DUNE-PRISM Questions and Scope

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For the DUNE-PRISM Working Group

NDDG Meeting

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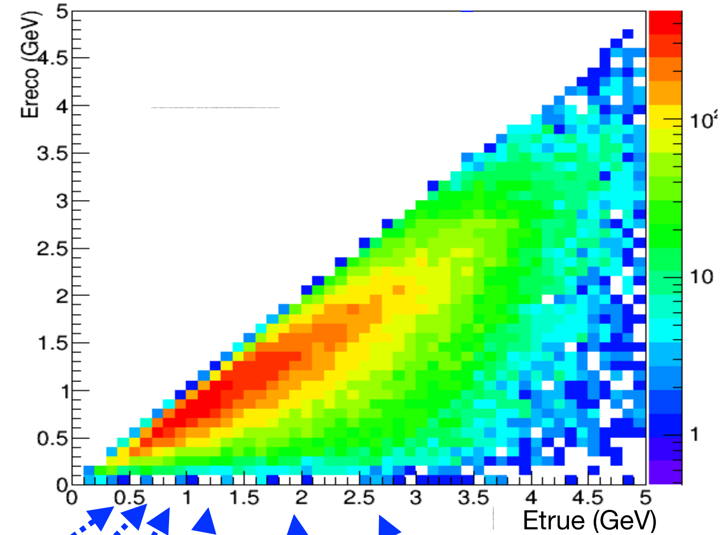
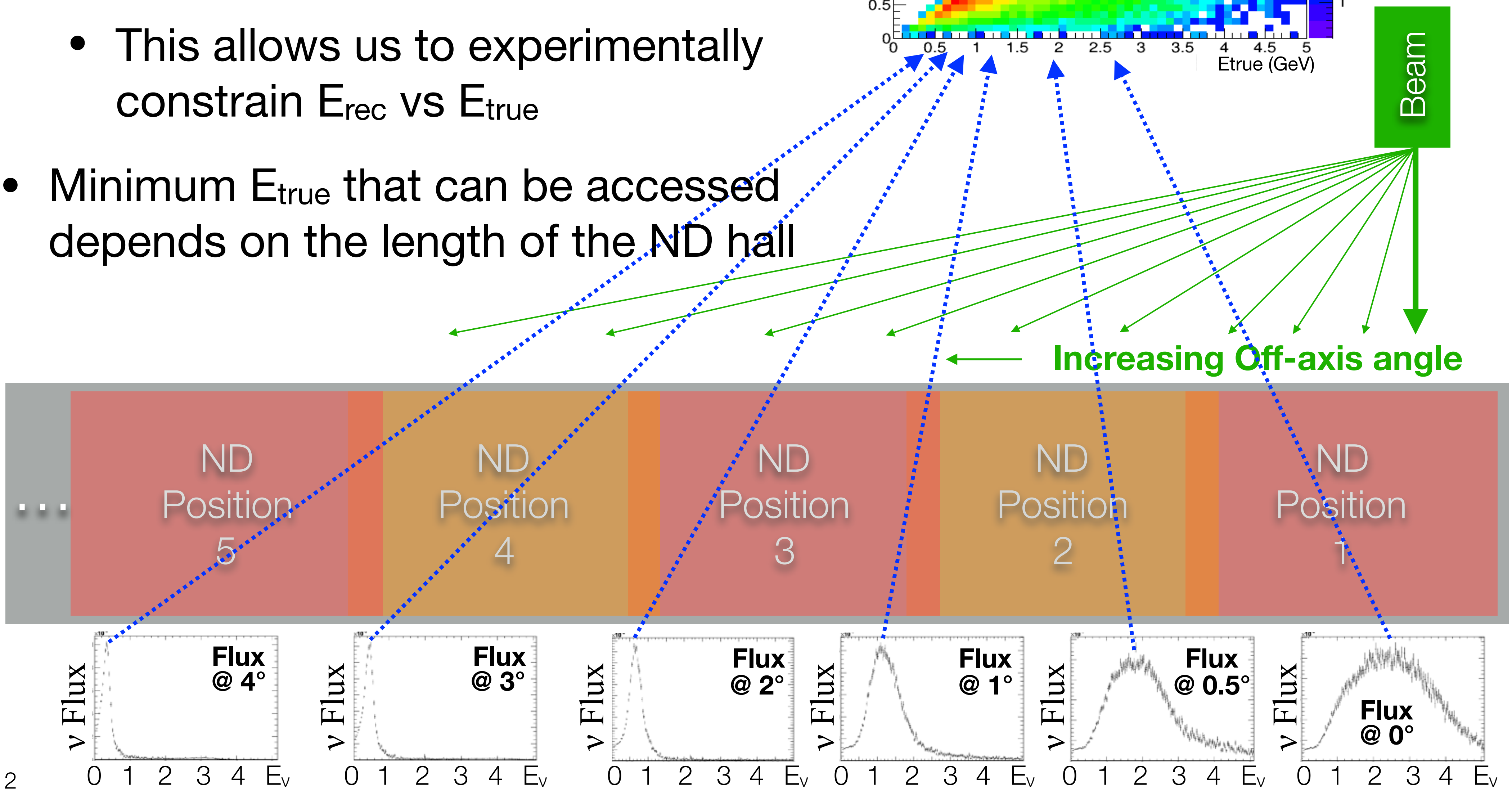
DUNE-PRISM

- By moving the near detector off-axis, we can measure increasingly lower E_ν spectra
    - This allows us to experimentally constrain E_{rec} vs E_{true}
- Minimum E_{true} that can be accessed depends on the length of the ND hall

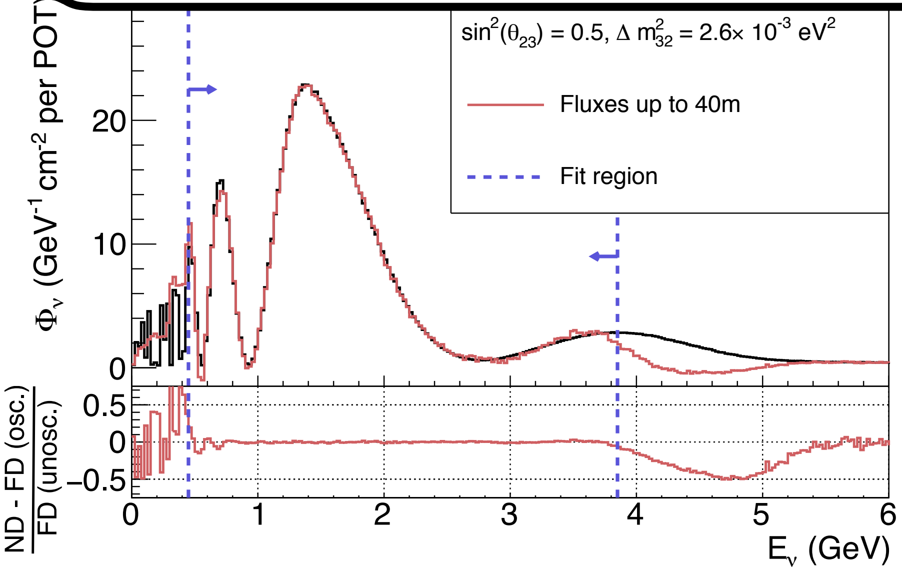




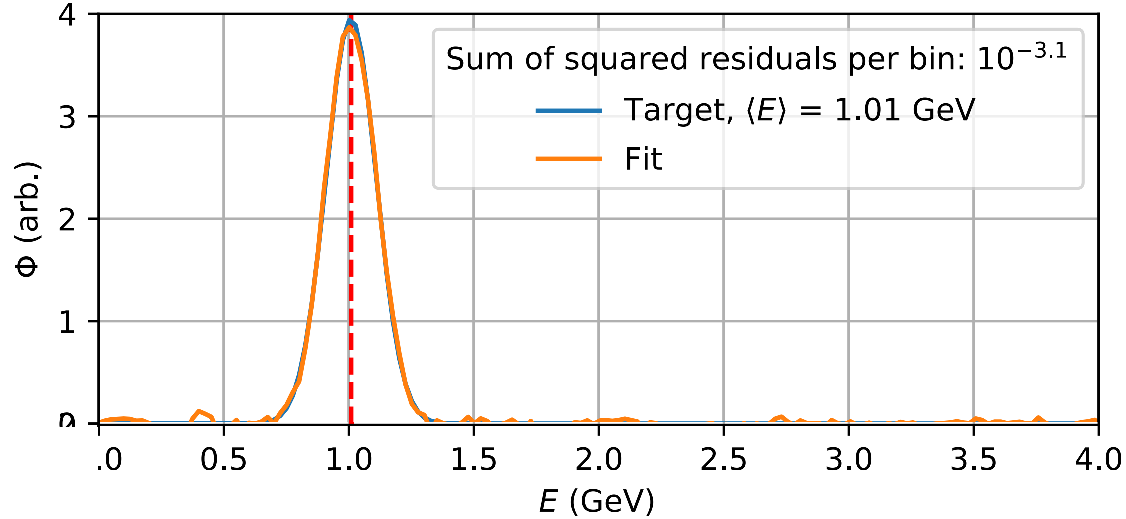
Creating New E_ν Spectra

- By taking linear combinations of measurements at different off-axis positions, we can determine observable distributions for a wide variety of energy spectra

Oscillated Fluxes at the ND!



Gaussian Beams



- Gaussian fluxes allow us to directly measure E_{rec} for a given E_{true}
- Oscillated fluxes allow us to directly measure oscillated far detector observables at the near detector

Questions From Management

- (1) Enumerate and, to the extent possible in the available time, quantify the various ways in which accessing the lowest energy off-axis spectra help to enhance DUNE's sensitivity to CP violation or other key oscillation measurements.

- (2) For PRISM arguments related to the second oscillation maximum, discuss the importance of the second oscillation maximum to DUNE's oscillation sensitivity, both as an enhancement to sensitivity when included together with the first oscillation maximum, and separately as a dedicated lower-energy analysis region with its own sensitivity (and possibly different systematic uncertainties).

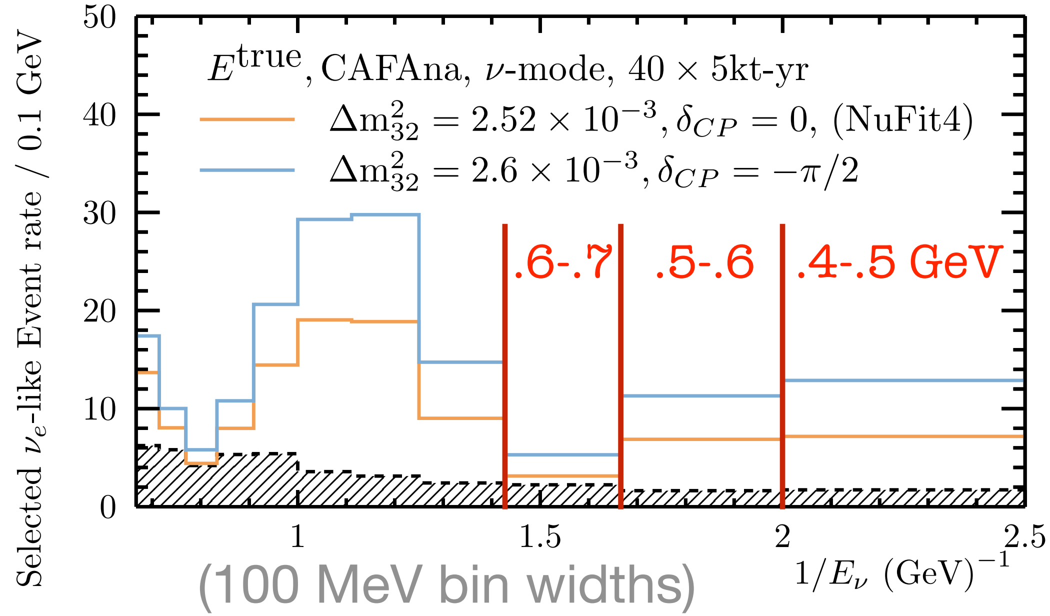
- (3) Based on your conclusions in (1) and (2), propose two off-axis travel distances and articulate the benefits at each (e.g., the nominal travel and a descoped option like 27 m). Ideally, the smaller distance would already offer much of the PRISM benefit to the oscillation measurement. Itemize clearly the loss of physics scope and/or risks that are introduced when considering the smaller travel distance versus the longer one.

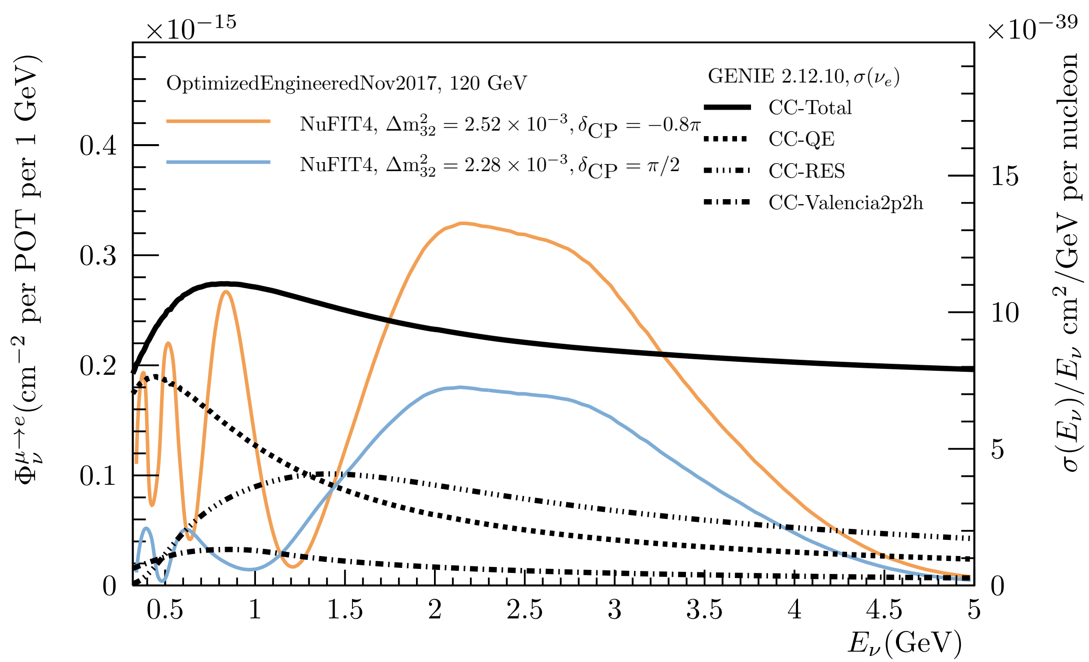
Why Was DUNE Designed with a Wide-Band Beam?

- The DUNE Interim Design Report (IDR) states: “A detailed description of the physics objectives of DUNE is provided in Volume 2 of the DUNE conceptual design report (CDR)”
    - The CDR states: “The difference in probability amplitude for different values of δ_{CP} is larger at higher oscillation nodes, which correspond to energies less than 1.5 GeV. Therefore, a **broadband experiment**, capable of measuring not only the rate of ν_e appearance, but of **mapping out the spectrum** of observed oscillations **down to energies of at least 500 MeV**, is desirable.” (emphasis added)
    - The higher oscillation maxima are critical confirming the full PMNS picture within which δ_{CP} is defined
        - They also provide an independent δ_{CP} measurement with a larger fractional CP effect, different flux, different cross sections, and different detector effects
- These physics objectives are fundamental to the current design of the experiment (e.g. wide-band beam, current baseline, and all the DUNE flux optimization effort)
    - (ancillary physics goals include non-standard interactions (NSIs), sterile neutrino searches, tau neutrino appearance, dark matter searches, and a variety of neutrino-nucleus measurements)

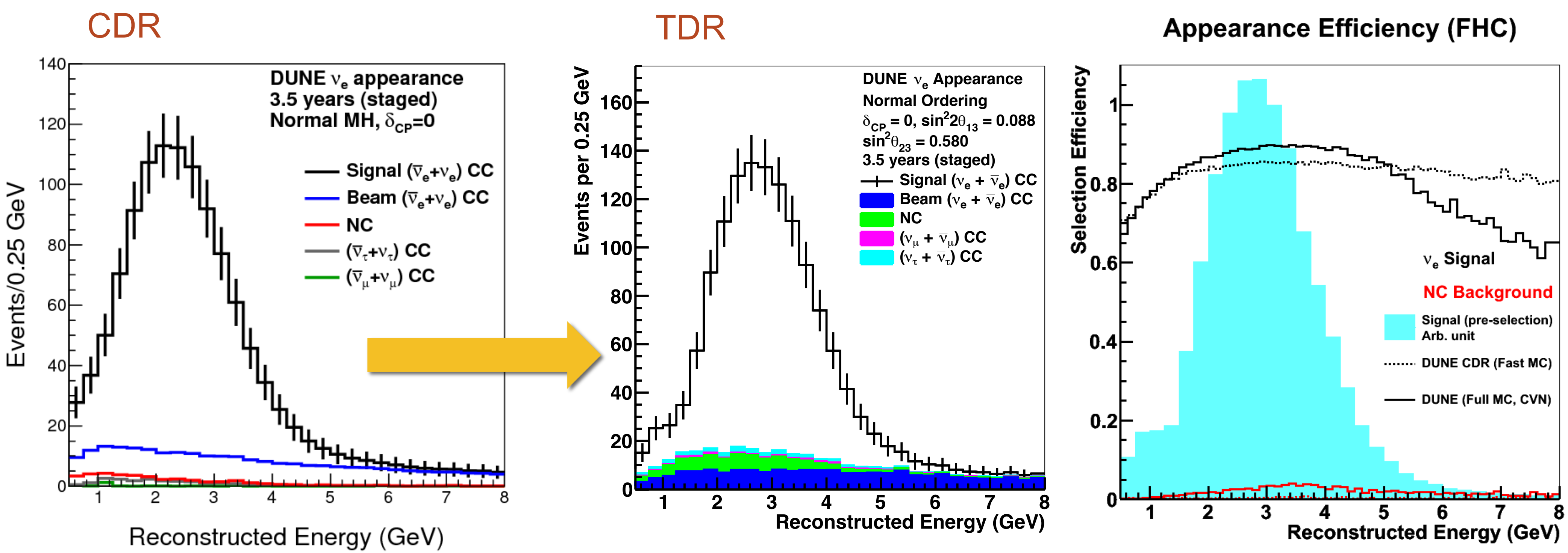
How Low in E_ν is Important?

- Far detector has events down to ~250 MeV
    - We are already losing useful events if we can't use E_ν < 500 MeV
- Top plot shows the event rate in $1/E_\nu$
    - A "small" extra bin in E_ν is a "large" extra bin in osc. space
    - The shape depends strongly on oscillation parameters (that's why they're so valuable!)
- Bottom plot shows 2 oscillated fluxes
    - Higher osc. peaks can move a lot with osc. parameters
    - At low energies, exclusive cross sections are changing rapidly (strong dependence on models)





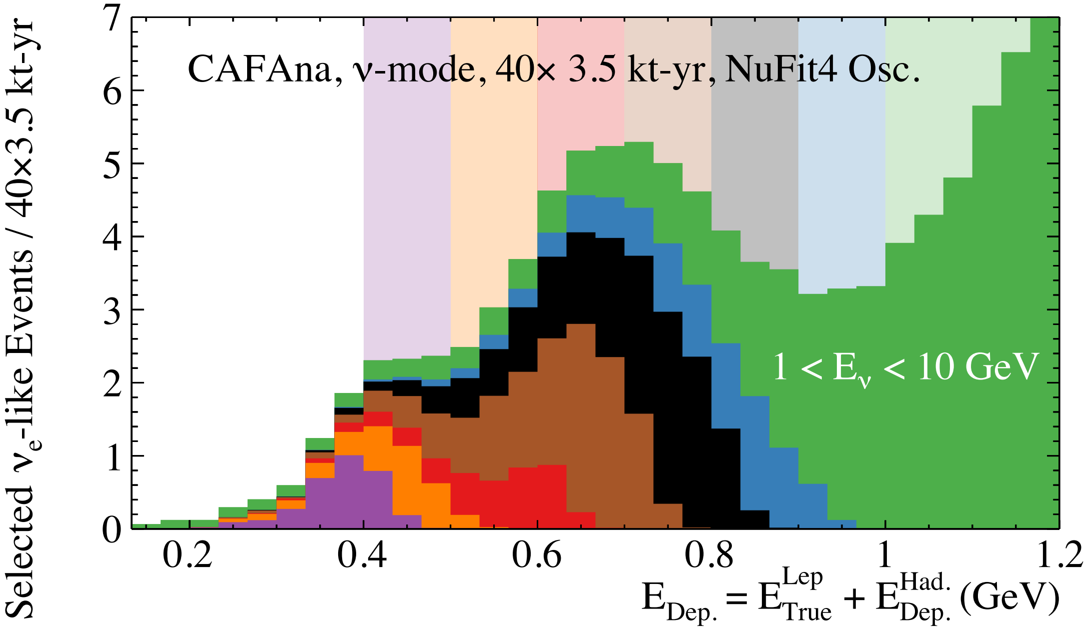
Previous Low-E_ν Studies



- All previous studies have a cutoff at 500 MeV in E_{rec} (which corresponds to a higher cutoff in E_{true})
- Event reconstruction has not yet been optimized at low energies
  - Efficiency at low E_ν decreased from CDR to TDR
  - Can use muon angle, final hadron kinematics, … ?
- How well will we eventually do with resolution, efficiency, & backgrounds?

Why is Low E_ν Difficult?

- E_ν feed-down from higher energy events can easily wash out sensitivity at low E_ν
  - Here, E_{rec} is true lepton energy + deposited hadronic energy (i.e. no model-dependent correction applied)



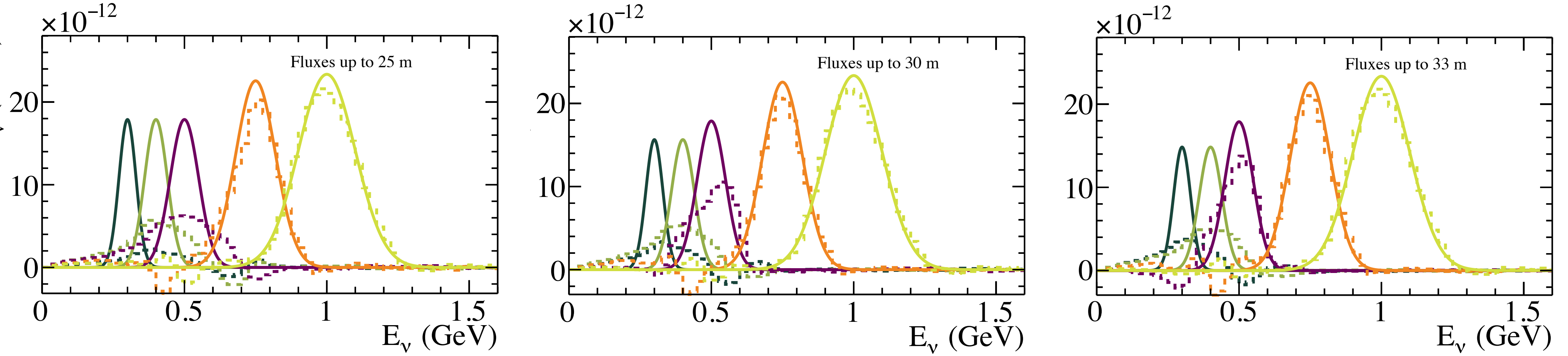
<u>Main Points</u>

1. Significant effort will be needed to optimize our resolution (and efficiency) at low-E_ν as much as possible

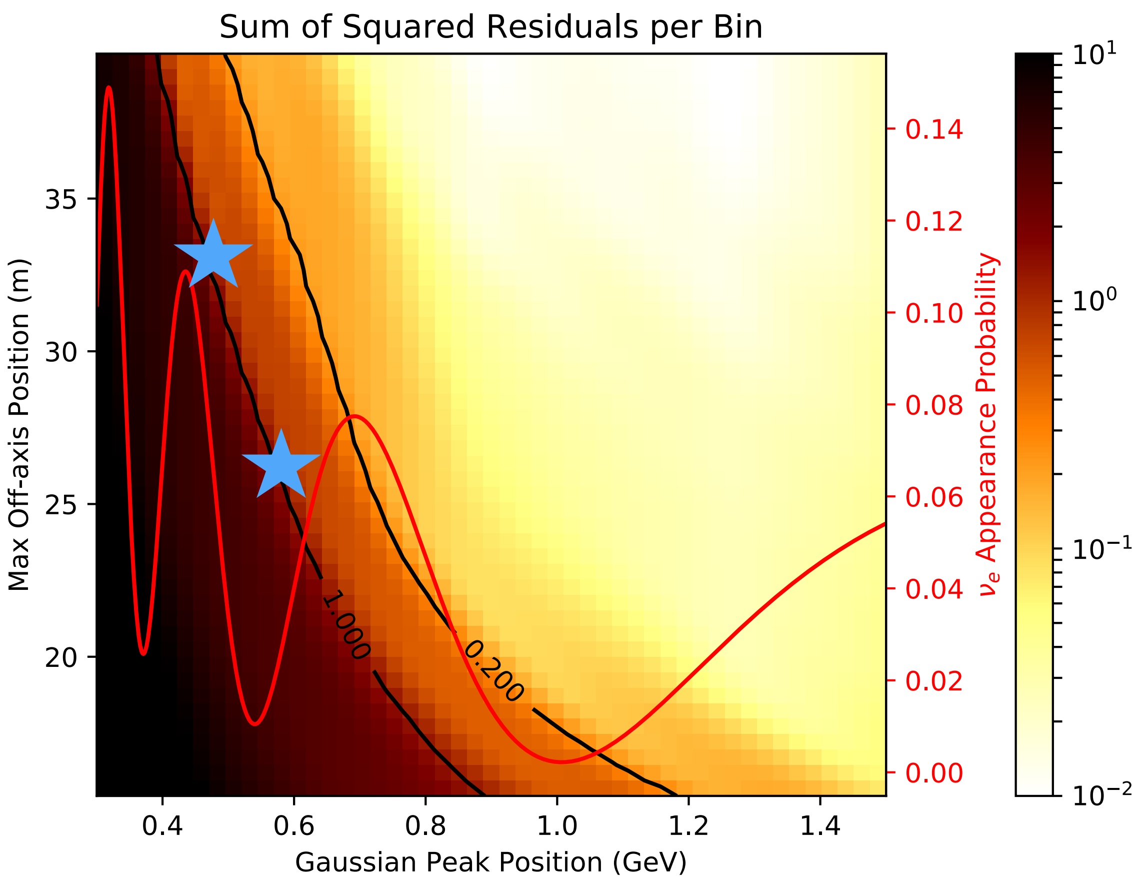
2. Regardless of the resolution we ultimately achieve, we must be able to calibrate $E_{true} \rightarrow E_{rec}$ (i.e. E_{rec} feed-down) as precisely as possible

   - Without DUNE-PRISM measurements at low-E, this will be very difficult to achieve without high-precision cross section (and flux) modeling

DUNE-PRISM Gaussian Fluxes

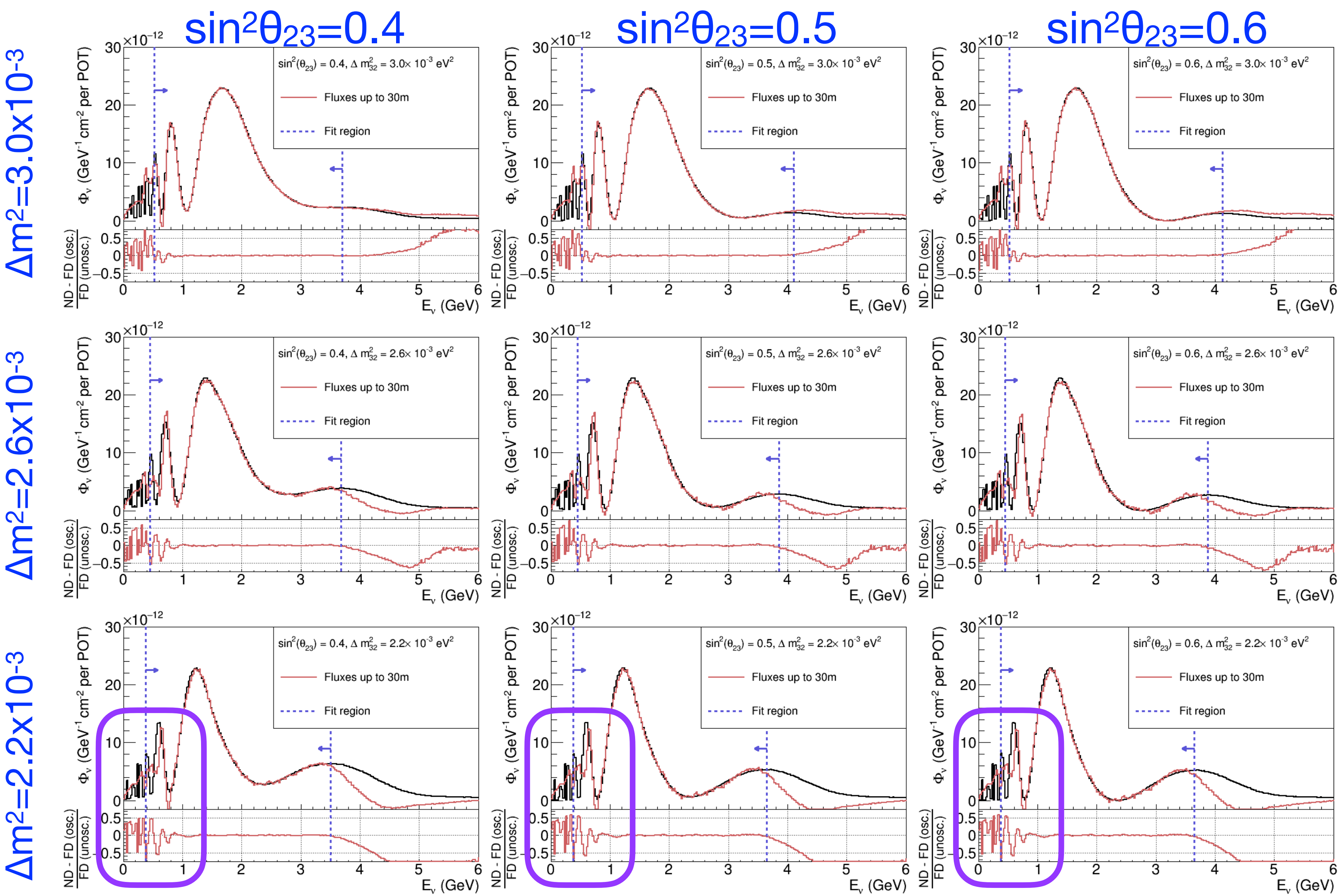


- To reach 500 MeV with DUNE-PRISM Gaussians, 33m off-axis is needed
- ~Linear relationship between maximum off-axis position & minimum $1/E_\nu$ that can be constrained
  - If maximum off-axis position is reduced to 27 m, low-E_ν reach is degraded to 600 MeV



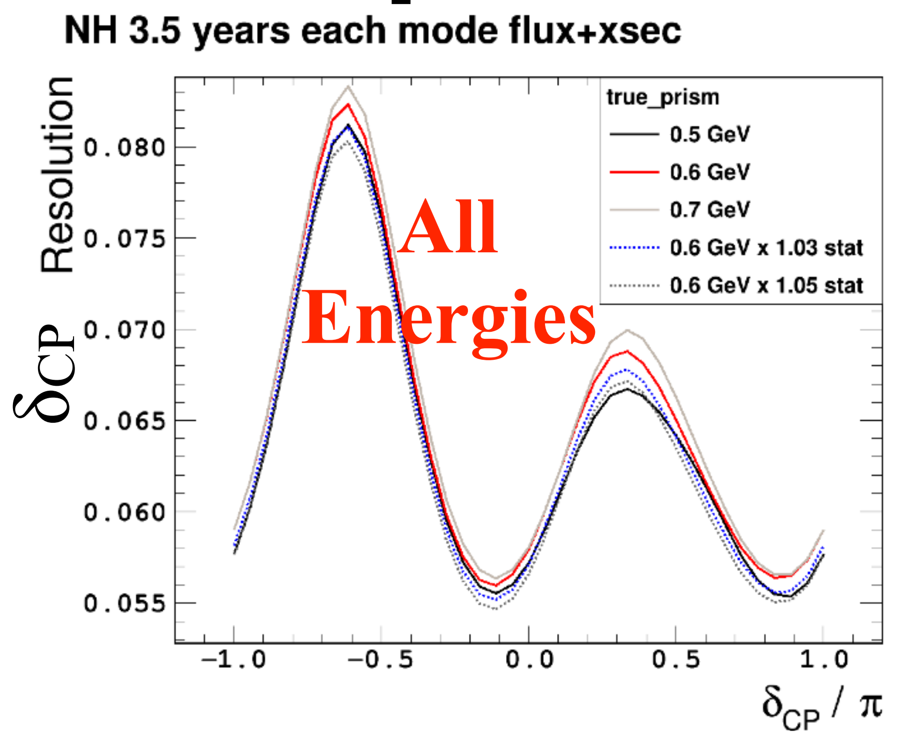
Similar Story With Osc. Fluxes

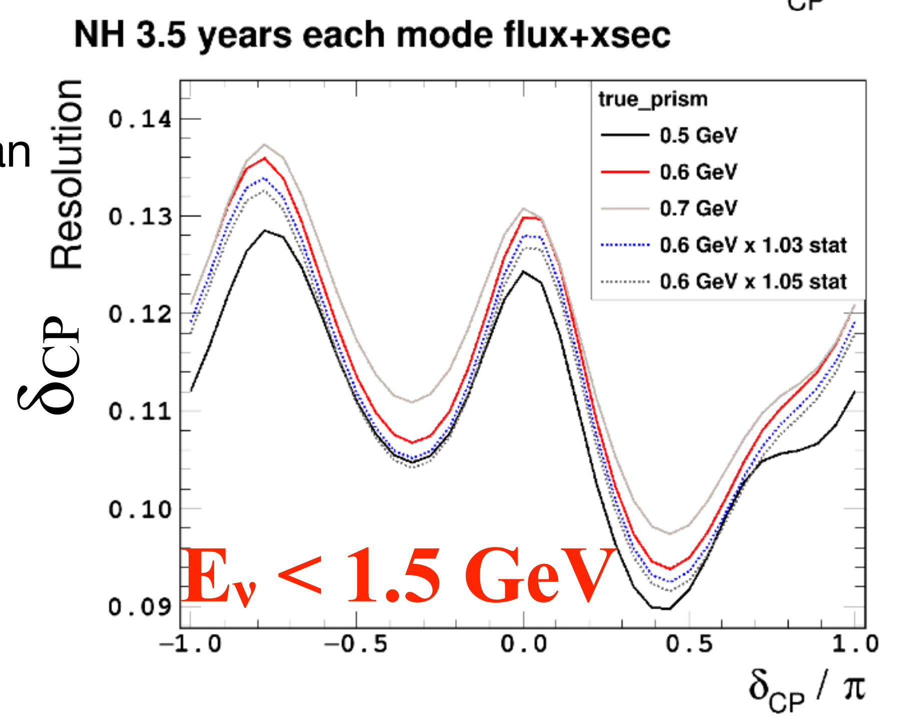
- For off-axis fluxes up to 30m, begin to see fit degradation above 500 MeV



Potential Osc. Impact

- Goal is to gain some understanding of how useful low energy events might eventually be (e.g. ~10 years from now)
    - Try to focus on the difference between the "all-energies" fit (top) and the "<1.5 GeV only" fit (bottom)
- Using latest CAFAna near/far fit, but:
    - Only flux+xsec systematics
        - (Ultimate detector uncertainties are not yet known, particularly at low-E_ν)
    - Assuming perfect energy reconstruction
        - (idealized "bracketing case" to see what we can gain from improvements in energy resolution)
    - Flat 85% efficiency for all E_ν, & only beam ν_e background (NC and ν_μ bkg is already very small)
- Large gains in δ_{CP} resolution (esp. for higher osc. max) when adding the 500-600 MeV bin
    - Additional gains may be realized by pushing the energy threshold down further





Answers to Management

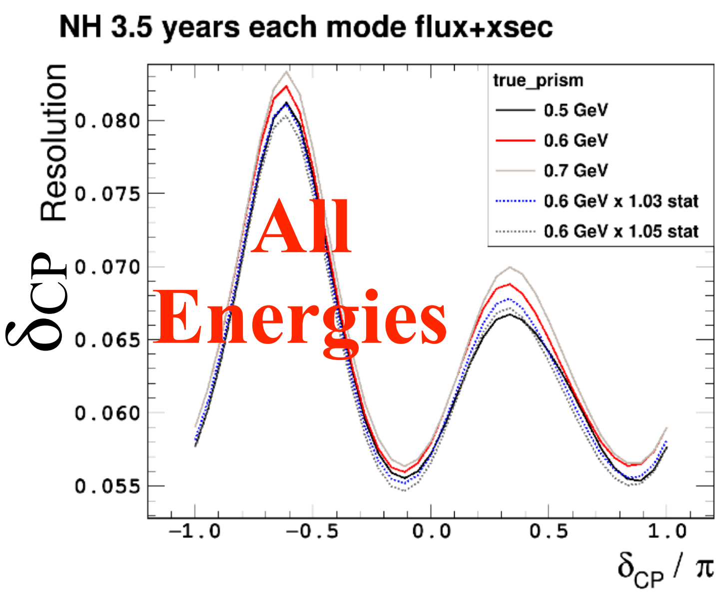
- **(1) Enumerate and, to the extent possible in the available time, quantify the various ways in which accessing the lowest energy off-axis spectra help to enhance DUNE's sensitivity to CP violation or other key oscillation measurements.**

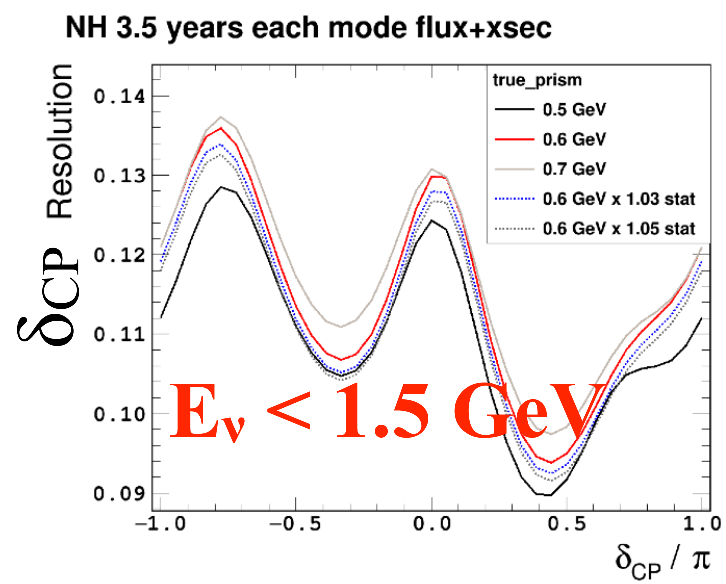
- The ability to measure higher oscillation maxima is a primary driver of the current DUNE experimental design (e.g. wide-band beam, baseline, flux optimization)
  - This region is critical confirming the full PMNS picture within which δ_{CP} is defined
  - Low E_ν provides an independent δ_{CP} measurement with a larger fractional CP effect, different flux, different cross sections, and different detector effects
- Ancillary physics goals include non-standard interactions (NSIs), sterile neutrino searches, tau neutrino appearance, dark matter searches, and a variety of neutrino-nucleus measurements
  - Precise control of $E_{true} \rightarrow E_{rec}$ over the full energy range is important for most of these measurements
  - Recent theory papers and talks discuss importance of DUNE-PRISM to CP violation measurements in sub-GeV atmospheric neutrinos & dark photon searches (much more to come over the next several years)

arXiv:1903.10505, arXiv:1904.02751, https://tinyurl.com/y3jcln2y, https://absuploads.aps.org/presentation.cfm?pid=15148

Answers to Management

- **(2) For PRISM arguments related to the second oscillation maximum, discuss the importance of the second oscillation maximum to DUNE's oscillation sensitivity, both as an enhancement to sensitivity when included together with the first oscillation maximum, and separately as a dedicated lower-energy analysis region with its own sensitivity (and possibly different systematic uncertainties).**
- The results for δ_{CP} resolution (described previously) are below
  - A detailed understanding of the energy resolution (i.e. the primary physics goal of DUNE-PRISM) is critical in this low-E_ν region



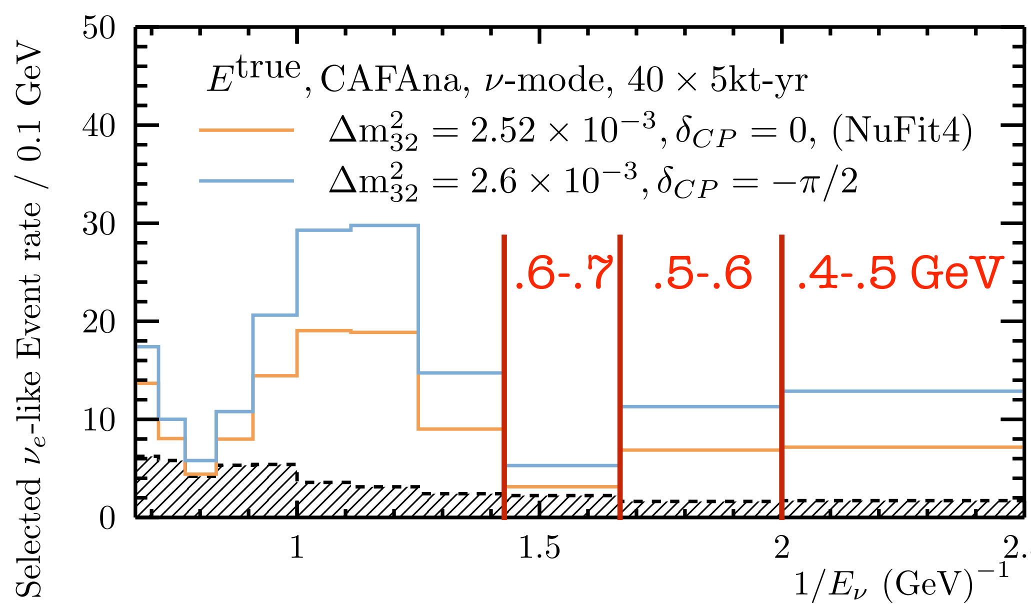


Answers to Management

- **(3) Based on your conclusions in (1) and (2), propose two off-axis travel distances and articulate the benefits at each (e.g., the nominal travel and a descoped option like 27 m). Ideally, the smaller distance would already offer much of the PRISM benefit to the oscillation measurement. Itemize clearly the loss of physics scope and/or risks that are introduced when considering the smaller travel distance versus the longer one.**
- Already, at 33 m, DUNE-PRISM cannot constrain events below 500 MeV
- Reducing the off-axis reach to 27 m further restricts the accessible range to events above 600 MeV
- Given the importance of a precise understanding of energy resolution at low-E_ν, these low energy events will be difficult to use without a direct DUNE-PRISM constraint

Note that different choices of oscillation parameters result in substantial shifts between bins

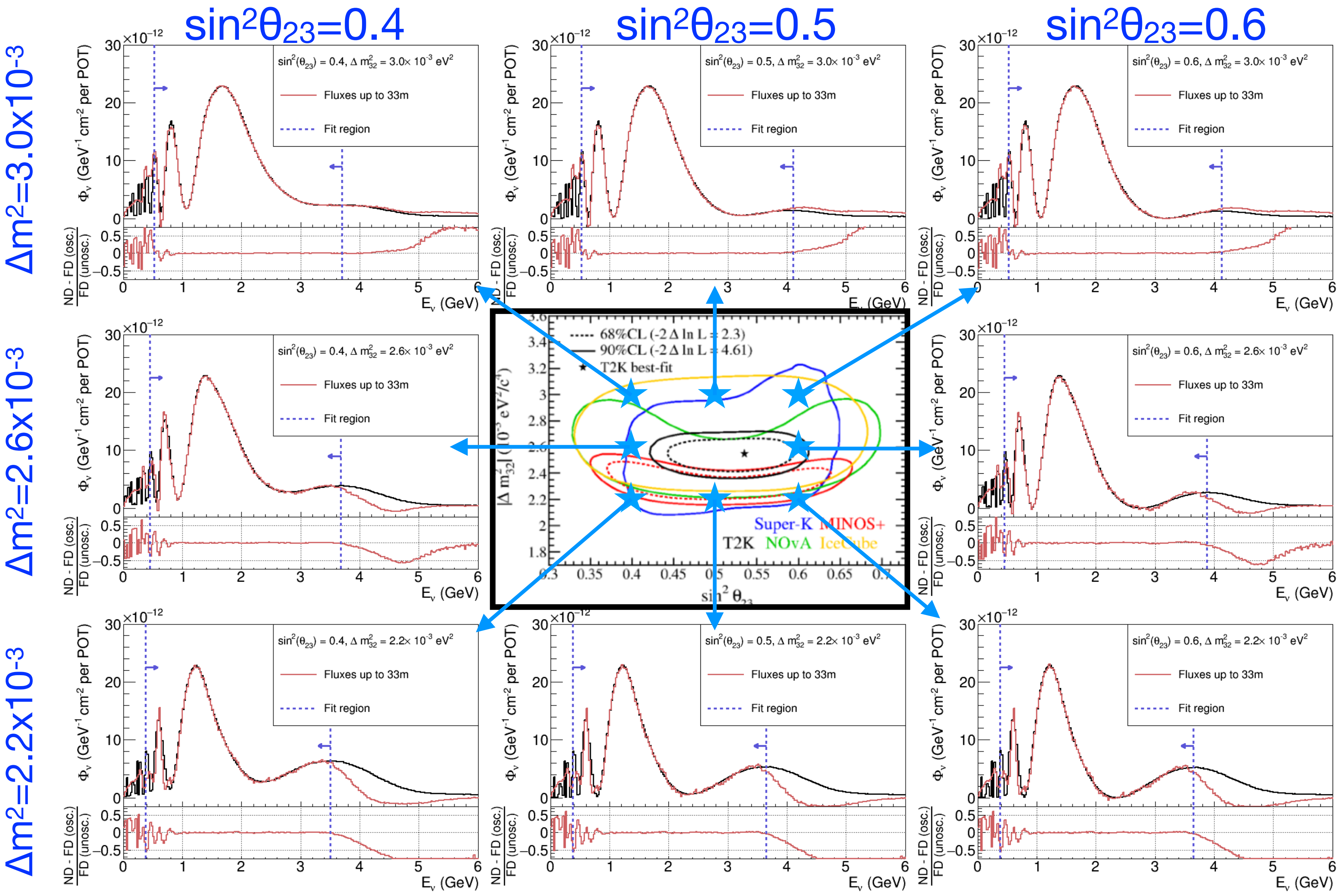
(this effect, and the increased effect of δ_{CP} (3x, 5x, …), illustrate why this region is so valuable for oscillations)



Supplement

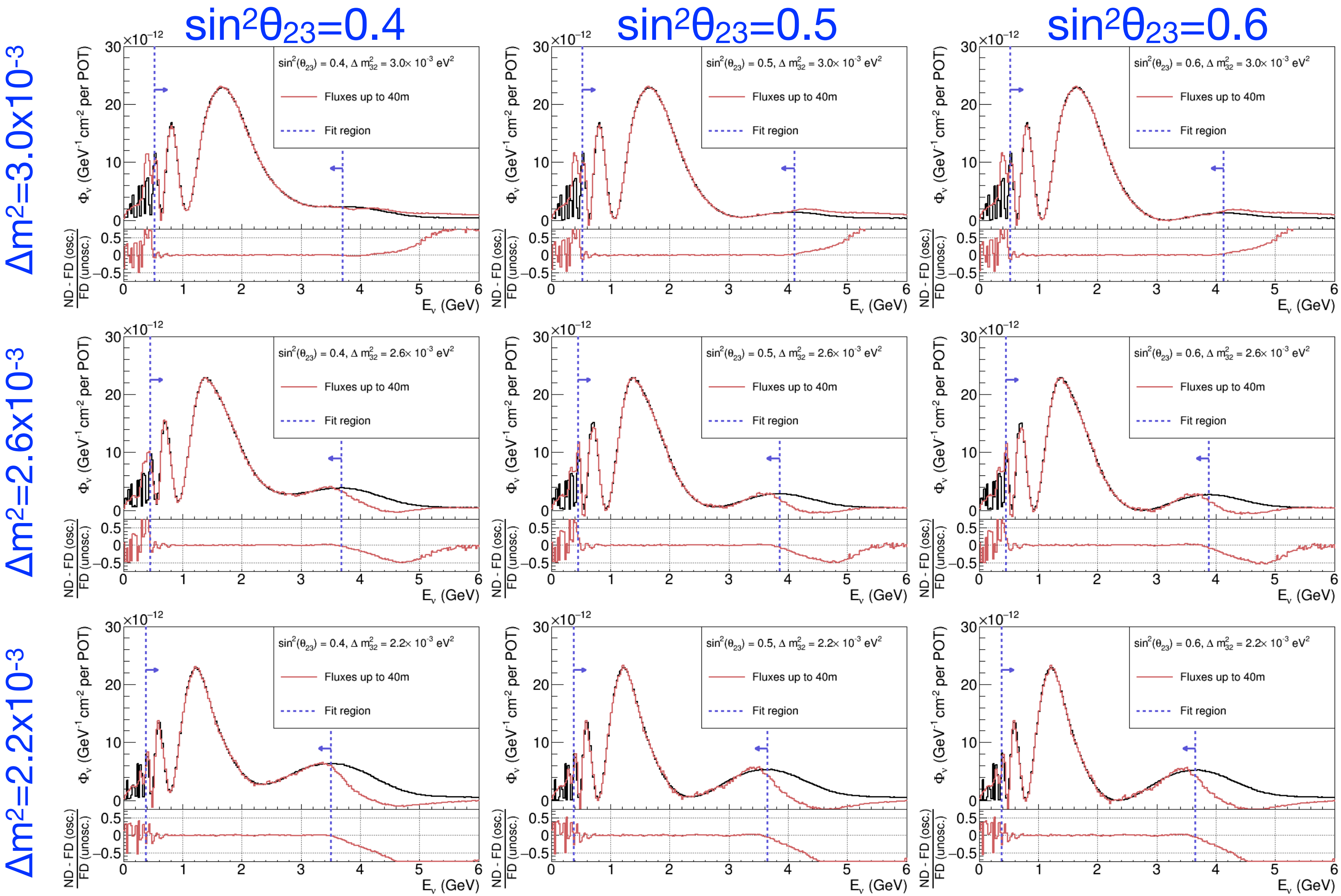
Oscillated Flux Fits

- DUNE-PRISM can match the far detector oscillated spectra for all currently allowed values of oscillation parameters



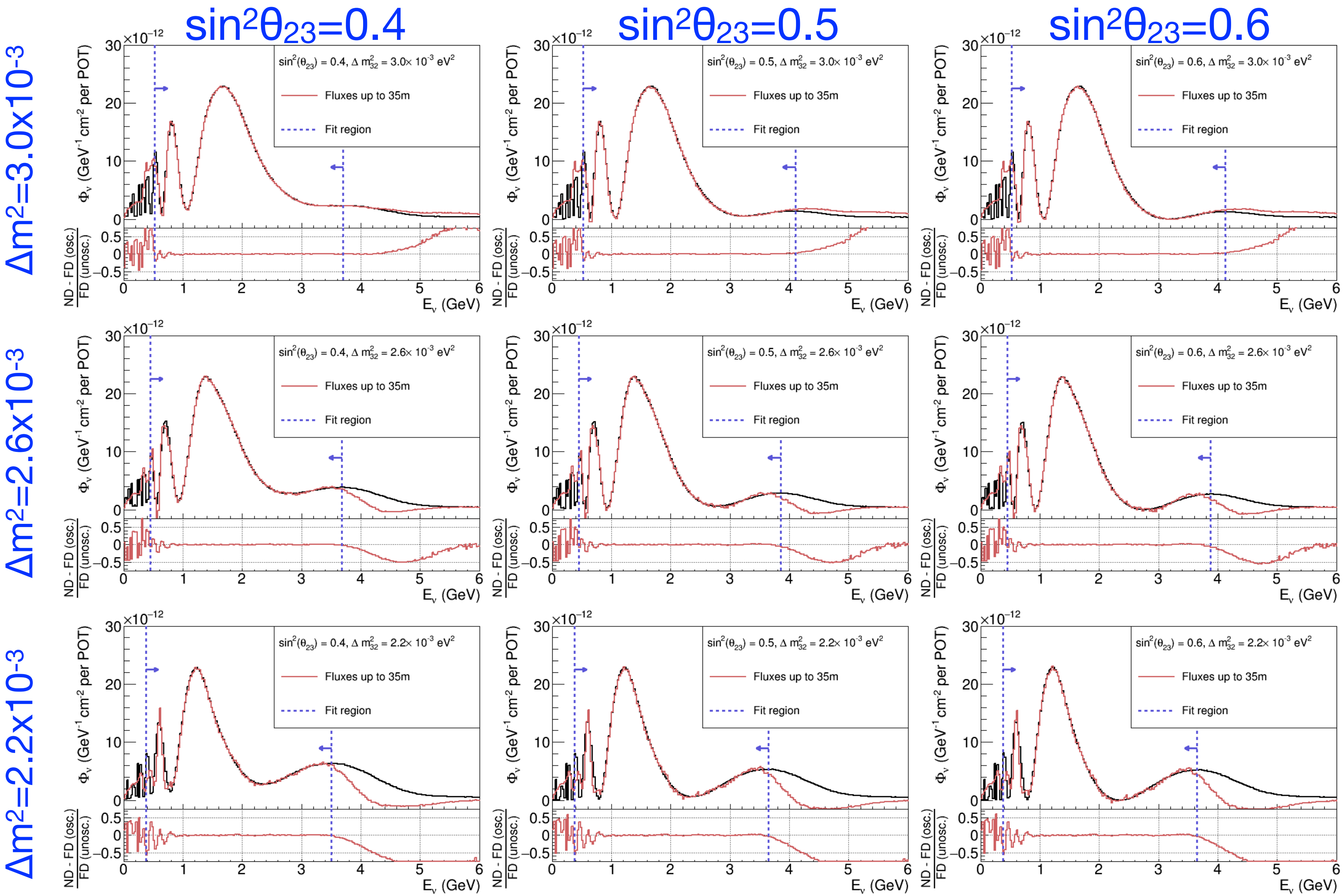
Fluxes Up to 40 m Off-Axis

- Can even somewhat resolve the peak below the 3rd oscillation maximum for all values of Δm_{32}^2



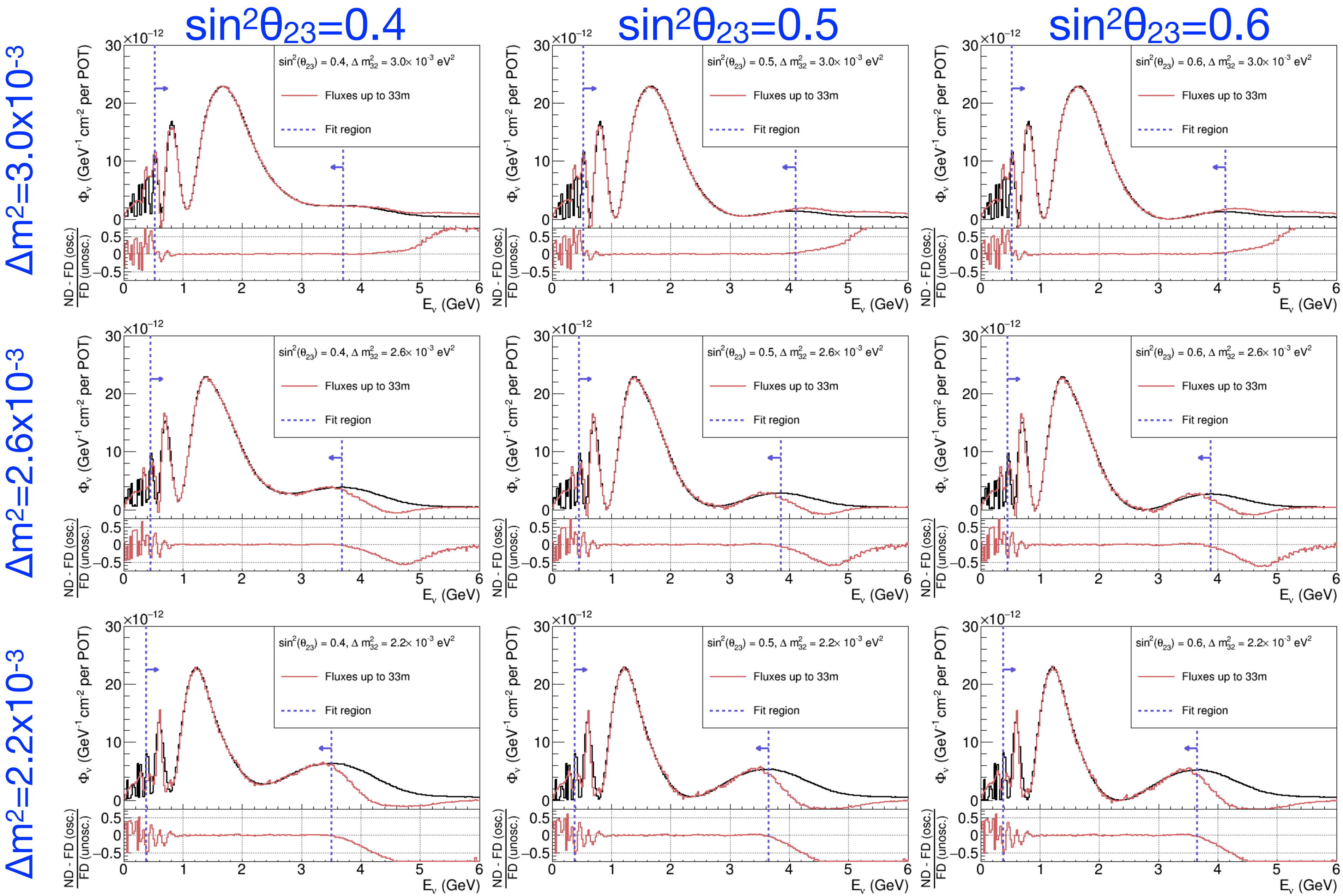
Fluxes Up to 35 m Off-Axis

- Can still generally resolve bump below 2nd oscillation maximum for all values of Δm_{32}^2, although some fluctuations are seen in the ratio to the unoscillated flux



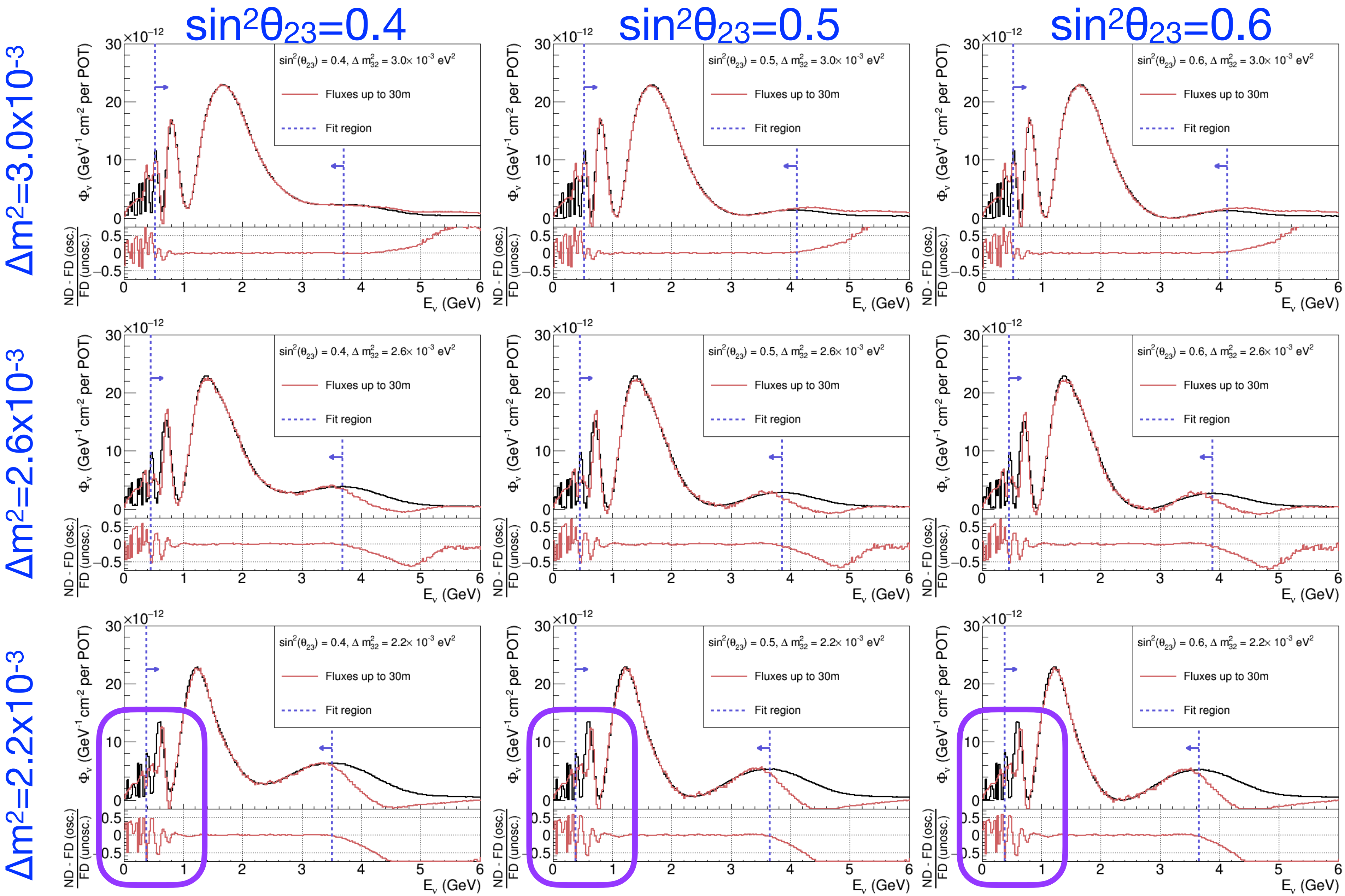
Fluxes Up to 33 m Off-Axis

- Can still generally resolve bump below 2nd oscillation maximum for all values of Δm_{32}^2, although some fluctuations are seen in the ratio to the unoscillated flux



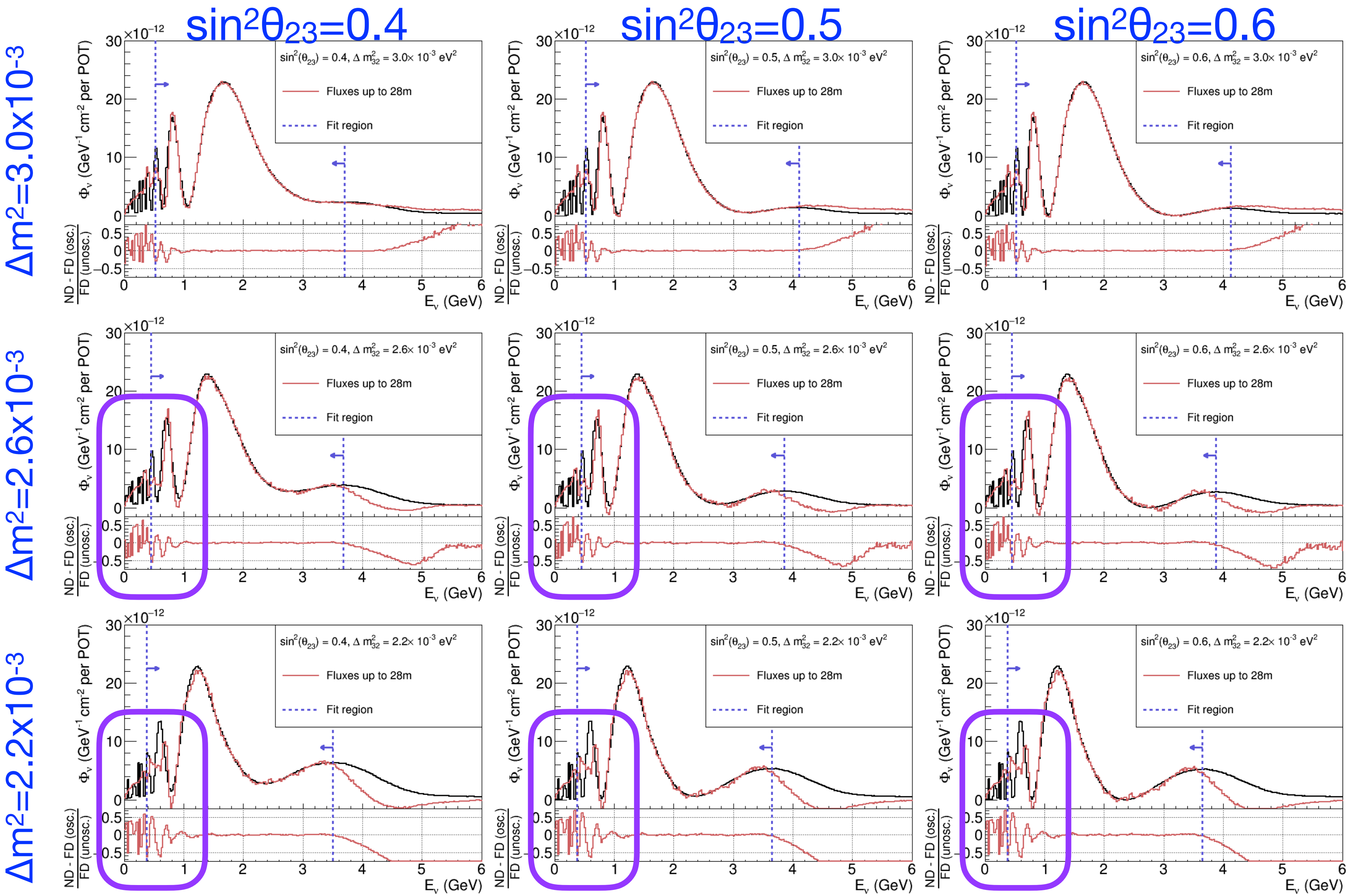
Fluxes Up to 30 m Off-Axis

- Poor fits around the 2nd oscillation maximum for low Δm_{32}^2 region; ability to constrain systematics in this region may be compromised

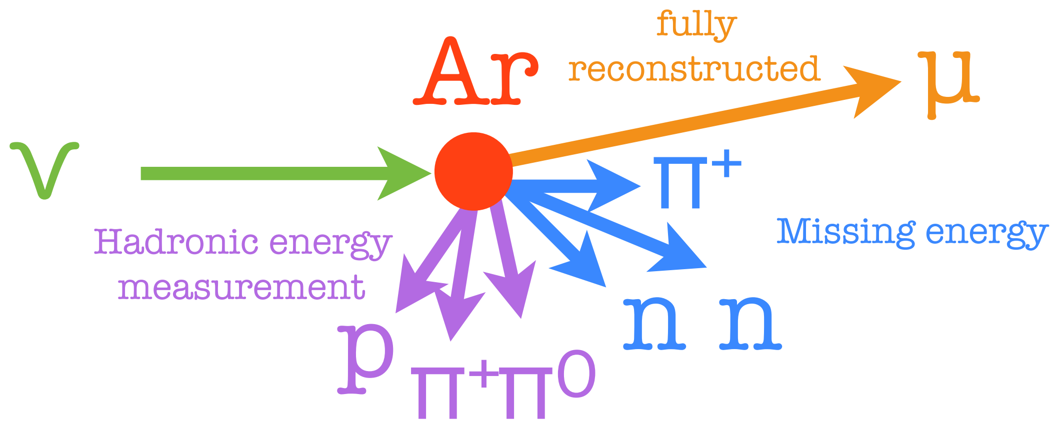


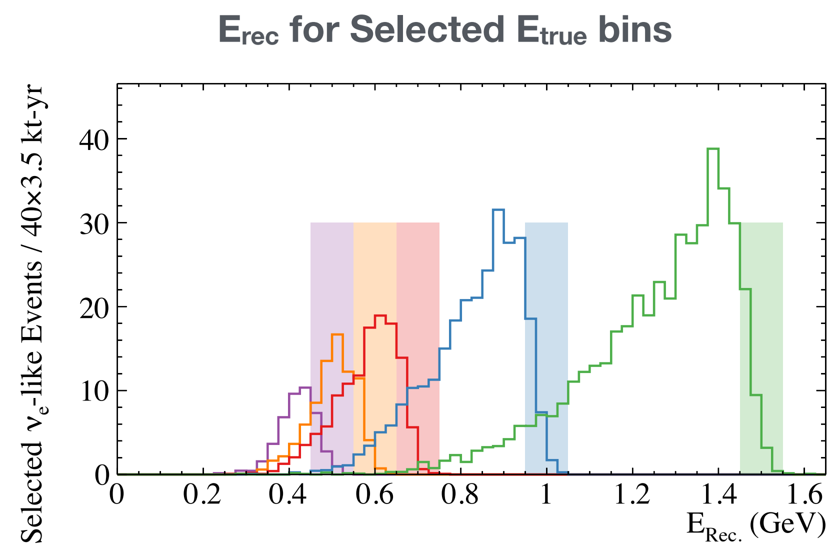
Fluxes Up to 28 m Off-Axis

- Very poor fits around the 2nd oscillation maximum for low Δm_{32}^2; limiting to 28 m can cause harm to 2nd oscillation maximum physics

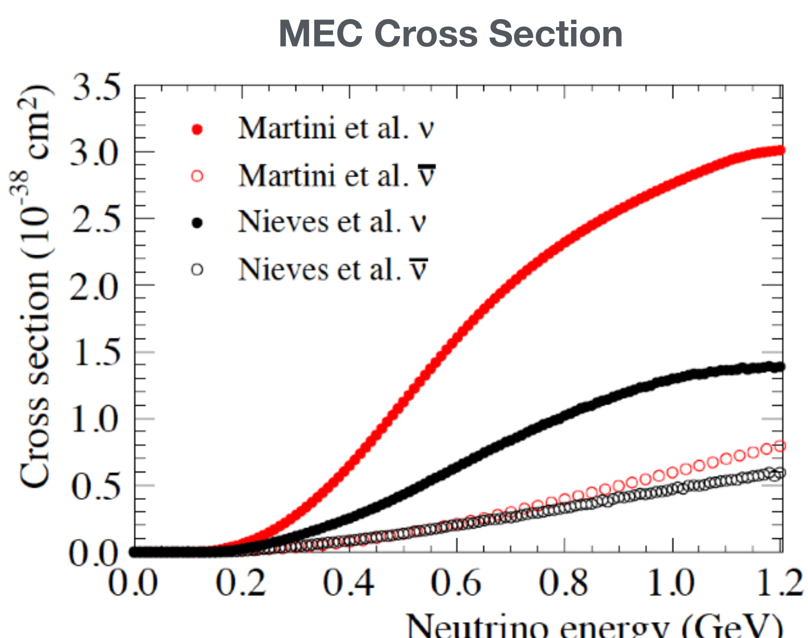


The E_ν Measurement Problem



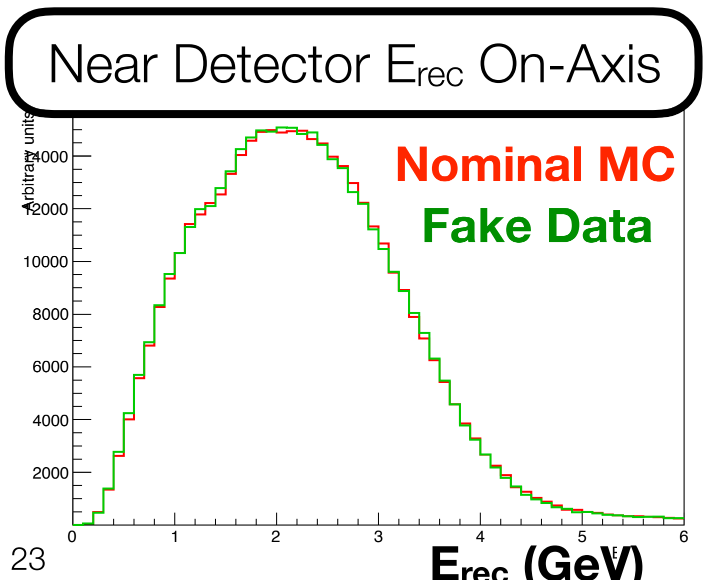


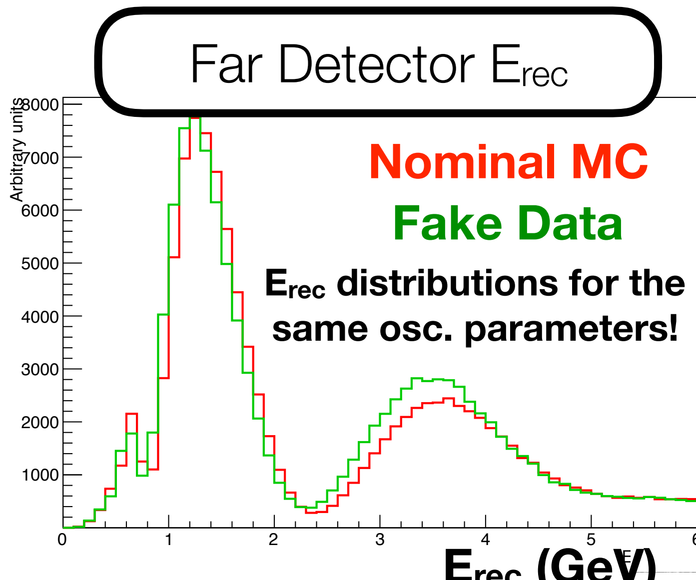
- Typically, E_ν is "measured" via the observed final state
  - However, the final state is subject to **missing energy** (e.g. neutrons) & **nuclear physics** (e.g. MEC, FSI, off-shell effects, …)
  - This causes smearing of E_{rec} relative to E_{true} (typically feed-down)
- E_{rec} ➜ E_{true} translation depends on **poorly understood neutrino interaction models**
  - 1p1h, 2p2h, npnh, RPA, pion production, FSI, multi-pi transition, DIS, etc.
- Within DUNE, the near detector (ND) will be used to experimentally constrain E_{rec} ➜ E_{true} using off-axis measurements

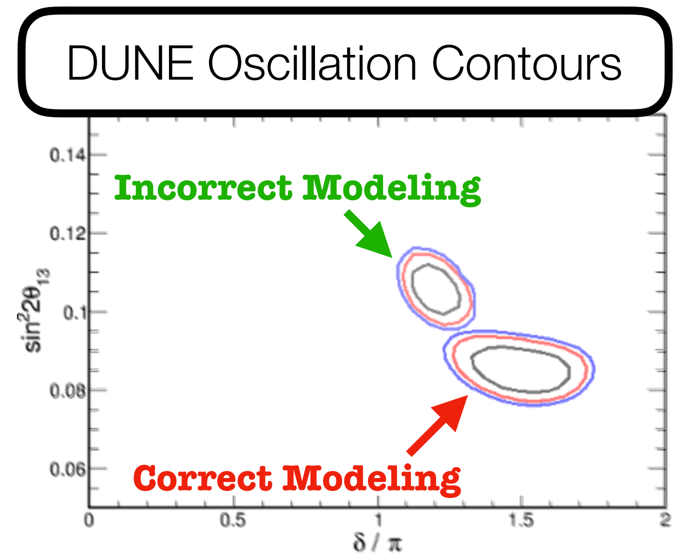


Mismodeling $E_{true} \rightarrow E_{rec}$ Can Produce Biases

- In every long-baseline ν experiment:
    1. Event rate distributions are measured in the near detector
    2. The ν flux and ν cross section modeling are tuned to make the ND MC match ND data distributions
- **The problem**: there are many degenerate cross section model adjustments that can make (on-axis) ND MC match ND data (even if the flux prediction is perfect)
    - The wrong model can have a substantial impact at the far detector, even if it provides agreement in ~all on-axis near detector observables
    - i.e. **DUNE may report incorrect oscillation parameters without any evidence of a problem** if we use only on-axis ND measurements







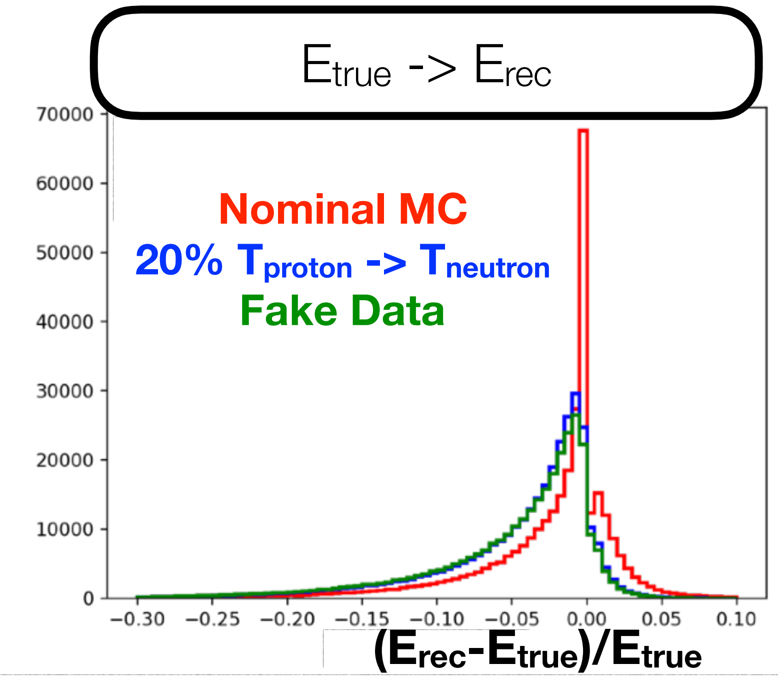
Using DUNE-PRISM Information

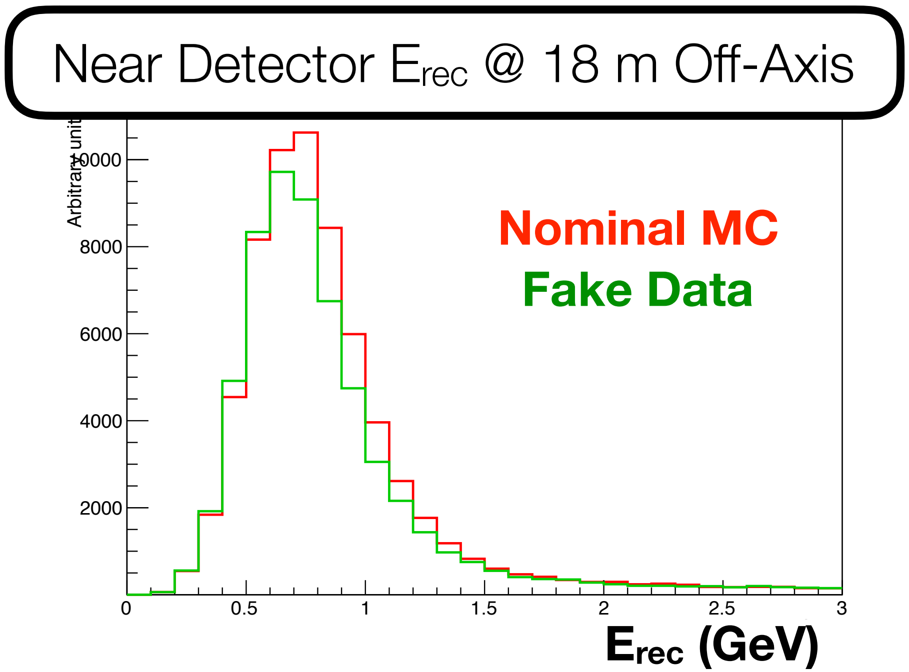
- Near detector measurements with a continuously varying energy spectra can be used to constrain cross section modeling and E_{true} ➜ E_{rec} mapping in two distinct ways:

1. Off-axis measurements will likely identify incorrect cross section models that nonetheless produce data/MC agreement on-axis (due to degenerate model effects)
    - This information will allow for iterative model improvements with theorists and model builders
2. Measurements of the continuously varying E_{ν} peak position in each off-axis slice can be combined to produce a data-driven far detector prediction that naturally incorporates unknown cross section effects
    - (more on this in 2 slides)

Identifying Poor Cross Section Modeling

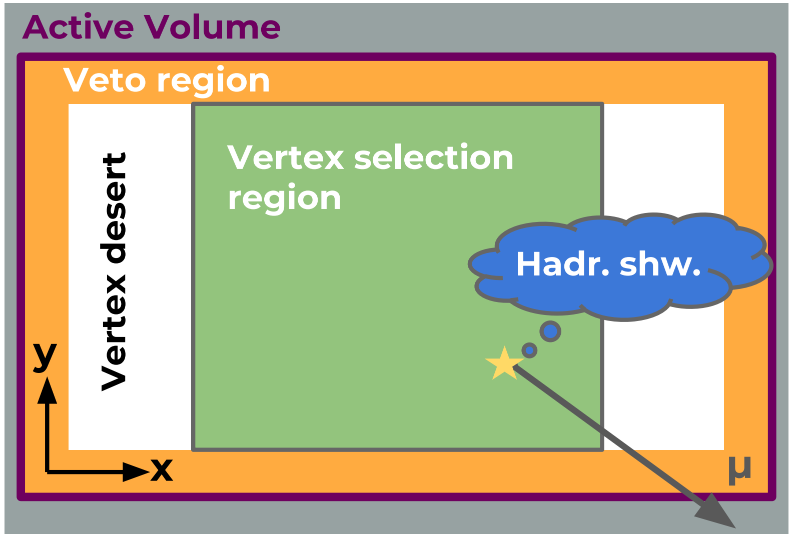
- The previously shown fake data were produced by:
  - Transferring 20% of proton kinetic, T_p, energy to (unseen) neutrons
  - Adjusting other parts of the cross section model ($d\sigma/dT_p$, pion production, angular distributions, etc.) to achieve nearly perfect agreement in ~all ND observables
    - In every LBL experiment, cross section models are adjusted to make ND data match ND MC
    - Wrong choices for how to "fix" the ND data/MC agreement can result in an incorrect E_{true} -> E_{rec} relationship (and, hence, the wrong answer for δ_{CP})
- By making off-axis measurements, cross section modeling problems can be clearly identified

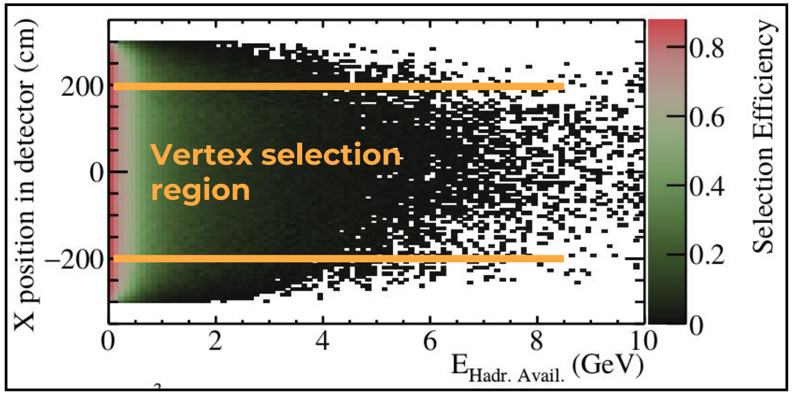


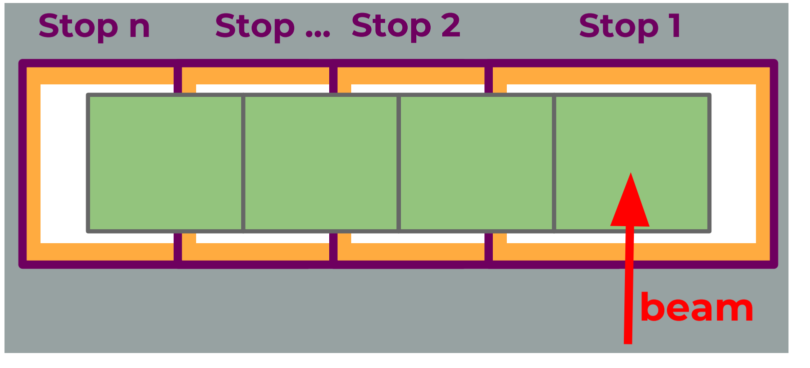


Off-Axis Efficiency

- ND event selection requires minimal hadronic energy in the outer 50 cm of the active LAr
    - Ensures containment of non-neutron hadronic energy
- Events near the veto region often leak hadronic energy into the veto region
    - This produces a model-dependent efficiency drop
- To minimize model-dependent efficiency differences between off-axis slices, the fiducial volume is separated from the veto region by 1.5 m
- With the currently assumed 7-m-wide LAr detector, 8 off-axis positions are required for continuous coverage up to 32 m off-axis







Flux Uncertainties

- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
    - Yes! But only relative flux errors are important!
    - Significant cancelation between PRISM and far detector variations
- **Normalization uncertainties will cancel** in the PRISM analysis
    - Cancelations persist, even for the PRISM linear combination
- Variations that affect off-axis angle shape are most important
    - Horn current, beam direction, alignment, etc.
- First analyses indicate that flux variations do not significantly impact PRISM analyses