Independent

Reaction

Spectrum

Precision

Measurement

DUNE-PRISM : Removing neutrino interaction model dependence with a movable neutrino detector

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On Behalf of the *DUNE Collaboration*

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Introduction

- Entering a new era of **long-baseline (LBL) neutrino oscillation physics** where we are no longer limited by our statistics

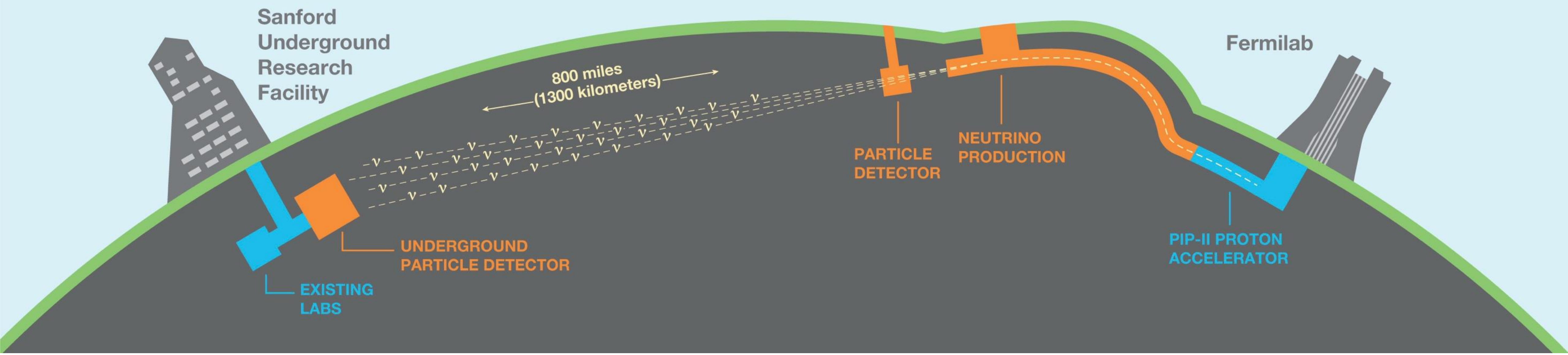
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Not statistically limited – **systematically limited** neutrino oscillation experiment
- Control **systematic uncertainties** with a **near detector (ND)**
- Precision Reaction Independent Spectrum Measurement (**PRISM**) technique **reduces dependence on the neutrino interaction model**

Deep Underground Neutrino Experiment

Observe $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

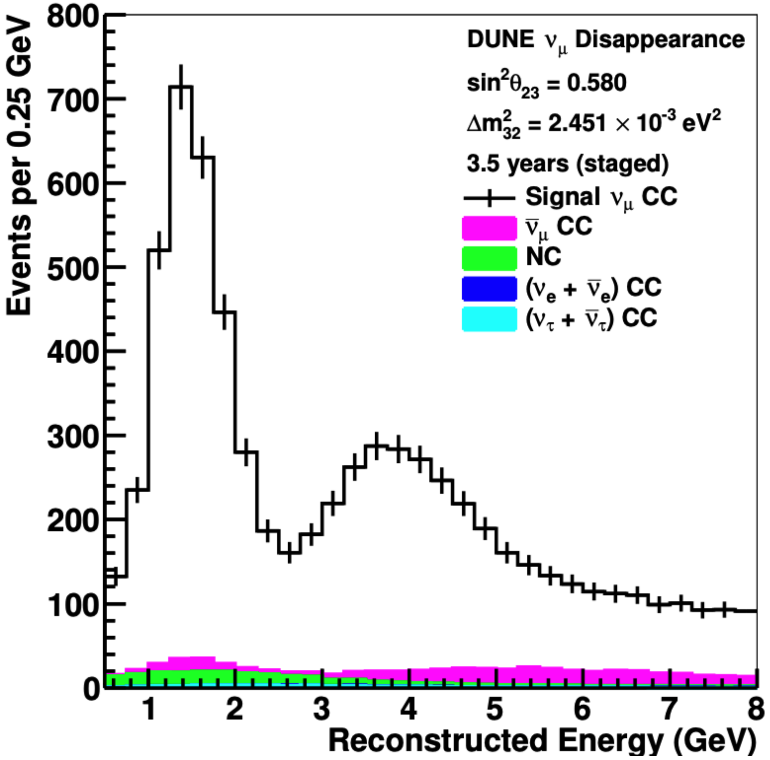
Measure δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}, mass ordering



Measuring Neutrino Oscillations

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

Measure oscillated event rate in reconstructed energy at Far Detector



arXiv: 2002.03005 [hep-ex]

Measuring Neutrino Oscillations

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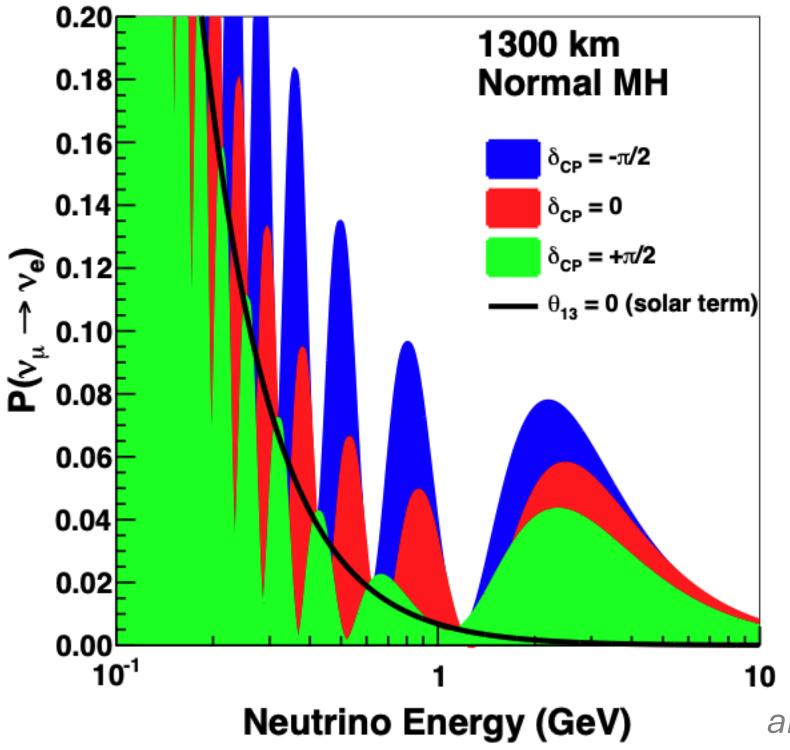


arXiv: 2002.03005 [hep-ex]

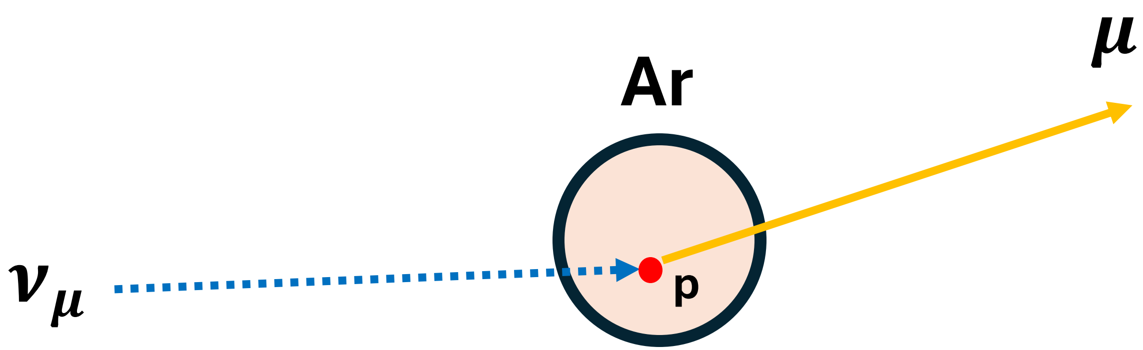
Extract oscillation probability (function of true energy!)

Measuring Neutrino Oscillations

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

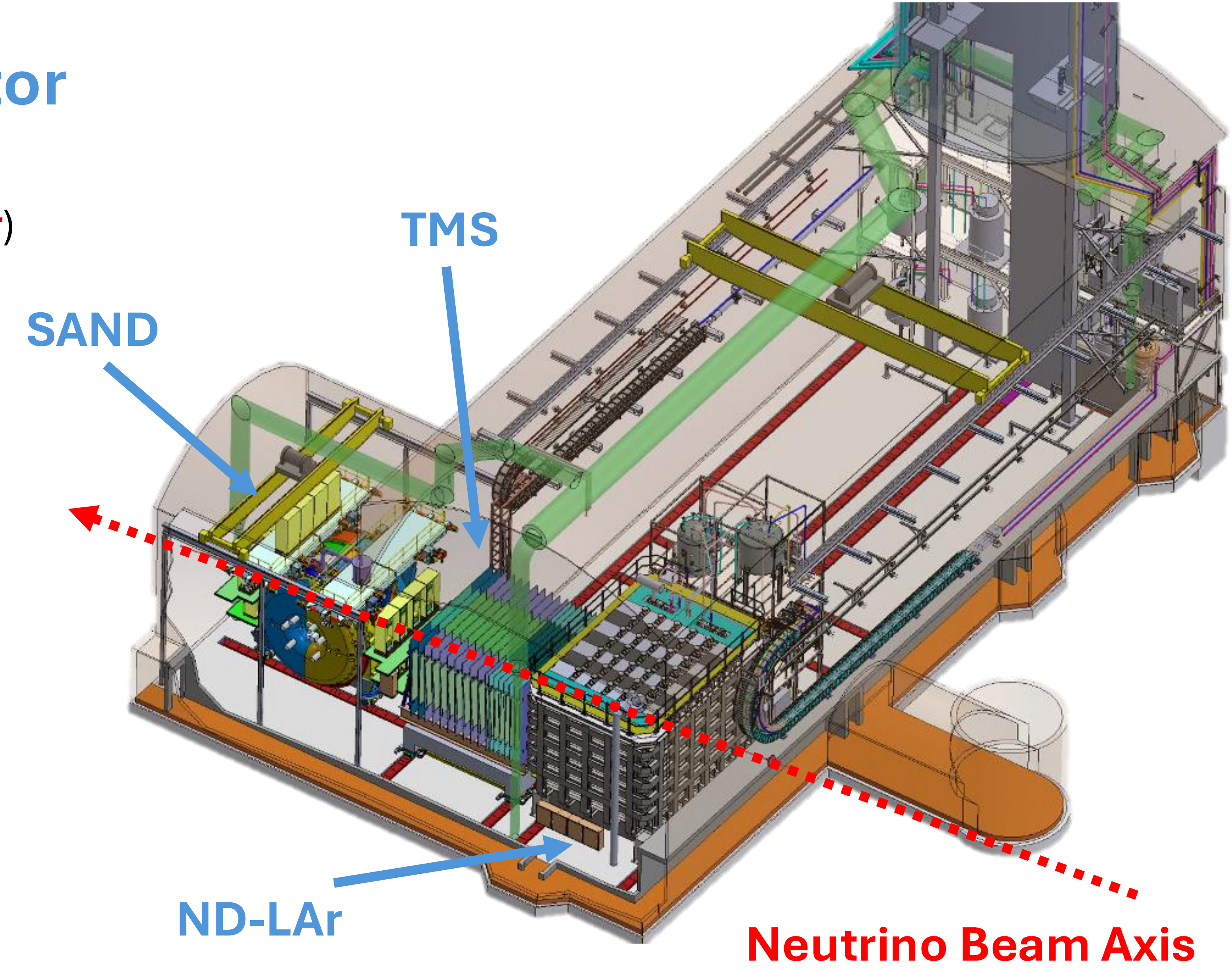
Success requires accurate models of:

- Neutrino flux
- The detector
- **Neutrino-nucleus cross section**



DUNE Near Detector

- Segmented LArTPC (**ND-LAr**)
- System for on-Axis Near Detection (**SAND**)
- Temporary Muon Spectrometer (**TMS**)



DUNE Near Detector

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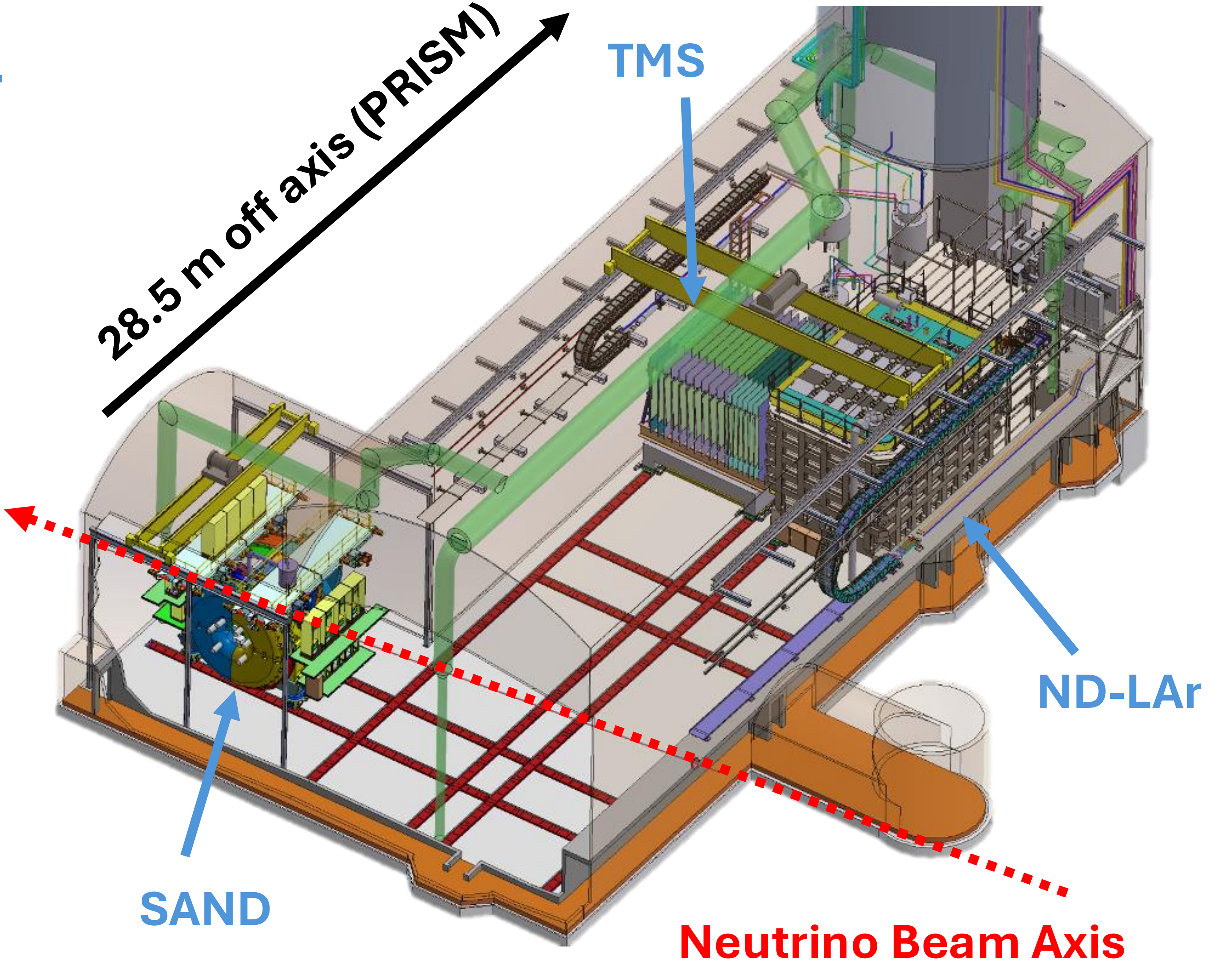
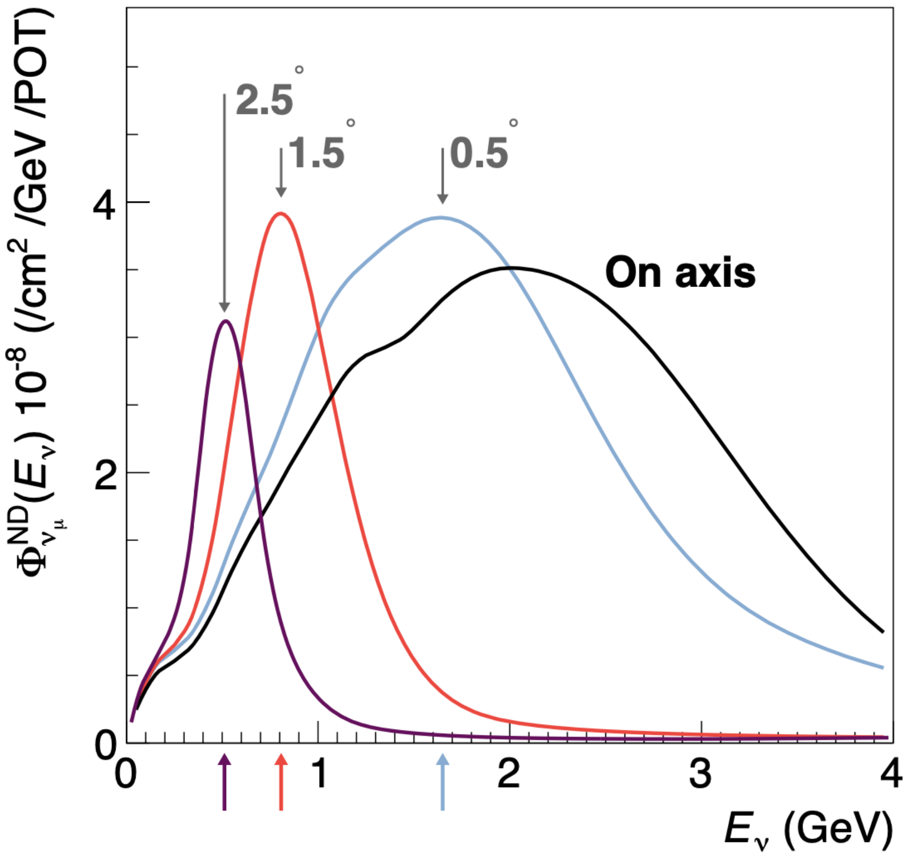
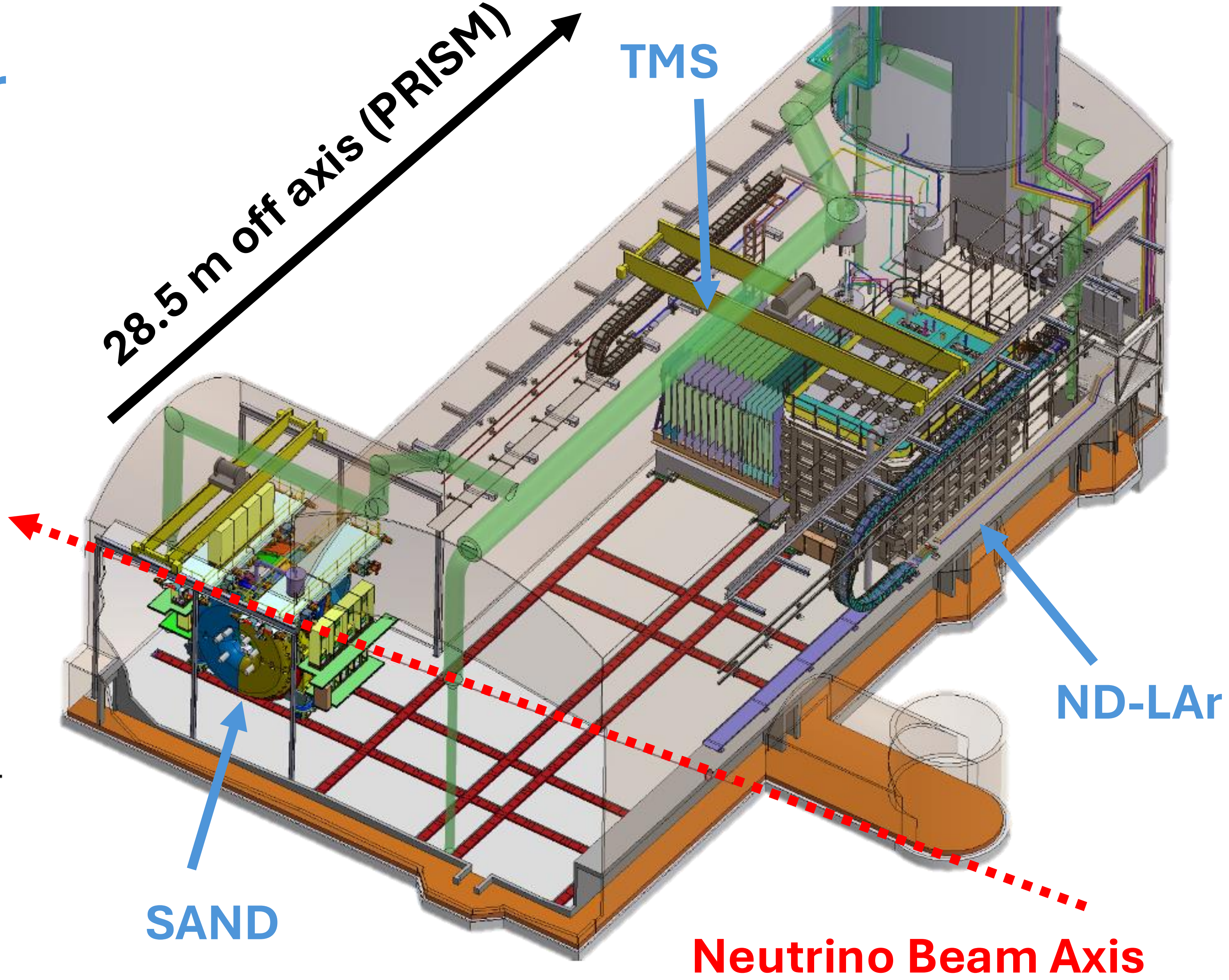


DUNE Near Detector

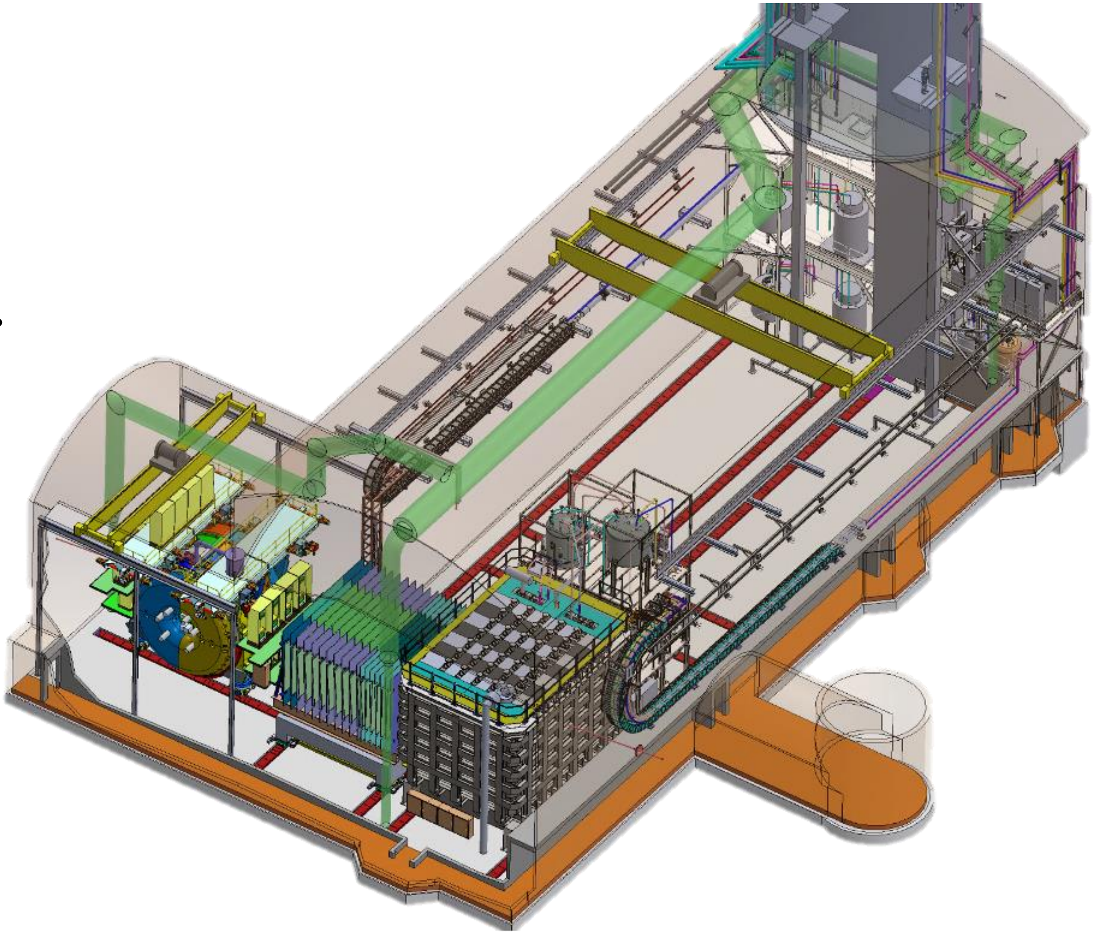


arXiv:2103.13910 [physics.ins-det]



DUNE Near Detector

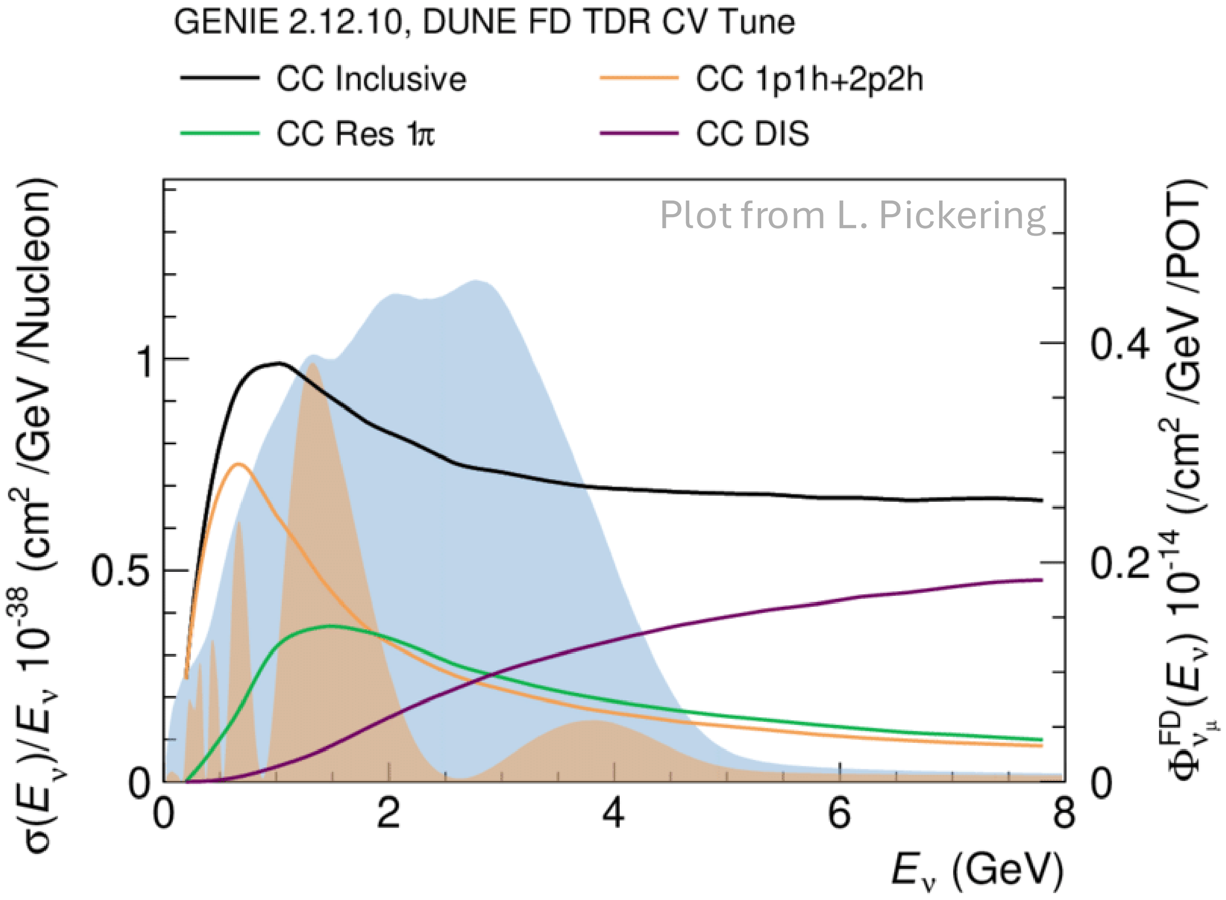
- Precise oscillation measurement
  - limited by systematic uncertainties
- Traditional measurement with a **fixed ND**...
  - Measure neutrinos at **high rates**
  - Compare data to model prediction
  - Reduce uncertainties in **Φ** & **σ** according to **Φ** $\times$ **σ** measurement



DUNE Near Detector

BUT …

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



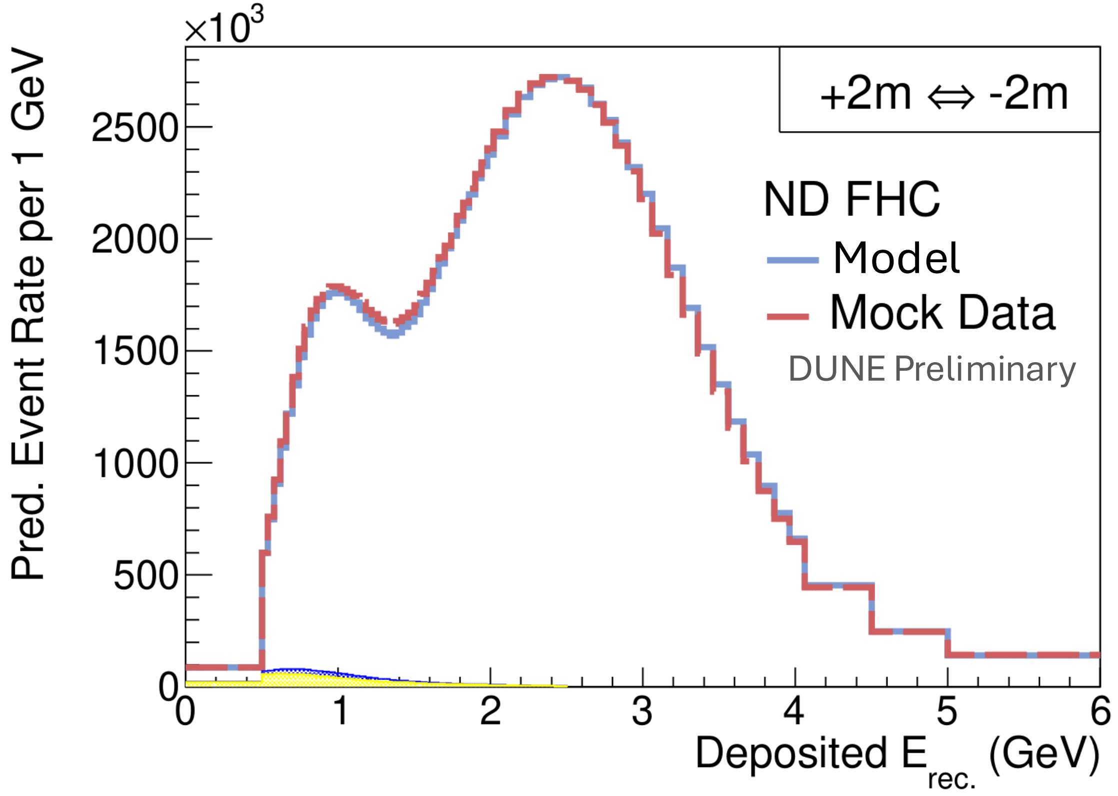
What happens if the neutrino interaction model is wrong?

An example from DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

What Can Go Wrong?

- Possible to have a **good fit** at the **fixed ND** but $E_{true} \rightarrow E_{obs}$ model is wrong
- Test **different reality** where:
  - Moved **20%** of **proton energy** to (unobserved) neutrons
  - Make (**incorrect**) **changes** to ND model to make ND model match data

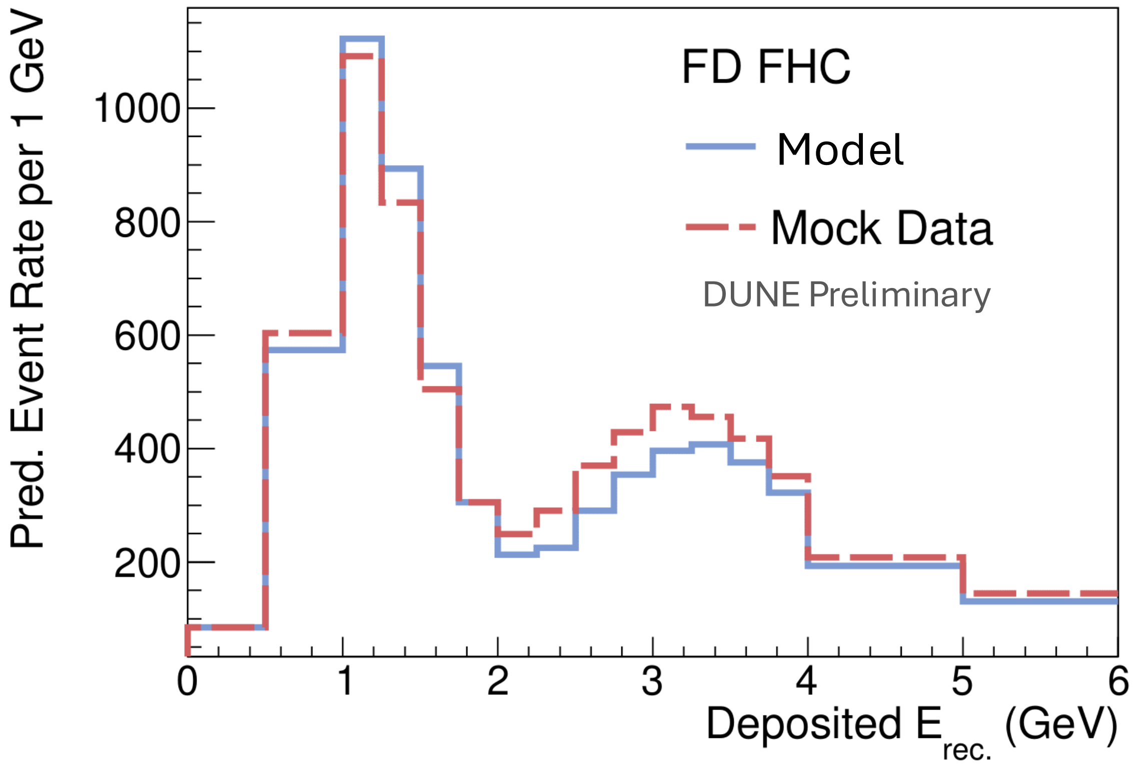
Event rate from a fixed on-axis DUNE ND



(Dip due to gap between ND-LAr and TMS)

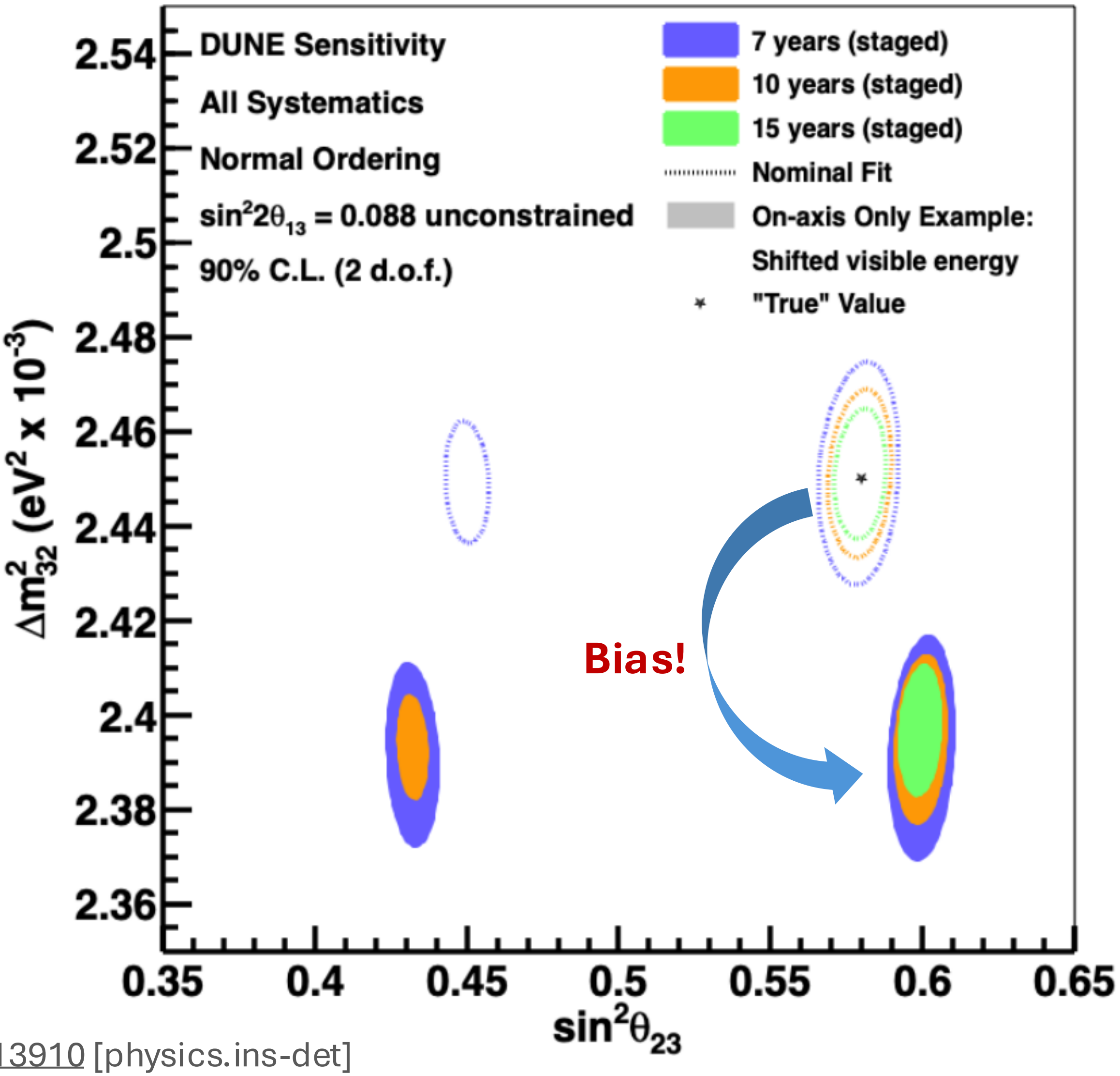
What Can Go Wrong?

- Possible to have a **good fit** at the **fixed ND** but **$E_{true} \rightarrow E_{obs}$** model is wrong
- Case Study:
  - In the **oscillated flux** at the **FD** agreement between MC and data **bad** – but oscillation parameters are the same
  - 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 $E_{true} \rightarrow E_{obs}$ model is wrong
- A 'traditional' fixed-ND oscillation analysis could get **biased contours**
  - And we would **not know it**!



arXiv:2103.13910 [physics.ins-det]

Independent

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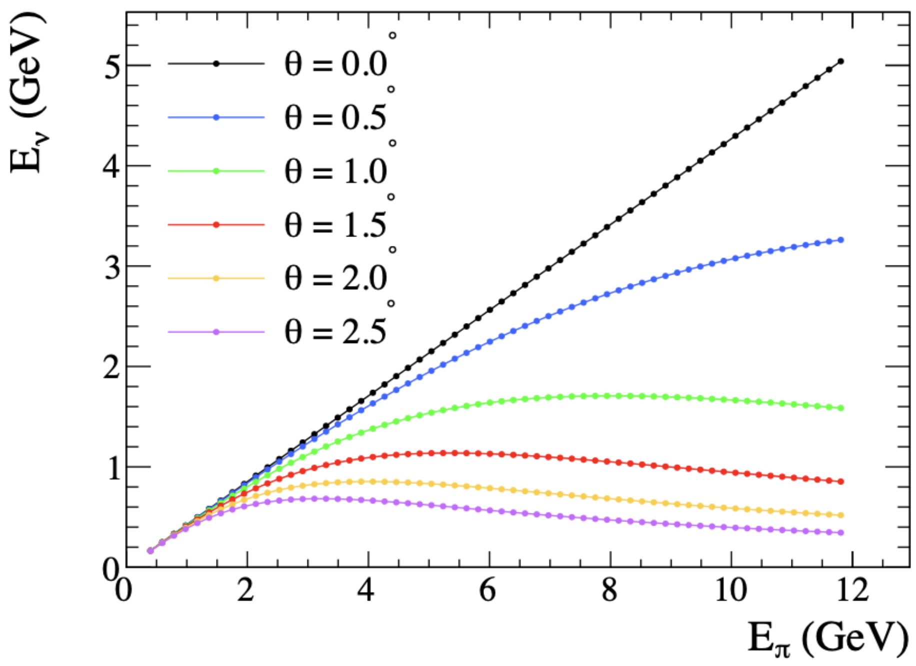
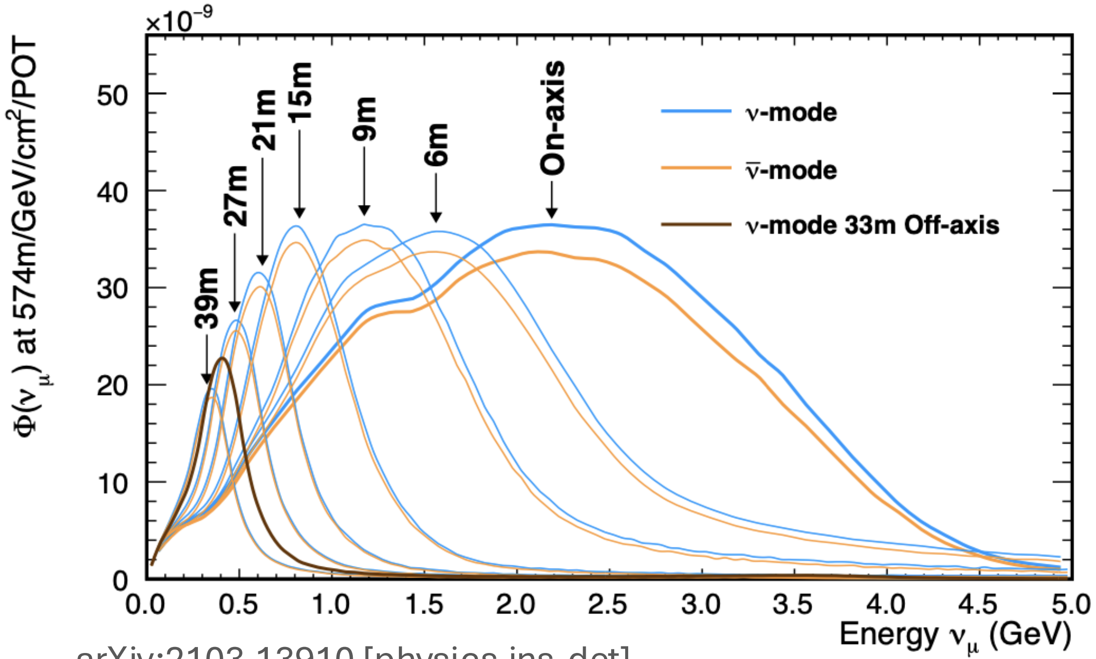
What is the PRISM technique and how can it help?

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Precision Reaction Independent Spectrum Measurement

- 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**





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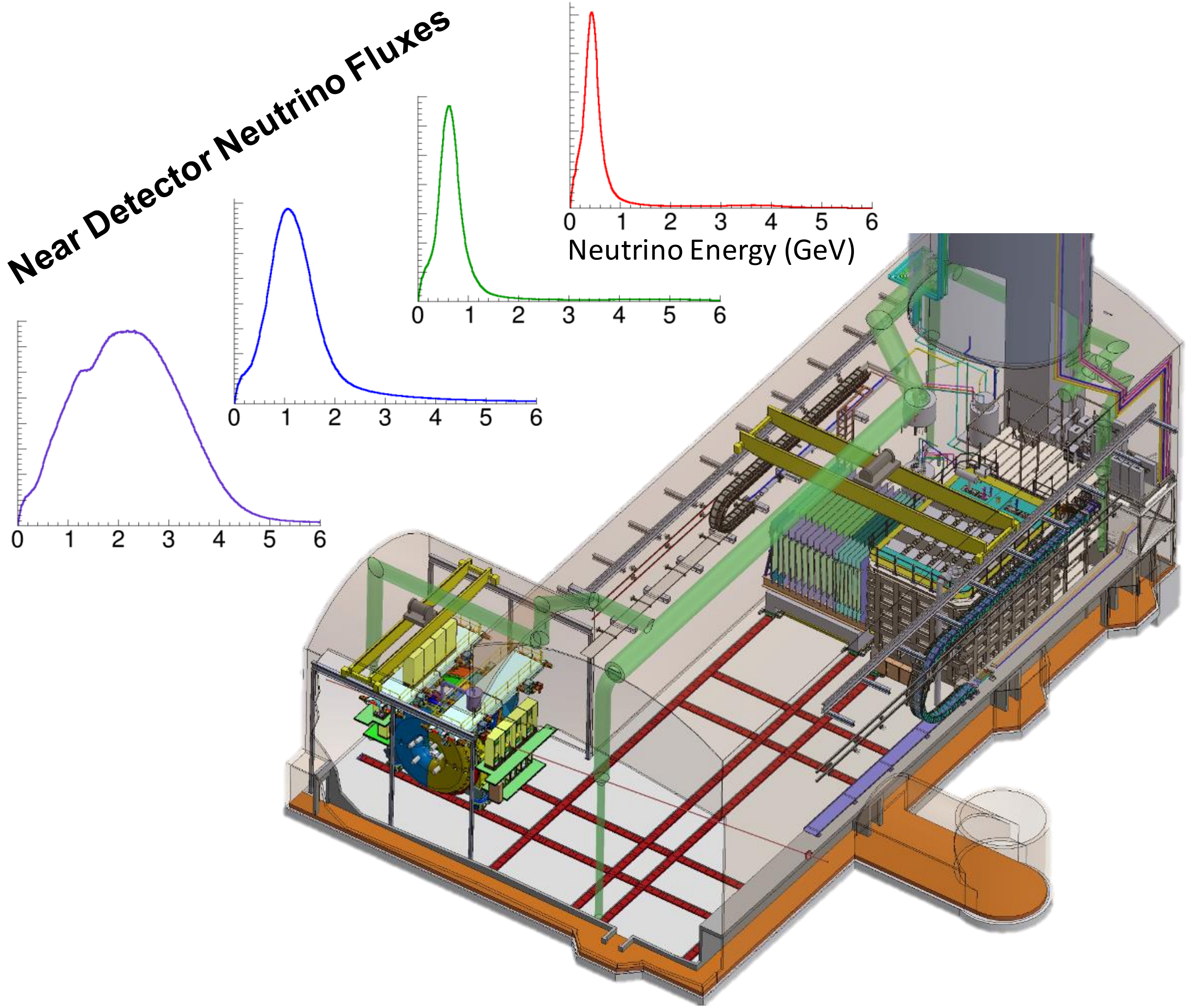
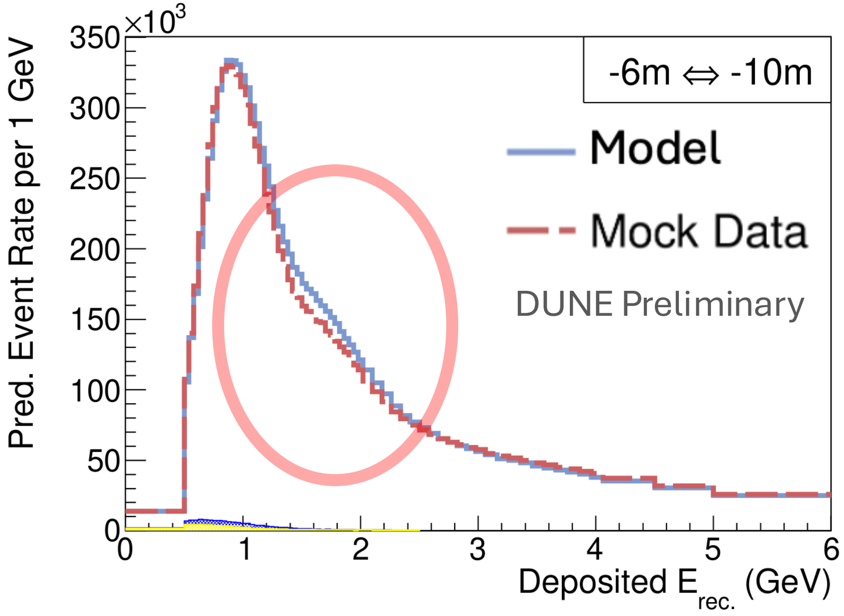
DUNE-PRISM

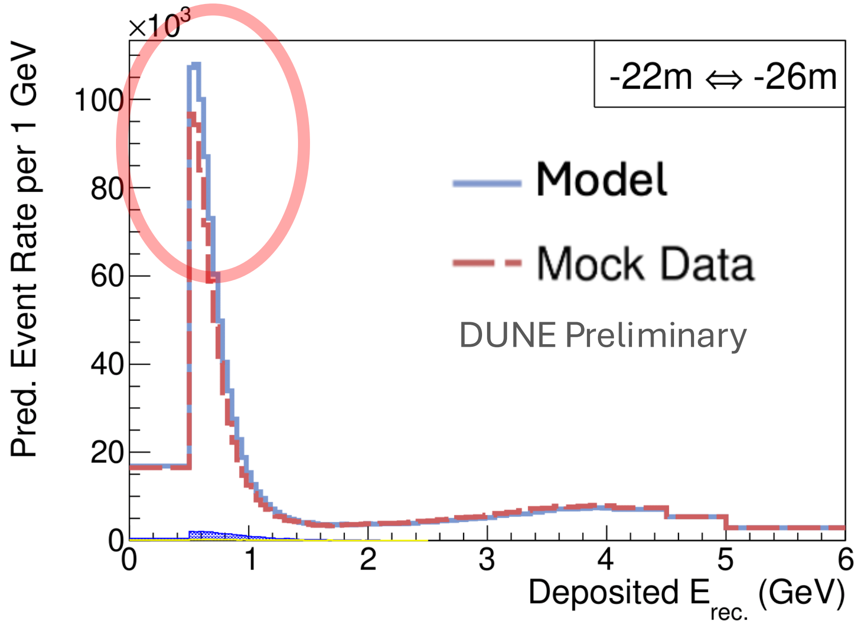
- DUNE near detector **moves off axis**
- Measure **different neutrino fluxes**
- ND-LAr is a LArTPC – **liquid argon** (LAr) like DUNE far detector!
- Can we spot cross section mis-modelling with these extra fluxes?

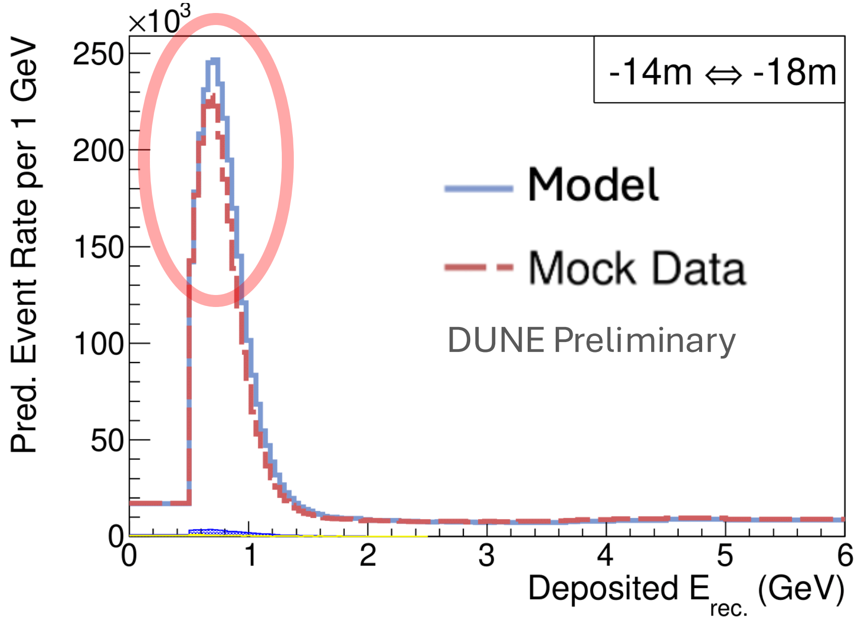


Why PRISM?

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







Two Approaches to Using Off-Axis Data

Model Dependent

Use off-axis data to better **constrain** and **tune** the **cross-section model**

Biases less likely when testing the model in many fluxes

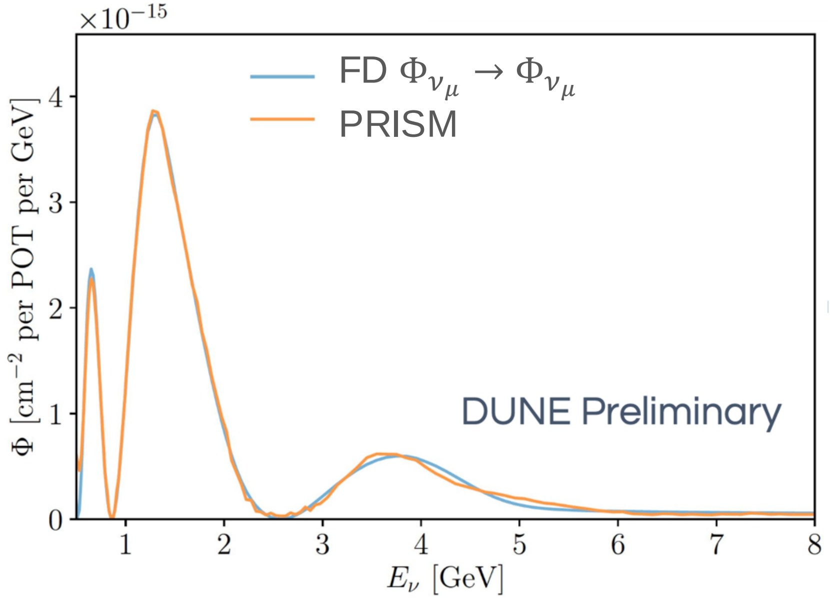
Model Independent

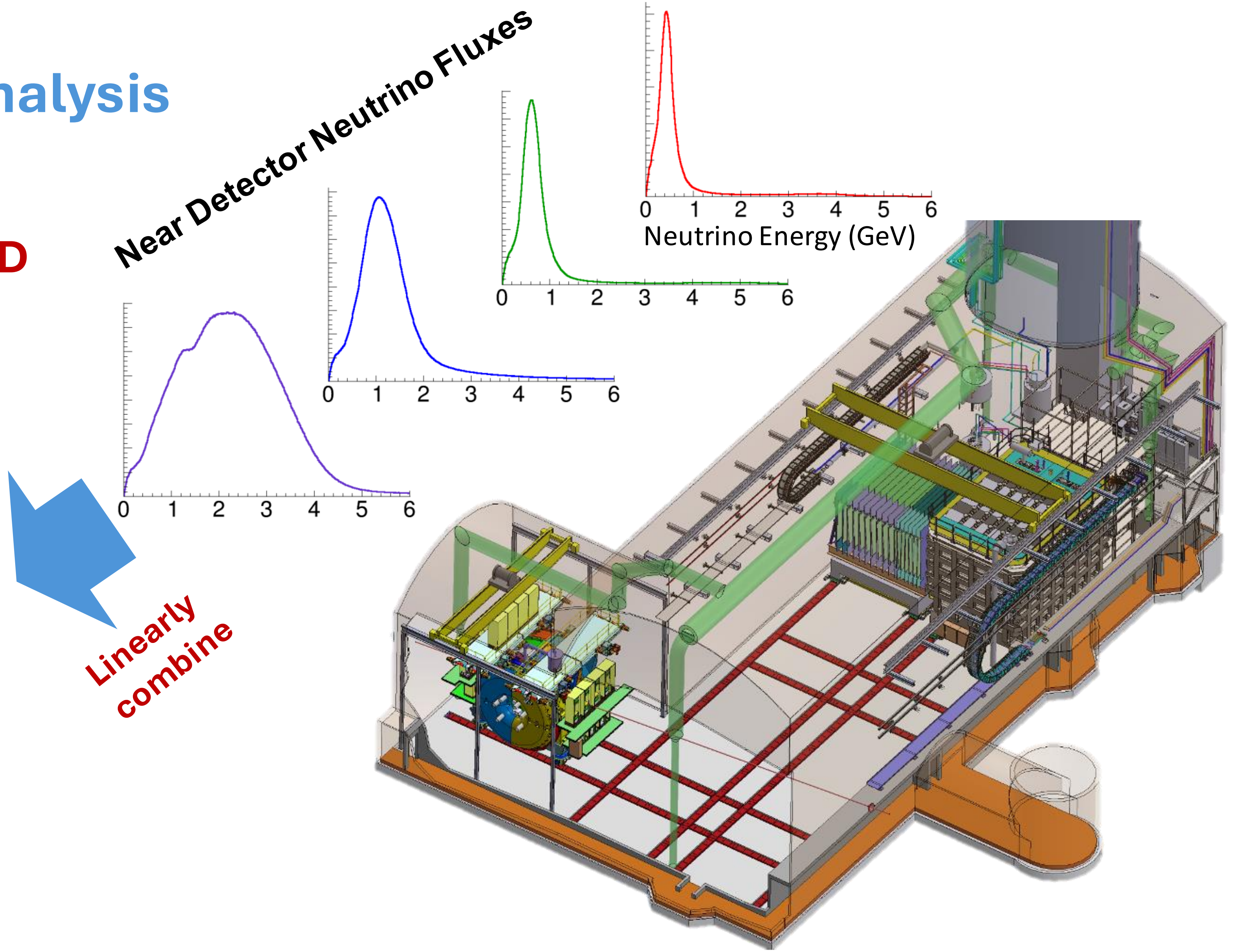
Linearly combine off-axis data to produce **data-driven predictions** of the FD energy spectra

Oscillation analysis now has **minimal dependence** on the **cross-section model**

PRISM Oscillation Analysis

linearly combine fluxes to produce a prediction of the **FD event rate directly from ND data**



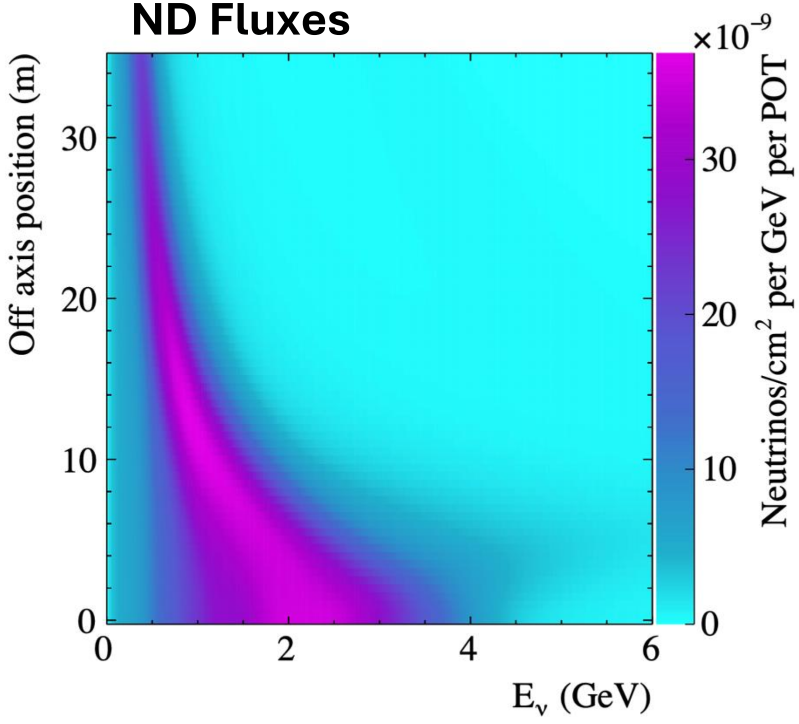


PRISM as an Oscillation Analysis

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

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

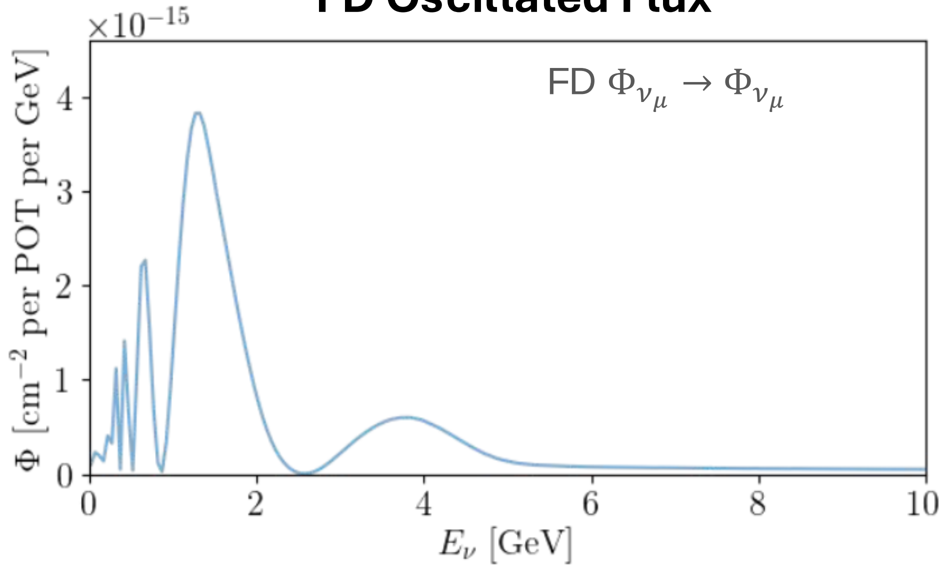
ND Fluxes



some vector, c

=

FD Oscillated Flux



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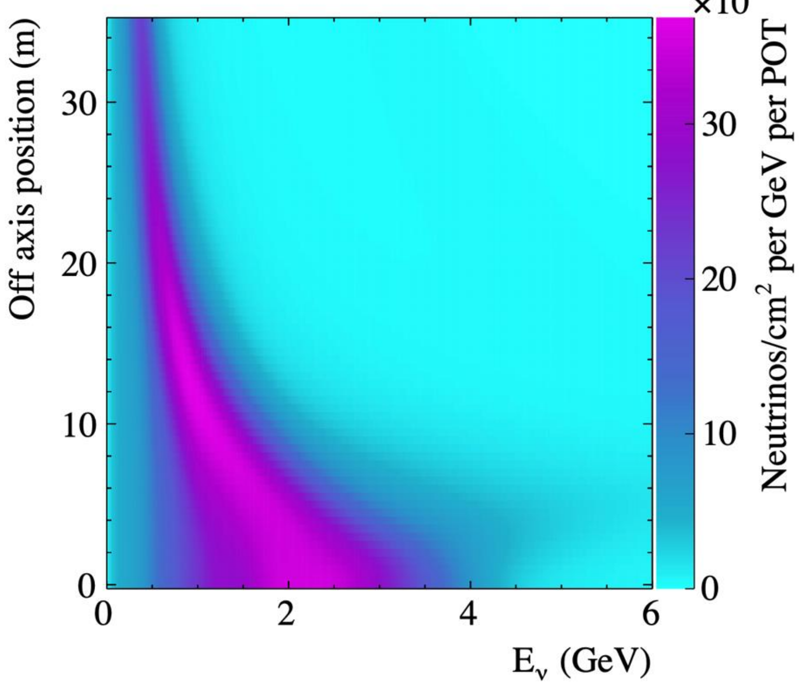

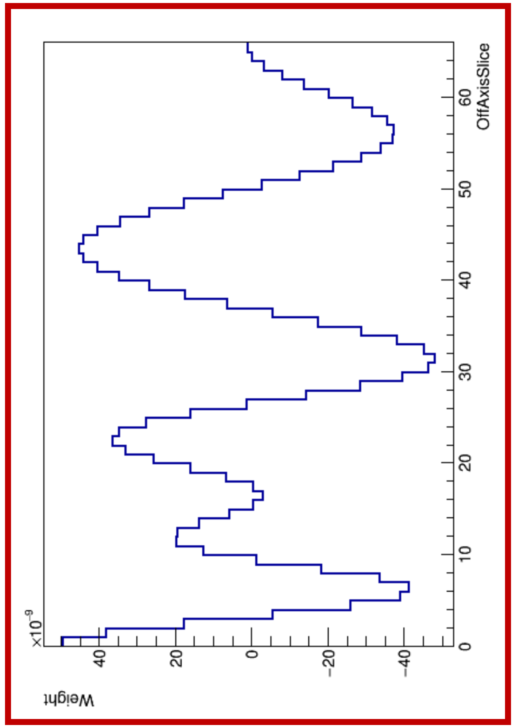

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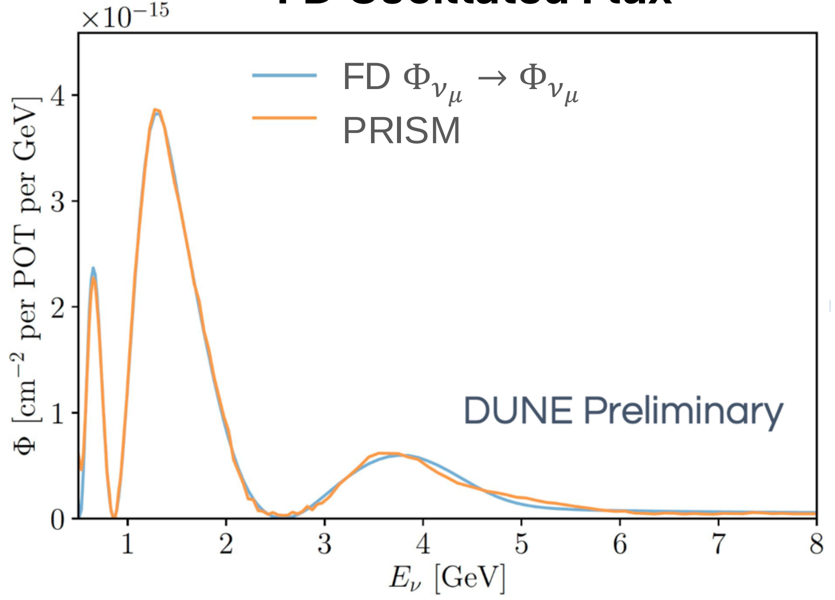
FD Oscillated Flux

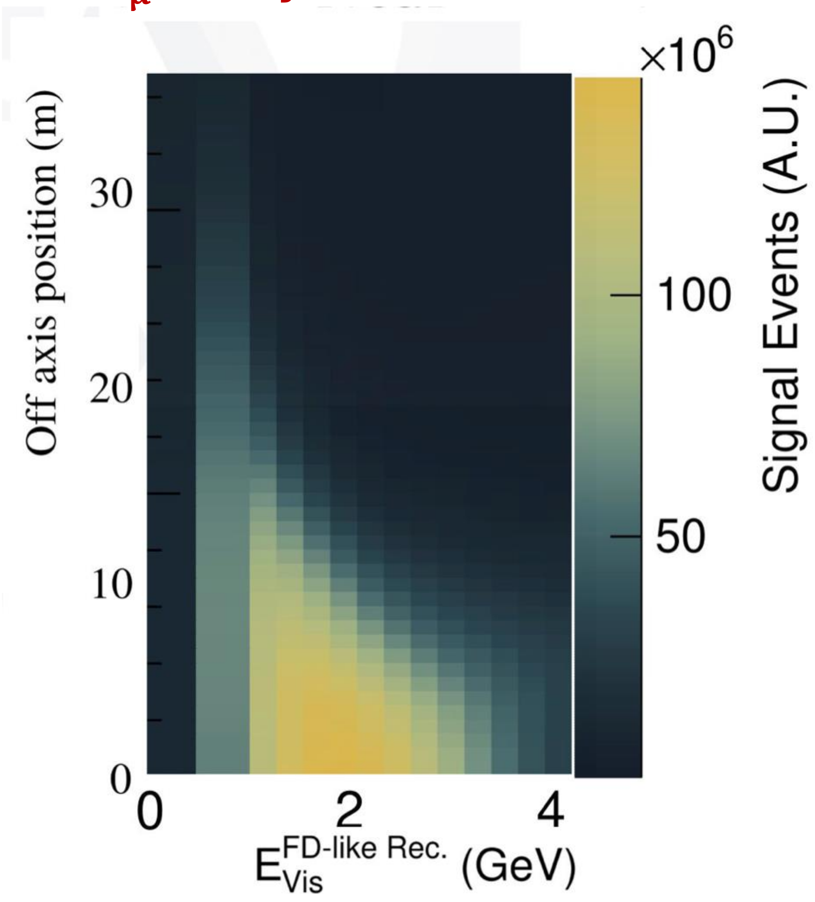


arXiv:2103.13910 [physics.ins-det]

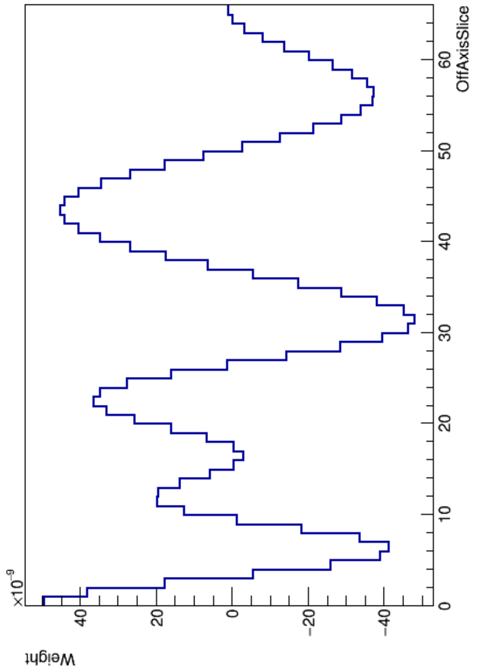
PRISM as an Oscillation Analysis

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

ν_μ data you measured at ND



Weights you calculated using the flux model



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Data-driven prediction of the FD oscillated event rate!

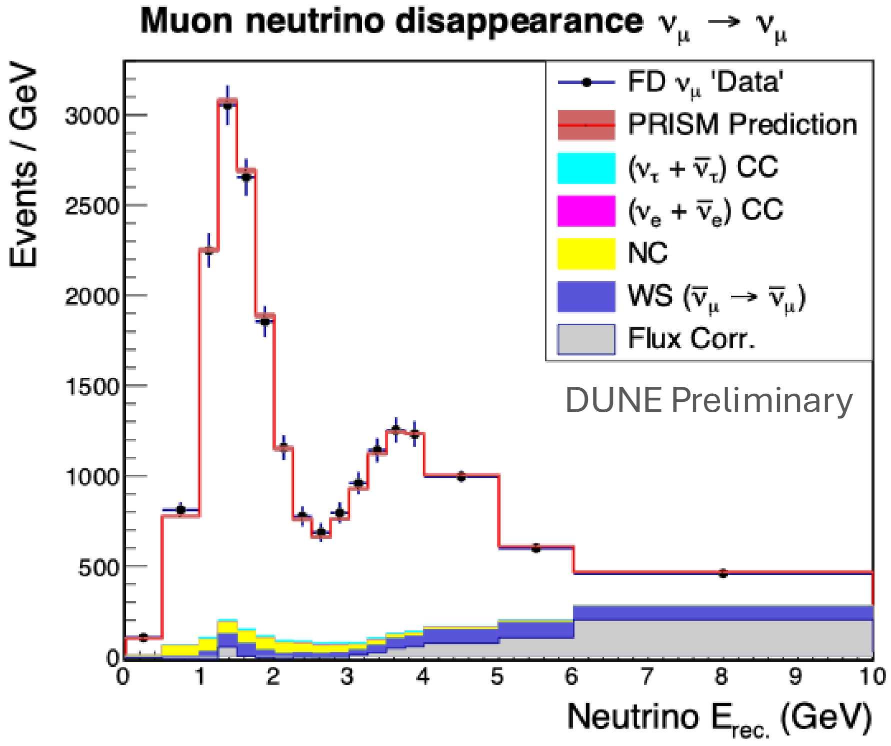

Figure from L. Pickering

arXiv:2103.13910 [physics.ins-det]

PRISM as an Oscillation Analysis

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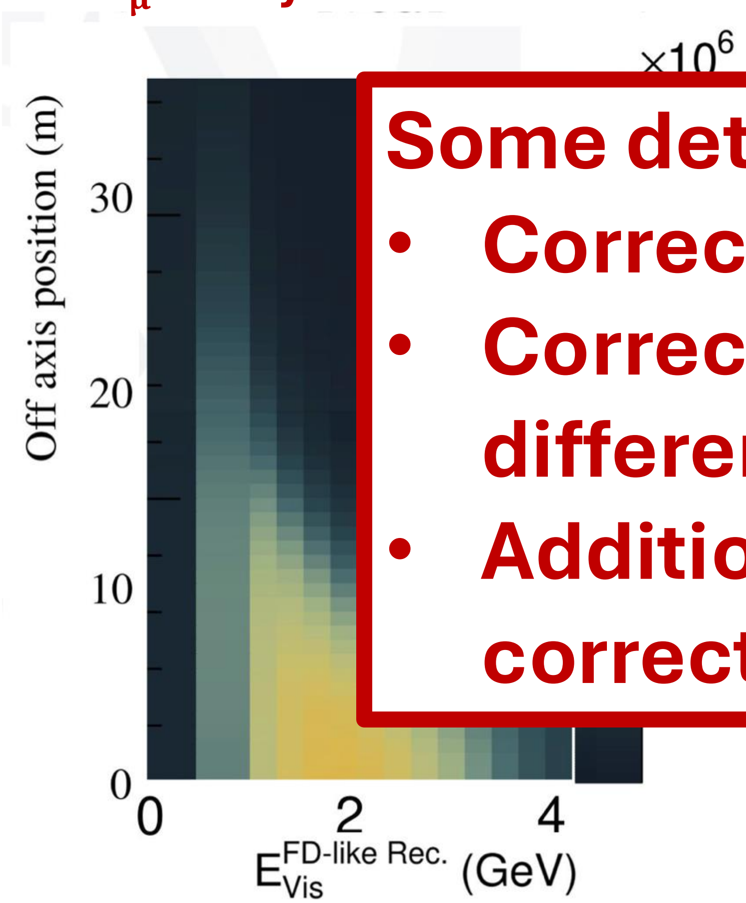

Weights you calculated using the flux model

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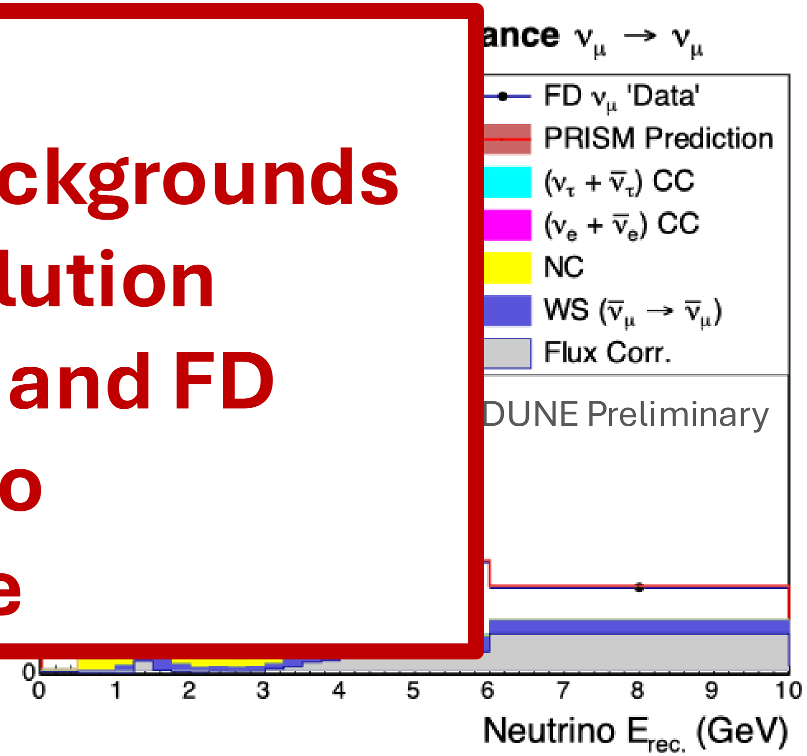
Data-driven prediction of the FD oscillated event rate!



Some details I skip:

- Correction for ND and FD backgrounds
- Correction efficiency & resolution differences between the ND and FD
- Additional cross section ratio correction for ν_e appearance

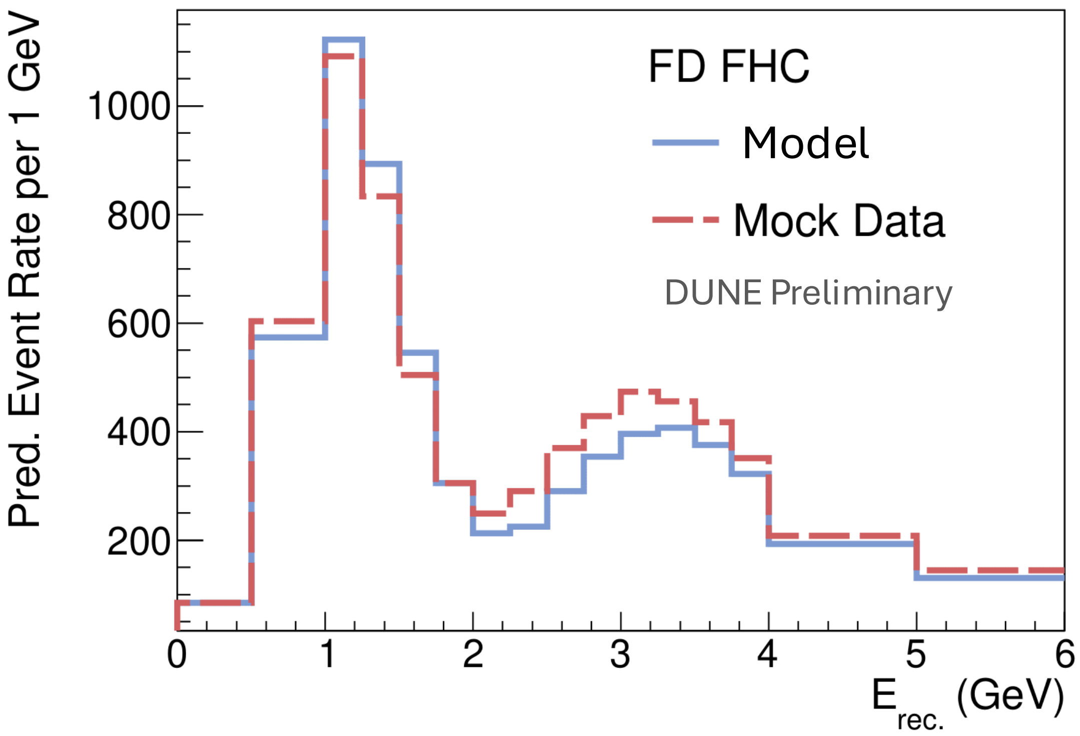
Figure from L. Pickering

arXiv:2103.13910 [physics.ins-det]

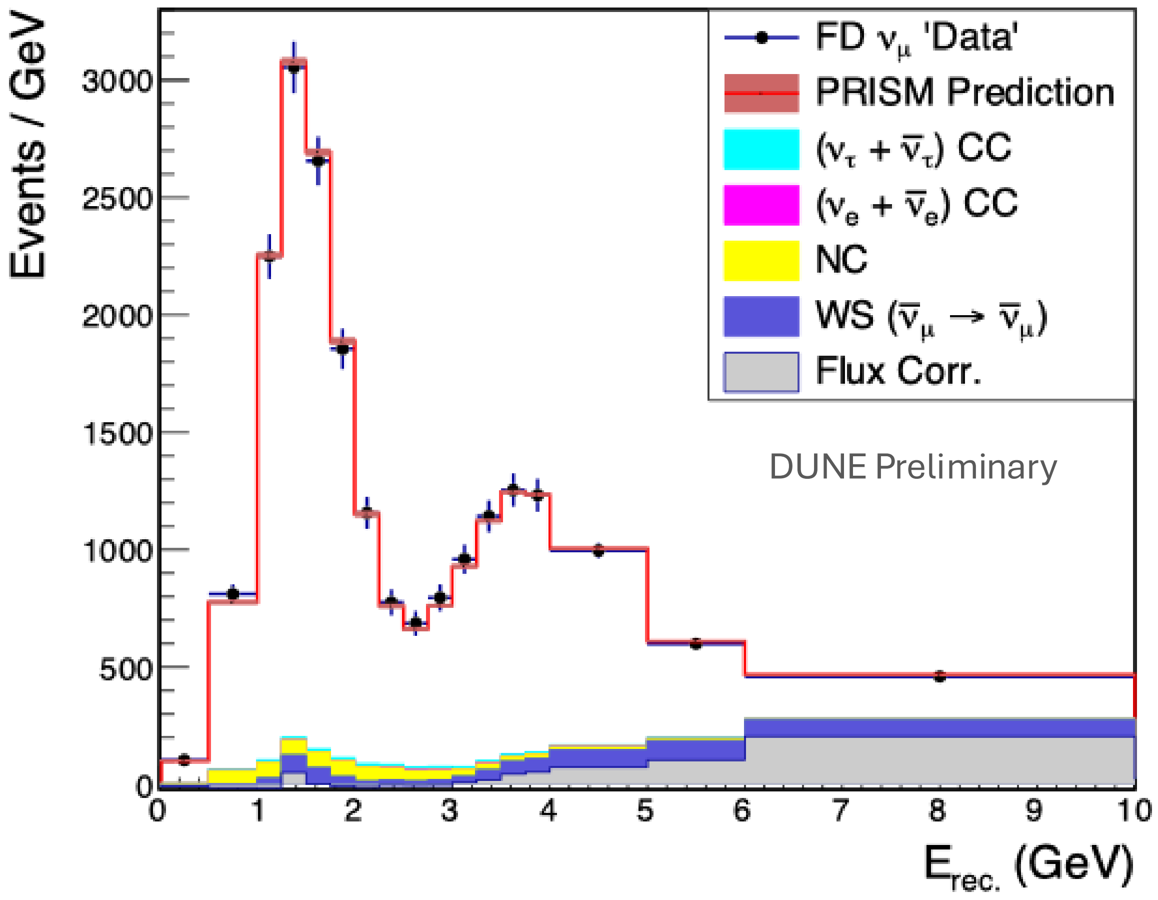
PRISM Fixes Oscillation Analysis

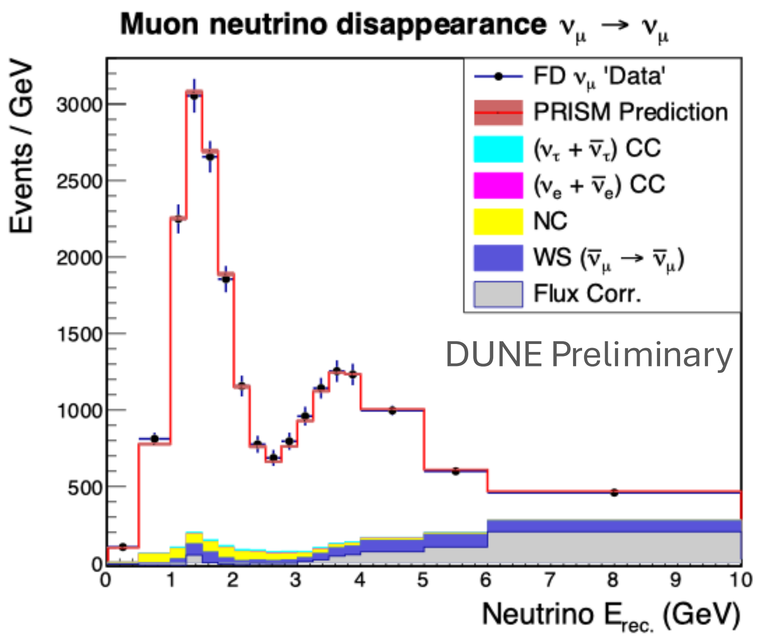
Prediction is made from ND data:
Naturally includes correct neutrino interaction physics

Model-dependent prediction

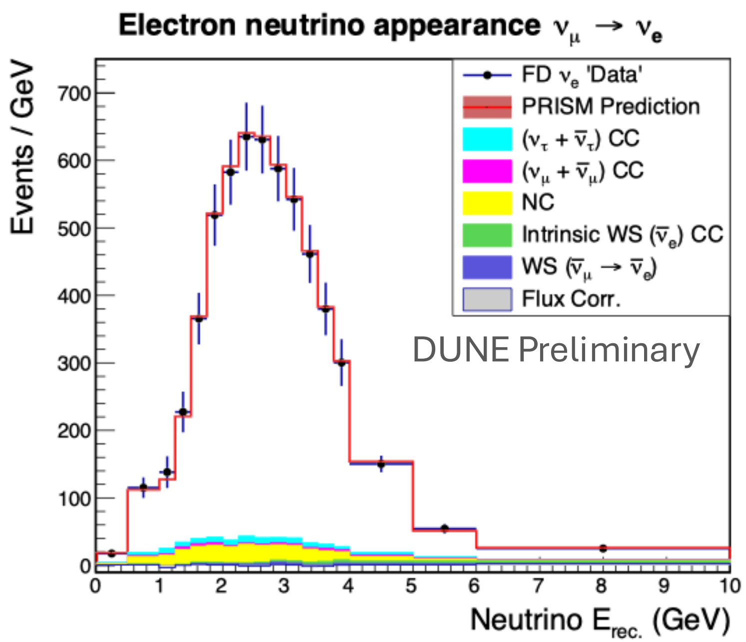


Muon neutrino disappearance $\nu_\mu \rightarrow \nu_\mu$

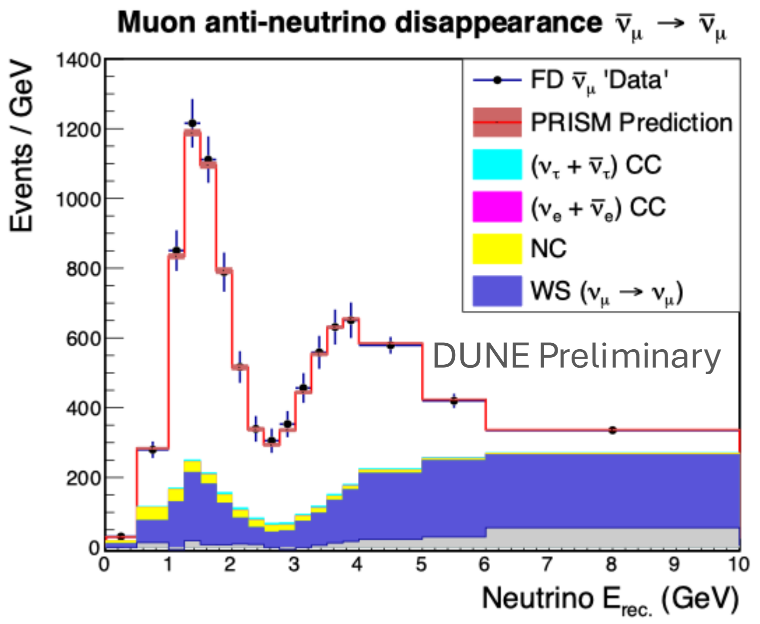




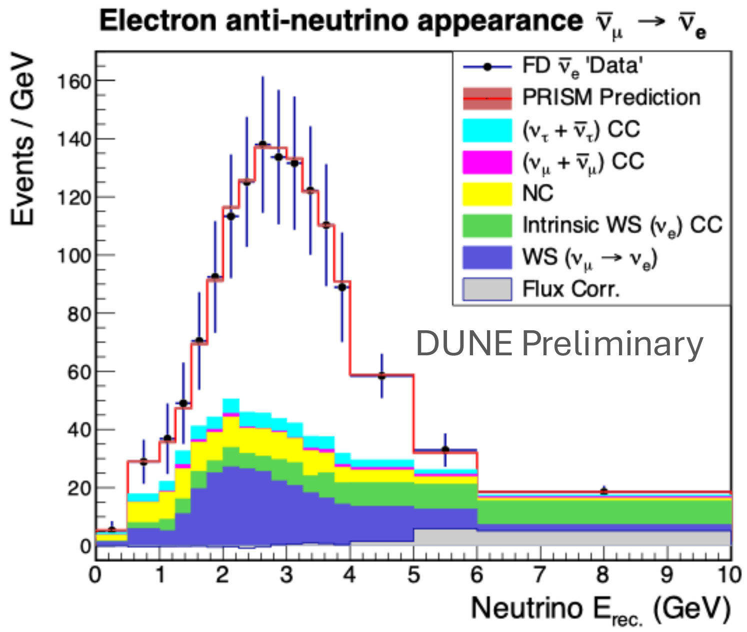
Muon neutrino disappearance $\nu_\mu \rightarrow \nu_\mu$
Events / GeV
FD ν_μ 'Data'
PRISM Prediction
$(\nu_\tau + \bar{\nu}_\tau)$ CC
$(\nu_e + \bar{\nu}_e)$ CC
NC
WS $(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$
Flux Corr.
DUNE Preliminary
Neutrino $E_{rec.}$ (GeV)



Electron neutrino appearance $\nu_\mu \rightarrow \nu_e$
Events / GeV
FD ν_e 'Data'
PRISM Prediction
$(\nu_\tau + \bar{\nu}_\tau)$ CC
$(\nu_\mu + \bar{\nu}_\mu)$ CC
NC
Intrinsic WS $(\bar{\nu}_e)$ CC
WS $(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
Flux Corr.
DUNE Preliminary
Neutrino $E_{rec.}$ (GeV)



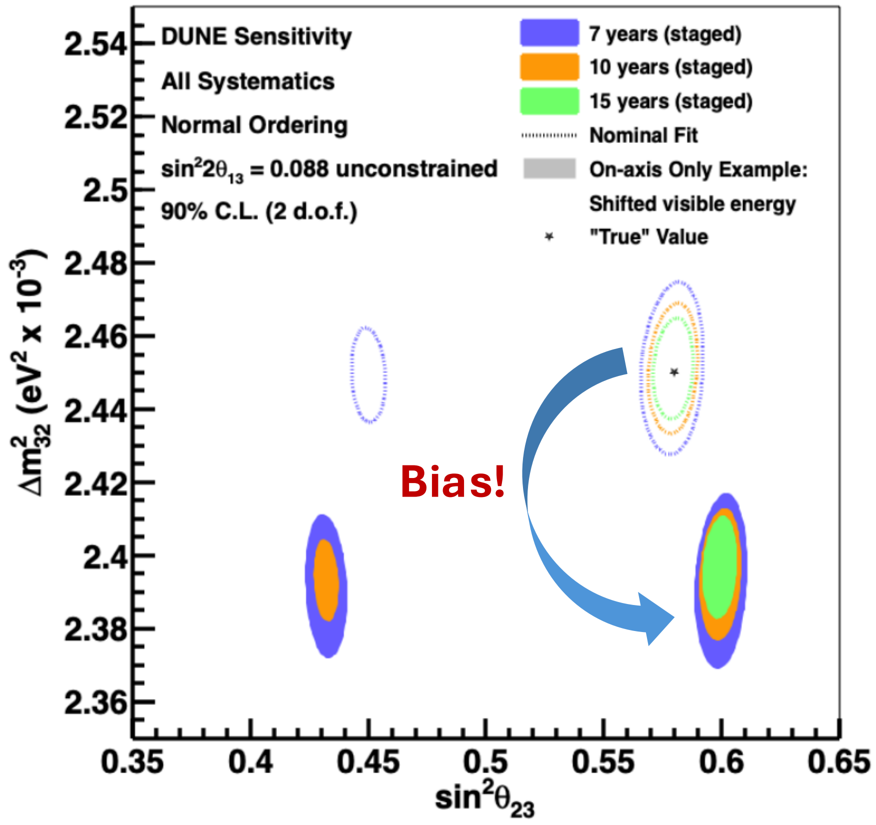
Muon anti-neutrino disappearance $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
Events / GeV
FD $\bar{\nu}_\mu$ 'Data'
PRISM Prediction
$(\nu_\tau + \bar{\nu}_\tau)$ CC
$(\nu_e + \bar{\nu}_e)$ CC
NC
WS $(\nu_\mu \rightarrow \nu_\mu)$
DUNE Preliminary
Neutrino $E_{rec.}$ (GeV)



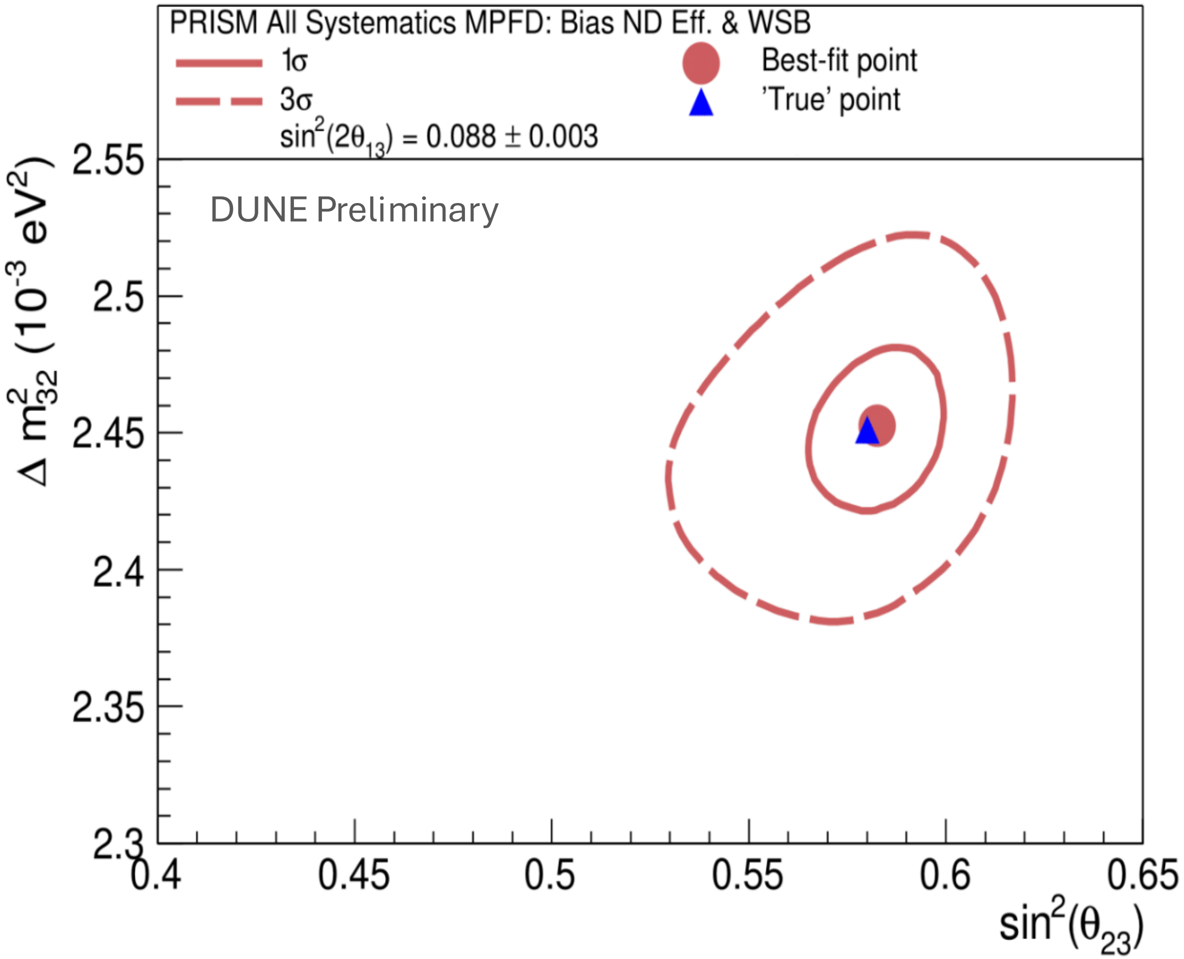
Electron anti-neutrino appearance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Events / GeV
FD $\bar{\nu}_e$ 'Data'
PRISM Prediction
$(\nu_\tau + \bar{\nu}_\tau)$ CC
$(\nu_\mu + \bar{\nu}_\mu)$ CC
NC
Intrinsic WS (ν_e) CC
WS $(\nu_\mu \rightarrow \nu_e)$
Flux Corr.
DUNE Preliminary
Neutrino $E_{rec.}$ (GeV)

PRISM Fixes Oscillation Analysis

'Traditional' oscillation analysis with a fixed ND



Resolve bias with a data-driven PRISM oscillation analysis

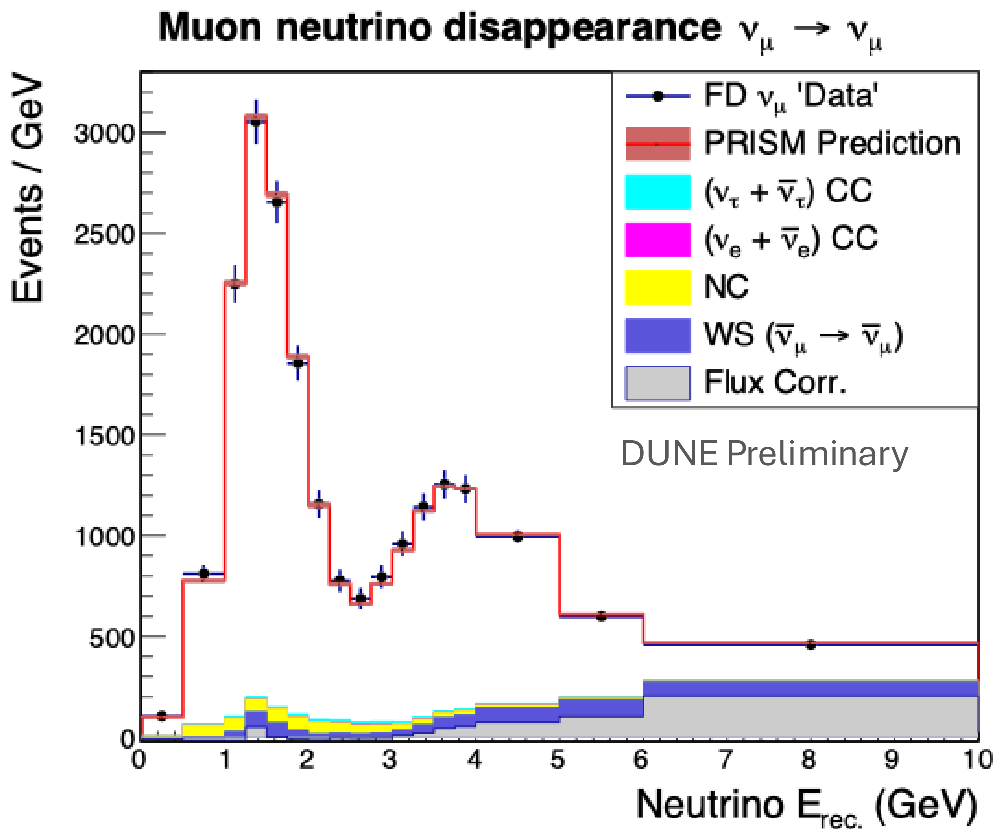


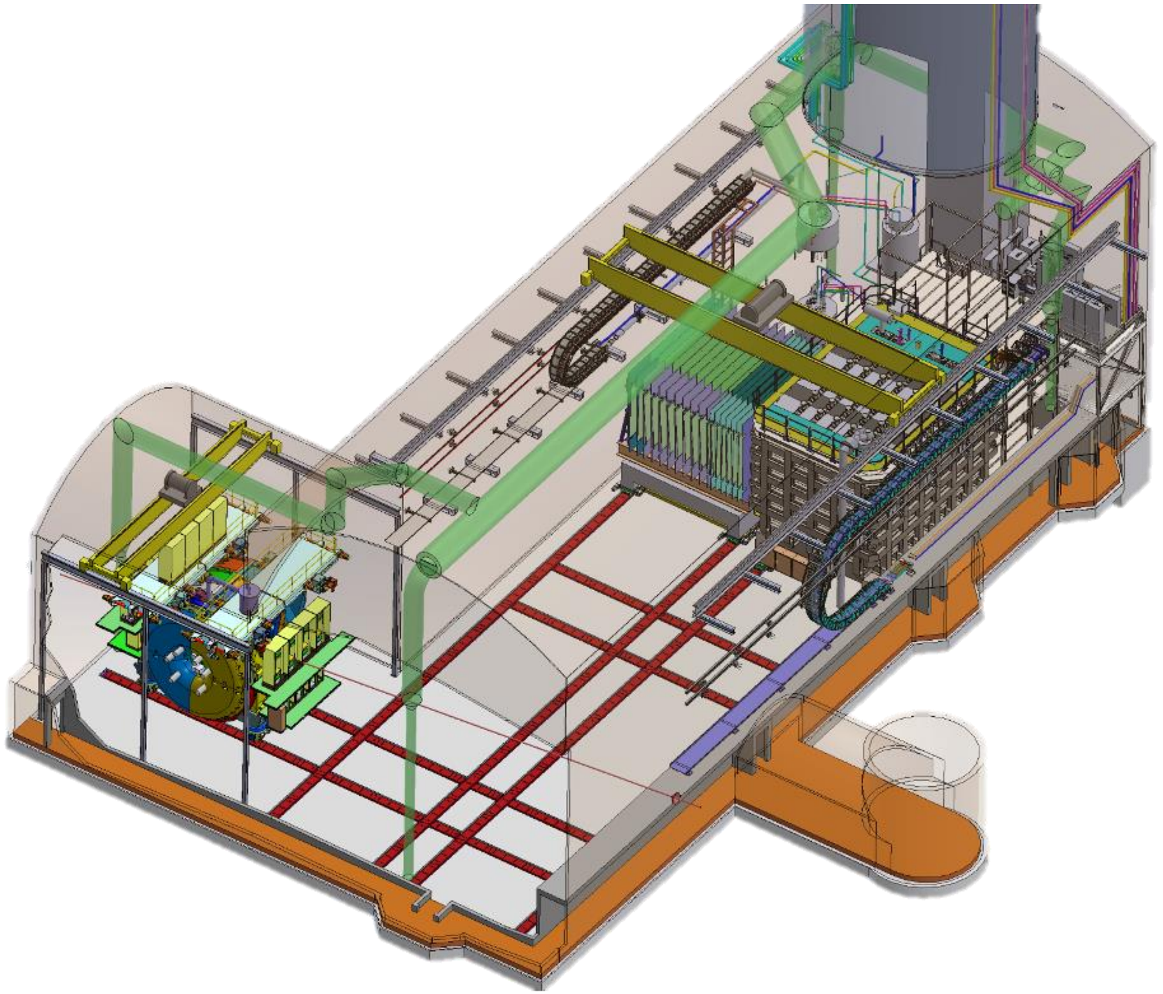
Conclusions

- Entering a **new precision era** of **neutrino oscillations** – **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 $\Phi \times \sigma$ degeneracy!
- DUNE-PRISM is a key component of the DUNE ND design and central to its physics program
- Demonstrated great potential in reducing cross section systematic uncertainty and **limiting the risk oscillation measurement bias**

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Thank you for listening!

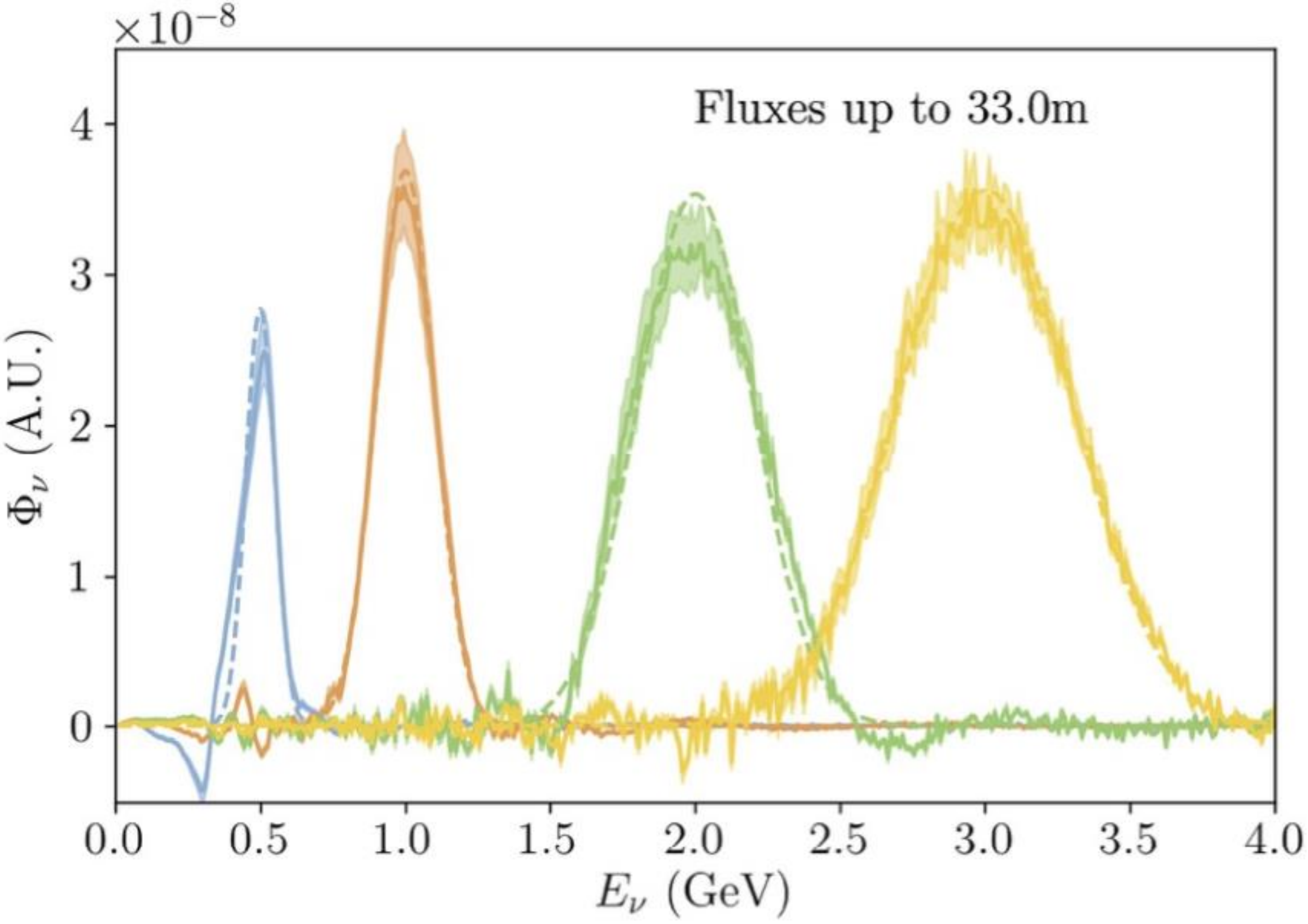




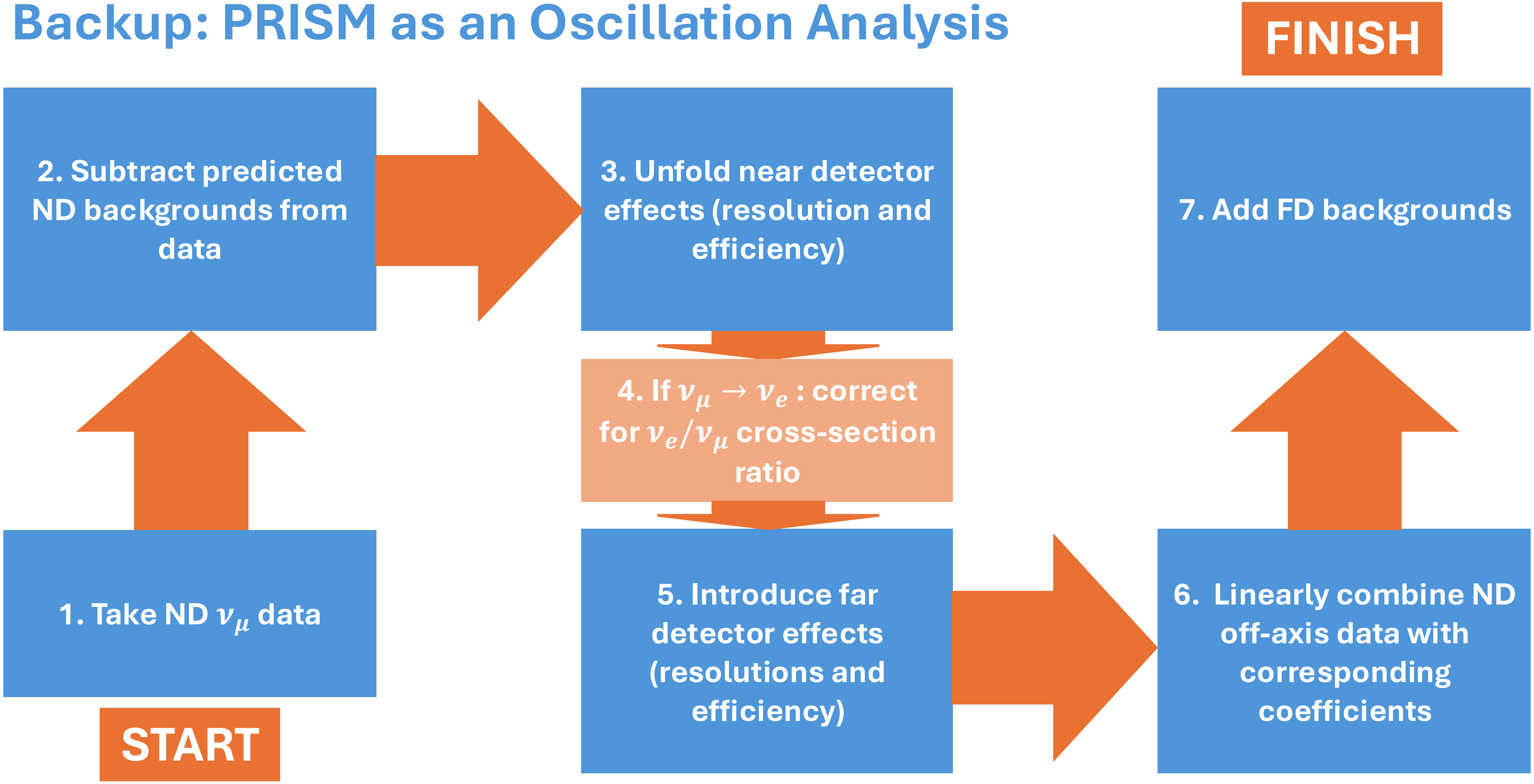
Backup: ND Event Rates 1-Year Run Plan

		ND-LAr				ND-GAr
		All int.	Selected			All int.
Stop	Run duration	$N_{\nu_\mu CC}$	N_{Sel}	WSB	NC	$N_{\nu_\mu CC}$
On axis (293 kA) m	14 wks.	21.6M	10.1M	0.2%	1.3%	580,000
On axis (280 kA) m	1 wk.	1.5M	690,000	0.3%	1.3%	40,000
4 m off axis m	12 dys.	2.3M	1.2M	0.3%	1.0%	61,000
8 m off axis m	12 dys.	1.3M	670,000	0.5%	0.9%	35,000
12 m off axis m	12 dys.	650,000	330,000	0.8%	0.7%	17,000
16 m off axis m	12 dys.	370,000	190,000	1.1%	0.7%	10,000
20 m off axis m	12 dys.	230,000	120,000	1.3%	0.7%	6,200
24 m off axis m	12 dys.	150,000	75,000	1.8%	0.7%	4,100
28 m off axis m	12 dys.	110,000	50,000	2.1%	0.8%	2,900
30.5 m off axis m	12 dys.	87,000	39,000	2.3%	0.7%	2,300

Backup: Gaussian Target



Backup: PRISM as an Oscillation Analysis



Backup: PRISM as an Oscillation Analysis

FINISH

2. Subtract predicted ND backgrounds from

3. Unfold near detector effects (resolution and

7. Add FD backgrounds

Coefficients calculated using the flux simulation – totally interaction model dependent!

ratio

1. Take ND ν_μ data

5. Introduce far detector effects (resolutions and efficiency)

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

START

Backup: PRISM as an Oscillation Analysis

FINISH

2. Subtract predicted ND backgrounds from data

3. Unfold near detector effects (resolution and efficiency)

4. If $\nu_\mu \rightarrow \nu_e$: correct for ν_e/ν_μ cross-section ratio

5. Introduce far detector effects (resolutions and efficiency)

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

Will be replaced with a data-driven efficiency correction and ML-based resolution correction

Correction for detector differences currently done with MC smearing matrices – interaction model dependent!

Backup: Need Model Independent Efficiency Correction