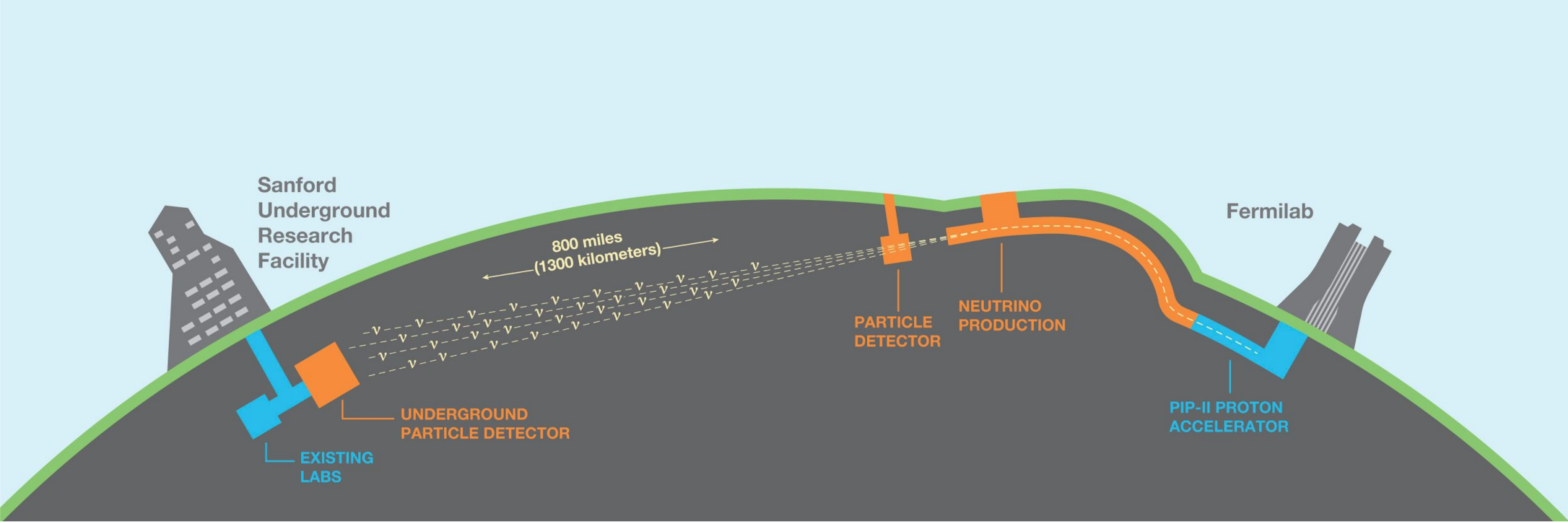
Overcoming Neutrino Interaction Mis-modeling with DUNE-PRISM

APS: Division of Particles and Fields 2019
Northeastern University, Boston
2019-08-01
Luke Pickering for the DUNE collaboration

MICHIGAN STATE UNIVERSITY

DEEP UNDERGROUND NEUTRINO EXPERIMENT

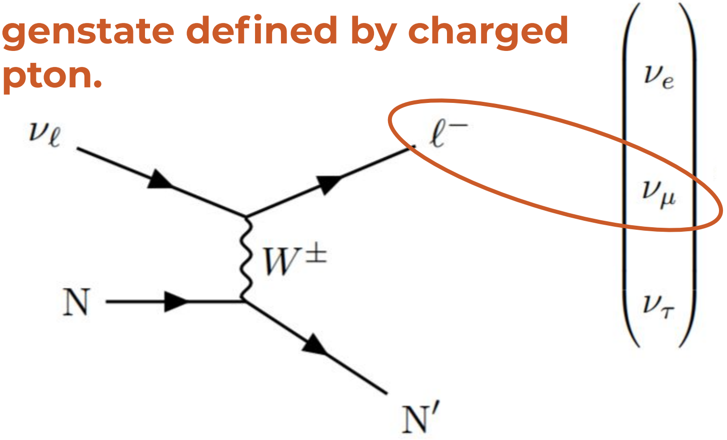
DUNE: Deep Underground Neutrino Experiment



Do say: I love DUNE!, **Don’t say**: <*anything*> the DUNE experiment <*anything else*>

Oscillations

1) Interaction with matter in flavor eigenstate defined by charged lepton.



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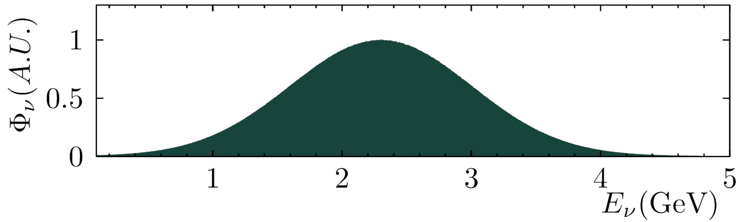

***e.g.* Neutrinos from accelerators created as muon neutrinos from pion and kaon decays**

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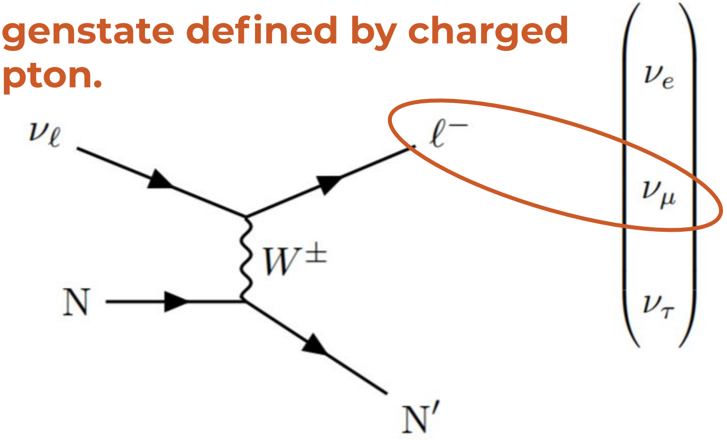

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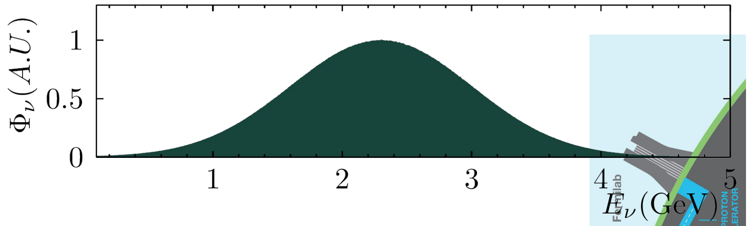

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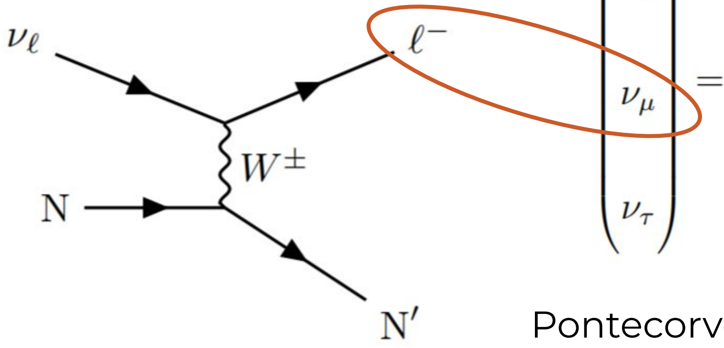
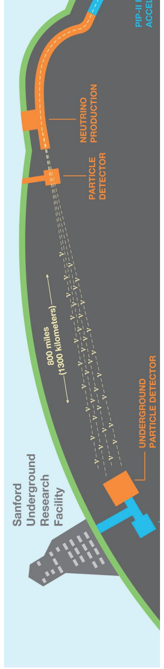


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}}_{\mathbf{M}_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

2) Propagate as superposition of mass/energy eigenstates over experimental baseline (1300 km)



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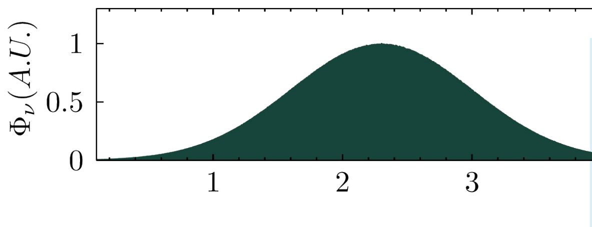

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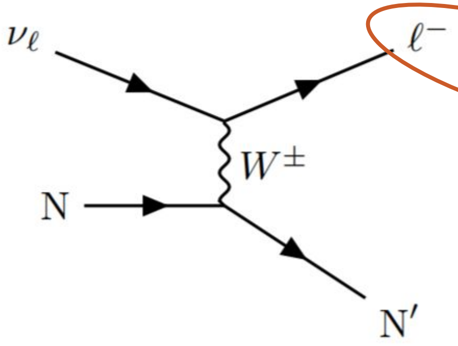

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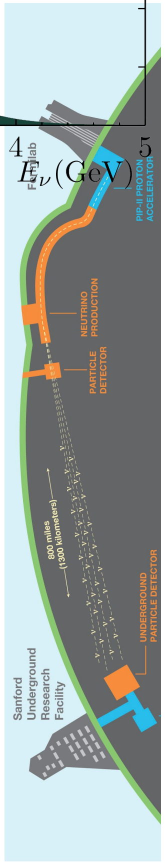
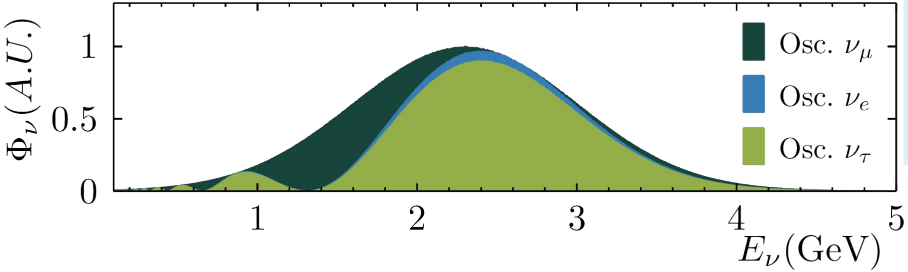
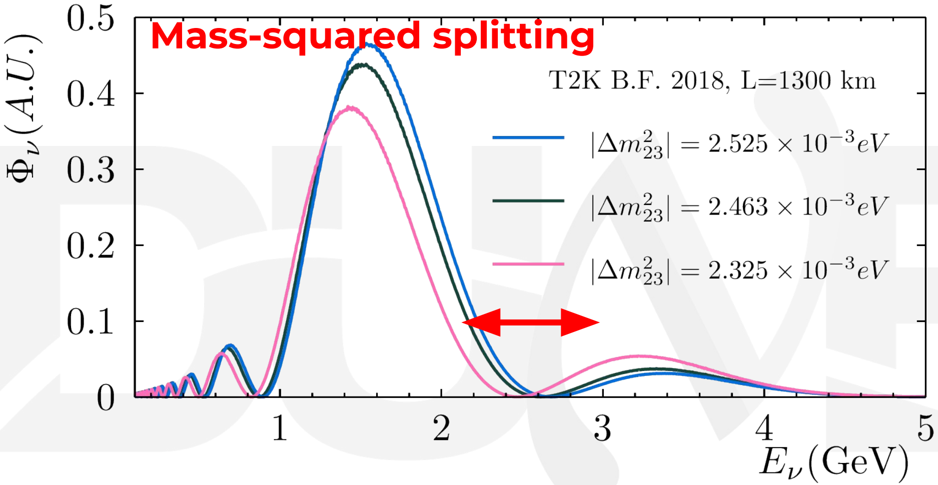
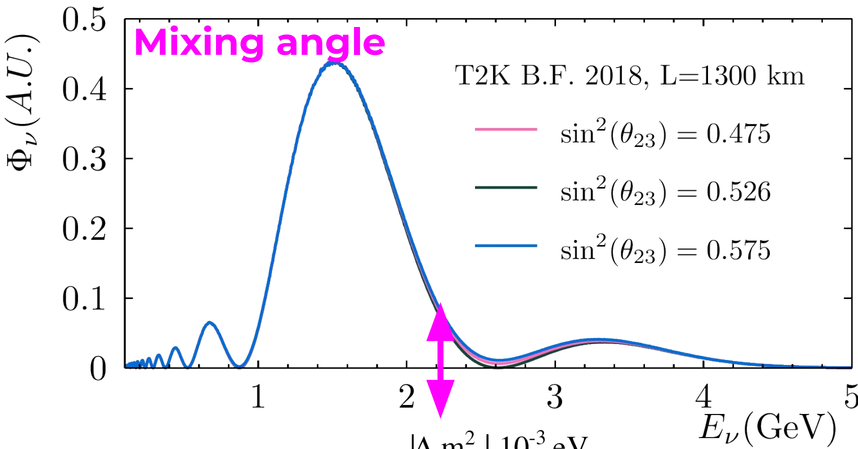


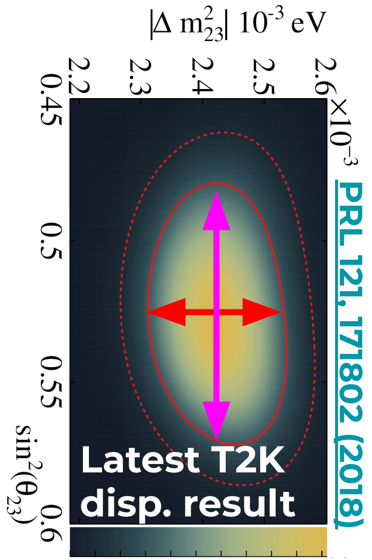
3) Projecting back to flavor eigenstates reveals a different flavor mixture.
(if $|\Delta m^2_{ij}| \neq 0$)



Disappearance at the Far detector







PRL 121, 171802 (2018)

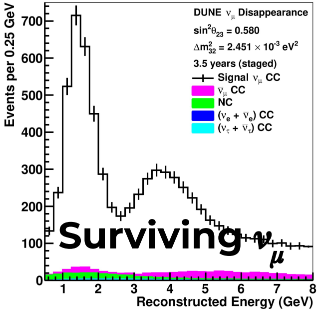
- ‘Surviving’ muon neutrinos show characteristic oscillation shape.
- Use details of spectra to infer physics parameters of interest (mixing angles, mass differences, CPV phase)
- Similarly compare to ‘appeared’ electron spectra.

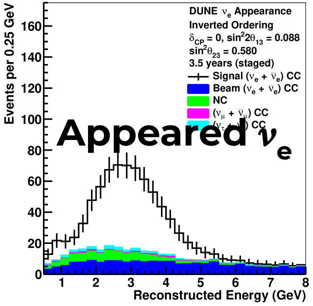
An Oscillation Analysis (OA) in one slide

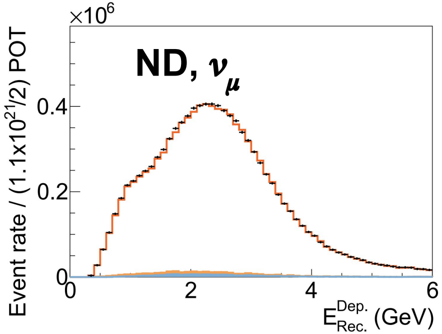
- Constrained prediction of oscillated observables
- Data → Infer oscillation probabilities

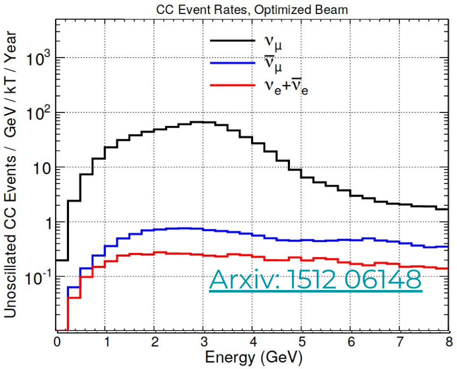
- Predict observables
- Data → constrain interaction physics

Predict neutrino flux from beam sim.









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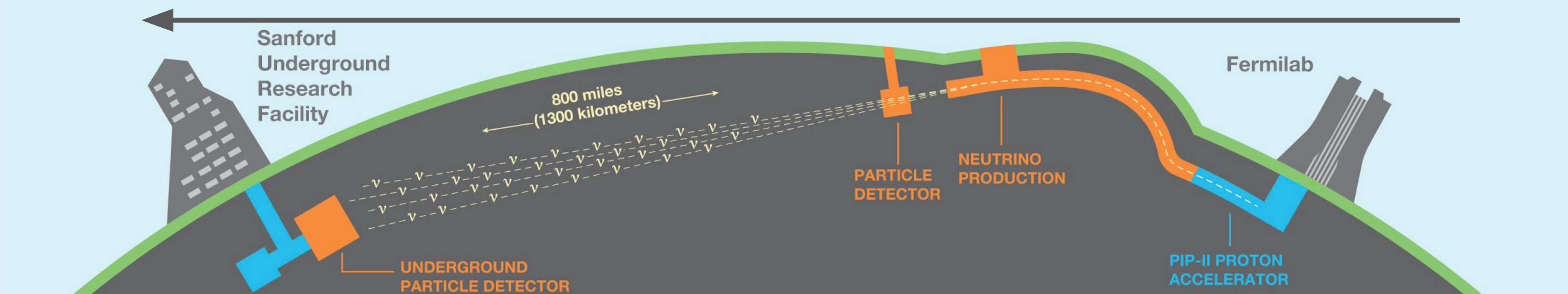
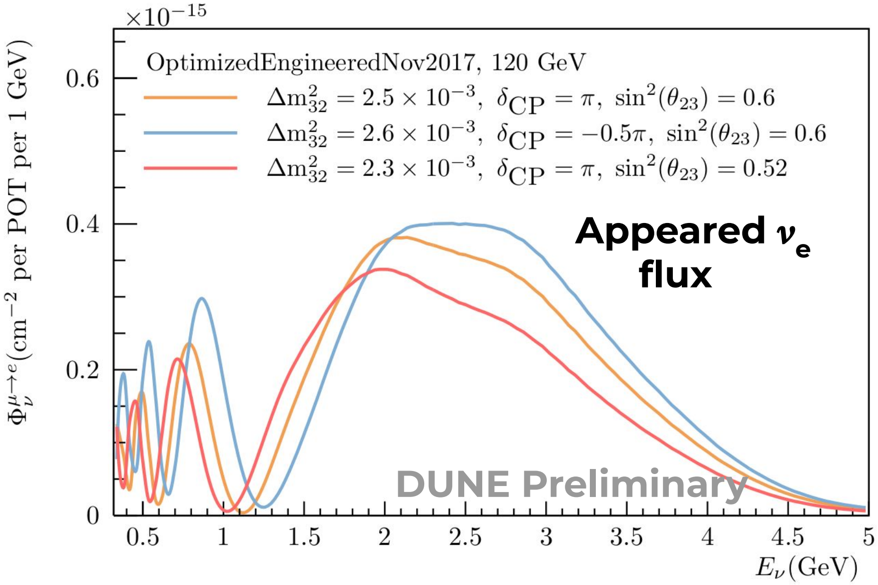


Why are neutrino interaction models important?

$$N_{\text{far}}\left(\mathbf{x}_{\text{obs}}\right) = \int d\mathbf{x}_{\text{true}}\, \underbrace{\mathbf{D}_{\text{far}}\left(\mathbf{x}_{\text{obs}}|\mathbf{x}_{\text{true}}\right)}_{\text{Smearing, Eff., Pur.}} \underbrace{N_{\text{targ}}\sigma\left(\mathbf{x}_{\text{true}}\right)\Phi_{\text{far}}\left(E_\nu\right)P_{osc}\left(E_\nu\right)}_{N_{\text{Int}}(\mathbf{x}_{\text{true}})}$$

$$N_{\text{near}}\left(\mathbf{x}_{\text{obs}}\right) = \int d\mathbf{x}_{\text{true}}\, \underbrace{\mathbf{D}_{\text{near}}\left(\mathbf{x}_{\text{obs}}|\mathbf{x}_{\text{true}}\right)}_{\text{Smearing, Eff., Pur.}} \underbrace{N_{\text{targ}}\sigma\left(\mathbf{x}_{\text{true}}\right)\Phi_{\text{near}}\left(E_\nu\right)}_{N_{\text{Int}}(\mathbf{x}_{\text{true}})}$$

- Observe event rate not neutrino flux
- Cannot perfectly reconstruct neutrino energy
- Require models to predict observables and infer oscillation features in true neutrino energy spectra
- Mis-modelling in reconstructed energy feed-down → biased parameter measurements.



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Need to understand this!

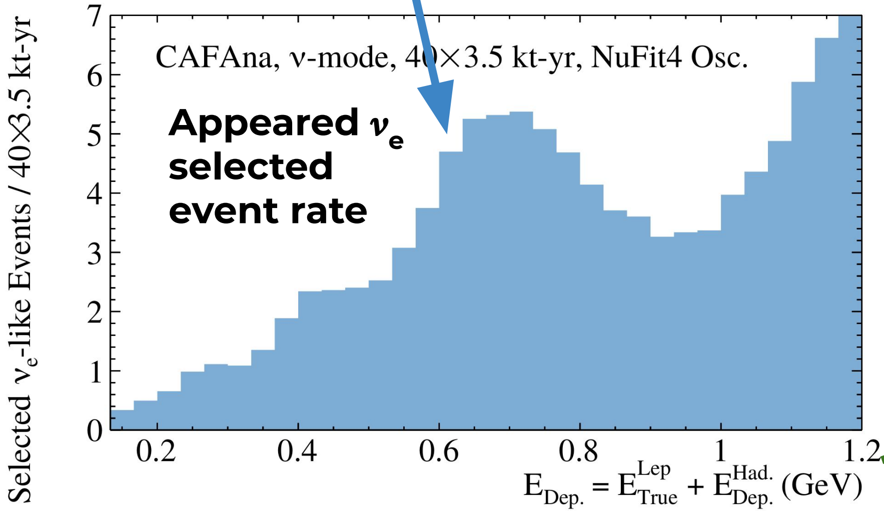
e)

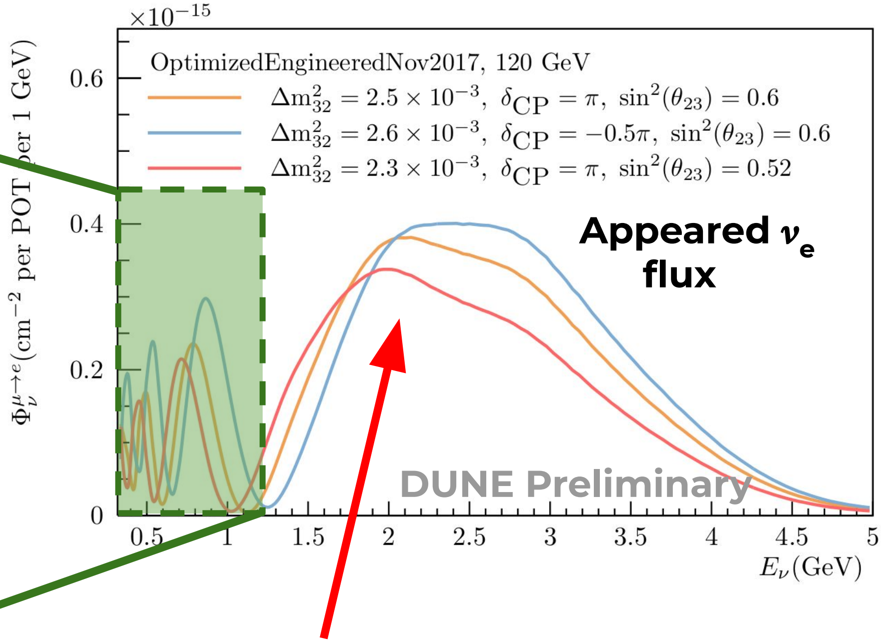
What we actually see

N_{near}

$$\underbrace{\qquad\qquad}_{\text{Smearing, Eff., Pur.}}\ \underbrace{\qquad\qquad}_{N_{\mathrm{Int}}\left(\mathbf{x}_{\mathrm{true}}\right)}$$

- Observe event rate not neutrino flux





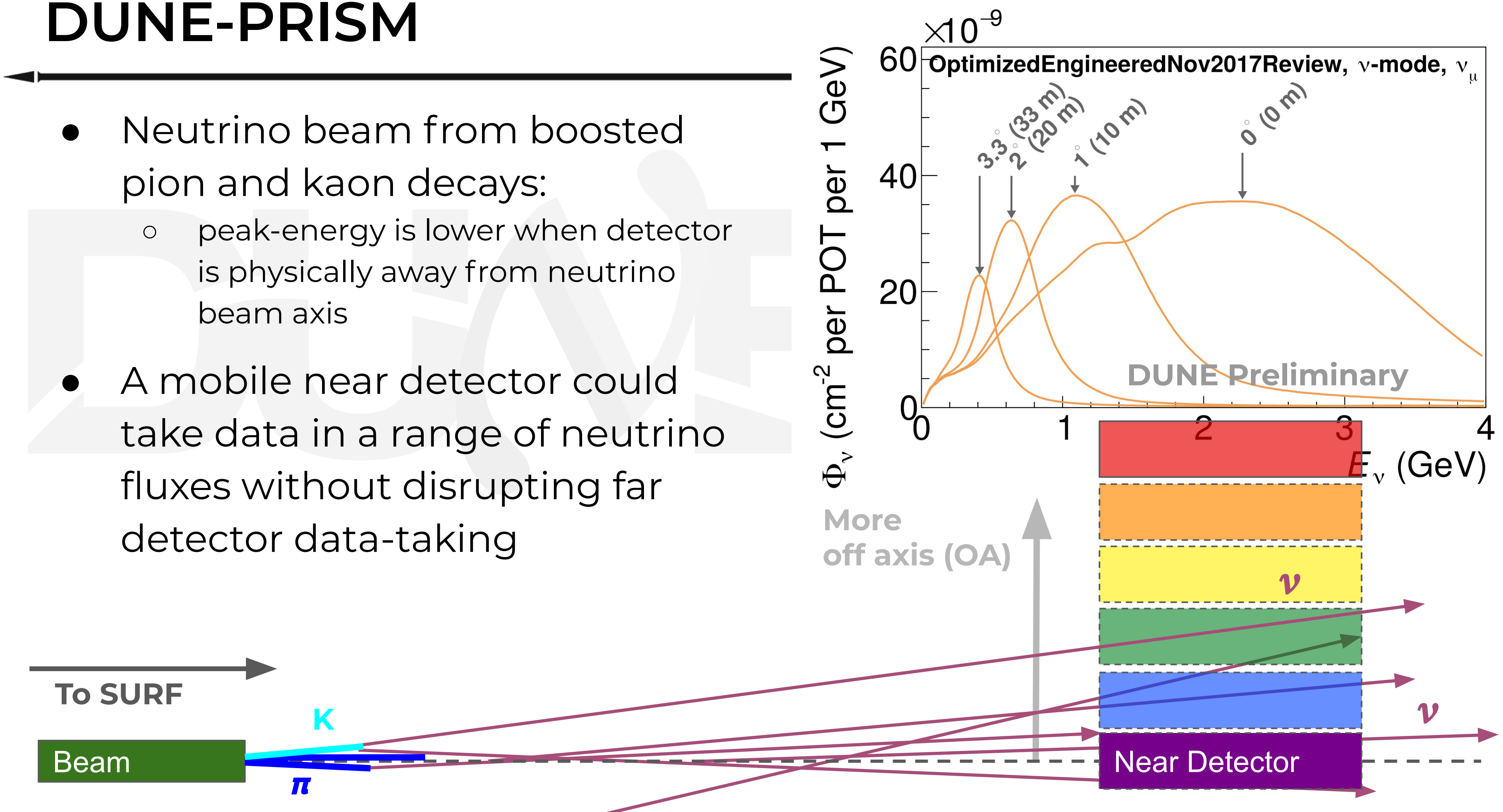
measurements.

What we want to understand

Spotting a Problem

DUNE-PRISM

- Neutrino beam from boosted pion and kaon decays:
  - peak-energy is lower when detector is physically away from neutrino beam axis
- A mobile near detector could take data in a range of neutrino fluxes without disrupting far detector data-taking

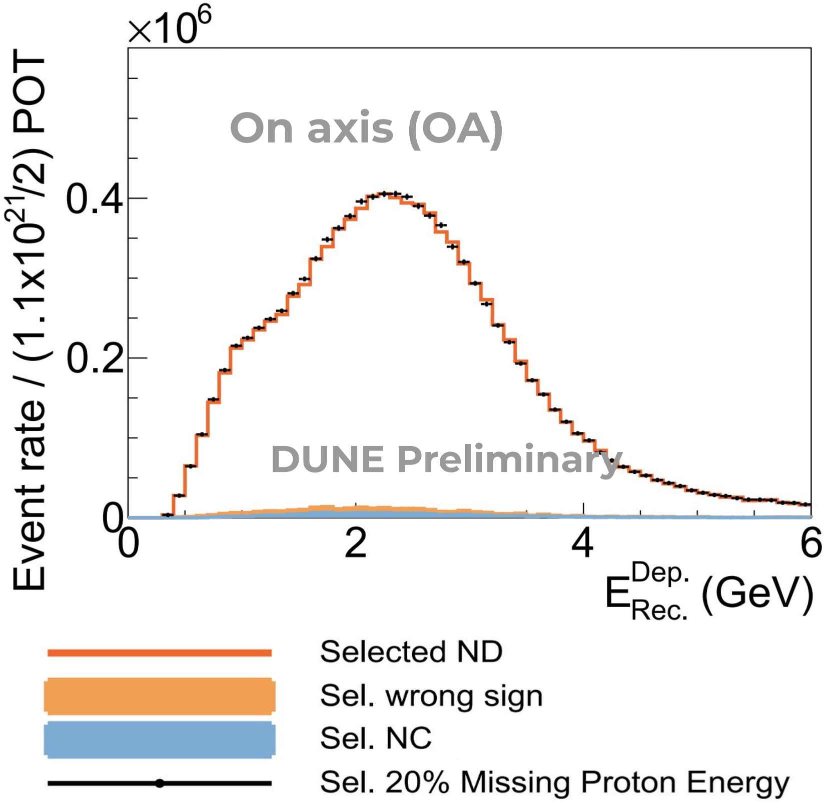


Improvise

$$N_{\rm near}\left(\mathbf{x}_{\rm obs}\right) = \int d\mathbf{x}_{\rm true}\,\underbrace{\mathbf{D}_{\rm near}\left(\mathbf{x}_{\rm obs}|\mathbf{x}_{\rm true}\right)}_{\text{Smearing, Eff., Pur.}}\,\underbrace{N_{\rm targ}\sigma\left(\mathbf{x}_{\rm true}\right)\Phi_{\rm near}\left(E_\nu\right)}_{N_{\rm Int}(\mathbf{x}_{\rm true})}$$

- Problems in flux/interaction/detector modelling can be hard to deconvolve by single event rate measurement (*e.g.* on-axis (OA) only)

- **Case study**: 20% proton KE → neutron and apply plausible new xsec to make hard to see on axis.



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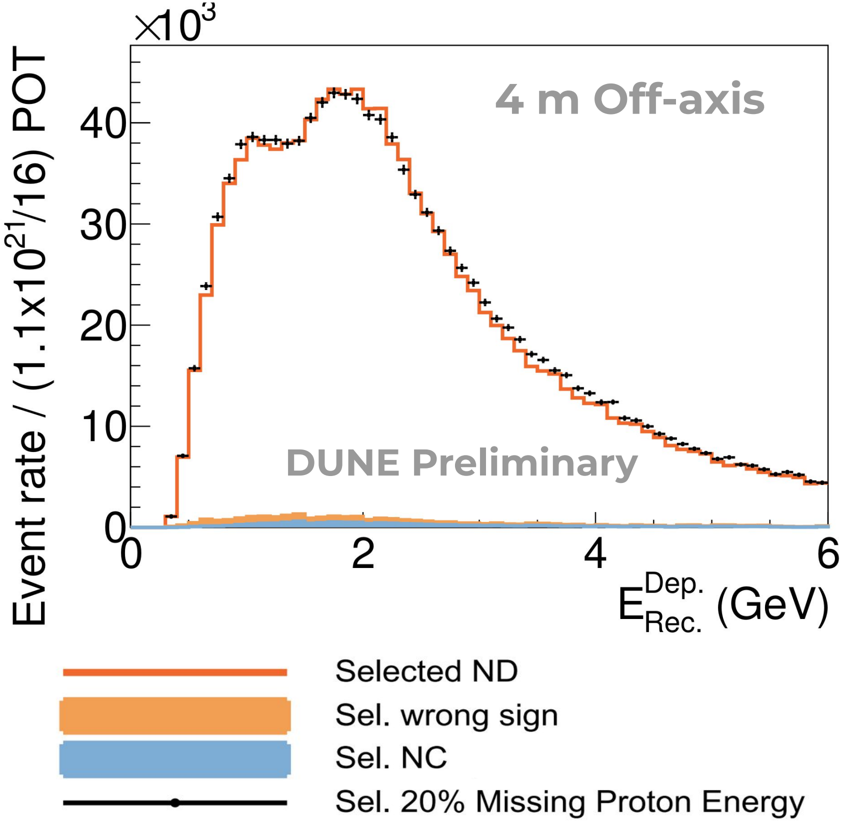

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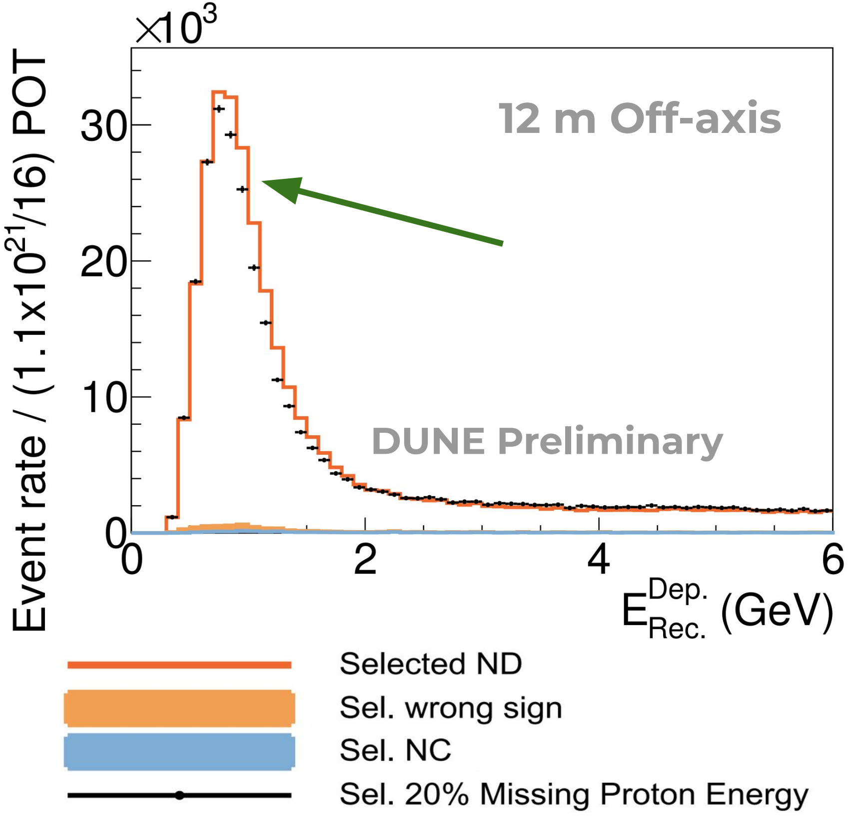
  - **The same combination of modelling problems unlikely to describe the data well.**



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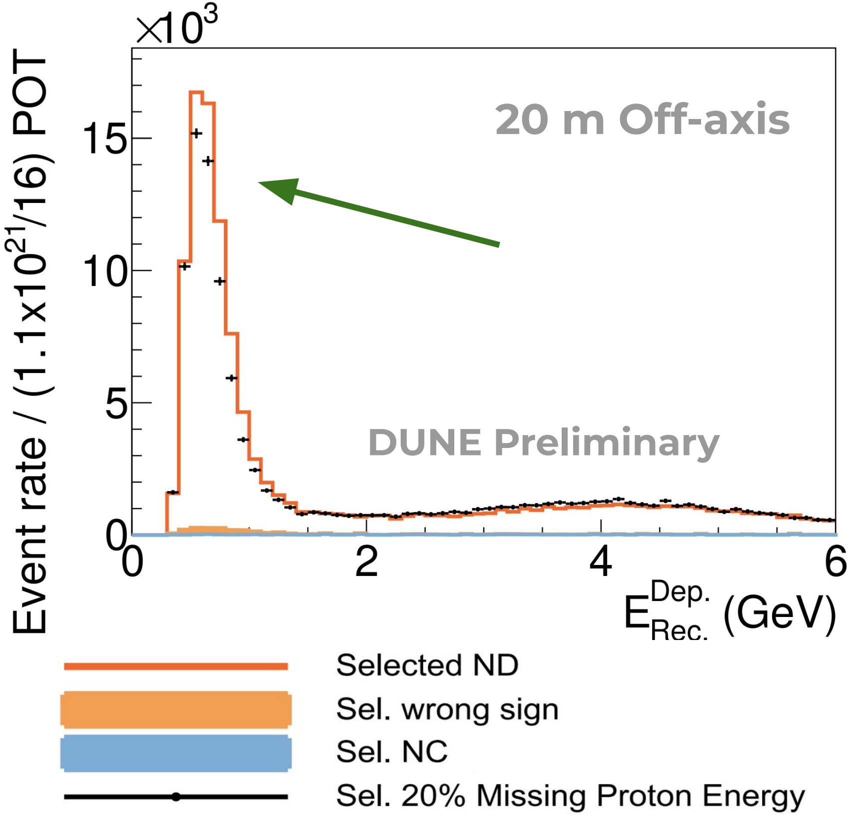

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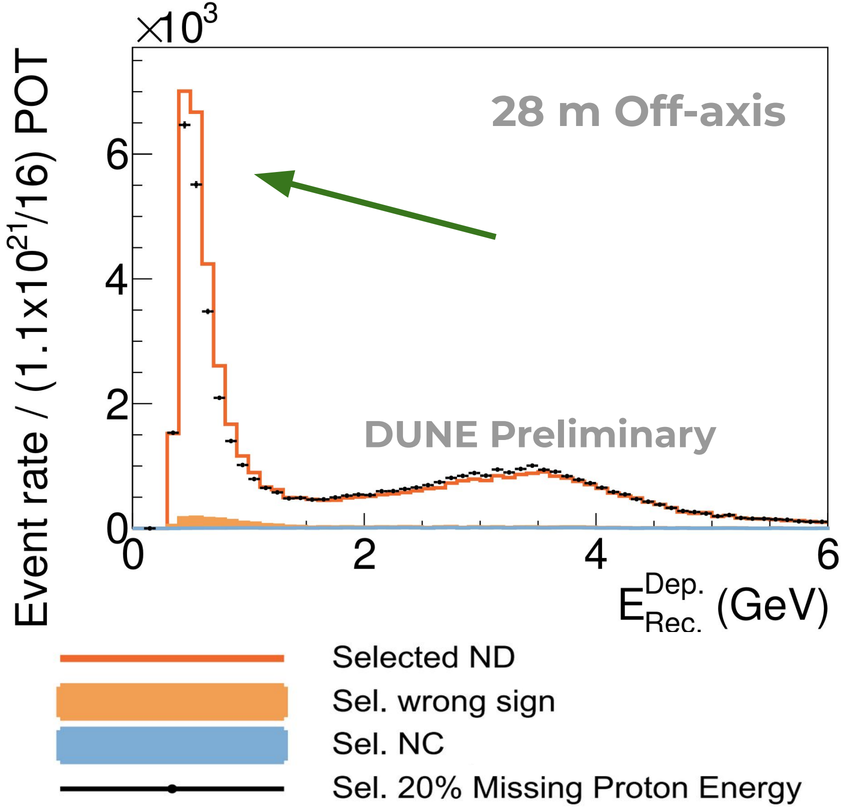
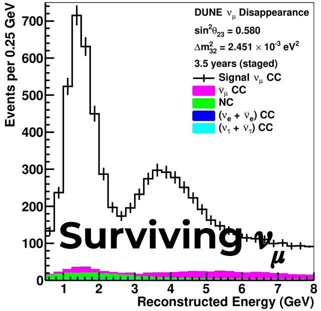
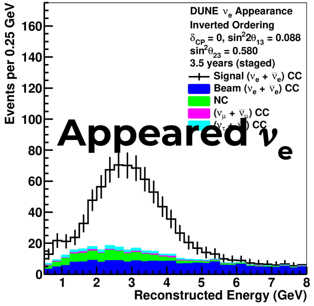


Sidestepping a Problem

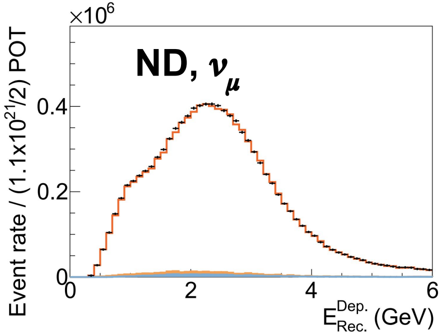
What Do We Really Want To Know?

- Constrained prediction of oscillated observables
- Data → Infer oscillation probabilities

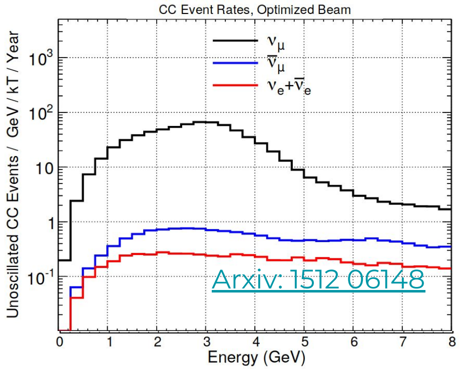




- Predict observables
- Data → constrain interaction physics



Predict neutrino flux from beam sim.

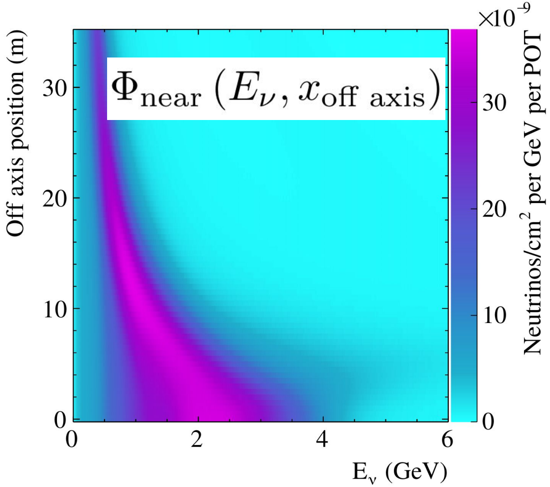


Arxiv: 1512 06148

- Ultimately need a **prediction of the FD observable** event rate for a given oscillation.
- Can predict FD flux for any oscillation hypothesis with flux model, but energy feed-down means we can only predict observables with an interaction model…
- Can we use the ND data to tell us about the feed-down **without invoking an interaction model**?

Adapt

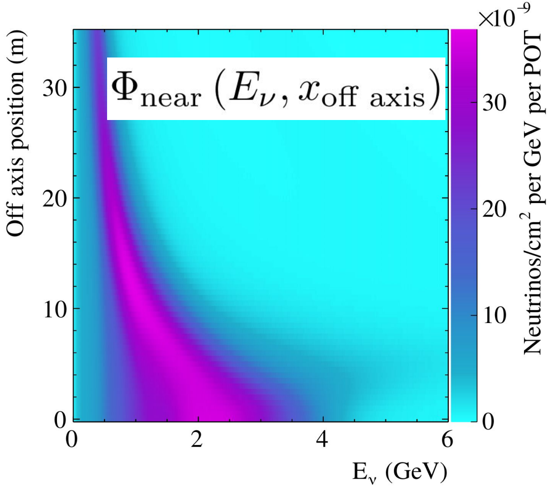
- Predict Near flux spectrum.

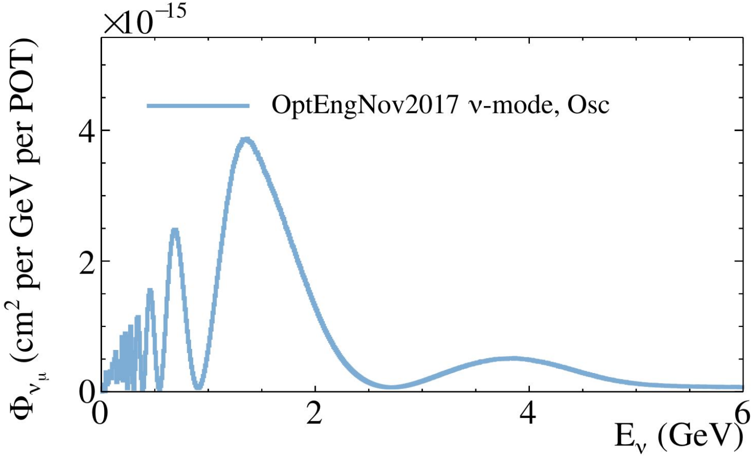


Adapt

- Predict Near flux spectrum.
- Can predict Far flux under various oscillation hypotheses

$$\Phi_{\text{far}}\left(E_{\nu}\right)P_{osc}\left(E_{\nu}\right)$$





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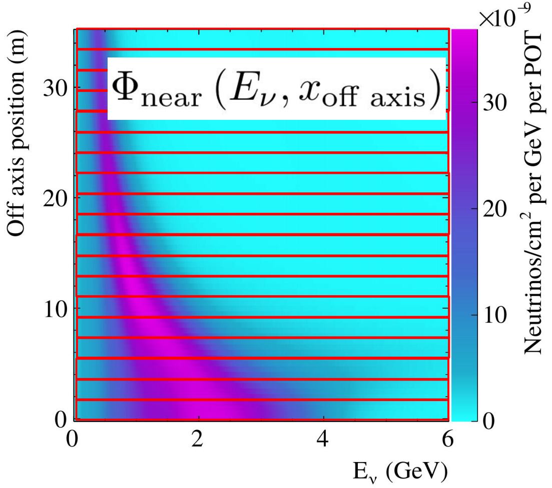
- Use Near flux energy spectrum at different off axis positions as a linear basis and solve:



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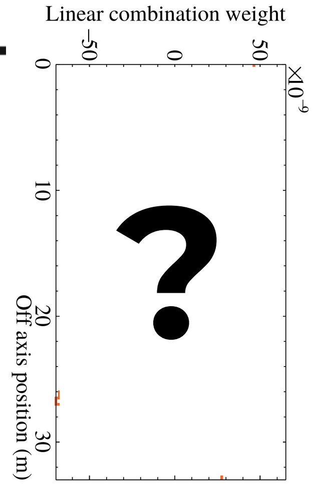

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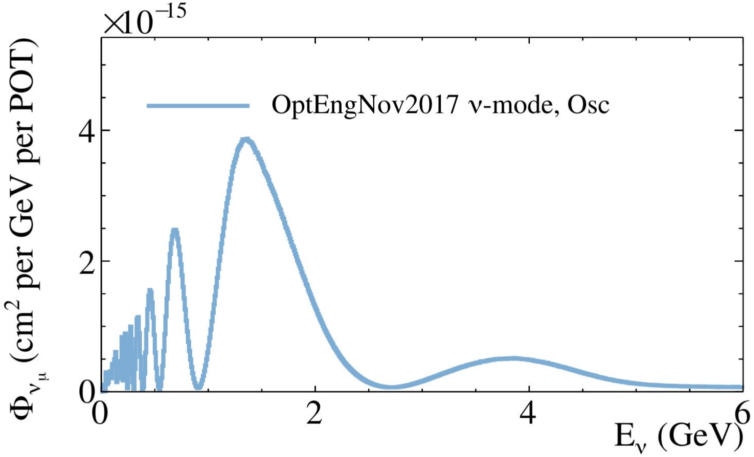

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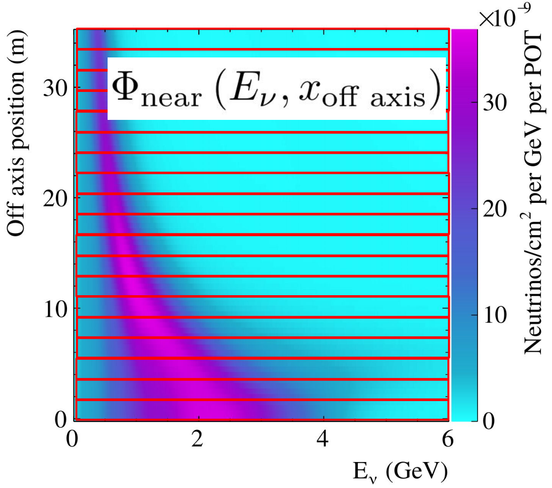
$$\Phi_{\mathrm{near}}\left(E_\nu, x_{\mathrm{off\ axis}}\right)\times\vec{c}=\Phi_{\mathrm{far}}\left(E_\nu\right)P_{osc}\left(E_\nu\right)$$

- Each oscillation hypothesis yields a different set of weighting coefficients: $\vec{c}$



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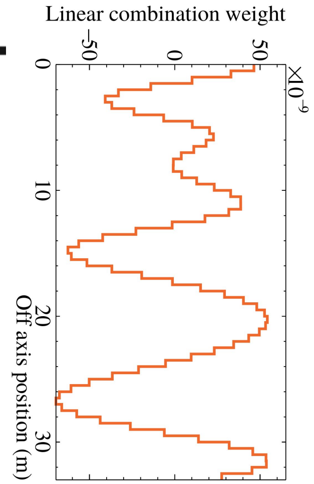

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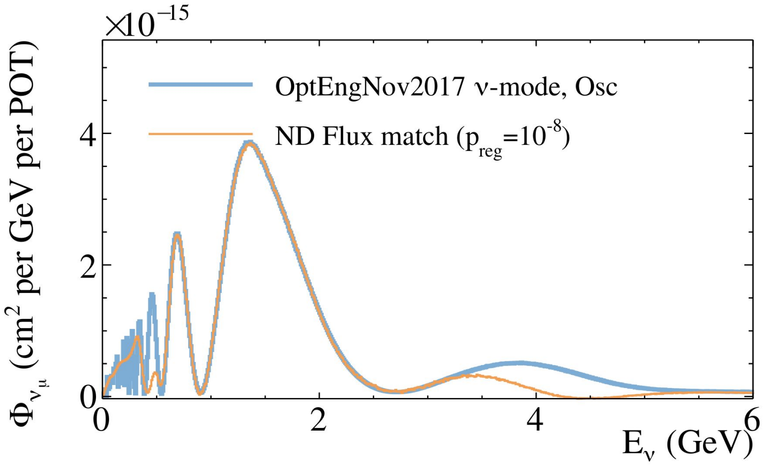
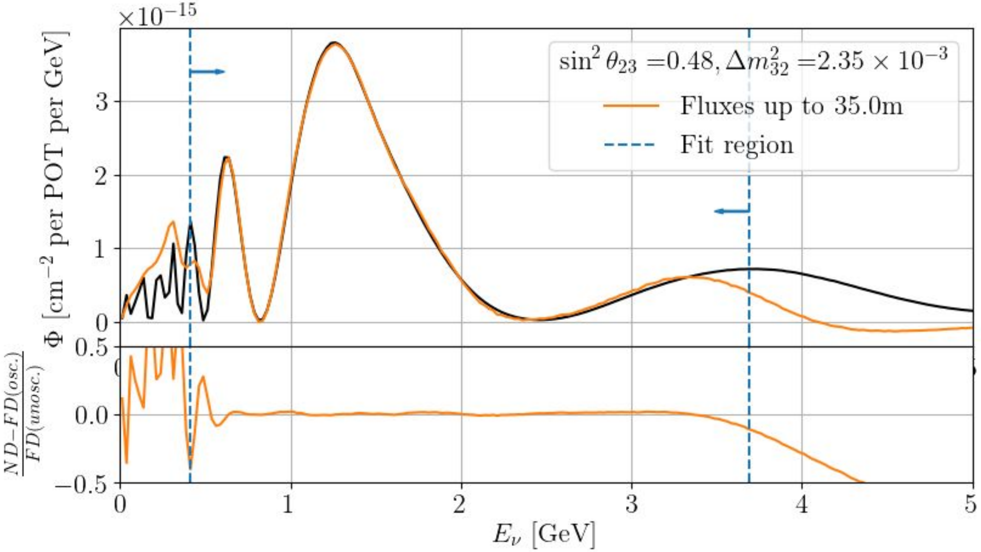
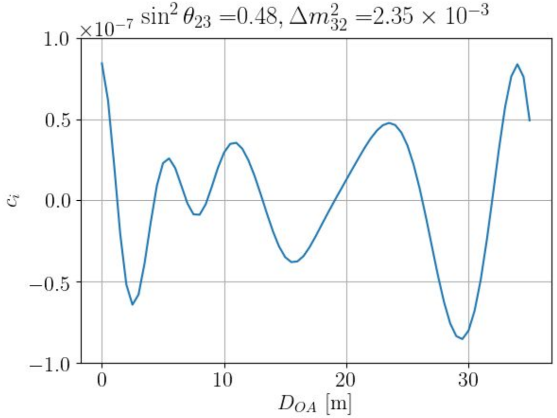
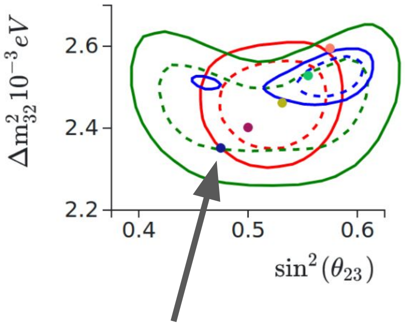


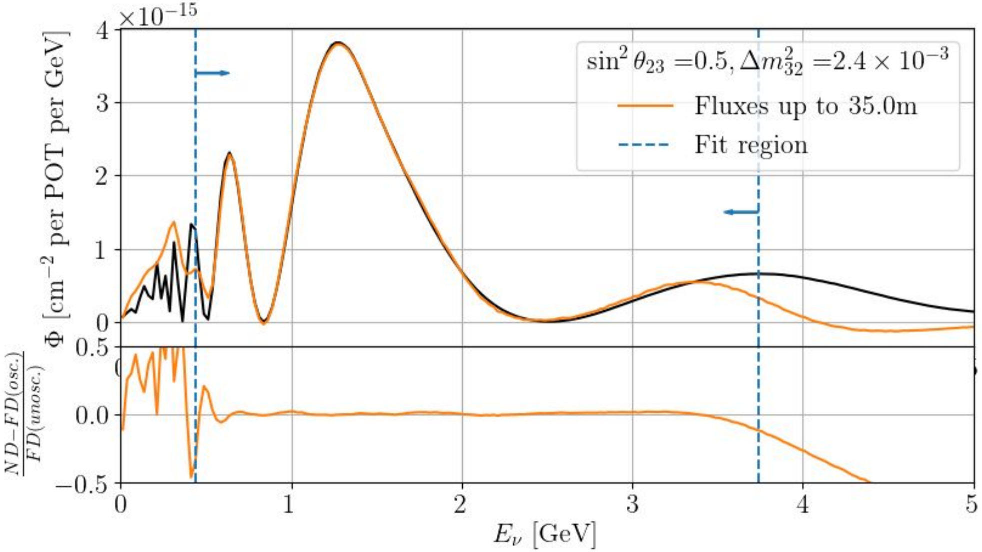




OscProb.js



T2K 2018
NOvA 2018
NuFit v4



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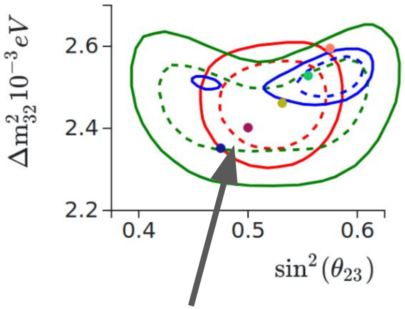

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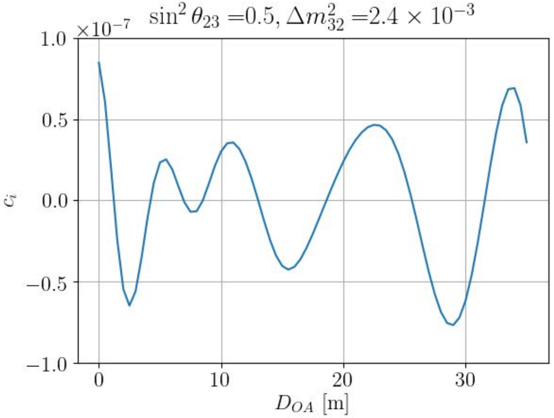

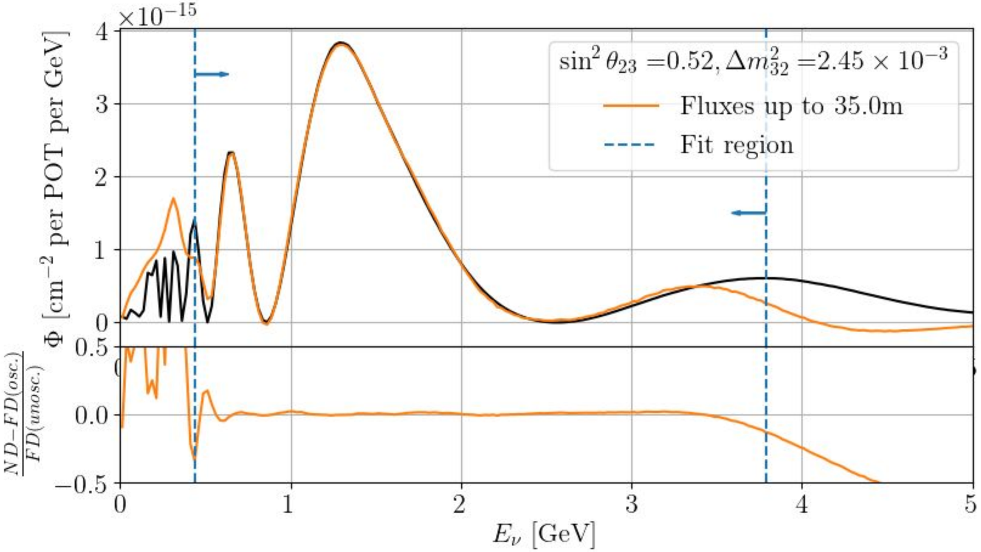

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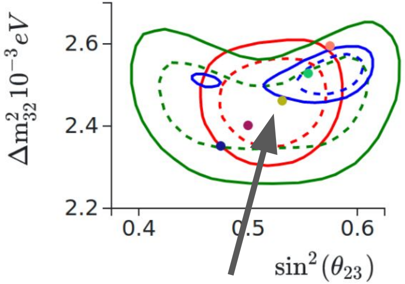
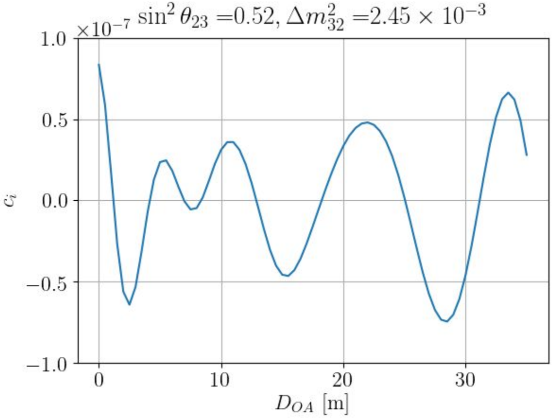
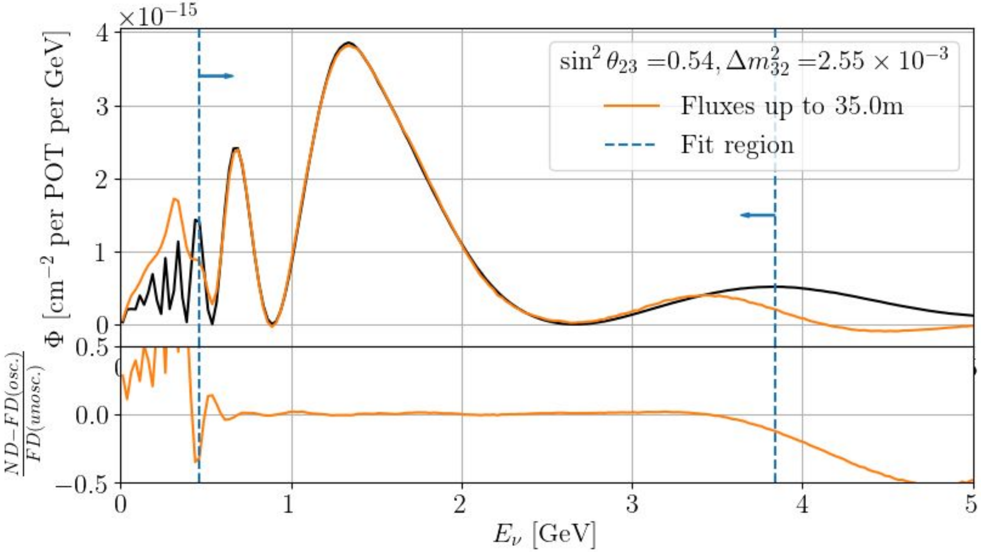
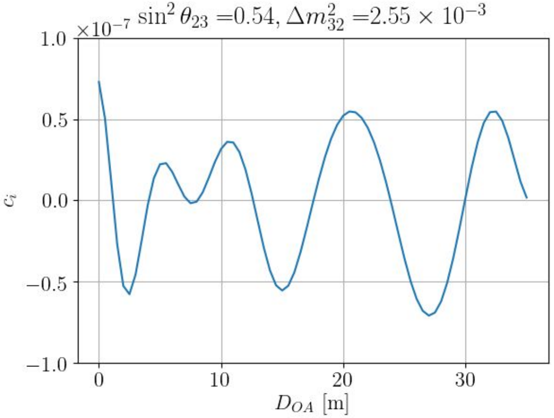




T2K 2018
NOvA 2018
NuFit v4





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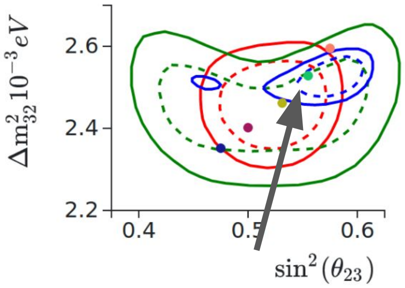
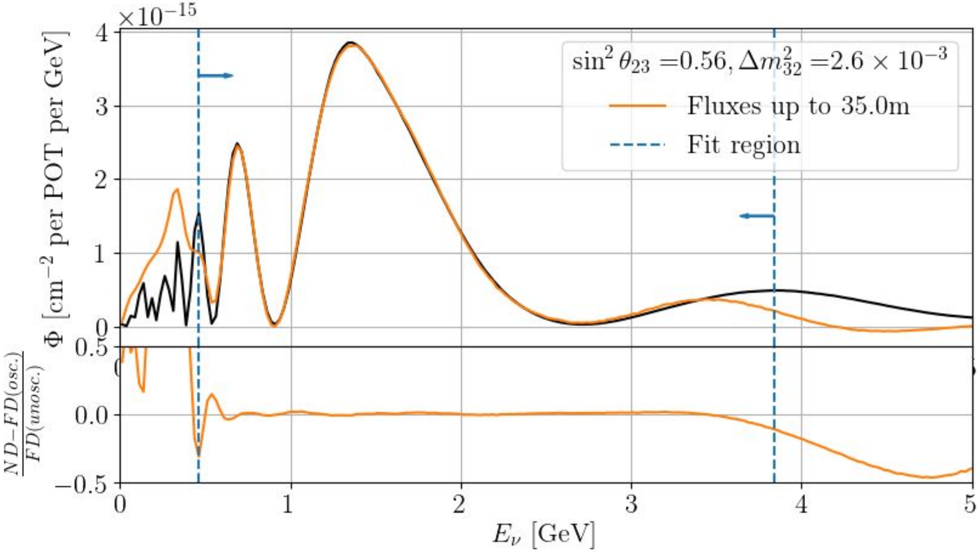
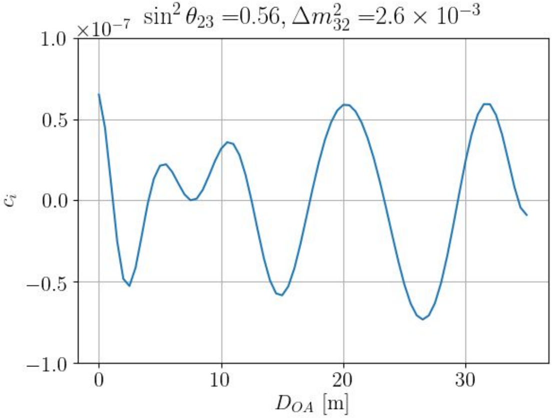
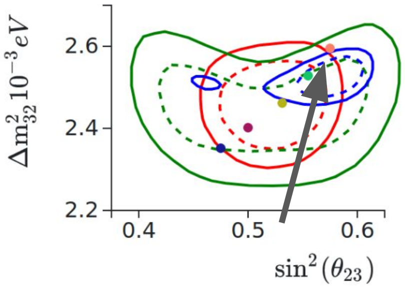


T2K 2018
NOvA 2018
NuFit v4





OscProb.js



T2K 2018

NOvA 2018

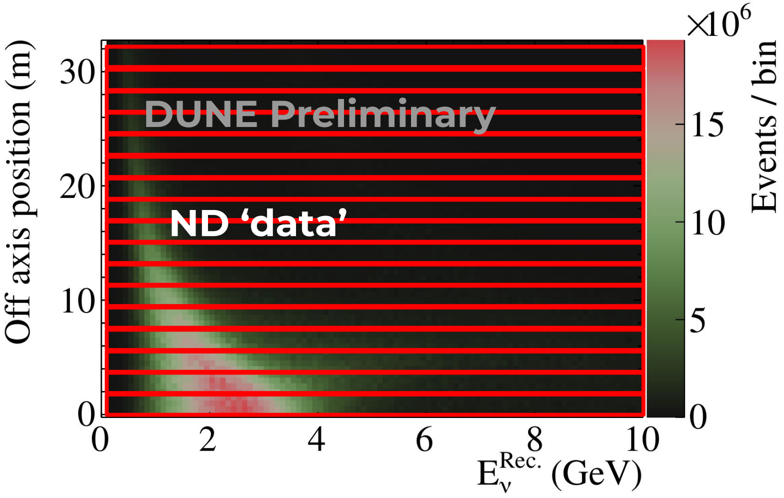
NuFit v4

Adapt

- If we can take an ND measurement with $\Phi_{\text{near}}(E_\nu) = \Phi_{\text{near}}(E_\nu, x_{\text{off axis}}) \times \vec{c} = \Phi_{\text{far}}(E_\nu) P_{osc}(E_\nu)$ then $N_{\text{near}}(\mathbf{x}_{\text{obs}})$ is the same as $N_{\text{far}}(\mathbf{x}_{\text{obs}})$ up to detector effects!

$$N_{\text{near}}(\mathbf{x}_{\text{obs}}) = \int d\mathbf{x}_{\text{true}} \underbrace{\mathbf{D}_{\text{near}}(\mathbf{x}_{\text{obs}}|\mathbf{x}_{\text{true}})}_{\text{Smearing, Eff., Pur.}} \underbrace{N_{\text{targ}}\sigma(\mathbf{x}_{\text{true}})\Phi(E_\nu)}_{N_{\text{Int}}(\mathbf{x}_{\text{true}})}$$

$$N_{\text{far}}(\mathbf{x}_{\text{obs}}) = \int d\mathbf{x}_{\text{true}} \underbrace{\mathbf{D}_{\text{far}}(\mathbf{x}_{\text{obs}}|\mathbf{x}_{\text{true}})}_{\text{Smearing, Eff., Pur.}} \underbrace{N_{\text{targ}}\sigma(\mathbf{x}_{\text{true}})\Phi(E_\nu)P_{osc}(E_\nu)}_{N_{\text{Int}}(\mathbf{x}_{\text{true}})}$$



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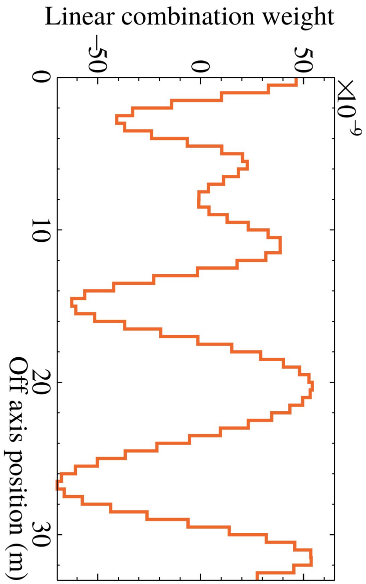

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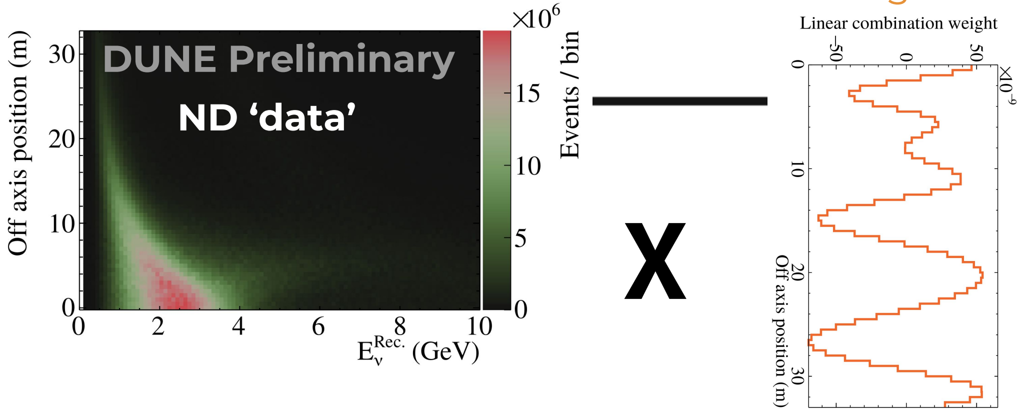
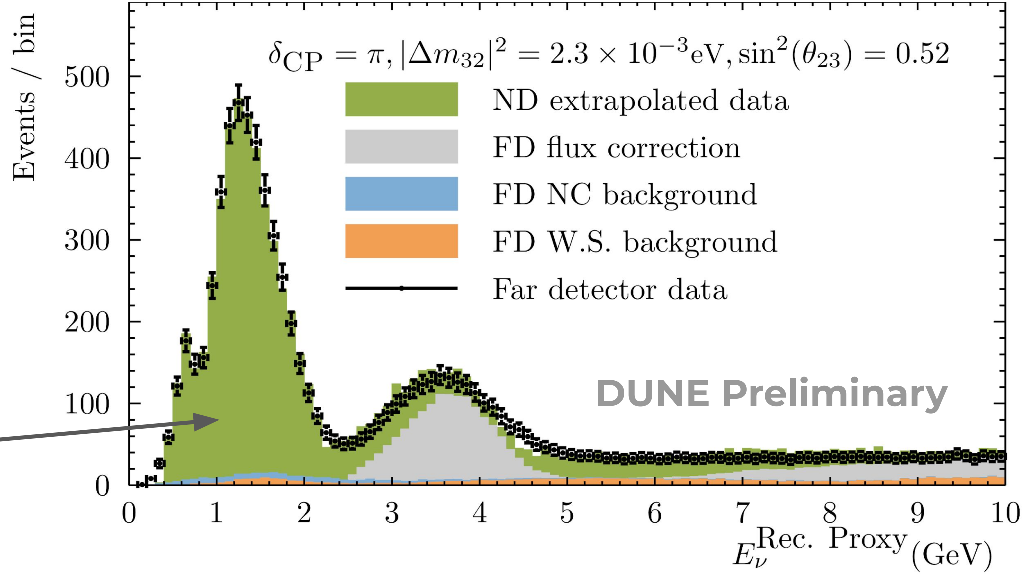
FD prediction

Overcome

- **Aim:** Rearrange ND data to predict FD
    - Unknown XSec features automatically transferred
    - Minimize XSec dependence and take advantage of ND/FD flux cancellations
    - N/F detector differences must be included in any analysis
- Robust to mis-modelling in observable energy distribution as use near ***data*** to fill most of the far 'prediction'!





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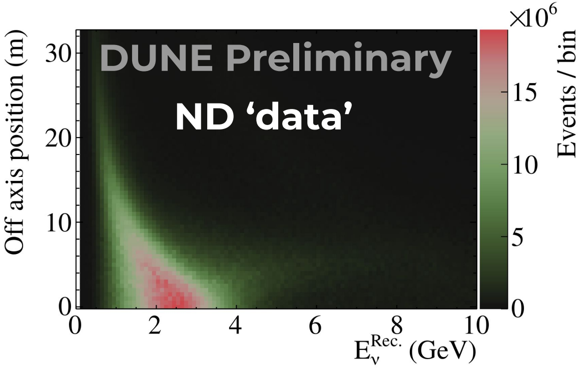

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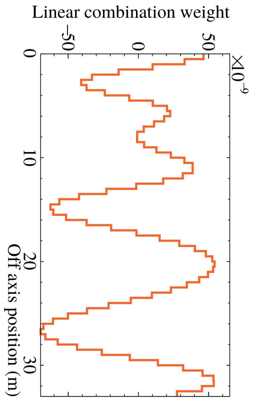

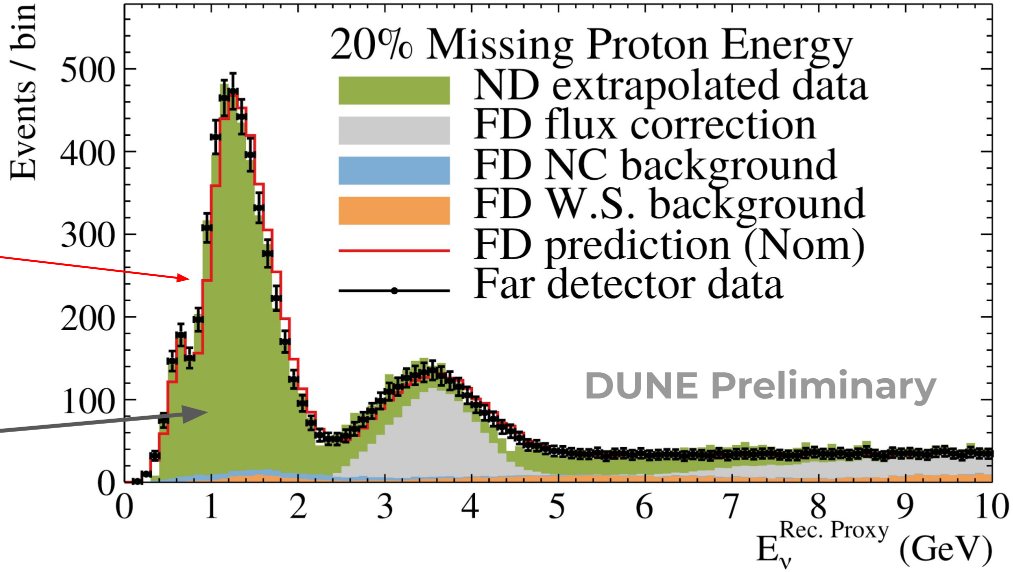

Summary

- Problems in neutrino interaction models can be hard to see & fix with on-axis near detector only
- Comparing data taken in different neutrino energy spectra can illuminate such mis-modelling.
- Using linear combination of near detector data to make far detector predictions can result in an oscillation analysis that is robust to a large range of cross-section modelling problems.

Thanks for listening

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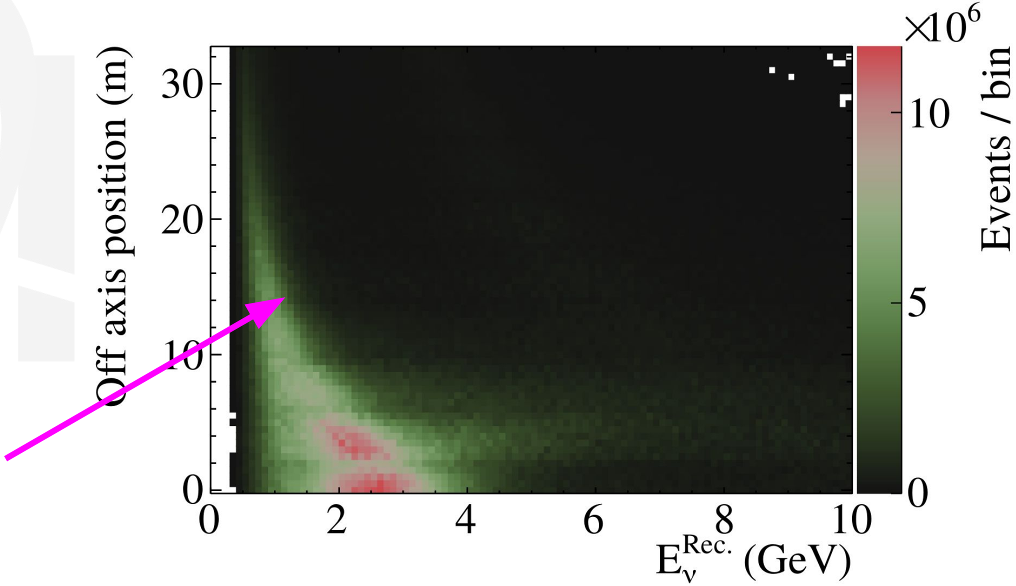
DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE-PRISM Propagation

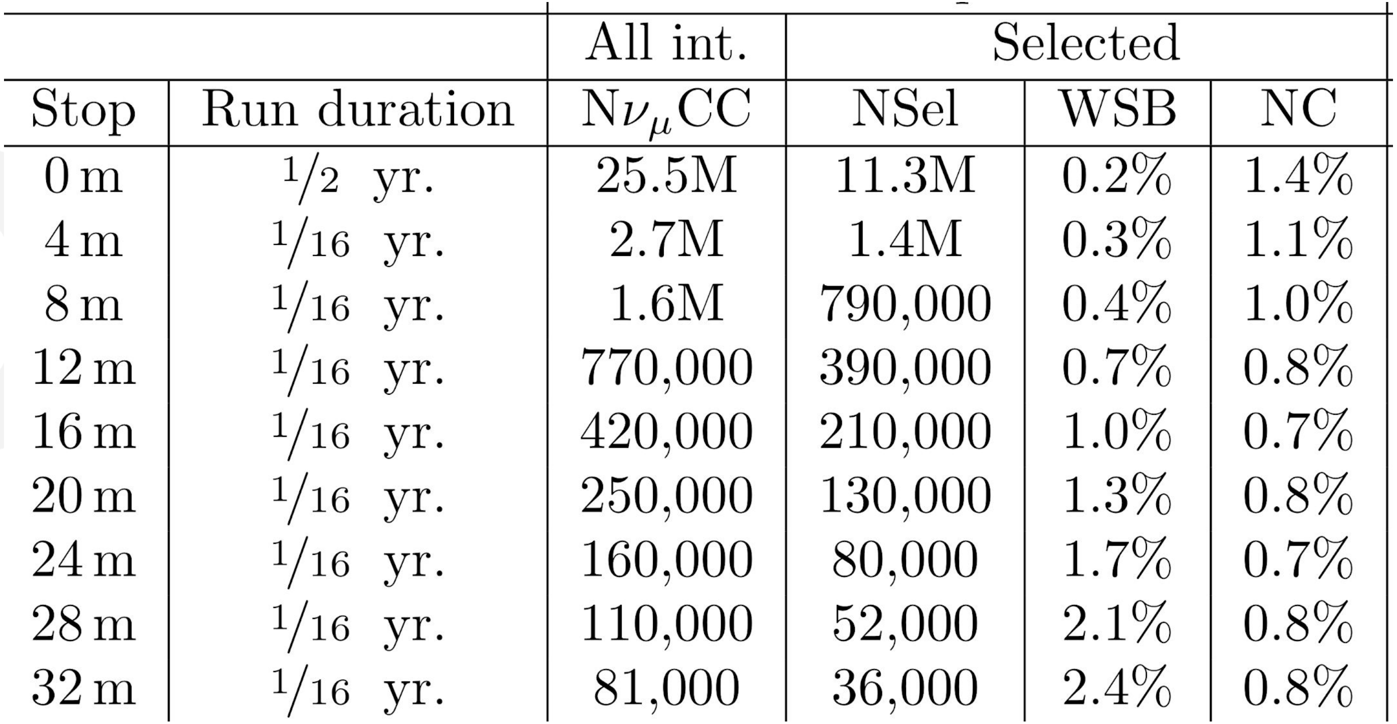
- **Aim:** Rearrange ND data to predict FD
    - Unknown XSec features automatically transferred
    - Minimize XSec dependence and take advantage of N/F flux cancellations
    - N/F detector difference unavoidable in any analysis
- In each systematic universe/fit step:
    1. Select data at ND
    2. Subtract ND backgrounds with MC prediction
    3. Correct for differences in N/F selection, resolution, fiducial mass
    4. Perform Flux match
    5. Linearly combine ND data
    6. Add FD Flux match MC correction
    7. Add FD backgrounds with MC prediction
    8. Evaluate GOF

Selected ND Event Rate

- Taking more granular steps near on-axis can mitigate edge-effects in the selection.
    - Future: Optimize stop plan



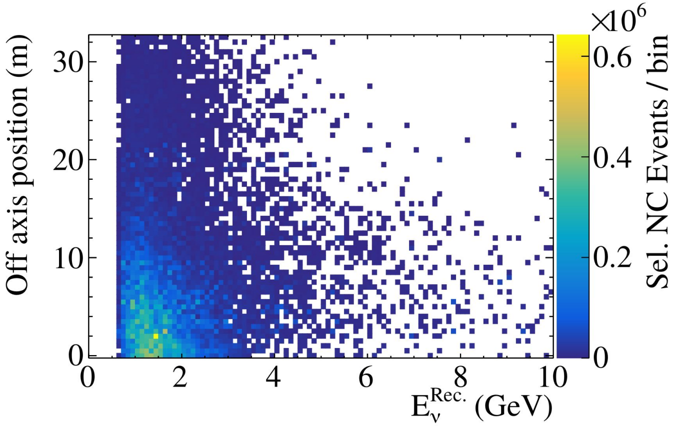
Predicted Event Rate Off Axis

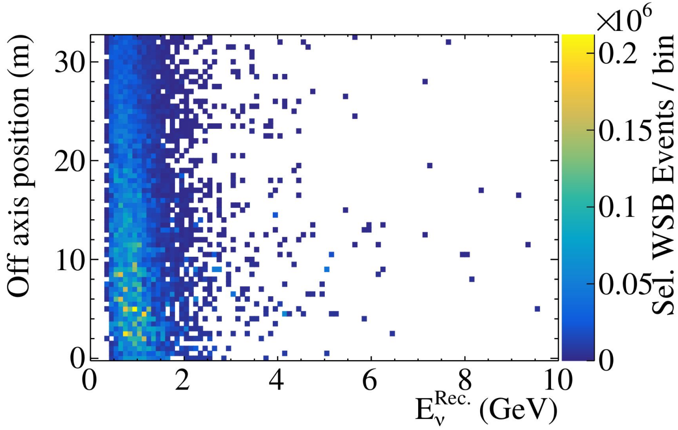


		All int.	Selected		
Stop	Run duration	$N\nu_\mu CC$	NSel	WSB	NC
0 m	1/2 yr.	25.5M	11.3M	0.2%	1.4%
4 m	1/16 yr.	2.7M	1.4M	0.3%	1.1%
8 m	1/16 yr.	1.6M	790,000	0.4%	1.0%
12 m	1/16 yr.	770,000	390,000	0.7%	0.8%
16 m	1/16 yr.	420,000	210,000	1.0%	0.7%
20 m	1/16 yr.	250,000	130,000	1.3%	0.8%
24 m	1/16 yr.	160,000	80,000	1.7%	0.7%
28 m	1/16 yr.	110,000	52,000	2.1%	0.8%
32 m	1/16 yr.	81,000	36,000	2.4%	0.8%

ND Backgrounds

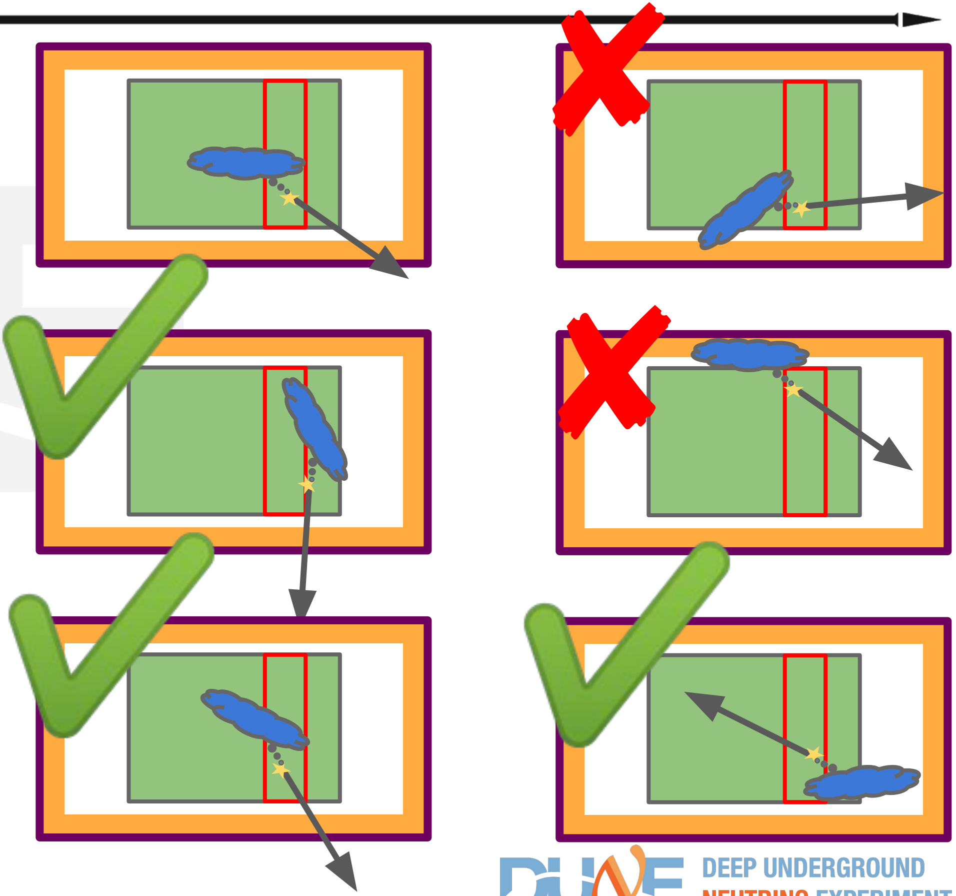
- Backgrounds that do not oscillate and vary differently as a function of off-axis position are subtracted before propagation.
- Most common:
    a. Neutral Current (Use on-axis to constrain ND and FD NCBkg)
    b. Wrong sign (worse in nubar-mode, use tracker to constrain WSBkg).
    c. Intrinsic nue
- These will get added back into the Far prediction later.





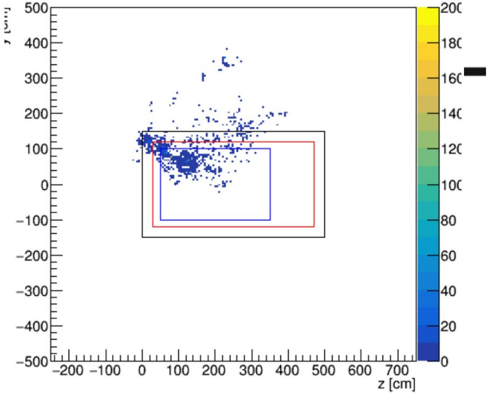
Selection Efficiency

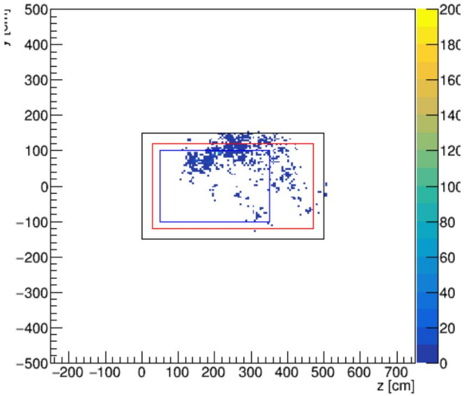
- Must correct for differences in ND/FD selection efficiency.
- Want to avoid asking GENIE everywhere possible.
- Aim to develop data-driven geometric efficiency correction:
    a. Throw away events outside acceptance ND-FD high acceptance union
    b. Add MC events that are in FD but outside ND

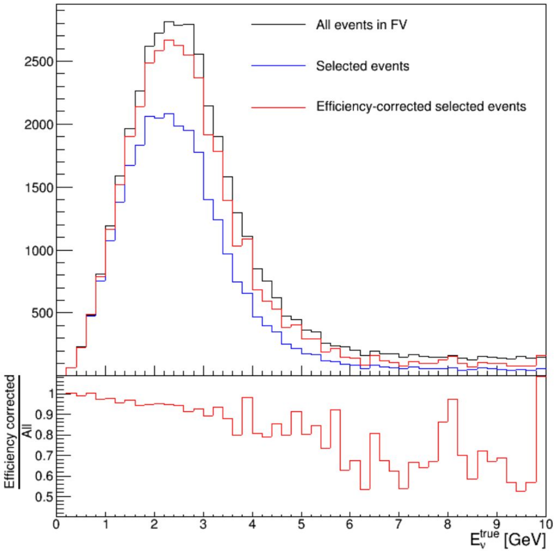


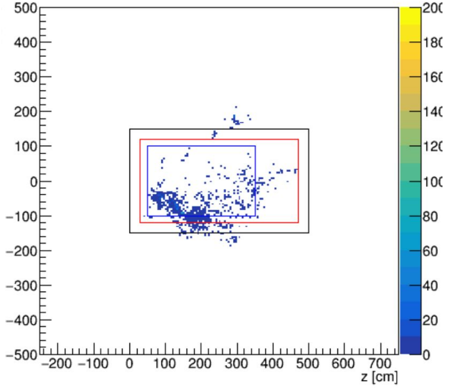
Geometric Efficiency

- Preliminary work by Cris Vilela:
- Random translation and rotation of energy deposits in selection volume
    a. Suggests 95% of events can be corrected in a model-independent data-driven way at the oscillation peak
    b. As expected from Chris Marshalls ND acceptance studies.
    c. Even higher fraction at lower energies.



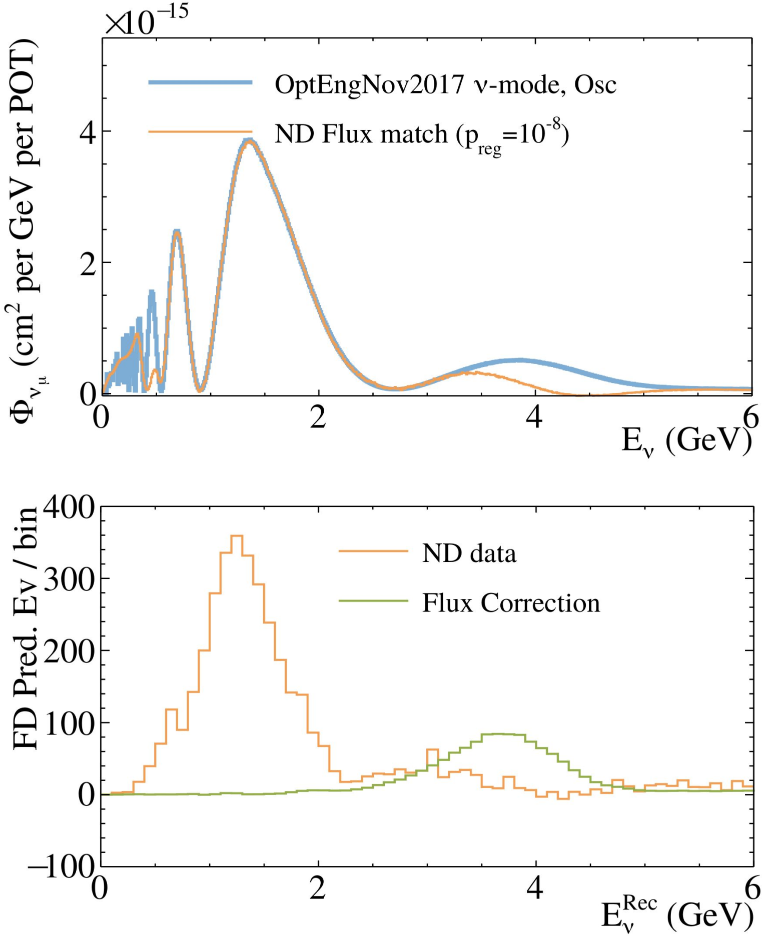






Flux Matching Correction

- Flux matching not perfect in general:
  - Especially at higher energy due to on-axis configuration
- Difference between 'target' and 'matched' filled in with FD MC predictions.
  - This 'filling in' is the same as the tuned-prediction 'dead-reckoning' that makes the entire FD comparison in the standard analysis.
  - **Here:** Majority of FD prediction built with ND data.



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FD Backgrounds

- Add back in any sources of FD background that we removed before:
  - Oscillated wrong sign background (Can use nu-mode ND data to build nubar-mode FD wrong sign prediction).
  - NC Backgrounds (Use on-axis ND to understand NCBkg.(