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Neutrinos through a PRISM

Rutherford Appleton Laboratory
Luke Pickering
2020-11-17

Pronouns: He/Him/His

MICHIGAN STATE UNIVERSITY

My Background

- PhD On T2K At Imperial College London
- PDRA at Michigan State since July 2017
  - T2K
    - Neutrino Interactions Working Group Convener
  - DUNE
    - DUNE-PRISM working group convener
    - A leader analyzer for the recent TDR oscillation sensitivity study
    - Motivating DUNE beam neutrino flux uncertainties
  - NUISANCE
    - Lead developer of framework for comparing and tuning neutrino interaction generator predictions to published cross section data.

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This Talk

- Primer: Neutrino Oscillations
- State of the Nation: A T2K Perspective
- Introduction to DUNE
- The DUNE-PRISM Concept

Big Picture Neutrino Questions

What are the precise values of the neutrino oscillation parameters?

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What is the mass ordering of the neutrino mass states?

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What are the precise values of the neutrino oscillation parameters?

Experiment

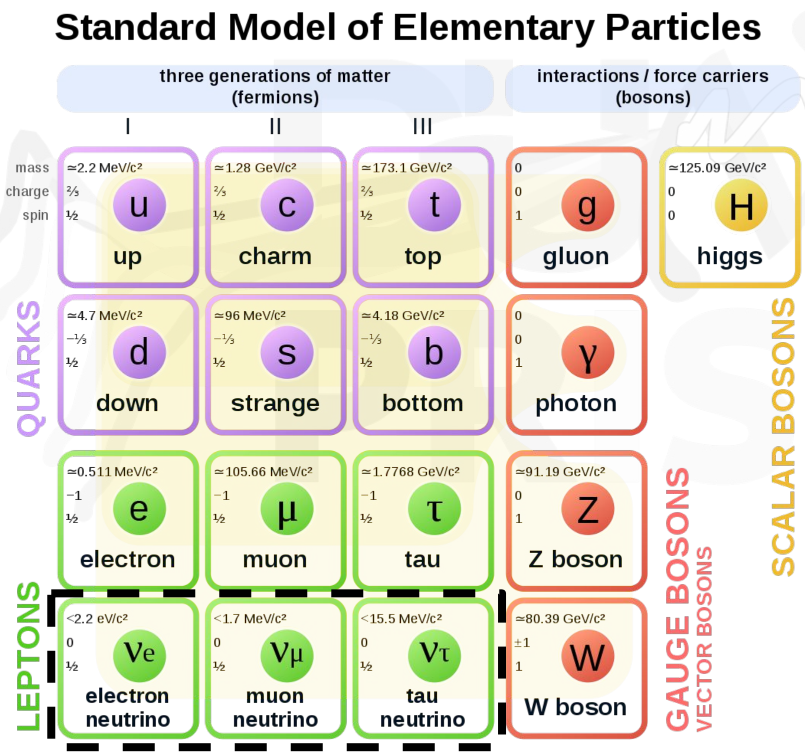
Is there significant CP violation in the neutrino sector?

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

Theory

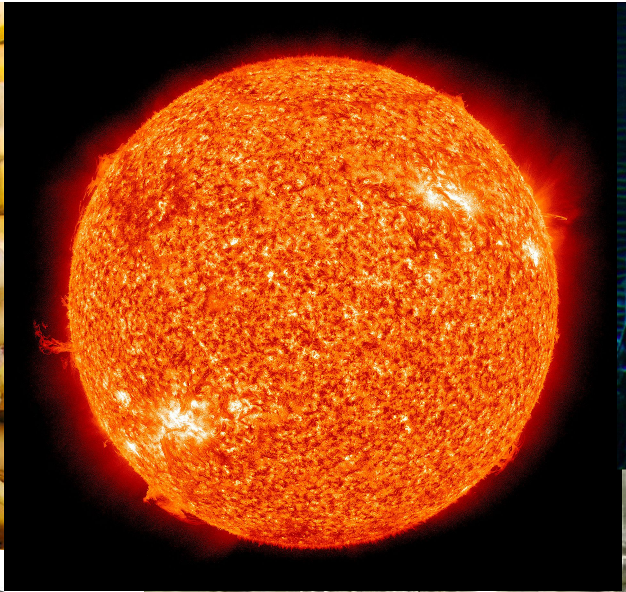
Primer: Neutrino Oscillations

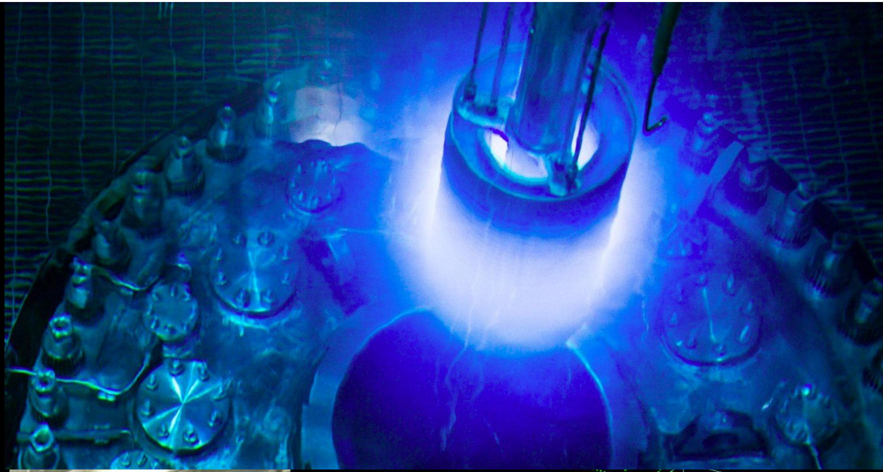
Neutrinos

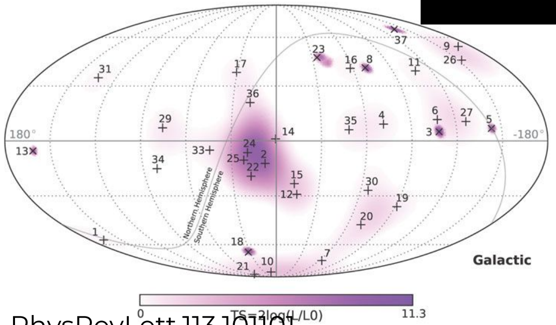


- Three generations of matter:
  - Three neutrinos paired with charged leptons: electron, muon, tau.
- Neutrinos are:
  - Electro-magnetically neutral
  - Massless within the standard model
  - Interact via mainly via the weak force.
  - Absurdly abundant

Neutrino Sources







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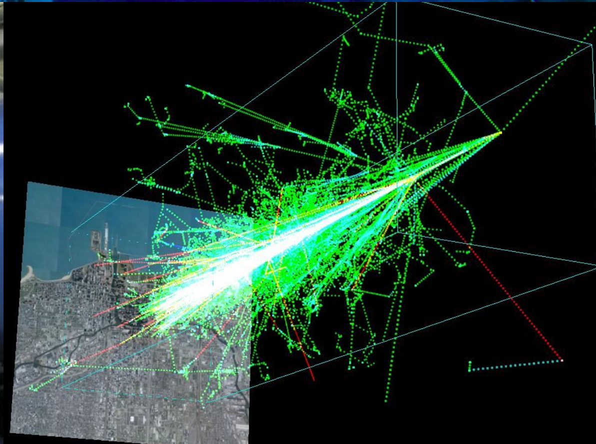


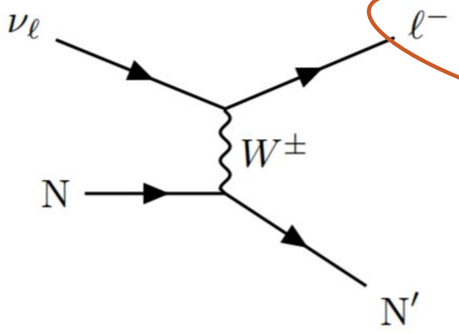
Neutrino Oscillation: PMNS

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

Pontecorvo–Maki–Nakagawa–Sakata

Neutrino Oscillation: PMNS

Flavor eigenstate defined by paired charged lepton.



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

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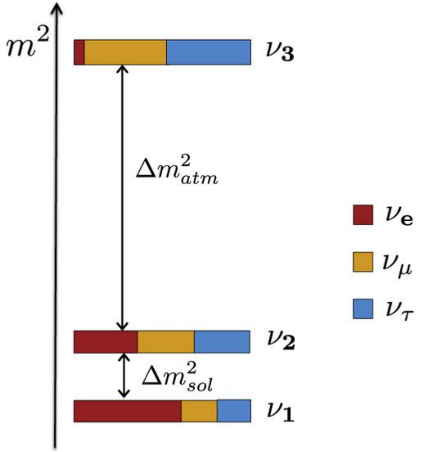

Pontecorvo–Maki–Nakagawa–Sakata

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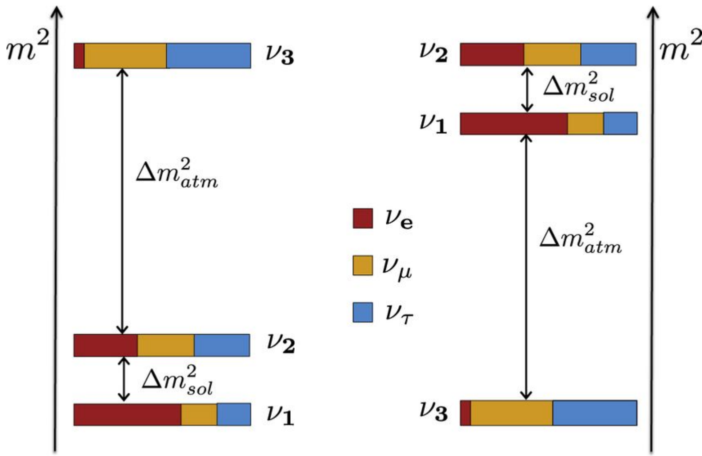
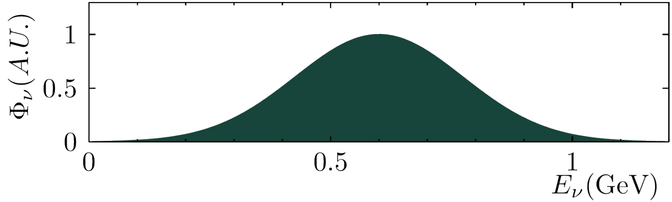
Pontecorvo–Maki–Nakagawa–Sakata



Which mass ordering?

Neutrino Oscillation: PMNS



Start with a beam of muon neutrinos

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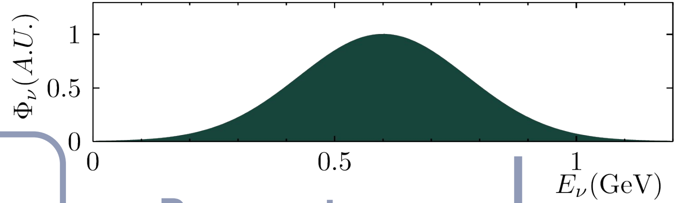

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Pontecorvo–Maki–Nakagawa–Sakata

Propagate as superposition of mass/energy eigenstates.

Neutrino Oscillation: PMNS

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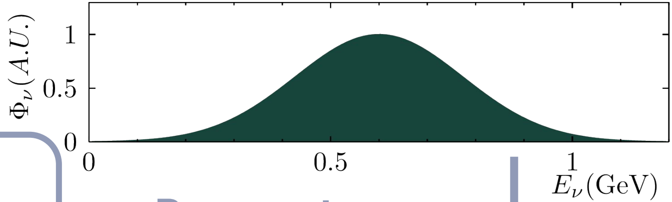

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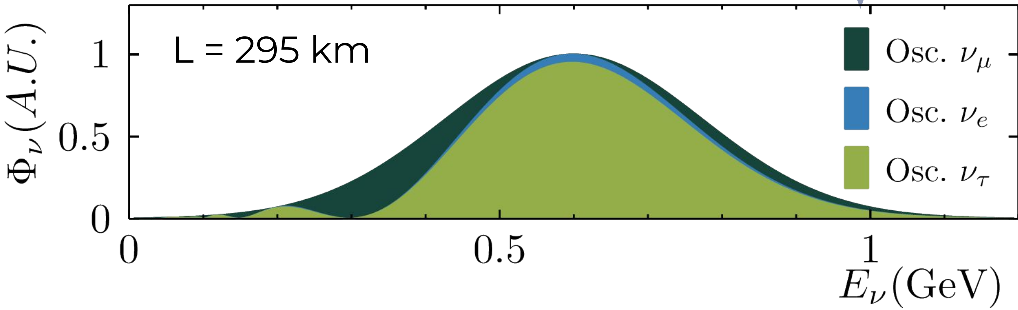
Pontecorvo–Maki–Nakagawa–Sakata

Propagate as superposition of mass/energy eigenstates.

Later measure some superposition of flavor states



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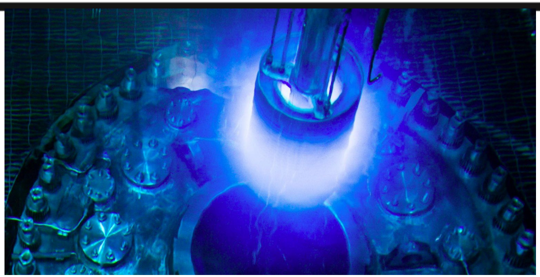
Pontecorvo–Maki–Nakagawa–Sakata

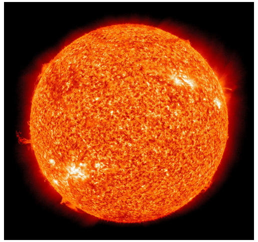
Re-parameterizing the PMNS

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

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

Re-parameterizing the PMNS





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Atmospheric /Accelerator **Reactor** **Solar**

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Oscillation Channels

- Long baseline experiments study two oscillation channels:

Muon neutrino disappearance

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

Electron neutrino appearance

$$\nu_\mu \rightarrow \nu_\mathrm{e}$$

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Muon Neutrino Disappearance

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

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

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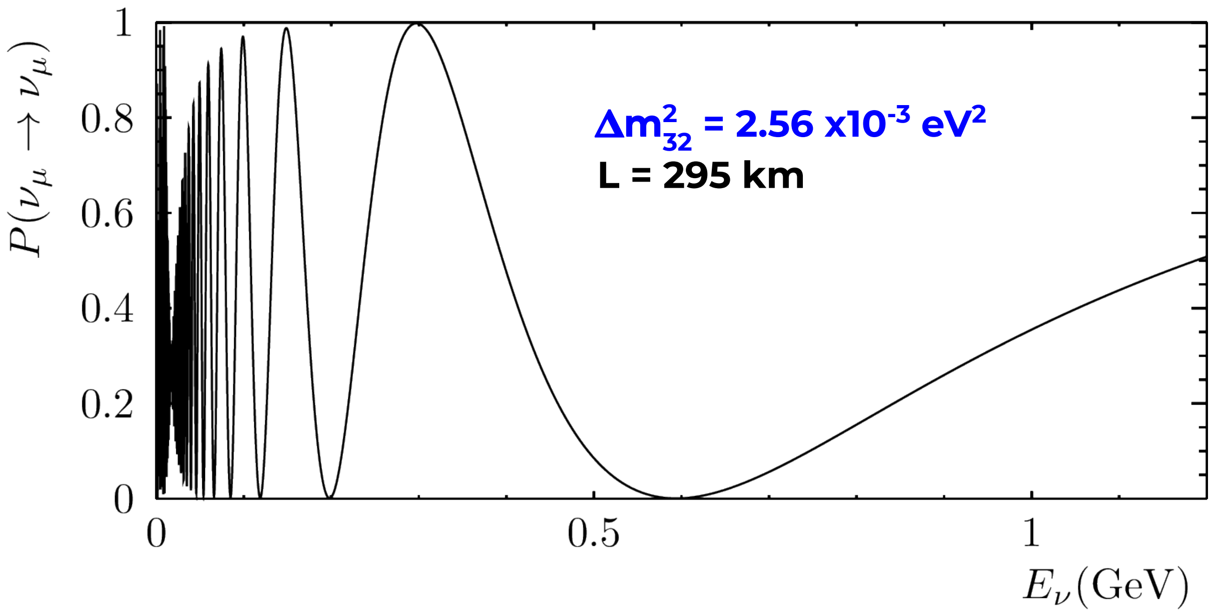
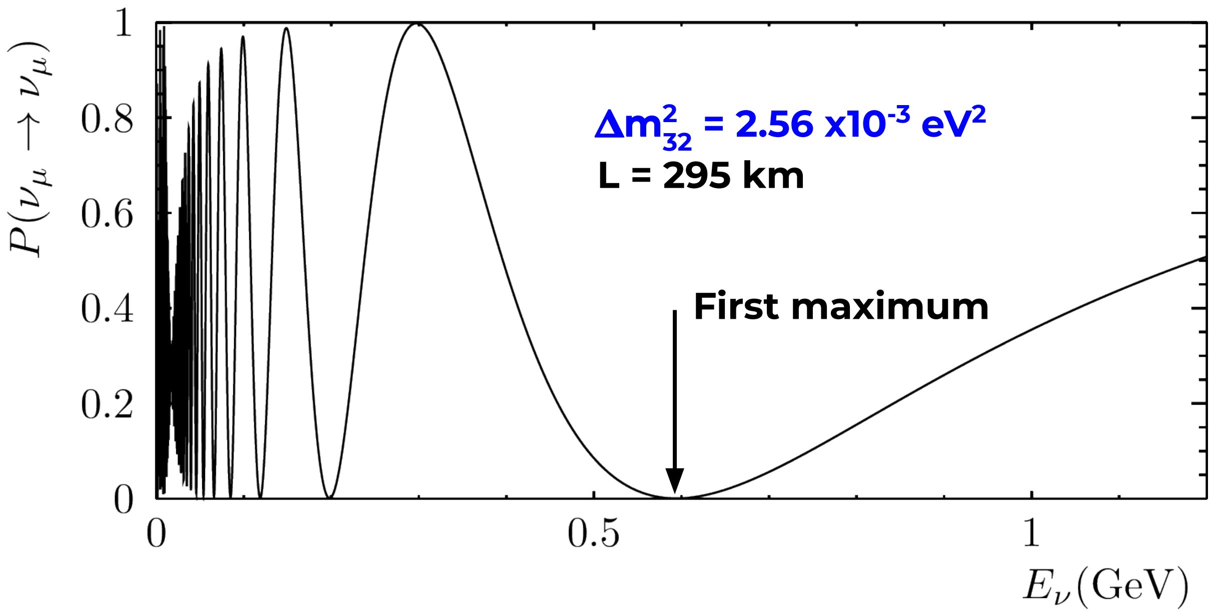


Muon Neutrino Disappearance

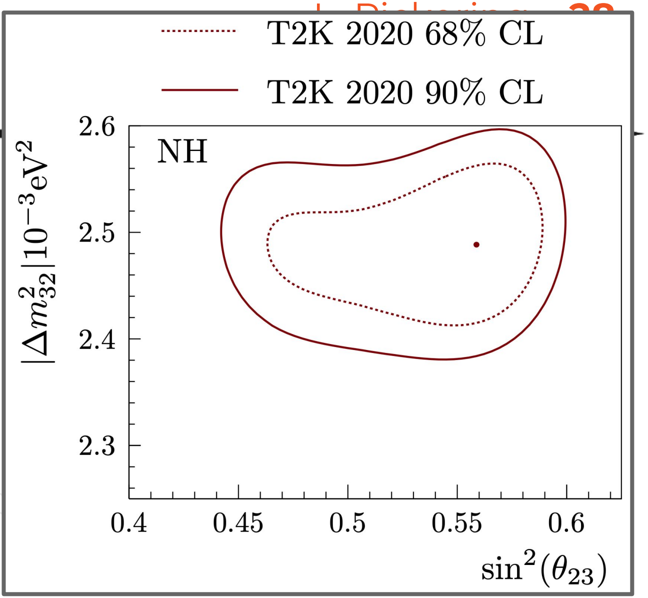
- To leading order, muon neutrino survival probability depends on **mixing angles**, and **mass-squared splittings**.
- Choose L/E for maximum effect:

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

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



Disappearing Act



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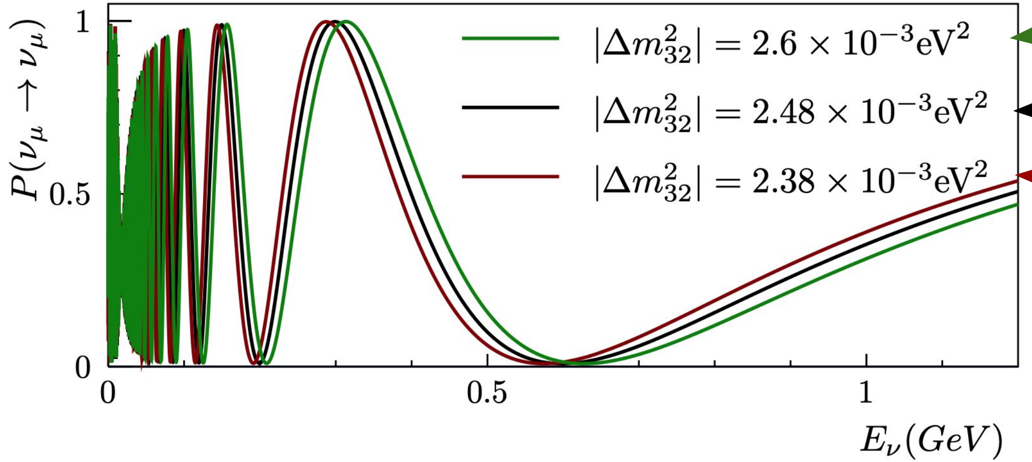
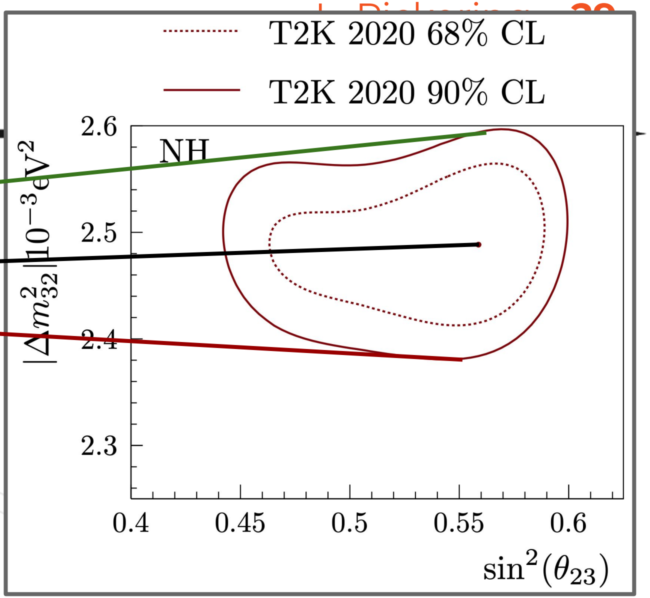
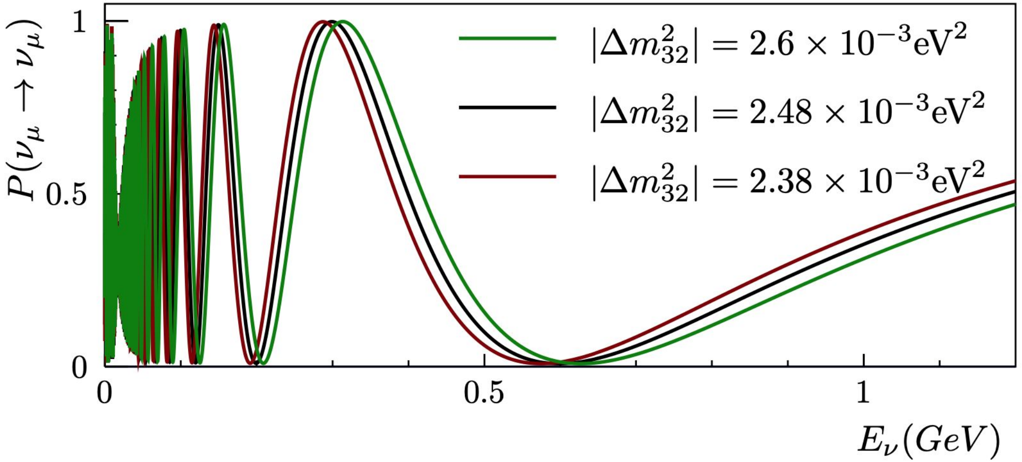
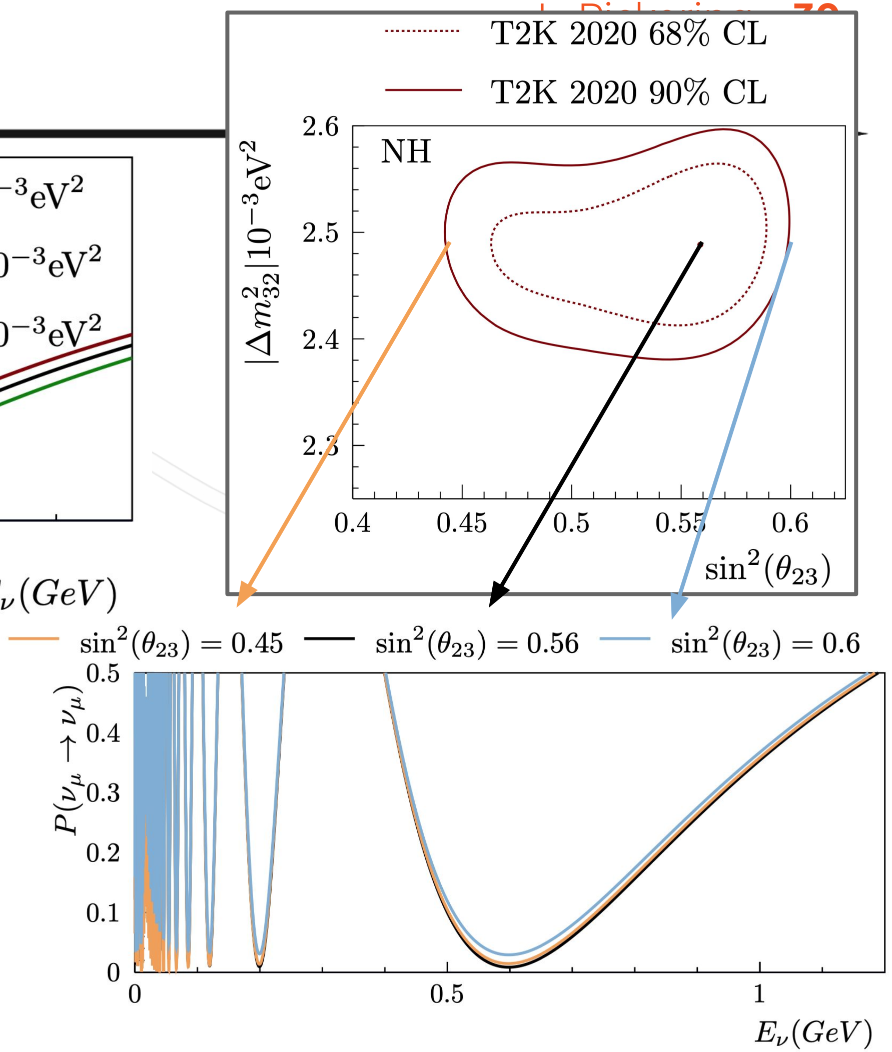




- Mass-squared splitting shifts the 'dip'

Disappearing Act





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

Oscillation Channels

- Long baseline experiments study two oscillation channels:

Muon neutrino disappearance

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

Electron neutrino appearance

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

Electron Neutrino Appearance

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

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

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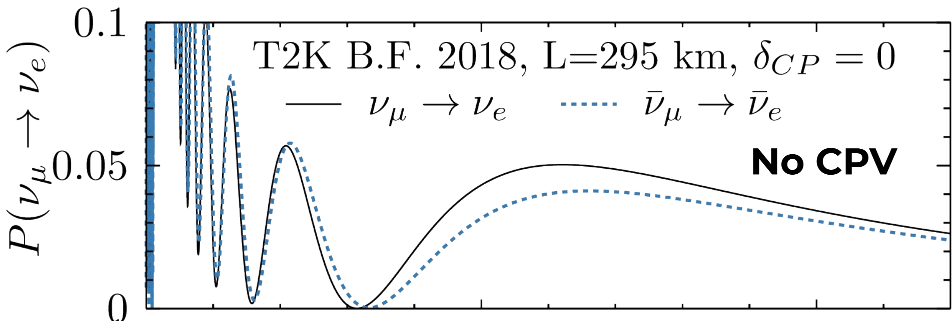

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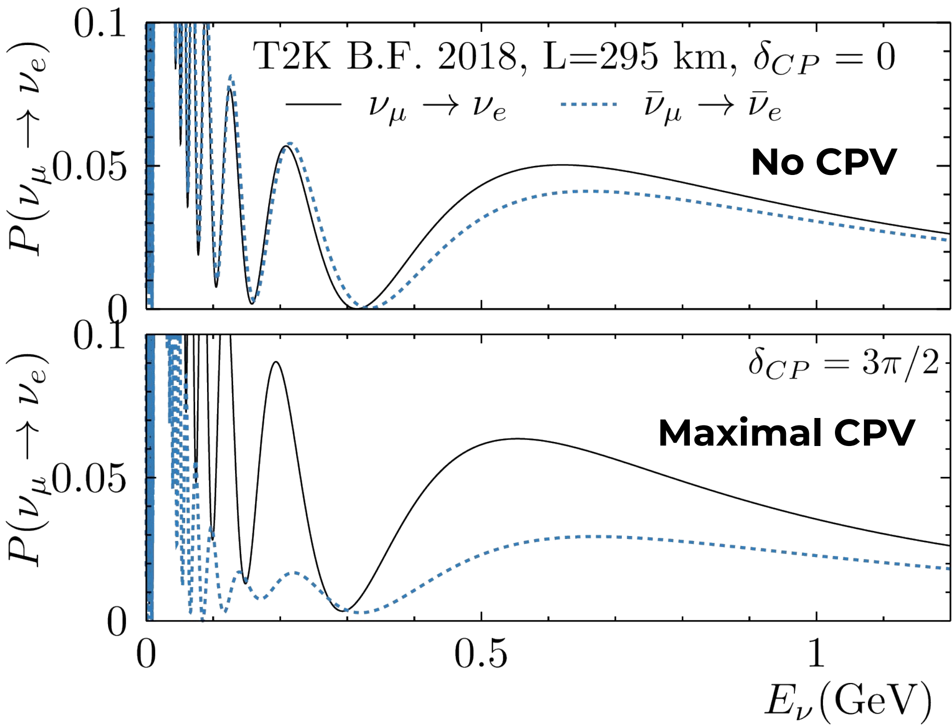

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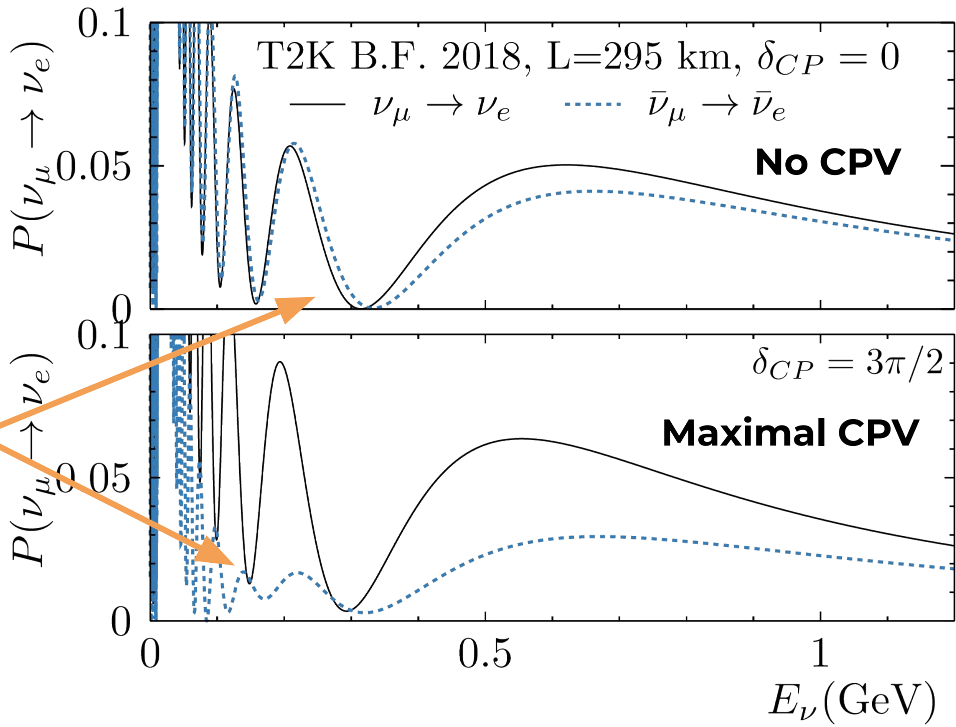
What is the value of δ_{CP}?

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



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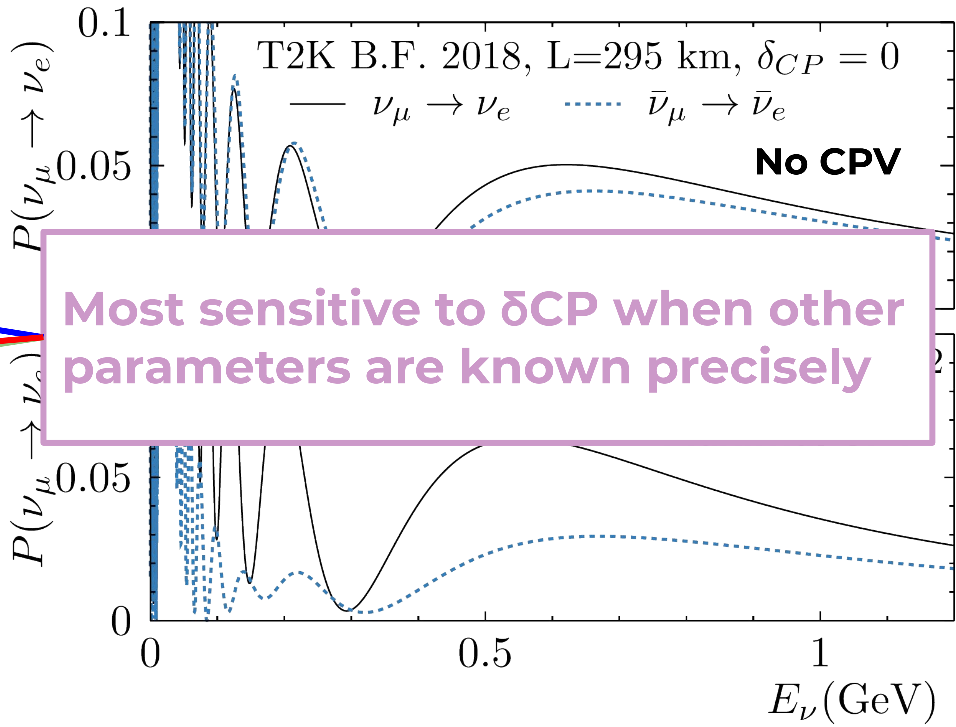
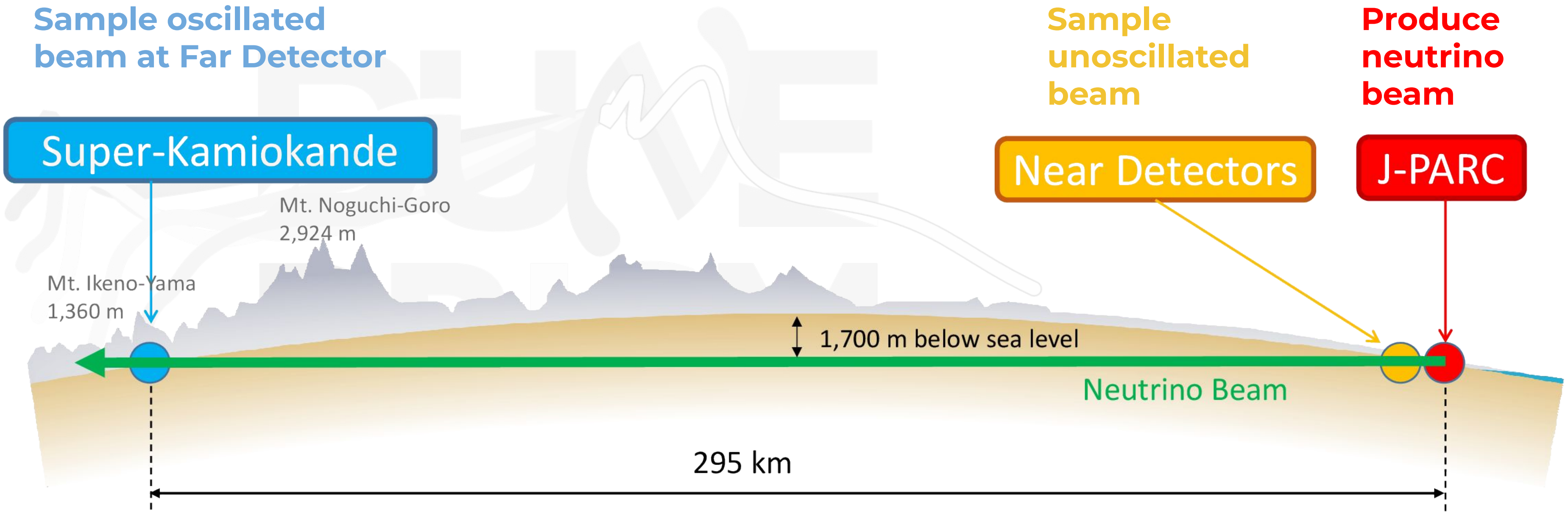


Most sensitive to δCP when other parameters are known precisely

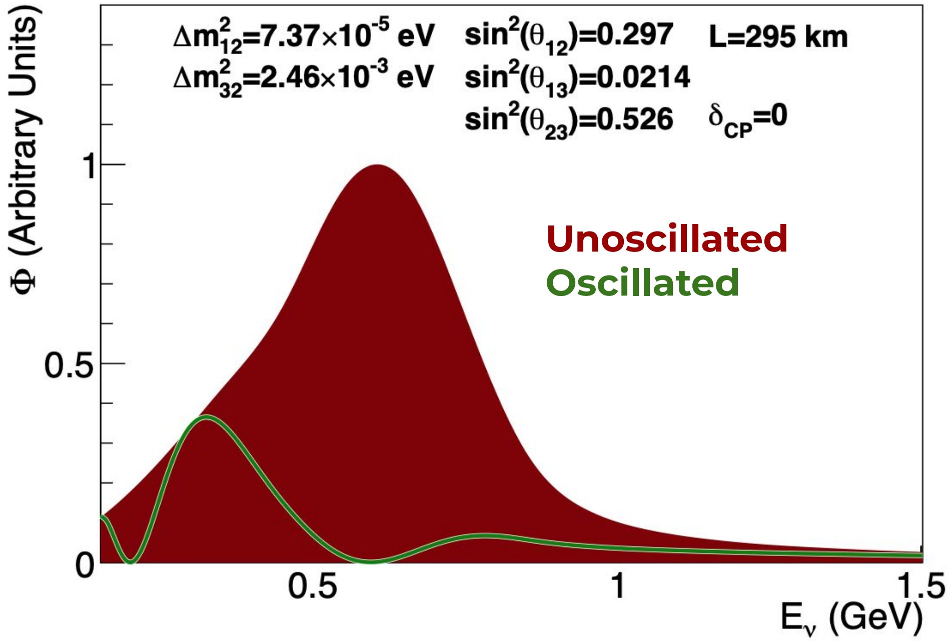
Measuring Neutrino Oscillations with T2K

Measuring Neutrino Oscillations



Measuring Oscillation Parameters

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



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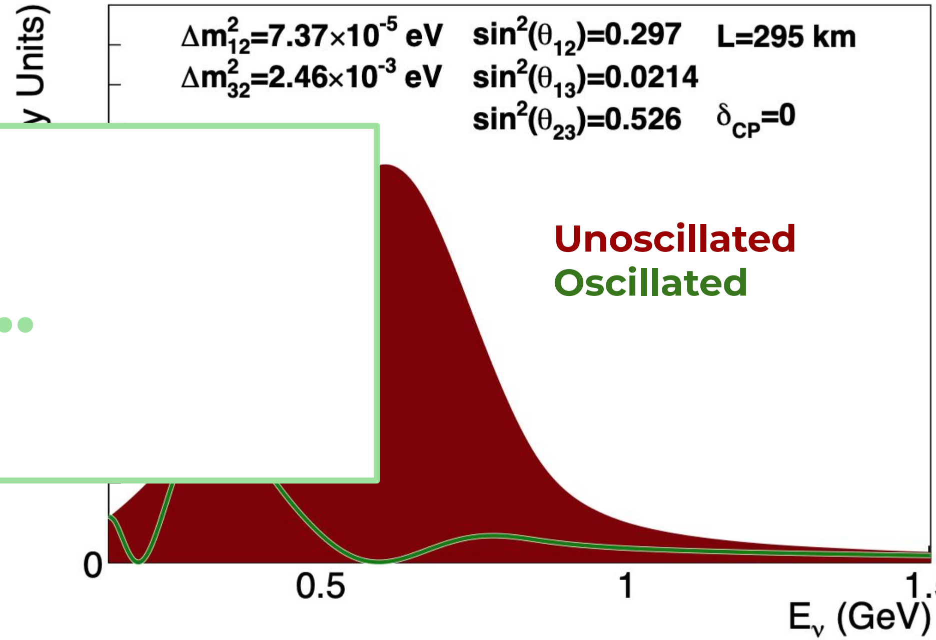
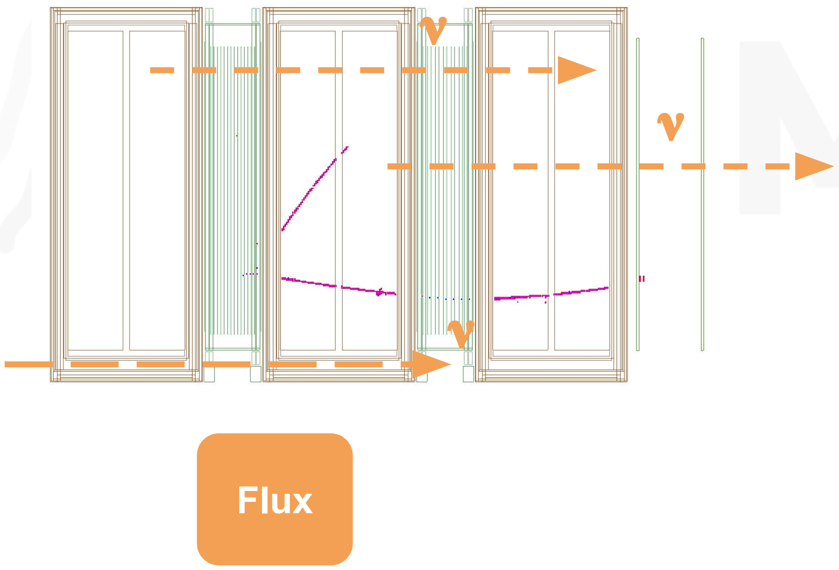


But...

Measuring Oscillation Parameters

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



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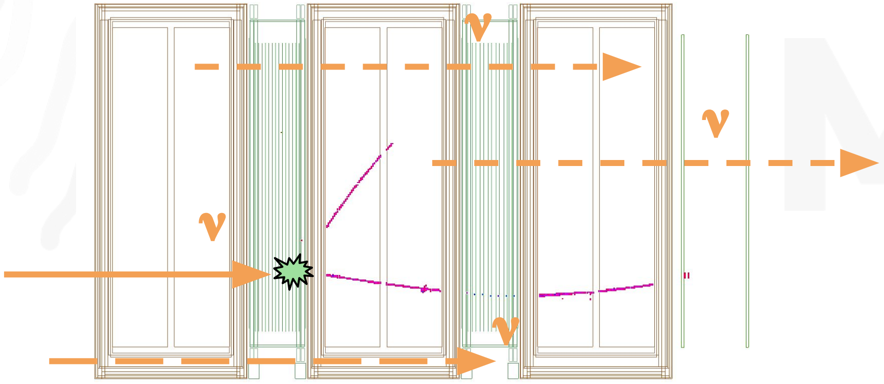
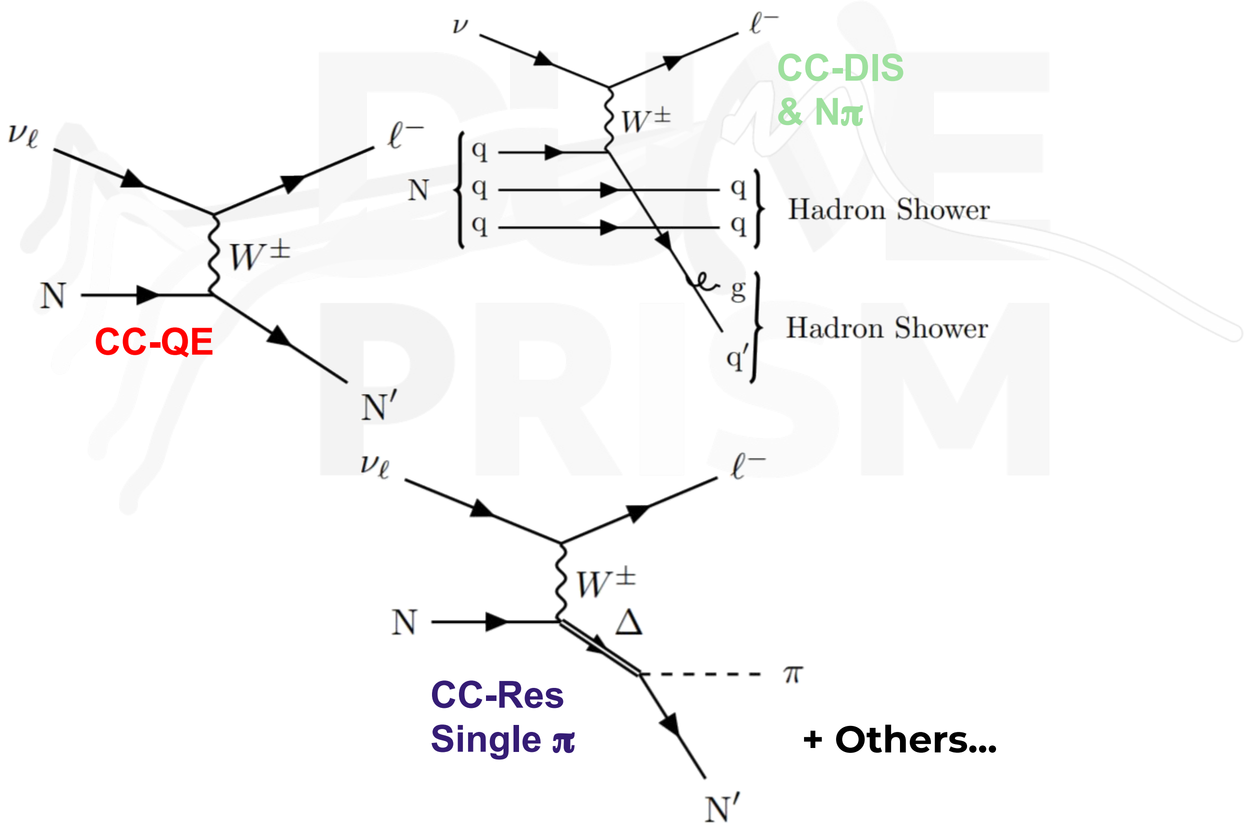


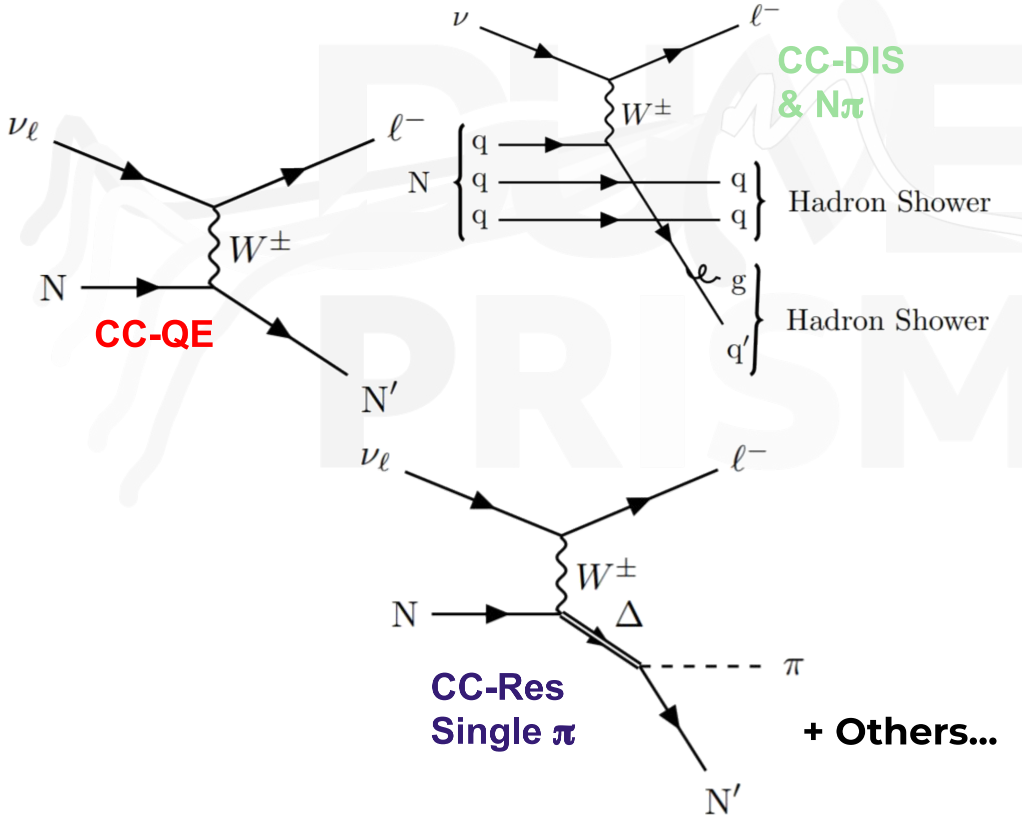
Number of events = Flux · Cross section

Measuring Oscillations: Interactions



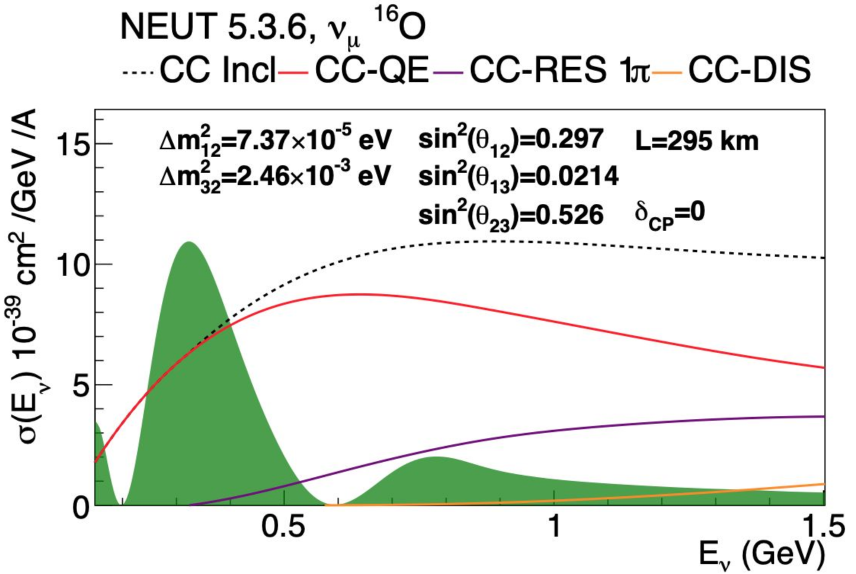
+ Others…

Measuring Oscillations: Interactions



+ Others...

NEUT: Acta Phys.Polon. B40 (2009) 2477-2489



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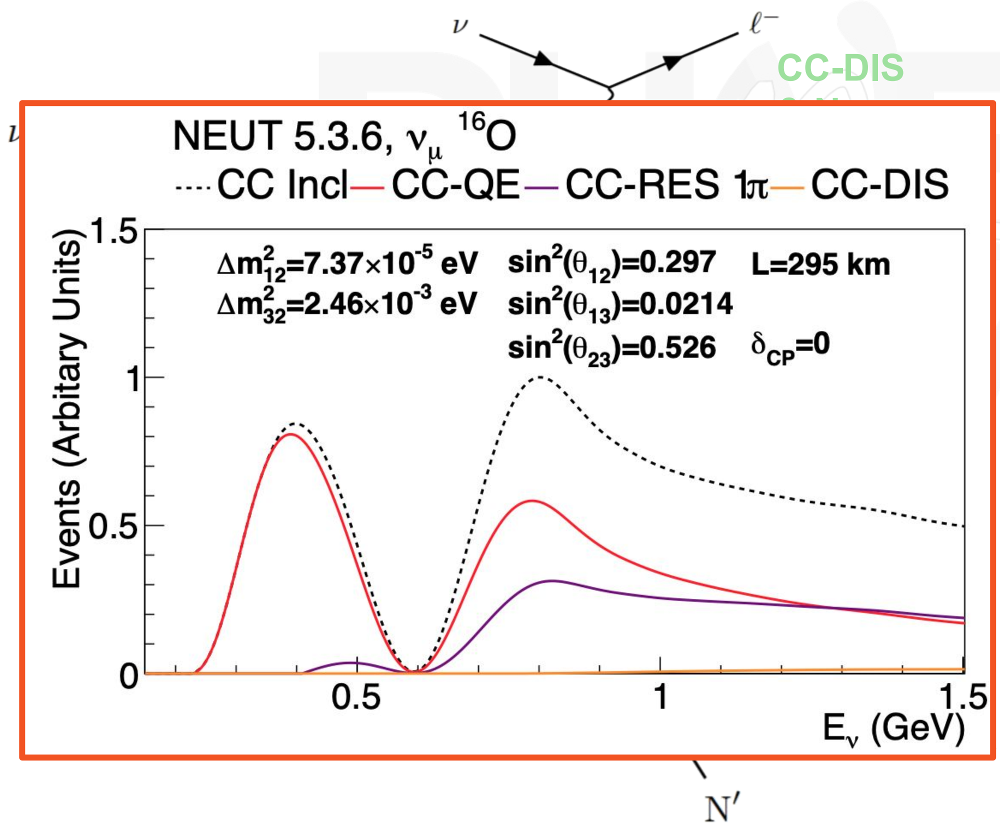

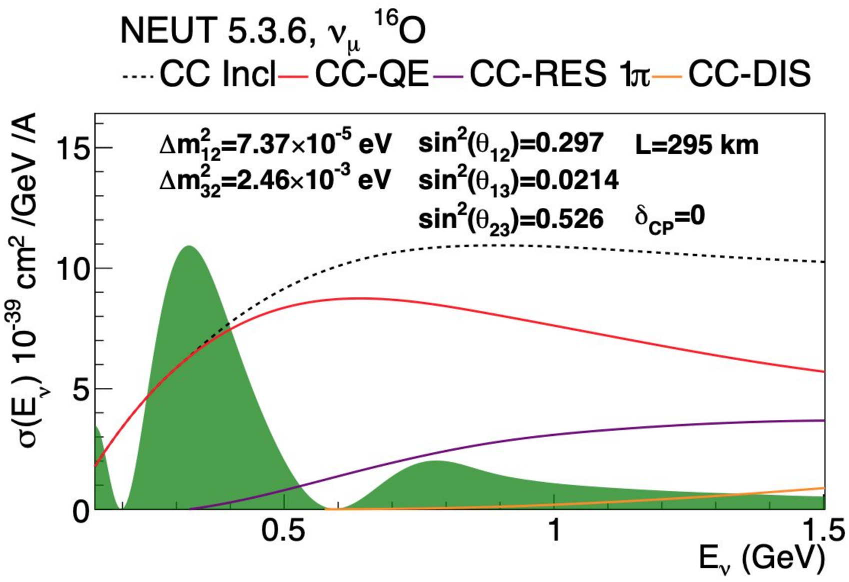

Measuring Oscillation Parameters

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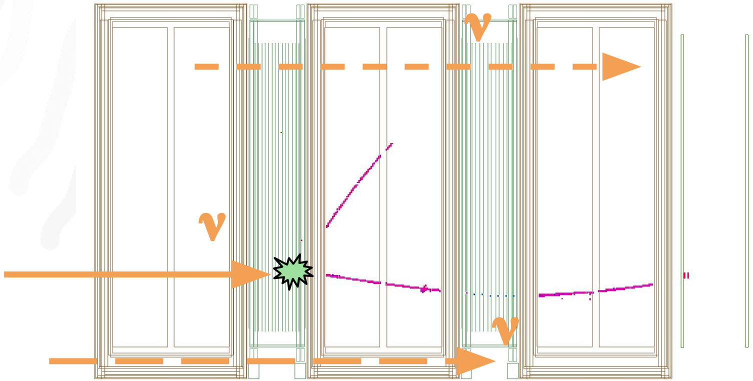

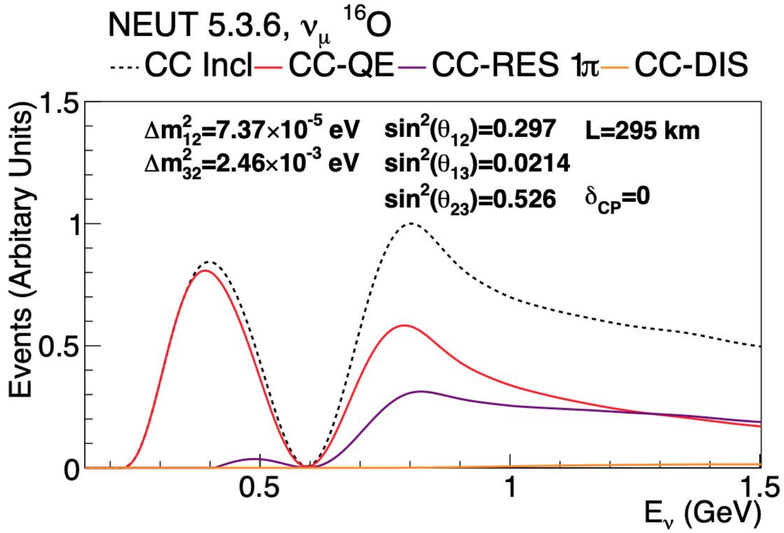

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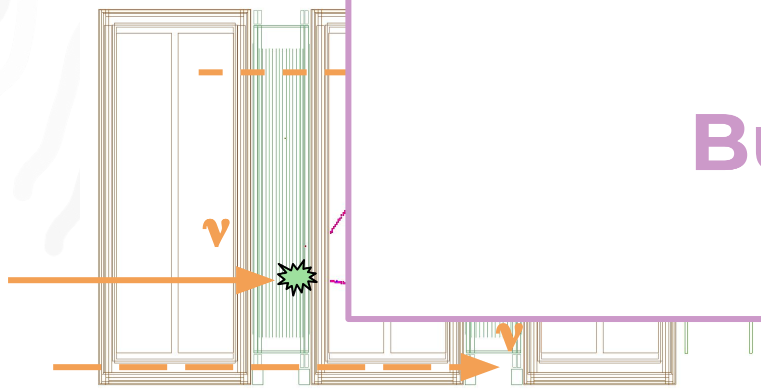

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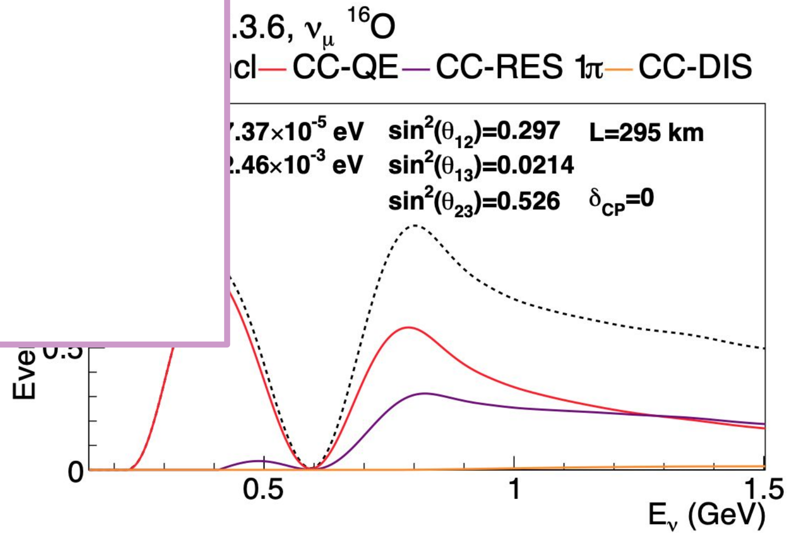

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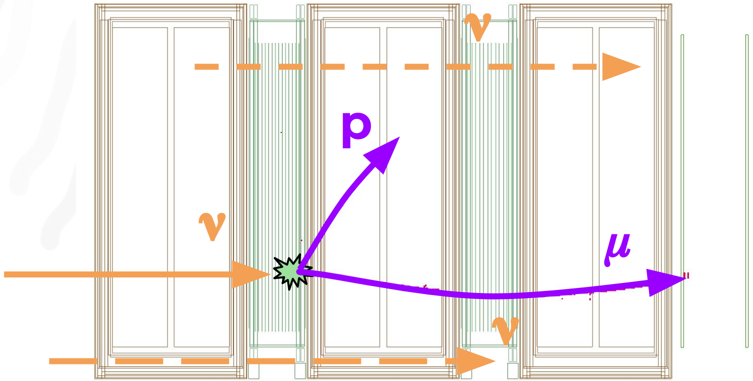

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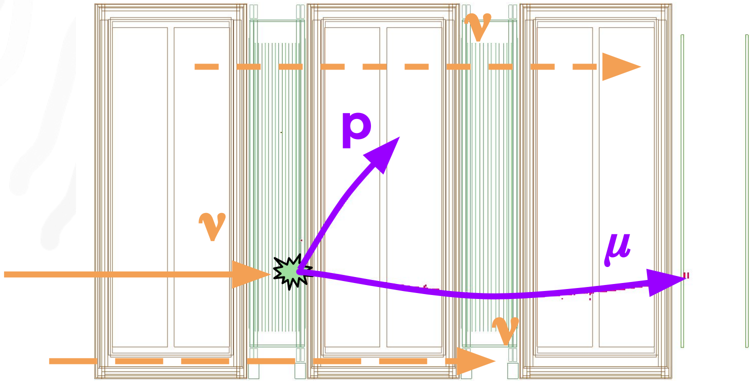

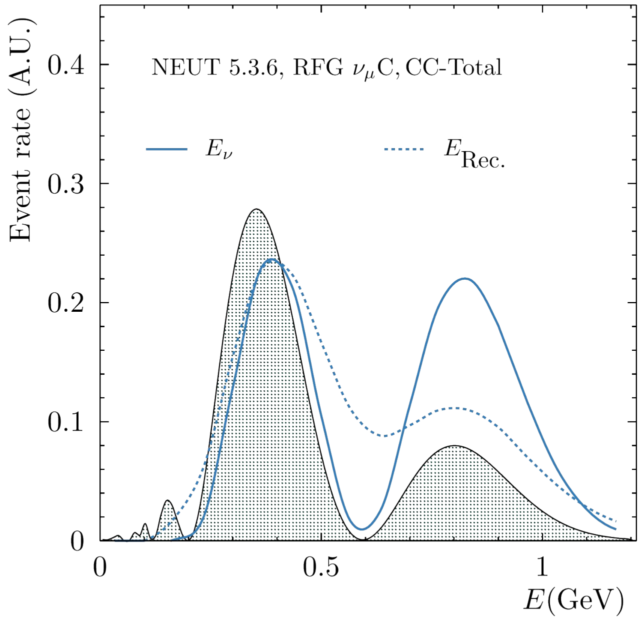

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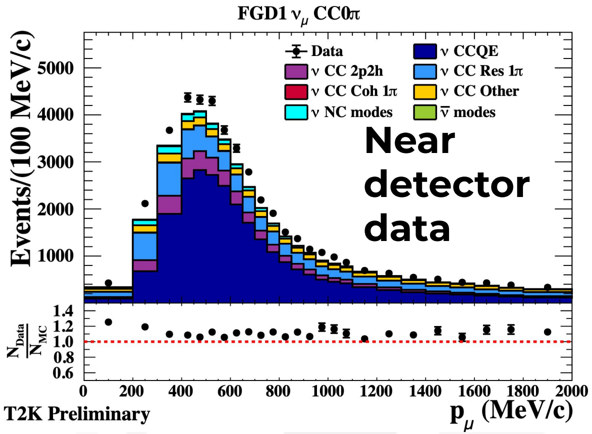
The T2K Oscillation Analysis



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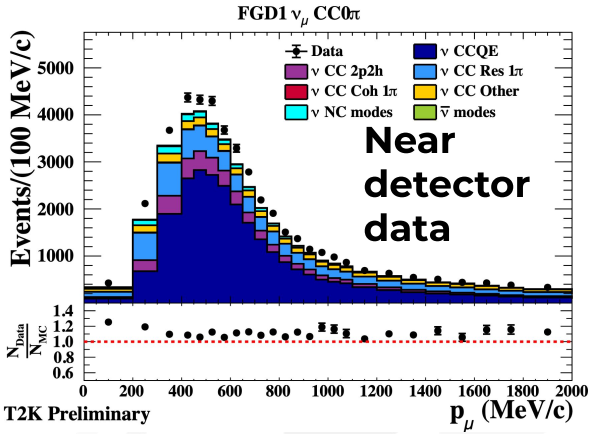

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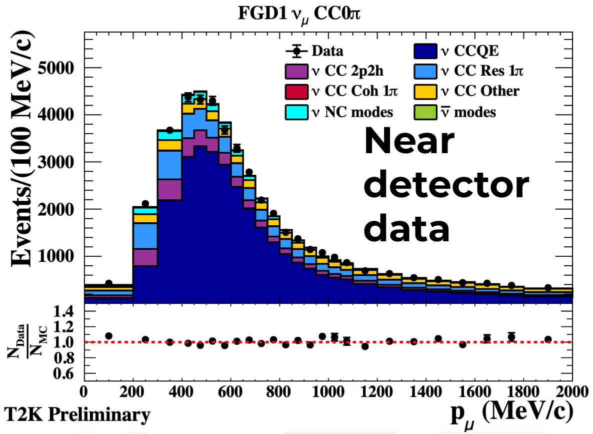

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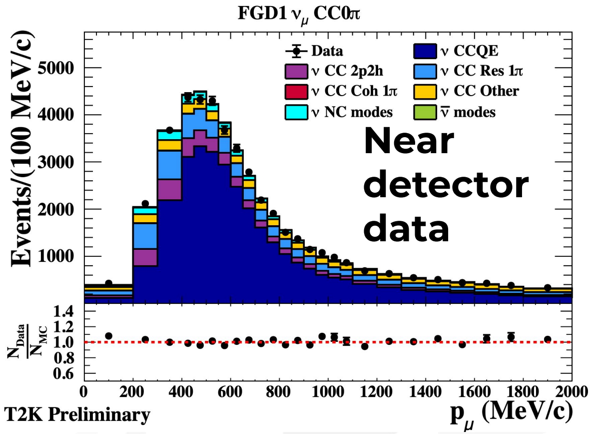

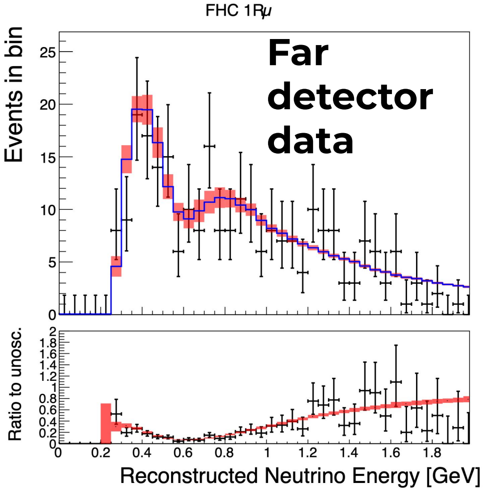

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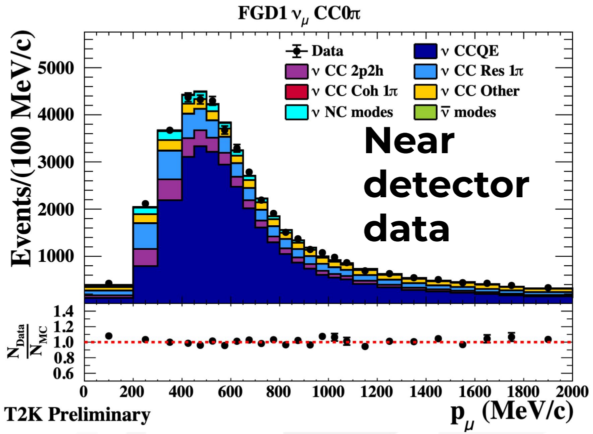

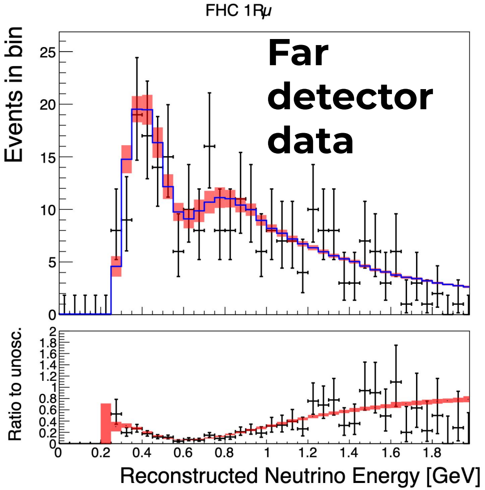

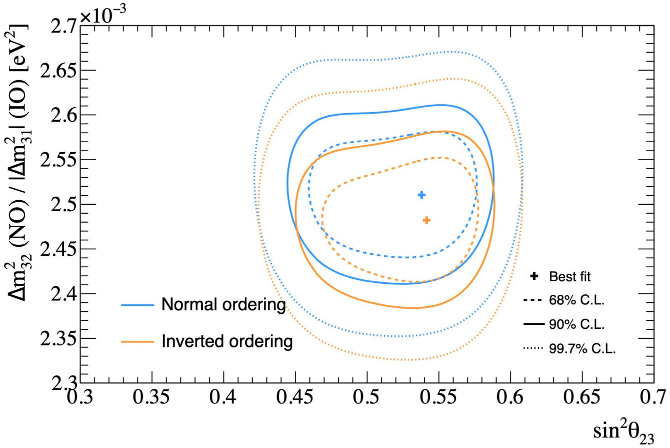

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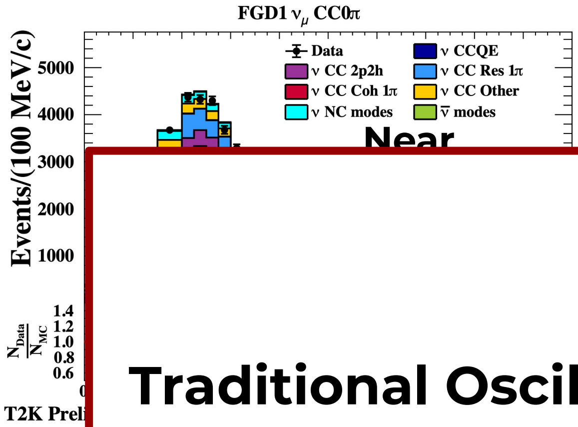

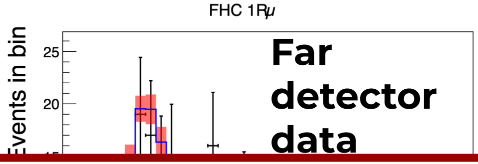

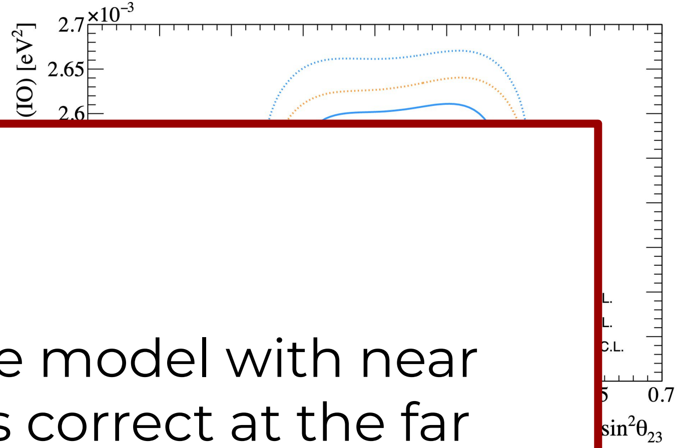

Traditional Oscillation Analyses: Tune model with near detector data, and have to assume it is correct at the far detector.

- oscillation hypothesis.
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Model-driven Extrapolation

- What if the model isn't correct? We can end up:
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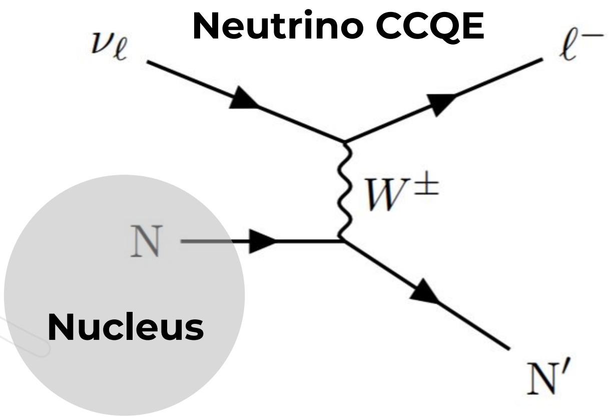
An Example from T2K

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



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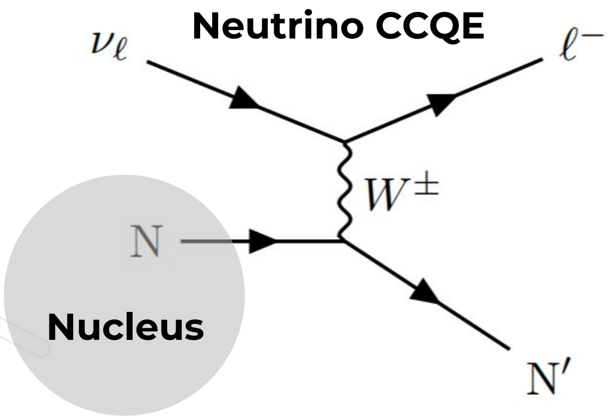

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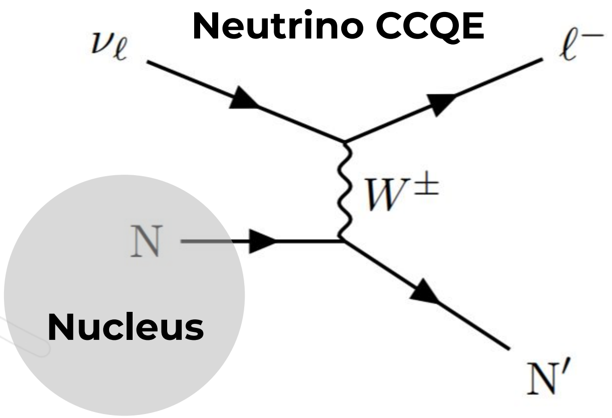

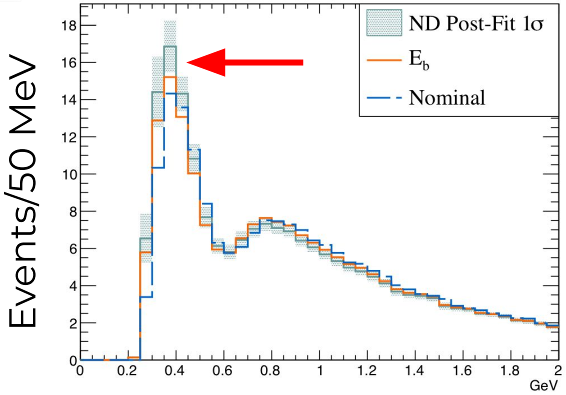

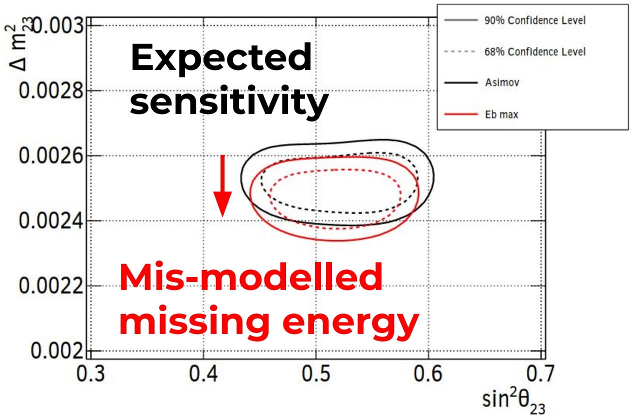

State of the Nation

Neutrino Oscillation: Where are we now?

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PDG 2020:
Neutrino Masses, Mixing, and Oscillations

$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.547 \pm 0.021 \quad \text{(Inverted order)}$$
$$\sin^2(\theta_{23}) = 0.545 \pm 0.021 \quad \text{(Normal order)}$$
$$\Delta m^2_{32} = (-2.546^{+0.034}_{-0.040}) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{(Inverted order)}$$
$$\Delta m^2_{32} = (2.453 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{(Normal order)}$$
$$\sin^2(\theta_{13}) = (2.18 \pm 0.07) \times 10^{-2}$$

Neutrino Oscillation: Where are we now?

- Evidence for neutrino oscillation is overwhelming: *c.f.* 2015 Nobel Prize
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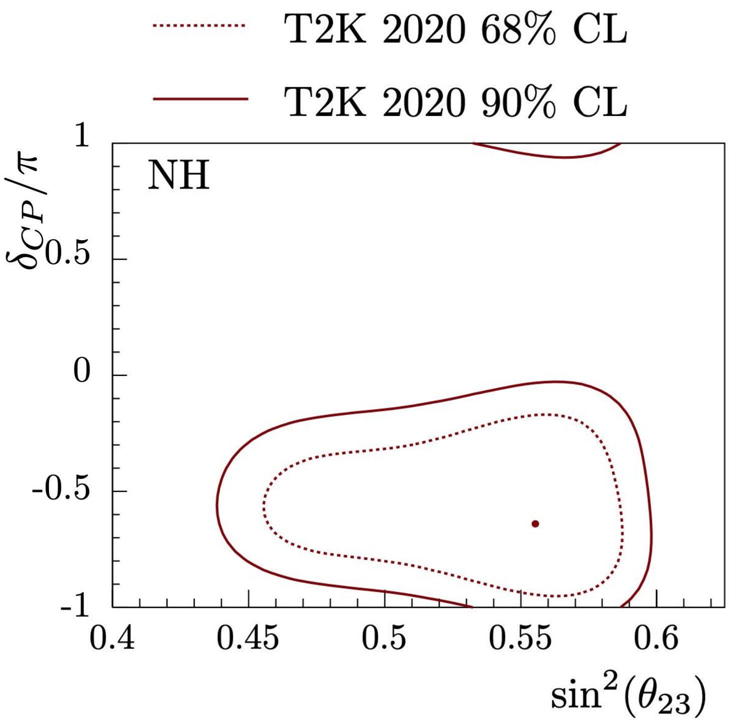

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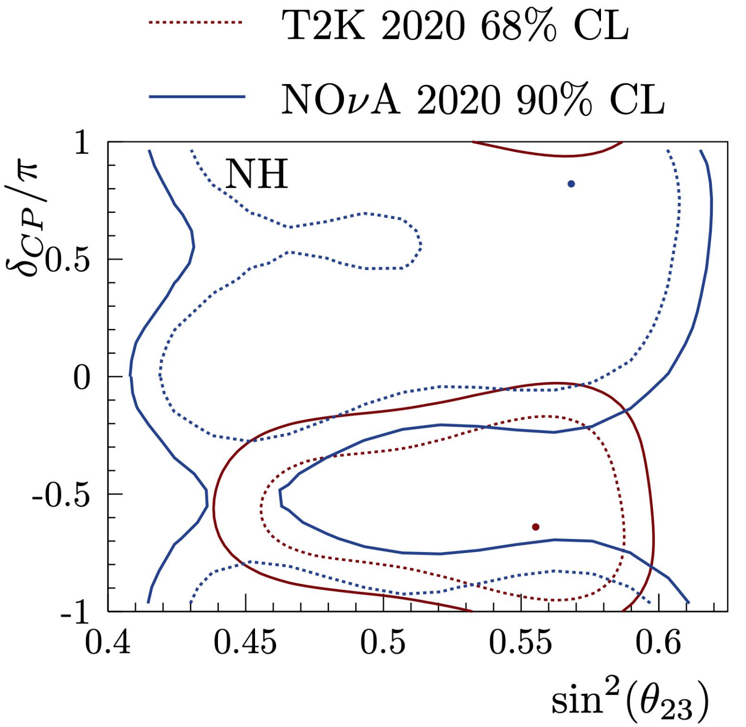
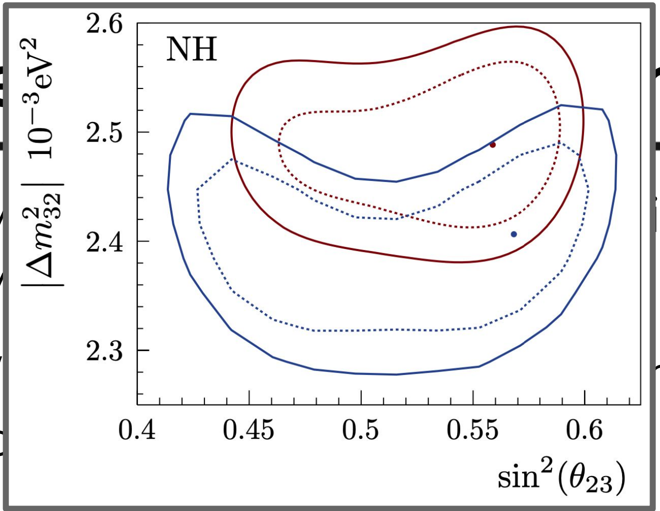


Ne… n: Where are we now?



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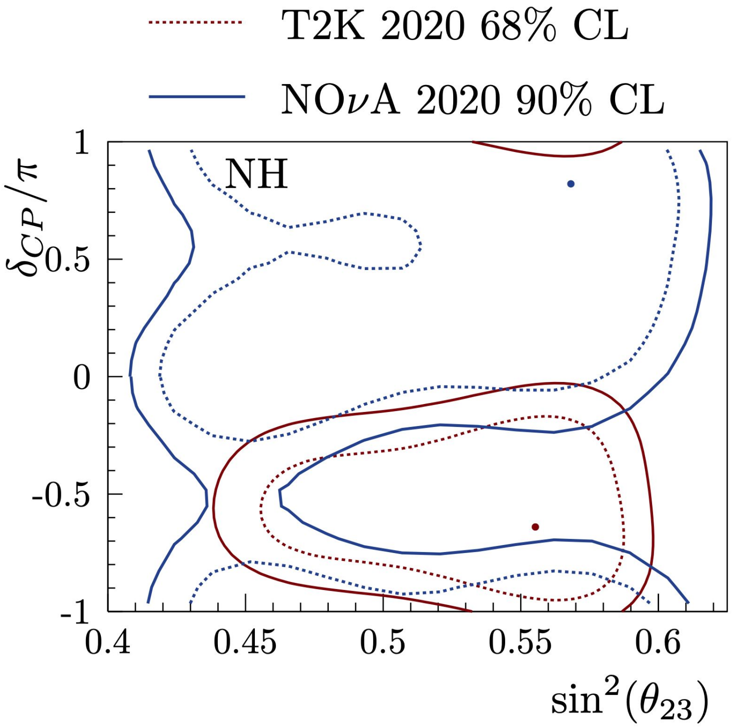

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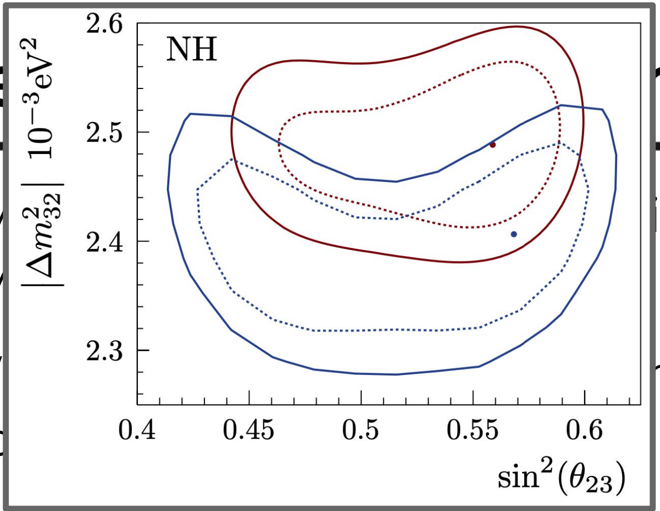

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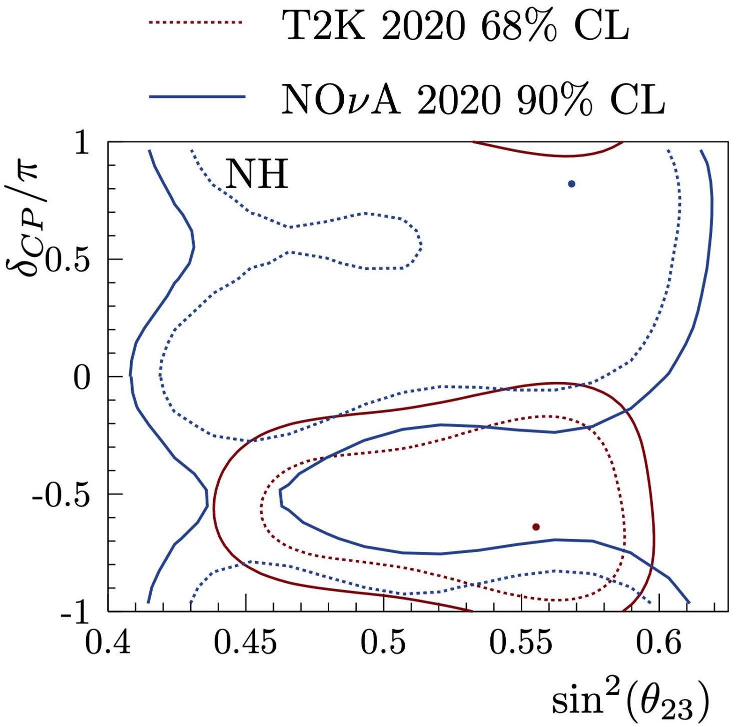
  - **Need new experiment for definitive 'five sigma' result...**



The Deep Underground Neutrino Experiment

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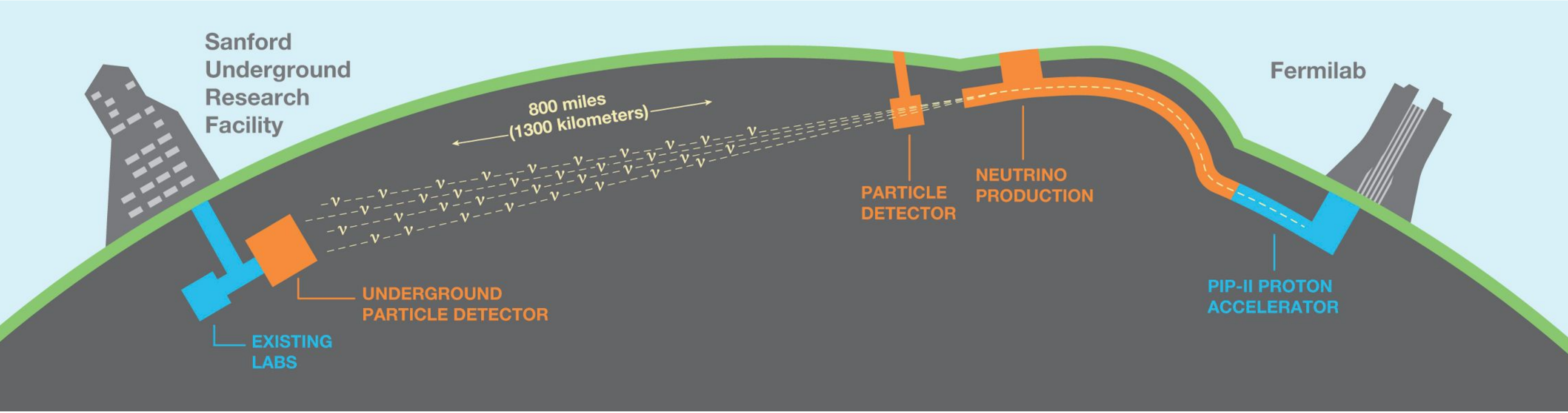

Collaboration

- >1100 Collaborators
- 34 Countries

PMNS Oscillations

- Unprecedented sensitivity to osc. params.
- Measurement of δ_{CP} and mass ordering

Rich Physics Program

- Solar ν's
- Geo ν's
- SN ν's
- ~~Banana ν's~~
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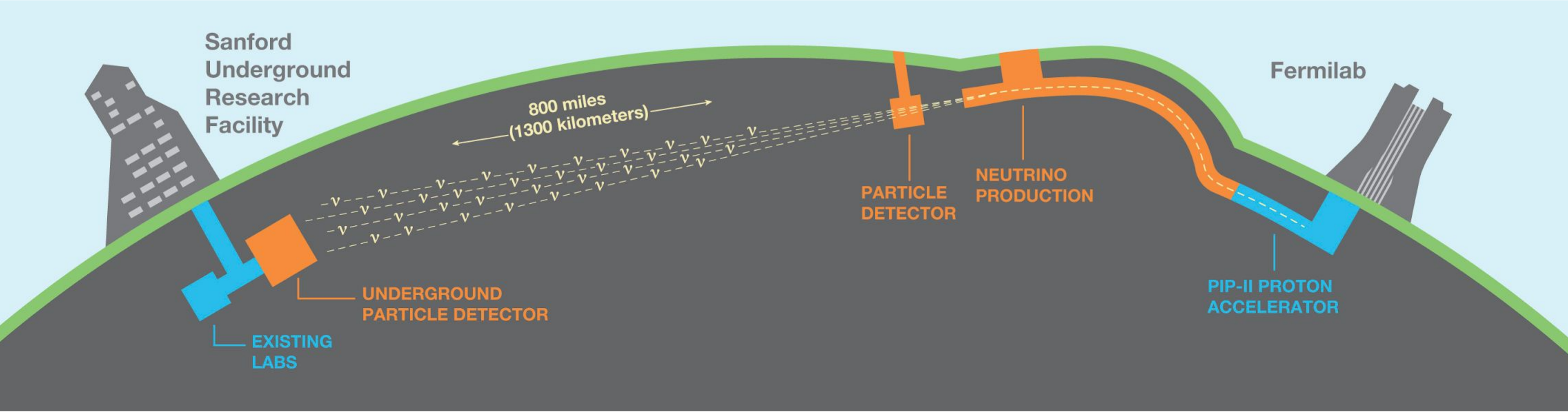

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Expected to take data at the end of the decade

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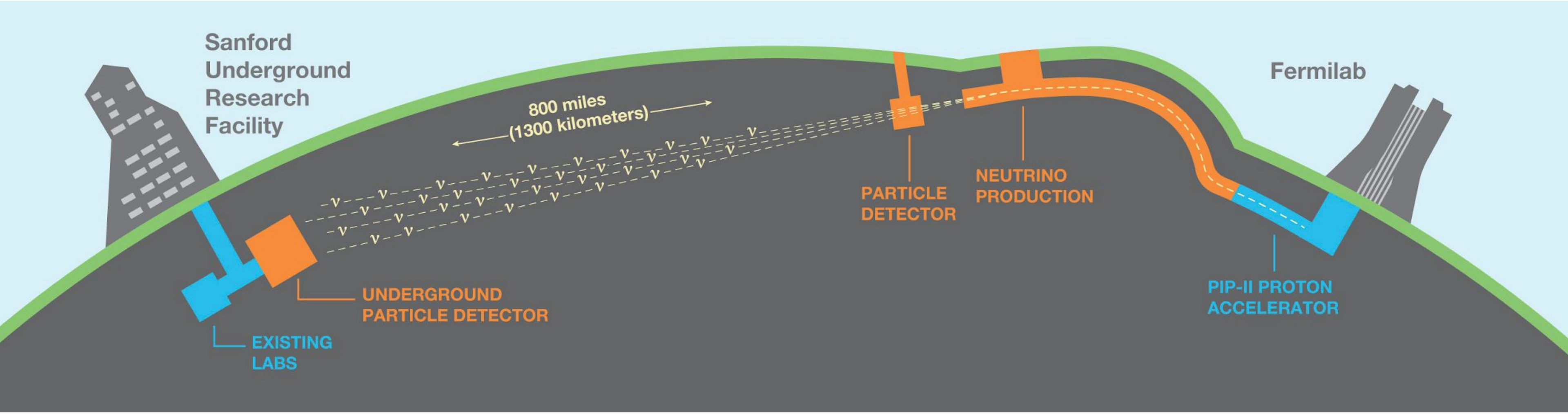
The Deep Underground Neutrino Experiment

- **Far Detector**
- **Near Detector**
- **Neutrino beam**



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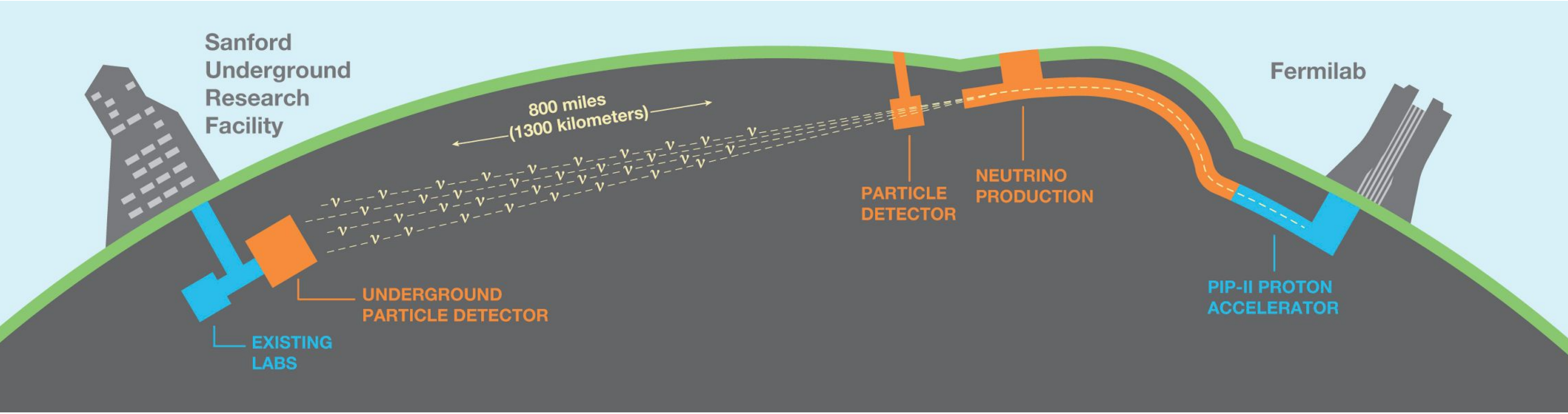
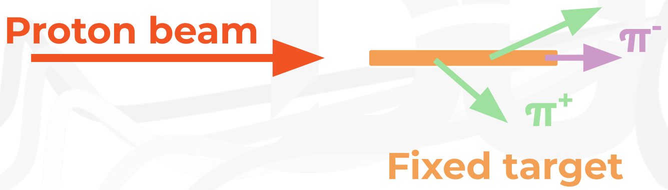


Producing a Beam of Neutrinos



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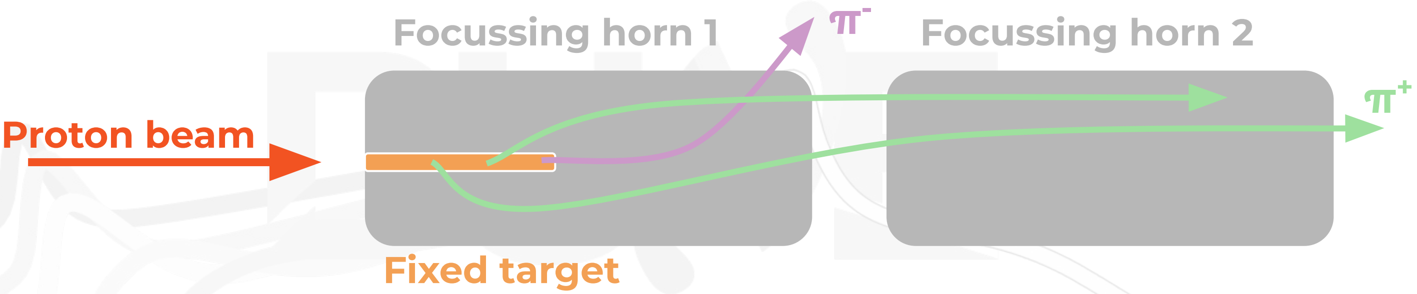

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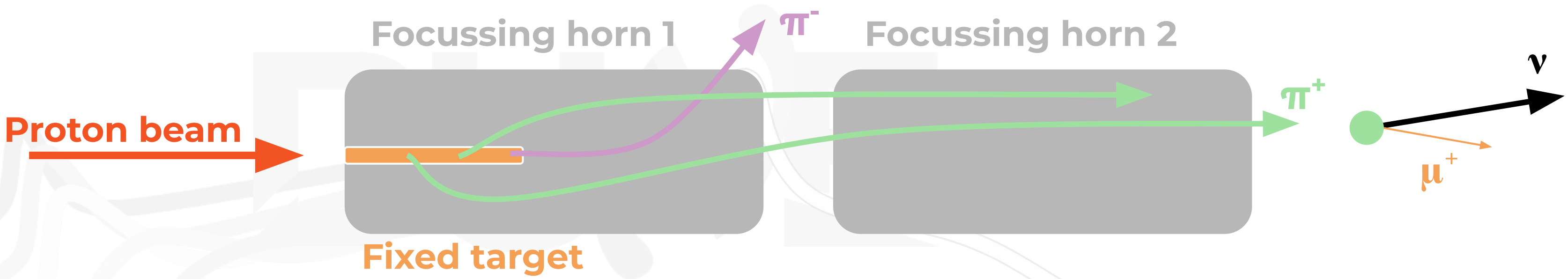

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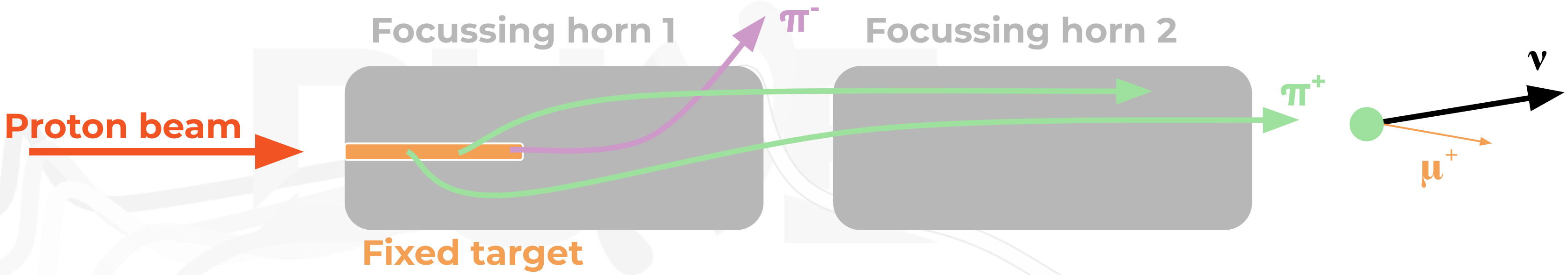

Neutrino mode, focussing positive particles

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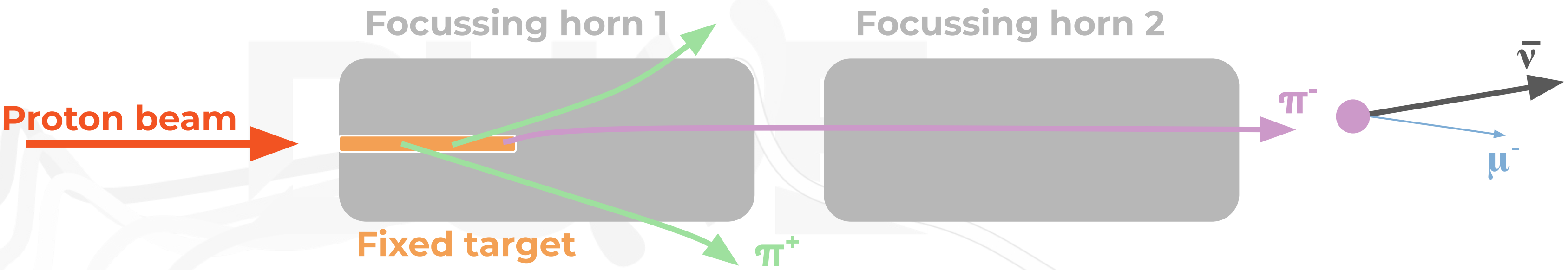
- The horn current can be inverted to produce mostly anti-neutrinos

Producing a Beam of Neutrinos



Anti-neutrino mode, focussing negative particles

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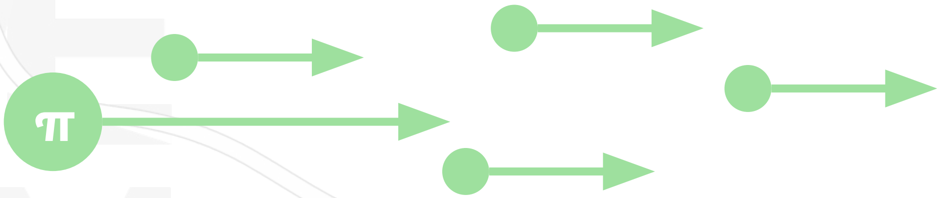
Off Axis Fluxes



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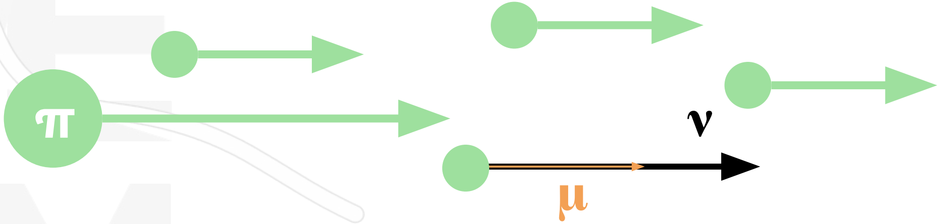

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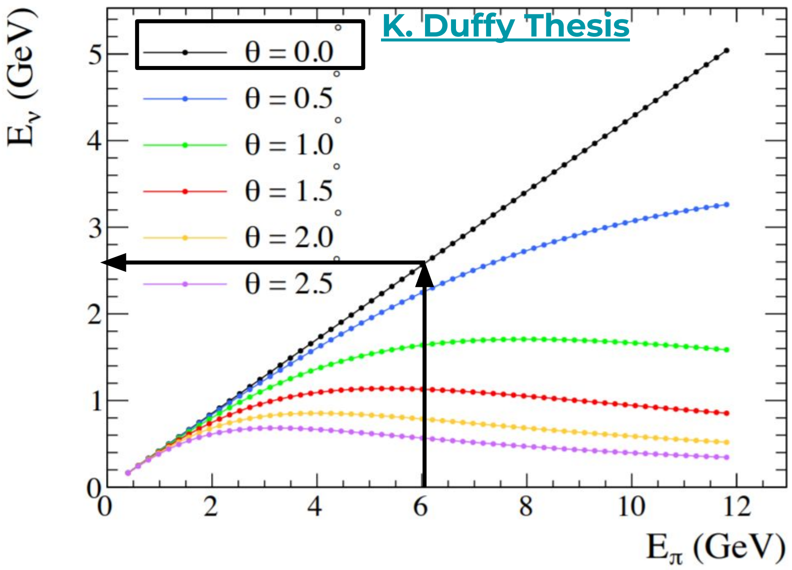
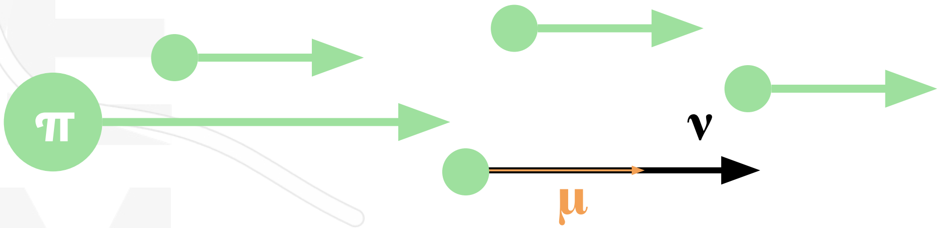
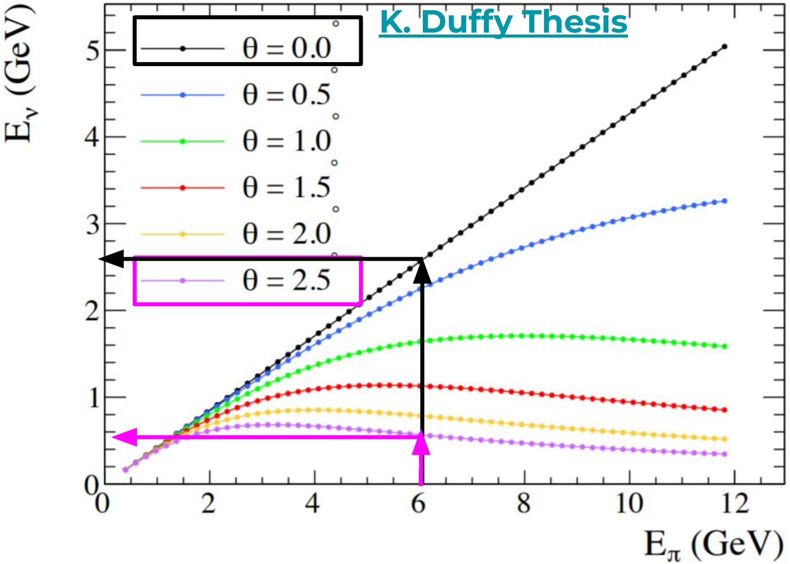
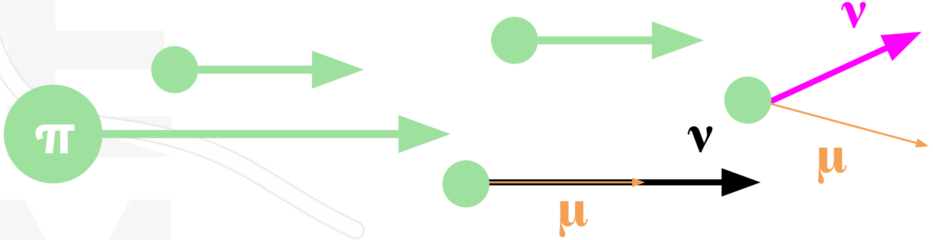




Off Axis Fluxes

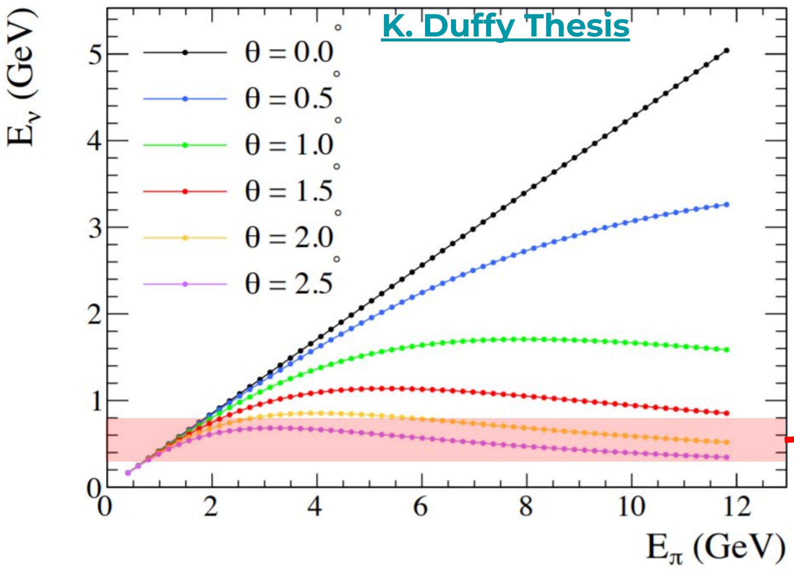
- Boosted π decay kinematics result in lower energy neutrinos off beam axis.

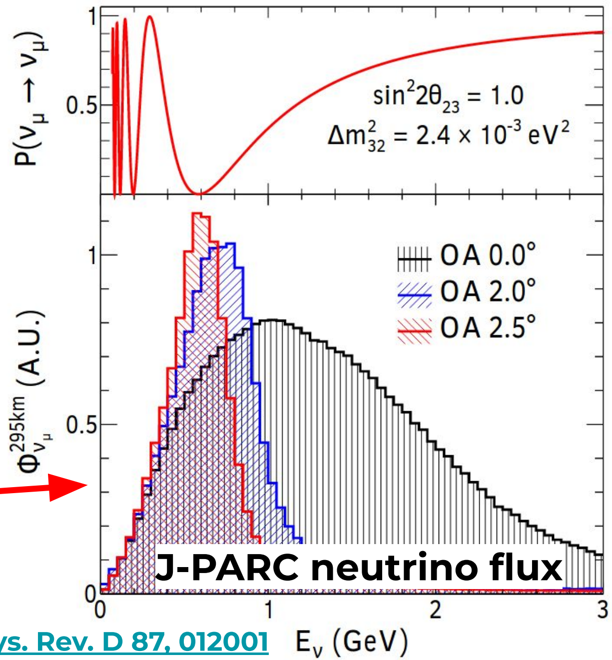




Off Axis Fluxes

- 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





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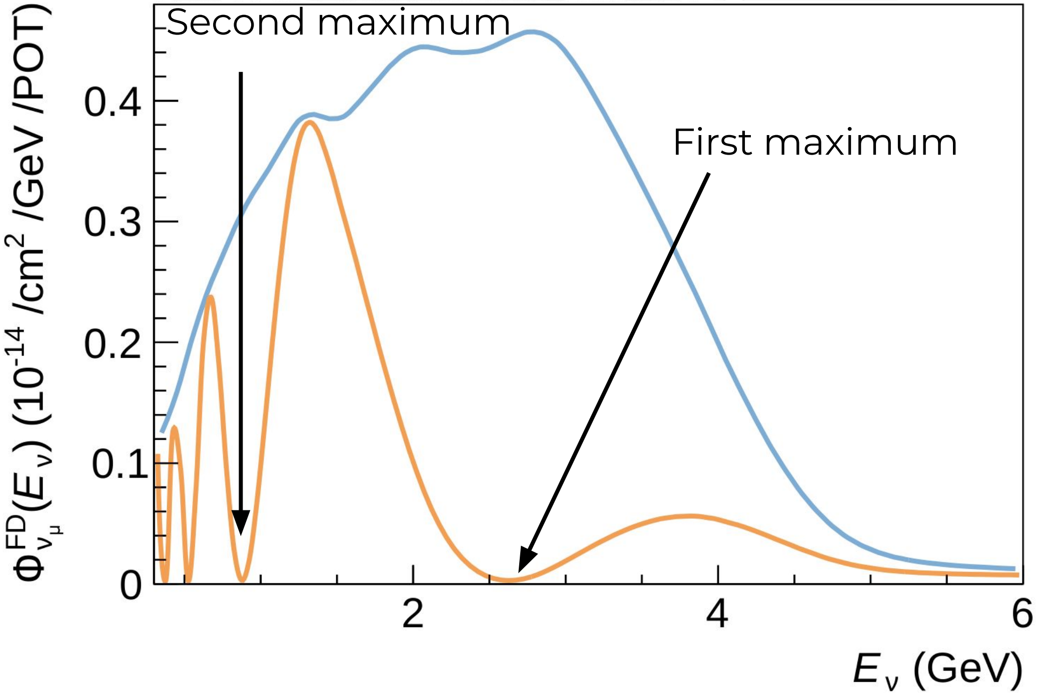
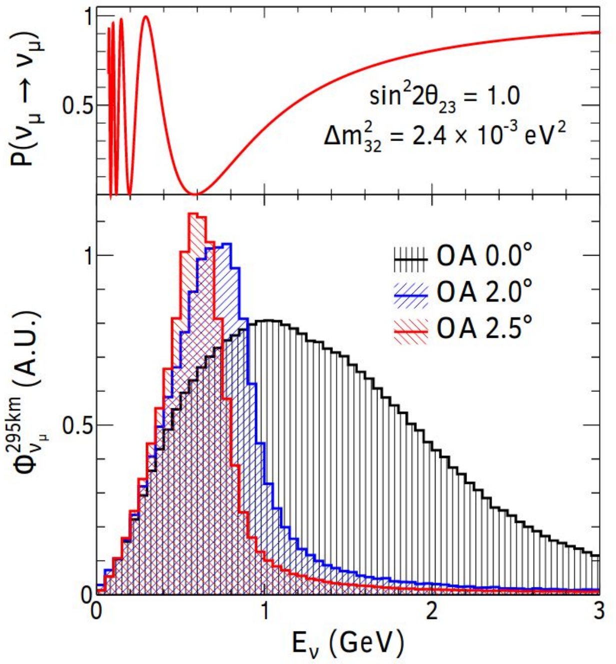
LBNF: The DUNE Neutrino Beam

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





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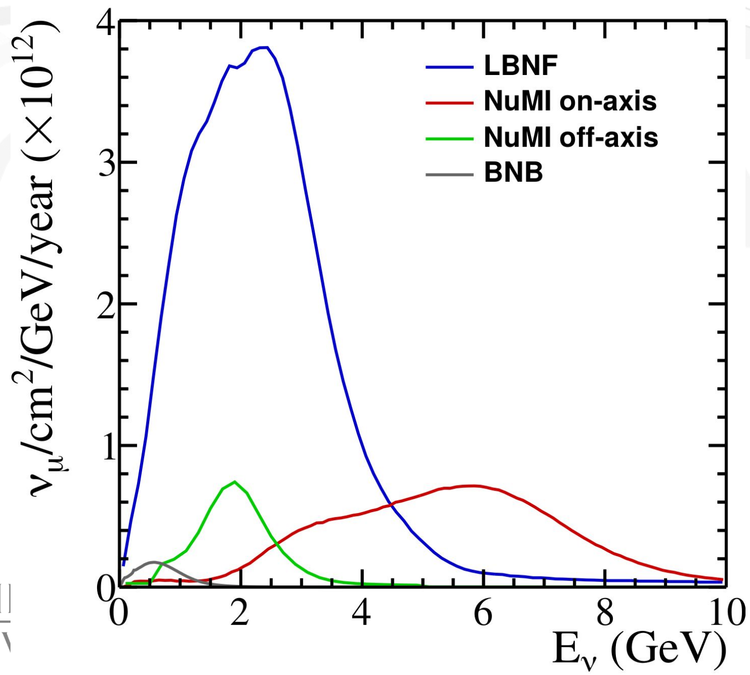
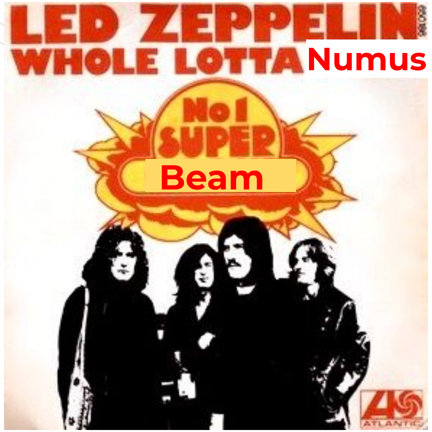
- **Unprecedented neutrino rate**





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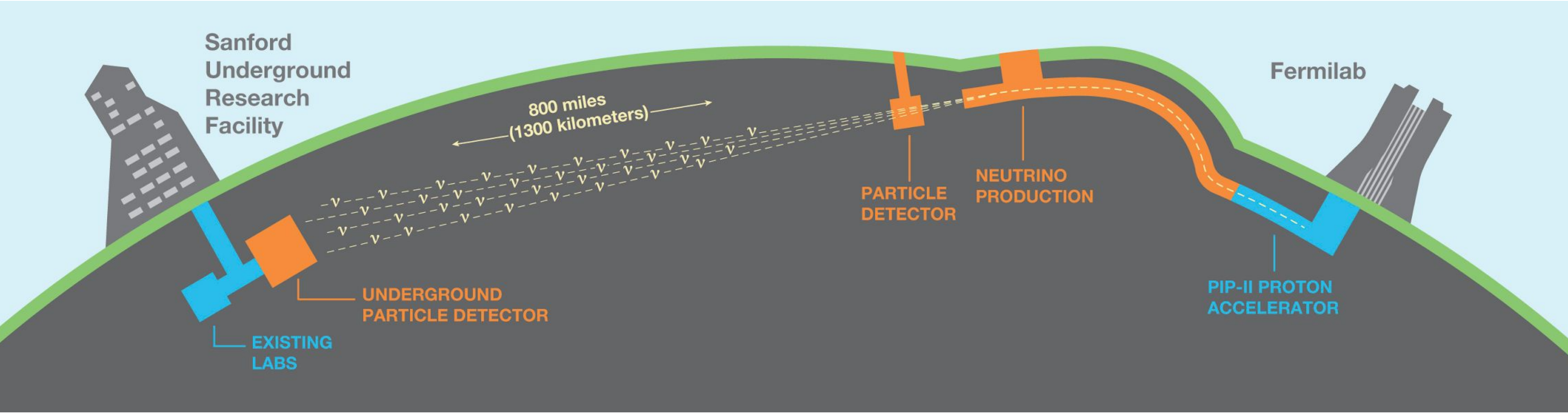
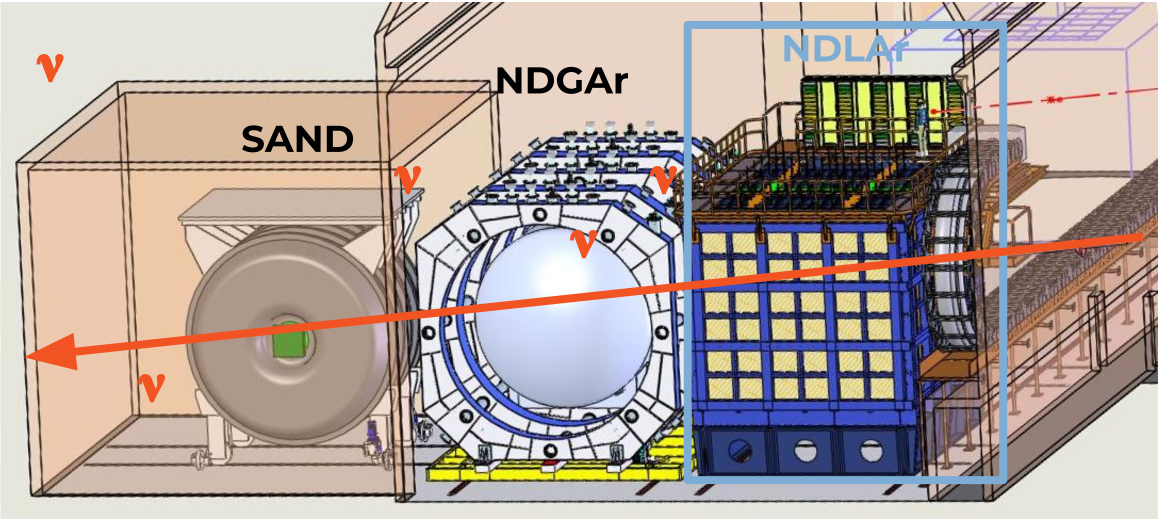


DUNE Near Detector Concept

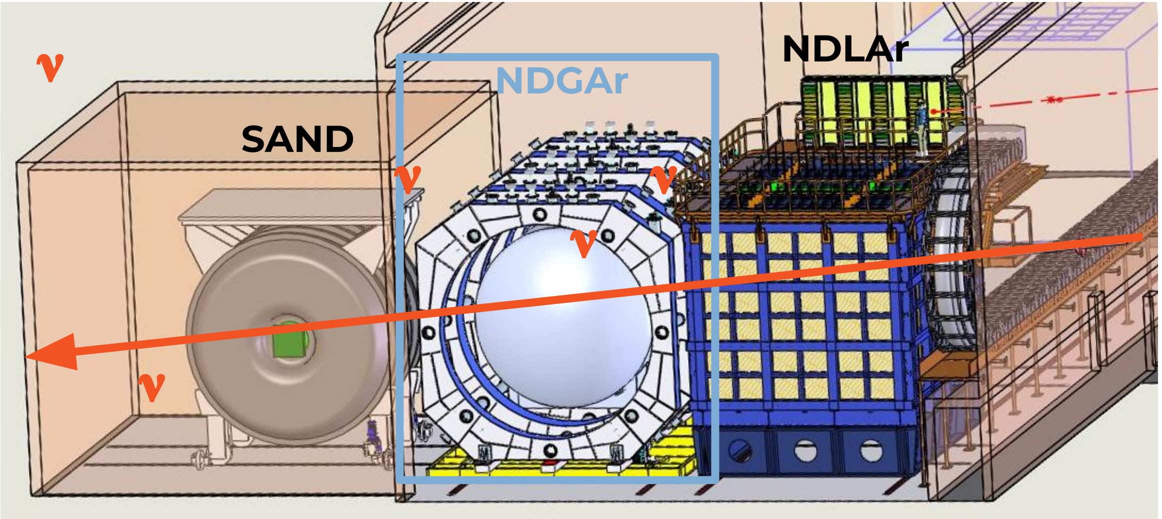
- **NDLAr**: LAr TPC
  - Primary target, similar to FD



DUNE Preliminary	NDLAr FV				NDGAr 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

DUNE Near Detector Concept

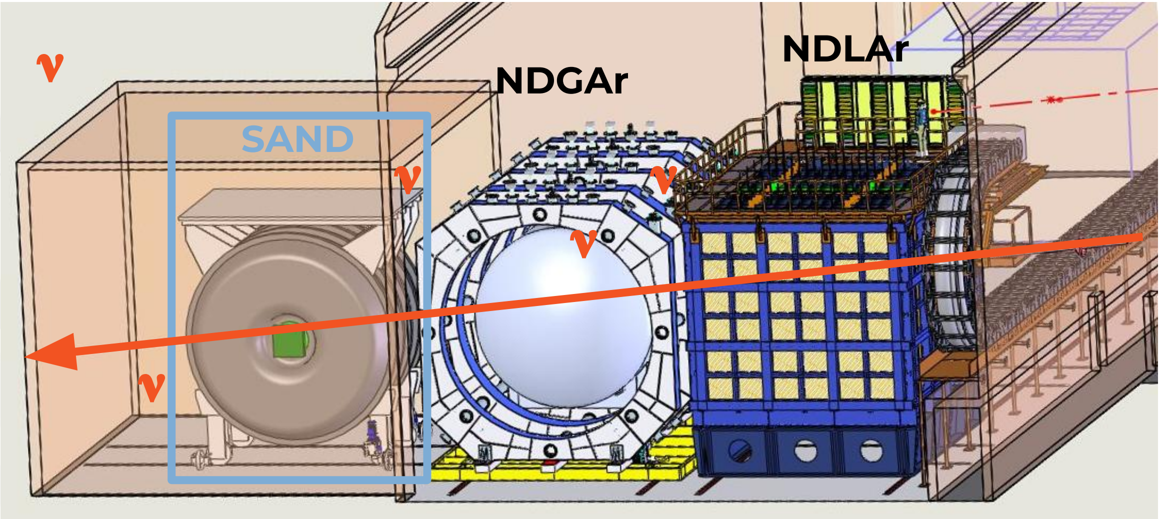
- **NDLAr**: LAr TPC
  - Primary target, similar to FD
- **NDGAr**: GAr TPC + ECal + Low mass magnet
  - Charge/momentum/PID
  - Low threshold neutrino target



DUNE Preliminary	NDLAr FV				NDGAr 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

DUNE Near Detector Concept

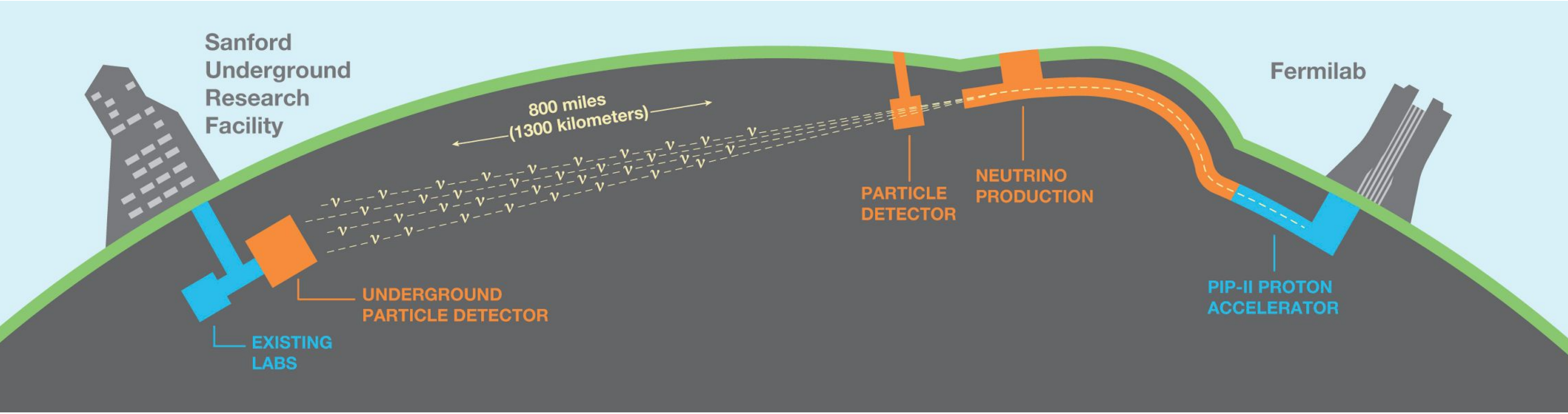
- **ArgonCube**: LAr TPC
  - Primary target, similar to FD
- **MPD**: GAr TPC + ECal + Low mass magnet
  - Charge/momentum/PID
  - Low threshold neutrino target
- **SAND**: 3D plastic scintillator detector inside a superconducting solenoid:
  - Beam monitor
  - Neutrino interaction physics



DUNE Preliminary	NDLAr FV				NDGAr 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

The Deep Underground Neutrino Experiment

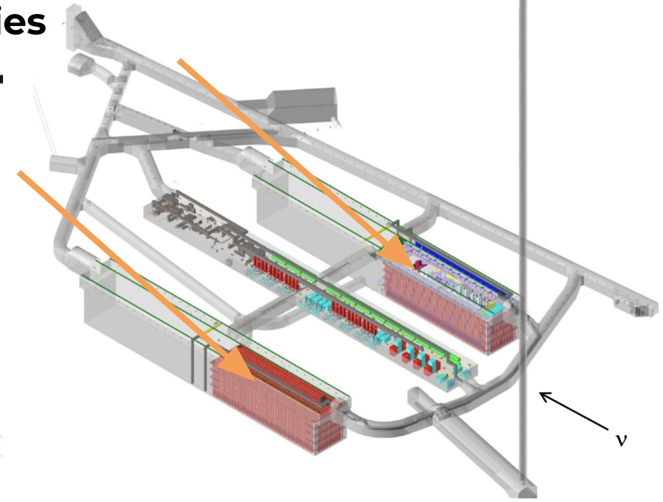
- **Far Detector**
- Near Detector
- Neutrino beam



Far Detector

- 4x**10 kT LAr TPCs**

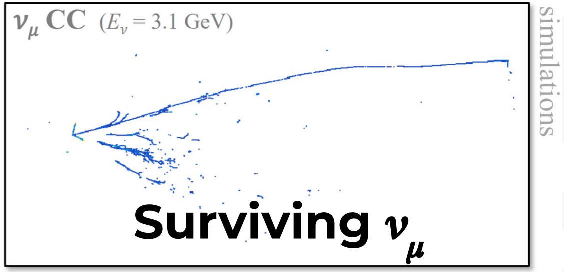
SURF underground facilities



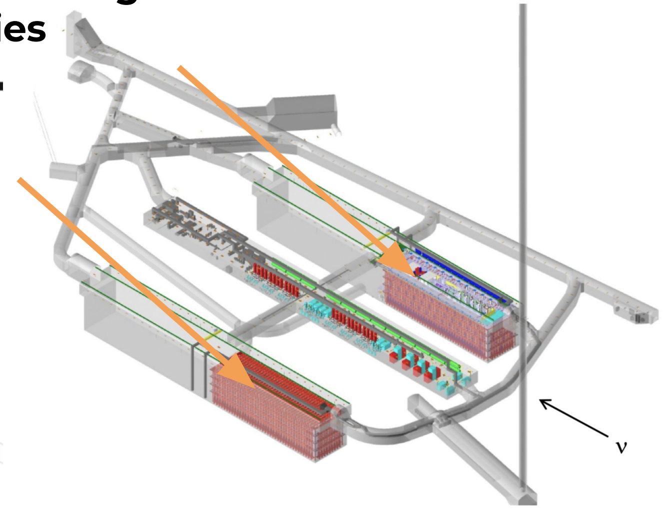
R. Patterson FNAL JETP

Far Detector

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



SURF underground facilities



R. Patterson FNAL JETP

Far Detector

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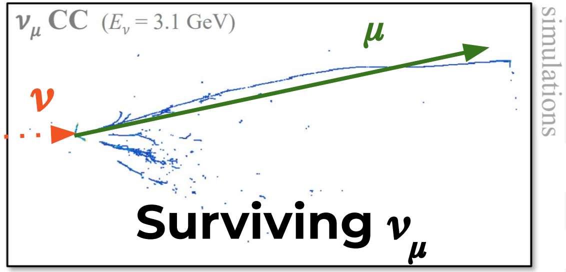
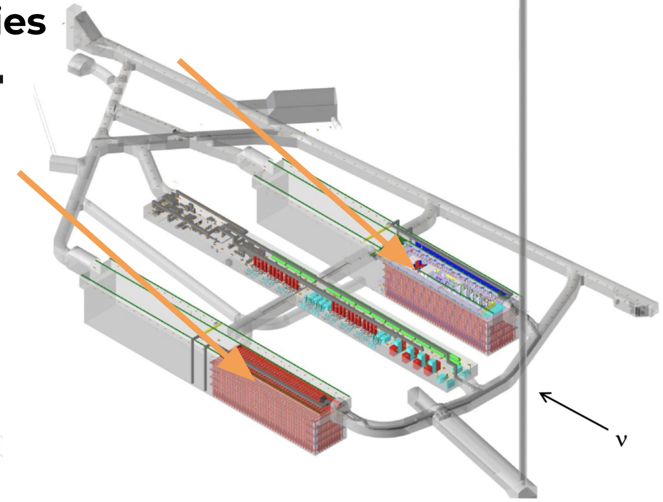


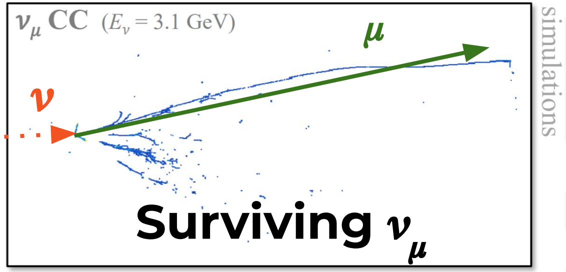
SURF underground facilities

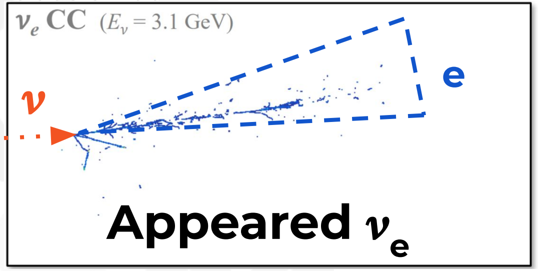


R. Patterson FNAL, JETP

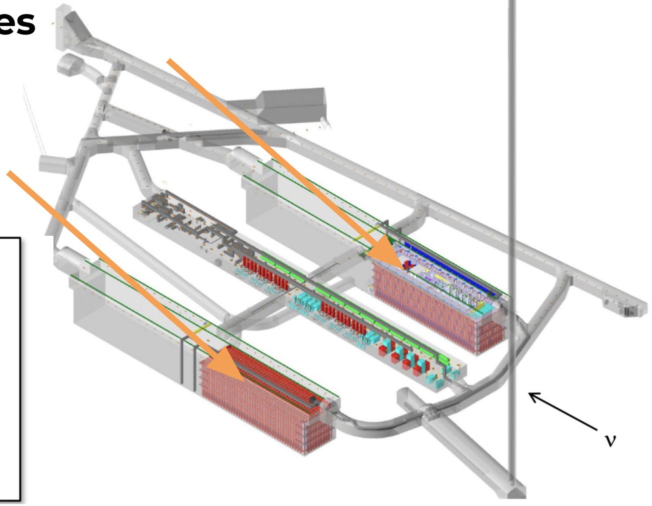
Far Detector

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





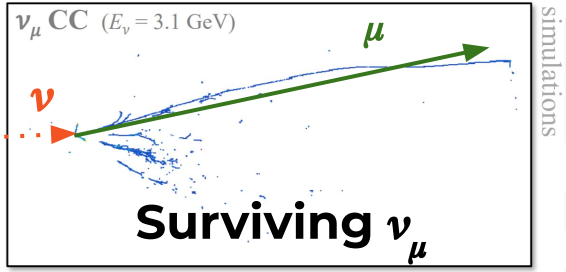
SURF underground facilities

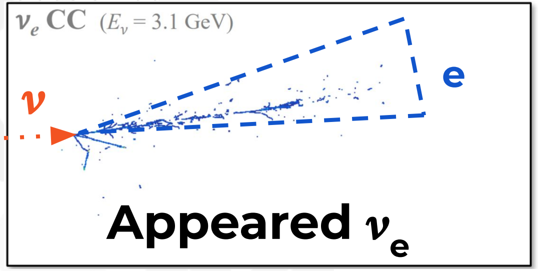


R. Patterson FNAL JETP

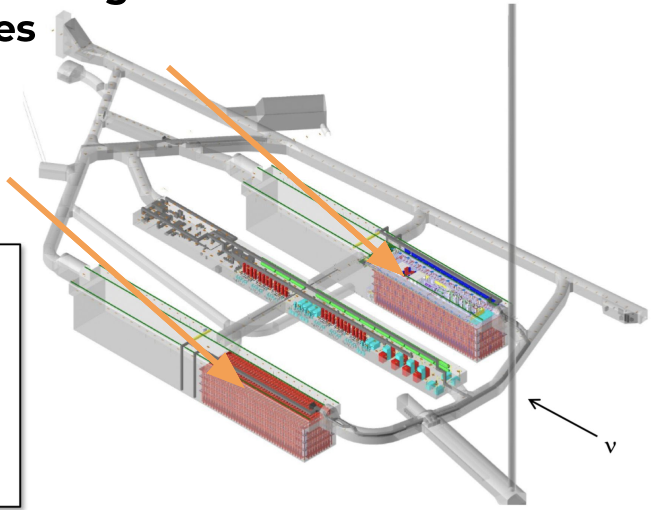
Far Detector

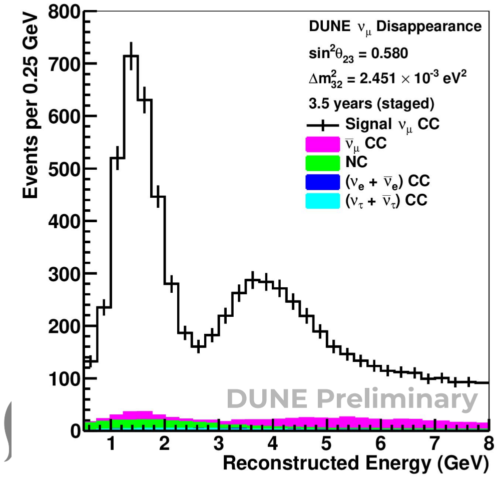
- 4x**10 kT LAr TPC**s:
  - Unprecedented FD event resolution and event rate!

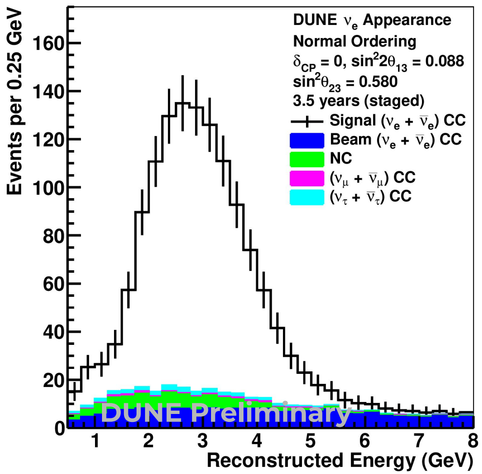




SURF underground facilities







R. Patterson FNAL JETP

DUNE PRISM

Oscillation Analysis On DUNE

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...

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

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

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

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

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

Want to know this

Oscillations at the Far Detector

- Why c
  - Bec
  - Co
  - Ca

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

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

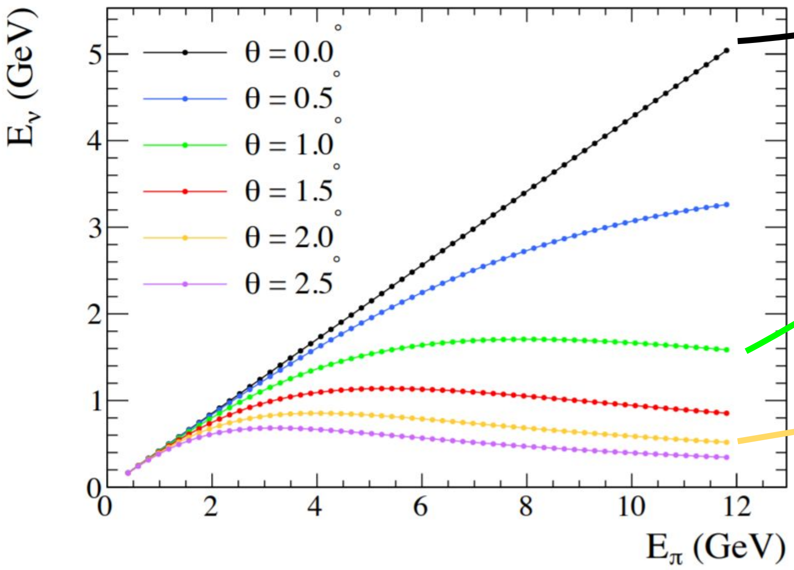
$$N_{\text{far}}\left(E_{\text{obs}}\right) = \int dE_\nu \, \Phi_{\text{far}}\left(E_\nu\right) \cdot P_{osc}\left(E_\nu\right) \cdot \sigma\left(E_\nu\right) \cdot \mathbf{D}_{\text{far}}$$

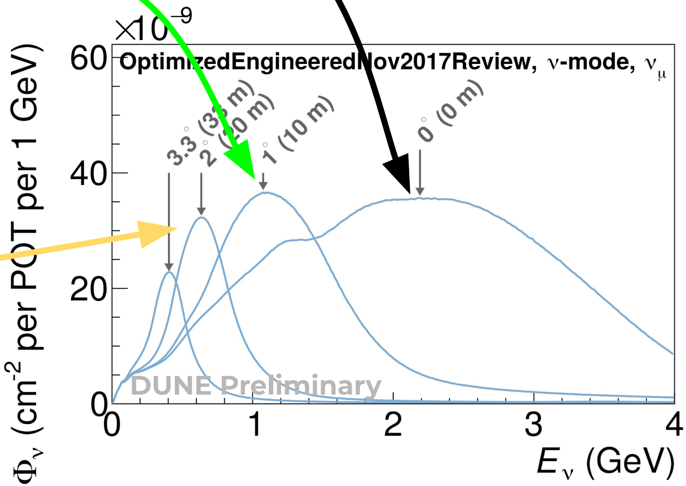
Want to know this

DUNE PRISM

Precision Reaction-Independent Spectrum Measurement

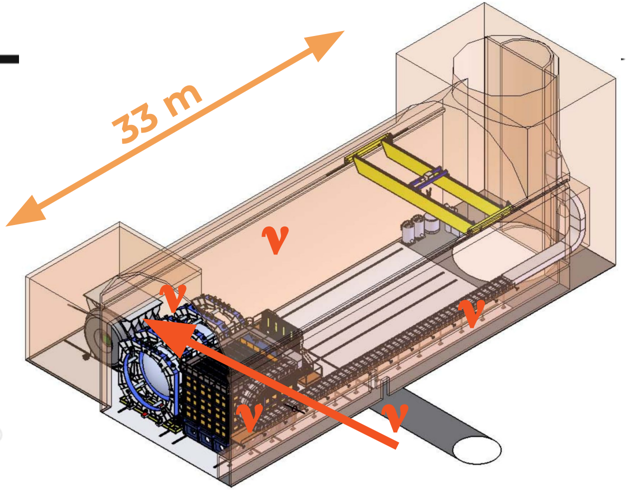
Off Axis at the Near Detector

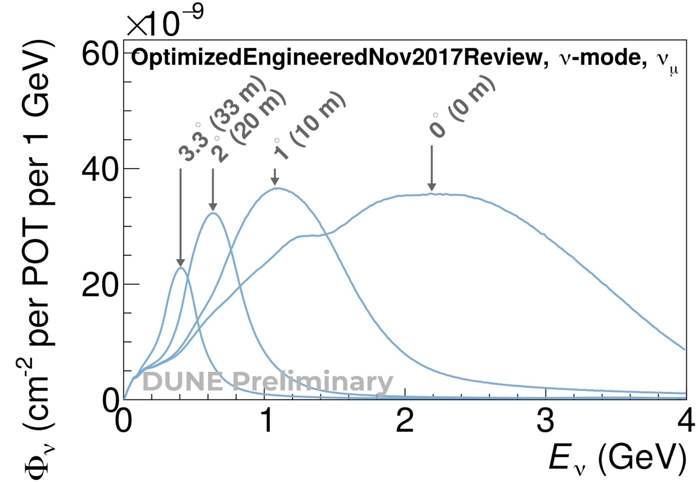




Off Axis at the Near Detector

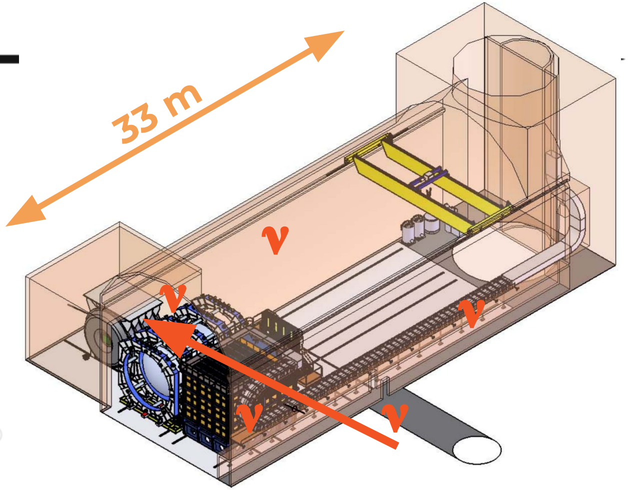
- Use a mobile Near Detector
  - Sample different neutrino energy spectra at different positions

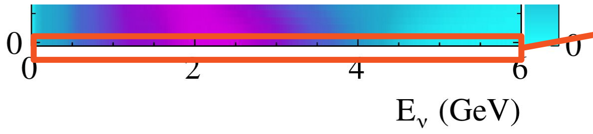


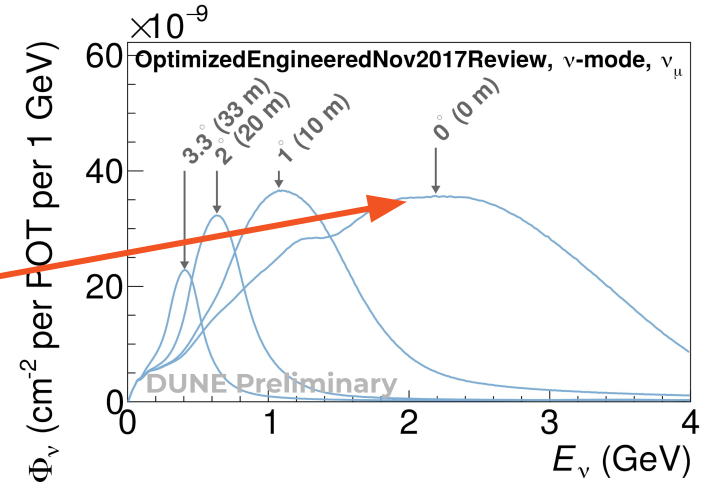


Off Axis at the Near Detector

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







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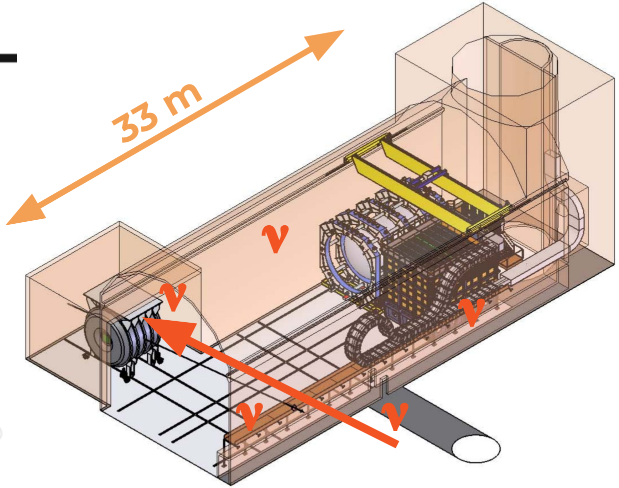

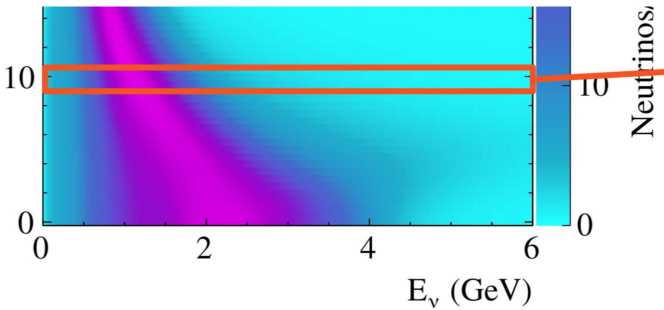

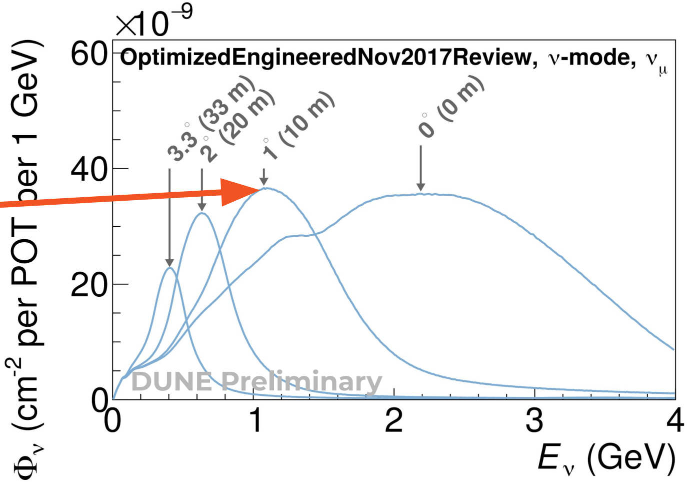

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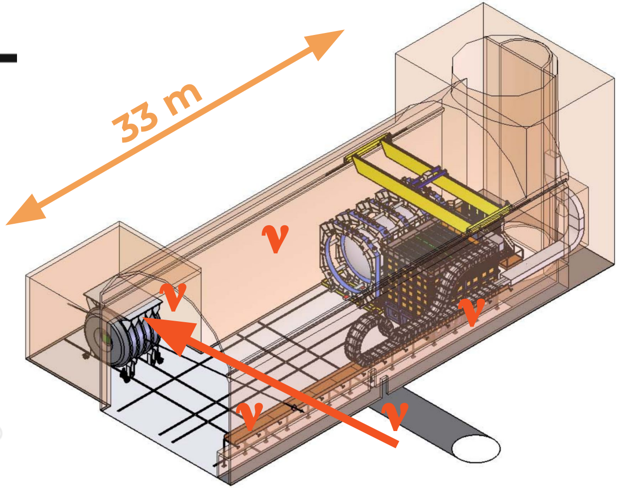

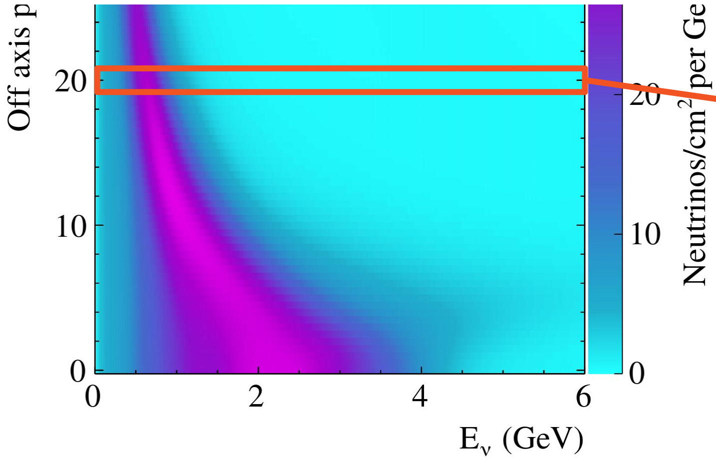

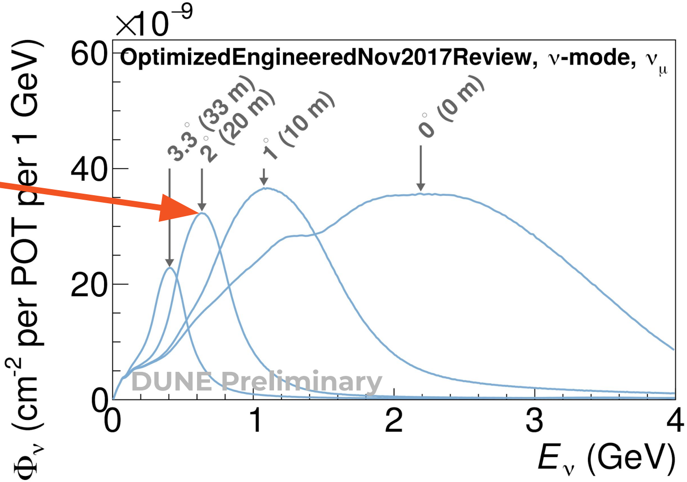

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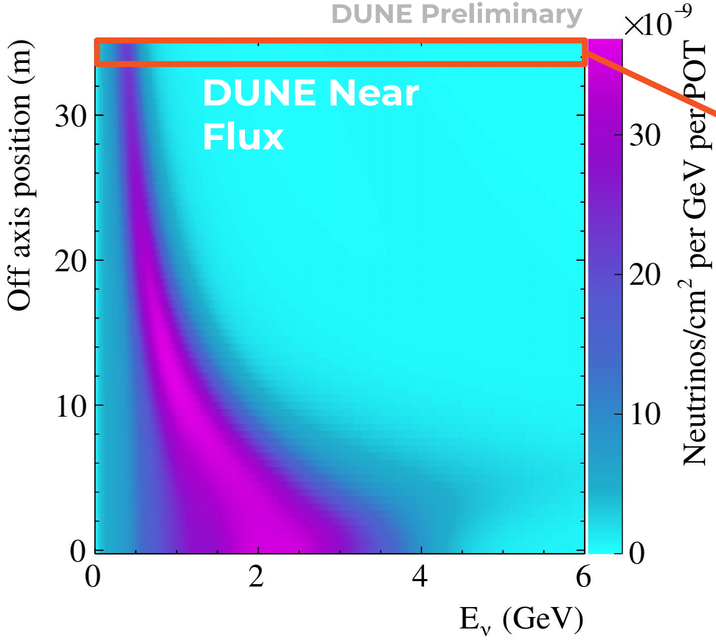
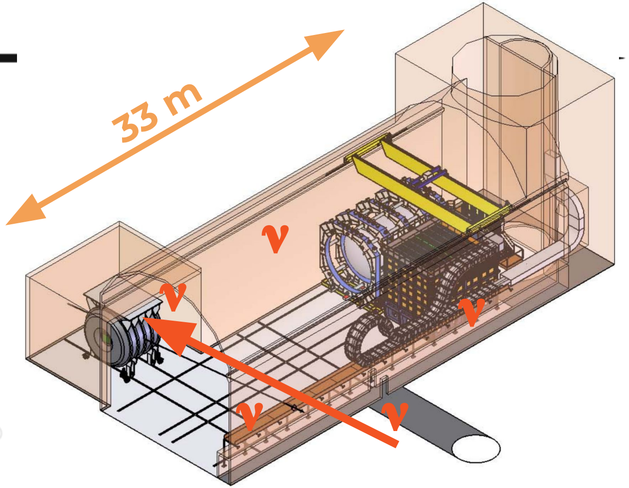
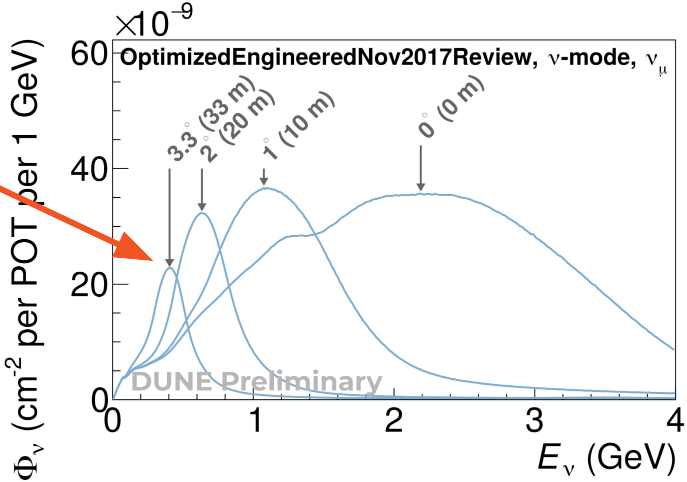


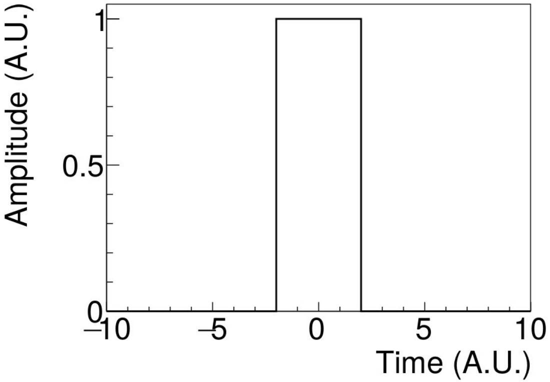




A Quick Aside

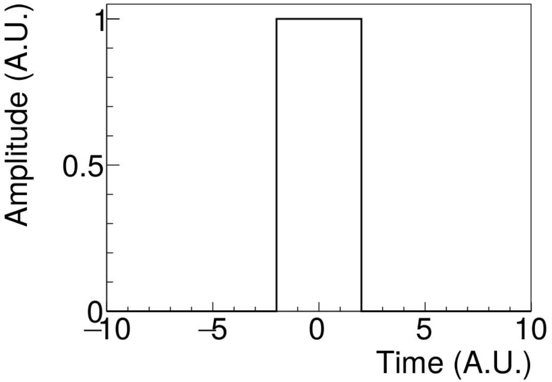
Discrete Fourier Transforms

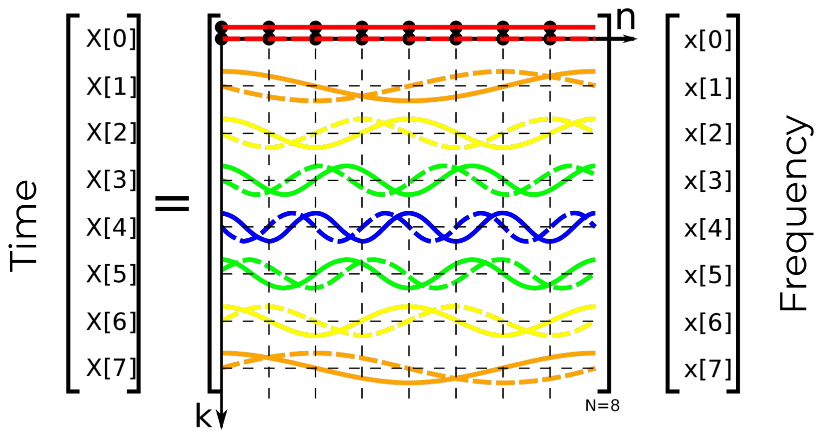
- Approximate function as a linear sum of sines and cosines



Discrete Fourier Transforms

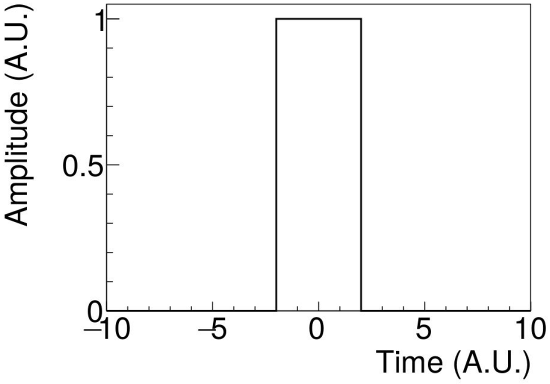
- Approximate function as a linear sum of sines and cosines

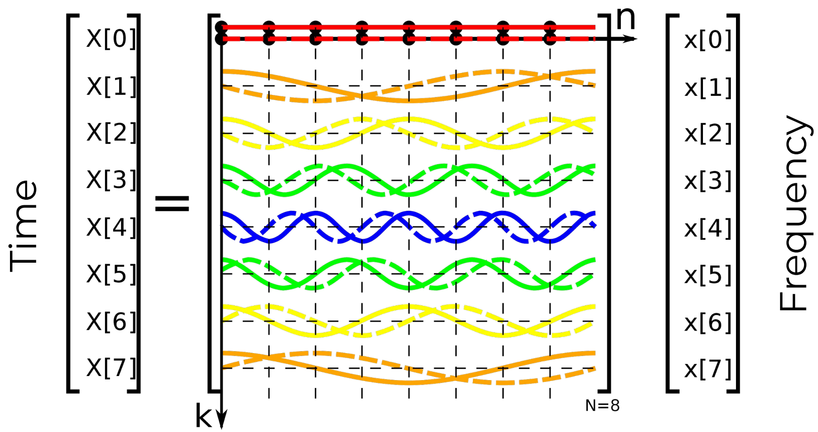




Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines





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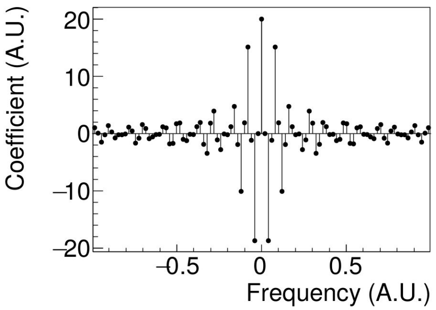
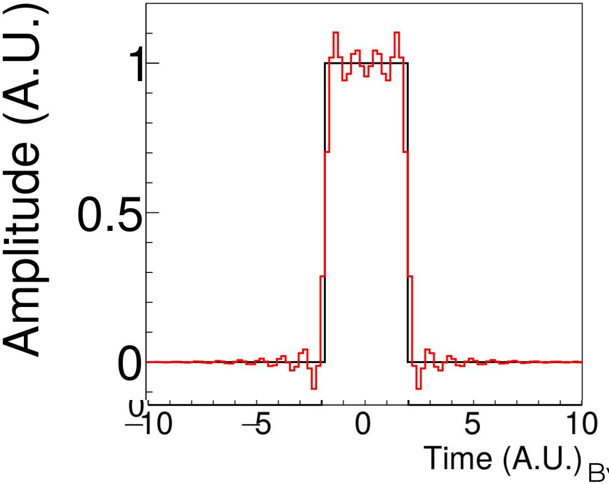
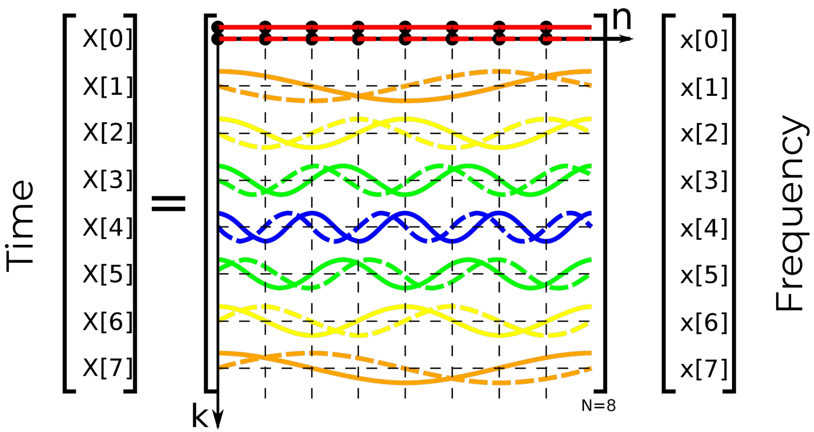


Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines





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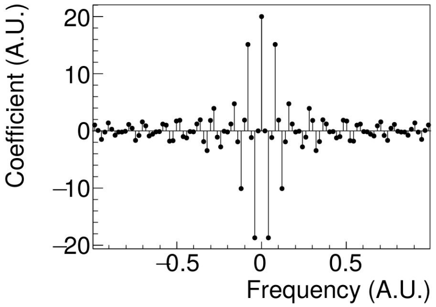
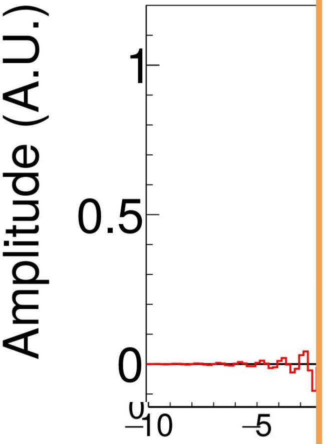
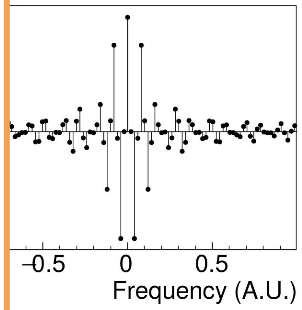


Discrete Fourier Transforms

- Approximate function as a linear sum of sines and



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



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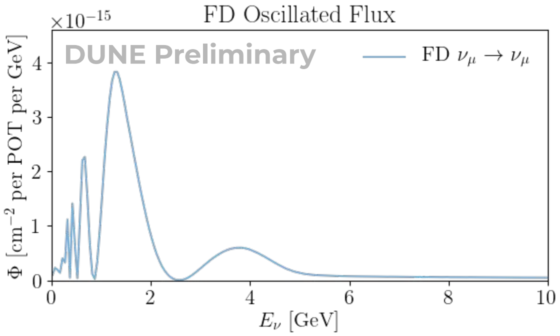
https://commons.wikimedia.org/w/index.php?curid=3570075

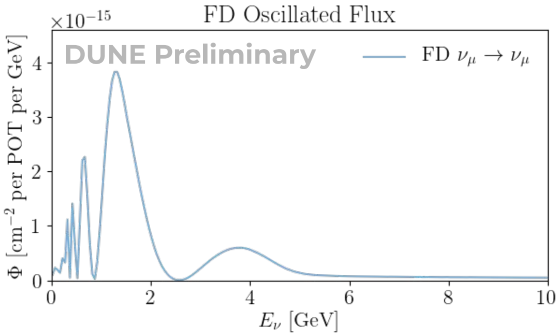
Building an Oscillated Flux

- Want to measure oscillated flux at the near detector

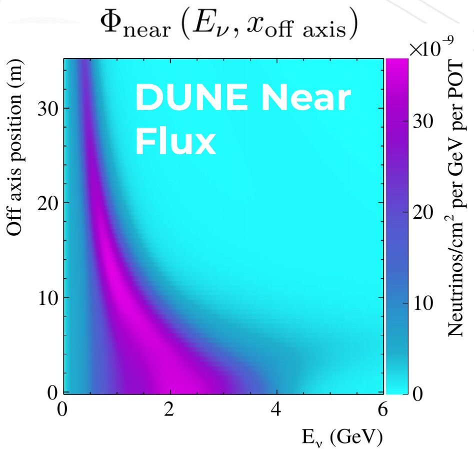


Building an Oscillated Flux

- Want to measure oscillated flux at the near detector
  - **Try to decompose into a linear sum of off-axis near detector fluxes (*c.f.* Discrete FT)**



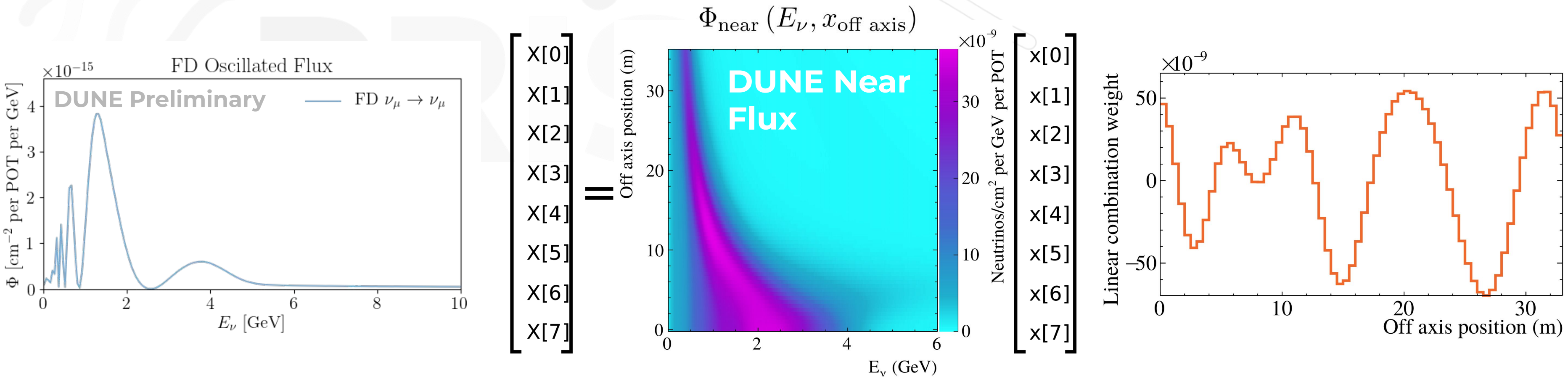
[X[0], X[1], X[2], X[3], X[4], X[5], X[6], X[7]] =



[x[0], x[1], x[2], x[3], x[4], x[5], x[6], x[7]]

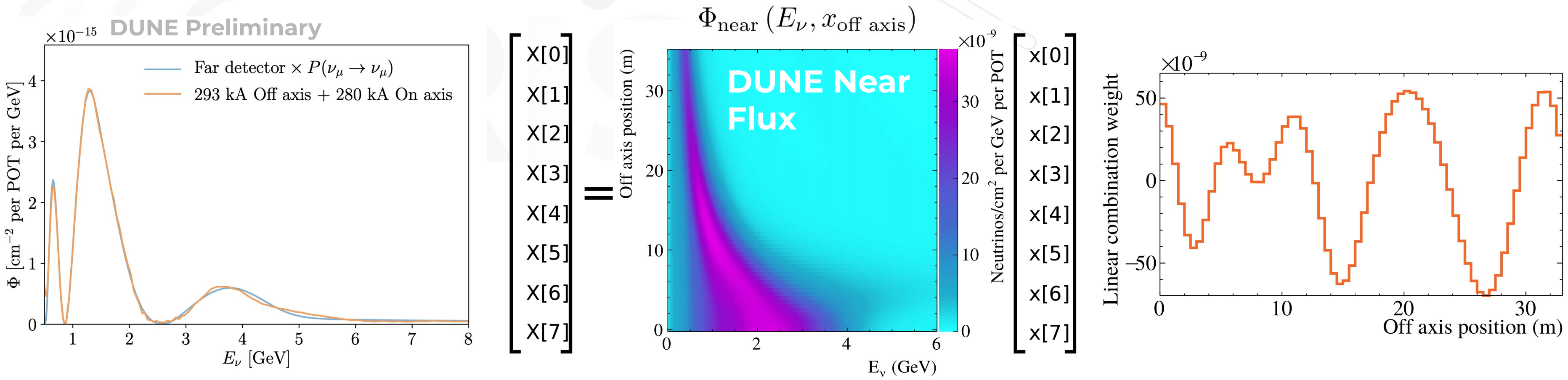
Building an Oscillated Flux

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



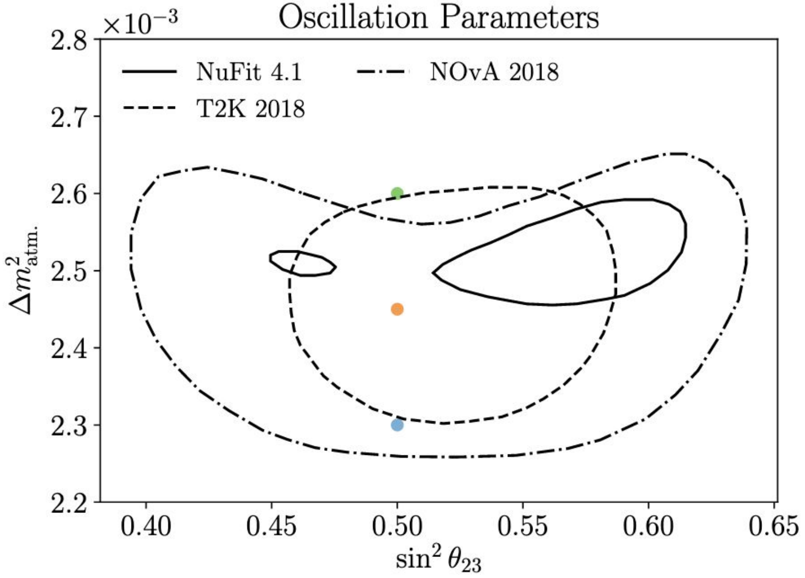
Building an Oscillated Flux

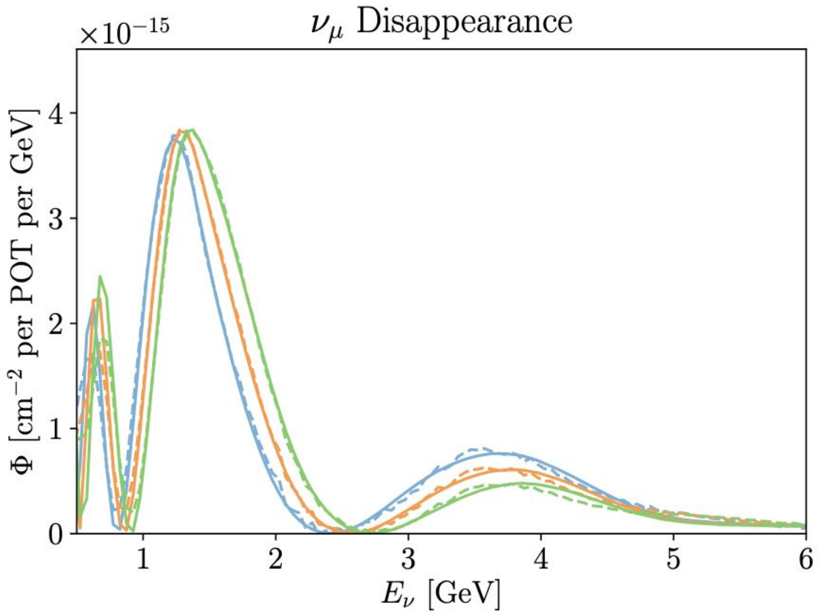
- Want to measure oscillated flux at the near detector
  - Try to decompose into a linear sum of off-axis near detector fluxes (*c.f.* Discrete FT)
  - Solve for weights at each off axis position
  - **How good is the approximation?**



Building More Oscillated Fluxes

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





How does that help?

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

How does that help?

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

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

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

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

How does that help?

- **Use the PRISM method to build:** $\Phi_{\text{near}}\left(E_\nu, x_{\text{off axis}}\right) \times \vec{c} = \Phi_{\text{far}}\left(E_\nu\right) P_{osc}\left(E_\nu\right)$
- **Cross sections are not position dependent**

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

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

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

How does that help?

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

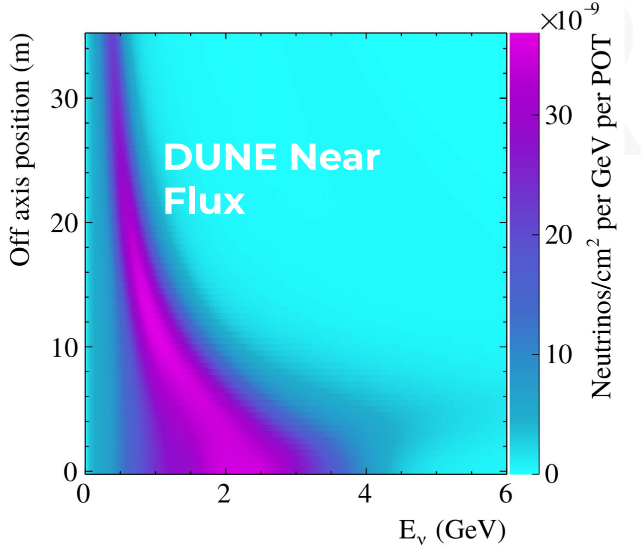
$$N_{near}(E_{obs}) = \int dE_\nu \, \Phi_{near}(E_\nu) \cdot \sigma(E_\nu) \cdot \mathbf{D}_{near}$$

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

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

Building a Far Detector prediction

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



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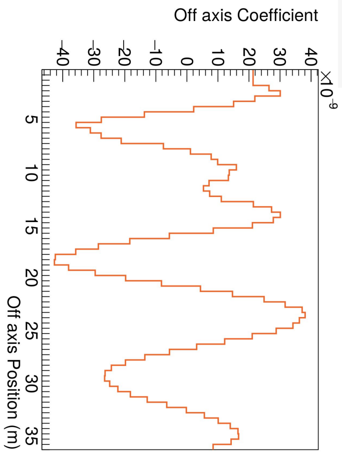

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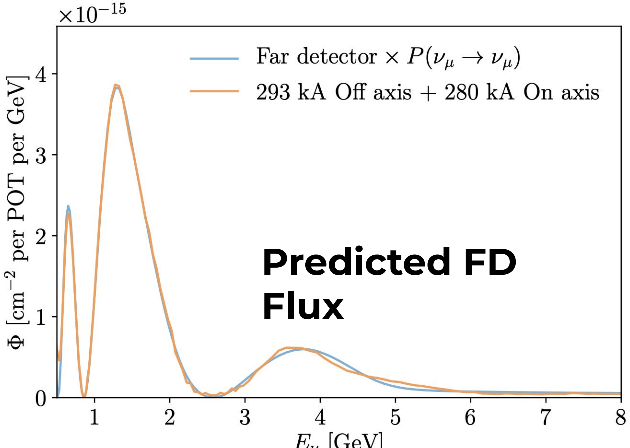

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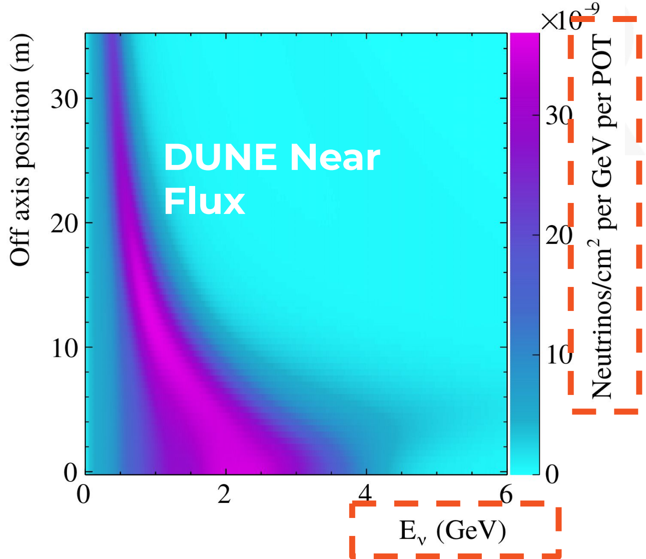

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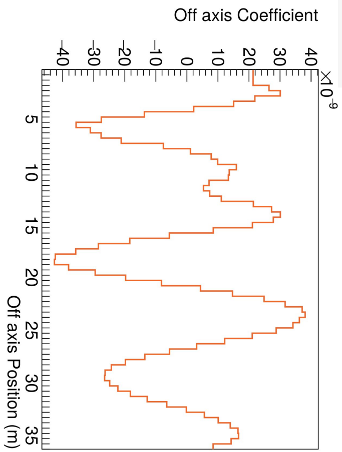

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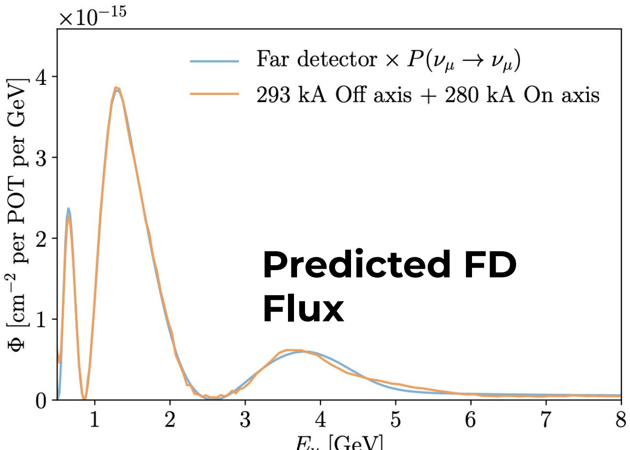

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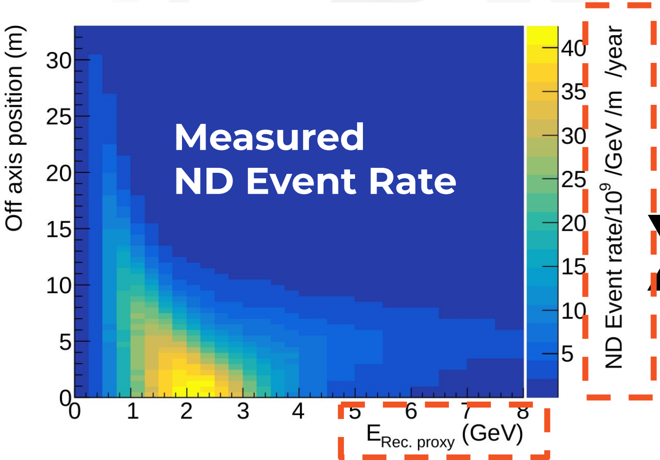

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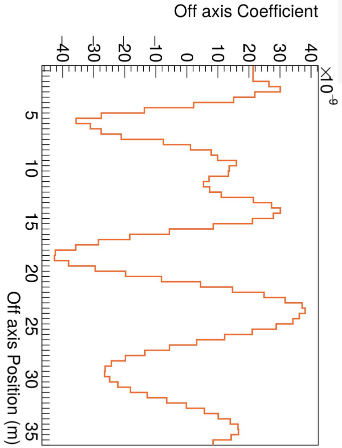

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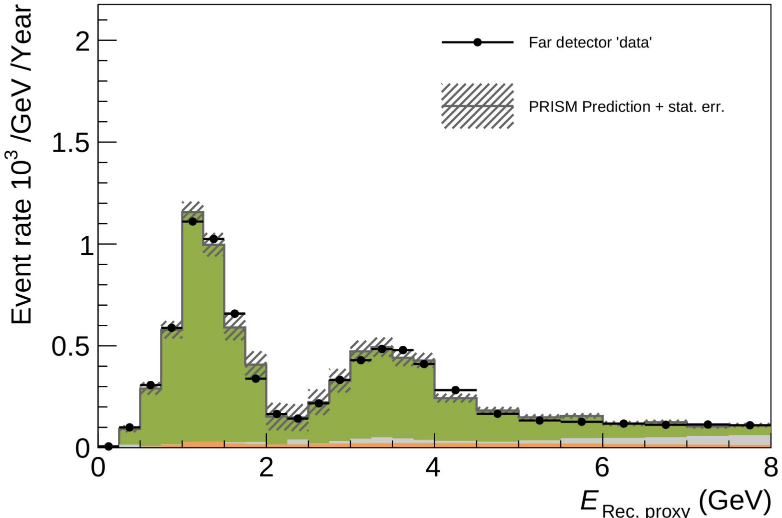
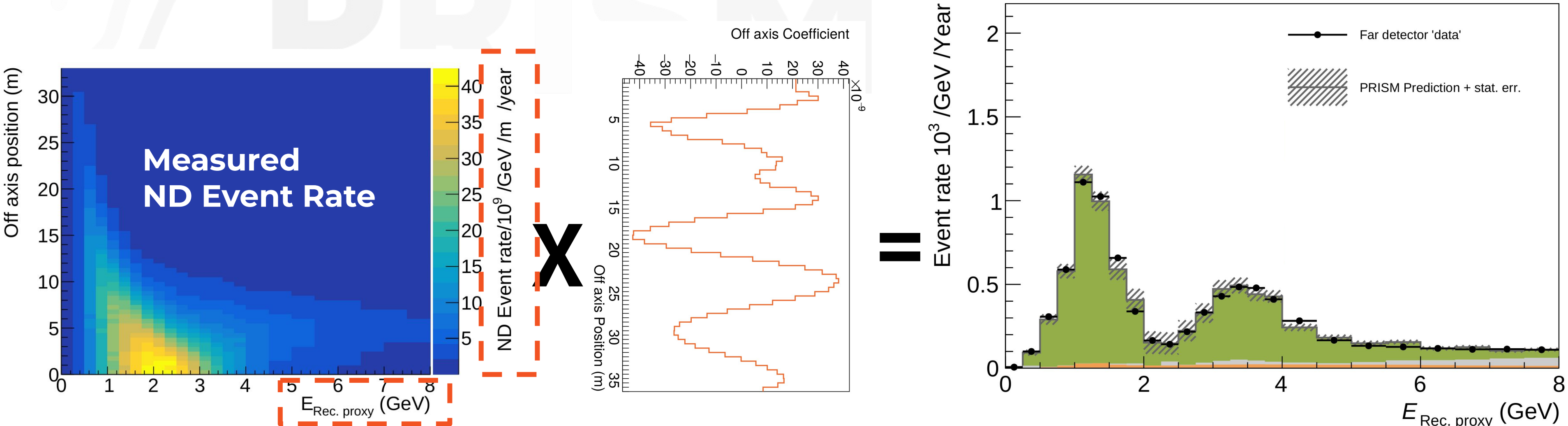


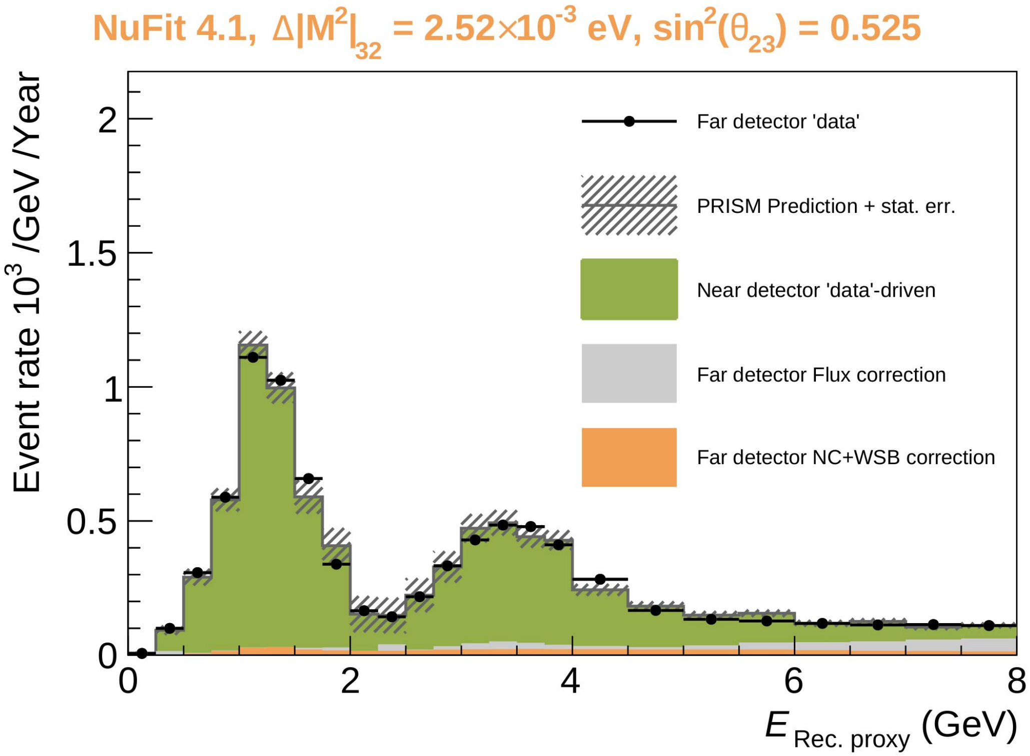
Building a Far Detector prediction

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



The Full PRISM prediction

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



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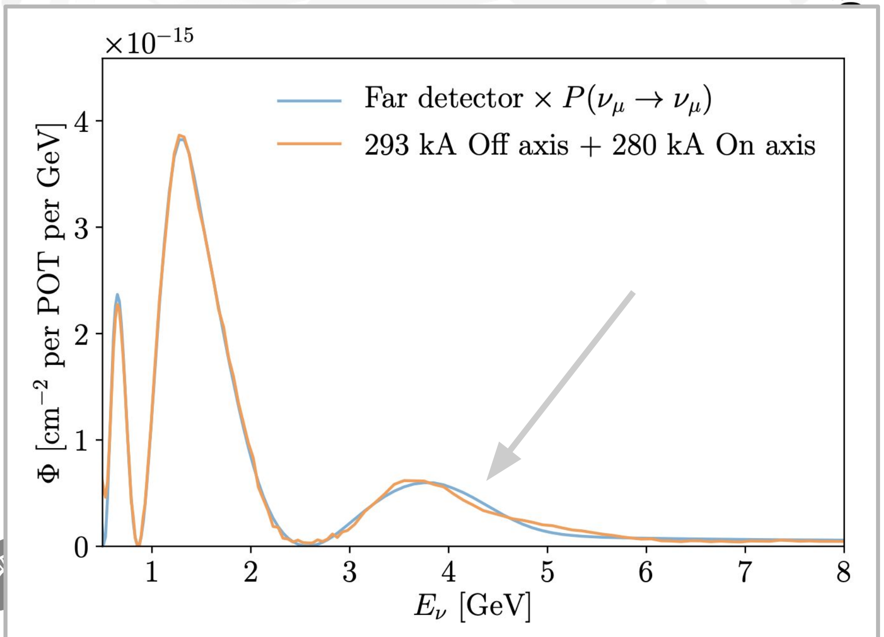
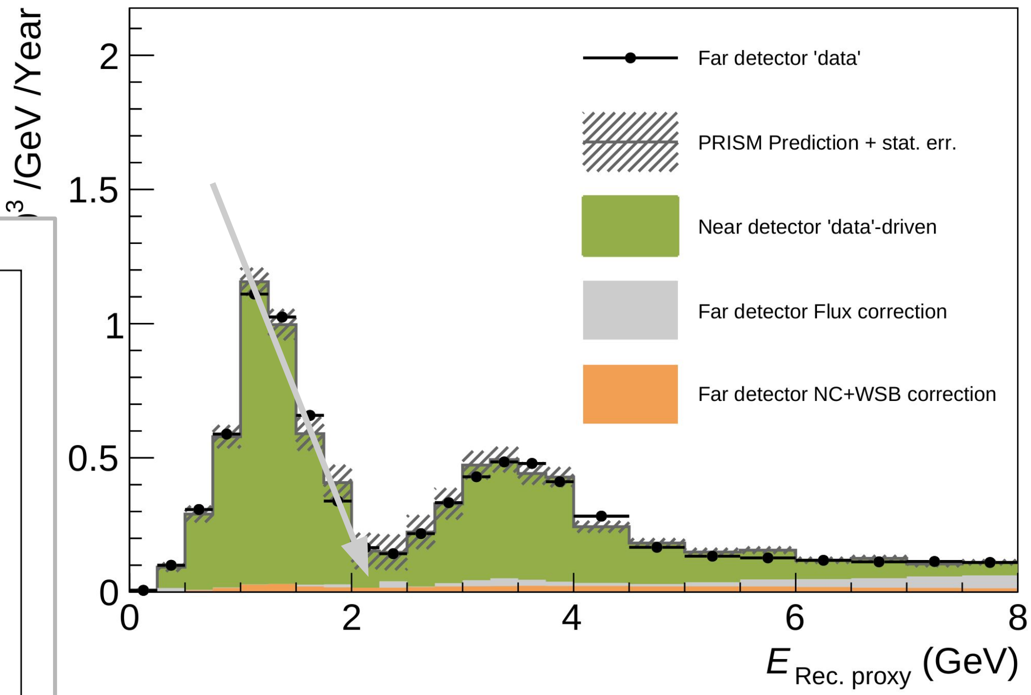


NuFit 4.1, $\Delta|M^2|_{32}$ = 2.52×10^{-3} eV, $\sin^2(\theta_{23})$ = 0.525



The Full PRISM prediction

- Do have to correct for:
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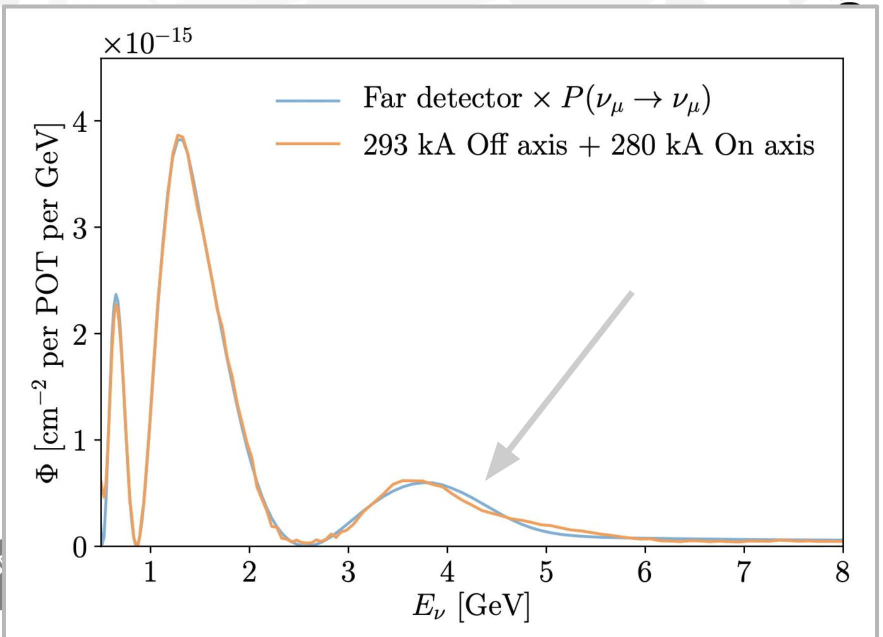

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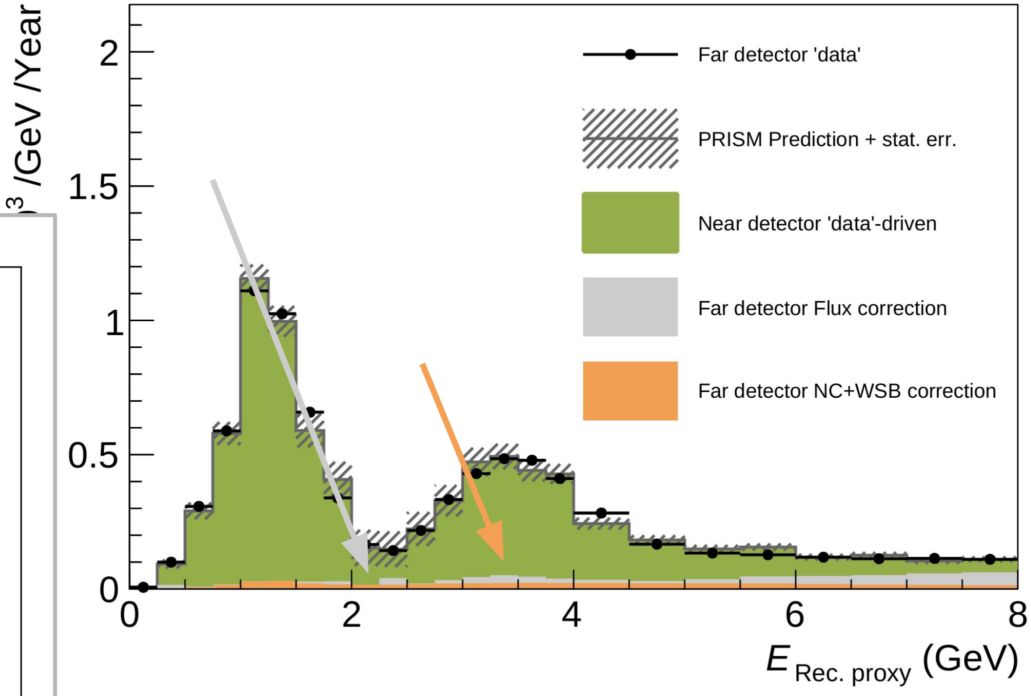

The Full PRISM prediction

- Do have to correct for:
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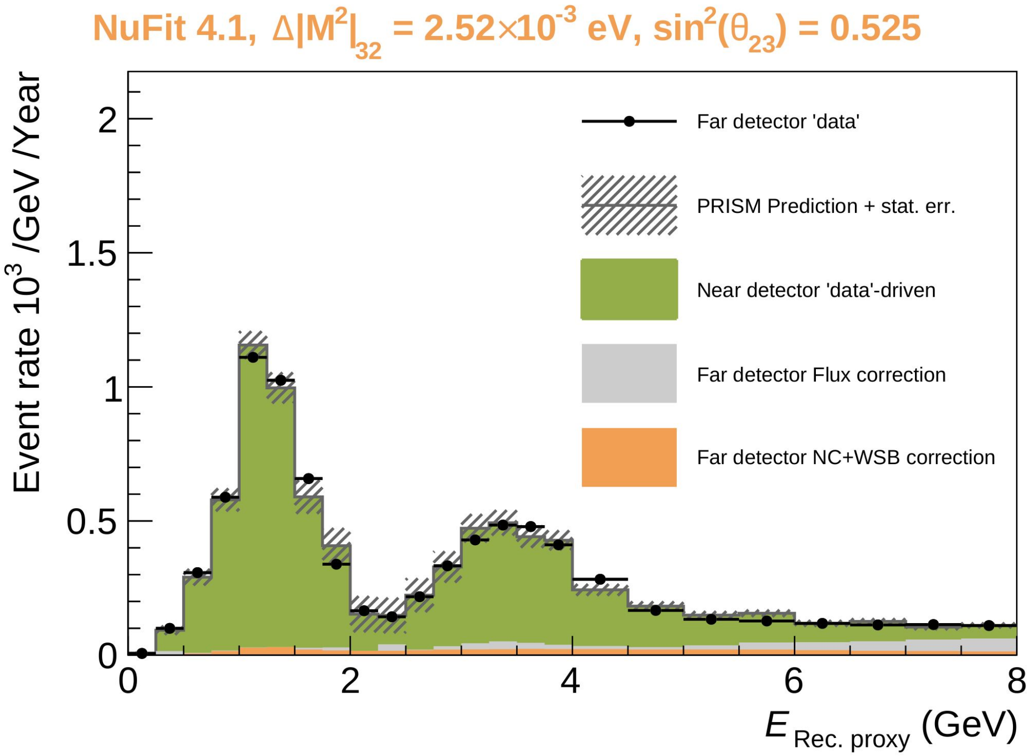
- Majority of oscillated far prediction is rearranged near detector signal data.



The Full PRISM prediction

- Do have to correct for:
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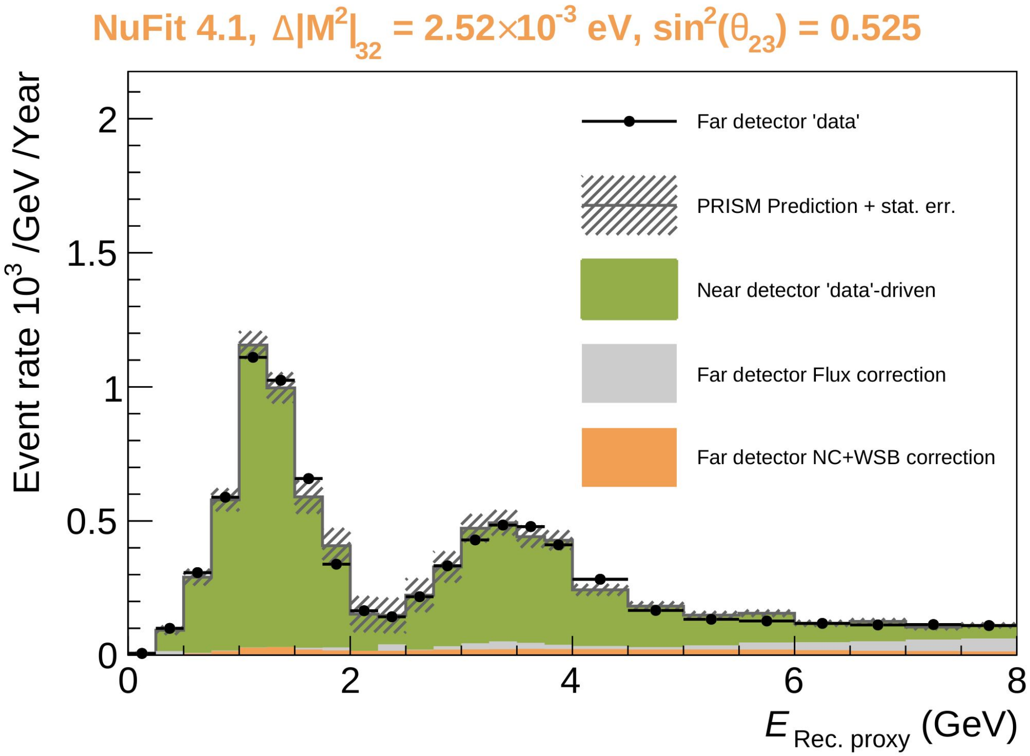
  - PRISM transfers near detector 'constraint' even if the near detector sample is mis-modelled.



The Full PRISM prediction

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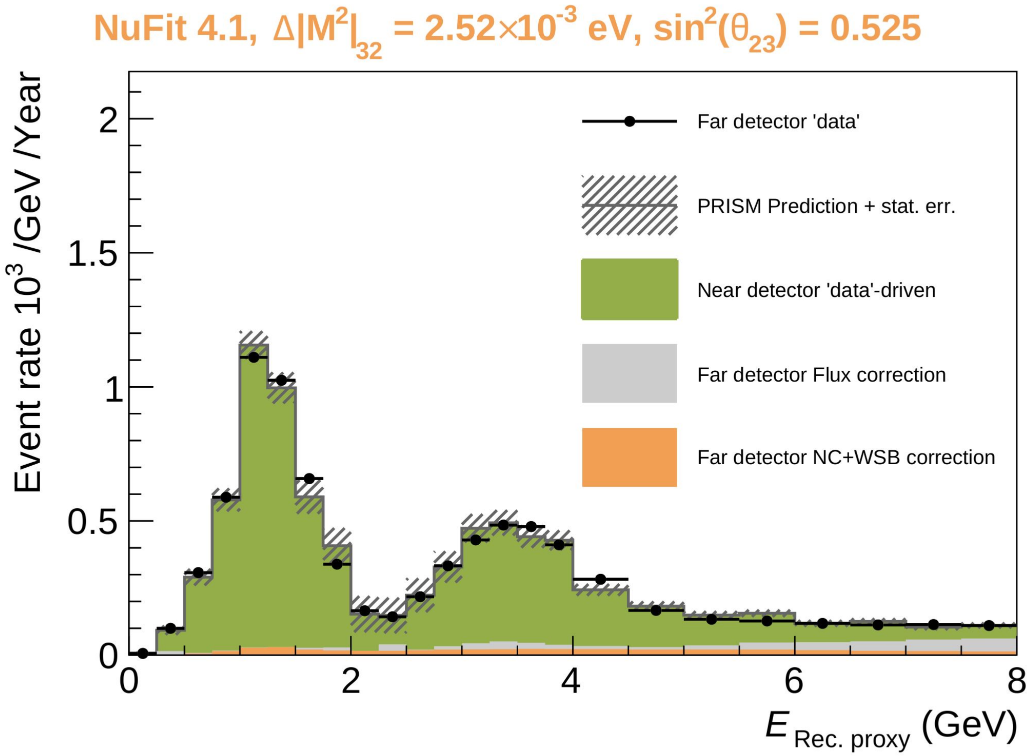
  - Imperfect flux matching
  - Backgrounds in the near and far selection
- Majority of oscillated far prediction is rearranged near detector signal data.
  - PRISM transfers near detector 'constraint' even if the near detector sample is mis-modelled.
- **In a traditional analysis, the whole spectrum would be a predicted by a model.**



Putting PRISM Into Practice

A 'mock' data Study

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

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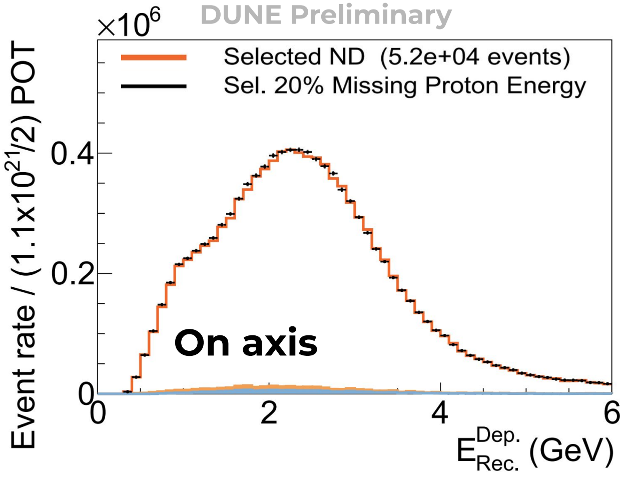
  - Move 20% of proton KE to neutrons but fit model to on-axis ND data.



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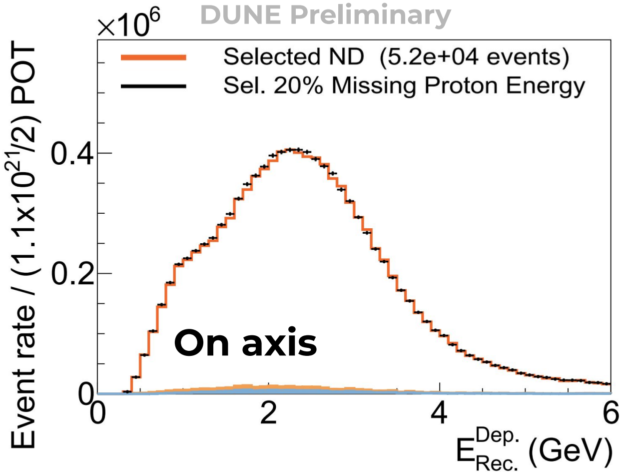
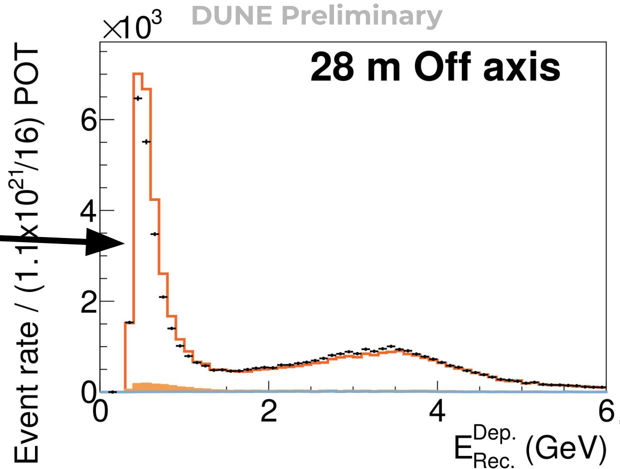
  - **Not able to simultaneously describe on an off axis data with incorrect model**





A 'mock' data Study

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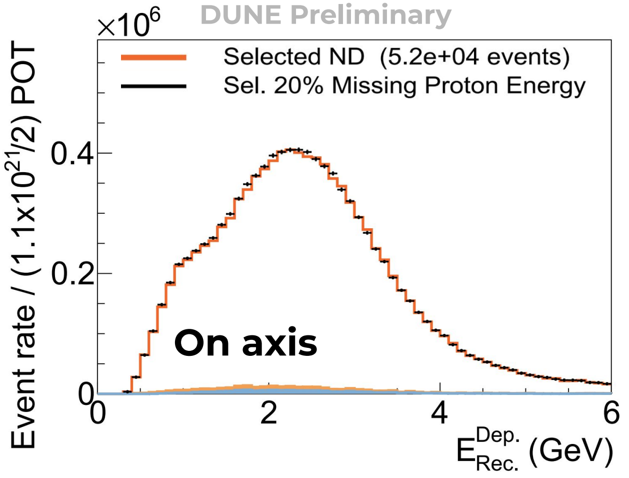
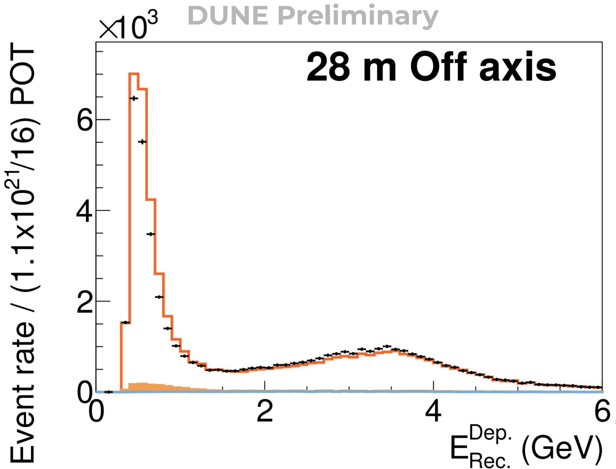
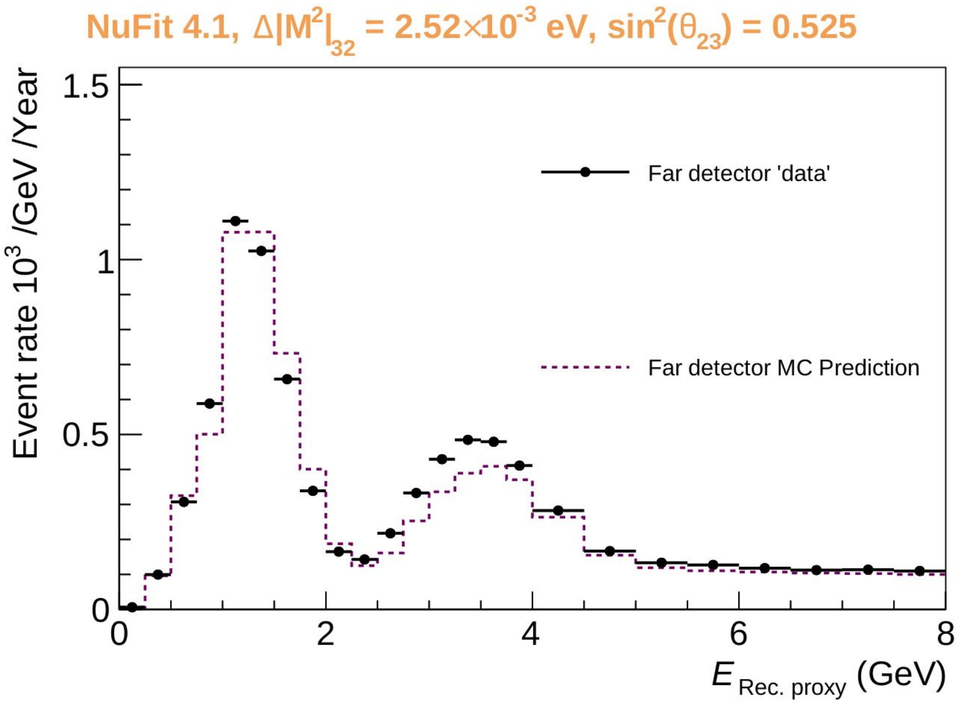
- Can imagine a world where the model can be fit to near detector data, but $E^{\nu}_{True} \Rightarrow E^{\nu}_{Obs}$ is wrong.
- Case Study:
  - Move 20% of proton KE to neutrons but fit model to on-axis ND data.
  - Not able to simultaneously describe on an off axis data with incorrect model
  - But not obvious how to incorporate this in a traditional analysis...





Mock Data Spectrum

- If we had trusted the on axis near detector fit:
  - $E^{\nu}_{True} \Rightarrow E^{\nu}_{Obs}$ would be wrong
  - For the correction oscillation hypothesis the tuned model would not predict the observed data



Mock Data Spectrum

- If we had trusted the on axis near detector fit:
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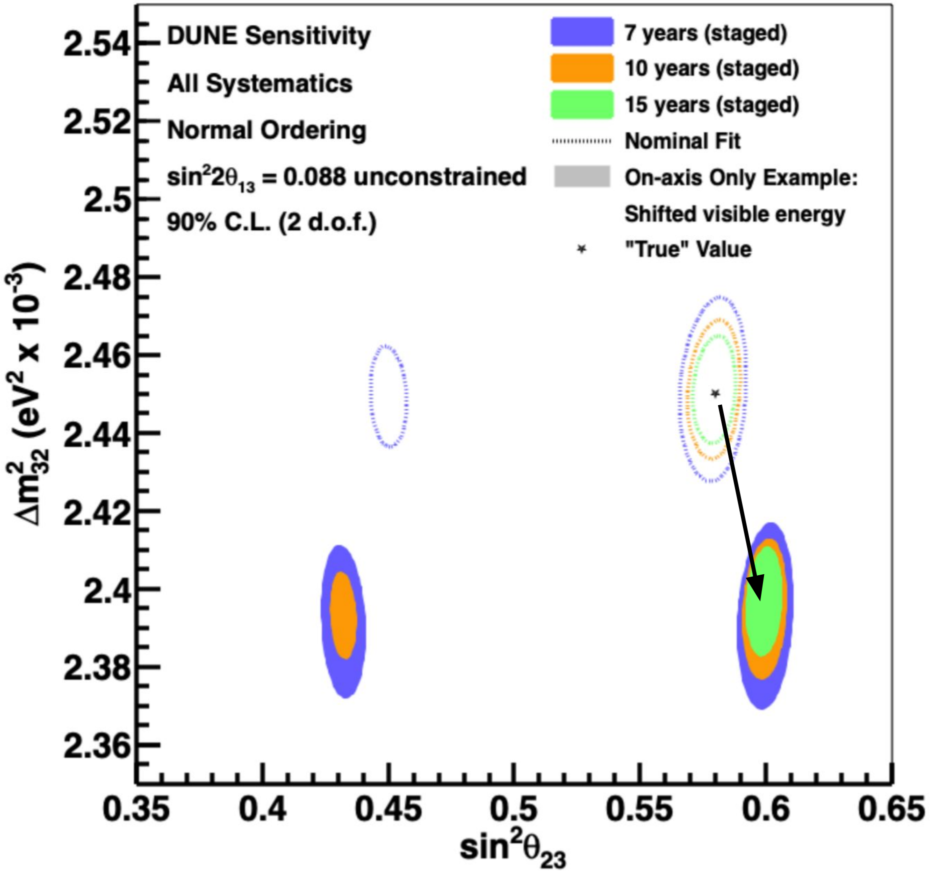
  - **Would extract biased oscillation parameter values**



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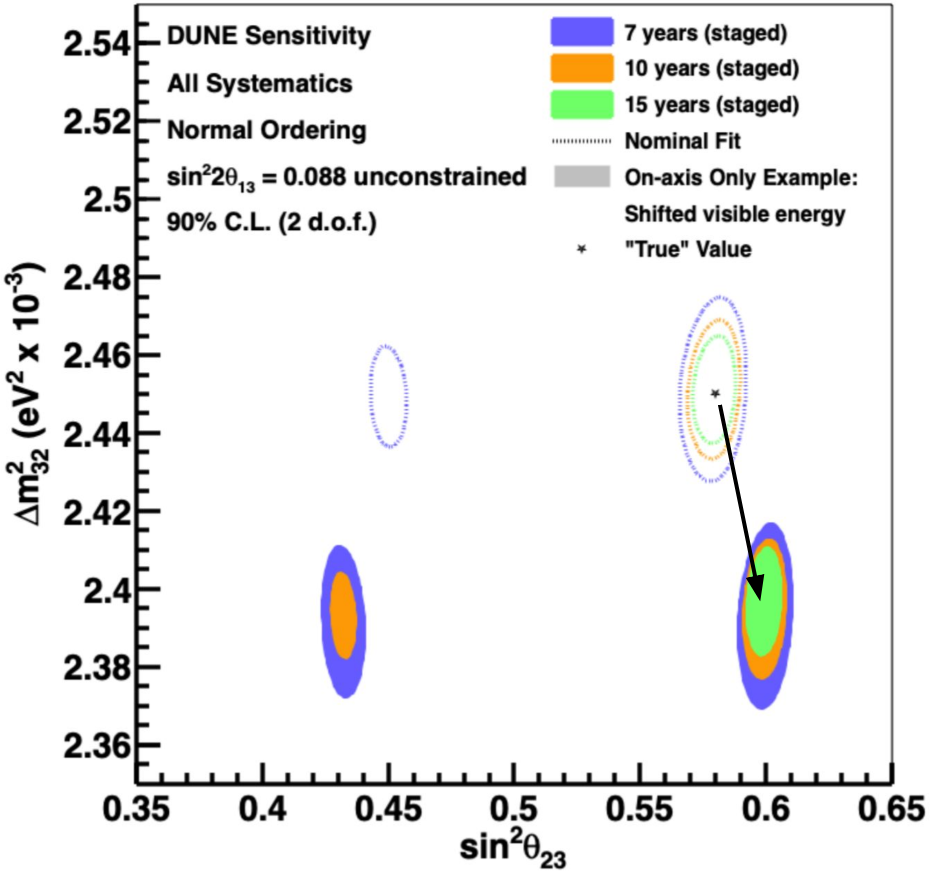
    - **We wouldn't know we were wrong**
    - **More data wouldn't help**



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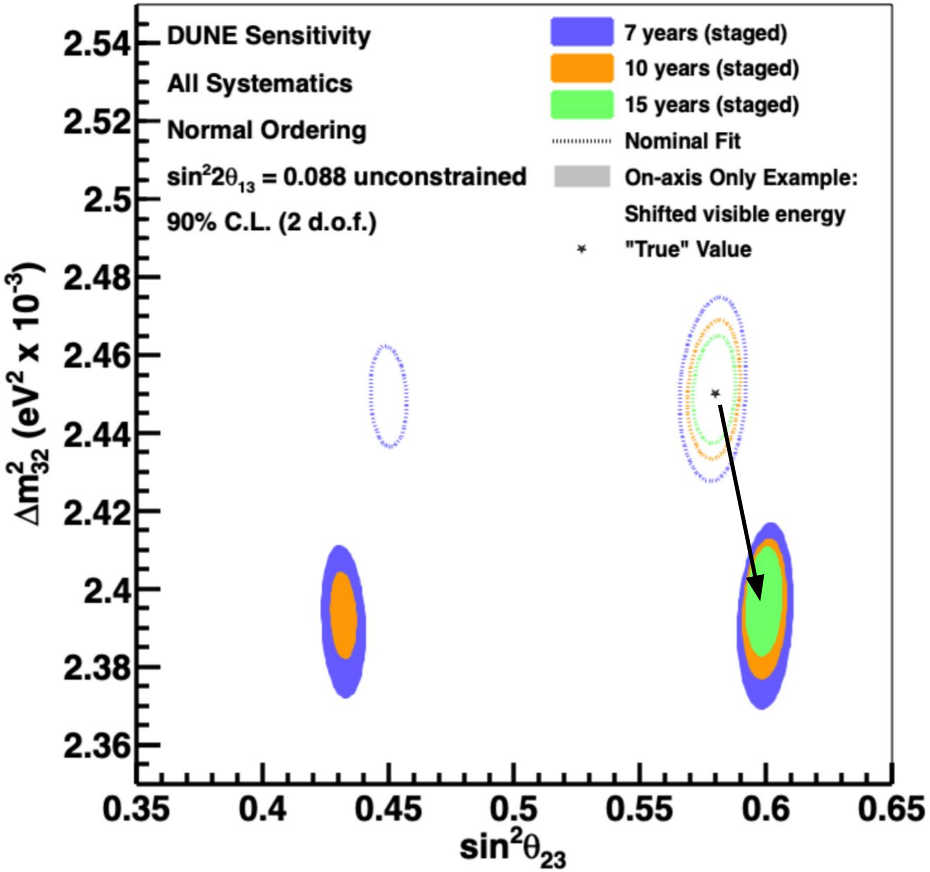
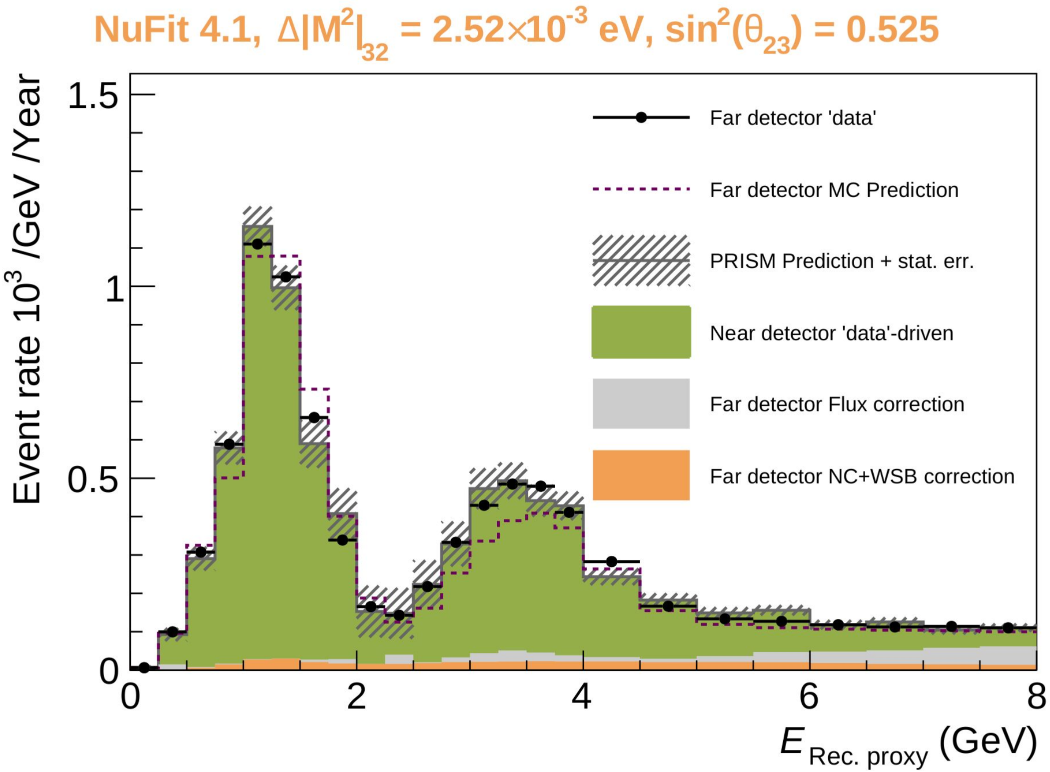
  - Would extract biased oscillation parameter values
    - We wouldn't know we were wrong
    - More data wouldn't help
- **What if we ask PRISM?**



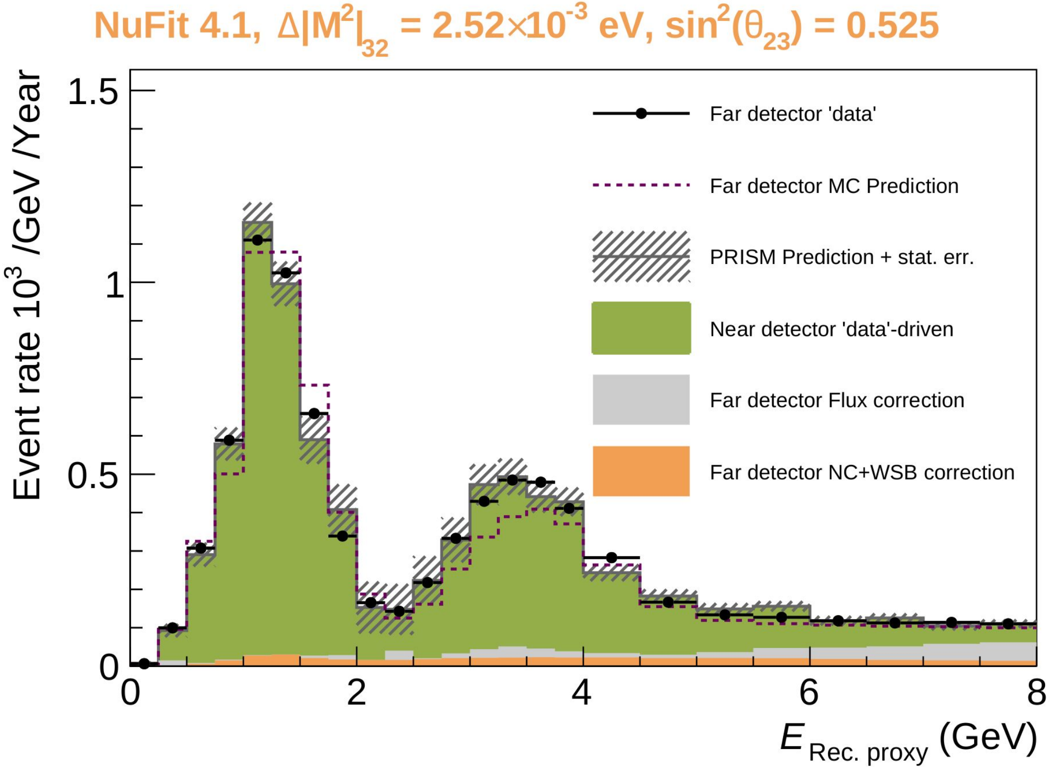
Let PRISM Have a Go

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



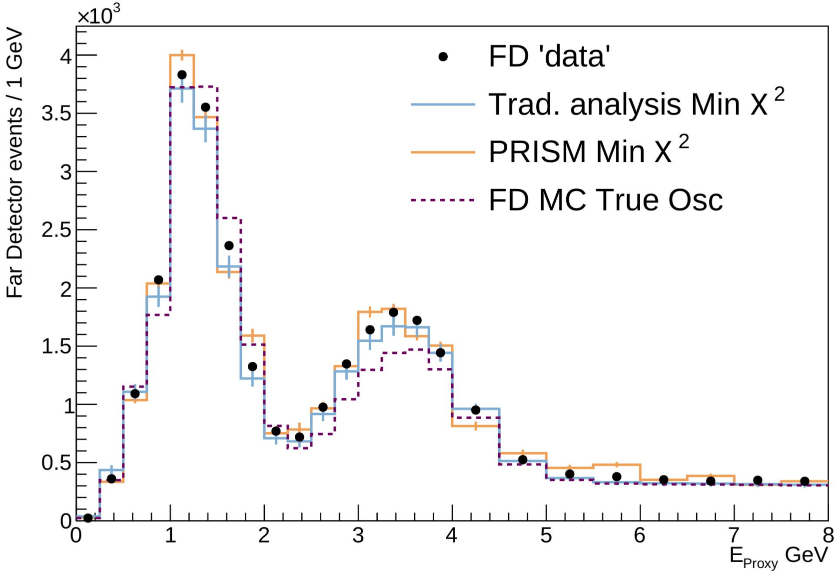
Let PRISM Have a Go

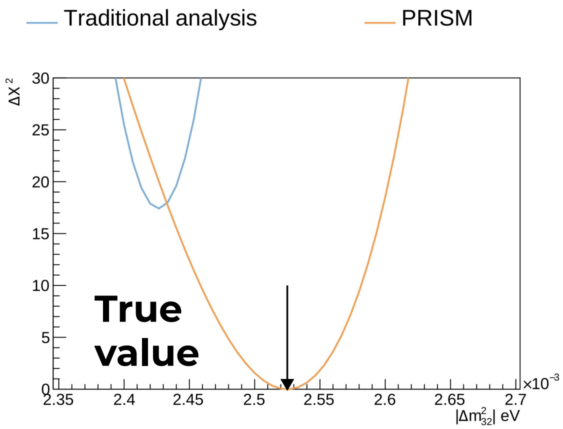
- PRISM Predicts far detector observation well even with incorrect interaction model!
    - **The direct extrapolation of near detector data largely side-steps the modelling problem.**



PRISM Prediction

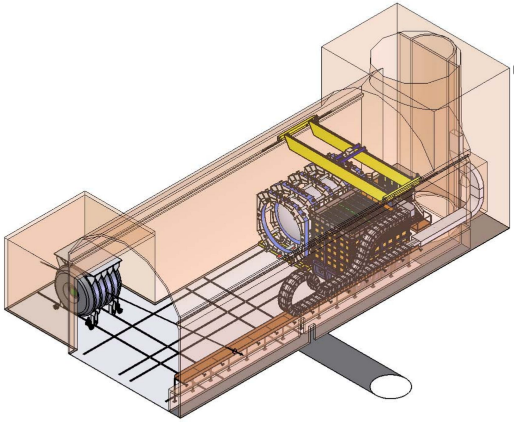
- Oscillation parameters can absorb poor interaction modelling.
- As expected, the traditional analysis would be badly biased.
- For this study, PRISM showed no such bias.

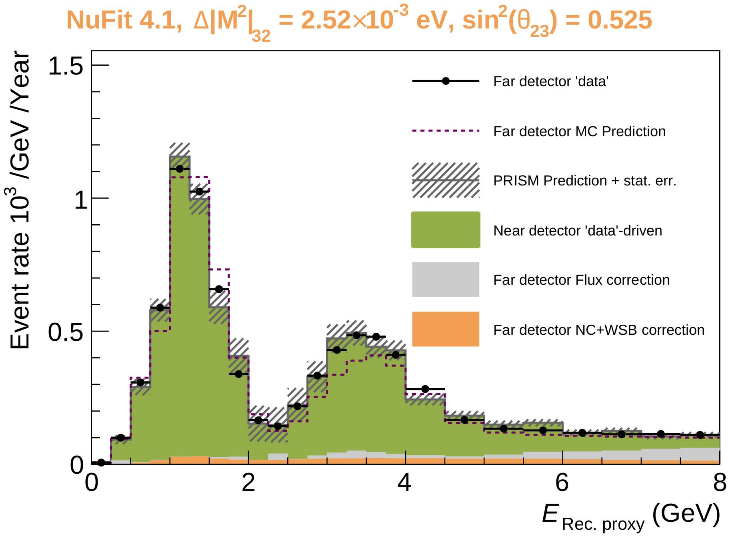




DUNE-PRISM Summary

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





Thanks for listening

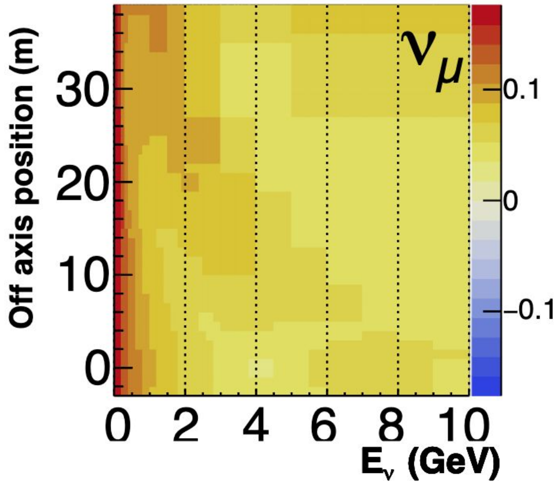
DUNE-PRISM

Flux Uncertainties

Flux Systematics

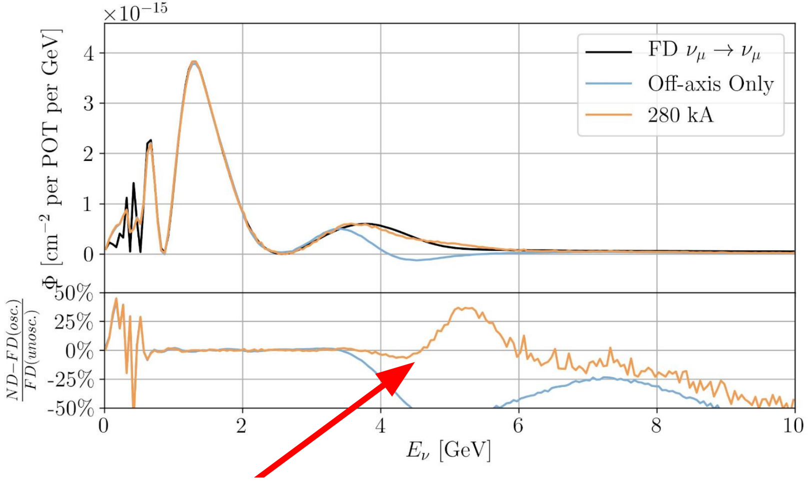
- For each step of an oscillation analysis:
  - flux systematic parameters may move
  - flux predictions change
  - must re-determine PRISM coefficients.

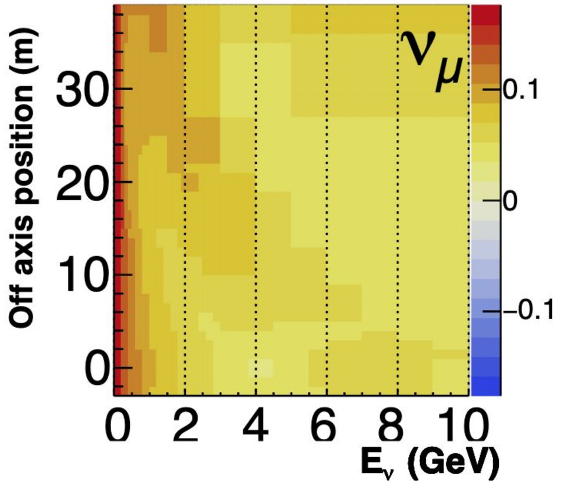
Example rate variation from flux parameter



Flux Systematics

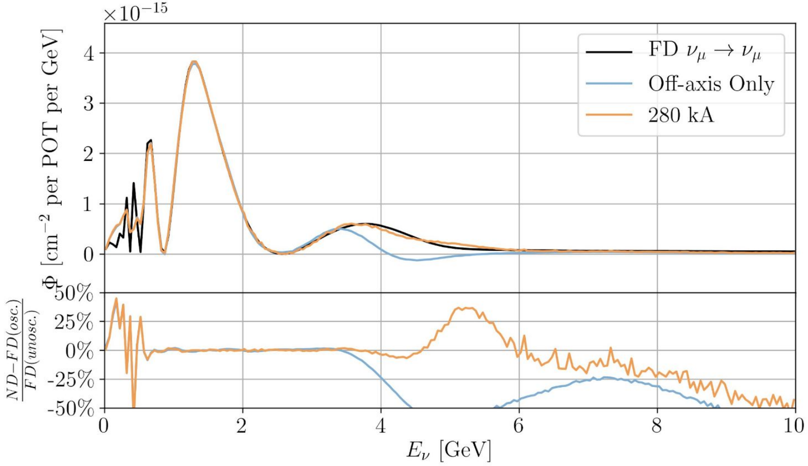
- For each step of an oscillation analysis:
  - flux systematic parameters may move
  - flux predictions change
  - must re-determine PRISM coefficients.
- Different coefficients change the flux matching residual
  - The residual correction uses FD MC
  - This sets the scale that signal cross-section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

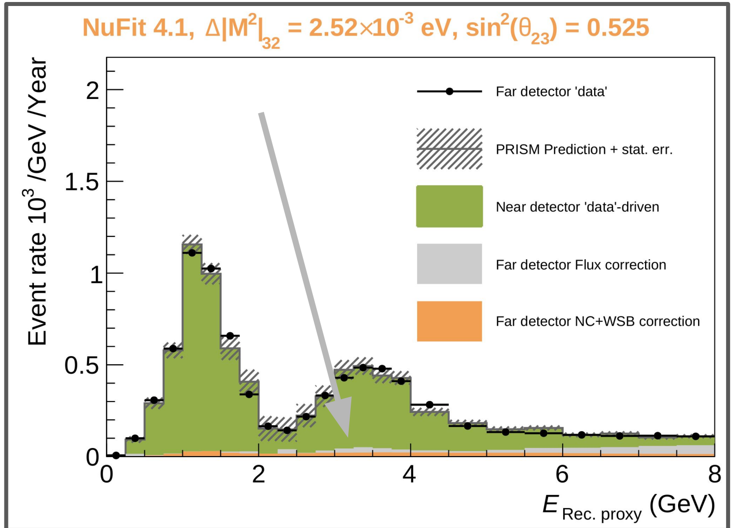




Flux Systematics

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

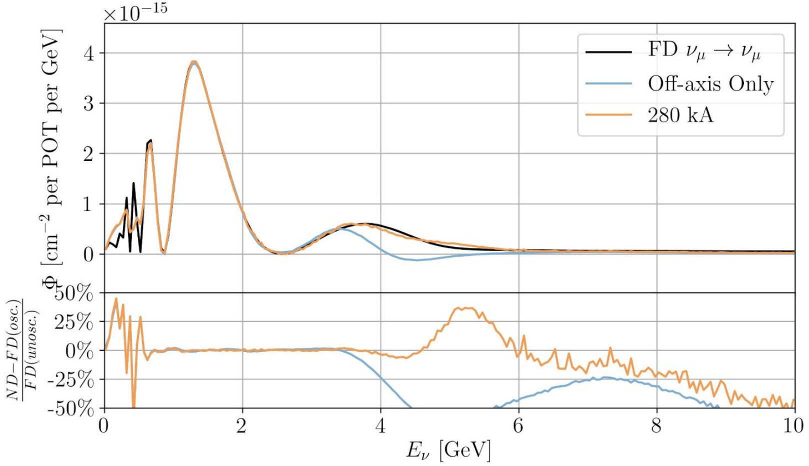


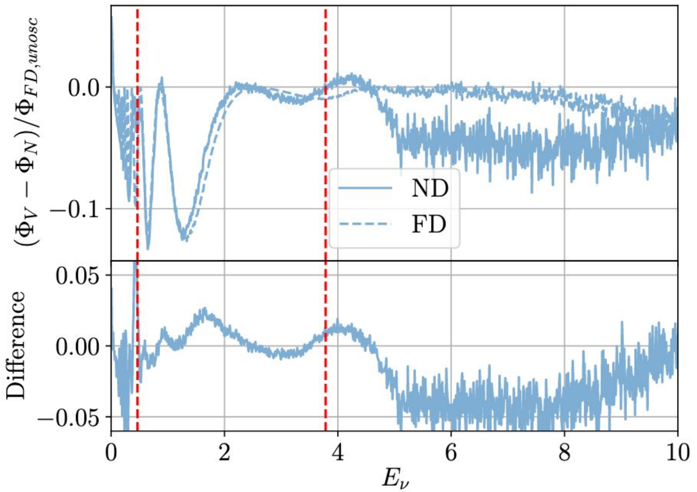


Flux Systematics

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

- Take a given systematic variation and study how much the FD flux prediction and the PRISM prediction vary relative to nominal to each other.
    - **e.g. one systematically varied hadron production universe.**





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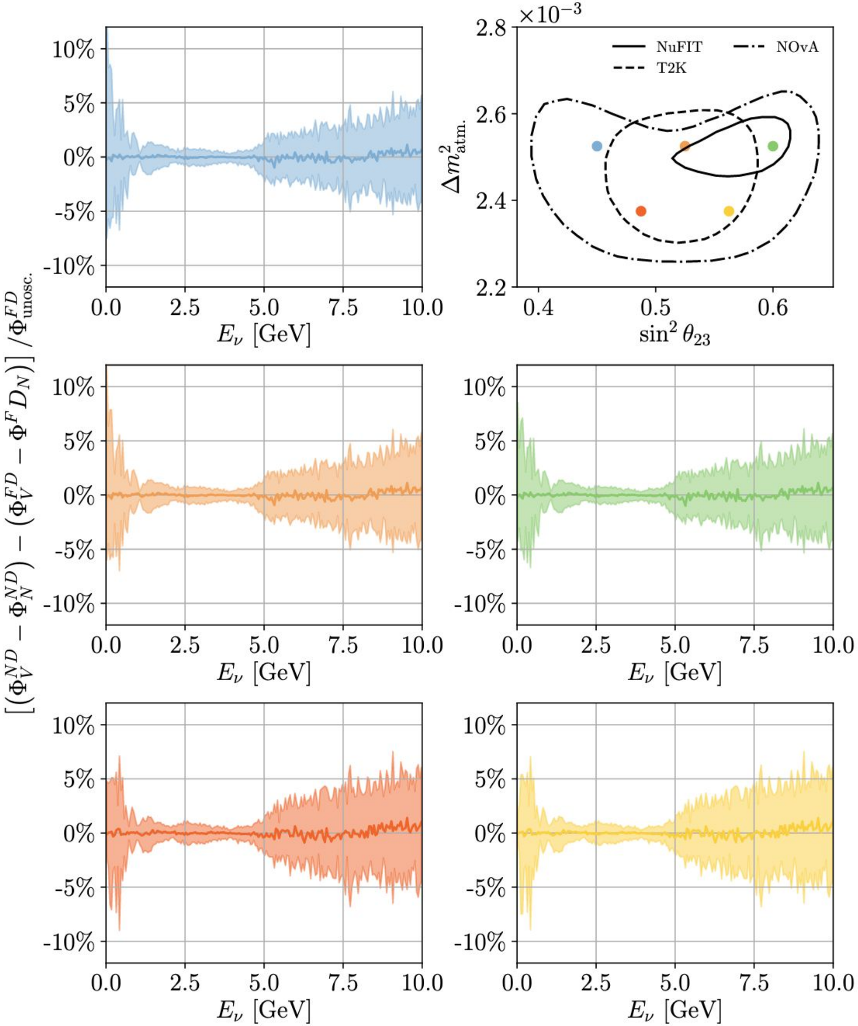
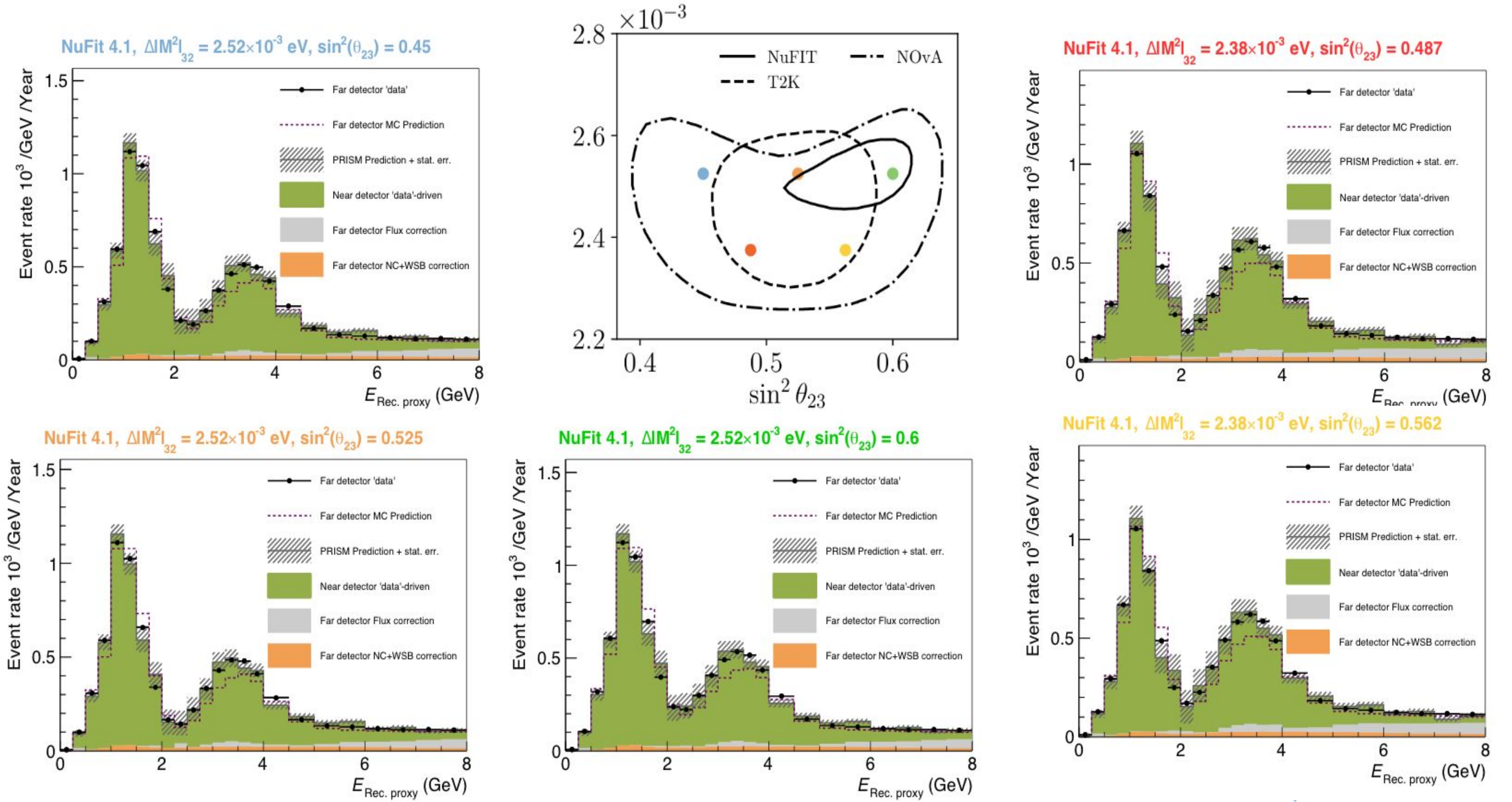
    - **e.g. 100 hadron production universes**

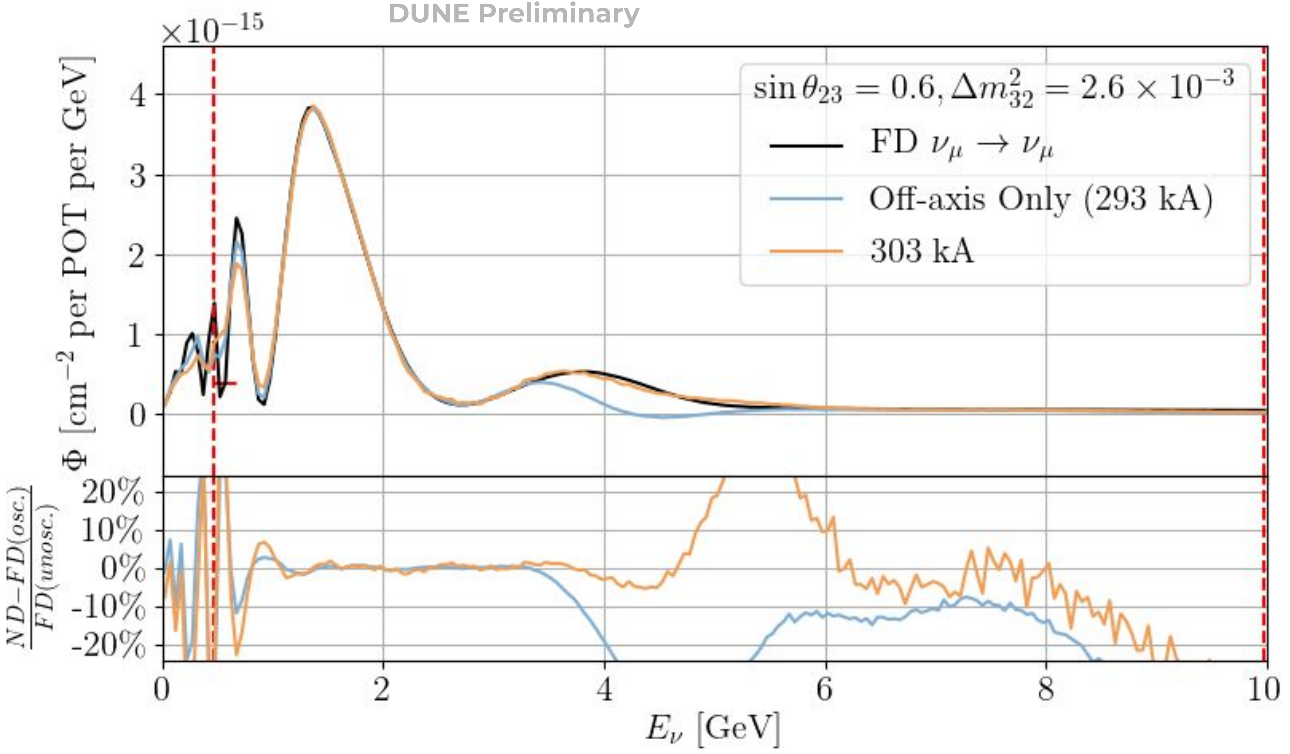


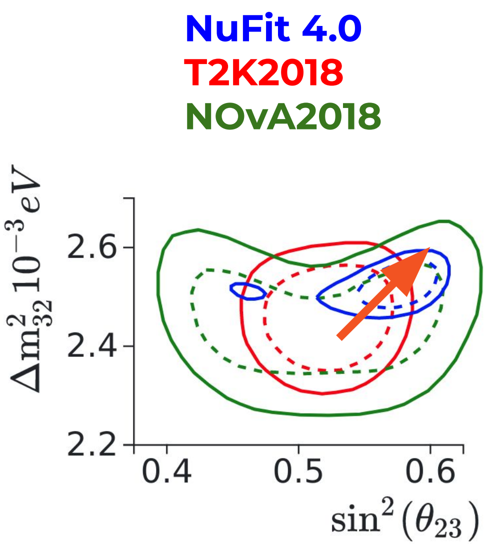
Other Oscillation Parameters


NuFit 4.1, ΔlM²l₃₂ = 2.52×10⁻³ eV, sin²(θ₂₃) = 0.45
NuFit 4.1, ΔlM²l₃₂ = 2.38×10⁻³ eV, sin²(θ₂₃) = 0.487
NuFit 4.1, ΔlM²l₃₂ = 2.52×10⁻³ eV, sin²(θ₂₃) = 0.525
NuFit 4.1, ΔlM²l₃₂ = 2.52×10⁻³ eV, sin²(θ₂₃) = 0.6
NuFit 4.1, ΔlM²l₃₂ = 2.38×10⁻³ eV, sin²(θ₂₃) = 0.562
Far detector 'data'
Far detector MC Prediction
PRISM Prediction + stat. err.
Near detector 'data'-driven
Far detector Flux correction
Far detector NC+WSB correction
Event rate 10³ /GeV /Year
E Rec. proxy (GeV)
×10⁻³
NuFIT
NOvA
T2K
sin² θ₂₃

Does it work everywhere?

Try it yourself!





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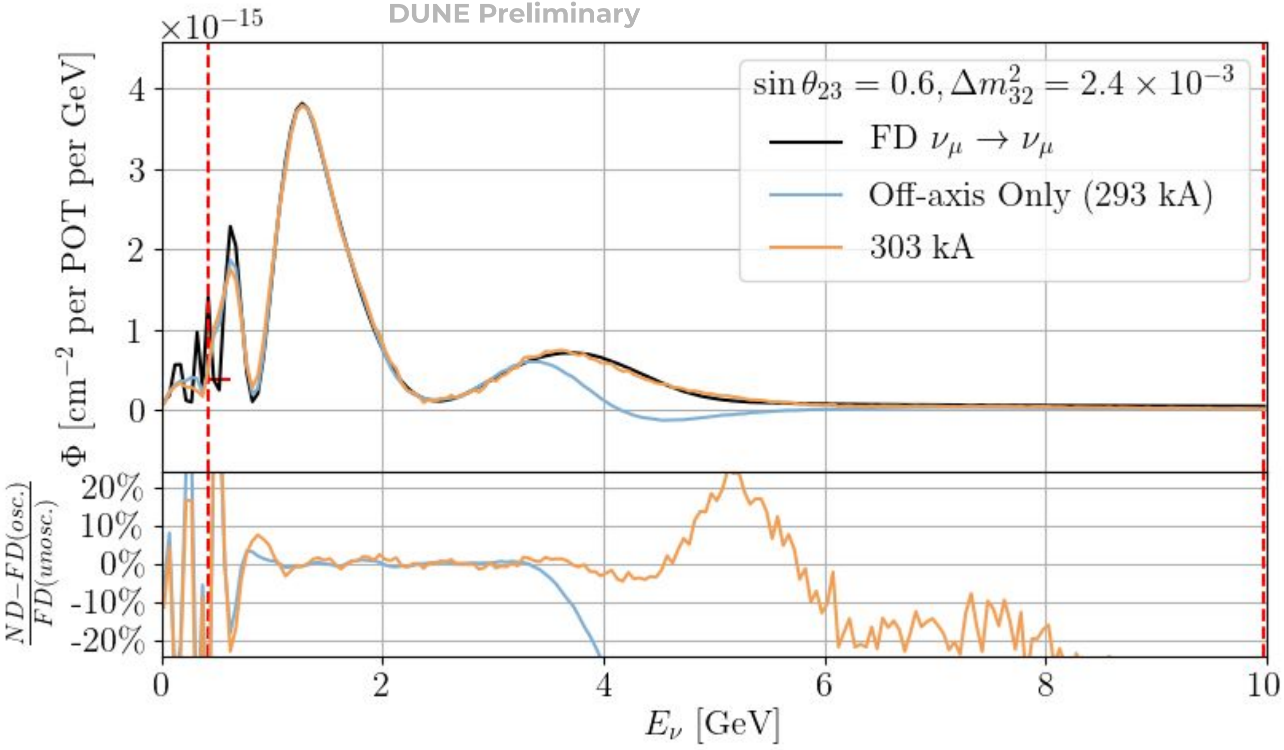
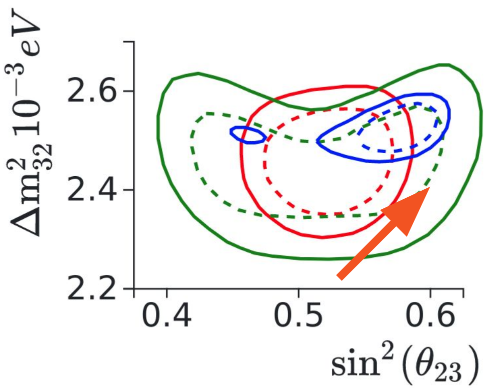


NuFit 4.0
T2K2018
NOvA2018



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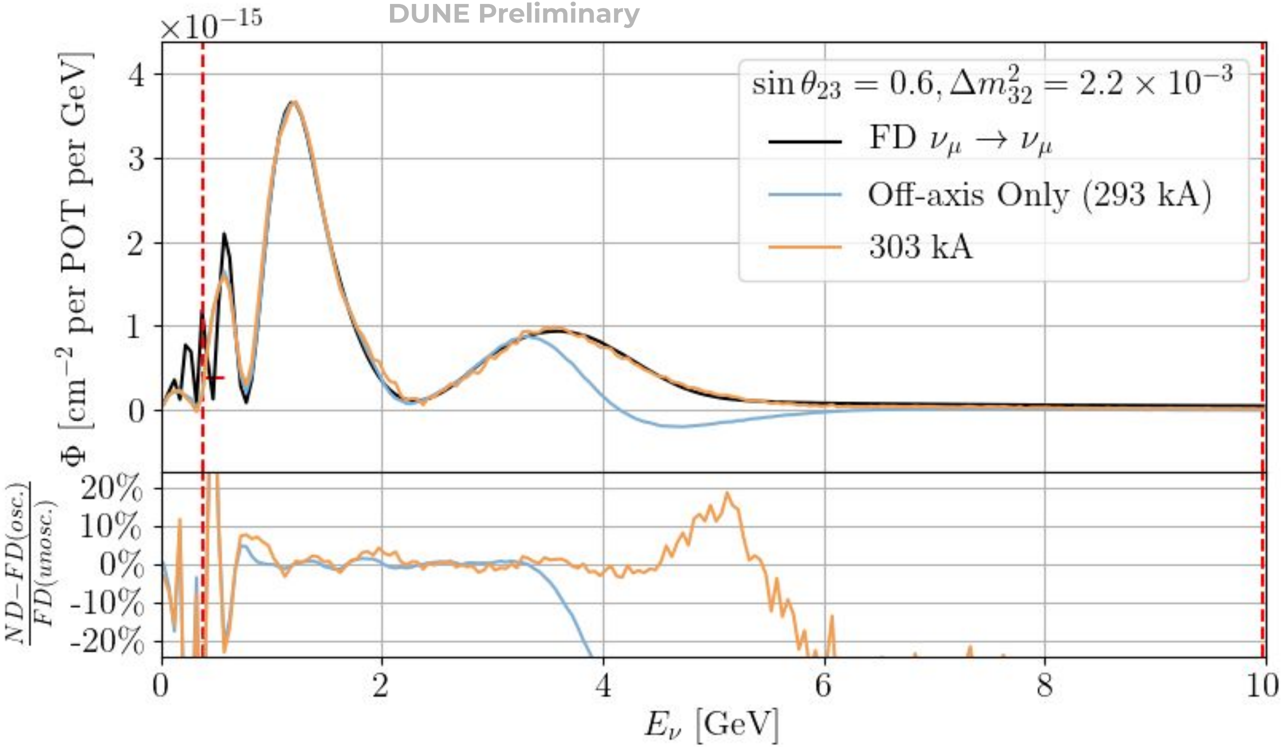
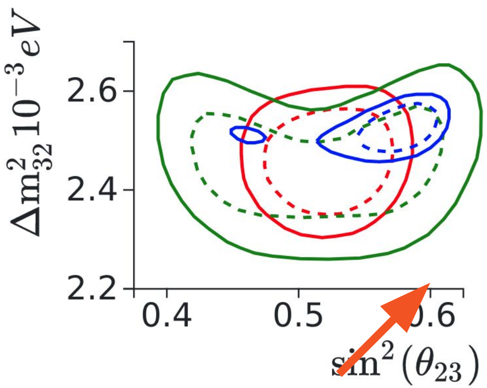
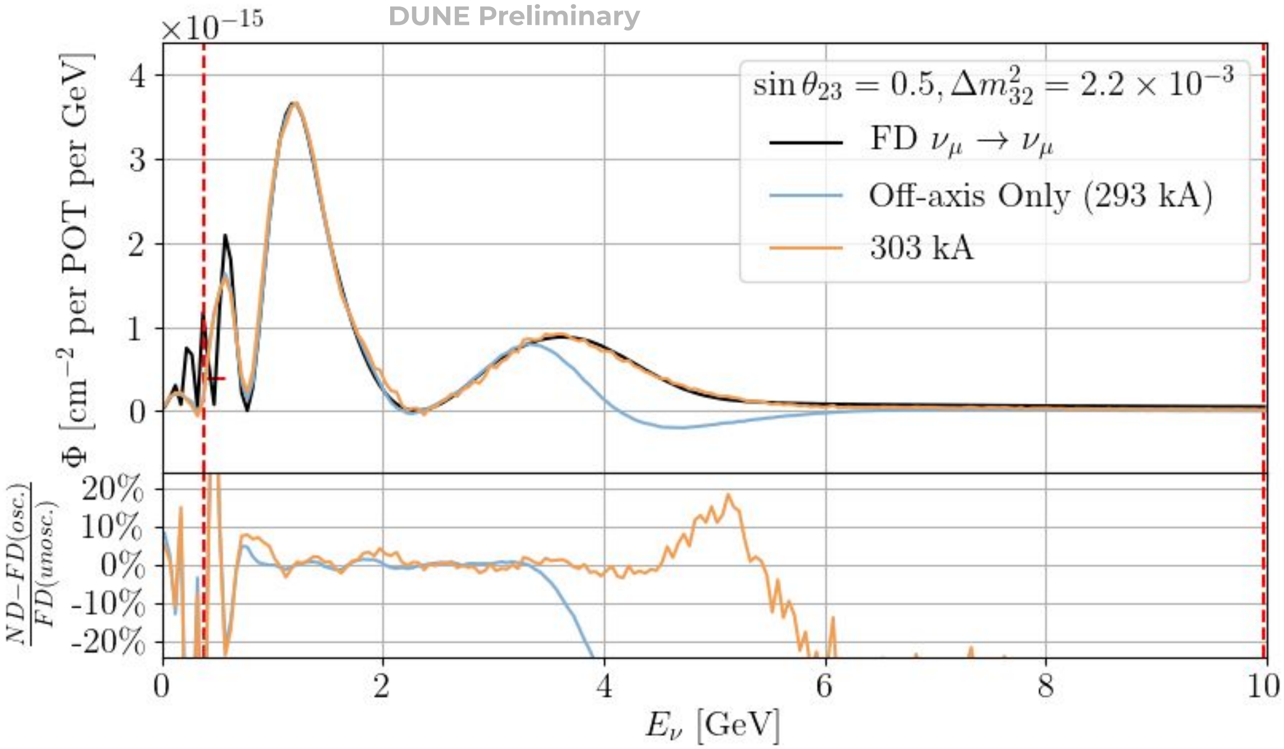
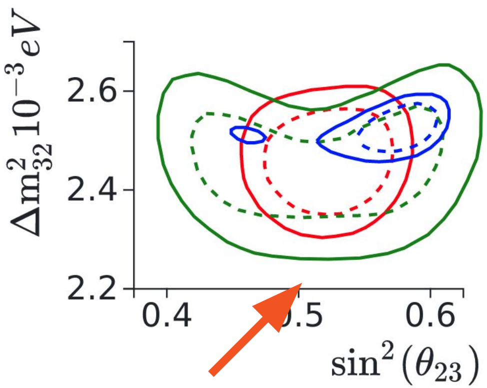




Does it work everywhere?

[Try it yourself!]





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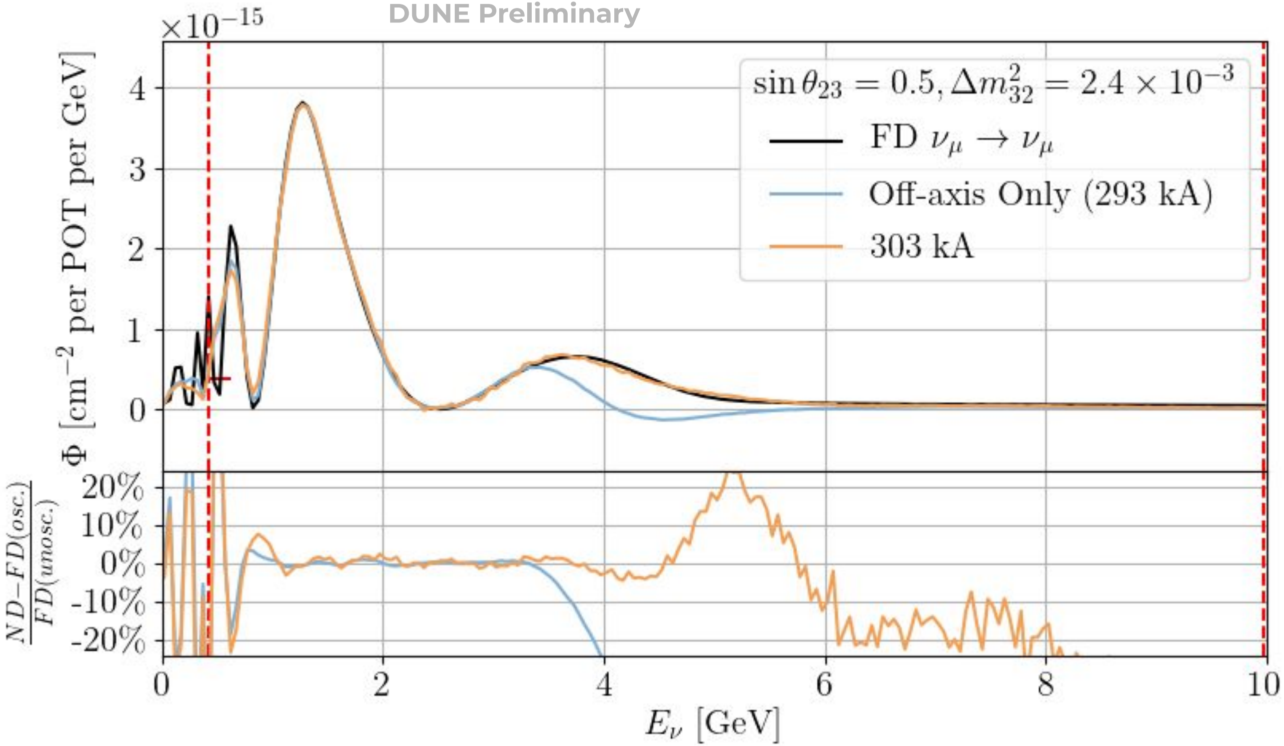

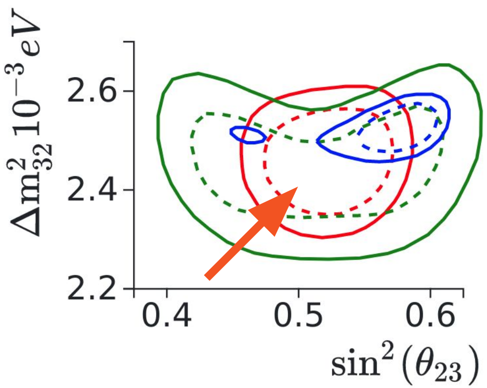

DUNE PRISM

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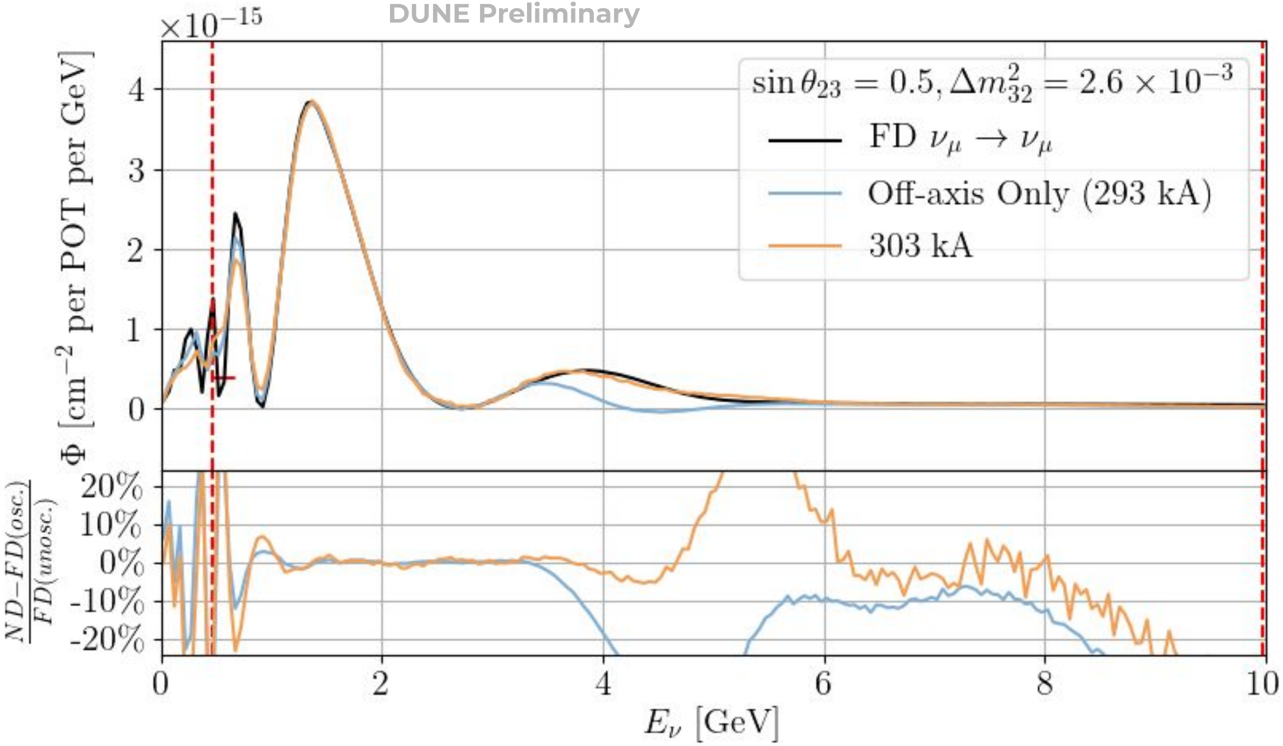

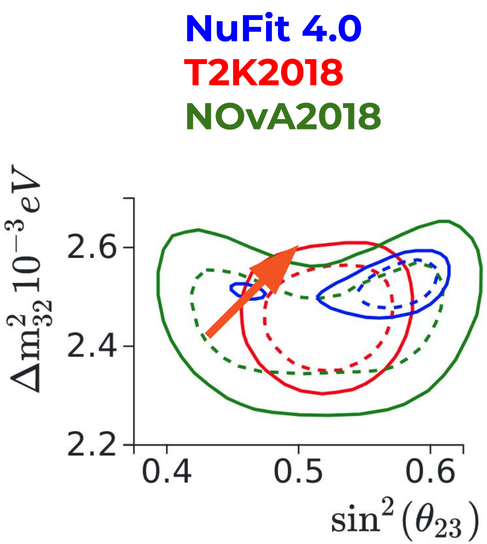

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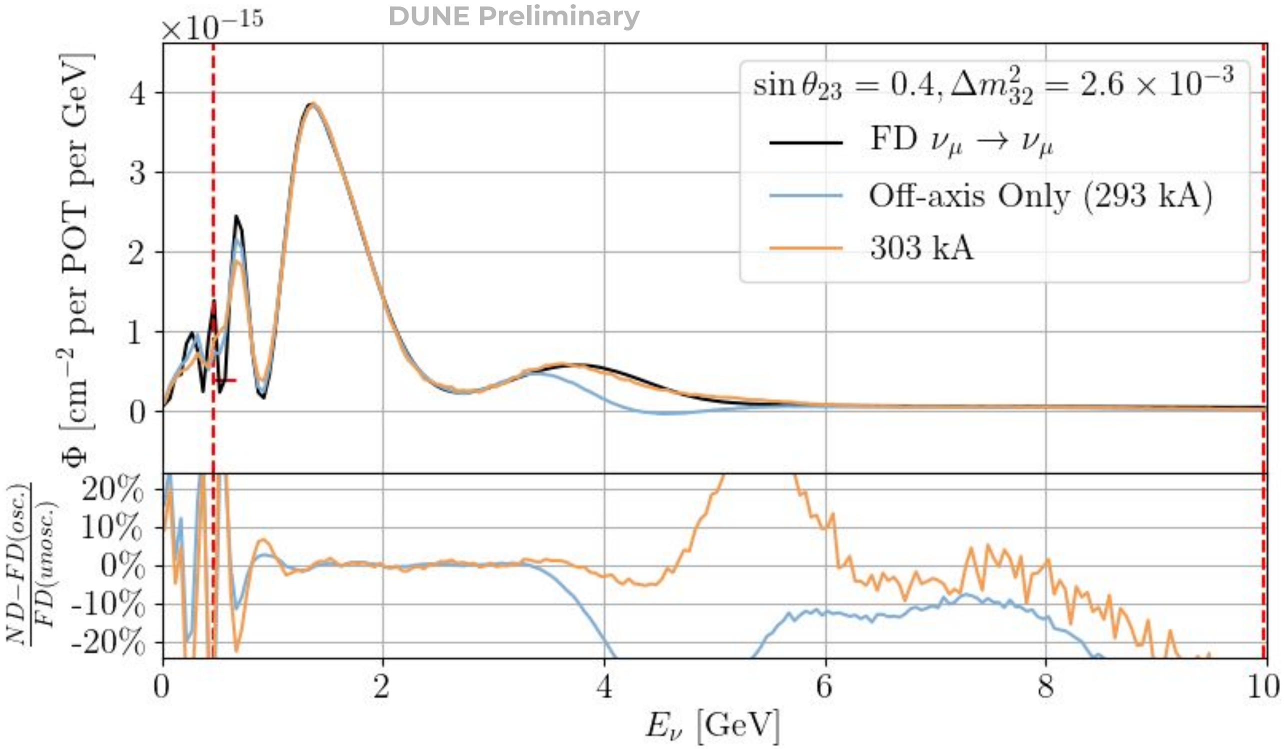

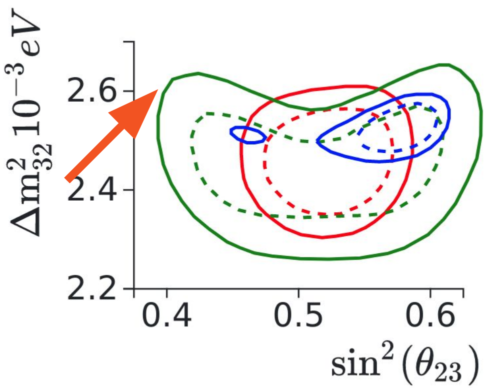

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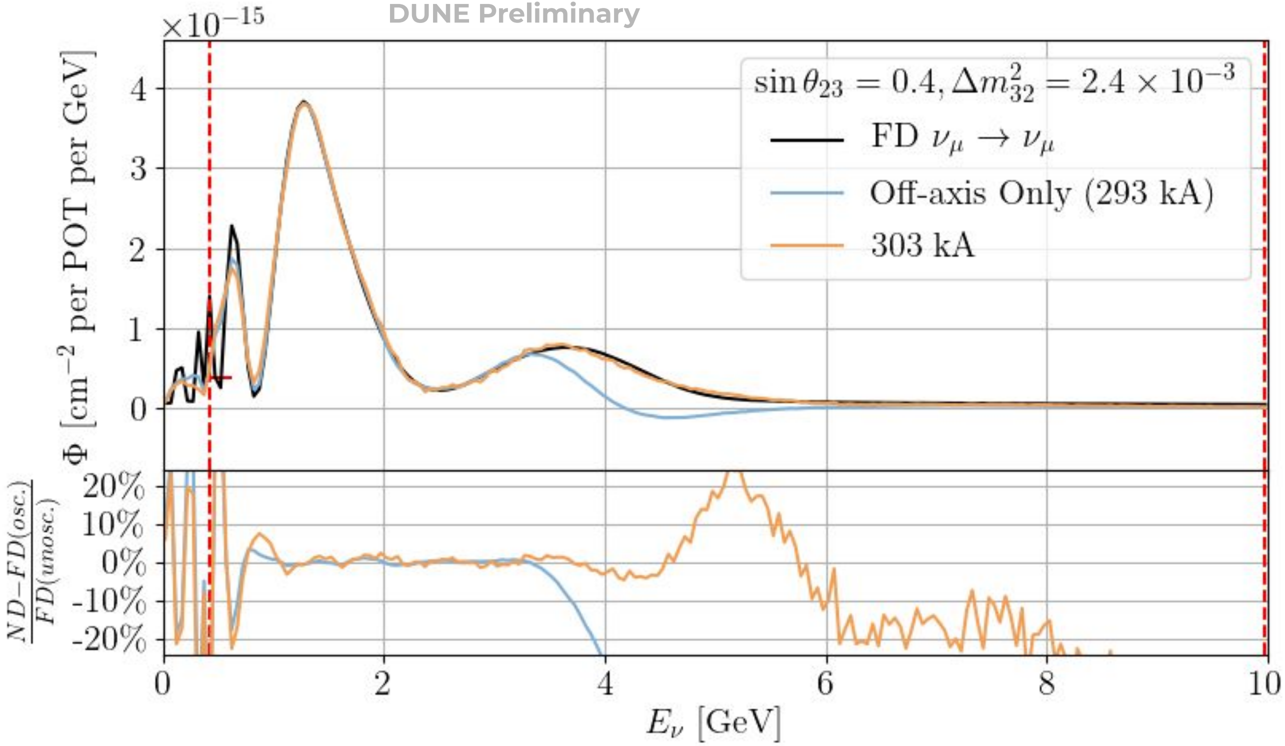
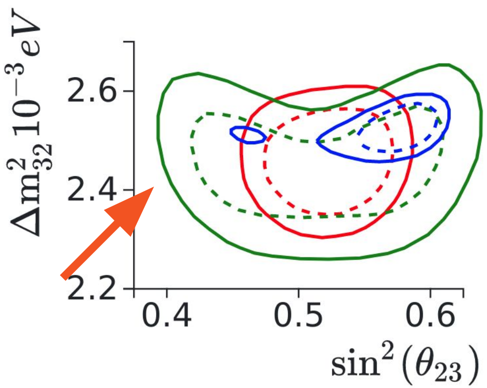


NuFit 4.0
T2K2018
NOvA2018



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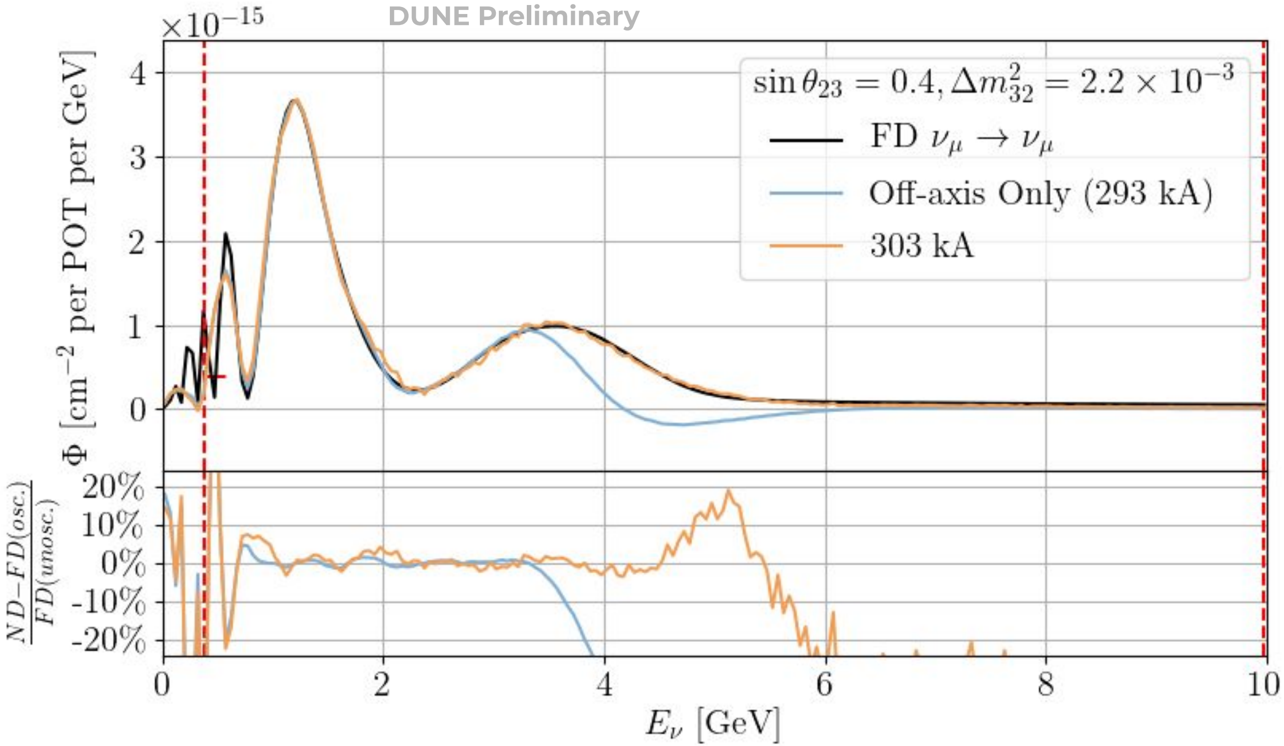
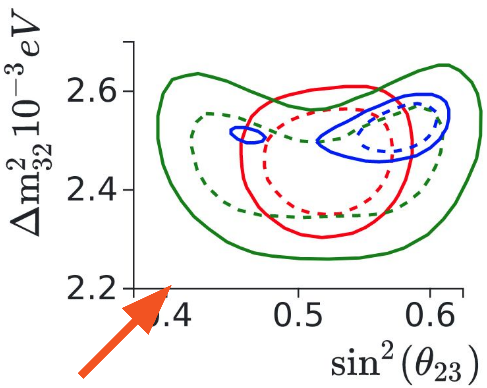
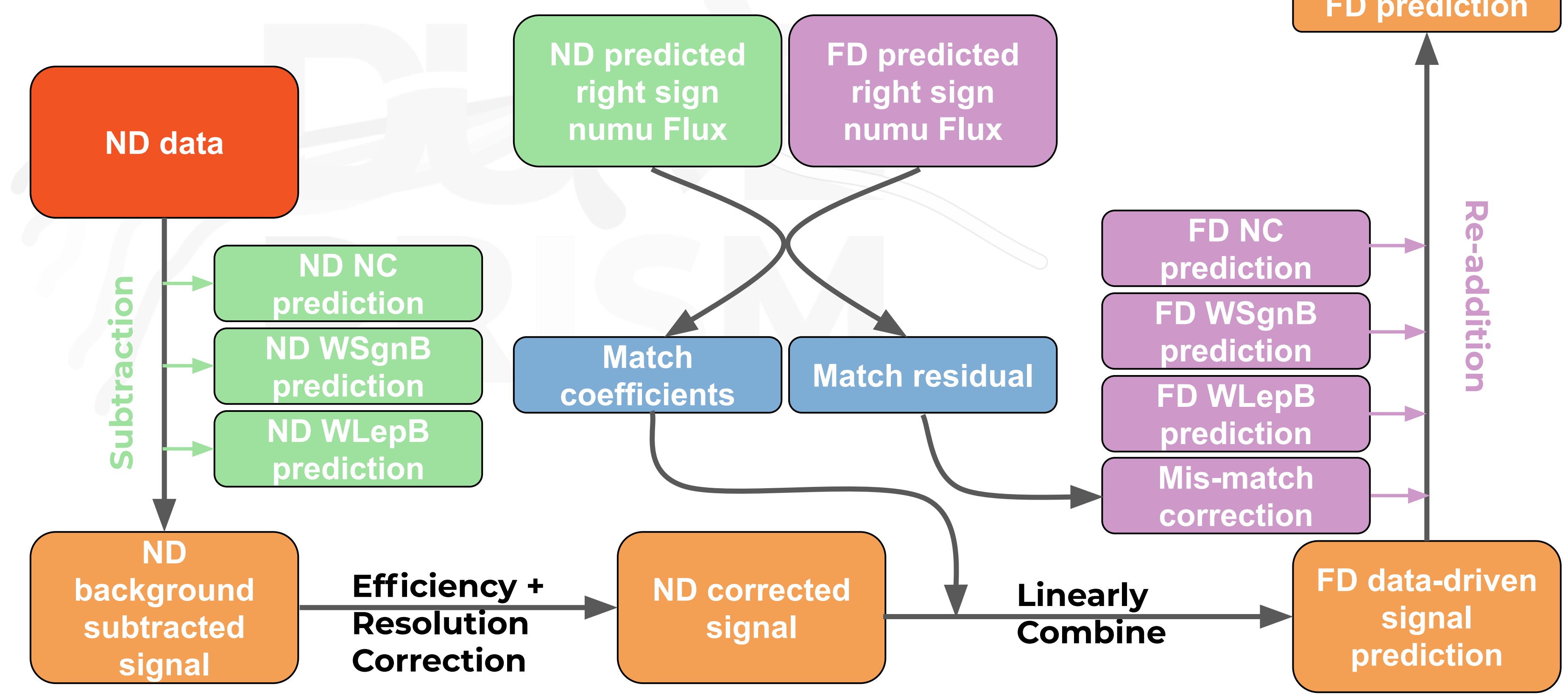




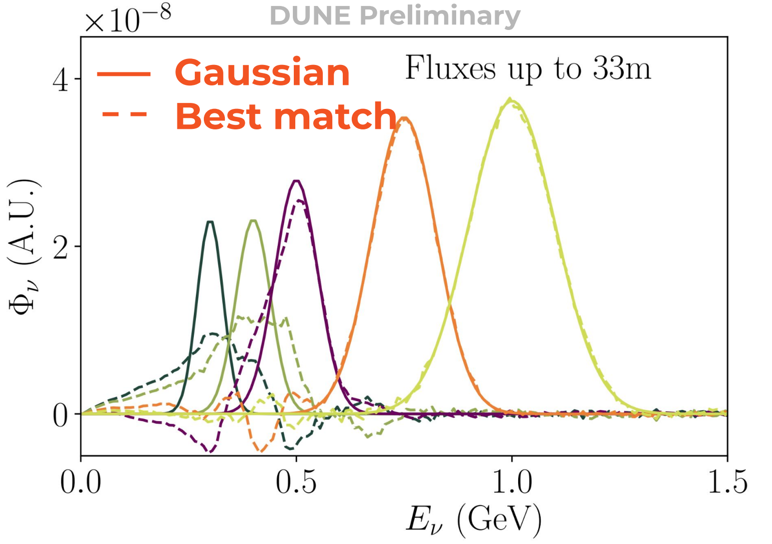
Analysis Flow: Disappearance

ND Data, ND MC, Corrected Data, FD MC



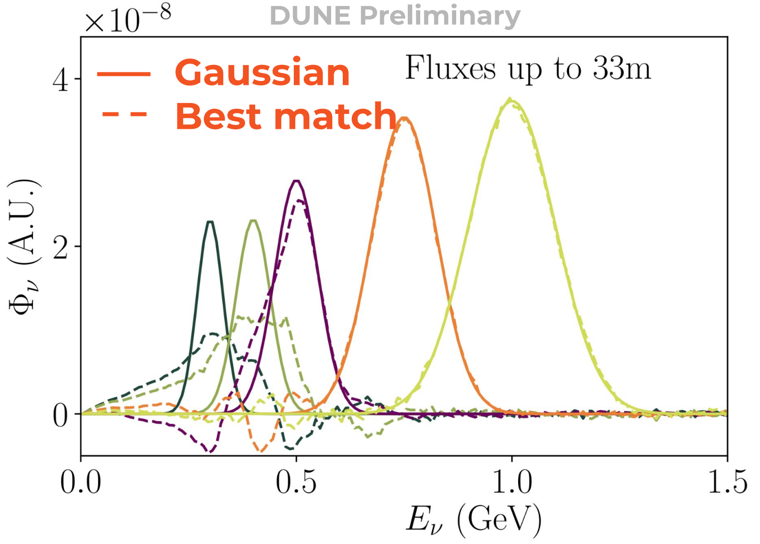
Narrow-band fluxes

- Also of interest to construct narrow band flux measurements.

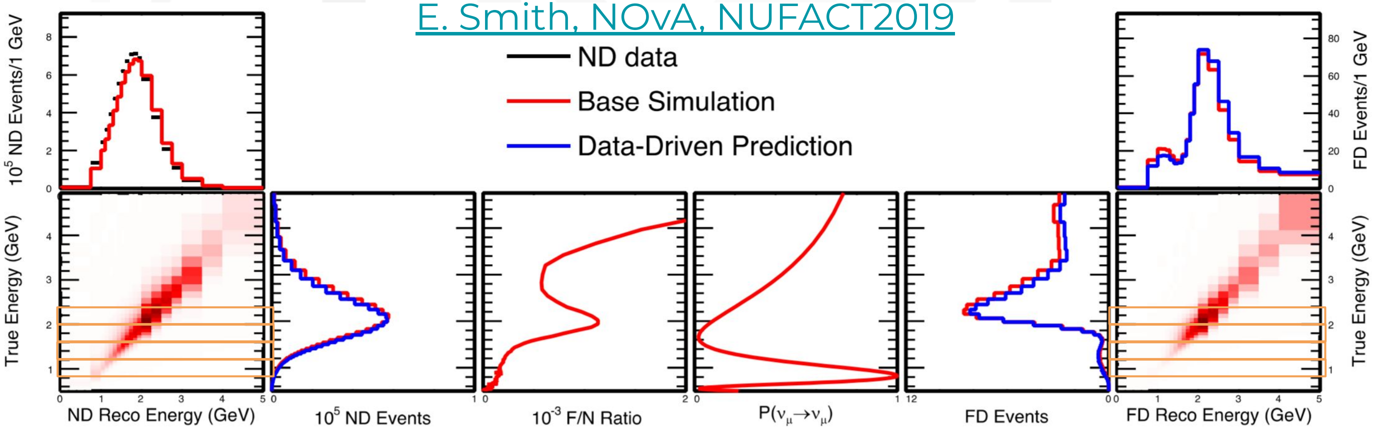


Narrow-band fluxes

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

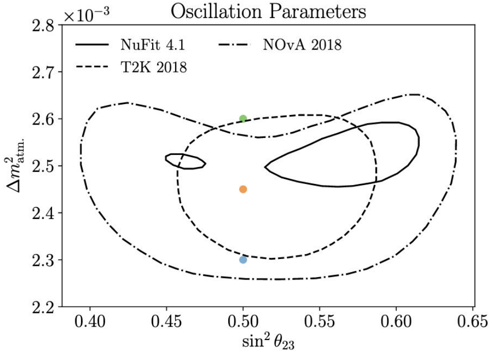


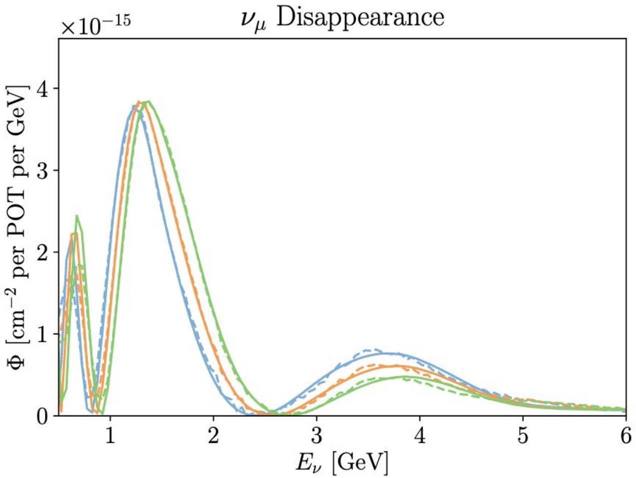
E. Smith, NOvA, NUFACT2019



Appearance

Is this the only Game we can Play?





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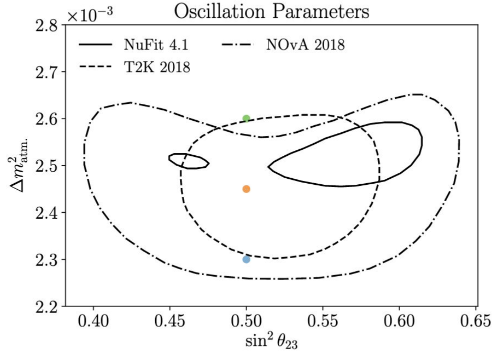
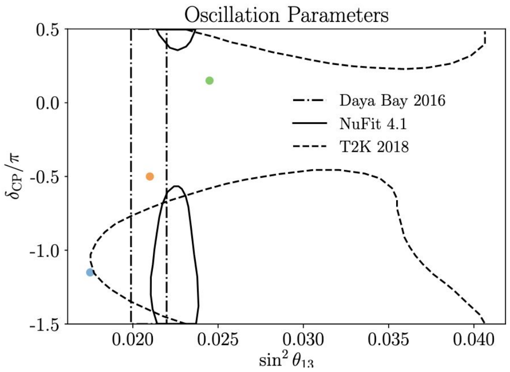
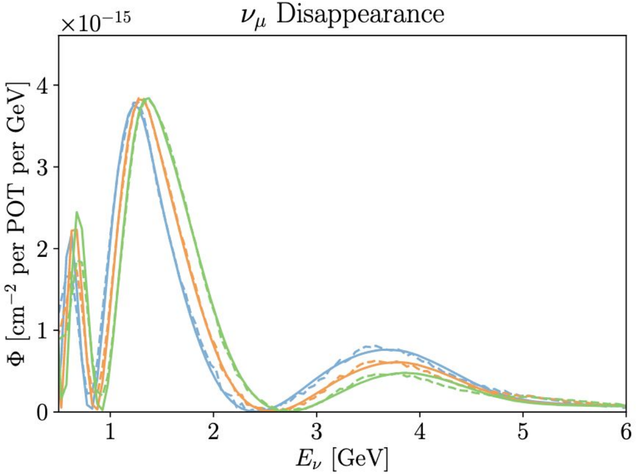
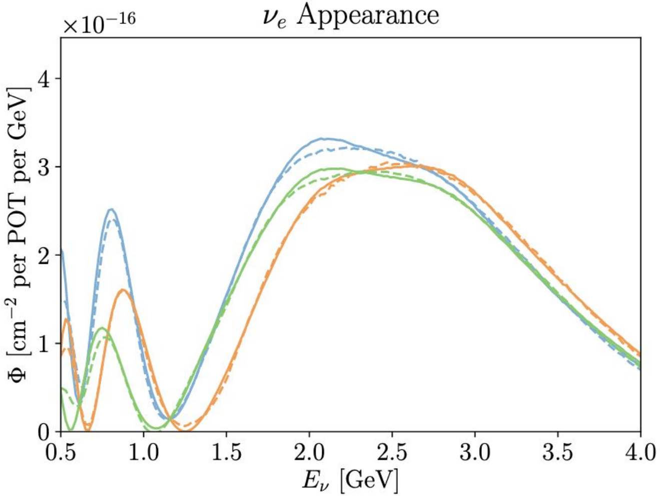


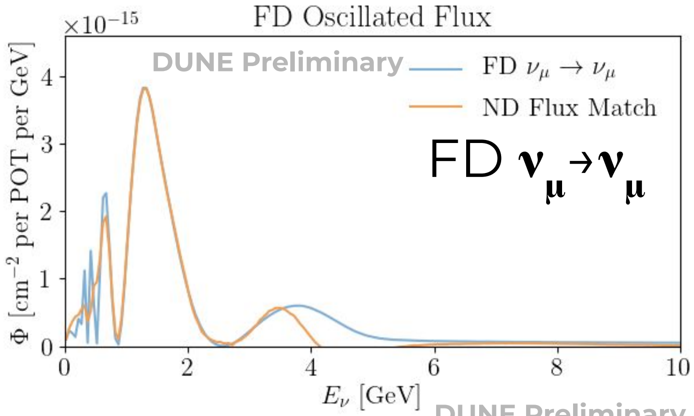


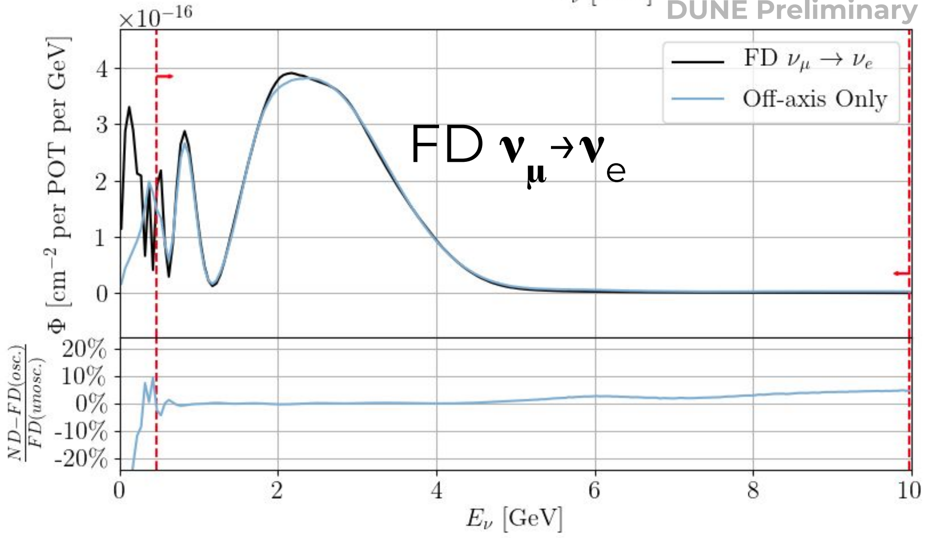




Fixing for an appearance

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





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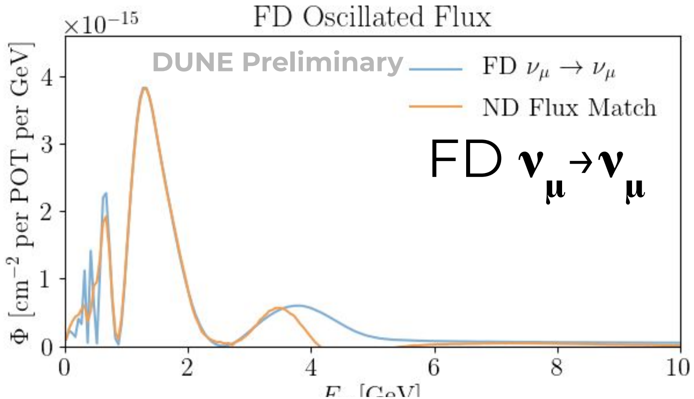
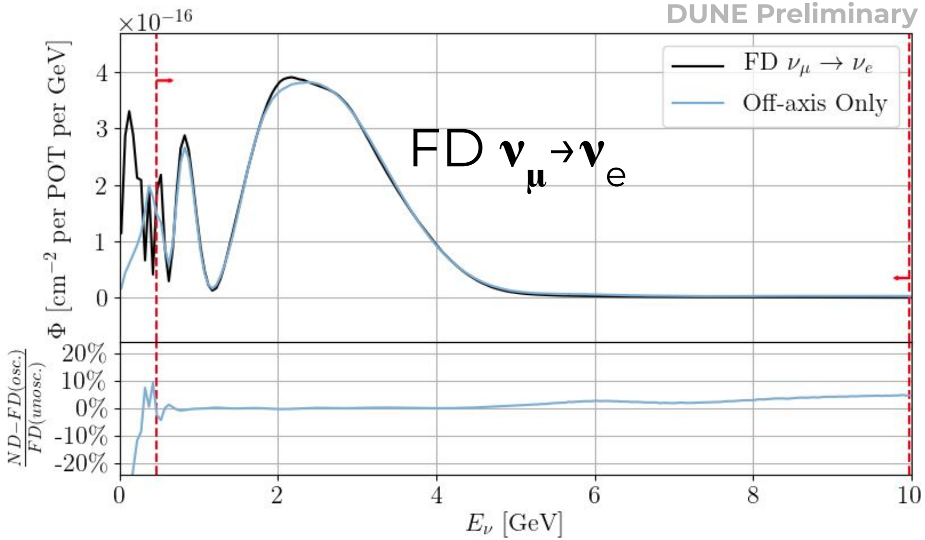
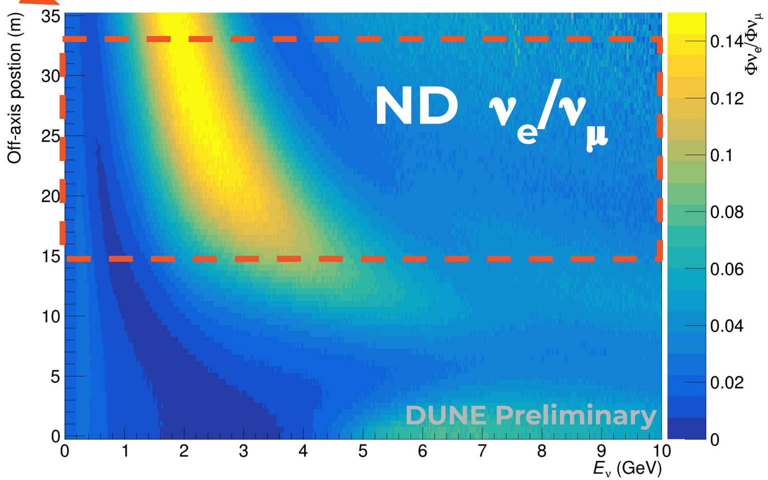
- Instead:
  - Use ND $\boldsymbol{\nu}_\mu$ sample
  - Build appeared FD $\boldsymbol{\nu}_e$ flux
- **Have to correct for electron/muon reconstruction & cross-section differences.**





ND nue fits

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



MICHIGAN STATE UNIVERSITY

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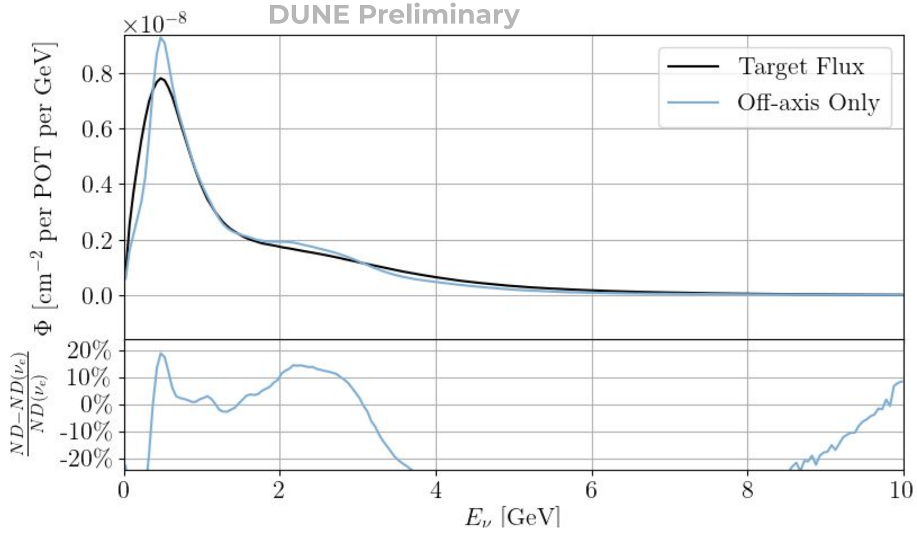

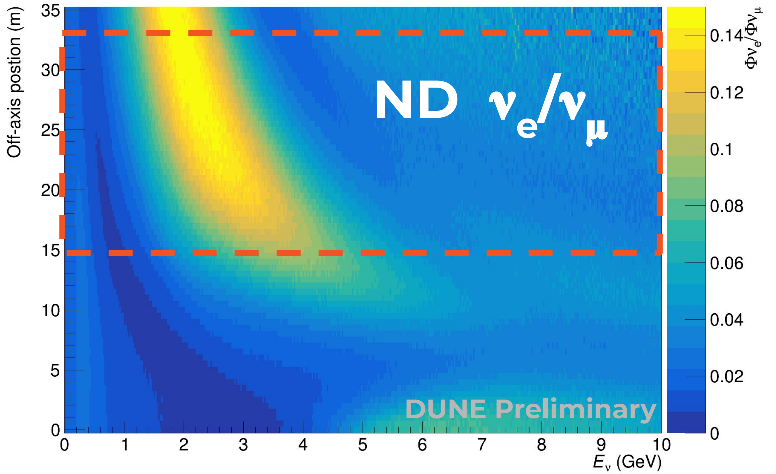

Near Far Differences

Geometric Efficiency Estimate

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

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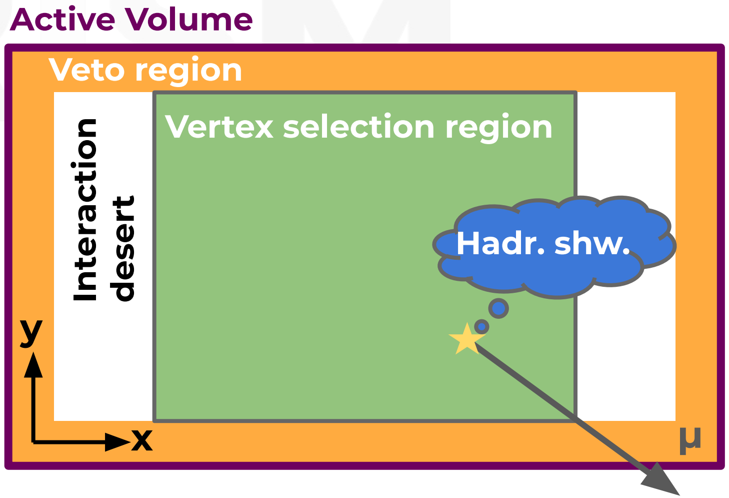
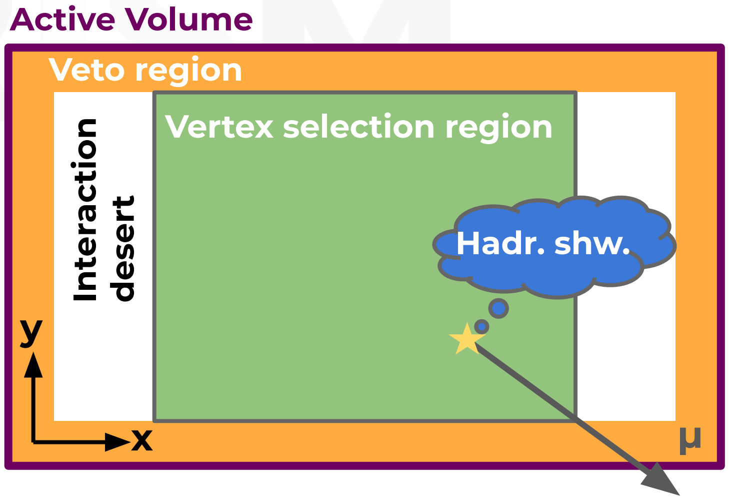


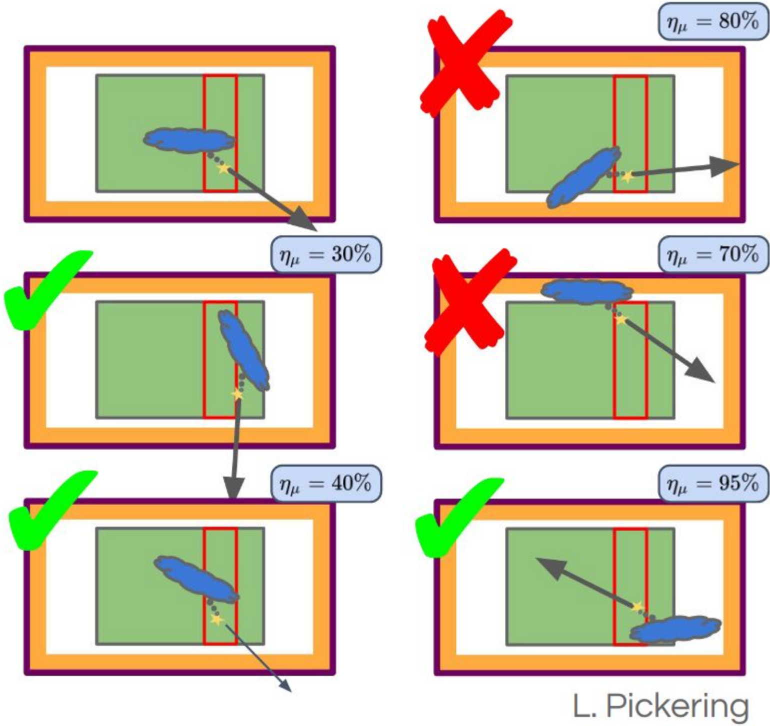
Geometric Efficiency Estimate

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



Geometric Efficiency Estimate

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

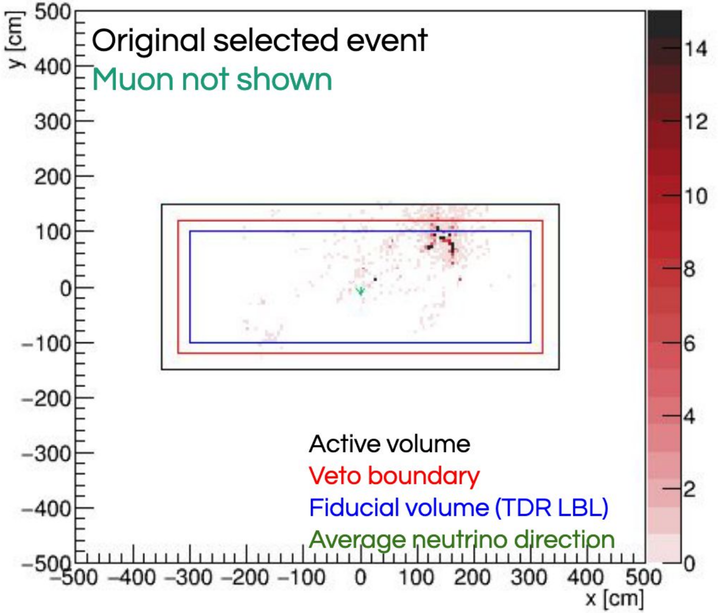


$$\eta = \frac{0\times0.8+1\times0.3+0\times0.70+1\times0.4+1\times0.95}{5} = 33\%$$

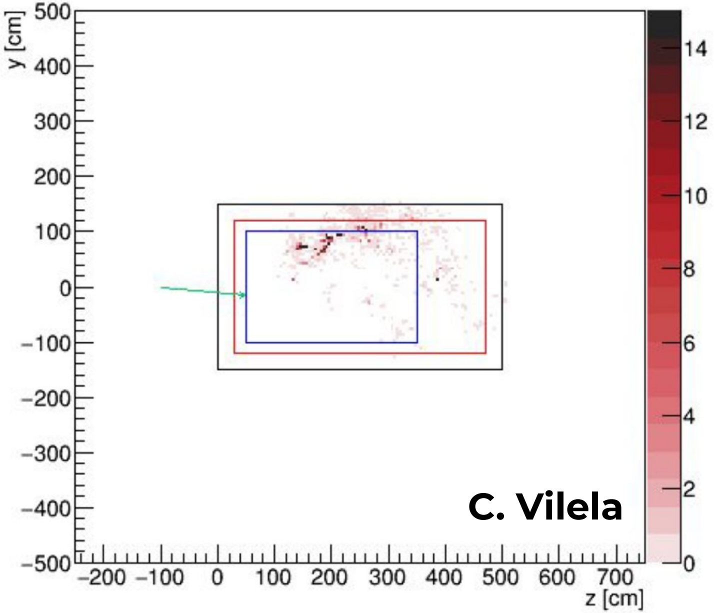
Hadronic Shower Selection

- Exploit symmetry of interactions in LAr ND:
  - Translation around an off axis bin
  - Rotation around beam axis.

XY View

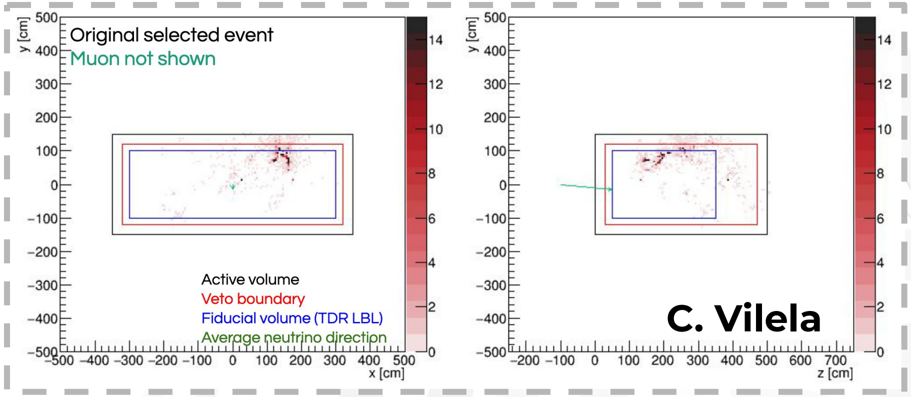


YZ View



C. Vilela

Hadronic Shower Selection



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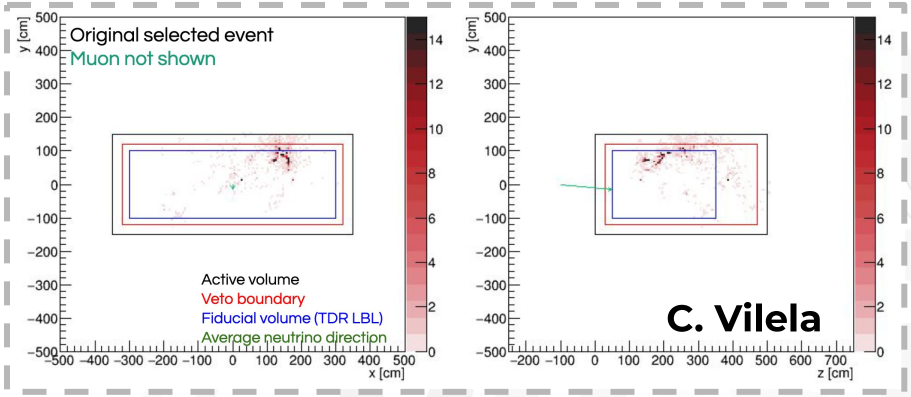

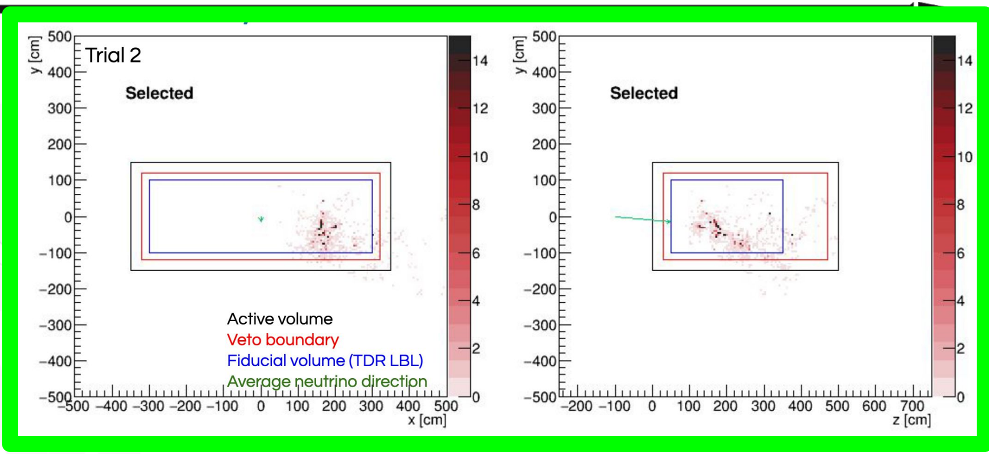

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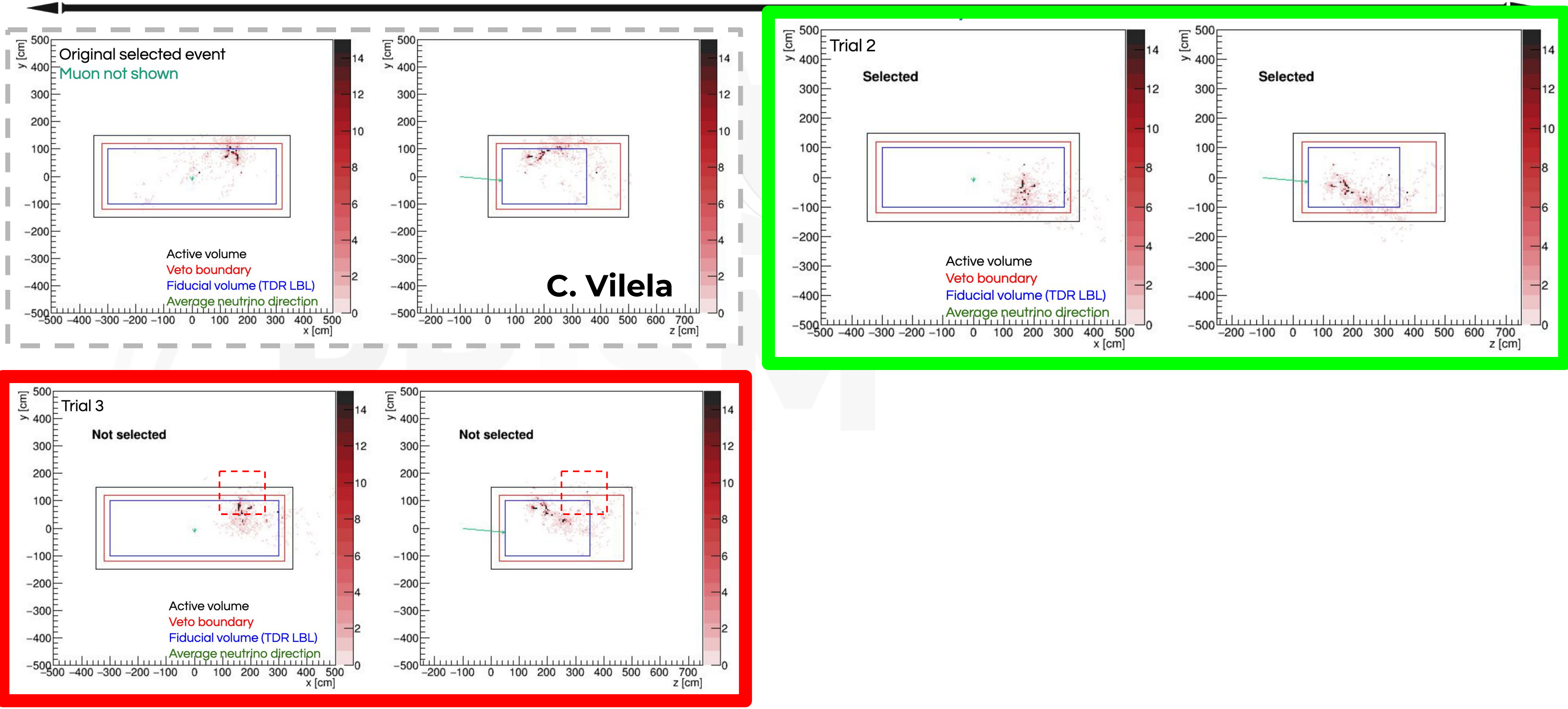

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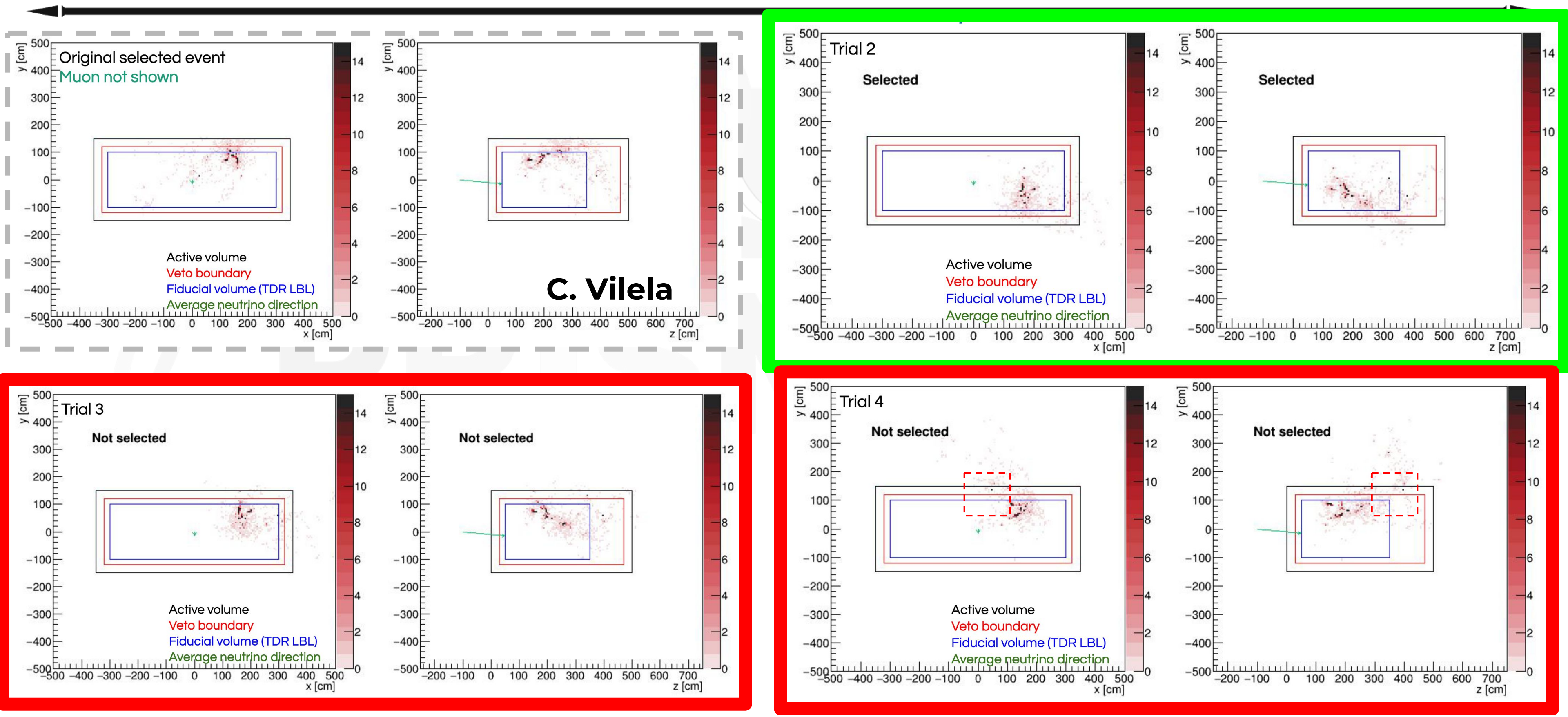
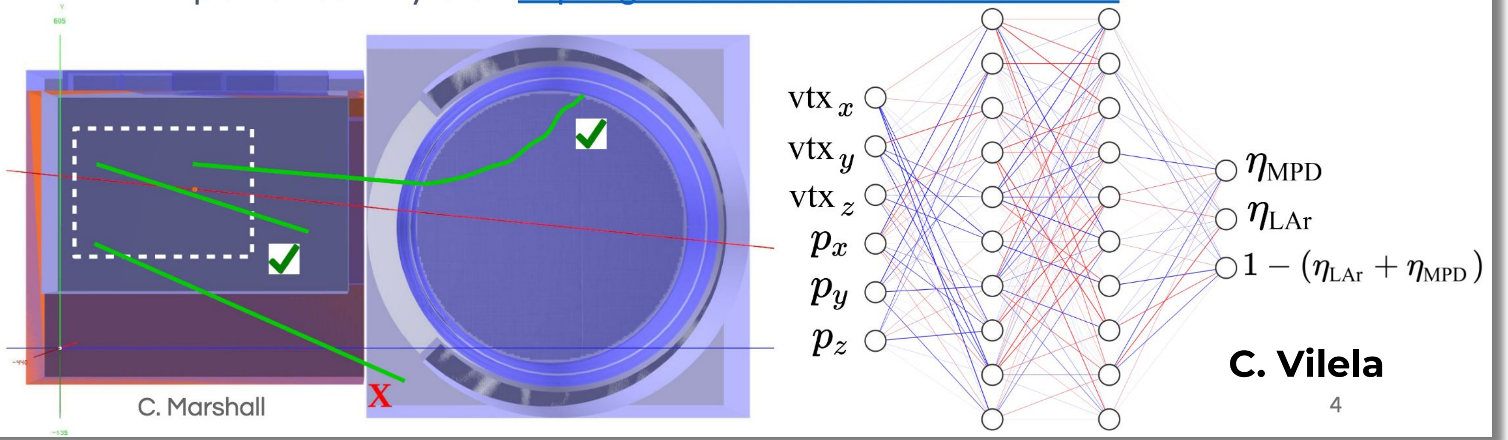


Muon Selection Efficiency

- Train neural network to predict fate of muon as a function of its position and momentum.
  - Output is the probability for the muon to be sampled in the **tracker**, be **contained** in the liquid argon, or **not** be **selected**.
- For initial studies use true position and momentum, but plan to use reconstructed quantities in the future.
- Start with simple neural network with 2 hidden layers with 64 nodes each and ReLU activation.
  - Implemented in PyTorch: https://github.com/cvilelasbu/MuonEffNN



ND/FD Efficiency Differences

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ND/FD Efficiency Differences

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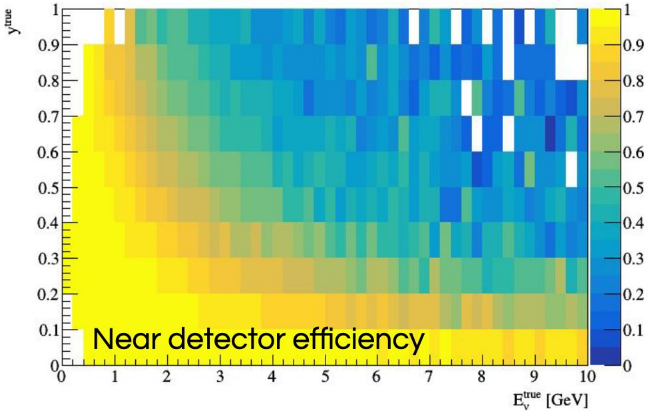
  - High energy/very inelastic events result in large showers that are rarely well contained by the ND
  - Never get a good constraint on such events from the data.



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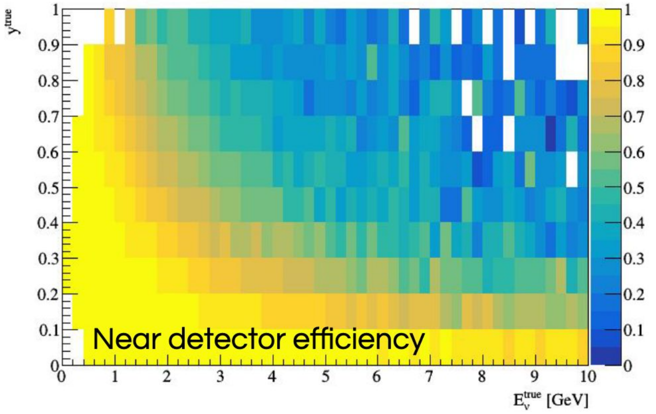

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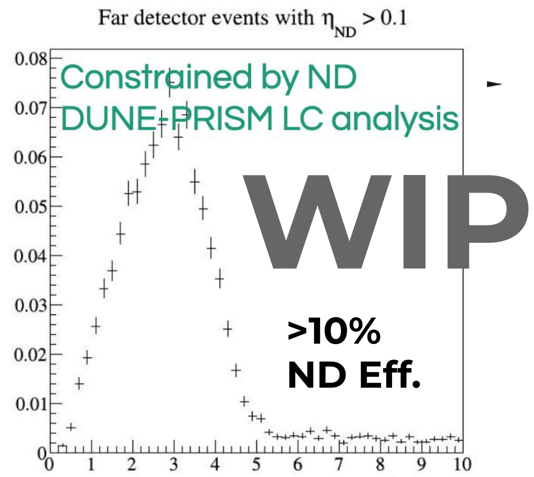
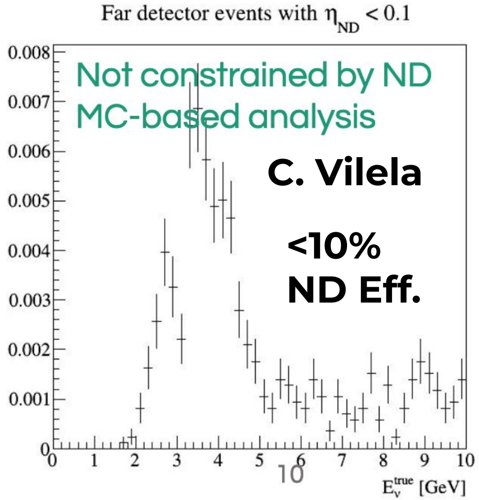
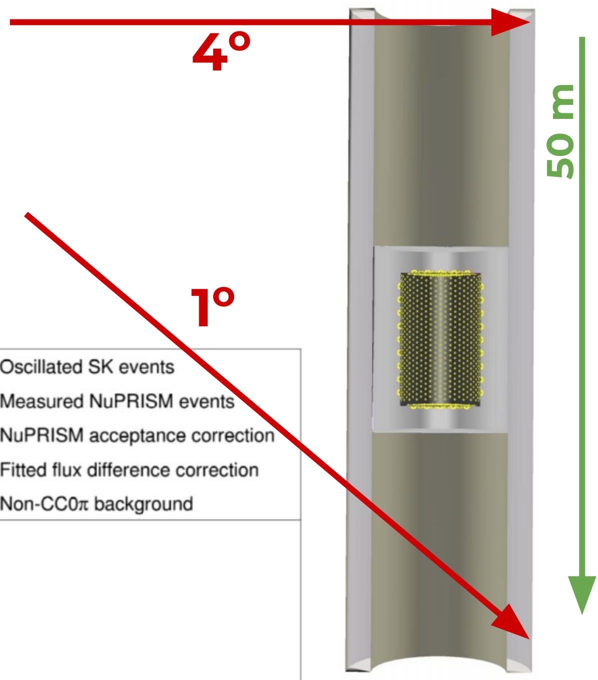
  - High energy/very inelastic events result in large showers that are rarely well contained by the ND
  - Never get a good constraint on such events from the data.
  - This is true regardless for any analysis, not just PRISM.
- Can apply event-by-event efficiency algorithms on FD data and determine which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

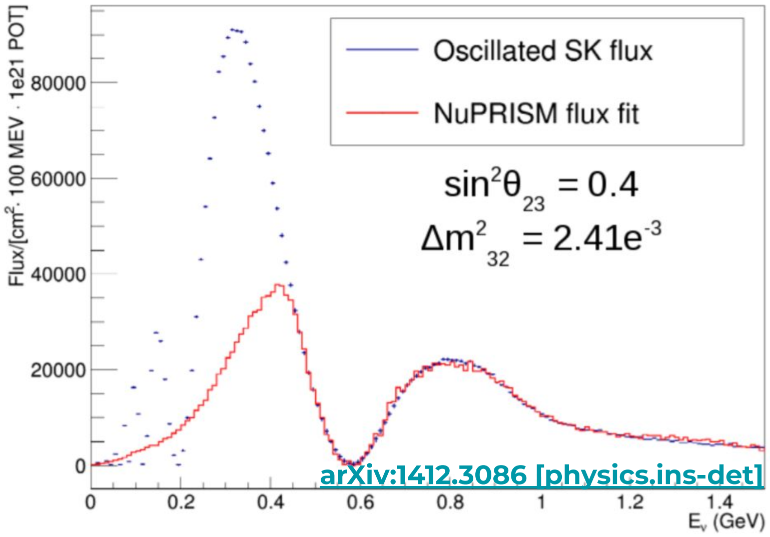




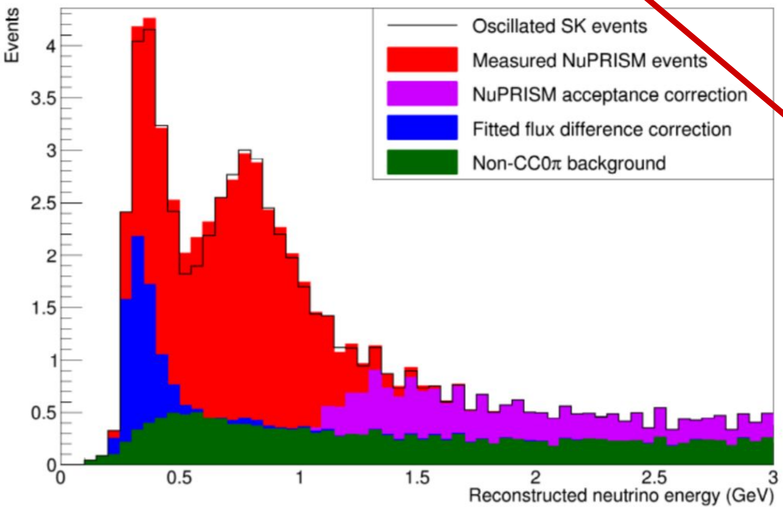
νPRISM

- 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]



Hand Picked Fake Data

INTRODUCTION

C. Vilela: DUNE Jan 2019

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

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

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

Sum over mesons:
- If undetected, ~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).

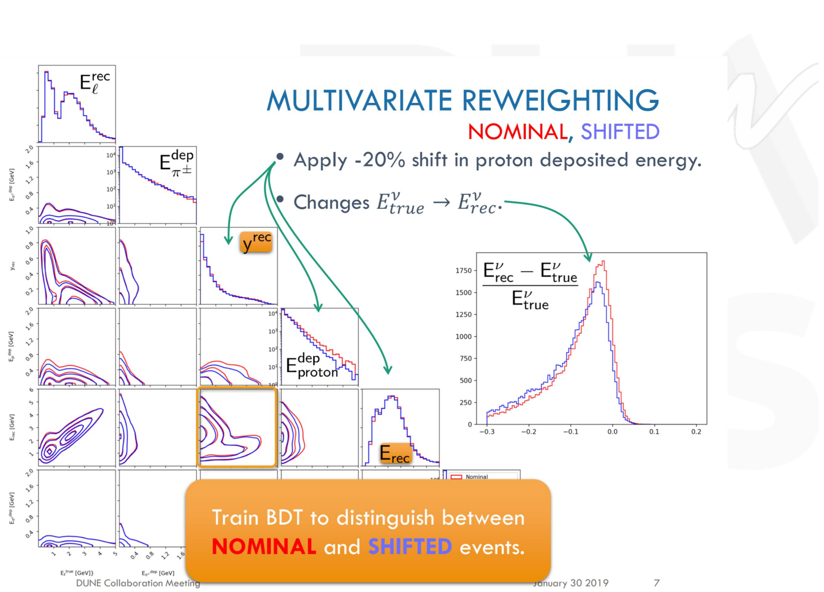
MULTIVARIATE REWEIGHTING

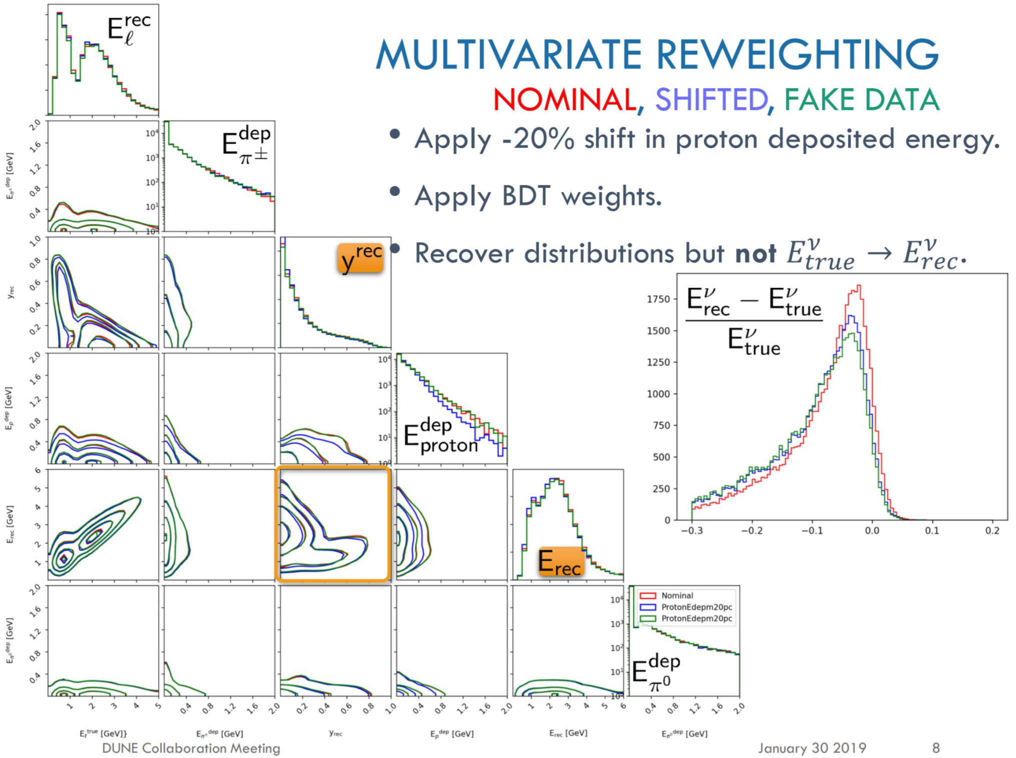
- Train a BDT to classify ND CC events as either **nominal** or **shifted** based on the following six variables:
  - Lepton energy, energy deposits due to protons, $\pi^{\pm}$s and π^{0}.
  - E^{ν}_{rec} and y_{rec} $(= 1 - E^{lep}_{rec}/E^{\nu}_{rec})$.
    - Oscillation analysis uses these variables.
- 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

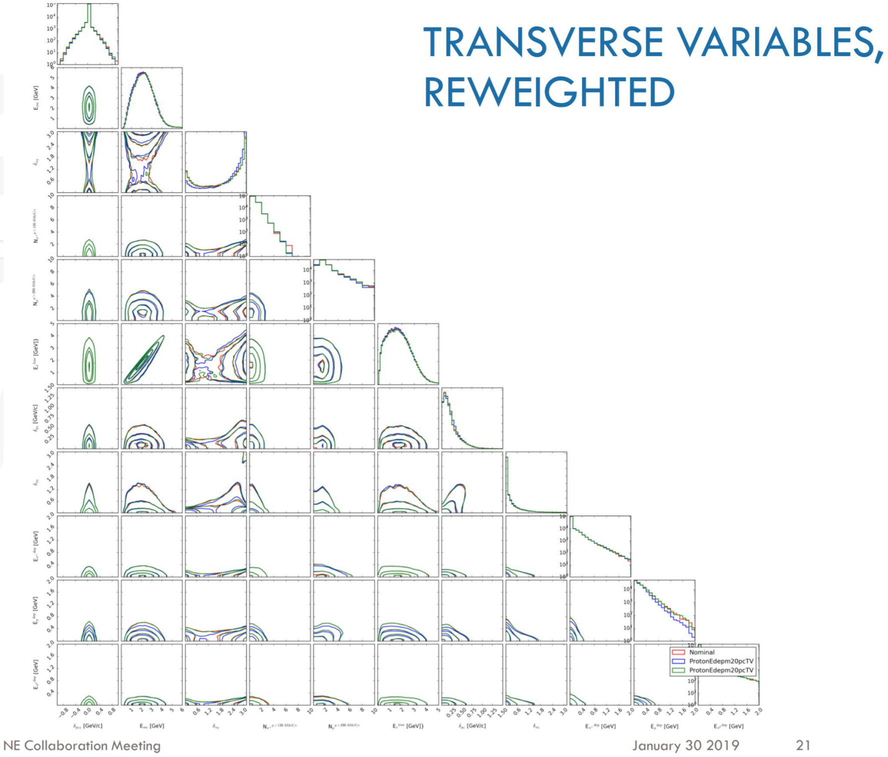
C. Vilela: DUNE Jan 2019





More Observables

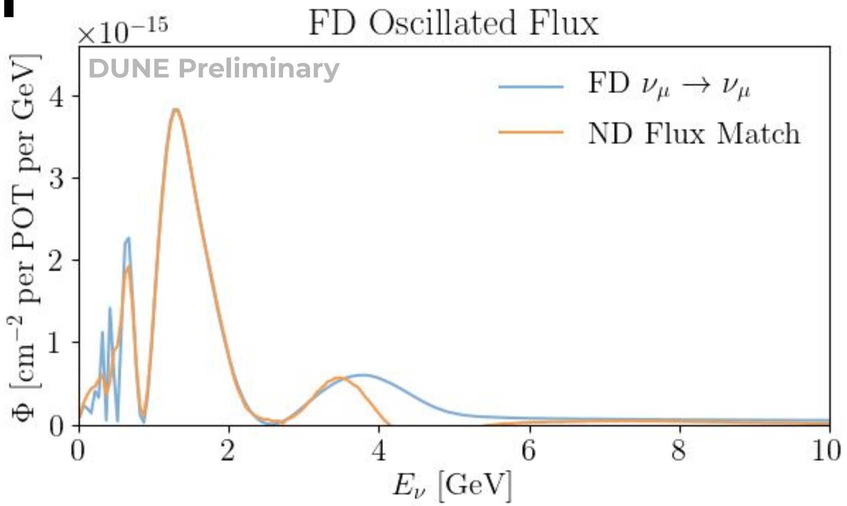
- There are limits to this technique, but they're much further off than multi-dimensional histogram reweighting.
- It's still reweighting, cannot change total phase space.
- Doesn't always produce a consistent model, for medium sized sets, weights can be noisey.



Horn Current

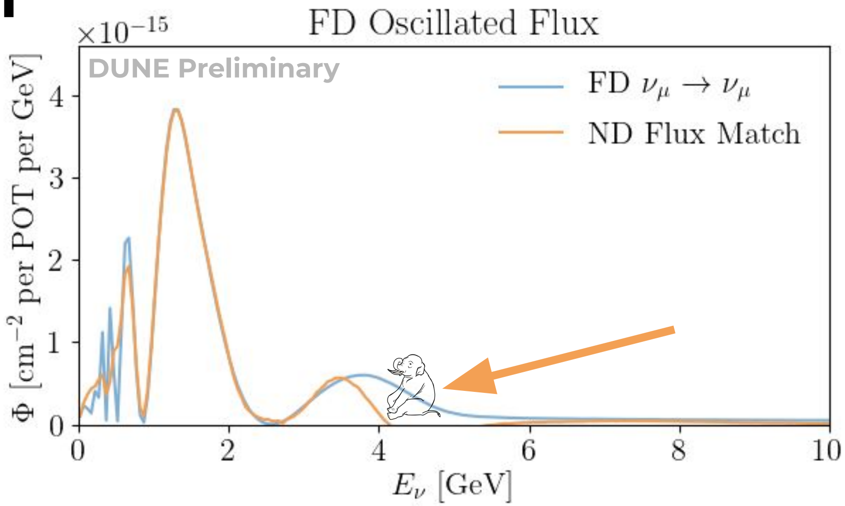
Flux Mismatch Correction

- Elephant in the room



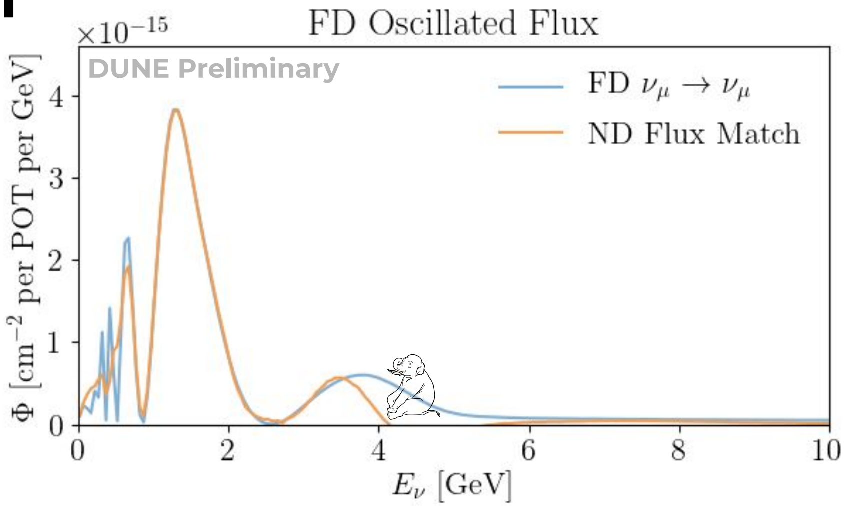
Flux Mismatch Correction

- **Elephant in the room**



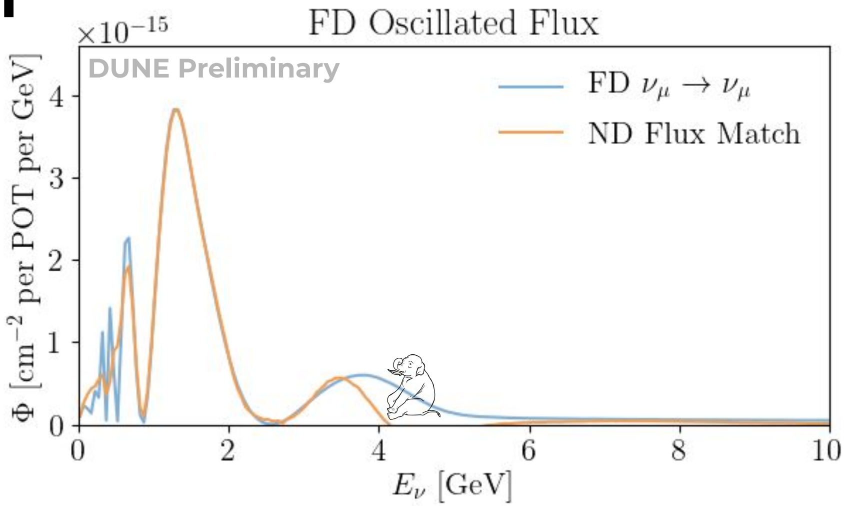
Flux Mismatch Correction

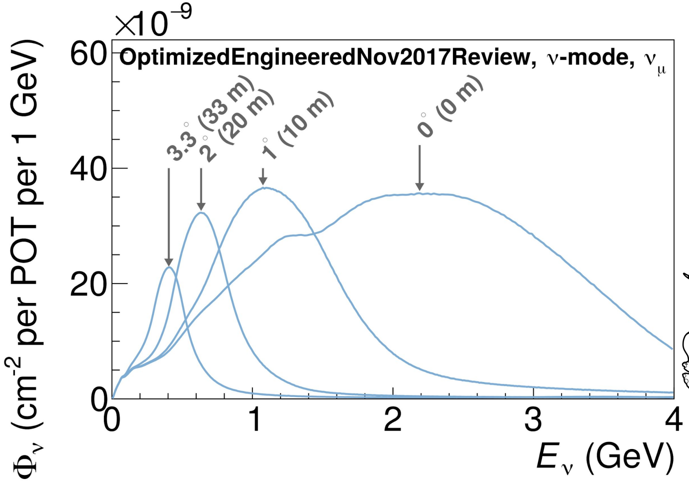
- Have to correct for this mismatch by using far detector simulation:
  - Want to minimize model assumptions wherever possible…



Flux Mismatch Correction

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





Flux Mismatch Correction

- Have to c
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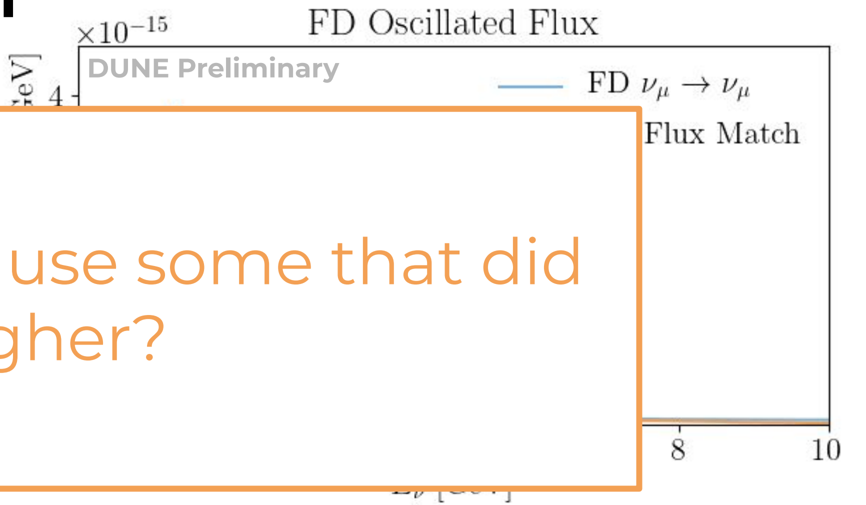
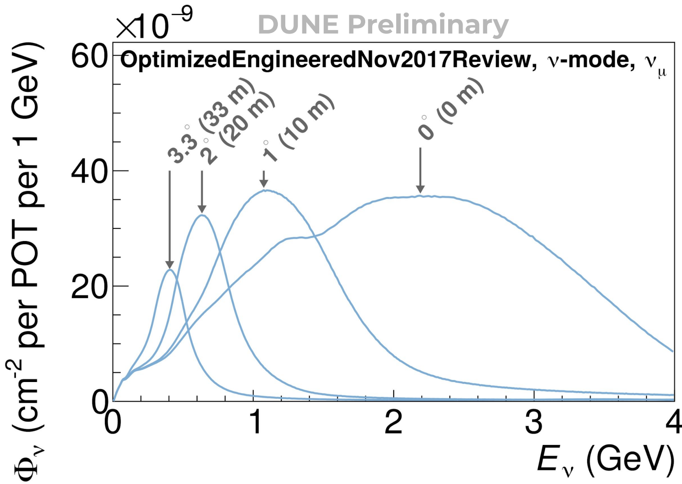
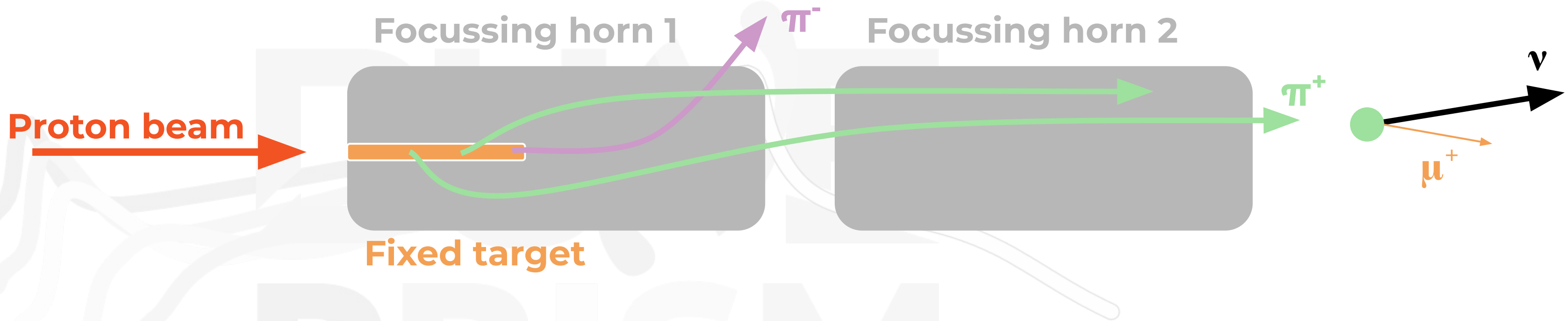
  fluxes pe

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



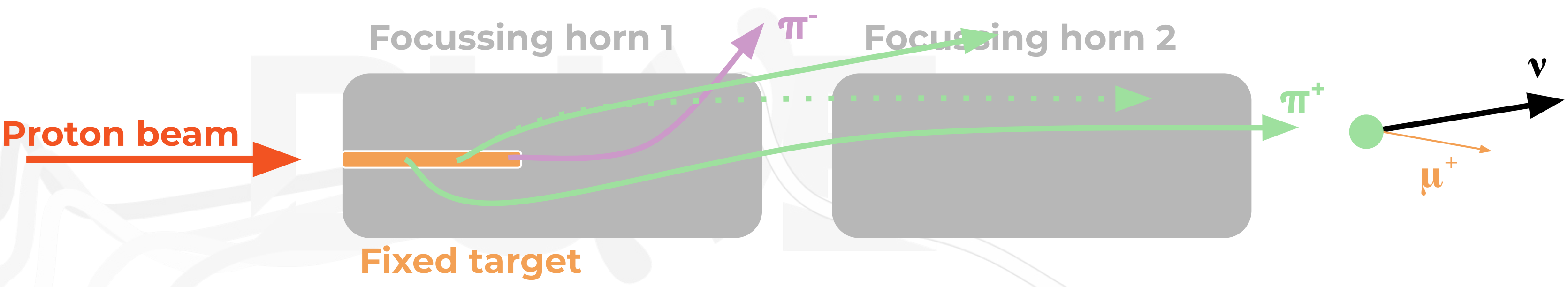


Special Horn Current Runs



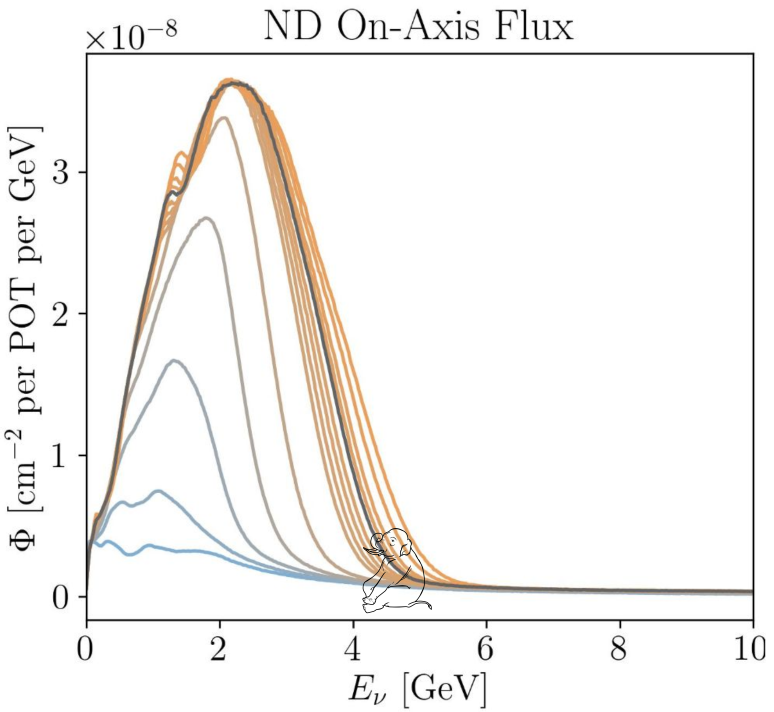
- If we vary the current in the magnetic horns, we change their momentum acceptance

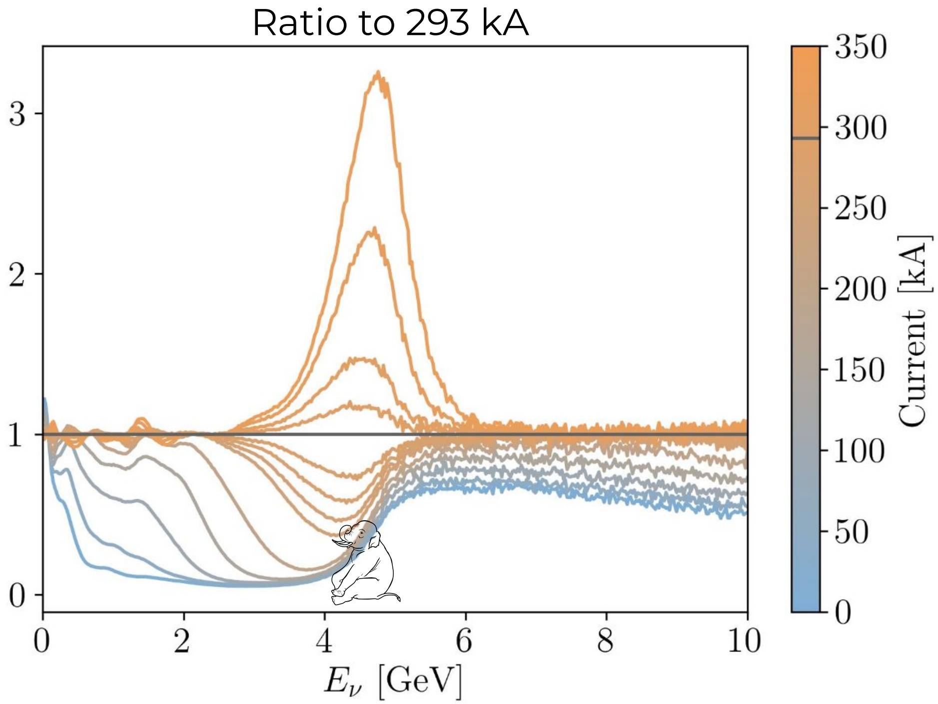
Special Horn Current Runs



- 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...

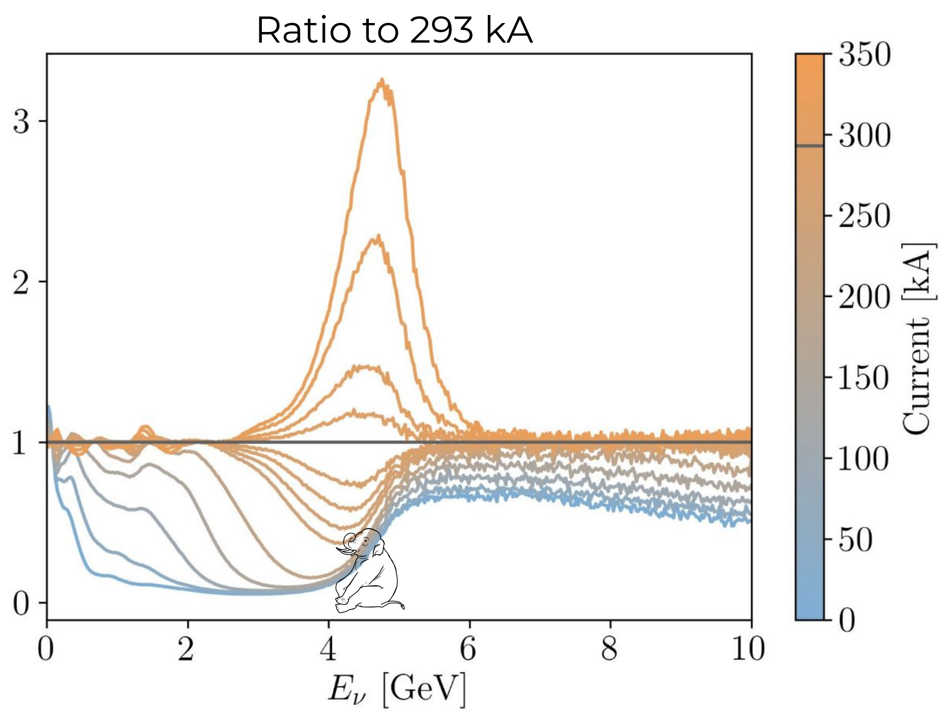
Special Horn Current Runs





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

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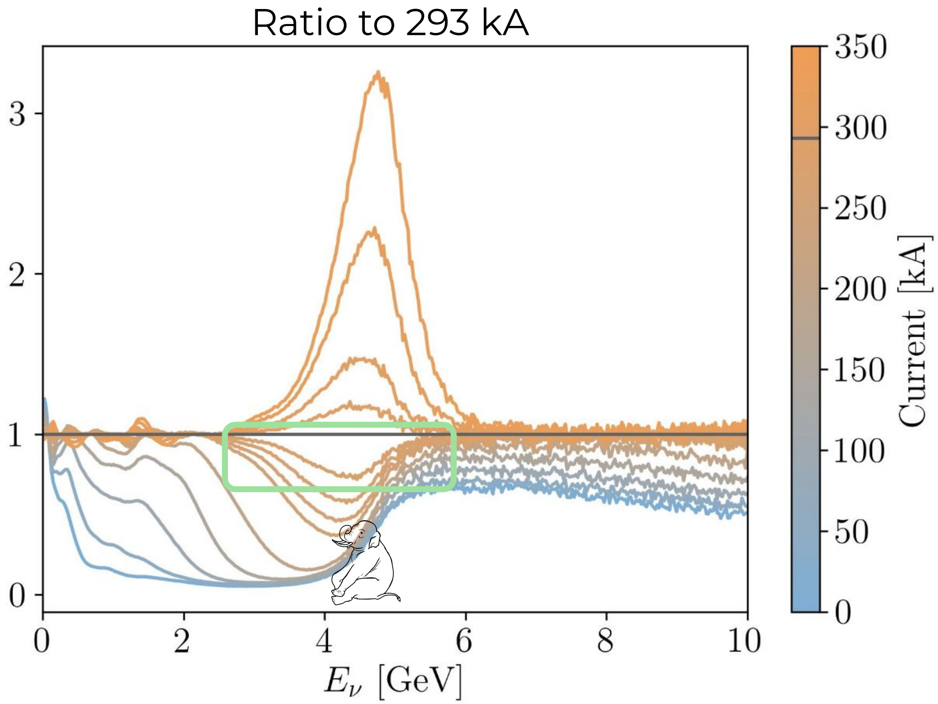
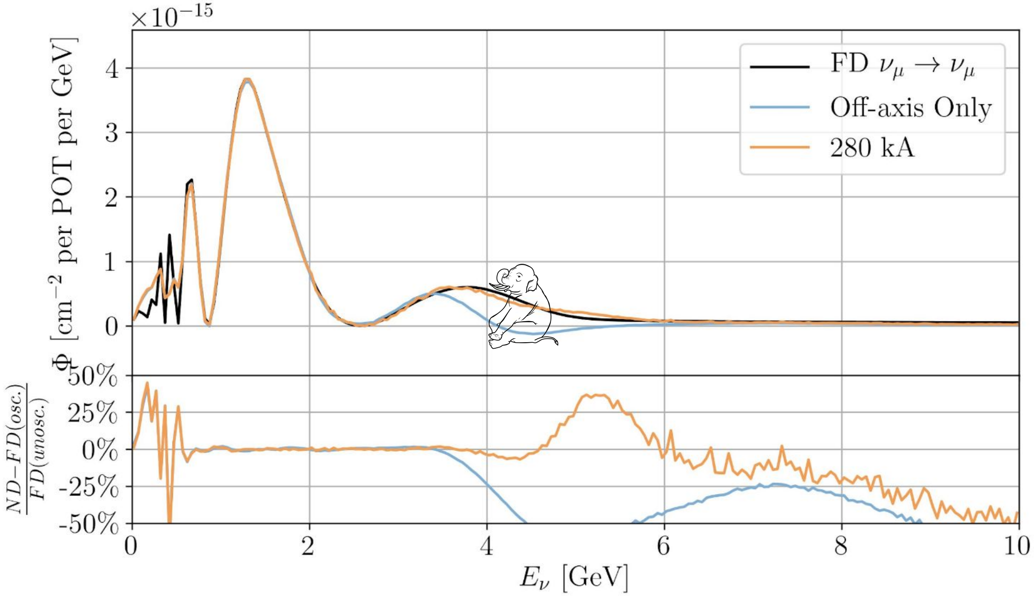
  - Less change in far detector exposure
- Lower currents are better:
  - Current horn and power supply designed with 293 kA as the operating current.

- **280 kA looks useful**

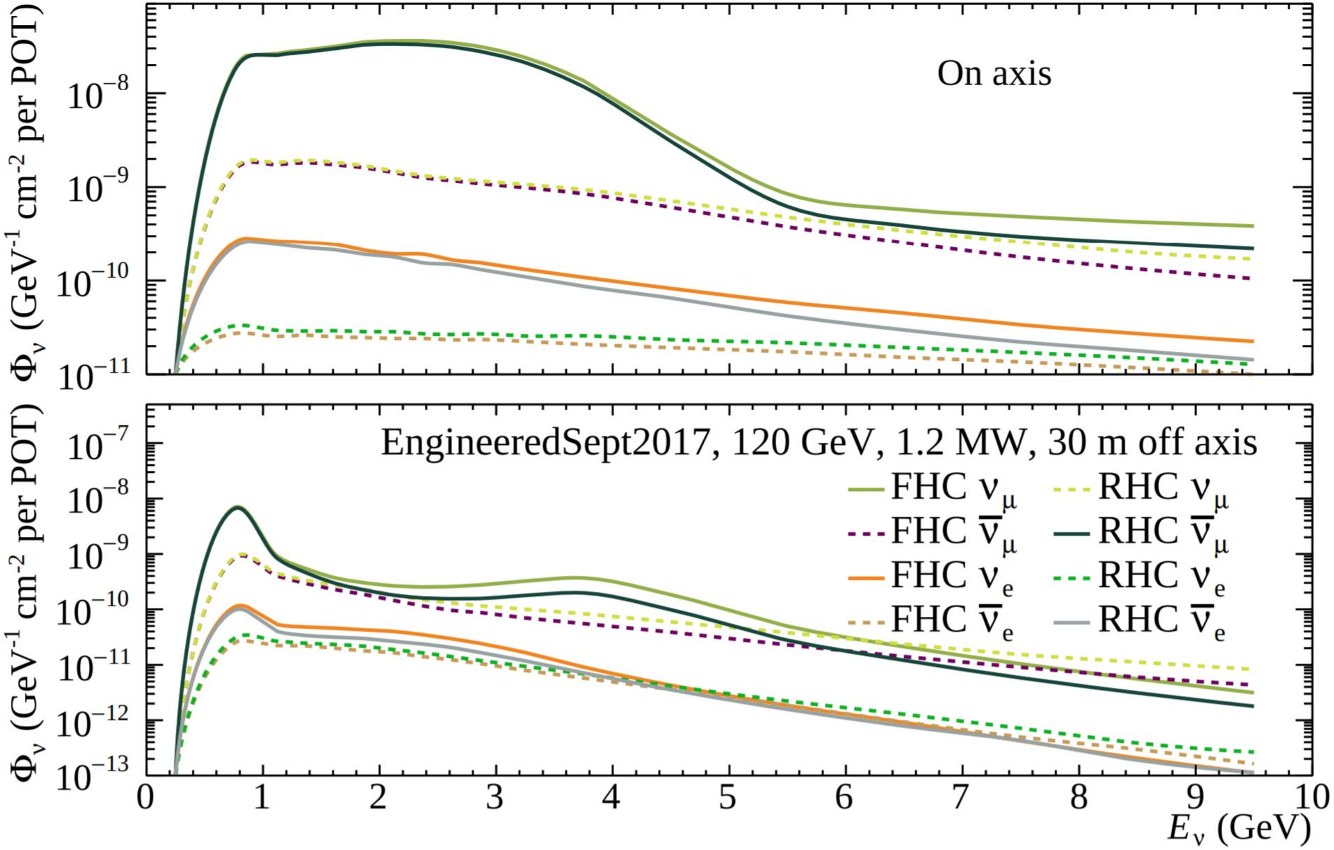


Special Horn Current Runs

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



Parent Species Off axis.



Special Horn Current Runs

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

D. Douglas, T. Lord