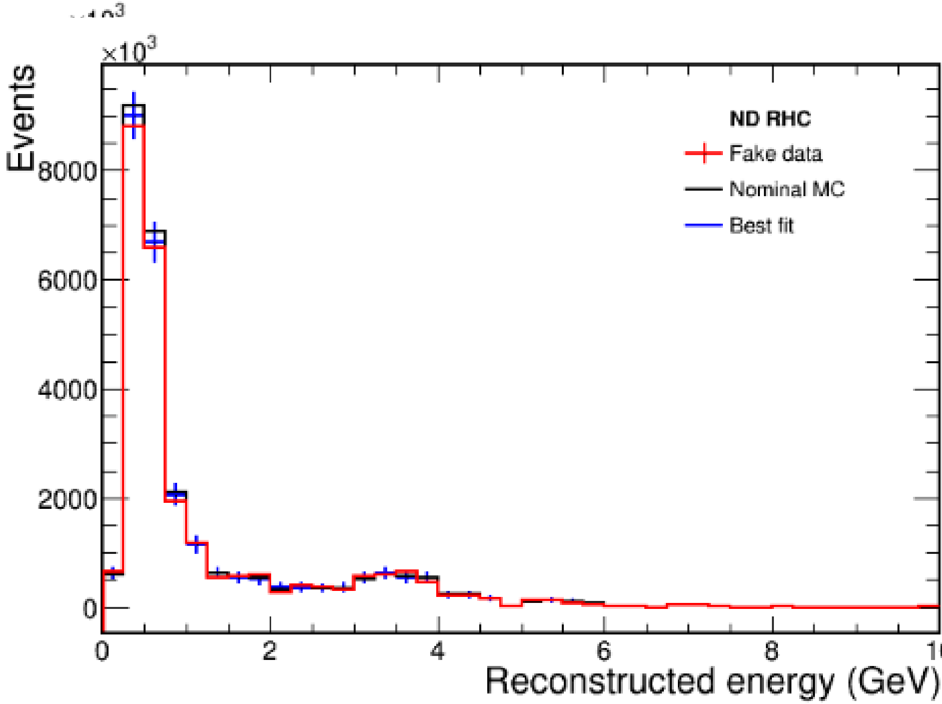




LOOK AT THE FAKE DATA THROUGH A PRISM

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



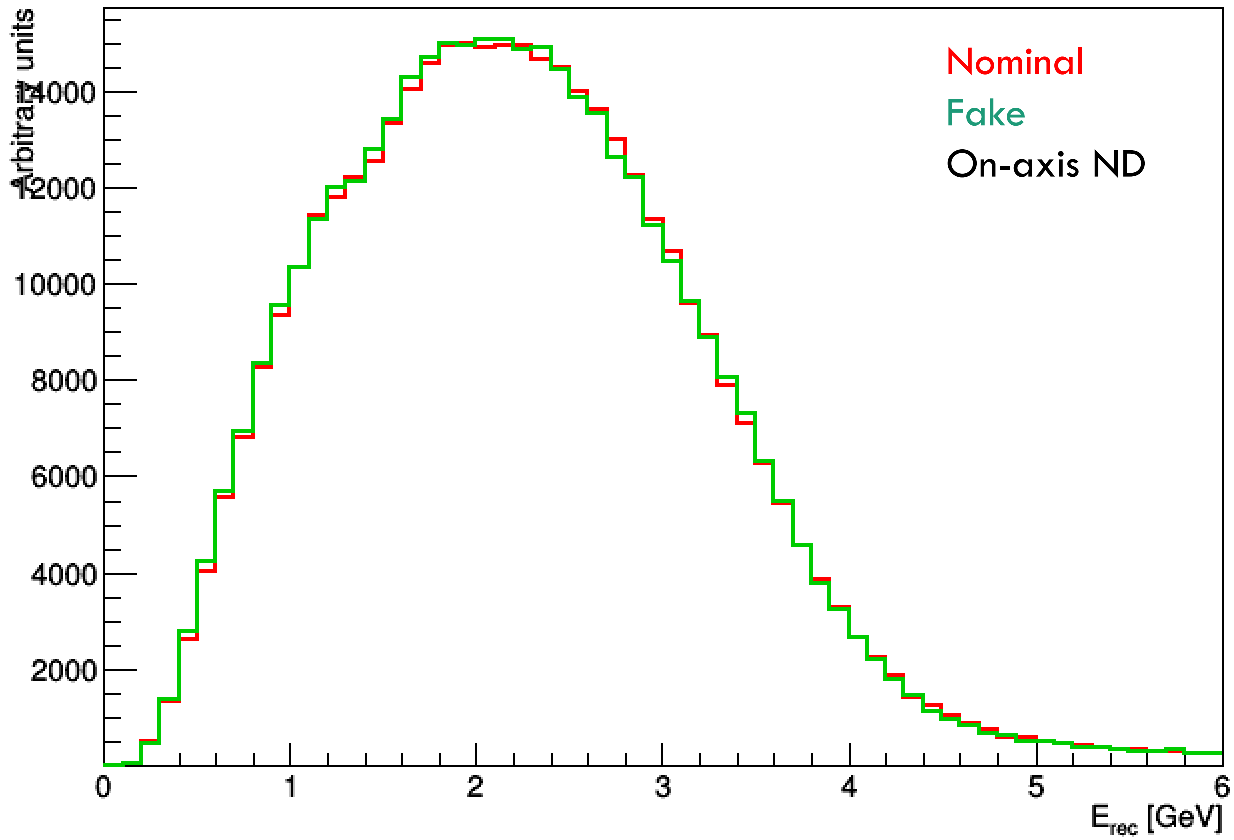


EVENT RATES

Offset	10^{19}POT	CCInc							NCInc
		μ contained			μ exit, $T_{\mu}^{exit} > 50$MeV			ν_e	ν_μ
		ν_μ	$\epsilon_{\nu_\mu,CC}$	$\bar{\nu}_\mu/\nu_\mu$	ν_μ	$\epsilon_{\nu_\mu,CC}$	$\bar{\nu}_\mu/\nu_\mu$		
0 m	55	6.6E5	3%	1%	5.3E6	22%	3%	6.2E4	1.8E6
3 m	4.58	5.5E4	3%	1%	4.1E5	22%	3%	5.0E3	1.4E5
6 m	4.58	5.8E4	4%	1%	3.0E5	22%	4%	4.3E3	1.1E5
9 m	4.58	6.0E4	7%	2%	1.9E5	22%	4%	3.4E3	7.5E4
12 m	4.58	5.9E4	12%	3%	1.1E5	22%	5%	2.5E3	5.2E4
15 m	4.58	5.4E4	18%	3%	6.2E4	20%	6%	2.2E3	3.7E4
18 m	4.58	4.6E4	22%	4%	3.8E4	18%	8%	1.7E3	2.7E4
21 m	4.58	3.9E4	27%	5%	2.5E4	17%	9%	1.4E3	2.1E4
24 m	4.58	3.1E4	30%	6%	1.7E4	16%	9%	1.2E3	1.6E4
27 m	4.58	2.6E4	32%	7%	1.2E4	15%	10%	9.8E2	1.3E4
30 m	4.58	2.1E4	33%	7%	9.6E3	16%	12%	8.3E2	1.0E4
33 m	4.58	1.7E4	35%	8%	7.5E3	15%	13%	7.6E2	8.3E3
36 m	4.58	1.2E4	35%	8%	6.1E3	16%	15%	6.7E2	6.6E3
Totals		ν_μ	—	$\bar{\nu}_\mu$	ν_μ	—	$\bar{\nu}_\mu$	ν_e	ν_μ
All	110	1.1E6	—	1.6E4	6.5E6	—	2.2E5	8.7E4	2.3E6

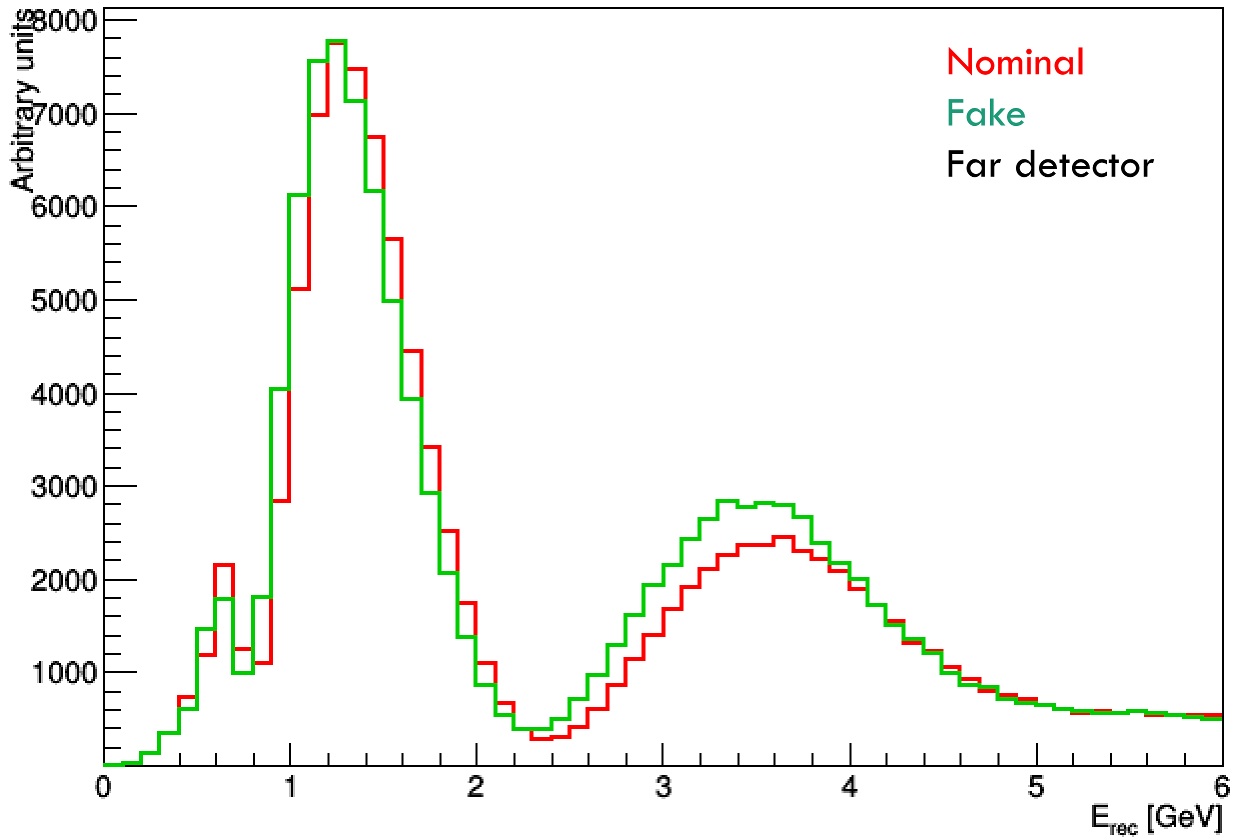
ON-AXIS NEAR DETECTOR

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



FAR DETECTOR

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



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_{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.

*A. Rogozhnikov, J.Phys.Conf.Ser. 762 (2016) no.1, 012036 [arXiv:1608.05806]

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

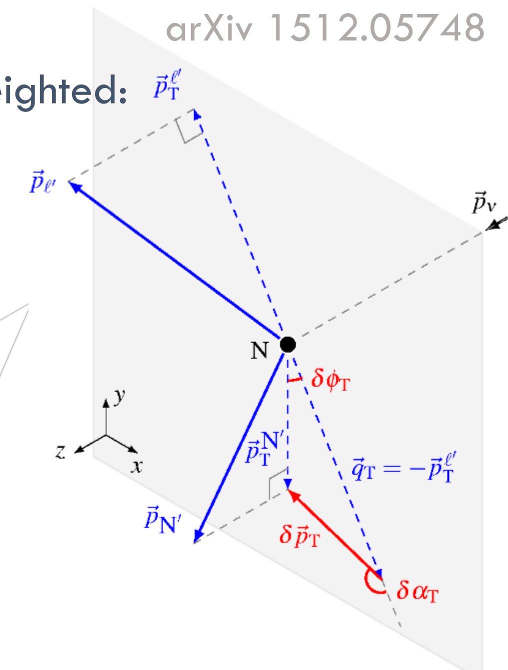
IS AN ON-AXIS MPT SENSITIVE TO THIS TYPE OF MISMODELLING?

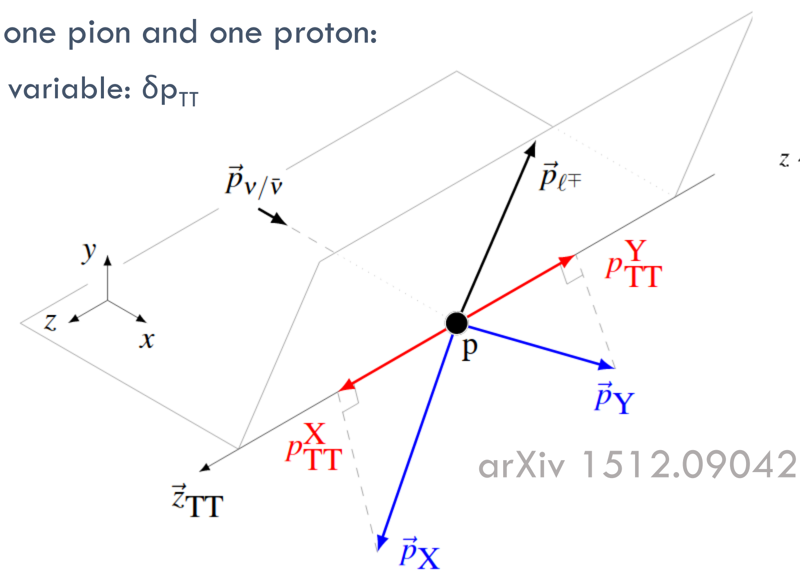
- The proposed multi-purpose tracker will be able to measure tracks precisely down to low thresholds.
- Are we able to reweight kinematic-balance distributions measured by a MPT and still get a biased E_{rec} model?
- Add the following variables to the list of observables to be reweighted:
  - Number of protons and charged pions above tracking threshold.
  - For events with exactly one tracked proton and no tracked pions:
    - Single transverse kinematics: δp_T, $\delta\alpha_T$ and $\delta\phi_T$
  - For events with exactly one pion and one proton:
    - Double transverse 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

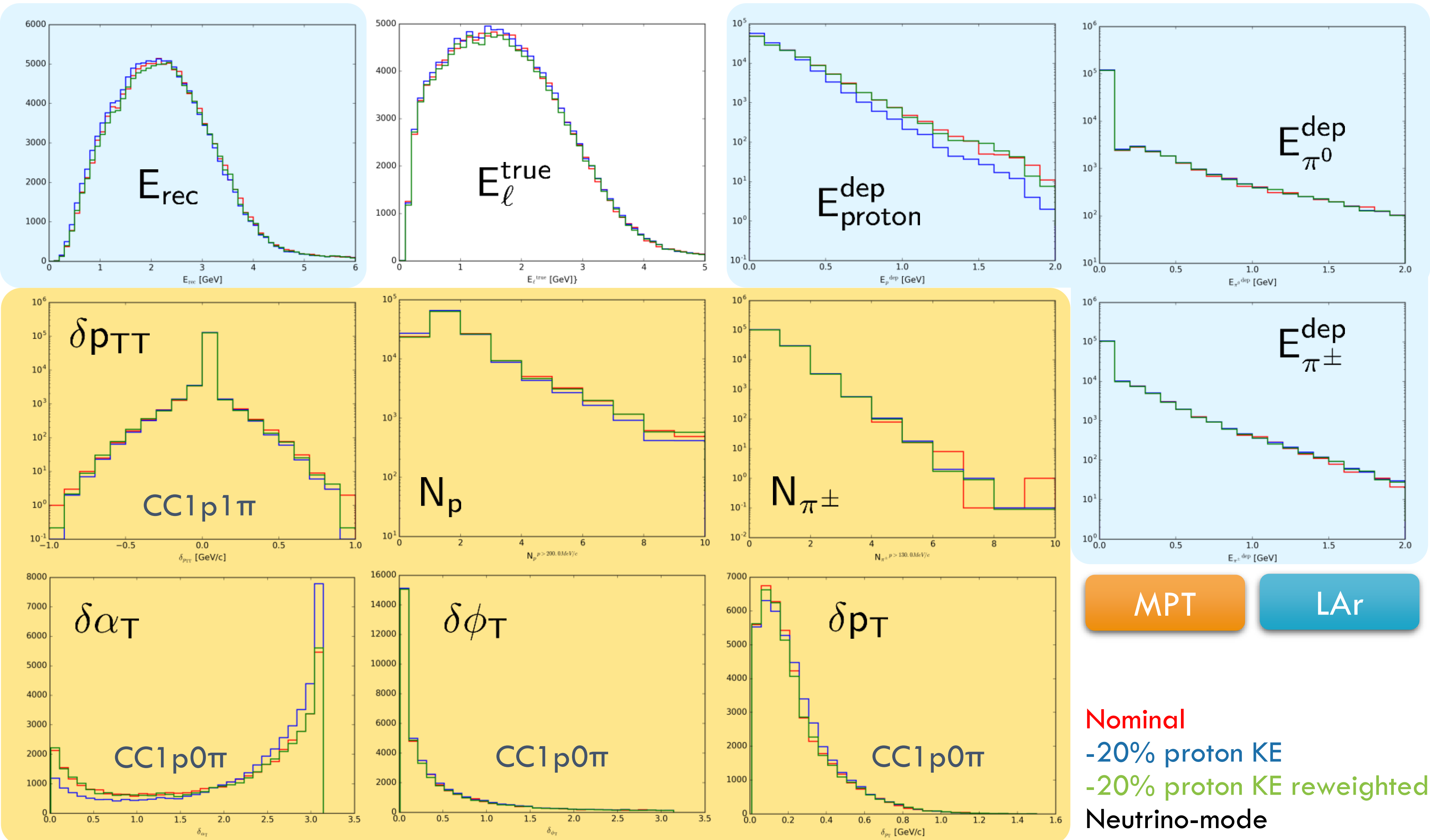
arXiv 1512.05748





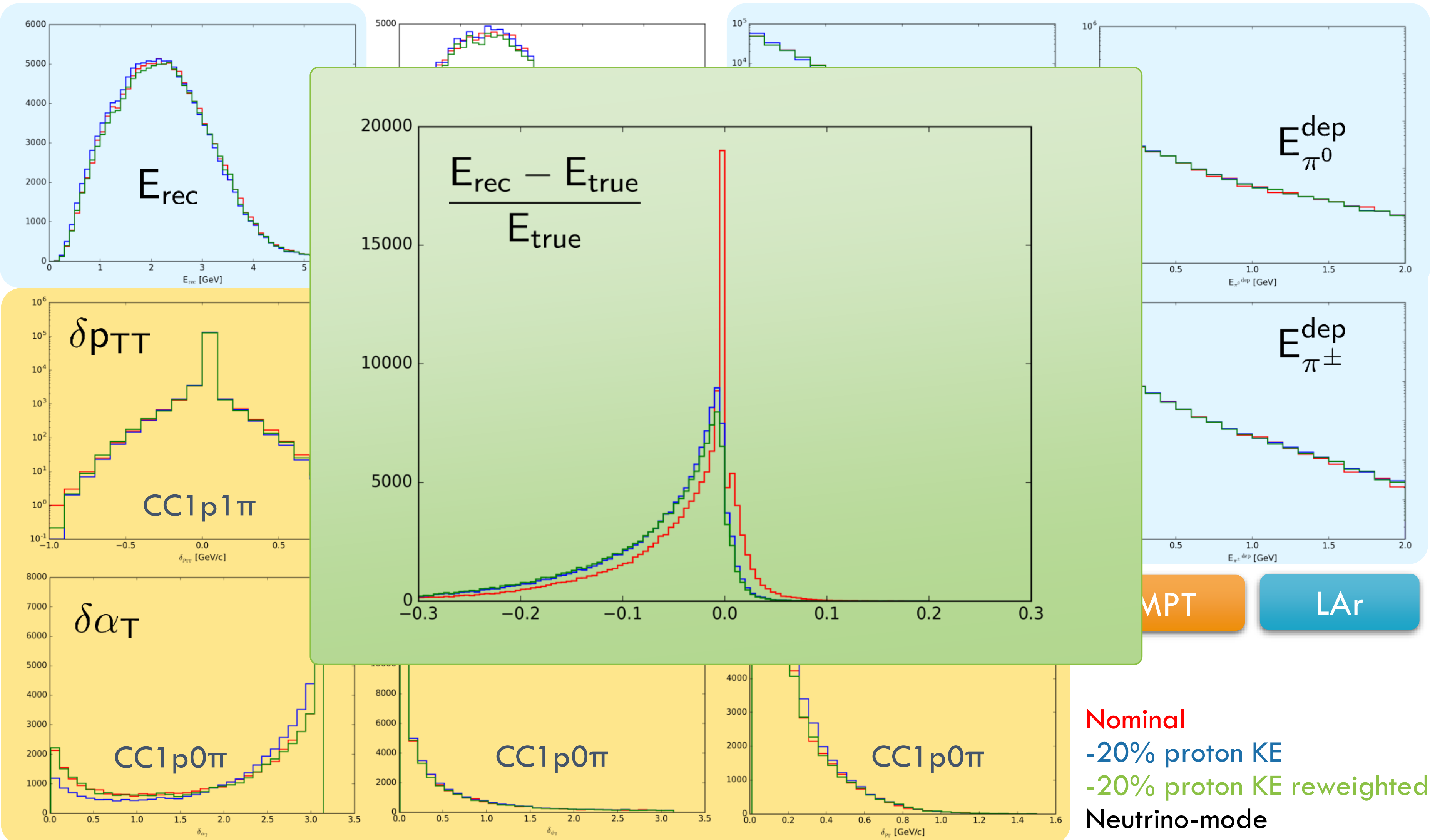
arXiv 1512.09042

TRANSVERSE VARIABLES, REWEIGHTED

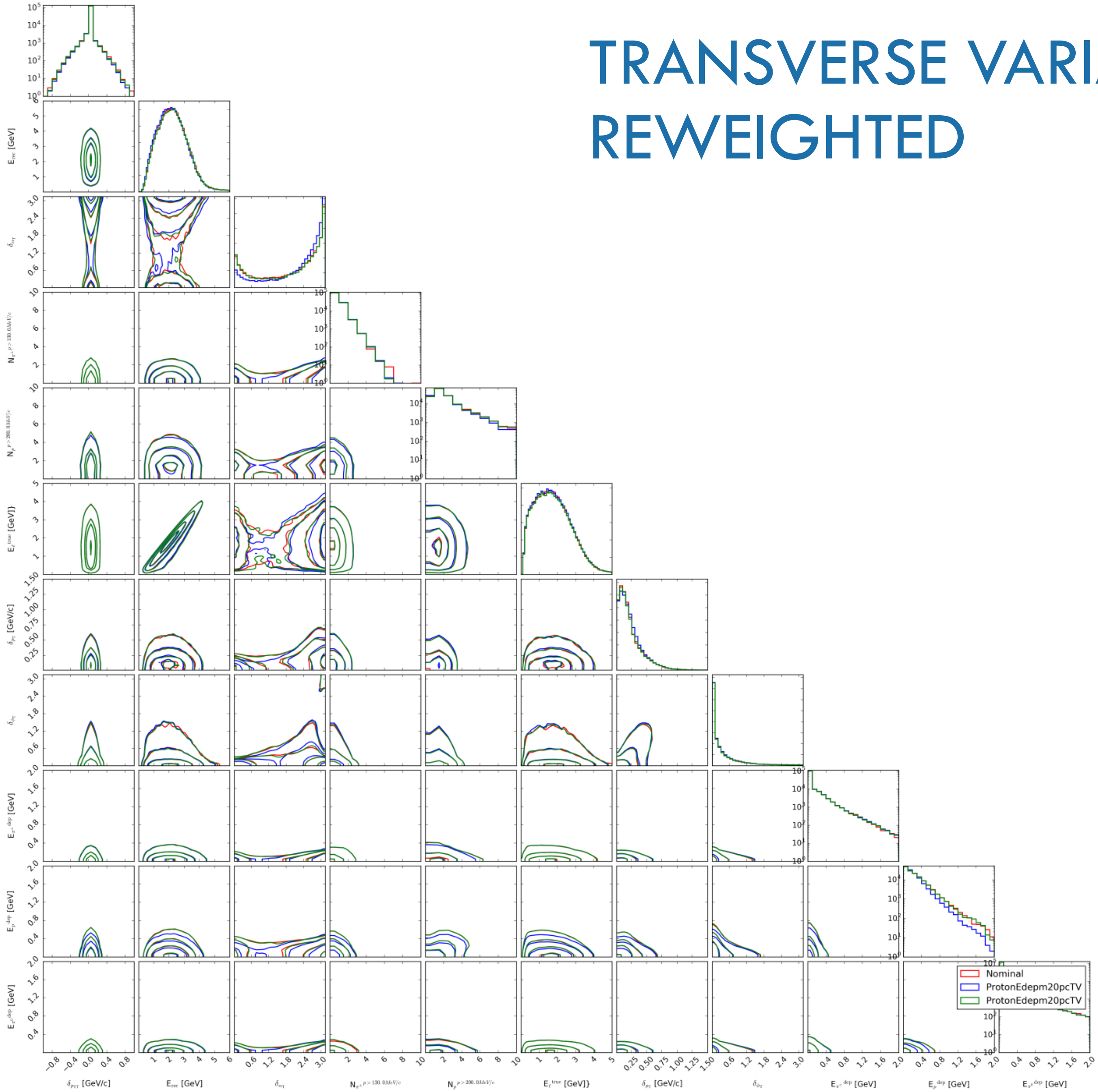


Nominal
-20% proton KE
-20% proton KE reweighted
Neutrino-mode

TRANSVERSE VARIABLES, REWEIGHTED



TRANSVERSE VARIABLES, REWEIGHTED

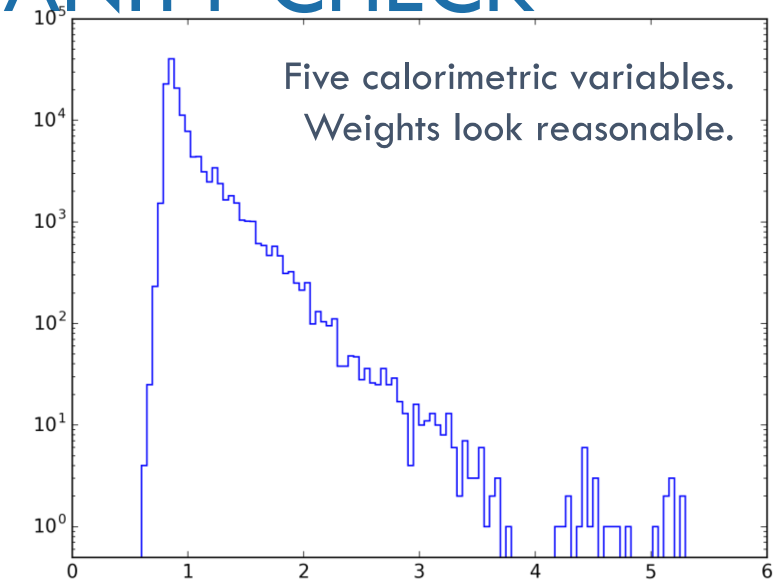


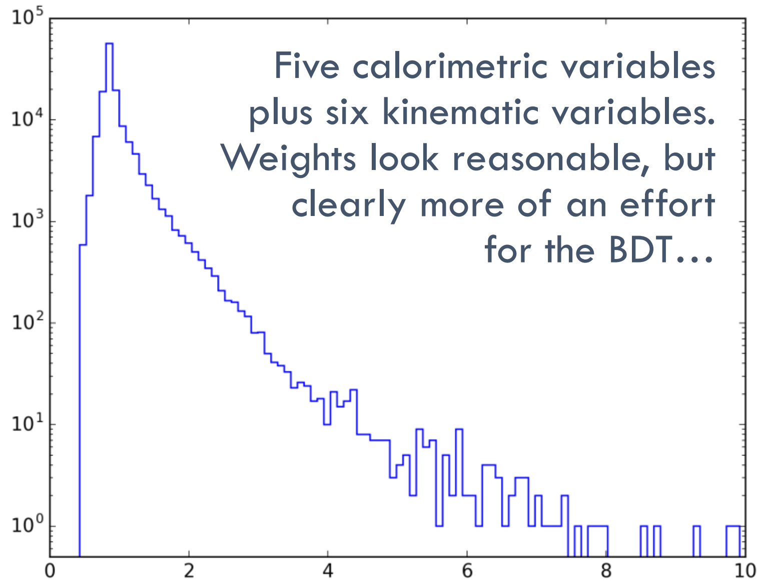
(AN ATTEMPT AT) A SANITY CHECK

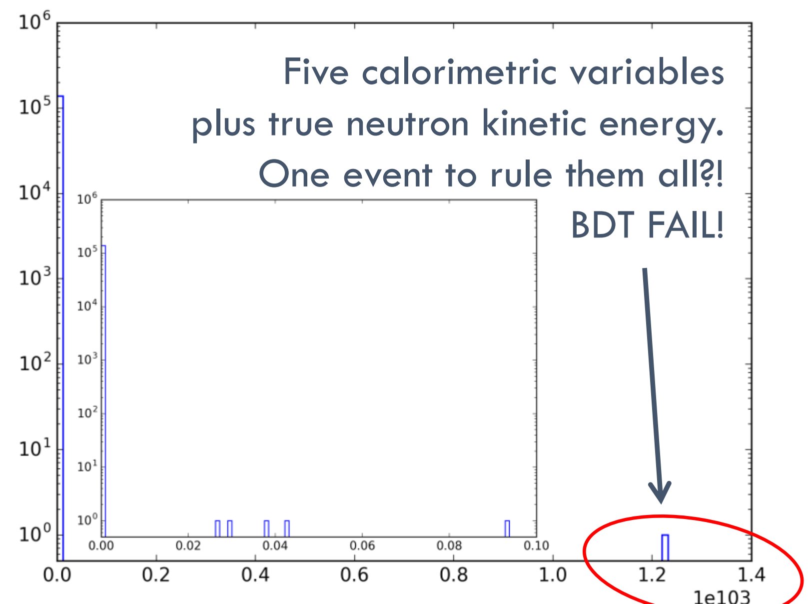
- If we had complete knowledge of the final state for every event we wouldn't expect this type of reweighting to work.
  - Or at least not without somehow "correcting" the E_{rec} response…
- But how would that manifest itself in the distributions we have been looking at?
- Try reweighting initial five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

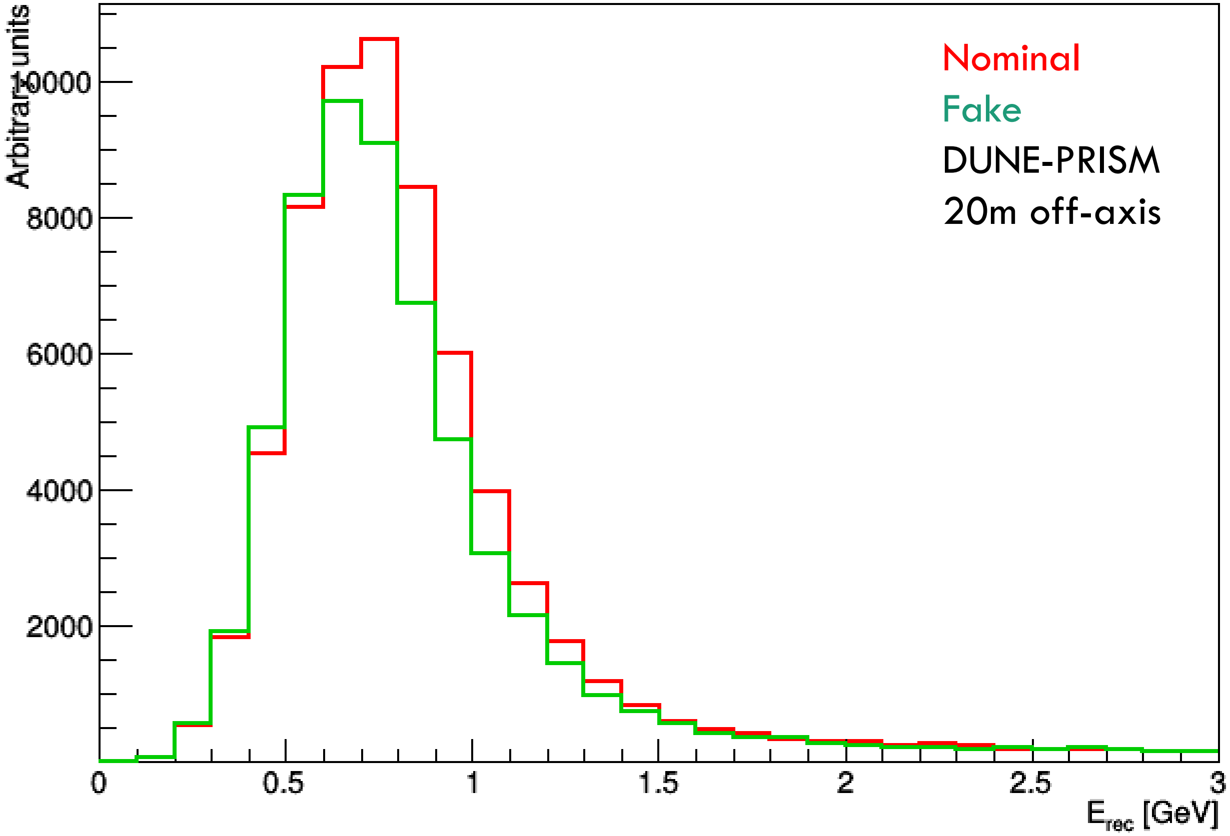






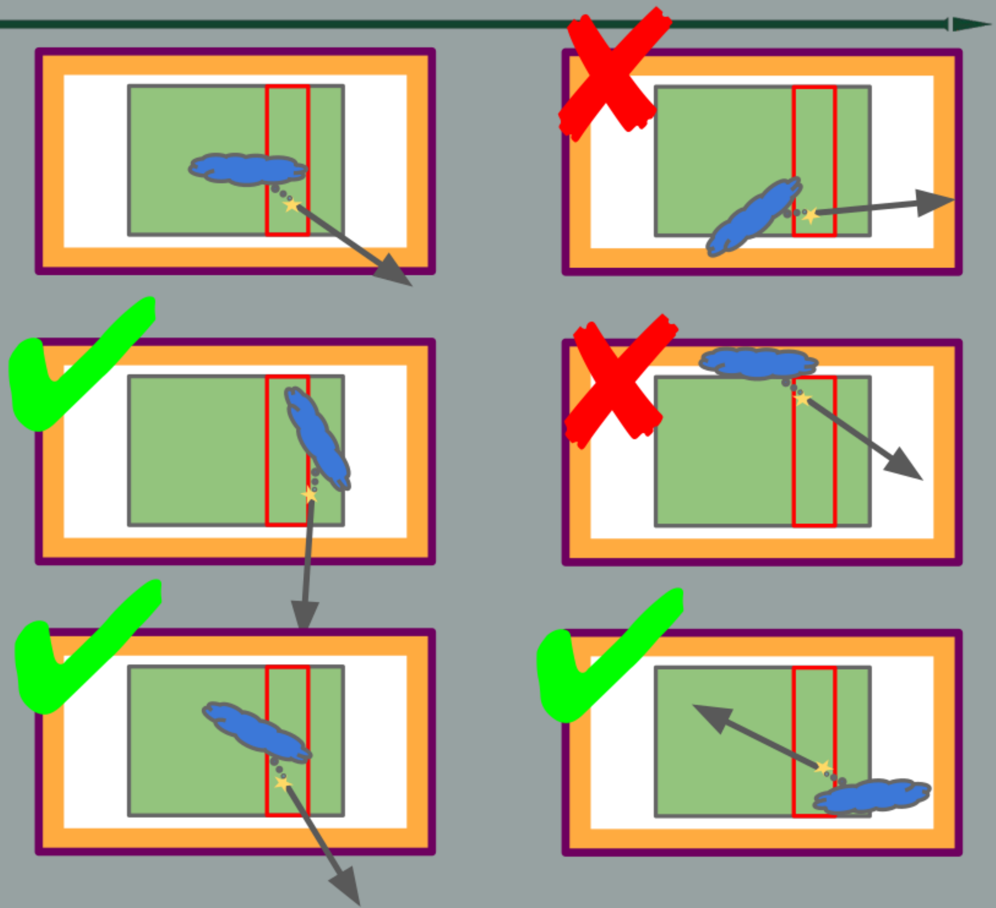
DUNE-PRISM 20 METRES OFF-AXIS

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

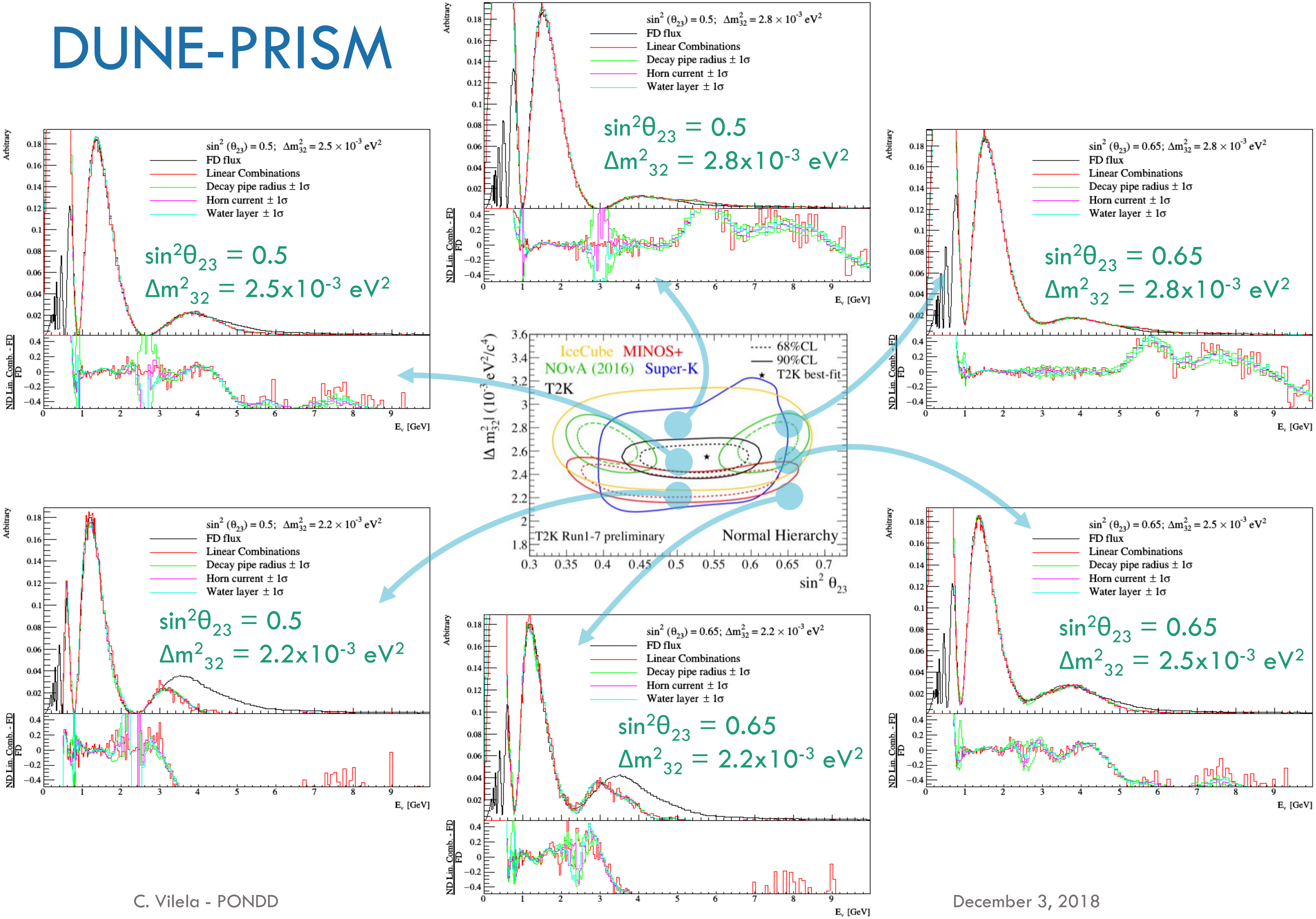


Geometric efficiency correction

- 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?



DUNE-PRISM


sin² (θ₂₃) = 0.5; Δm²₃₂ = 2.8 × 10⁻³ eV²
FD flux
Linear Combinations
Decay pipe radius ± 1σ
Horn current ± 1σ
Water layer ± 1σ
$\sin^2\theta_{23} = 0.5$
$\Delta m^2_{32} = 2.8\times10^{-3}\ eV^2$
Arbitrary
ND Lin. Comb. - FD / FD
E_ν [GeV]
sin² (θ₂₃) = 0.5; Δm²₃₂ = 2.5 × 10⁻³ eV²
$\sin^2\theta_{23} = 0.5$
$\Delta m^2_{32} = 2.5\times10^{-3}\ eV^2$
sin² (θ₂₃) = 0.65; Δm²₃₂ = 2.8 × 10⁻³ eV²
$\sin^2\theta_{23} = 0.65$
$\Delta m^2_{32} = 2.8\times10^{-3}\ eV^2$
IceCube MINOS+
NOvA (2016) Super-K
T2K
68%CL
90%CL
T2K best-fit
T2K Run1-7 preliminary
Normal Hierarchy
|Δ m²₃₂| (10⁻³ eV²/c⁴)
sin² θ₂₃
sin² (θ₂₃) = 0.5; Δm²₃₂ = 2.2 × 10⁻³ eV²
$\sin^2\theta_{23} = 0.5$
$\Delta m^2_{32} = 2.2\times10^{-3}\ eV^2$
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