# DUNE-PRISM Scope

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For the DUNE-PRISM Working Group
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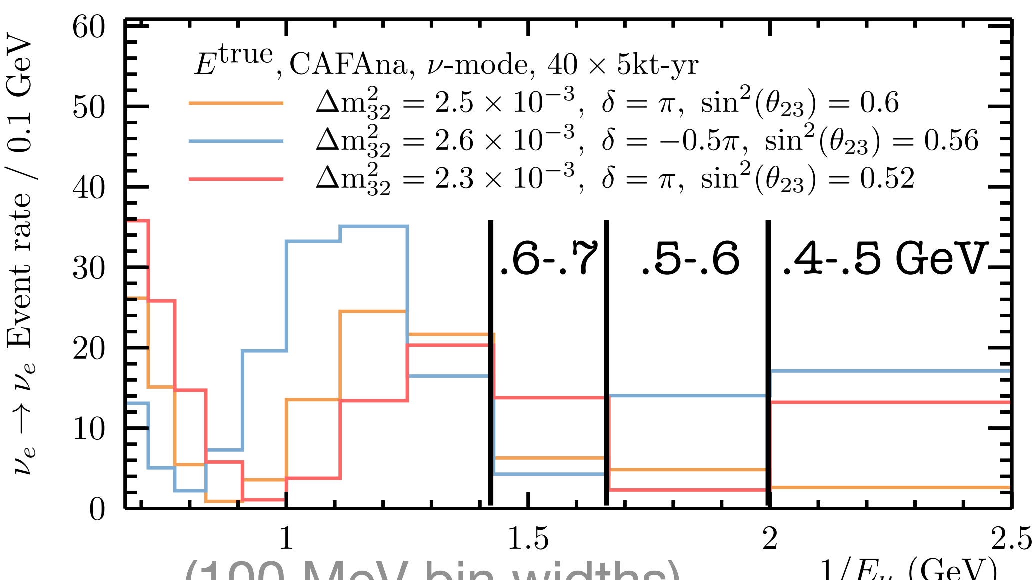
# Overview

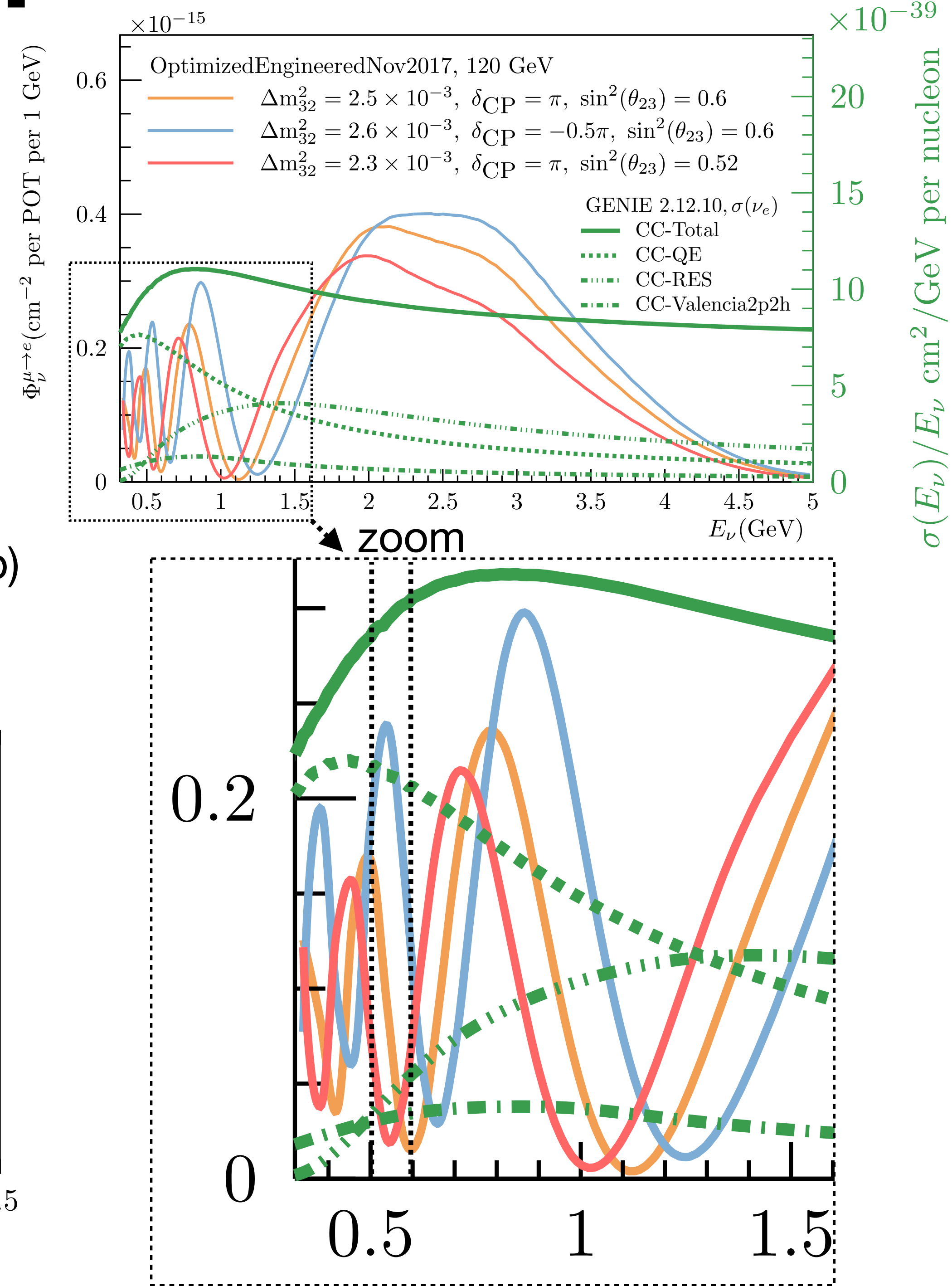
- Descoping DUNE-PRISM involves shortening the hall length
  - This reduces the low energy reach of DUNE-PRISM
- Baseline experimental goals have been defined as measuring oscillations down to at least 500 MeV (wide-band beam, stated in CDR, Flux Optimization, etc.)
  - We have flux and efficiency at low energy
  - Oscillation information per energy bin increases as we probe lower in energy (oscillations are a function of $L / E_\nu$ ; CP effect grows at lower energies)
  - The value of this information is to study the full PMNS framework within which $\delta_{CP}$ is defined (rather than how much they contribute to the combined $\delta_{CP}$ sensitivity)
- Low energy is difficult without DUNE-PRISM
  - Exclusive cross sections are varying quickly (near thresholds)
  - Energy feed-down from higher energies can wash out the oscillation information

# Energy Dependence

- Events with high oscillation information content occur below 500 MeV
  - Oscillation sensitivity given by these events on will depend on efficiency, backgrounds, & energy feed-down (more on next slide)
- At 500 MeV, the oscillation feature width (“peak-to-depth”) is ~90 MeV (more in backup)
- Cross sections are varying at low energy

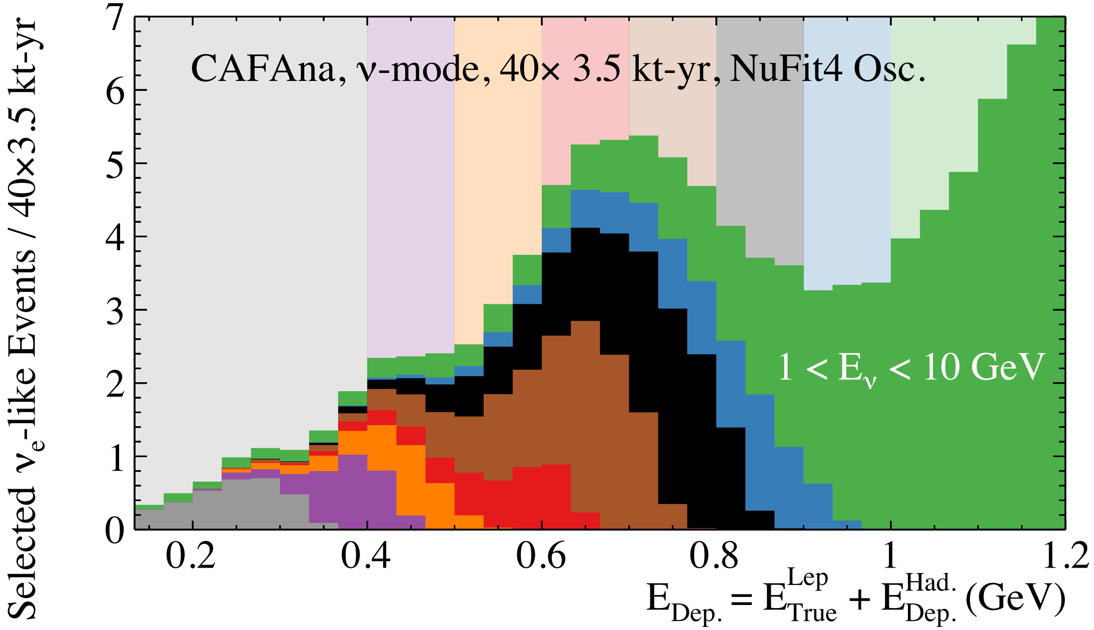



(100 MeV bin widths)



# Energy Reconstruction

- $E_\nu$ feed-down from higher energy events can easily wash out sensitivity at low $E_\nu$
    - True energy bins shown as colored bars in the background
    - Here, $E_{rec}$ is true lepton energy + deposited hadronic energy (i.e. no model-dependent correction applied)




<u>Main Points</u>

1. More effort is planned to optimize our resolution (and efficiency and background rejection) at low-$E_\nu$ as much as possible

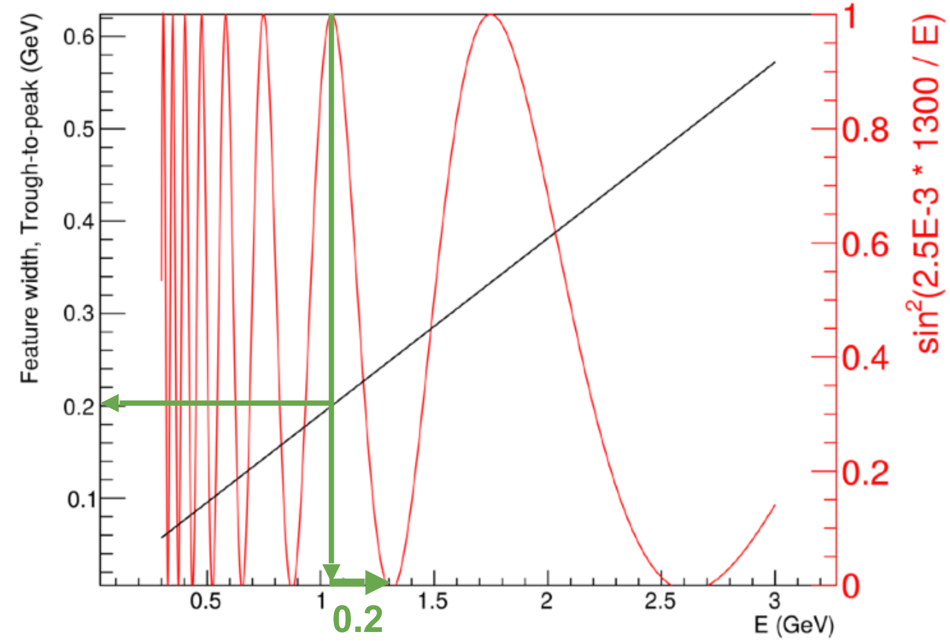
2. Regardless of the resolution we ultimately achieve, we need to calibrate $E_{true} \rightarrow E_{rec}$ (i.e. $E_{rec}$ feed-down) as precisely as possible

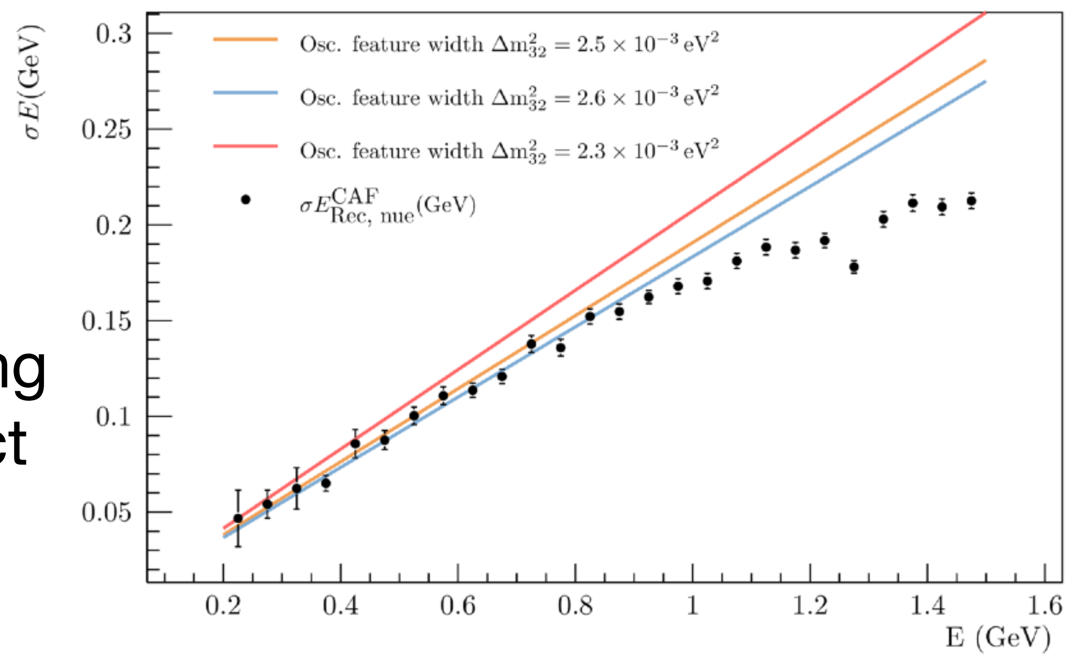
    - This is more difficult without direct measurement from DUNE-PRISM

# $E_\nu$ Resolution vs Osc. Features

- Oscillation peak-to-trough distance scales linearly with energy
- The energy resolution also scales linearly with energy
- Current LBL fractional $E_{rec}$ resolution is flat at ~20% below 0.8 GeV
- Bottom line: energy resolution is not a limiting factor in determining how low in energy we can extract oscillation features

"Peak-to-Trough" Width vs $E_\nu$

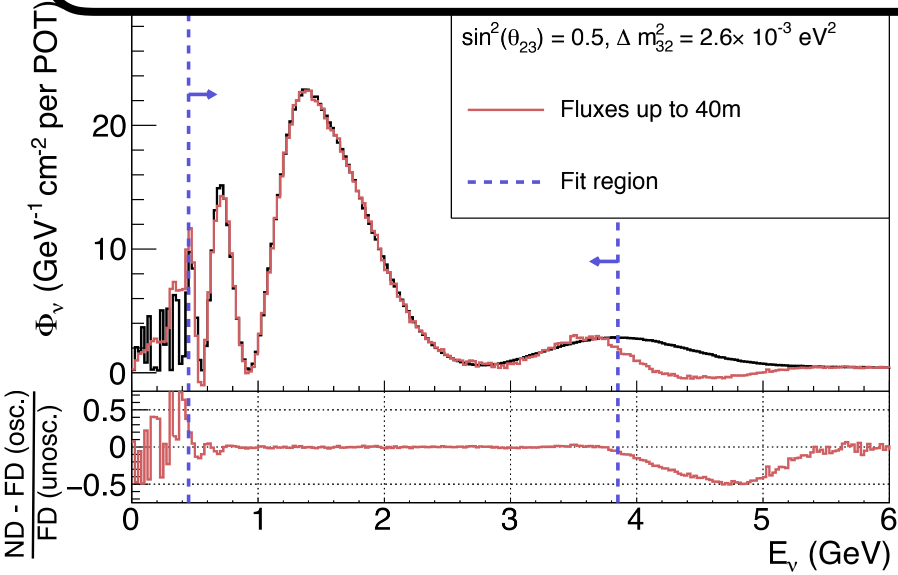


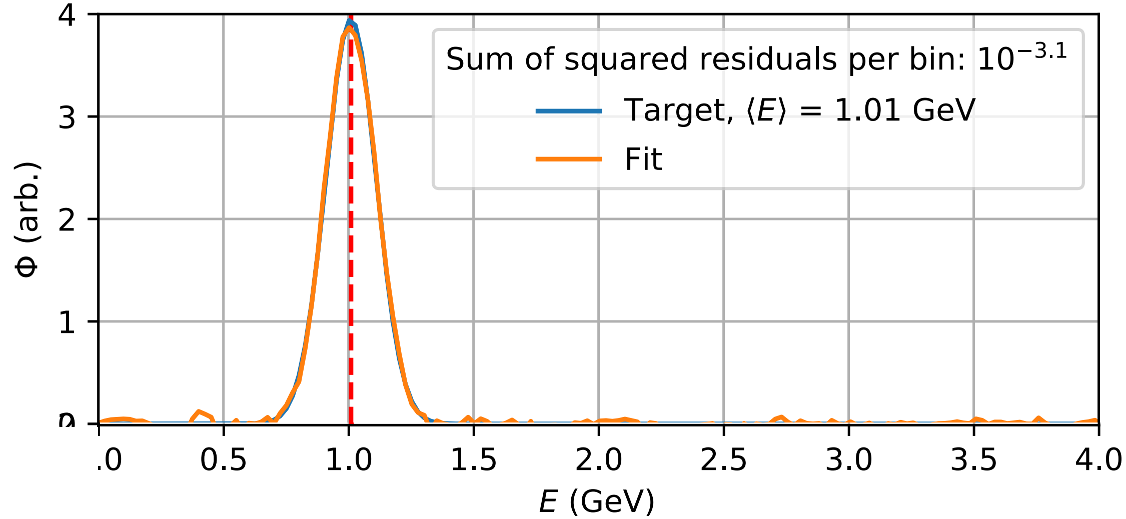
# Creating New $E_\nu$ Spectra

- 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!

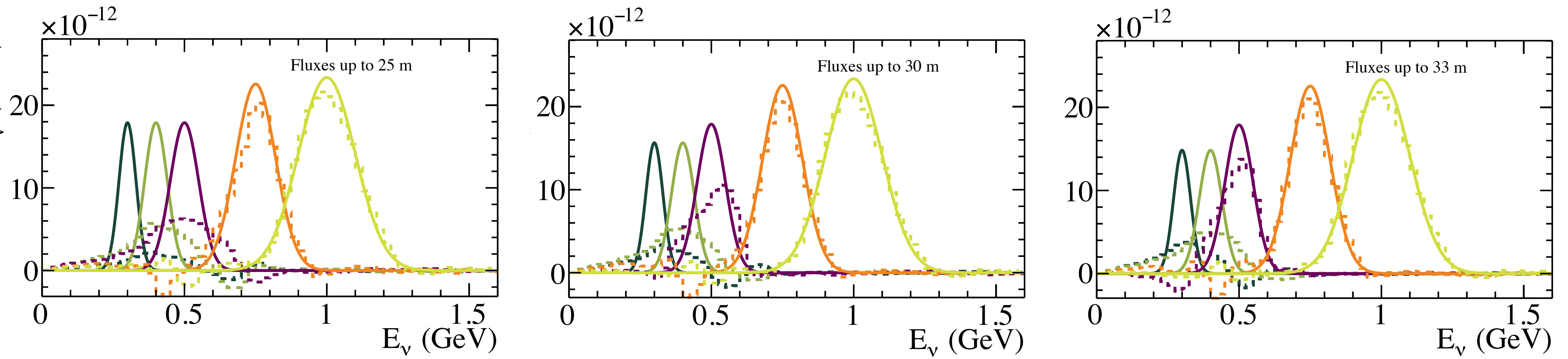



Gaussian Beams

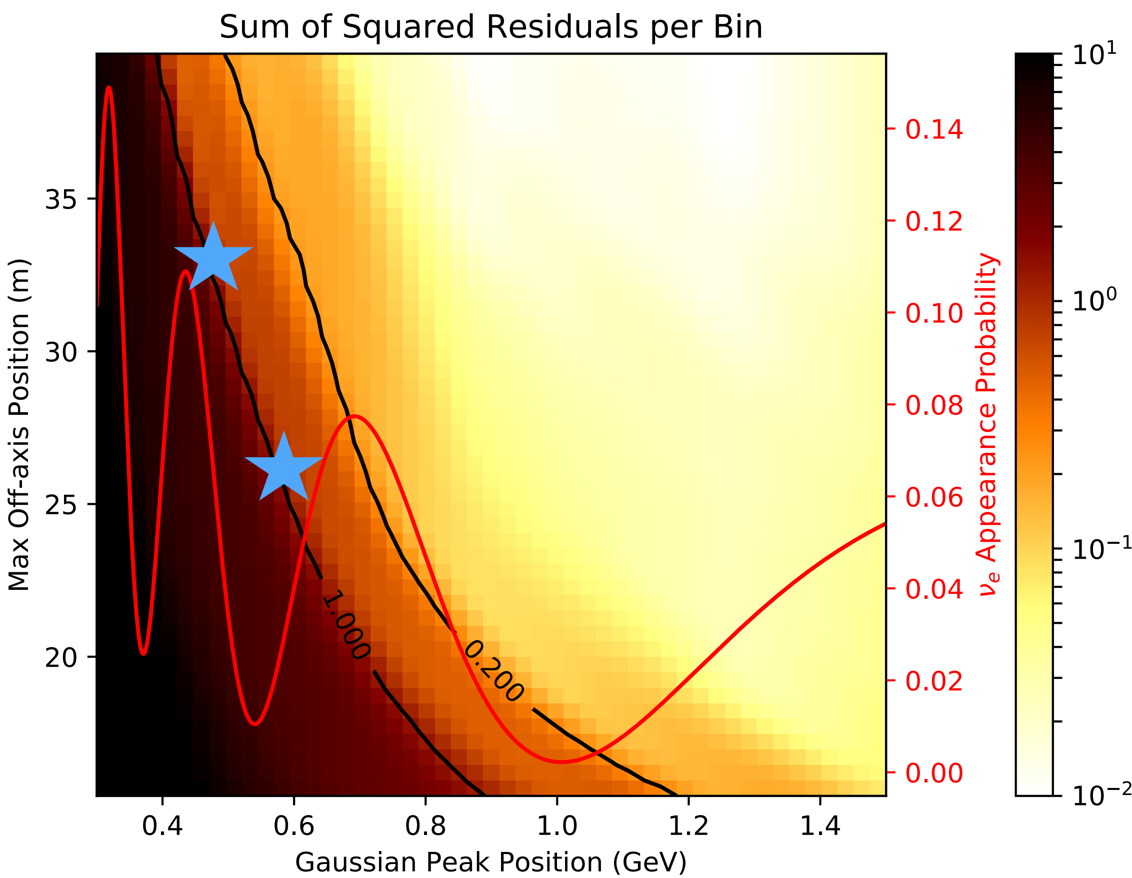



- Gaussian fluxes allow us to directly measure $E_{rec}$ for a given $E_{true}$
- Oscillated fluxes allow us to directly measure oscillated far detector observables at the near detector

# DUNE-PRISM Gaussian Fluxes



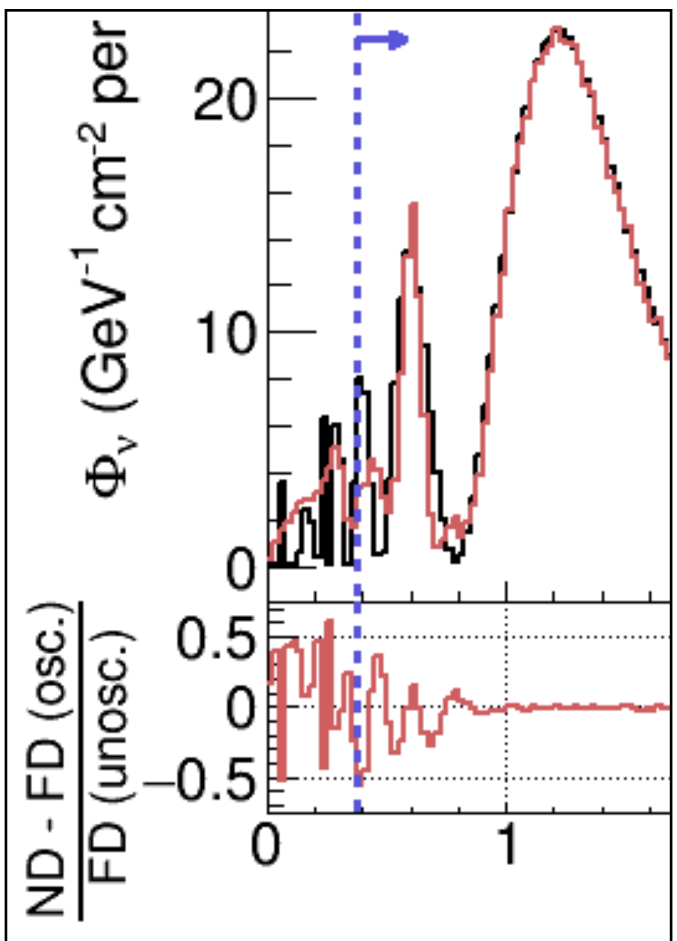

- To reach 500 MeV with DUNE-PRISM Gaussian fluxes, measurements up to 33 m off-axis are needed
  - ~Linear relationship between maximum off-axis position & minimum $1/E_\nu$ that can be constrained
- If maximum off-axis position is reduced to 27 m, low-$E_\nu$ reach is degraded to 600 MeV



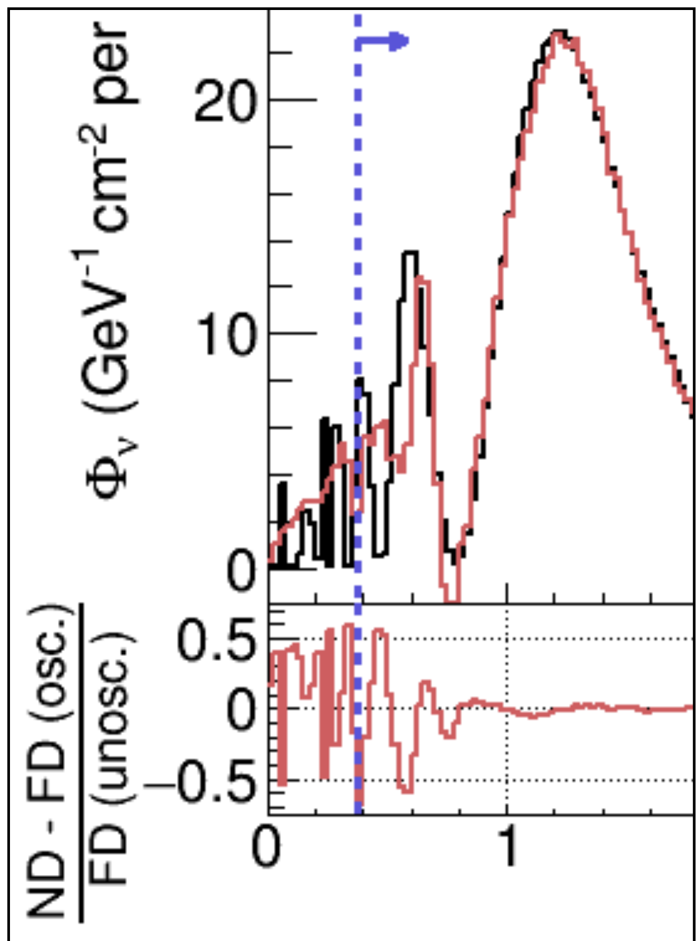
# Similar Story With Osc. Fluxes

- $\nu_\mu$ disappearance flux matching ($\sin^2\theta_{23}$=0.5 & $\Delta m_{32}^2$=2.2x$10^{-3}$ eV$^2$)
- Fit degradation seen as far off-axis angles are removed

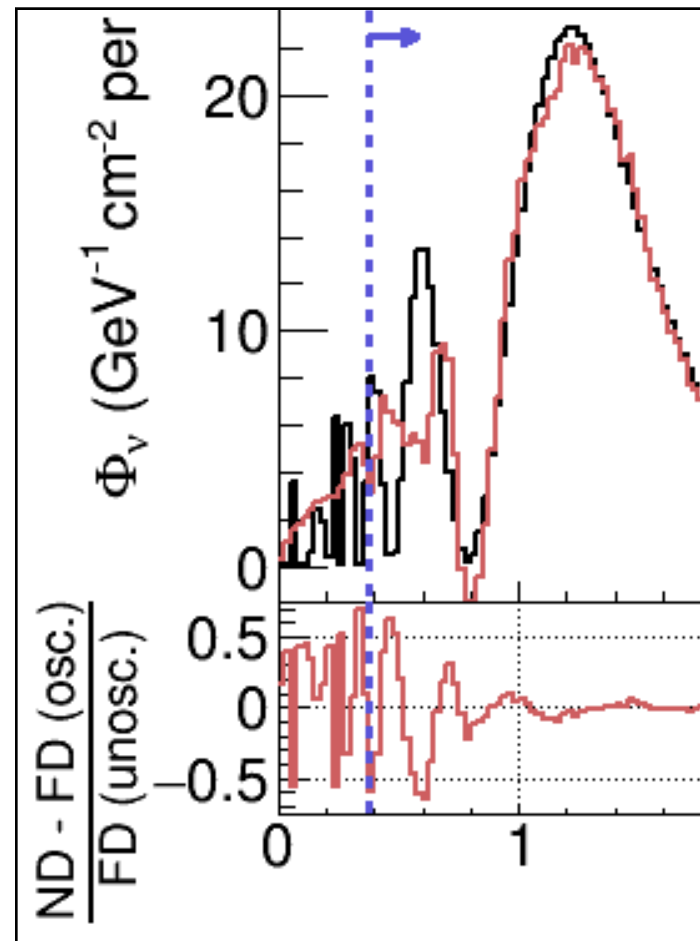
Up to 33m




Up to 30m




Up to 28m



# Summary

- Low energy provides additional useful oscillation physics to probe full PMNS picture (even if the CP constraint is somewhat smaller)

- At low energies, it is difficult to correctly sort Erec bin content into Etrue bins

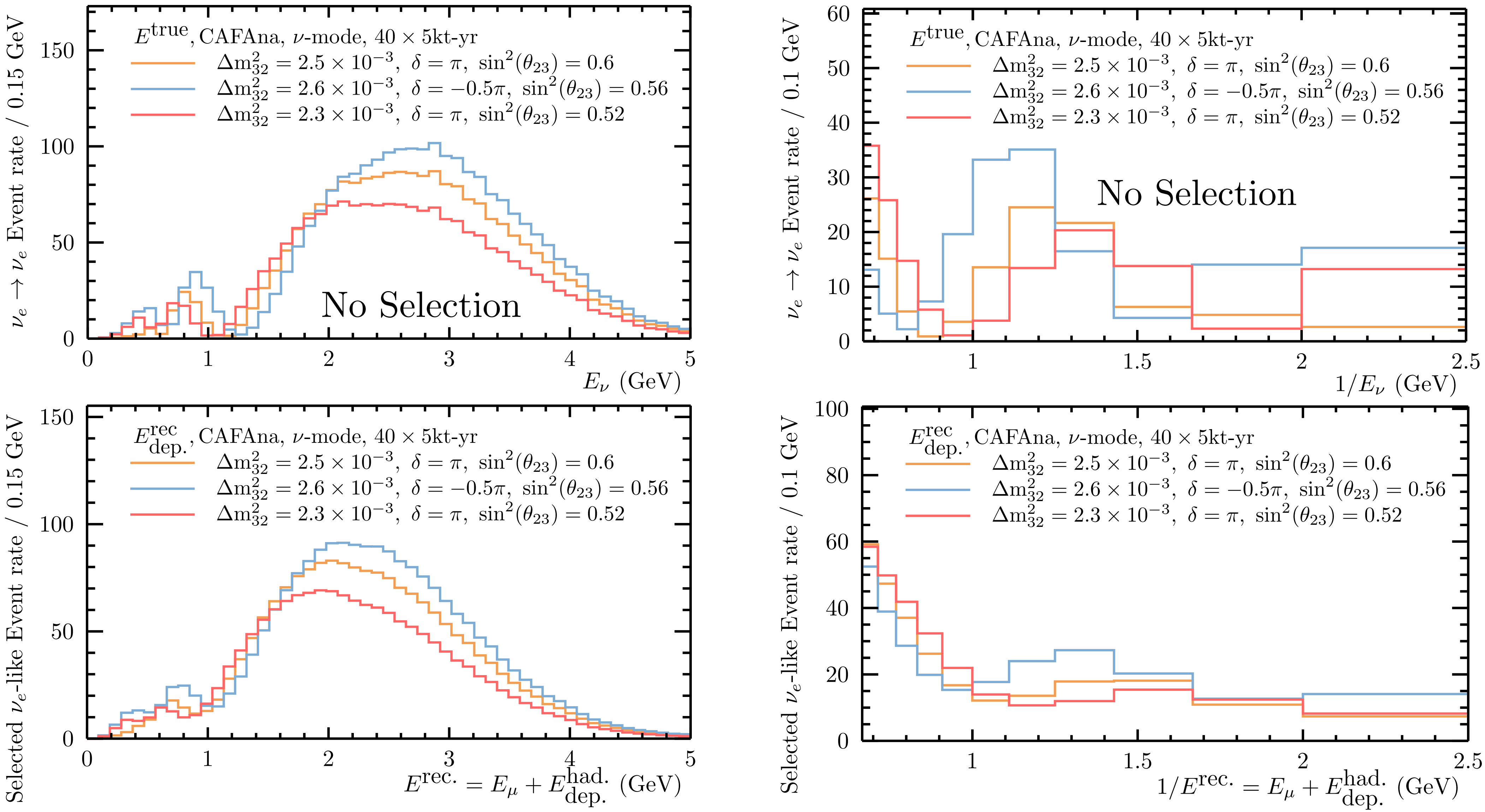
    - Due to Erec feed-down & rapidly varying cross section models

- DUNE-PRISM can provide a data-driven constraint of Etrue → Erec down to 500 MeV (600 MeV) with measurements up to 33 m (27 m) off-axis

- (Also other physics possibilities, e.g. dark photons or CPV in sub-GeV atmospheric neutrinos)

# Supplement

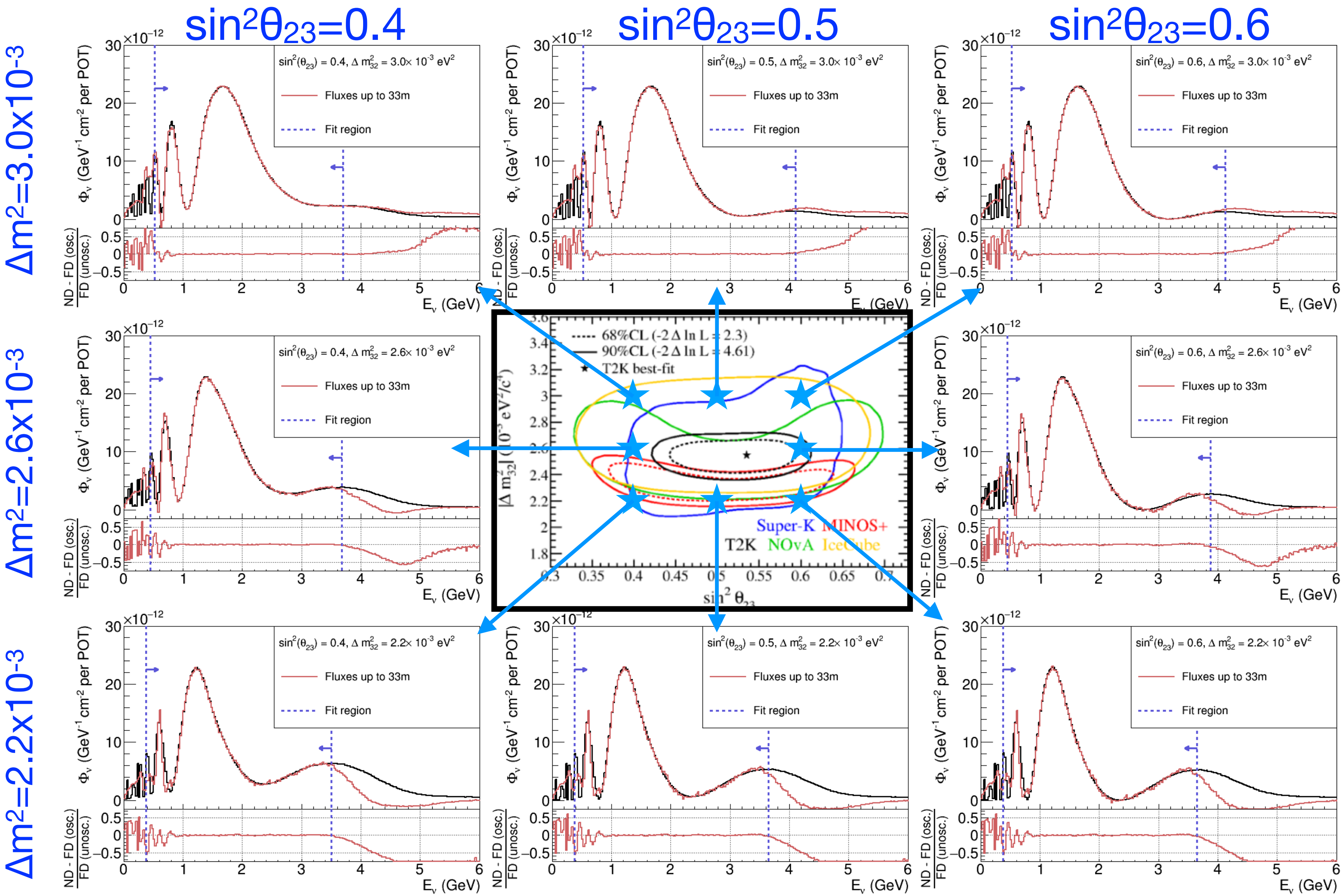
# Event Rates




- Unselected true Enu, and custom Erec with official selection

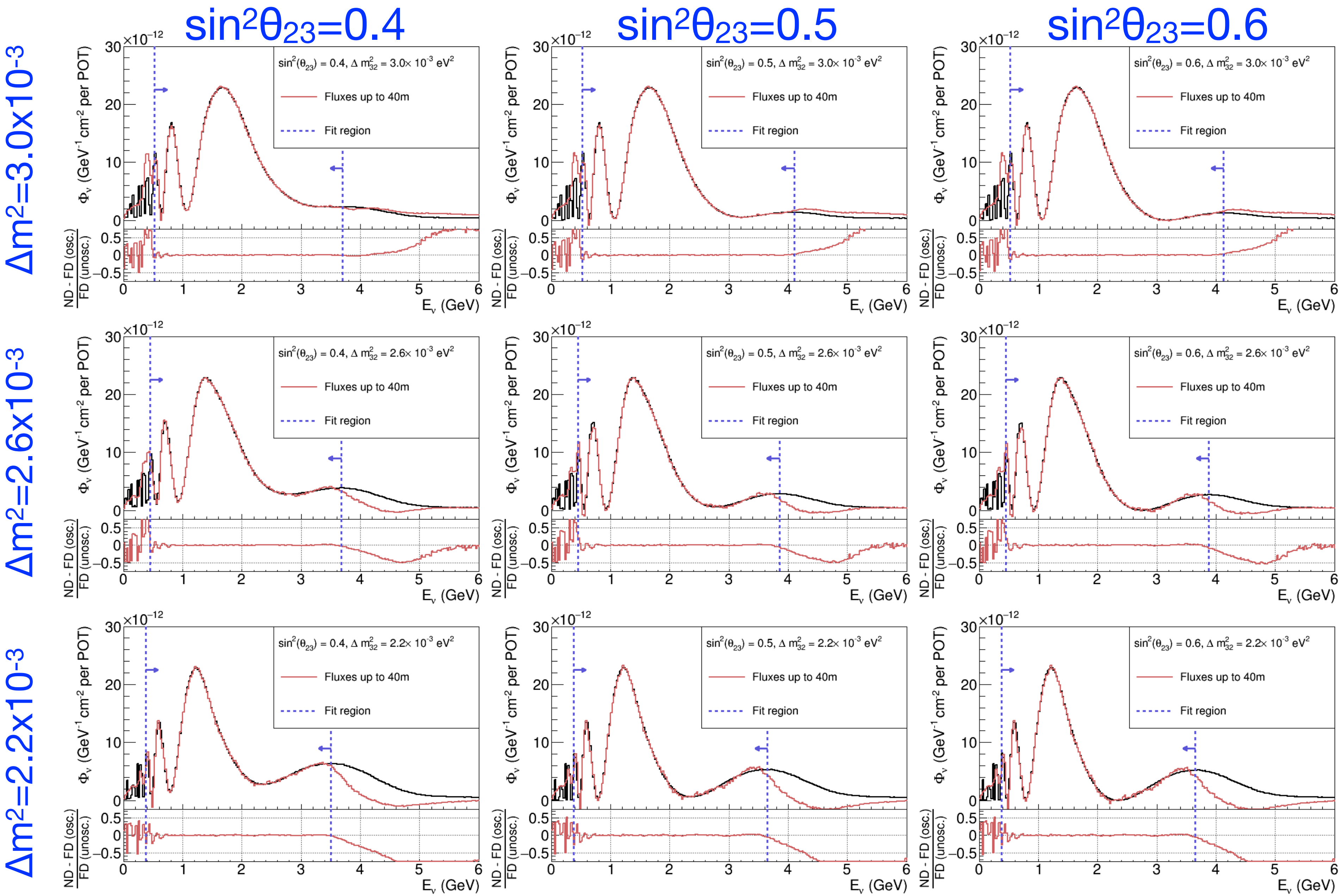
# Oscillated Flux Fits

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



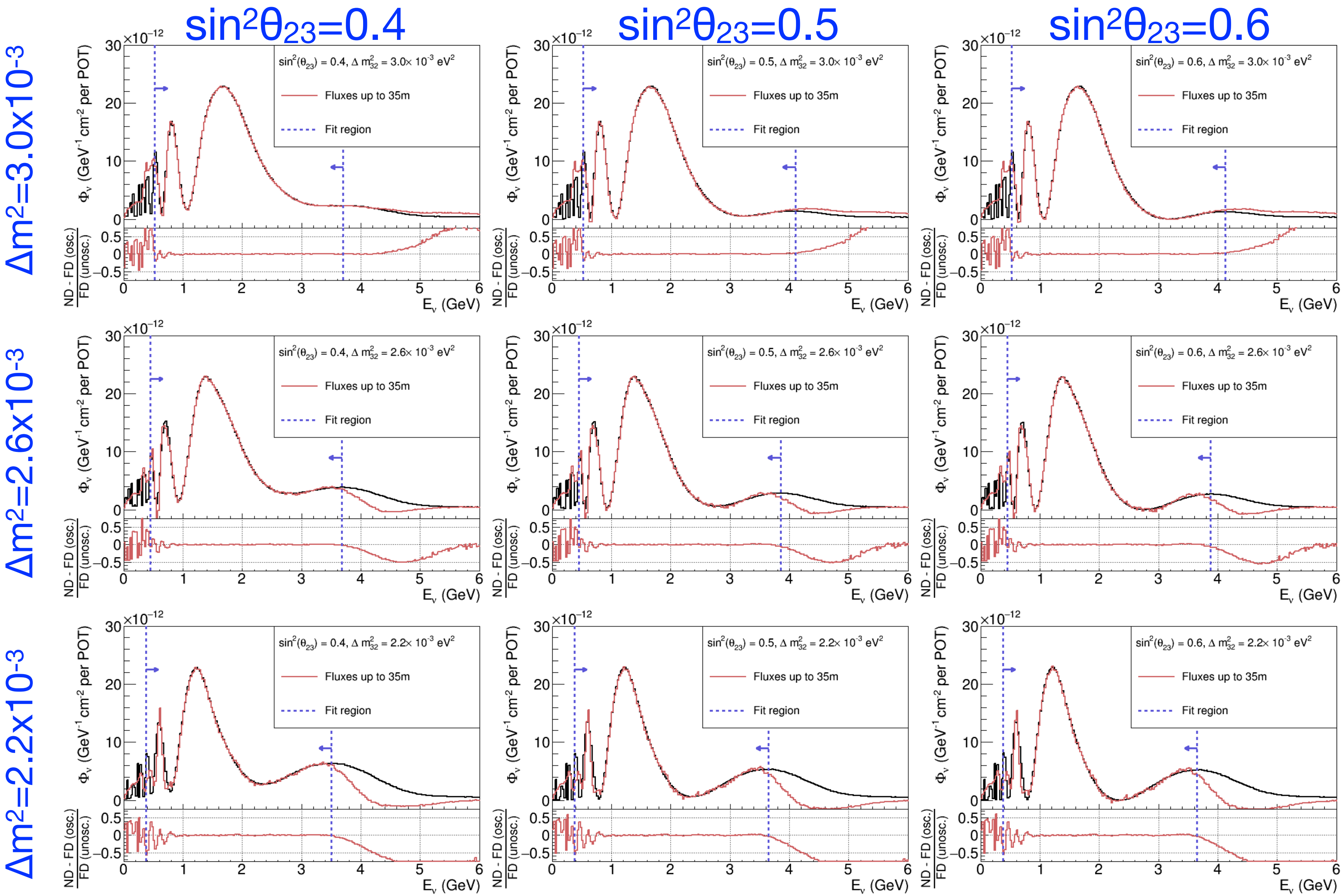
# Fluxes Up to 40 m Off-Axis

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



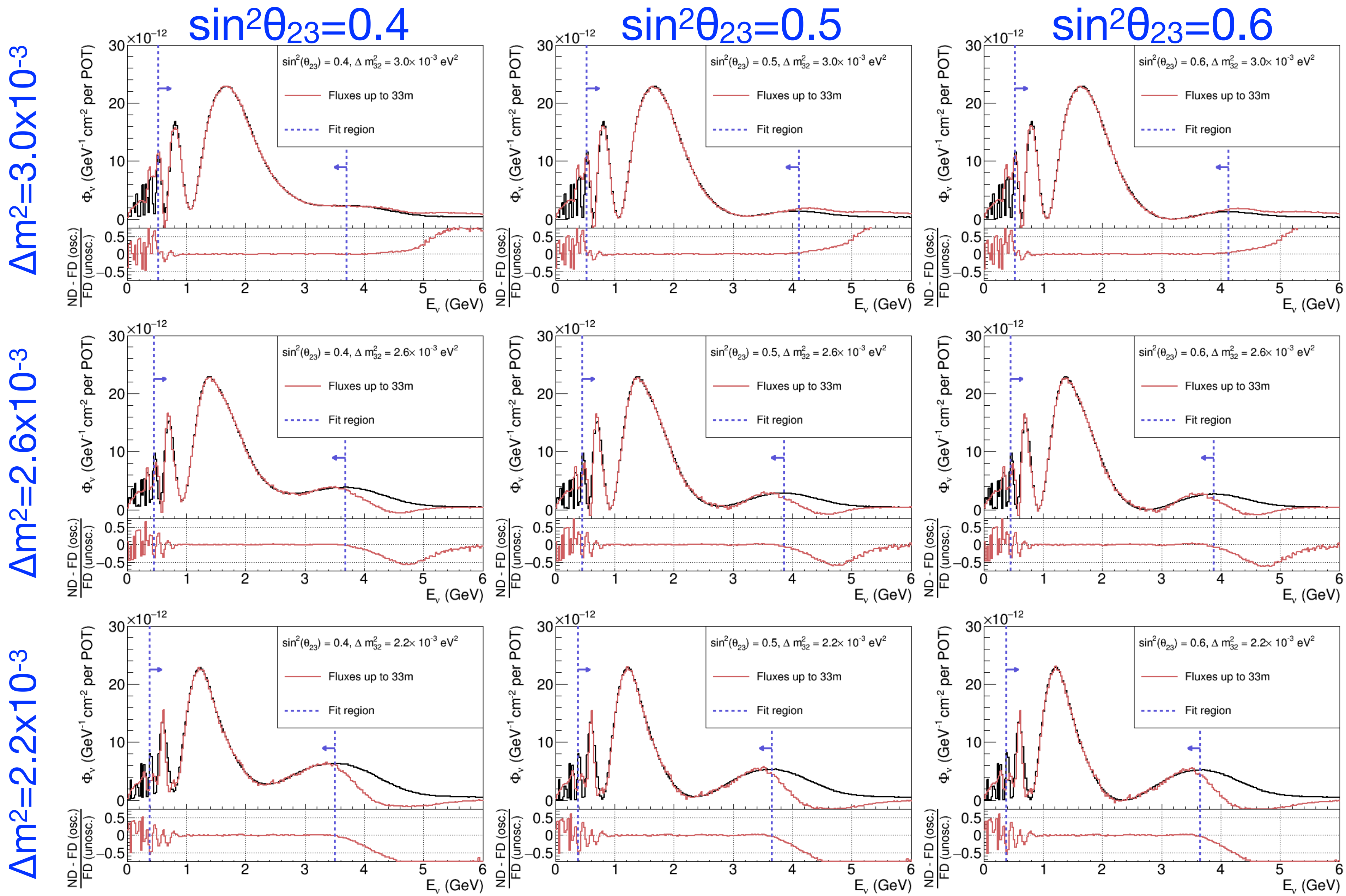
# Fluxes Up to 35 m Off-Axis

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



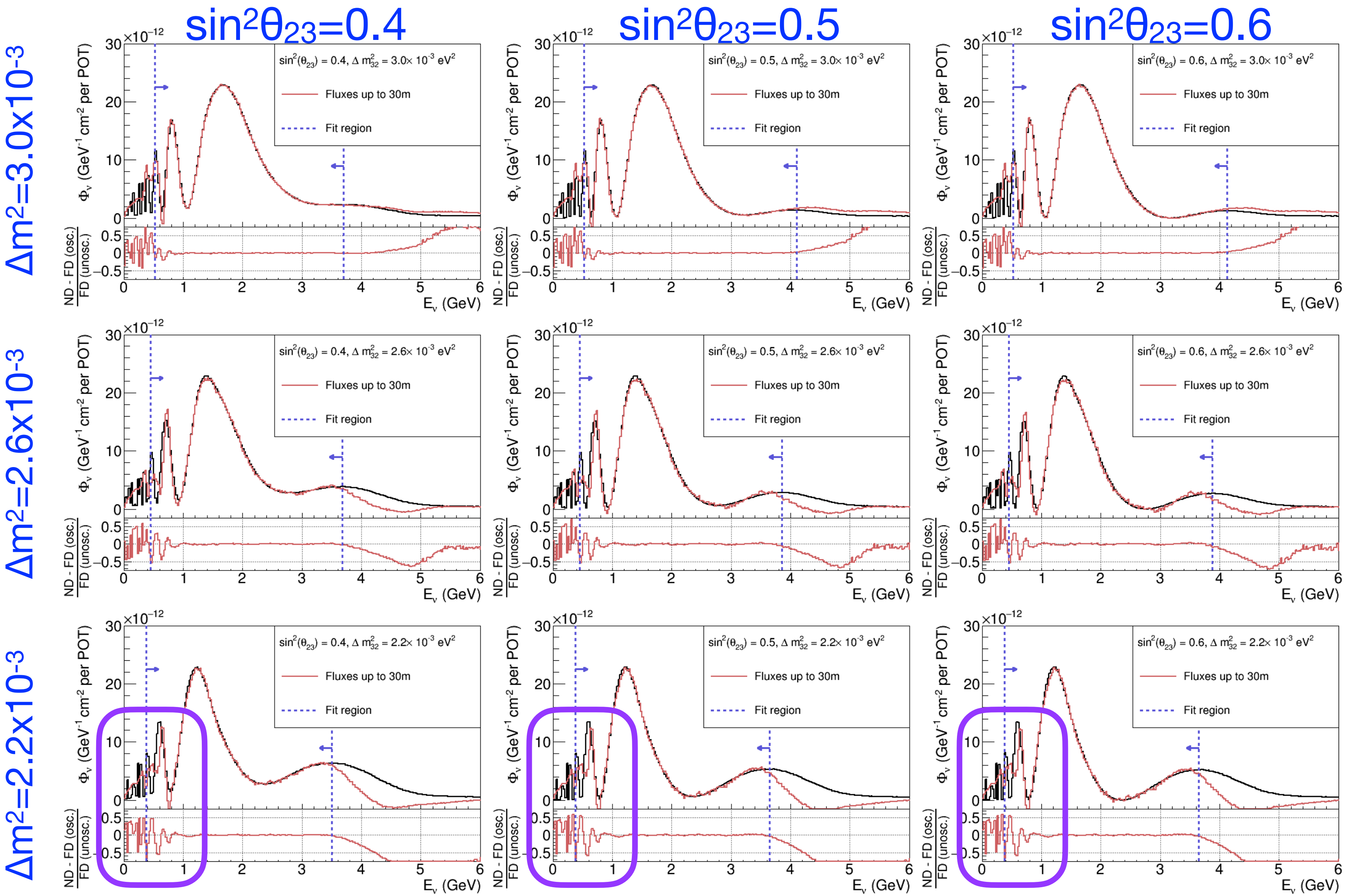
# Fluxes Up to 33 m Off-Axis

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



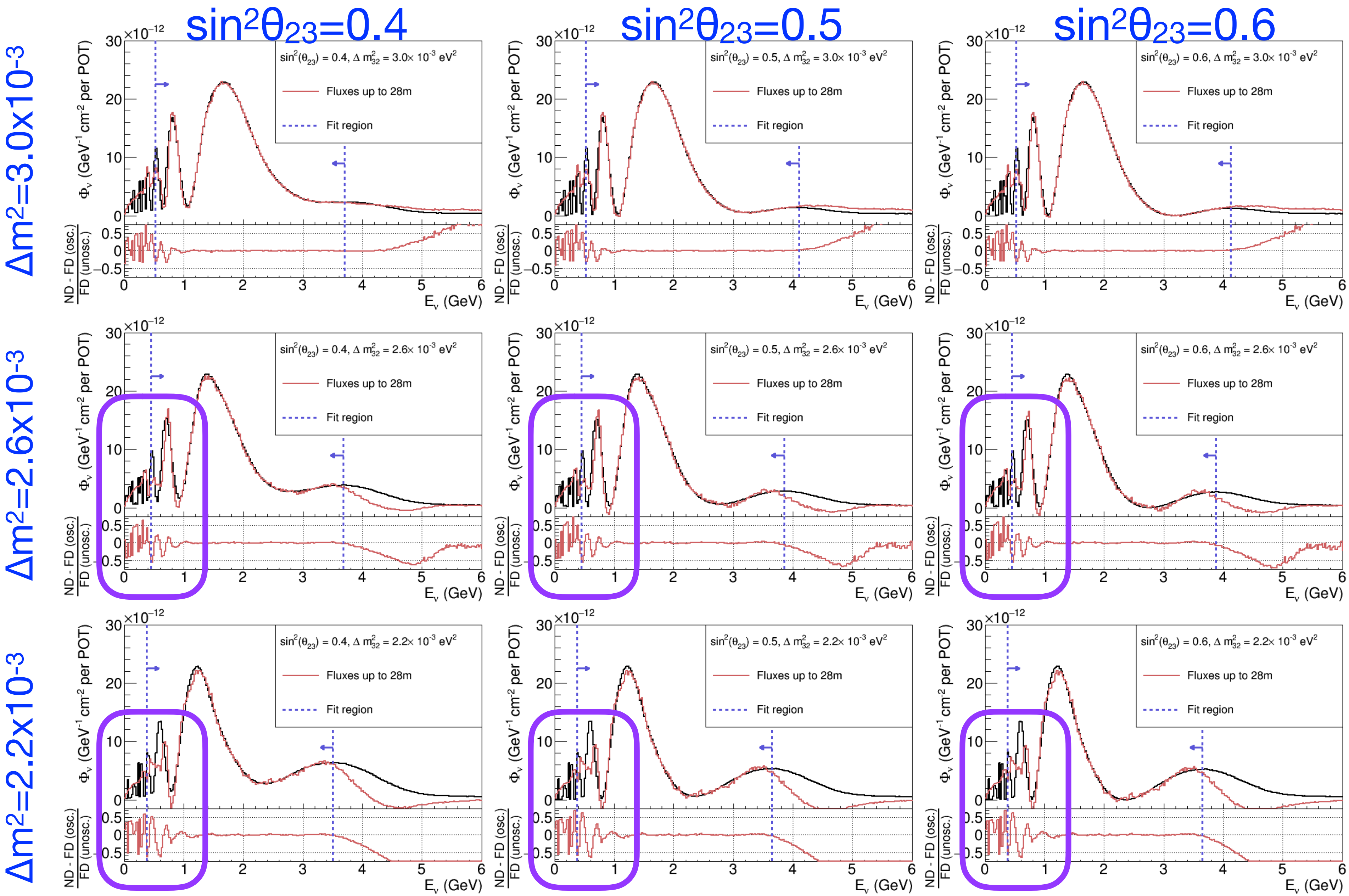
# Fluxes Up to 30 m Off-Axis

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

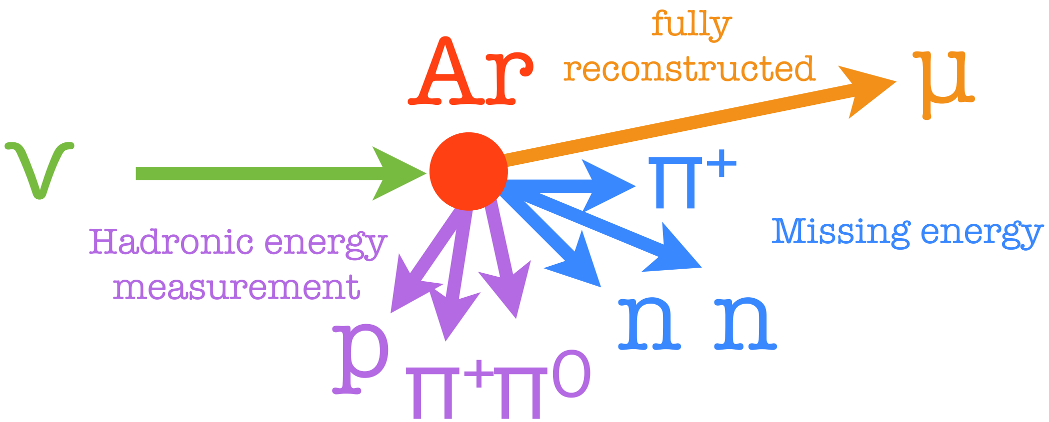


# Fluxes Up to 28 m Off-Axis

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

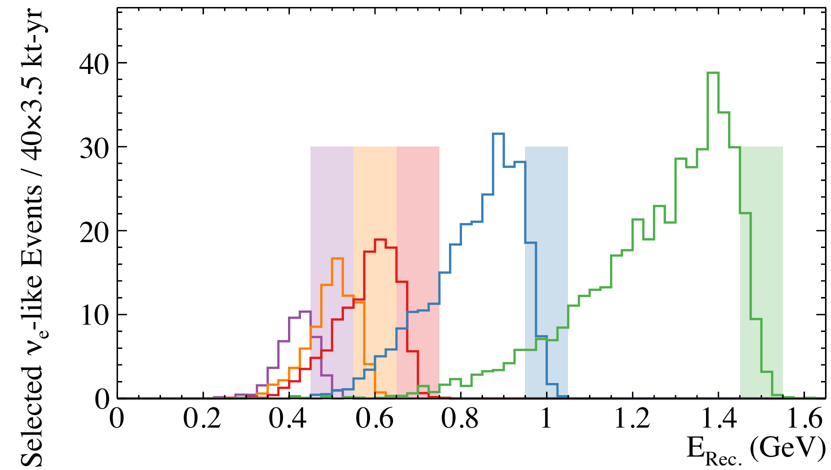


# The $E_\nu$ Measurement Problem




- Typically, $E_\nu$ 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

**$E_{rec}$ for Selected $E_{true}$ bins**




**MEC Cross Section**