DUNE-PRISM

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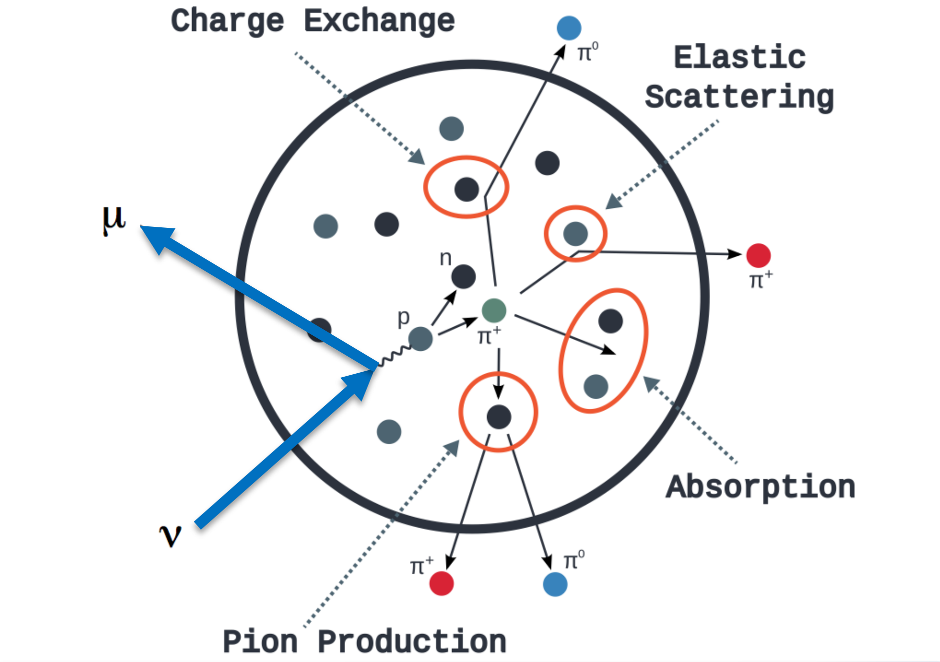
DUNE Near Detector Conceptual Design Review
7 July 2020

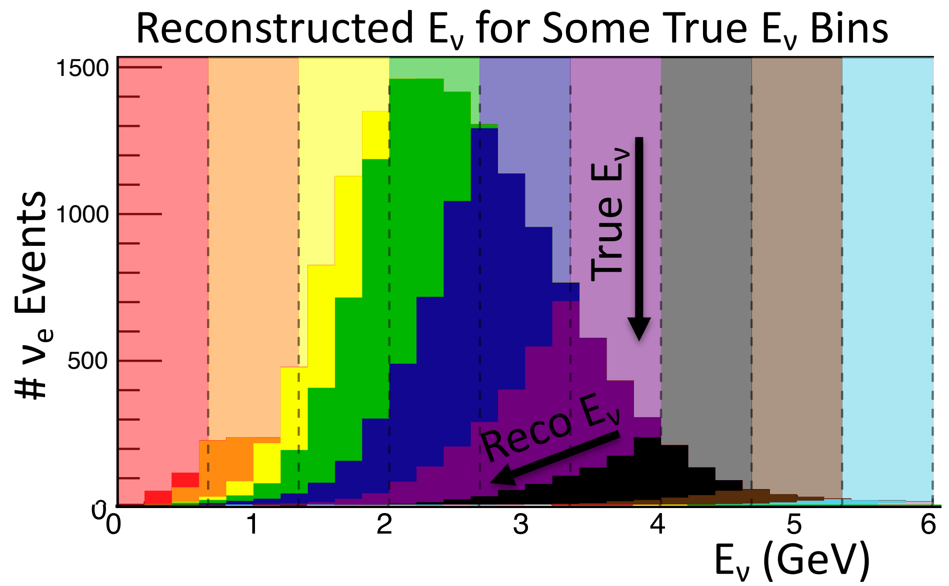
Outline

- Physics Motivations for DUNE-PRISM
- Concept Overview
- Analysis Techniques
- Design Requirements

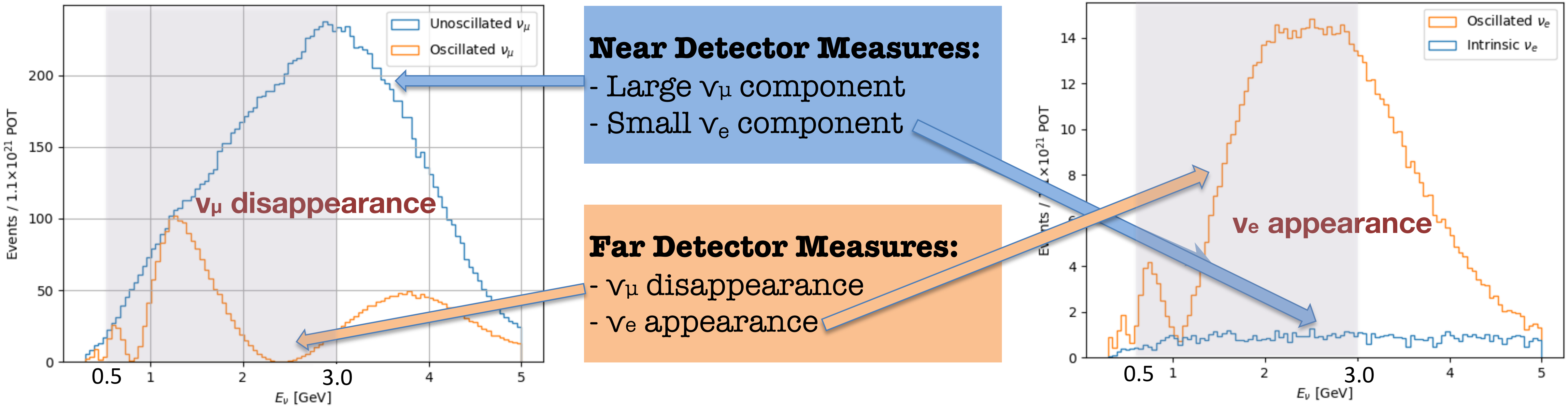
Systematic Uncertainties in ν–Ar Scattering

- One of the main limitations in achieving 2-3% systematic uncertainties is our understanding neutrino-nucleus interactions
  - DUNE’s predecessors, T2K & NOvA, have only reached ~7-8% uncertainties using simpler, and much better studied, nuclear targets (C/O)
- Neutrino-argon interactions are subject to a variety of poorly understood nuclear effects
  - e.g. Intra-nuclear scattering & nucleon-nucleon correlations
  - Final state composition and kinematics are difficult to model
- The observed neutrino energy depends on the details of the hadronic final state
  - e.g. much of the energy carried by neutrons is lost
- The “feed-down” of the reconstructed E_ν in each true E_ν bin is subject to substantial modeling uncertainties





Impact of ν–Ar Mismodeling on Oscillation Measurements



Near Detector Measures:
- Large ν_μ component
- Small ν_e component

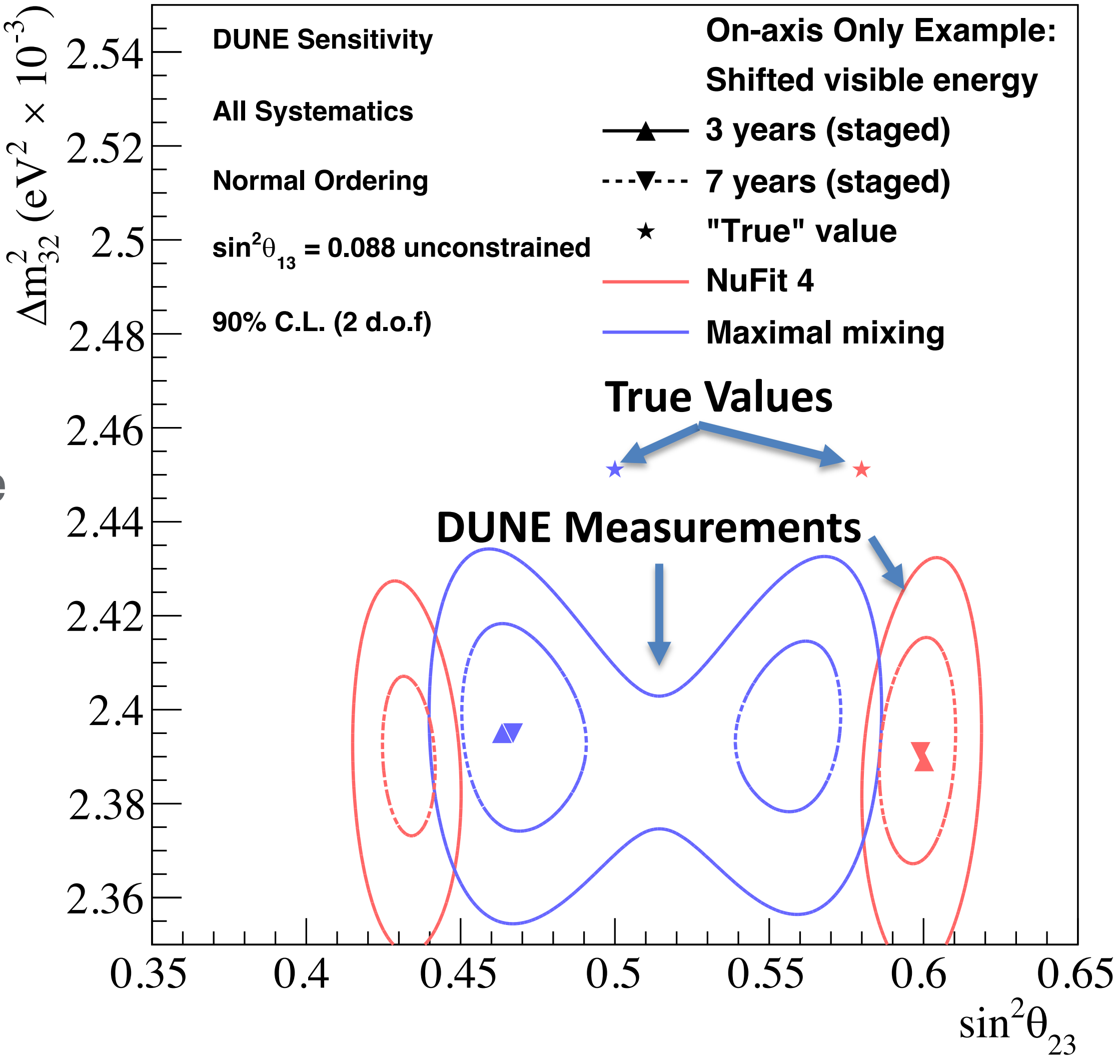
Far Detector Measures:
- ν_μ disappearance
- ν_e appearance

- Shouldn't cross section effects cancel in a near/far ratio?
- No, since the near and far spectra are very different (mostly due to oscillations)
  - E_{REC} feed-down has a gradual effect at the ND, but smears oscillation features at the FD
  - ν-Ar mismodeling can bias osc. parameter measurements, even with perfect ND data/MC agreement (see next slide)
- To move beyond T2K & NOvA to the 2-3% systematic uncertainty level, qualitatively new, data-driven constraints are needed on E_{TRUE} ➔ E_{REC} feed-down

Measurement Biases due to Poor ν–Ar modeling

- Near detectors allow us to correct ν–Ar mismodeling
  - However, if we choose the wrong corrections to force agreement with our near detector data, our oscillation parameter measurements can be biased
- Test case: What if 20% of the neutrino energy carried by final state protons were actually carried by neutrons?
  - In response, DUNE physicists might incorrectly choose to modify cross sections (e.g. dσ/dE$_{proton}$) to match the on-axis near detector data
- A full near+far detector fit of this test case produces strong biases in measured oscillation parameters
- **Summary**: even with perfect data/MC agreement in an on-axis near detector, DUNE may still get the wrong answer

DUNE Oscillation Parameter Bias After 3 Years (with only on-axis near detector measurements)



DUNE-PRISM Off-Axis Measurements

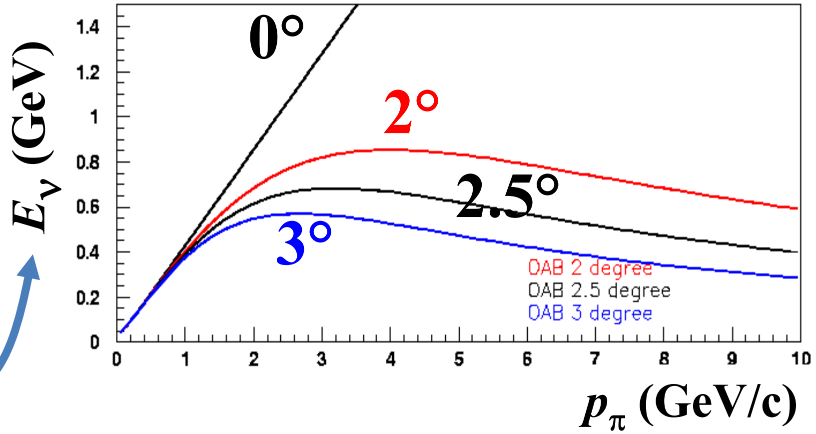
- Neutrino beams are produced via 2-body decays of charged pions
- As a detector is placed increasingly "off-axis", the energy spectrum narrows, and peaks at lower E_ν
- Moving the detector allows us to scan across incident neutrino energy
  - Provides a set of neutrino "test beams" to across a range of true energies
- This allows us to directly measure reconstructed E_ν as a function of true E_ν

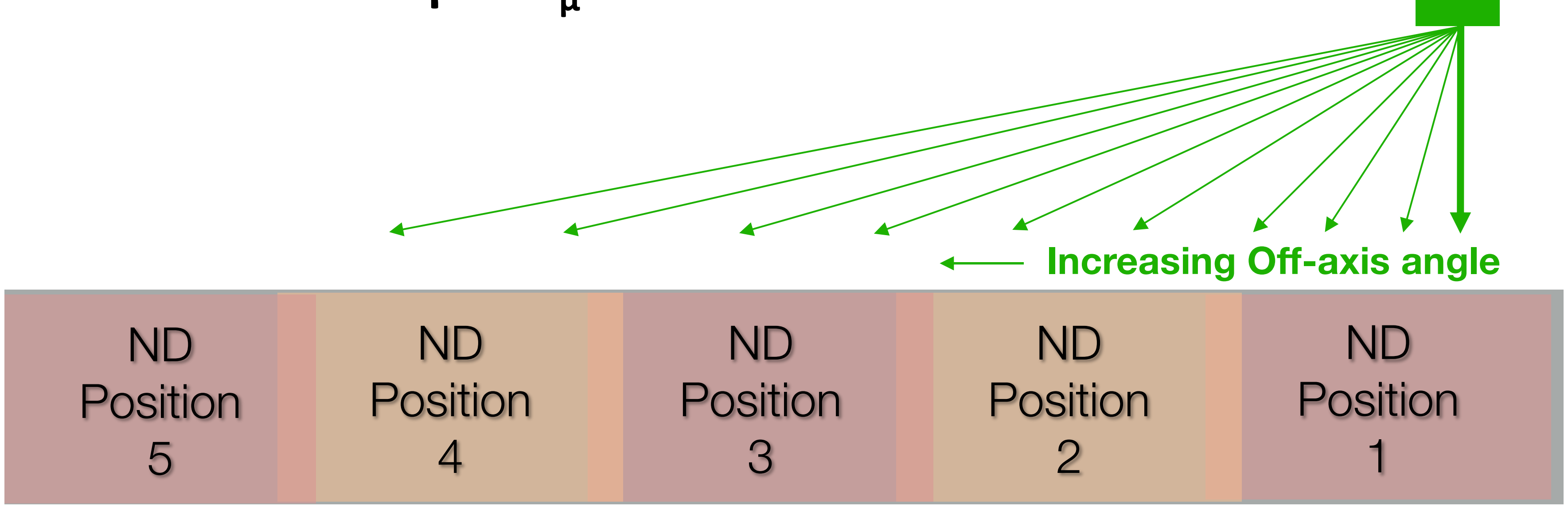
How to Make a Neutrino Beam

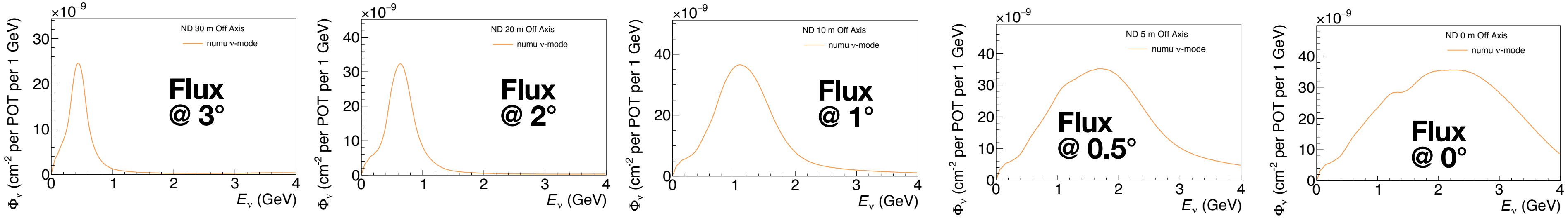
$p + \text{target} \rightarrow \pi^+$

(2-body decay)

$\mu^+ + \nu_\mu$

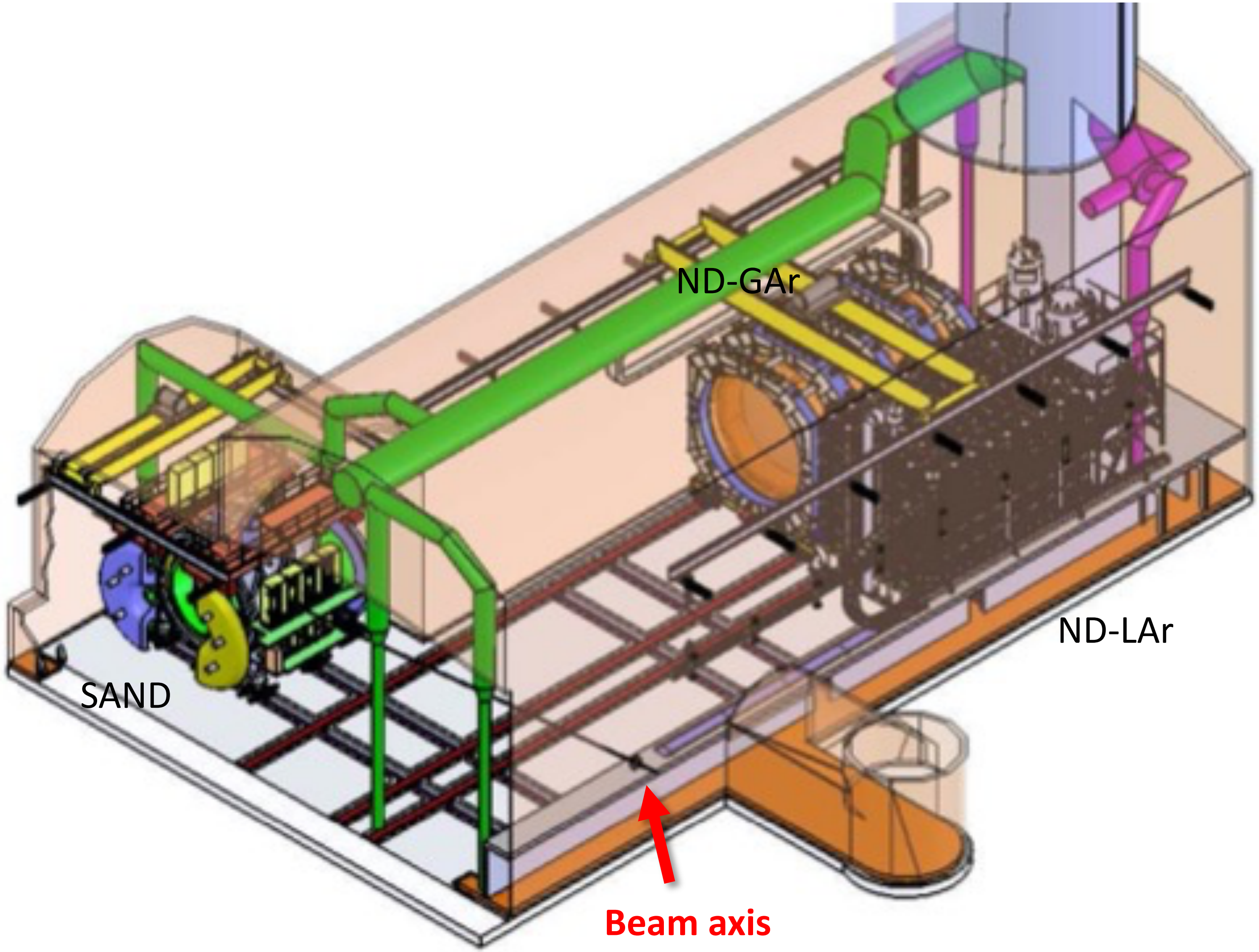






DUNE-PRISM Layout

- Both the ND-GAr and ND-LAr detectors move off-axis using powered Hilman “skates” rolling on box beams
  - More details in tomorrow’s talk by R. Flight
- The detectors can be placed at arbitrary positions along the off-axis direction
- The SAND detector remains on-axis to monitor the beam



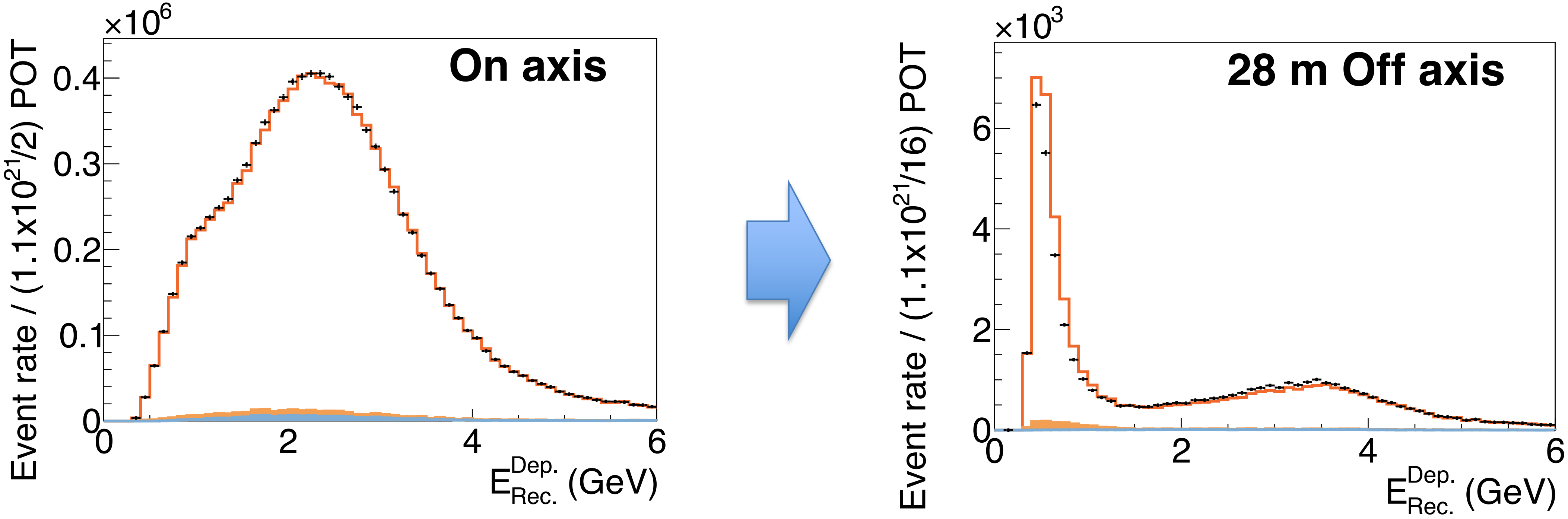
Uses of DUNE-PRISM Data

1. **Identify** cross section mis-modeling that can produce biased oscillation parameter measurements
   - By looking off-axis (changing the E_ν spectrum), we can identify mis-modeling problems that are caused by incorrect tuning of models to on-axis data
2. **Overcome** cross section mis-modeling problems (2 approaches):
   a) **Standard approach**: Develop a cross section model that can describe the near detector data
      - It is now much more difficult to make "incorrect" model adjustments, since these adjustments must now match the data with many energy spectra that peak across the oscillation region

   b) **Data-driven approach**: Take linear combinations of off-axis measurements to produce a FD prediction composed of ND data
      - Any unknown cross section effects are directly incorporated into the far detector spectrum prediction

Use 1: Identifying Modeling Issues

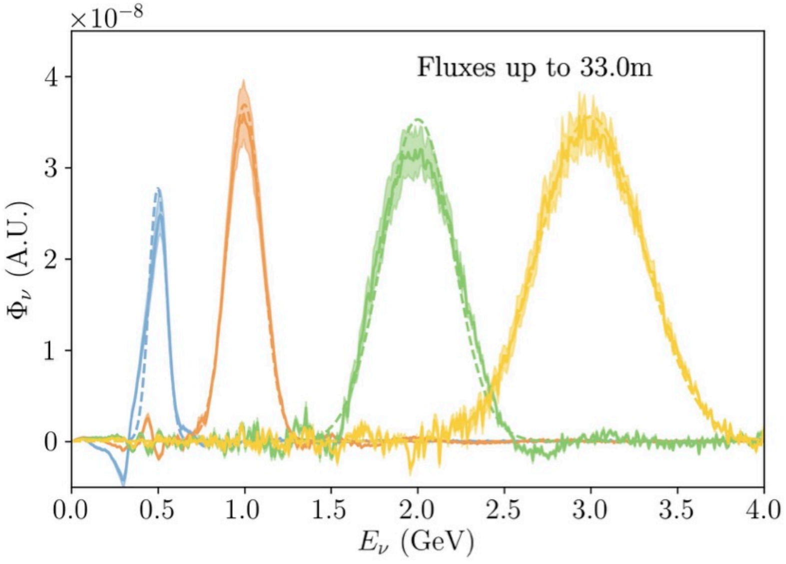
- With DUNE-PRISM, the missing proton KE test case can be compared to nominal MC at many different off-axis positions
- The previously “hidden” modeling problems can clearly be seen off-axis
  - ND off-axis spectra span the FD E_ν spectrum, so modeling can be verified within the E_ν range relevant for DUNE oscillation physics



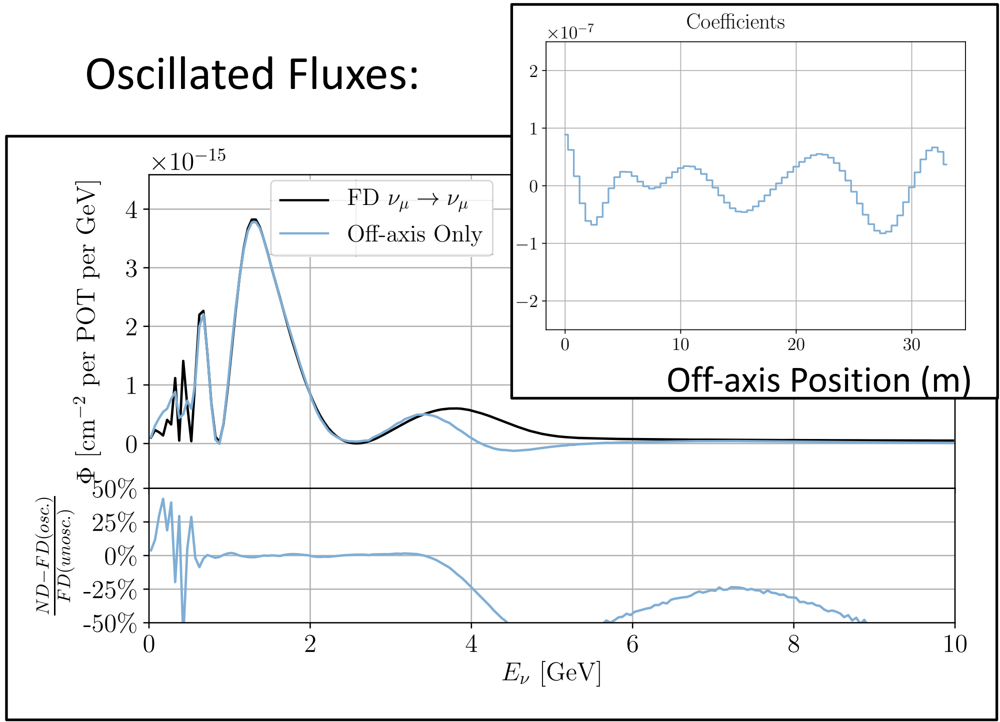
Use 2b: (Part 1) Flux Matching

- The flux predictions at each off-axis position can be linearly combined to match any user-defined flux
  - The same combination can then be applied to any observable (e.g. E_{rec})
- 2 types of fluxes are of particular interest:
  - A Pseudo-monoenergetic flux (e.g. Gaussian)
    - Can be used to measure a reconstructed distribution for a known true energy (similar to electron scattering)
    - e.g. it is now possible to make the first ever measurements of neutral current interactions vs E_ν
  - A FD oscillated flux
    - We can now produce oscillated fluxes at the ND!
    - Allows for a direct measurement of the oscillated FD E_{rec} distribution at the ND (for any choice of oscillation parameters)

Gaussian Fluxes:

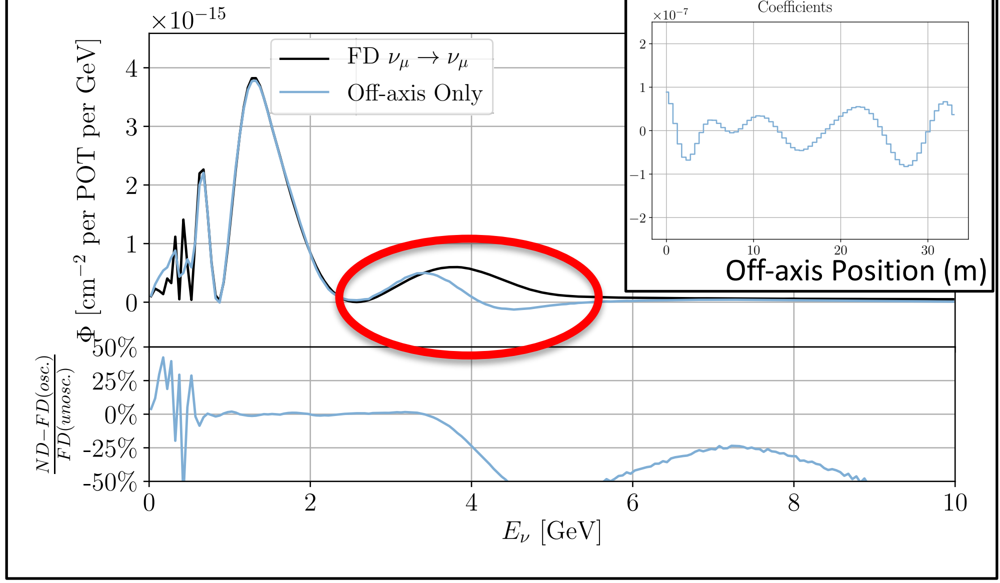


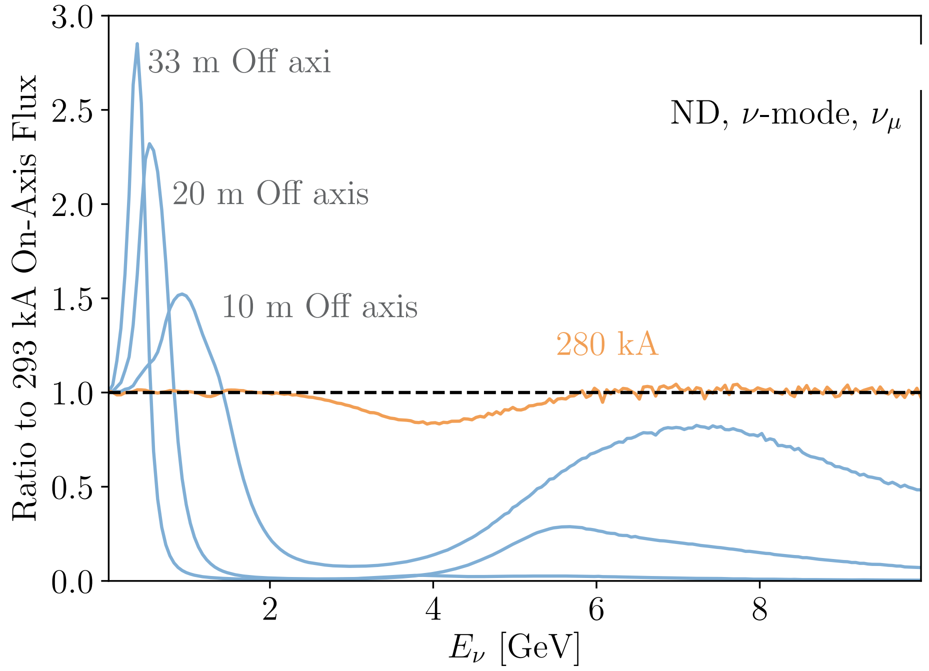
Oscillated Fluxes:



Special 280 kA Horn Current Run

- It's difficult to get agreement at high energies using only off-axis fluxes
  - Highest energy flux available is the on-axis flux
- By adding a 1 week special run each year at a slightly lower horn current (293 kA -> 280 kA), we gain additional high-energy information





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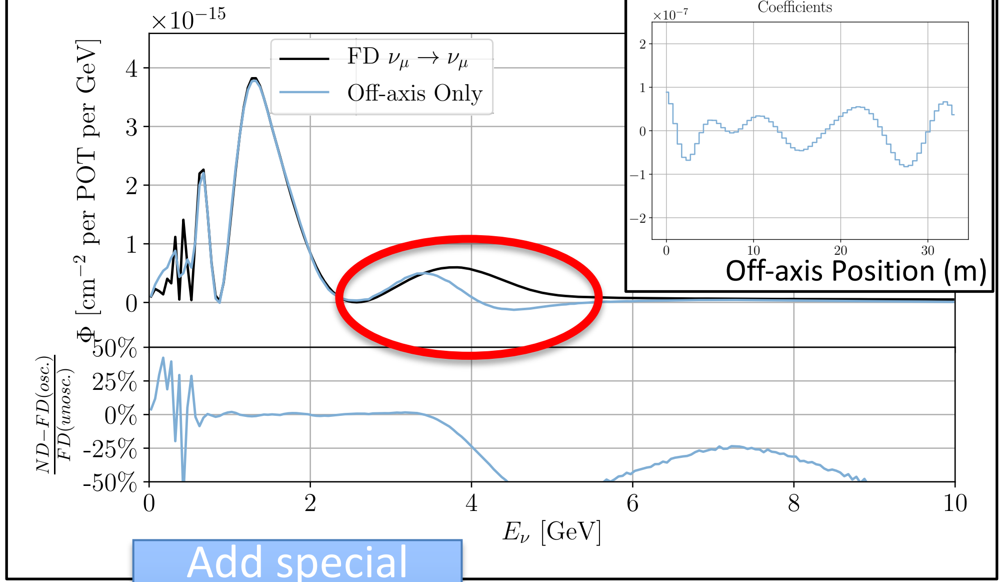
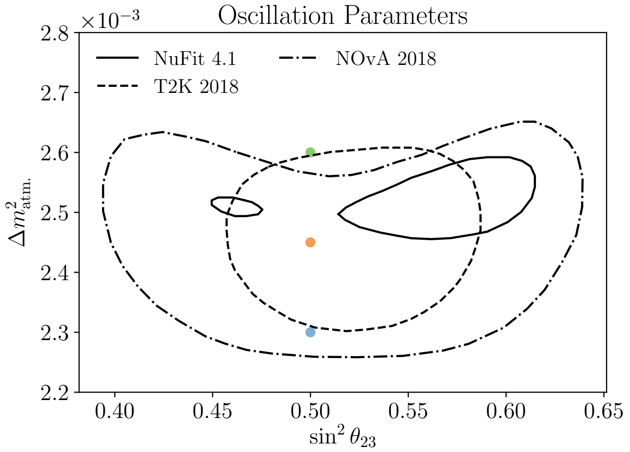
  - We can now match the far detector oscillated spectrum for any choice of oscillation parameters

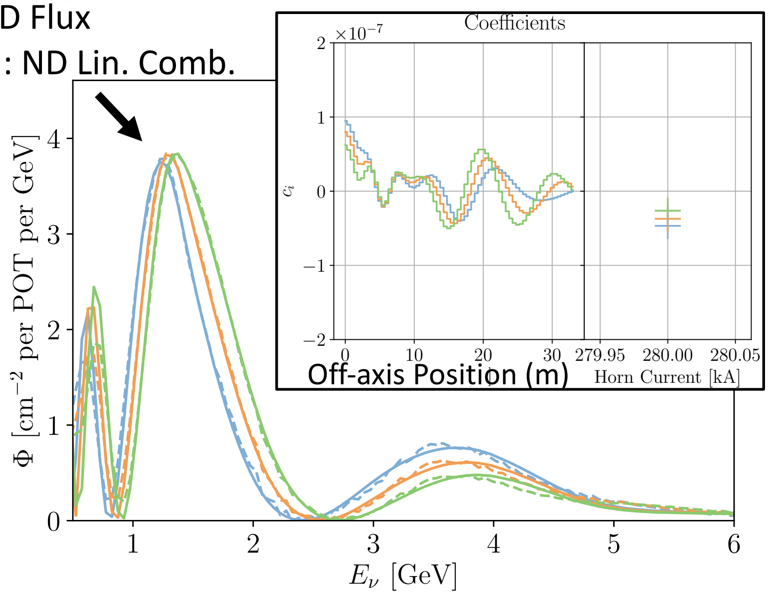


Add special 280 kA run

Solid: FD Flux

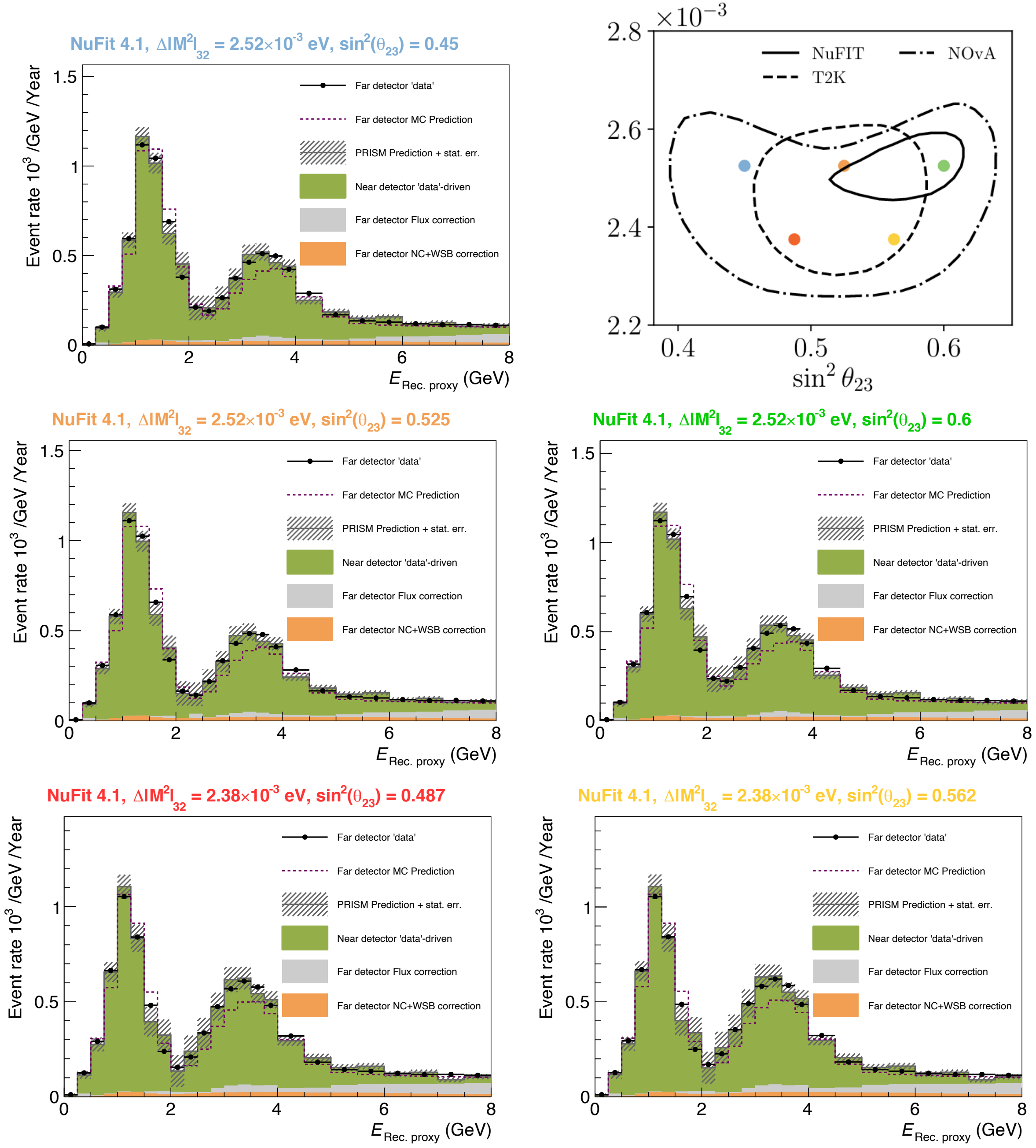
Dashed: ND Lin. Comb.





Linear Combination Analysis Removes Biases

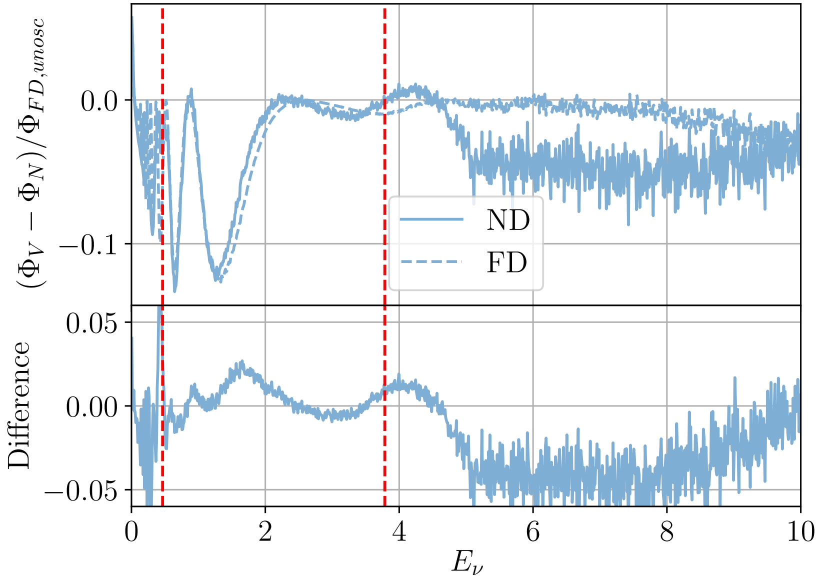
- Let's revisit our E_{proton} mismodeling test case
- By constructing the FD prediction from linear combinations of ND data (solid green), we correctly predict the correct shape of the FD E_{rec} spectrum (black data points)
  - i.e. we no longer have the shift in seen the standard, ND constrained, model extrapolation (red dashed)
  - This holds true across the entire allowed parameter space
- A correction is included for the small residual mismatch in the ND to FD flux matching (solid gray)
- The backgrounds are also shown (solid orange)



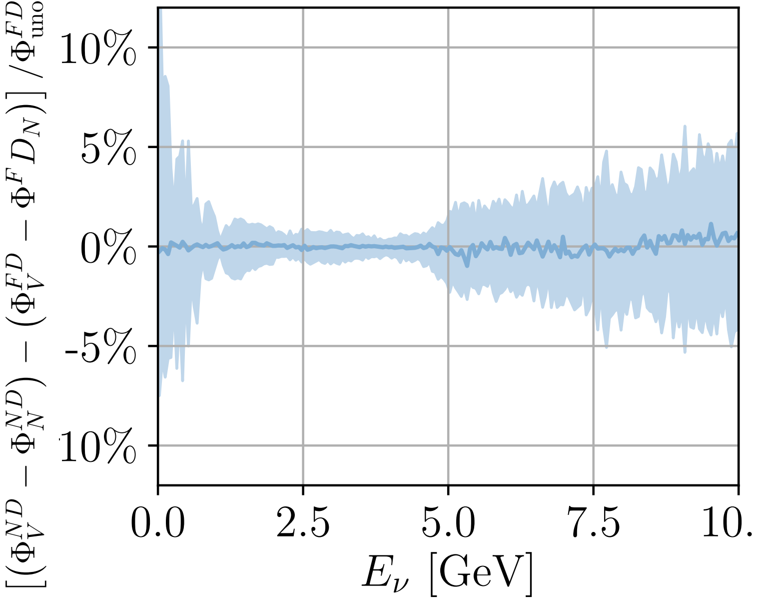
Systematic Uncertainties (Flux)

- Having the near and far detectors in the same neutrino beam is critical to minimize systematic uncertainties due to the flux modeling
- The top plot shows a large variation in the hadron production model
  - The FD flux, and the matched ND linear combination flux, both move by nearly the same amount (up to ~5 GeV)
  - The residual difference (bottom plot) gives the actual systematic uncertainty
    - The correction for this residual difference is the only part of the analysis susceptible to signal cross section modeling uncertainties (higher order effect)
- The total flux systematic uncertainty due to all variations is given in the bottom plot
- This analysis is also susceptible to detector uncertainties, and cross section modeling uncertainties on the (relatively small) backgrounds

Example Large Flux Variation



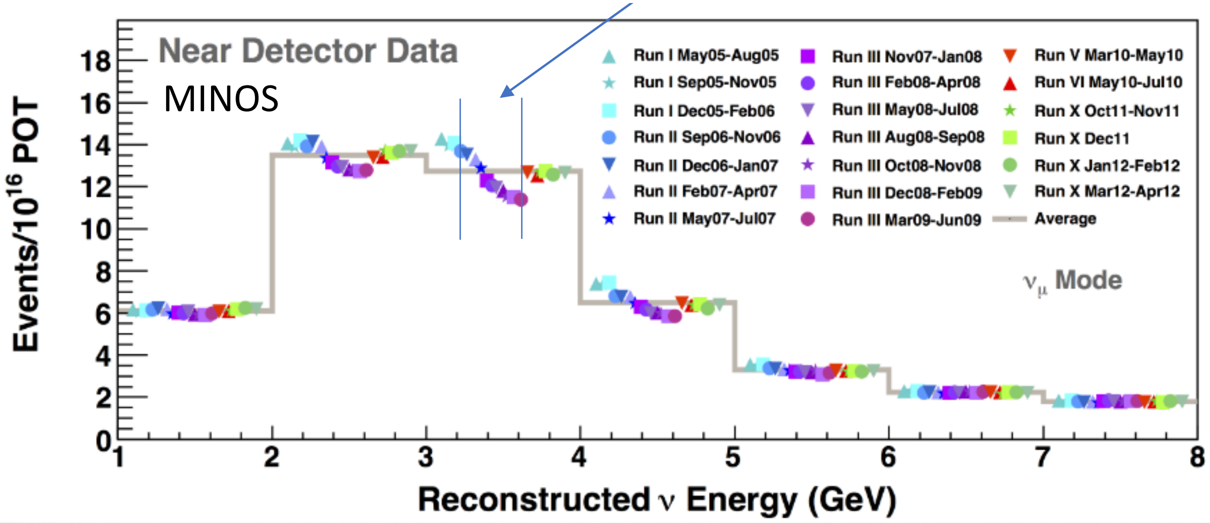
Total Flux Uncertainty



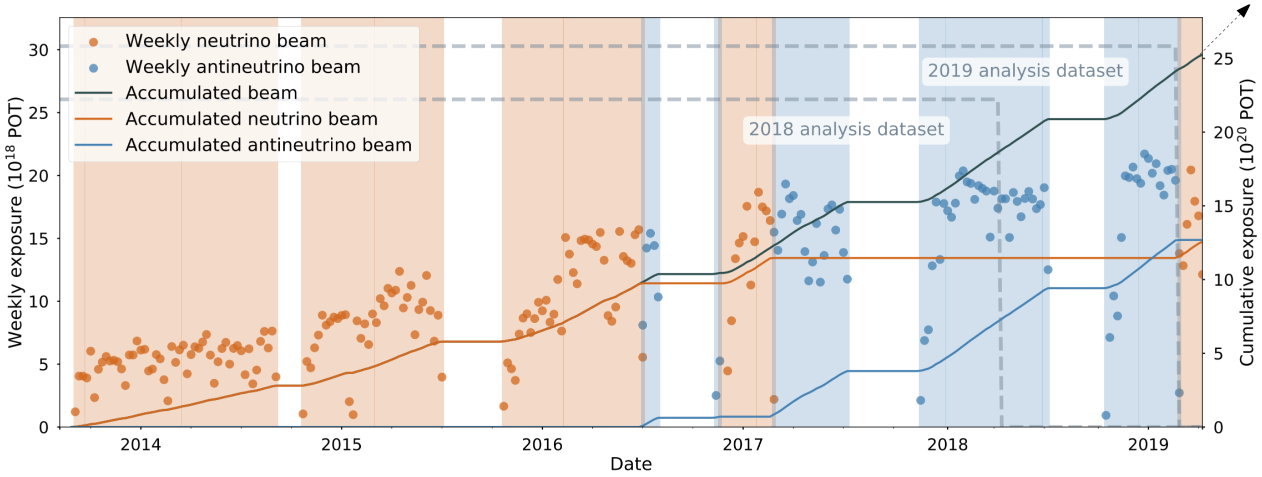
Movement Frequency

- NuMI experienced some intermittent issues affecting E_ν spectrum
  - e.g. target degradation, horn direction changes
- There may be issues with combining off-axis data from runs taken in different years
  - If flux changes cannot be properly simulated, extra systematics may be required when determining correlations between flux uncertainties at different off-axis positions
- Our goal is to take a full suite of off-axis measurements each year (i.e. run)

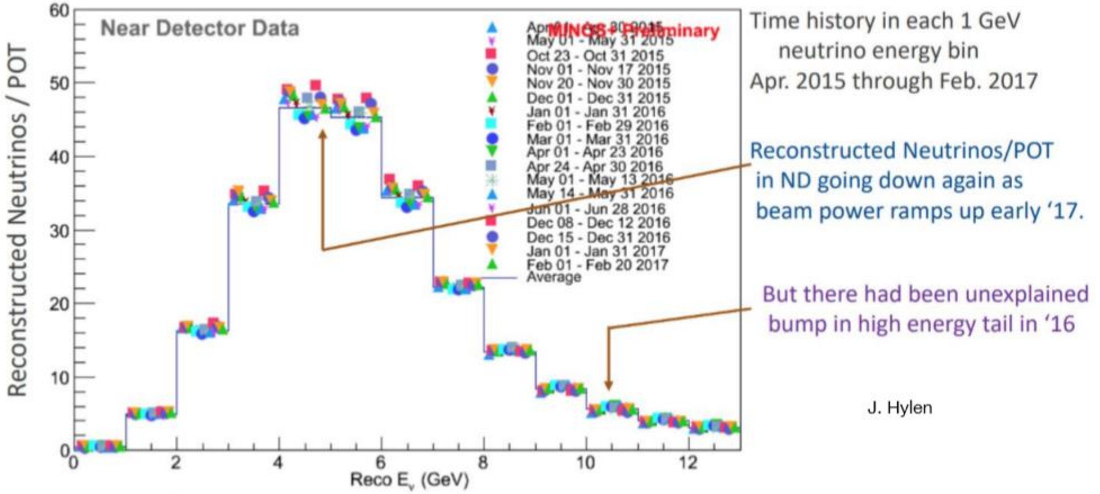
NuMI Target Degradation (3 year period)



NuMI Data Runs



NuMI Horn Tilt (Bushing Failure)



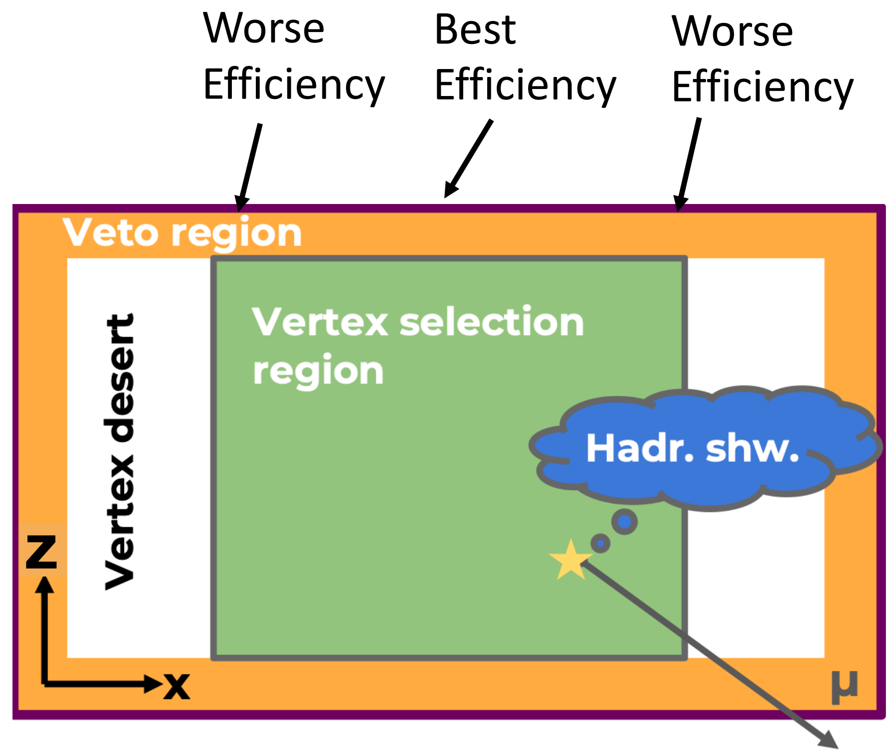
Time history in each 1 GeV neutrino energy bin Apr. 2015 through Feb. 2017

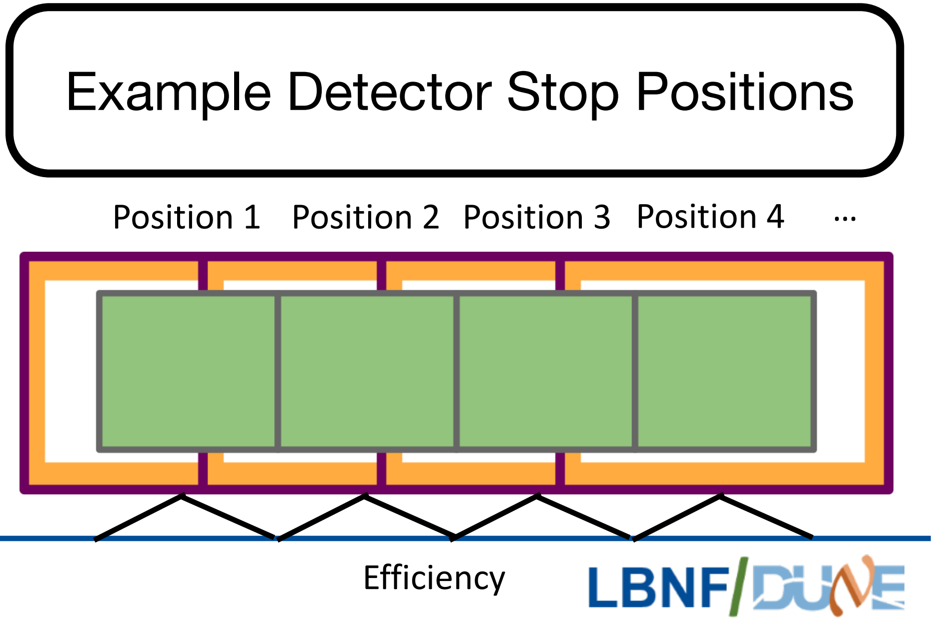
Reconstructed Neutrinos/POT in ND going down again as beam power ramps up early '17.

But there had been unexplained bump in high energy tail in '16

Detector Acceptance

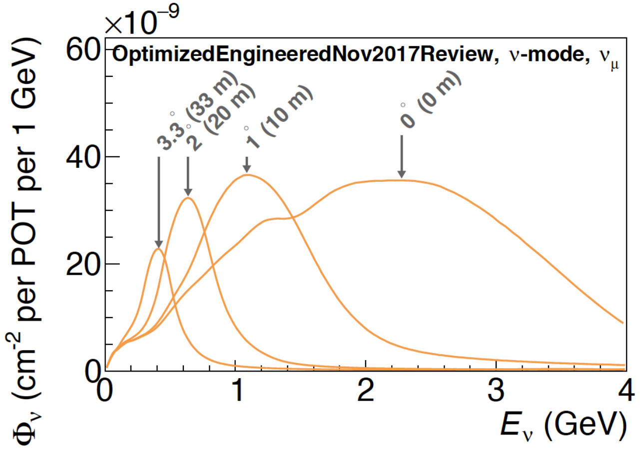
- We reject events with hadronic energy in outer ~30 cm
  - …to guarantee that we've contained all of the energy
- This means that events near the edge of the detector have worse efficiency
  - This is not desirable, since our ability to correct for this effect depends on the same poor modeling we are trying to avoid
- We don't want to repeatedly put the detector in the same off-axis positions each time we sample the off-axis range

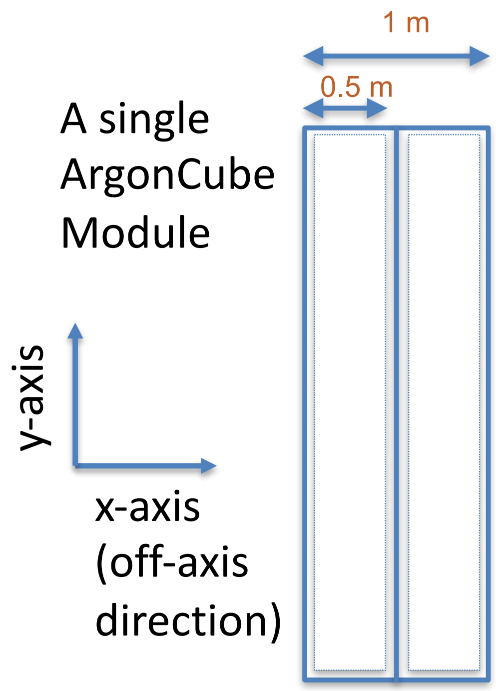




Sampling Granularity

- The distance scale for flux variations (especially near-on-axis) and detector variations is ~10 cm
  - LAr FV is likely to exclude interactions in or near the ArgonCube module walls
- To avoid consistently sampling the same off-axis regions with “bad” detector regions, we require position control at ±3 cm (goal: ±1 cm)
  - This level of control will keep the LAr and MPD sufficiently aligned to avoid changes to the muon acceptance vs off-axis angle
- We also require a secondary monitoring system to measure the actual achieved detector position at ±1 cm (goal: ±1 mm)



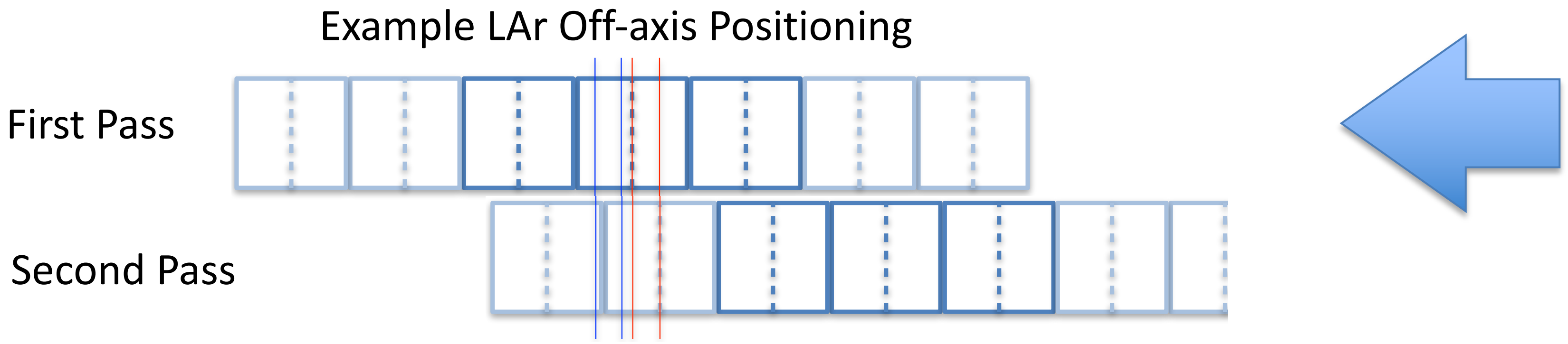

1 m

0.5 m

A single ArgonCube Module

y-axis

x-axis (off-axis direction)


Example LAr Off-axis Positioning

First Pass

Second Pass

Detector Positioning Requirements

- Our current assumption is 50% on-axis running for flux measurements (e.g. nu-e scattering)
  - Alternating between on-axis and each new off-axis position allows for frequent detector performance verifications (time-dependent effects)
- The LAr fiducial volume is 4 m wide, so the minimum required number of additional detector positions to span the full off-axis range is 8 (for 30.5 m)
- To avoid efficiency differences among off-axis positions, our goal is to access an additional set of ~7 ”half-stops” within each beam run
  - (note that the number of substops does not affect the statistics collected in each 50 cm off-axis interval)
- Assuming 56% uptime, this corresponds to ~1 week per position, including substops
  - To achieve < 5% deadtime, we require the detector to move between 2 arbitrary positions (and resuming taking high-quality data) within an 8-hour shift
    - This places requirements on ND-LAr & ND-GAr to limit ramp down & ramp up to 1 hour each
    - System must reach speeds up to 10 cm/min (easily achievable with current design)
- Analysis is ongoing to determine the minimum statistics needed in each off-axis interval, but it appears we will not be limited by statistics at any off-axis position.

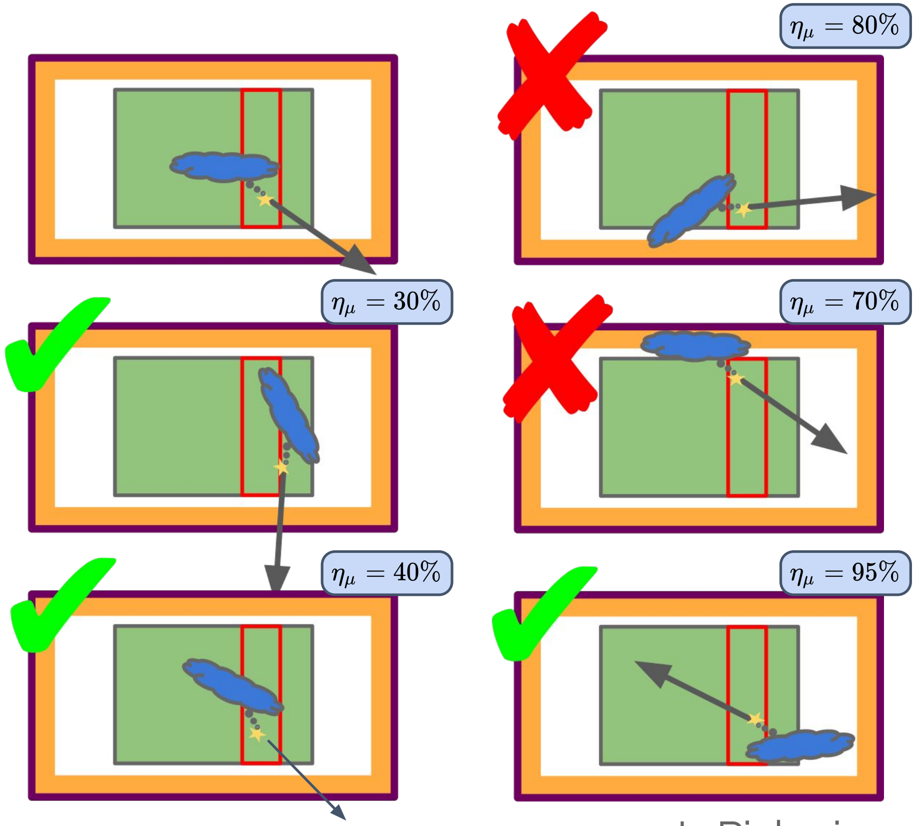
Summary

- With only an on-axis near detector, it is possible for DUNE to measure biased oscillation parameters due to the difficulty in properly modeling ν–Ar interactions at the GeV scale
- Making measurements over a continuous off-axis range breaks degeneracies in the mapping of E_{true} to E_{rec}, and provides sufficient constraints to detect ν–Ar modeling problems
  - This information can be used to produce a far detector prediction with a substantially reduced dependence on cross section modeling
- The system design allows for moving the detectors weekly to collect data over the entire off-axis range
- Design details will be given in tomorrow's talk by R. Flight
  - Requirements are achievable with commercially available products

Backup

Data-driven efficiency

- Use symmetries of neutrino interactions in ArgonCube:
  - Symmetric wrt translations in the LAr volume.
  - Symmetric wrt rotations around beam axis.
- Algorithm:
  - For a given **selected** ND event, rotate and translate 3D **hadronic** energy deposits **and** reconstructed **muon vertex** and **momentum** vectors N times.
  - For the **hadronic** side:
    - Count how many of the trials would have passed the hadronic containment cut.
    - Take the ratio to the total number of trials get the “geometric” efficiency for that event.
  - For the **muon** side:
    - Use a **neural network** trained on particle gun MC to estimate the muon selection efficiency for a given translation/rotation.
  - **Combine** both to get event-level efficiency.

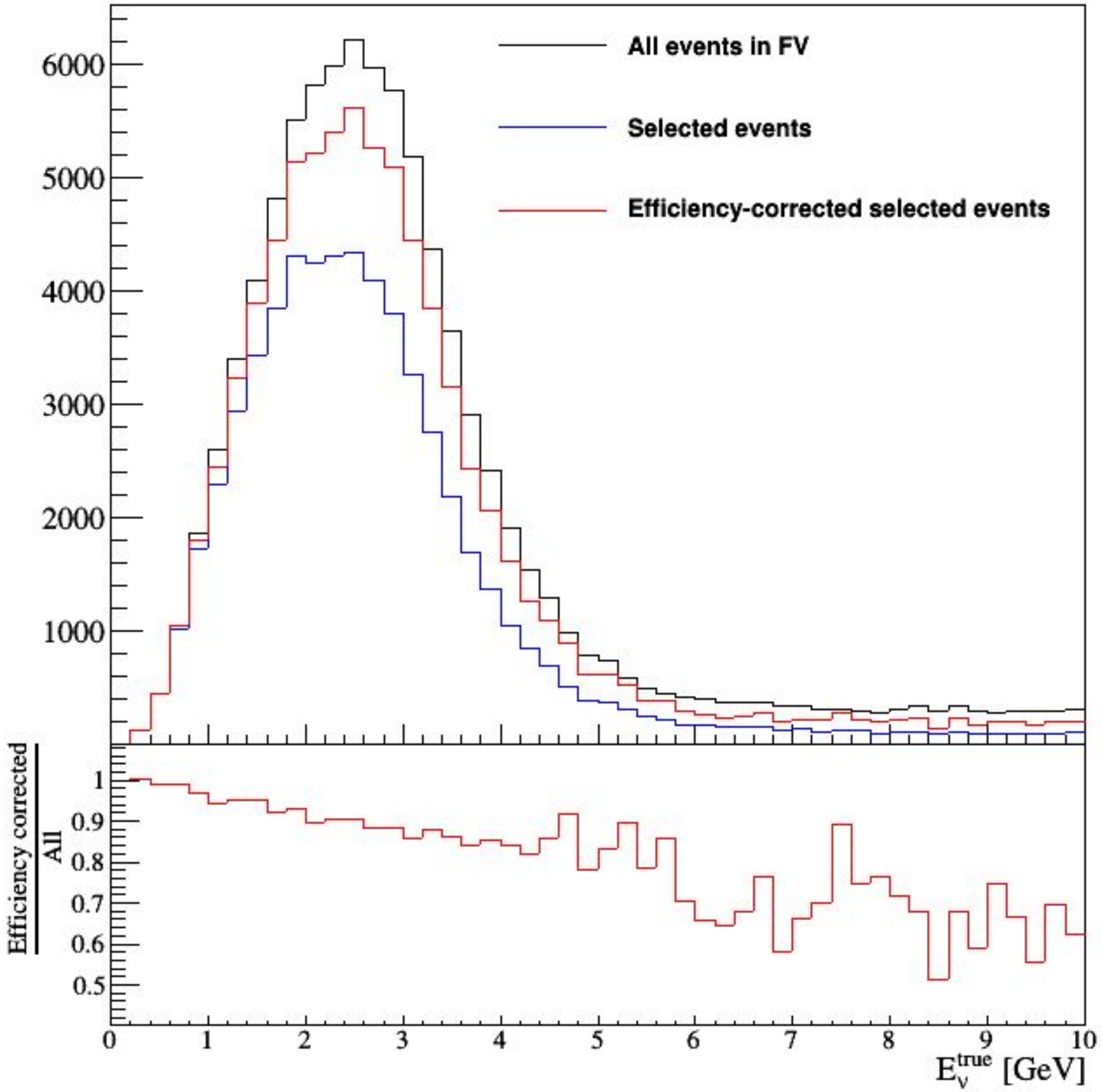


L. Pickering

$$\eta = \frac{0\times0.8+1\times0.3+0\times0.70+1\times0.4+1\times0.95}{5} = 33\%$$

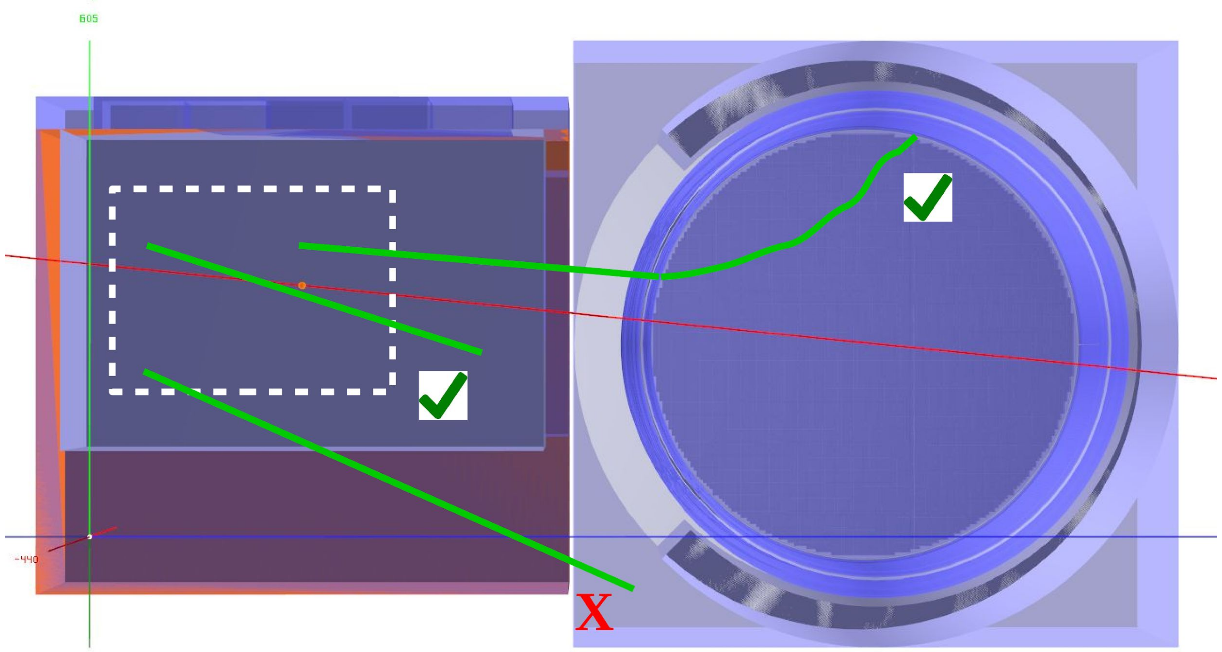
Hadronic Geometric Efficiency

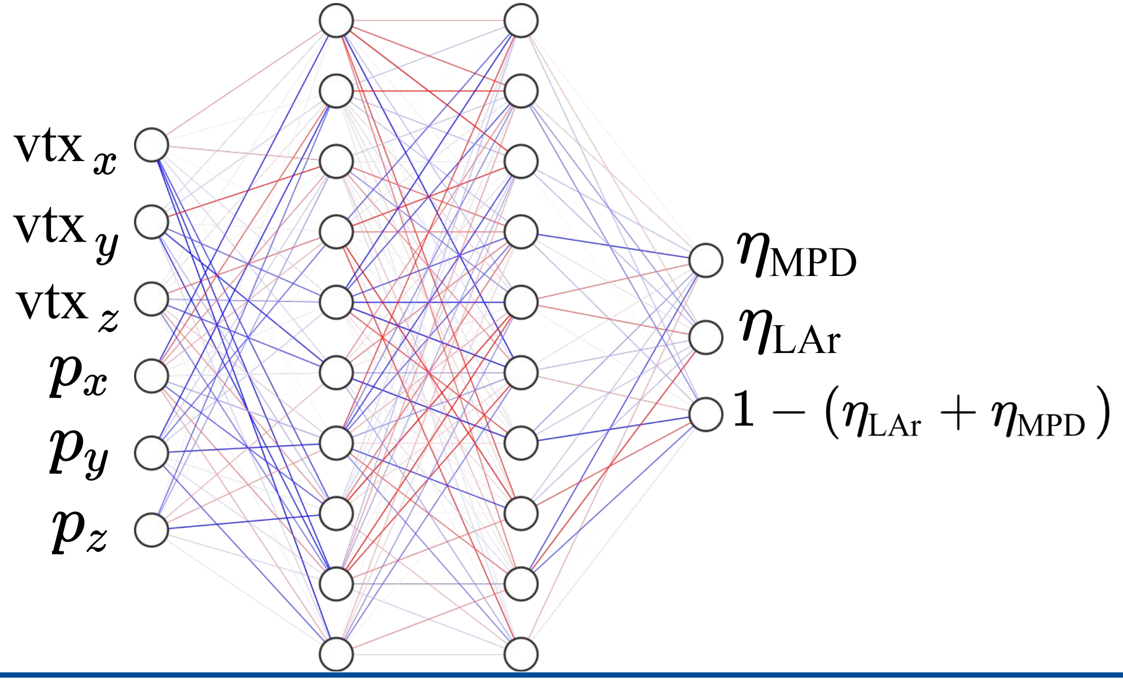
- The geometric efficiency correction can only correct for the events that have sufficiently high efficiency in the near detector
  - The remaining phase space (largely at high E_ν), cannot be directly observed at the near detector
    - Hadronic showers are too large to ever be contained
- At the first oscillation maximum, ~90% of events can be observed at the ND



Muon efficiency neural network

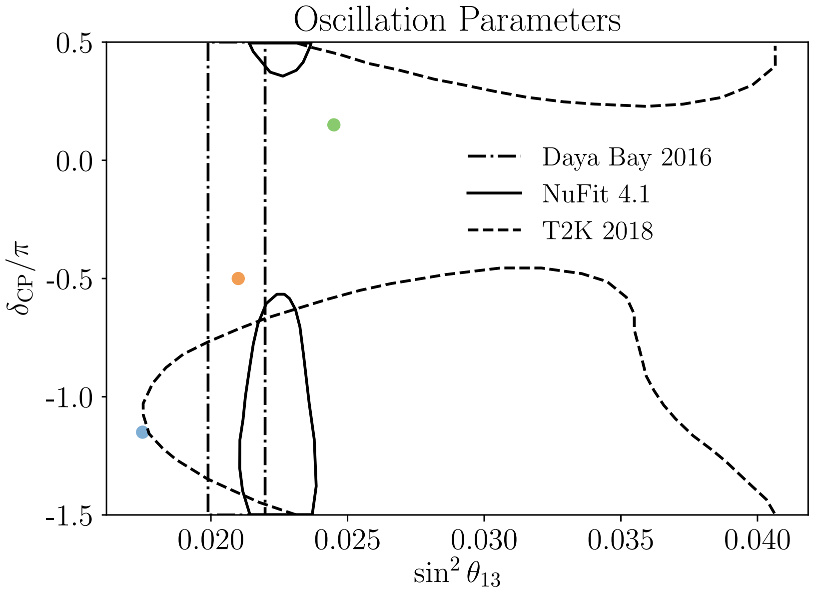
- Train neural network to predict fate of muon as a function of its position and momentum.
  - Output is the probability for the muon to be sampled in the **tracker**, be **contained** in the liquid argon, or **not** be **selected**.
- For initial studies use true position and momentum, but plan to use reconstructed quantities in the future.
- Start with simple neural network with 2 hidden layers with 64 nodes each and ReLU activation.
  - Implemented in PyTorch: https://github.com/cvilelasbu/MuonEffNN

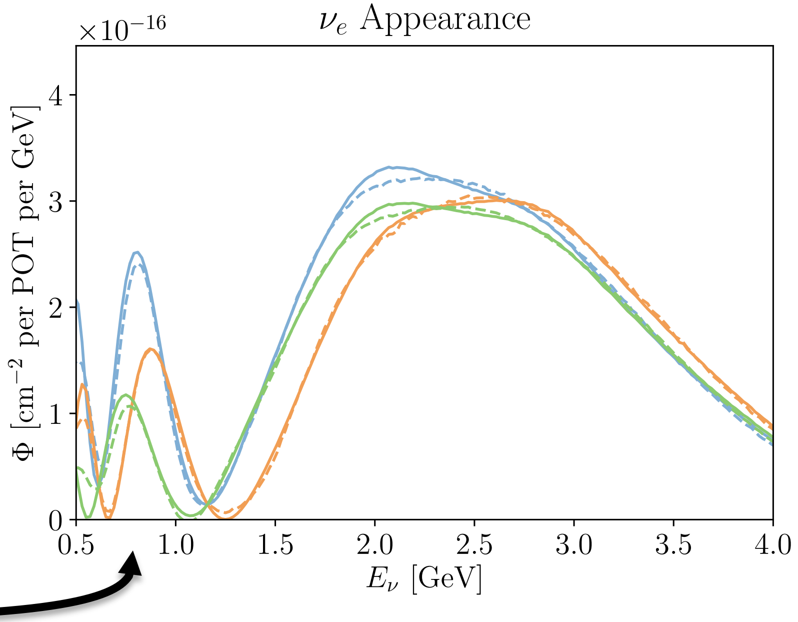


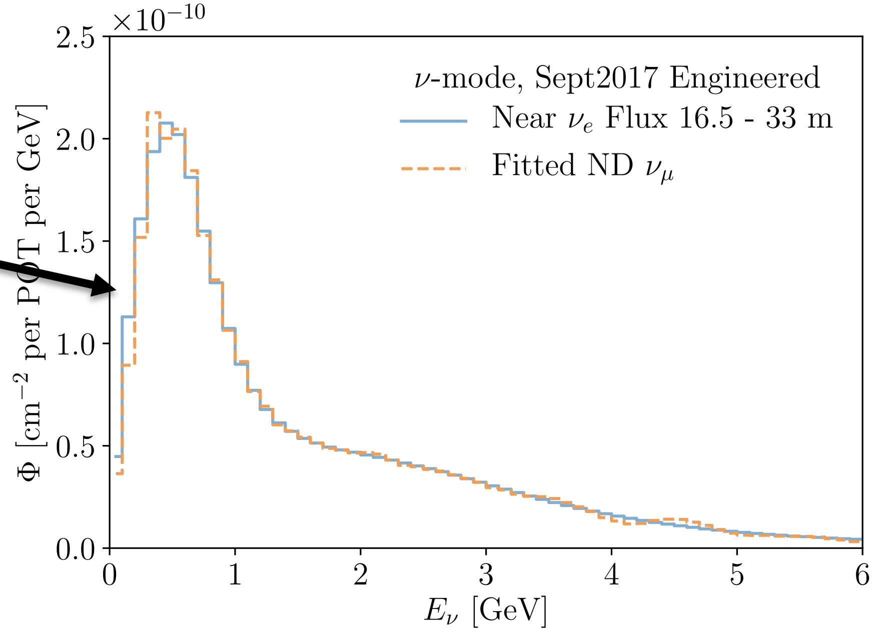


ν_e Appearance

- Flux match the **ND off-axis ν_μ** spectra to **FD ν_e** spectrum (for a given set of osc. params)
  - Analogous to the ν_μ disappearance analysis; this is correct if $\sigma(\nu_e)/\sigma(\nu_\mu) = 1$
- To measure a correction for $\sigma(\nu_e)/\sigma(\nu_\mu) \neq 1$, flux match **ND off-axis ν_μ** spectra to **ND ν_e** spectrum
- Finally, backgrounds can be (largely) measured by on-axis ND ν_e sample
  - More detailed corrections to exclusive background channels can be made with Gaussian ν_μ fluxes







An initial "4-flavor" DUNE-PRISM linear combination oscillation analysis is nearing completion

Example (Unoptimized) Run Plan

		ND-LAr				ND-GAr
		All int.	Selected			All int.
Stop	Run duration	N$_{\nu_\mu CC}$	N$_{Sel}$	WSB	NC	N$_{\nu_\mu CC}$
On axis (293 kA) m	14 wks.	21.6M	10.1M	0.2%	1.3%	580,000
On axis (280 kA) m	1 wk.	1.5M	690,000	0.3%	1.3%	40,000
4 m off axis m	12 dys.	2.3M	1.2M	0.3%	1.0%	61,000
8 m off axis m	12 dys.	1.3M	670,000	0.5%	0.9%	35,000
12 m off axis m	12 dys.	650,000	330,000	0.8%	0.7%	17,000
16 m off axis m	12 dys.	370,000	190,000	1.1%	0.7%	10,000
20 m off axis m	12 dys.	230,000	120,000	1.3%	0.7%	6,200
24 m off axis m	12 dys.	150,000	75,000	1.8%	0.7%	4,100
28 m off axis m	12 dys.	110,000	50,000	2.1%	0.8%	2,900
30.5 m off axis m	12 dys.	87,000	39,000	2.3%	0.7%	2,300