# Near detectors in neutrino oscillation analyses and the PRISM technique

Precision
Reaction
Independent
Spectrum
Measurement

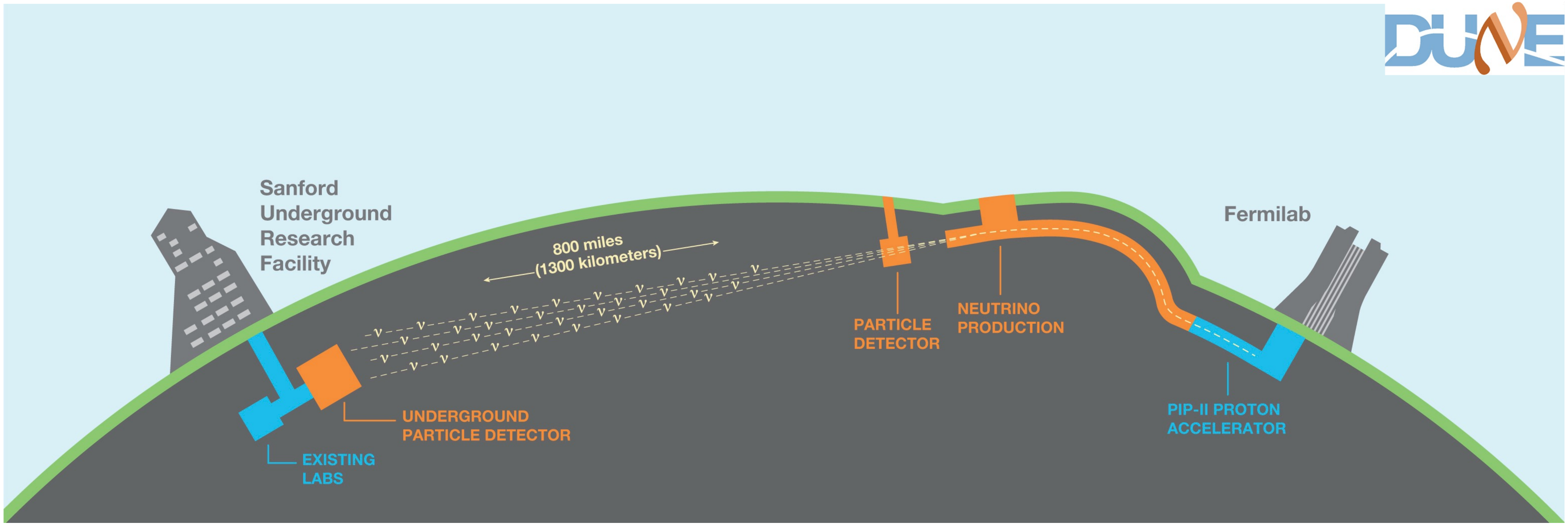
Ciaran Hasnip
EDSU Tool 2024
06/06/2024

# Introduction

- Entering a new **precision era** of **long-baseline (LBL) neutrino oscillation physics**
- Controlling **systematic uncertainties** is more important than ever
- Control **systematic uncertainties** with a **near detector (ND)**
- Precision Reaction Independent Spectrum Measurement (**PRISM**) technique **reduces dependence on the neutrino interaction model**
- I will focus mostly on **DUNE** – technique applied in **several experiments**

# Measuring Neutrino Oscillations

$$N_{osc}(E_\nu^{rec}) = \int dE_\nu^{true}\, \Phi(E_\nu^{true})\, \sigma(E_\nu^{true})\, P(\alpha \to \beta, E_\nu^{true})\, S(E_\nu^{true}, E_\nu^{reco})$$



# Measuring Neutrino Oscillations

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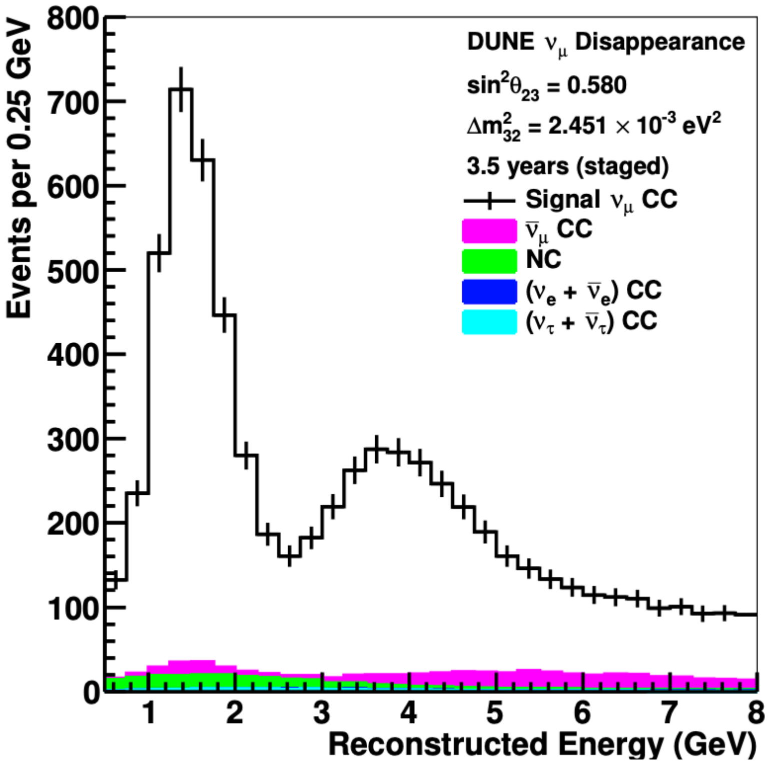
Measure oscillated event rate in reconstructed energy




*arXiv: 2002.03005 [hep-ex]*

# Measuring Neutrino Oscillations

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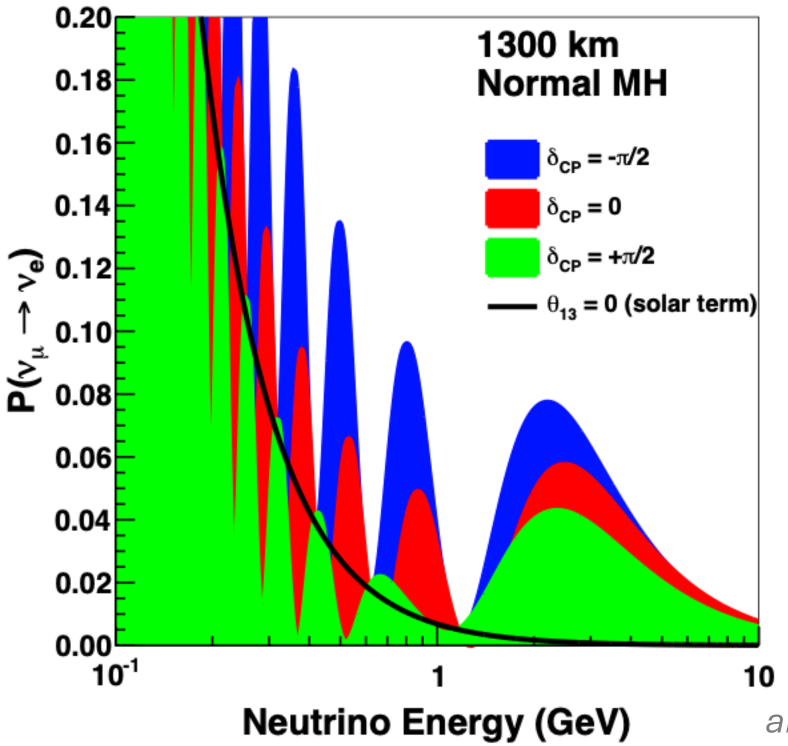



*arXiv: 2002.03005 [hep-ex]*

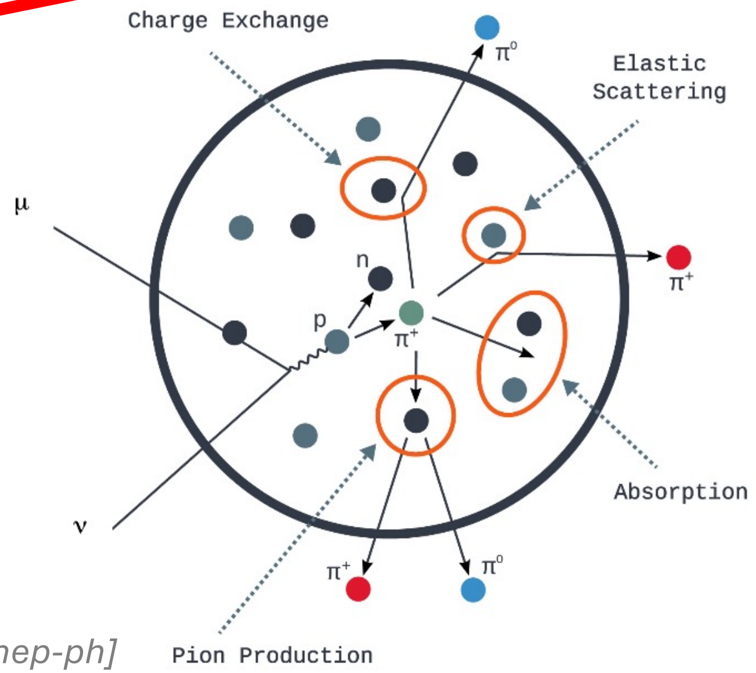
**Extract oscillation probability (function of true energy!)**

# Measuring Neutrino Oscillations

$$N_{osc}(E_\nu^{rec}) = \int dE_\nu^{true}\, \Phi(E_\nu^{true})\, \sigma(E_\nu^{true})\, P(\alpha \to \beta, E_\nu^{true})\, S(E_\nu^{true}, E_\nu^{reco})$$

**Success requires accurate models of:**

- Neutrino flux
- The detector
- **<u>Neutrino-nucleus cross section</u>**

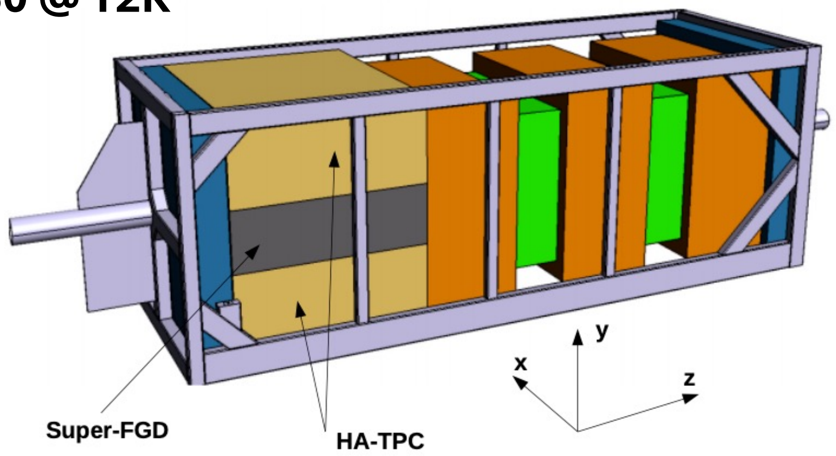



*arXiv:1706.03621v2 [hep-ph]*

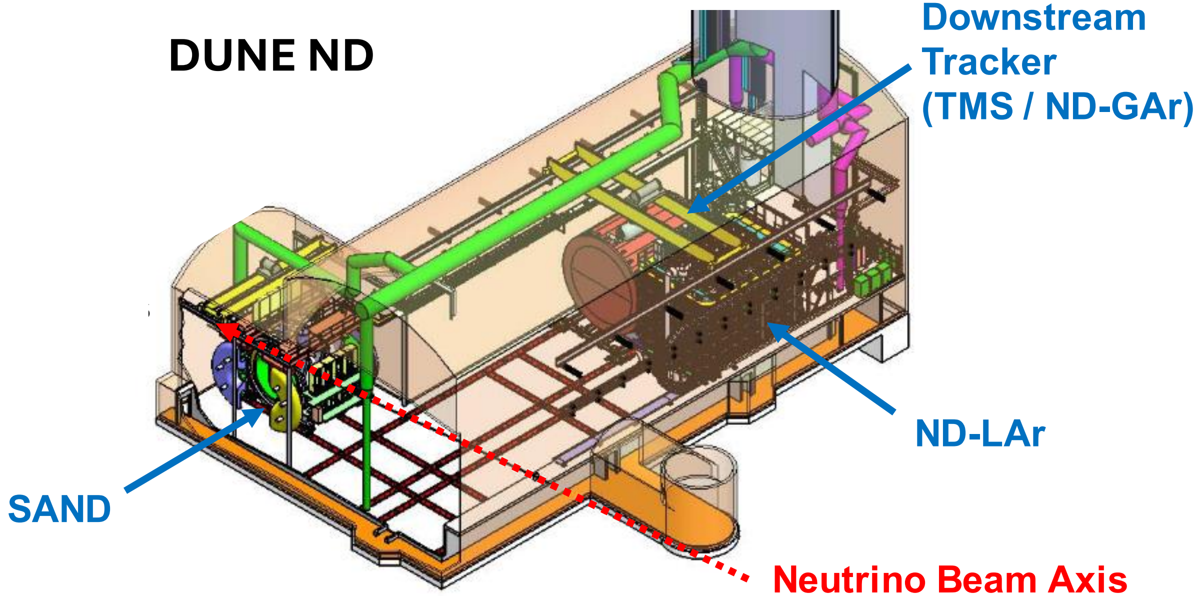
# Near Detectors (ND)

- Precise oscillation measurement
  - ➢ limited by systematic uncertainty in **cross section** and **flux** models
- Use a **near detector (ND)** to measure **unoscillated neutrinos** at **high rates**
  - ➢ Compare data to model prediction
  - ➢ Reduce uncertainties in $\boldsymbol{\Phi}$ & $\boldsymbol{\sigma}$ according to $\boldsymbol{\Phi \times \sigma}$ measurement
  - ➢ Extrapolate constrained $\boldsymbol{\Phi \times \sigma}$ model to FD for oscillation measurement

**ND280 @ T2K**



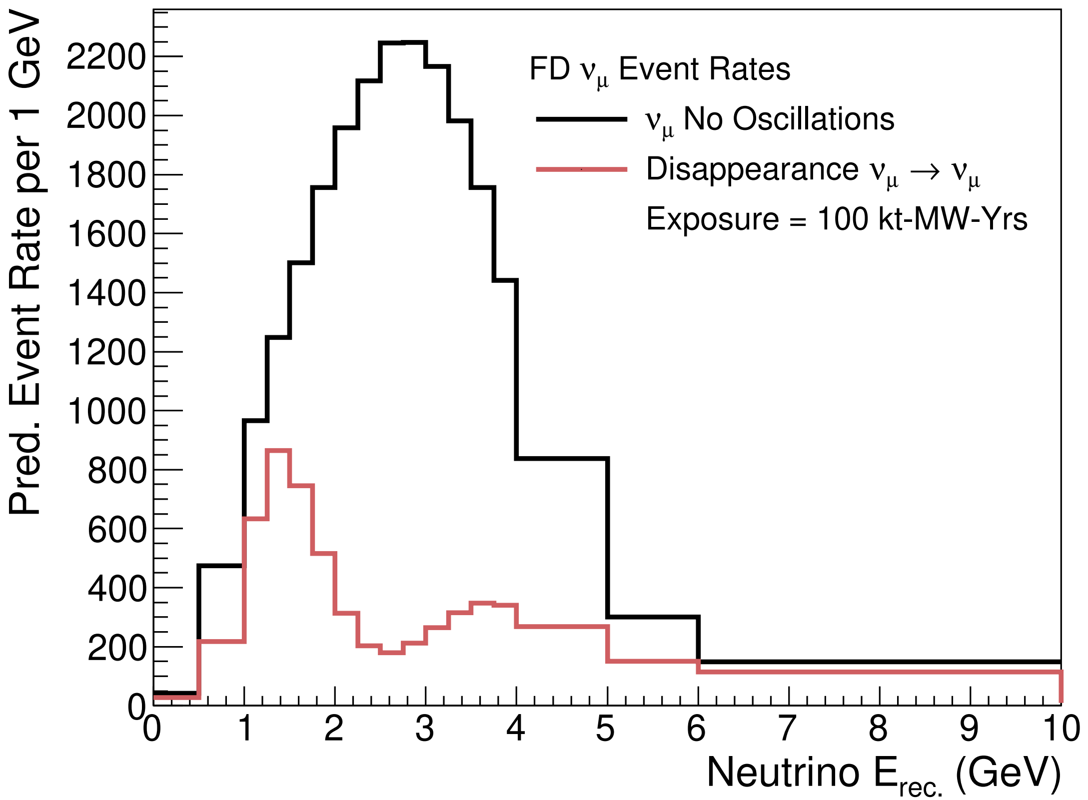

**DUNE ND**



# Near Detectors (ND)

BUT ...

- Very **different $E_\nu$ spectra** in the **Near/Far** detectors due to **oscillations** (and detector differences)
  - ➢ We constrained $\mathbf{\Phi}\times\boldsymbol{\sigma}$ - will our $\boldsymbol{\sigma}$ model be correct in new flux $\mathbf{\Phi_{osc}}$?
- Plenty of ways to mis-model $\boldsymbol{\sigma}$:
  - ➢ Unobserved **neutral hadrons**, **final state interactions** and other complex **nuclear effects**

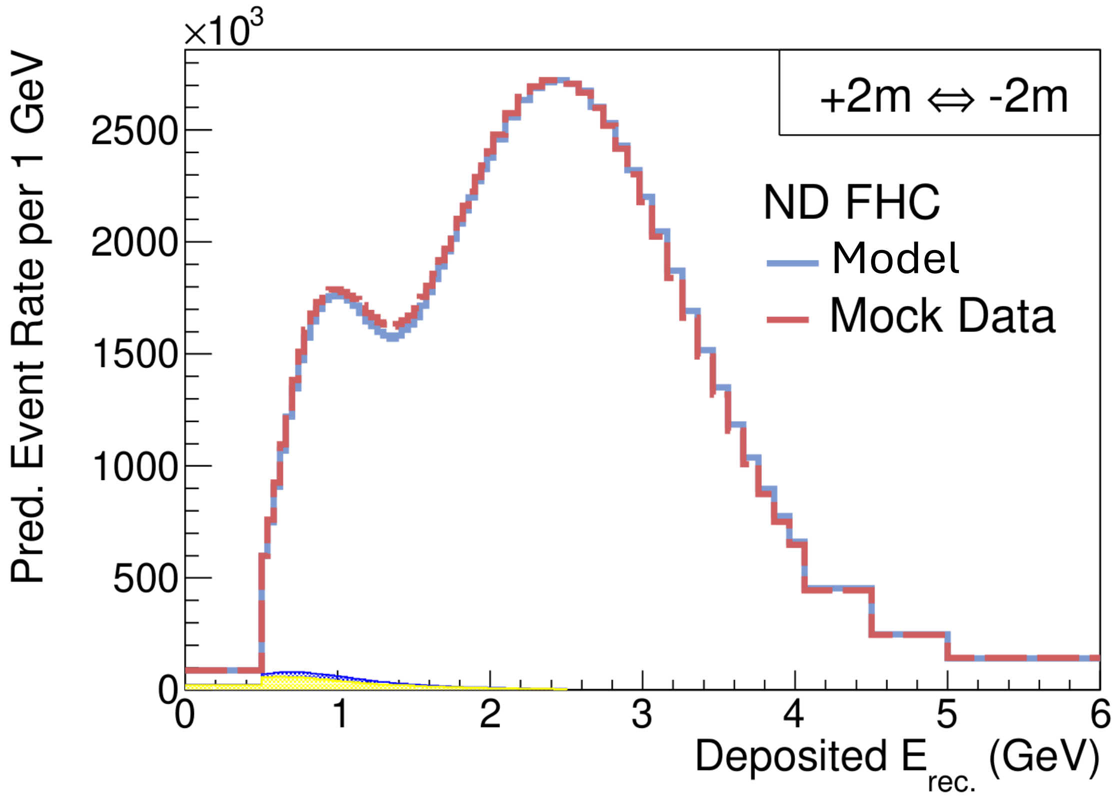


# What happens if the neutrino interaction model is wrong?

## An example from DUNE

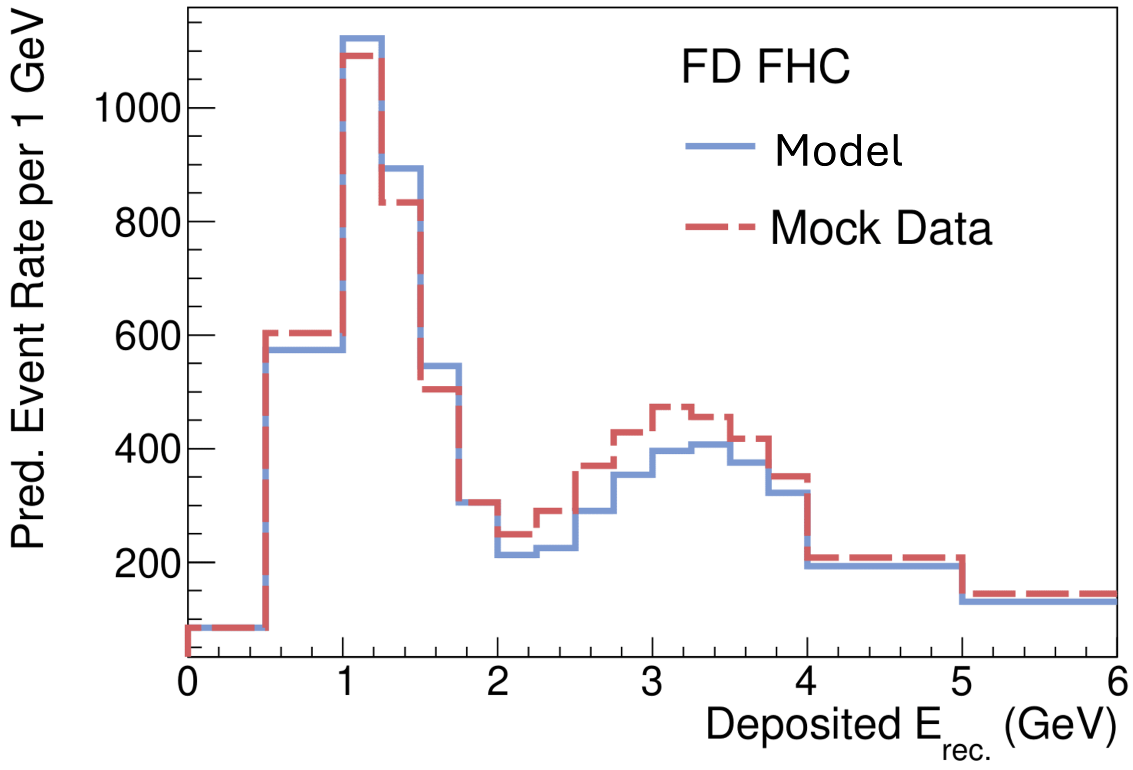
# What Can Go Wrong?

- What if the **interaction model** is **wrong** and you did not realise?
- Possible to have a **good fit** at the **ND** but **$E_{true}$ → $E_{obs}$** model is wrong
- Case Study:
  - Move **20%** of **proton energy** to (unobserved) neutrons
  - Additional (but **incorrect**) **changes** to ND model to make ND model match data



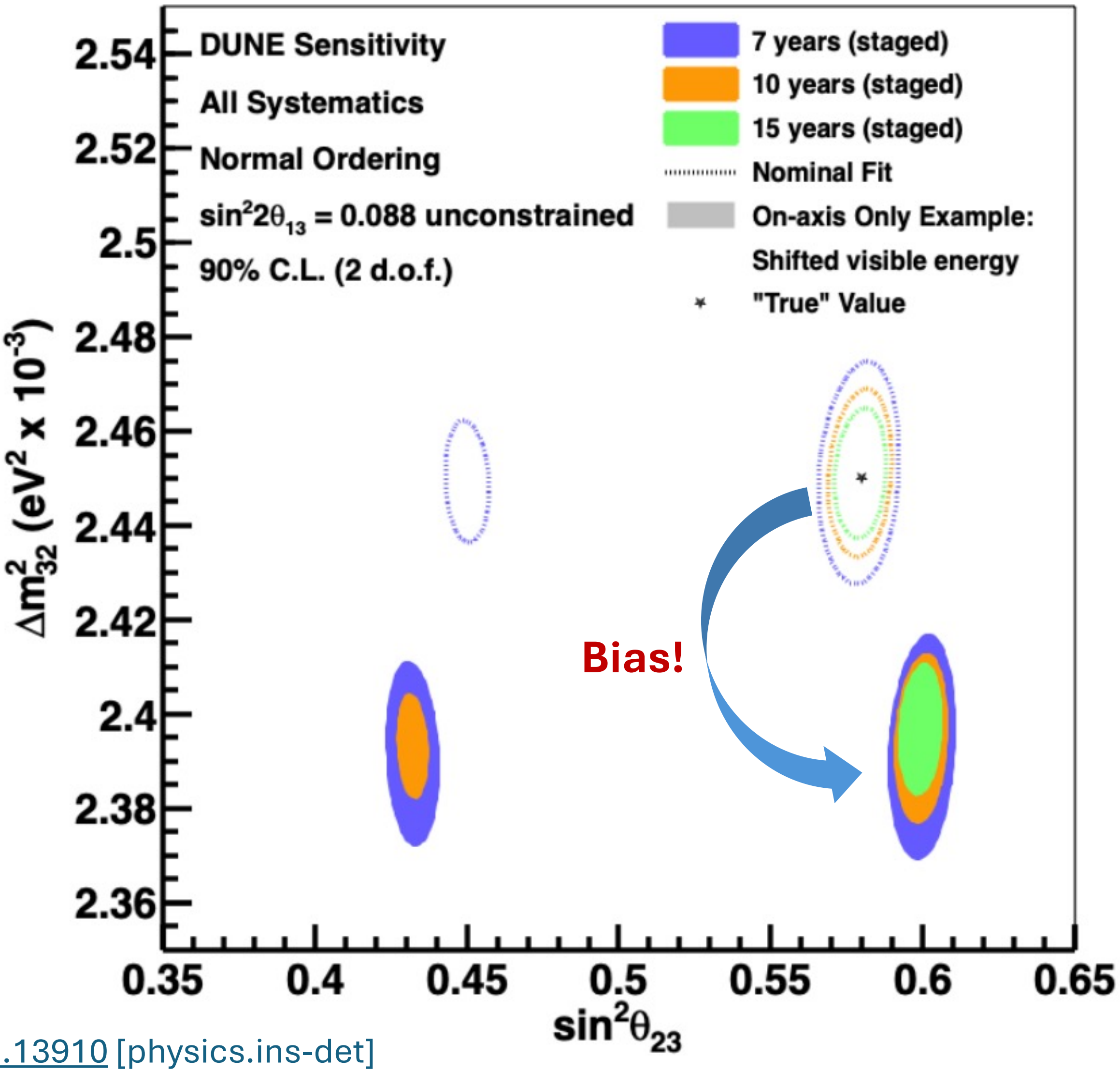
# What Can Go Wrong?

- Possible to have a **good fit** at the **ND** but **$E_{true}$ → $E_{obs}$** model is wrong
- Case Study:
  - In the **oscillated flux** at the **FD** agreement between MC and data **bad**
  - Think our model is good – **alter the oscillation parameters** to achieve a good fit



# What Can Go Wrong?

- Possible to have a **good fit** at the **ND** but **$E_{true}$ → $E_{obs}$** model is wrong
- A 'traditional' on-axis oscillation analysis could get **biased contours**
  - And we would **not know it**!



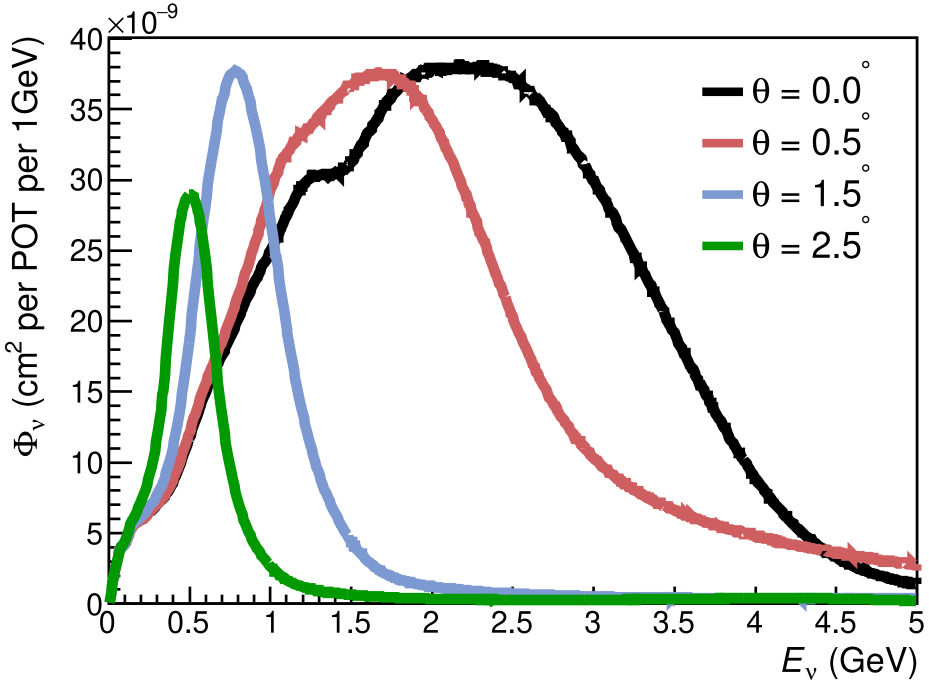

arXiv:2103.13910 [physics.ins-det]

Precision
Reaction
Independent
Spectrum
Measurement

# What is the PRISM technique and how can it help?

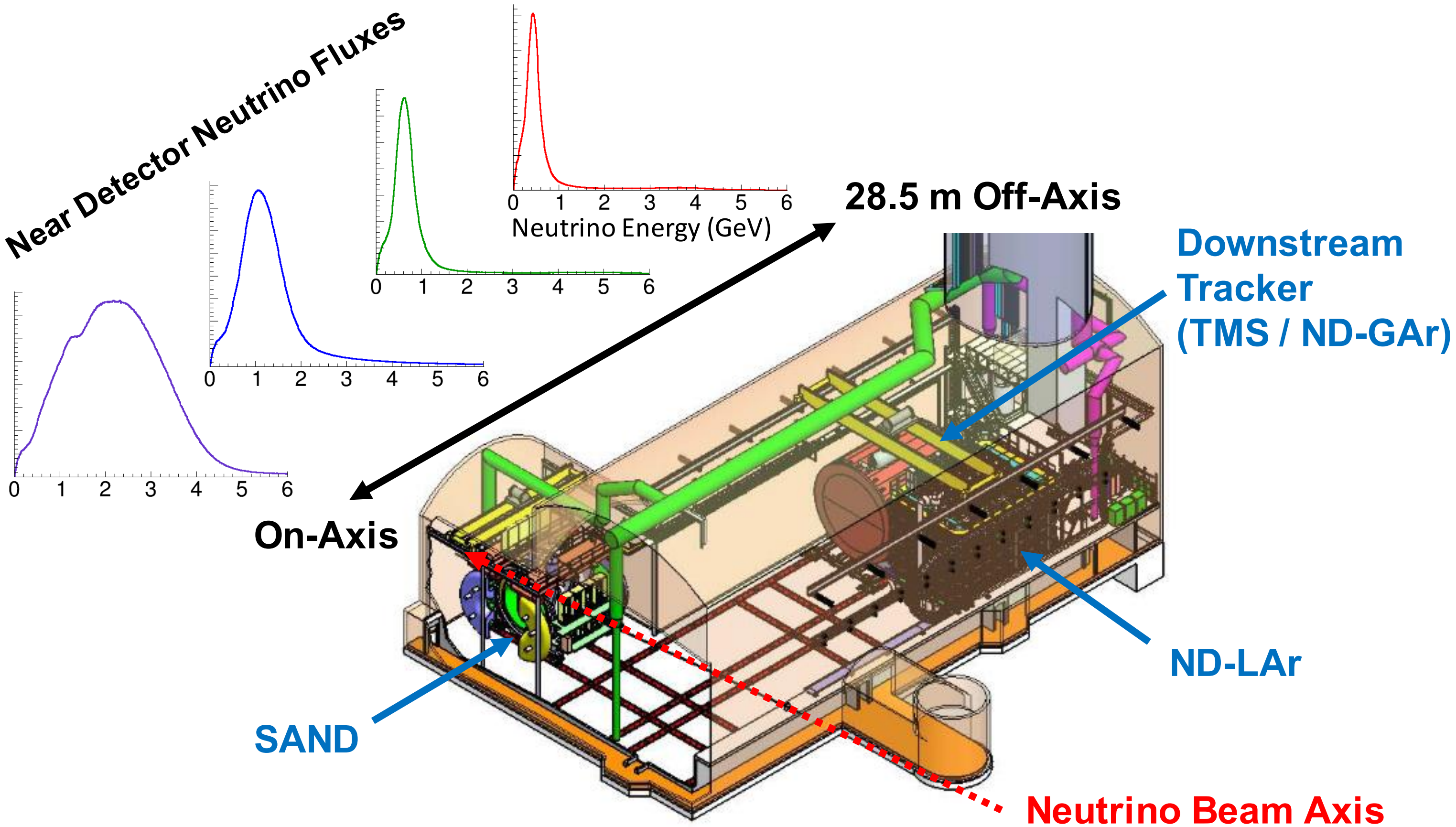
# Precision Reaction Independent Spectrum Measurement (PRISM)

- The **bias** was **not spotted** because we only tested our **σ model** in a **single flux** – what if we had **many fluxes**?
- Neutrino beam “Off-Axis Effect” (used by T2K and NOvA) - neutrino flux **narrows** and peaks at **lower energies** further **off-axis**



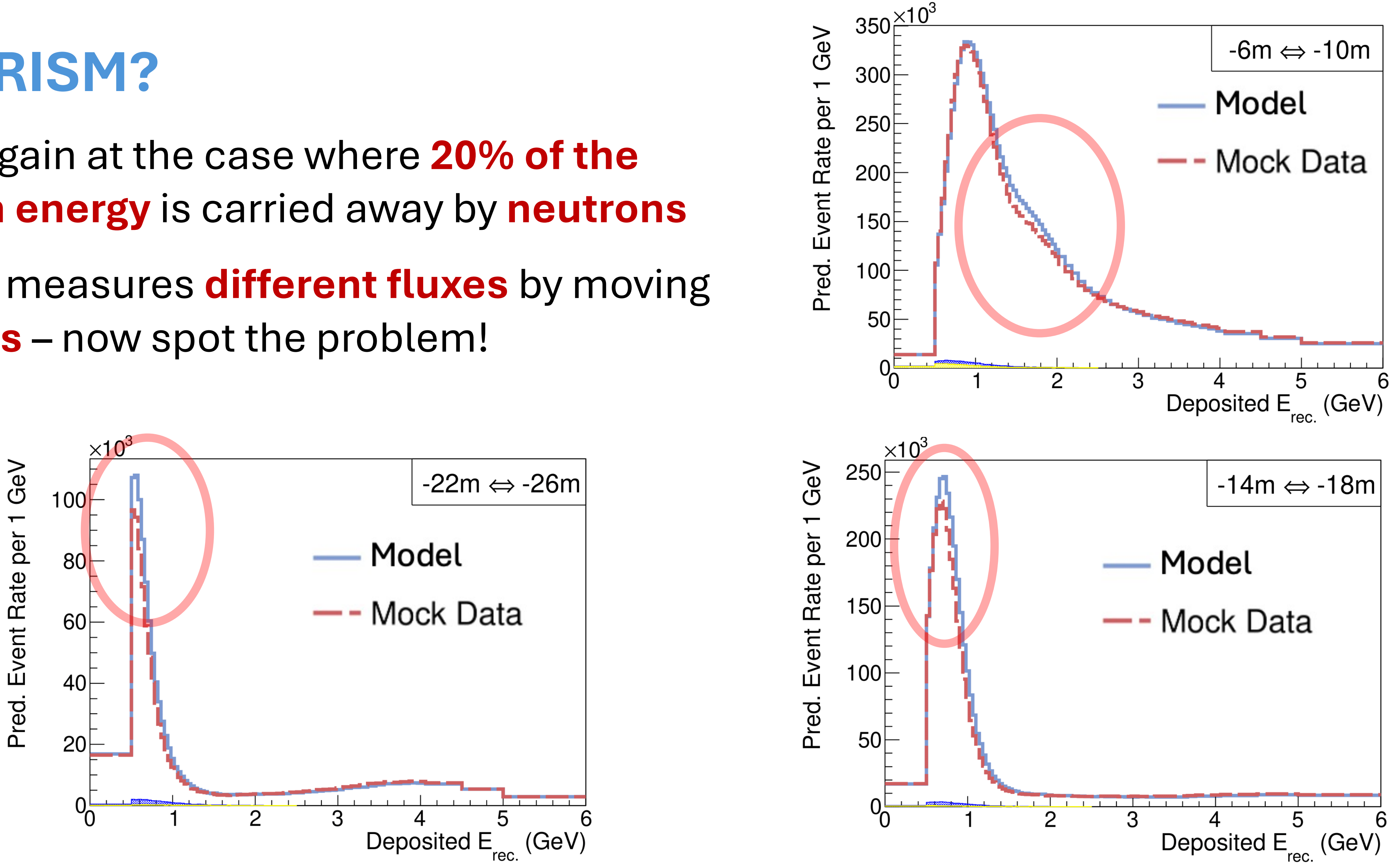
# DUNE-PRISM

- DUNE near detector **moves off axis**
- Measure **different neutrino fluxes**
- ND-LAr is a LArTPC – **liquid argon** (LAr) like DUNE far detector!
- Can we spot cross section mis-modelling with these extra fluxes?



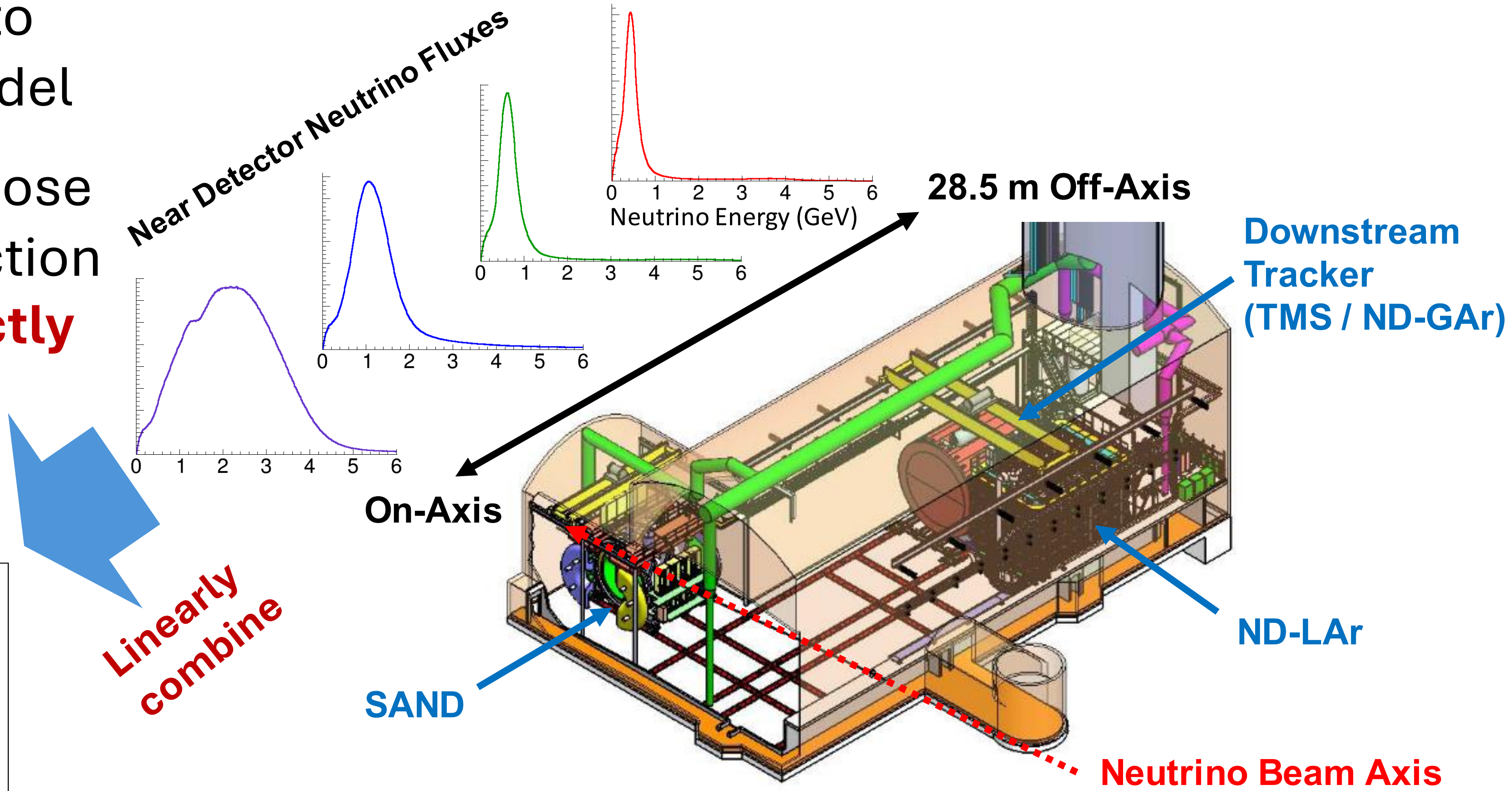
# Why PRISM?

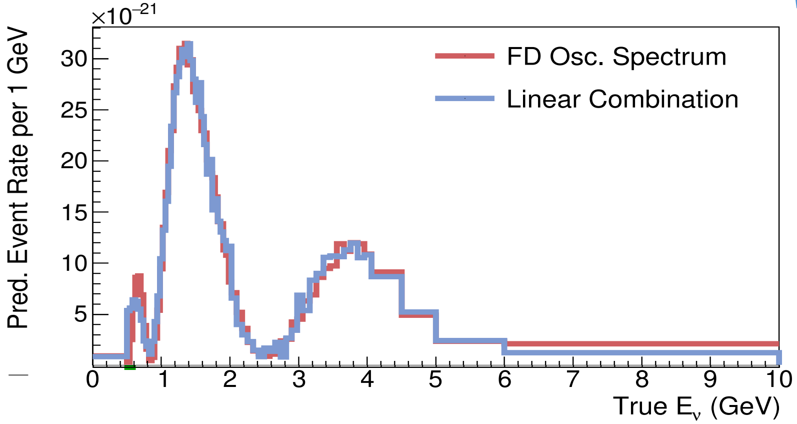
- Look again at the case where **20% of the proton energy** is carried away by **neutrons**
- PRISM measures **different fluxes** by moving **off-axis** – now spot the problem!



# PRISM as an Oscillation Analysis

- Could use off-axis fluxes to better constrain our **σ** model
- OR… **linearly combine** those fluxes to produce a prediction of the **FD event rate directly from ND data**



# PRISM as an Oscillation Analysis

- Could use o
  better const
- OR… **linear**
  fluxes to pro
  of the **FD ev**
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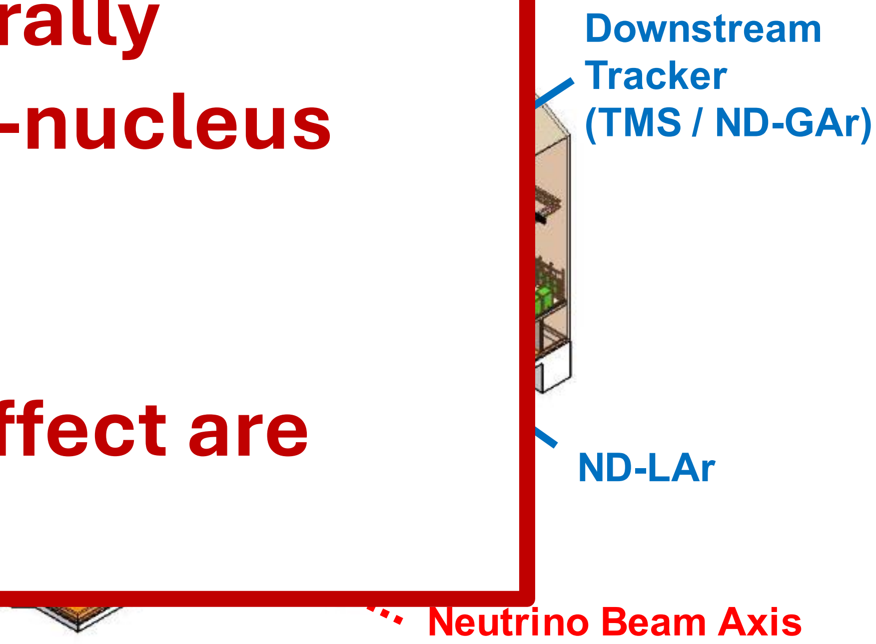
**Linear combination oscillation analysis:**

**A data-driven prediction naturally includes the correct neutrino-nucleus interaction physics**

**Any <u>unknown</u> cross section effect are automatically accounted for!**

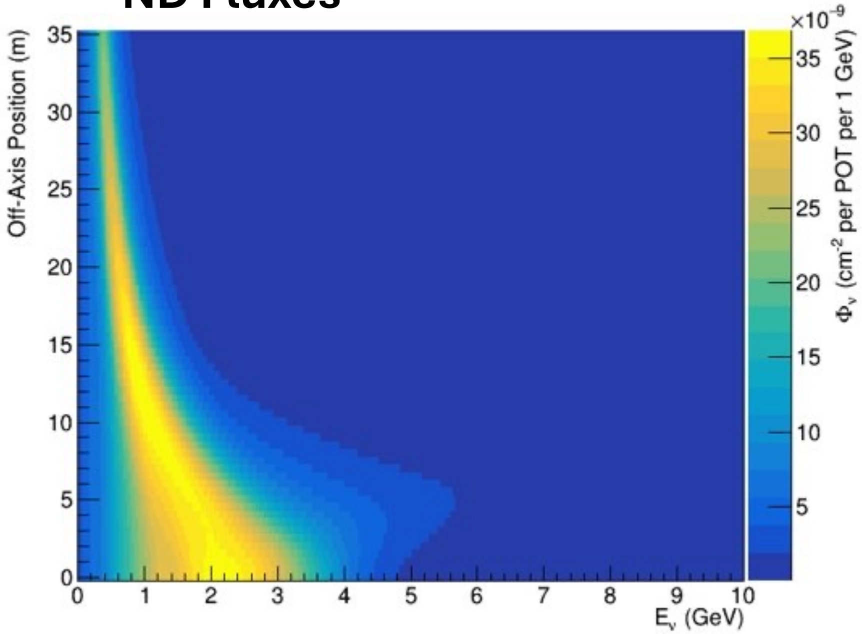



# PRISM as an Oscillation Analysis

- Match the ND $\nu_\mu$ fluxes to the FD oscillated flux
- Just solving a **linear algebra problem** with the flux
- Mathematically, this is **N***c* = *F* – we solve for *c*!

N.B. we can match to **any target shape**

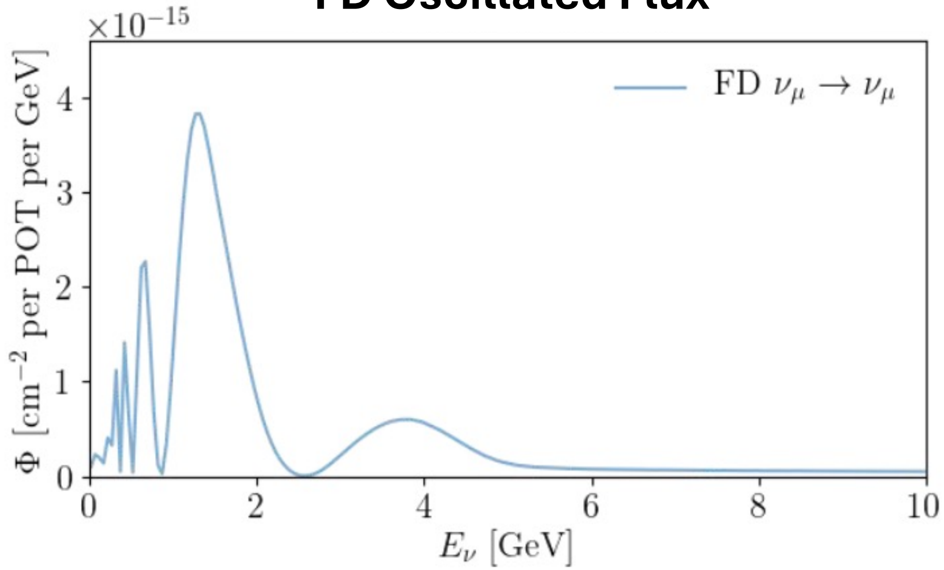
**ND Fluxes**




**some vector, c**

=

**FD Oscillated Flux**




arXiv:2103.13910 [physics.ins-det]

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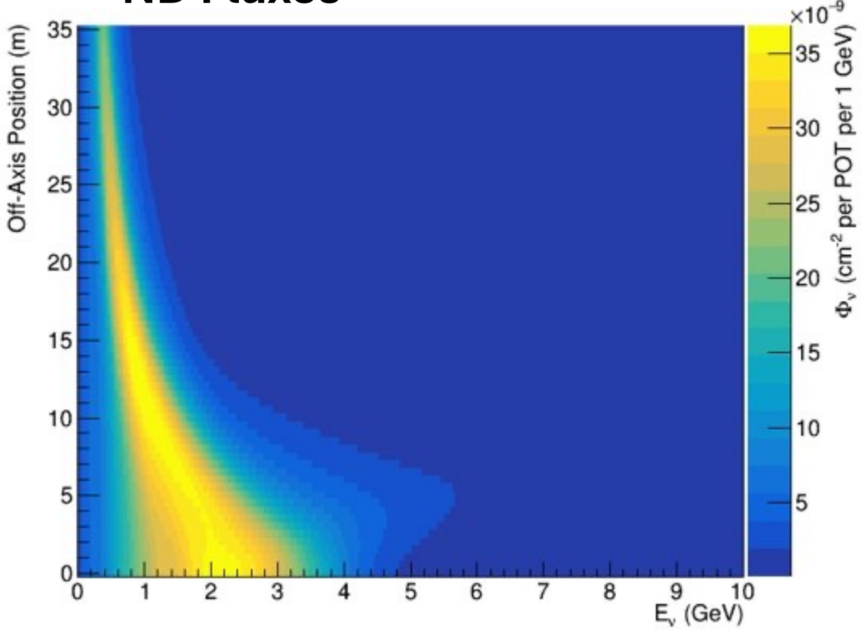
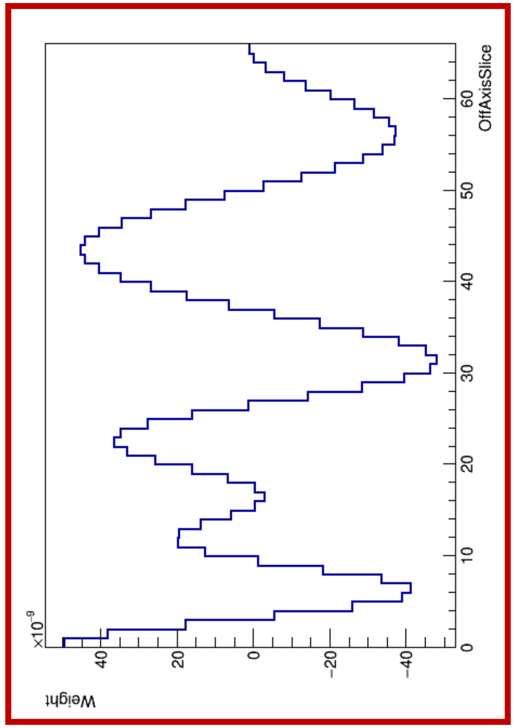
**ND Fluxes**

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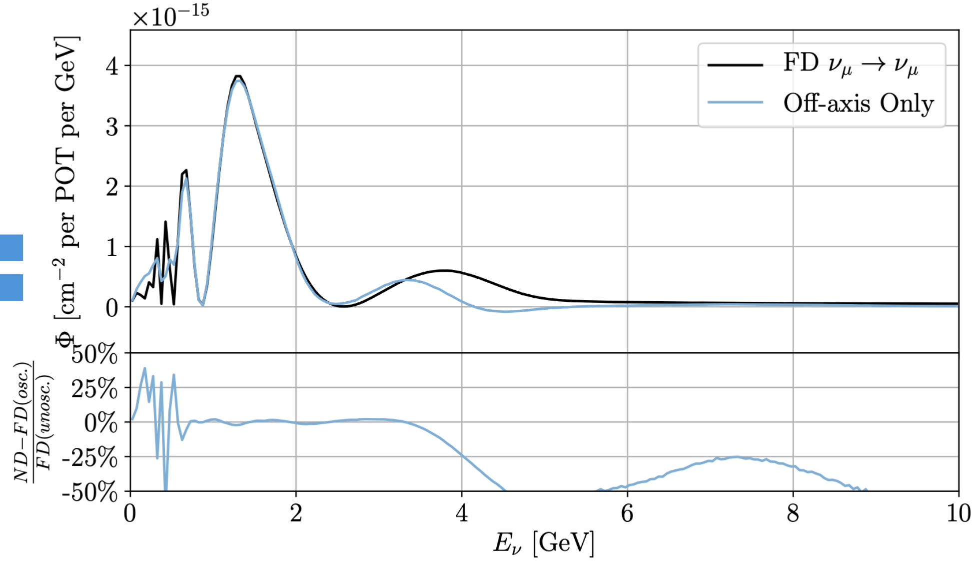
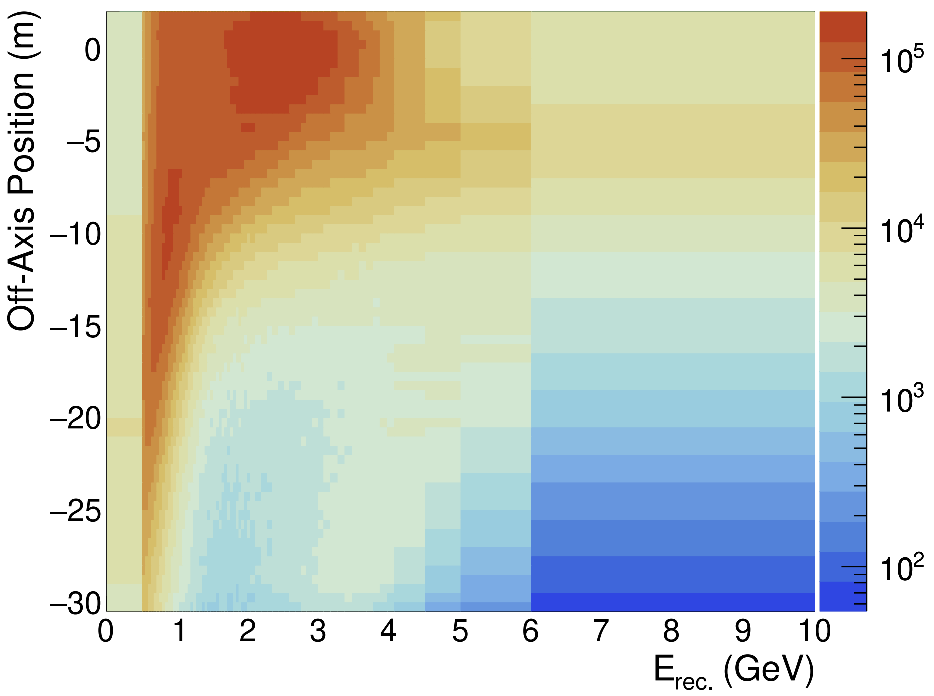
**FD Oscillated Flux + Combined ND Fluxes**



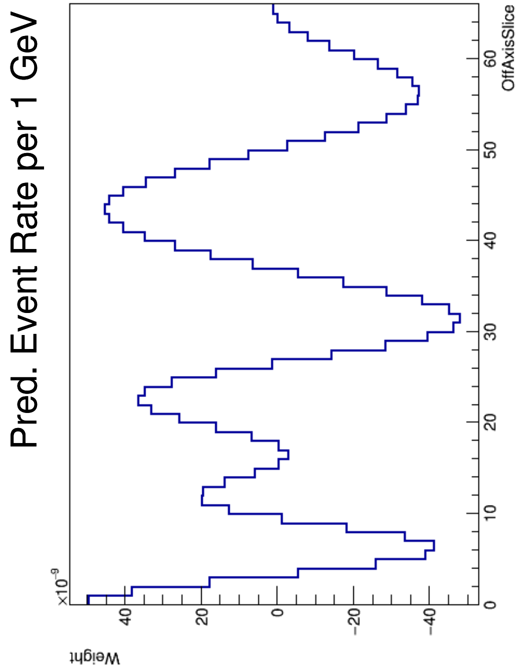

arXiv:2103.13910 [physics.ins-det]

# PRISM as an Oscillation Analysis

$\nu_\mu$ data you measured at ND

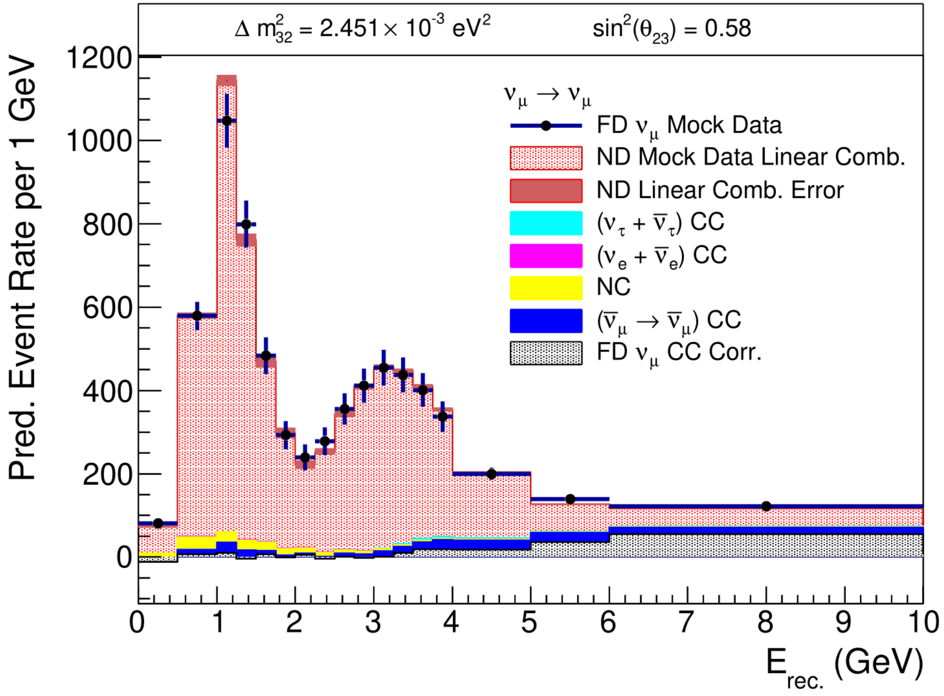



Weights you calculated using the flux model

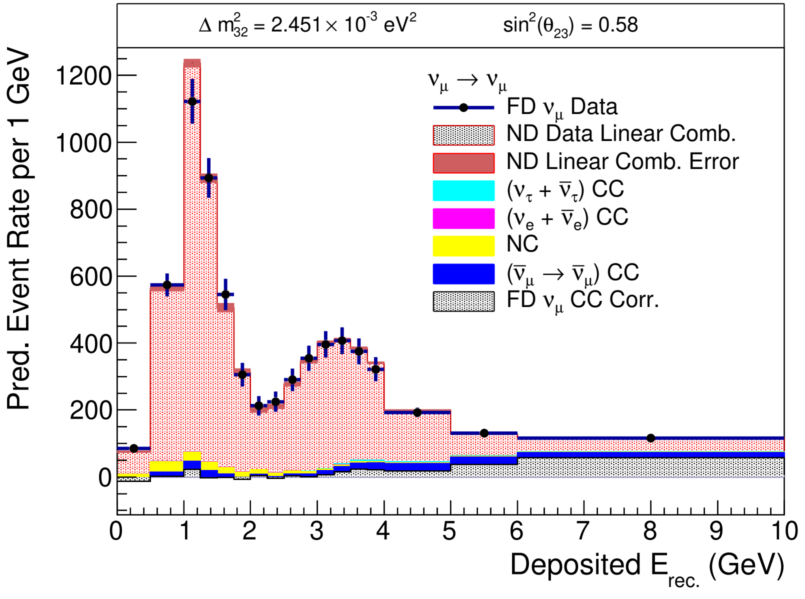



$\nu_\mu \rightarrow \nu_\mu$

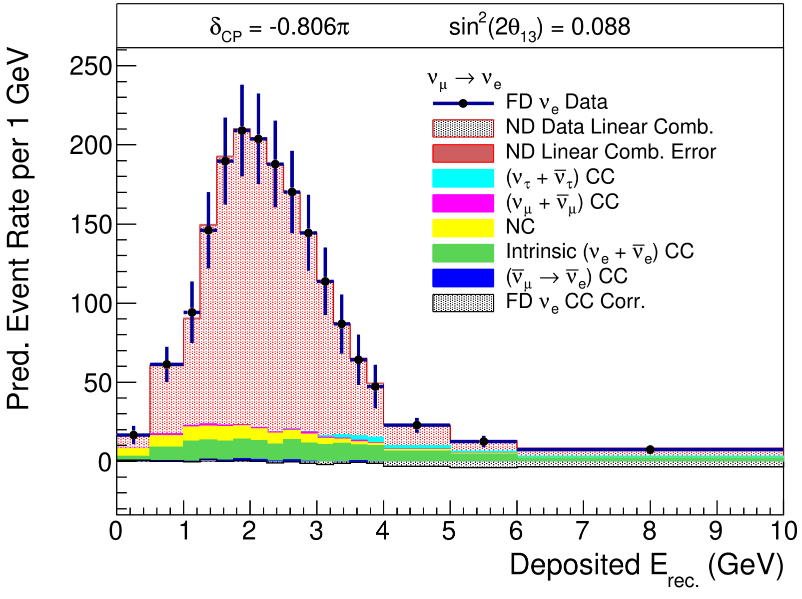
Data-driven prediction of the FD oscillated event rate!



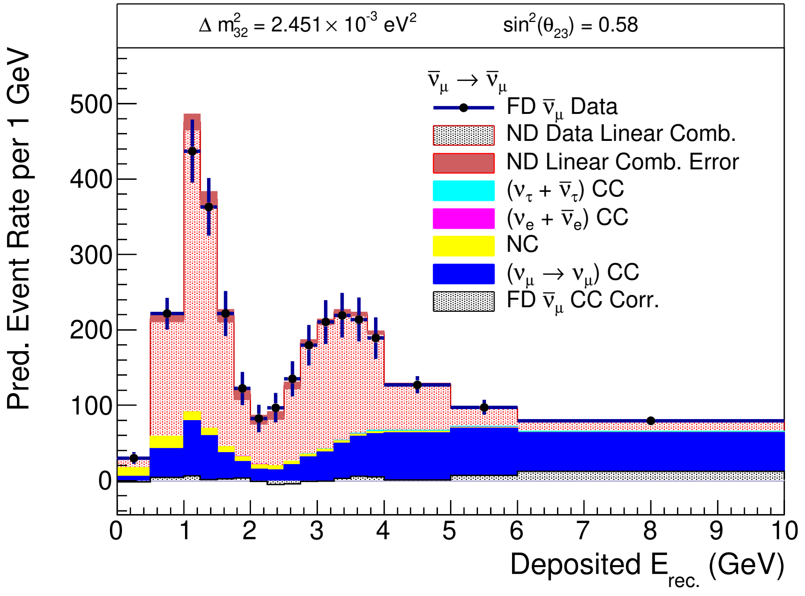
$\nu_\mu \rightarrow \nu_\mu$



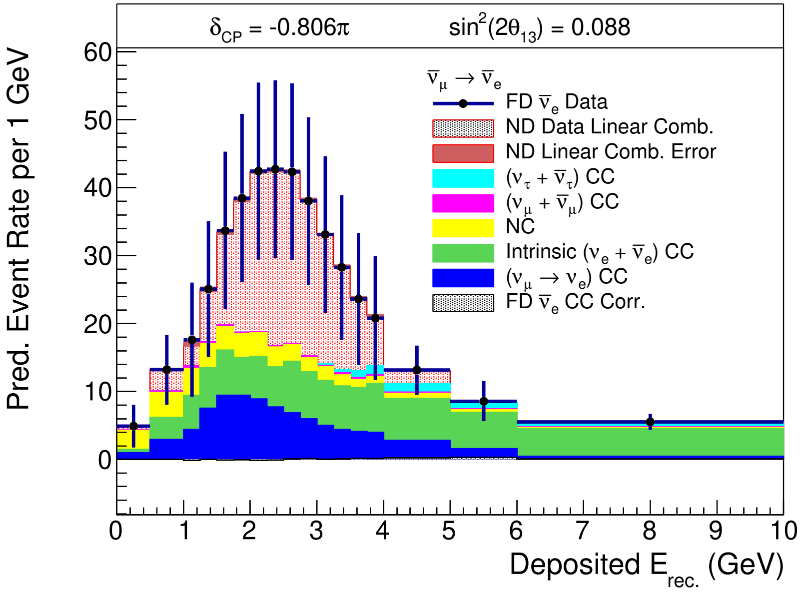

$\nu_\mu \rightarrow \nu_e$




$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$



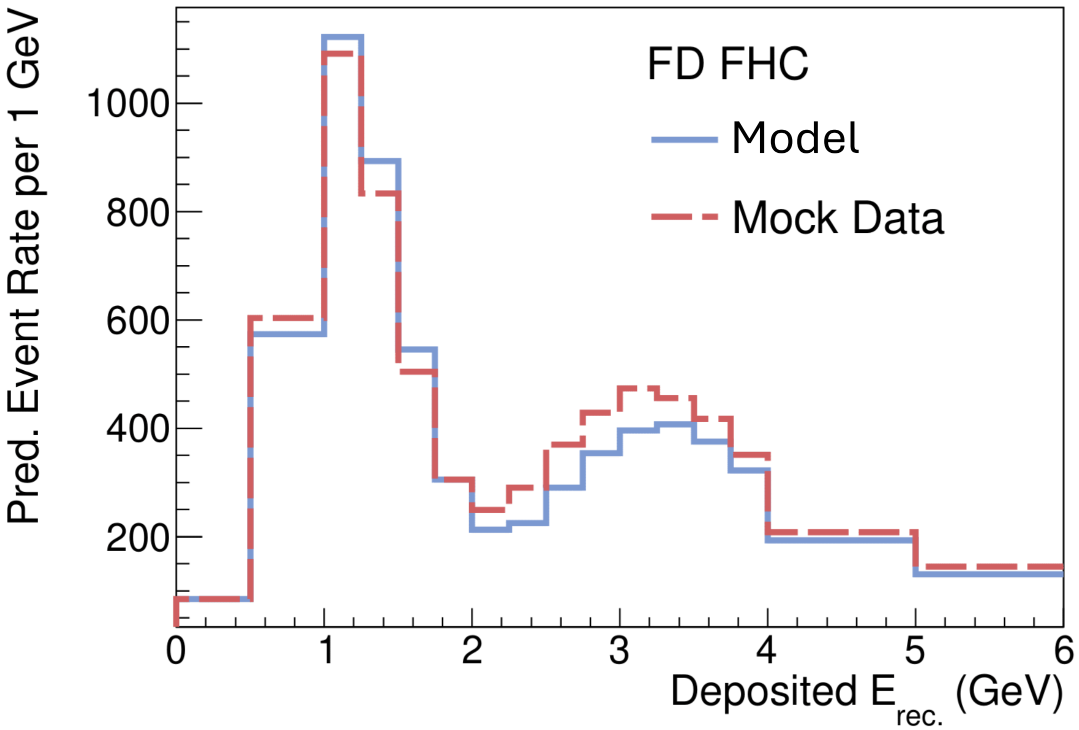

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



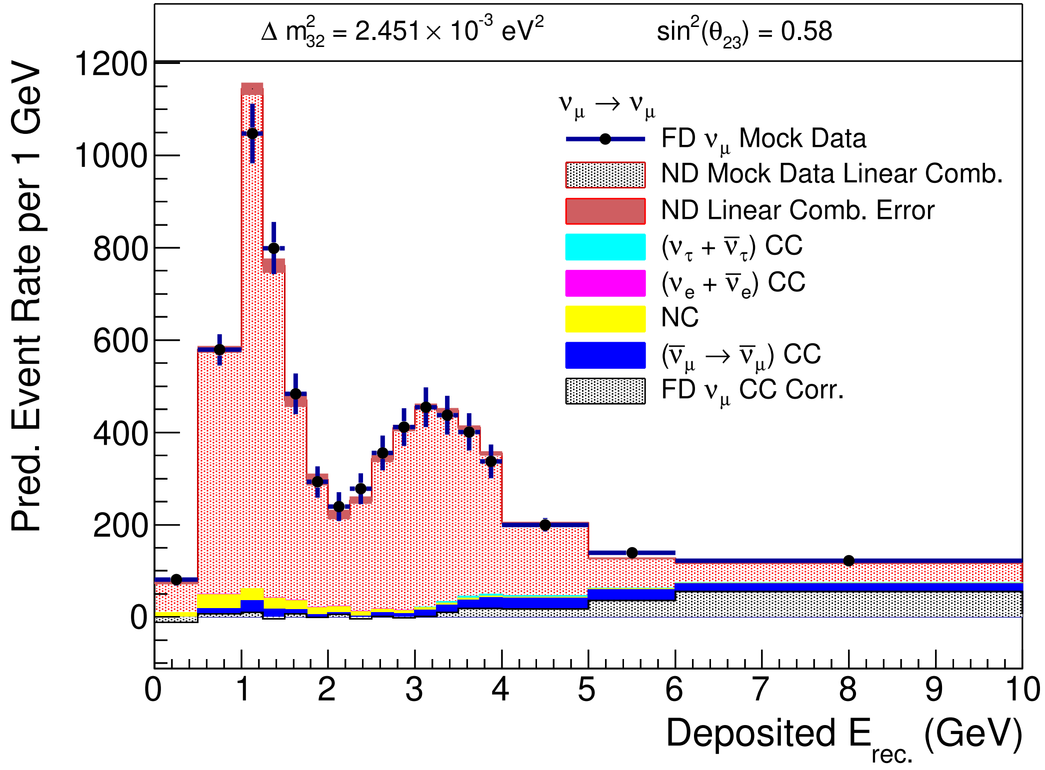
# PRISM Fixes Oscillation Analysis

**Back to 20% missing proton energy example**

**Move oscillation parameters to get a good fit = bias!**

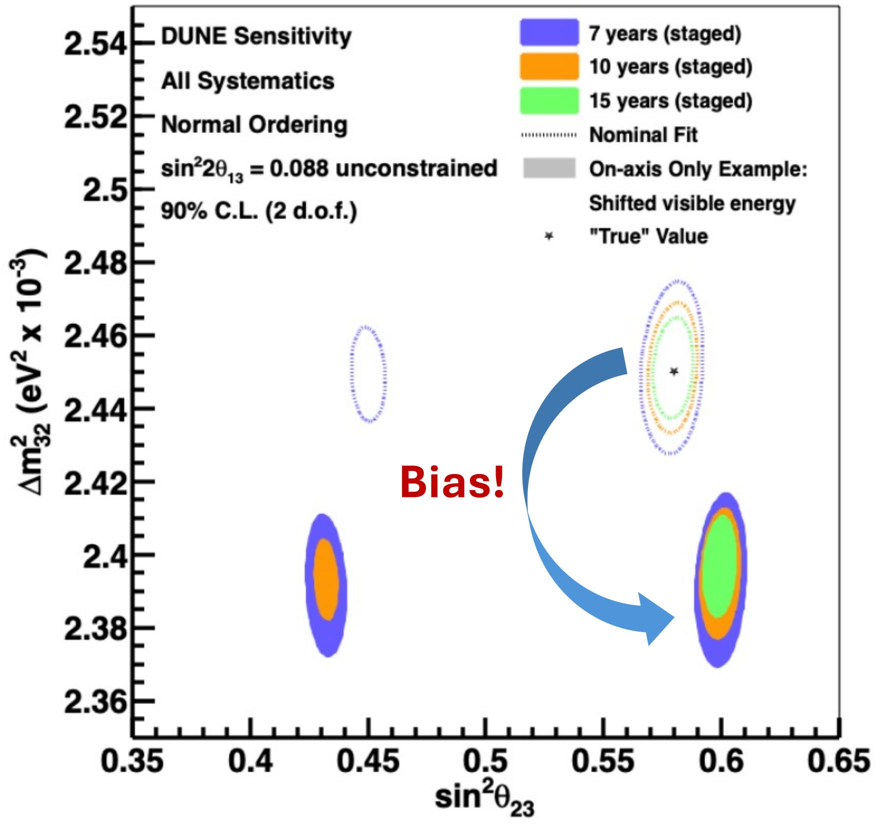



**Prediction is made from ND data! Resolve bias!**

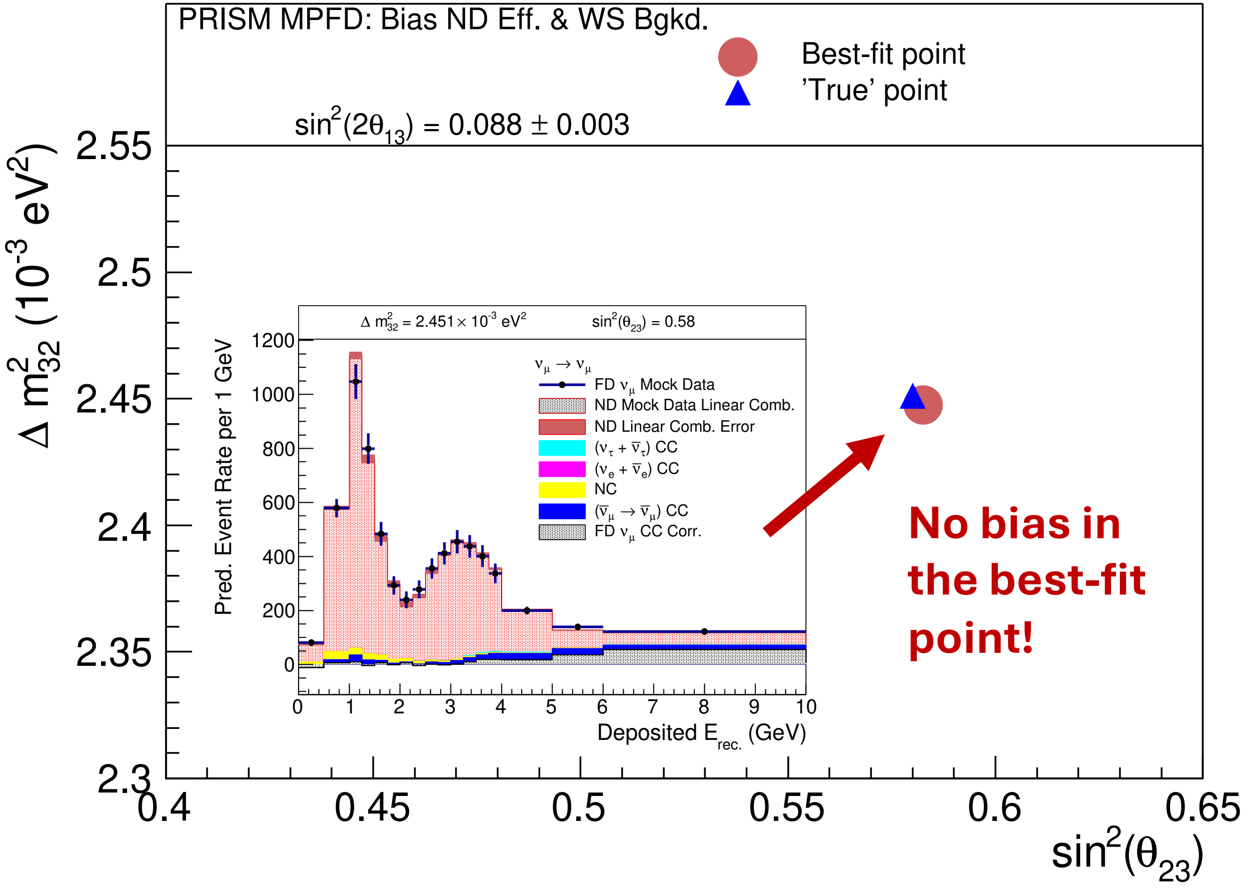


# PRISM Fixes Oscillation Analysis

**'Traditional' oscillation analysis with a fixed on-axis ND**




**Resolve bias with a data-driven PRISM oscillation analysis**




**No bias in the best-fit point!**

## How else can we use the PRISM technique?

## Cross section measurement

# Neutrino Cross-Section Measurement

$$\langle \sigma \rangle = \frac{N_{interactions}}{E \cdot \varepsilon \cdot N_{targets} \int \Phi \, dE_\nu}$$

Energy

Efficiency

Number of target nucleons

**Integrated flux**

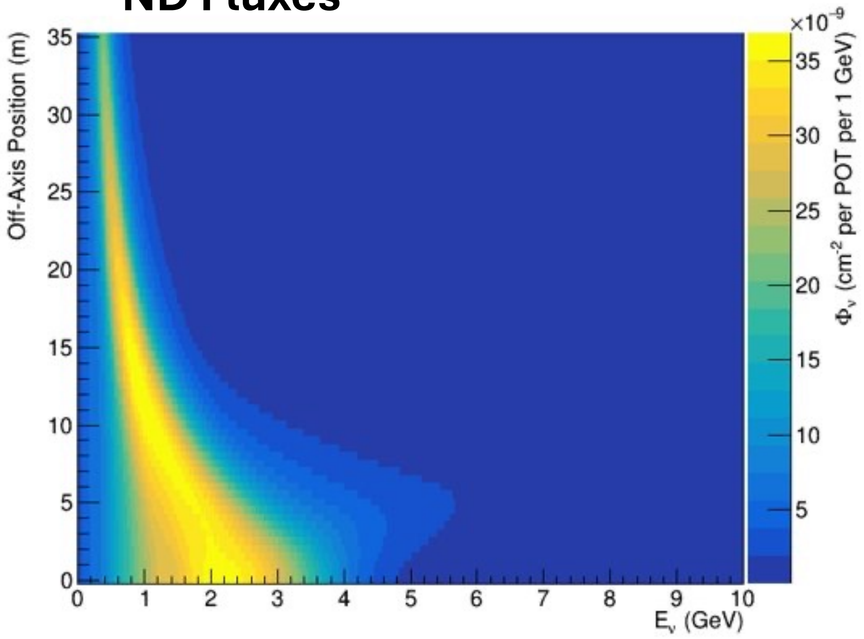
- Measure neutrino cross sections in a **broad neutrino flux**
- Limited ability to **separate** the different **interaction types**
  - ➢ What if we had a **single fixed neutrino energy**?

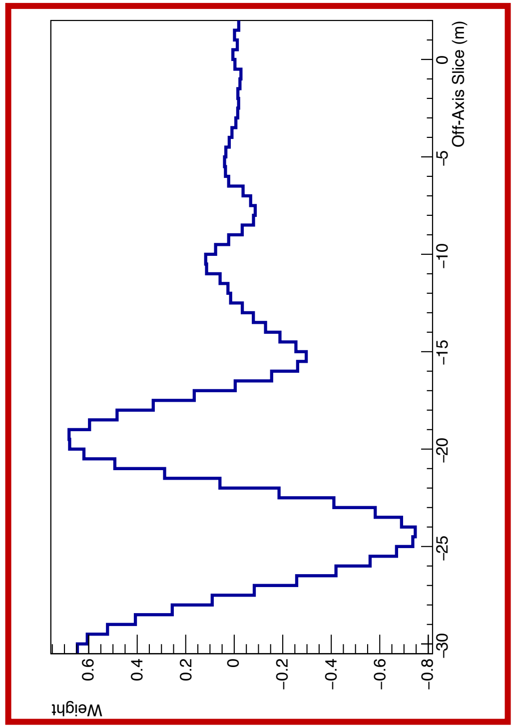
# Neutrino Cross-Section Measurement - PRISM

- Produce a **mono-energetic neutrino flux** by linearly combining ND fluxes to match a **narrow gaussian**

- Solve for **coefficients**, apply those coefficients as weights to the measured ND data in a linear sum

**ND Fluxes**

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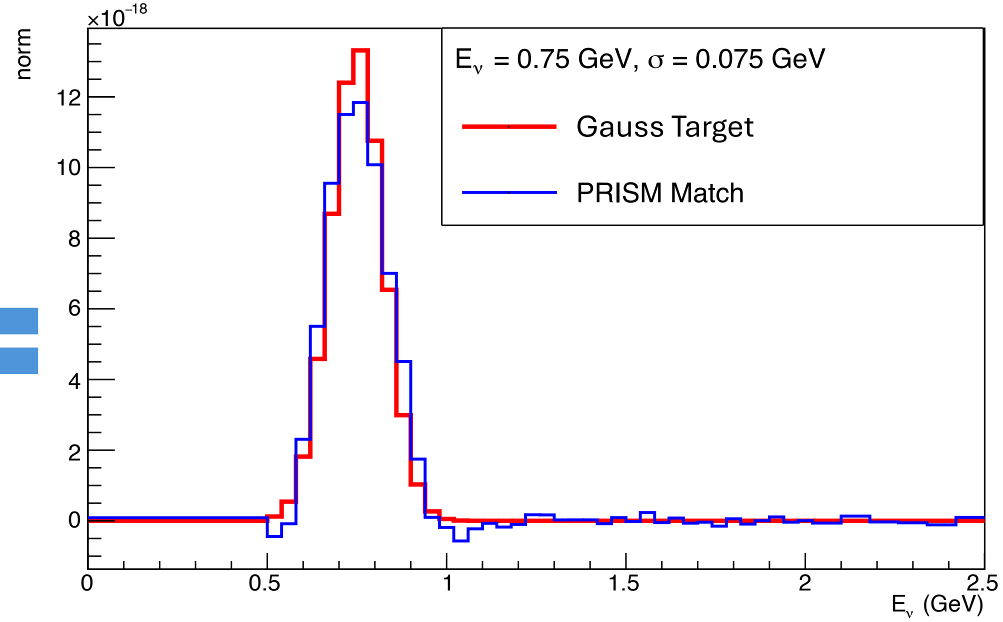
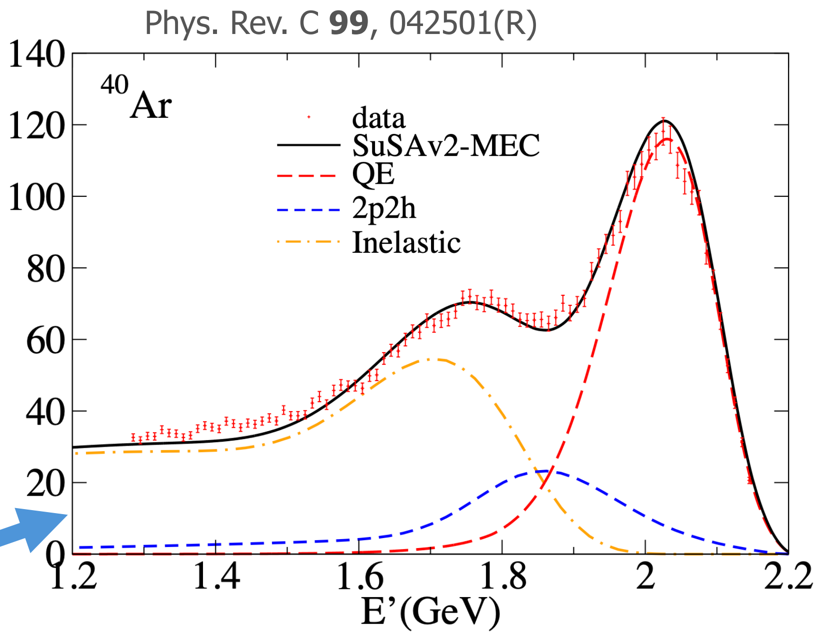
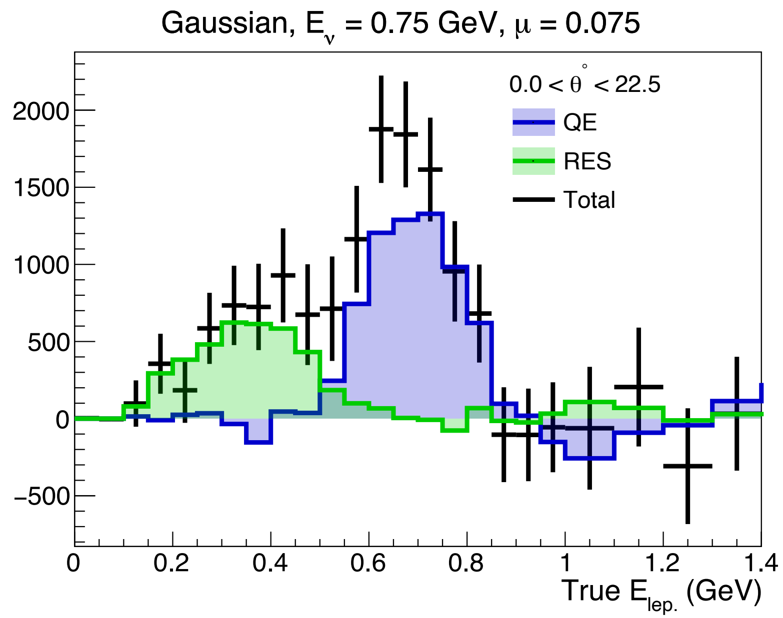


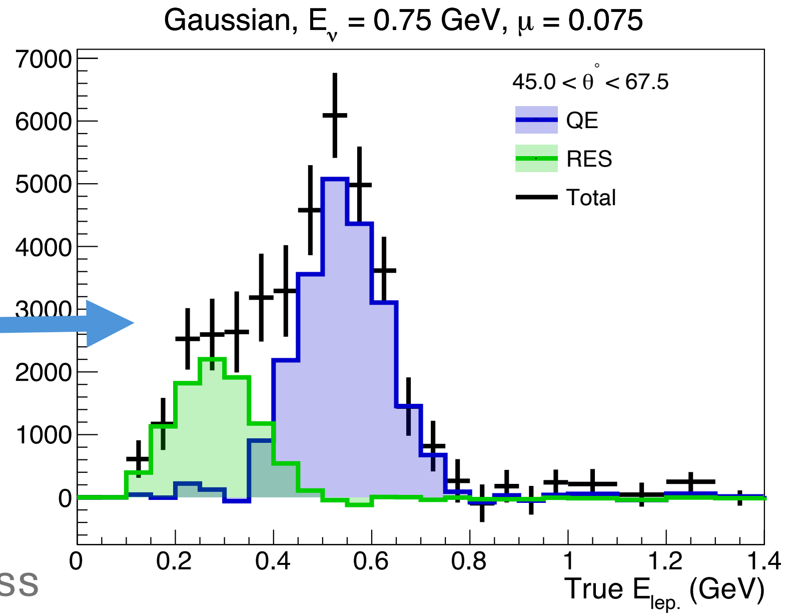
# PRISM Gaussian Flux

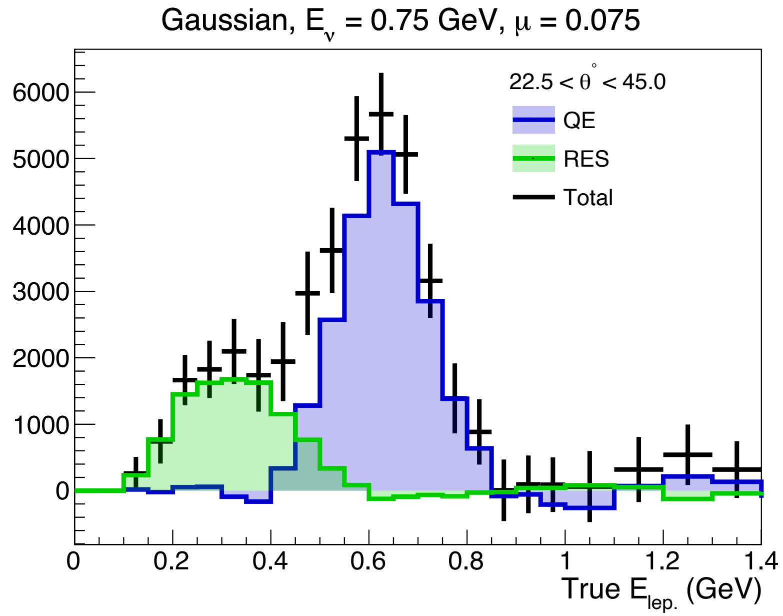
**Electron scattering** separates different **interaction types** – **known electron energy**




**PRISM gaussian linear combination** – allows for **separation** of interaction types (See report by Amir Gruber)




Work in progress

# It is not just a DUNE-thing!

# T2K Cross-Section Analysis with Multiple Detectors

- Cross-section measurements with **multiple NDs** at different off-axis positions
- Different neutrino **fluxes**
- Break the $\Phi\times\sigma$ degeneracy

Example: PHYSICAL REVIEW D 108, 112009 (2023)

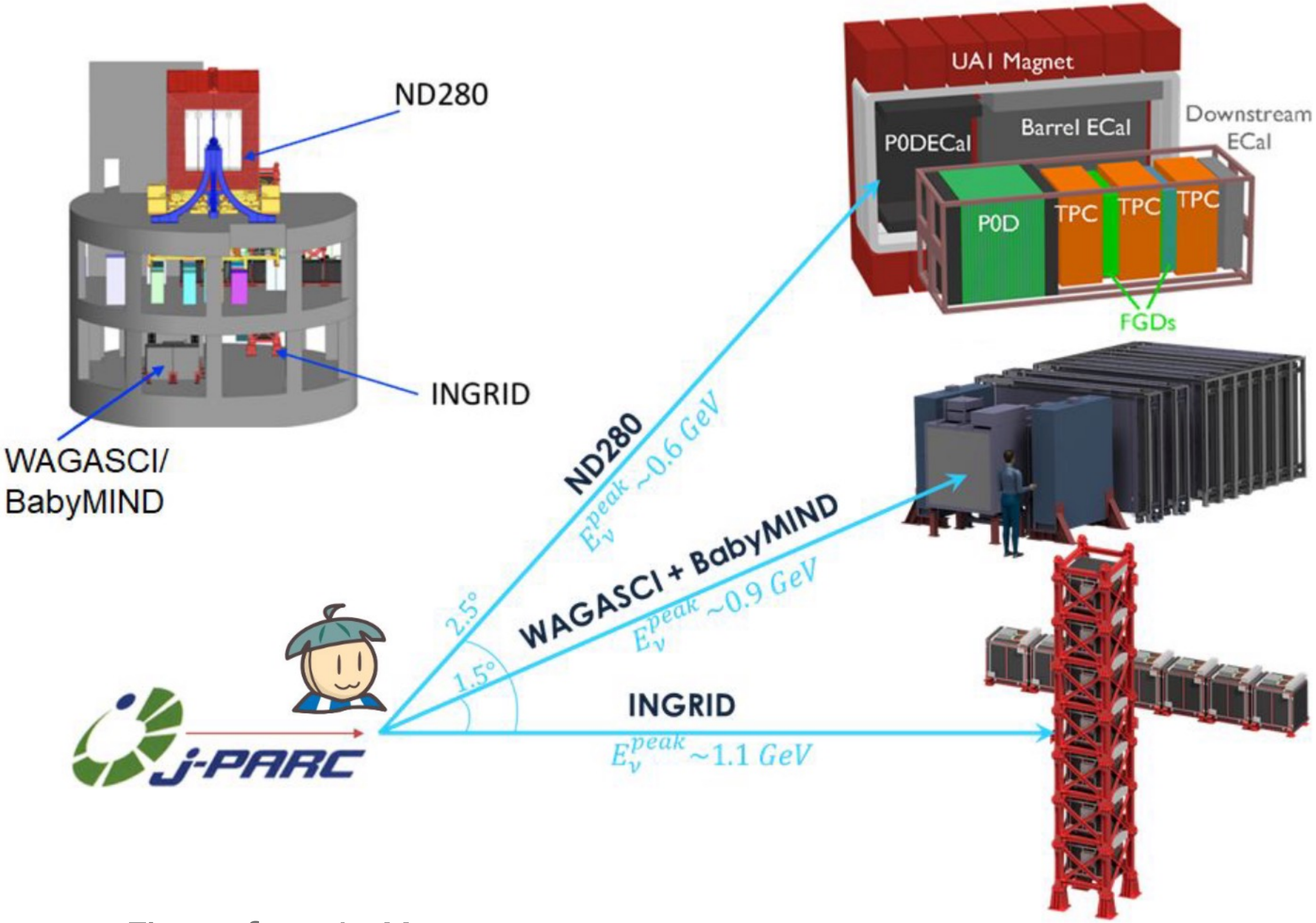
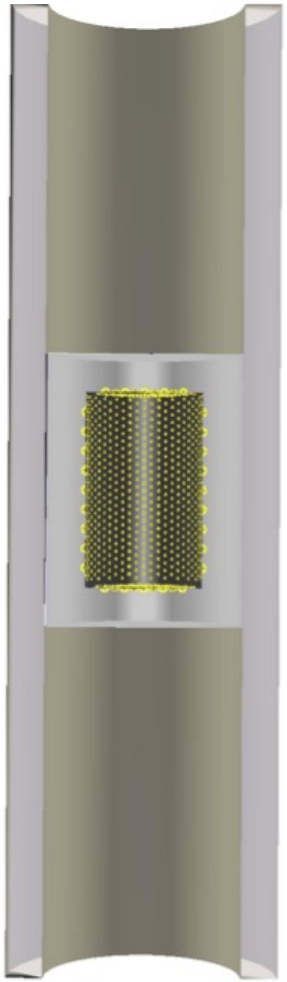
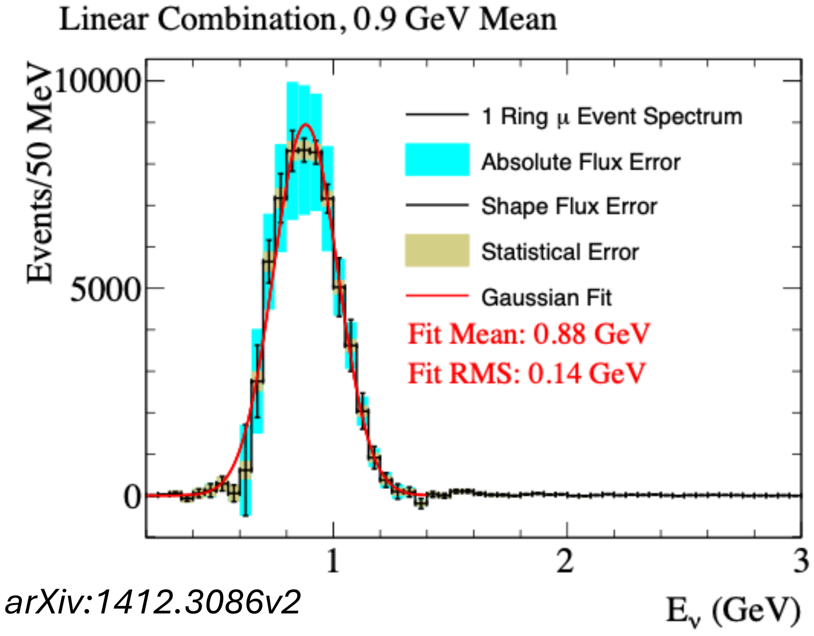



Figure from L. Munteanu

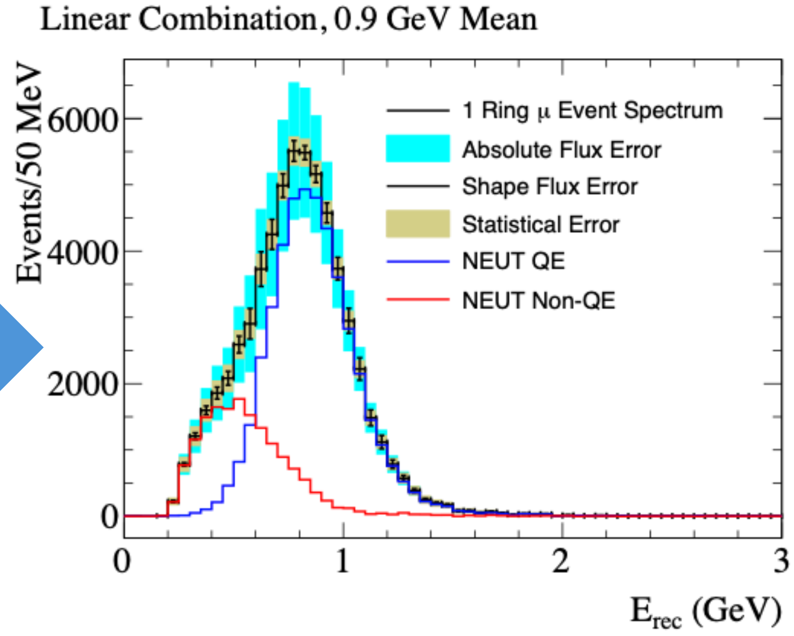
# Intermediate Water Cerenkov Detector (IWCD / nuPRISM)



- Additional **near detector** to measure different **Hyper-K off-axis** fluxes – **$H^2O$ target**!
- Produce **mono-energetic flux** through linear combination

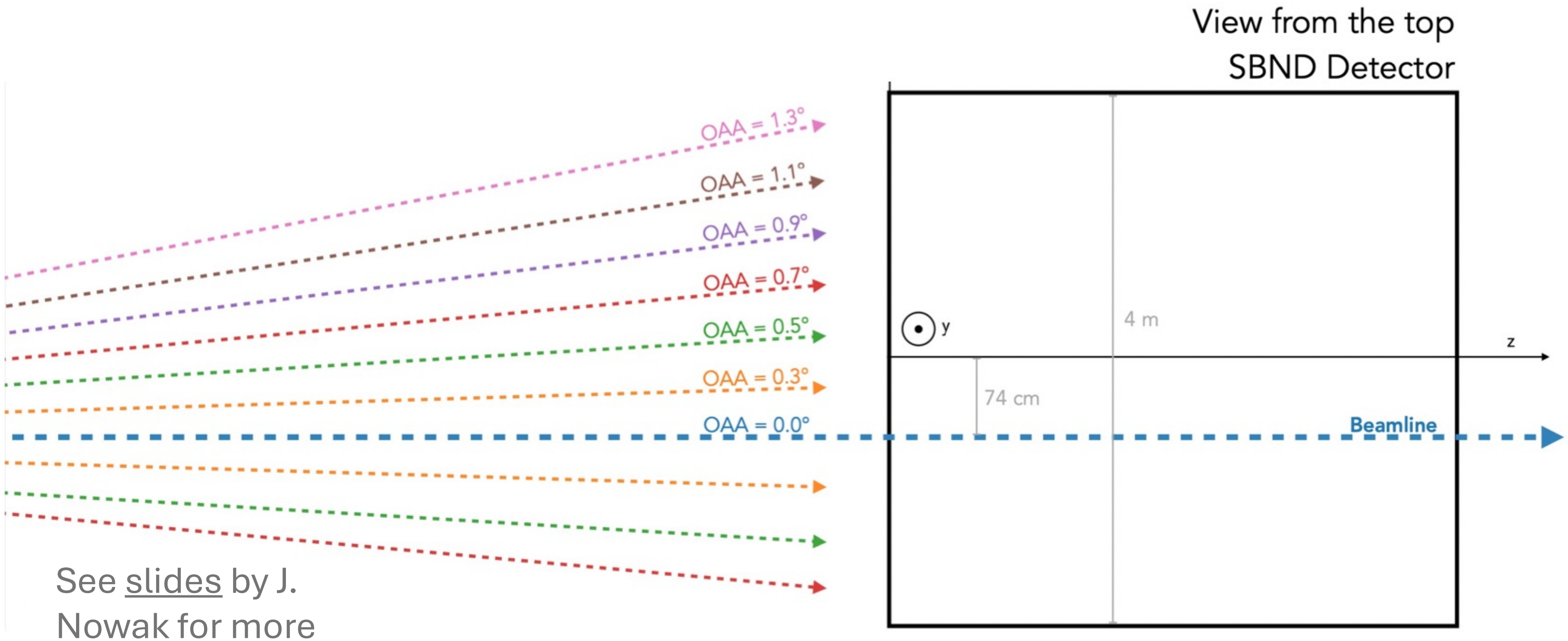


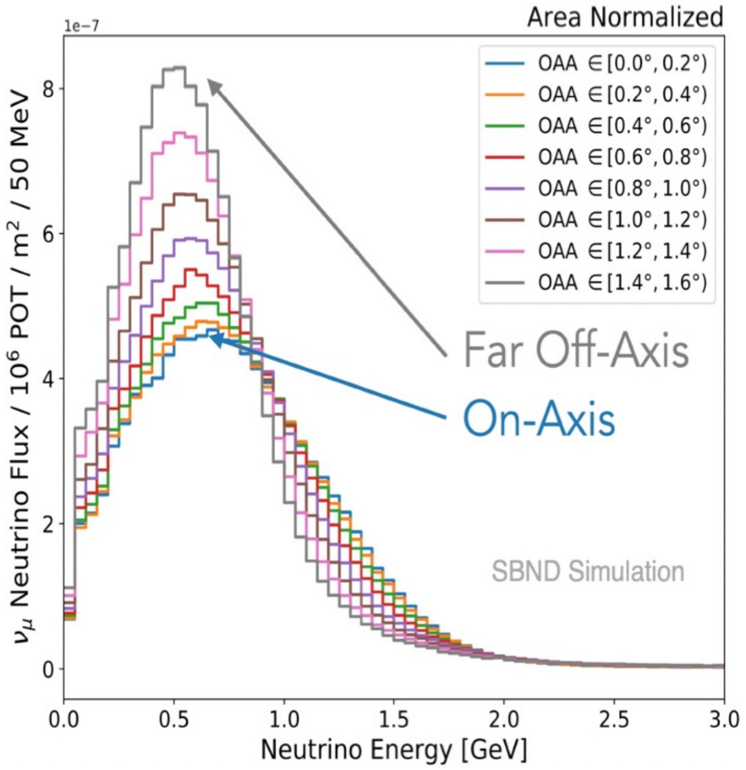

*arXiv:1412.3086v2*



# SBND-PRISM

- Short Baseline Near Detector (SBND) is only **100m** from the **Booster** neutrino beam source – no movement!
- Different parts of the detector measure **different off-axis angles**!



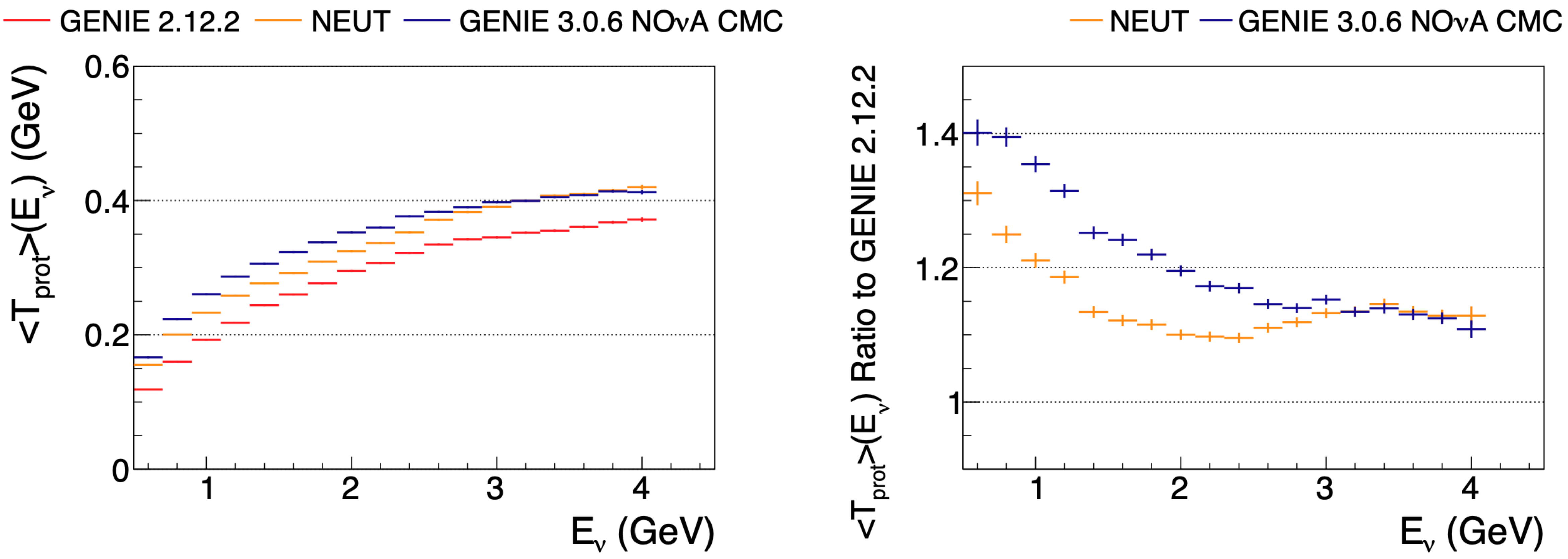

See slides by J. Nowak for more details

# Summary and Conclusions

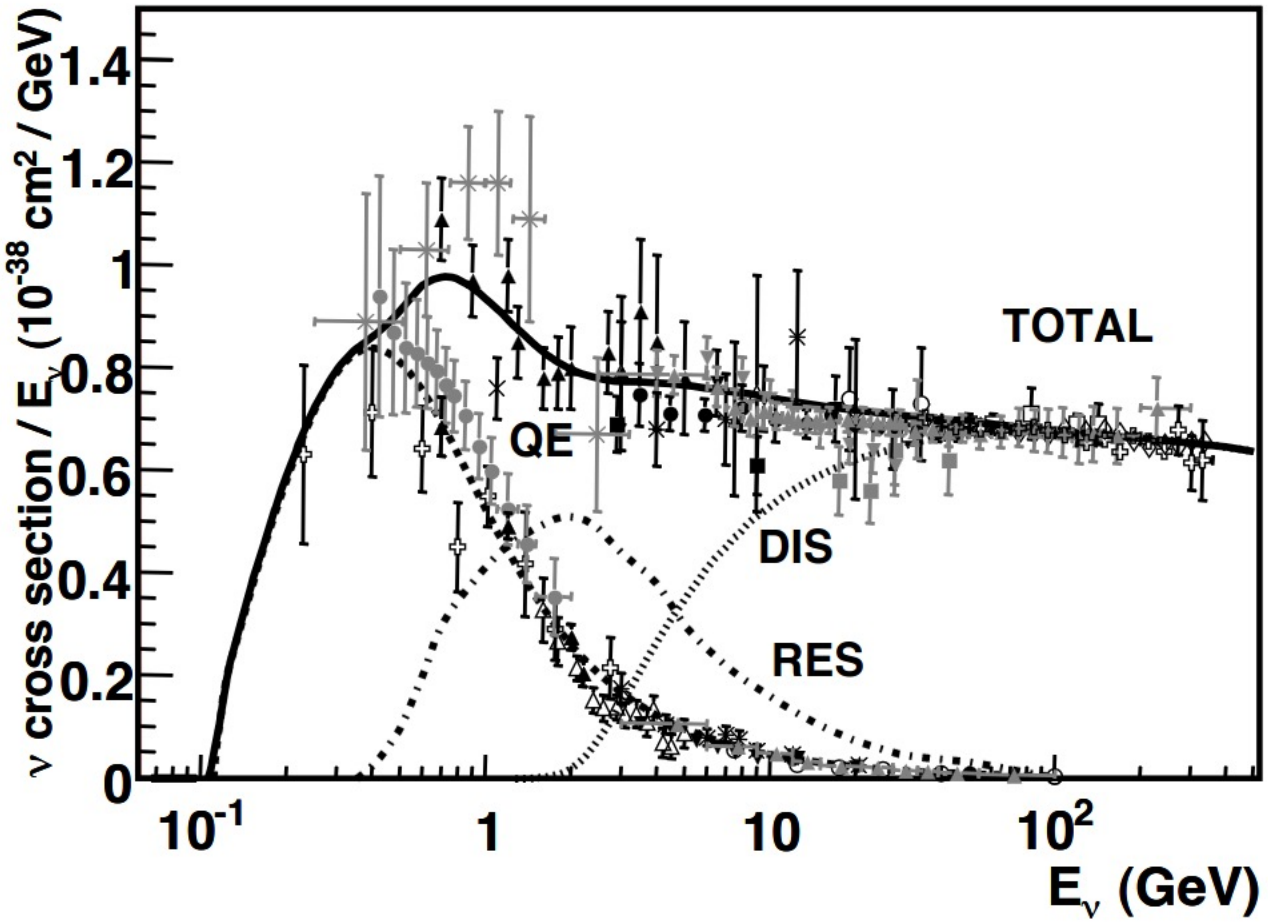
- Entering a **new precision era** of **neutrino oscillations** (DUNE + Hyper-K) – **controlling systematic uncertainties** more vital than ever!
- Challenge to constrain/tune cross section models measuring event rates in a **single broad neutrino flux**
  - PRISM technique addresses this by providing **many neutrino fluxes** – breaks the $\mathbf{\Phi \times \sigma}$ degeneracy!
- Planned use in **DUNE** and **Hyper-K**
- Demonstrated great potential in reducing cross section systematic uncertainty and **limiting the risk oscillation measurement bias**

# Thank you for listening!

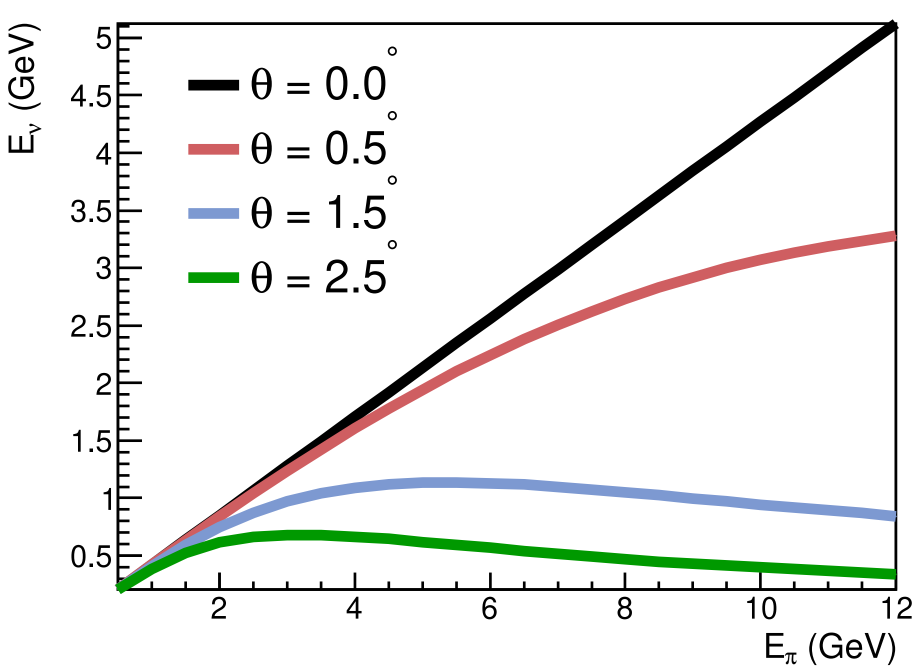
# Proton Energy Model Dependence

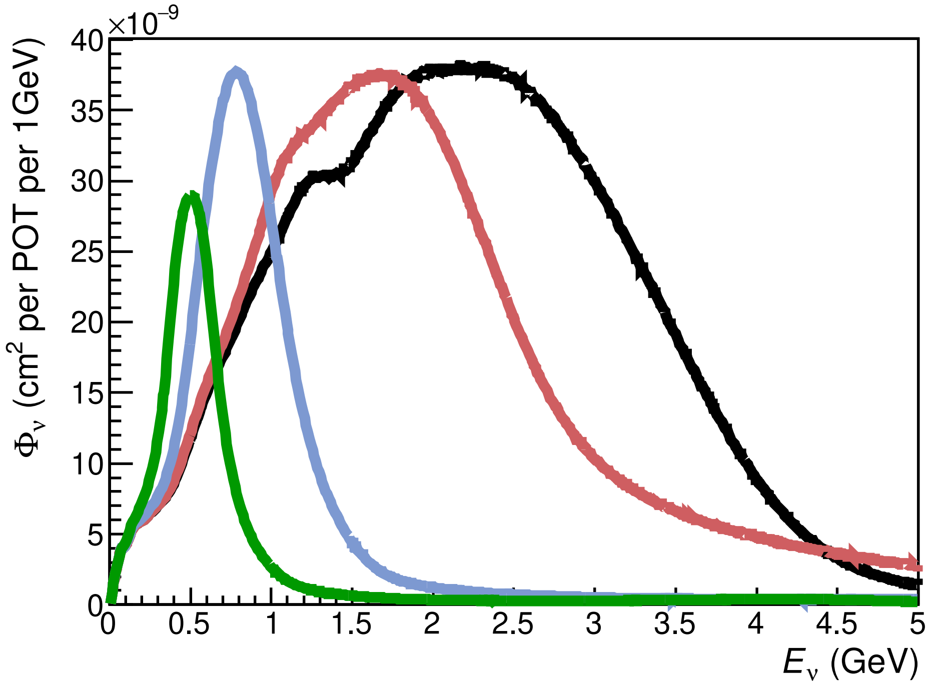


# Cross Section



# Pion Decay Kinematics



# PRISM Prediction

FINISH

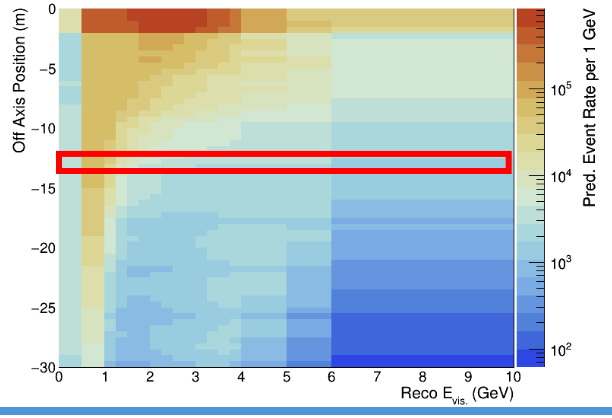
2. Subtract predicted ND backgrounds from data

3. Unfold near detector effects (resolution and efficiency)

6. Add FD backgrounds

1. Take ND data

START




4. Introduce far detector effects (resolutions and efficiency)

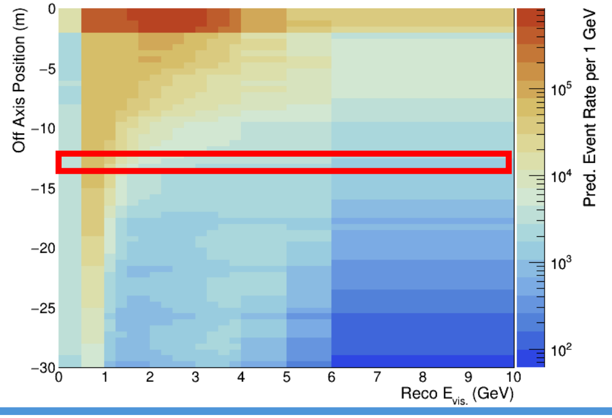
5. Linearly combine ND off-axis data with corresponding coefficients

# PRISM Prediction

**FINISH**

**START**

1. Take ND data




2. Subtract predicted ND backgrounds from data

3. Unfold near detector effects (resolution and efficiency)

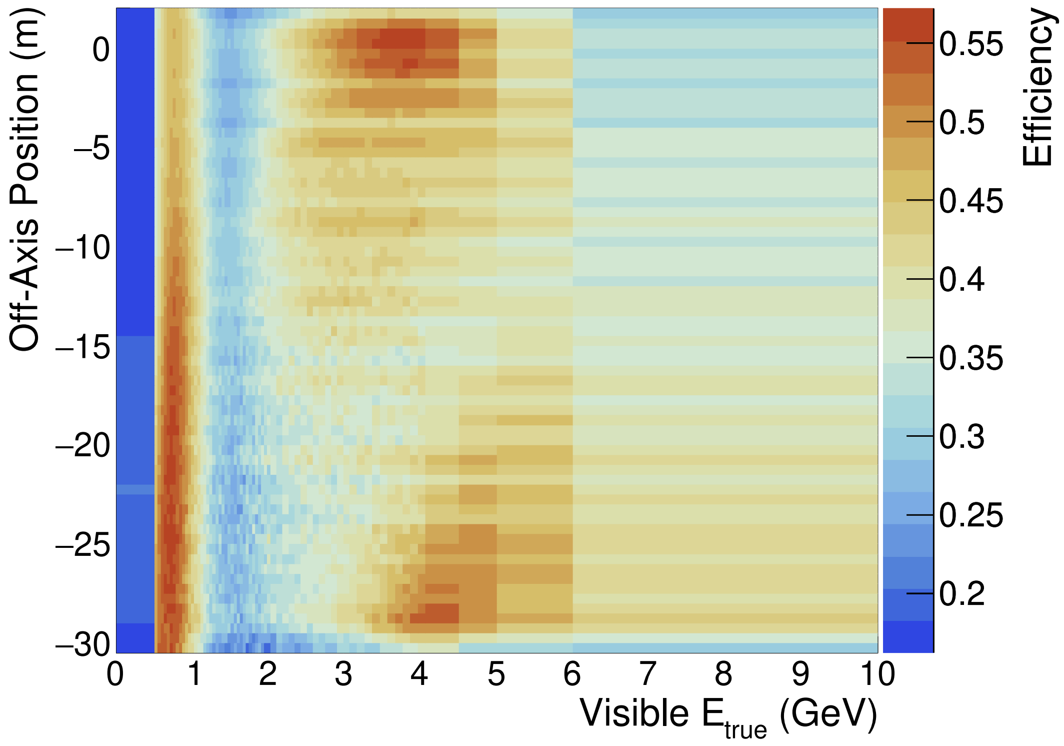
4. Correct for nue/numu x-section ratio

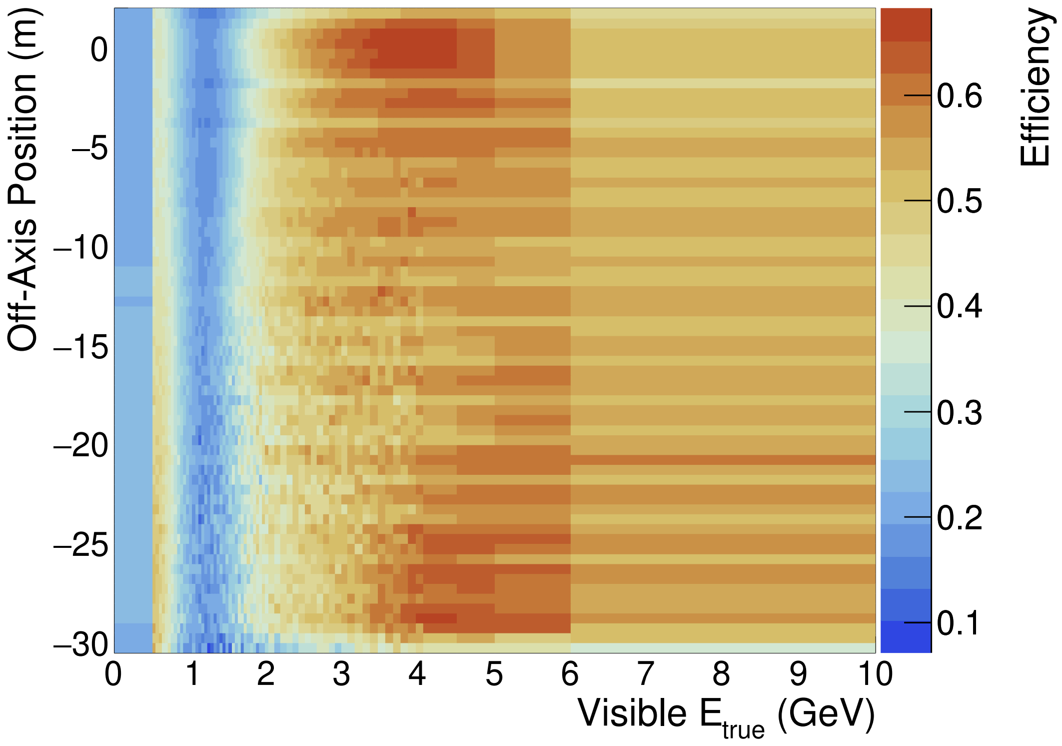
5. Introduce far detector effects (resolutions and efficiency)

6. Linearly combine ND off-axis data with corresponding coefficients

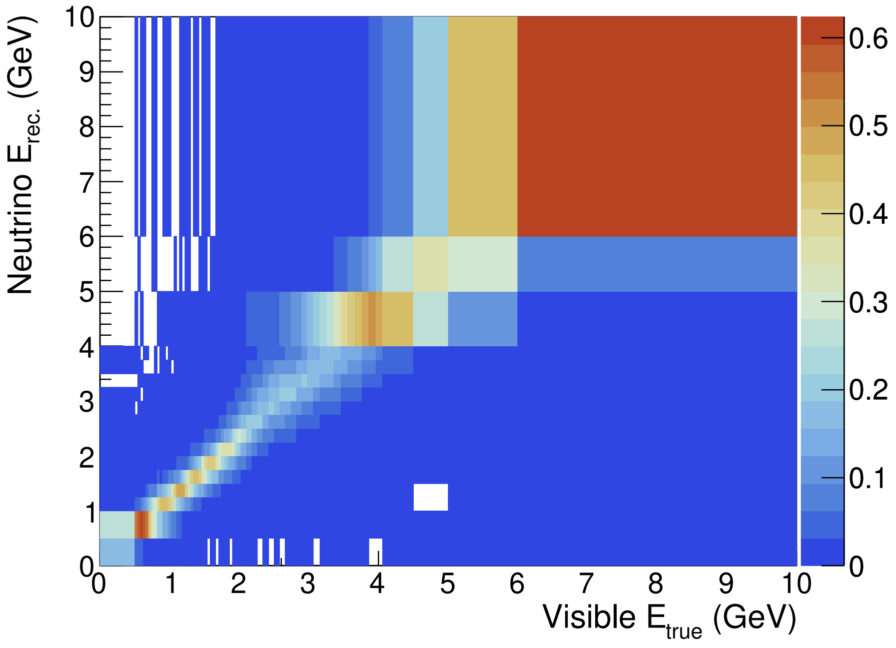
7. Add FD backgrounds

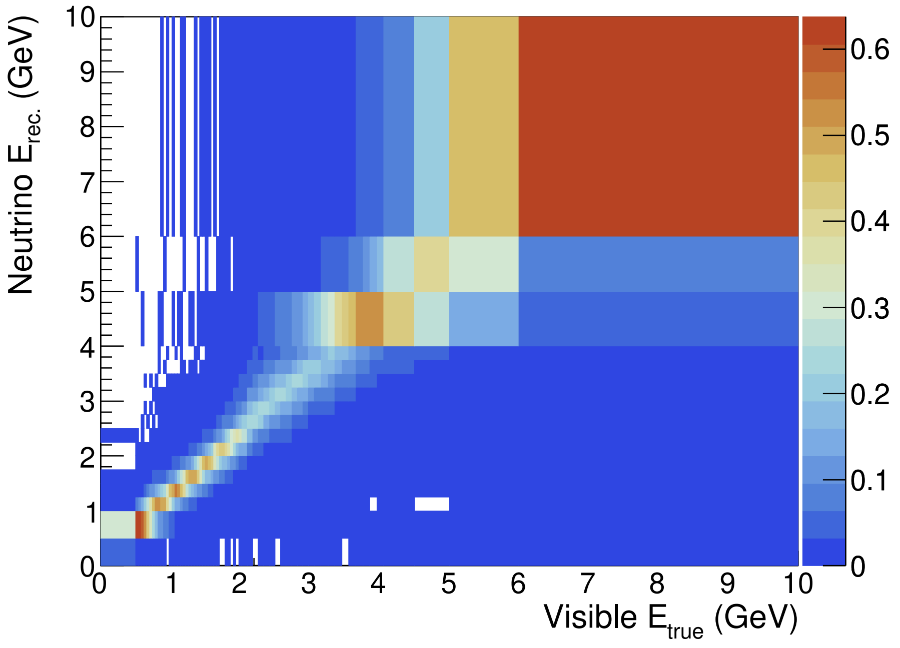
# ND Selection Efficiency



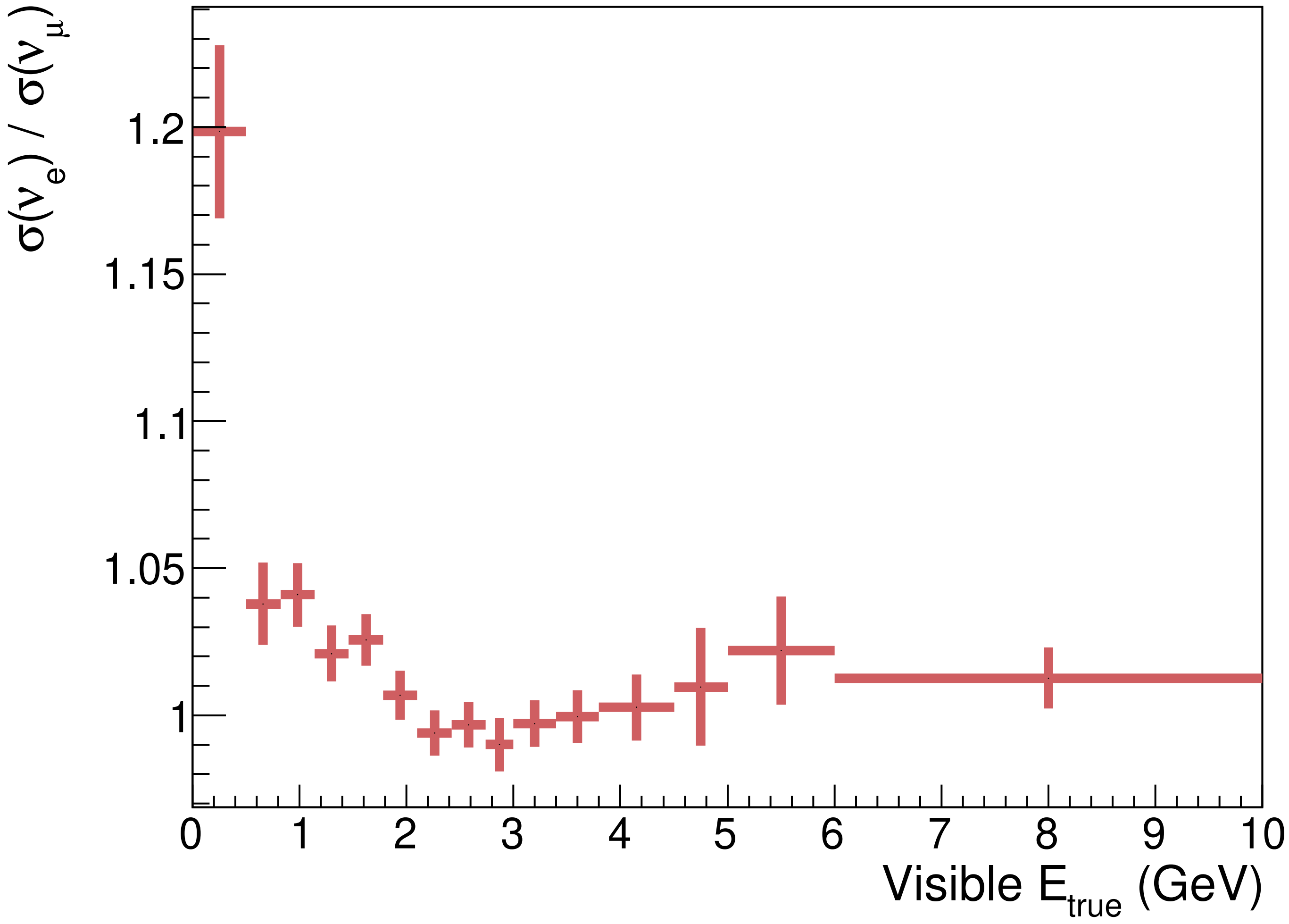



# FD Resolution (numu and numubar)

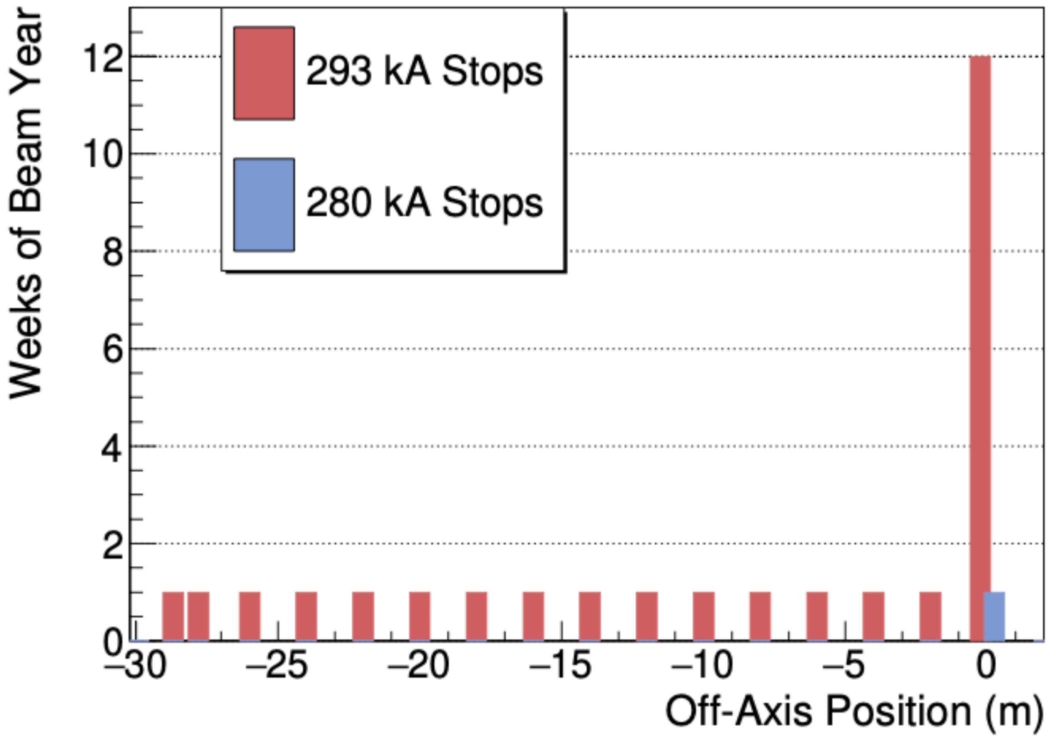


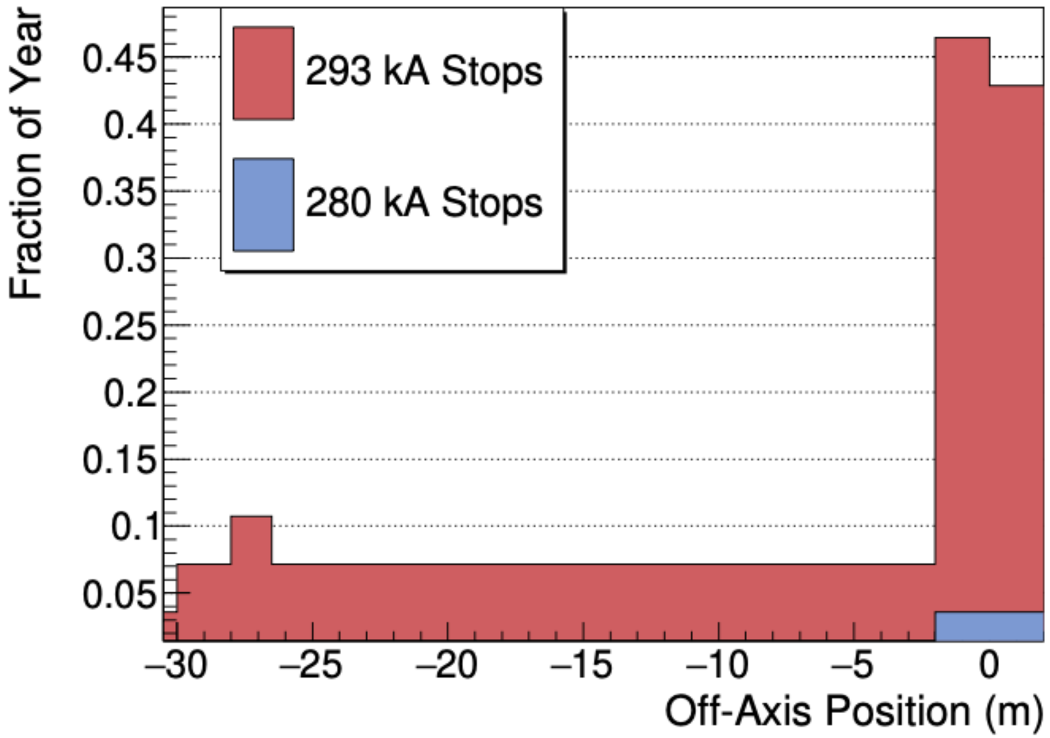



# Nue/Numu Cross Section Ratio



# Run Plans Weighting



# Extrapolated ND Data With Run Plans Weighting