Supported by U.S. DOE: Award DE-SC0015903

Overcoming Neutrino Interaction Mis-modeling with DUNE-PRISM

Imperial College London
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2020-05-06

Pronouns: He/Him/His

MICHIGAN STATE UNIVERSITY

DUNE PRISM

This Talk

- Primer: Neutrino Oscillations
- Introduction to DUNE
- The PRISM Concept

Big Picture Neutrino Questions

What is the mass ordering of the neutrino mass states?

Is there significant CP violation in the neutrino sector?

What are the precise values of the remaining neutrino oscillation parameters?

Could neutrino sector CP violation explain the matter/anti-matter asymmetry?

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I believe that the biggest barrier to progress is neutrino interaction mis-modelling.

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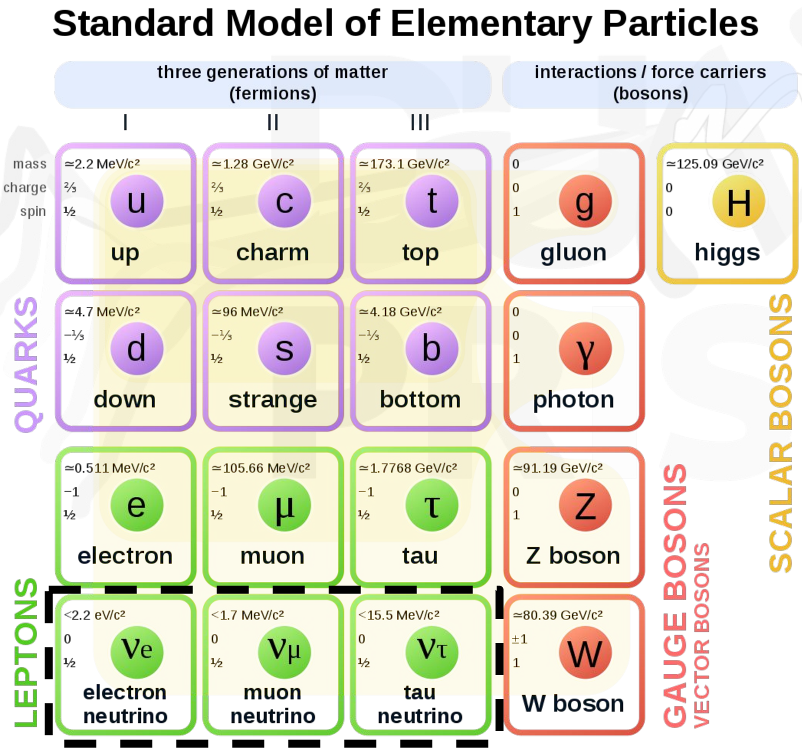
Primer: Neutrino Oscillations

Neutrinos

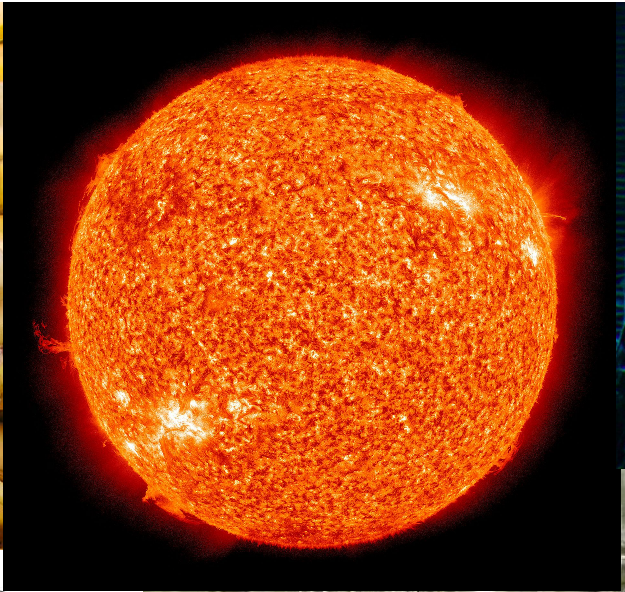


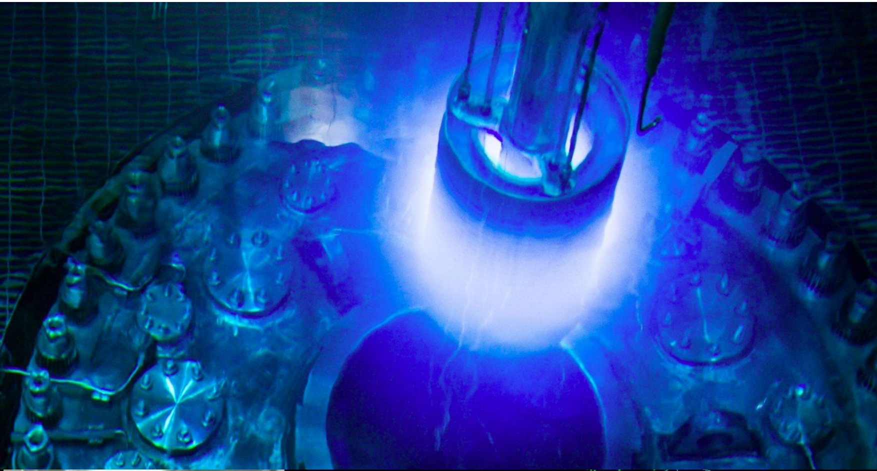
Standard Model of Elementary Particles

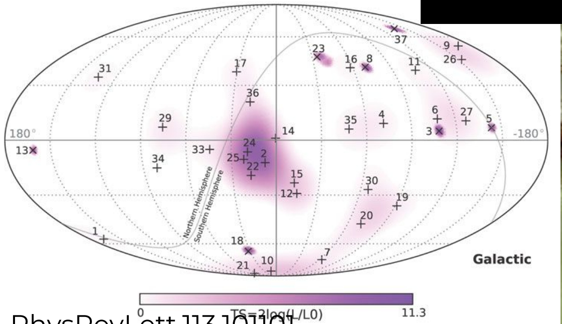
	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃125.09 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	
LEPTONS	<2.2 eV/c² 0 ½ ν_e electron neutrino	<1.7 MeV/c² 0 ½ ν_μ muon neutrino	<15.5 MeV/c² 0 ½ ν_τ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS

- Three generations of matter:
  - Three neutrinos paired with charged leptons: electron, muon, tau.
- Neutrinos are:
  - Electro-magnetically neutral
  - Massless within the standard model
  - Interact via mainly via the weak force.
  - Absurdly abundant

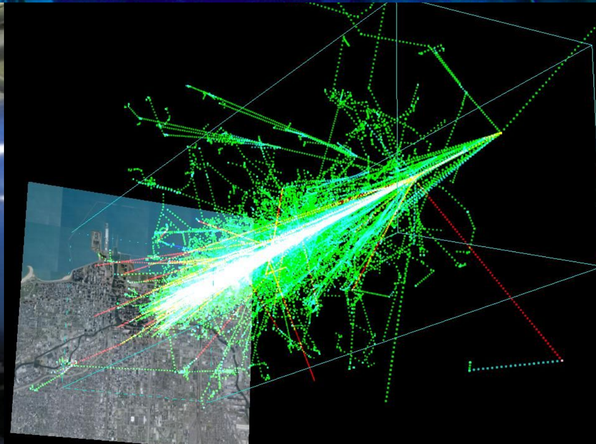
Neutrino Sources





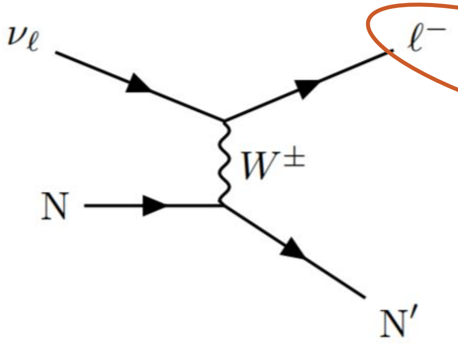


PhysRevLett.113.101101



Neutrino Oscillation: PMNS

Interaction with matter in flavor eigenstate defined by charged lepton.



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}}_{\mathbf{M}_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

Neutrino Oscillation: PMNS

Journal of Physics G: Nuclear and Particle Physics. 43. 10.1088/0954-3899/43/8/084001

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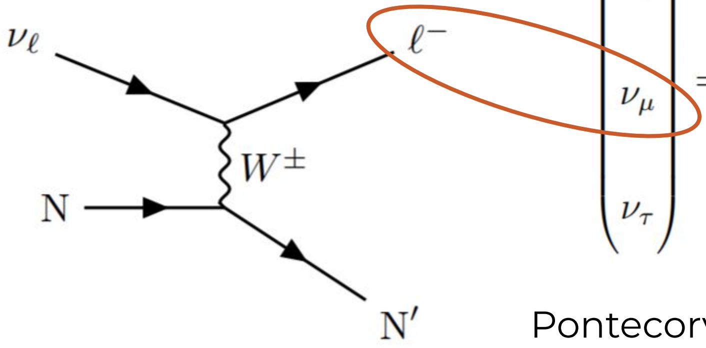

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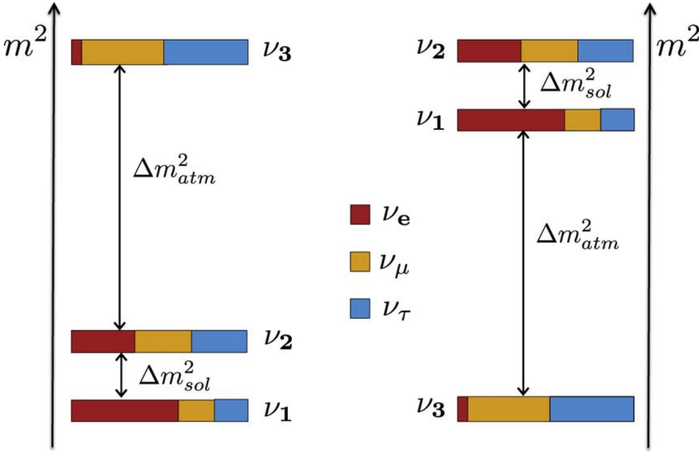
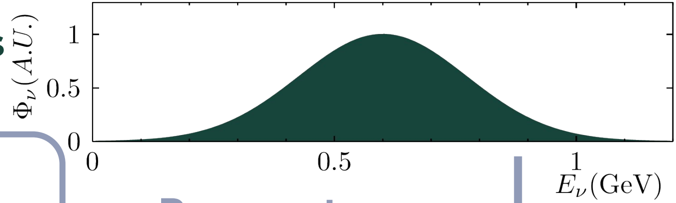


Which mass ordering?

Neutrino Oscillation: PMNS

***e.g.* created as muon neutrinos**



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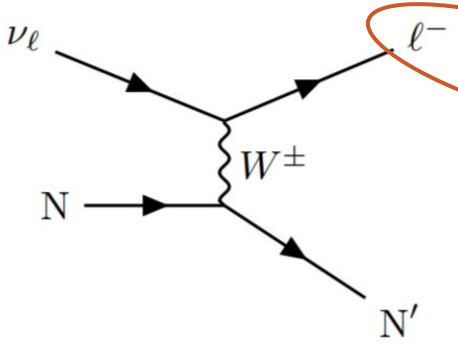

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Pontecorvo–Maki–Nakagawa–Sakata

Propagate as superposition of mass/energy eigenstates.

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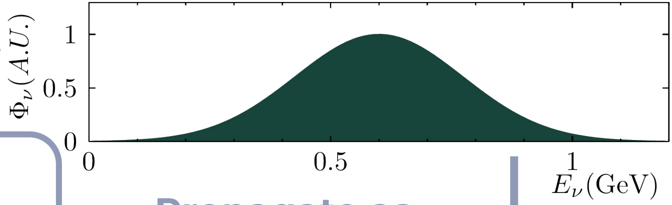

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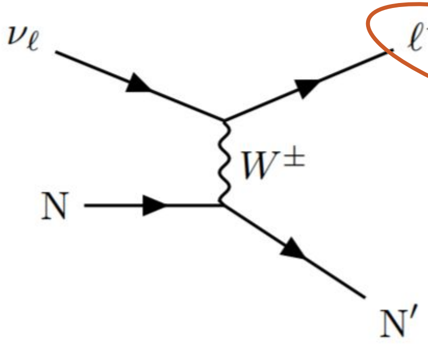

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Pontecorvo–Maki–Nakagawa–Sakata

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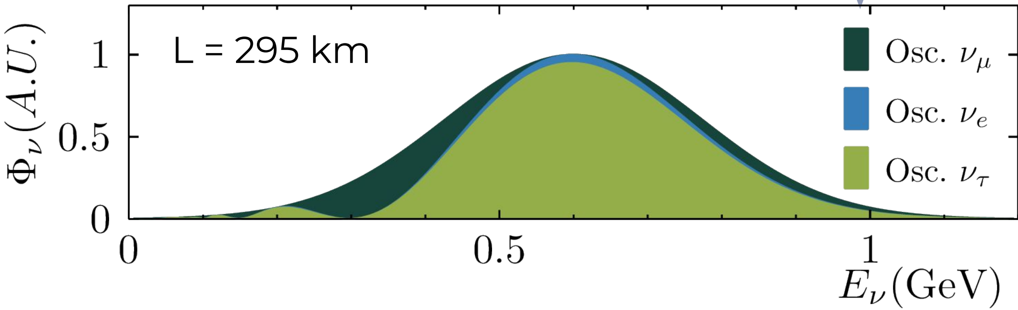

Projecting back to flavor eigenstates reveals a different flavor mixture.
(if $|\Delta m^2_{ij}| \neq 0$)

Re-parameterizing the PMNS

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric /Accelerator

Reactor

Solar

- Unitarity lets us re-parameterize PMNS matrix in terms of:
  - Three mixing angles: $C_{ij} = \cos(\theta_{ij})$
  - CP violating phase: $0<\delta_{CP}<2\pi$

Muon Neutrino Disappearance

- To leading order, muon neutrino survival probability depends on **mixing** **angles**, and **mass-squared splittings**.

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32}L}{4E} + (\text{solar, matter effect terms})$$

Muon Neutrino Disappearance

- To leading order, muon neutrino survival probability depends on **mixing angles**, and **mass-squared splittings**.
- Choose L/E for maximum effect:

$$\sin^2\left(\Delta m^2_{23} {}^{L}/_{4E}\right) \simeq 1$$

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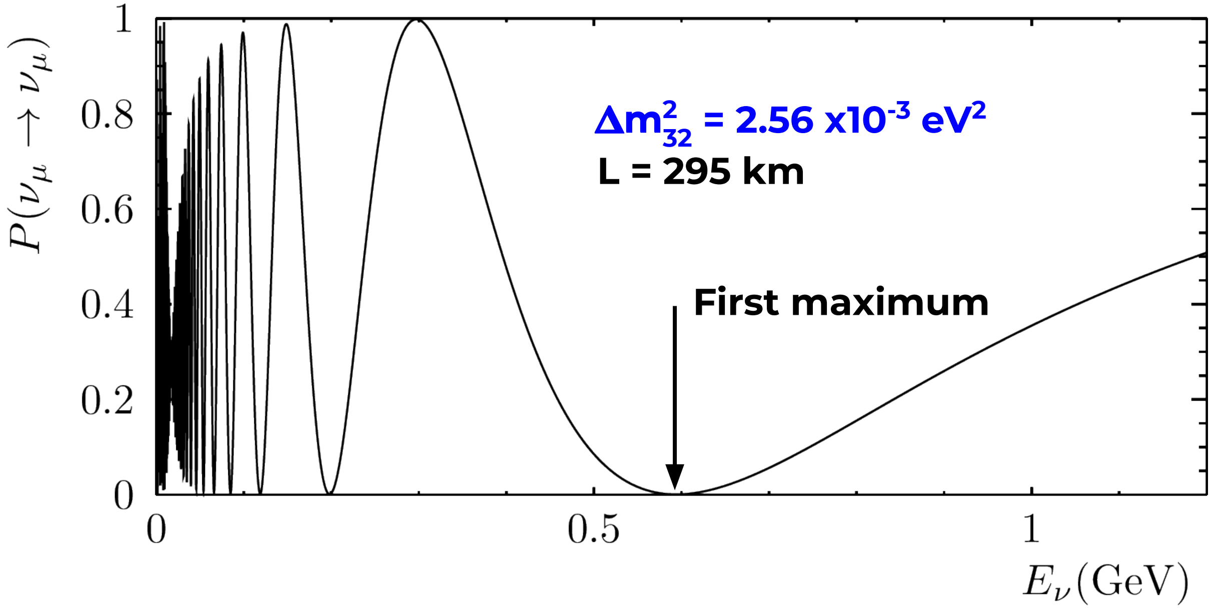

Electron Neutrino Appearance

- Electron neutrino appearance probability has ‘**CP odd**’ term.
    - Sign flip between matter and antimatter.

$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq\ & \boldsymbol{\sin^2\theta_{23}}\boldsymbol{\sin^2 2\theta_{13}}\sin^2\frac{\boldsymbol{\Delta m^2_{32}}L}{4E} \\
& (+)-\Big[\sin 2\theta_{12}\boldsymbol{\sin 2\theta_{23}}\boldsymbol{\sin 2\theta_{13}\cos\theta_{13}} \\
& \times \sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\boldsymbol{\Delta m^2_{32}}L}{4E}\boldsymbol{\sin\delta_{CP}}\Big] \\
& + (\text{CP-even, solar, matter effect terms})
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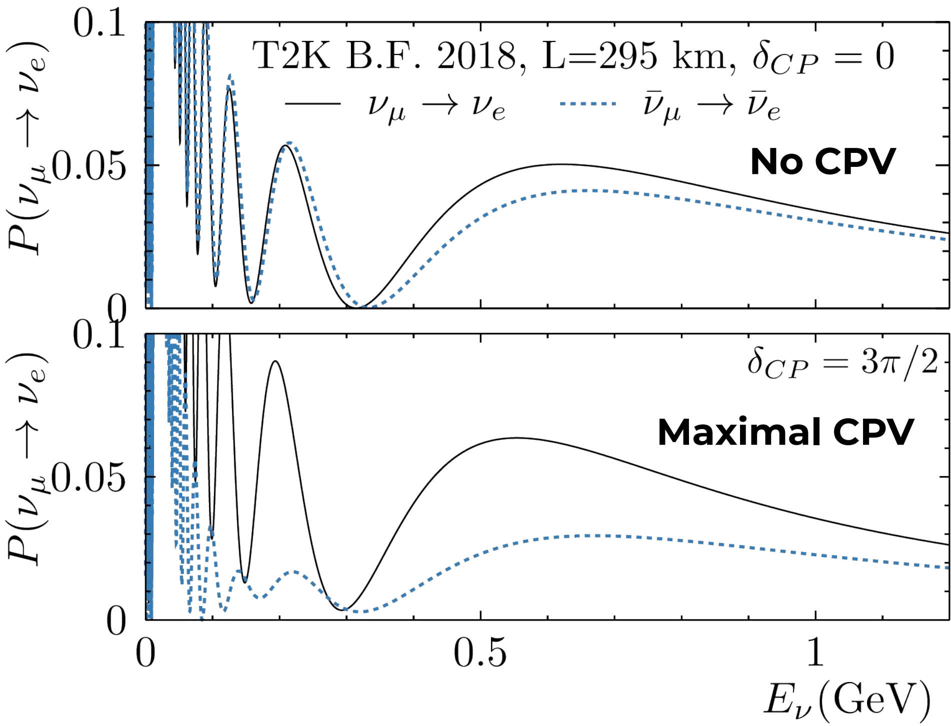

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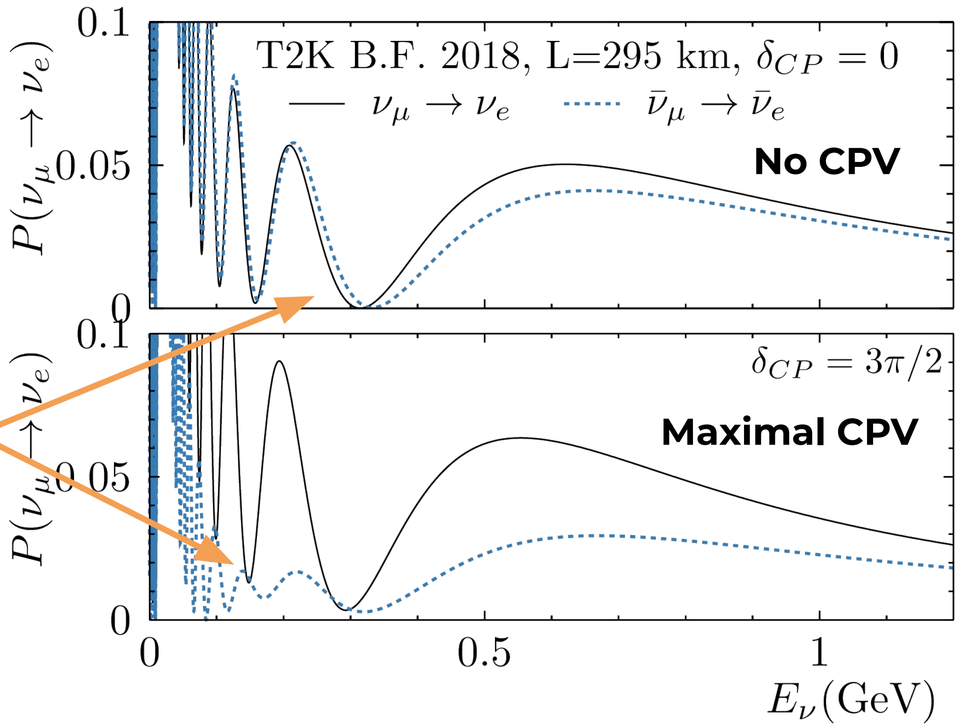
What is the value of δ_{CP}?

+ (CP-even, solar, matter effect terms)



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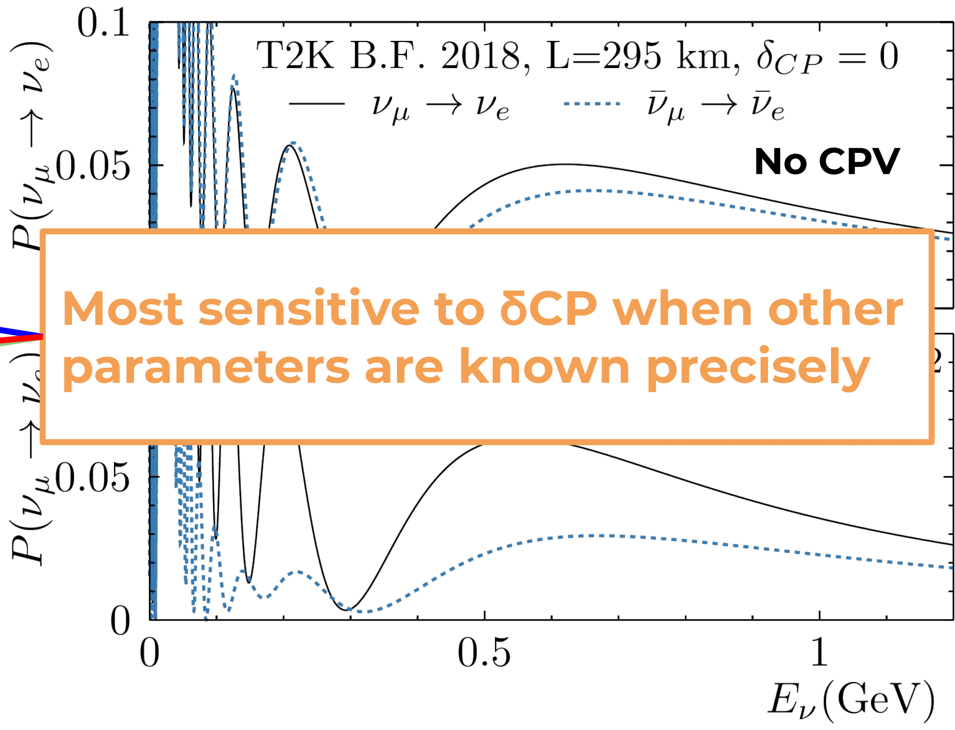
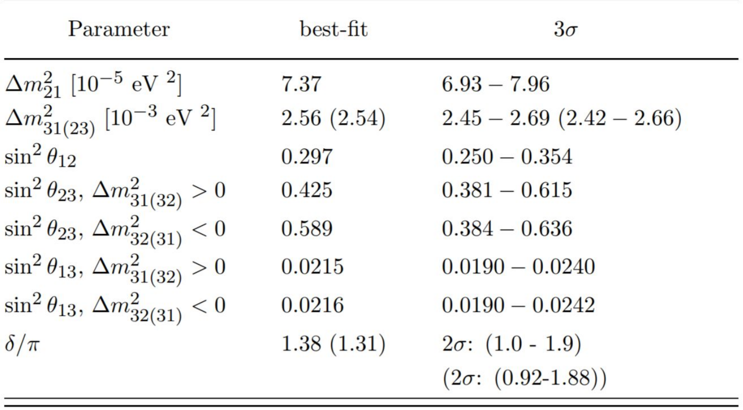


Most sensitive to δCP when other parameters are known precisely

Neutrino Oscillation: What Now?

- Evidence for neutrino oscillation is overwhelming: *c.f.* 2015 Nobel Prize
- We know: all mixing angles and both mass-squared splittings ≠ 0.

PDG 2018:
Neutrino Masses, Mixing, and Oscillations



Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Phys. Rev. D97, 072001 (2018)

Neutrino Oscillation: What Now?

- Evidence for neutrino oscillation is overwhelming: *c.f.* 2015 Nobel Prize
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- **Search for CP violation in the neutrino sector**—*i.e.* measure δ_{CP}
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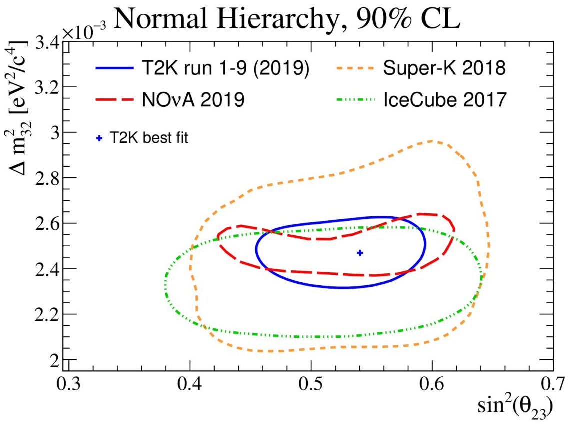

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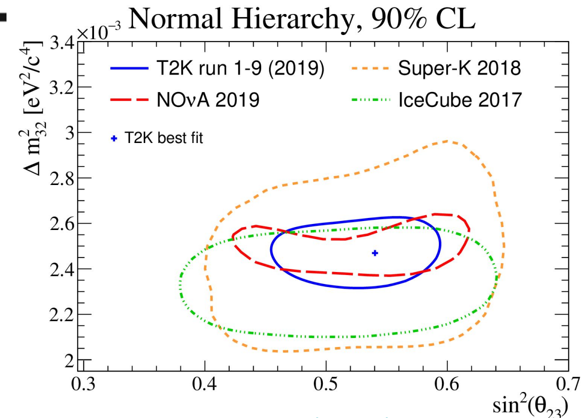
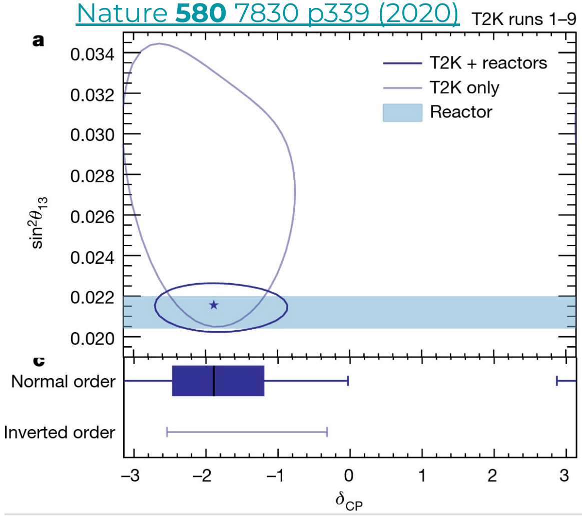
- **Search for CP violation in the neutrino sector**—*i.e.* measure δ_{CP}
    - Most sensitivity when other parameters are well known
    - Current generation experiments have some sensitivity to δ_{CP}, but disagree on the best fit…
    - Need new experiment for definitive 'five sigma' result…



Nature **580** 7830 p339 (2020)



The Deep Underground Neutrino Experiment

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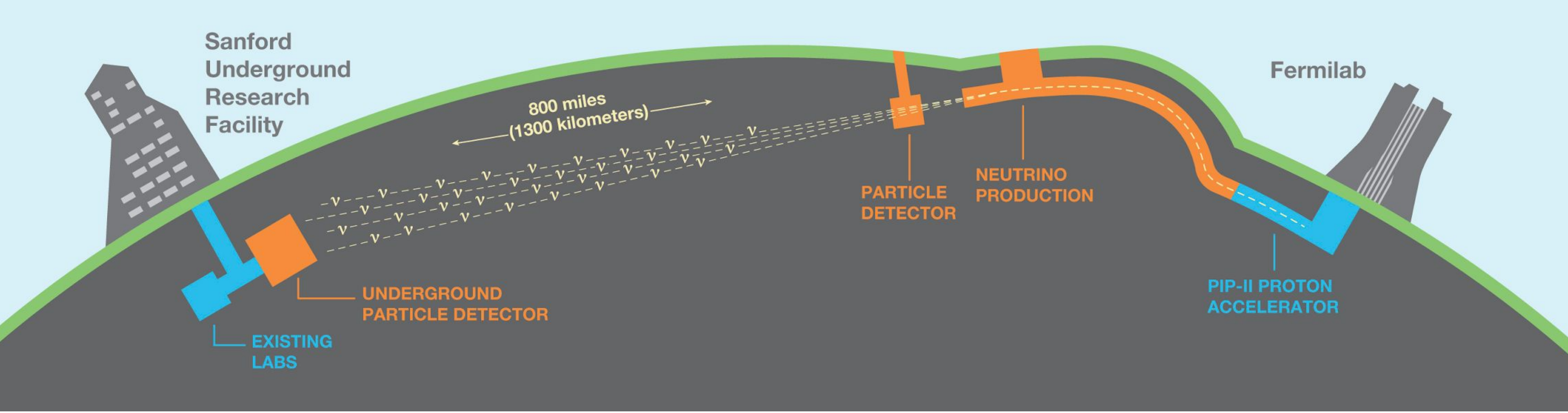

Collaboration

- >1100 Collaborators
- 34 Countries

PMNS Oscillations

- Unprecedented sensitivity to osc. params.
- Measurement of $\boldsymbol{\delta}_{CP}$ and mass ordering

Rich Physics Program

- Solar $\boldsymbol{\nu}$'s
- Geo $\boldsymbol{\nu}$'s
- SN $\boldsymbol{\nu}$'s
- ~~Banana $\boldsymbol{\nu}$'s~~
- NSI
- Sterile $\boldsymbol{\nu}$'s
- Cross sections

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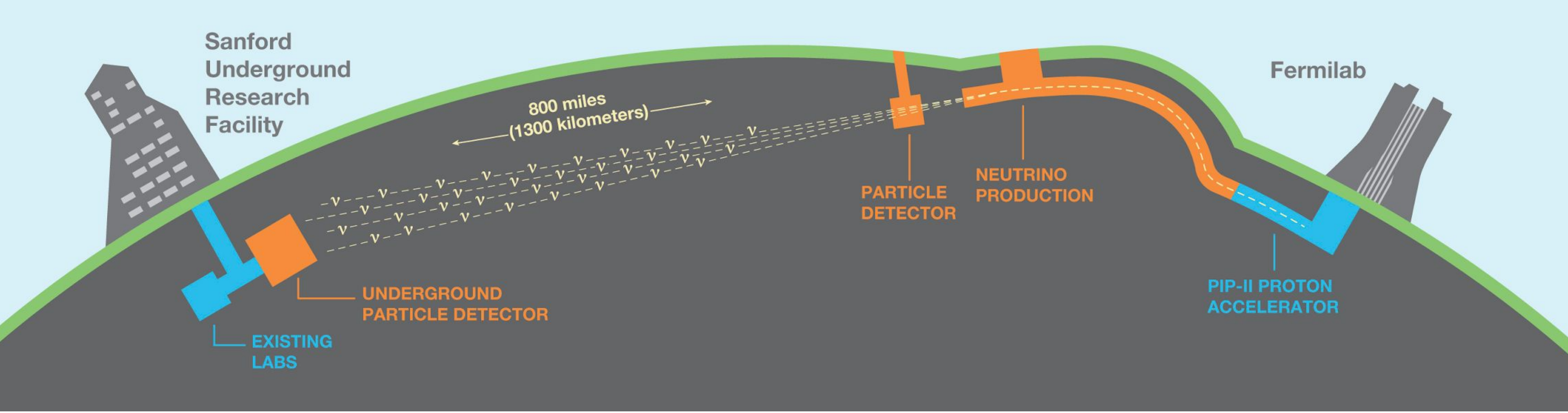

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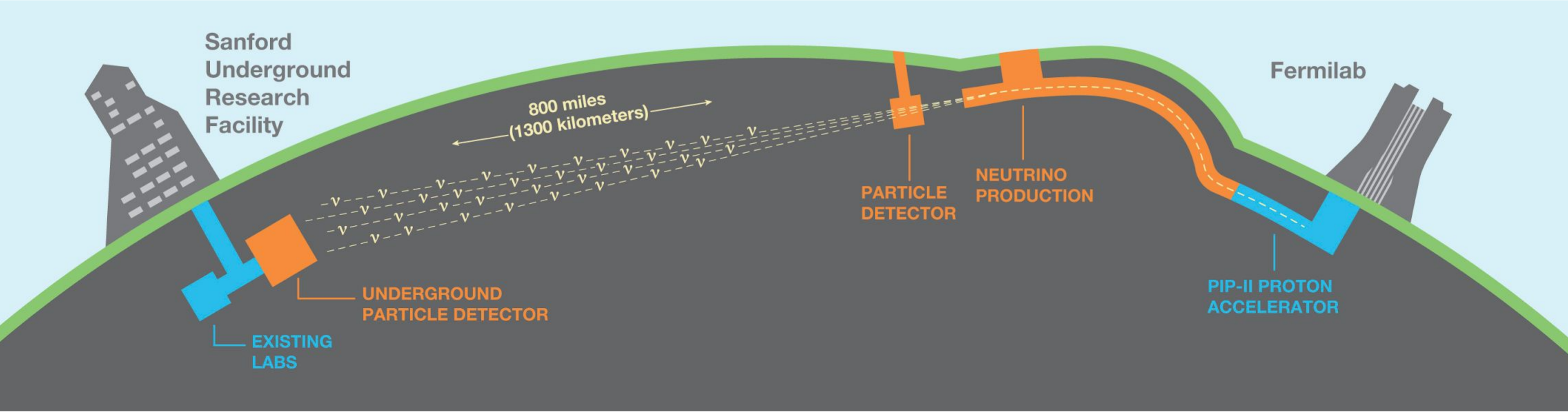
The Deep Underground Neutrino Experiment

- Sample osc. beam
- Infer osc. params

- Sample unosc. beam
- Constrain flux*xsec

- Produce neutrino beam



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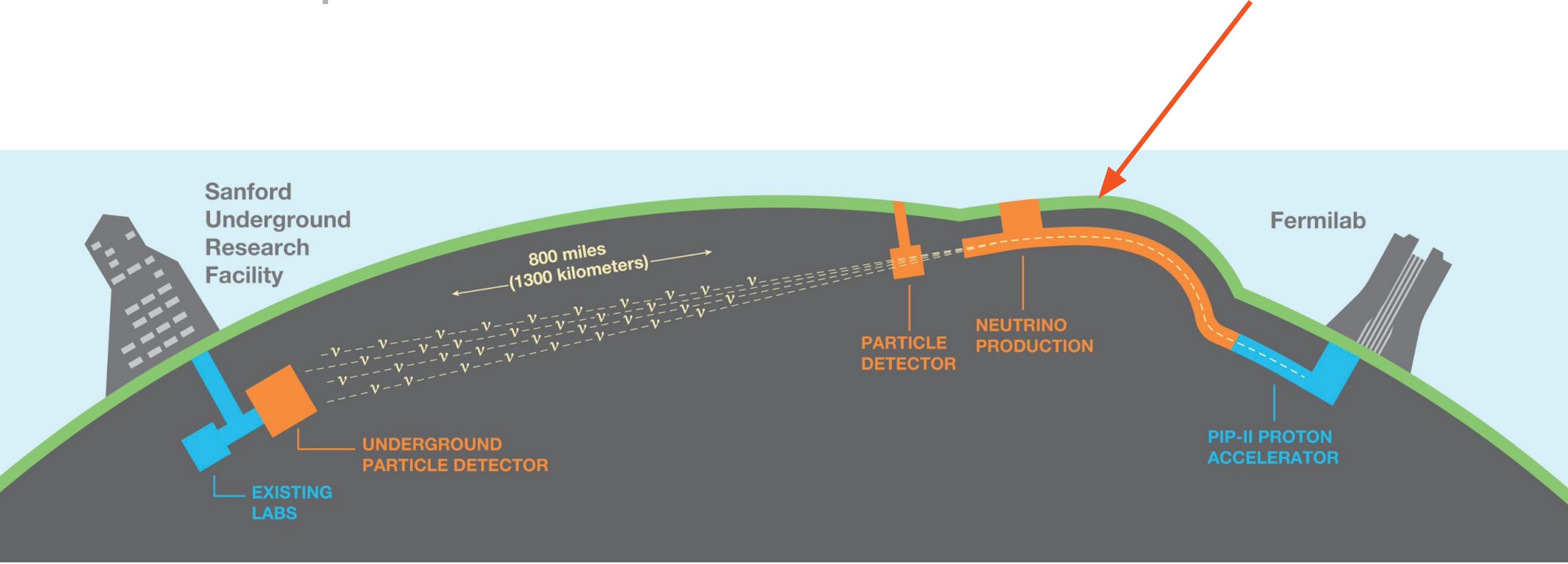
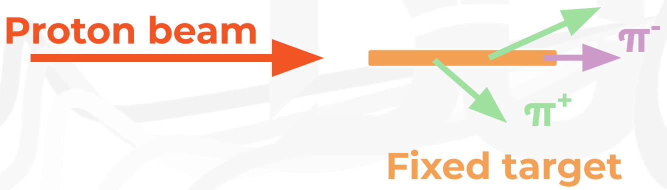
- **Produce neutrino beam**

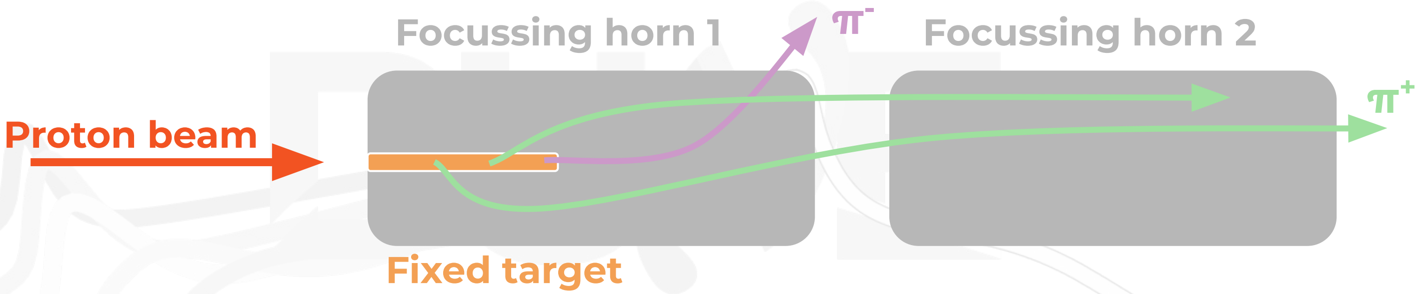


Producing a Beam of Neutrinos



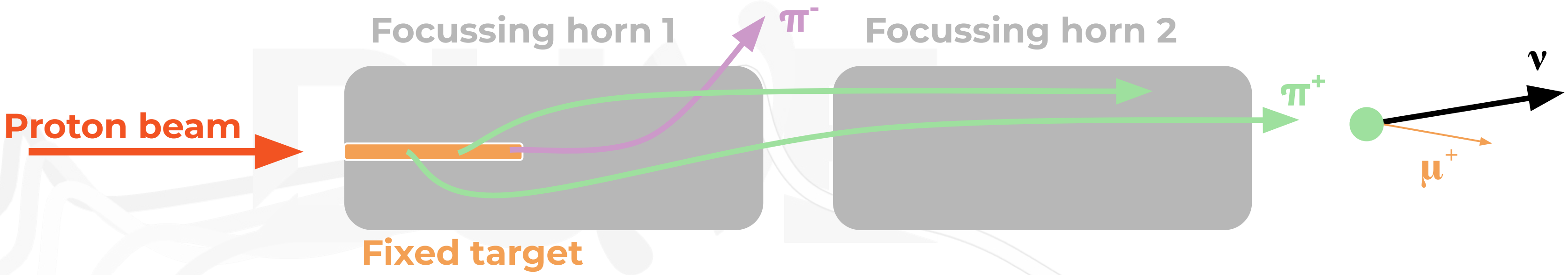
- Proton beam strikes a fixed target producing secondary hadrons: mostly pions and kaons

Producing a Beam of Neutrinos



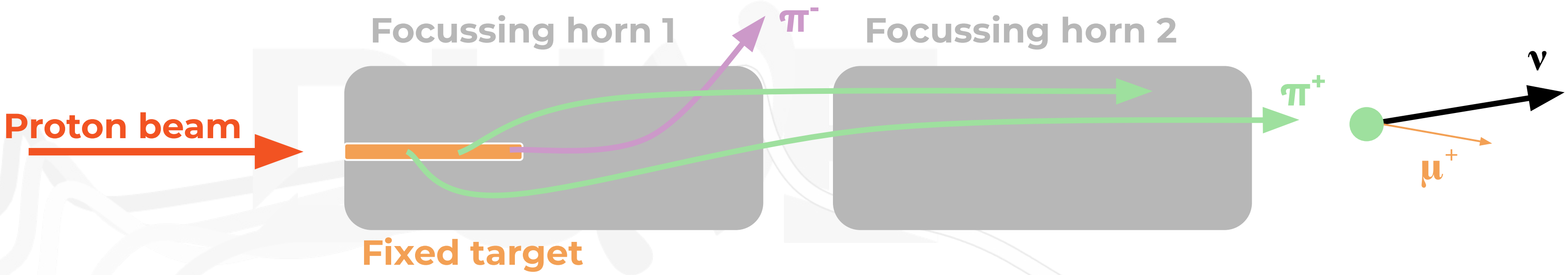
- Proton beam strikes a fixed target producing secondary hadrons: mostly pions and kaons
- These are sign-selected and focussed by one or more magnetic horns.

Producing a Beam of Neutrinos



- 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.

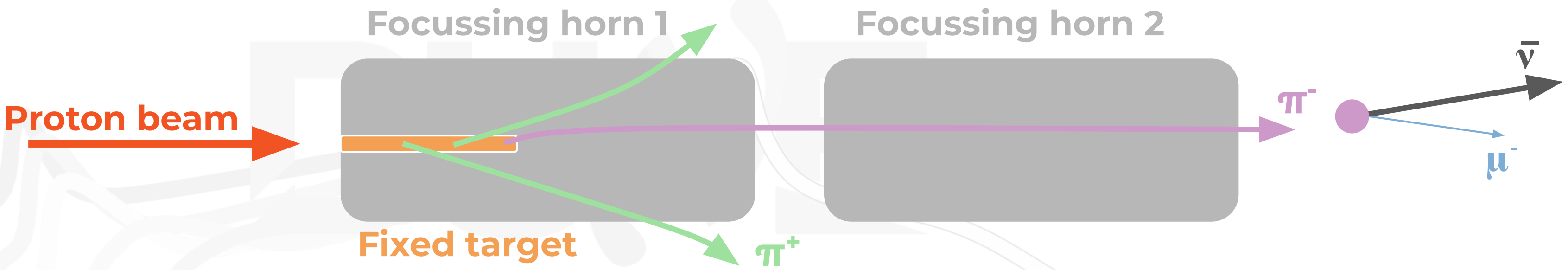
Producing a Beam of Neutrinos



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

Producing a Beam of Neutrinos



Anti-neutrino mode, focussing negative 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.
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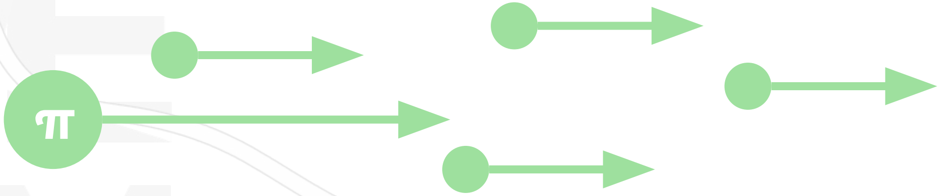
Off Axis Fluxes



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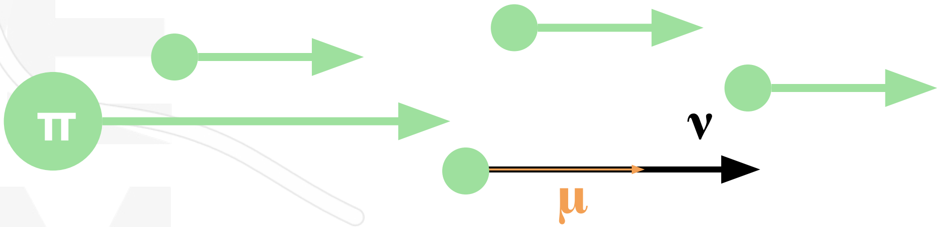

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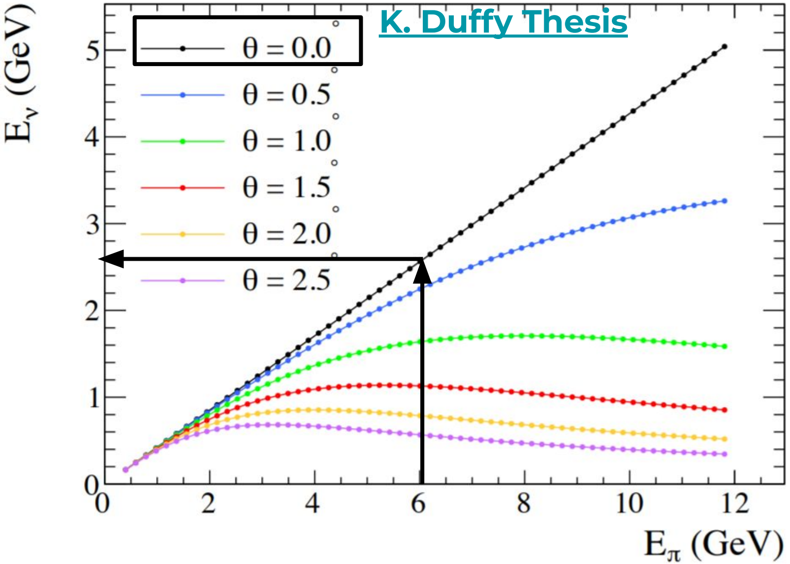
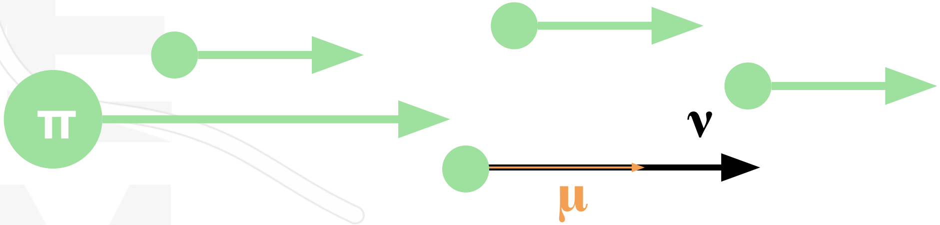
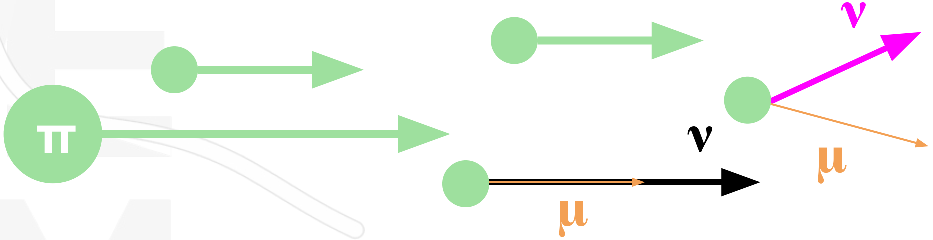
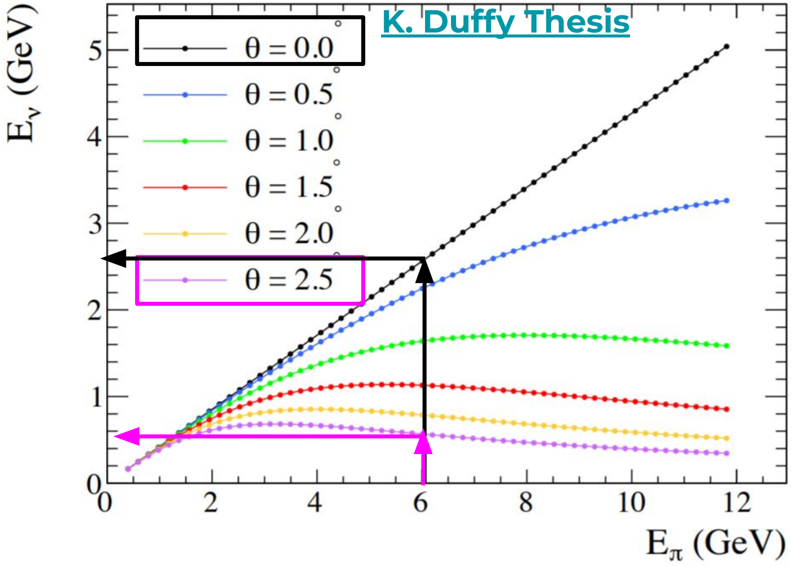




Off Axis Fluxes

- Boosted π decay kinematics result in lower energy neutrinos off beam axis.

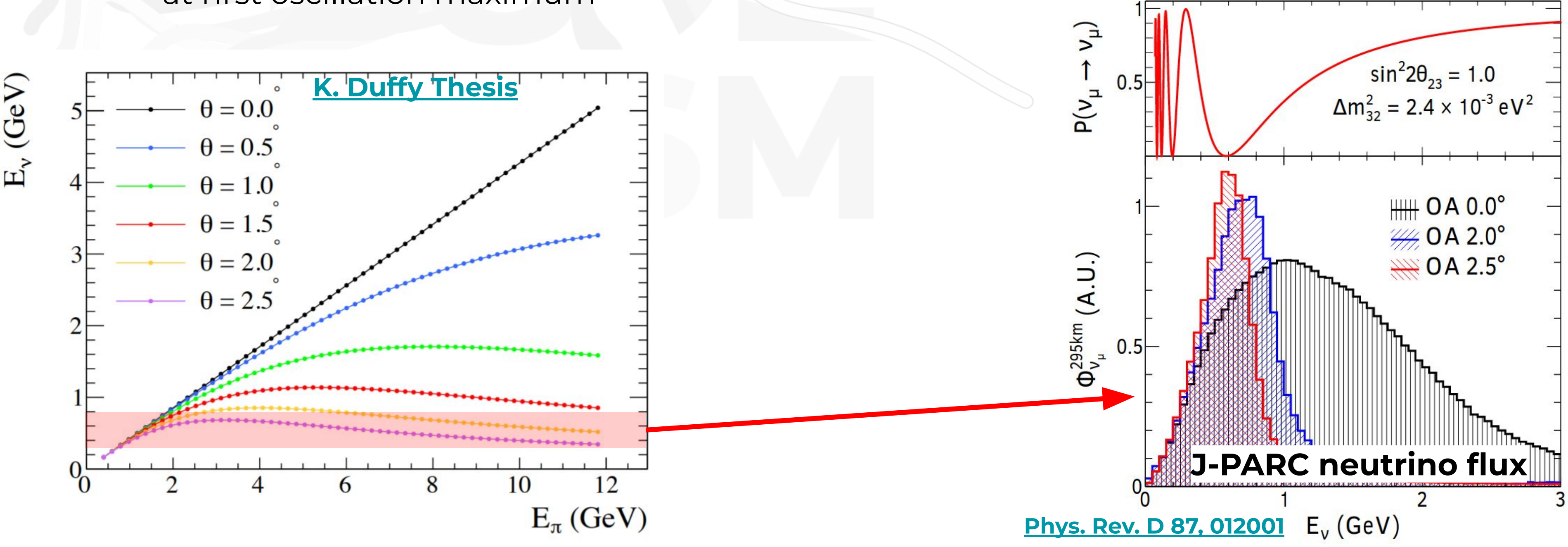




K. Duffy Thesis

Off Axis Fluxes

- Boosted π 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

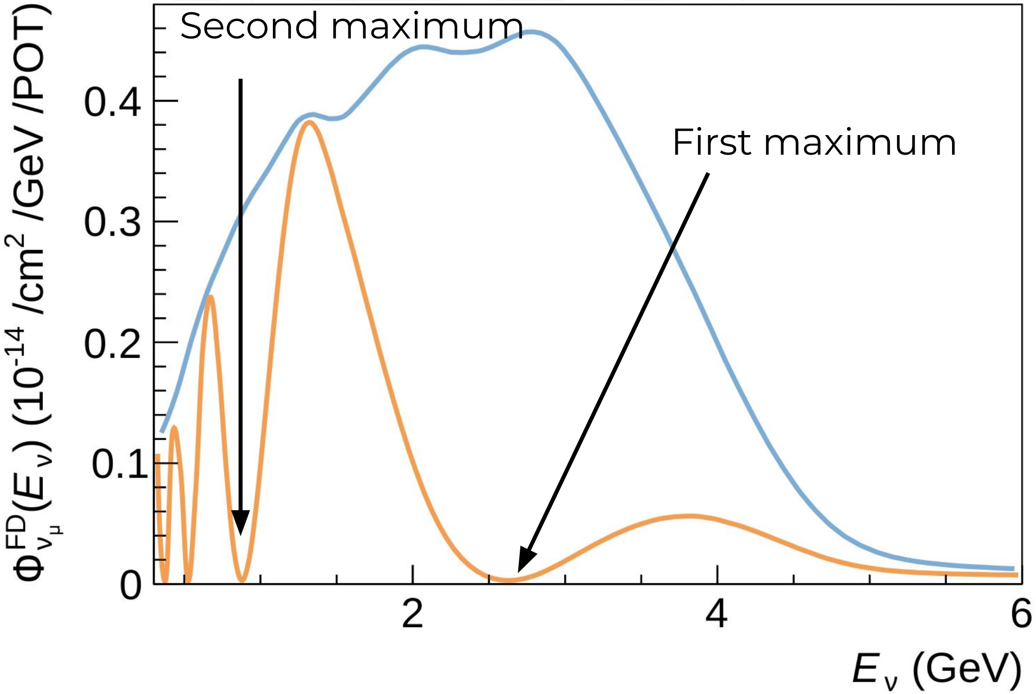


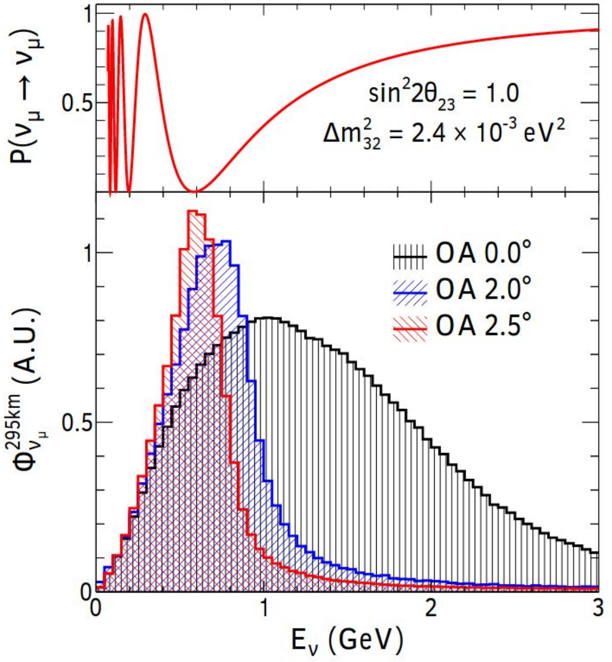
K. Duffy Thesis

Phys. Rev. D 87, 012001

LBNF: The DUNE Neutrino Beam

- By contrast, DUNE will use an on axis, wide band beam:
  - Access to physics at higher order oscillation maxima





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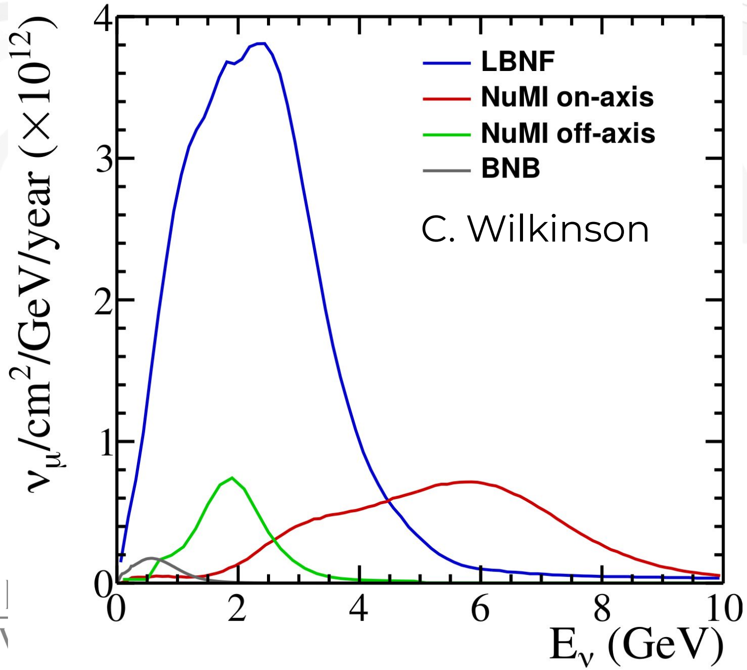
- **Unprecedented neutrino interaction rate**



C. Wilkinson

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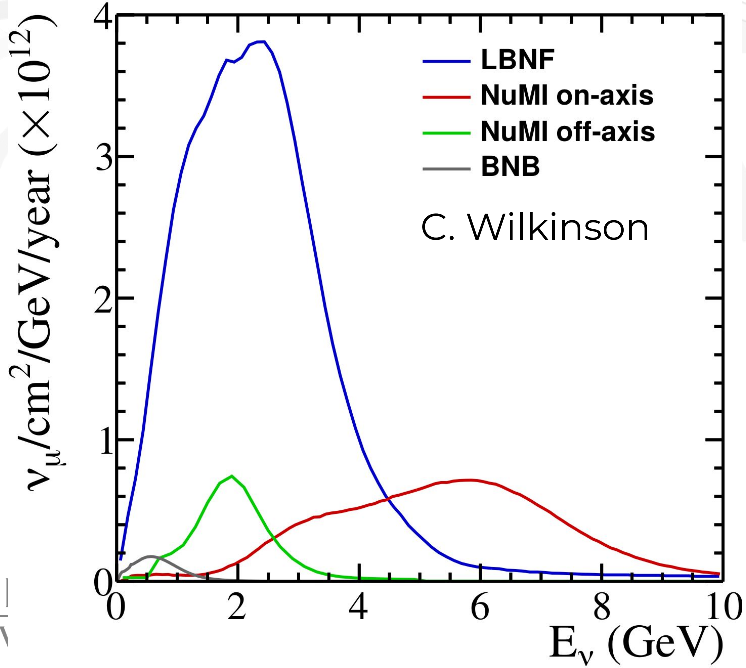
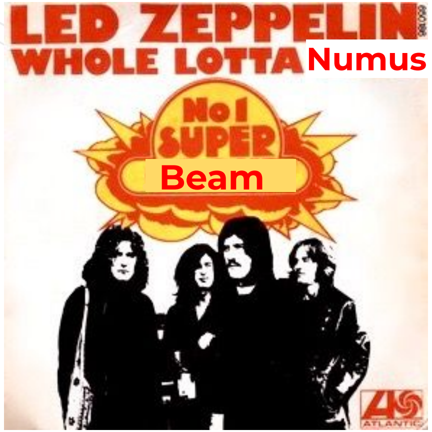


C. Wilkinson

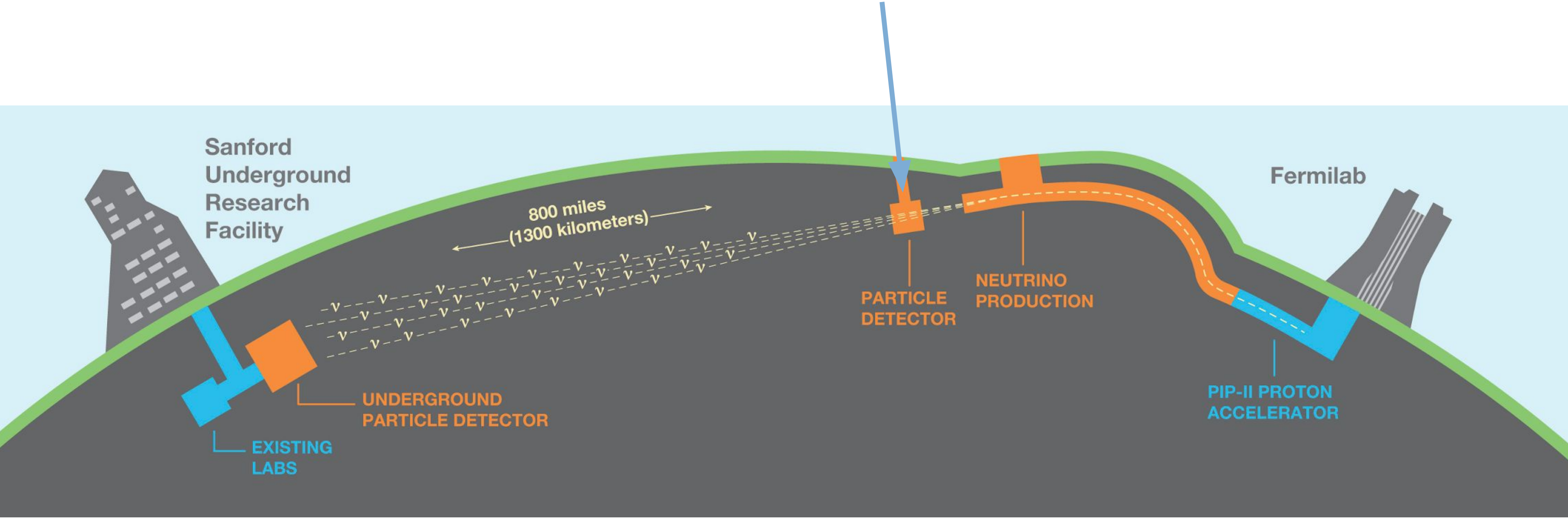


The Deep Underground Neutrino Experiment

- Sample osc. beam
- Infer osc. params

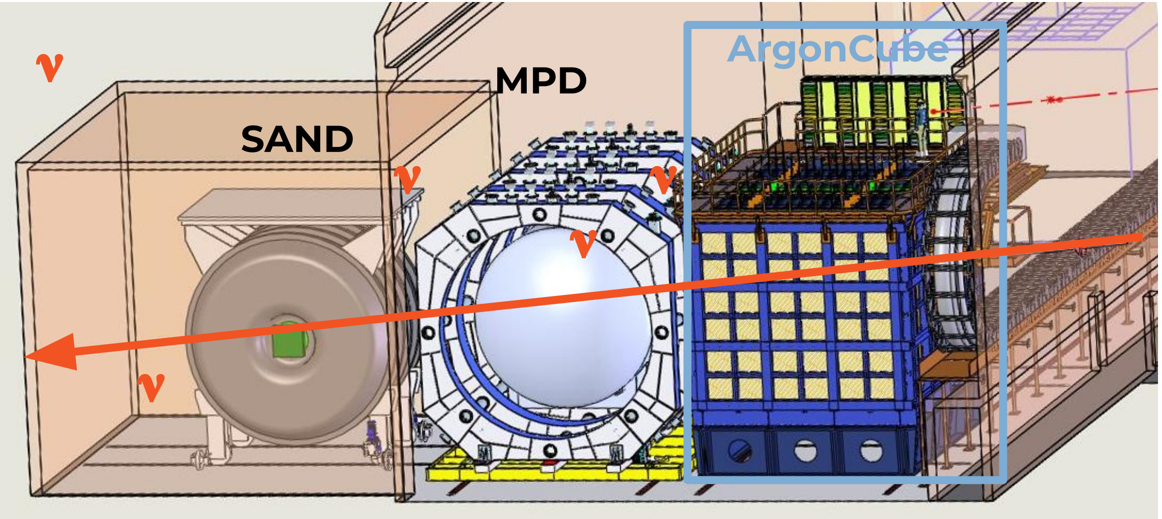
- Sample unosc. beam
- Constrain flux*xsec

- Produce beam



DUNE Near Detector Concept

- **ArgonCube**: LAr TPC
  - Primary target, similar to FD



DUNE Preliminary	**ArgonCube FV**				**MPD FV**
	All int.	Selected			All int.
Run duration	$N\nu_\mu CC$	NSel	WSB	NC	$N\nu_\mu CC$
$^1/_2$ yr.	25.5M	11.3M	0.2%	1.4%	680,000

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- **MPD**: GAr TPC + ECal + Low mass magnet
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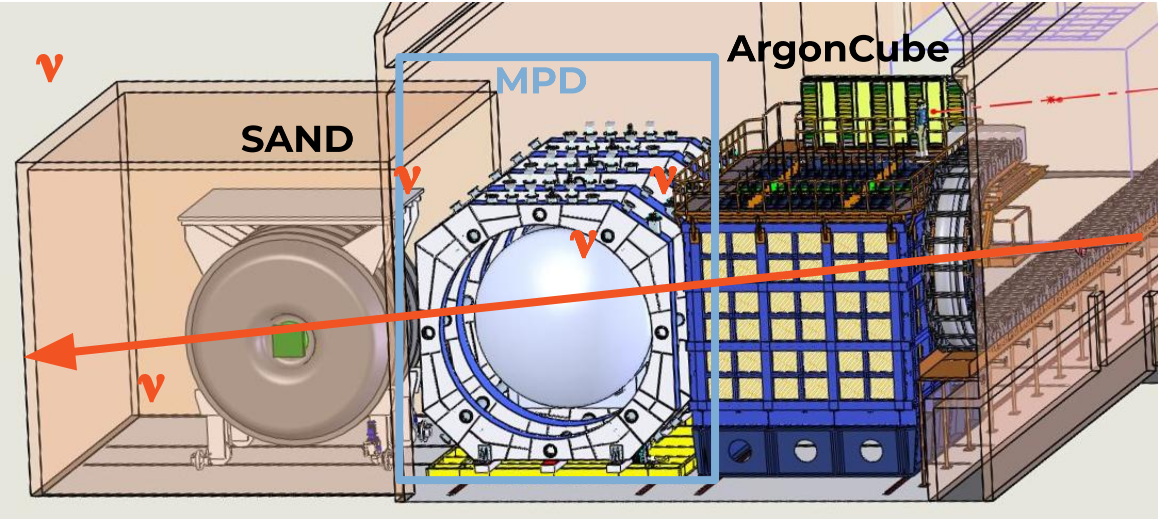
  - Low threshold neutrino target



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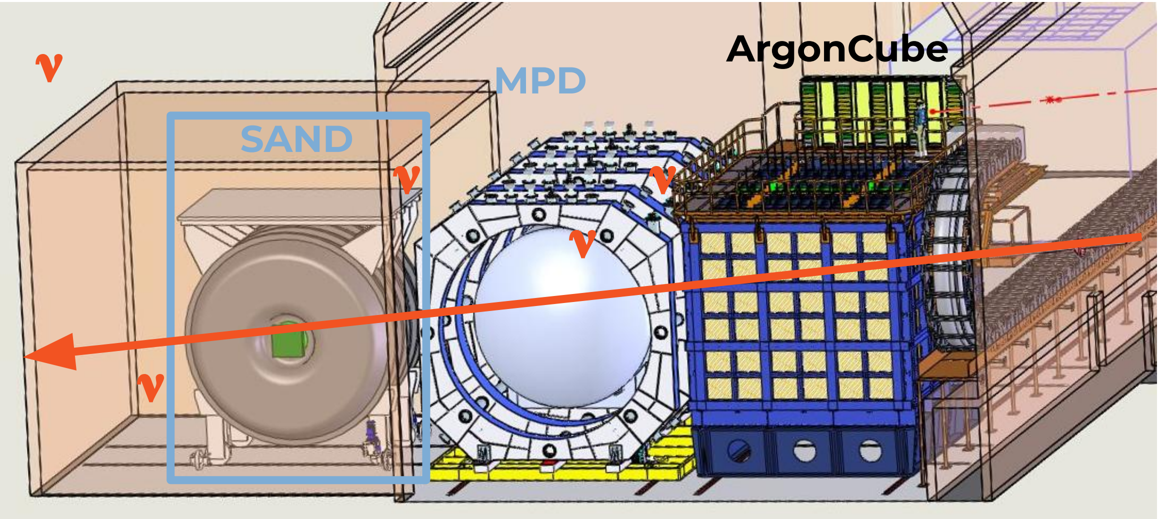
DUNE Near Detector Concept

- **ArgonCube**: LAr TPC
    - Primary target, similar to FD
- **MPD**: GAr TPC + ECal + Low mass magnet
    - Charge/momentum/PID
    - Low threshold neutrino target
- **SAND**: 3D plastic scintillator detector inside a superconducting solenoid:
    - Beam monitor



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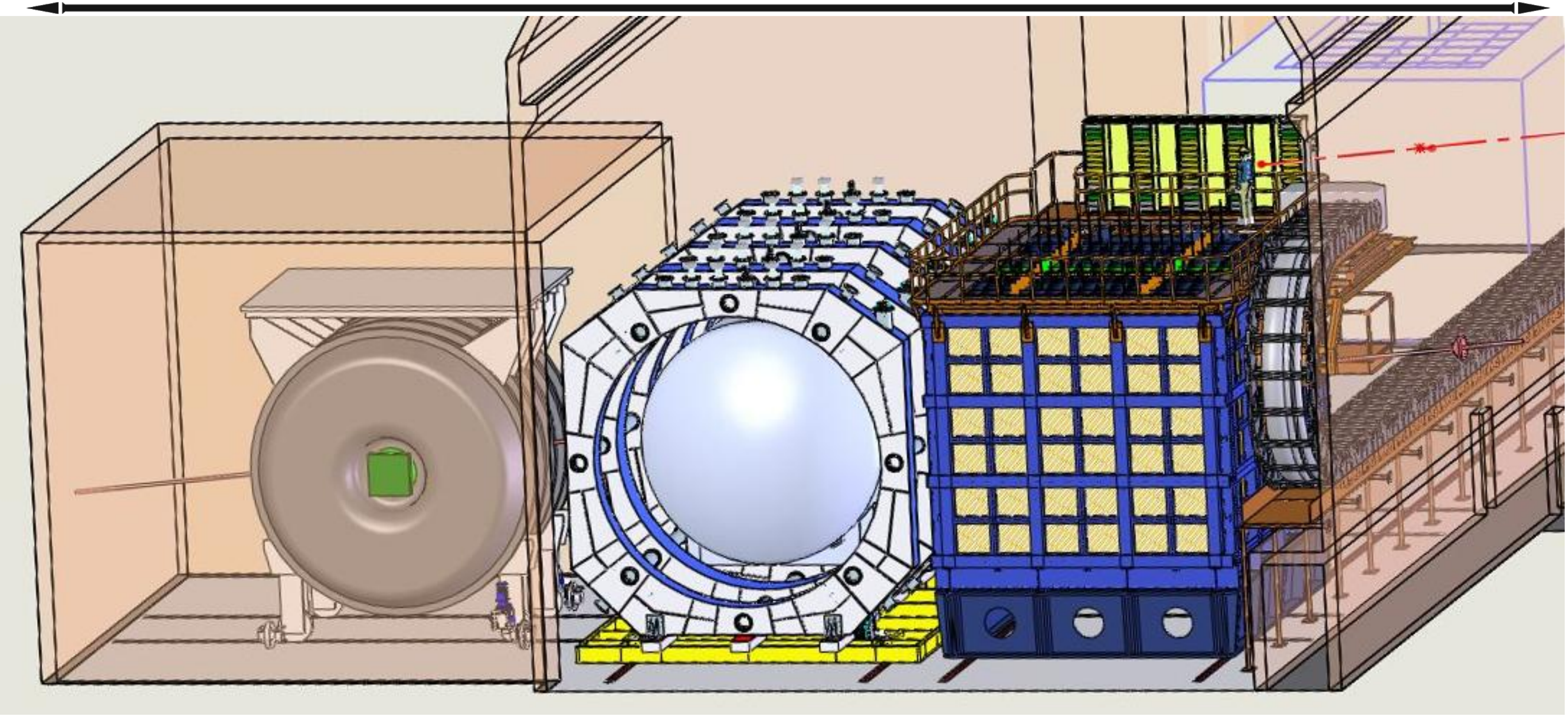

DUNE Near Detector Concept

CarBON

GArGON

LArGON

https://hiveminer.com/Tags/gargon/

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- Infer osc. params

- Sample unosc. beam
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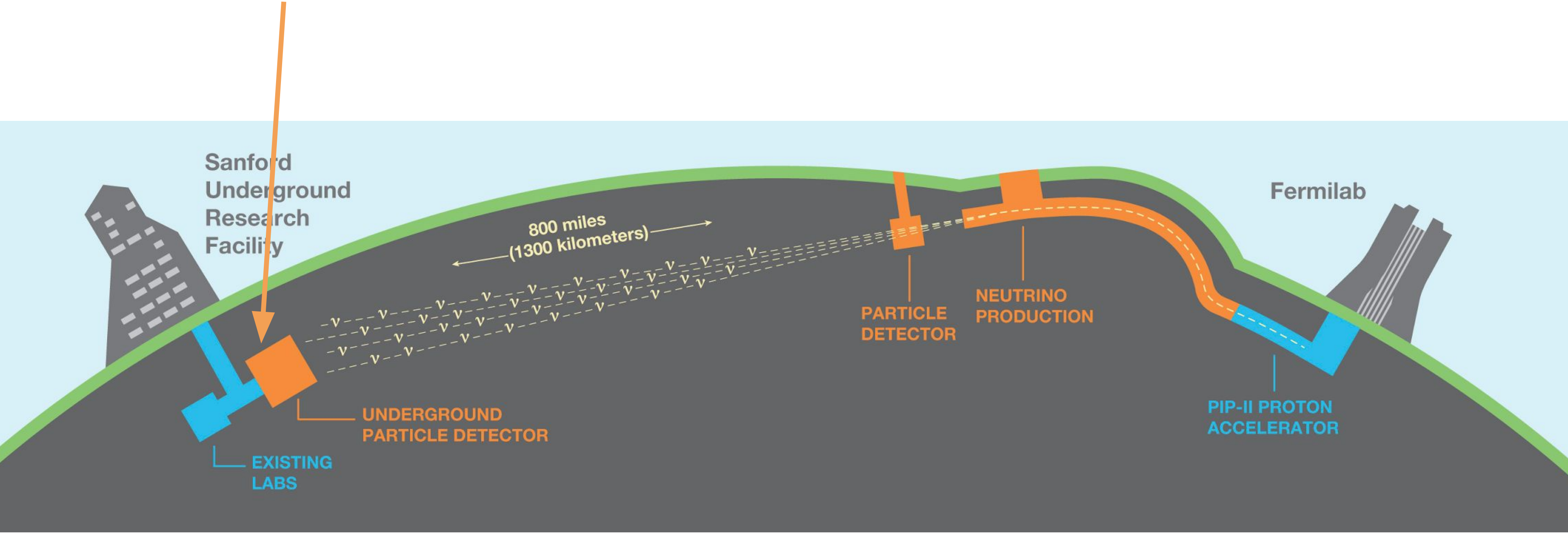
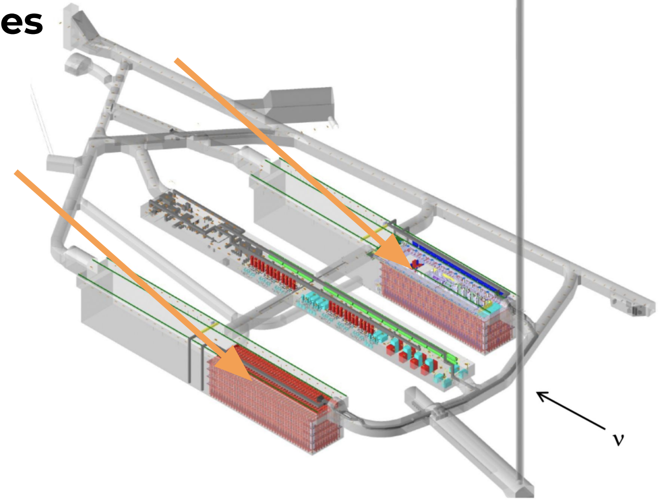


Far Detector

- 4x**10 kT LAr TPC**s

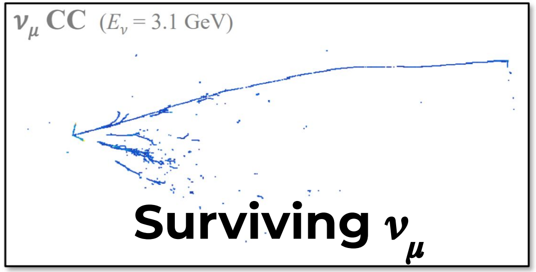
SURF underground facilities



R. Patterson FNAL, JETP

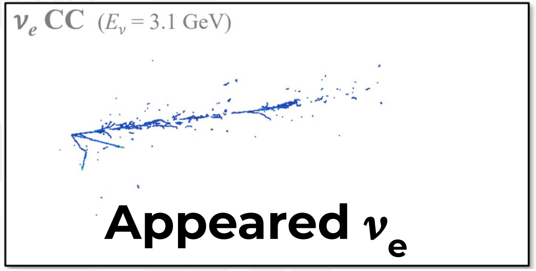
Far Detector

- 4x**10 kT LAr TPC**s:
  - Unprecedented FD event resolution



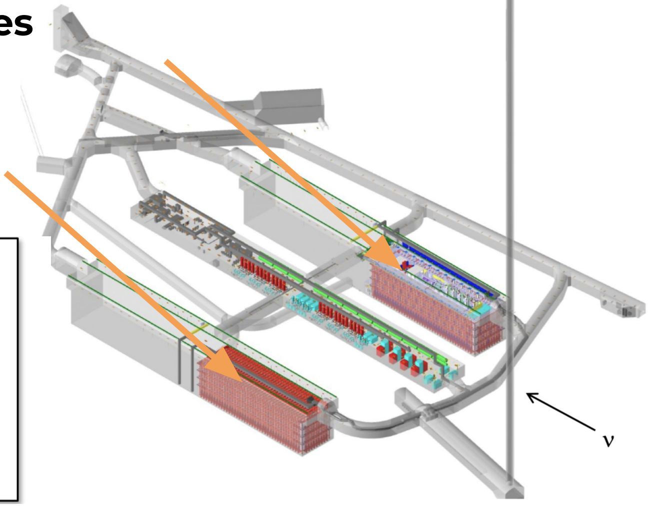
Surviving ν_μ

simulations



Appeared ν_e

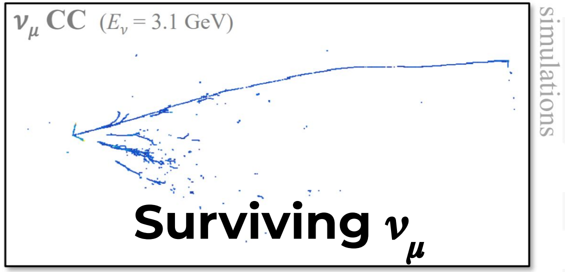
SURF underground facilities



R. Patterson FNAL JETP

Far Detector

- 4x**10 kT LAr TPC**s:
    - Unprecedented FD event resolution and event rate!



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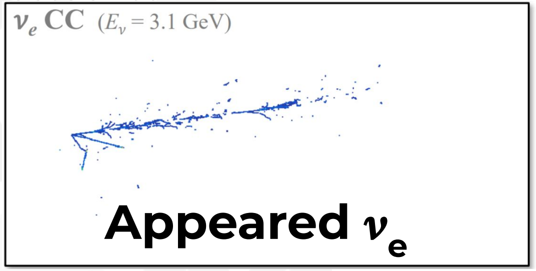

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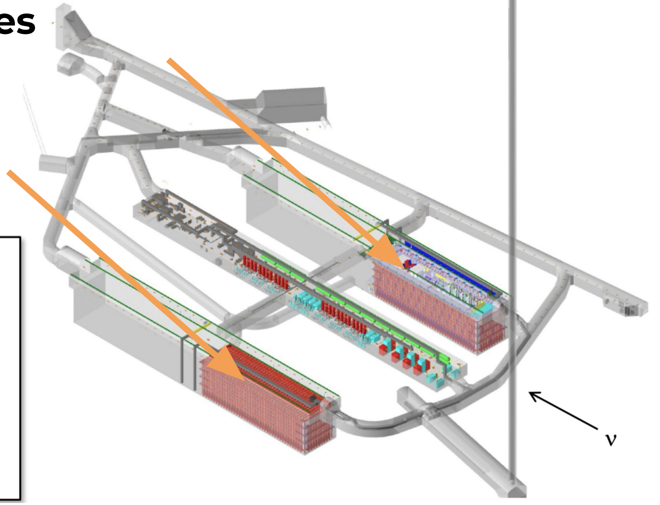
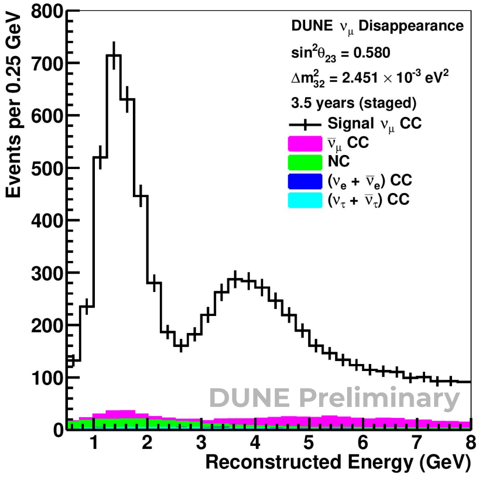
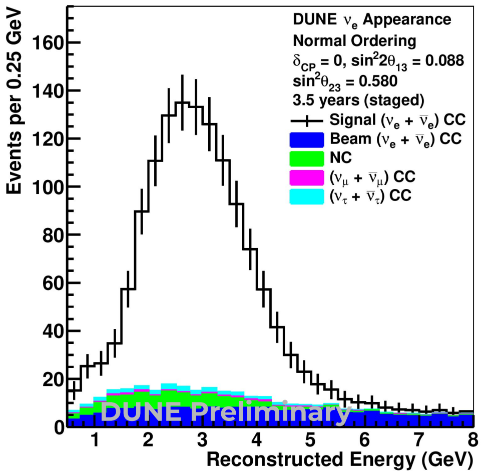




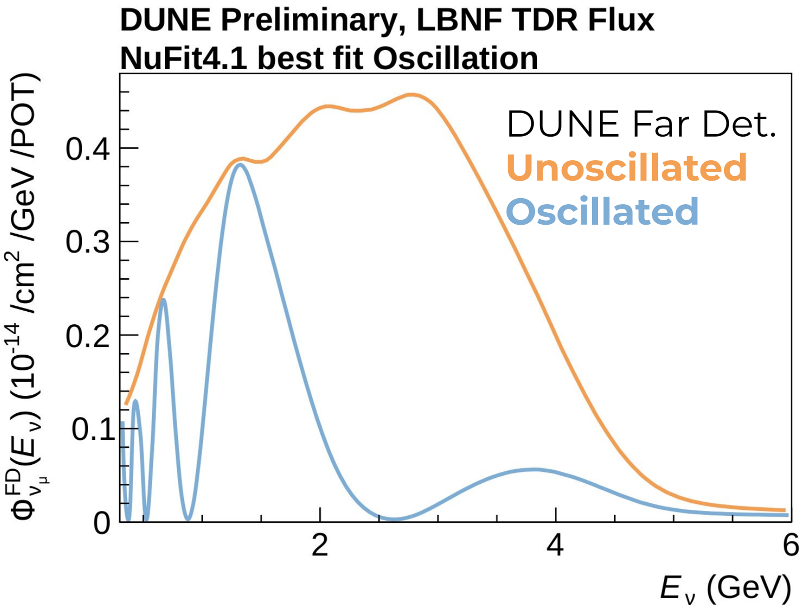


R. Patterson FNAL, JETP

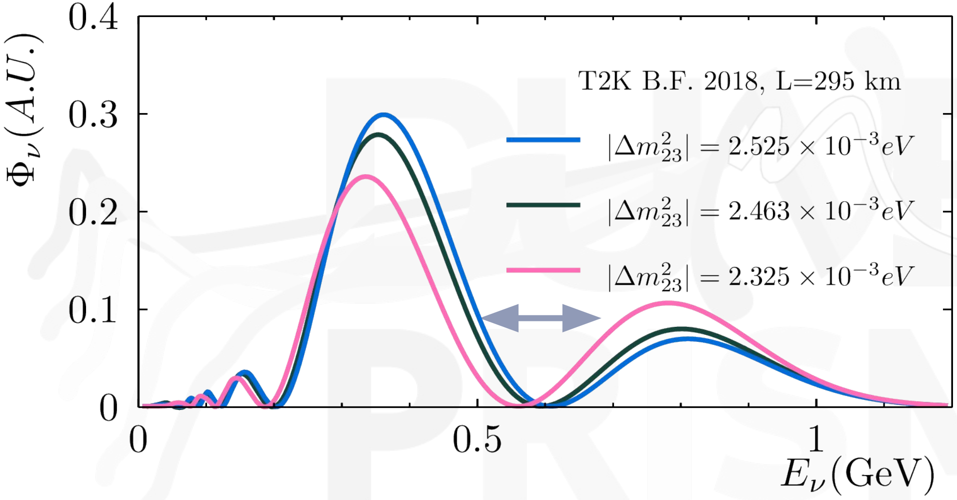
Measuring Oscillations

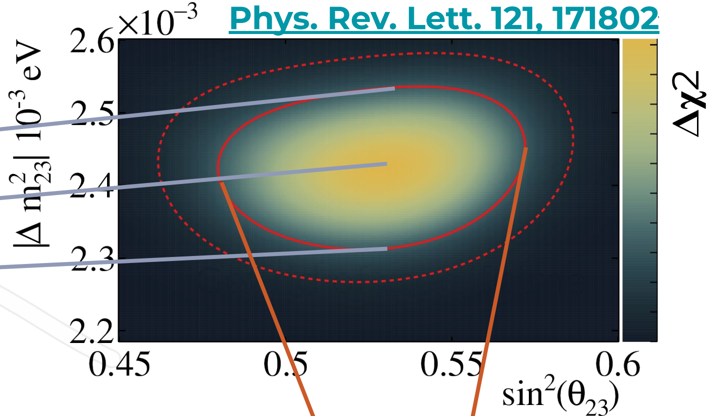
Inferring Oscillation Parameters

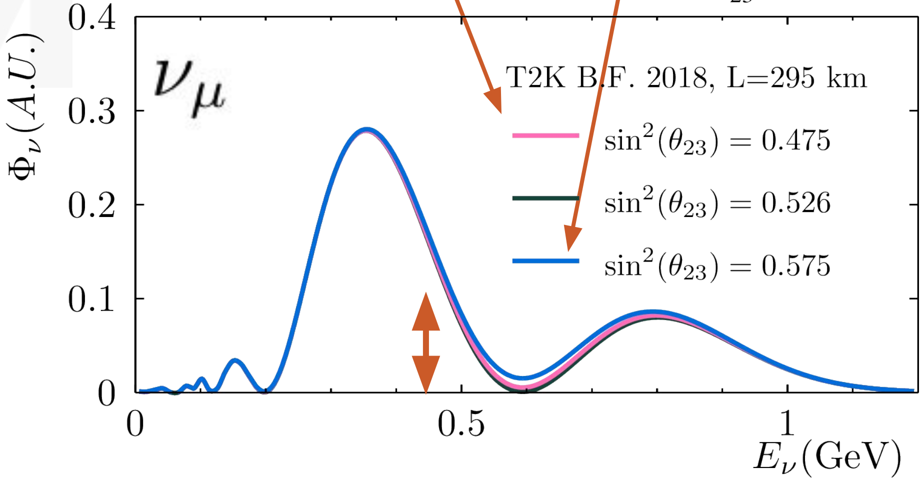
- Shouldn’t be too hard
  - Sophisticated detectors
  - Powerful neutrino beams
- Look for signature 'oscillation' shape in flux at the 'far' detector...



Signature Oscillation Shape



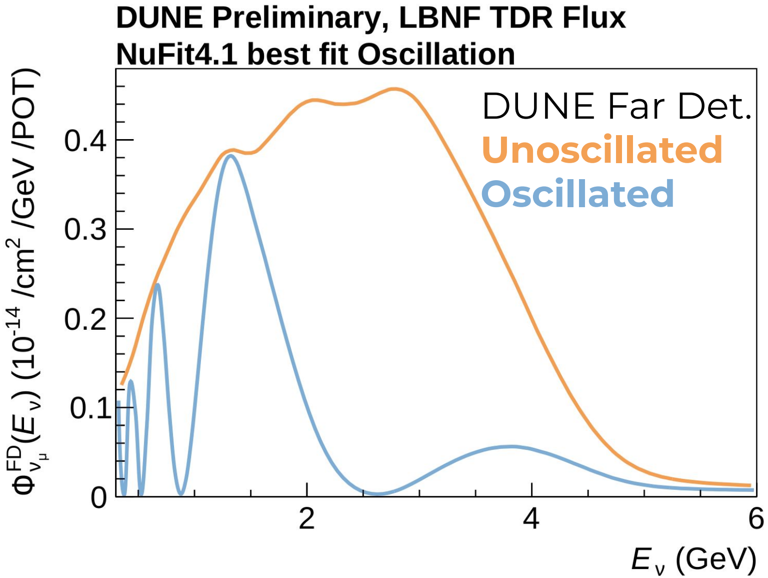




- Mass-squared splitting shifts the ‘dip’
- Mixing angle determines the depth of the ‘dip’

Inferring Oscillation Parameters

- **Look for signature 'oscillation' shape in flux at the far detector**



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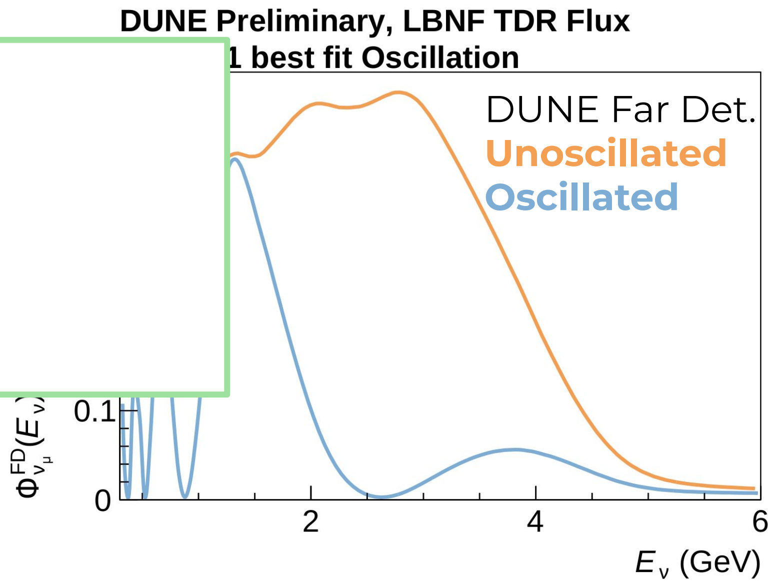
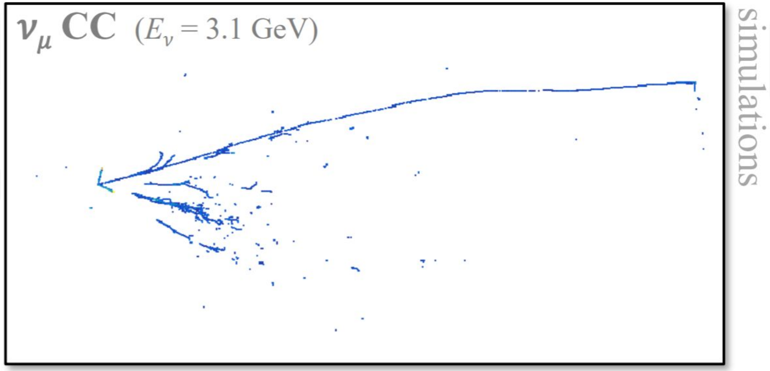


But...

Inferring Oscillation Parameters

- Look for signature ‘oscillation’ shape in flux at the far detector
- **We cannot observe the flux, only the event rate**



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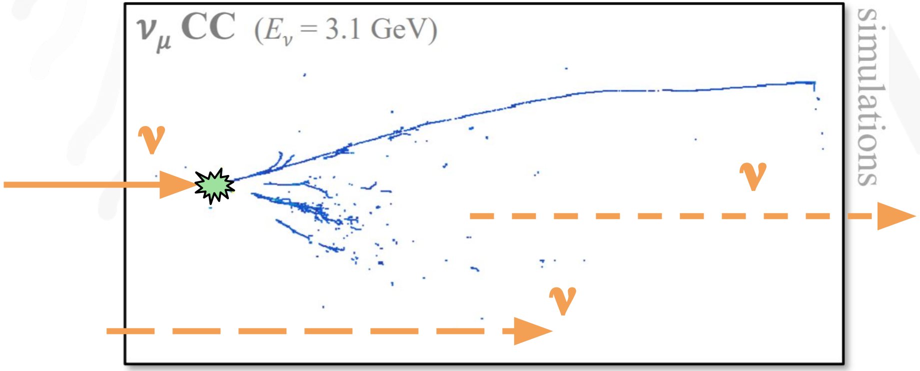

Number of events = **Flux** · **Cross section**

Inferring Oscillation Parameters

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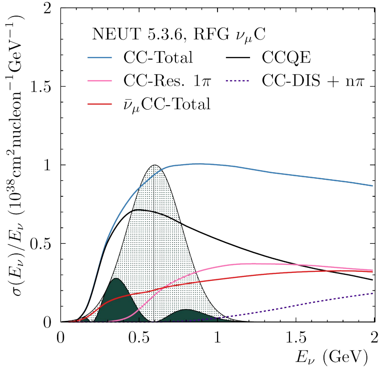
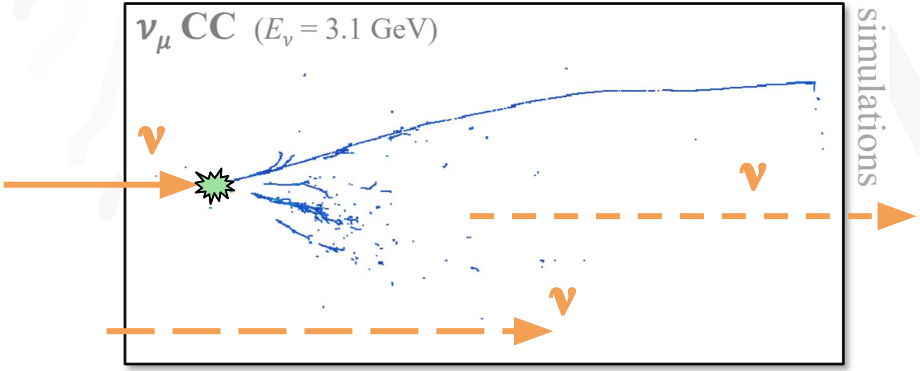
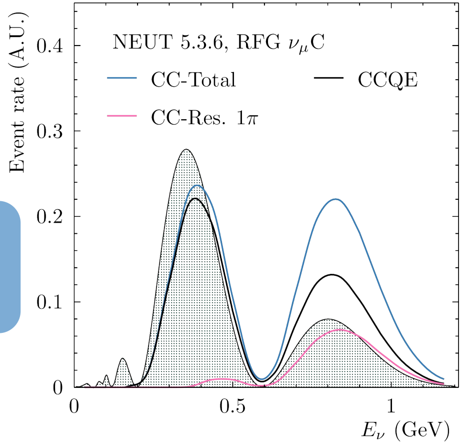
Flux · **Cross section**





Number of events



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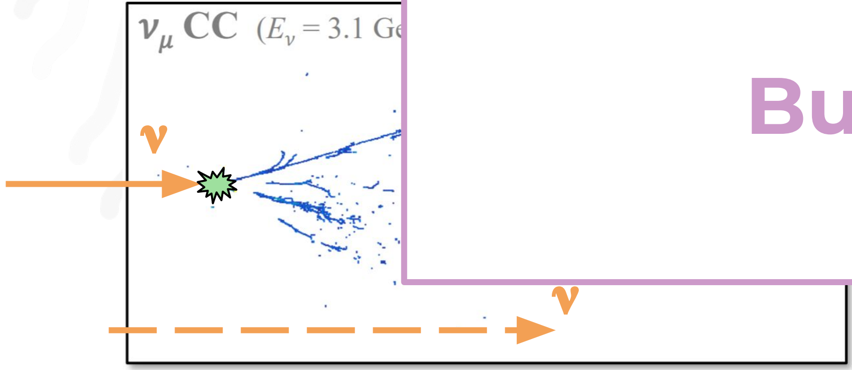

But...

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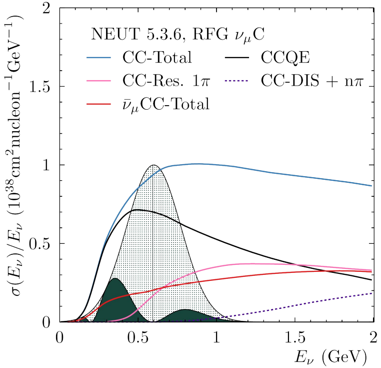
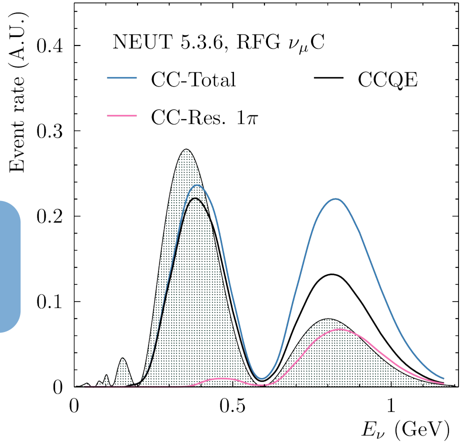


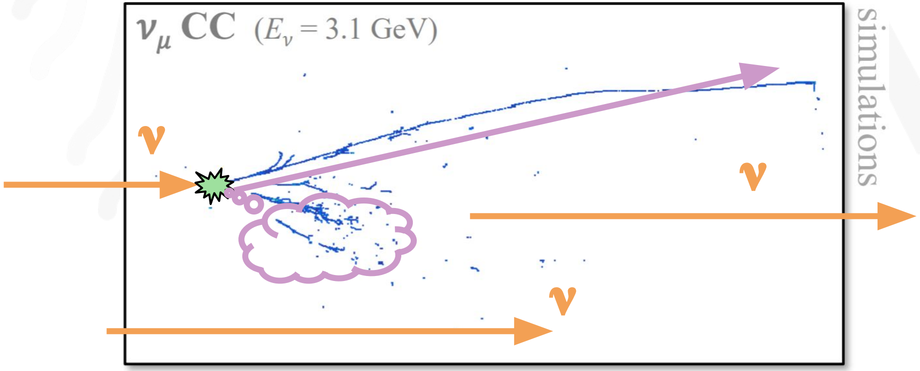
Number of events



Number of events = **Flux** · **Cross section**

Inferring Oscillation Parameters

- Look for signature 'oscillation' shape in flux at the far detector…
- We cannot observe the flux, only the event rate
- **We have to reconstruct the energy from observables**



Number of observed events = **Flux** · **Cross section** · **Detector effects**

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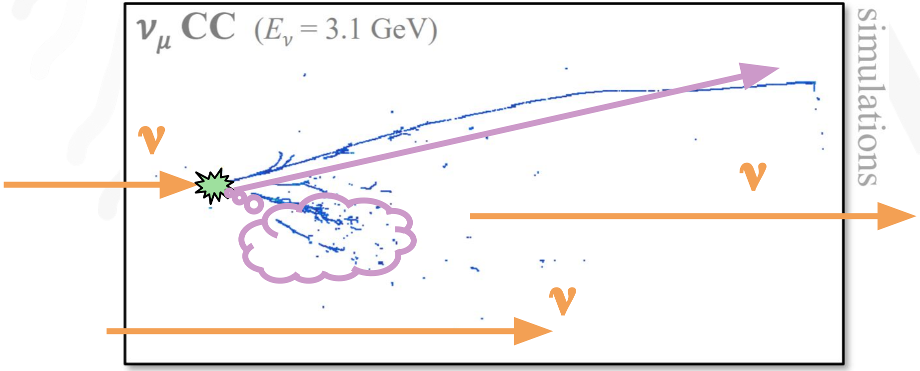

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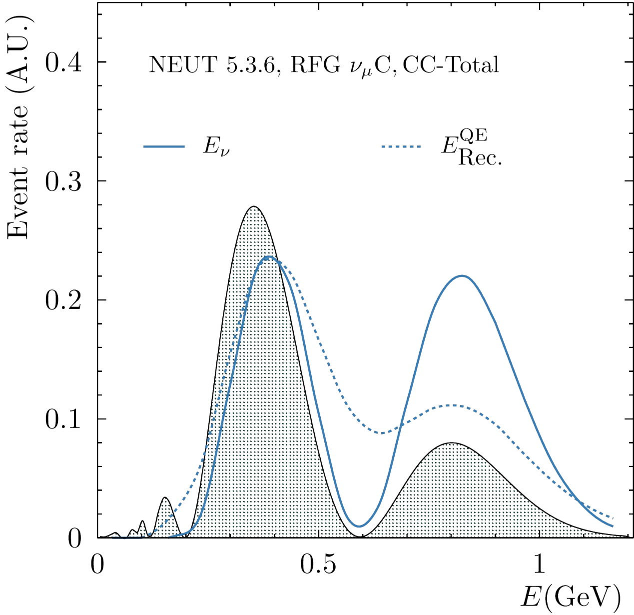
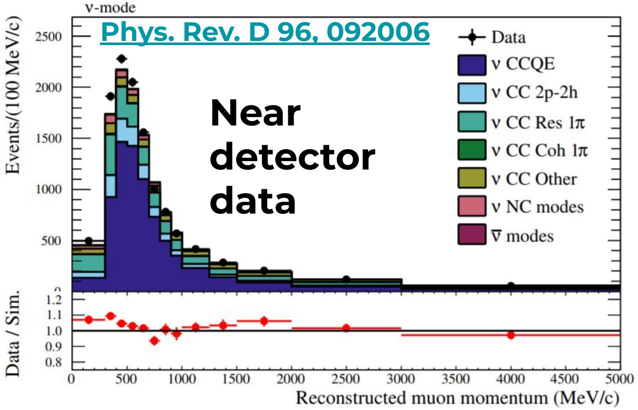


Current Long Baseline Neutrino Oscillation Analysis

An Oscillation Analysis

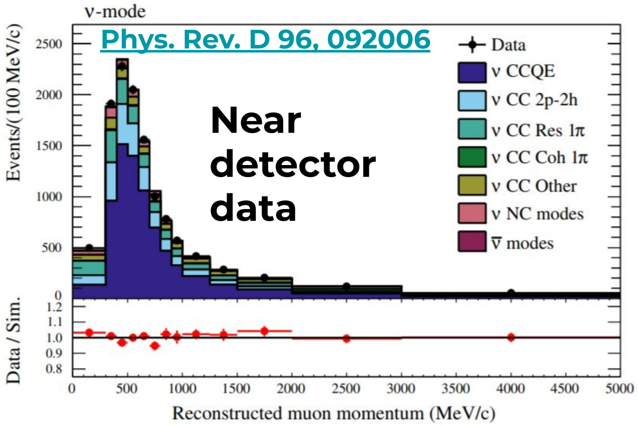


Phys. Rev. D 96, 092006

Near detector data

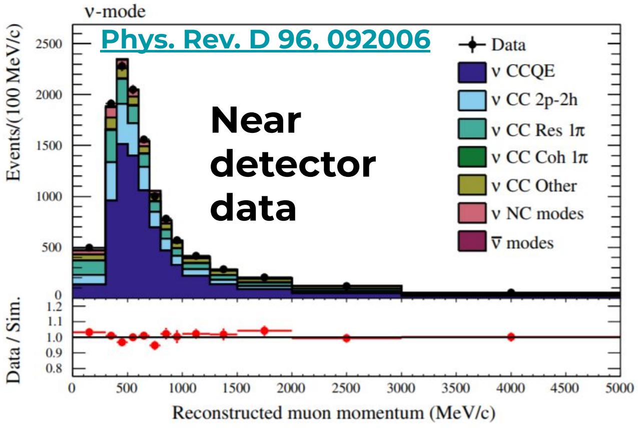
- Wiggle model parameters at the Near Detector

An Oscillation Analysis

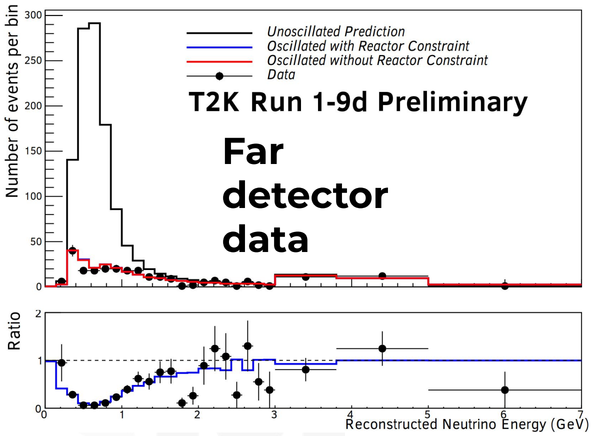


- **Wiggle model parameters at the Near Detector**
  - Uses near detector data to constrain model parameters (flux, detector, cross section)

An Oscillation Analysis



Phys. Rev. D 96, 092006



- Wiggle model parameters at the Near Detector
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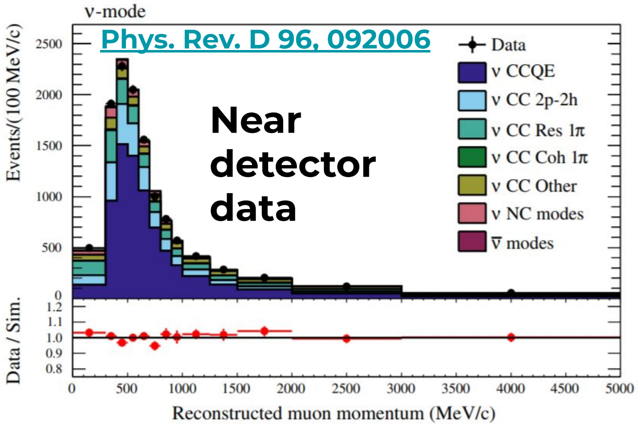
- **Trust model + uncertainties to predict far detector data for a given oscillation hypothesis.**

An Oscillation Analysis


Phys. Rev. D 96, 092006

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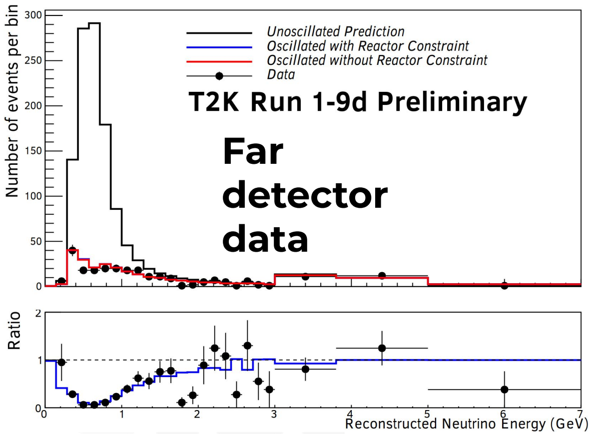
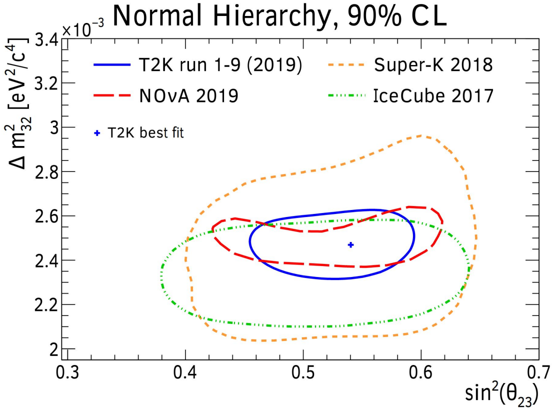

T2K Run 1-9d Preliminary

Far detector data


Normal Hierarchy, 90% CL

- Wiggle model parameters at the Near Detector
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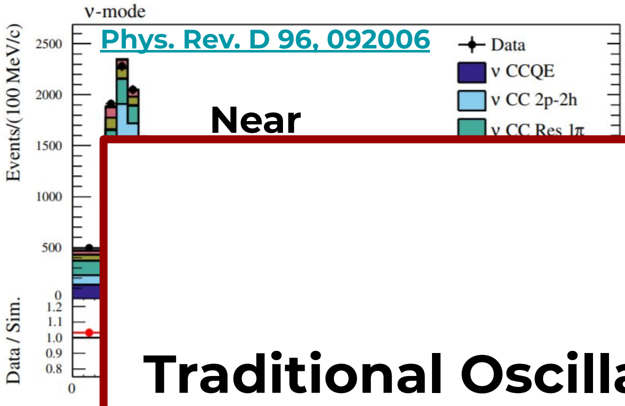
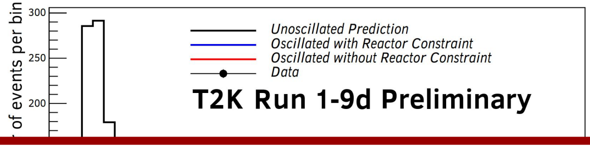
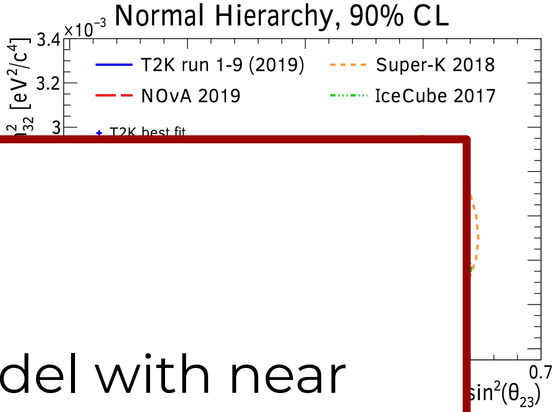
- **Infer oscillation parameters from observed data**

An Oscillation Analysis



Phys. Rev. D 96, 092006





Traditional Oscillation Analyses: Tune model with near detector data, and have to assume it is correct at the far detector.

-
- oscillation hypothesis.
- **Infer oscillation parameters from observed data**

Model-driven Extrapolation

- What if the model isn't correct? We can end up:
  - ⇒ Attributing data/MC discrepancy to the wrong energy range at the near detector

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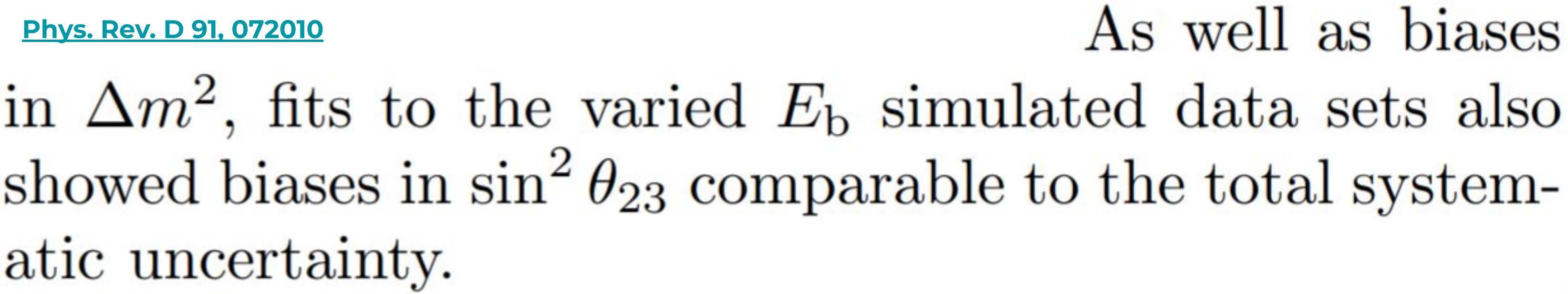
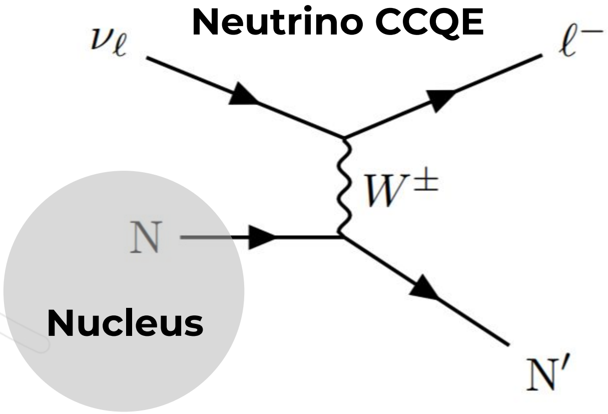
[Phys. Rev. D 91, 072010](https://doi.org/10.1103/PhysRevD.91.072010)



As well as biases in Δm^2, fits to the varied E_b simulated data sets also showed biases in $\sin^2\theta_{23}$ comparable to the total systematic uncertainty.

Example: My Work on T2K

- Uncertain 'missing energy' for interactions with bound nucleons.
-



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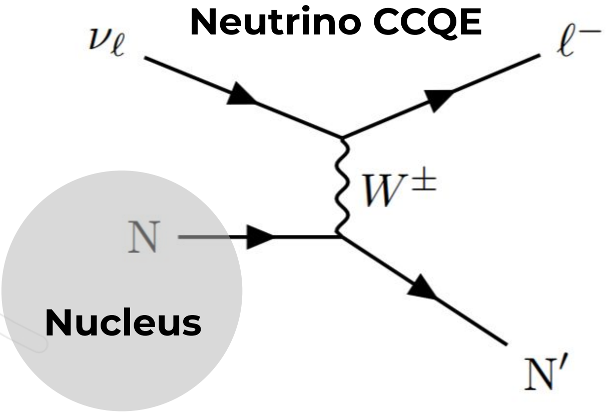
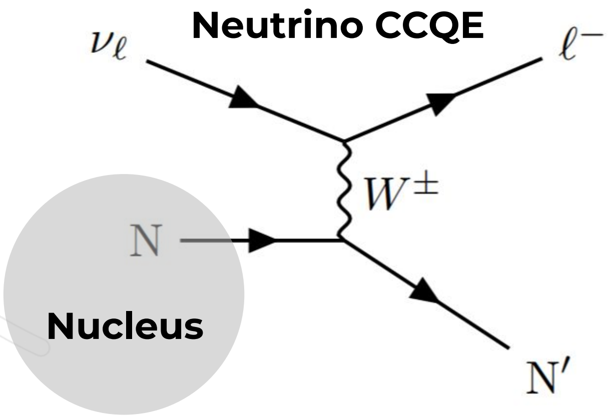
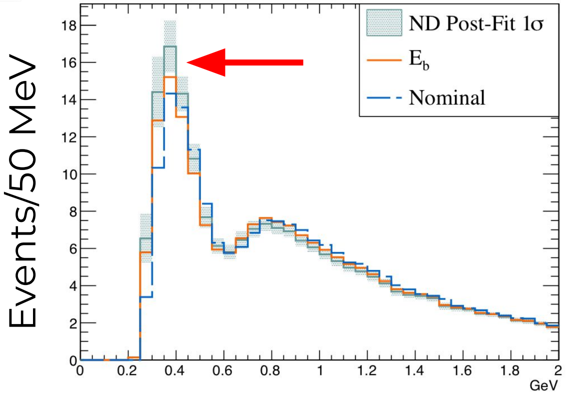
- **More missing energy → less visible muon energy** for the same true neutrino energy.

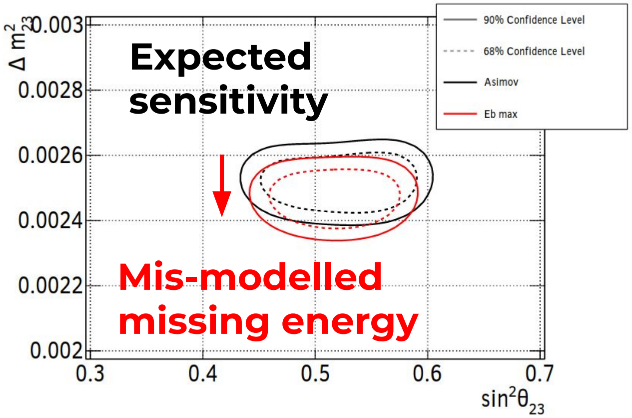


Example: My Work on T2K

- Uncertain 'missing energy' for interactions with bound nucleons.
- **More missing energy → less visible muon energy** for the same true neutrino energy.
- Incorrect prediction at far detector induces significant biases in Δm^2_{23}







Oscillations at the Far Detector

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

Number of near detector events = Flux · Cross section · Detector effects

Number of far detector events = Flux · Oscillation probability · Cross section · Detector effects

Want to know this

Oscillations at the Far Detector

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

$$N_{\mathrm{near}}\left(E_{\mathrm{obs}}\right) = \int dE_\nu \, \Phi_{\mathrm{near}}\left(E_\nu\right) \cdot \sigma\left(E_\nu\right) \cdot \mathbf{D}_{\mathrm{near}}$$

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

Want to know this

Oscillations at the Far Detector

- 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

$$N_{\text{near}}\left(E_{\text{obs}}\right) = \int dE_\nu \, \Phi_{\text{near}}\left(E_\nu\right) \cdot \sigma\left(E_\nu\right) \cdot \mathbf{D}_{\text{near}}$$

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Want to know this

Oscillations at the Far Detector

- Why c
    - Bec
    - Cor
    - Car

What if we could make near detector measurements, in an oscillated flux?

$$N_{\text{near}}\left(E_{\text{obs}}\right) = \int dE_{\nu}\, \Phi_{\text{near}}\left(E_{\nu}\right) \cdot \sigma\left(E_{\nu}\right) \cdot \mathbf{D}_{\text{near}}$$

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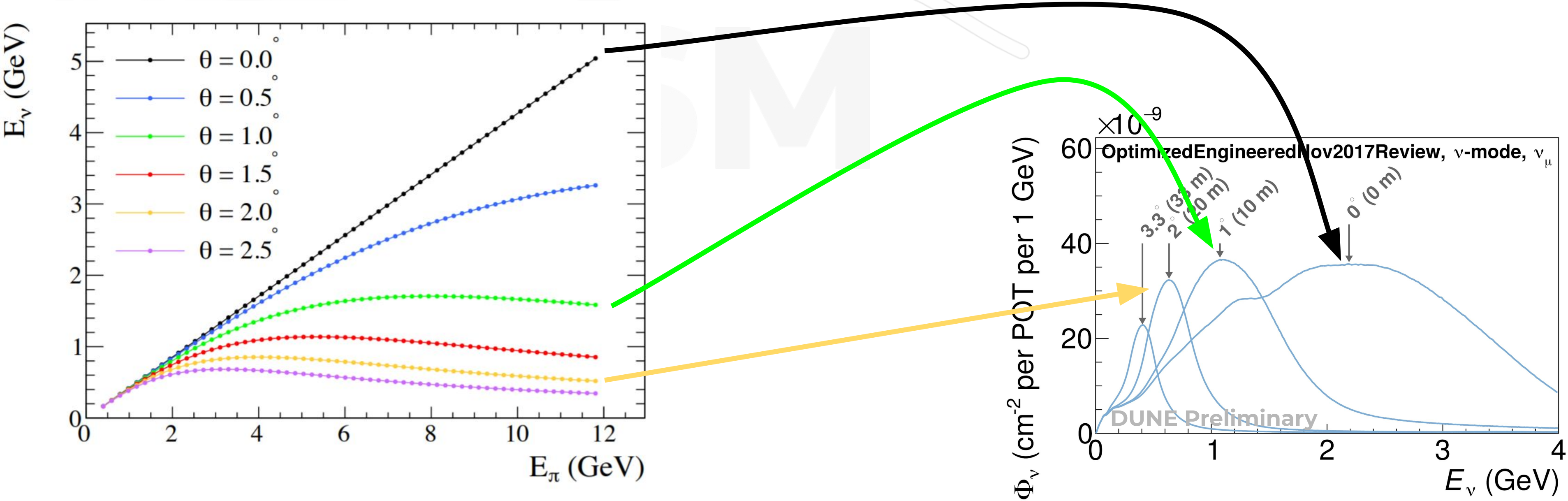
Want to know this

DUNE PRISM

Precision Reaction-Independent Spectrum Measurement

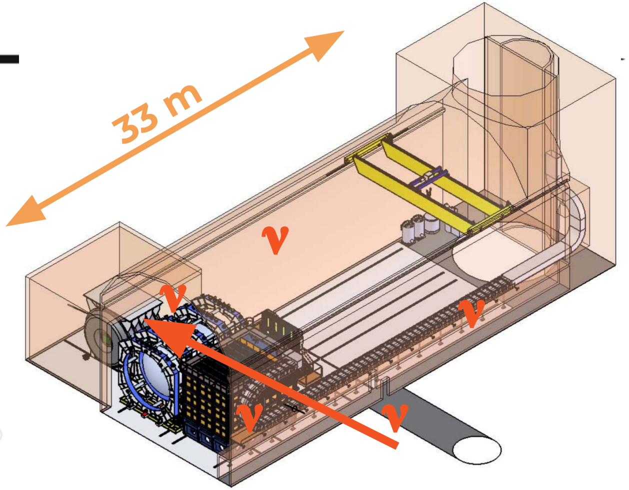
DUNE Off Axis

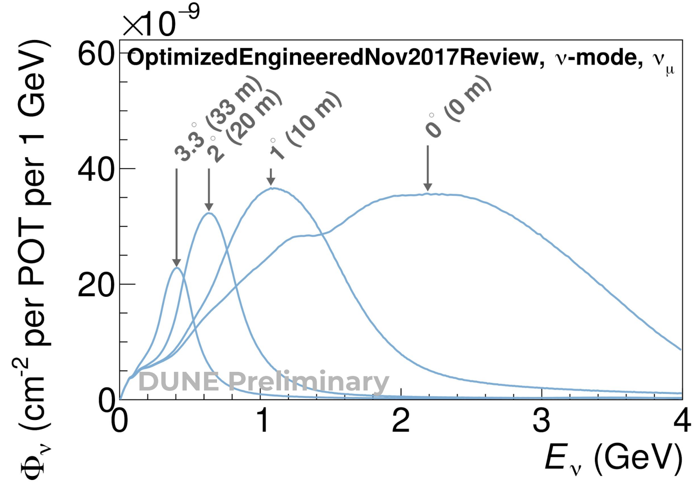
- Sample different fluxes at different off axis angles.



Off Axis at the Near Detector

- Sample different fluxes at different off axis positions.





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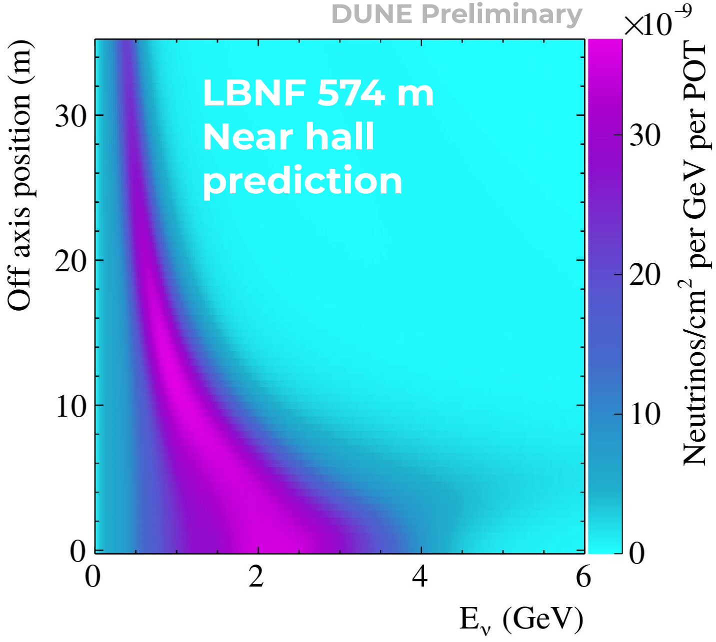

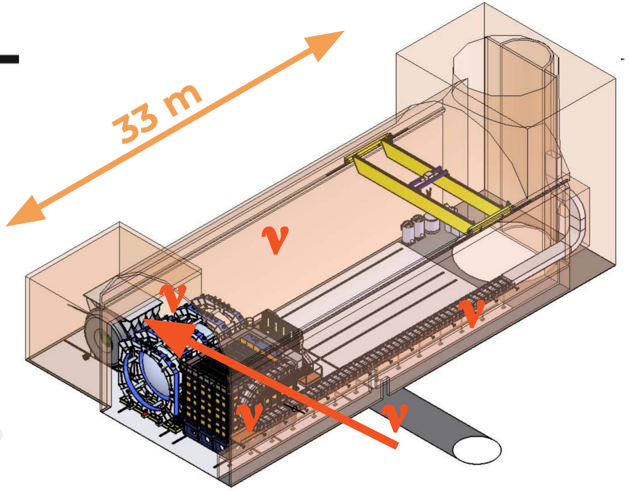

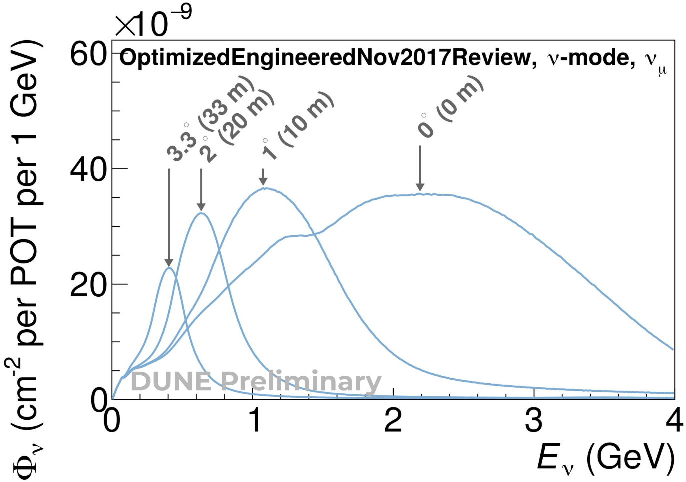

Off Axis at the Near Detector

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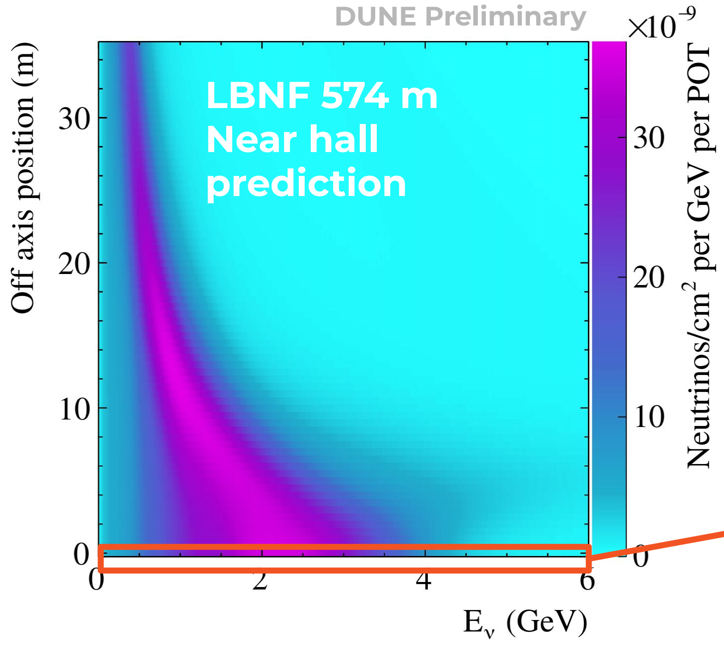

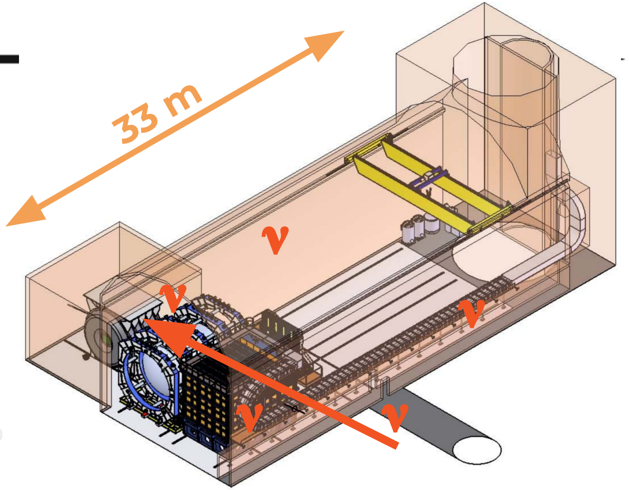

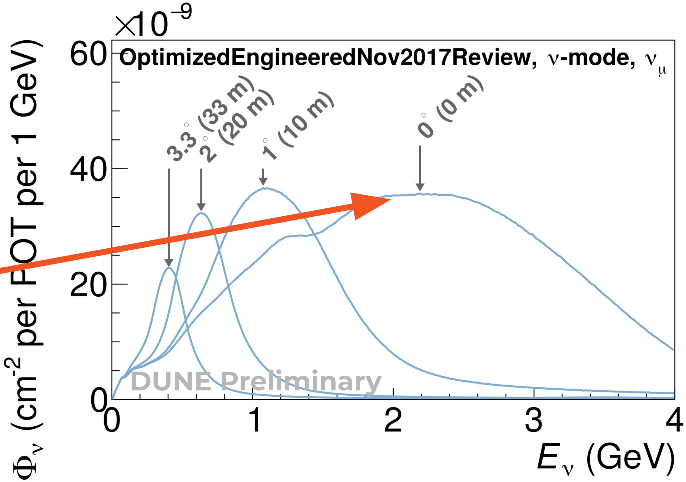

Off Axis at the Near Detector

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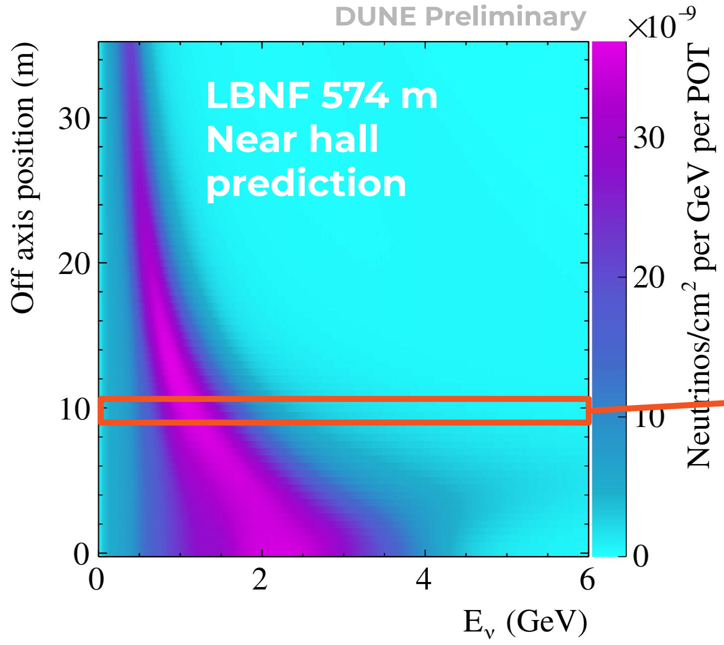
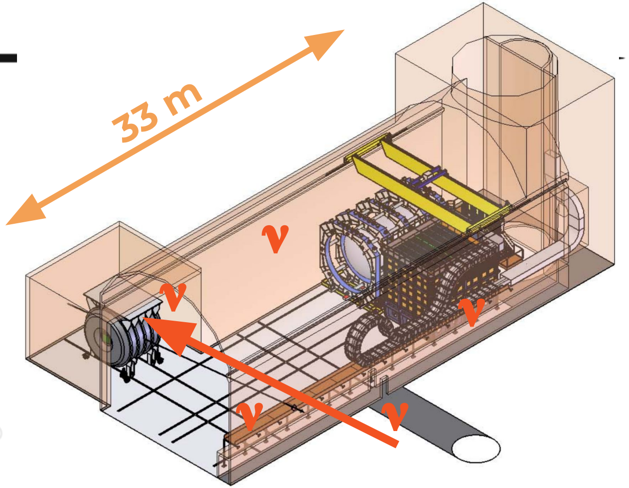
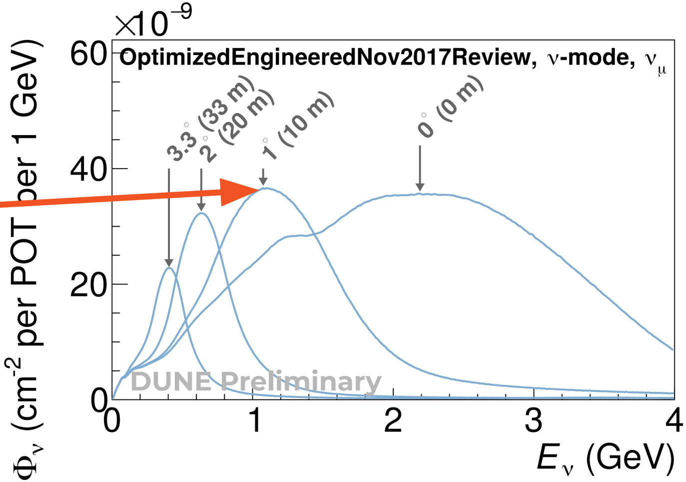
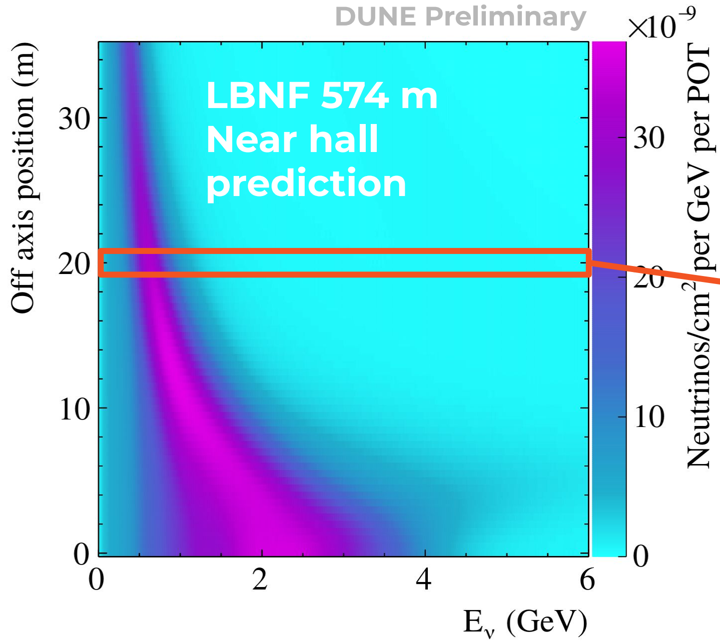


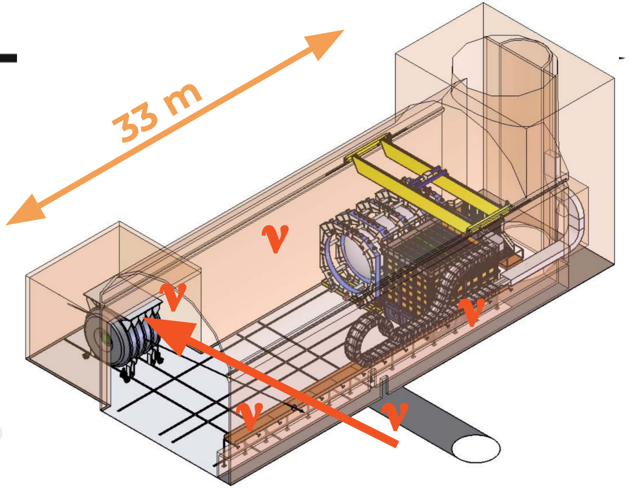


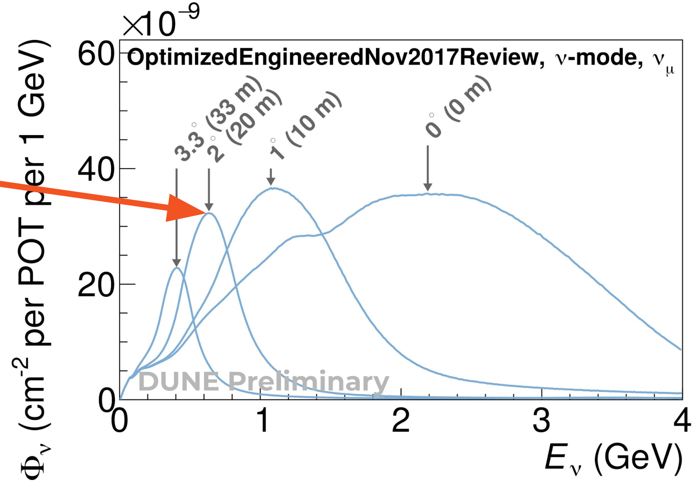


Off Axis at the Near Detector

- Sample different fluxes at different off axis positions.







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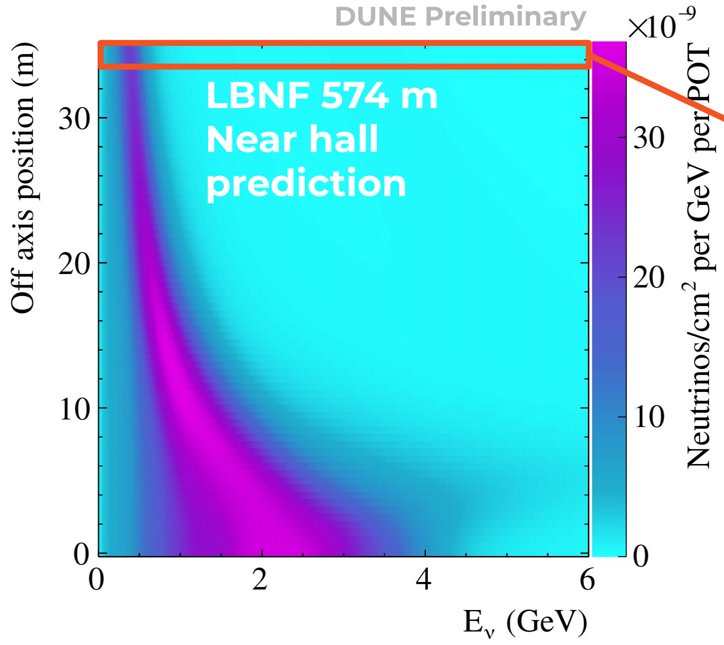
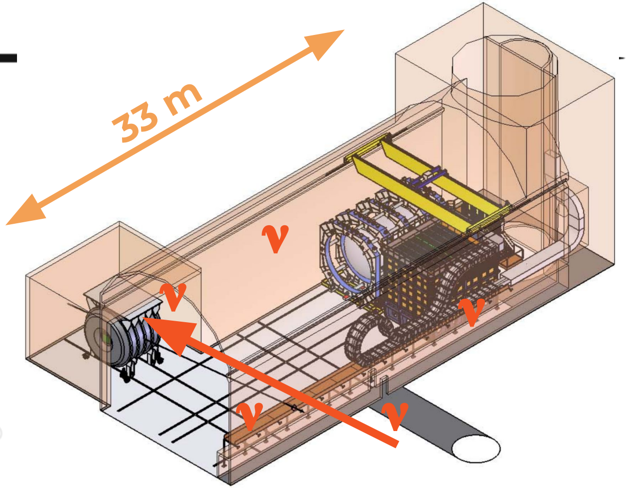
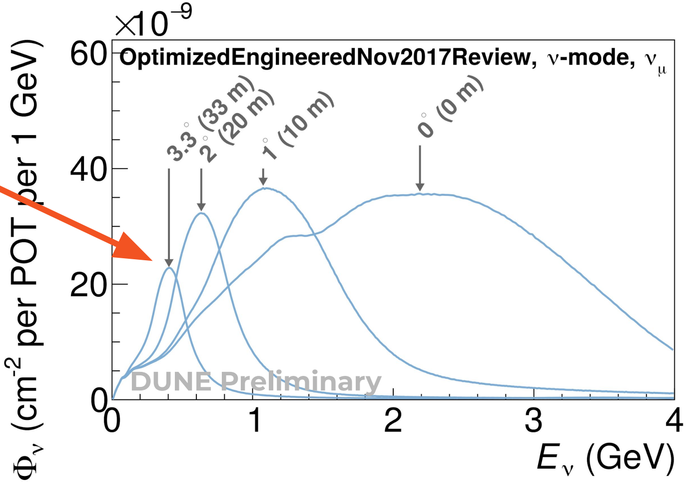
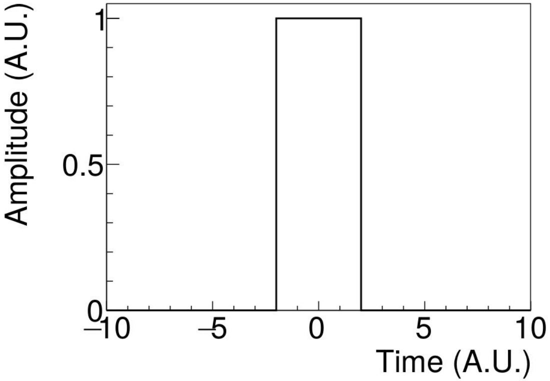

LBNF 574 m
Near hall
prediction





Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines



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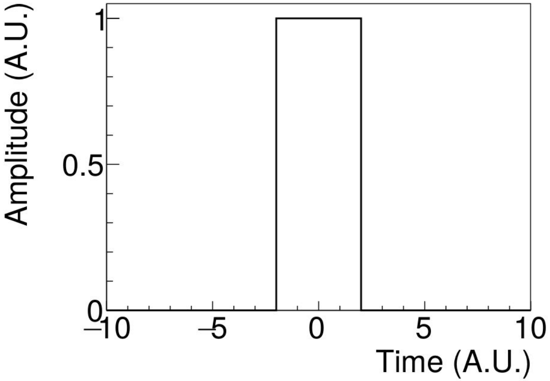

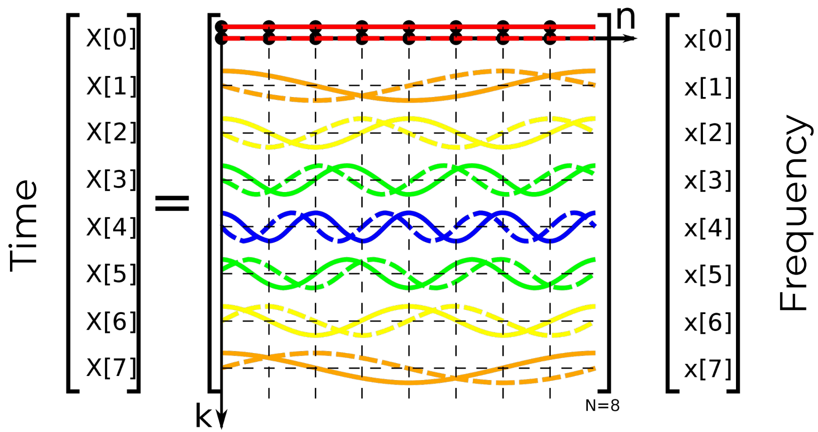

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Discrete Fourier Transforms

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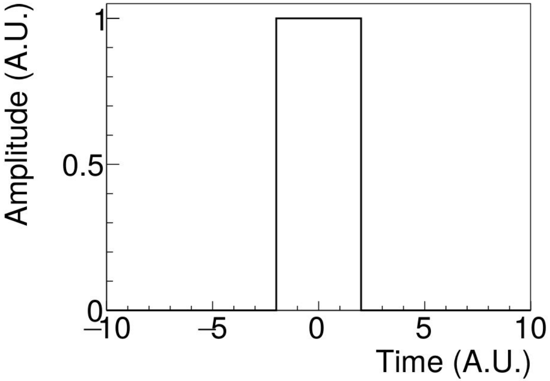

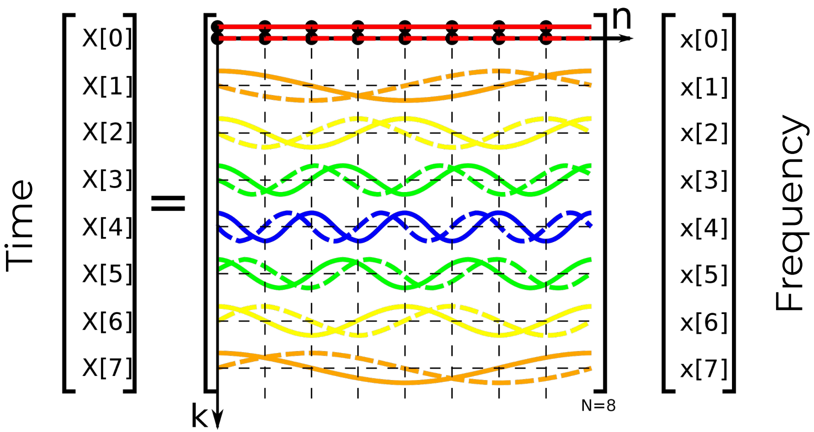

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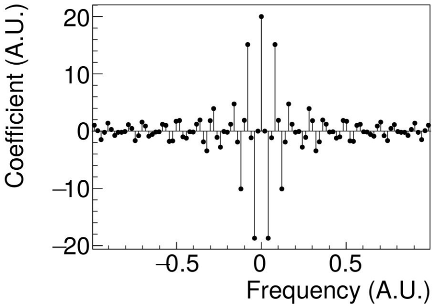

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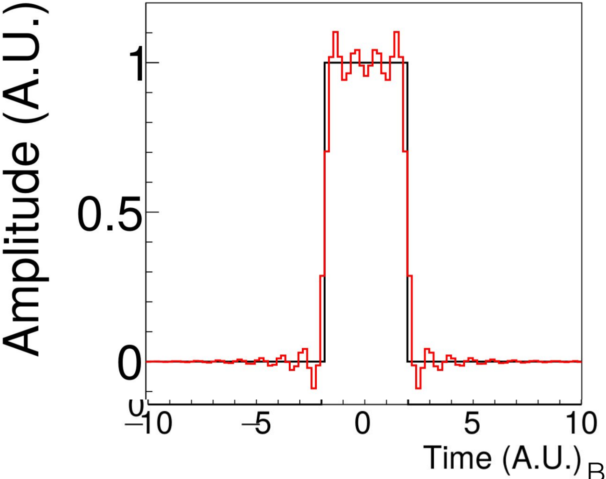

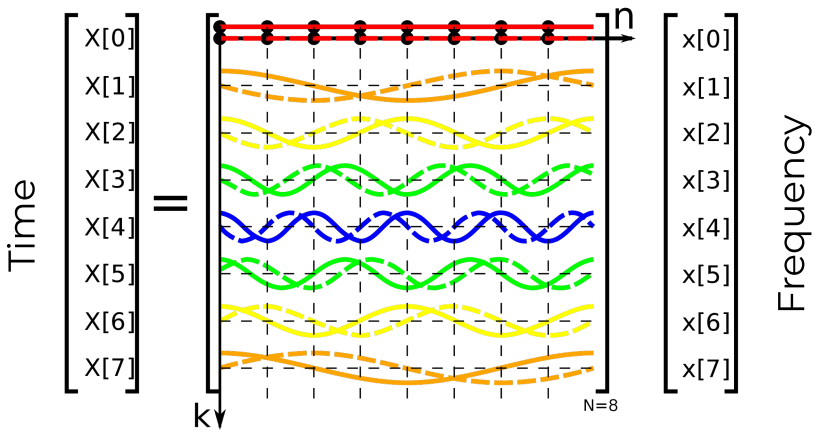

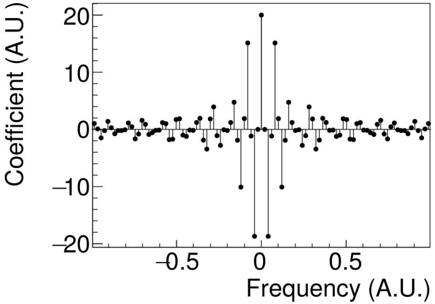

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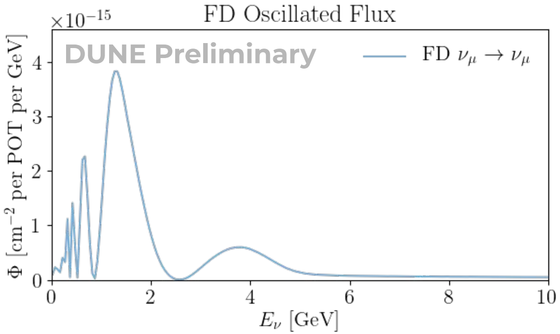
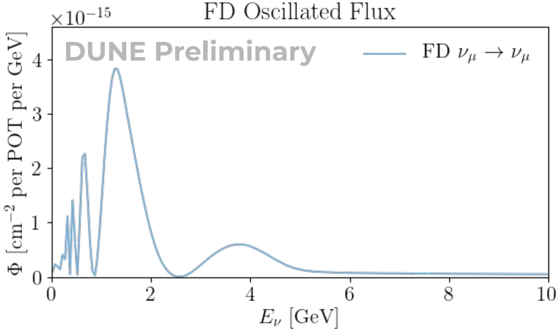
Matching the Far Detector Flux

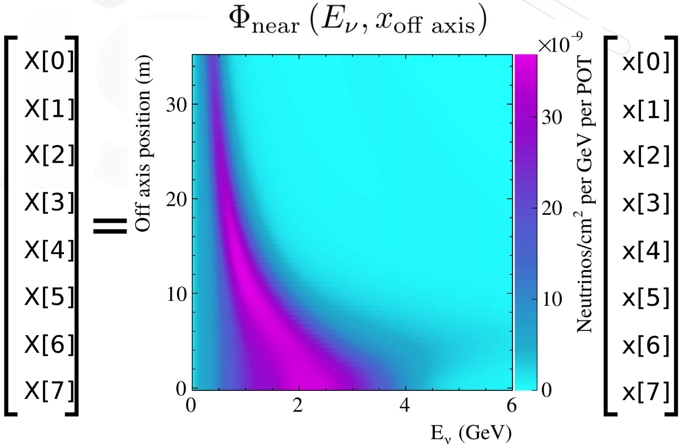
- Would like to approximate an oscillated far detector flux at the near detector



Matching the Far Detector Flux

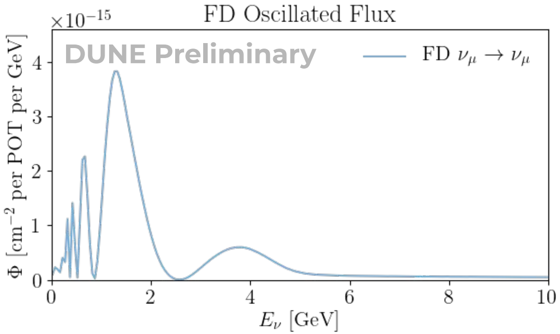
- Would like to approximate an oscillated far detector flux at the near detector: **Try a linear sum of off axis near detector fluxes!**

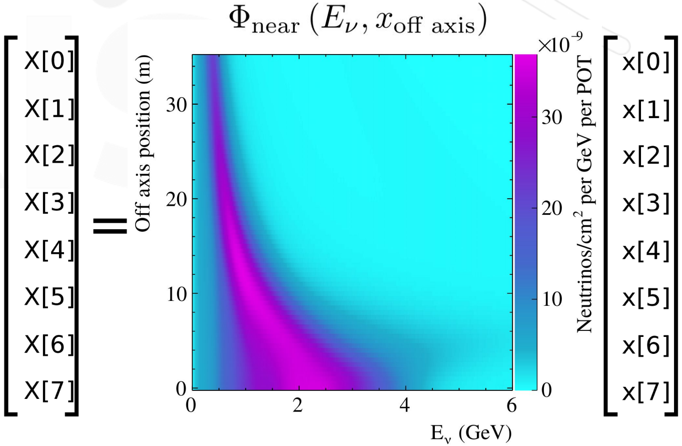


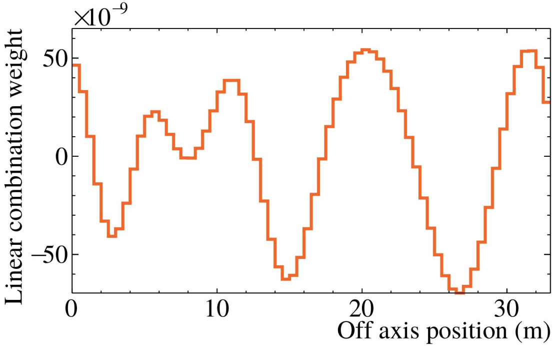


Matching the Far Detector Flux

- Would like to approximate an oscillated far detector flux at the near detector: **Try a linear sum of off axis near detector fluxes!**
    - Determine a linear combination of near detector off axis fluxes that reproduces the oscillated far detector flux.

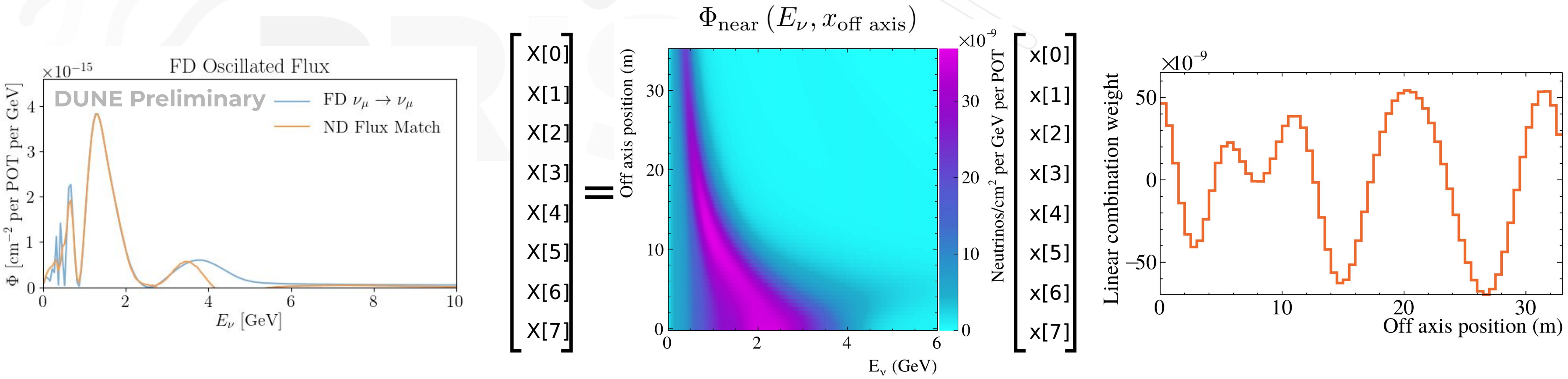






Matching the Far Detector Flux

- Use the 2D flux prediction at the near detector to approximate an oscillated far detector flux
  - Determine a linear combination of near detector off axis fluxes that reproduces the oscillated far detector flux.



How does that help?

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

$$N_{\text{near}}\left(E_{\text{obs}}\right) = \int dE_\nu\, \Phi_{\text{near}}\left(E_\nu\right) \cdot \sigma\left(E_\nu\right) \cdot \mathbf{D}_{\text{near}}$$

$$\Phi_{\text{near}}\left(E_\nu, x_{\text{off axis}}\right) \times \vec{c}$$

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

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- **Cross sections are not position dependent**

$$\Phi_{\text{near}}\left(E_\nu, x_{\text{off axis}}\right) \times \vec{c}$$

$$N_{\text{near}}\left(E_{\text{obs}}\right) = \int dE_\nu\, \Phi_{\text{near}}\left(E_\nu\right) \cdot \sigma\left(E_\nu\right) \cdot \mathbf{D}_{\text{near}}$$

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

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- **Cross sections are not position dependent**
- **When we pick the correct oscillation hypothesis:**
  - **Signal event rates are the same near and far!**

$$N_{\mathrm{near}}\left(E_{\mathrm{obs}}\right) = \int dE_{\nu}\, \Phi \left(E_{\nu}\right) \cdot \sigma\left(E_{\nu}\right) \cdot \mathbf{D}_{\mathrm{near}}$$

$$\Phi_{\mathrm{near}}\left(E_{\nu}, x_{\mathrm{off\ axis}}\right) \times \vec{c}$$

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

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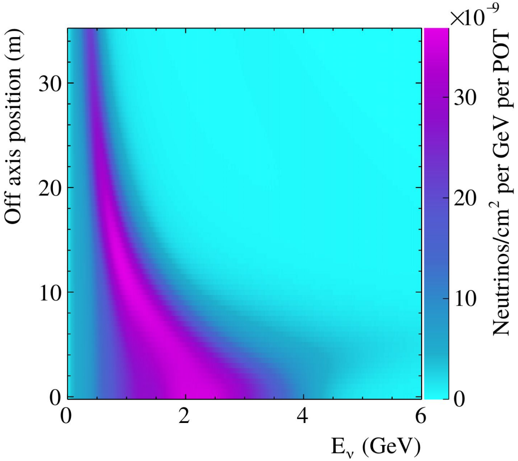
- Cross sections are not position dependent

The novel DUNE-PRISM Technique: Make near detector measurements in oscillated far detector fluxes!

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

Building a far detector prediction

- Have so far been matching fluxes



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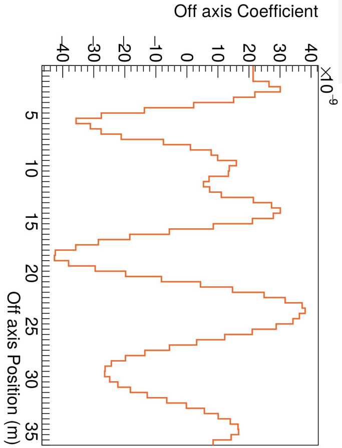

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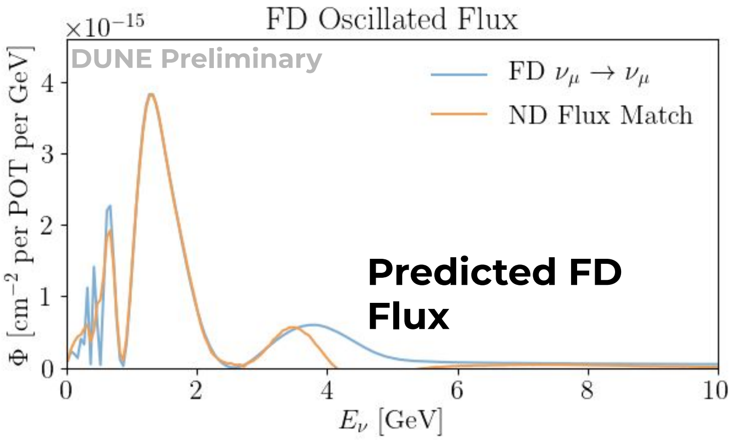
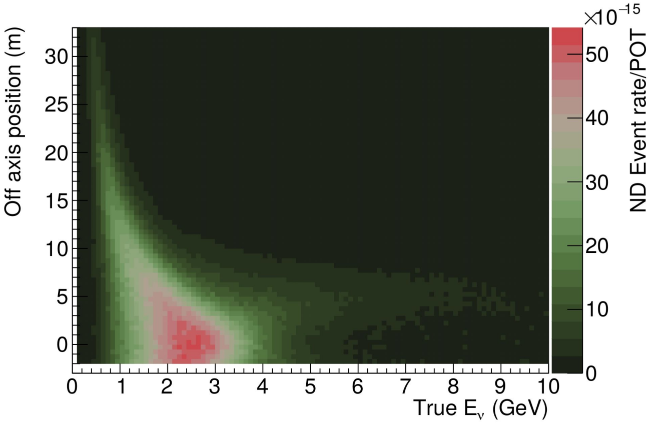


Predicted FD Flux

Building a far detector prediction

- Have so far been matching fluxes:
  - PRISM flux matching only depends on the off axis position of an interaction
  - Can use the same linear combination coefficients for **event rate.**

Number of events = **Flux** · **Cross section**



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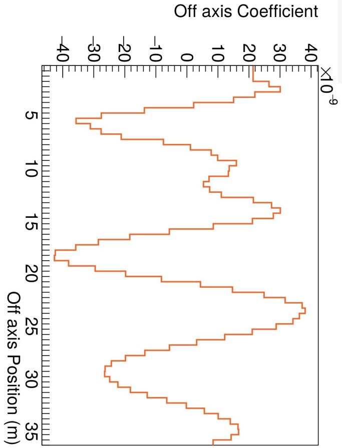

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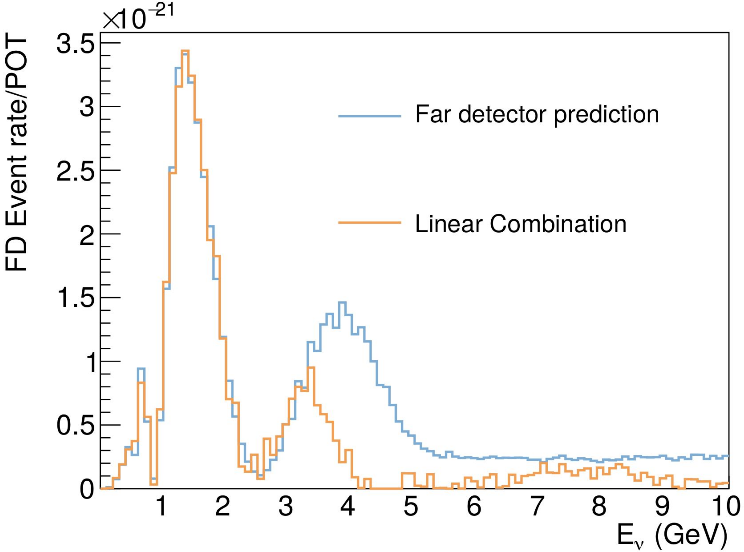
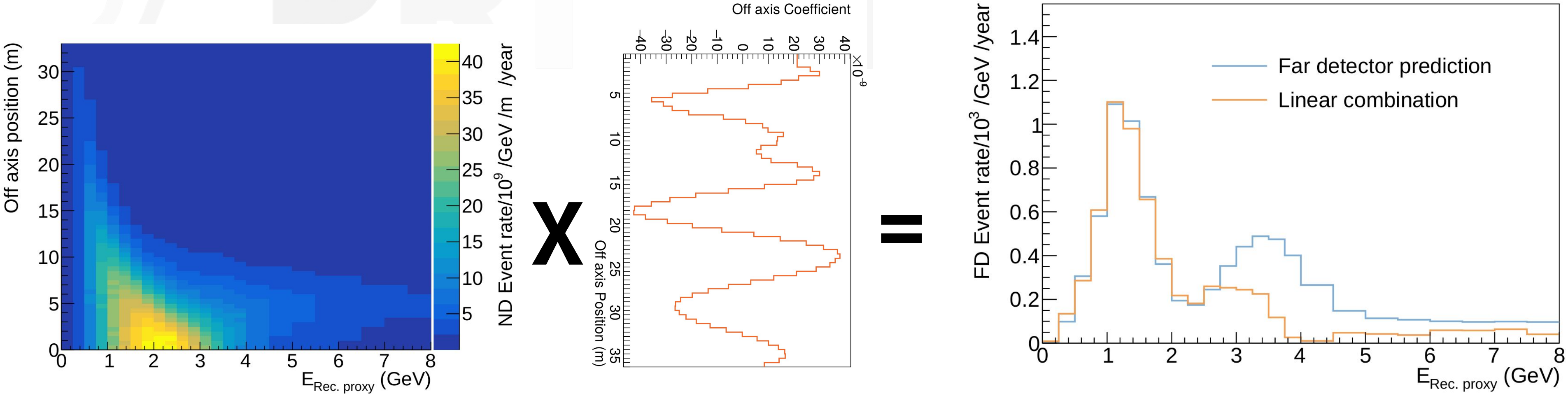


Building a far detector prediction

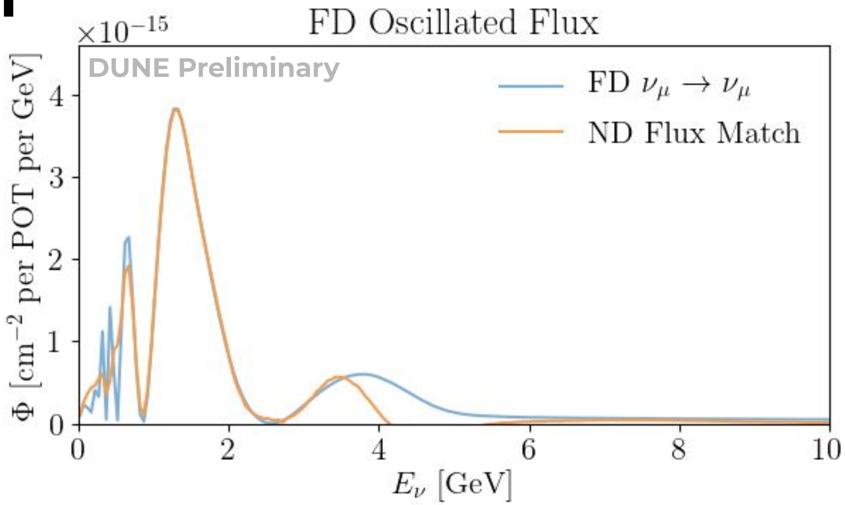
- Have so far been matching fluxes:
  - PRISM flux matching only depends on the off axis position of an interaction
  - Can use the same linear combination coefficients for event rate.
  - Can predict the event rate in any **near detector observable**

Number of observed events = **Flux** · **Cross section** · **Detector effects**



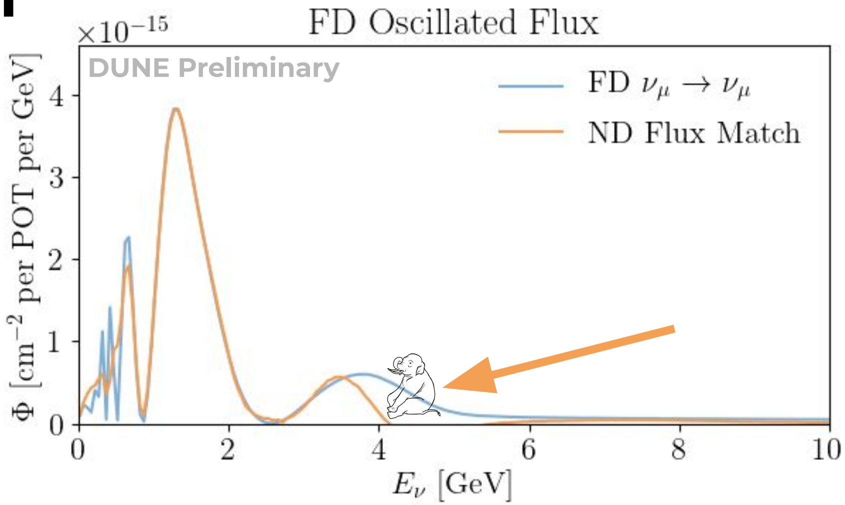
Flux Mismatch Correction

- Elephant in the room



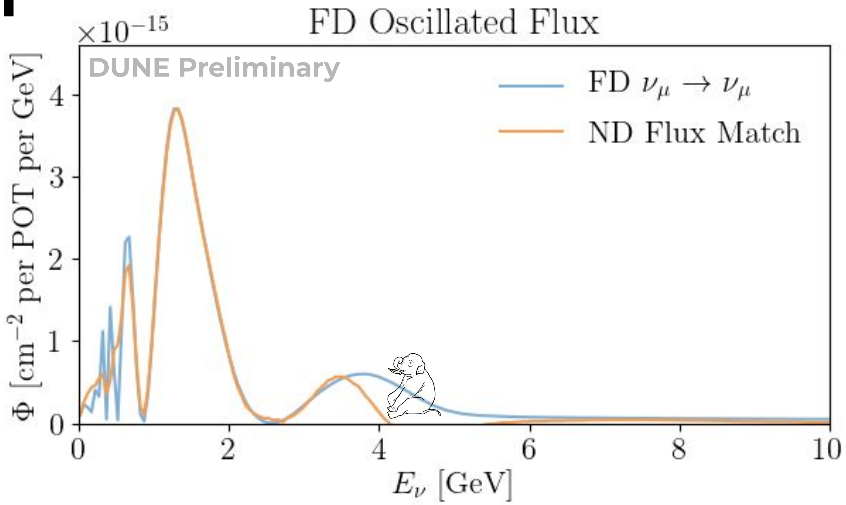
Flux Mismatch Correction

- **Elephant in the room**



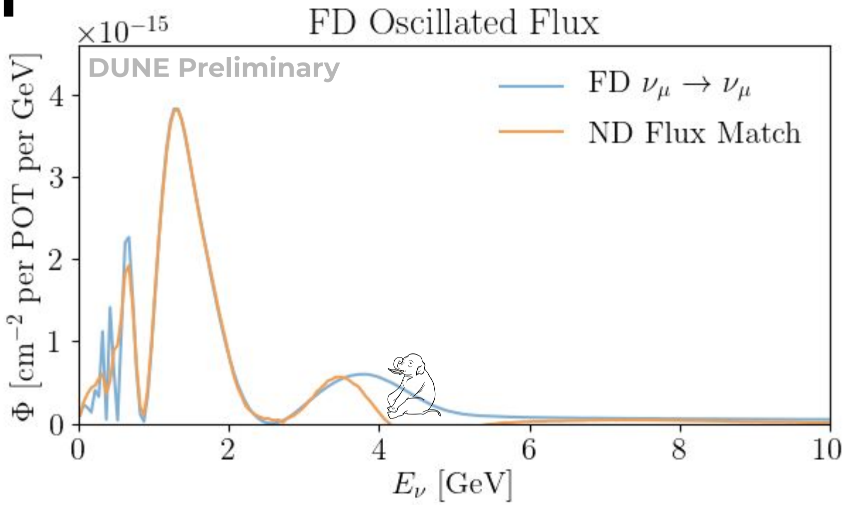
Flux Mismatch Correction

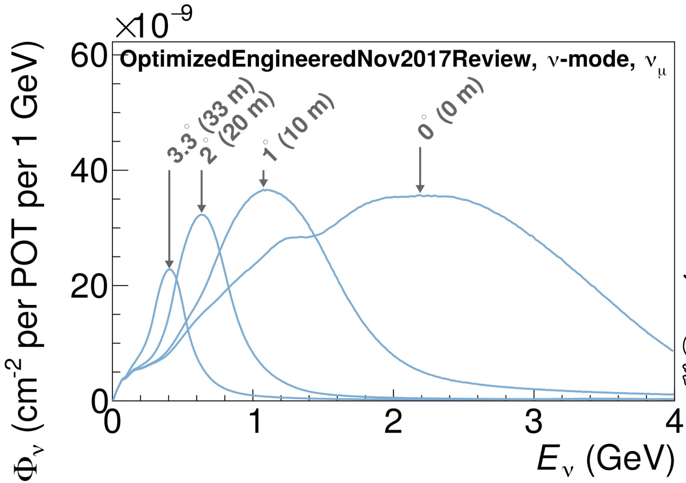
- Have to correct for this mismatch by using far detector simulation:
  - Want to minimize model assumptions wherever possible…



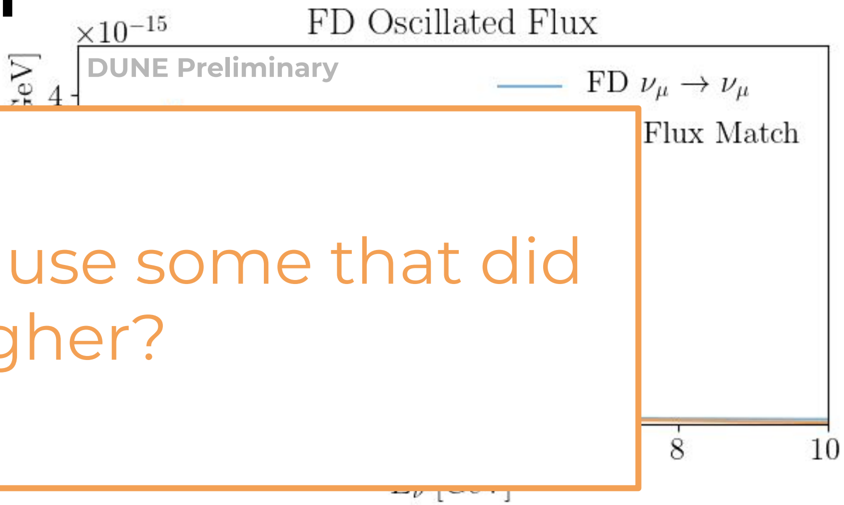
Flux Mismatch Correction

- 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 c
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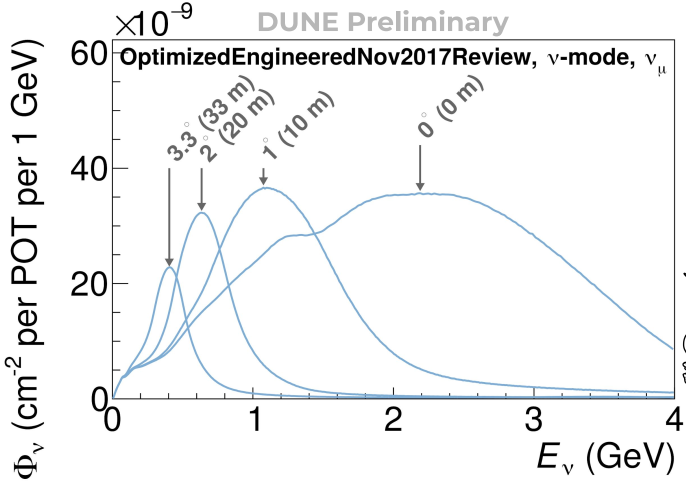
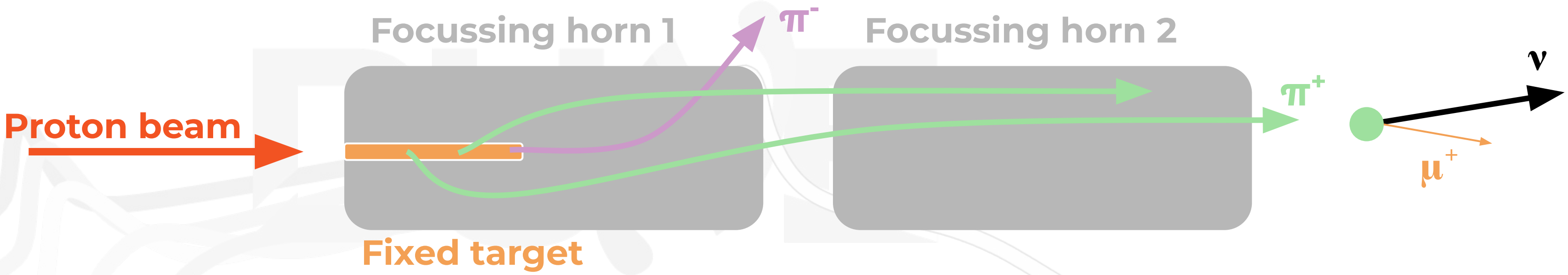
  - Want t
    where
- This happ
  fluxes pe

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

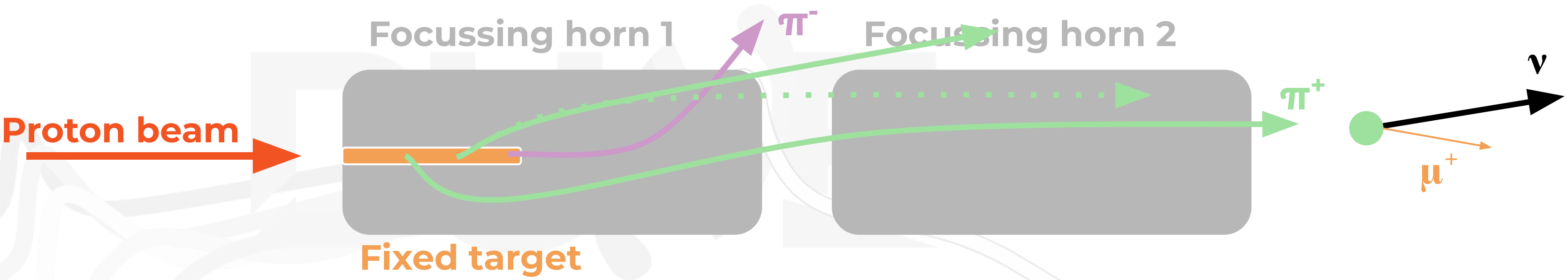


Special Horn Current Runs



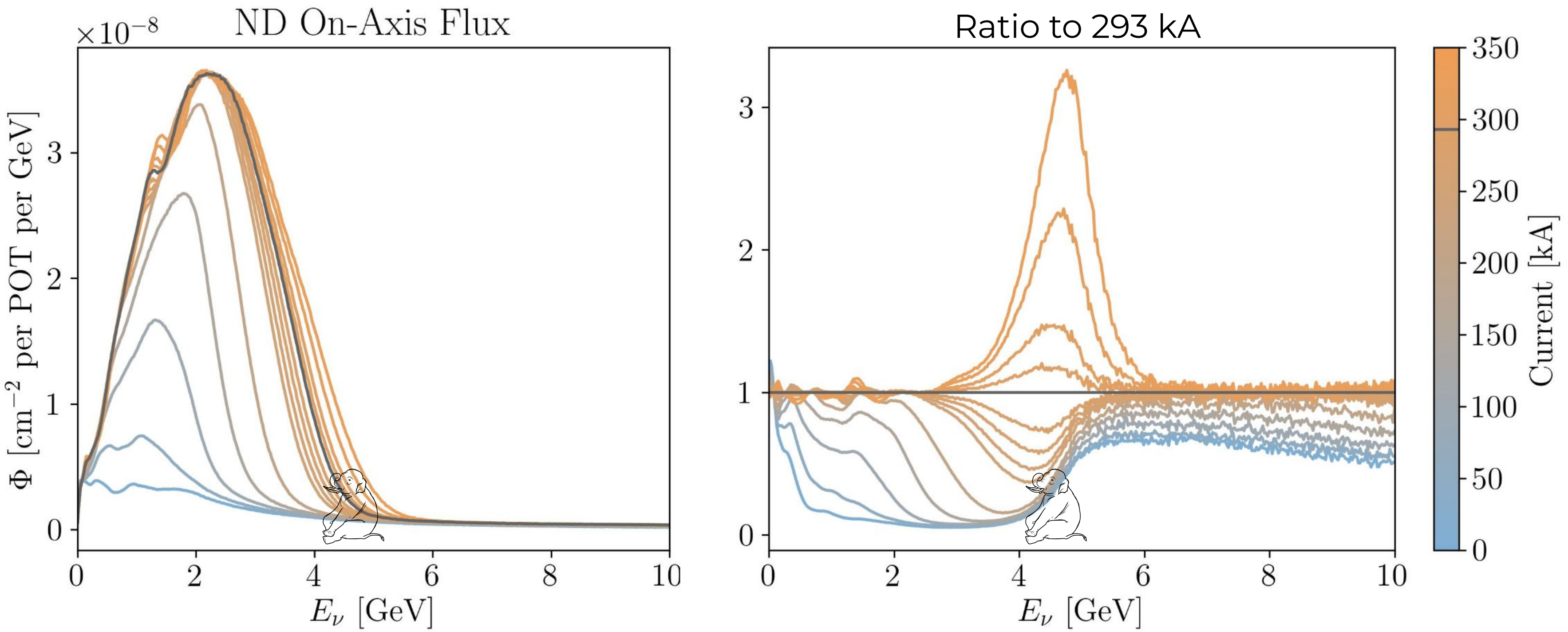
- If we vary the current in the magnetic horns, we change their momentum acceptance

Special Horn Current Runs



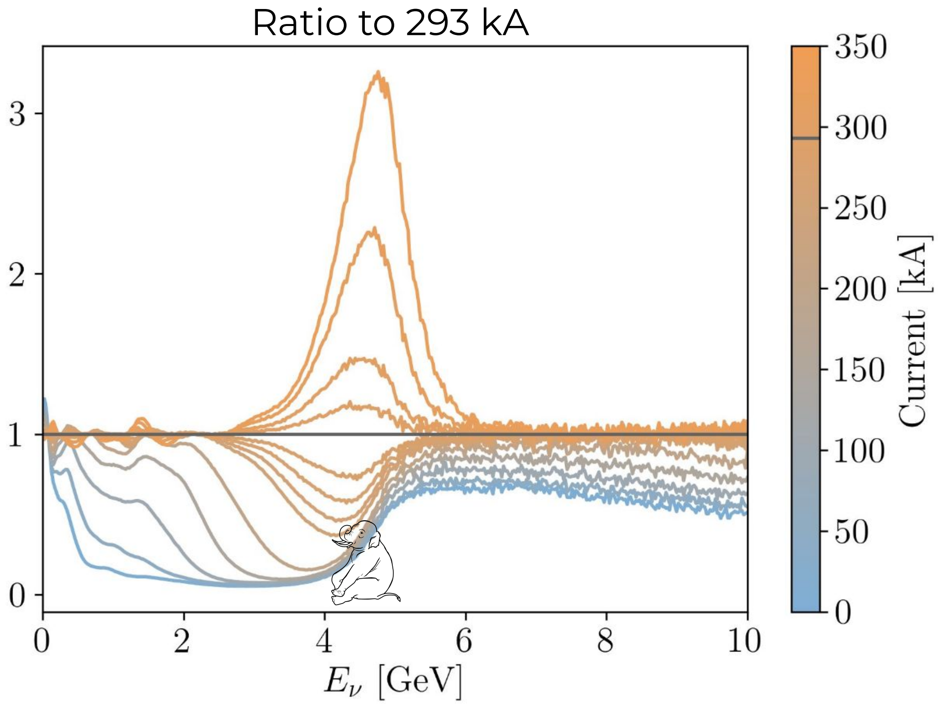
- If we vary the current in the magnetic horns, we change their momentum acceptance:
  - For a lower current, some higher energy pions might not be well focussed…

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:
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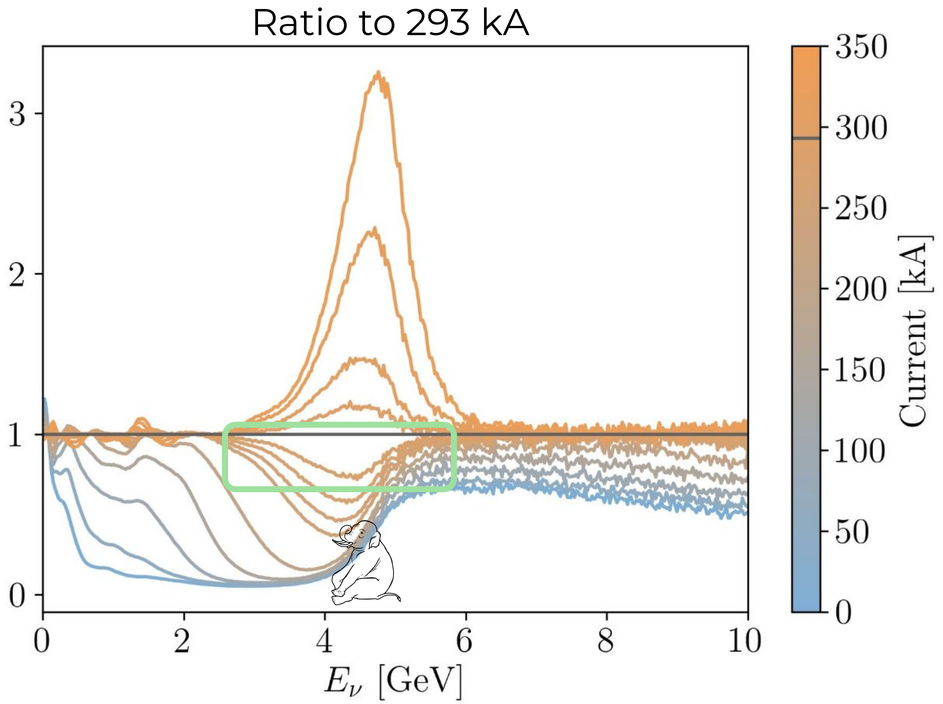
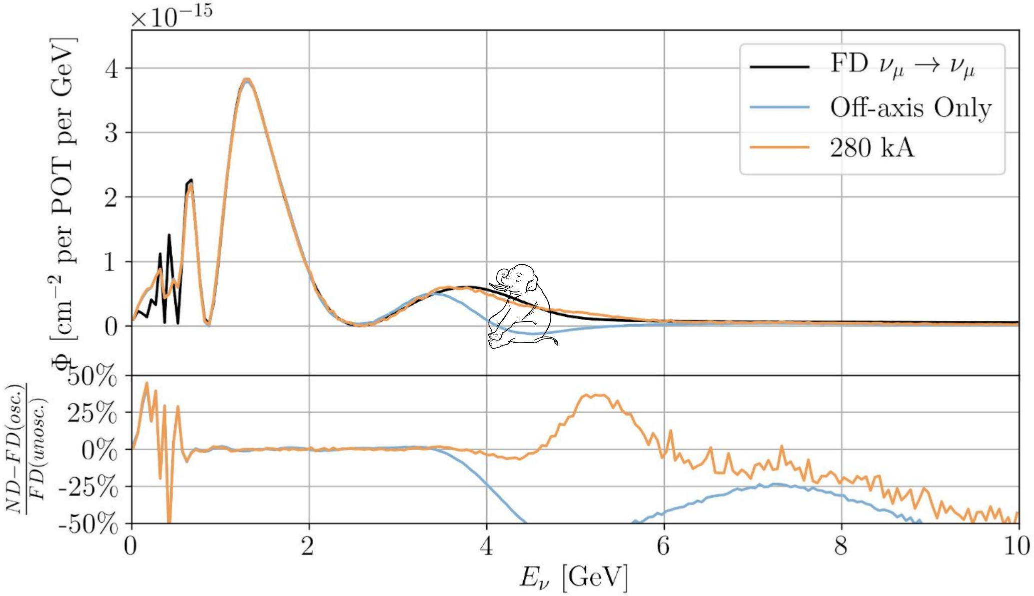
- Lower currents are better:
  - Current horn and power supply designed with 293 kA as the operating current.
- **280 kA looks useful**



Special Horn Current Runs

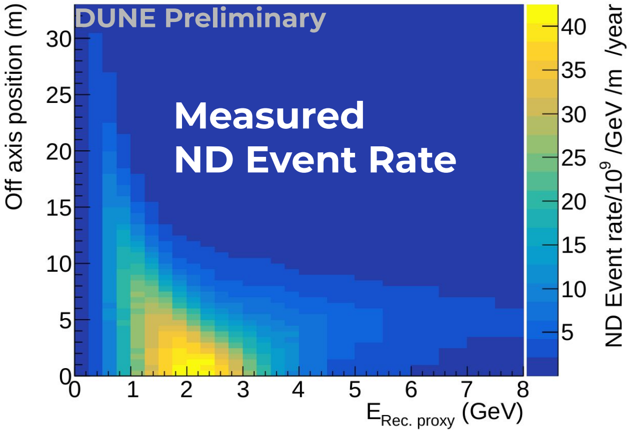
- Including an on-axis run at 280 kA drastically improves the flux matching!
    - Much less far detector model correction required.



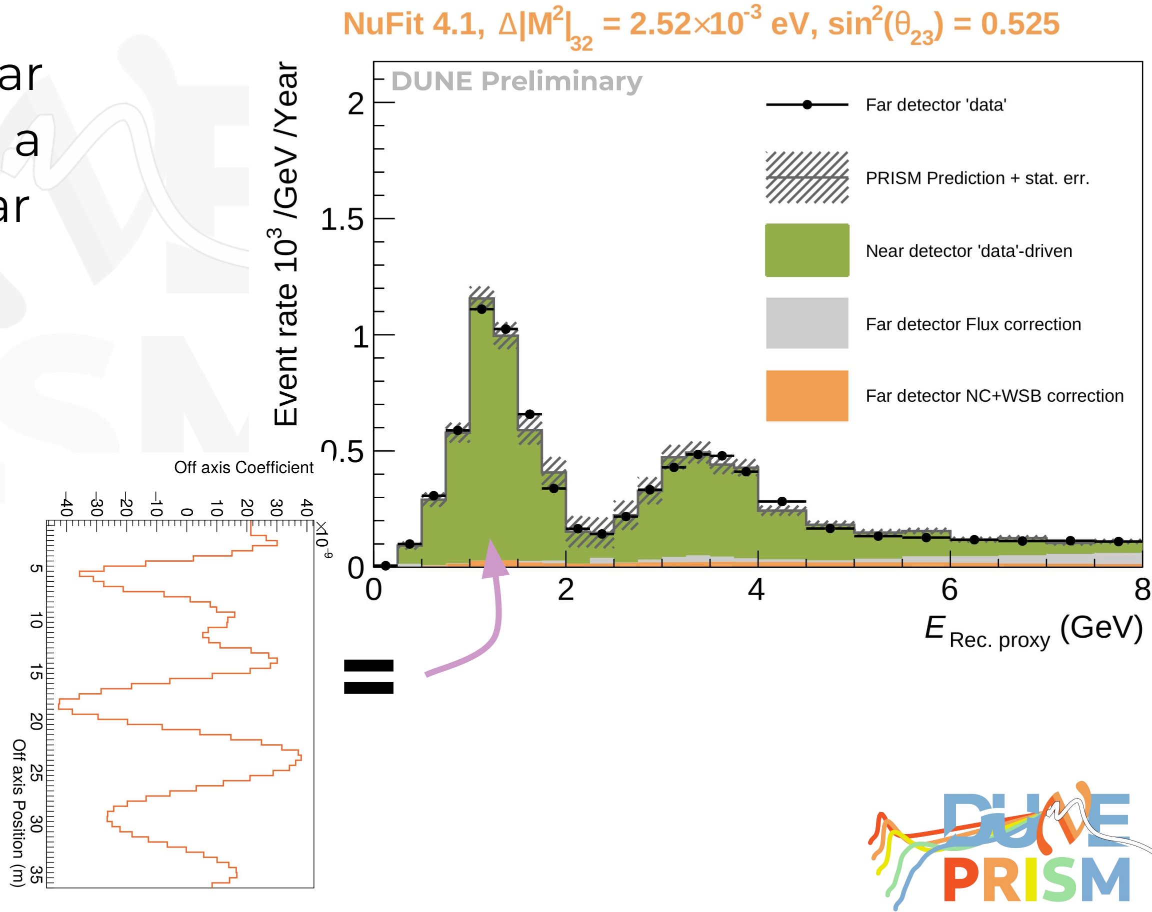
PRISMing it all together...

The PRISM prediction

- Now we can predict the far detector event rate using a linear combination of near detector observables!

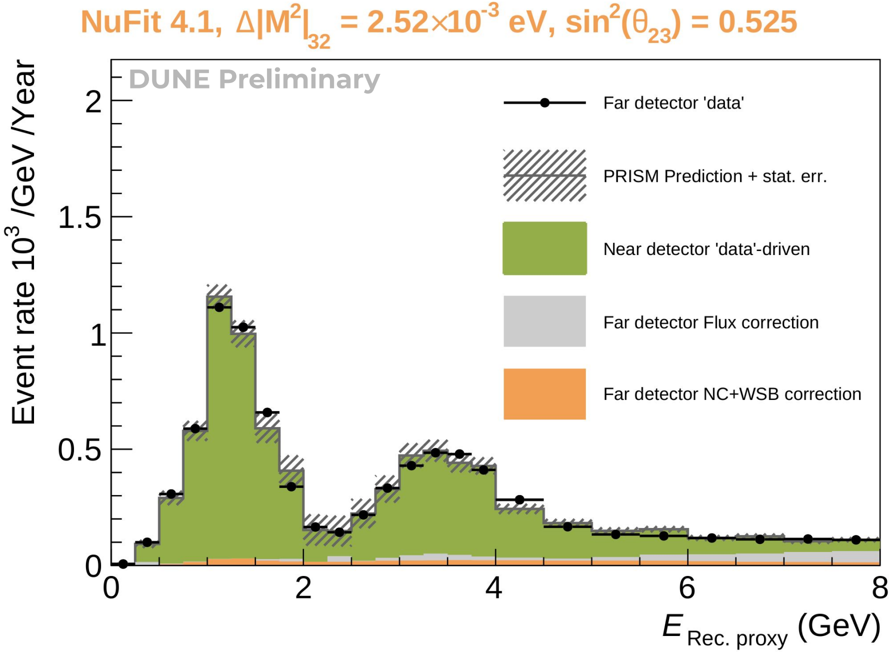


X



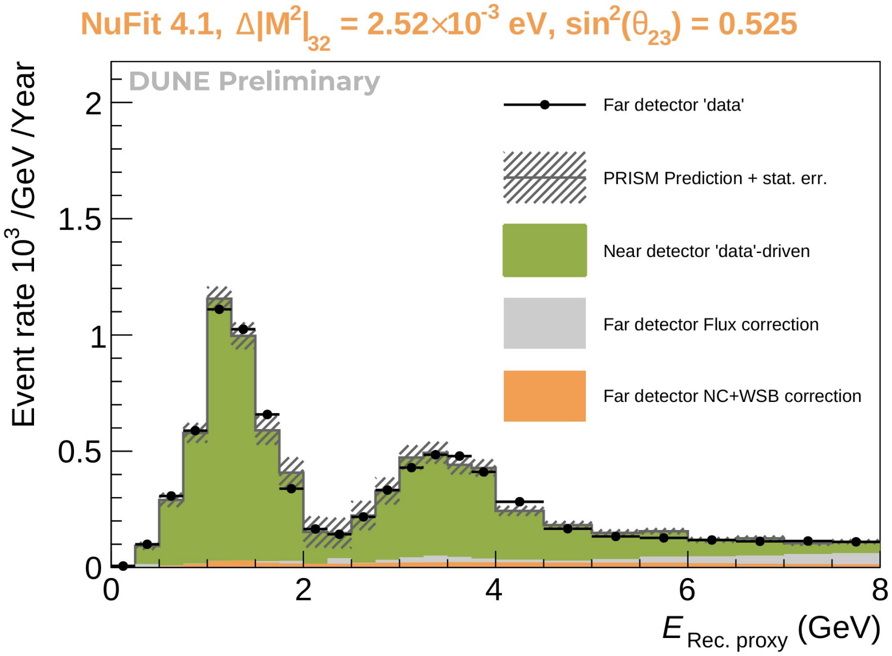
The PRISM prediction

- As the majority of the prediction is rearranged near detector data:
    - PRISM transfers near detector 'constraint' even if the near detector sample is mis-modelled.



The PRISM prediction

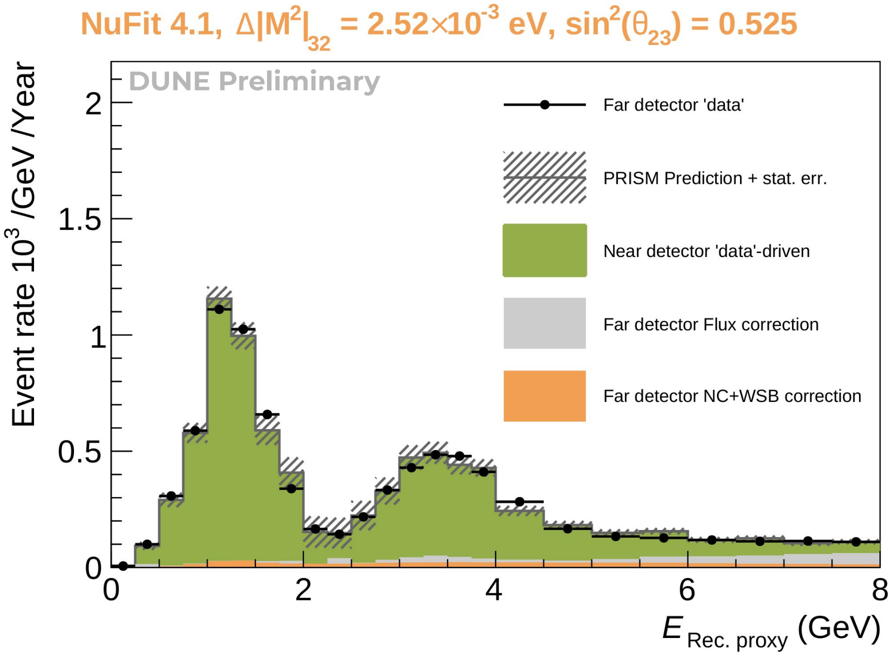
- As the majority of the prediction is rearranged near detector data:
    - PRISM transfers near detector 'constraint' even if the near detector sample is mis-modelled.
- **In a traditional analysis, the whole spectrum would be 'correction'.**



The PRISM prediction

- As the majority of the

PRISM Oscillation Analysis: Rearranges near detector data to predict far detector observables with minimal dependence on interaction models.



A Test Case

A 'mock' data Study

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

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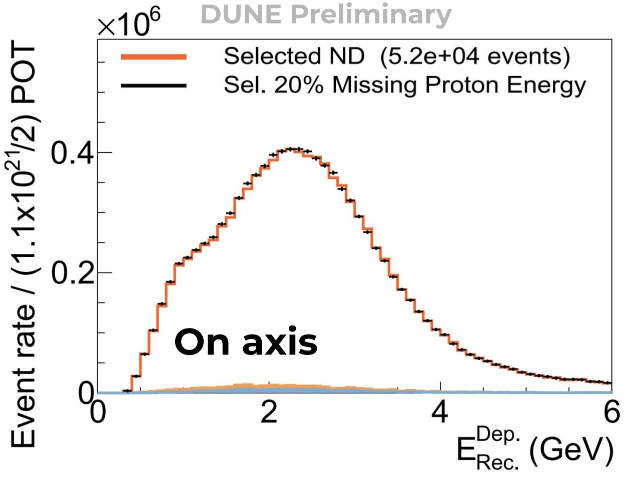
    - Move 20% of proton KE to neutrons but on-axis ND fit still works well



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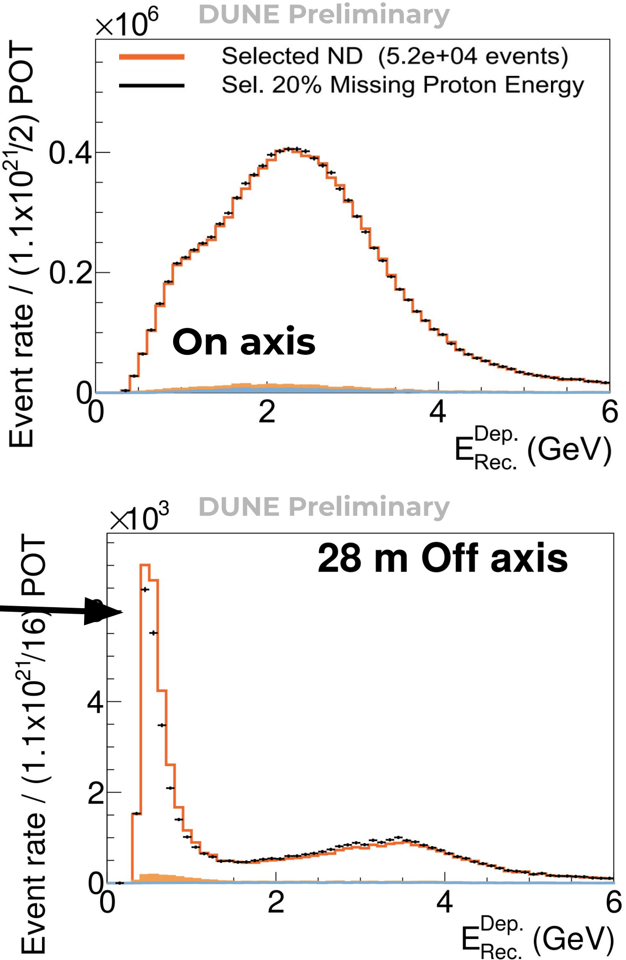

A 'mock' data Study

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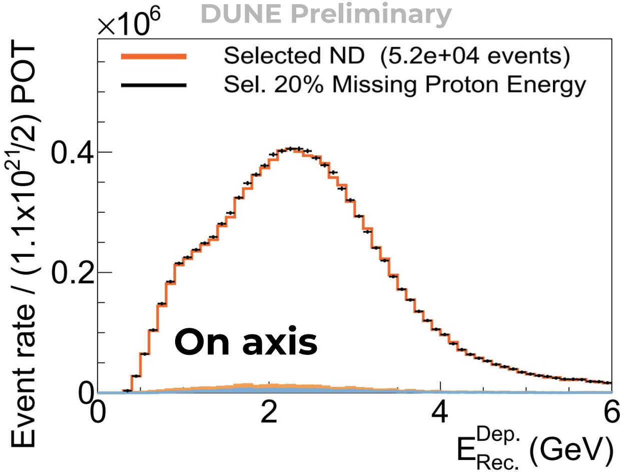
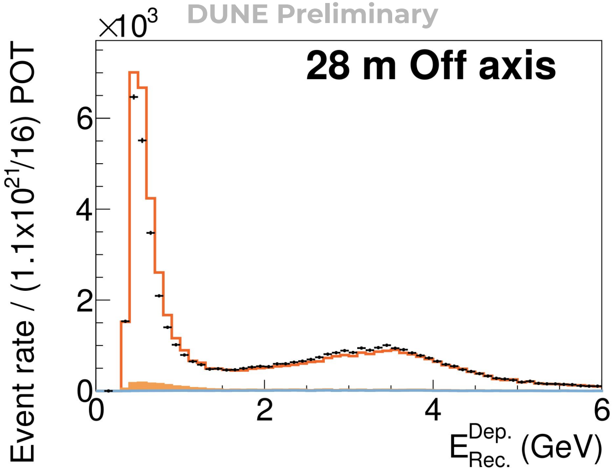
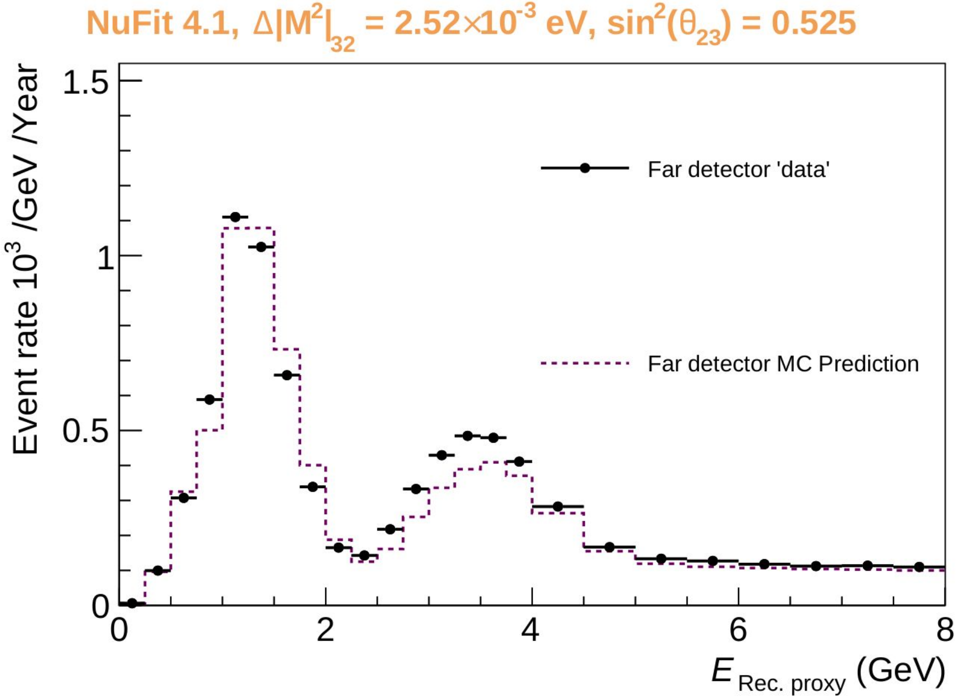
- Can imagine a world where the model predicts the near detector data well, but $E^{\nu}_{\text{True}} \Rightarrow E^{\nu}_{\text{Obs}}$ is wrong.
- Case Study:
    - Move 20% of proton KE to neutrons but on-axis ND fit still works well
    - Clearly visible off axis
    - But not obvious how to handle it in a traditional analysis...





Mock Data Spectrum

- If we had trusted the on axis near detector constraint:
    - We would make a poor prediction of the data, even with the correct oscillation hypothesis.



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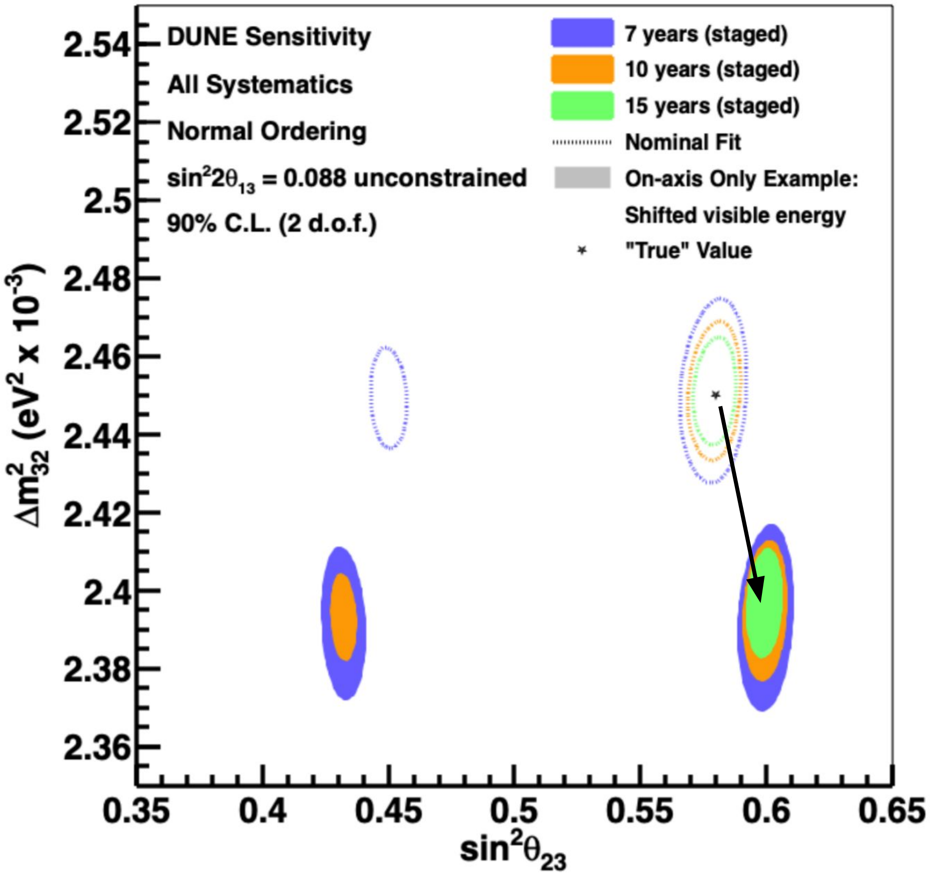

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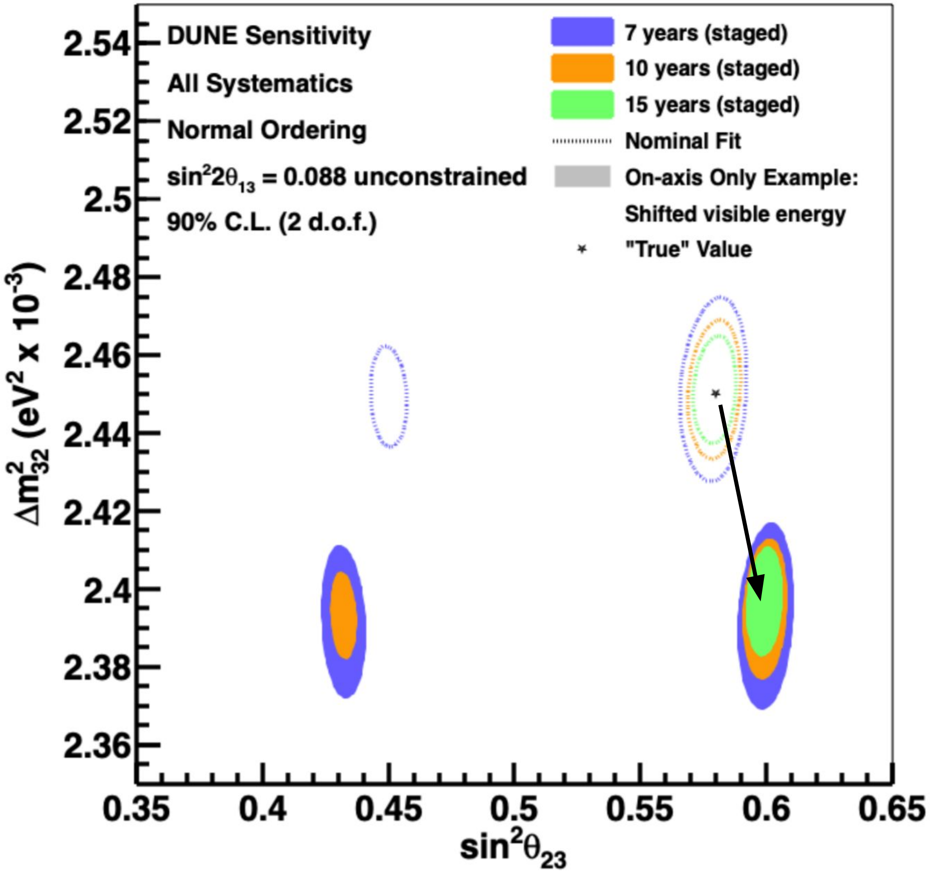
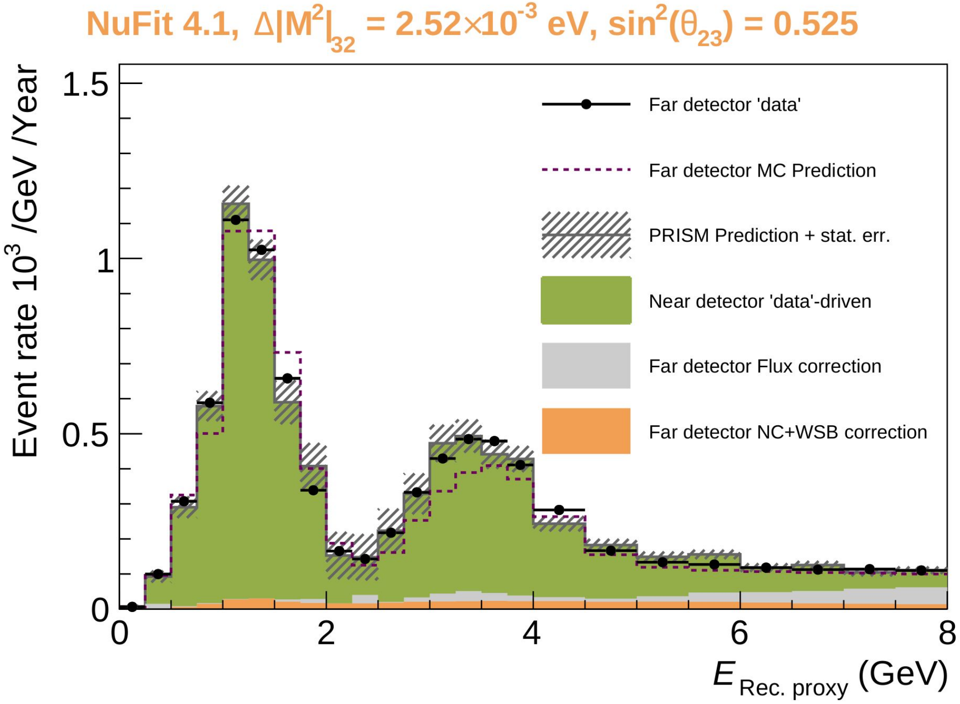
- What about if we ask PRISM?



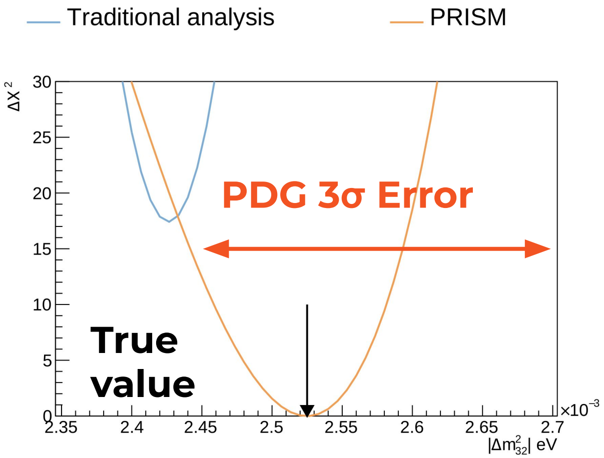
PRISM Prediction

- If we had trusted the on axis near detector constraint:
    - We would make a poor prediction of the data, even with the correct oscillation hypothesis.
    - Would have extracted biased results, well outside quoted error estimates.
- What about if we ask PRISM?
    - **The direct extrapolation of near detector data largely side-steps the modelling problem!**



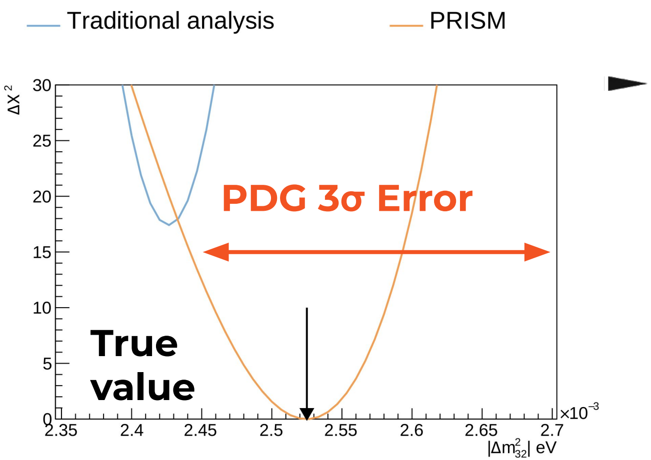
PRISM Prediction

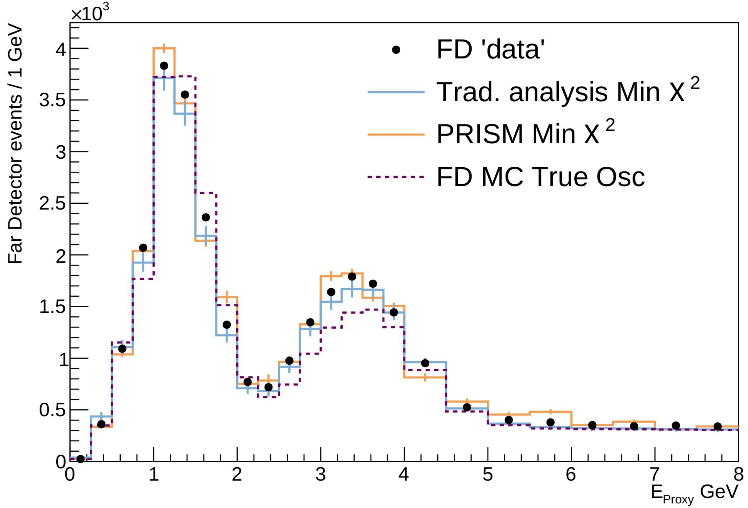
- What might have been the best fit?
  - In this case, the traditional analysis would be badly biased.



PRISM Prediction

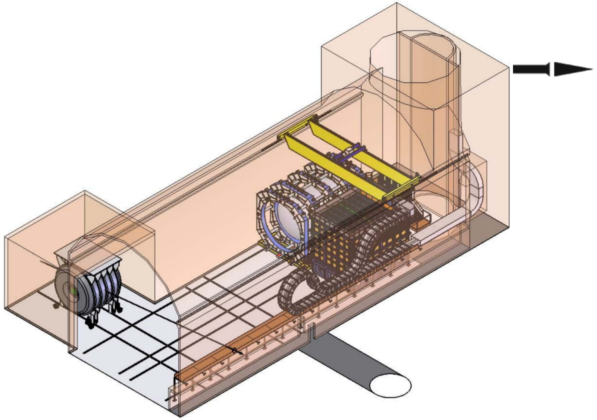
- What might have been the best fit?
    - In this case, the traditional analysis would be badly biased.
- Oscillation parameters were varied to make up for a mismodelling.
- For this study, PRISM showed no such bias.

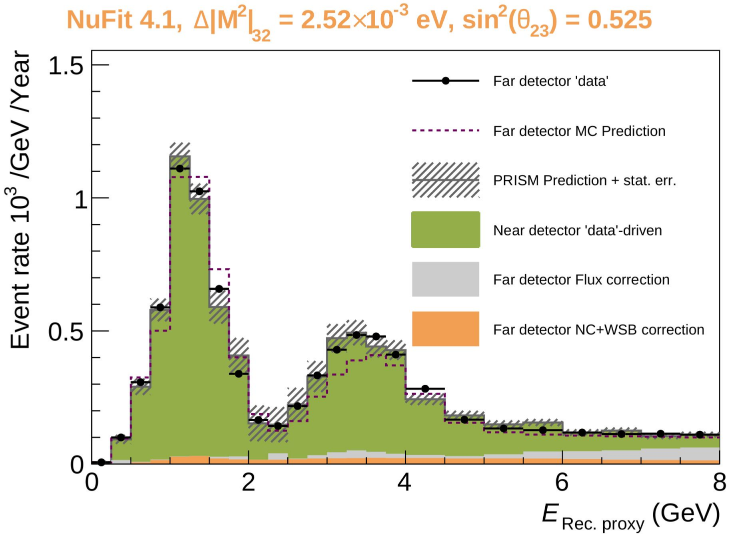




DUNE-PRISM Summary

- PRISM is now part of the DUNE reference design.
- A mobile near detector renders mis-modelling much easier to identify
- The novel PRISM analysis uses an extra degree of freedom and uses it to build a robust oscillation analysis, largely free of interaction model dependence

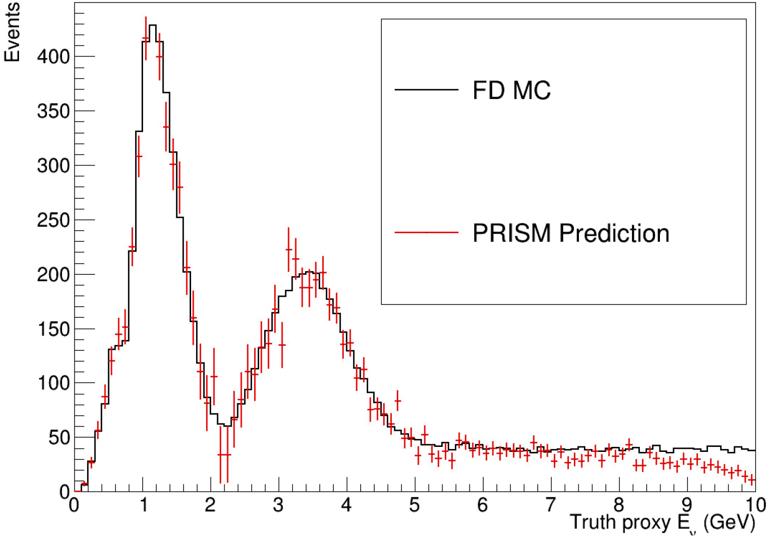


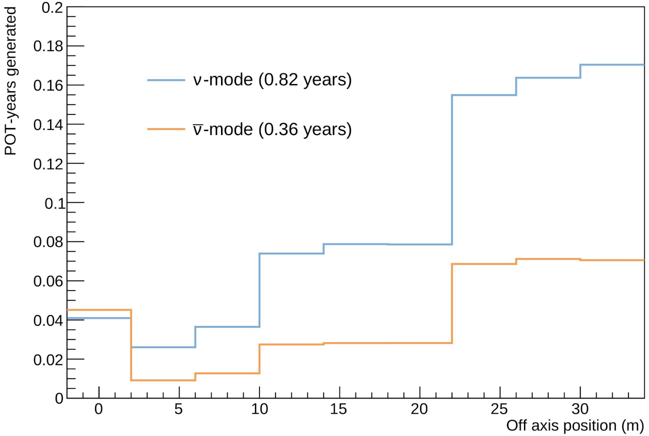


Thanks for listening

The Old Plan

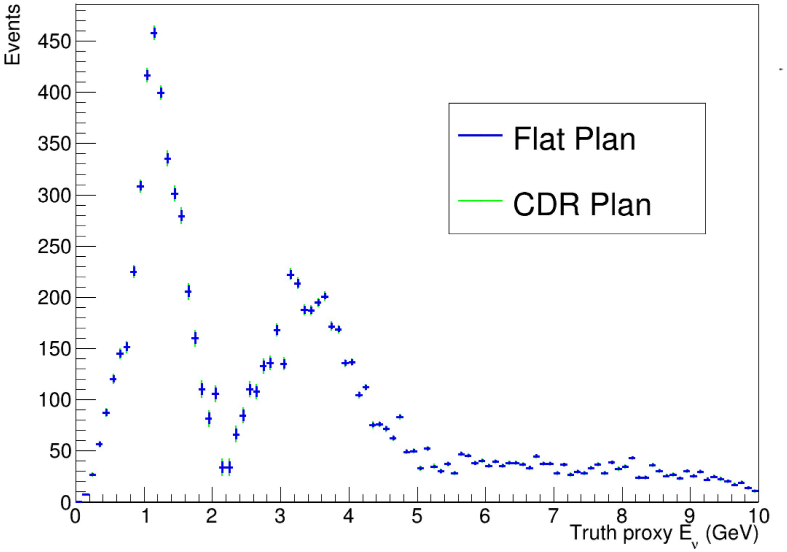
- Firstly, the 'true' MC stats error:
    - I.e. what I have been showing as the 'error' on the PRISM FD prediction.
- Comes from the actual simulated MC exposure.
    - Equivalent to 0.82 years with a (now known to be) sub-optimal exposure plan.

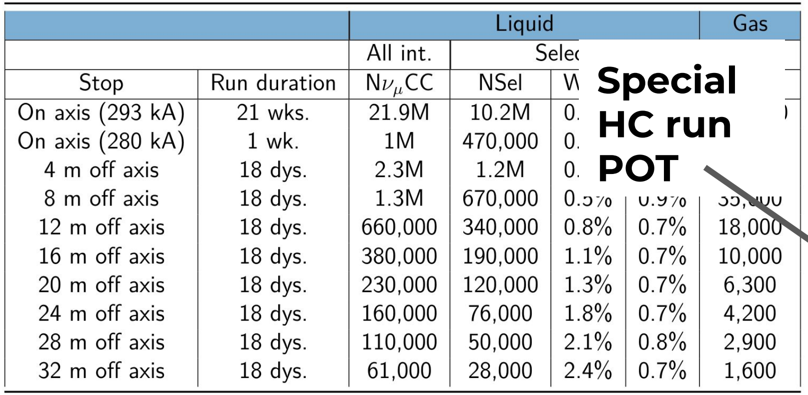




The Best Plan?

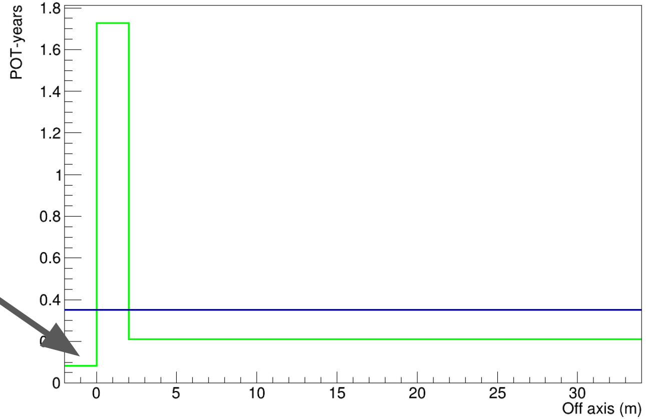
- Now, set ND errors to be sqrt(predicted rate).
- CDR run plan, with 3.5 years POT
- Very hard to see, but the CDR plan predicts slightly worse errors than a flat plan.
    - Haven't looked in to why, but now have the tools!





		Liquid				Gas
		All int.	Sele			
Stop	Run duration	Nν_μCC	NSel	W		
On axis (293 kA)	21 wks.	21.9M	10.2M	0.		)
On axis (280 kA)	1 wk.	1M	470,000	0.		
4 m off axis	18 dys.	2.3M	1.2M	0.		
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

Special HC run POT

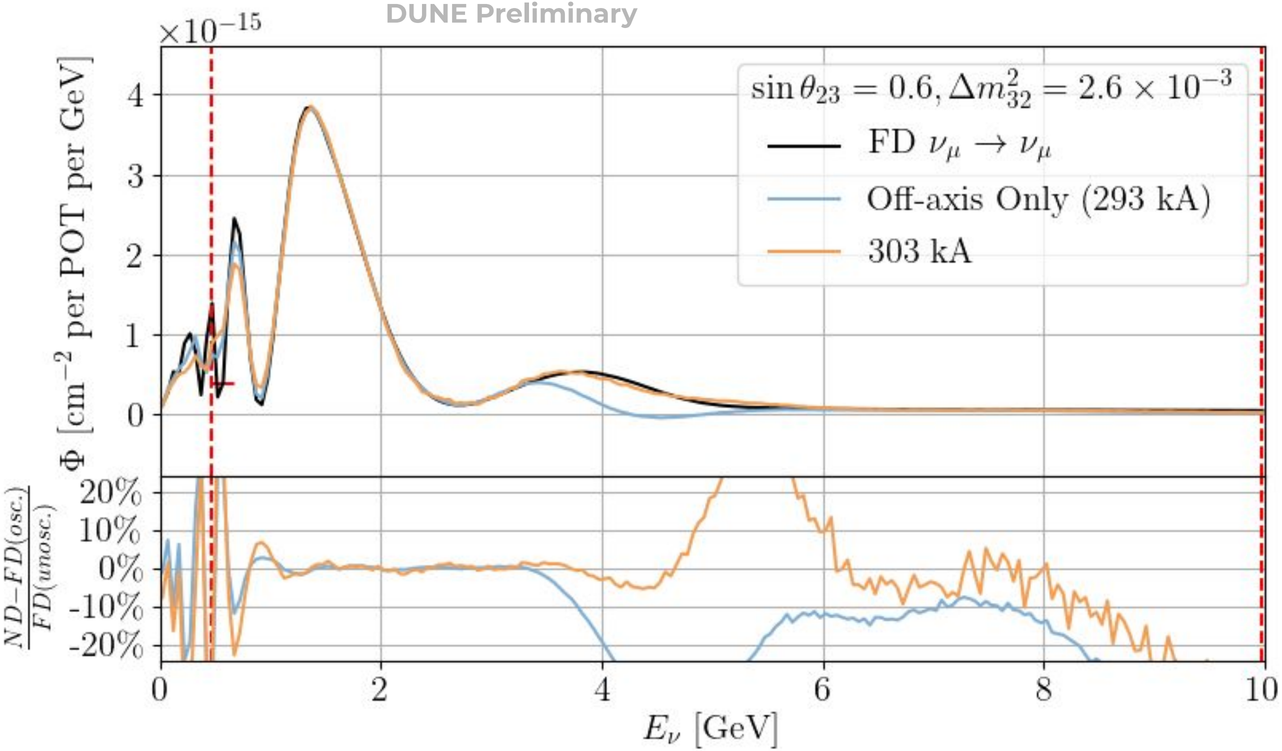


Pre-emptive Answers to Questions

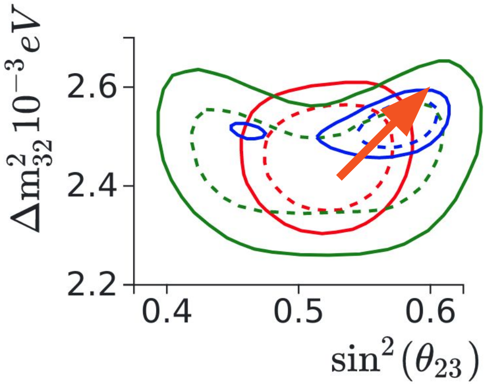
Does it work everywhere?

Try it yourself!

DUNE Preliminary



NuFit 4.0
T2K2018
NOvA2018



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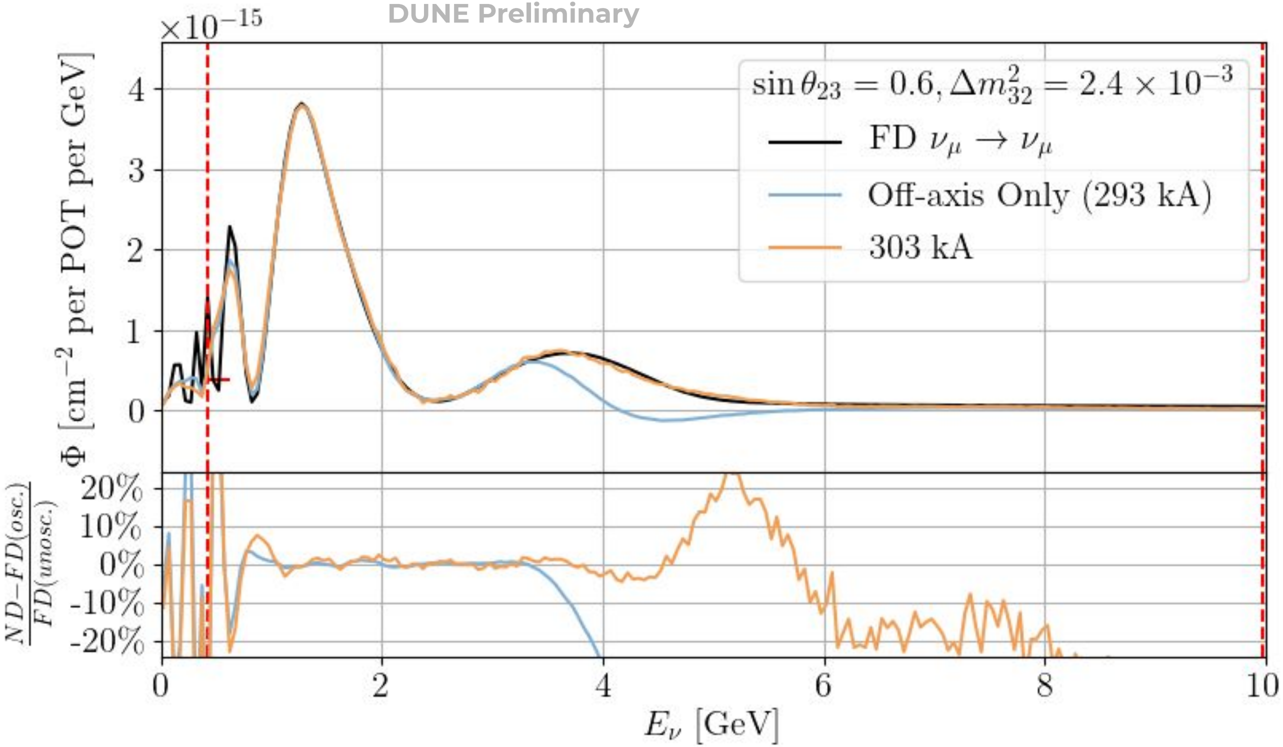

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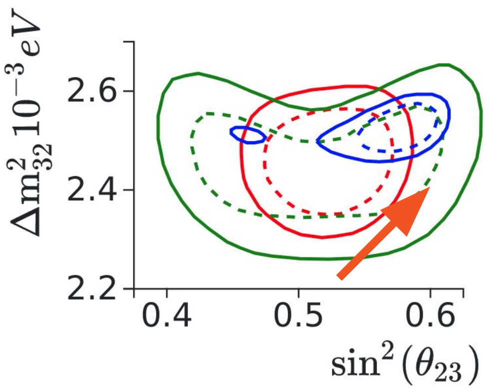

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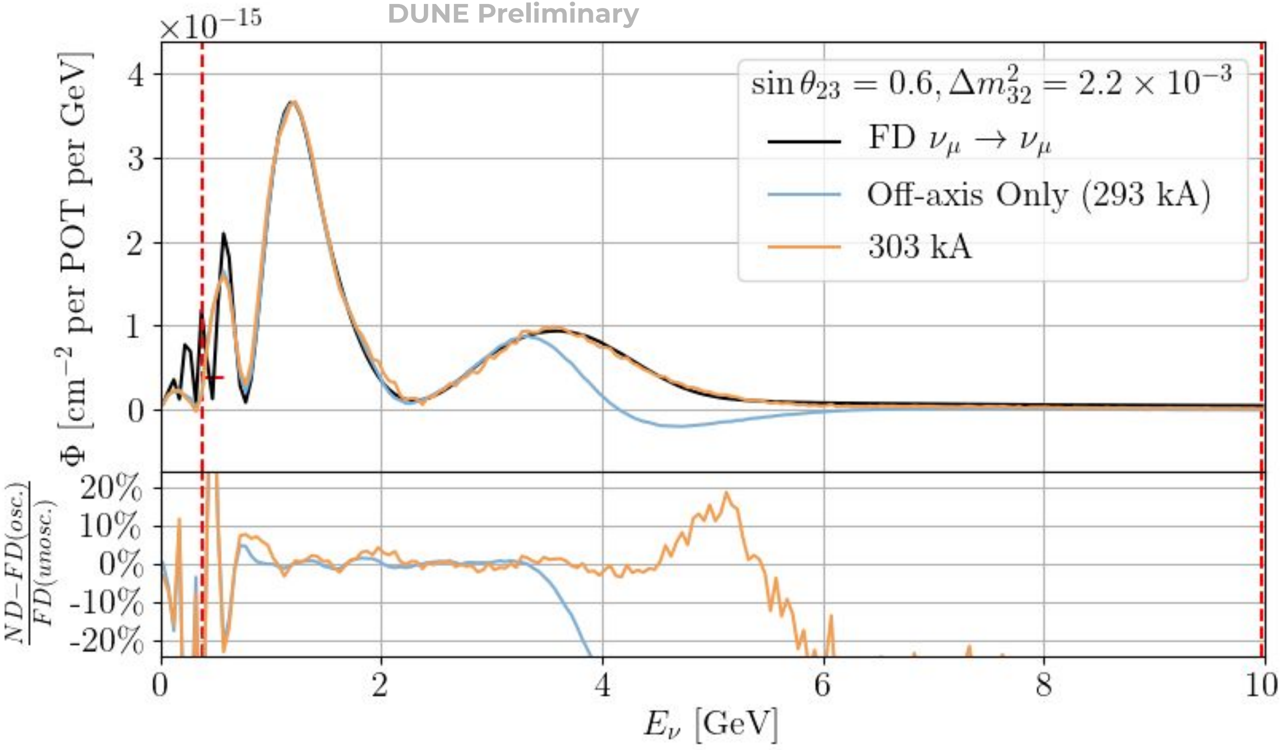

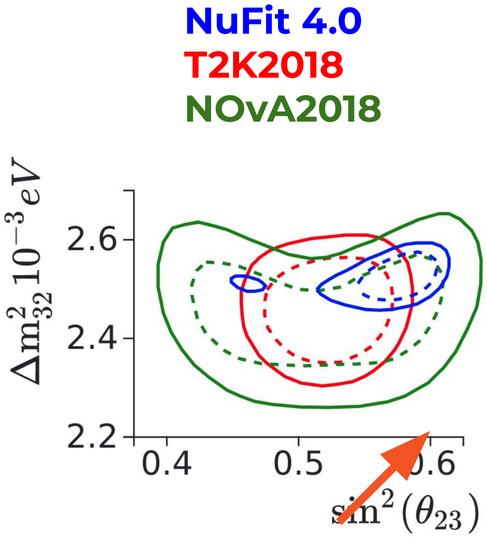

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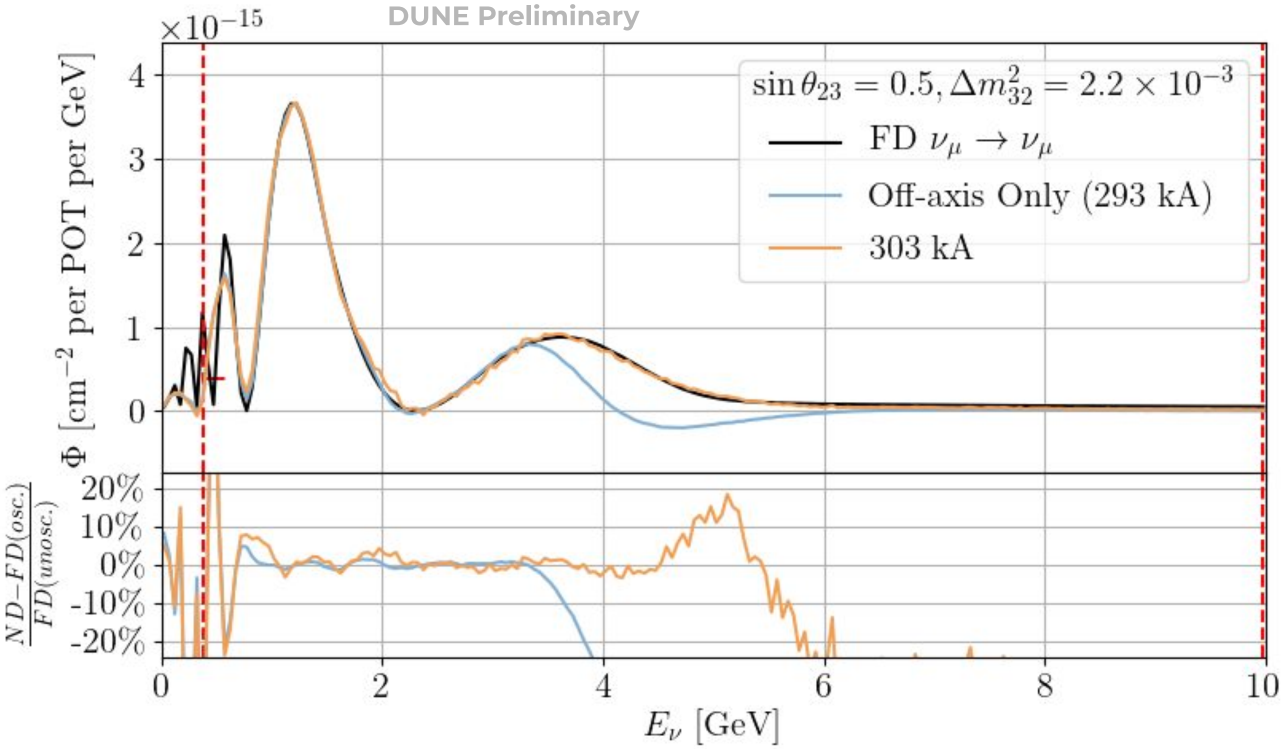

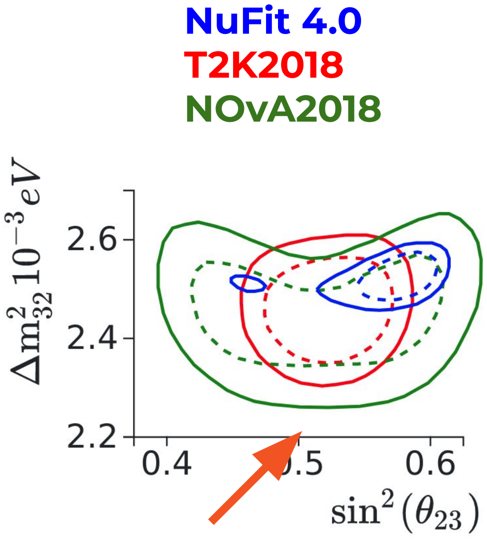

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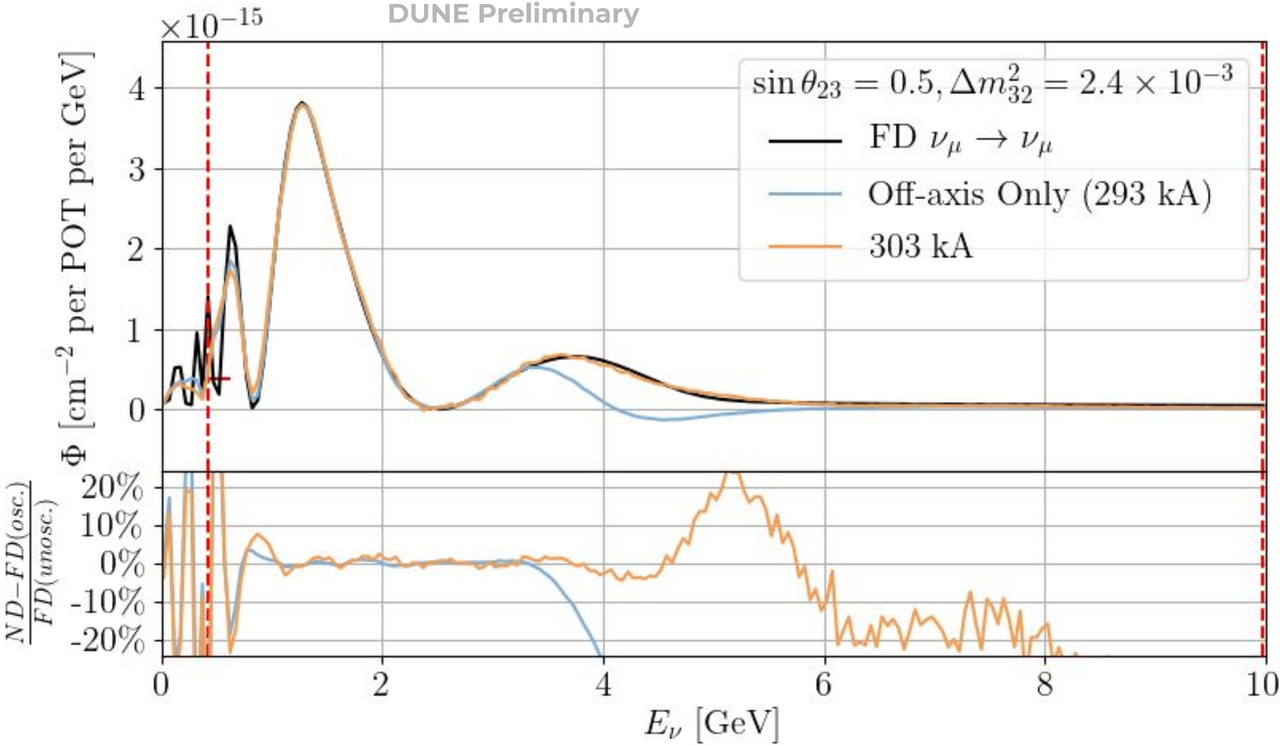

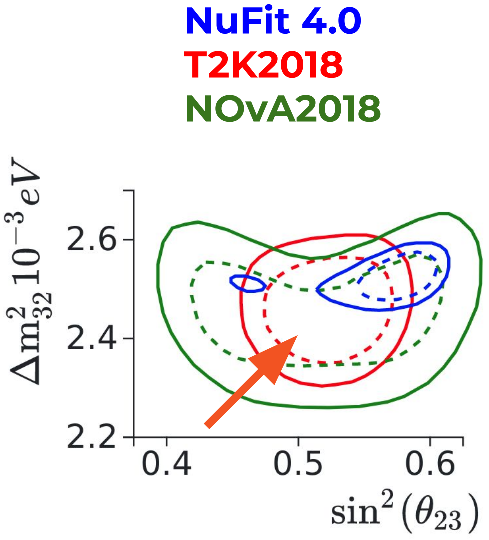

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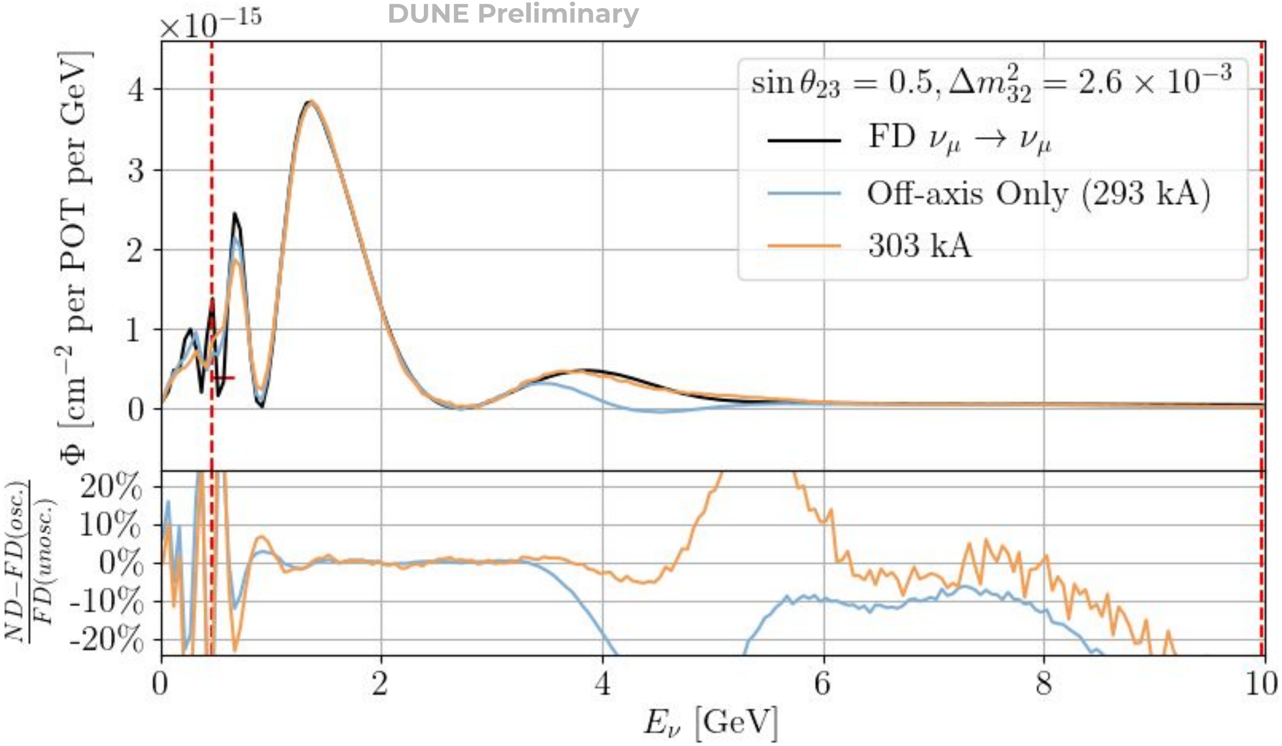

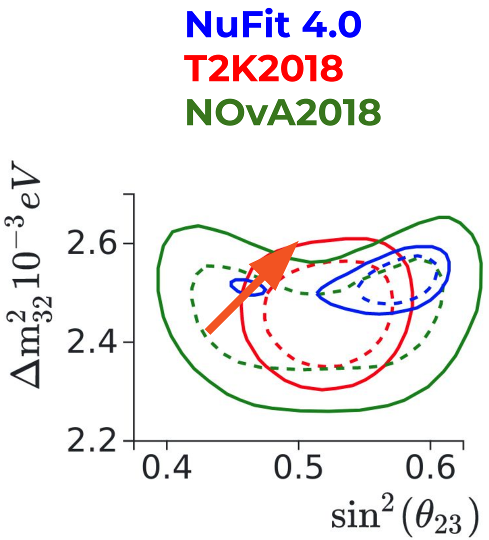

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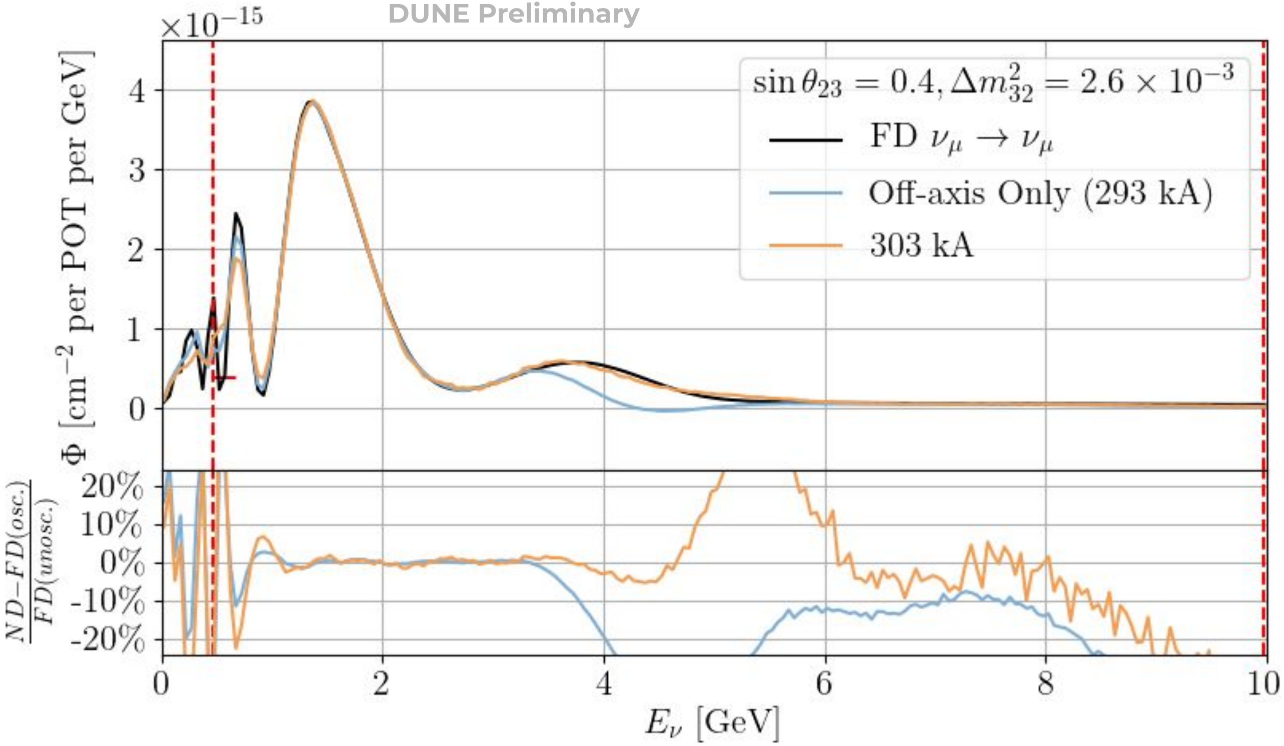

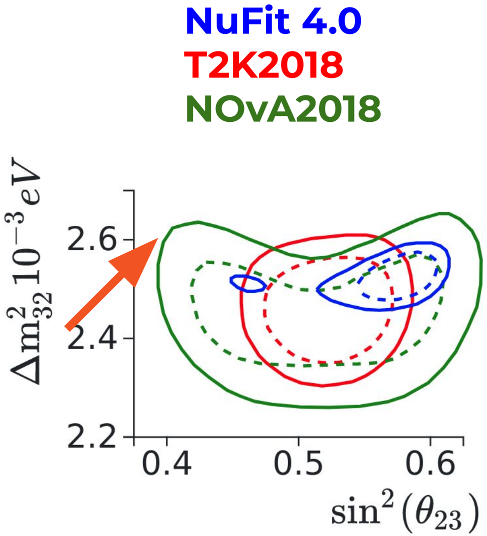

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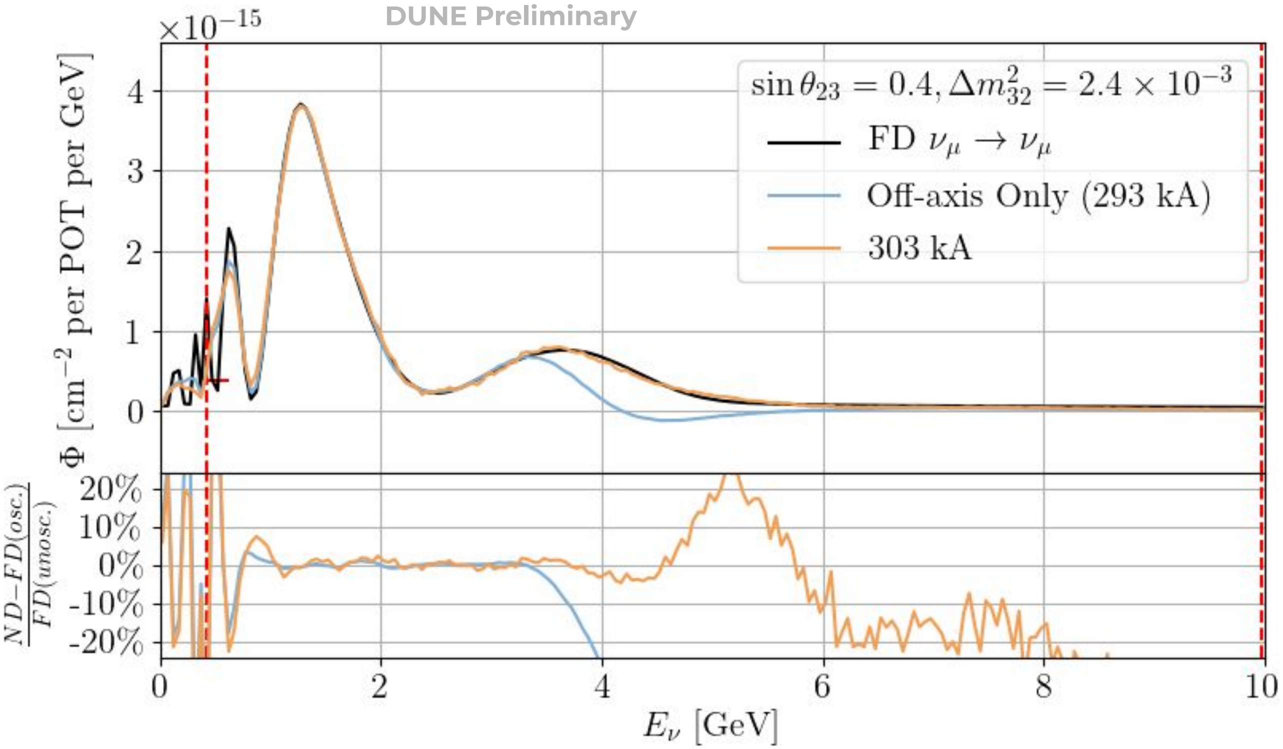

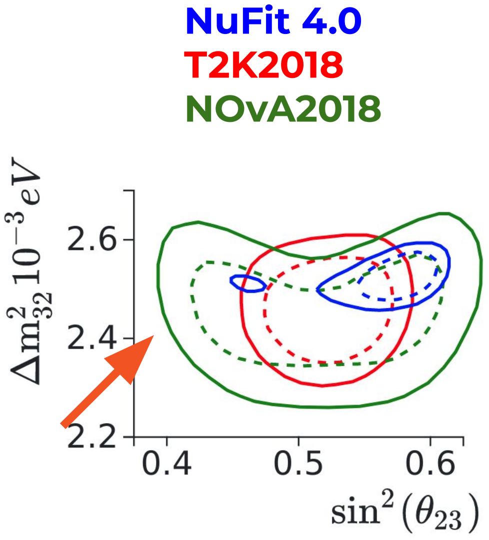

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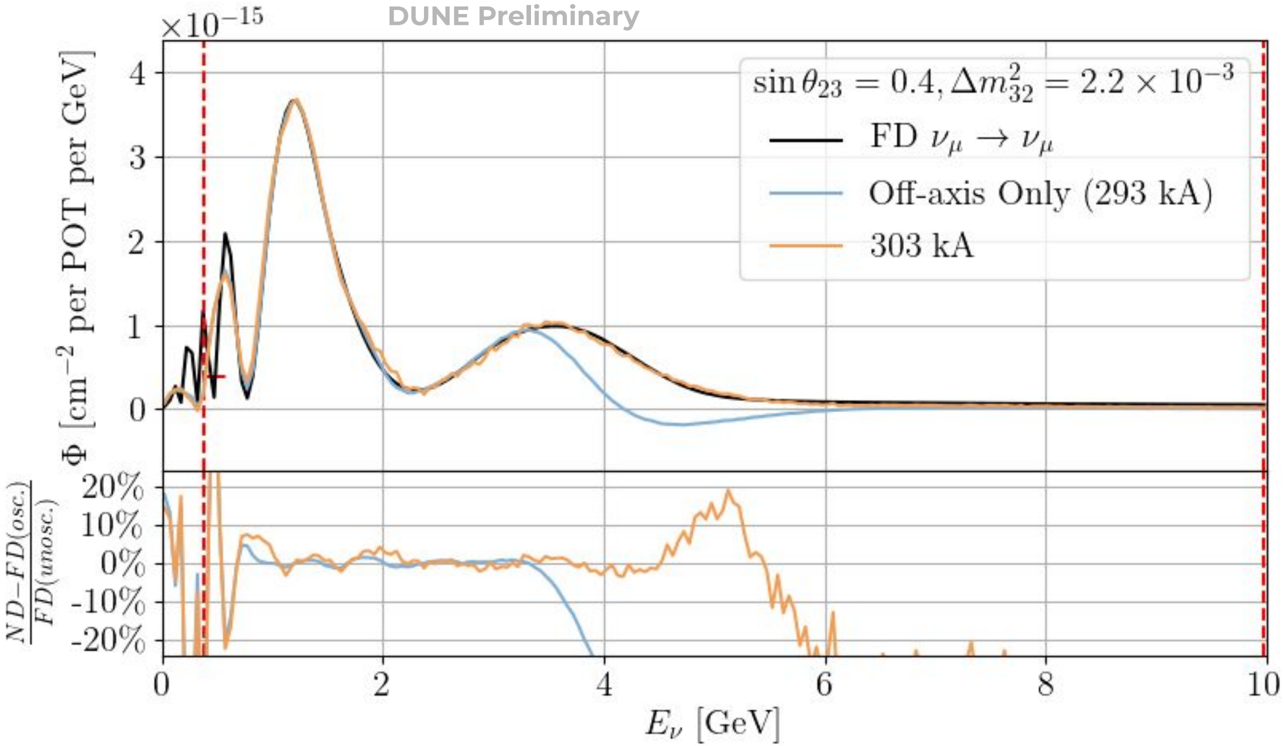

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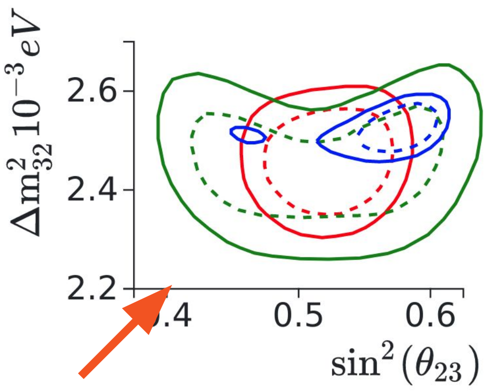
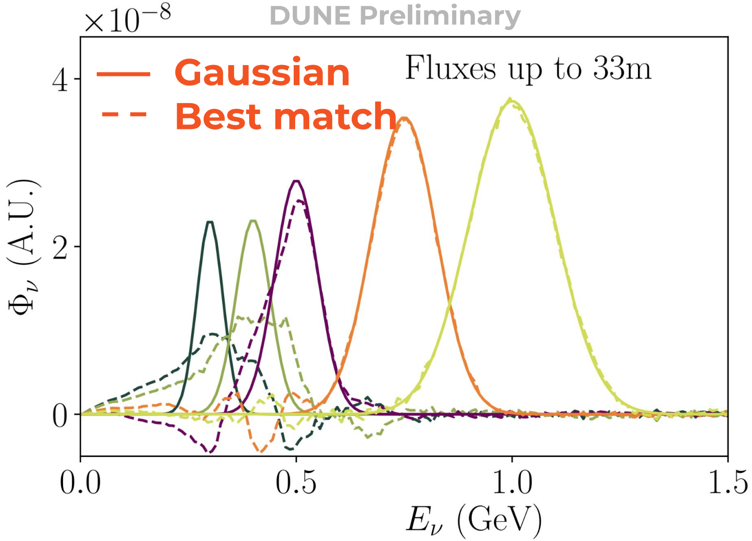


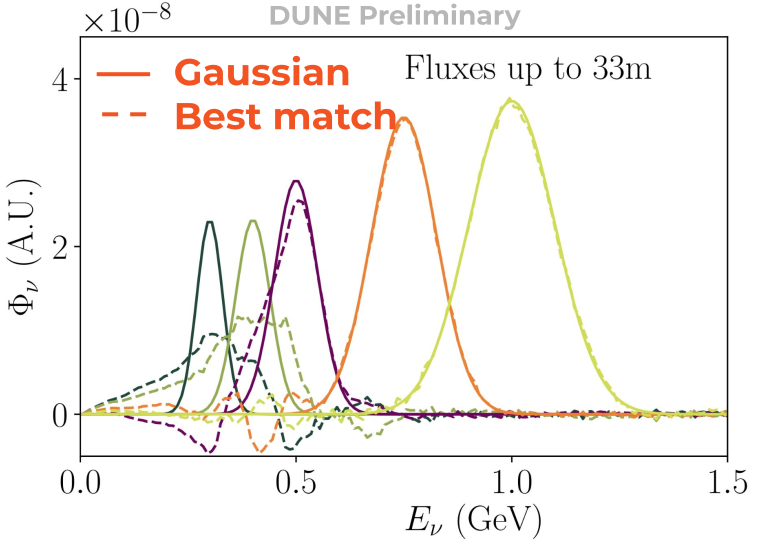
Narrow-band fluxes

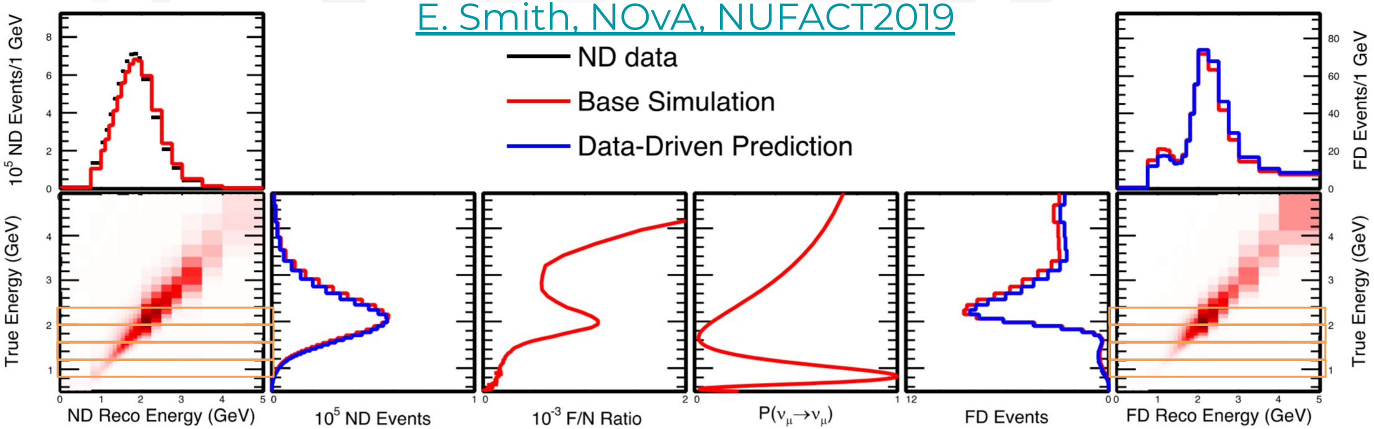
- Also of interest to construct narrow band flux measurements.



Narrow-band fluxes

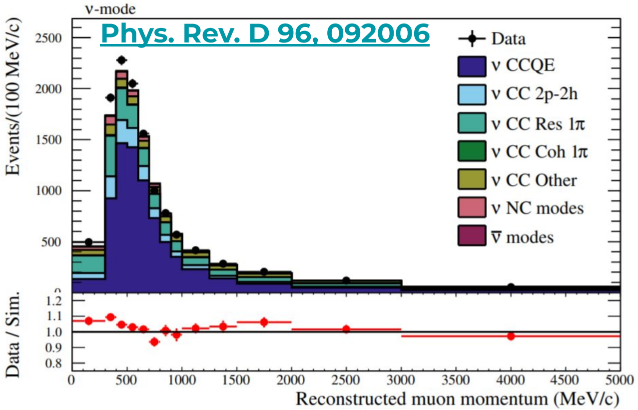
- Also of interest to construct fine band flux measurements.
  - **Can be used to probe the 'true' reconstructed energy bias and inform simulation improvements**





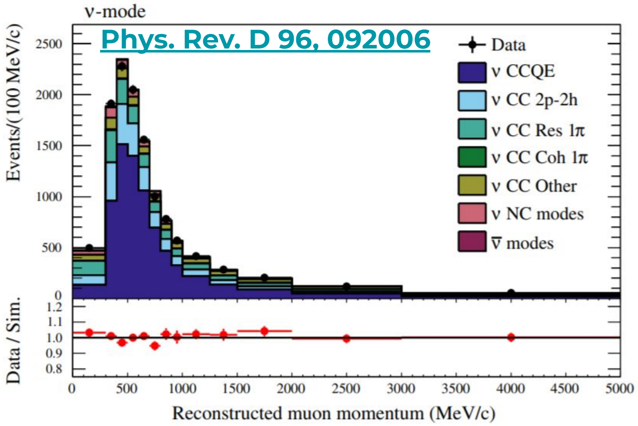
E. Smith, NOvA, NUFACT2019

Examples of OA: T2K



- Wiggle model parameters at the ND

Examples of OA: T2K



- **Wiggle model parameters at the ND**

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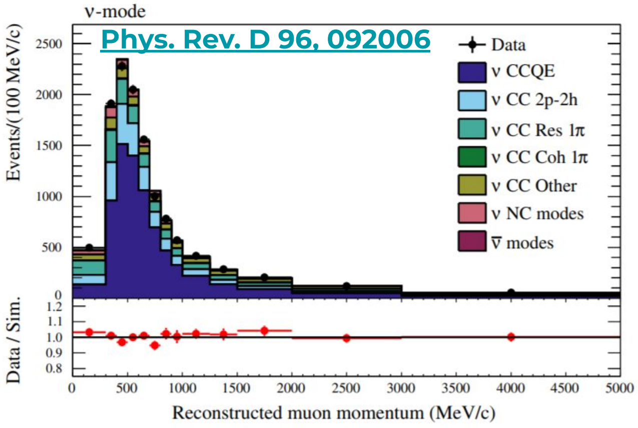
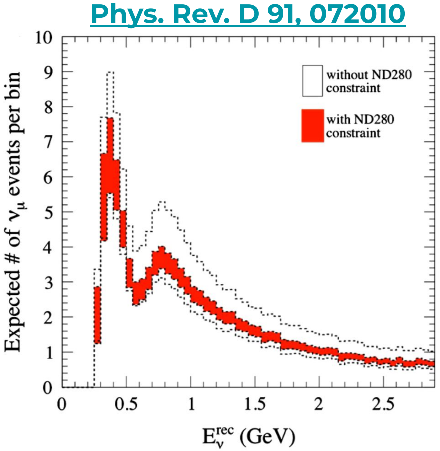
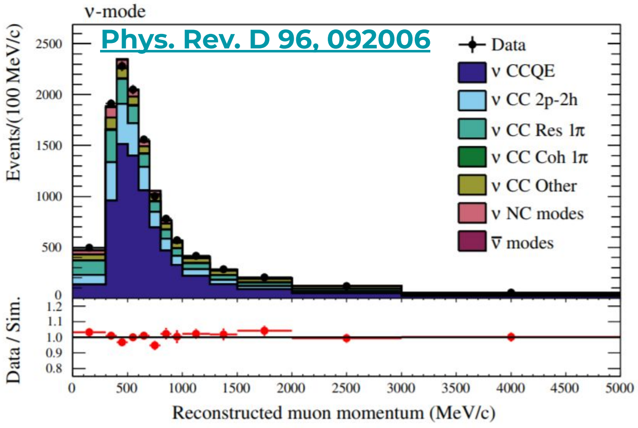


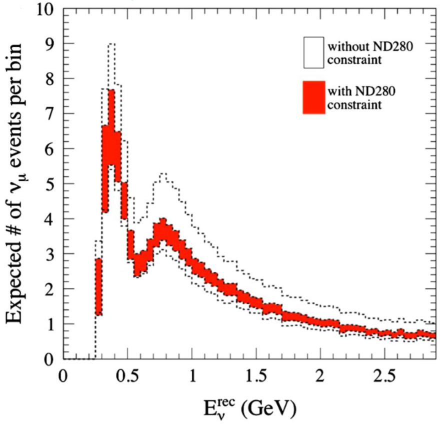


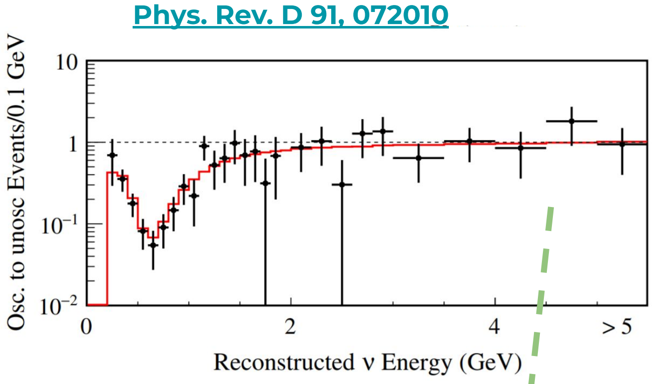
- Wiggle model parameters at the ND
- **Get correlated flux/xsec uncertainties**
- **Make predictions at the FD**

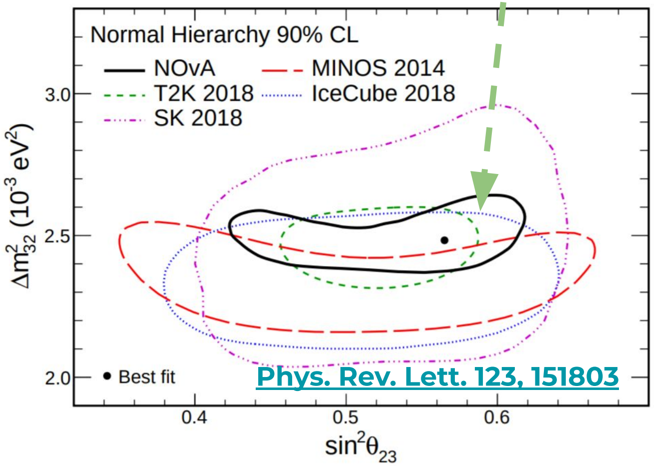
Examples of OA: T2K


Phys. Rev. D 96, 092006

Phys. Rev. D 91, 072010

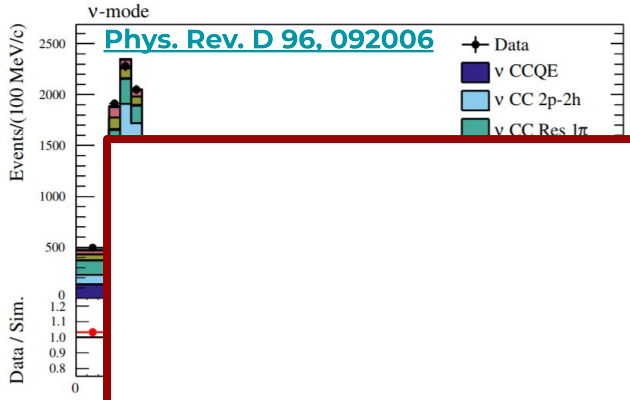



Phys. Rev. D 91, 072010


Phys. Rev. Lett. 123, 151803

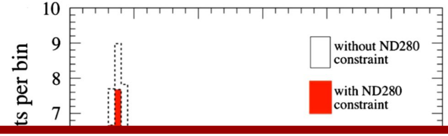
- Wiggle model parameters at the ND
- Get correlated flux/xsec uncertainties
- Make predictions at the FD
- **Infer oscillation parameters**

Examples of OA: T2K

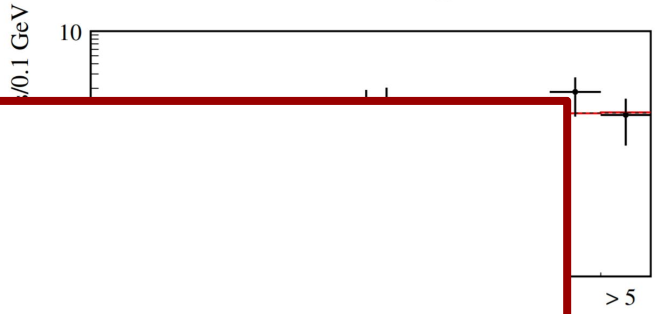


Phys. Rev. D 96, 092006

Phys. Rev. D 91, 072010



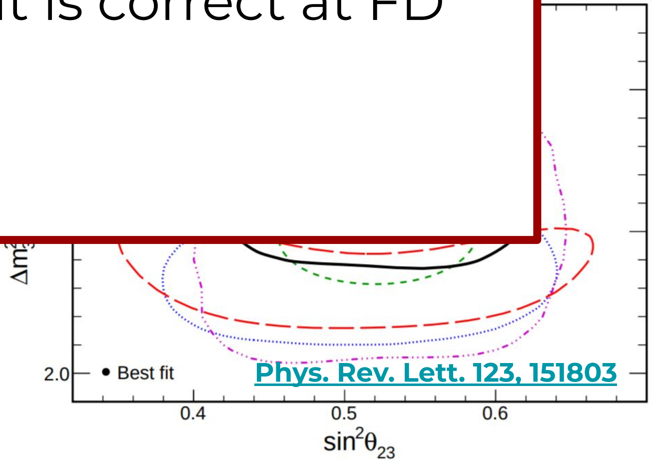
Phys. Rev. D 91, 072010



One Line: Tunes model to ND, assumes it is correct at FD*

*Two line: The T2K MaCh3 Analysis performs a simultaneous ND+FD fit

- **Infer oscillation parameters**



Phys. Rev. Lett. 123, 151803

Example of OA:

*WSB: Wrong Sign Background (nubar in nu-mode)

E. Smith, NOvA, NUFACT2019

1. **Measure observed event rate at the near detector**

Example of OA:

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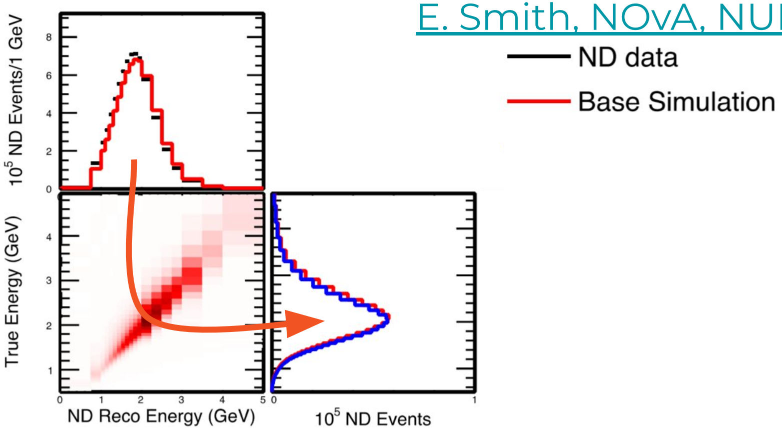

E. Smith, NOvA, NUFACT2019

1. Measure observed event rate at the near detector
2. **Use MC to predict true event rate at the near detector**

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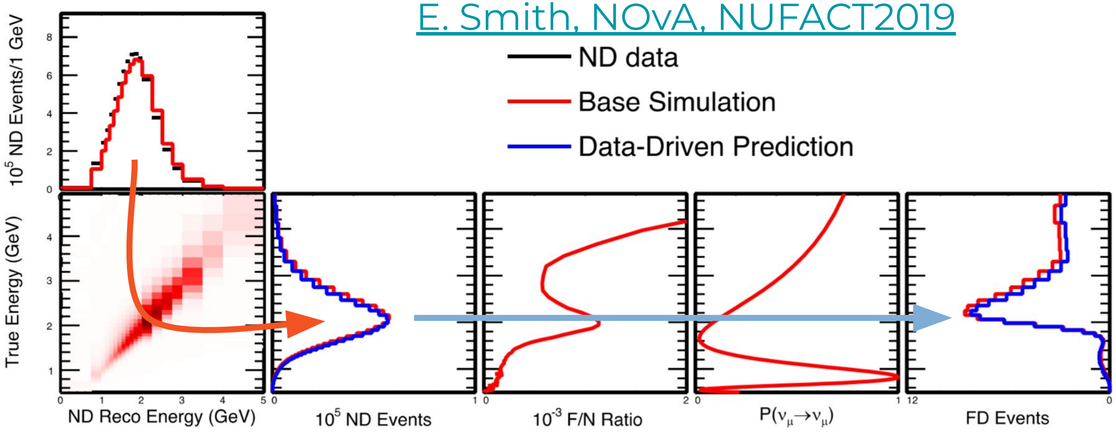

E. Smith, NOvA, NUFACT2019

1. Measure observed event rate at the near detector
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3. **Oscillate and correct for ND/FD differences**

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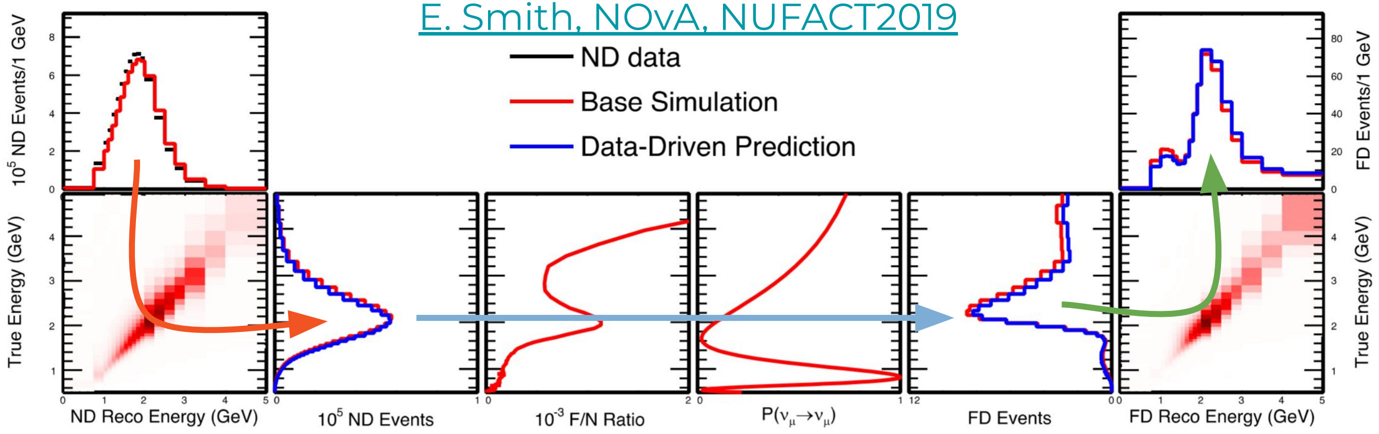
E. Smith, NOvA, NUFACT2019



1. Measure observed event rate at the near detector
2. Use MC to predict true event rate at the near detector
3. Oscillate and correct for ND/FD differences
4. **Use MC to predict observed event rate at the far detector**

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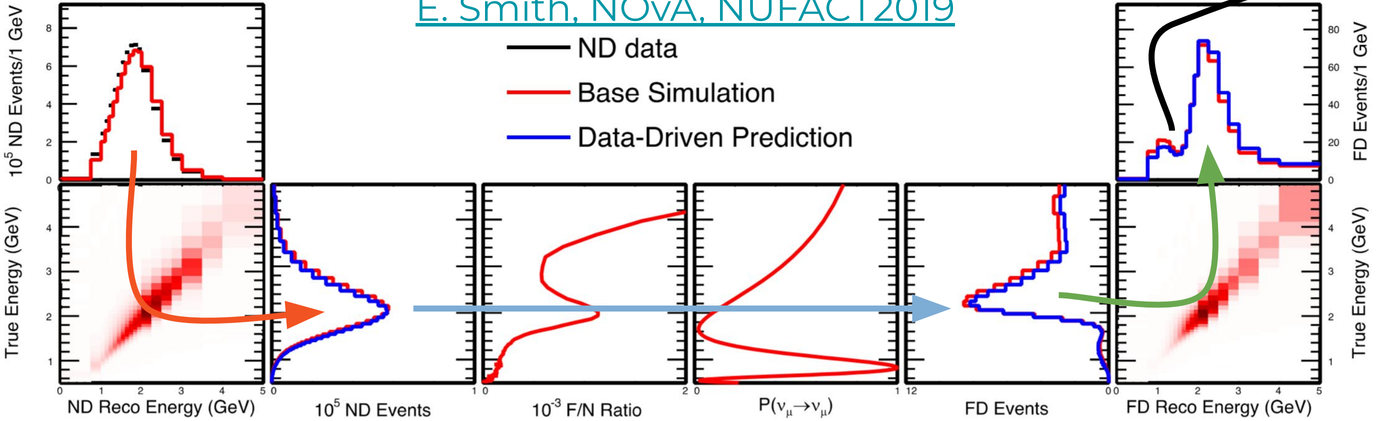
E. Smith, NOvA, NUFACT2019



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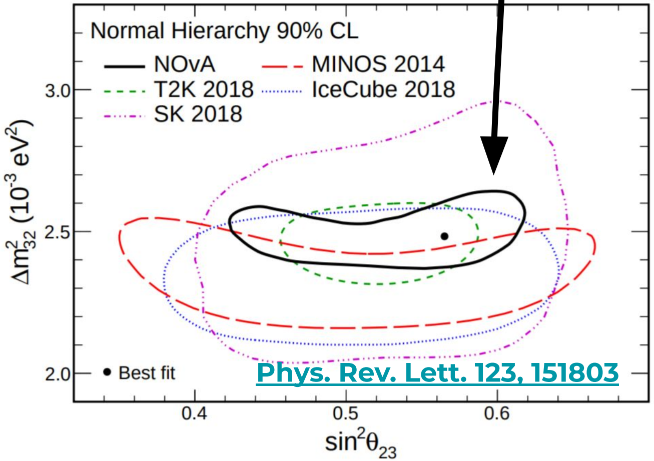

Phys. Rev. Lett. 123, 151803

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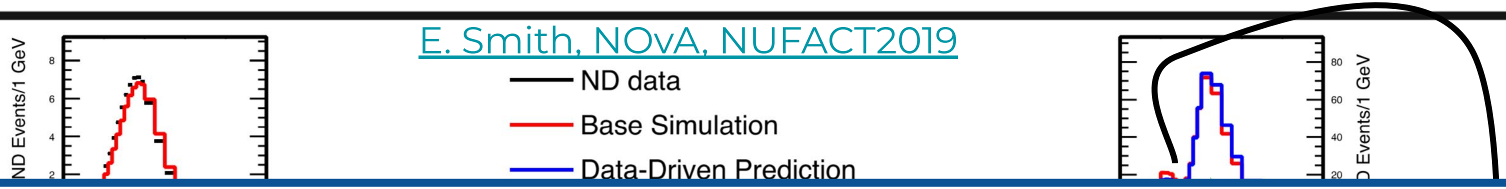
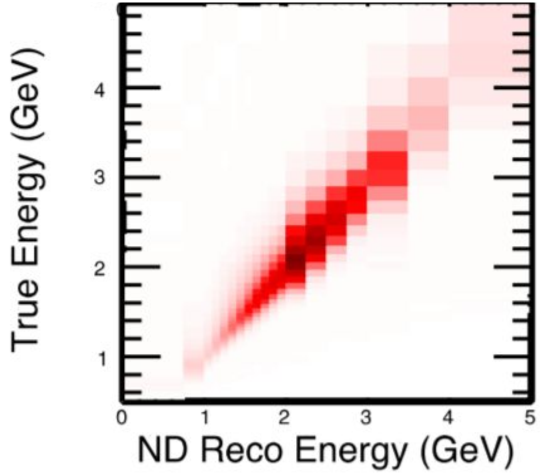


One Line: Extrapolates ND data by assuming model prediction for E^{ν}_{Obs} to E^{ν}_{True} relationship.



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2.
3.
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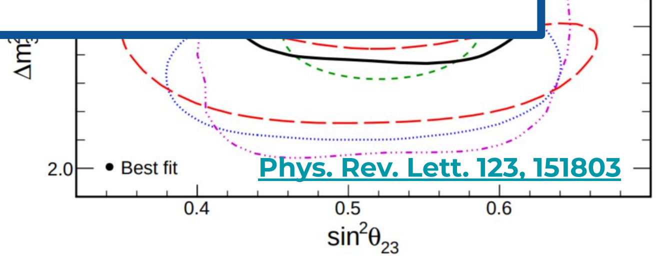

Phys. Rev. Lett. 123, 151803

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Fixing for an appearance

- For appearance, cannot match ND $\boldsymbol{\nu}_e \Rightarrow$ FD $\boldsymbol{\nu}_e$
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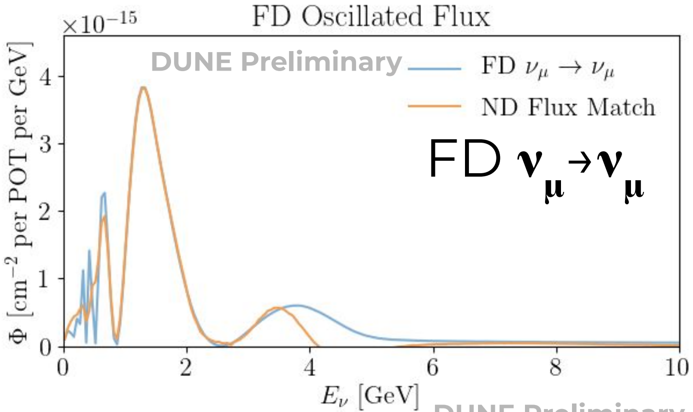

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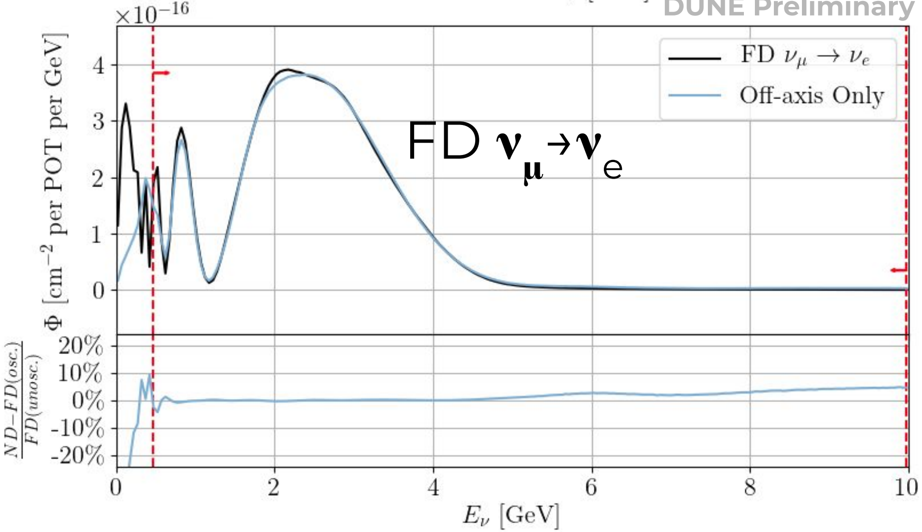

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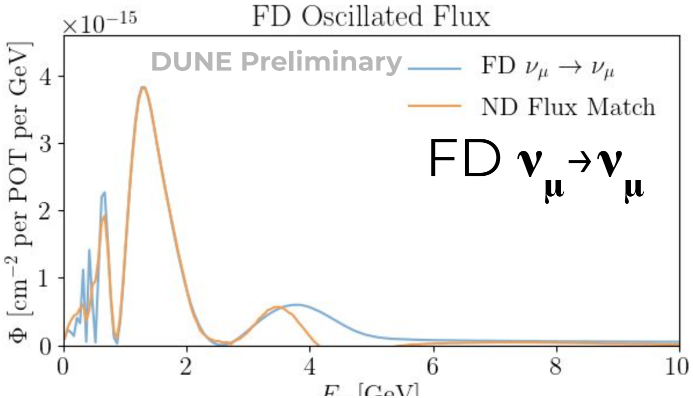
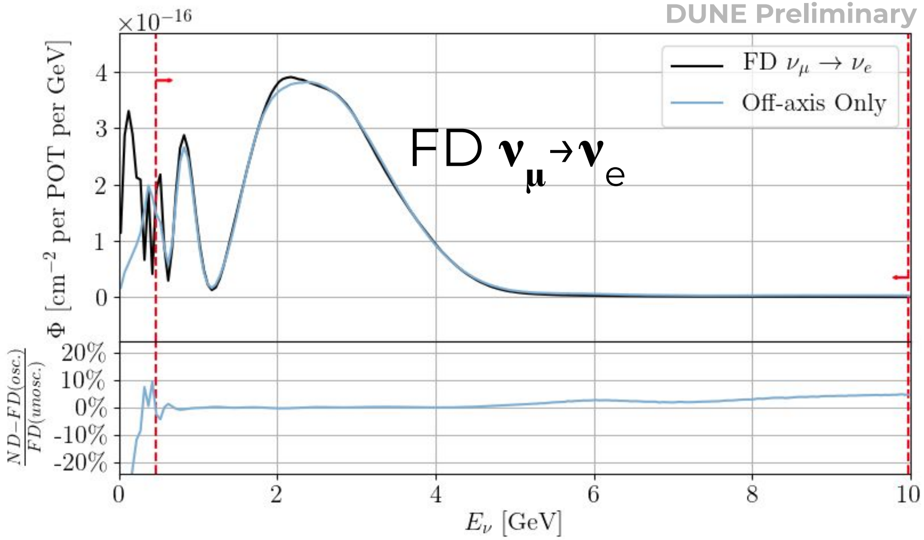
- **Have to correct for electron/muon reconstruction & cross-section differences.**



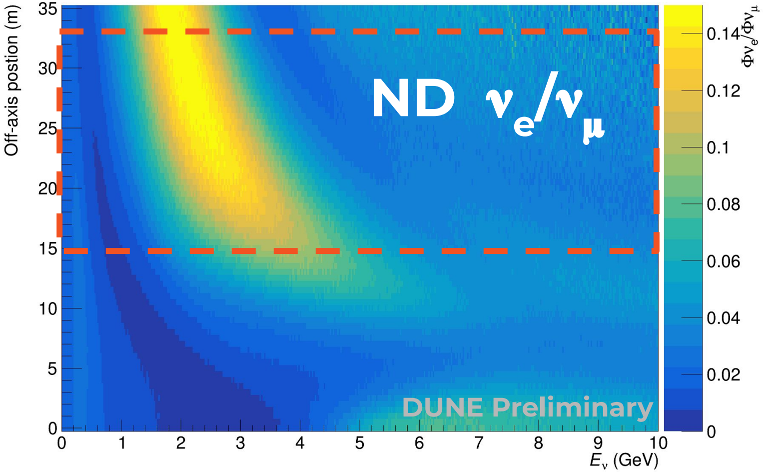
FD $\nu_\mu \to \nu_\mu$



FD $\nu_\mu \to \nu_e$

ND nue fits

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



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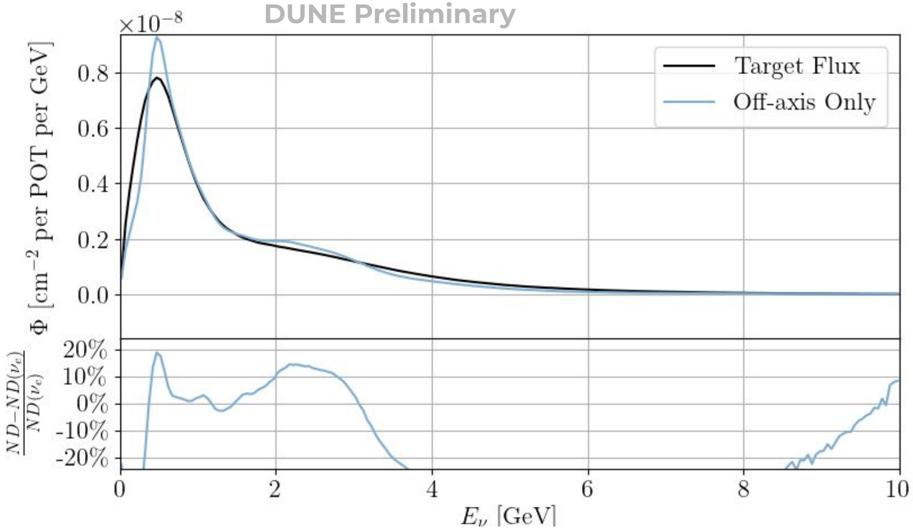

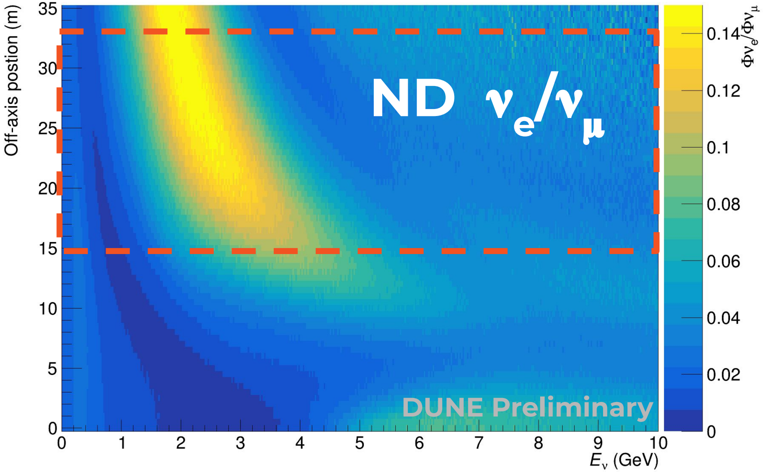

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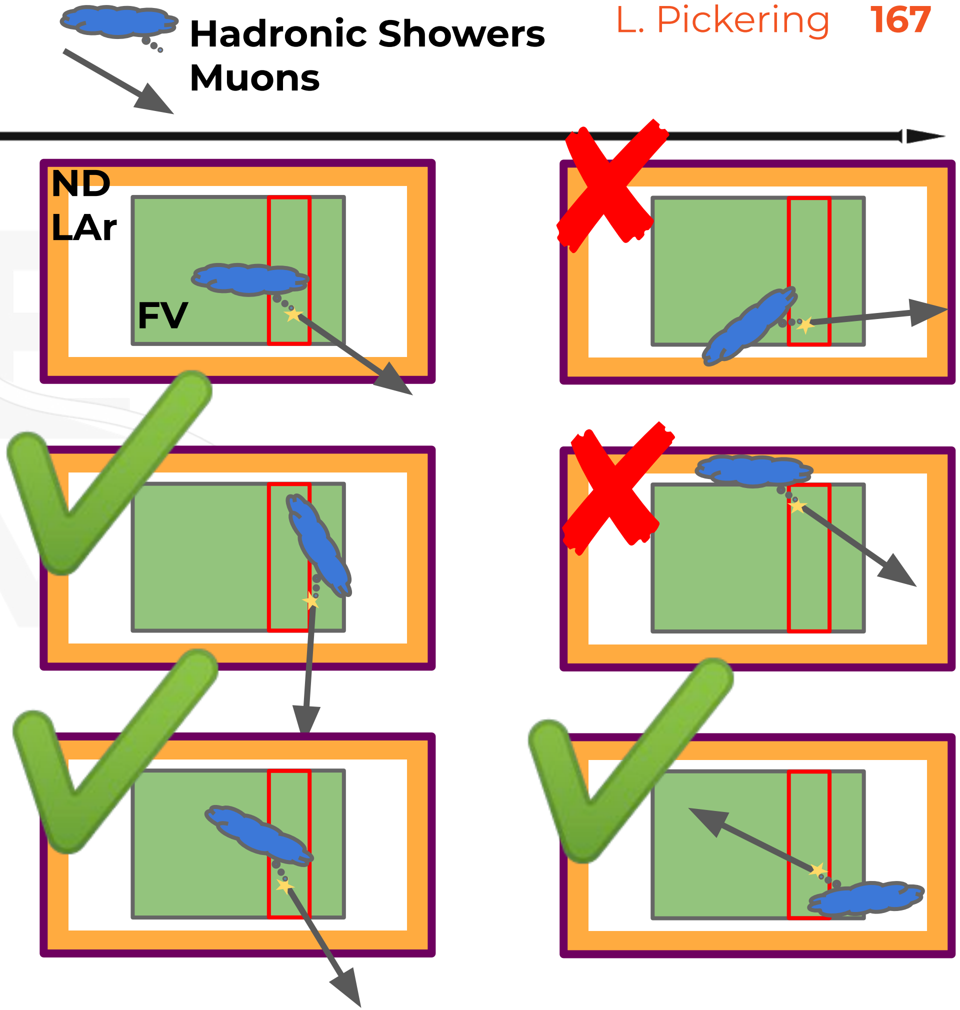

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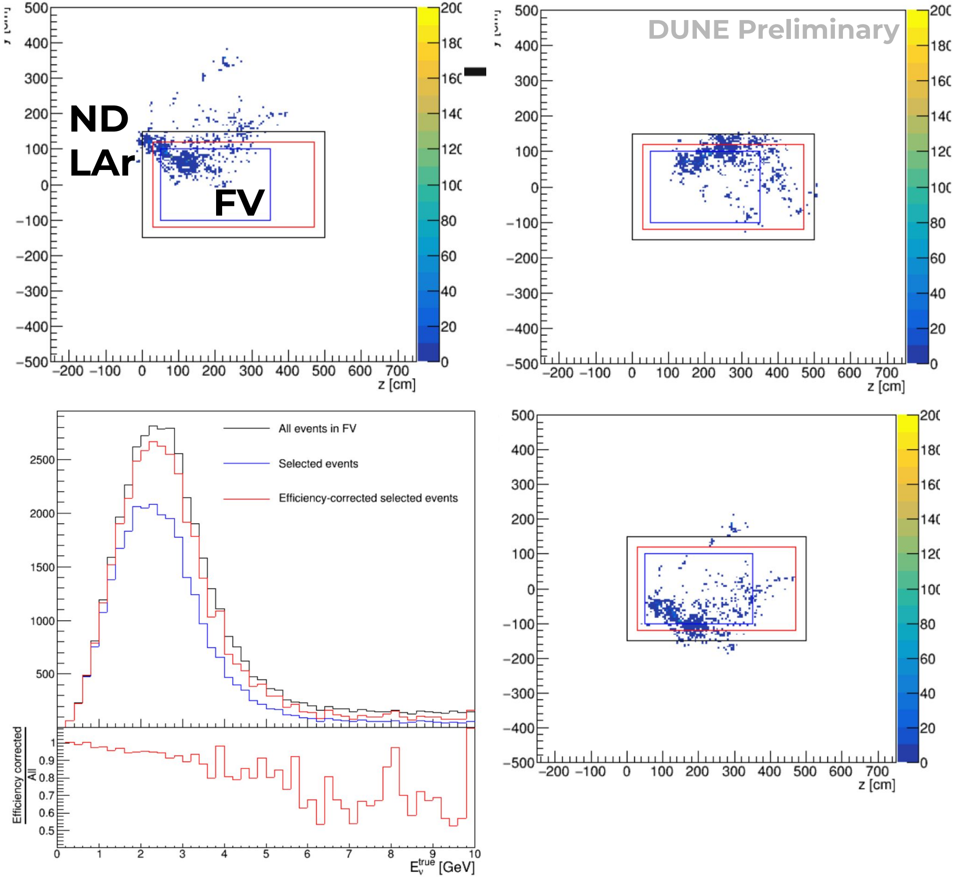

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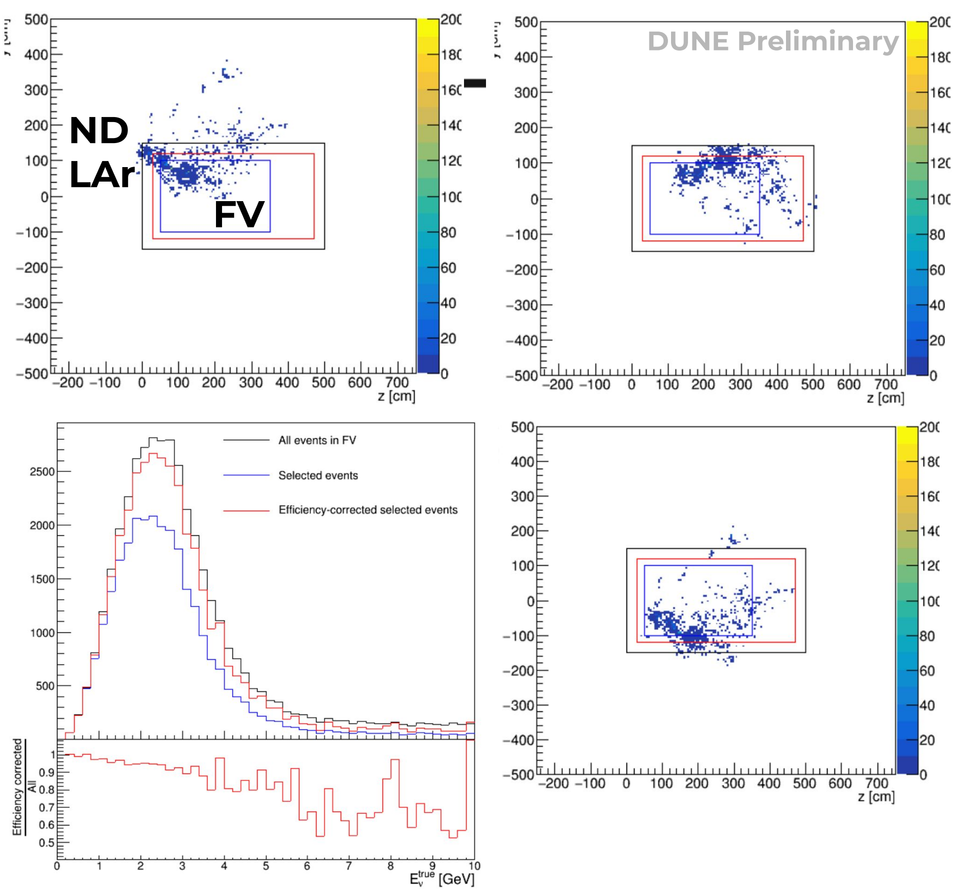
- **Also have to account for resolution difference ND/FD.**



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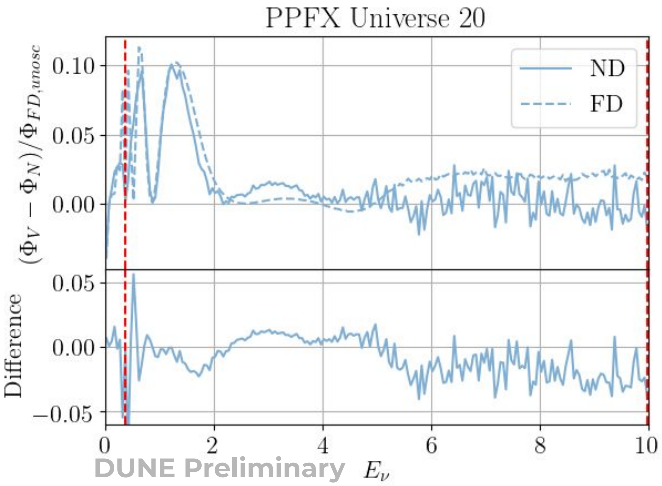
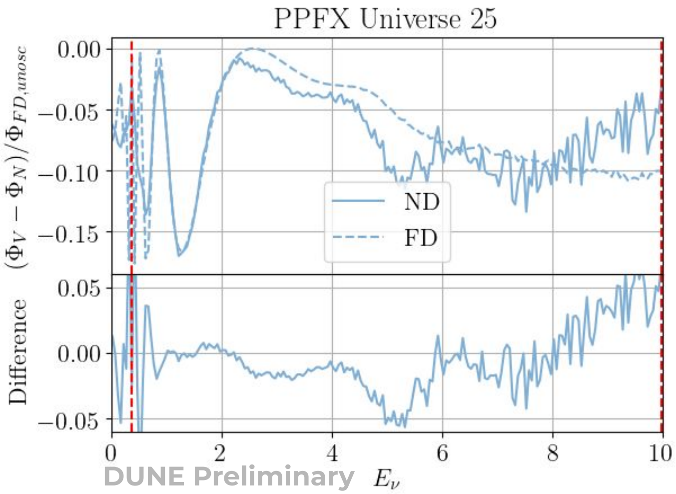
Flux Uncertainties

- Study how flux errors affect the flux matching:
  - Determine flux match coefficients for nominal prediction
  - Apply the same coefficients to systematically varied ND/FD predictions.
- **Here: hadron production uncertainties:**
  - e.g. two specific systematic universes





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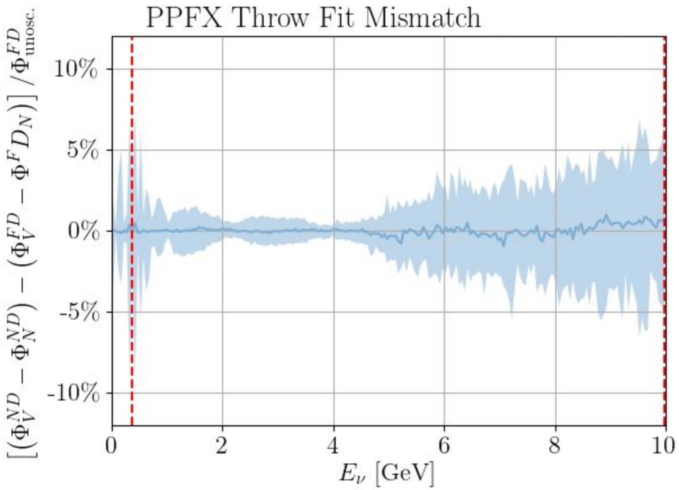

Flux Uncertainties

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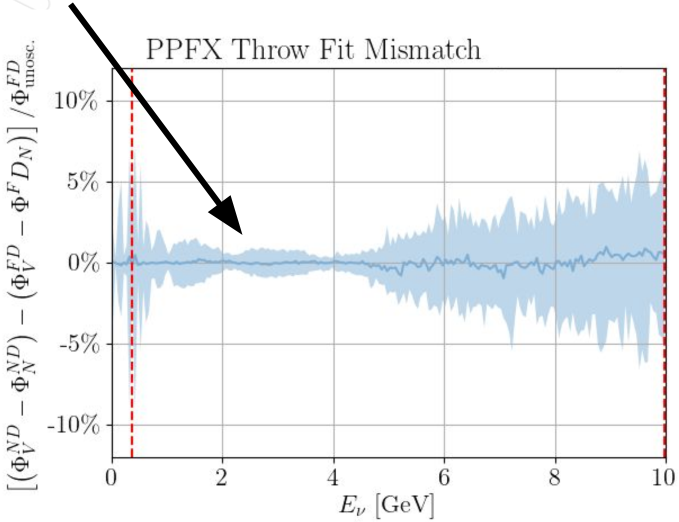
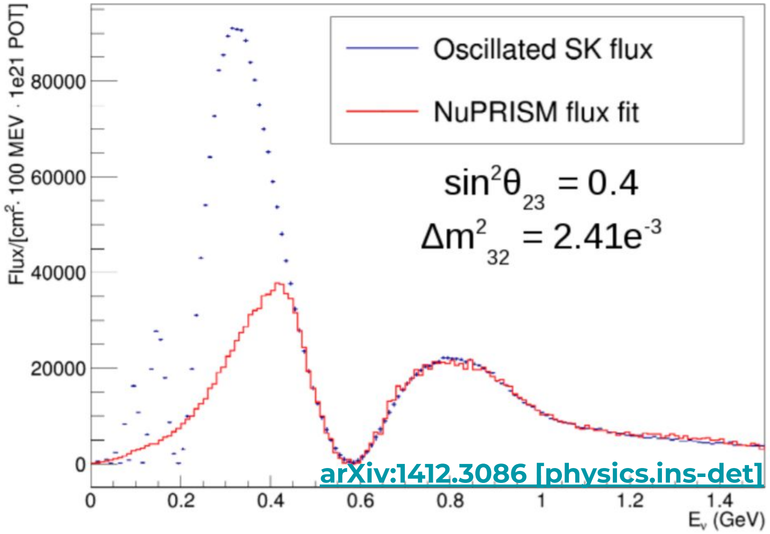
  - **Cancellations down to a few percent still observed!**

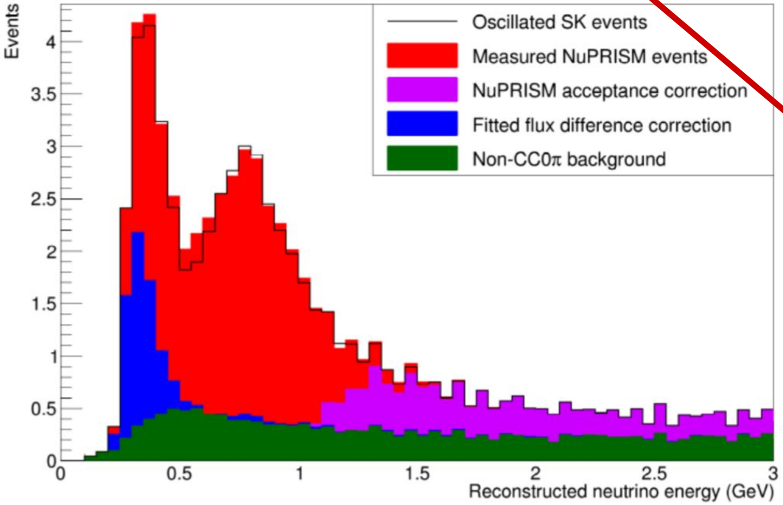


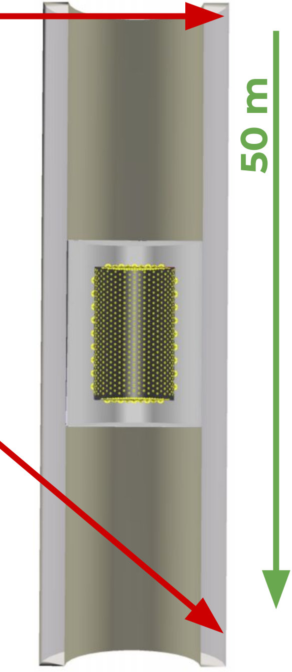
νPRISM

- 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



arXiv:1412.3086 [physics.ins-det]





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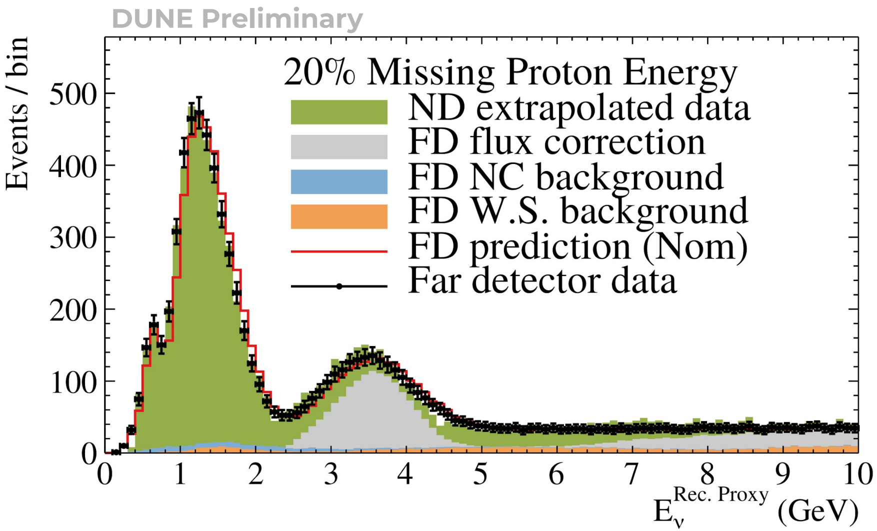
Flux Misfit Correction

- Elephant in the room



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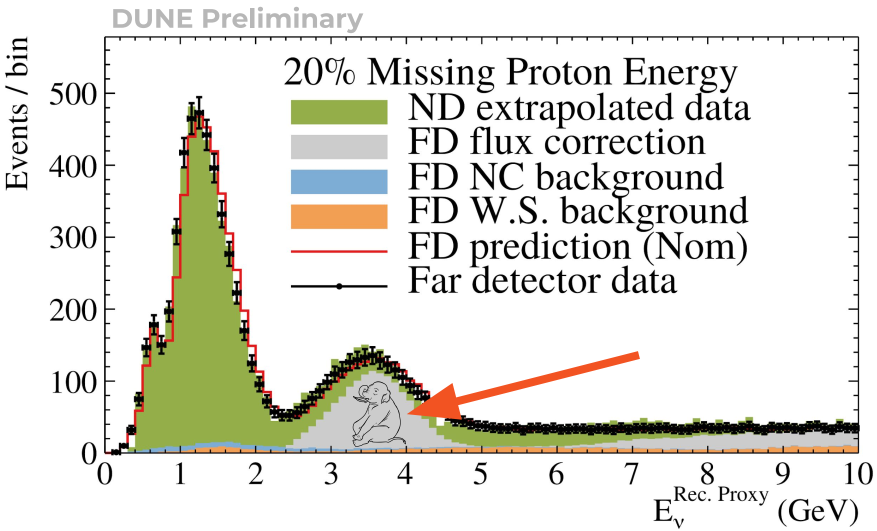

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Remaining complications

- Almost there, but we still have to deal with:
  - Making event rate predictions
  - Extrapolating observable quantities
  - Imperfect FD flux matching
  - Matching FD ν_e appearance spectrum
  - ND and FD backgrounds
  - ND/FD selection and reconstruction differences

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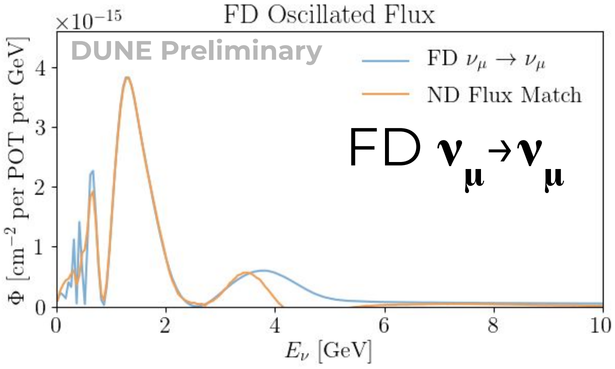
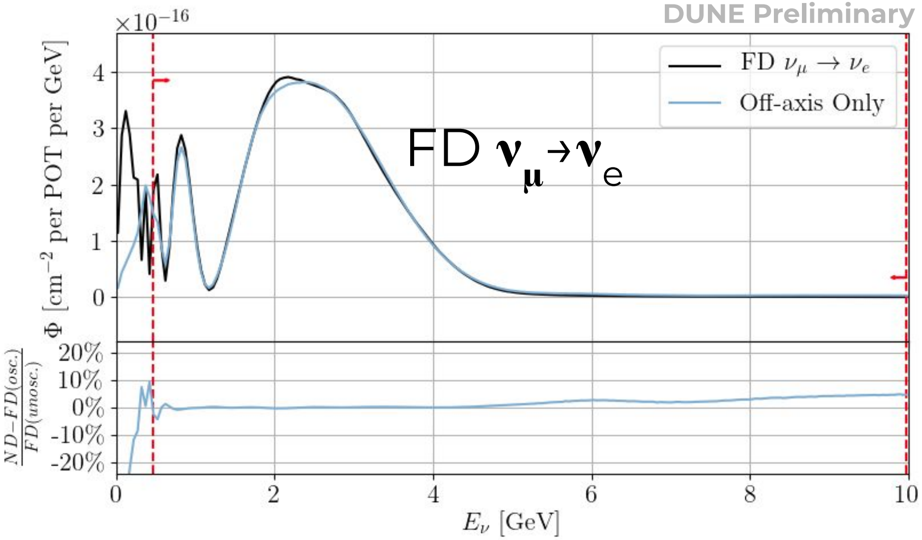


FD $\nu_\mu \to \nu_\mu$



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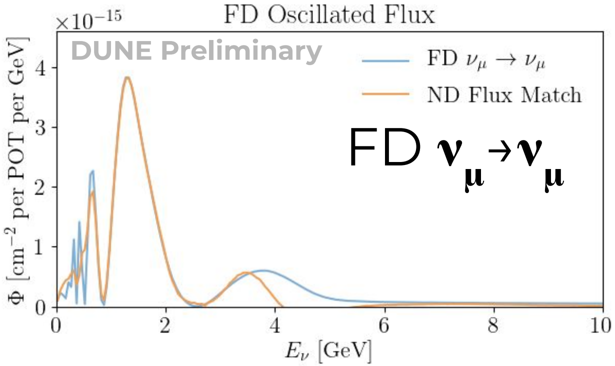
- **More in a few slides...**



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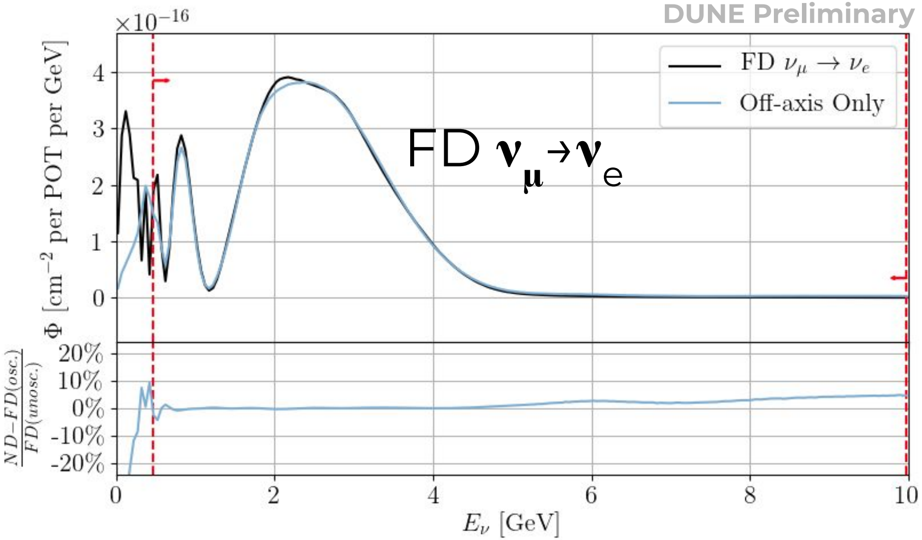

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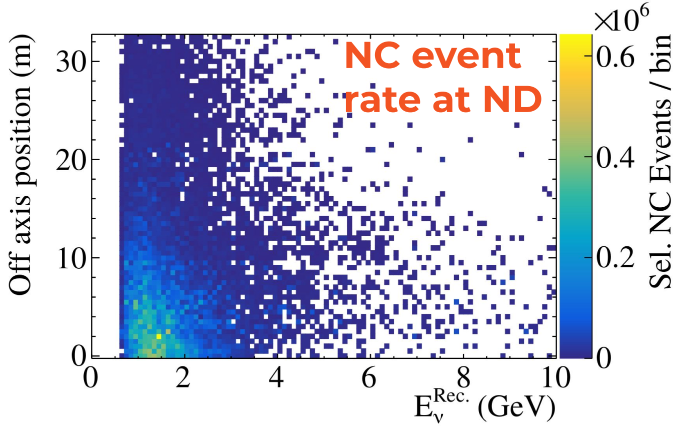
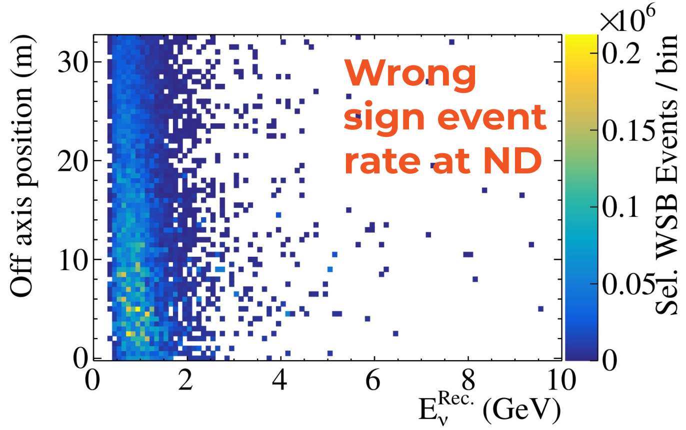

NC event rate at ND


Wrong sign event rate at ND

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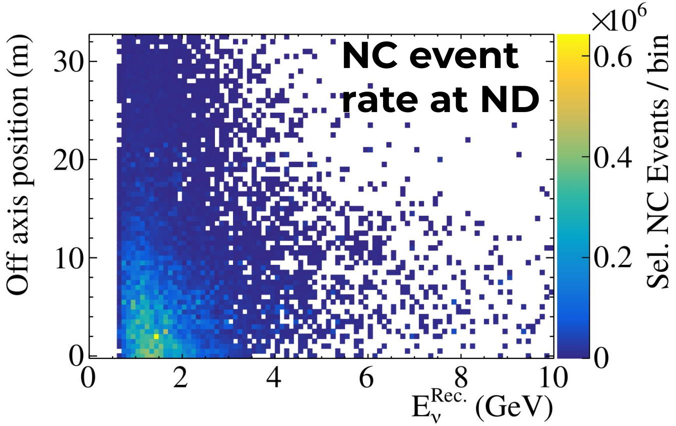
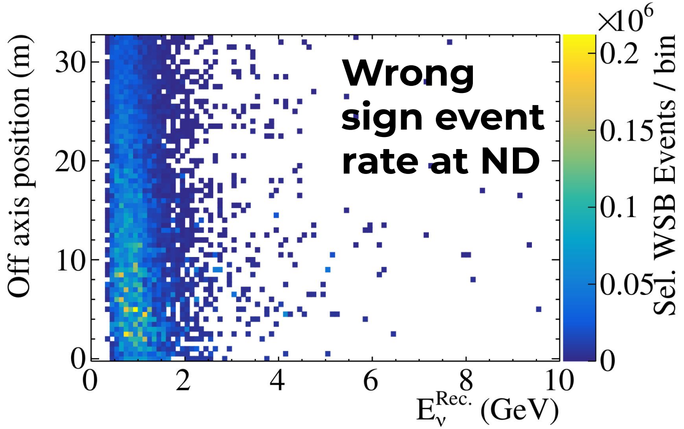


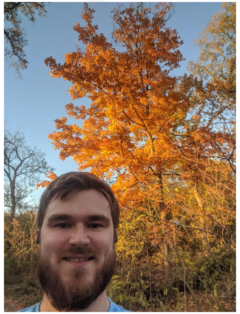


Join DUNE-PRISM!

- Lots of simulation and analysis investigations still to do
- If you are:
  - Interested in the technique,
  - you can think of other ways of using off axis fluxes,
  - or just want to ask more questions
  - Or have great ideas for a logo...
- Get in touch!

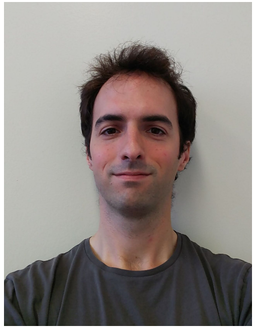

H. Tanaka


K. Mahn


L. Pickering


G. Yang

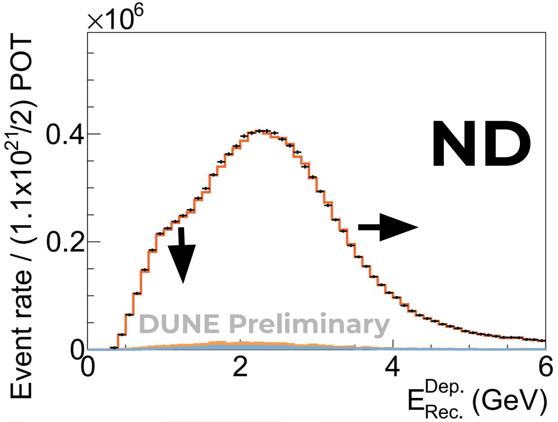

D. Douglas

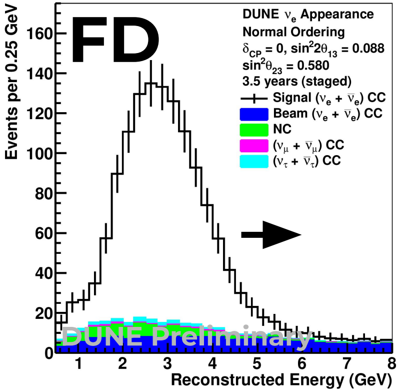

C. Vilela

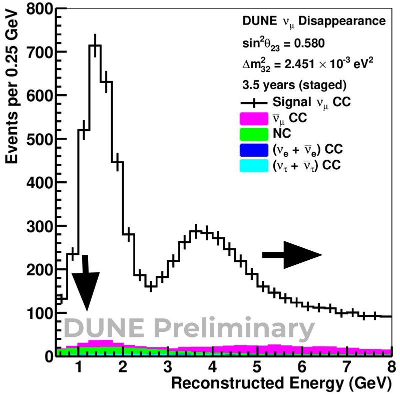

T. Lord


M. Wilking

Examples of OA: DUNE TDR







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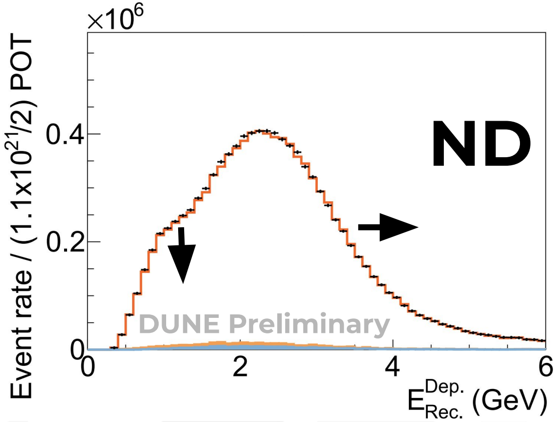
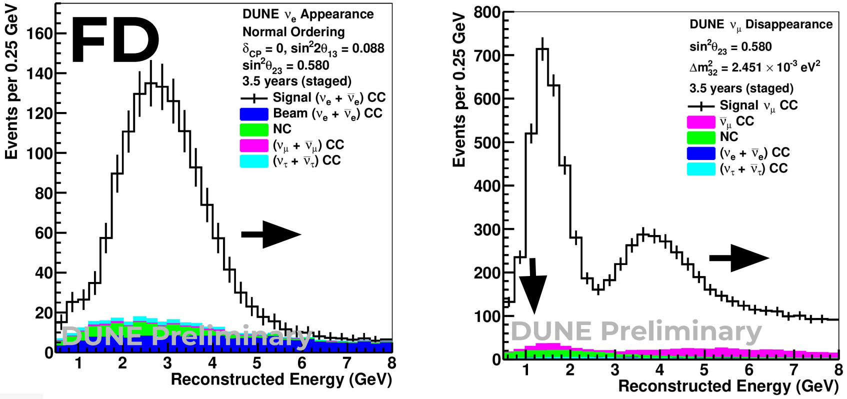
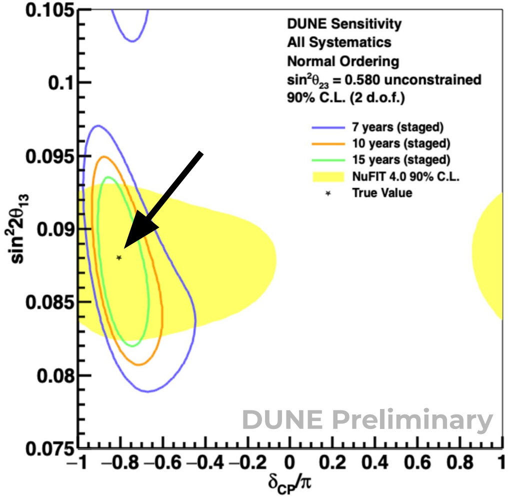
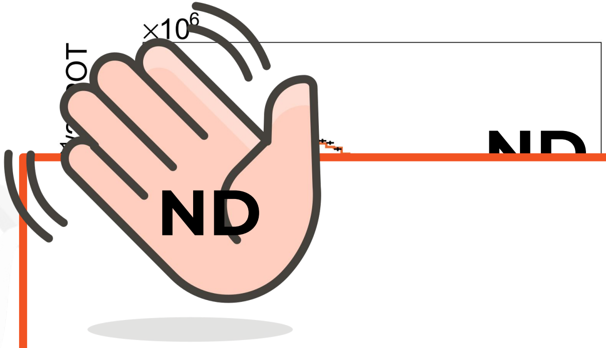


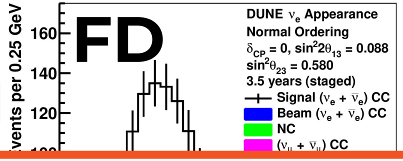


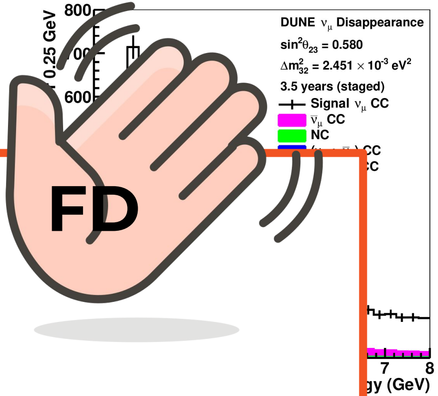
- Wiggle systematics at ND and FD simultaneously
- **Search for best fit oscillation parameter values**



Examples of OA: DUNE TDR

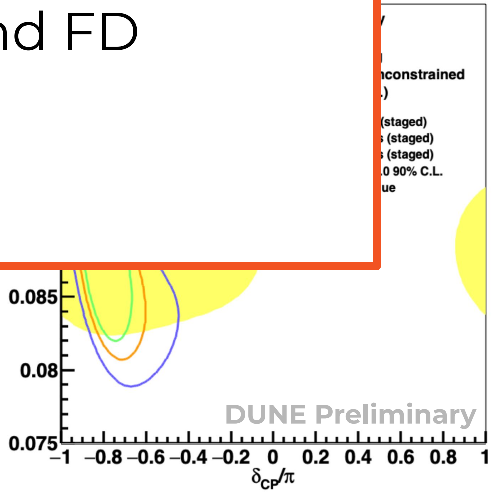






One Line: Similar to T2K, simultaneous ND and FD

- W
  F
- S
  parameter values

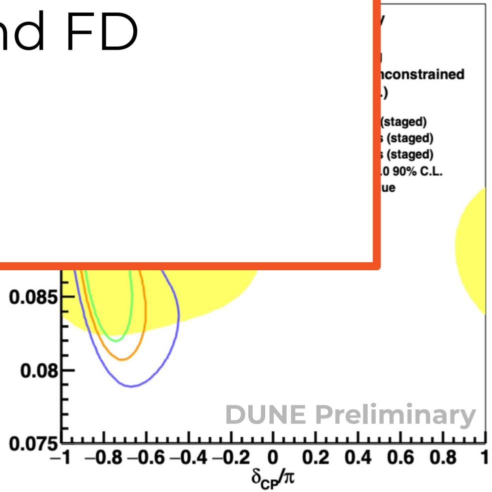


Examples of OA: DUNE TDR

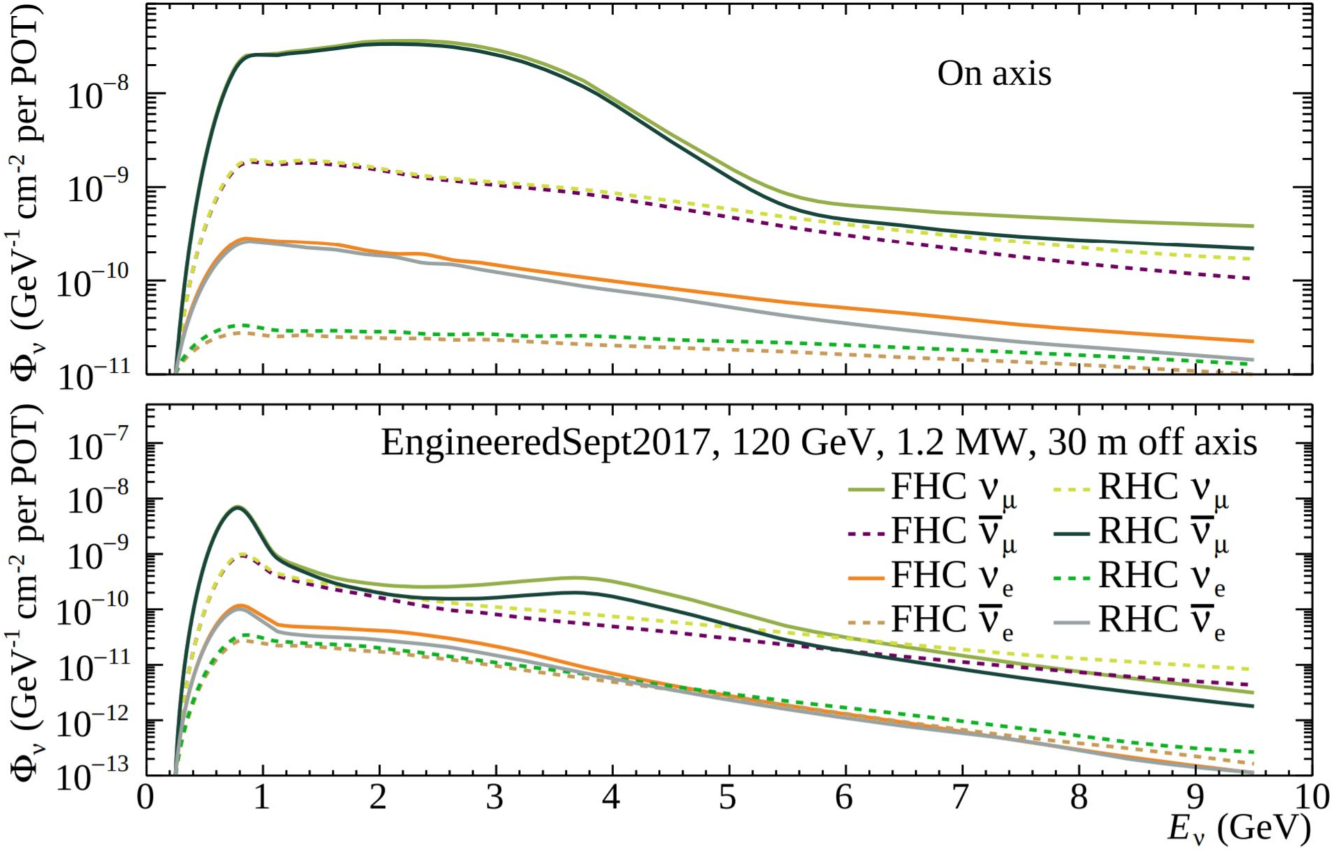
One Line: Similar to T2K, simultaneous ND and FD

Jazz hands OA!

- W
  F
- S
  parameter values



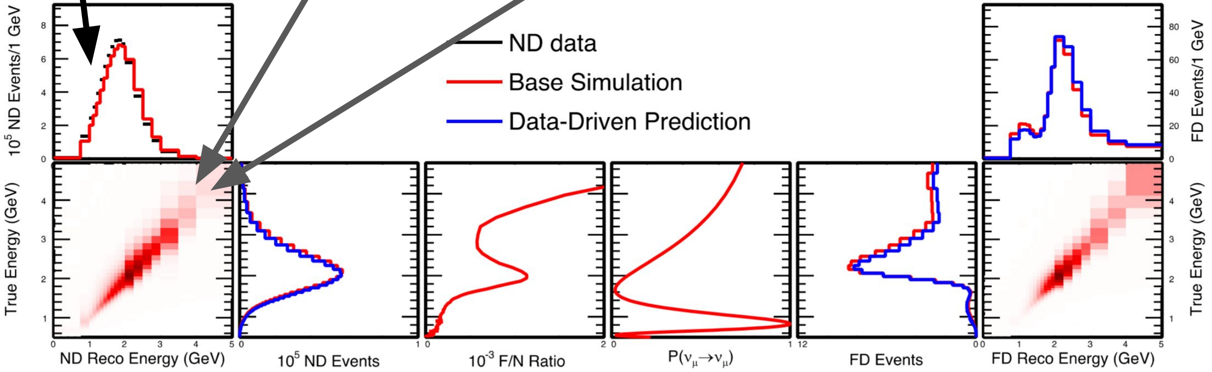
Parent Species Off axis.



Concrete Example: NOvA

$$N_{\rm near}\left(\mathbf{x}_{\rm obs}\right) = \int d\mathbf{x}_{\rm true}\, \boxed{\underbrace{\mathbf{D}_{\rm near}\left(\mathbf{x}_{\rm obs}|\mathbf{x}_{\rm true}\right)}_{\text{Smearing, Eff., Pur.}}}\, \underbrace{N_{\rm targ}\boxed{\sigma\left(\mathbf{x}_{\rm true}\right)}\Phi\left(E_\nu\right)}_{N_{\rm Int}\left(\mathbf{x}_{\rm true}\right)}$$

$$N_{\rm far}\left(\mathbf{x}_{\rm obs}\right) = \int d\mathbf{x}_{\rm true}\, \underbrace{\mathbf{D}_{\rm far}\left(\mathbf{x}_{\rm obs}|\mathbf{x}_{\rm true}\right)}_{\text{Smearing, Eff., Pur.}}\, \underbrace{N_{\rm targ}\sigma\left(\mathbf{x}_{\rm true}\right)\Phi\left(E_\nu\right)P_{osc}\left(E_\nu\right)}_{N_{\rm Int}\left(\mathbf{x}_{\rm true}\right)}$$



E. Smith, NOvA, NUFACT2019

Concrete Example: NOvA

$$N_{\rm near}\left(\mathbf{x}_{\rm obs}\right) = \int d\mathbf{x}_{\rm true}\, \underbrace{\mathbf{D}_{\rm near}\left(\mathbf{x}_{\rm obs}|\mathbf{x}_{\rm true}\right)}_{\text{Smearing, Eff., Pur.}} \underbrace{N_{\rm targ}\sigma\left(\mathbf{x}_{\rm true}\right)\Phi\left(E_\nu\right)}_{N_{\rm Int}\left(\mathbf{x}_{\rm true}\right)}$$

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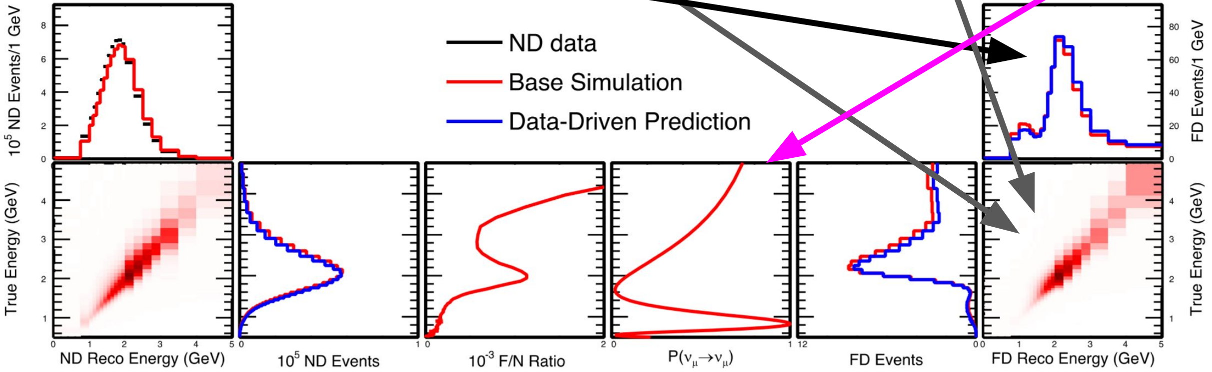

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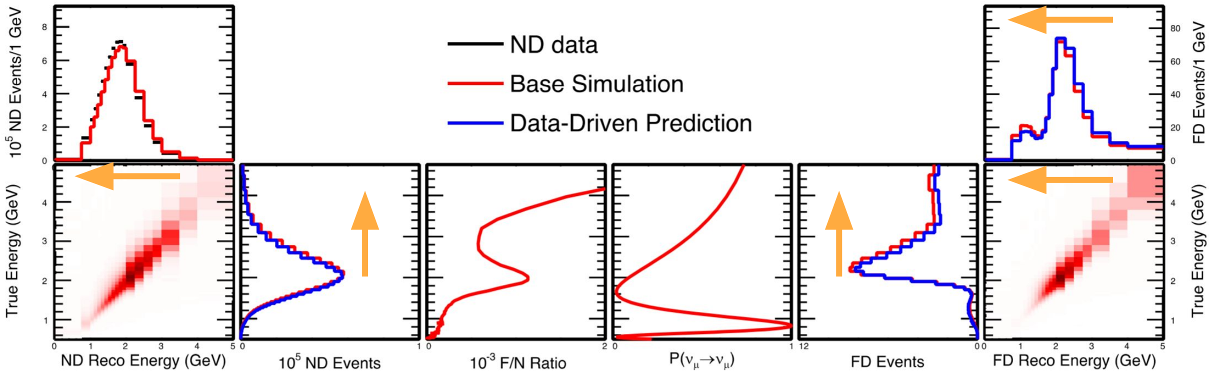
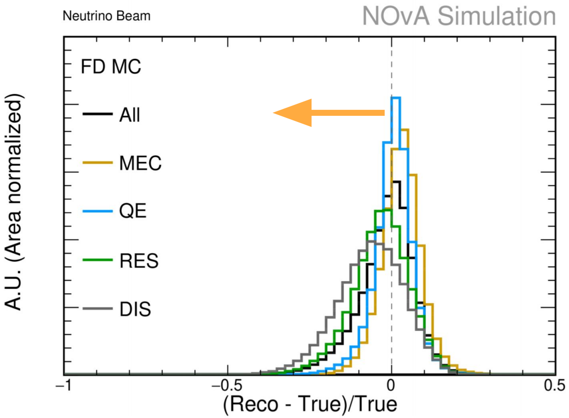
Concrete Example: NOvA

- If the models predicting **Observable → True** mappings are wrong then it is likely that inferred oscillation parameter constraints will also be wrong.
- … So we need them to be right!



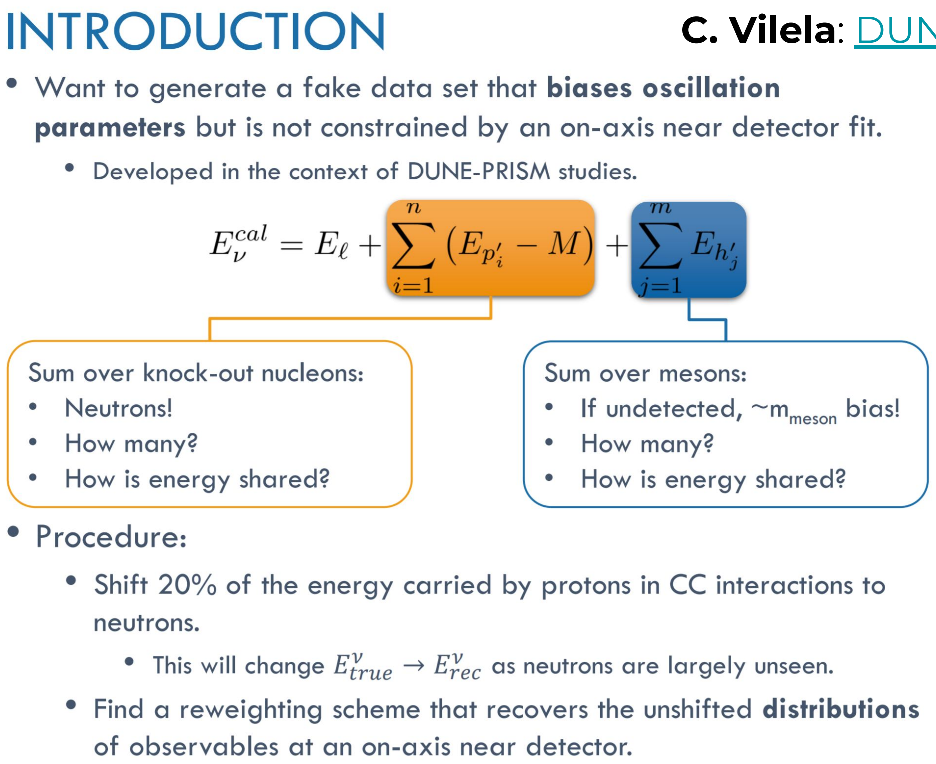
E. Smith, NOvA, NUFACT2019



J. Wolcott, NOvA, NUFACT2018

Hand Picked Fake Data

C. Vilela: DUNE Jan 2019



INTRODUCTION

- 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.

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

Sum over knock-out nucleons:
- Neutrons!
- How many?
- How is energy shared?

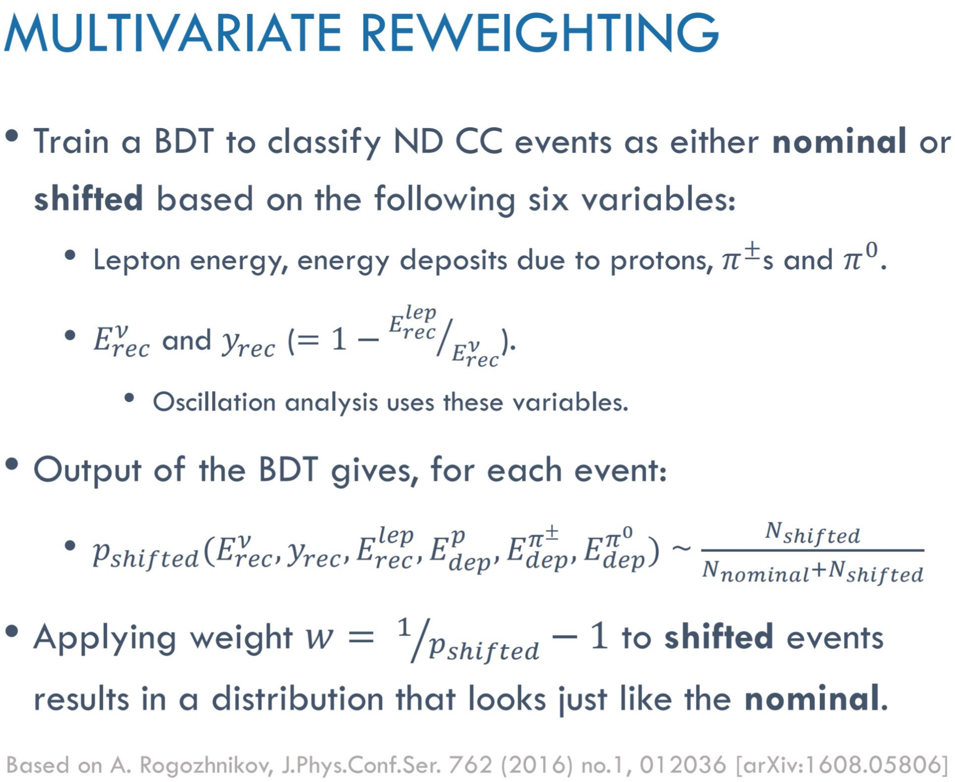
Sum over mesons:
- If undetected, ~m_{meson} bias!
- How many?
- How is energy shared?

- Procedure:
  - Shift 20% of the energy carried by protons in CC interactions to neutrons.
    - This will change $E^{\nu}_{true} \rightarrow E^{\nu}_{rec}$ 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).



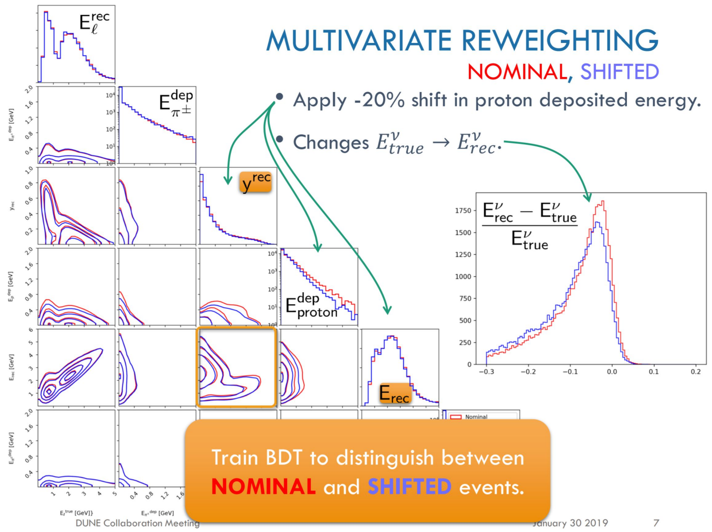
MULTIVARIATE REWEIGHTING

- 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 π^0.
  - E^{ν}_{rec} and y_{rec} $(= 1 - E^{lep}_{rec}/E^{\nu}_{rec})$.
    - Oscillation analysis uses these variables.
- Output of the BDT gives, for each event:
  - $p_{shifted}(E^{\nu}_{rec}, y_{rec}, E^{lep}_{rec}, E^{p}_{dep}, E^{\pi^{\pm}}_{dep}, E^{\pi^0}_{dep}) \sim \frac{N_{shifted}}{N_{nominal}+N_{shifted}}$
- 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



MULTIVARIATE REWEIGHTING

NOMINAL, SHIFTED

- Apply -20% shift in proton deposited energy.
- Changes $E_{true}^\nu \rightarrow E_{rec}^\nu$.

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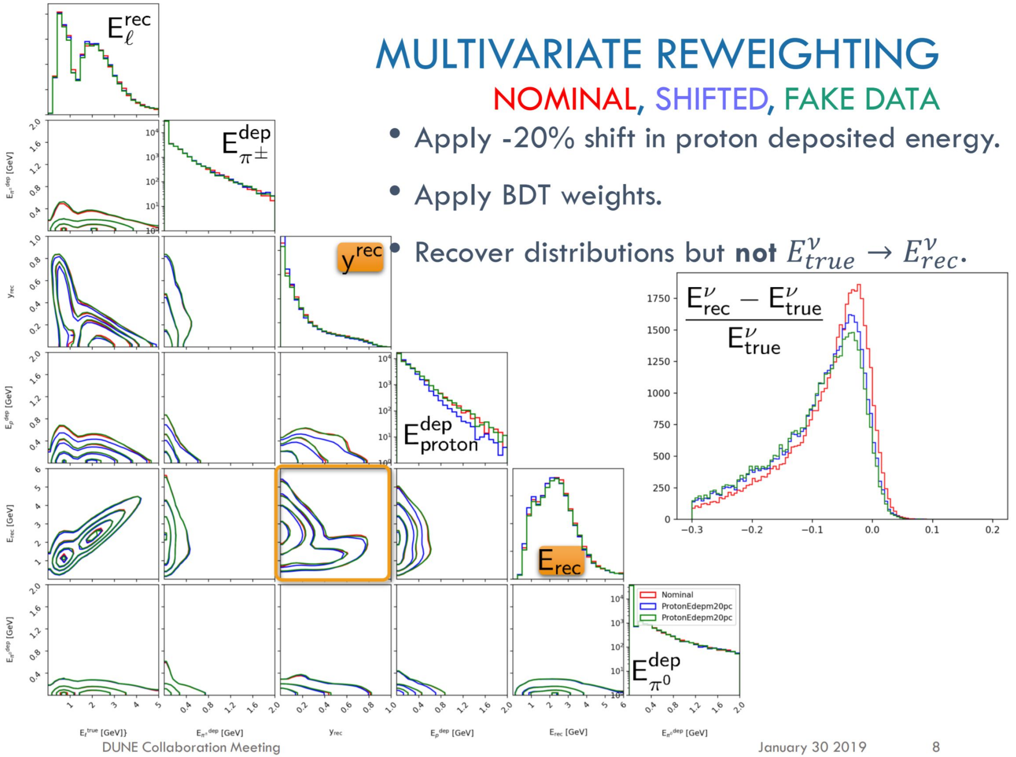
Train BDT to distinguish between **NOMINAL** and **SHIFTED** events.



MULTIVARIATE REWEIGHTING

NOMINAL, SHIFTED, FAKE DATA

- Apply -20% shift in proton deposited energy.
- Apply BDT weights.
- Recover distributions but **not** $E_{true}^\nu \rightarrow E_{rec}^\nu$.

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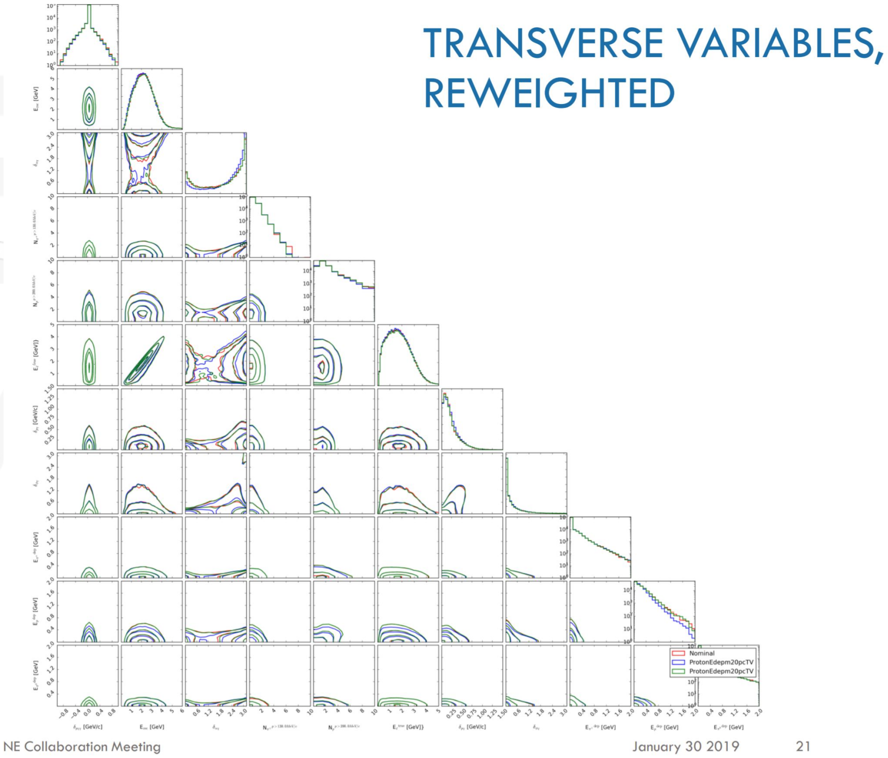
MO4R OBSERVABLES!

- 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 noisey.



TRANSVERSE VARIABLES, REWEIGHTED

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January 30 2019

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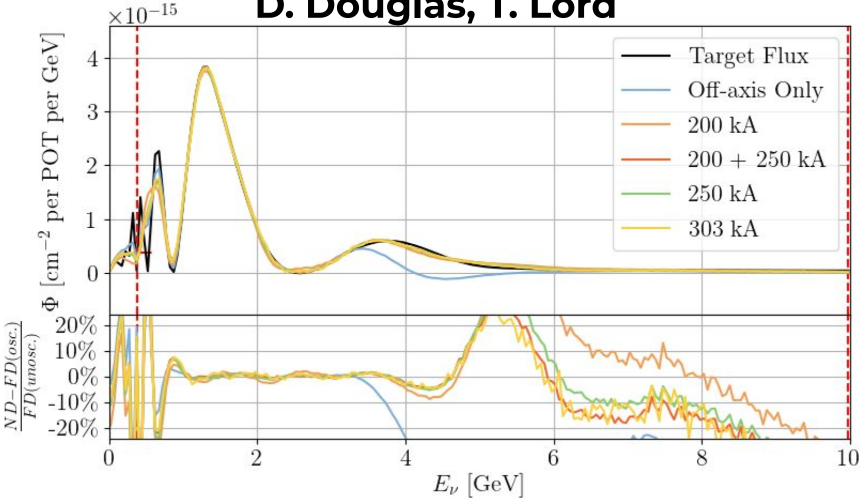
Special Horn Current Runs

- 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.**

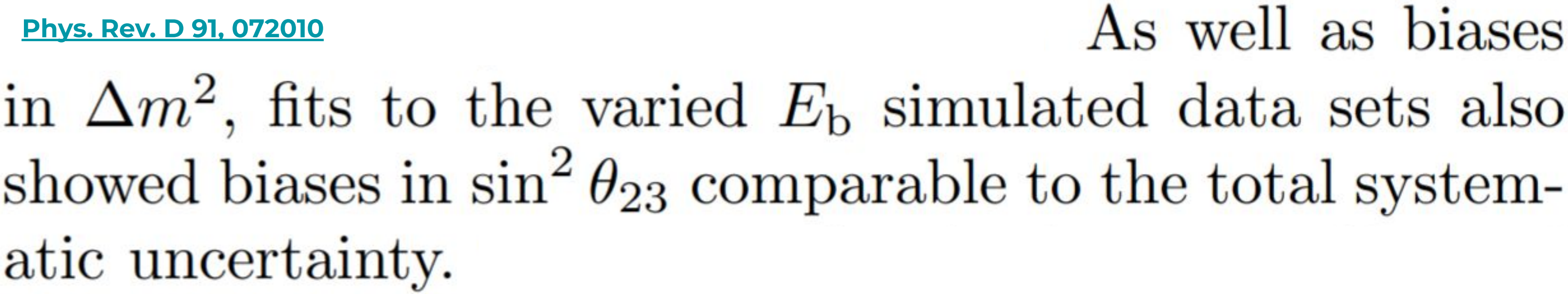
D. Douglas, T. Lord



Model-driven Extrapolation

- If model isn’t correct:
  - ⇒ Attribute data/MC discrepancy to the wrong energy range at the ND
  - ⇒ Predict wrong FD spectrum

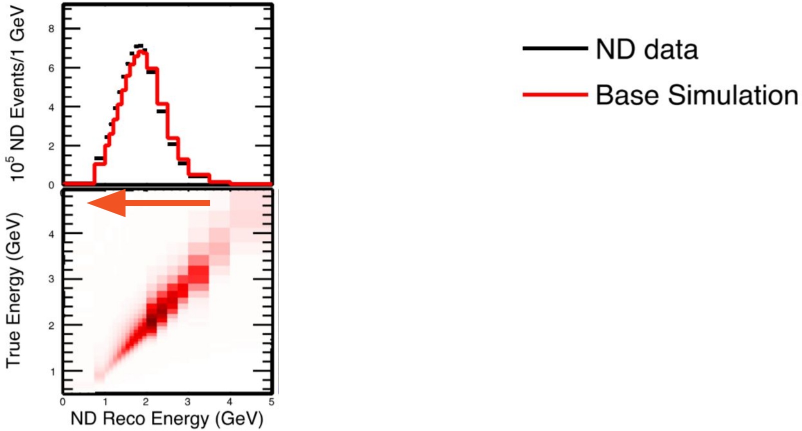
Phys. Rev. D 91, 072010



As well as biases in Δm^2, fits to the varied E_b simulated data sets also showed biases in $\sin^2\theta_{23}$ comparable to the total systematic uncertainty.

Model-driven Extrapolation

- If model isn't correct:
    - ⇒ Attribute data/MC discrepancy to the wrong energy range at the ND
    - ⇒ Predict wrong FD spectrum
- Errors in:
    - **Reconstructed energy**



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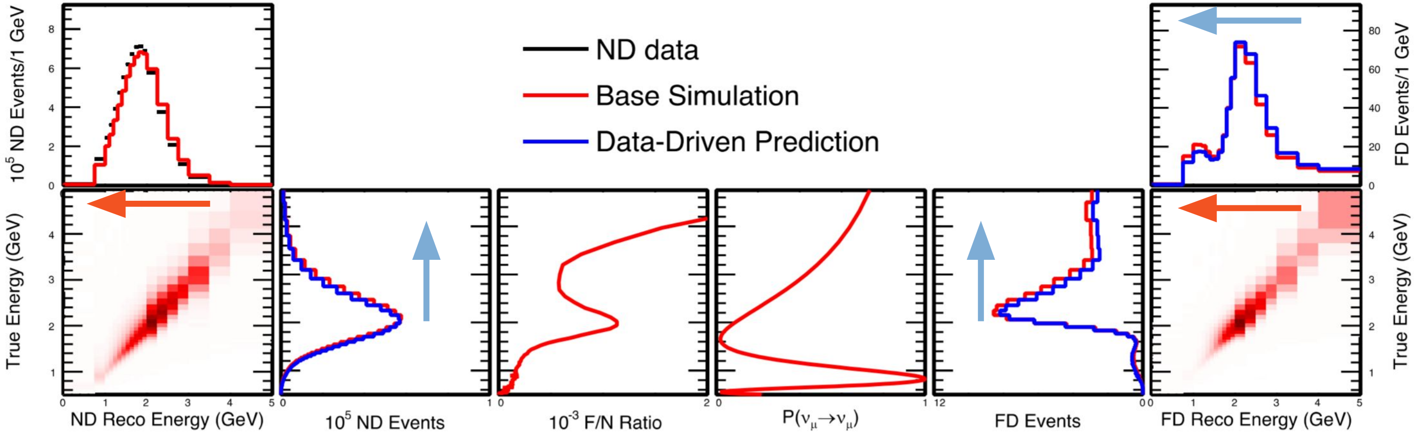
Model-driven Extrapolation

- If model isn't correct:
  - ⇒ Attribute data/MC discrepancy to the wrong energy range at the ND
  - ⇒ Predict wrong FD spectrum
- Errors in:
  - **Reconstructed energy ⇒ misplaced oscillation features in energy**



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