

# Neutrinos through a PRISM

NF01

Luke Pickering for the  
DUNE-PRISM Group  
2020-11-19

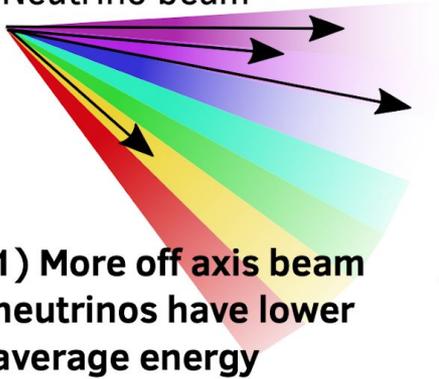
Mormon Row, Grand Teton NP



**Pronouns: He/Him/His**

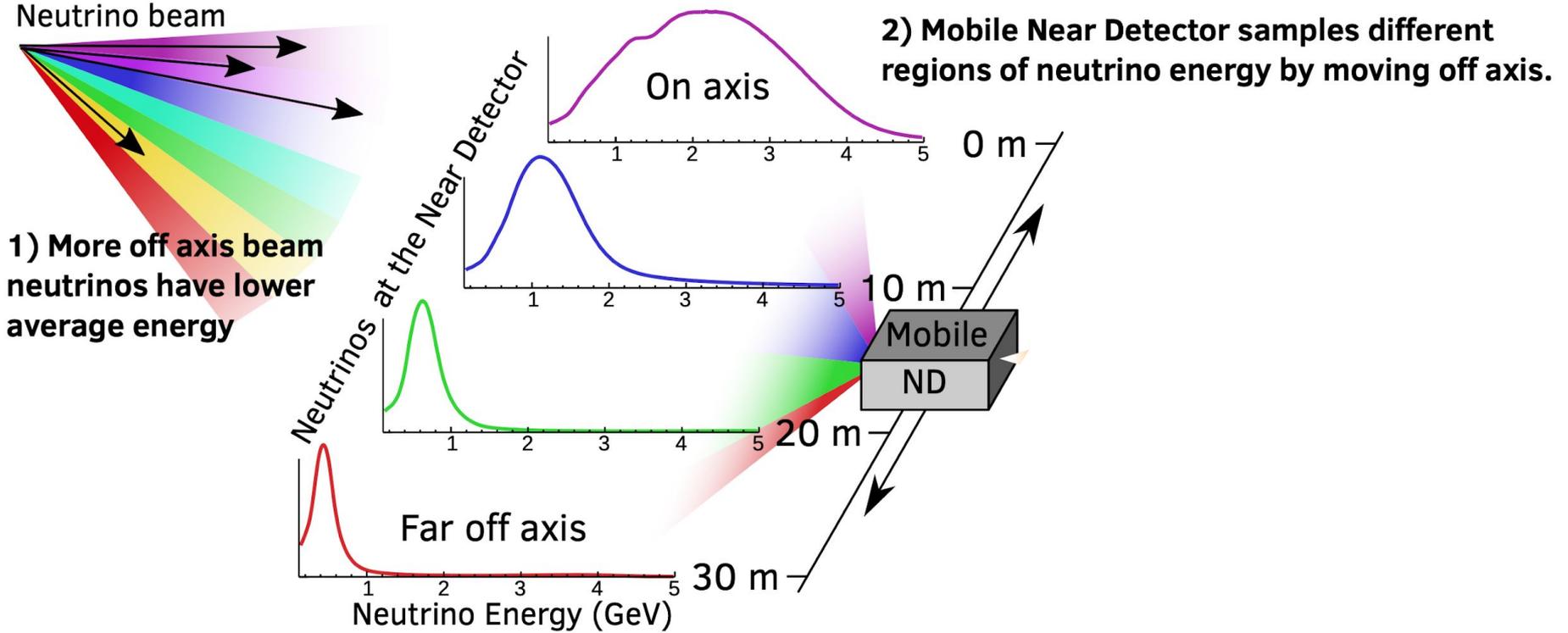
# PRISM In a Slide

Neutrino beam

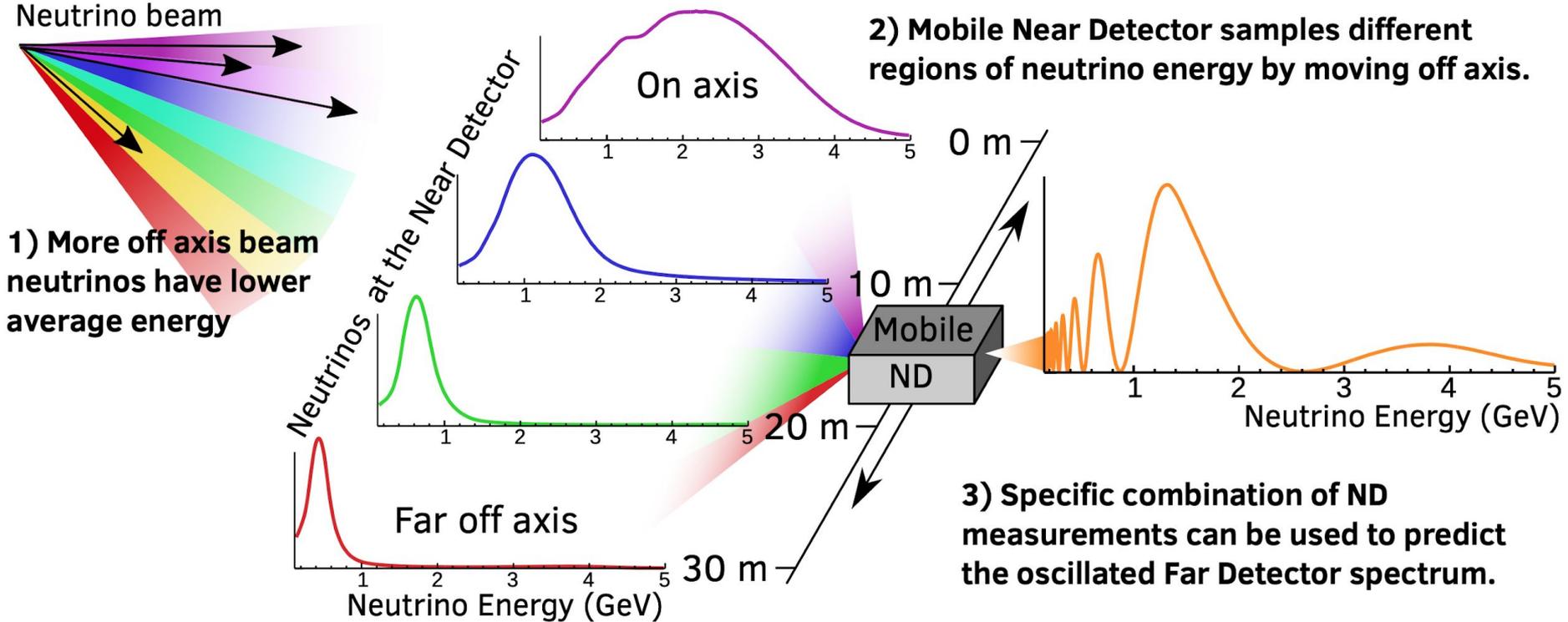


1) More off axis beam neutrinos have lower average energy

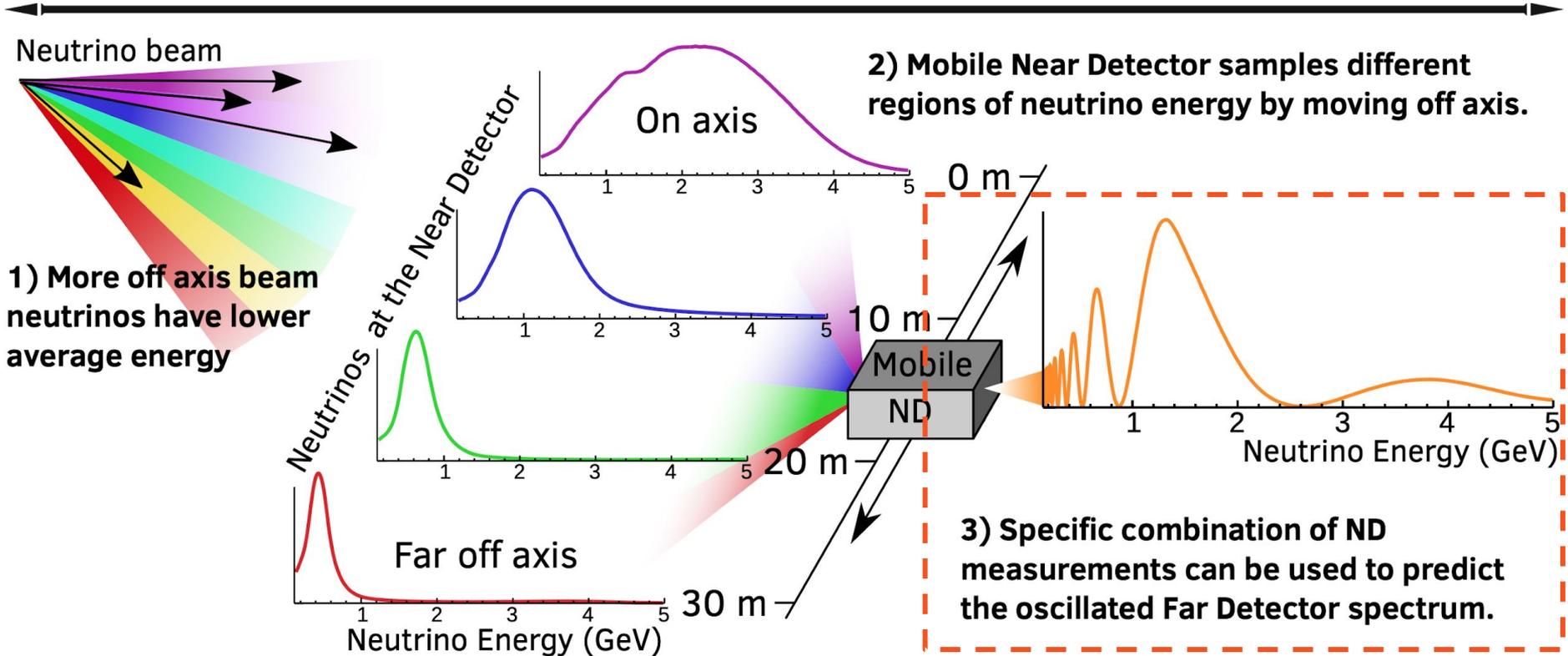
# PRISM In a Slide



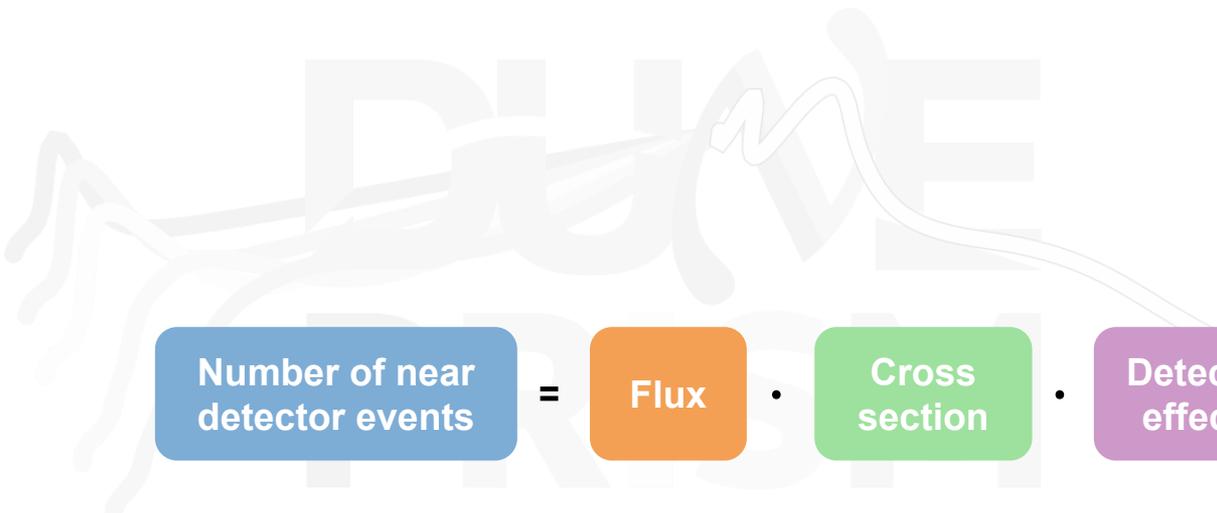
# PRISM In a Slide



# PRISM In a Slide



# Measuring Neutrino Oscillations



Number of near  
detector events

=

Flux

·

Cross  
section

·

Detector  
effects

# Measuring Neutrino Oscillations

Number of near  
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=

Flux

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Detector  
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Number of far  
detector events

=

Flux

·

Oscillation  
probability

·

Cross  
section

·

Detector  
effects

# Measuring Neutrino Oscillations

- Why can we not just look at near/far ratio?

Number of near  
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Number of far  
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Want to know this

# Measuring Neutrino Oscillations

- Why can we not just look at near/far ratio?
  - Because it isn't quite that simple...

$$N_{\text{near}}(E_{\text{obs}}) = \int dE_{\nu} \Phi_{\text{near}}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot D_{\text{near}}$$

$$N_{\text{far}}(E_{\text{obs}}) = \int dE_{\nu} \Phi_{\text{far}}(E_{\nu}) \cdot P_{\text{osc}}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot D_{\text{far}}$$

**Want to know this**

# Measuring Neutrino Oscillations

- Why can we not just look at near/far ratio?
  - Because it isn't quite that simple...
  - Convolution of detector effects with flux · cross section
  - Cannot directly compare near and far observables to extract oscillations

$$N_{\text{near}}(E_{\text{obs}}) = \int dE_{\nu} \Phi_{\text{near}}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot D_{\text{near}}$$

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**Want to know this**

# Oscillations at the Far Detector

- Why c
  - Bec
  - Con
  - Car

**But what if we could make near detector measurements, in an oscillated flux...?**

$$N_{\text{near}}(E_{\text{obs}}) = \int dE_{\nu} \Phi_{\text{near}}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot D_{\text{near}}$$

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**Want to know this**

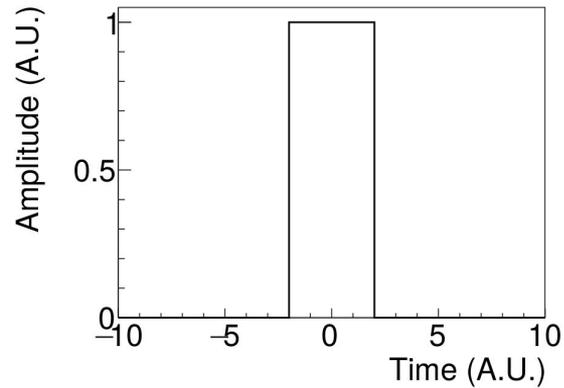


## A Quick Aside



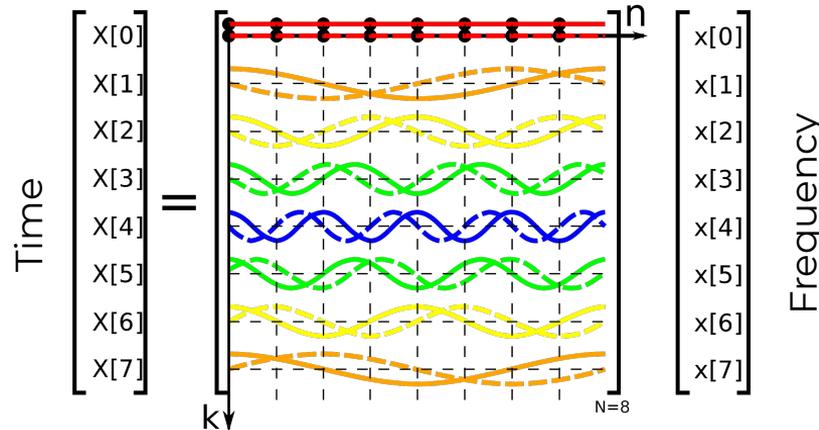
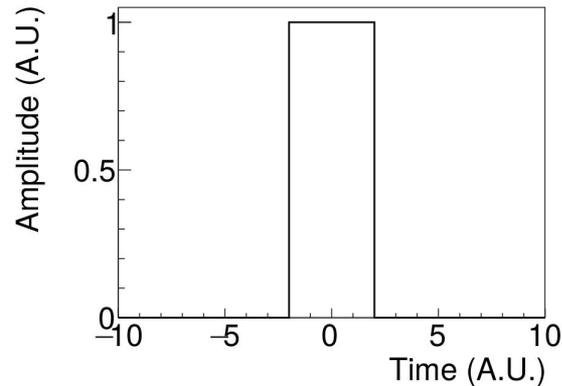
# Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines



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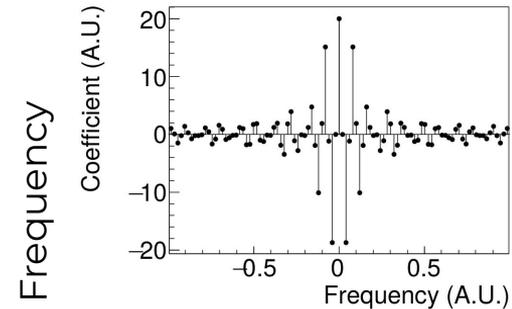
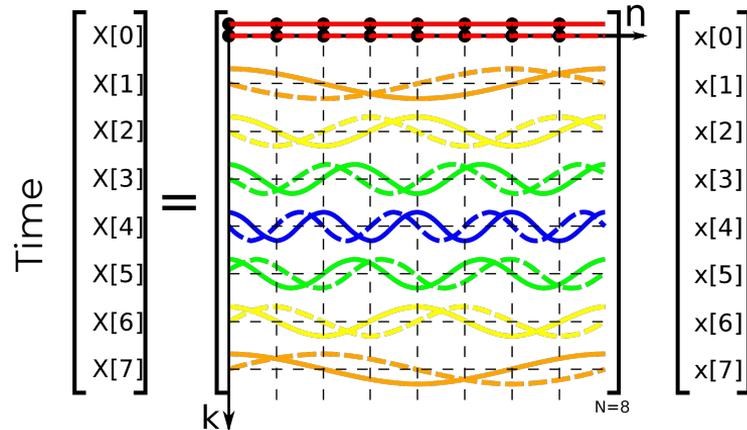
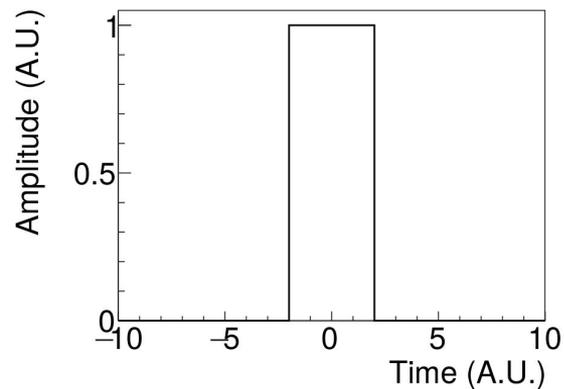


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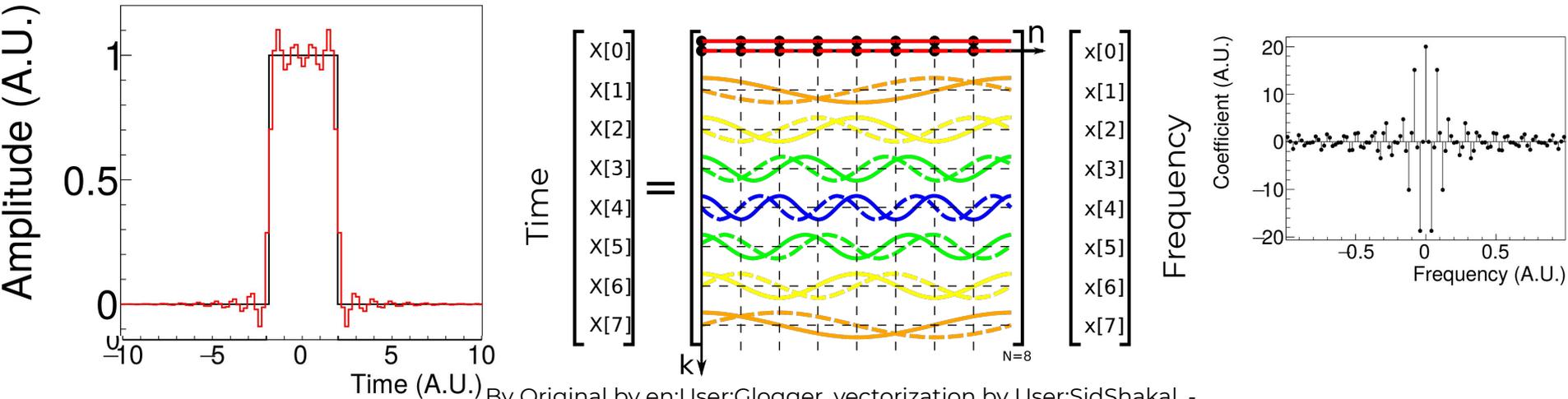


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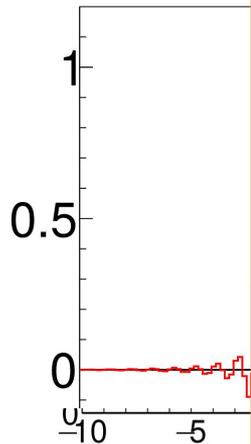


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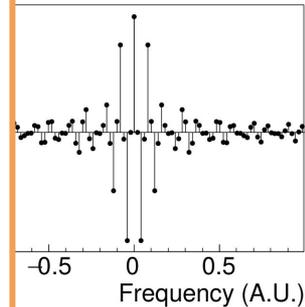
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- Approximate function as a linear sum of sines and

Amplitude (A.U.)



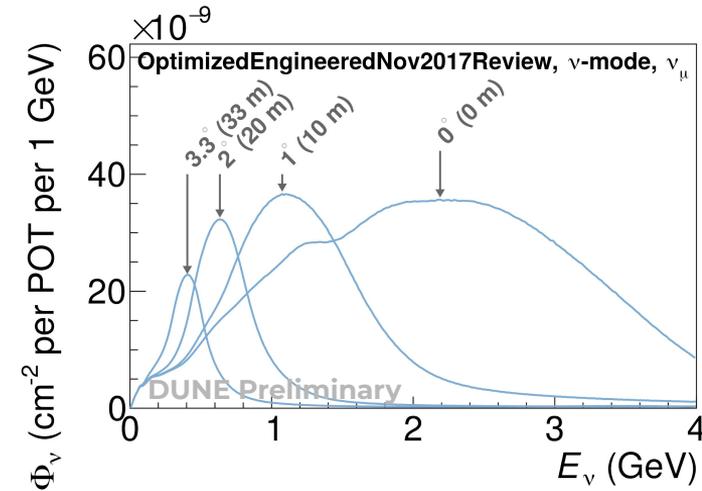
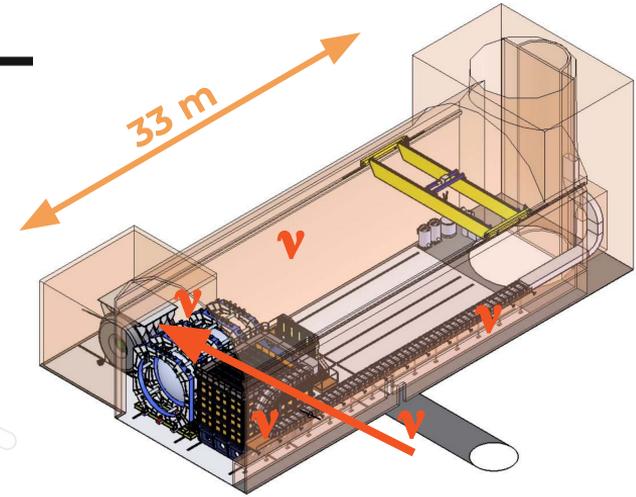
Maybe we can play a similar game with the DUNE near detector...



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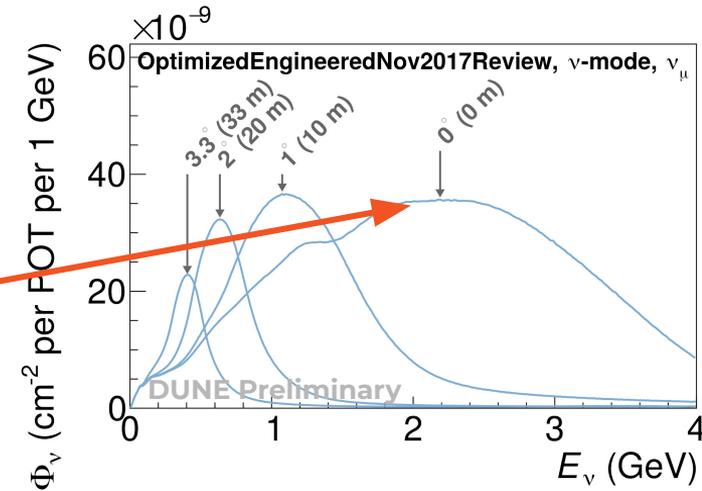
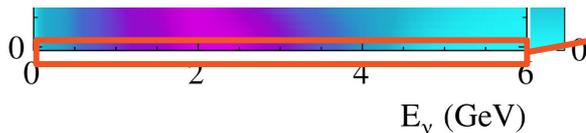
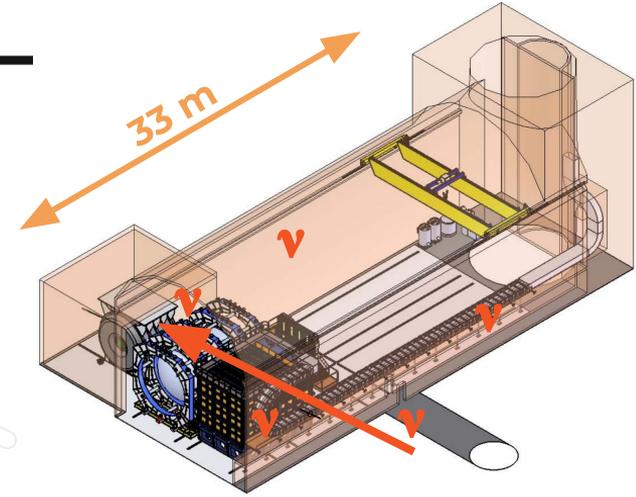
# Off Axis at the Near Detector

- Using a mobile Near Detector
  - Sample different neutrino energy spectra at different positions



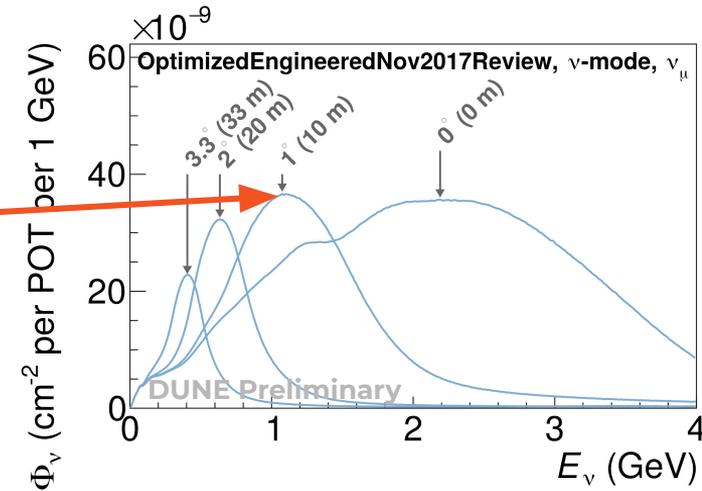
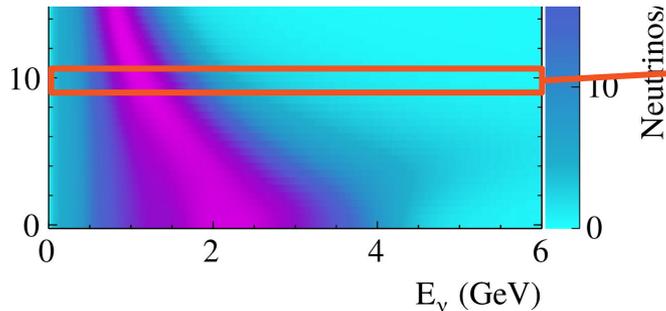
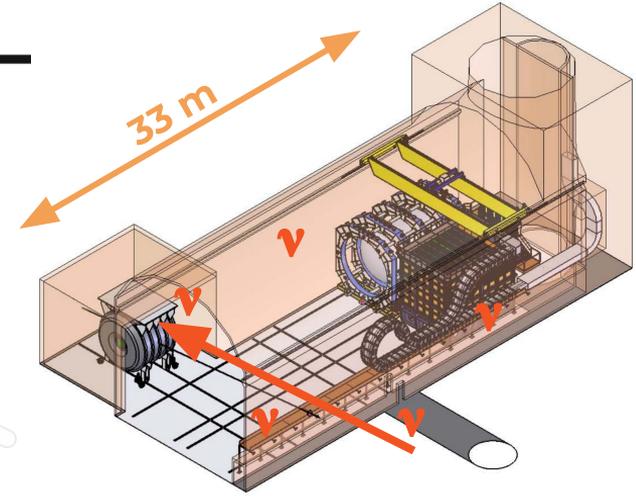
# Off Axis at the Near Detector

- Using a mobile Near Detector
  - Sample different neutrino energy spectra at different positions
  - Build up 2D measurement



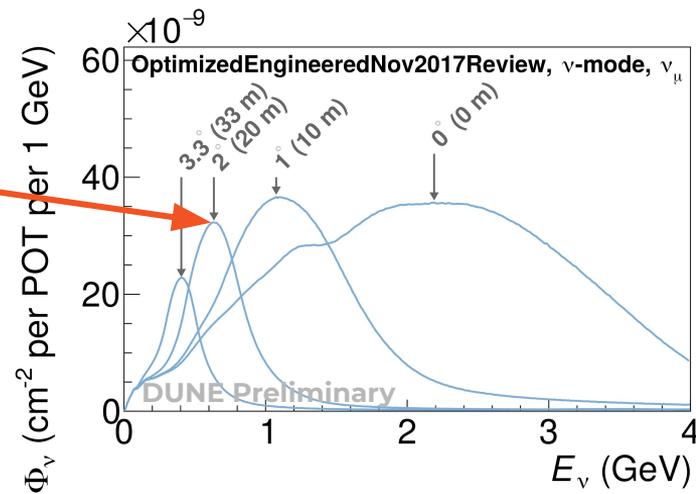
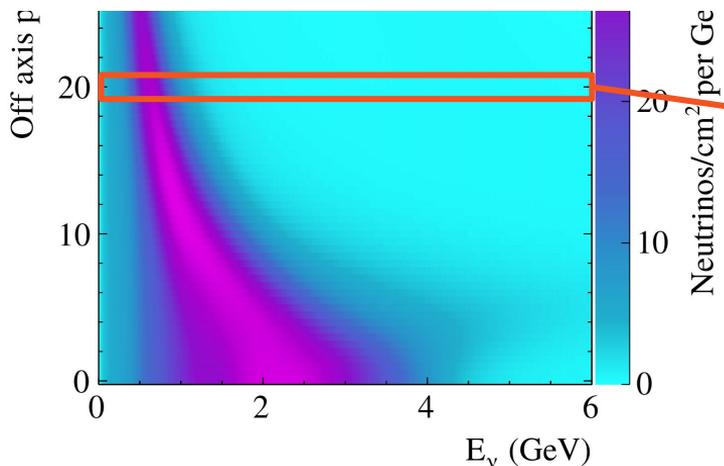
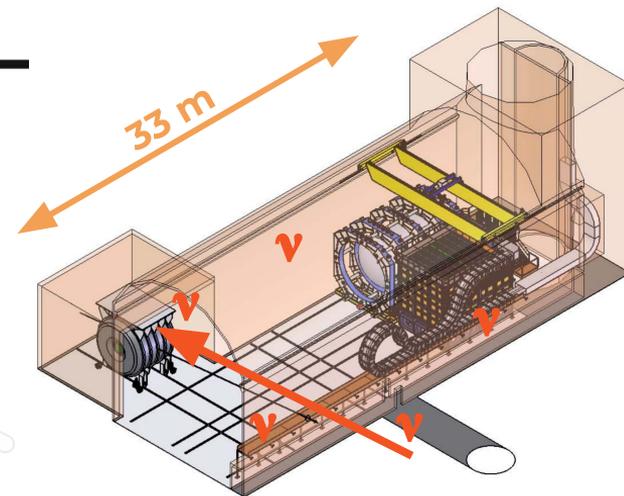
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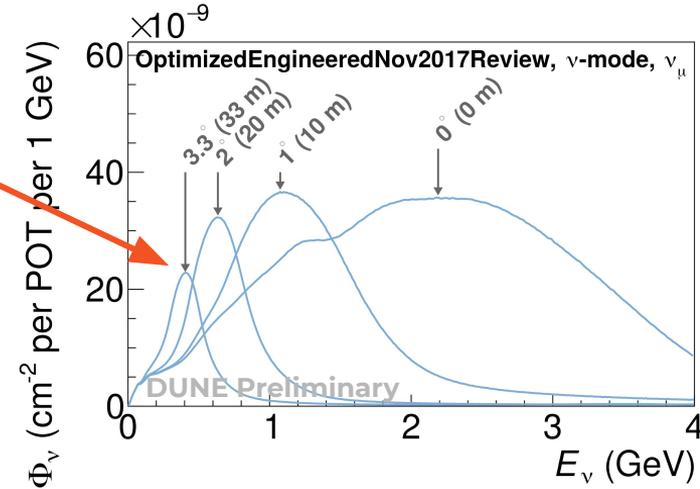
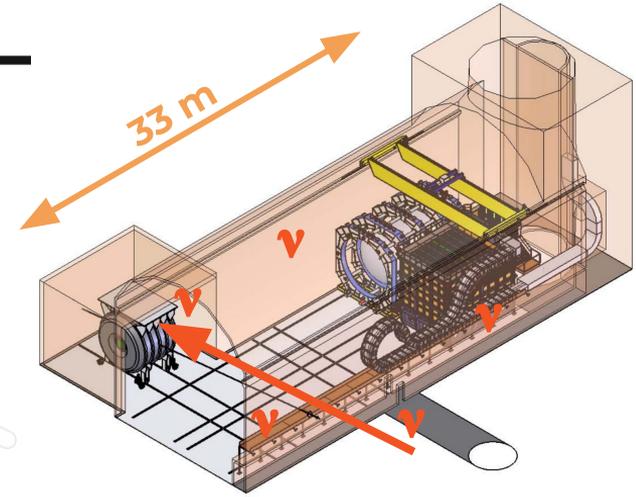
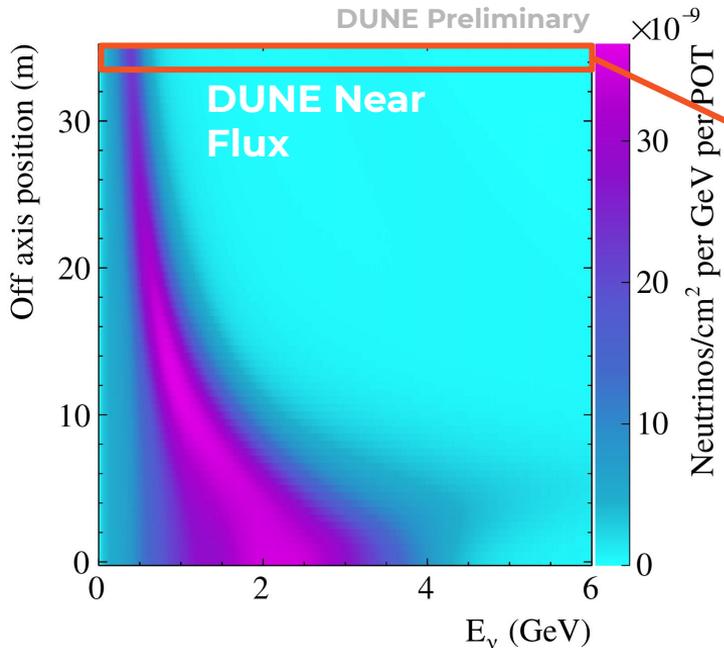
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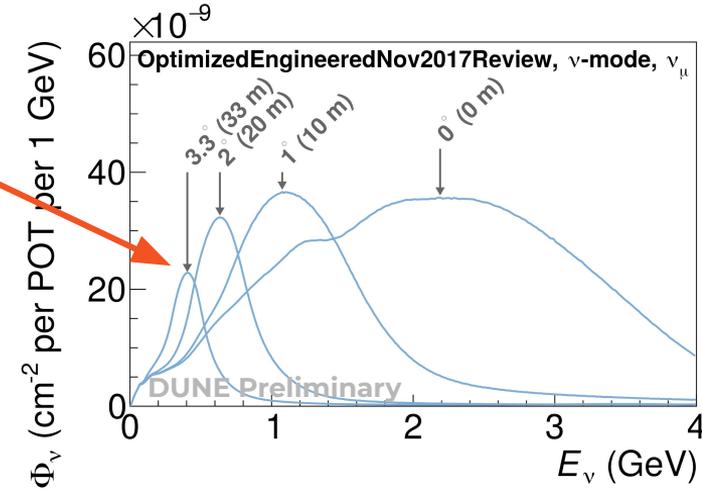
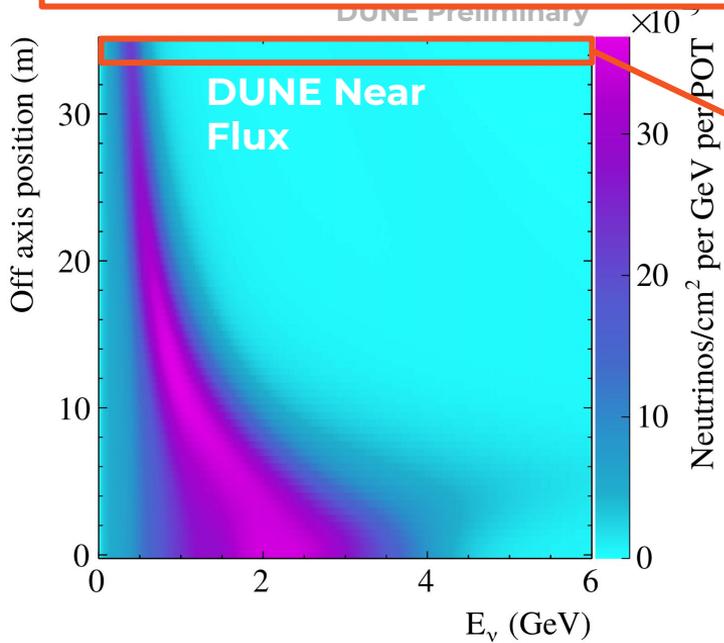
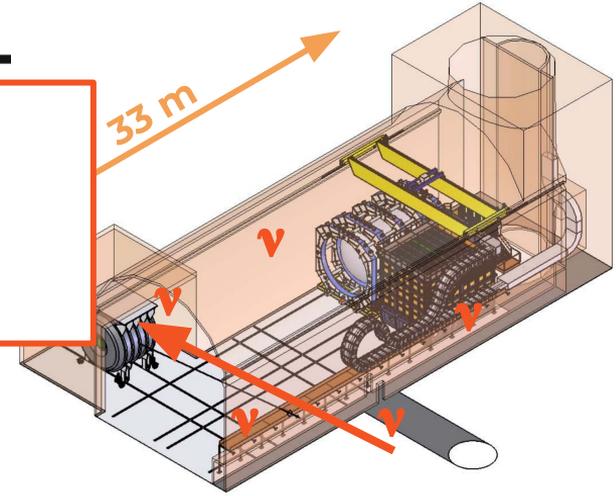
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# Off Axis at the Near Detector

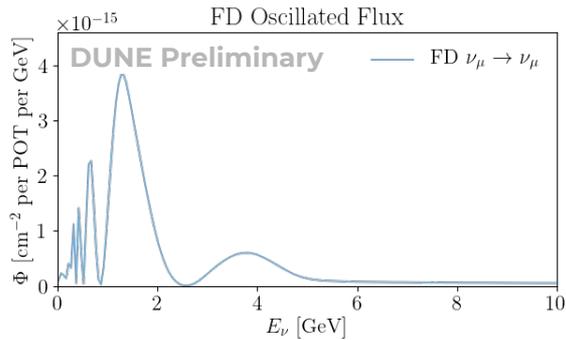
## Maximum off axis position sample at ~33m:

- Flux peaks at ~500 MeV
- Resolve second oscillation maximum



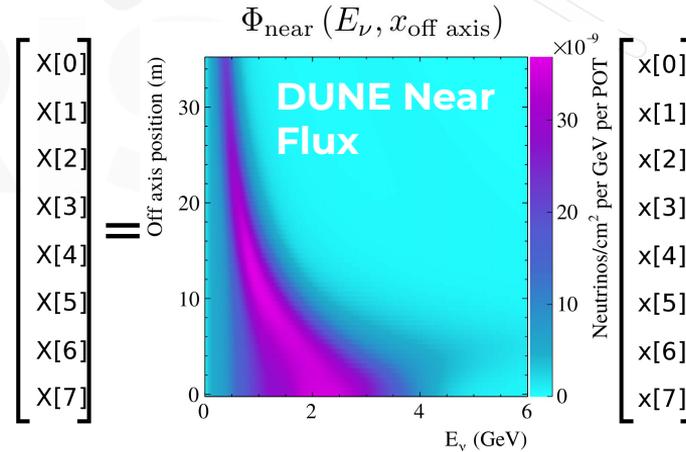
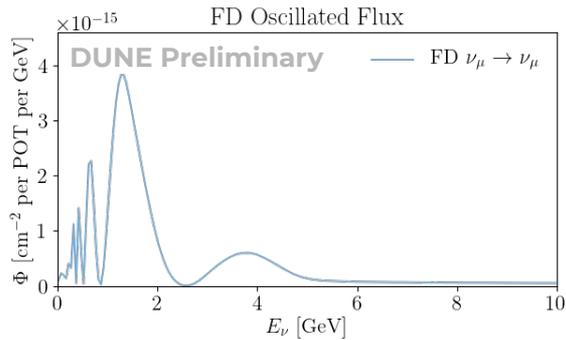
# Building an Oscillated Flux

- Want to measure oscillated flux at the near detector



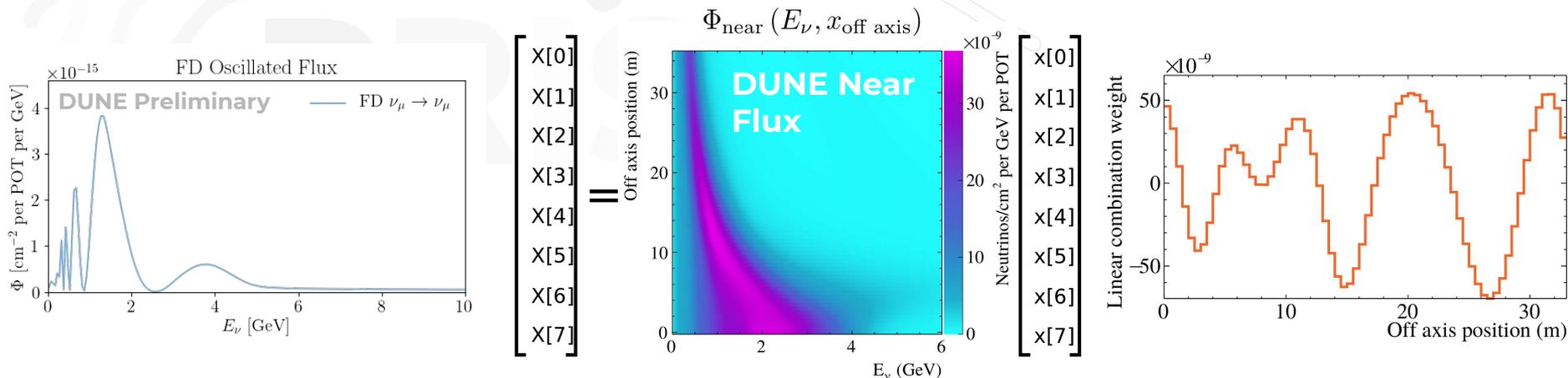
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  - **Try to decompose into a linear sum of off-axis near detector fluxes (c.f. Discrete FT)**



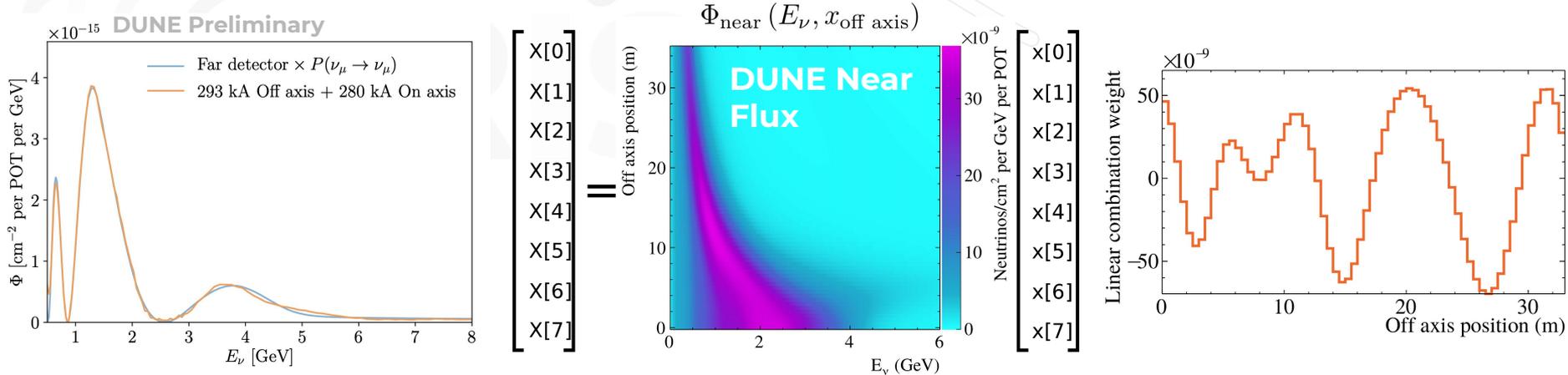
# Building an Oscillated Flux

- Want to measure oscillated flux at the near detector
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  - **Solve for weights at each off axis position**



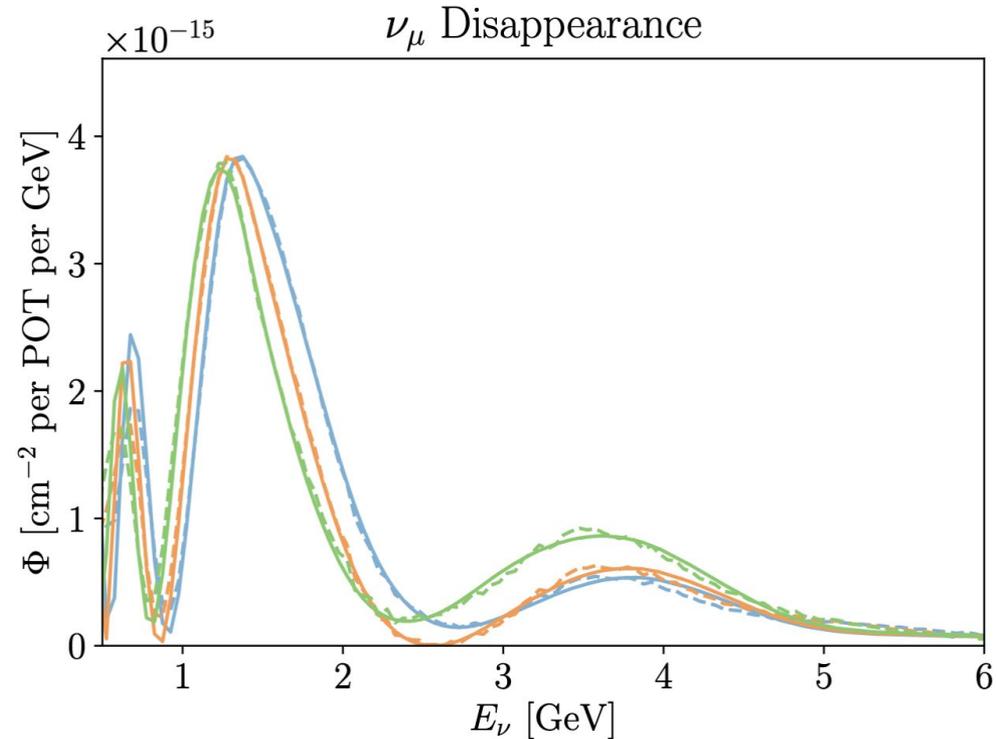
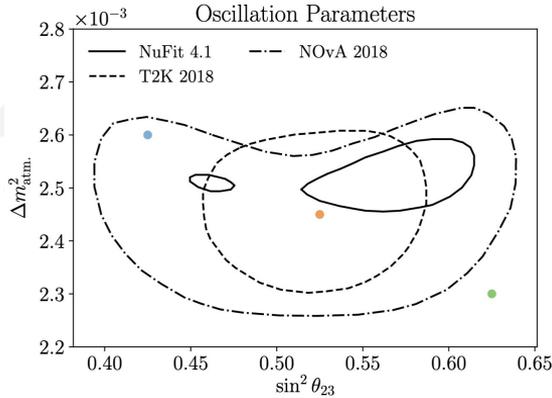
# Building an Oscillated Flux

- Want to measure oscillated flux at the near detector
  - Try to decompose into a linear sum of off-axis near detector fluxes (c.f. Discrete FT)
  - Solve for weights at each off axis position
  - **How good is the approximation?**



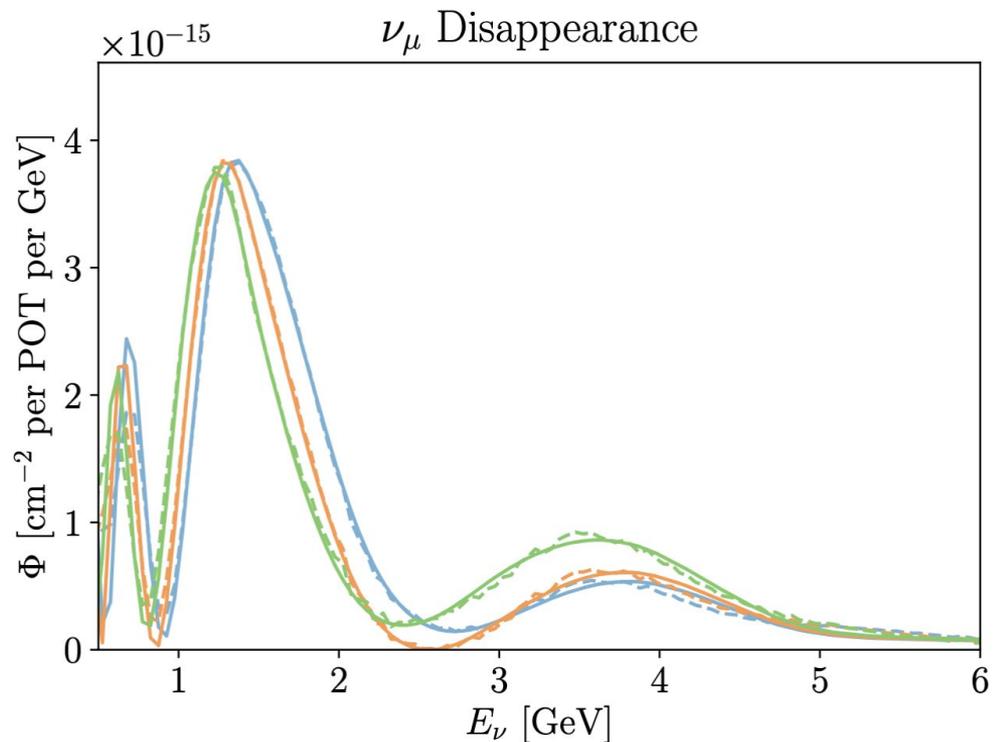
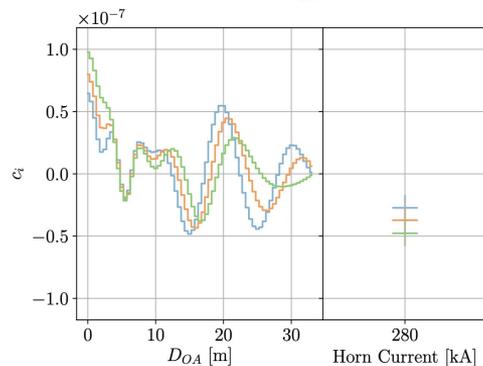
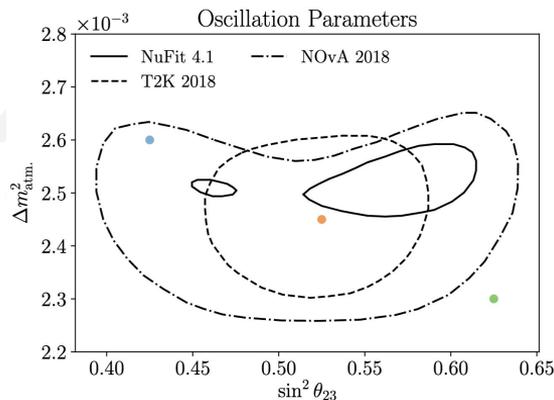
# Building Other Fluxes

- Can construct oscillated fluxes over the allowed parameter space



# Building Other Fluxes

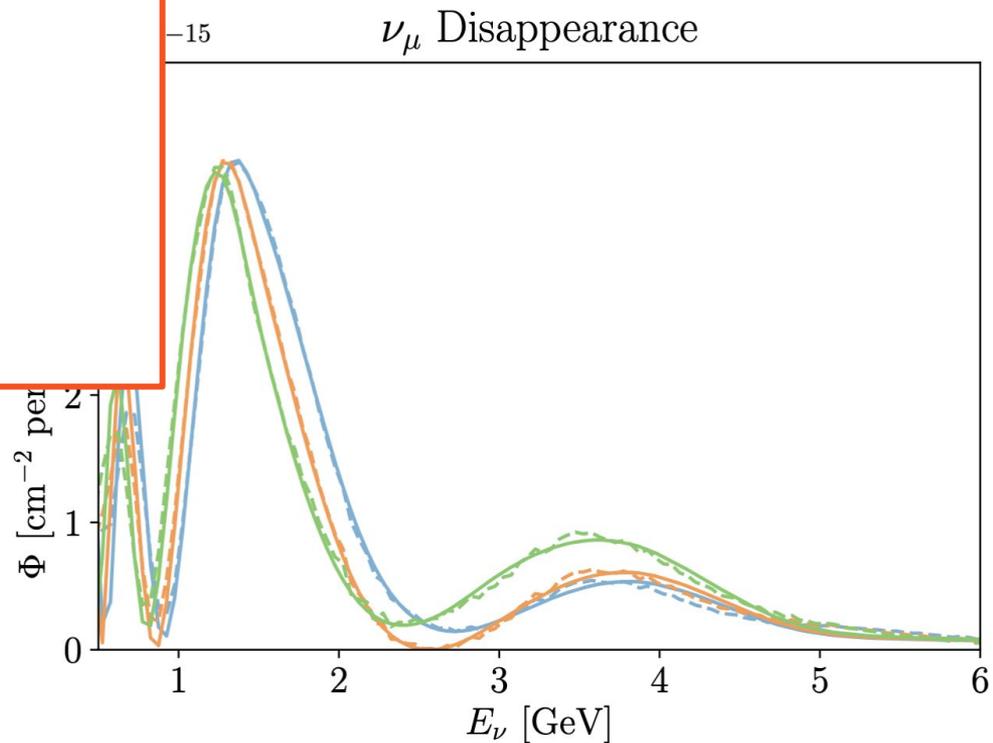
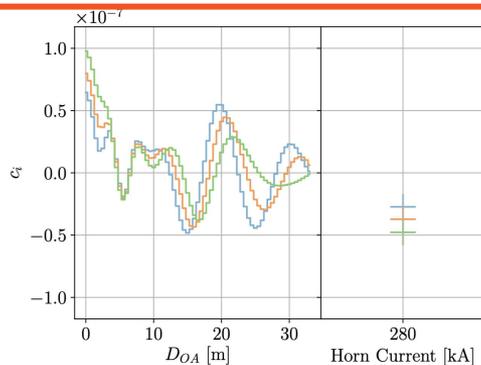
- Can construct oscillated fluxes over the allowed parameter space
  - Each set of oscillation parameters requires a different set of weights



# Building Other Fluxes

**Weights do not have intrinsic physical meaning...**

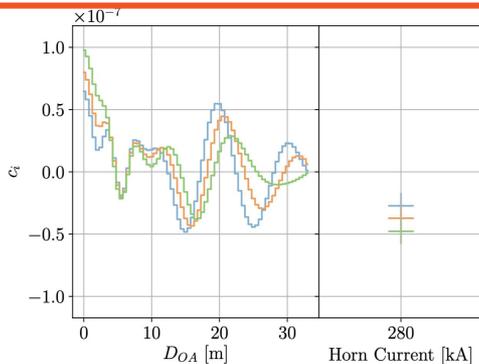
allowed parameter space  
different set of weights



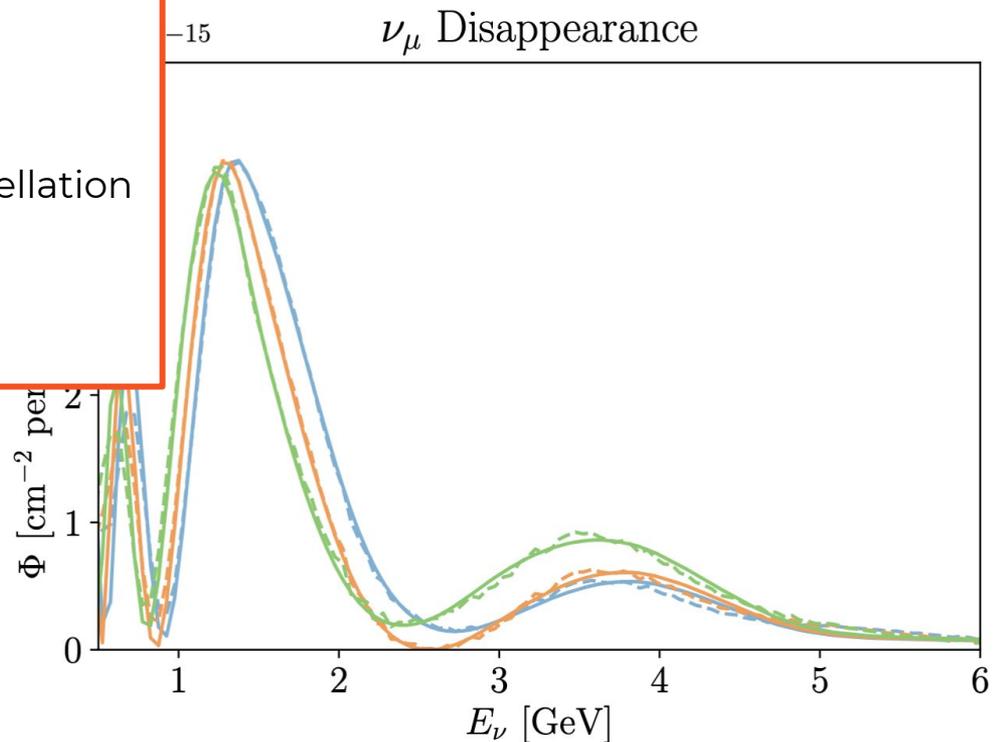
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**Weights do not have intrinsic physical meaning... but:**

- Some solutions have better statistical properties than others
- Some solutions may exhibit better cancellation of systematic uncertainties than others



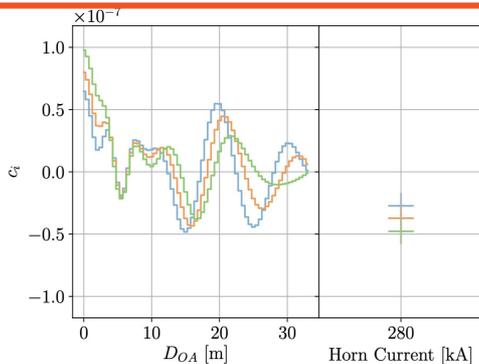
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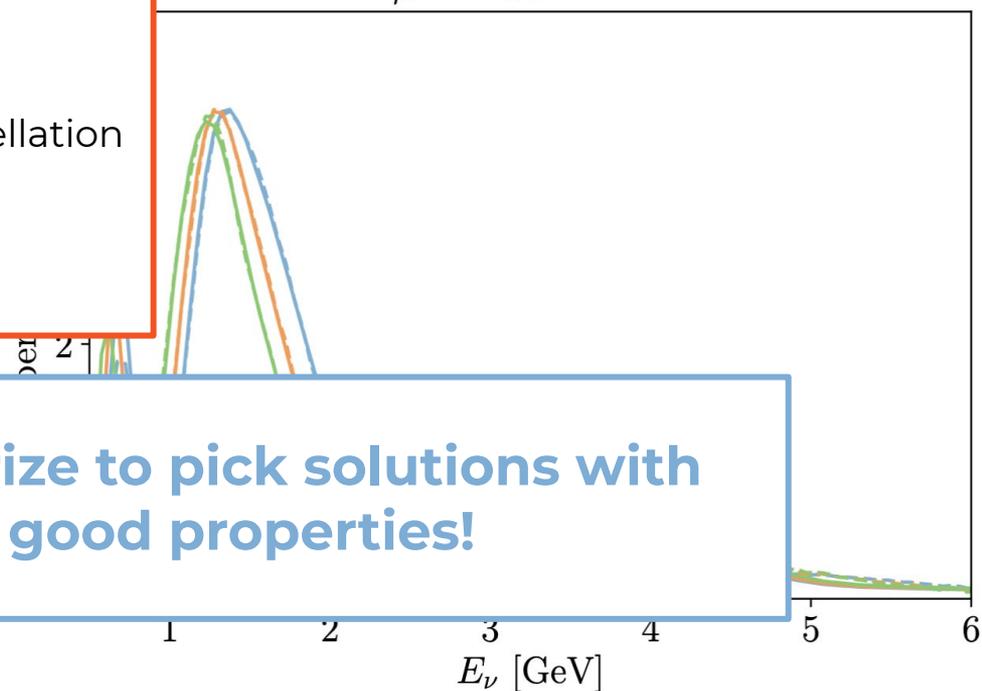
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allowed parameter space  
different set of weights

$\nu_\mu$  Disappearance



**Regularize to pick solutions with good properties!**

# How does that help?

- Use the PRISM method to build:  $\Phi_{\text{near}}(E_\nu, x_{\text{off axis}}) \times \vec{c} = \Phi_{\text{far}}(E_\nu) P_{\text{osc}}(E_\nu)$



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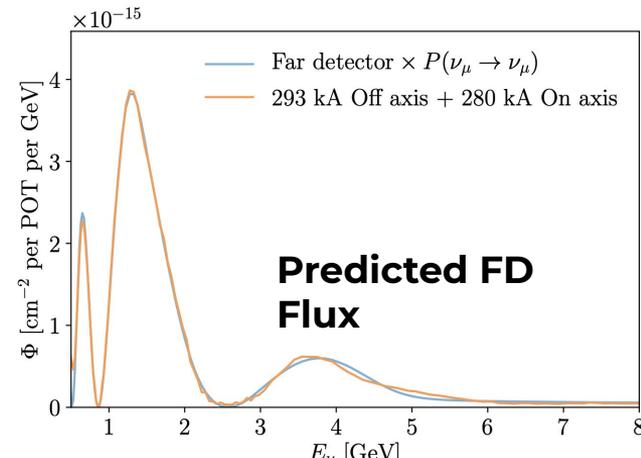
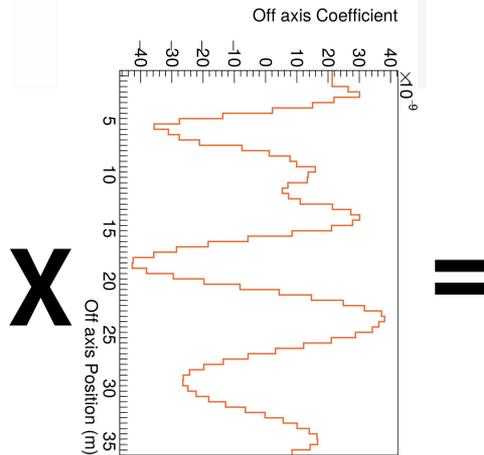
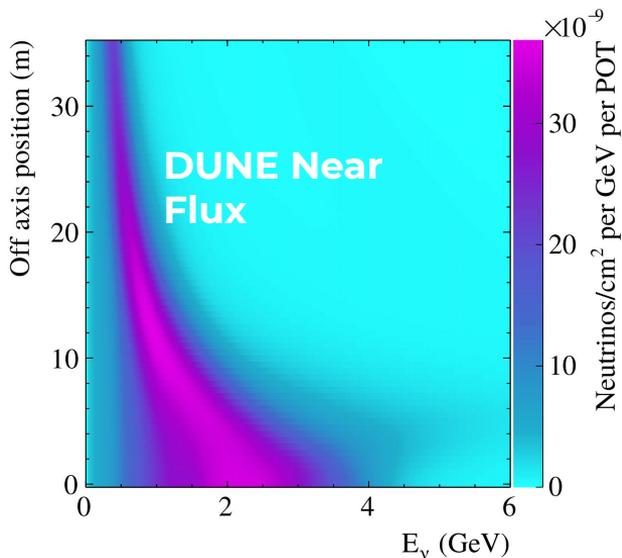
- **Use the PRISM method to build:**  $\Phi_{\text{near}}(E_\nu, x_{\text{off axis}}) \times \vec{c} = \Phi_{\text{far}}(E_\nu) P_{\text{osc}}(E_\nu)$
- **Cross sections are not position dependent**
- **When we pick the correct oscillation hypothesis:**
  - Signal event rates are the same near and far!

$$N_{\text{near}}(E_{\text{obs}}) = \int dE_\nu \Phi_{\text{near}}(E_\nu, x_{\text{off axis}}) \times \vec{c} \cdot \sigma(E_\nu) \cdot \mathbf{D}_{\text{near}}$$

$$N_{\text{far}}(E_{\text{obs}}) = \int dE_\nu \Phi_{\text{far}}(E_\nu) \cdot P_{\text{osc}}(E_\nu) \cdot \sigma(E_\nu) \cdot \mathbf{D}_{\text{far}}$$

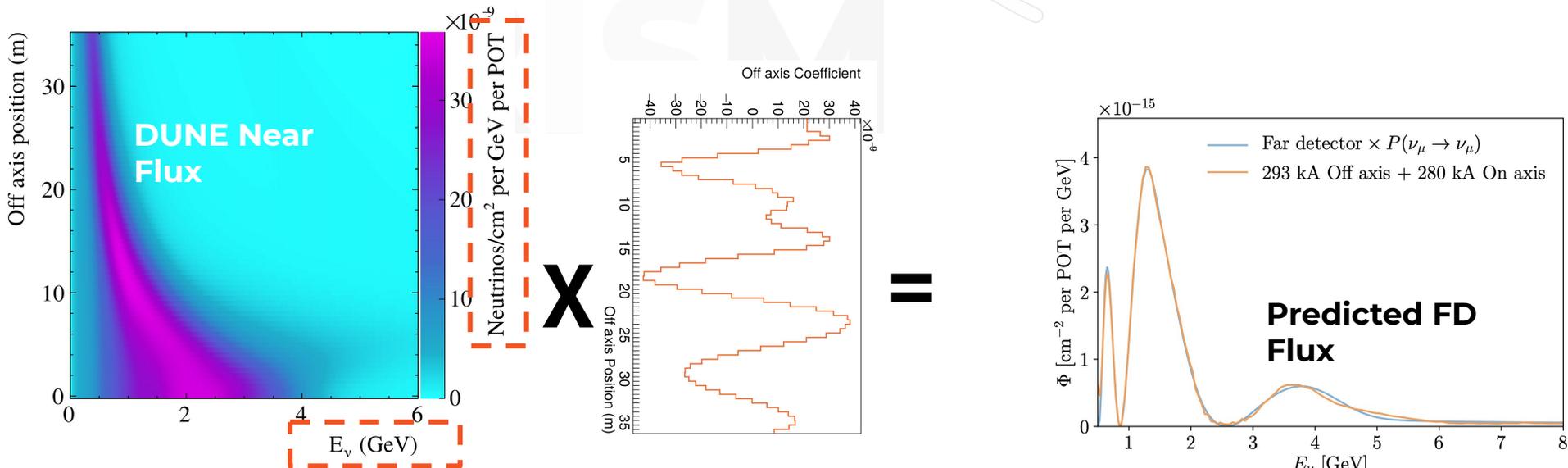
# Building a Far Detector prediction

- Linear sum only depends on off axis position and flux prediction.
  - The same weights can be applied to sampled interactions
  - in any observable quantity



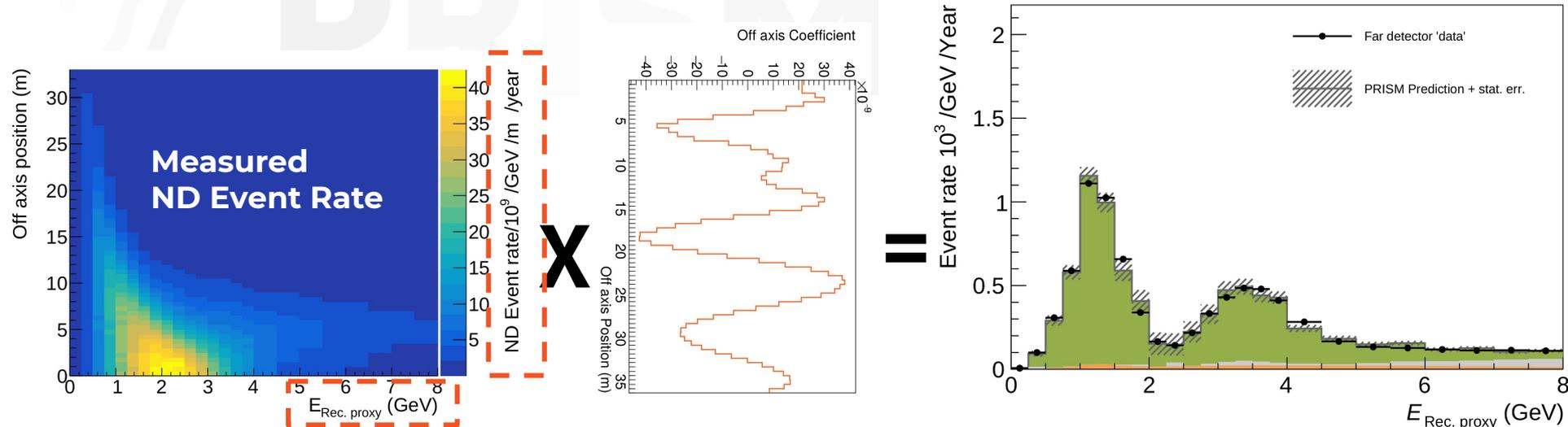
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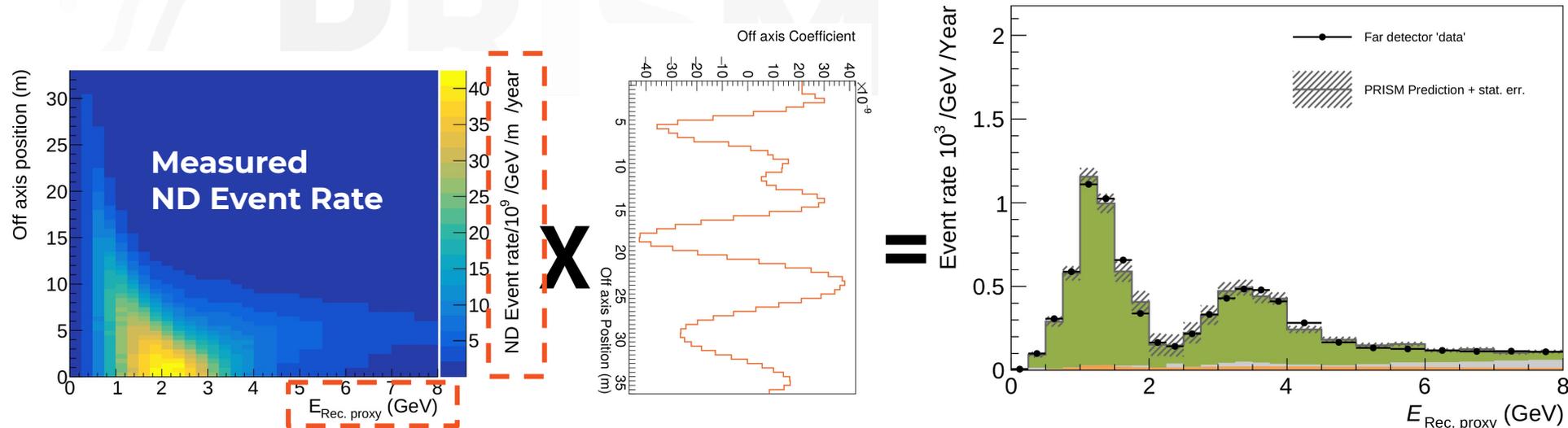
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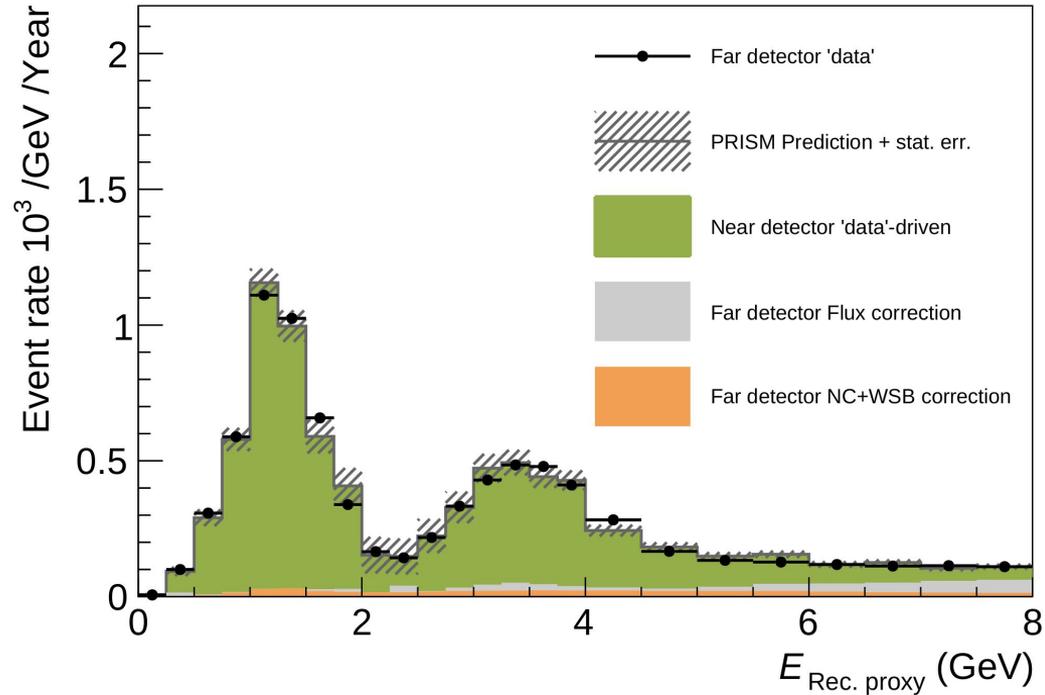
- Linear sum only depends on off axis position and flux prediction.
  - The same weights can be applied to sampled interactions
  - in any observable quantity
- The Power of PRISM:
  - Predicted the far detector observable signal event rate for some oscillation hypothesis
  - Have not yet invoked a neutrino interaction model!



# The Full PRISM prediction

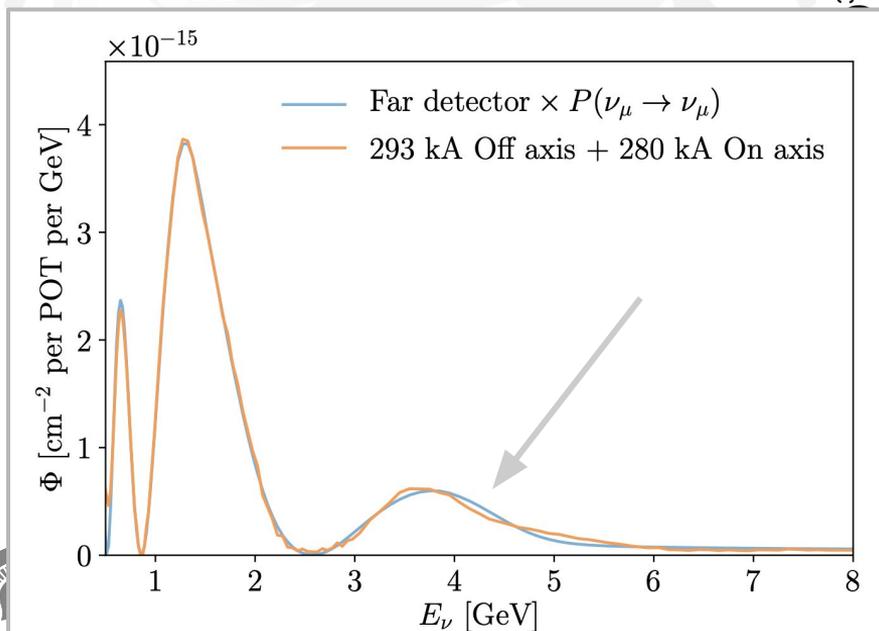
- Do still have to correct for:
  - Imperfect flux matching
  - Backgrounds in the near and far selection

NuFit 4.1,  $\Delta|M^2|_{32} = 2.52 \times 10^{-3} \text{ eV}$ ,  $\sin^2(\theta_{23}) = 0.525$

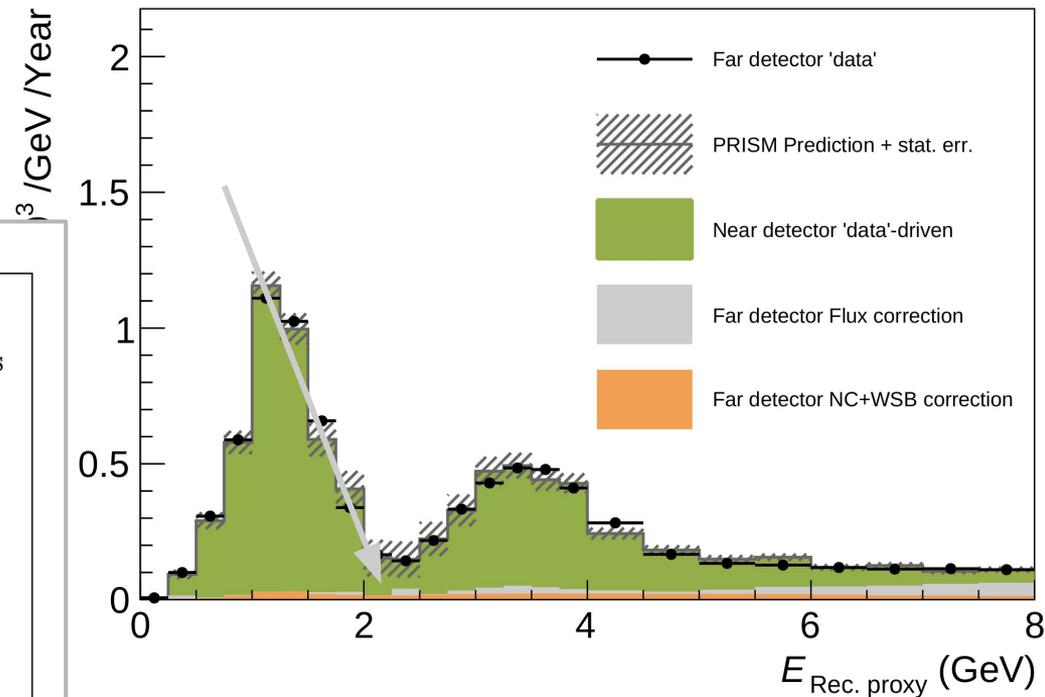


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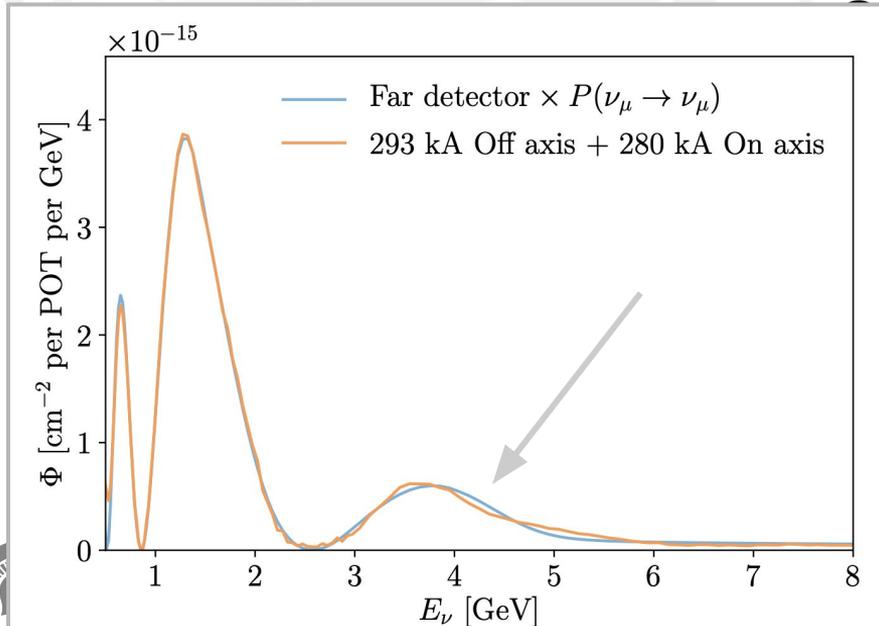


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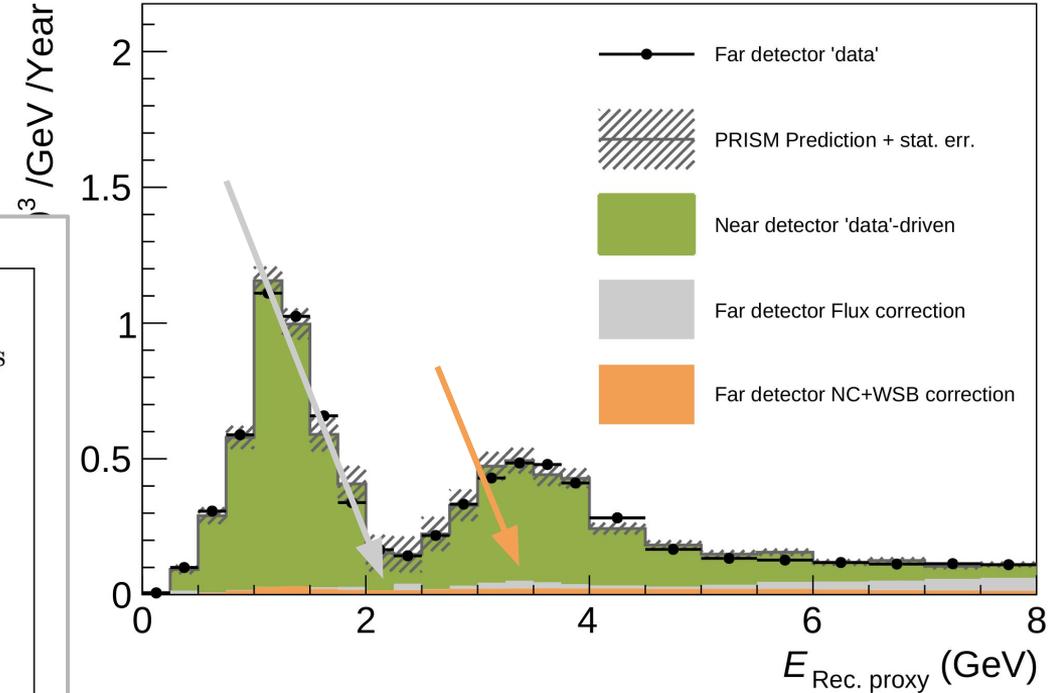


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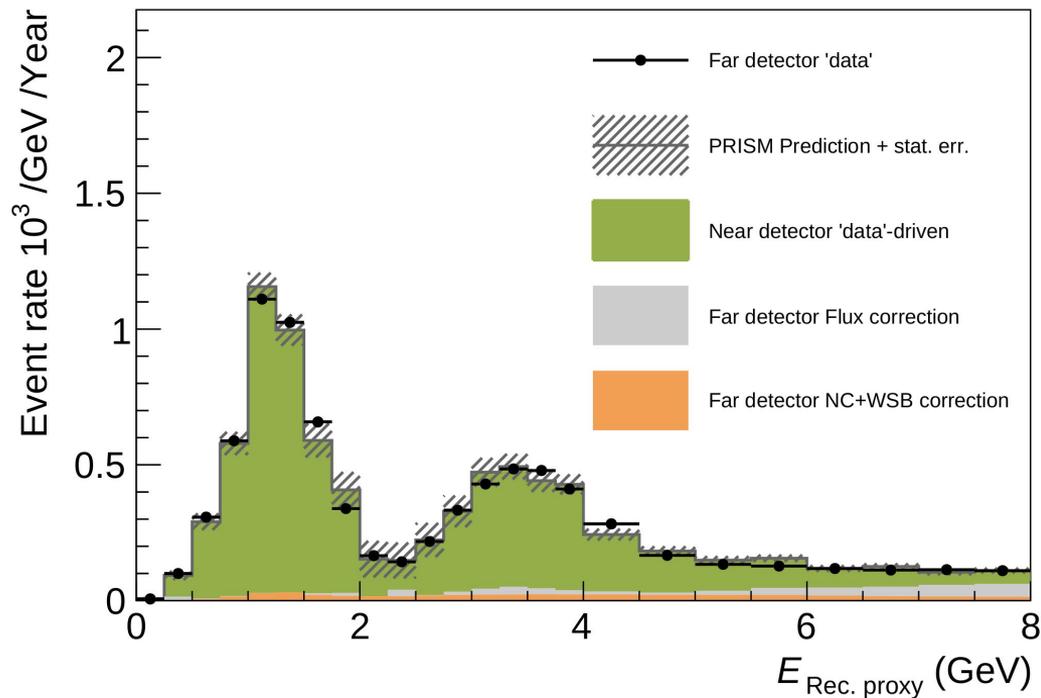
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- Do still have to correct for:
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  - Backgrounds in the near and far selection
- Majority of oscillated far prediction is rearranged near detector signal data.

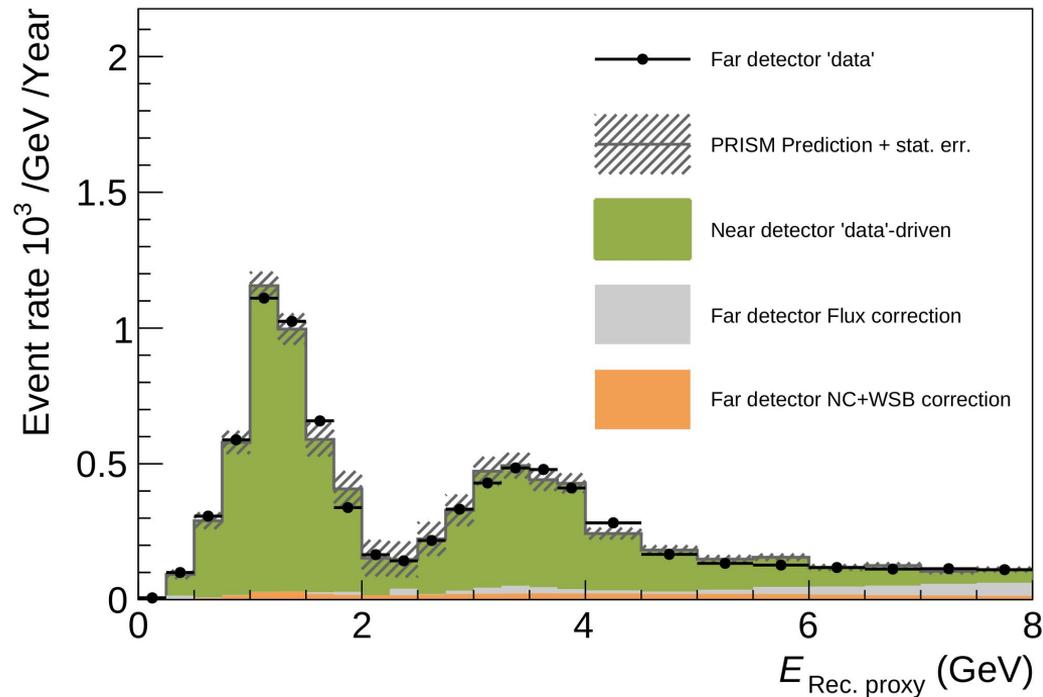
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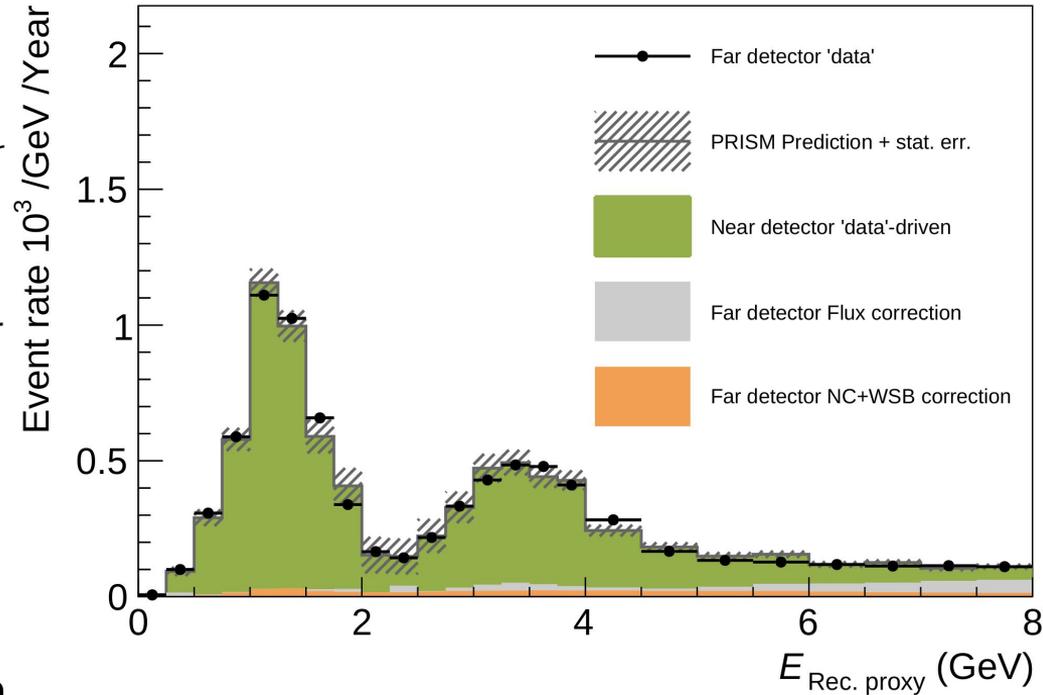
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- **In a traditional analysis, the whole spectrum would be a predicted by an ND-constrained model.**

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# Putting PRISM Into Practice



# A 'mock' data Study

---

- What if the interaction model is wrong but it was missed?

DUVE  
PRISM

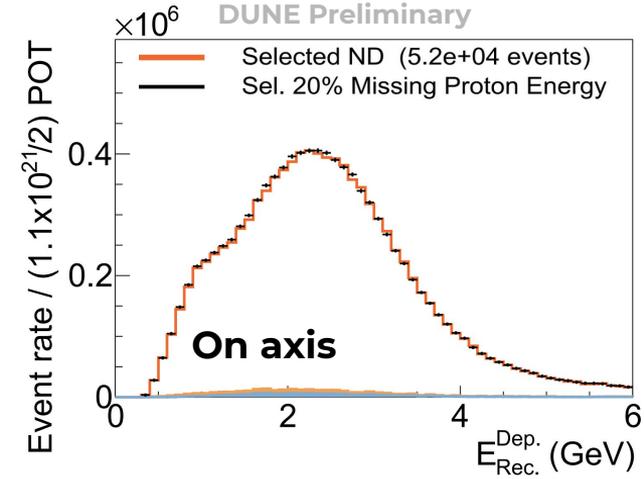
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PRISM

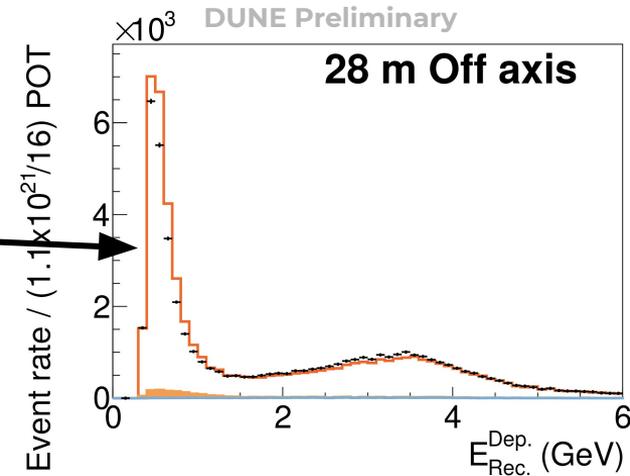
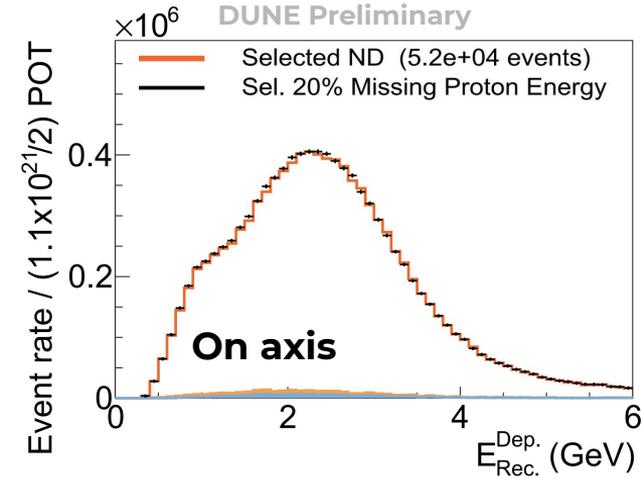
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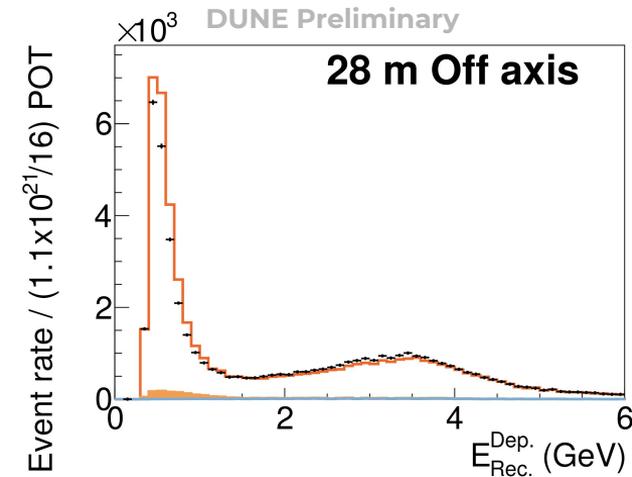
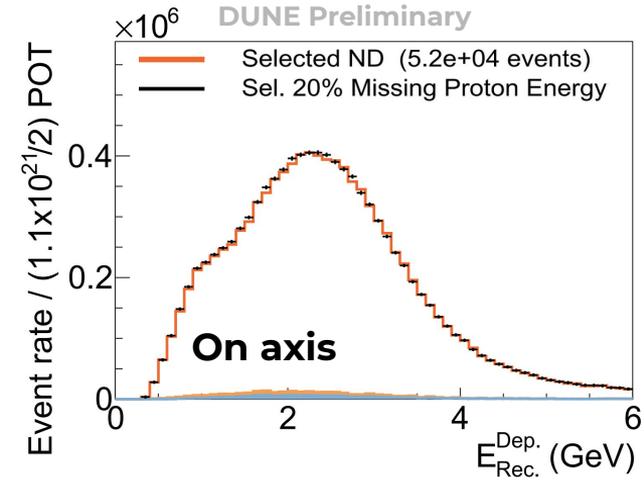
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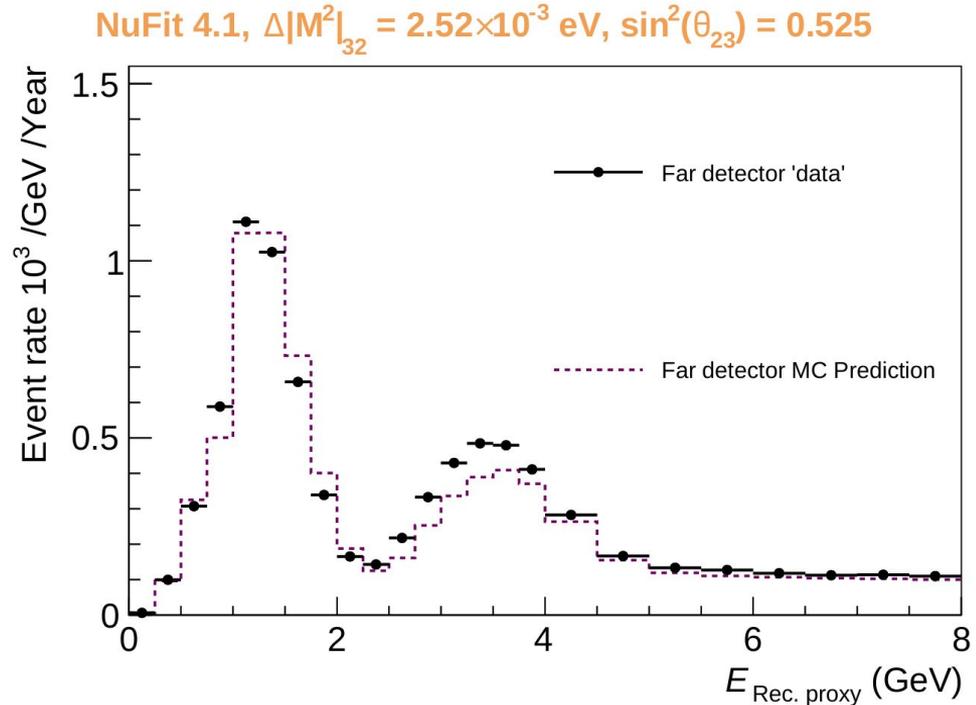
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- Case Study:
  - Move 20% of proton KE to neutrons but fit model to on-axis ND data.
  - Not able to simultaneously describe on an off axis data with incorrect model
  - But not obvious how to incorporate this in a traditional analysis...



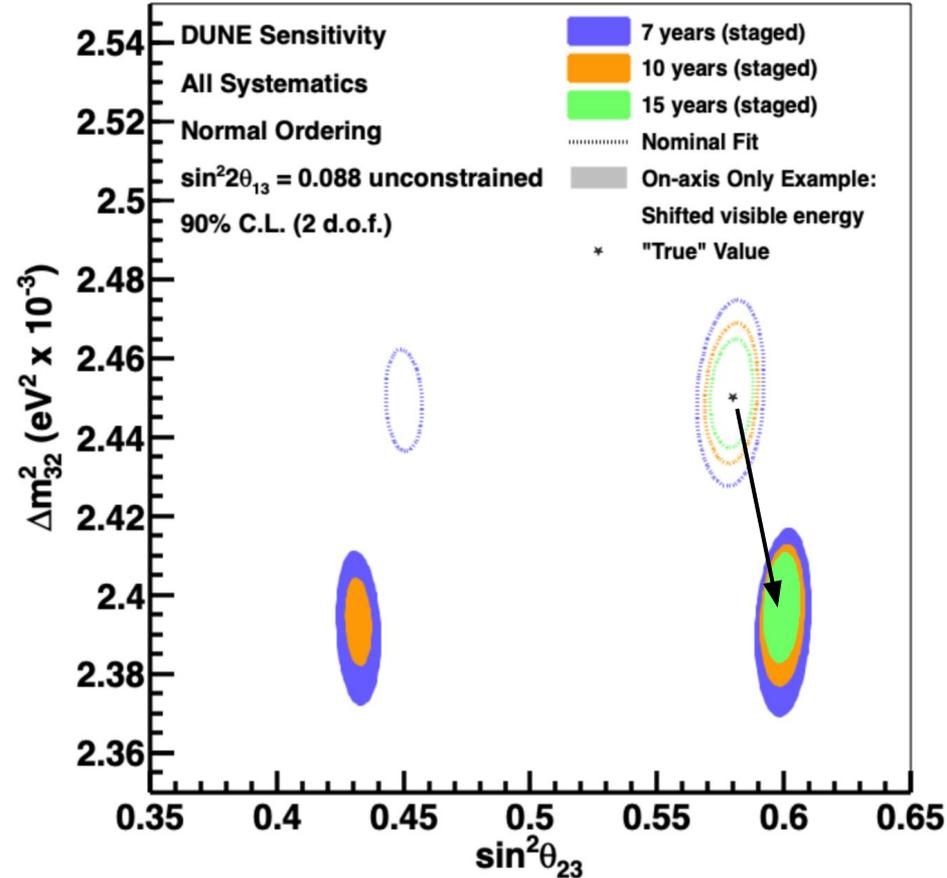
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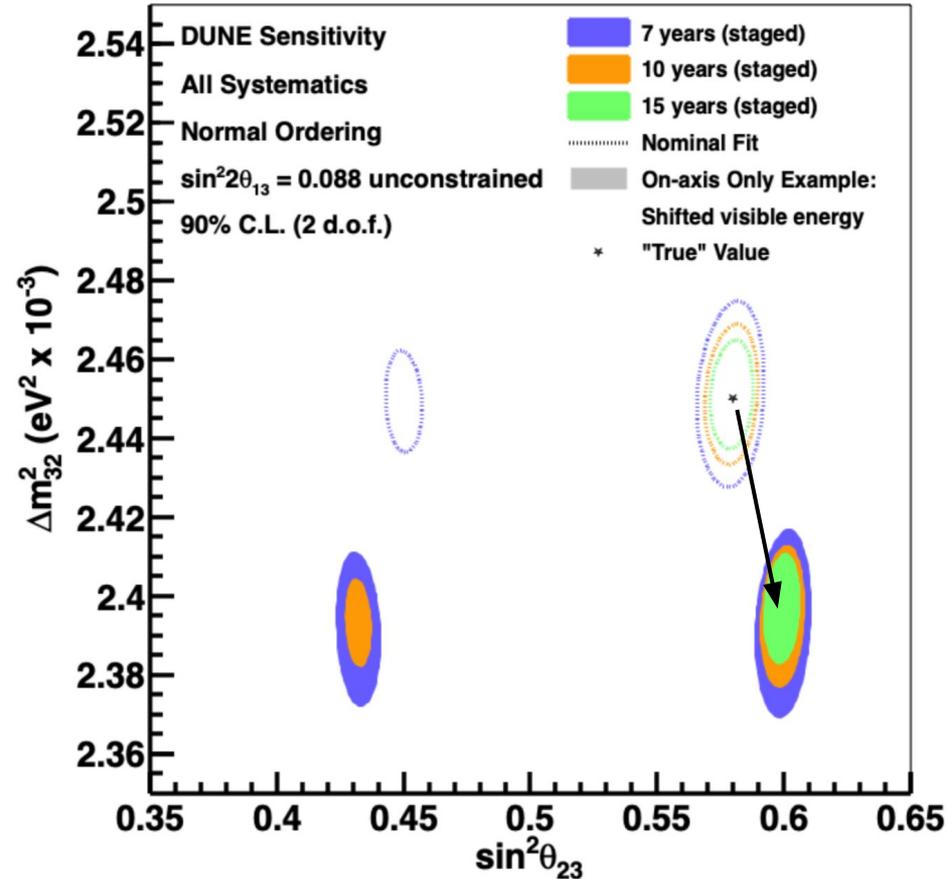
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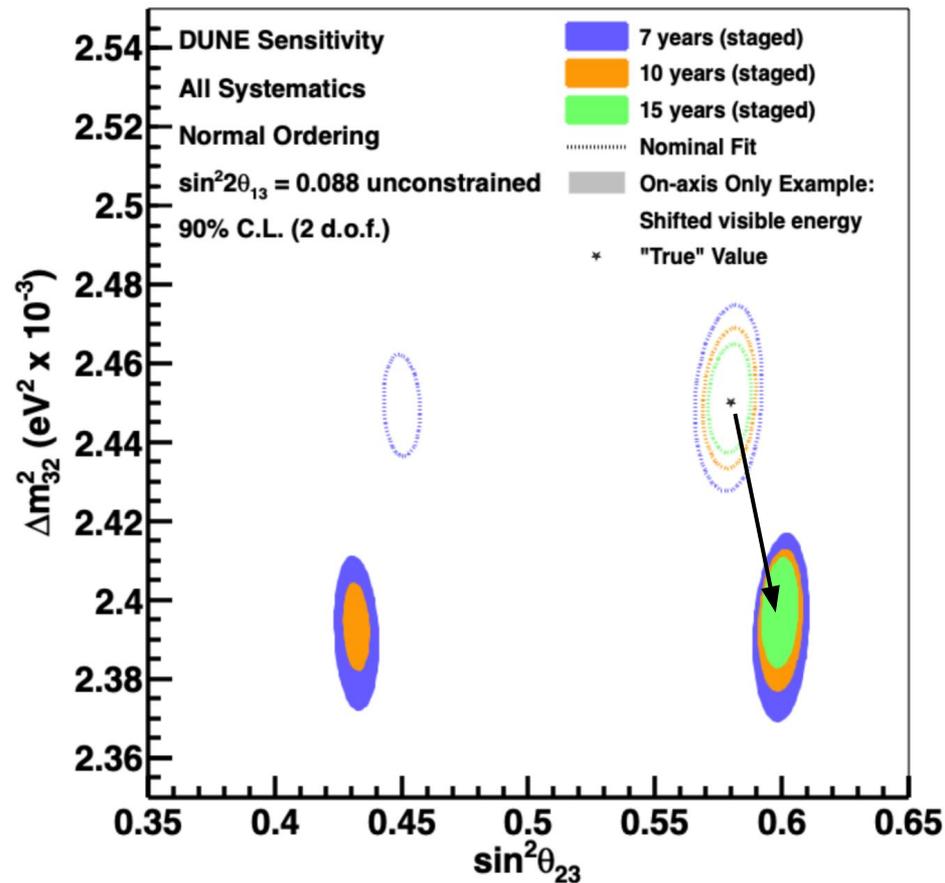
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    - **We wouldn't know we were wrong**
    - **More data wouldn't help**



# Mock Data Spectrum

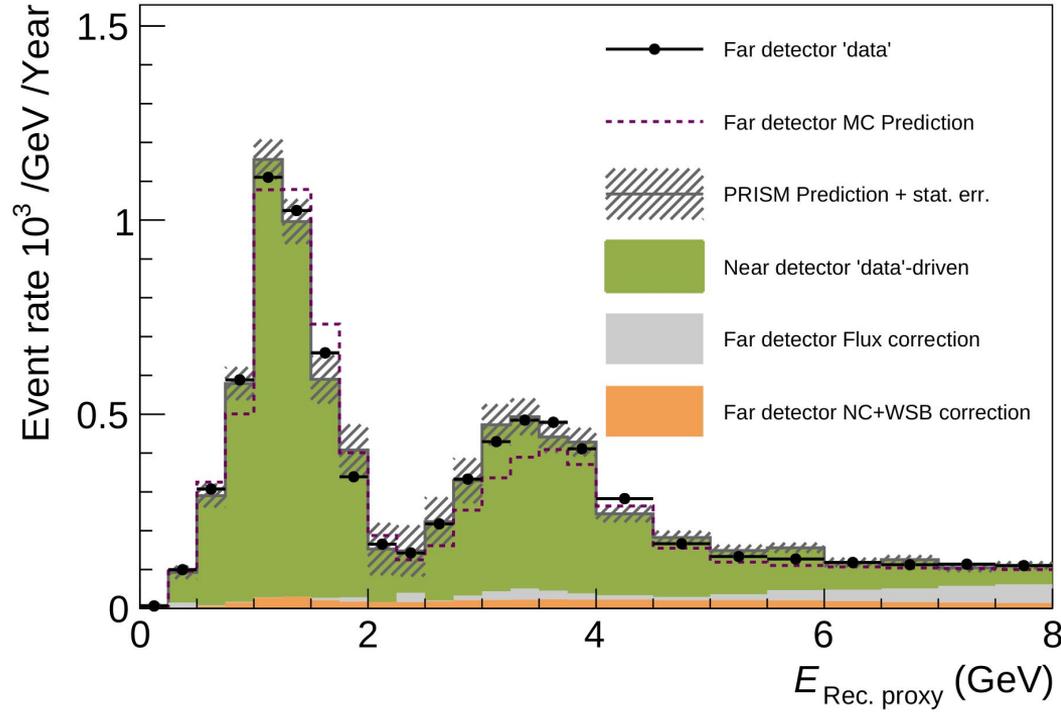
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    - We wouldn't know we were wrong
    - More data wouldn't help
- **What if we ask PRISM?**



# Let PRISM Have a Go

- PRISM Predicts far detector observation well even with incorrect interaction model!

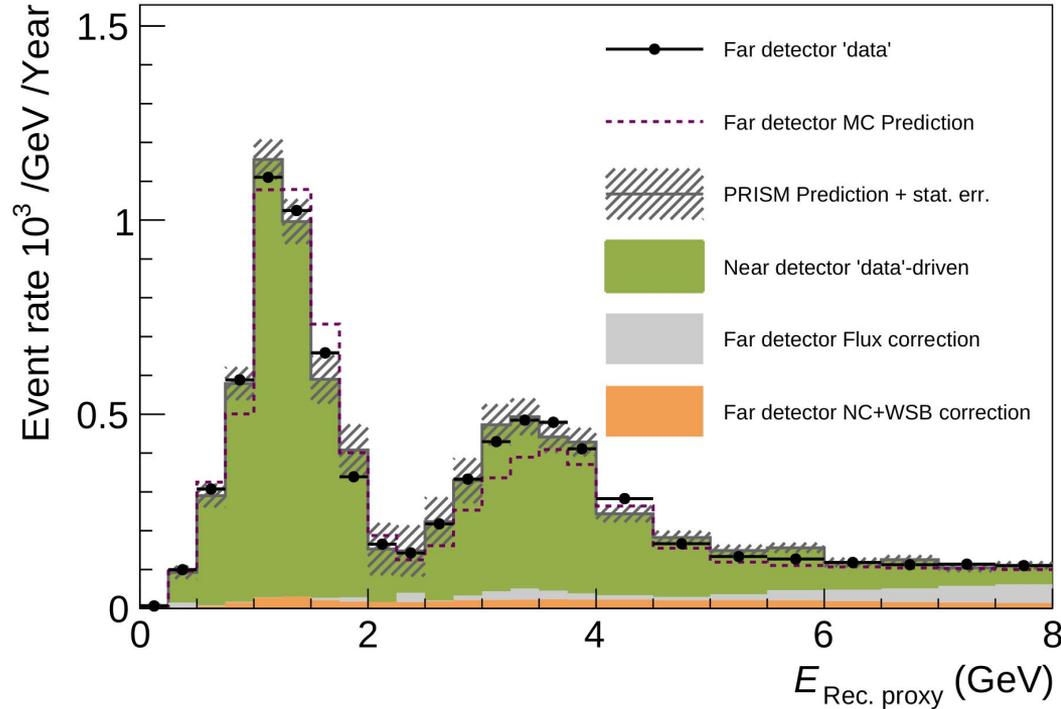
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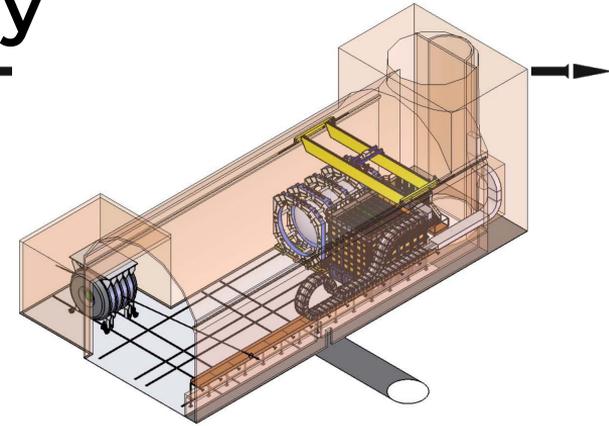
- PRISM Predicts far detector observation well even with incorrect interaction model!
  - **The direct extrapolation of near detector data largely side-steps the modelling problem.**

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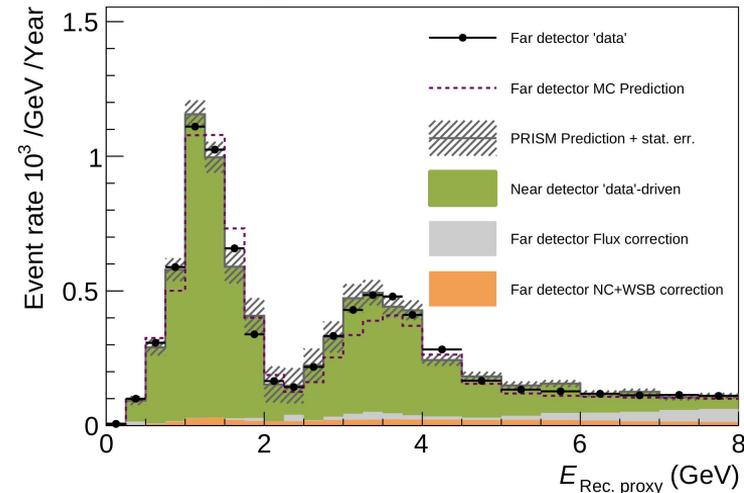


# DUNE-PRISM Analysis Summary

- **DUNE-PRISM is the critical analysis innovation that will enable DUNE to meet its oscillation physics goals.**
- A moveable near detector is now part of the DUNE design
- The DUNE-PRISM oscillation analysis will produce minimally biased results even without precise neutrino interaction models.



NuFit 4.1,  $\Delta|M^2|_{32} = 2.52 \times 10^{-3} \text{ eV}$ ,  $\sin^2(\theta_{23}) = 0.525$



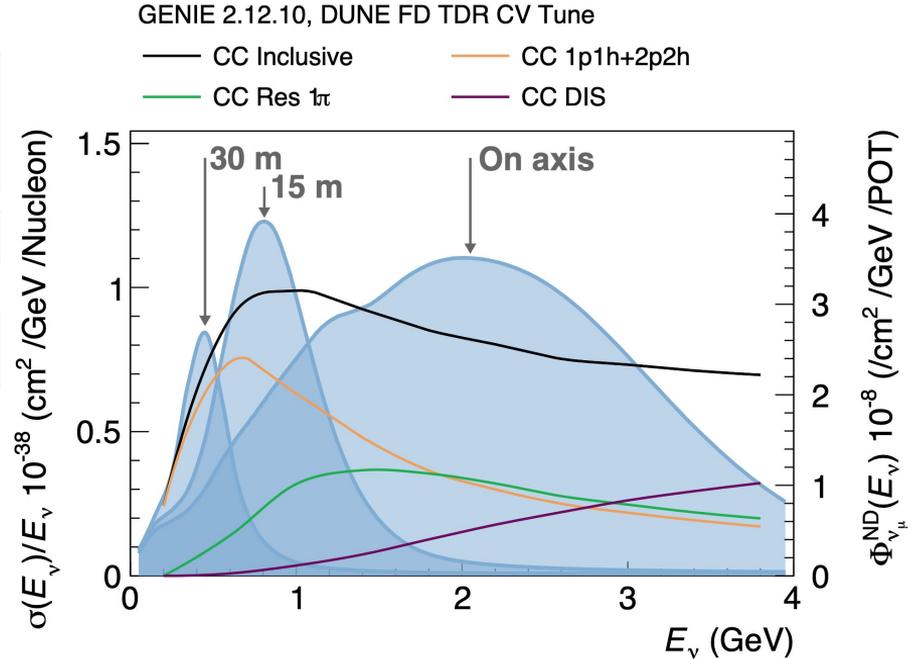


**Wait... There's More!**



# Measuring Cross Sections

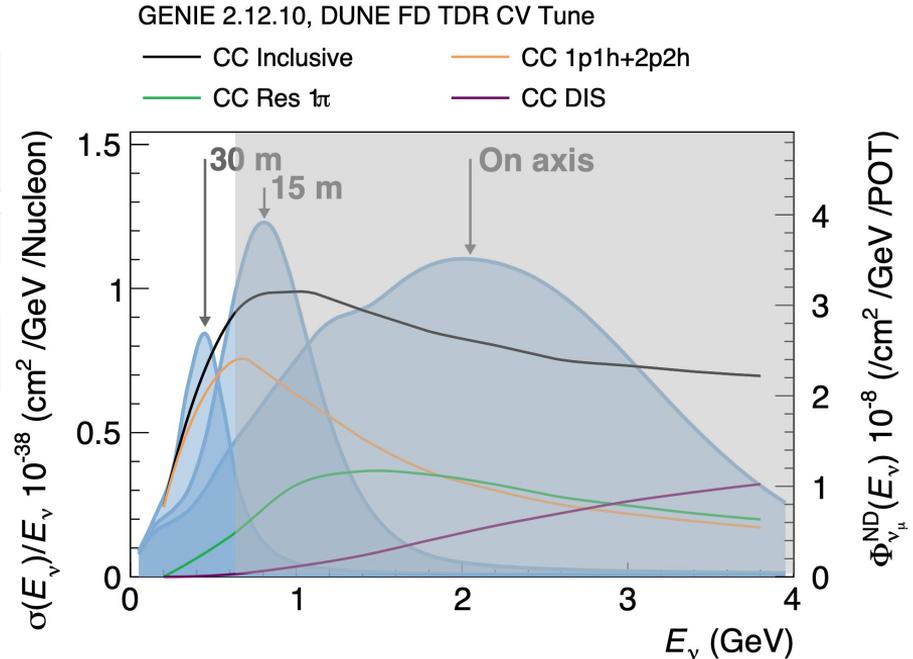
- Expect to take large interaction samples at all off axis positions.



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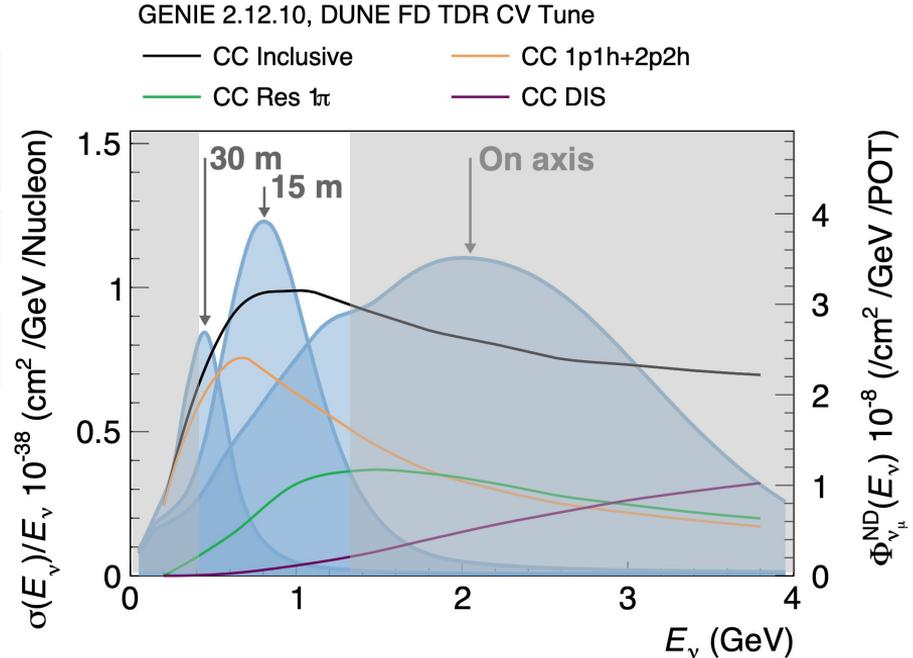
		Liquid				Gas
		All int.	Selected			All int.
Stop	Run duration	$N_{\nu_{\mu}CC}$	NSel	WSB	NC	$N_{\nu_{\mu}CC}$
On axis (293 kA)	21 wks.	21.9M	10.2M	0.2%	1.3%	590,000
On axis (280 kA)	1 wk.	1M	470,000	0.3%	1.4%	27,000
4 m off axis	18 dys.	2.3M	1.2M	0.3%	1.0%	61,000
8 m off axis	18 dys.	1.3M	670,000	0.5%	0.9%	35,000
12 m off axis	18 dys.	660,000	340,000	0.8%	0.7%	18,000
16 m off axis	18 dys.	380,000	190,000	1.1%	0.7%	10,000
20 m off axis	18 dys.	230,000	120,000	1.3%	0.7%	6,300
24 m off axis	18 dys.	160,000	76,000	1.8%	0.7%	4,200
28 m off axis	18 dys.	110,000	50,000	2.1%	0.8%	2,900
32 m off axis	18 dys.	61,000	28,000	2.4%	0.7%	1,600



# Measuring Cross Sections

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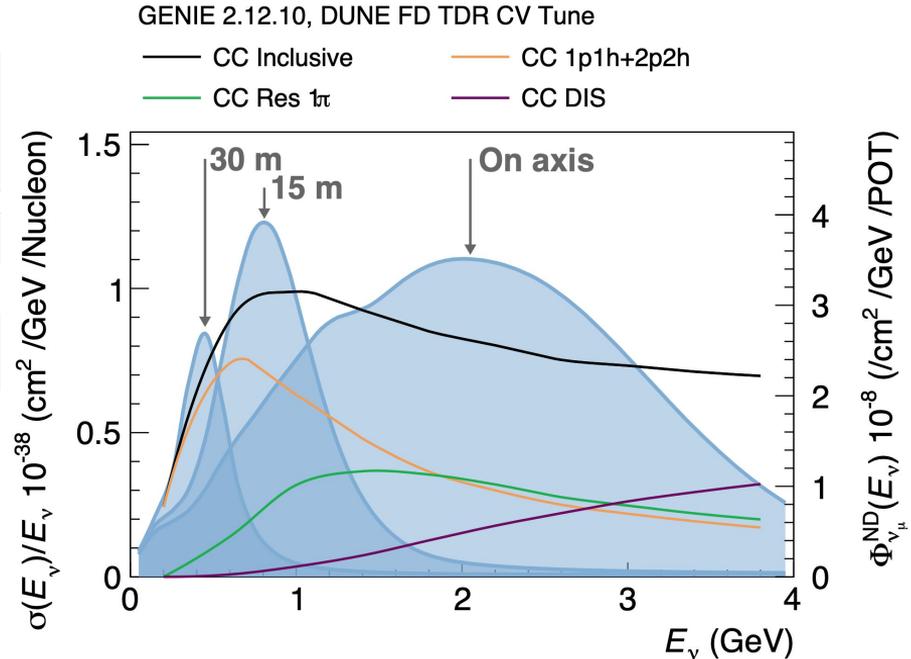
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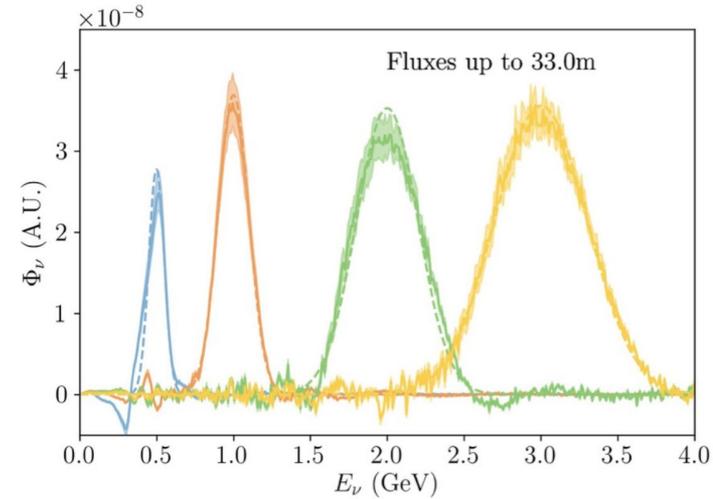
- Expect to take large interaction samples at all off axis positions.
  - Wealth of data in different energy ranges to begin to pick apart degeneracies in cross-section model

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		All int.	Selected			All int.
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# Narrow-band fluxes

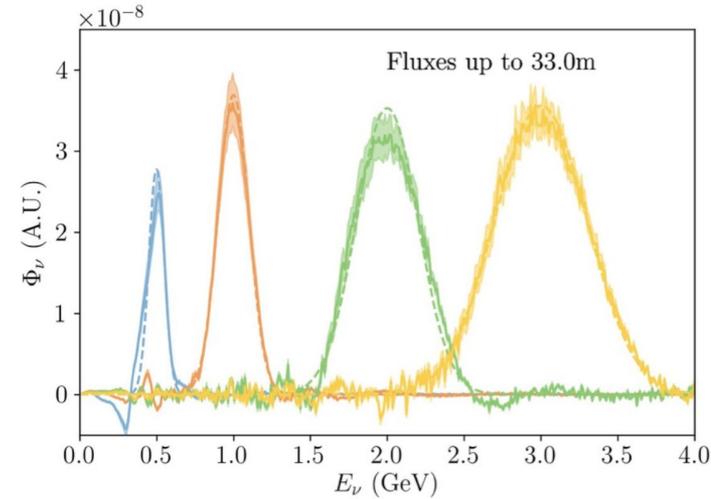
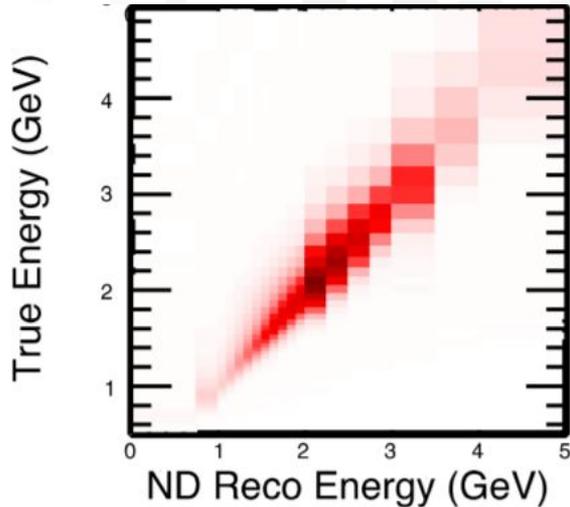
- Play the linear algebra game to build narrow-band fluxes.



# Narrow-band fluxes

- Play the linear algebra game to build narrow-band fluxes.
  - **Can probe the 'true' reconstructed energy bias and inform simulation improvements.**

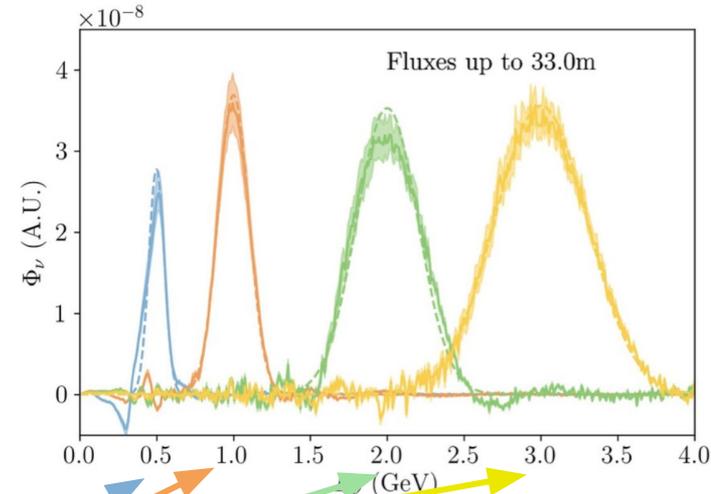
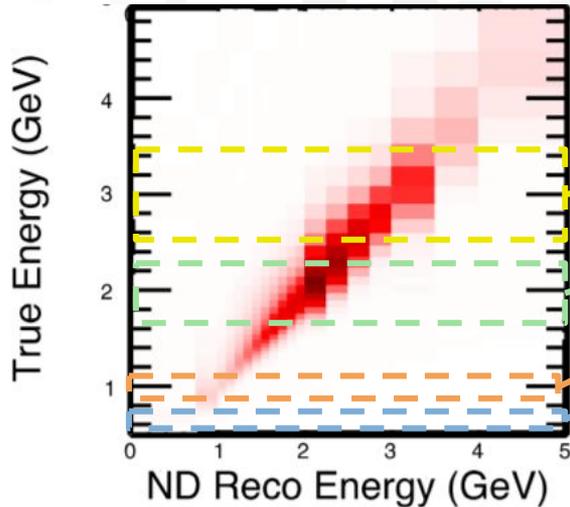
[E. Smith, NOvA, NUFAC2019](#)



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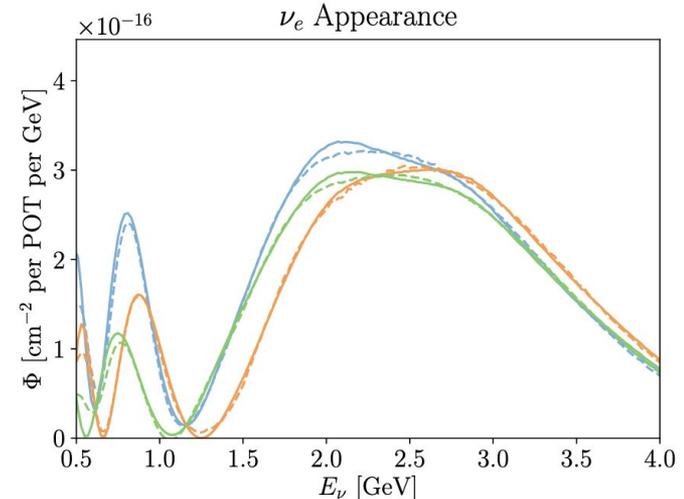
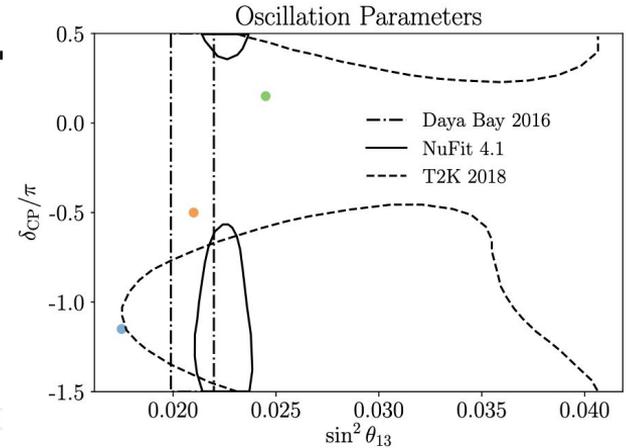
# Fits to Appeared $\bar{\nu}_e$

- So far focussed on disappearance spectrum.
  - Also need to incorporate appeared electron neutrinos.

PRISM

# Fits to Appeared $\nu_e$

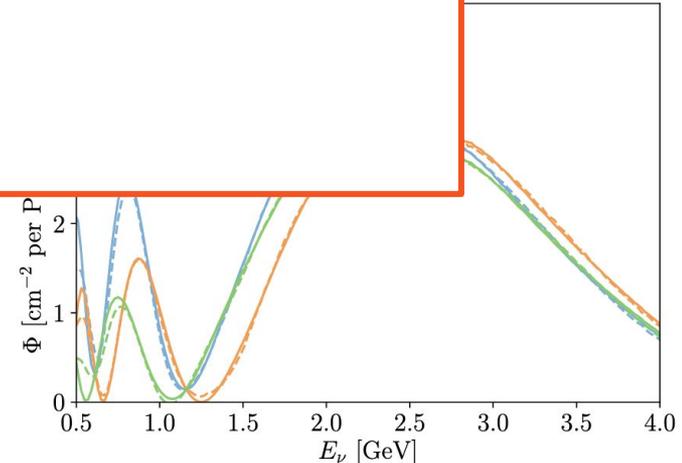
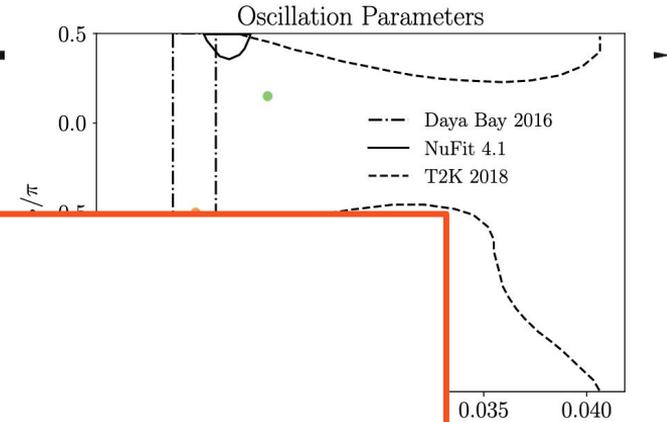
- So far focussed on disappearance spectrum.
  - Also need to incorporate appeared electron neutrinos.
- Can build the appeared  $\nu_e$  spectrum from near detector numus.
  - Here have to correct for  $\nu_{\mu}/\nu_e$  cross section ratio
  - More model-dependent than disappearance measurement.



# Fits to Appeared Nue

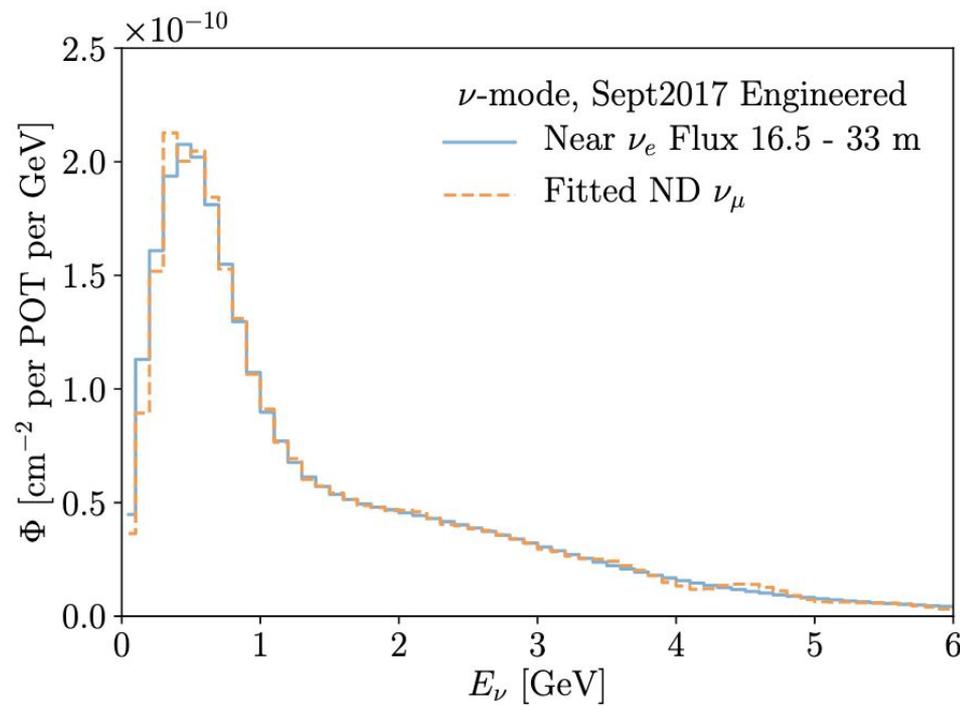
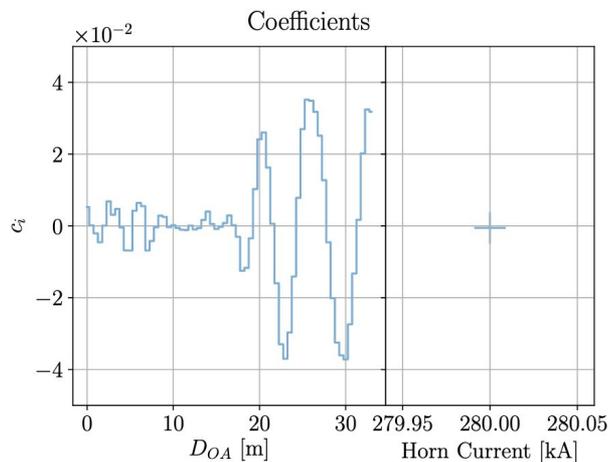
- So far focussed on disappearance spectrum.
  - Also need to fit to appeared neutrino spectrum
- Can build fits to appeared neutrino spectrum from near-threshold data.
  - Here have data from near-threshold section
  - More measurements needed to constrain

But...



# Fits to Near Detector Neutrinos

- Can also build near detector neutrino spectrum with near detector neutrino flux to constrain the cross-section ratio.
  - Will be neutrino-statistics limited
  - Studies on-going



# Fits to Near Detector Neutrino Spectrum

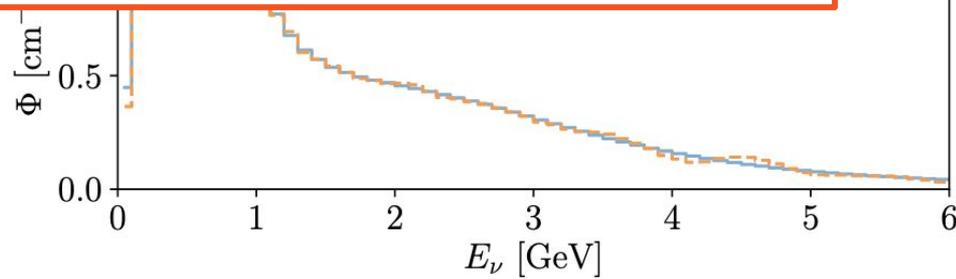
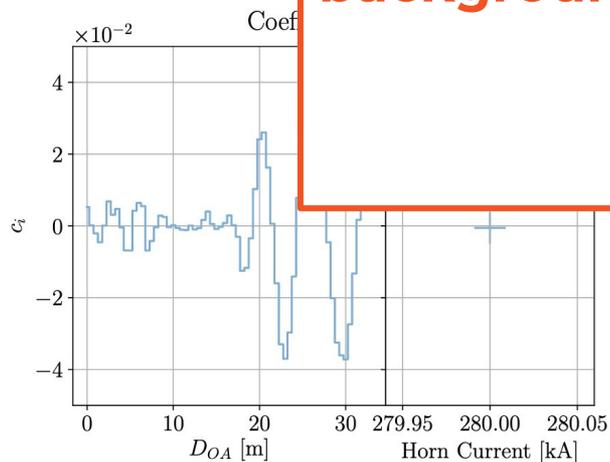
- Can also build near detector neutrino spectrum with near detector

numus to  
cross-sec

- Will be
- Studies

**Can do something similar with the wrong-sign background in anti-neutrino mode!**

ered  
33 m



# Other Ideas For Off-axis Beams

## DUNE-PRISM sensitivity to light dark matter

Valentina De Romeri, Kevin J. Kelly, and Pedro A. N. Machado  
 Phys. Rev. D **100**, 095010 – Published 8 November 2019

## Measuring the Weak Mixing Angle in the DUNE Near-Detector Complex

André de Gouvêa, Pedro A. N. Machado, Yuber F. Perez-Gonzalez, and Zahra Tabrizi  
 Phys. Rev. Lett. **125**, 051803 – Published 29 July 2020

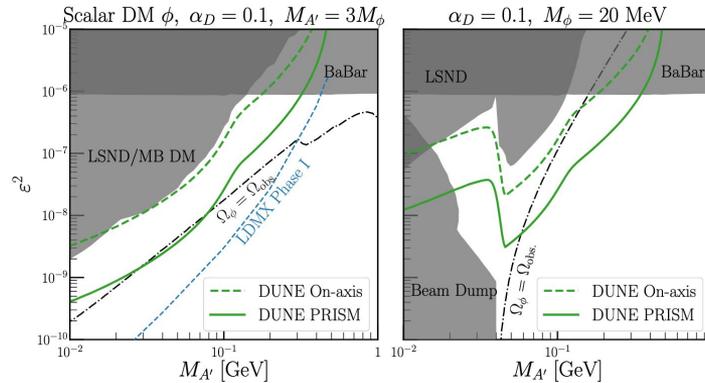
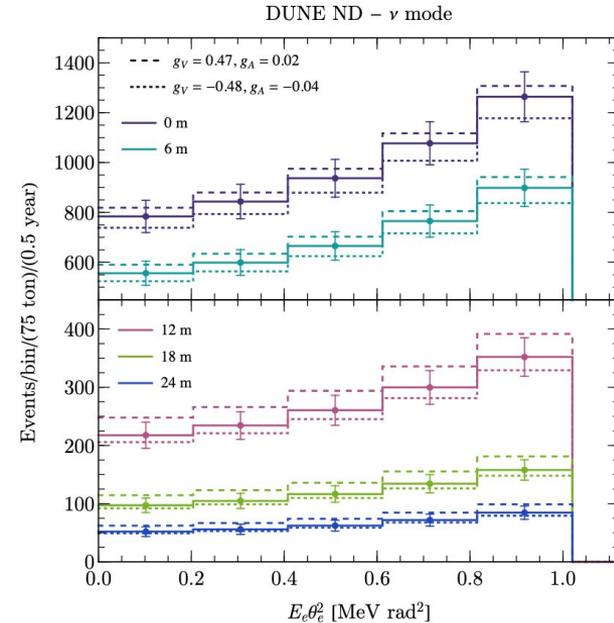


FIG. 5. Expected DUNE On-axis (dashed) and PRISM (solid) sensitivity at 90% C.L. using  $\phi e^- \rightarrow \phi e^-$  scattering. We assume  $\alpha_D = 0.1$  in both panels, and  $M_{A'} = 3M_\phi$  ( $M_\phi = 20$  MeV) in the left (right) panel. Existing constraints are shown in grey, and the relic density target is shown in a black dot-dashed line. We compare our results against the proposed LDMX experiment in blue [89].



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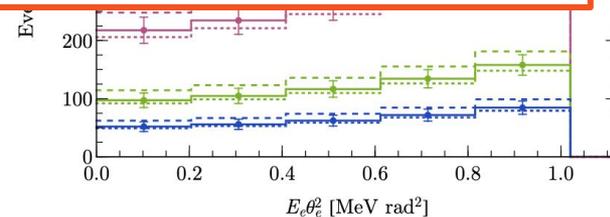
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**Your Idea goes here!**

**We can supply off-axis flux predictions and uncertainty matrix for your studies!**

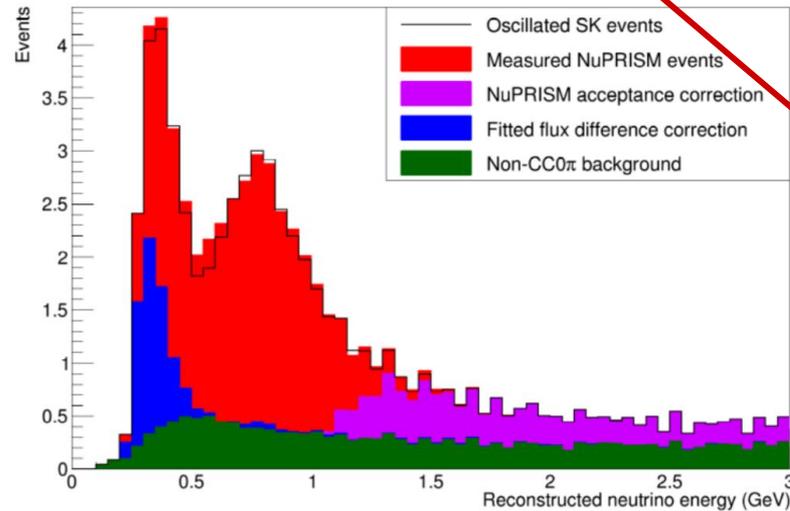
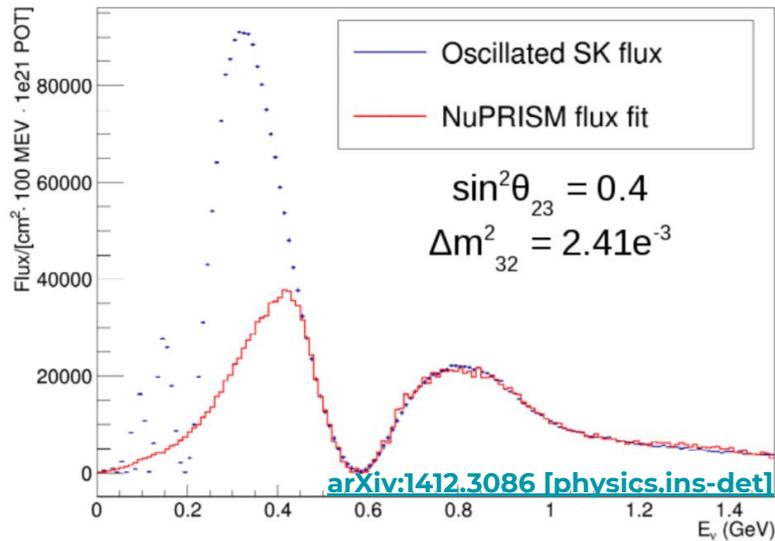
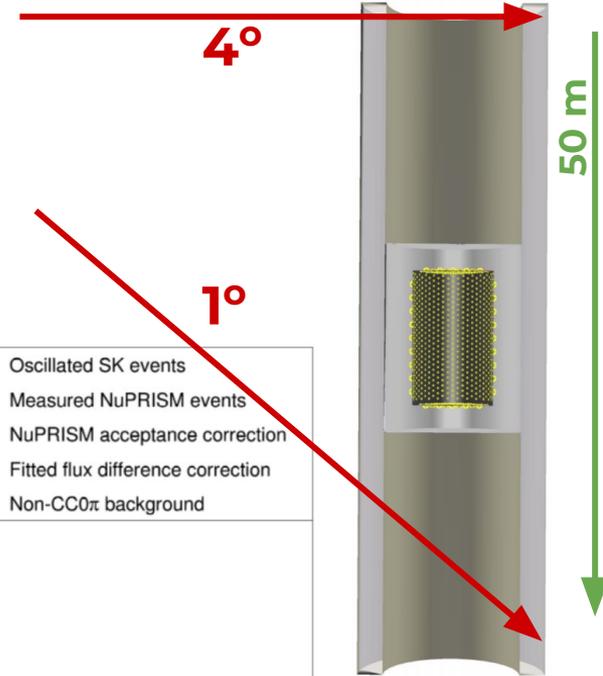
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# $\nu$ PRISM



- DUNE-PRISM born out of earlier work to build a mobile Water Cherenkov detector in the J-PARC beam for Hyper-K.
- [J-PARC PAC Proposal](#)



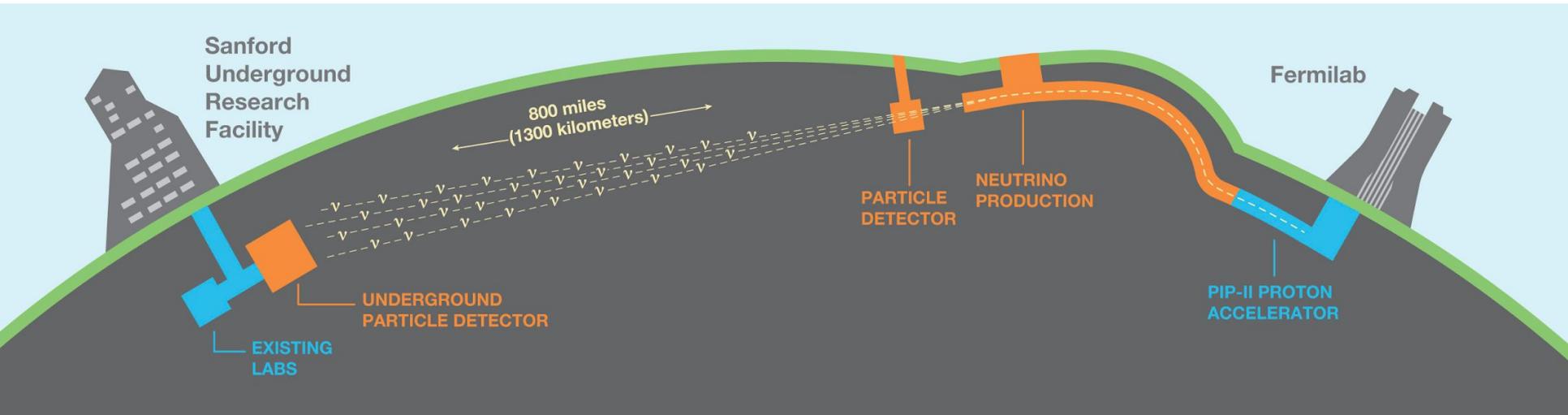


**Thanks for listening**

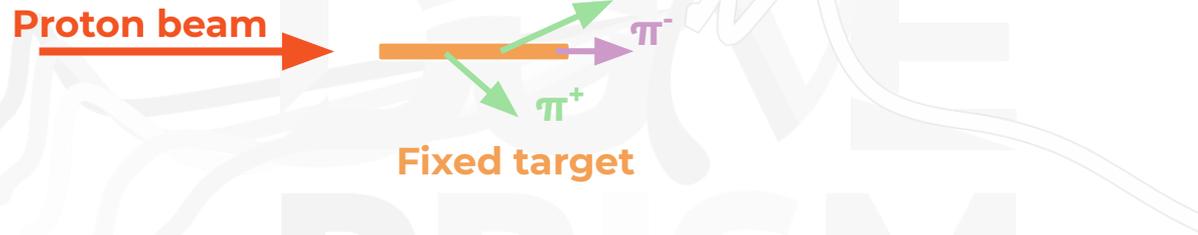


# The Deep Underground Neutrino Experiment

- Far Detector
- Near Detector
- Neutrino beam



# Producing a Beam of Neutrinos



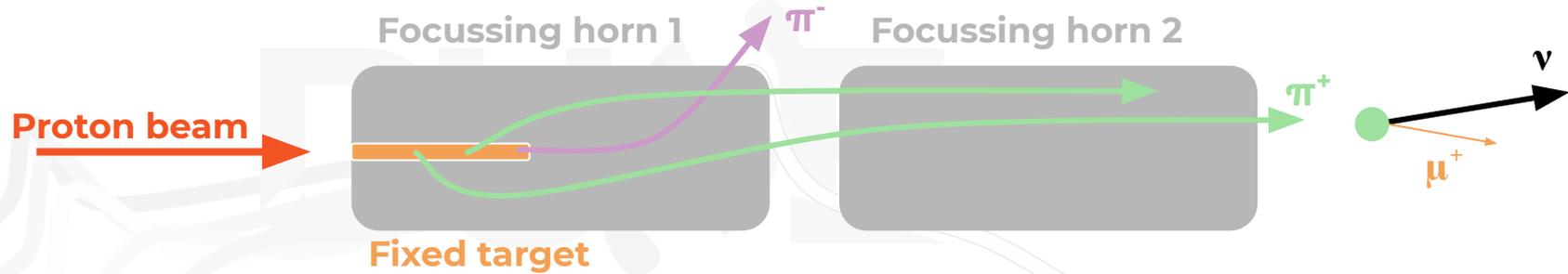
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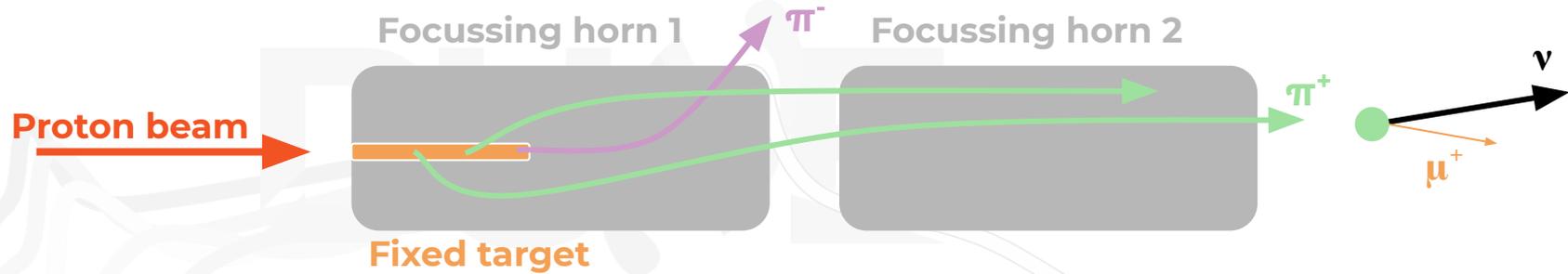
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- This secondary beam of particles decays to produce neutrinos.

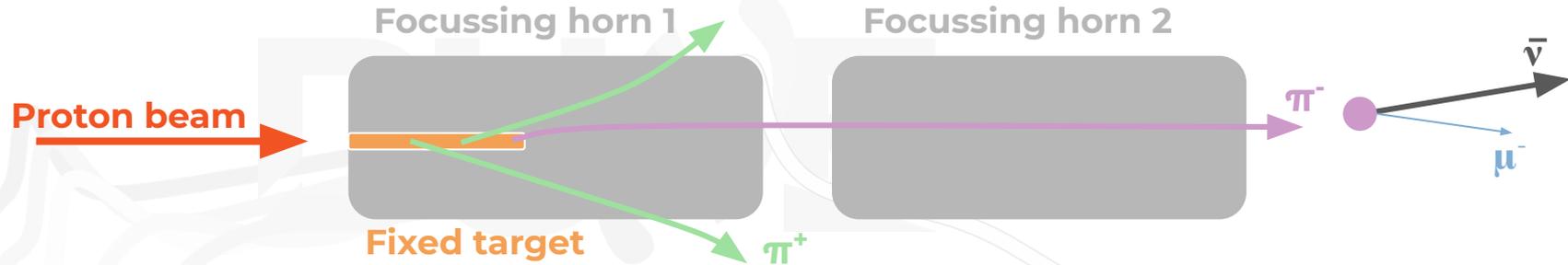
# Producing a Beam of Neutrinos



## Neutrino mode, focussing positive particles

- Proton beam strikes a fixed target producing secondary hadrons: mostly pions and kaons
- These are sign-selected and focussed by one or more magnetic horns.
- This secondary beam of particles decays to produce neutrinos.
- The horn current can be inverted to produce mostly anti-neutrinos

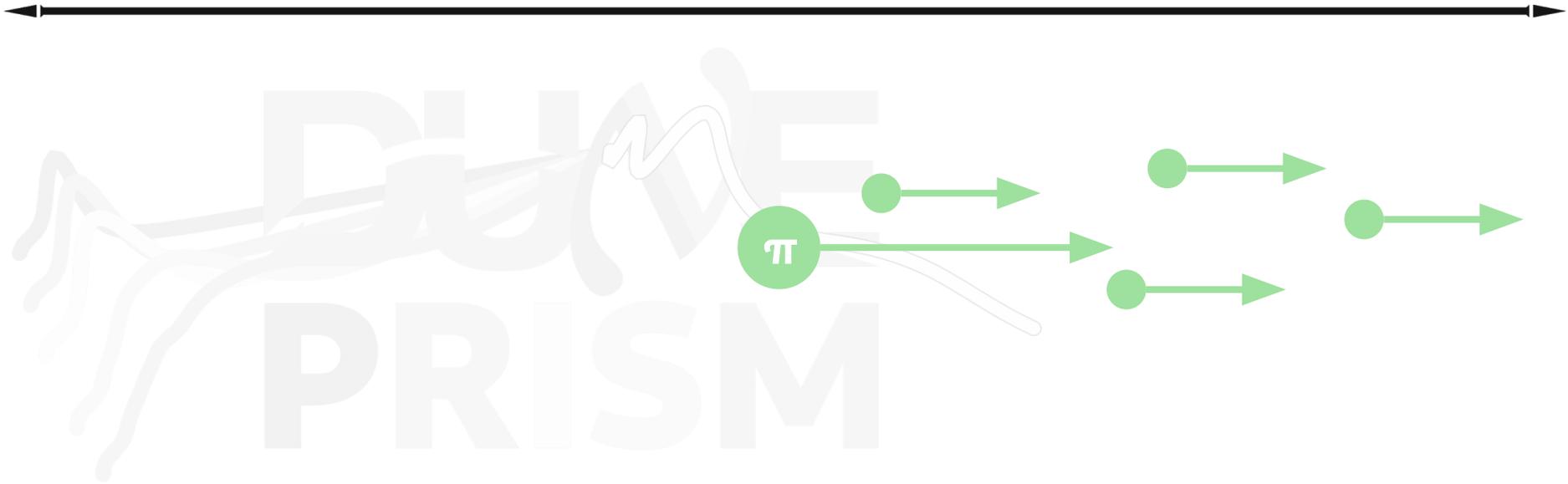
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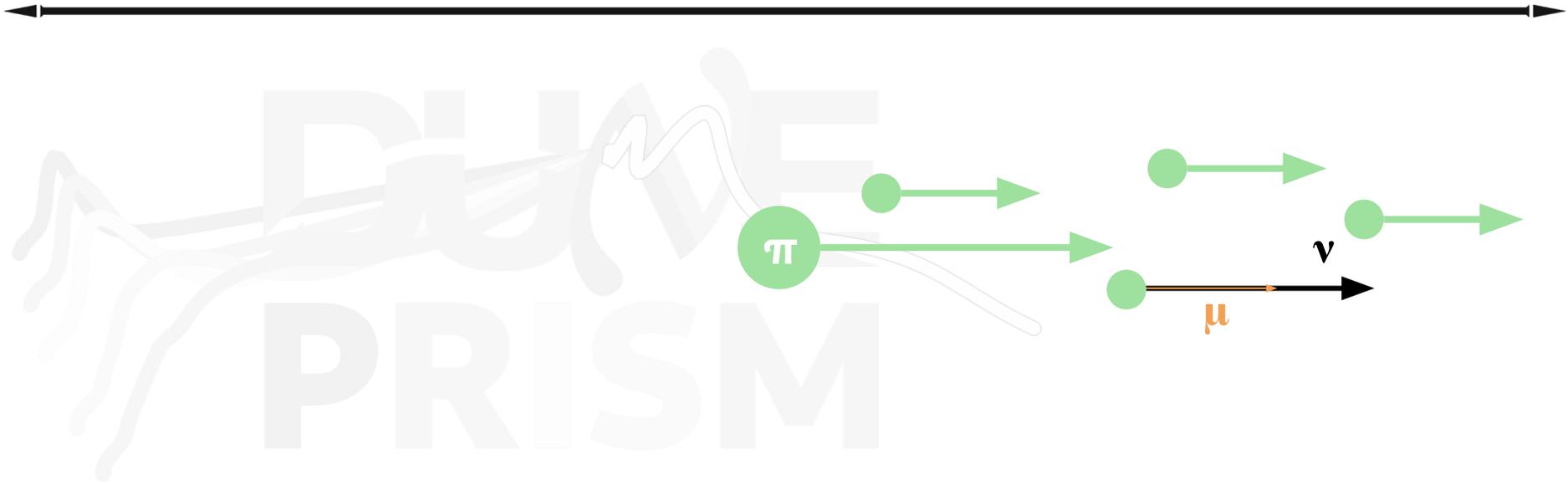
## Anti-neutrino mode, focussing negative particles

- Proton beam strikes a fixed target producing secondary hadrons: mostly pions and kaons
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- This secondary beam of particles decays to produce neutrinos.
- The horn current can be inverted to produce mostly anti-neutrinos

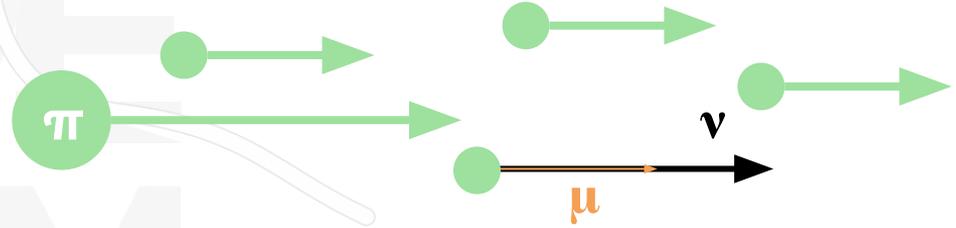
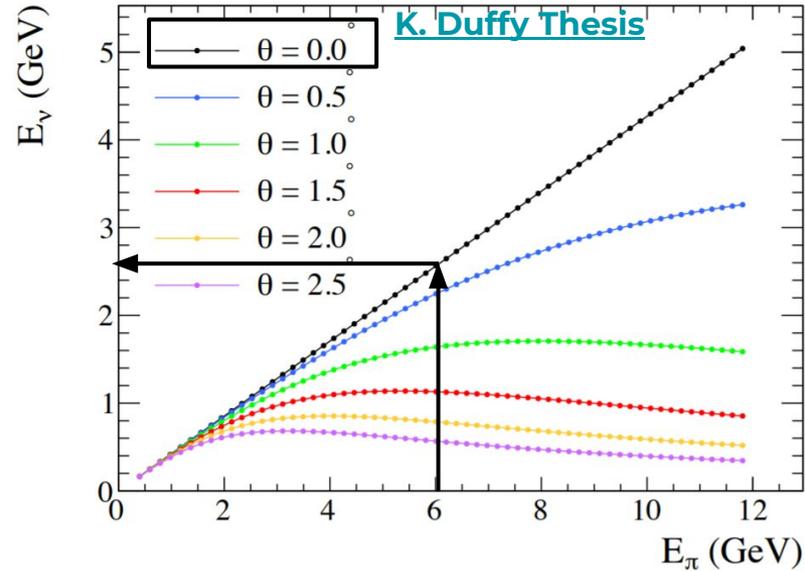
# Off Axis Fluxes



# Off Axis Fluxes

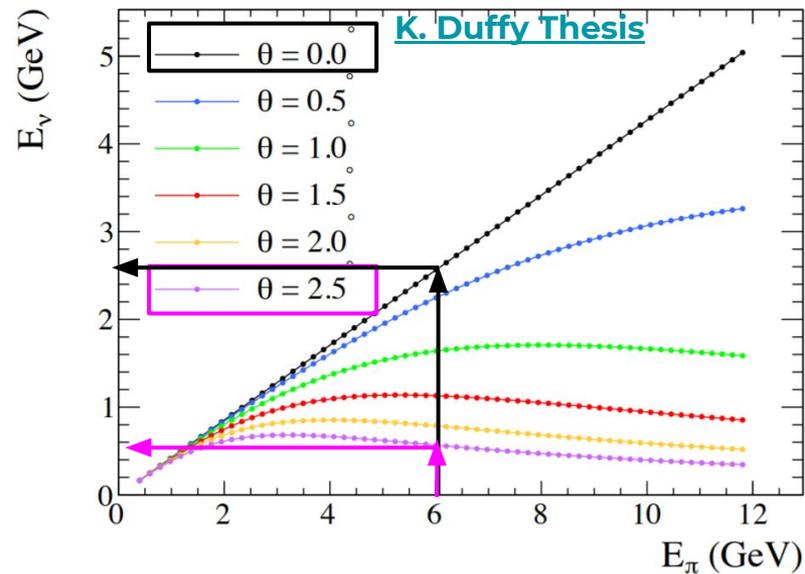
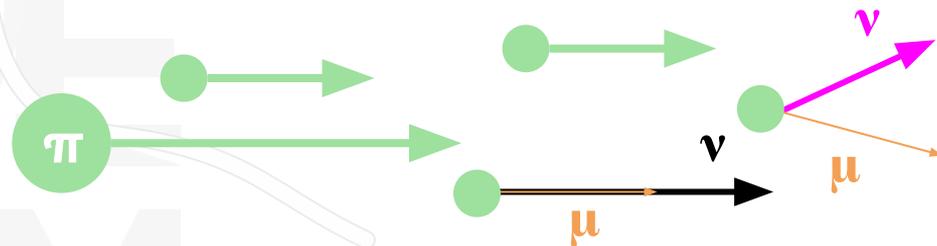


# Off Axis Fluxes



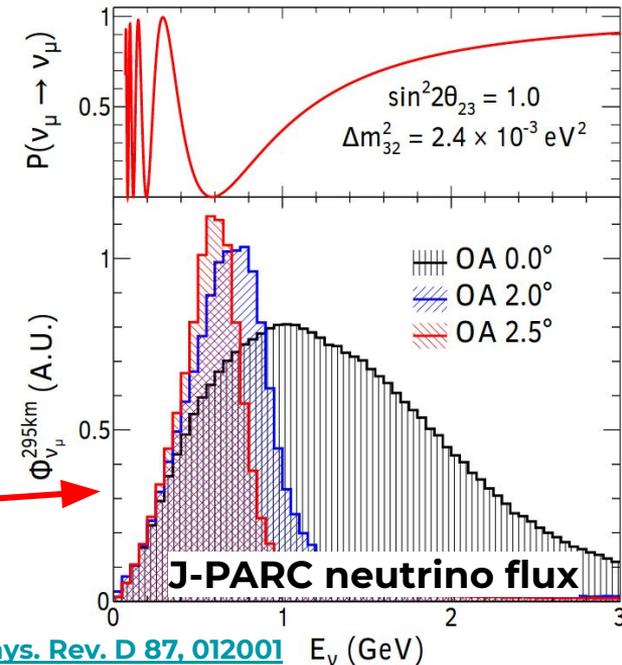
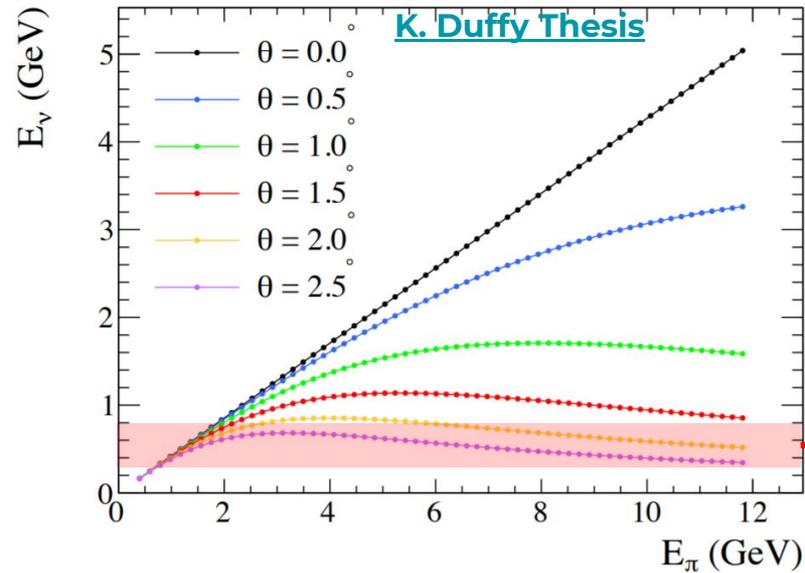
# Off Axis Fluxes

- Boosted  $\pi$  decay kinematics result in lower energy neutrinos off beam axis.



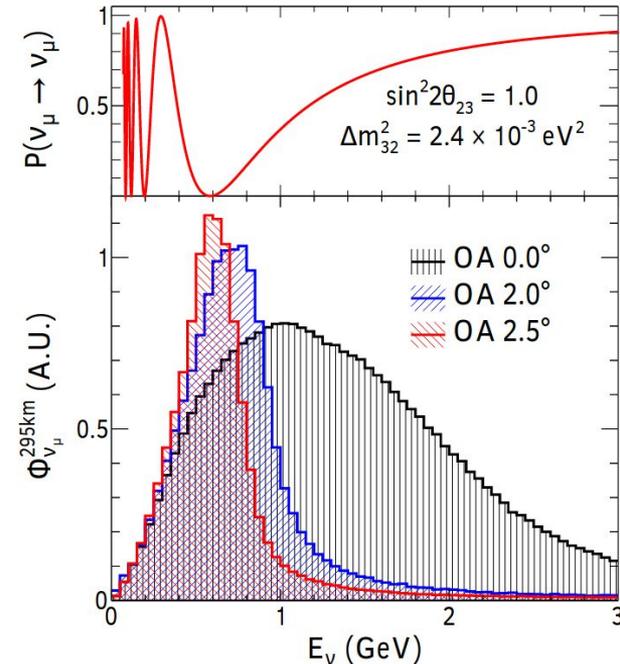
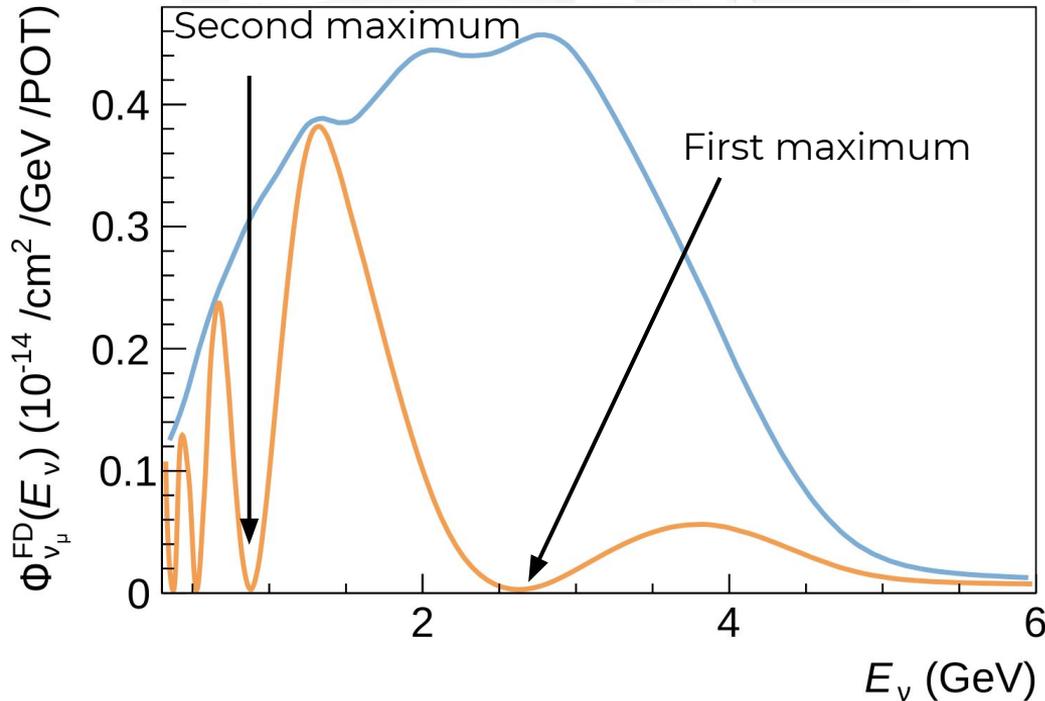
# Off Axis Fluxes

- Boosted  $\pi$  decay kinematics result in lower energy neutrinos off beam axis.
  - Exploited by T2K and NOvA to achieve narrow-band beam for maximal oscillation signal at first oscillation maximum



# LBNF: The DUNE Neutrino Beam

- By contrast, DUNE will use an on axis, wide band beam:
  - Access to physics at higher order oscillation maxima where non-standard oscillations expected to be stronger.



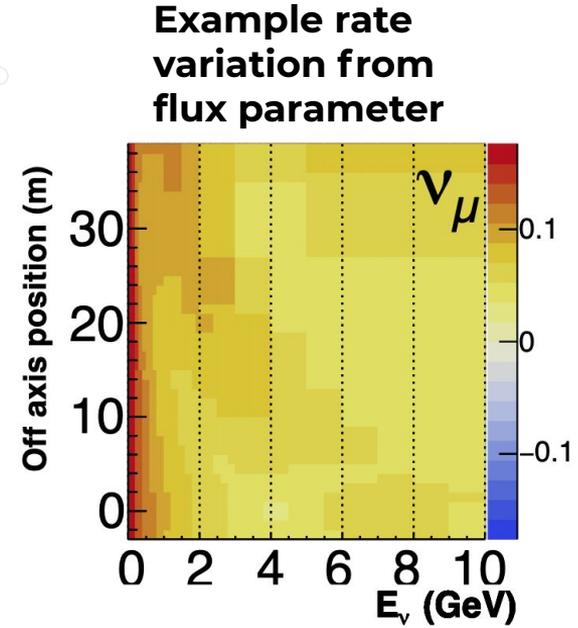


# Flux Uncertainties



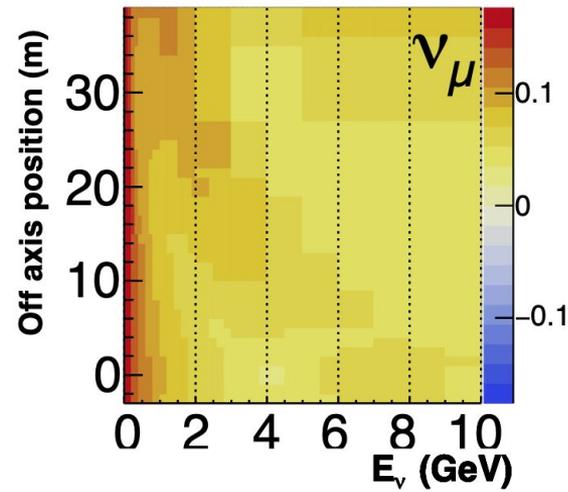
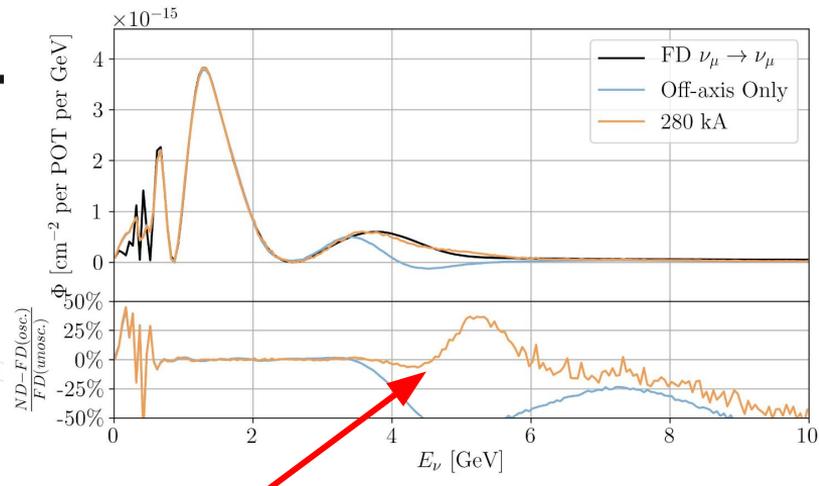
# Flux Systematics

- For each step of an oscillation analysis:
  - flux systematic parameters may move
  - flux predictions change
  - must re-determine PRISM coefficients.



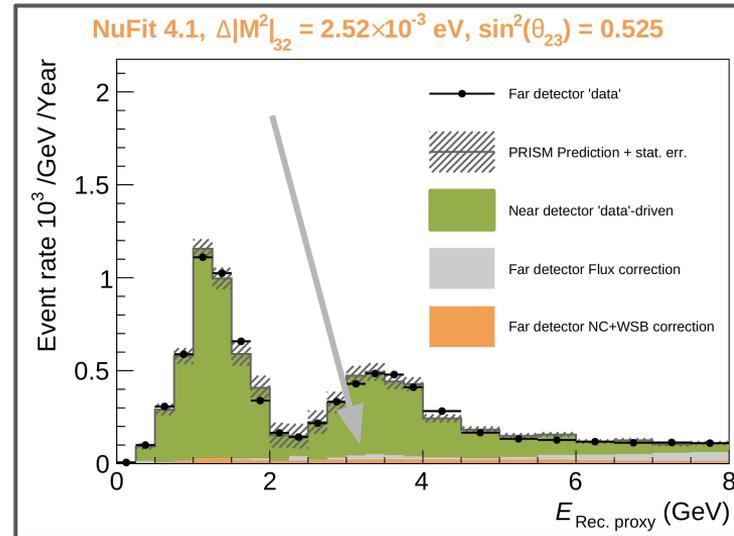
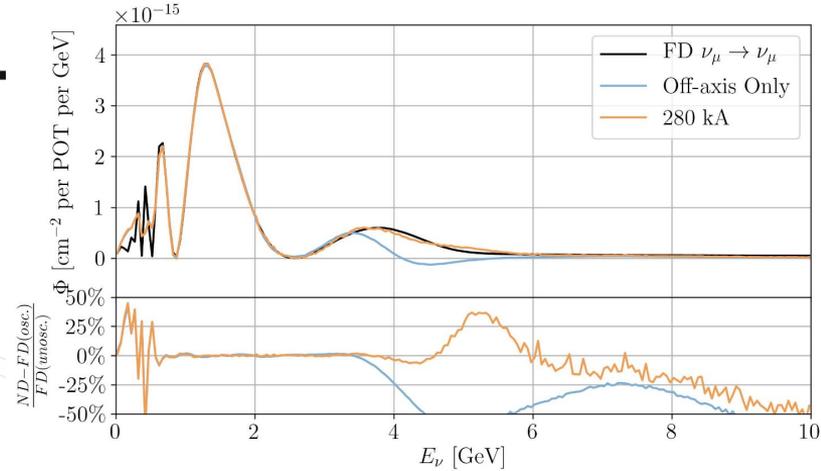
# Flux Systematics

- For each step of an oscillation analysis:
  - flux systematic parameters may move
  - flux predictions change
  - must re-determine PRISM coefficients.
- Different coefficients change the flux matching residual
  - The residual correction uses FD MC
  - This sets the scale that signal cross-section uncertainties enter.



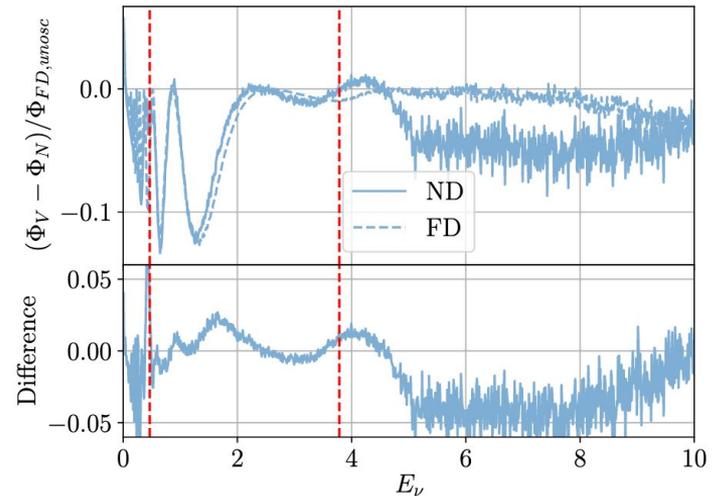
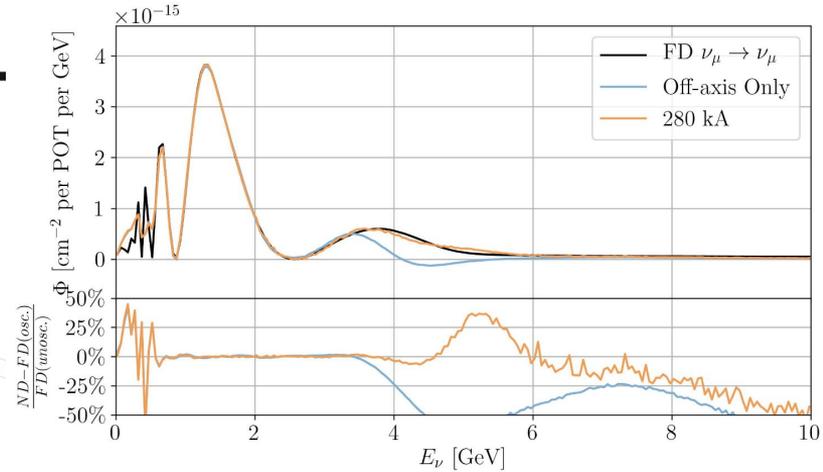
# Flux Systematics

- Flux systematics introduce cross-section dependence at the level that the PRISM prediction and the FD prediction don't 'track' each other.



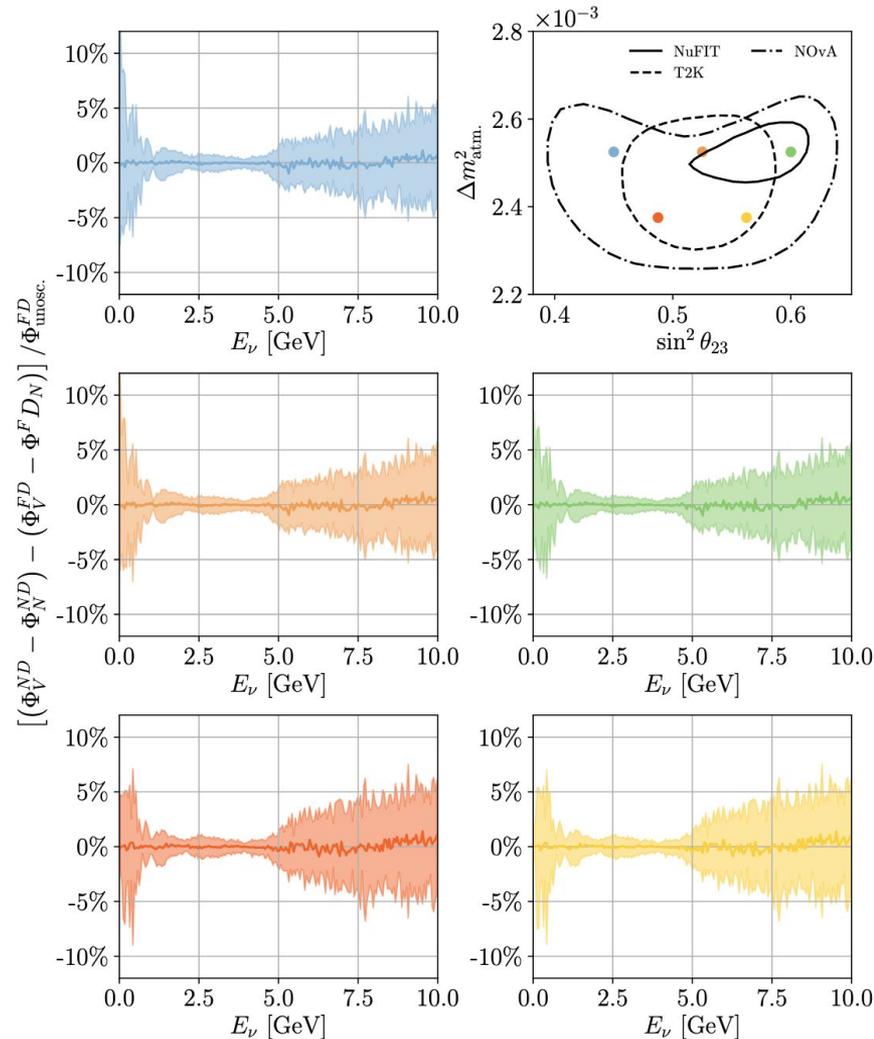
# Flux Systematics

- Flux systematics introduce cross-section dependence at the level that the PRISM prediction and the FD prediction don't 'track' each other.
- Take a given systematic variation and study how much the FD flux prediction and the PRISM prediction vary relative to nominal to each other.
  - **e.g. one systematically varied hadron production universe.**



# Flux Systematics

- Flux systematics introduce cross-section dependence at the level that the PRISM prediction and the FD prediction don't 'track' each other.
- Take a given systematic variation and study how much the FD flux prediction and the PRISM prediction vary relative to nominal to each other.
  - e.g. one systematically varied hadron production universe.
  - **e.g. 100 hadron production universes**

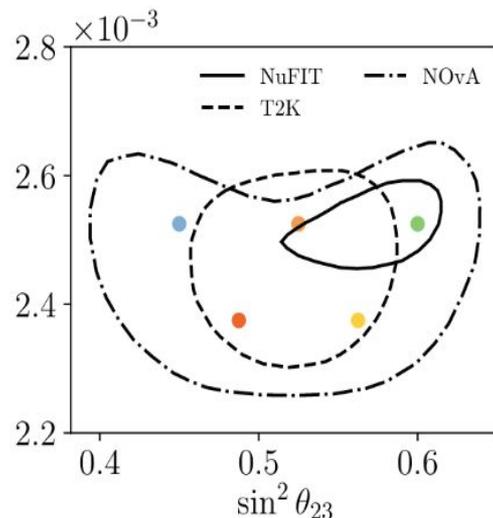
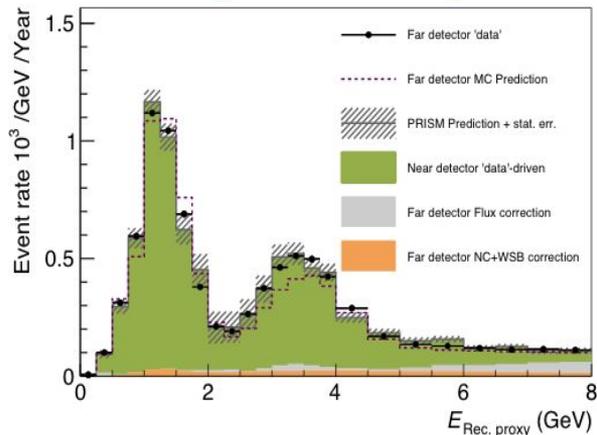




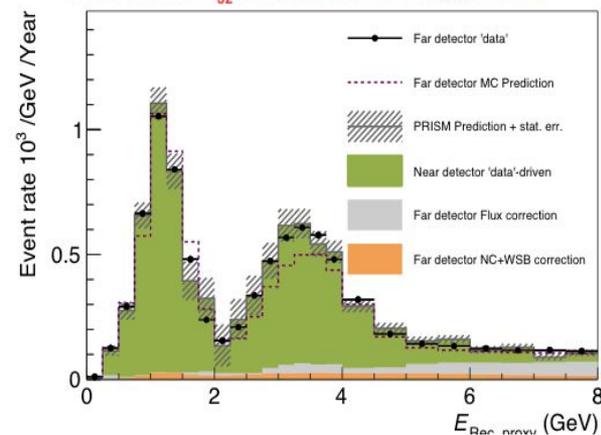
# Other Oscillation Parameters



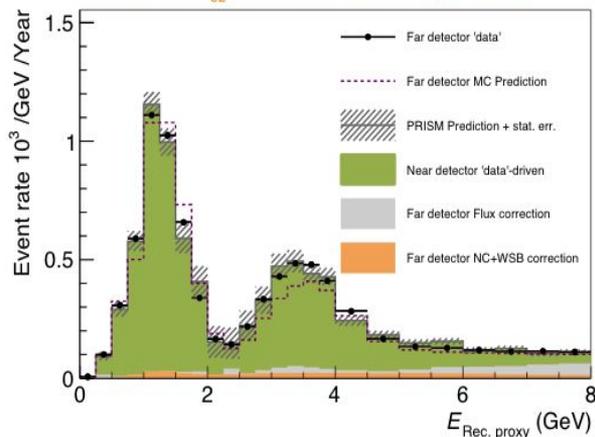
NuFit 4.1,  $\Delta\text{IM}^2_{32} = 2.52 \times 10^{-3}$  eV,  $\sin^2(\theta_{23}) = 0.45$



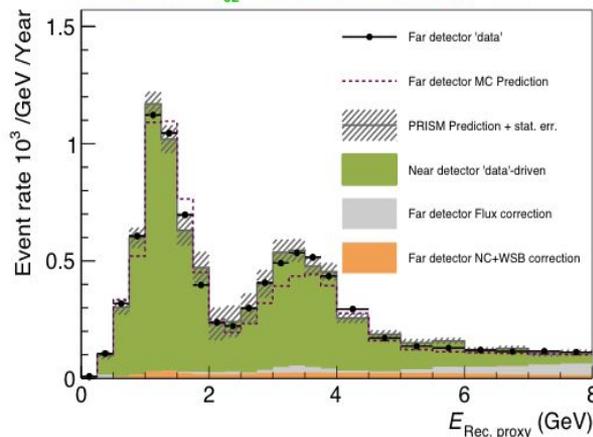
NuFit 4.1,  $\Delta\text{IM}^2_{32} = 2.38 \times 10^{-3}$  eV,  $\sin^2(\theta_{23}) = 0.487$



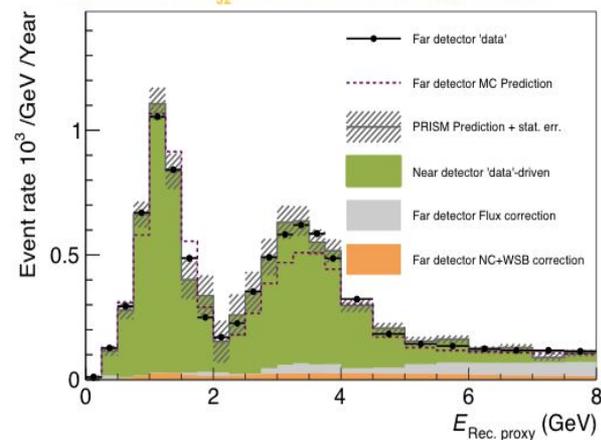
NuFit 4.1,  $\Delta\text{IM}^2_{32} = 2.52 \times 10^{-3}$  eV,  $\sin^2(\theta_{23}) = 0.525$



NuFit 4.1,  $\Delta\text{IM}^2_{32} = 2.52 \times 10^{-3}$  eV,  $\sin^2(\theta_{23}) = 0.6$

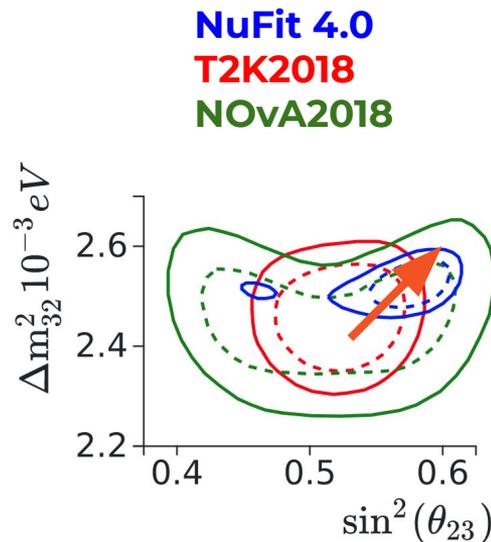
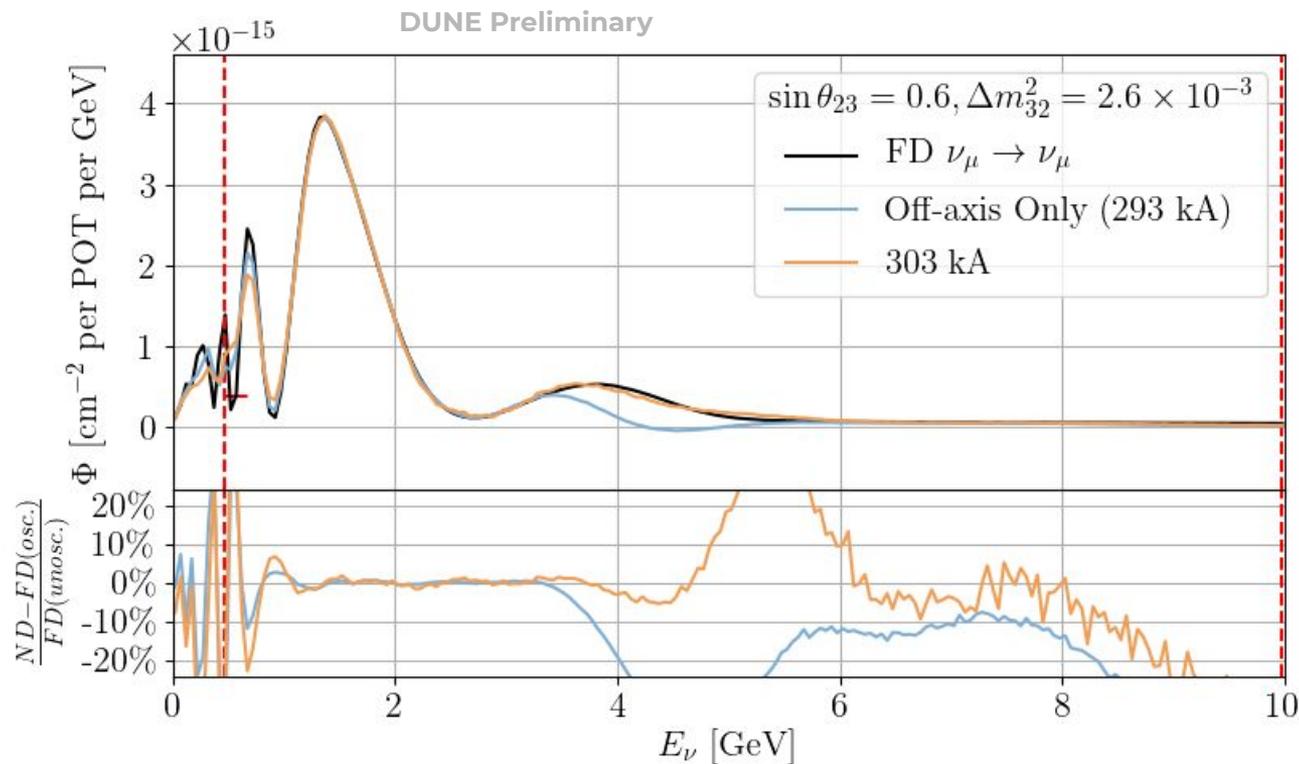


NuFit 4.1,  $\Delta\text{IM}^2_{32} = 2.38 \times 10^{-3}$  eV,  $\sin^2(\theta_{23}) = 0.562$

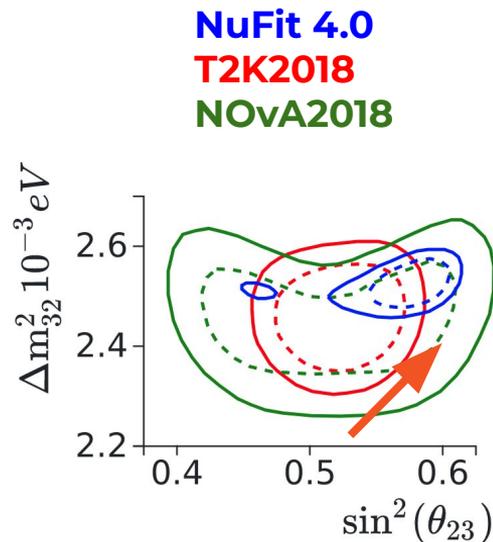
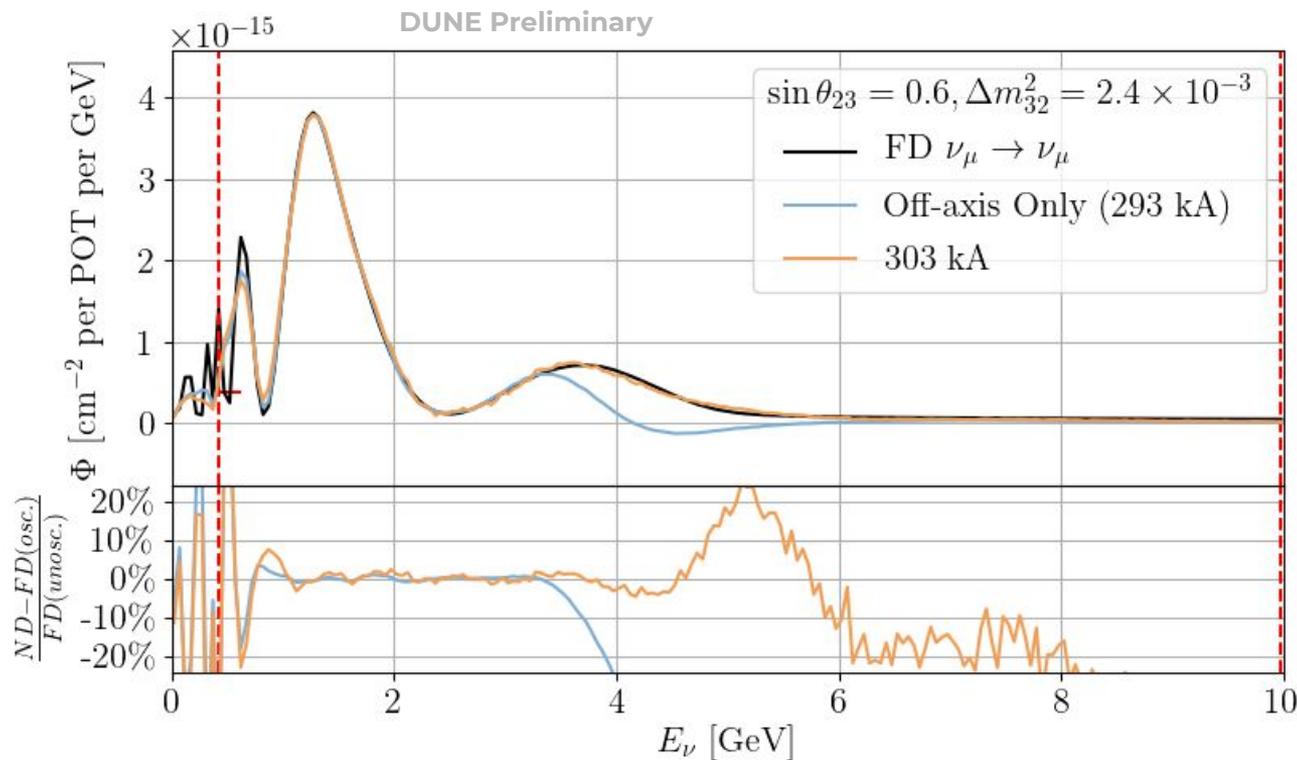


# Does it work everywhere?

[Try it yourself!](#)

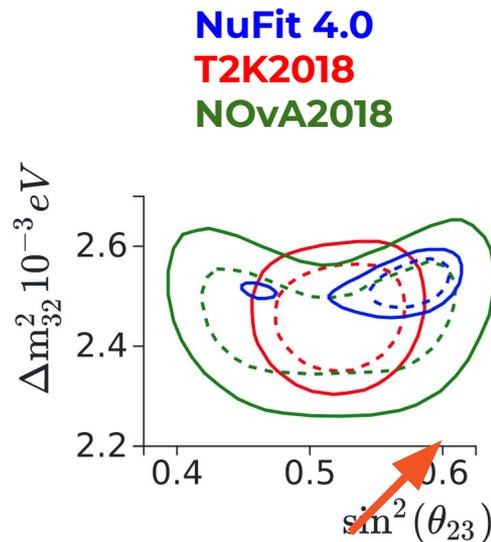
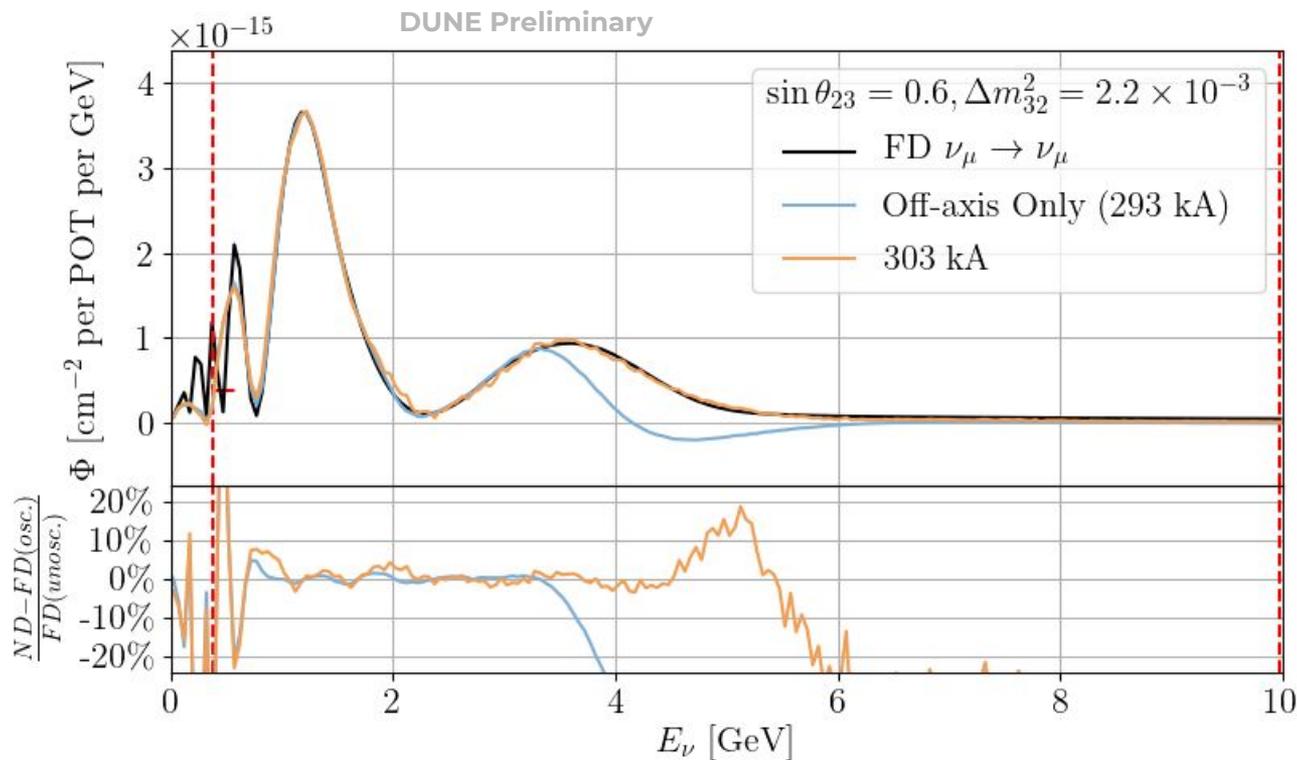


## Does it work everywhere?

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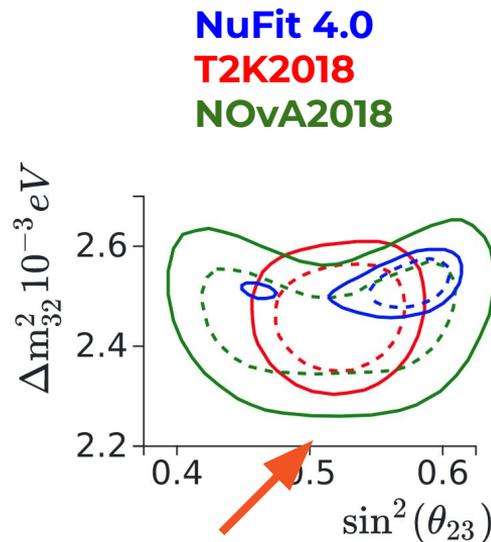
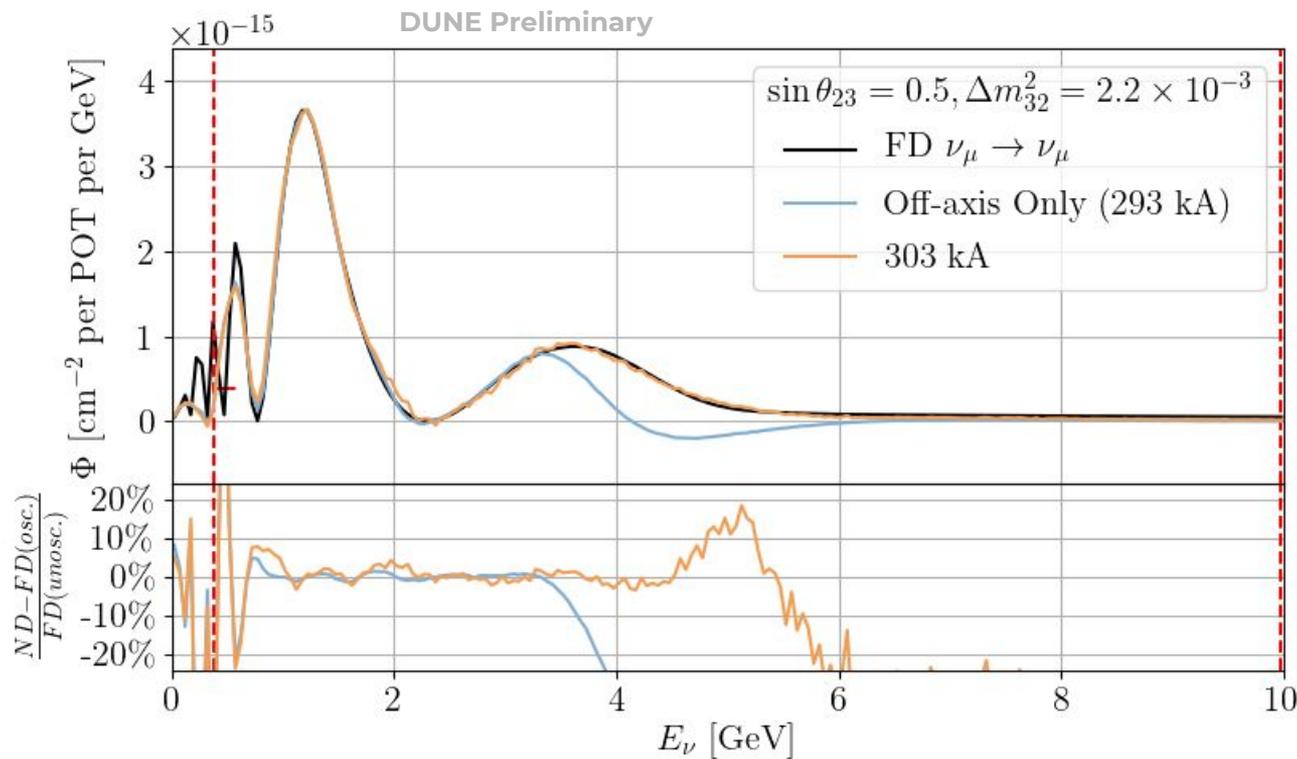
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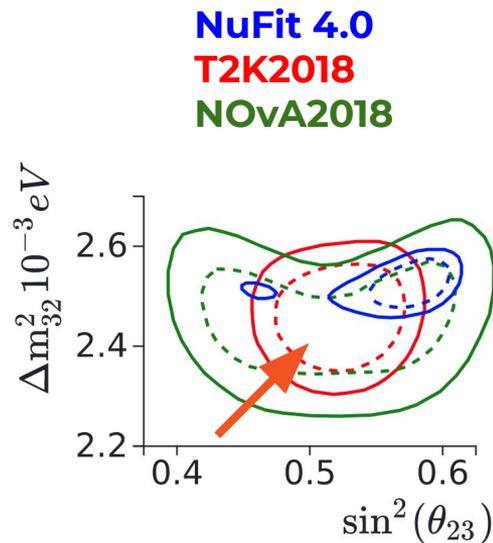
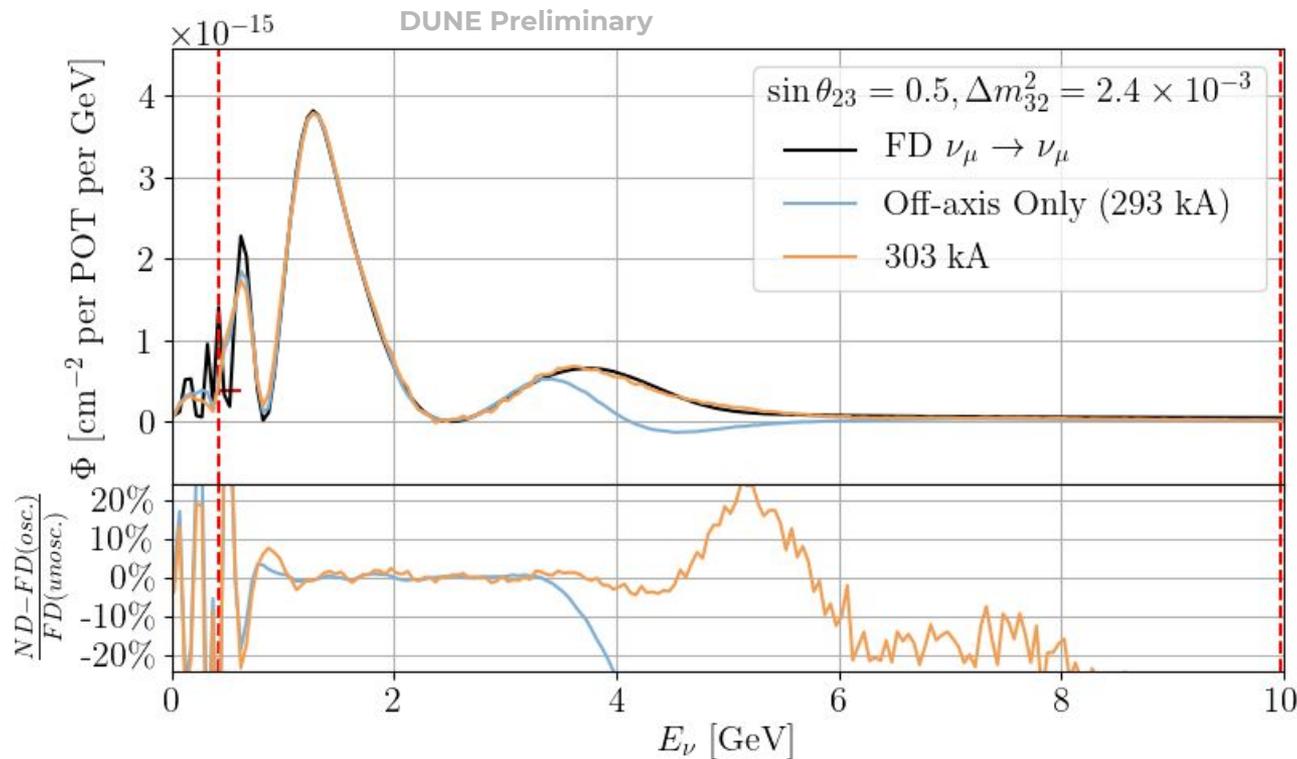
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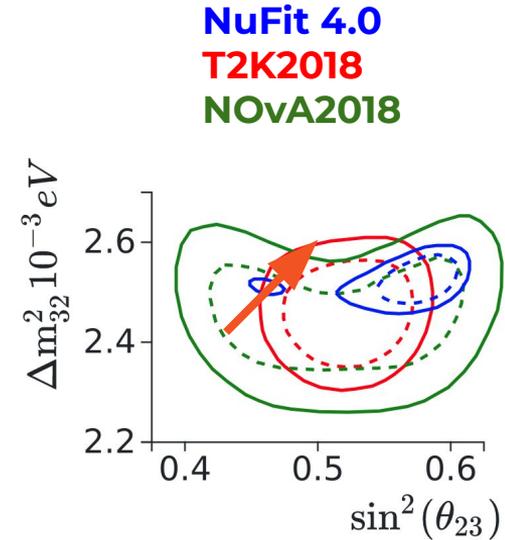
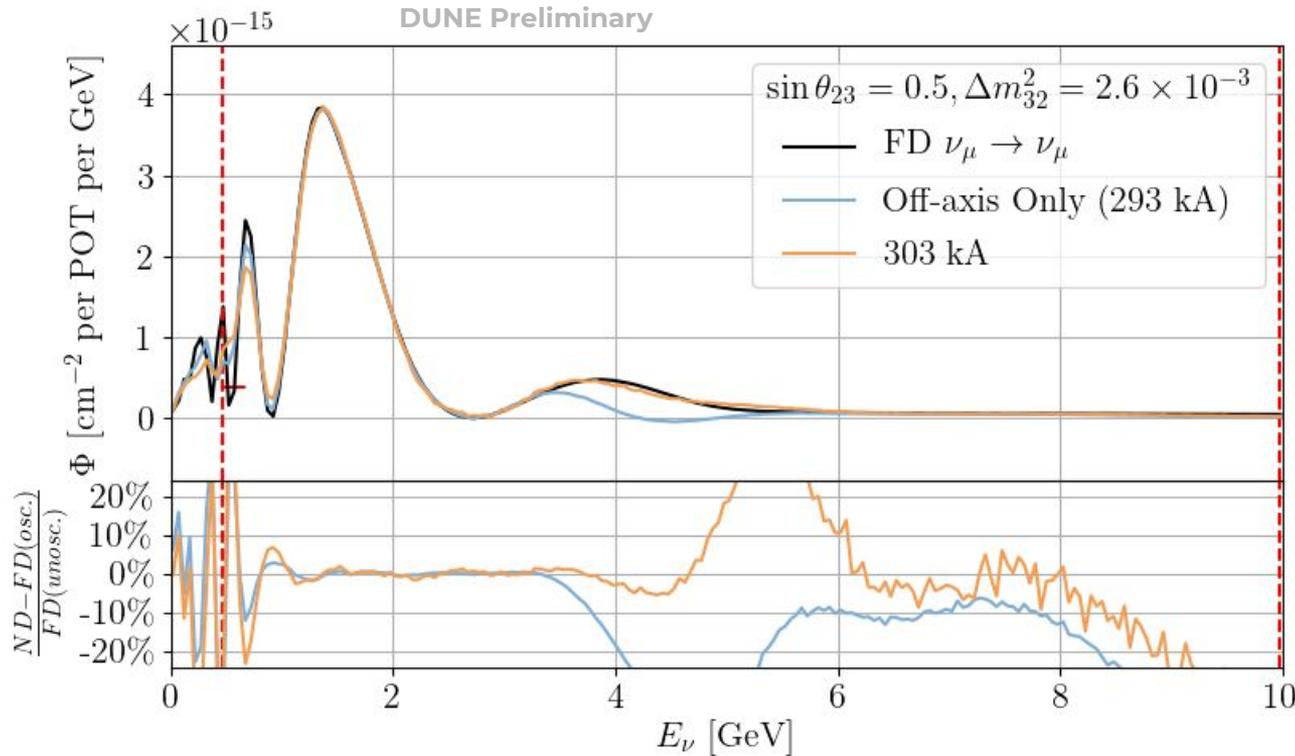
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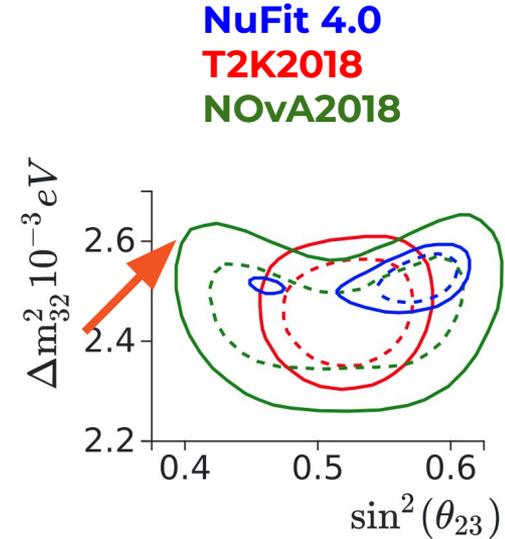
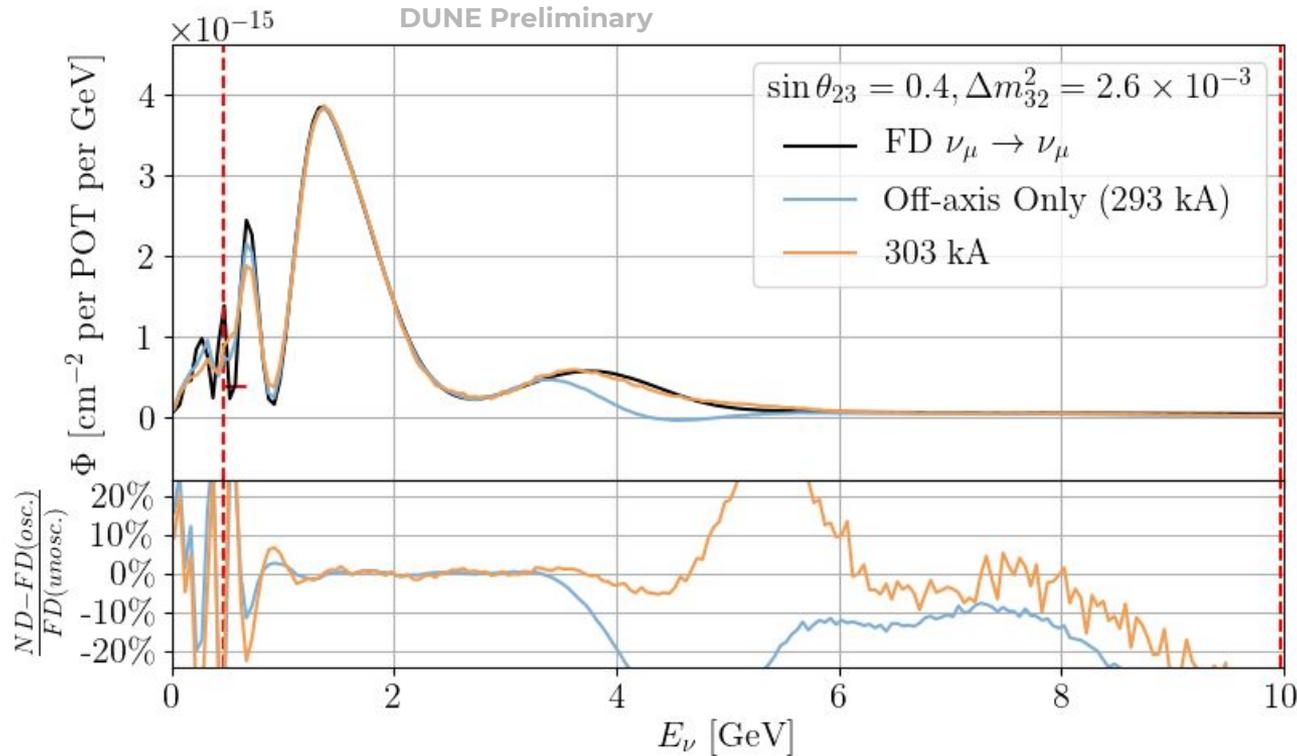


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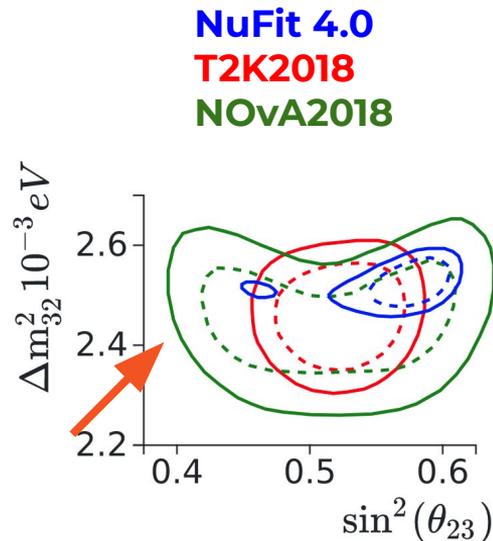
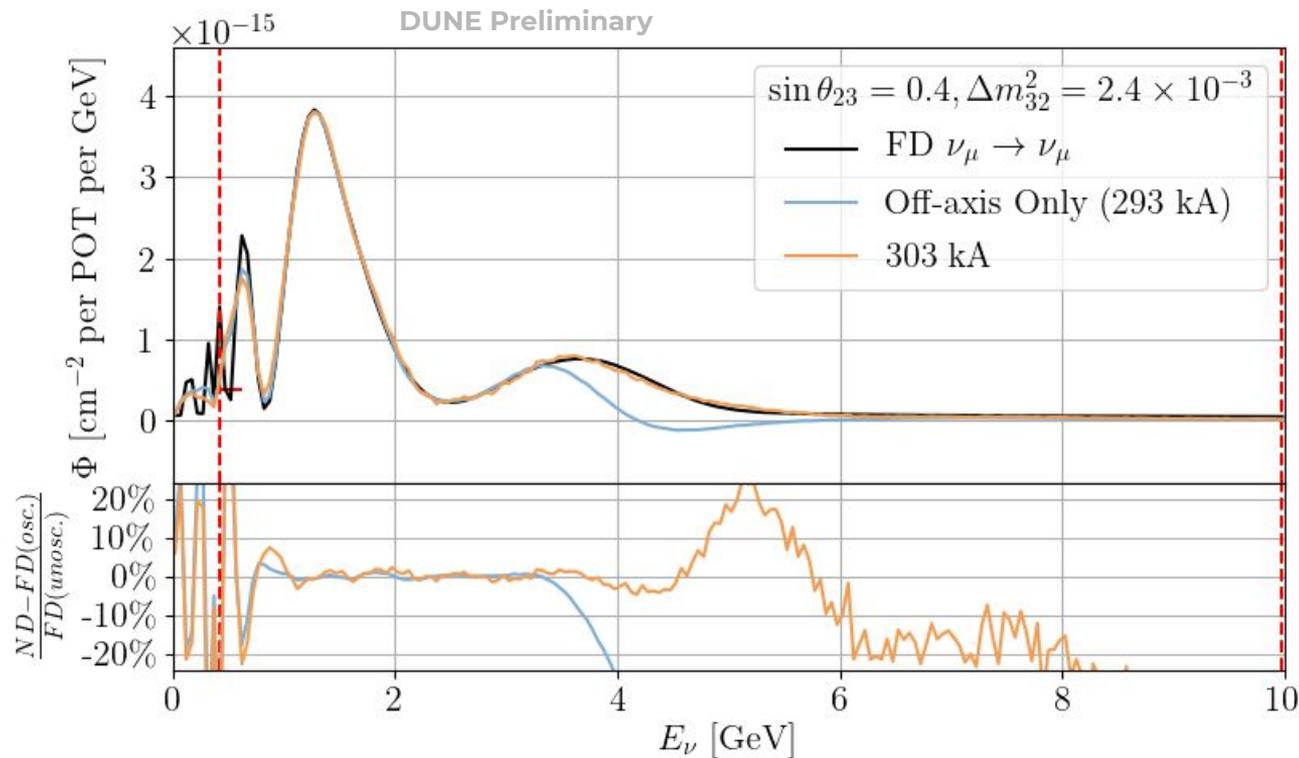


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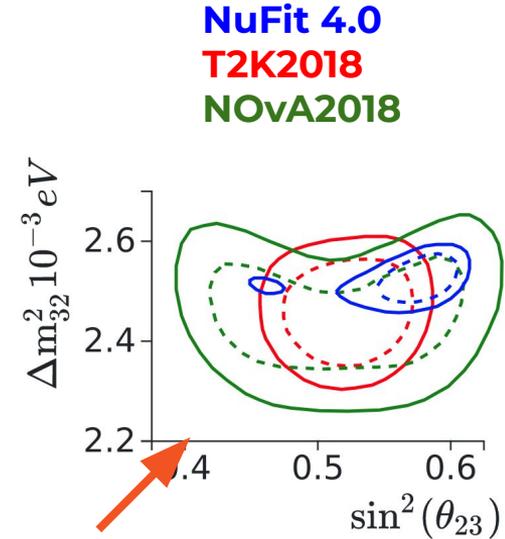
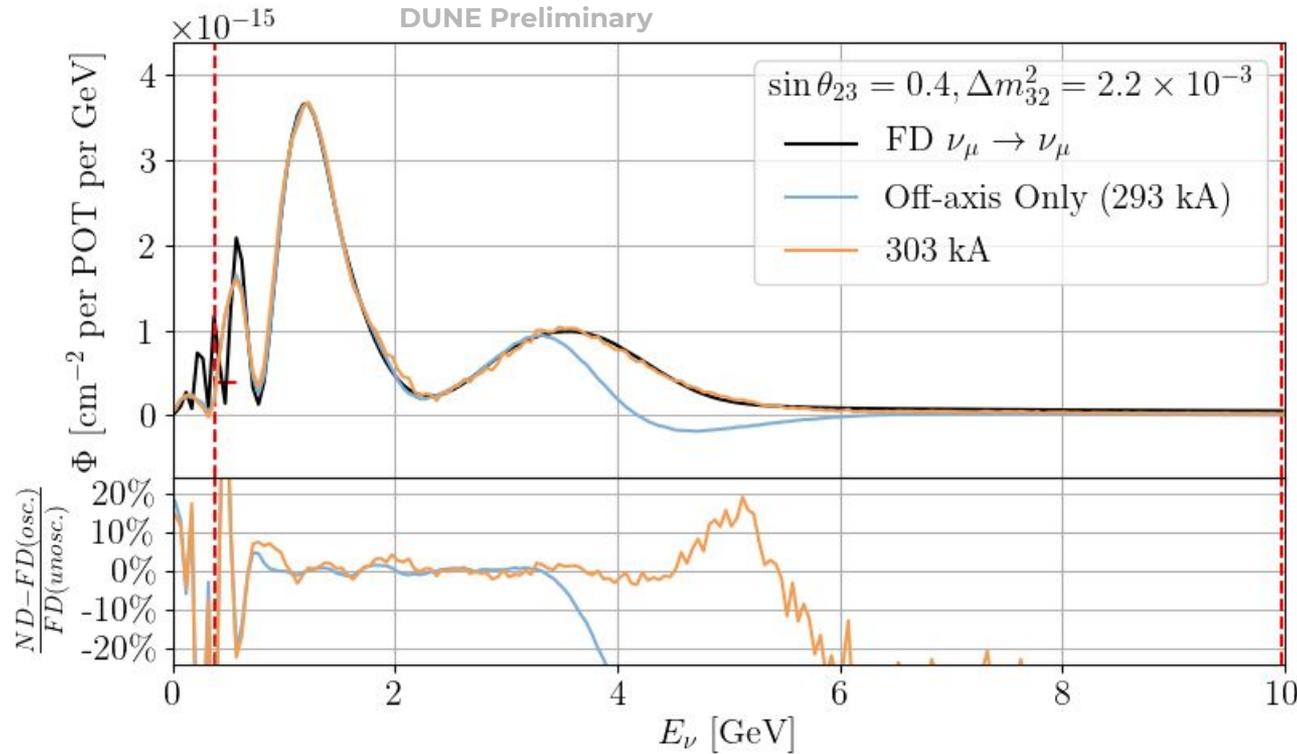
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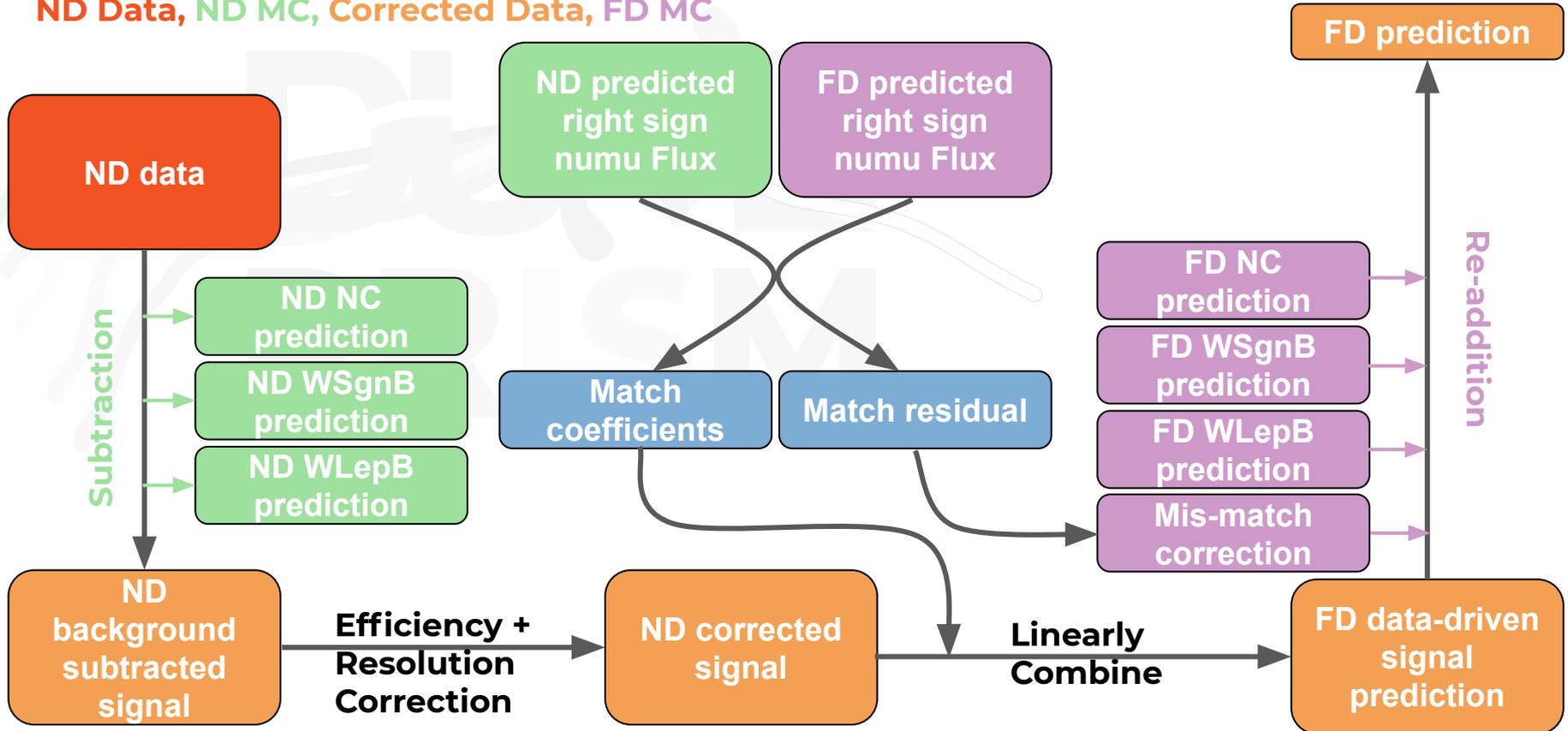
# Does it work everywhere?

[Try it yourself!](#)



# Analysis Flow: Disappearance

ND Data, ND MC, Corrected Data, FD MC

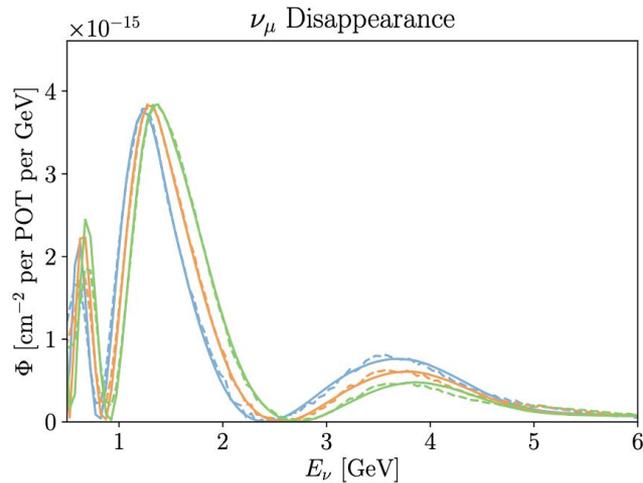
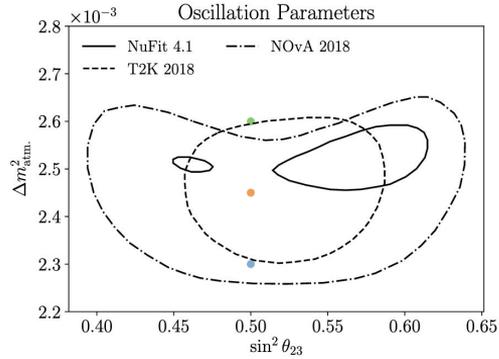




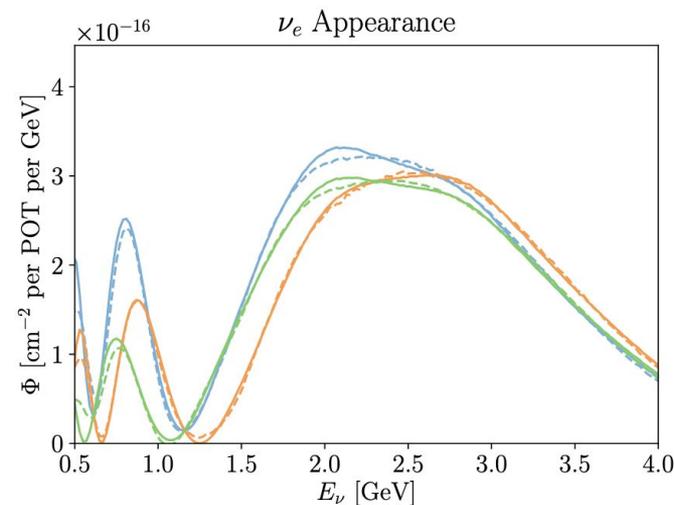
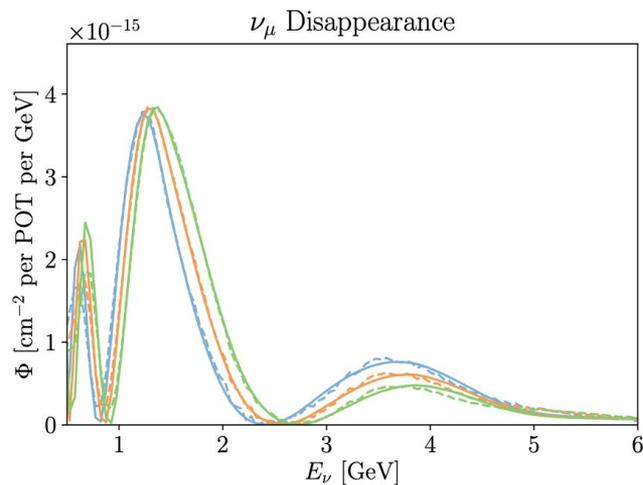
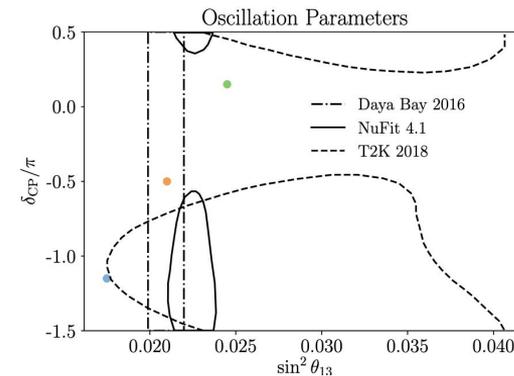
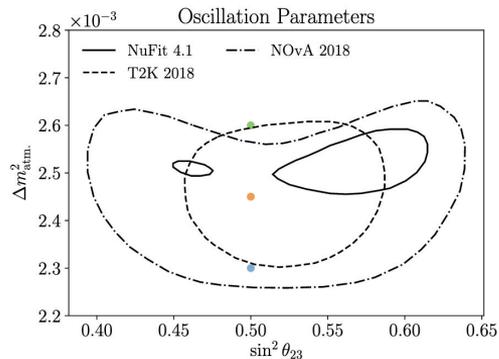
# Appearance



# Is this the only Game we can Play?

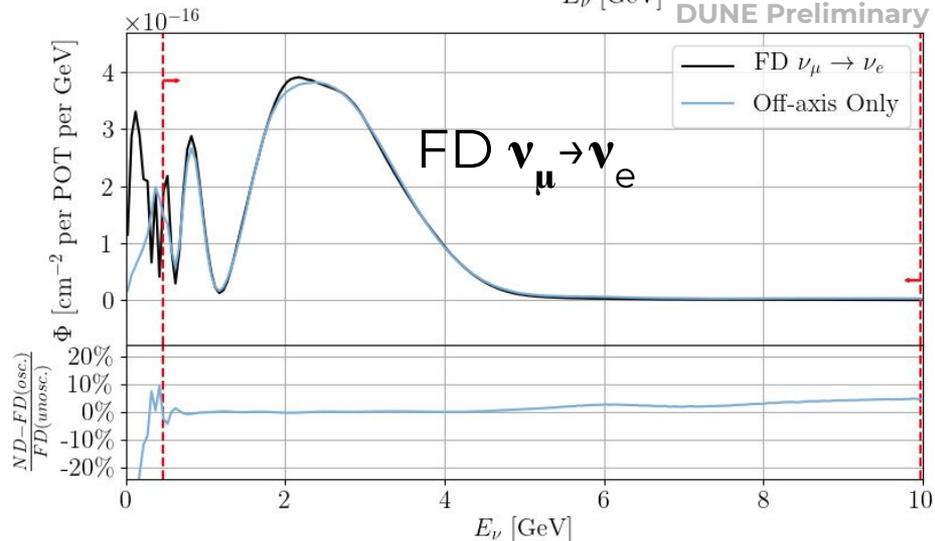
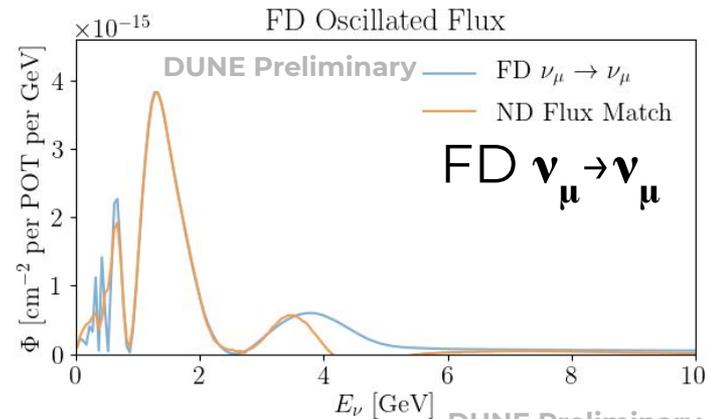


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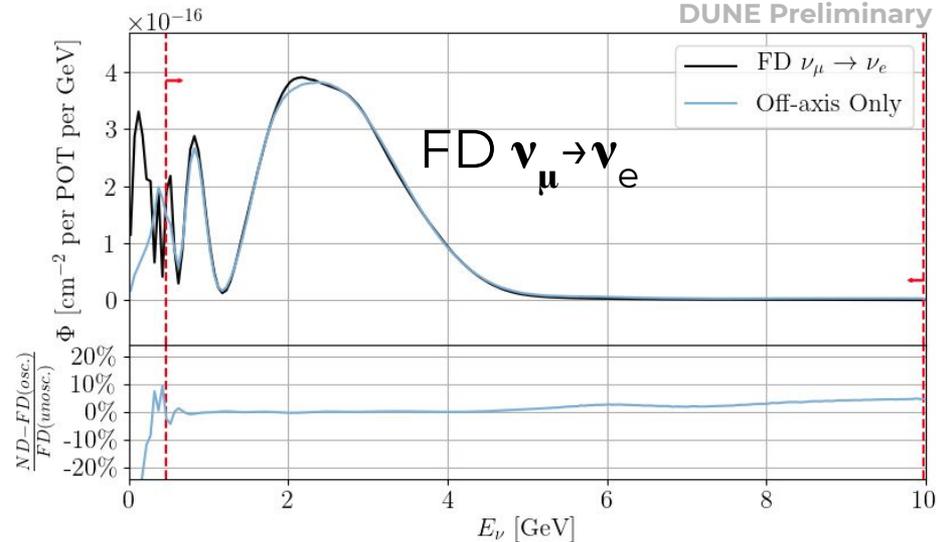
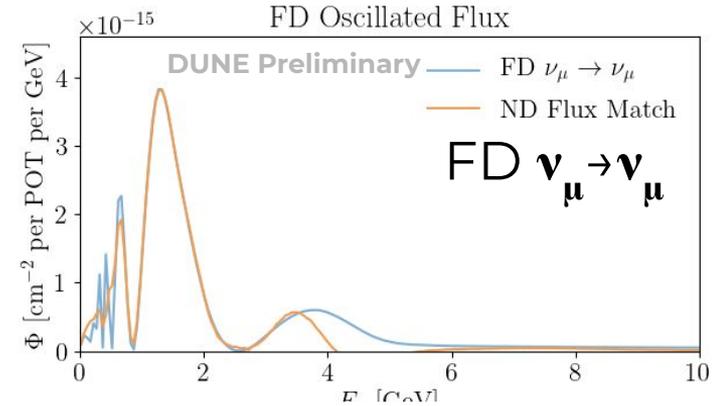
# Fixing for an appearance

- For appearance, cannot match ND  $\nu_e \Rightarrow$  FD  $\nu_e$
- Instead:
  - Use ND  $\nu_\mu$  sample
  - Build appeared FD  $\nu_e$  flux



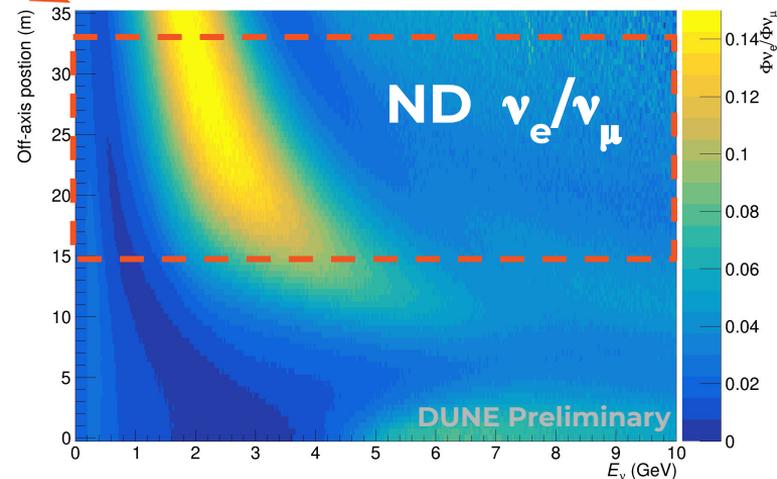
# Fixing for an appearance

- For appearance, cannot match ND  $\nu_e \Rightarrow$  FD  $\nu_e$
- Instead:
  - Use ND  $\nu_\mu$  sample
  - Build appeared FD  $\nu_e$  flux
- **Have to correct for electron/muon reconstruction & cross-section differences.**



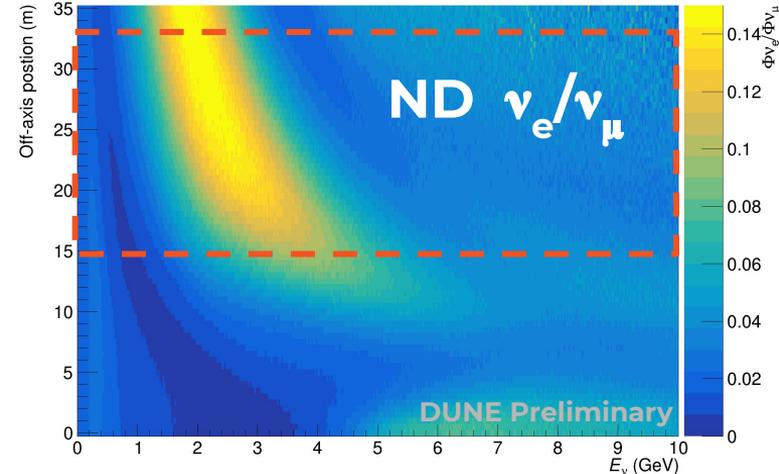
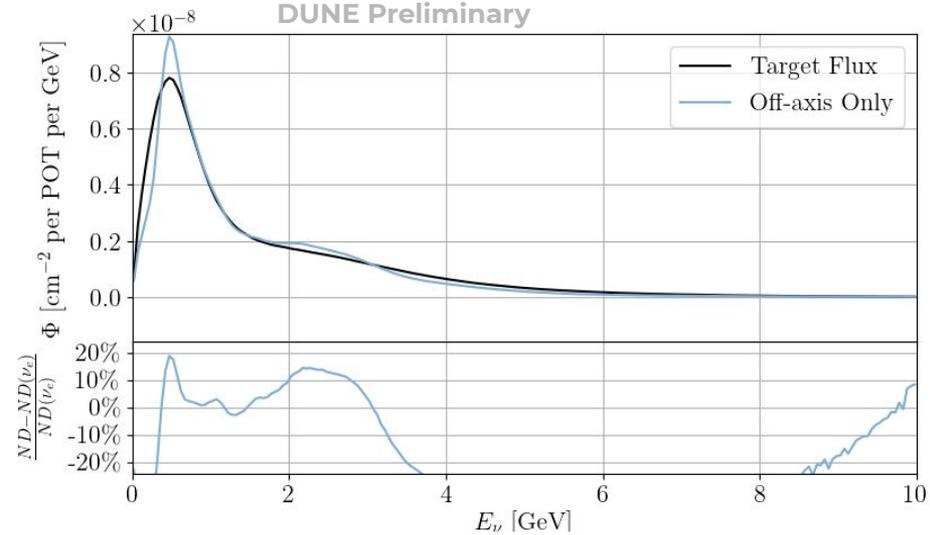
# ND nue fits

- Sample ND  $\nu_e$  flux while scanning off axis angle.
- **$\nu_e$  produced in 3-body decay: relative rate rises off axis.**
  - Match ND  $\nu_\mu$  to ND  $\nu_e$
- Use to check simulation of cross-section and reconstruction for  $\nu_\mu$  and  $\nu_e$  in a similar flux



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# Near Far Differences



# Geometric Efficiency Estimate

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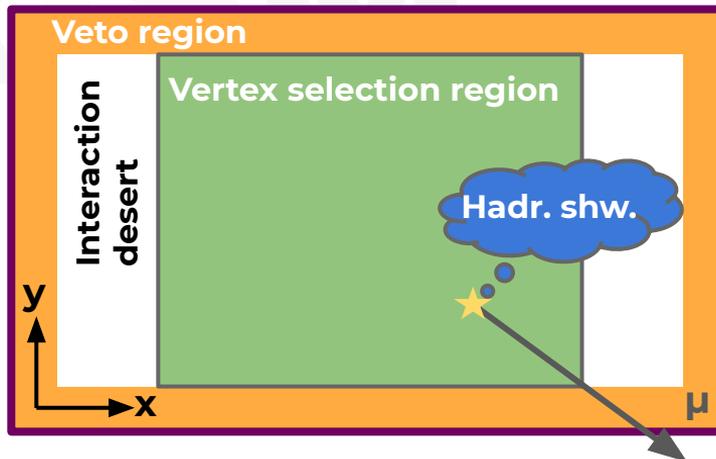
- Want to understand selection efficiency in an as-model-independent-way-as-possible.

DUVE  
PRISM

# Geometric Efficiency Estimate

- Want to understand selection efficiency in an as-model-independent-way-as-possible.

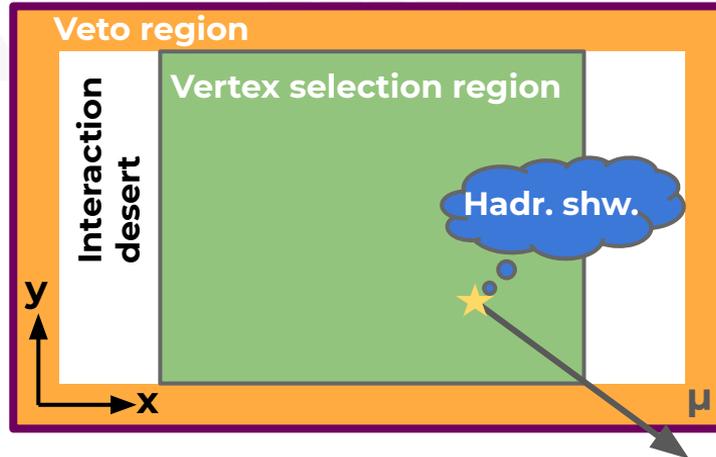
Active Volume



# Geometric Efficiency Estimate

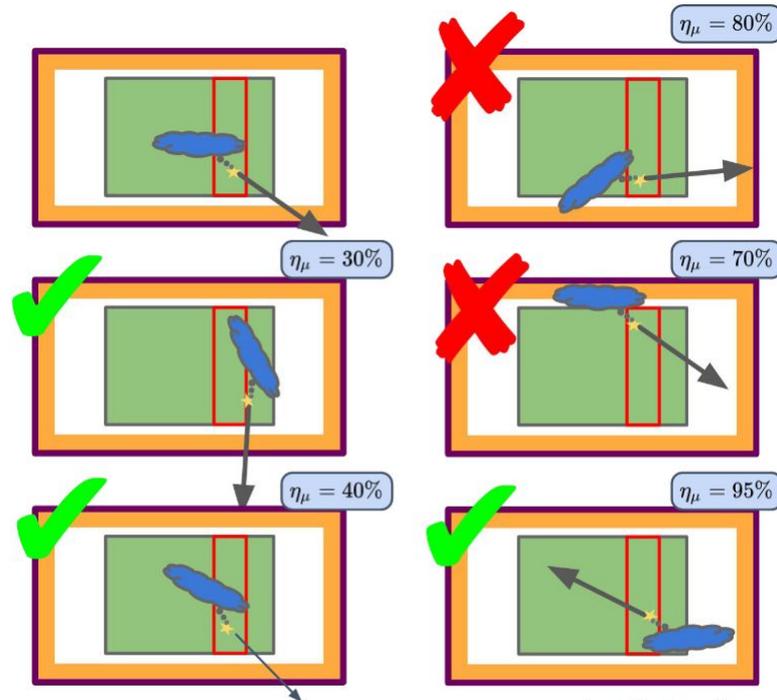
- Want to understand selection efficiency in an as-model-independent-way-as-possible.
  - **For a selected data event**, can estimate the probability of selecting an equivalent event geometrically.
  - ***Not just a model-based average as in current generation analyses***

## Active Volume



# Geometric Efficiency Estimate

- Exploit symmetry of interactions in LAr ND:
  - Translation around an off axis bin
  - Rotation around beam axis.
- How often would we have selected this event?
  - Does a rotation move observed hadronic deposits into the veto region?
  - For the Muon, train an NN to predict containment/selection by tracker.
  - Average over many toys to estimate efficiency.
- Ongoing work at Stony Brook and CERN, see [talk](#) by Cris Vilela for more details.

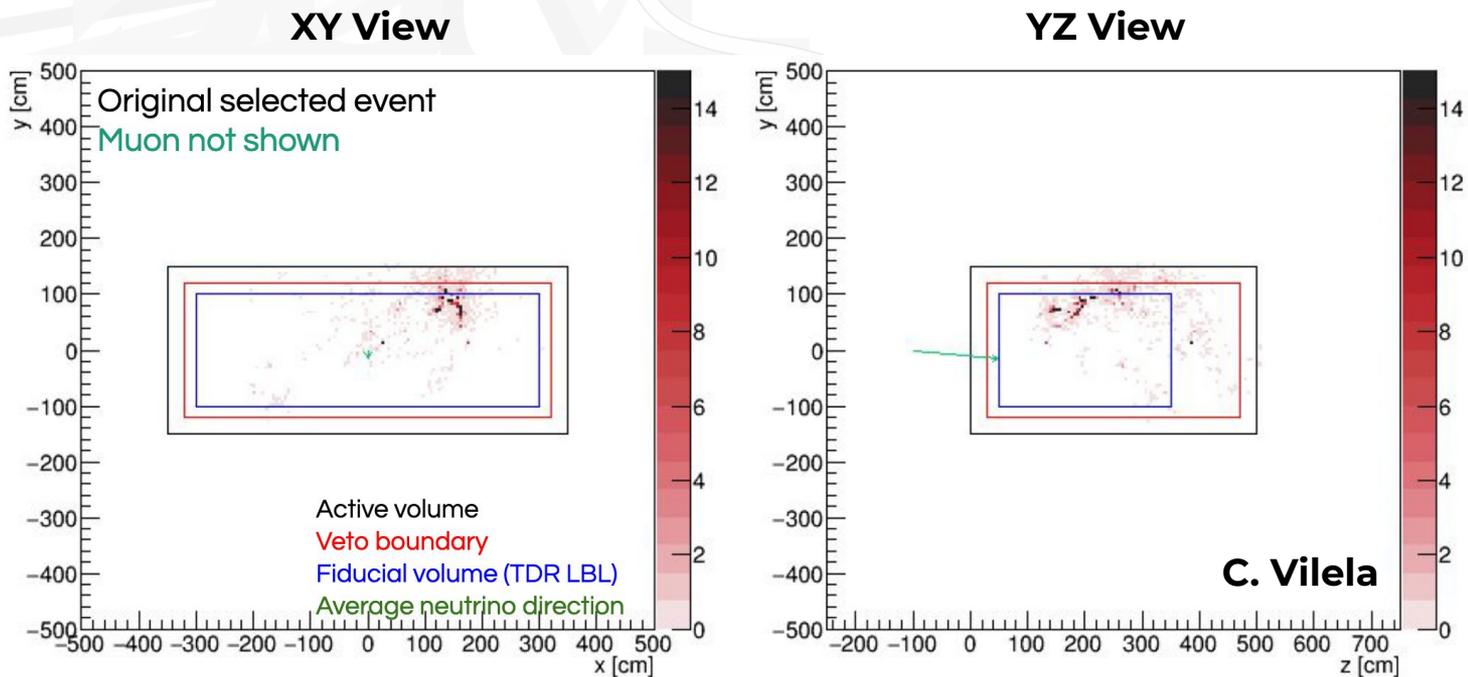


L. Pickering

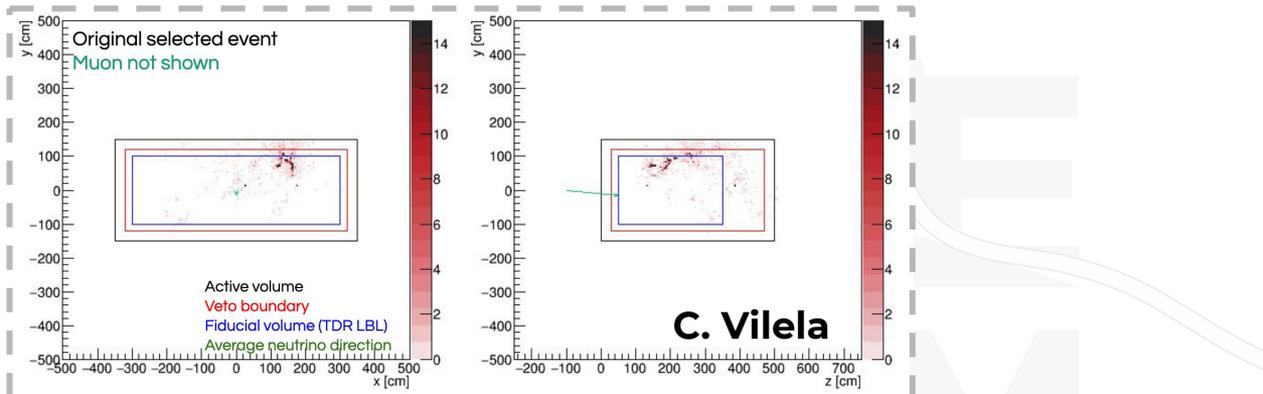
$$\eta = \frac{0 \times 0.8 + 1 \times 0.3 + 0 \times 0.70 + 1 \times 0.4 + 1 \times 0.95}{5} = 33\%$$

# Hadronic Shower Selection

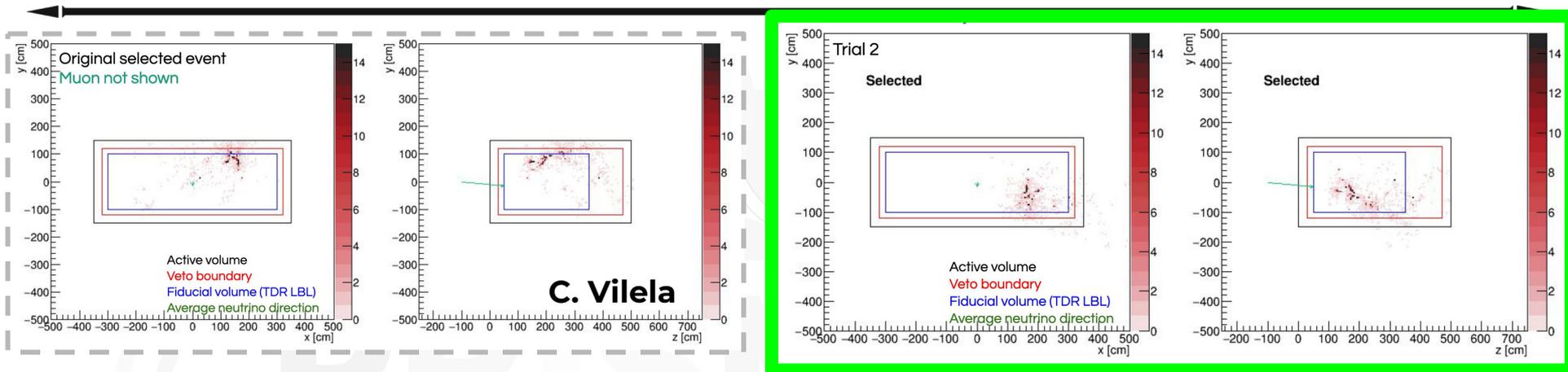
- Exploit symmetry of interactions in LAr ND:
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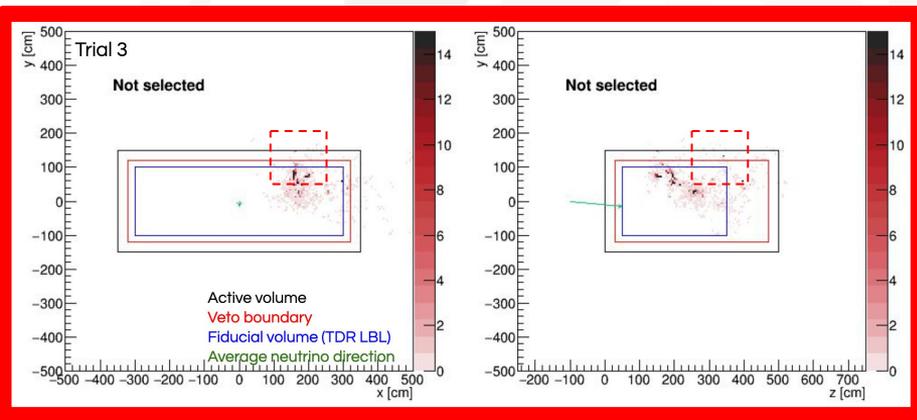
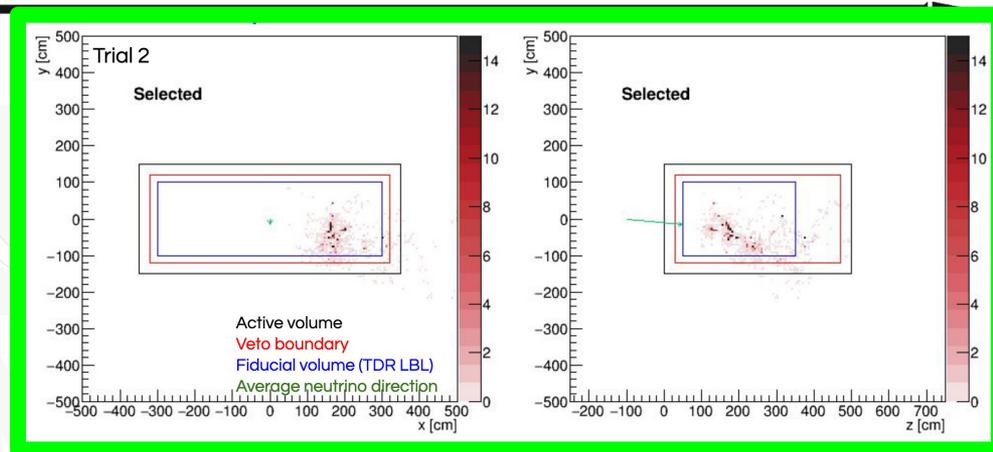
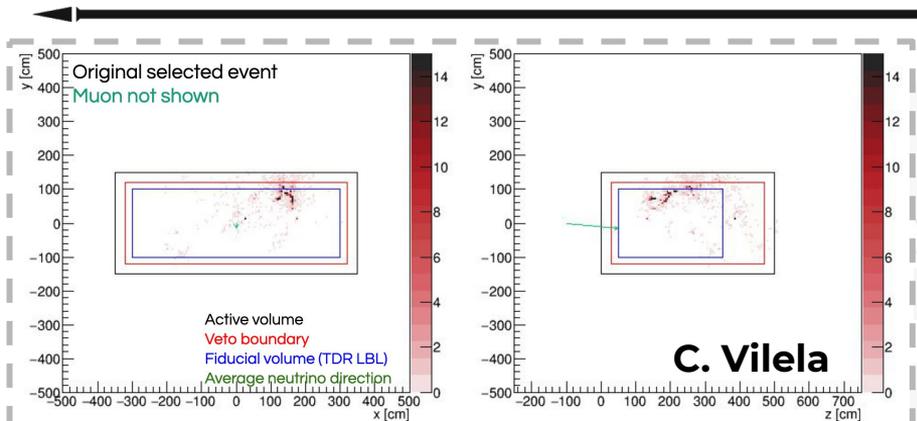
# Hadronic Shower Selection



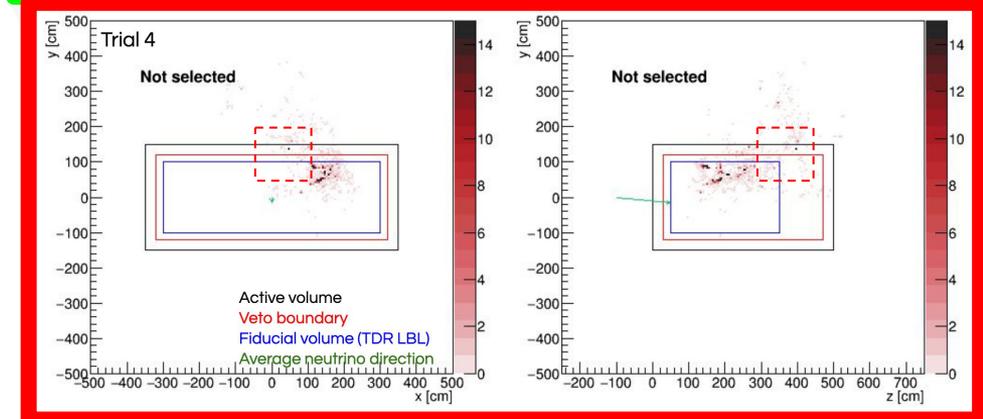
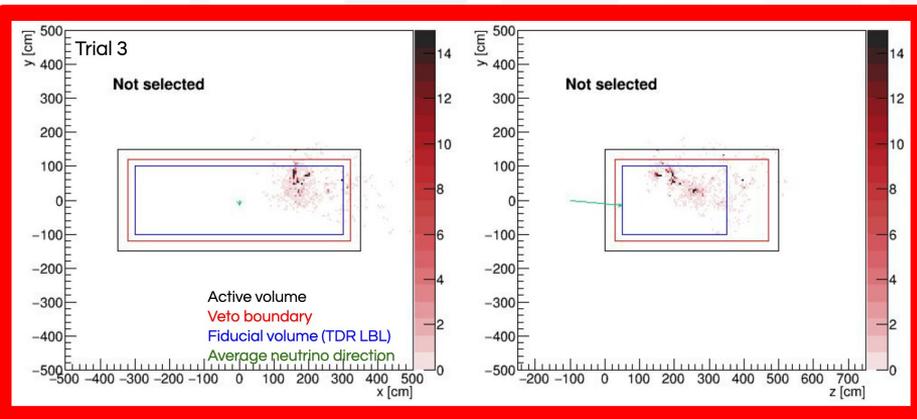
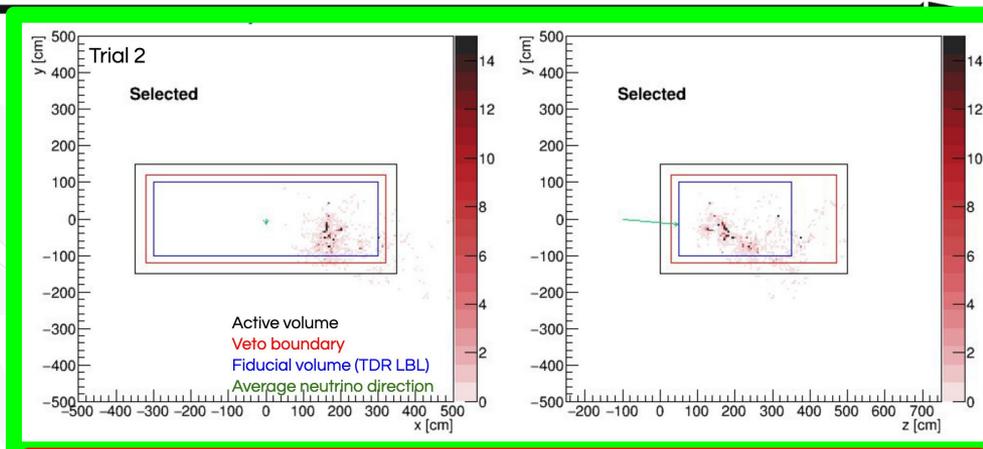
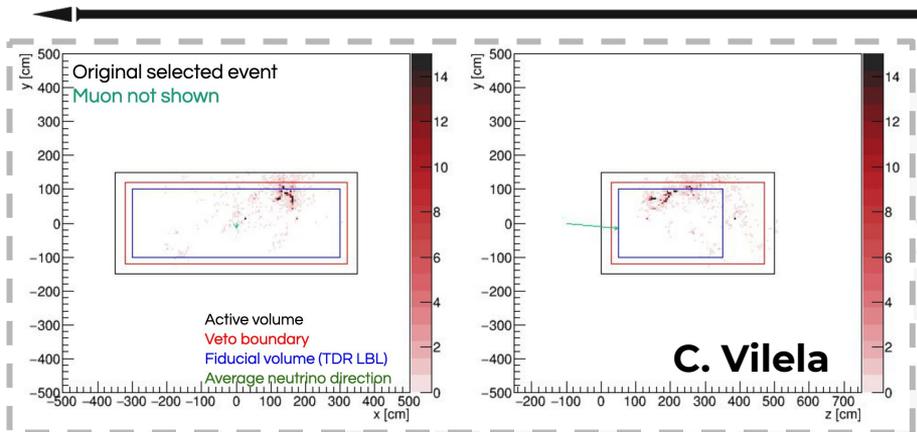
# Hadronic Shower Selection



# Hadronic Shower Selection

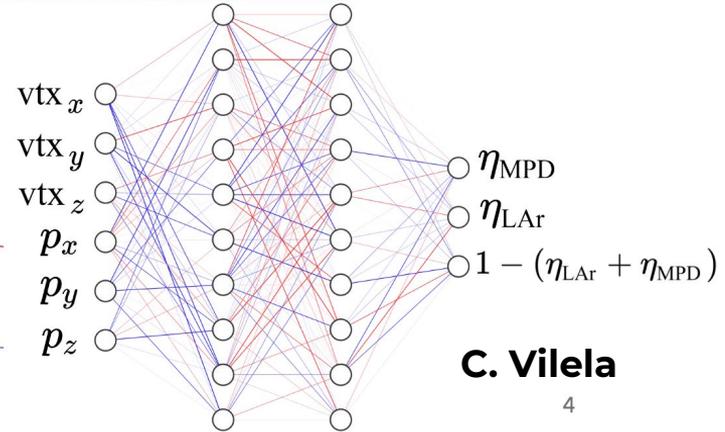
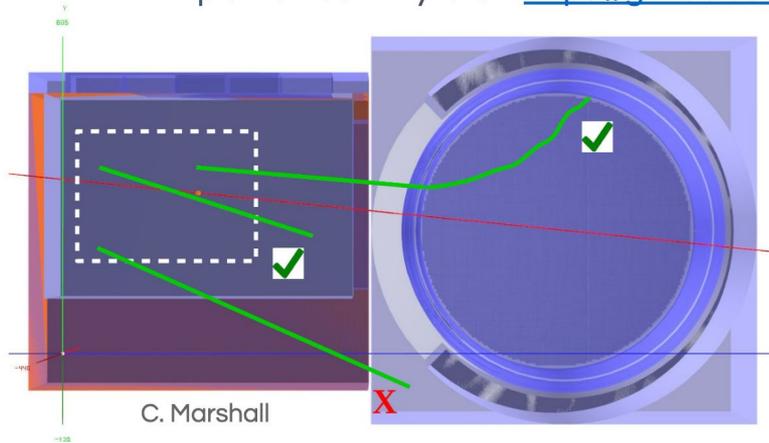


# Hadronic Shower Selection



# Muon Selection Efficiency

- 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>



# ND/FD Efficiency Differences

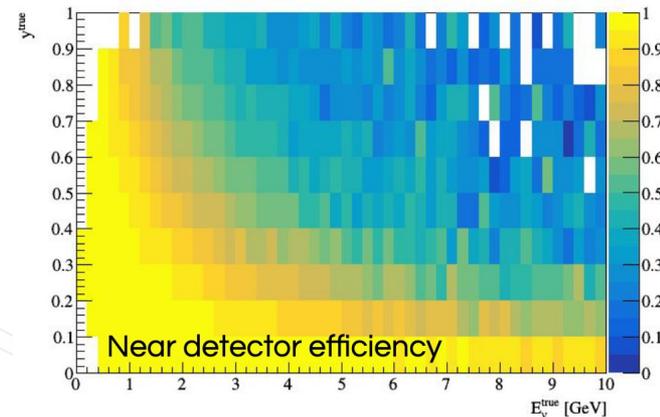
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- There will be some regions of kinematical phase space that are not well sampled by the near detector.

PRISM

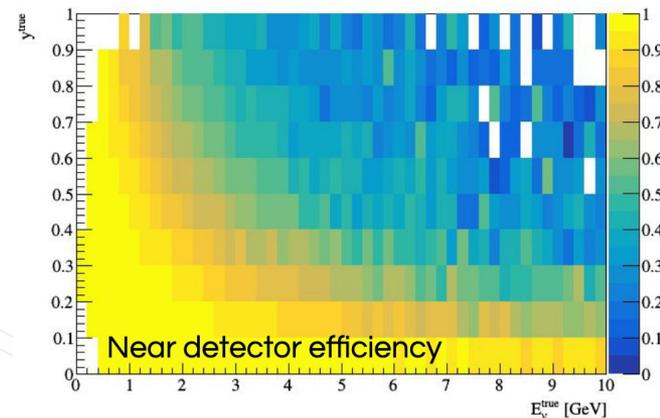
# ND/FD Efficiency Differences

- There will be some regions of kinematical phase space that are not well sampled by the near detector.
  - High energy/very inelastic events result in large showers that are rarely well contained by the ND
  - Never get a good constraint on such events from the data.



# ND/FD Efficiency Differences

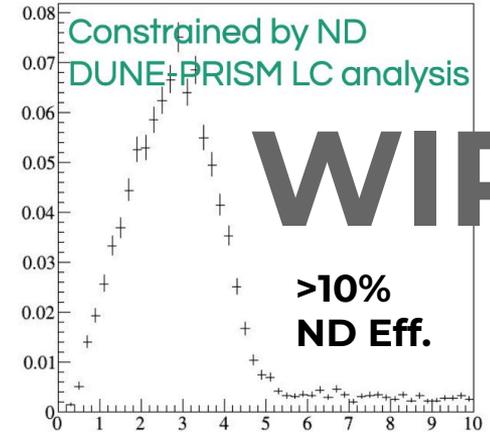
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  - High energy/very inelastic events result in large showers that are rarely well contained by the ND
  - Never get a good constraint on such events from the data.
  - This is true regardless for any analysis, not just PRISM.



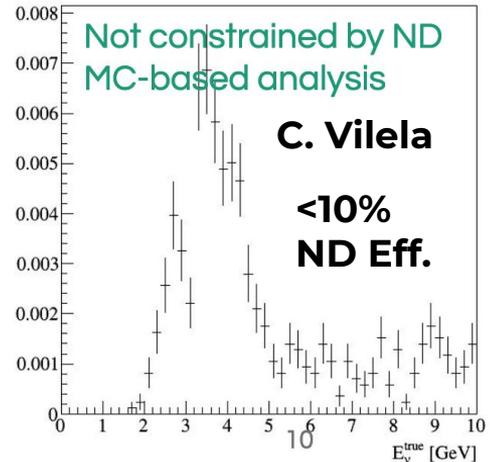
# ND/FD Efficiency Differences

- There will be some regions of kinematical phase space that are not well sampled by the near detector.
  - High energy/very inelastic events result in large showers that are rarely well contained by the ND
  - Never get a good constraint on such events from the data.
  - This is true regardless for any analysis, not just PRISM.
- Can apply event-by-event efficiency algorithms on FD data and determine which events are not well-constrained by the ND
  - Separate these into a separate sample which is compared to FD MC (as in a traditional analysis).

Far detector events with  $\eta_{\text{ND}} > 0.1$



Far detector events with  $\eta_{\text{ND}} < 0.1$



# Hand Picked Fake Data

## INTRODUCTION

C. Vilela: [DUNE Jan 2019](#)

- Want to generate a fake data set that **biases oscillation parameters** but is not constrained by an on-axis near detector fit.
  - Developed in the context of DUNE-PRISM studies.

$$E_{\nu}^{cal} = E_{\ell} + \sum_{i=1}^n (E_{p'_i} - M) + \sum_{j=1}^m E_{h'_j}$$

Sum over knock-out nucleons:

- Neutrons!
- How many?
- How is energy shared?

Sum over mesons:

- If undetected,  $\sim m_{\text{meson}}$  bias!
- How many?
- How is energy shared?

- Procedure:
  - Shift 20% of the energy carried by protons in CC interactions to neutrons.
    - This will change  $E_{true}^{\nu} \rightarrow E_{rec}^{\nu}$  as neutrons are largely unseen.
  - Find a reweighting scheme that recovers the unshifted **distributions** of observables at an on-axis near detector.

# Multivariate ReWeighting

C. Vilela: [DUNE Jan 2019](#)

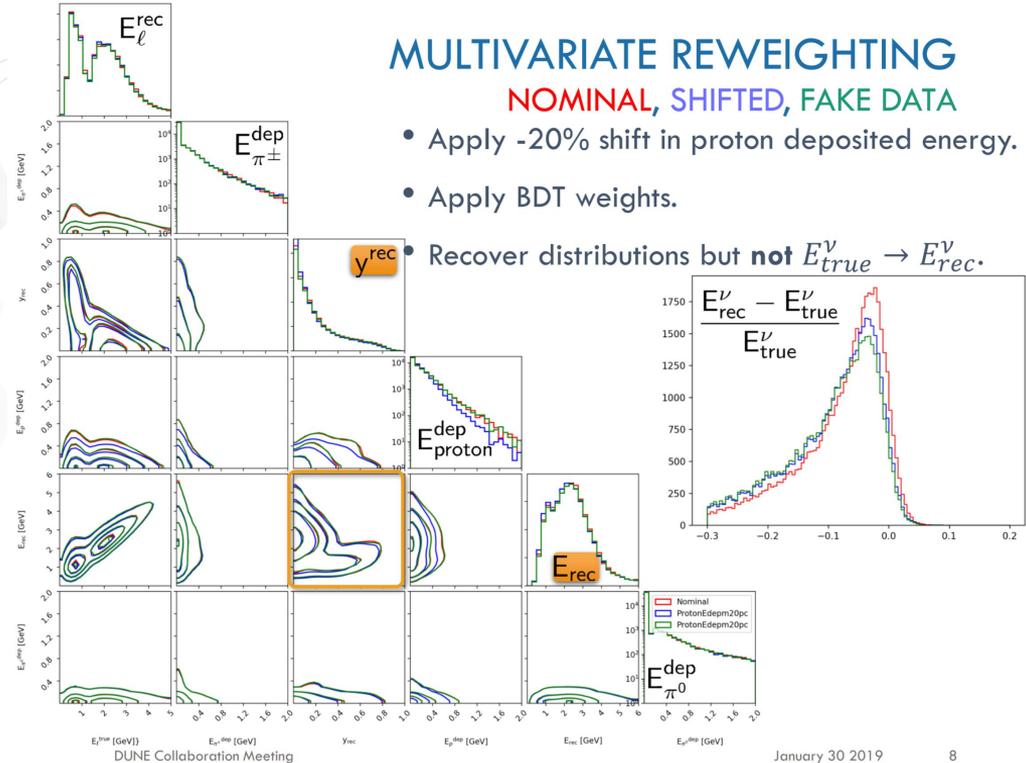
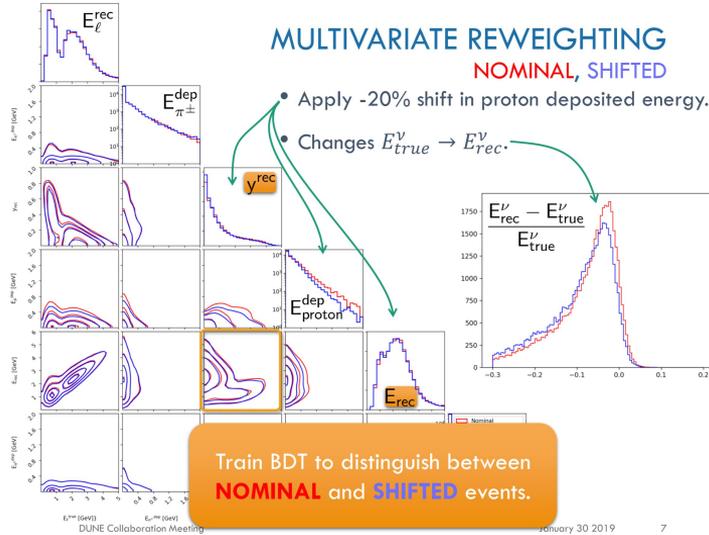
- Reweighting/Fake data technique that is being used more on T2K and DUNE (originated in Collider land).
- Get BDT to give you event weights that make your nominal MC look like something else in many distributions at once (but get the correlations correct).

## MULTIVARIATE REWEIGHTING

- Train a BDT to classify ND CC events as either **nominal** or **shifted** based on the following six variables:
  - Lepton energy, energy deposits due to protons,  $\pi^\pm$ s and  $\pi^0$ .
  - $E_{rec}^\nu$  and  $y_{rec} (= 1 - E_{rec}^{lep}/E_{rec}^\nu)$ .
    - Oscillation analysis uses these variables.
- Output of the BDT gives, for each event:
  - $p_{shifted}(E_{rec}^\nu, y_{rec}, E_{rec}^{lep}, E_{dep}^p, E_{dep}^{\pi^\pm}, E_{dep}^{\pi^0}) \sim \frac{N_{shifted}}{N_{nominal} + N_{shifted}}$
- Applying weight  $w = 1/p_{shifted} - 1$  to **shifted** events results in a distribution that looks just like the **nominal**.

Based on A. Rogozhnikov, J.Phys.Conf.Ser. 762 (2016) no.1, 012036 [arXiv:1608.05806]

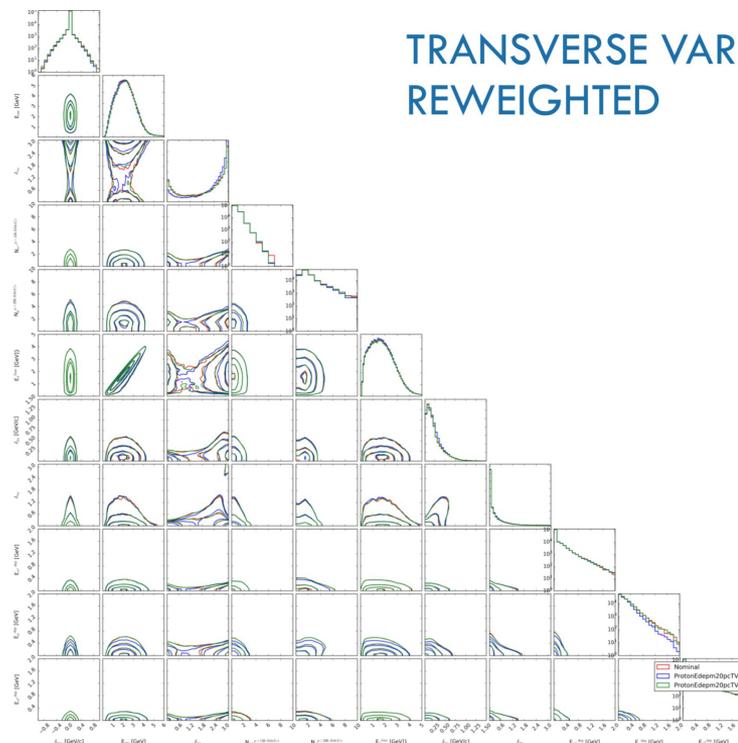
# Missing Proton Fake Data

C. Vilela: [DUNE Jan 2019](#)

# More Observables

- There are limits to this technique, but they're much further off than multi-dimensional histogram reweighting.
- It's still reweighting, cannot change total phase space.
- Doesn't always produce a consistent model, for medium sized sets, weights can be noisy.

TRANSVERSE VARIABLES,  
REWEIGHTED



NE Collaboration Meeting

January 30 2019

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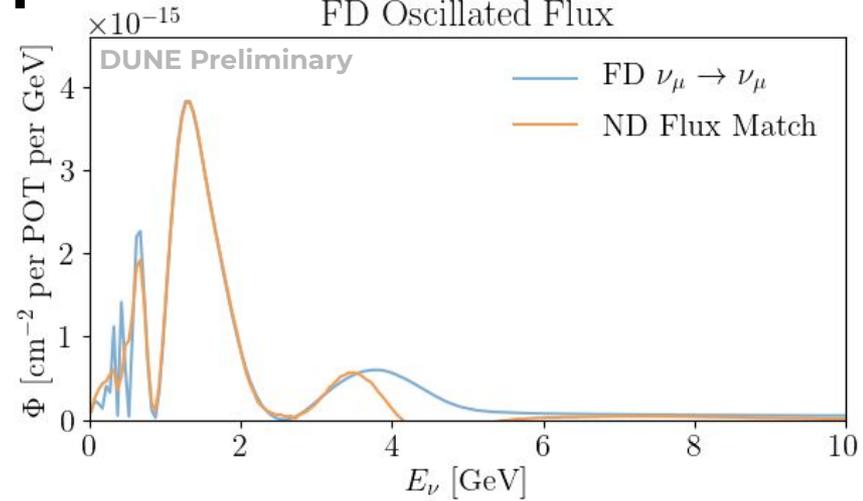


# Horn Current



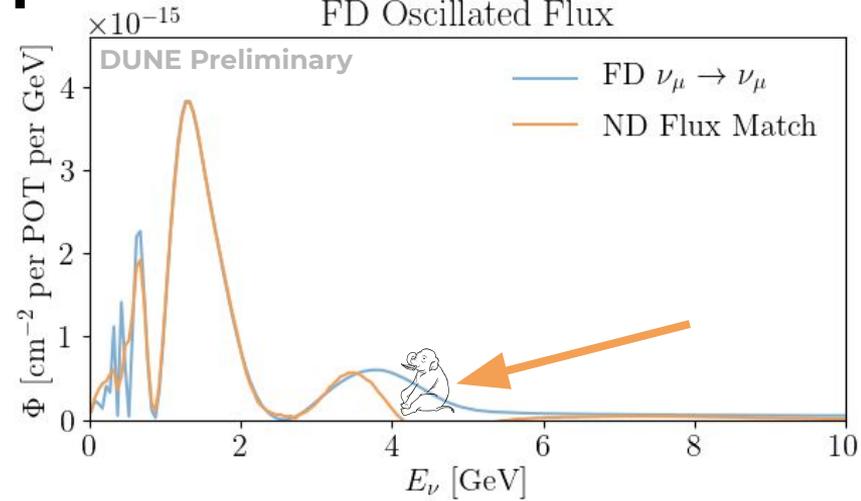
# Flux Mismatch Correction

- Elephant in the room



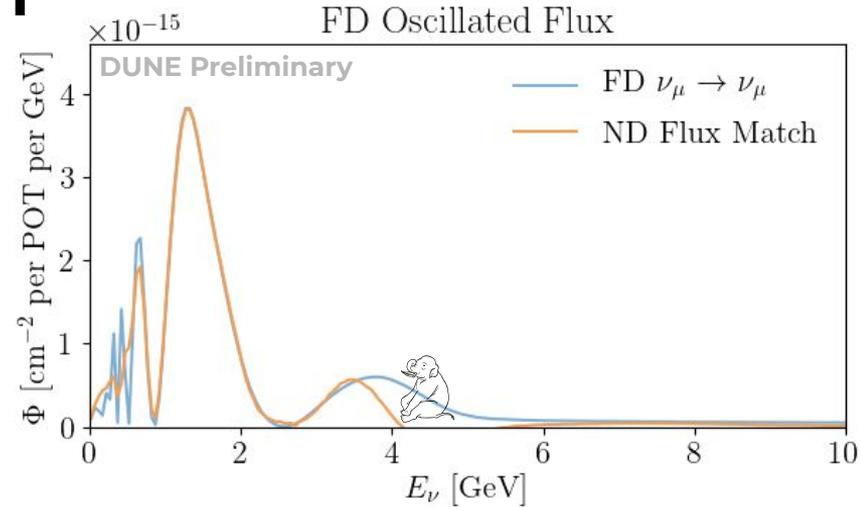
# Flux Mismatch Correction

- Elephant in the room



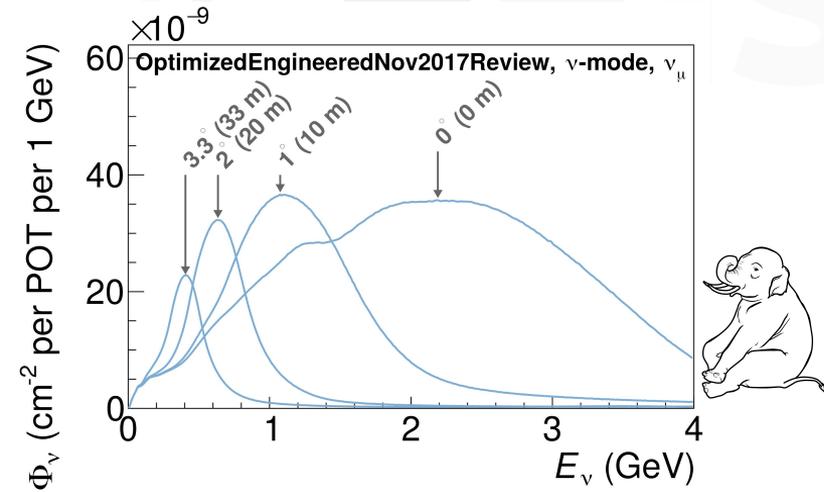
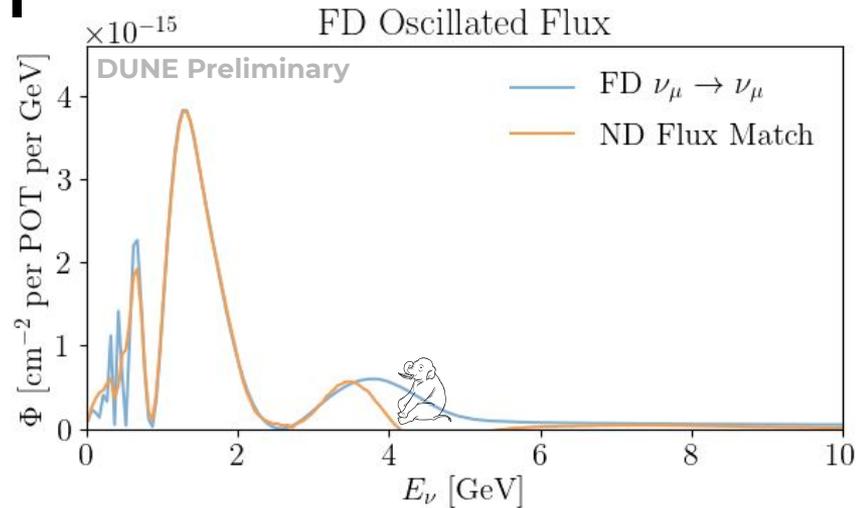
# Flux Mismatch Correction

- Have to correct for this mismatch by using far detector simulation:
  - Want to minimize model assumptions wherever possible...



# Flux Mismatch Correction

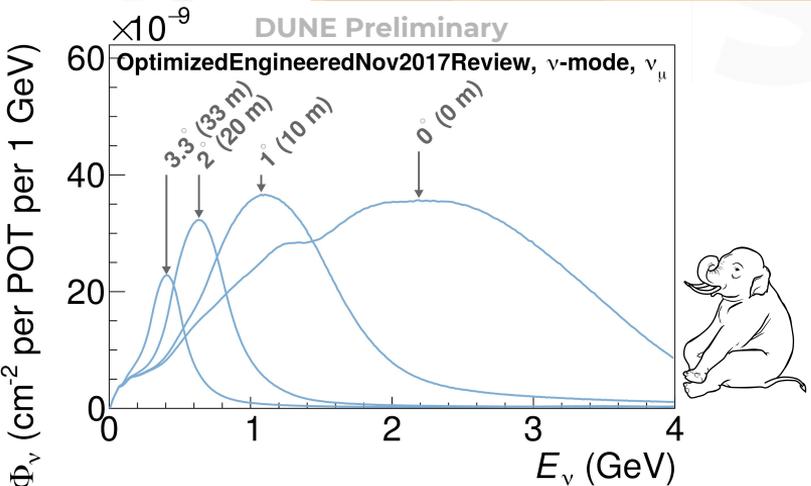
- Have to correct for this mismatch by using far detector simulation:
  - Want to minimize model assumptions wherever possible...
- This happens because no off axis fluxes peak higher than on axis



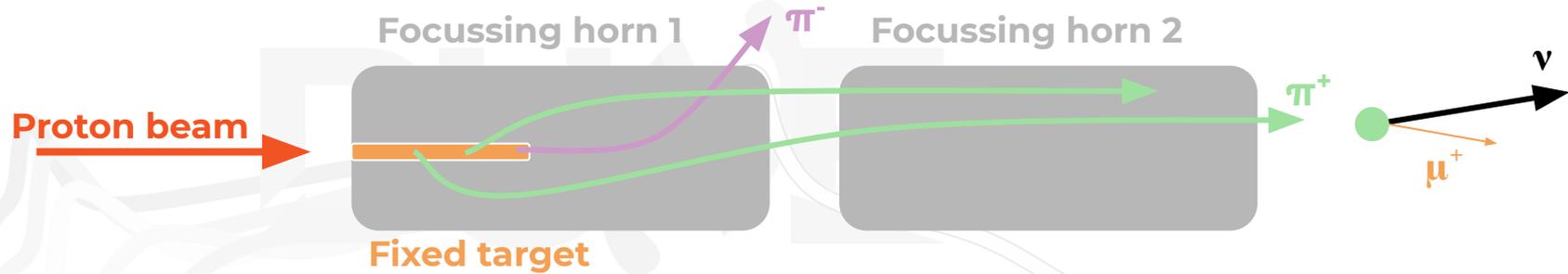
# Flux Mismatch Correction

- Have to correct by using
  - Want to know where
- This happens when fluxes peak

But what if we could use some that did peak higher?

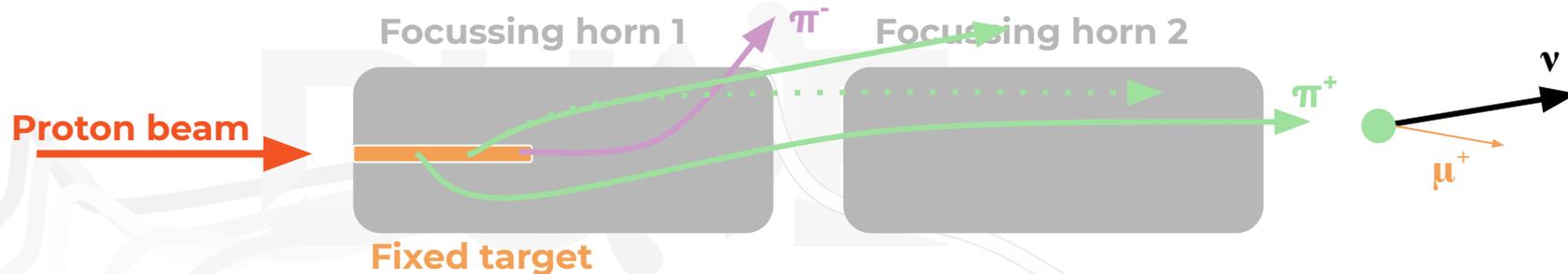


# Special Horn Current Runs



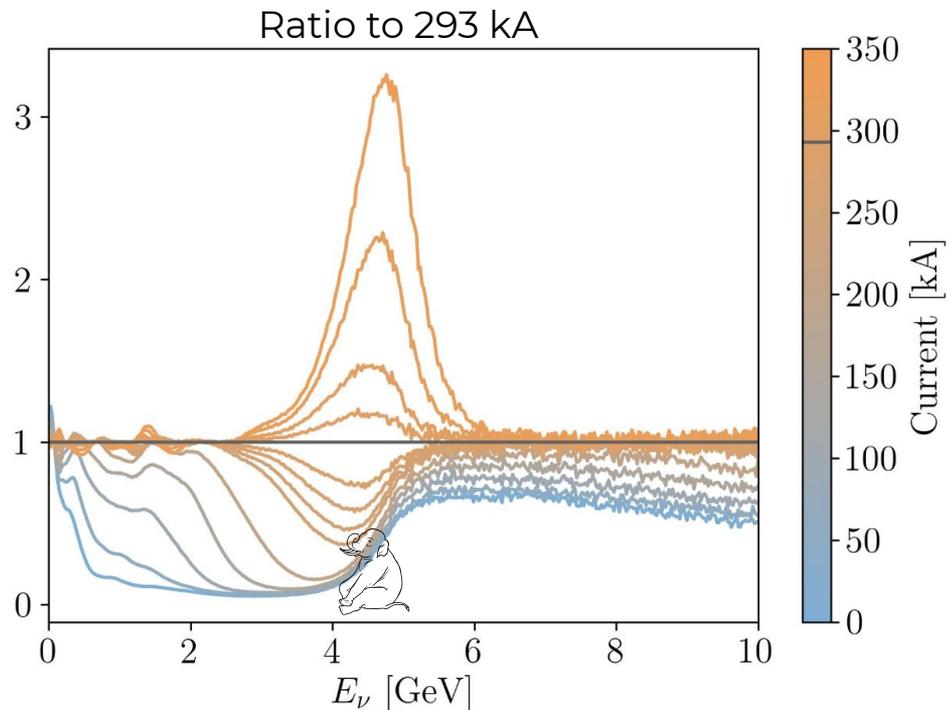
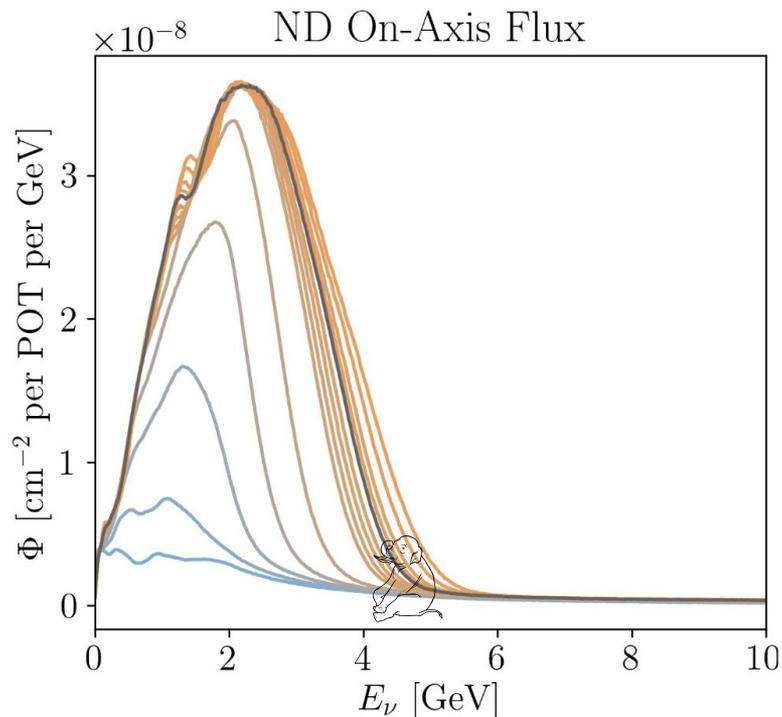
- If we vary the current in the magnetic horns, we change their momentum acceptance

# Special Horn Current Runs



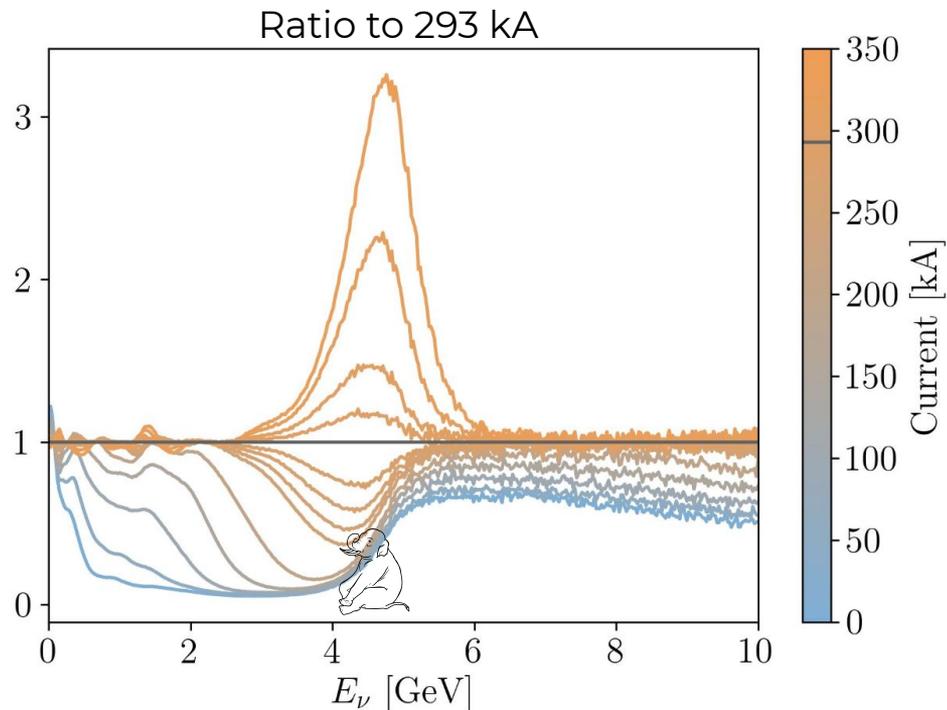
- If we vary the current in the magnetic horns, we change their momentum acceptance:
  - For a lower current, some higher energy pions might not be well focussed...

# Special Horn Current Runs



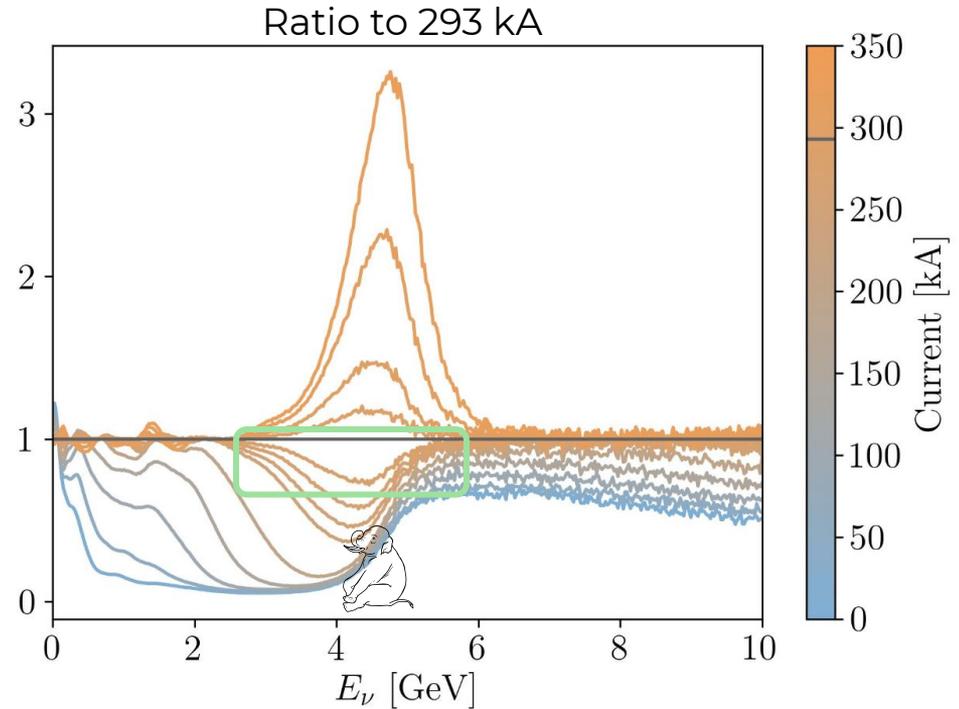
# Special Horn Current Runs

- Small variations are better:
  - Less change in far detector exposure
- Lower currents are better:
  - Current horn and power supply designed with 293 kA as the operating current.



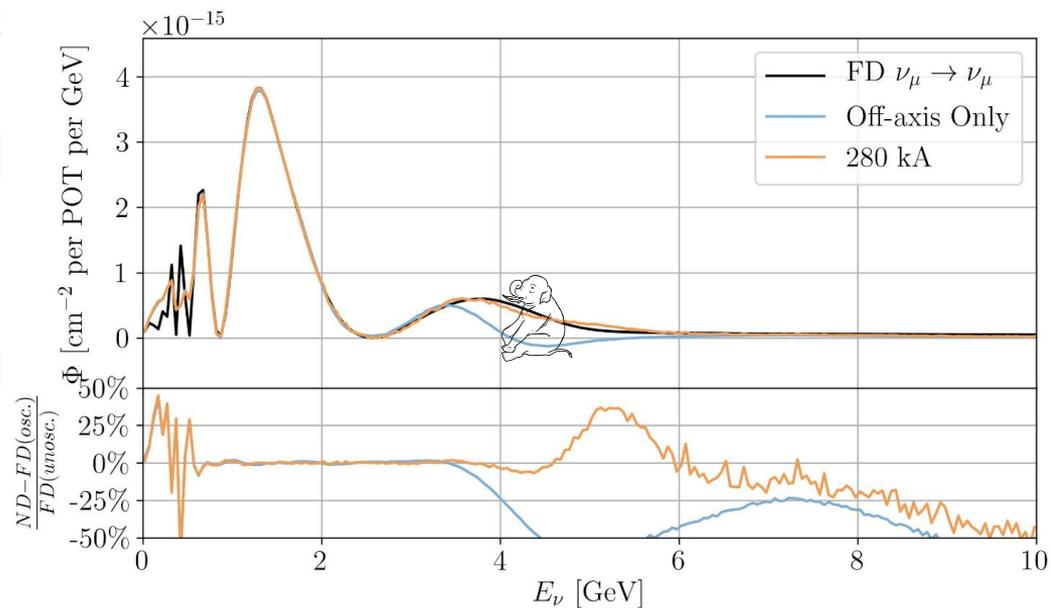
# Special Horn Current Runs

- Small variation are better:
  - Less change in far detector exposure
- Lower currents are better:
  - Current horn and power supply designed with 293 kA as the operating current.
- **280 kA looks useful**

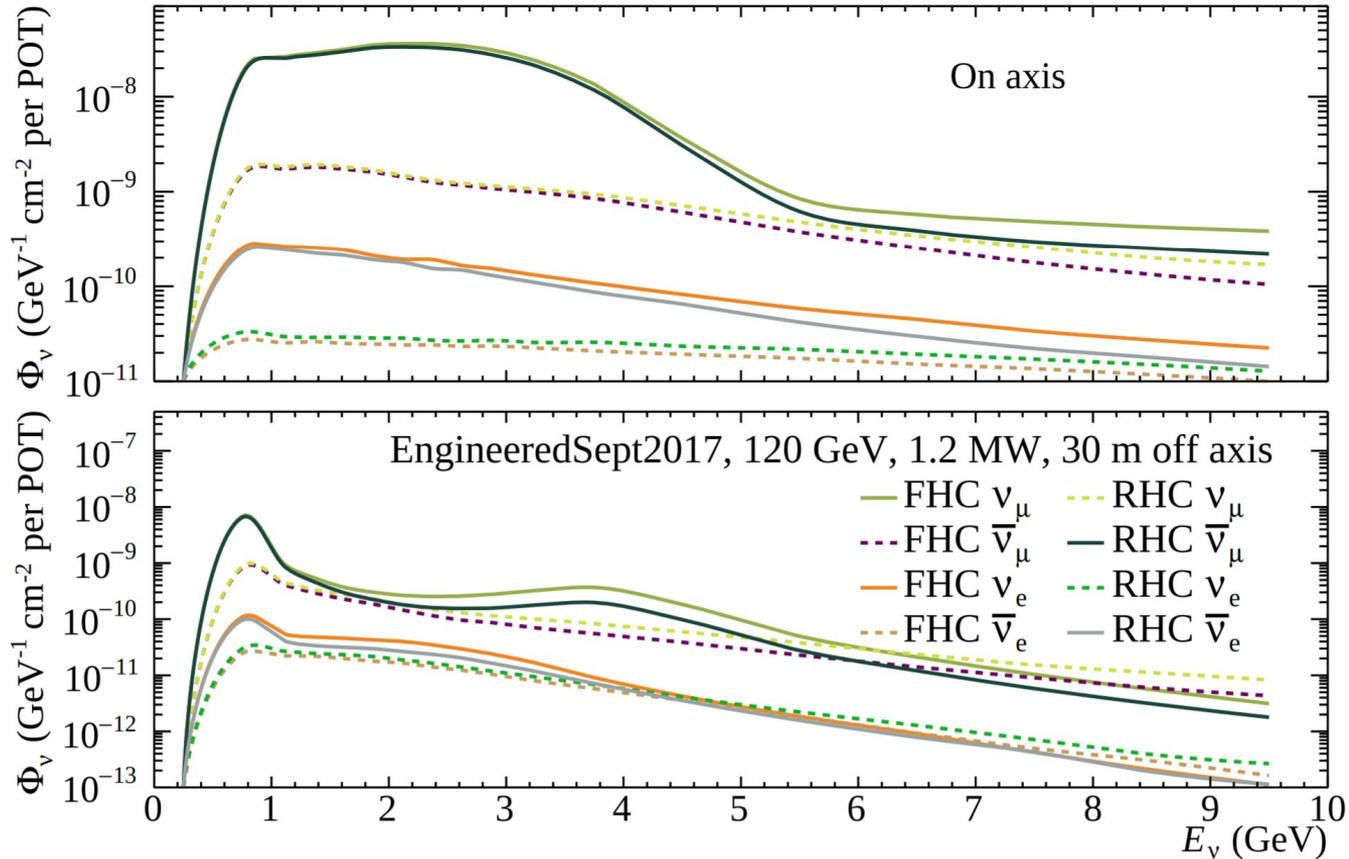


# Special Horn Current Runs

- Including an on-axis run at 280 kA drastically improves the flux matching!
  - Much less far detector model correction required.



# Parent Species Off axis.



# Special Horn Current Runs

- Can make flux predictions under different beam conditions:
  - e.g. Varied horn currents
- Seems to really change the game in terms of reducing the need for FD MC!
- Only need an on-axis sample:
  - minimal disruption of FD data taking.**

