DUNE-PRISM for DUNE Phase 2

Mike Wilking

DUNE ND Phase 2 Workshop

Imperial College London

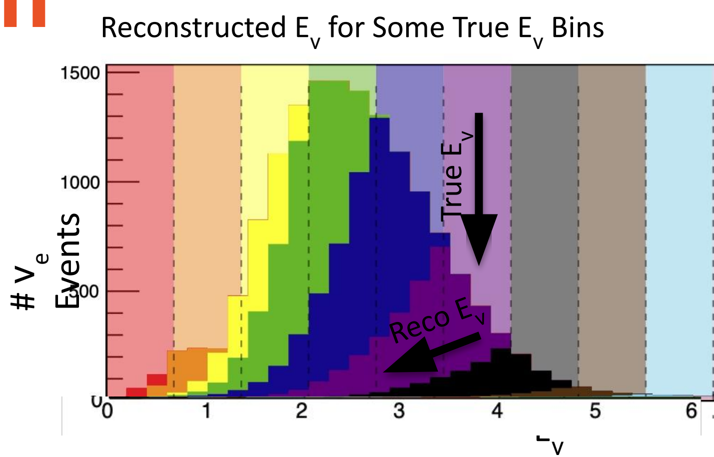
June 21st, 2023

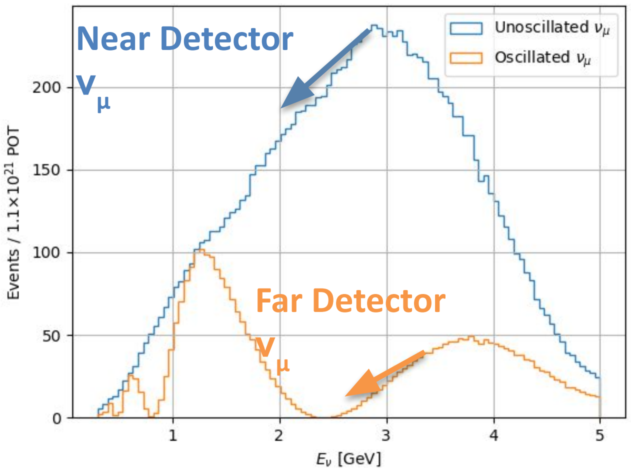
Overview

- The Role of DUNE-PRISM in DUNE Phase 1
  - The E_ν measurement problem, and what physicists usually do to fix it 😬
  - Fake data! What if energy sharing between protons & neutrons is not as we thought 😳
  - How should we design experiments to avoid these problems? 🤔
- DUNE-PRISM in DUNE Phase 2
  - Will additional off-axis measurements still be needed in DUNE phase 2? 🧐

The E_ν Measurement Problem

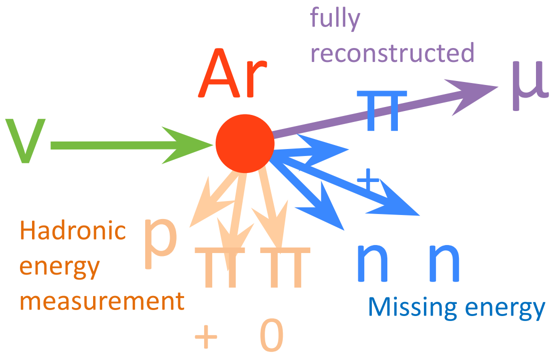
- Existing Long-Baseline neutrino experiments (e.g. T2K) are limited by our understanding neutrino-nucleus interactions (on much better studied C/O targets)
  - Very difficult to model GeV-scale nuclear physics
- The observed energy in the detector is always less than the incident neutrino energy
  - e.g. ~75% of the energy carried by neutrons is lost & nuclear binding energy is unobserved
- The "feed-down" of the reconstructed E_ν in each true E_ν bin "fills-in" the oscillation dip(s) at the far detector, but is difficult to constrain in an on-axis near detector
  - (due to the lack of features in the ND energy spectrum)

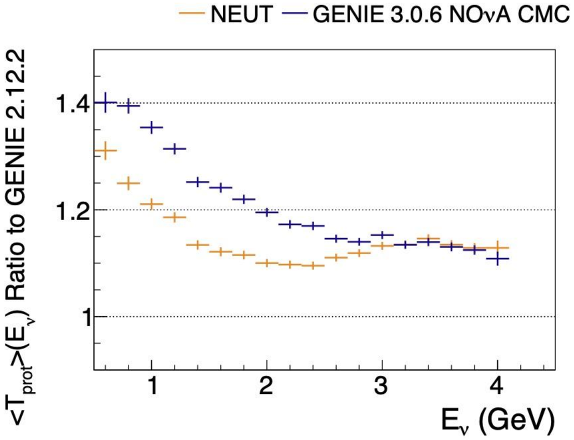




Cross Section Model Adjustments

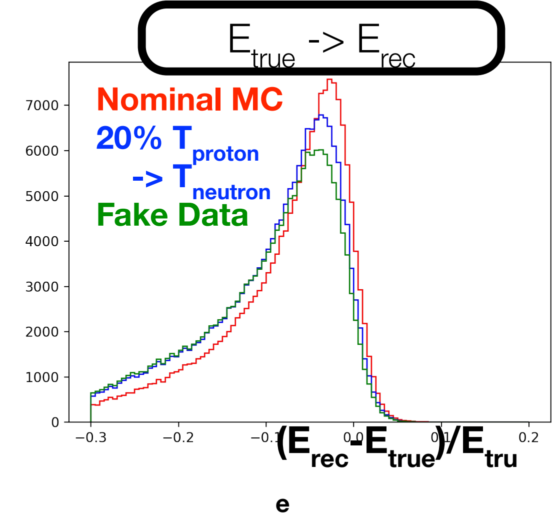
- If we knew our cross section model were correct, even with a large number of uncertain parameters, our high-statistics, on-axis ND sample would precisely (and correctly) constrain all model parameters
- However, we know there are many deficiencies in our cross section models, which can lead to biases in our extracted oscillation parameters
  - In practice, the neutrino flux and cross section model must always be "tuned" to make the near detector MC match the ND data
- **The problem**: there are many degenerate choices for cross section model adjustments that can produce agreement in an on-axis ND (even if the flux prediction is perfect)
  - If we choose the wrong cross section model modifications, we can introduce large biases at the far detector, even if the ND model agrees with the data in ~all observable distributions!
    - (Again, this is due to the lack of sharp oscillation features in the ND spectra)

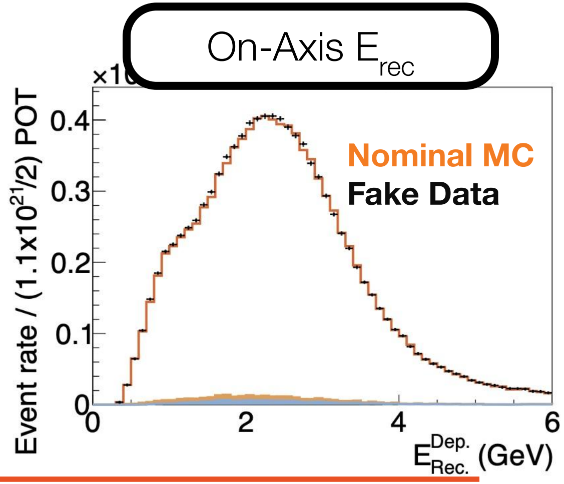




Missing Proton KE Fake Data

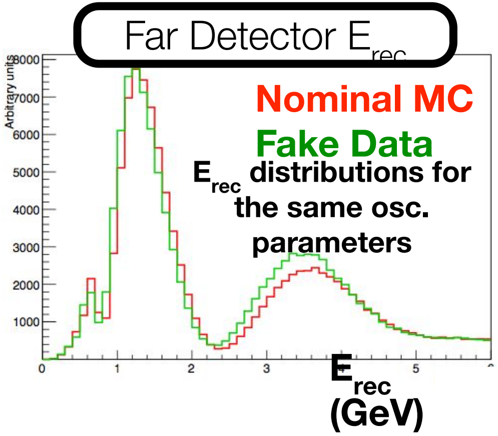
- To demonstrate the problems of inaccurate cross section modeling, a fake dataset was produced in which the sharing of energy between final state protons and neutrons was modified
  - 20% of the proton KE was transferred to unseen neutron energy
- The cross section model was then (incorrectly) adjusted to produce agreement in on-axis ND observables (via multi-dimensional reweighting of the model parameters)
  - This process is meant to demonstrate the effect of (incorrect) model tuning
- The result is a fake dataset that provides model agreement in an on-axis near detector (by design), but does ***NOT*** contain the same $E_{true} \rightarrow E_{rec}$ relationship as assumed by the model

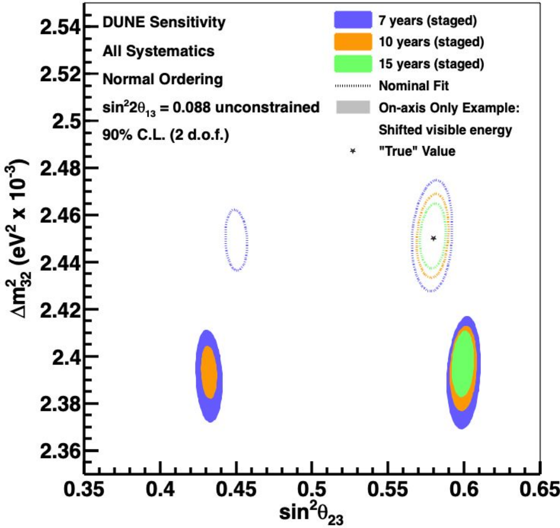




Oscillation Parameter Bias

- Despite good agreement in the ND, the bias is clearly apparent in the oscillated FD spectrum
  - The same oscillation parameters produce a different FD E_{rec} shape in the nominal MC and the fake data
- A full near + far detector fit of the fake data results in a biased measurement of oscillation parameters (well outside of 90% C.L. contours)
  - The fit quality is very good, since there is E_{rec} agreement (by design) in the high-statistics, on-axis near detector
- With only an on-axis near detector, DUNE could get the wrong answers for neutrino oscillation parameters with no evidence that anything were wrong



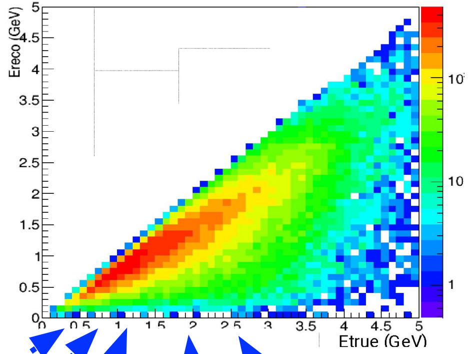


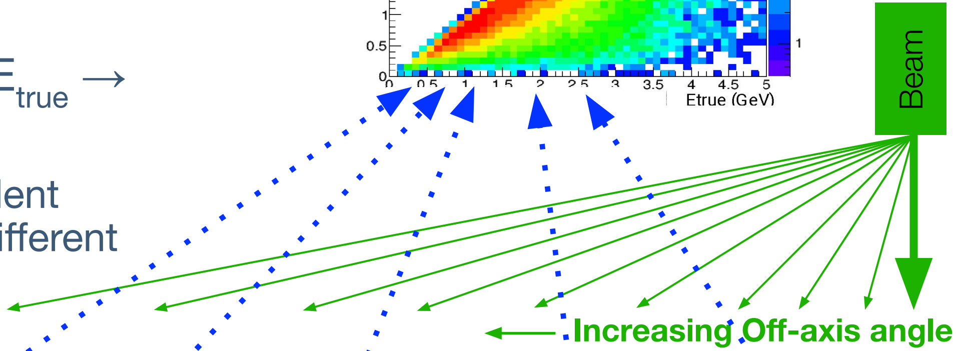
Analysis Design

- Constrained-Model Approach: use ND data to constrain flux and cross section model parameters
  - Then use this constrained model to produce predictions for oscillated far detector data
- Model-Insensitive Approach: propagate ND measurements to a FD prediction in a manner that is insensitive to flux and cross section model parameters
  - i.e. the model parameters do not get constrained by the fit
  - In this case, the fit results do not rely on the model details (GOOD!), but this only works if all reasonable model choices are unable to bias the fit results (HARD!)
- Any real analysis will lie on the continuum between these 2 approaches
  - Goal is to only constrain parameters using models that we really believe (e.g. ν–e scattering, beamline monitoring) and avoid constraining parameters in models with large uncertainties (e.g. ν–Ar scattering, beam hadron production)

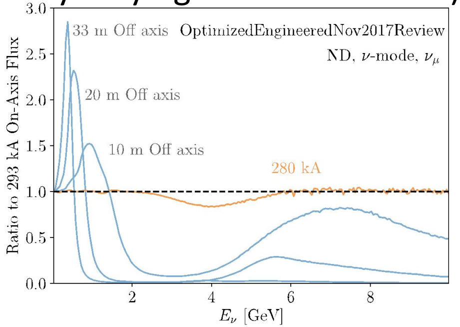
DUNE-PRISM

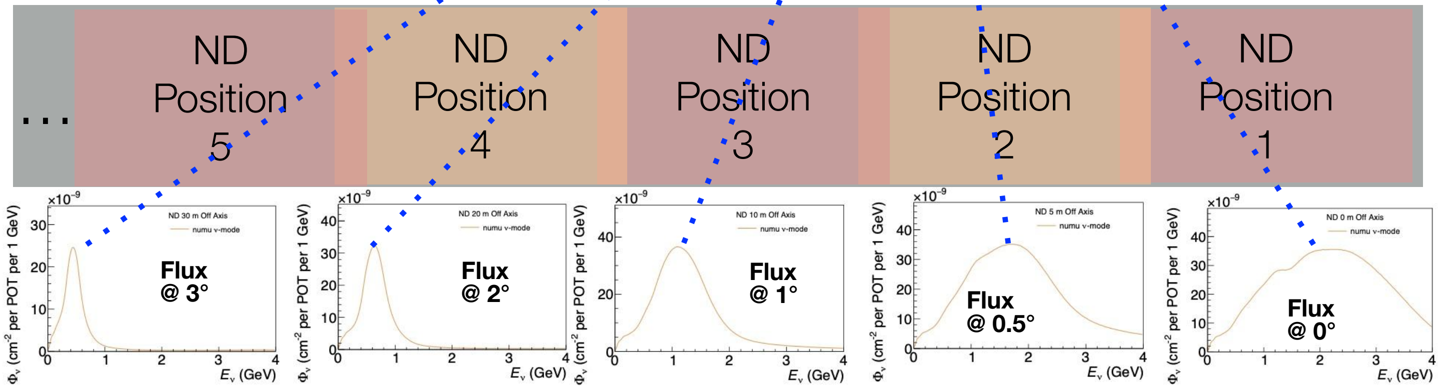
- By changing the off-axis angle of the detector, it is possible to sample a continuously changing energy spectrum
- This provides a strong constraint on the $E_{true} \rightarrow E_{rec}$ relationship
  - Each off-axis location provides an independent “neutrino test beam” measurement with a different incident neutrino spectrum





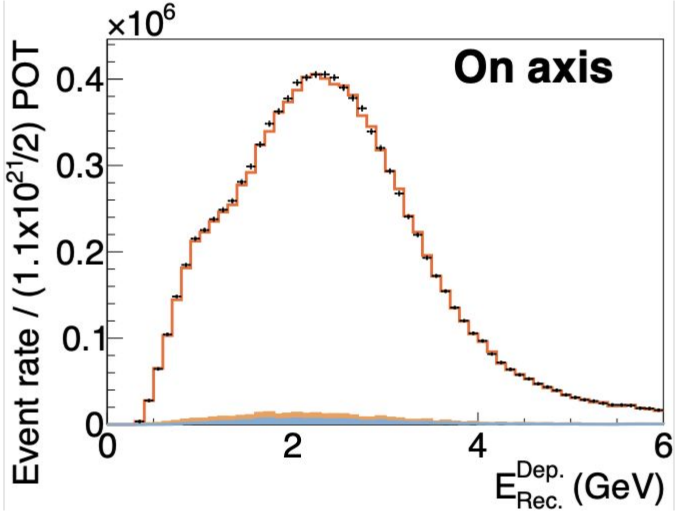
(An additional flux is obtained by varying the horn current)

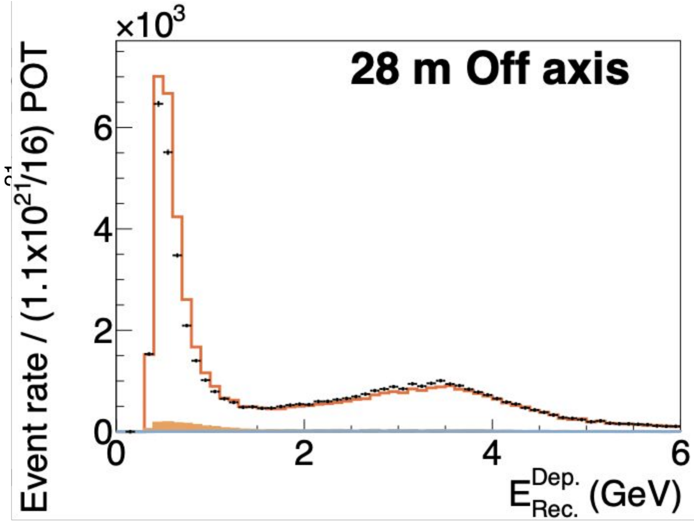




Identifying Modeling Issues

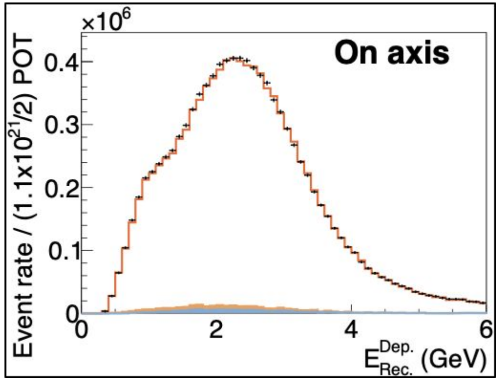
- With DUNE-PRISM, the missing proton KE fake data can be compared to nominal MC at many different off-axis positions
- The previously “hidden” modeling problems can clearly be seen off-axis
  - ND off-axis spectra span the FD E_ν spectrum, so modeling can be verified within the E_ν range relevant for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

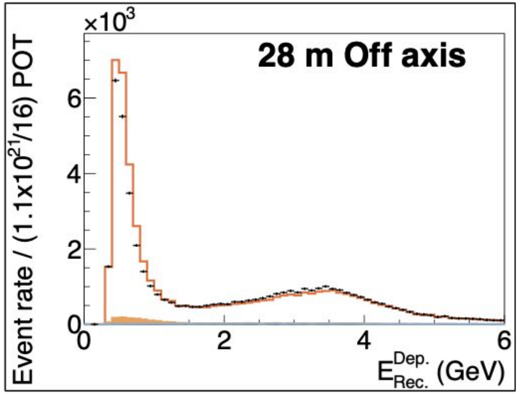




Overcoming Modeling Issues

- Constrained-model approach: Develop a model that can describe the near detector data
  - Now that we have near detector data for many energy spectra across the oscillation E_ν range, there is less potential for bias
    - It is less likely to get the right answer for the wrong reasons
  - This may allow for more empirical model corrections (rather than first-principles modifications), given the much higher bar these models must clear (data/MC agreement for all off-axis positions)
  - Or, given the historical difficulties in achieving ND data/MC agreement, this process still may not adequately converge
- Model-Insensitive Approach: Use the near detector data directly (via linear combinations) to compare to the far detector data
  - Any unknown modeling effects are directly incorporated into the FD spectrum prediction
  - However, some errors may not adequately cancel, so additional model constraints may be required (e.g. ex-situ data, beam monitoring)



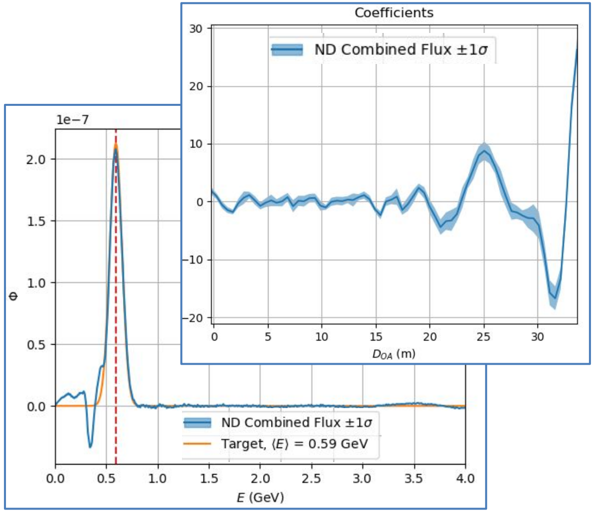


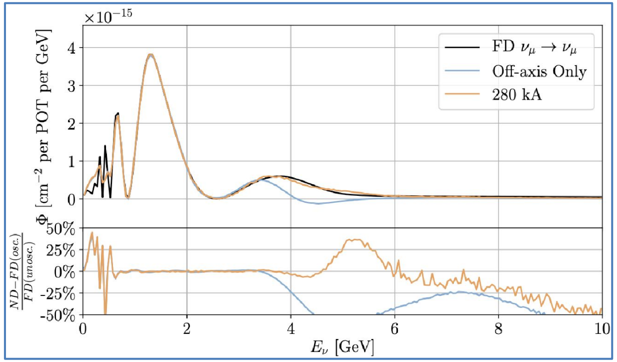
Toward a More Model-Insensitive Approach:

The DUNE-PRISM Linear Combination Analysis

Flux Matching (ND Linear Combinations)

- 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 distribution (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 measure neutral current interactions vs E_ν
  - A far detector 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)

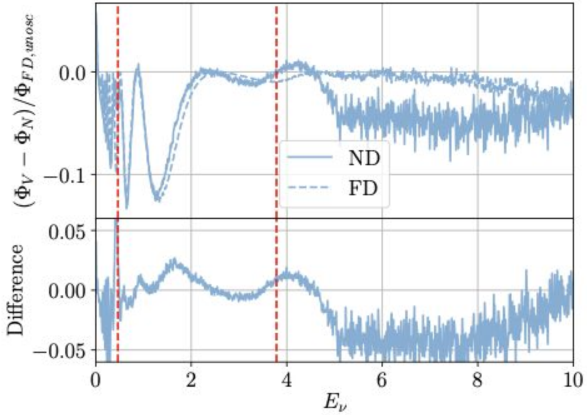




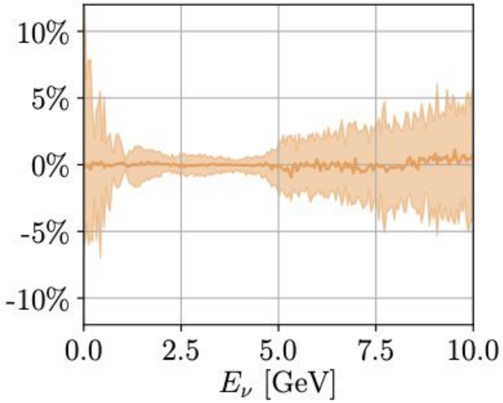
Flux Error Cancelation

- Since the ND fluxes and the FD flux both come from the same beam, there is significant error cancelation
  - ND linear combination variations are very similar to FD flux variations
- Top plot: a single (large) variation of a hadron production uncertainty
  - The effect in ND linear combination and FD is almost identical
  - Resulting error is the residual difference
- Repeating this procedure for all flux variations results in a very small residual error (~1% in the oscillation region)
  - Hadron production is (currently) not the dominant uncertainty in the linear combination analysis

Effect of 1 hadron production variation on the ND linear combination & FD



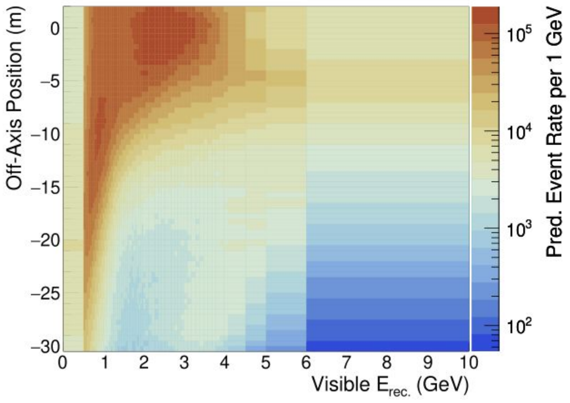
Total Uncertainty from Hadron Production

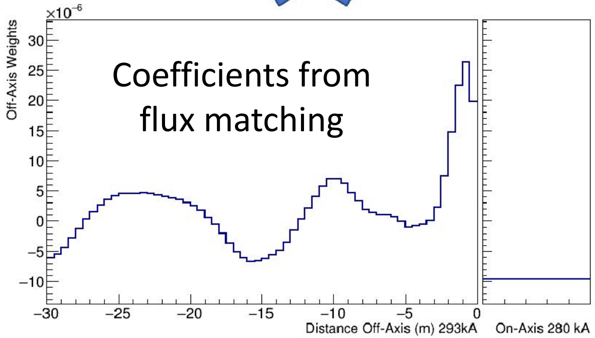


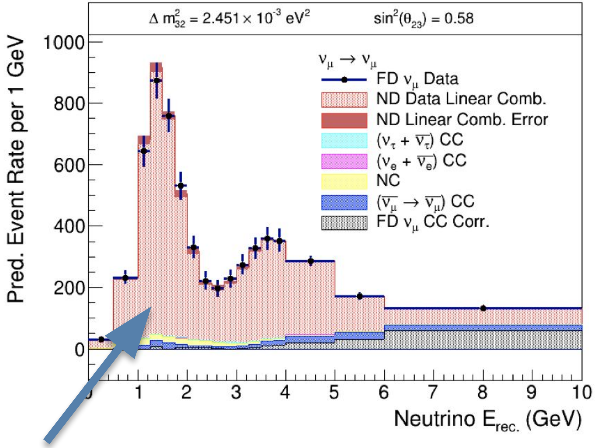
FD Event Rate Prediction

- The off-axis coefficients derived from the flux matching are applied to the ND data
- This produces a data-driven prediction of the far detector oscillated data
- The analysis variable is chosen to minimize dependence on missing energy
  - Reconstructed E_ν is not used
  - "E_{vis}" excludes energy from neutrons and binding energy
    - Should mainly be sensitive to detector effects (rather than cross section modeling)

Measured ND ν_μ Events

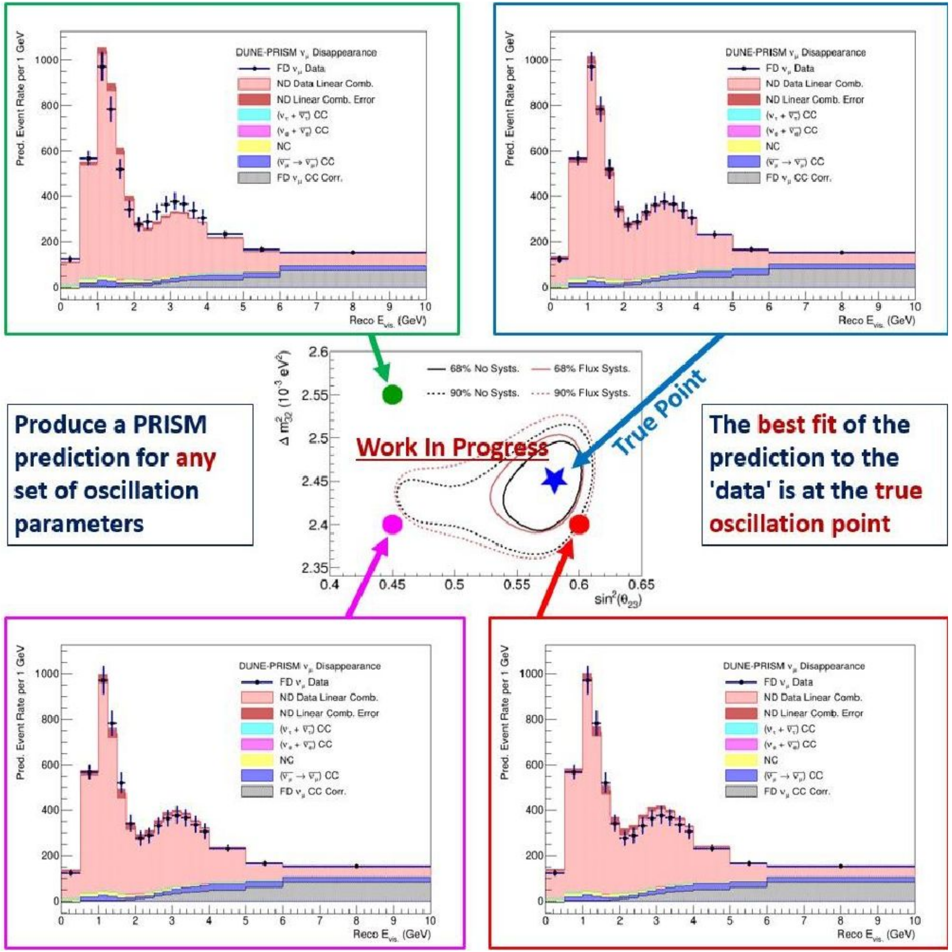






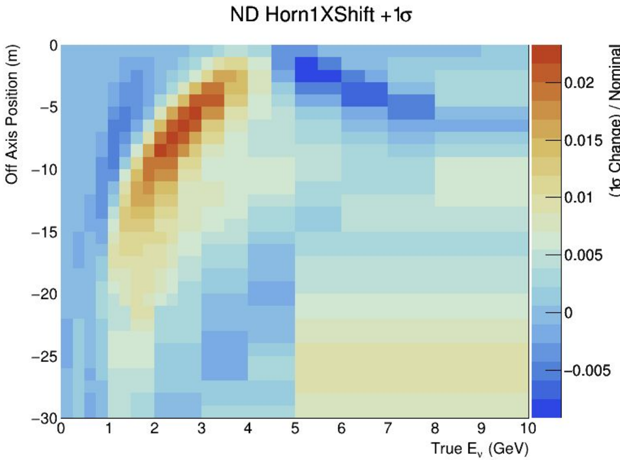
Oscillation Fits

- For each choice of oscillation (and systematic error) parameters, the translation of ND data to FD prediction is repeated
  - Each new prediction is compared to FD data to calculate the likelihood
  - The ND and FD data always remain unchanged throughout this process
- Systematic error (nuisance) parameters are constrained very little during the fit
  - Constraint comes from FD statistics
  - Non-data-driven components of the prediction incur the full flux & cross section uncertainties



Analysis Design, Revisited

- As these more data-driven analysis approaches are developed, there will be a need to constrain some parameters from in situ measurements (e.g. beam monitoring) and external data (e.g. hadron production experiments)
- Relatedly, there may be systematic uncertainties that result in important non-canceling uncertainties
  - Example: shifting the first target & horn a small amount (~1 mm) in the off-axis direction can produce larger effects in the near-off-axis positions relative to the effect on-axis
    - These beam focusing uncertainties don't cancel as well as, for example, hadron production uncertainties
  - As these effects are better understood, mitigating actions may be needed to avoid re-introducing dependencies on uncertain cross section models (e.g. more precise beam component monitoring; or using mobile detectors to monitor the off-axis beam)

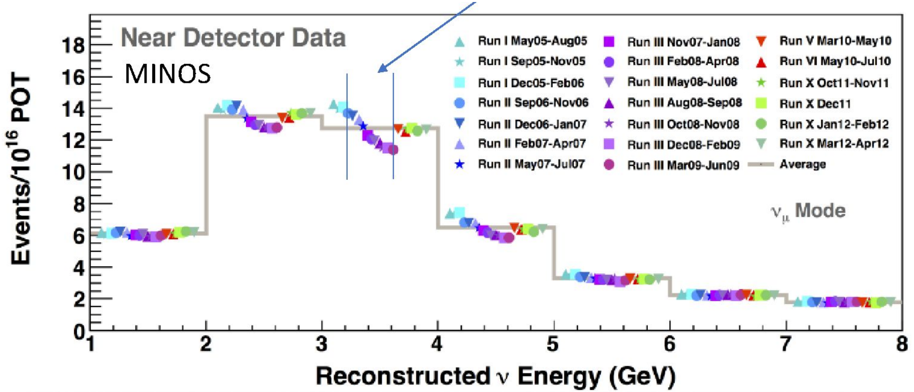


DUNE-PRISM in DUNE Phase 2

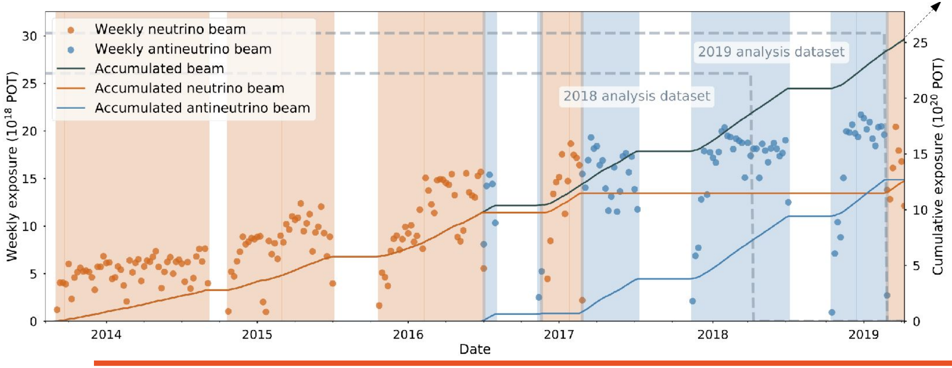
Phase 1 Requirements

- Lesson learned from NuMI: beams can change year-to-year
- In Phase 1, we require a full suite of off-axis measurements each year (weekly moves)
  - FD data is fit with ND data that experienced the same beam conditions
- In principle, translation between different beam conditions is possible
  - But only if beam changes are well simulated

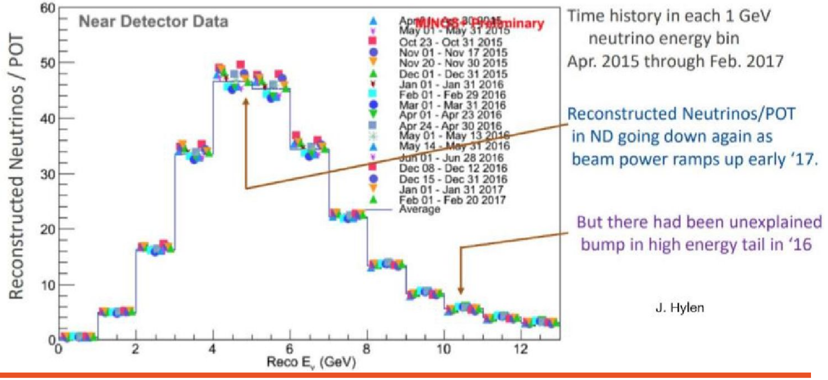
NuMI Target Degradation (3 year period)



NuMI Data Runs



NuMI Horn Tilt (Bushing Failure)



DUNE

Phase 2 Requirements?

- Phase 1 will collect very large samples across off-axis angles over many years
  - In principle, this could be enough data for the duration of the experiment
  - So perhaps additional measurements are not needed for DUNE Phase 2?
- However, if the beam experiences significant changes, this can cause problems if we are using old ND off-axis data for the LBL analysis
  - If these beam changes can be properly simulated, then the old ND can be reweighted to predict a new FD spectrum
    - SAND, and its E_ν monitoring capabilities, would be a critical tool to convince ourselves that we fully understand how to simulate such beam changes
- In Phase 2, DUNE will reach its ultimate precision
  - To discontinue the ND off-axis measurement program, we would need to be confident that we could deal with changes to the beam without introducing large systematic uncertainties ¯_(ツ)_/¯ 😥 🤯

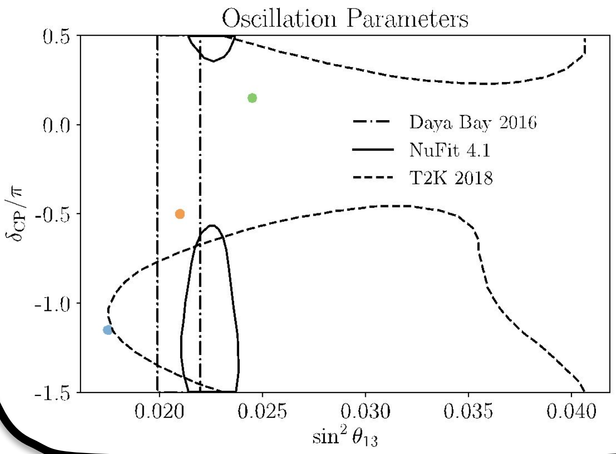
Summary

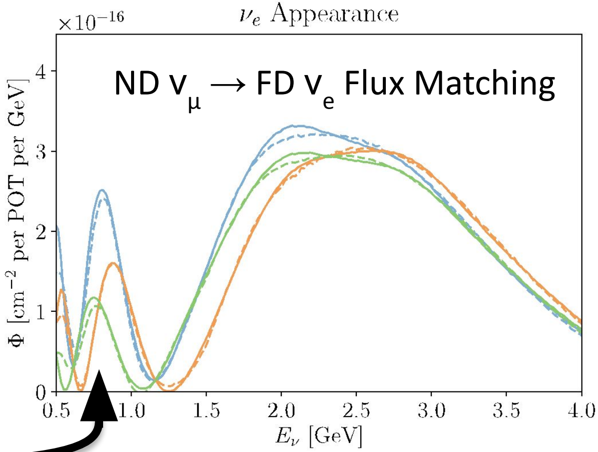
- The DUNE-PRISM ND measurement program provides an additional degree of freedom (continuously varying E_ν spectra) that can be used to disentangle the relationship between E_{true} & E_{rec}
- It is possible to use this information to design an analysis that is less sensitive to neutrino interaction modeling
  - Nuisance parameters (from flux, xsec, & det uncertainties) do not get constrained in the fit
    - This means that the fit results do not rely on the model details (GOOD!), but this only works if all reasonable model choices are unable to bias the fit results (HARD!)
  - Additional constraints (ideally from data, e.g. beam monitoring) may be needed to achieve DUNE sensitivity goals
- The ND statistics that DUNE collects in Phase 1 may be sufficient for Phase 2 oscillation parameter measurements
  - But only if changes to the beam can be understood (e.g. via SAND) and adequately simulated

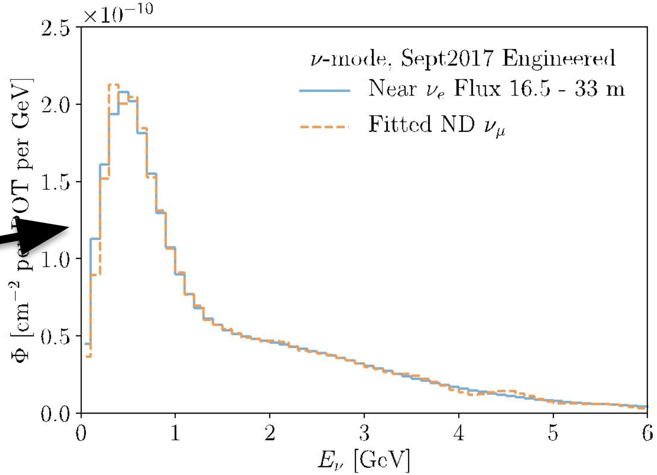
Backup

ν_e Appearance

- The same procedure can be used for 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
- Need to correct $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - This correction is most important at low energies (e.g. < 1 GeV)
  - At higher energies, $\sigma(\nu_e)/\sigma(\nu_\mu) \to 1$
  - Ongoing work: to measure a correction for σ(νe)/σ(νμ) ≠ 1, flux match ND off-axis ν_μ spectra to ND ν_e spectrum
- Existing 4-flavor fits currently use GENIE $\sigma(\nu_e)/\sigma(\nu_\mu)$ correction



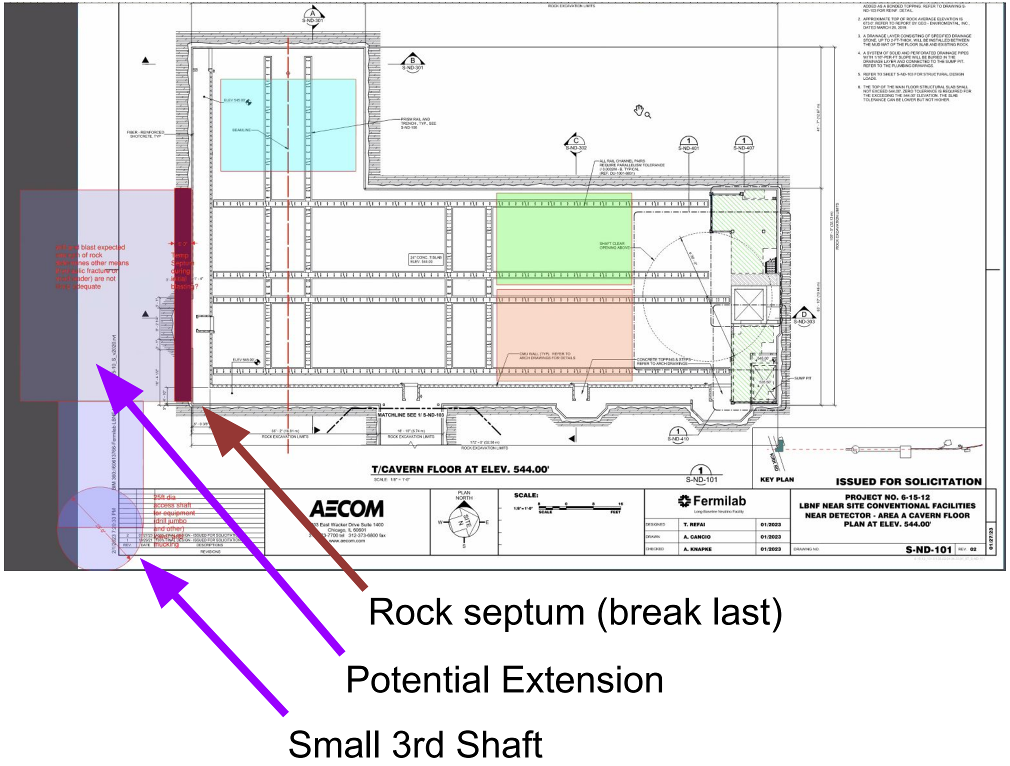




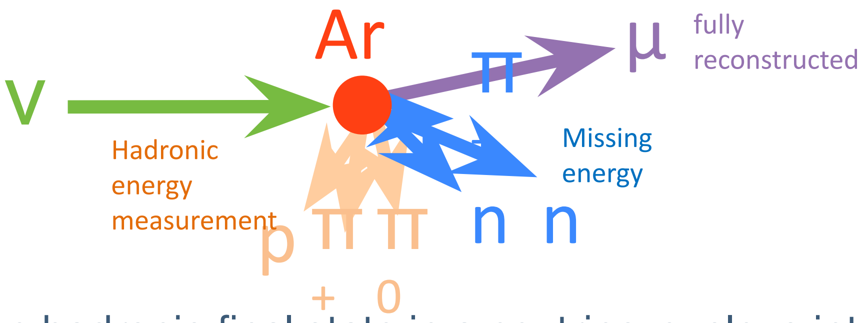
Possible ND Hall Extensions

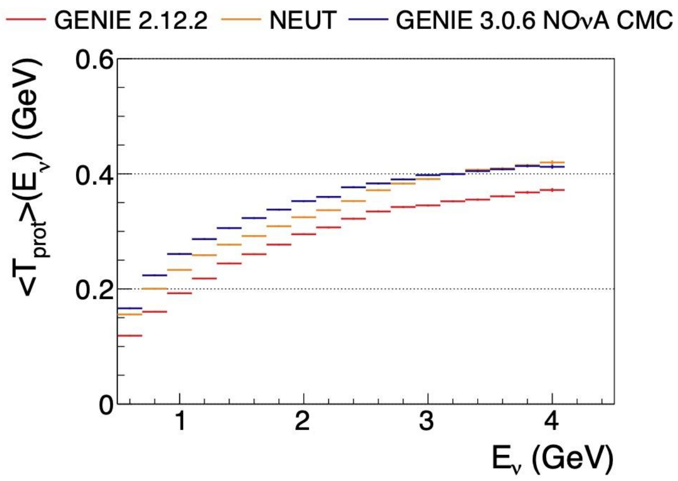
- The Fermilab engineers leading the development of the Phase 1 ND Hall (Tom Hamernik & Kennedy Hartsfield) took a preliminary look at technical feasibility of extending the ND Hall
  - How do we protect detectors that are already installed?
  - Is there enough space to deploy excavation equipment?
- Proposed solution is to create a small 3rd shaft and excavate the additional cavern space (last step: break barrier)
  - Initial look from Fermilab site rock experts revealed no show stoppers
  - Additional study on the impact of blasting vibrations on detectors is needed
- The PRISM range can then be extended, enabling additional detectors

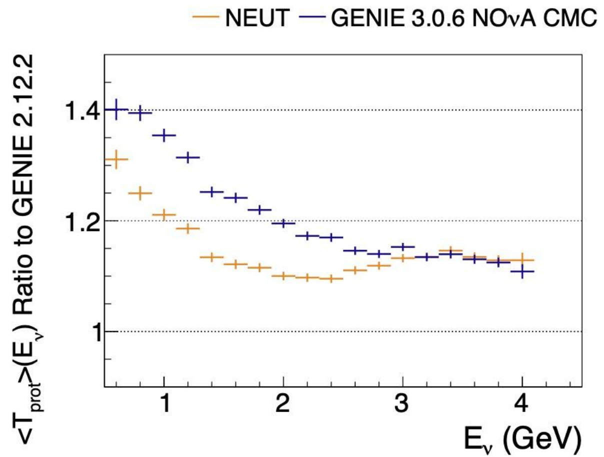
DUNE Near Detector Hall



Hadronic Energy Modeling







- The hadronic final state in a neutrino-nucleus interaction is relatively less-well understood than the leptonic final state
- The average kinetic energy carried by final state protons is compared for 2 versions of the GENIE neutrino interaction generator, and the most recent version of NEUT
  - Differences of ~20% can be seen through the DUNE oscillation region (but this is just a comparison of 2 models)
- Significant uncertainties exist in the fraction of hadronic energy carried by the various final state hadrons

TDR Analysis Cross Section Model

- The cross section model parameters used in the DUNE TDR analysis are shown here
- In addition to built-in GENIE parameters, some additional parameters were added to account for other important effects varied in T2K and NOvA

Eur. Phys. J. C 80, 978 (2020)

GENIE Xsec Parameters

Description	1σ
Quasielastic	
M_A^{QE}, Axial mass for CCQE	$^{+0.25}_{-0.15}$ GeV
QE FF, CCQE vector form factor shape	N/A
p_F Fermi surface momentum for Pauli blocking	$\pm30\%$
Low W	
M_A^{RES}, Axial mass for CC resonance	±0.05 GeV
M_V^{RES} Vector mass for CC resonance	$\pm10\%$
Δ-decay ang., θ_π from Δ decay (isotropic $\rightarrow$ R-S)	N/A
High W (BY model)	
A_{HT}, higher-twist in scaling variable ξ_w	$\pm25\%$
B_{HT}, higher-twist in scaling variable ξ_w	$\pm25\%$
C_{V1u}, valence GRV98 PDF correction	$\pm30\%$
C_{V2u}, valence GRV98 PDF correction	$\pm40\%$
Other neutral current	
M_A^{NCRES}, Axial mass for NC resonance	$\pm10\%$
M_V^{NCRES}, Vector mass for NC resonance	$\pm5\%$

GENIE FSI Parameters

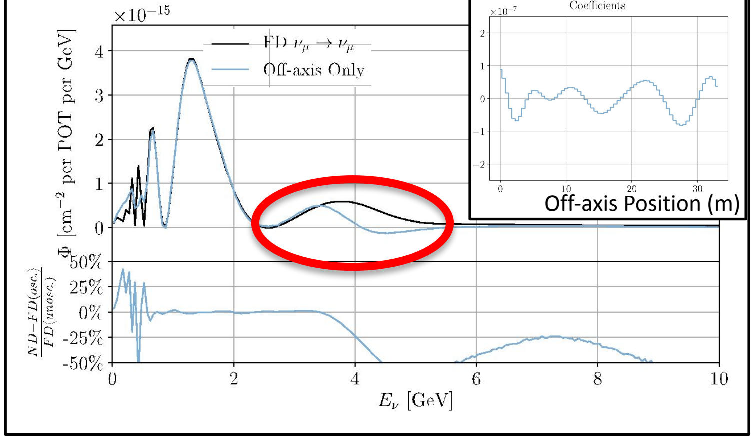
Description	1σ
N. CEX, Nucleon charge exchange probability	$\pm50\%$
N. EL, Nucleon elastic reaction probability	$\pm30\%$
N. INEL, Nucleon inelastic reaction probability	$\pm40\%$
N. ABS, Nucleon absorption probability	$\pm20\%$
N. PROD, Nucleon π-production probability	$\pm20\%$
π CEX, π charge exchange probability	$\pm50\%$
π EL, π elastic reaction probability	$\pm10\%$
π INEL, π inelastic reaction probability	$\pm40\%$
π ABS, π absorption probability	$\pm20\%$
π PROD, π π-production probability	$\pm20\%$

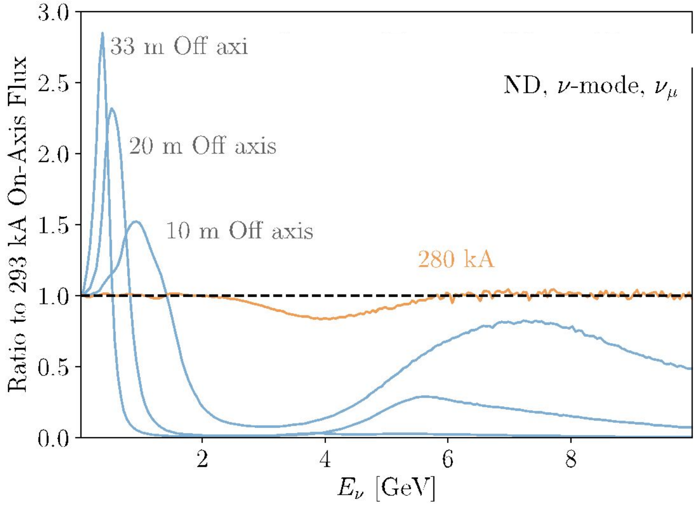
Additional Xsec Parameters

Uncertainty	Mode
BeRPA [A,B,D]	1p1h/QE
ArC2p2h [ν,$\bar{\nu}$]	2p2h
E_{2p2h} [A,B] [ν,$\bar{\nu}$]	2p2h
NR [ν,$\bar{\nu}$] [CC,NC] [n,p] [1π,2π,3π]	Non-res. pion
ν_e PS	ν_e,$\bar{\nu}_e$ inclusive
$\nu_e/\bar{\nu}_e$ norm	ν_e,$\bar{\nu}_e$ inclusive
NC norm.	NC

Horn Current Variations I

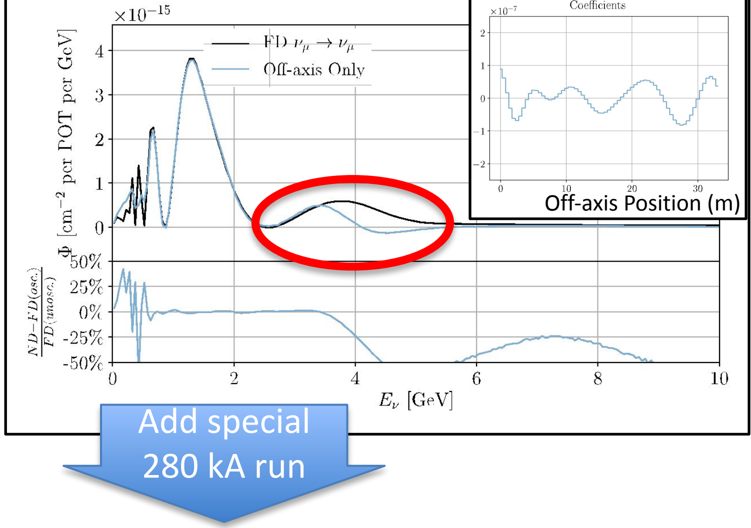
- It's difficult to get agreement at high energies using only off-axis fluxes
  - Highest energy flux available is the on-axis flux
- By adding a 1 week special run each year at a slightly lower horn current (293 kA -> 280 kA), we gain additional high-energy information

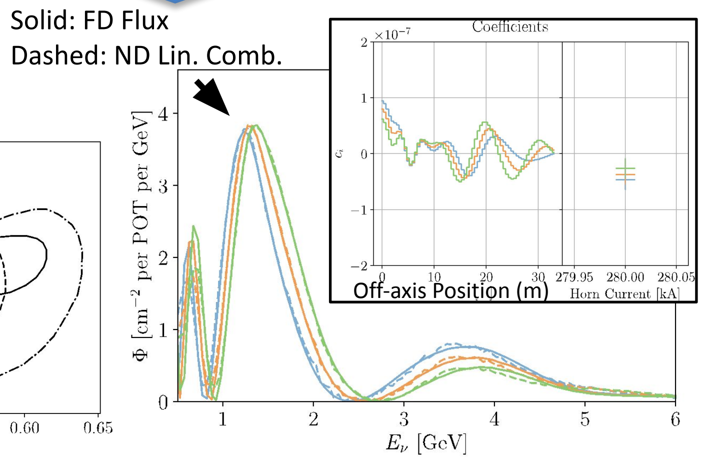


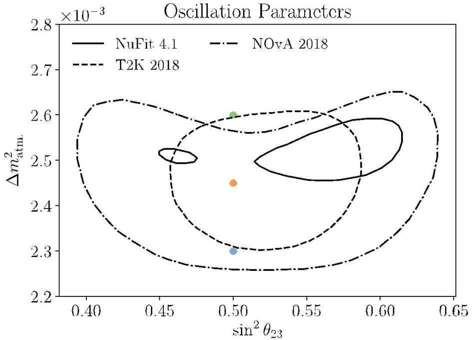


Horn Current Variations II

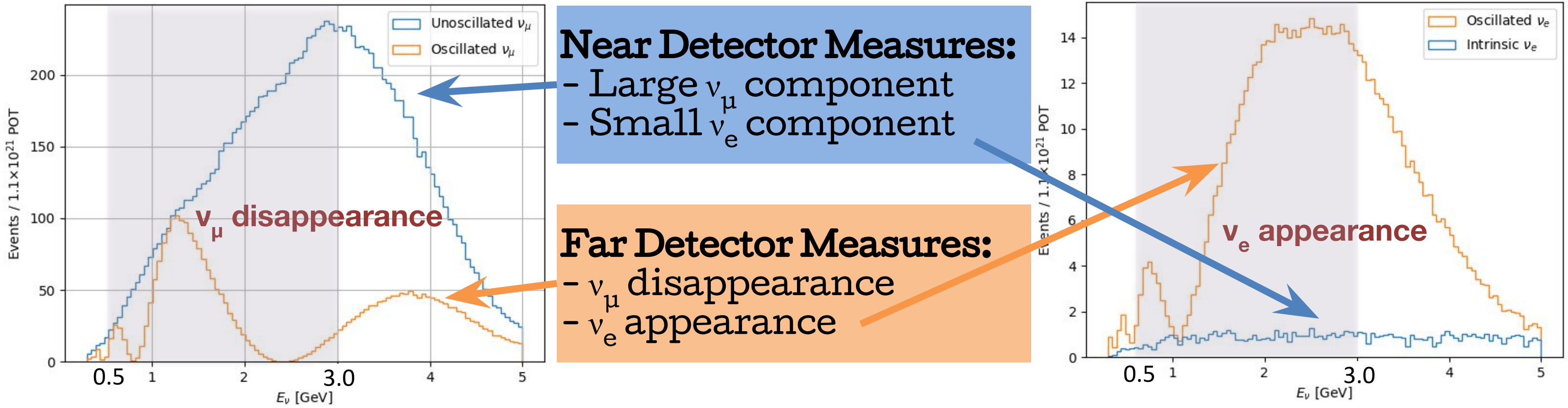
- It's difficult to get agreement at high energies using only off-axis fluxes
  - Highest energy flux available is the on-axis flux
- By adding a 1 week special run each year at a slightly lower horn current (293 kA -> 280 kA), we gain additional high-energy information
  - We can now match the far detector oscillated spectrum for any choice of oscillation parameters







Impact of ν–Ar Mismodeling on Oscillation Measurements



- 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
- To move beyond T2K & NOvA, qualitatively new, data-driven constraints are needed on E_{TRUE} ➔ E_{REC}

DUNE Ramp Up Plan

- Year 1: 2 FD (20 kt), 1.2 MW beam
  - 24 kt*MW*years
- Years 2-3: 3 FD (30 kt), 1.2 MW beam
  - 2 years * 36 kt*MW
  - 96 kt*MW*year integrated after 3 years
- Years 4-6: 4 FD (40 kt), 1.2 MW beam
  - 3 years * 48 kt*MW
  - 240 kt*MW*years integrated after 6 years
- Years 7-?: upgrade to 2.4 MW beam
  - 96 kt*MW
  - 624 kt*MW*years after 10 years