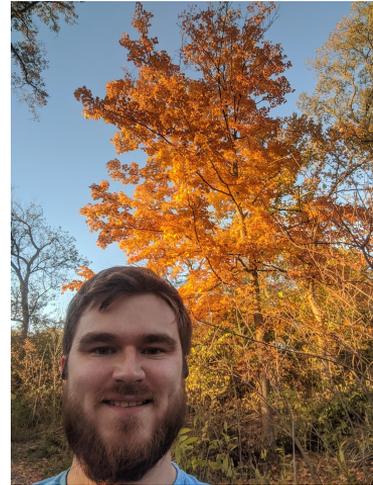


Overcoming Neutrino Interaction Mis-modeling with DUNE-PRISM

Neutrino Seminar Series, Fermilab
Luke Pickering for the DUNE
collaboration

2019-11-14

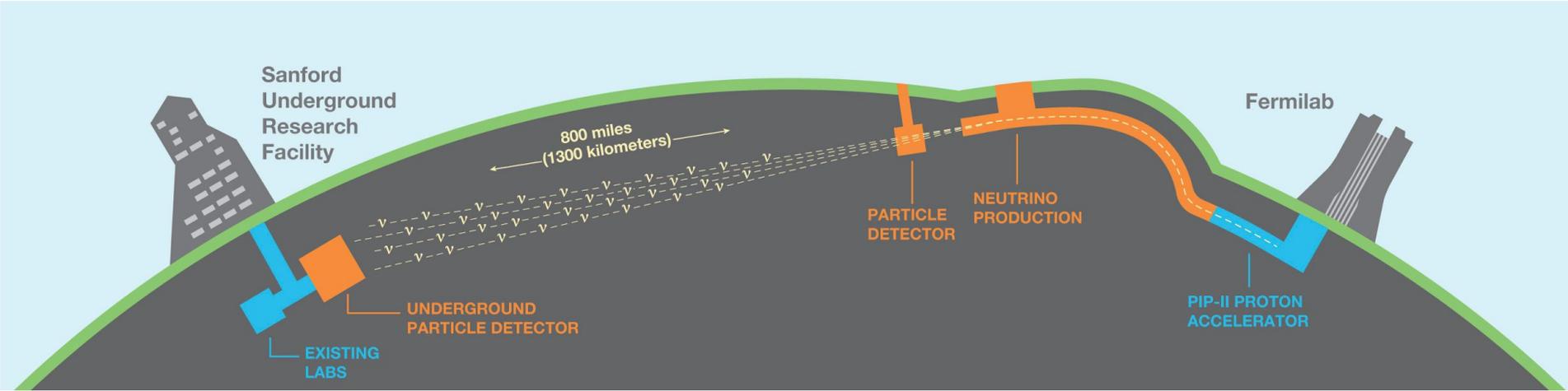
Pronouns: He/Him/His



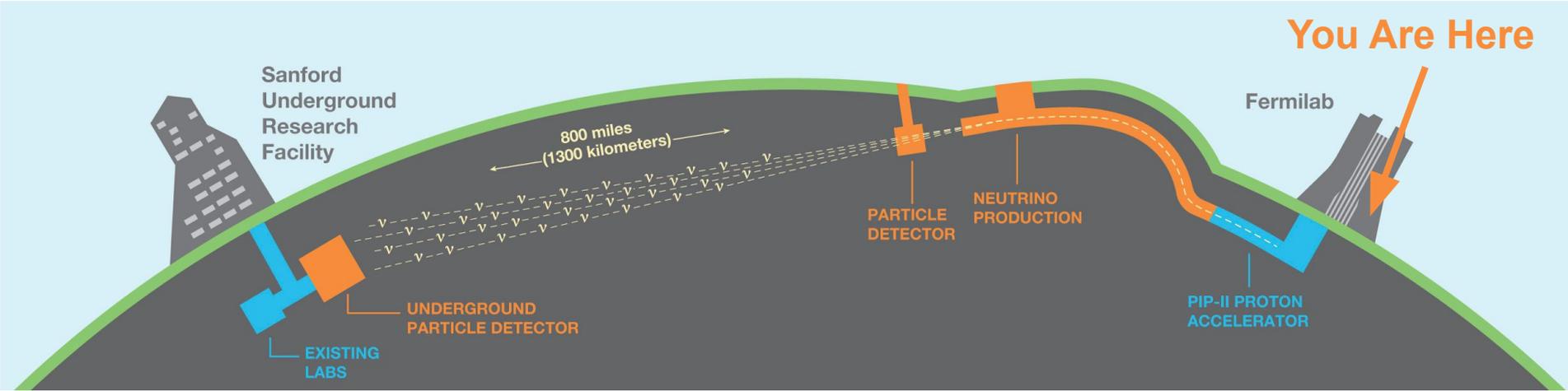
This Talk

- Introduction to DUNE
- Anatomy of an Oscillation Analysis
- The PRISM Concept
- Recent PRISM work

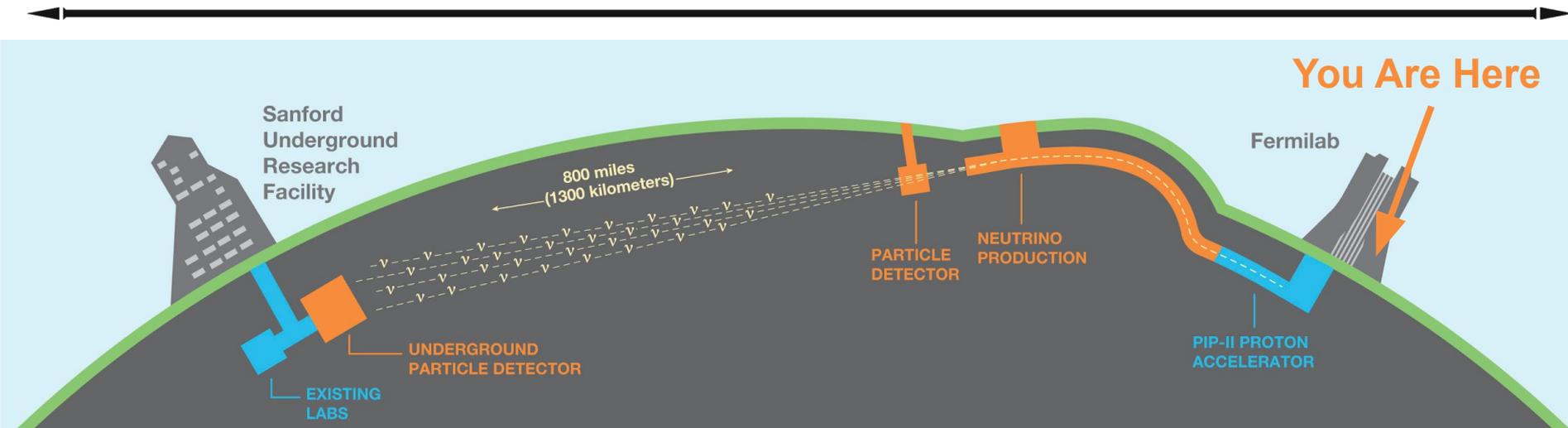
DUNE



DUNE



DUNE



Collaboration

- >1100 Collaborators
- 34 Countries

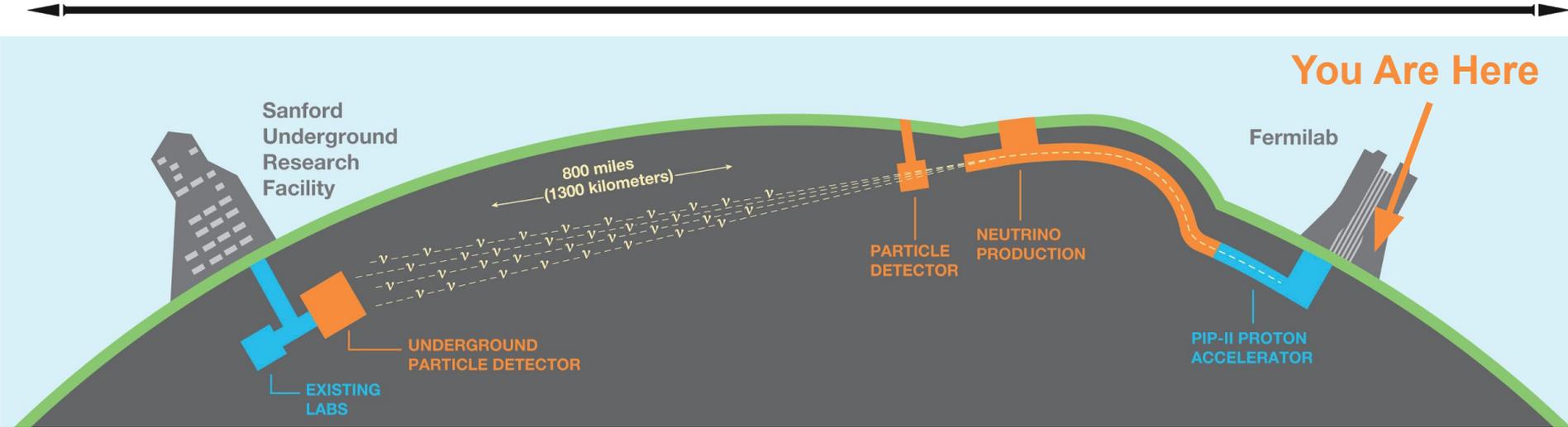
PMNS Oscillations

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

Rich Physics Program

- Solar ν 's
- Geo ν 's
- SN ν 's
- NSI
- Sterile ν 's
- σ_{ν}

DUNE



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PMNS Oscillations

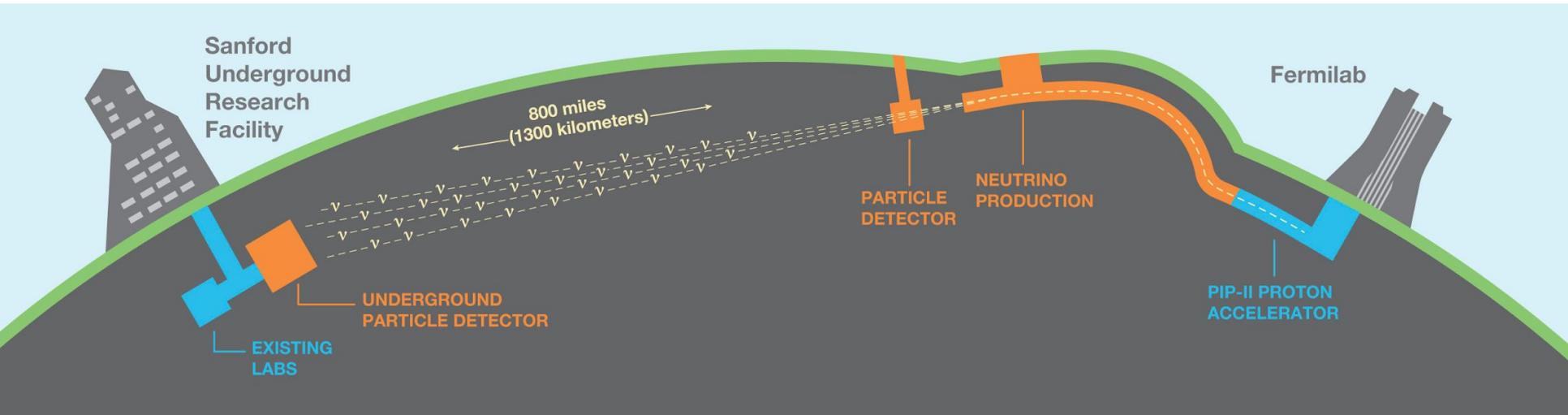
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- Solar ν 's
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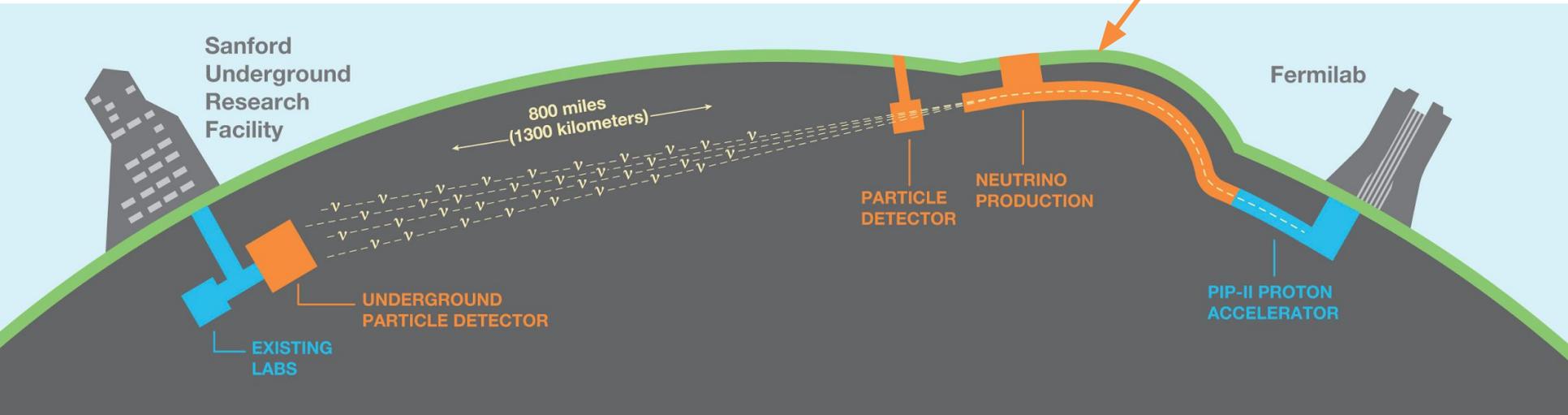
Anatomy of an Oscillation Analysis

- Sample osc. beam
- Infer osc. params
- Sample unosc. beam
- Constrain flux*xsec
- Produce beam



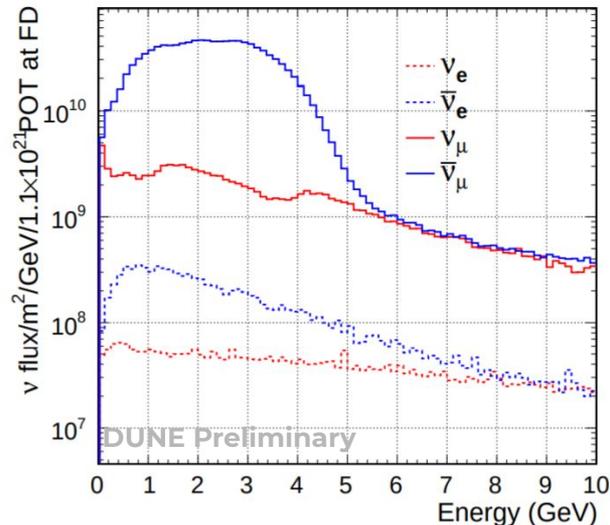
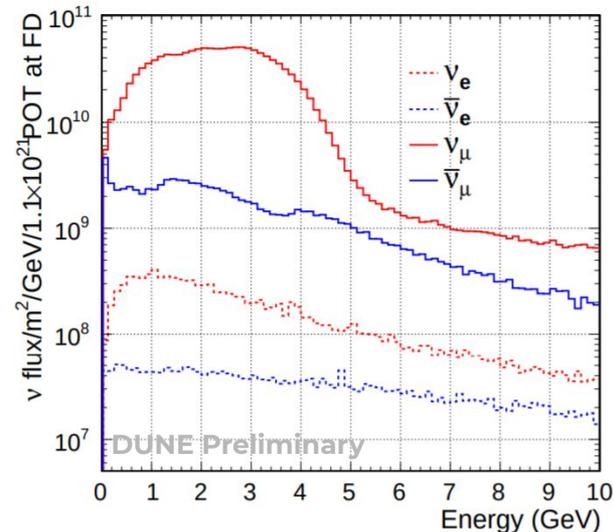
Anatomy of an Oscillation Analysis

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LBNF: The DUNE Neutrino Beam

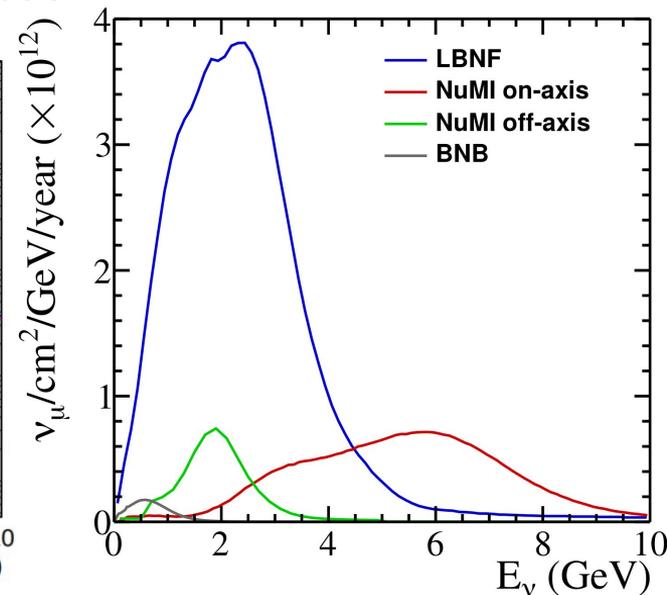
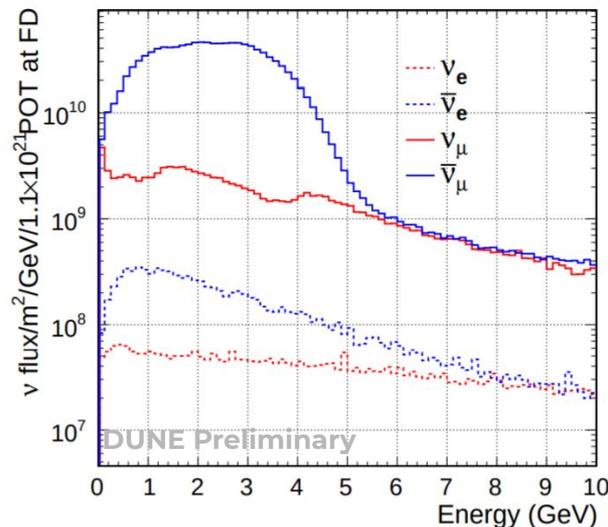
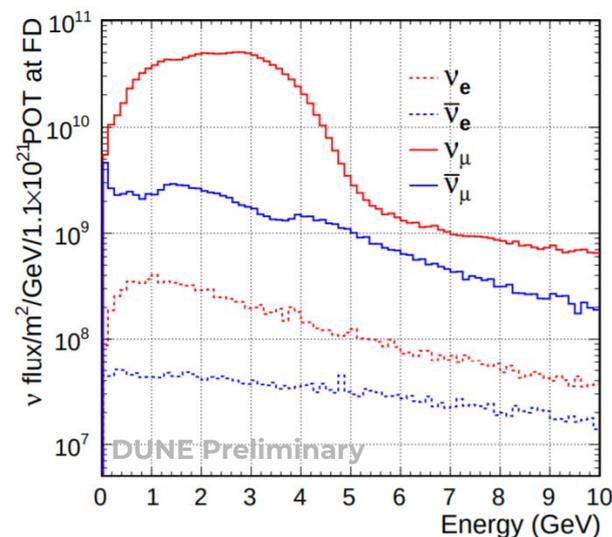
- 2.3 GeV peak energy, on axis, wide-band
- 120 GeV proton driver
- 1.1×10^{21} POT/beam year
- 1.2 MW, upgradeable to 2.4 MW



LBNF: The DUNE Neutrino Beam

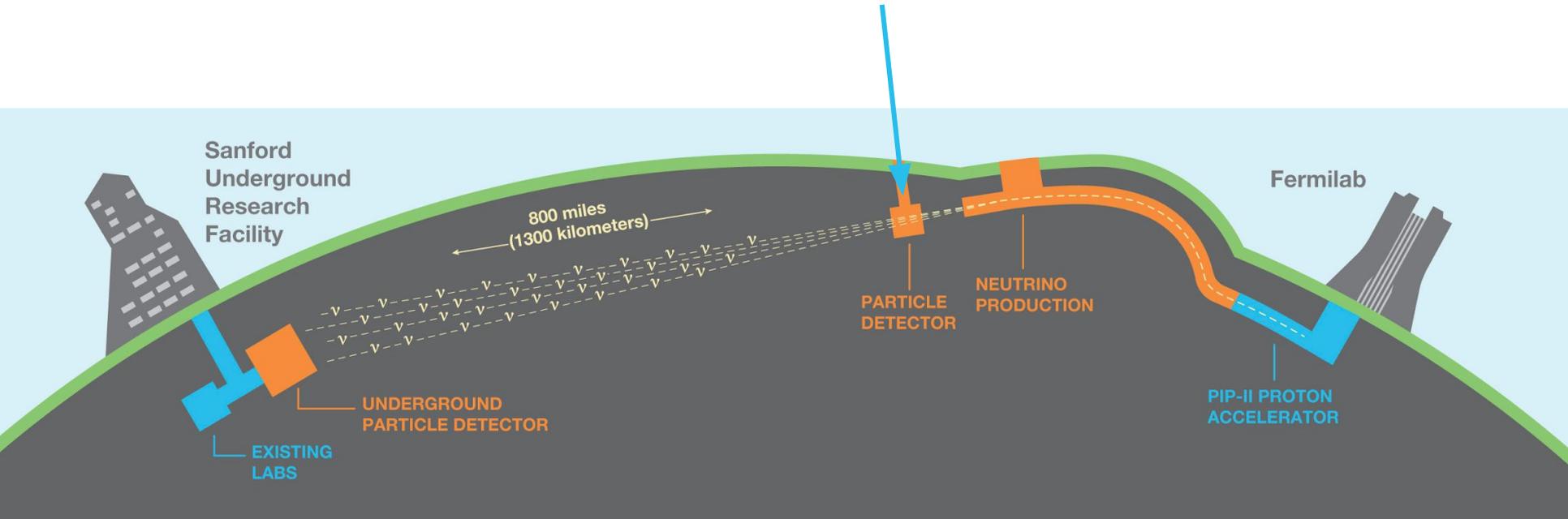
- 2.3 GeV peak energy, on axis, wide-band
- 120 GeV proton driver
- 1.1×10^{21} POT/beam year
- 1.2 MW, upgradeable to 2.4 MW
- **Unprecedented neutrino interaction event rates**

LED ZEPPELIN
WHOLE LOTTA Numus

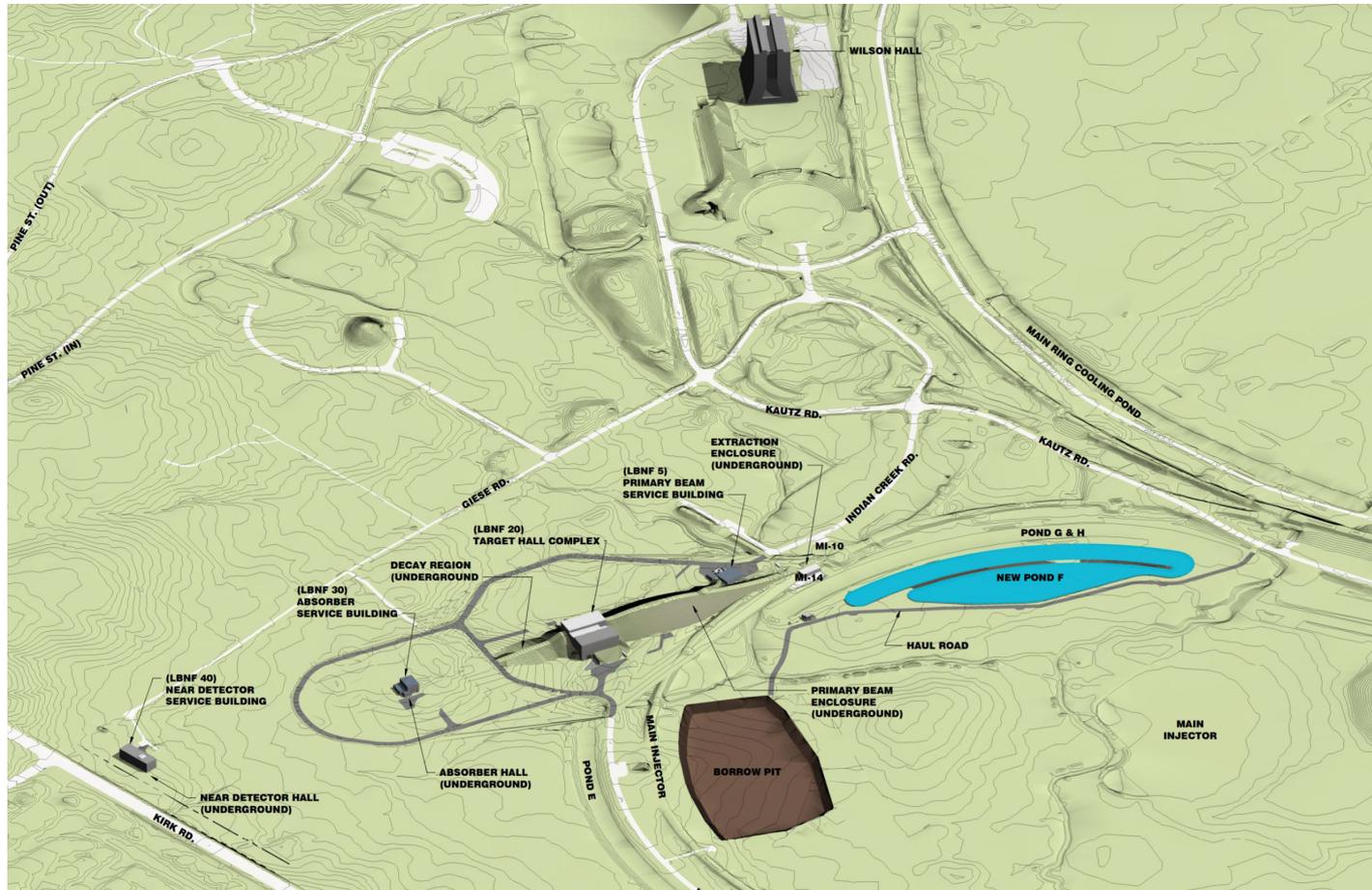


Anatomy of an Oscillation Analysis

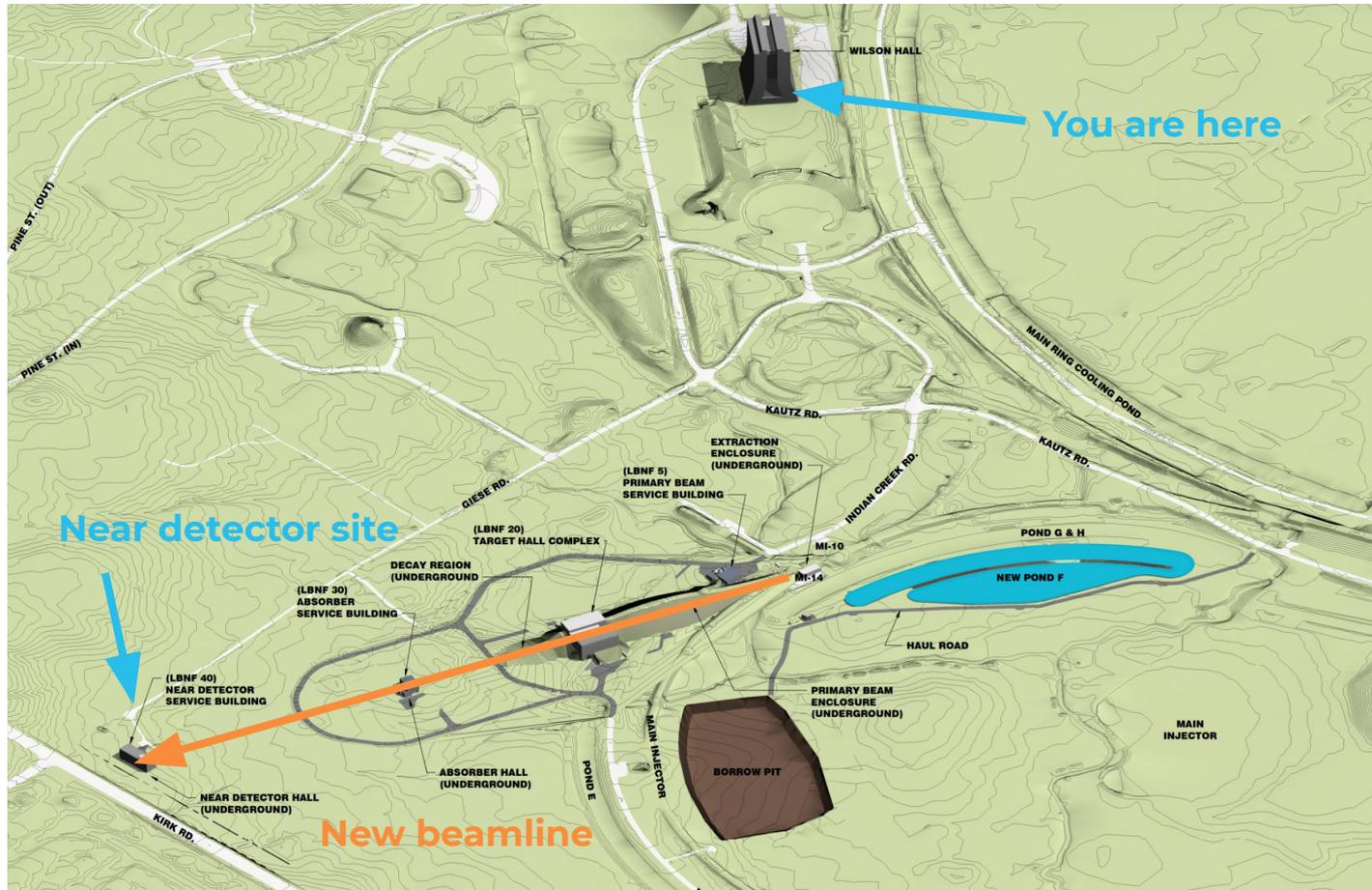
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DUNE Near Detector Facilities

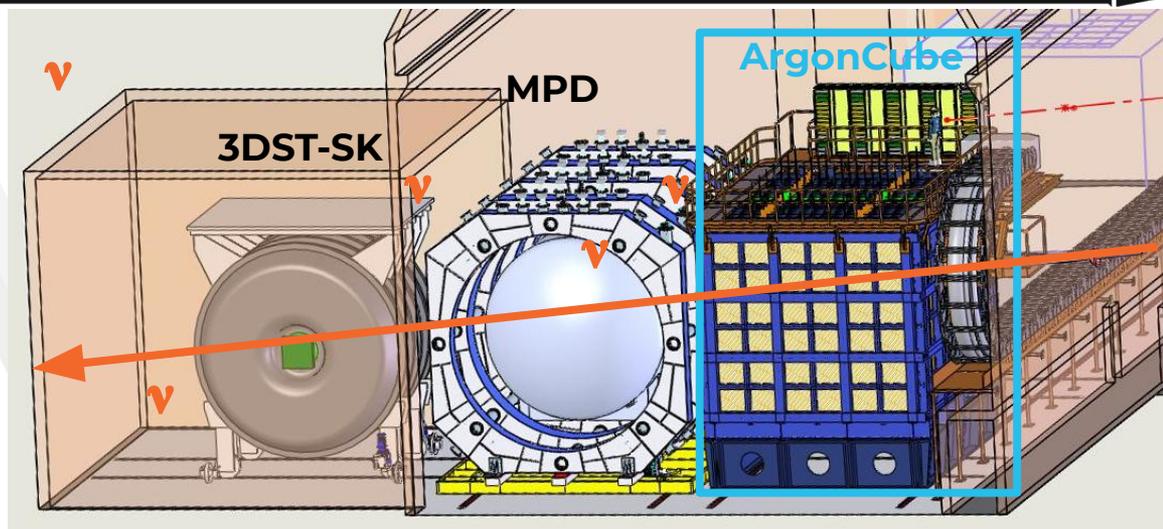


DUNE Near Detector Facilities



DUNE Near Detector Concept

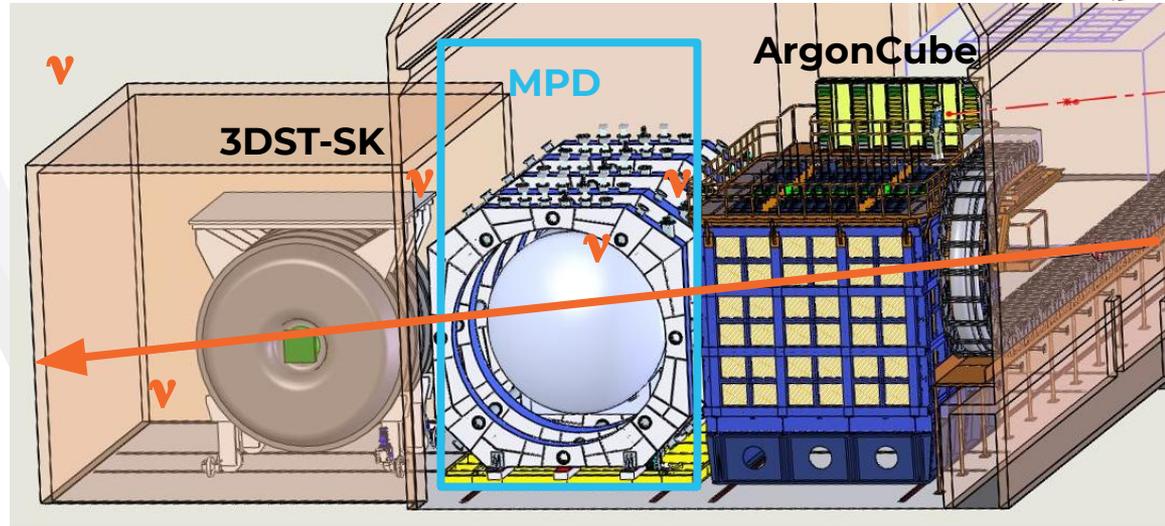
- **ArgonCube**: LAr TPC
 - Primary target, similar to FD



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

DUNE Near Detector Concept

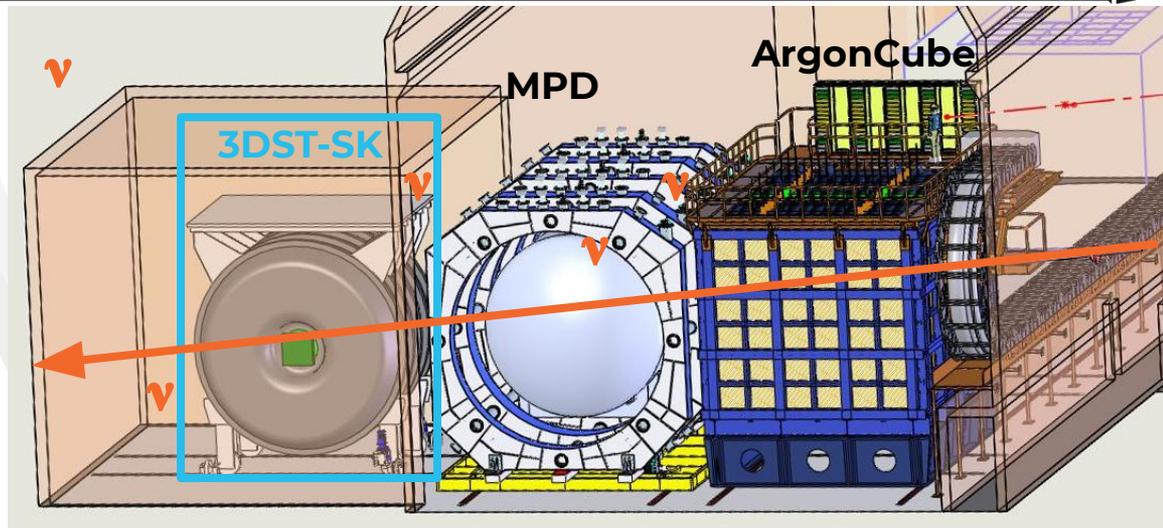
- **ArgonCube:** LAr TPC
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- **MPD:** GAr TPC + ECal + Low mass magnet
 - Charge/momentum/PID
 - Low threshold neutrino target



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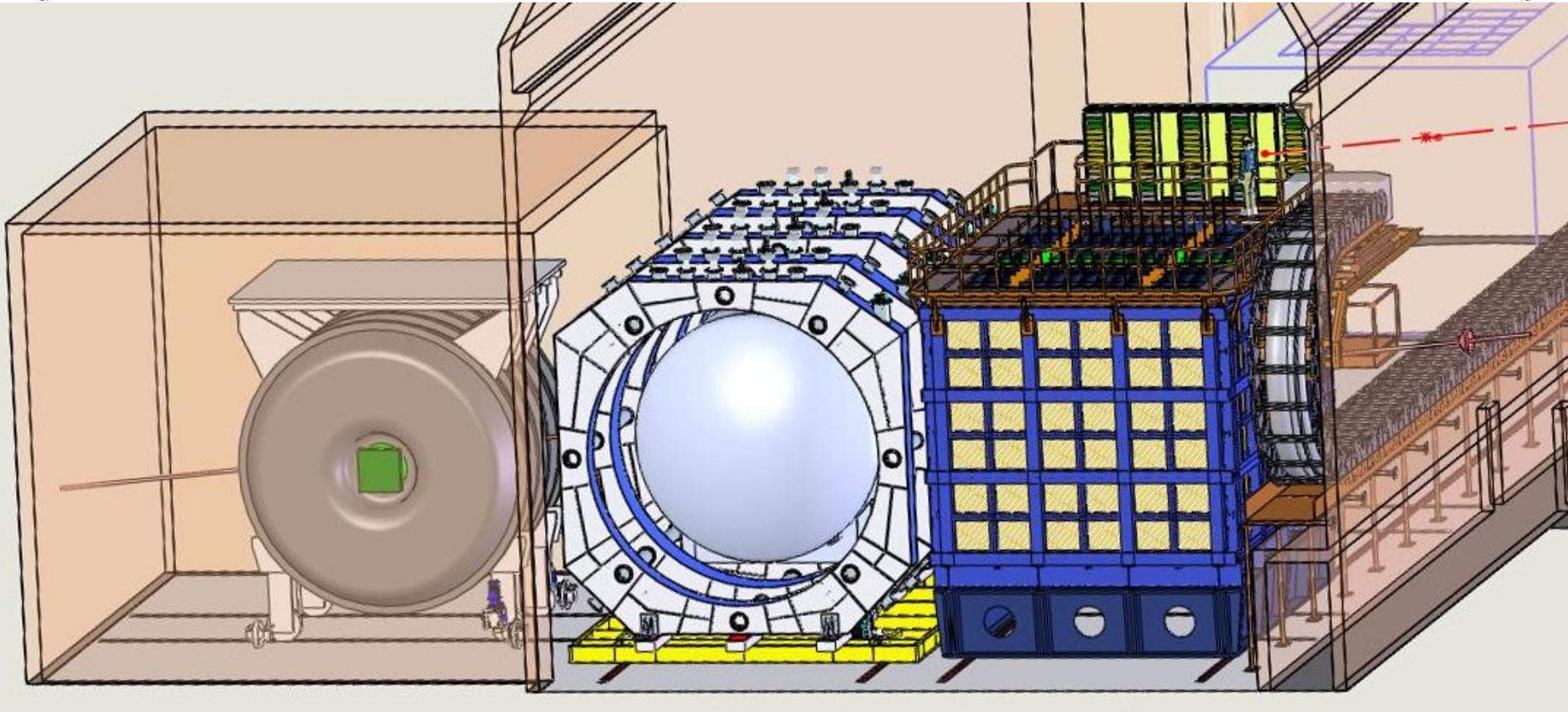
DUNE Near Detector Concept

- **ArgonCube:** LAr TPC
 - Primary target, similar to FD
- **MPD:** GAr TPC + ECal + Low mass magnet
 - Charge/momentum/PID
 - Low threshold neutrino target
- **3DST-SK:** 3D plastic scintillator cubes inside a superconducting solenoid.
 - Beam monitor
 - C12-target physics
 - Neutron detection capabilities



DUNE Preliminary	ArgonCube FV				MPD FV
	All int.	Selected			All int.
Run duration	$N\nu_{\mu}CC$	NSel	WSB	NC	$N\nu_{\mu}CC$
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DUNE Near Detector Concept

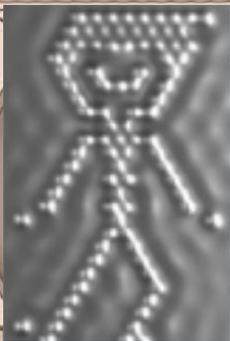


DUNE Near Detector Concept

CarBON

GArGON

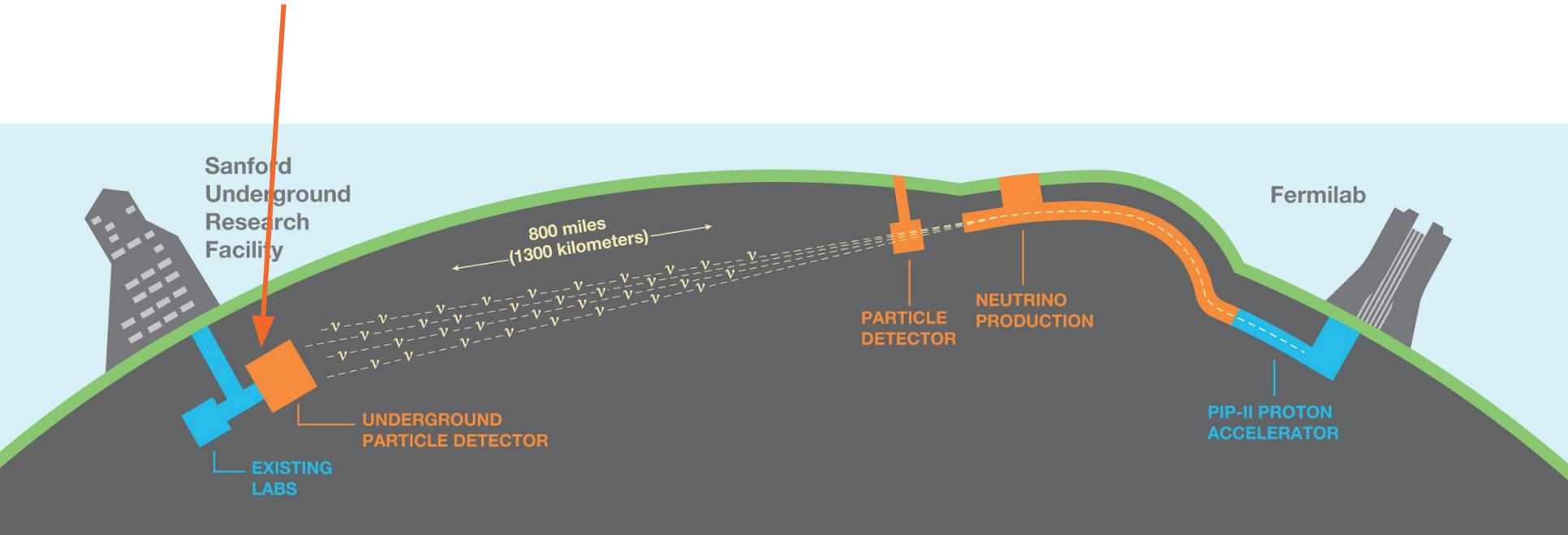
LArGON



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

Anatomy of an Oscillation Analysis

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- Infer osc. params
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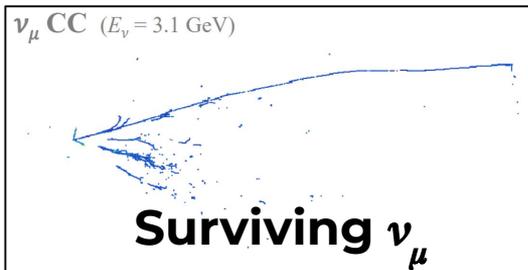
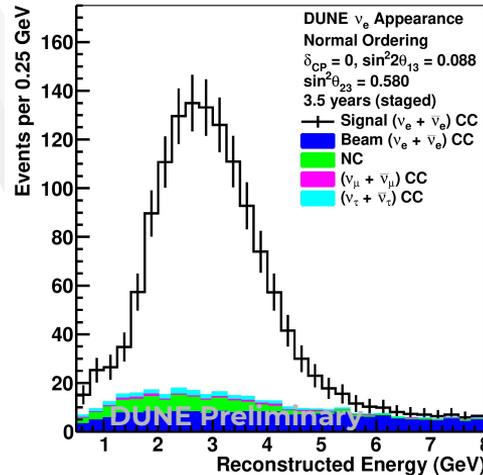
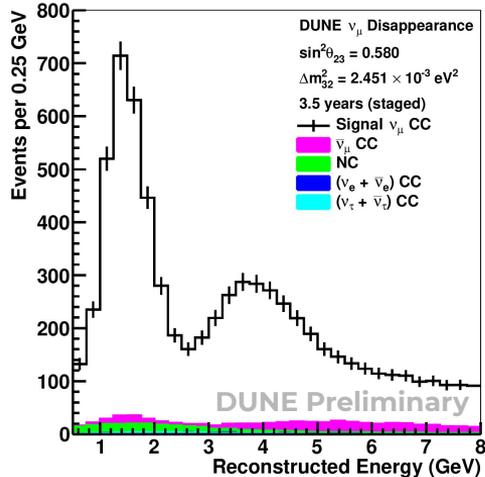
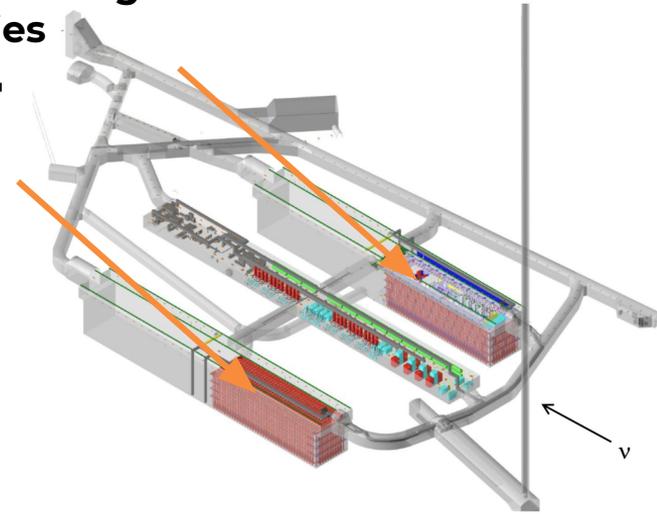


Far Detector

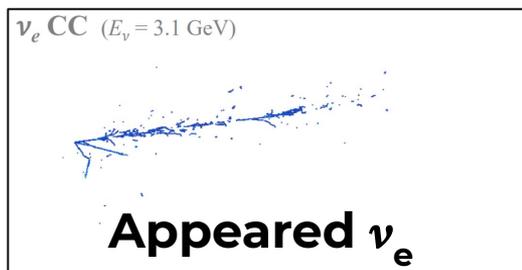
SURF underground facilities

L. Pickering 20

- **4x10 kT LAr TPCs:**
 - Unprecedented FD event resolution and event rate!



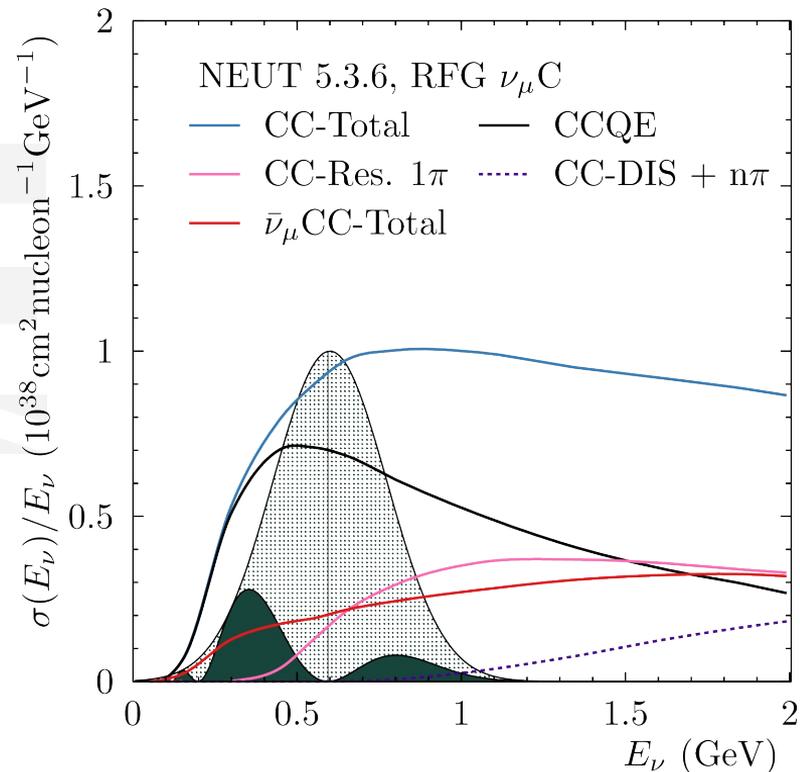
simulations



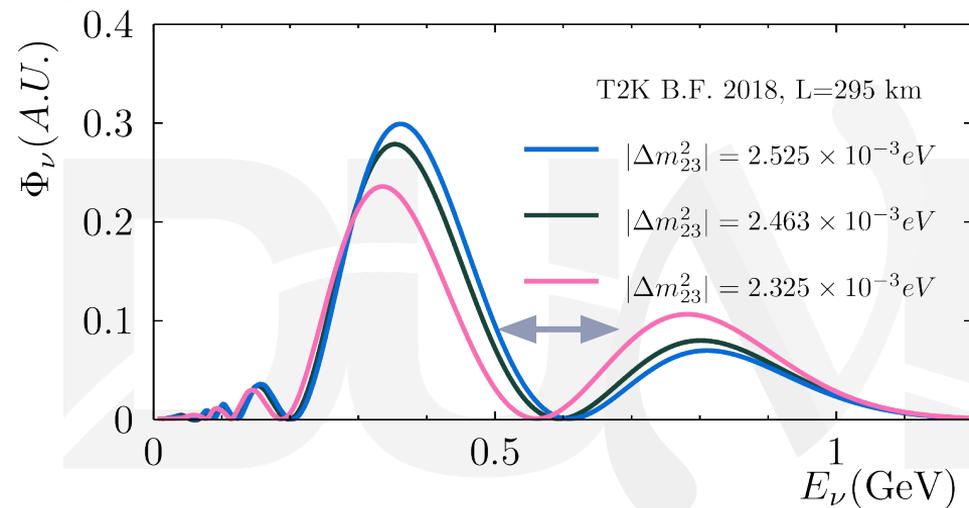
R. Patterson FNAL, JETP

Inferring Oscillation Parameters

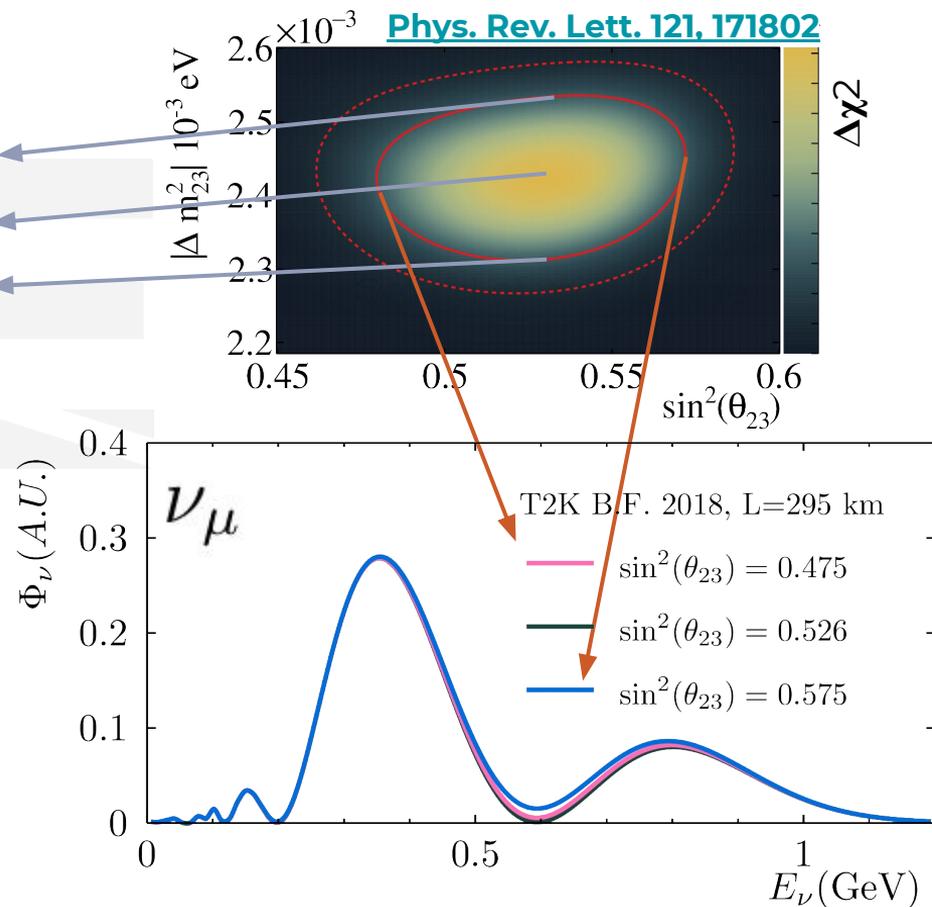
- Shouldn't be too hard
 - Sophisticated detectors
 - Insane beam power
- Look for signature 'oscillation' shape in flux at the far detector...



Signature Oscillation Shape

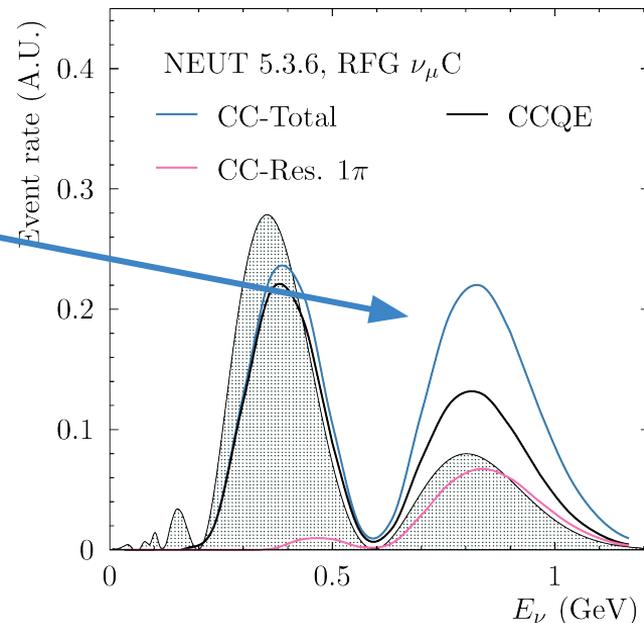
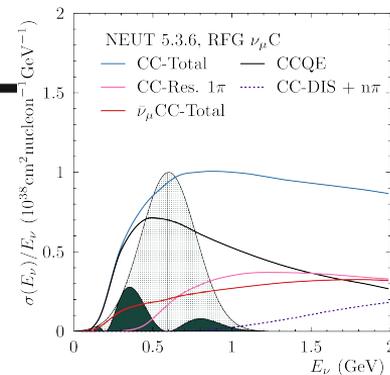


- Mass-squared splitting shifts the 'dip'
- Mixing angle determines the depth of the 'dip'



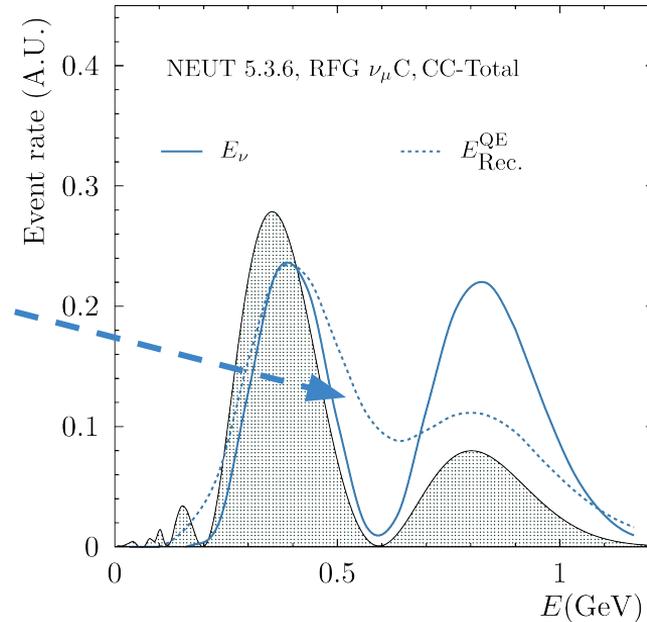
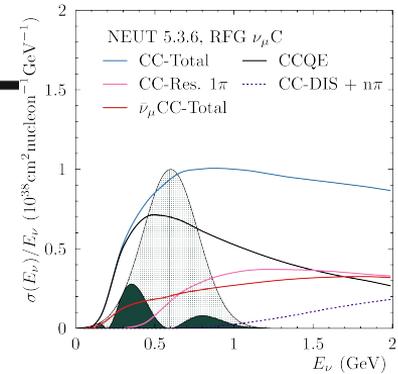
Inferring Oscillation Parameters

- Shouldn't be too hard
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- **But we see event-rate, not flux...**



Inferring Oscillation Parameters

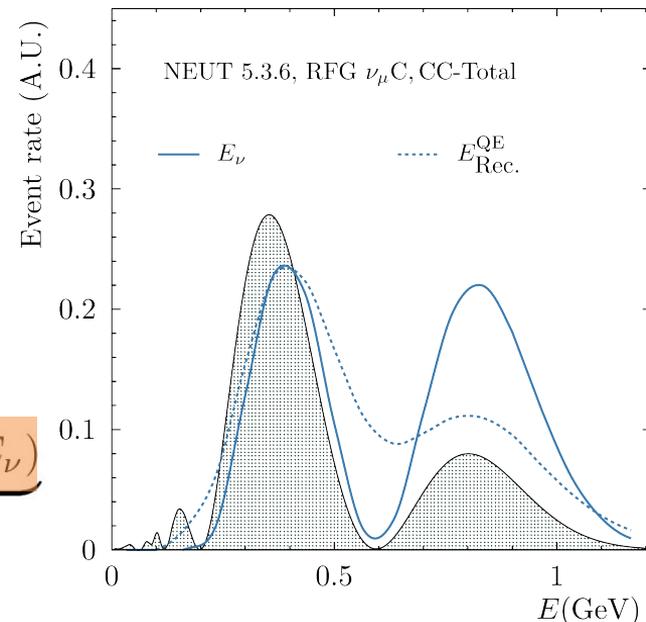
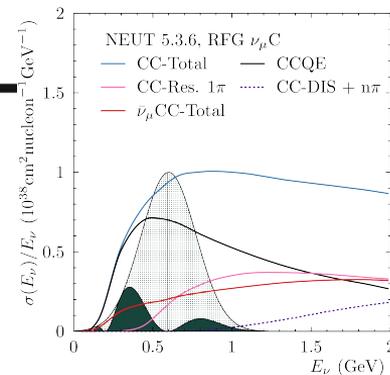
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 - Insane beam power
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- But we see event-rate, not flux...
- **But we don't see true neutrino energy...**



Inferring Oscillation Parameters

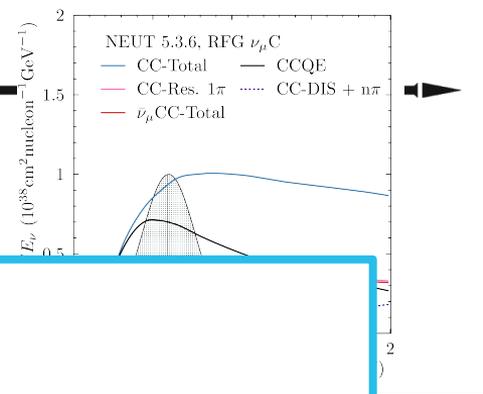
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 - Sophisticated detectors
 - Insane beam power
- **Look for signature 'oscillation' shape in flux at the far detector...**
- **But we see event-rate, not flux...**
- **But we don't see true neutrino energy...**

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



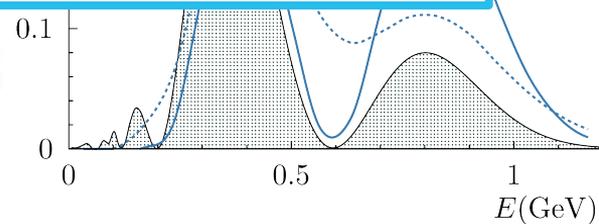
Inferring Oscillation Parameters

- Shouldn't be too hard
 - Sophisticated detectors



- **Cross sections are a big concern:**
 - Mismodelling
 - ⇒ Misunderstood oscillated flux
 - ⇒ Biased oscillation results
- Not clear this will be any different by the time of DUNE.

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



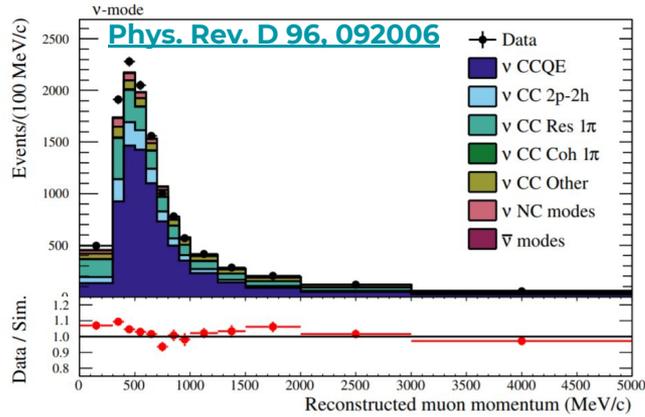
T2K



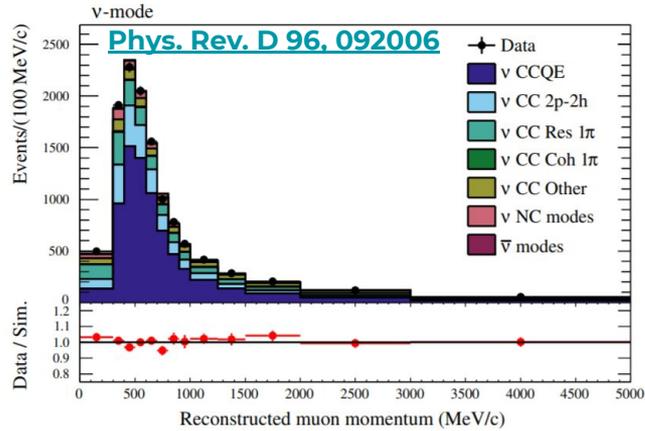
DUNE

Current Long Baseline Oscillation Analysis Methods

A thick black horizontal line with arrowheads at both ends, spanning the width of the slide below the title.

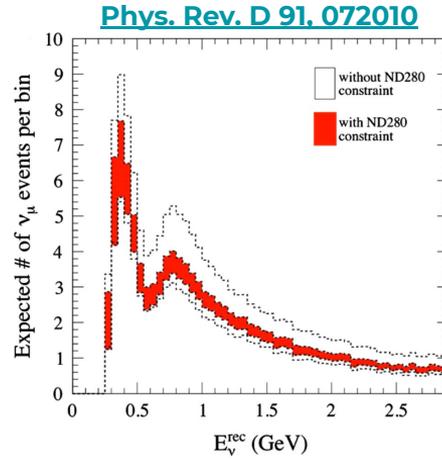
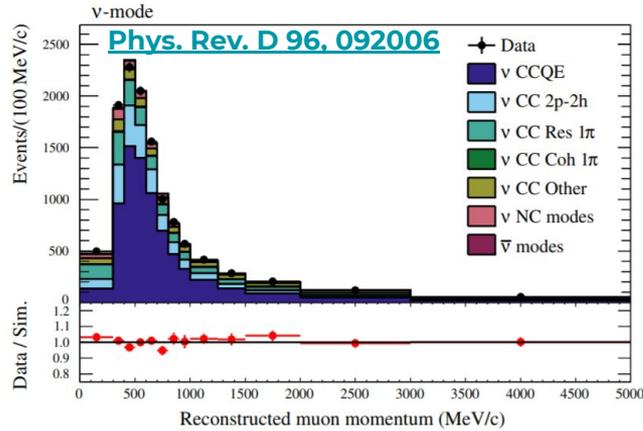
Examples of OA: **T2K**

- Wiggle model parameters at the ND

Examples of OA: **T2K**

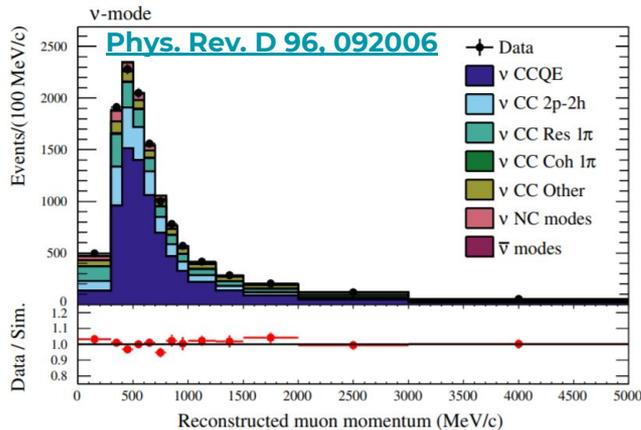
- Wiggle model parameters at the ND

Examples of OA:

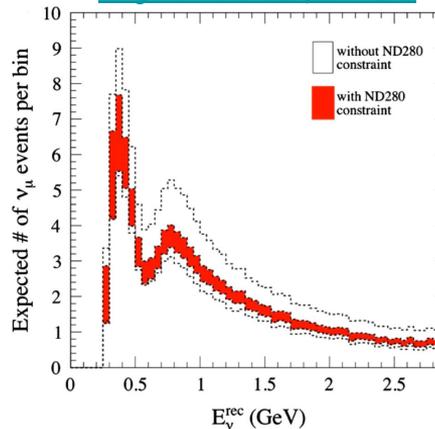


- Wiggle model parameters at the ND
- **Get correlated flux/xsec uncertainties**
- **Make predictions at the FD**

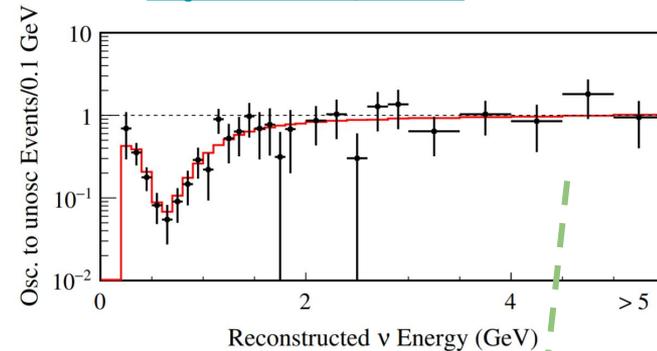
Examples of OA:



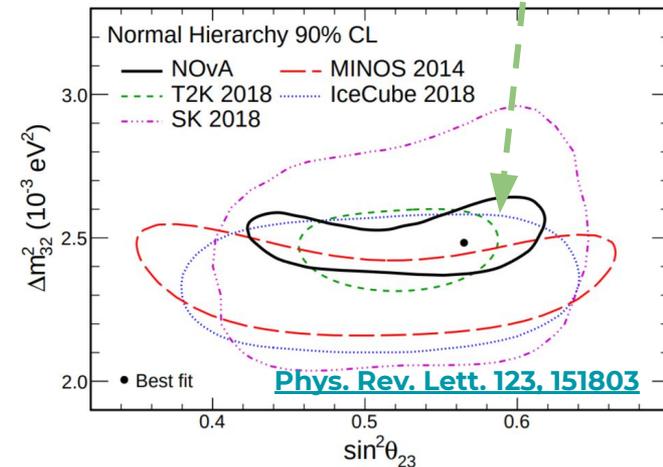
[Phys. Rev. D 91, 072010](#)

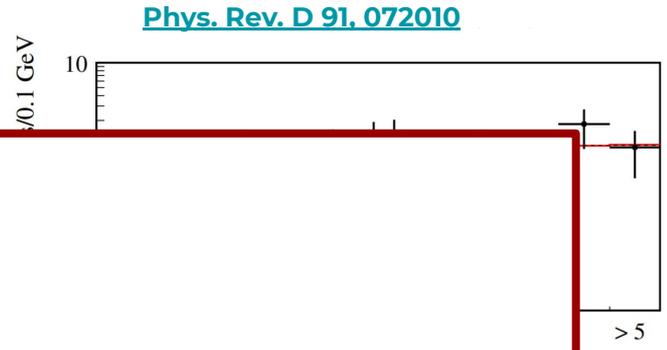
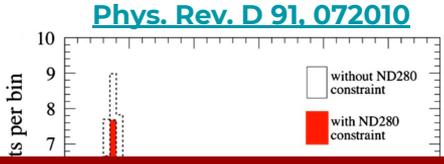
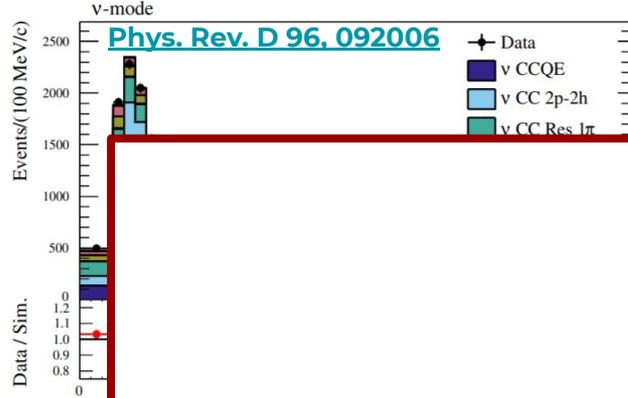


[Phys. Rev. D 91, 072010](#)



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

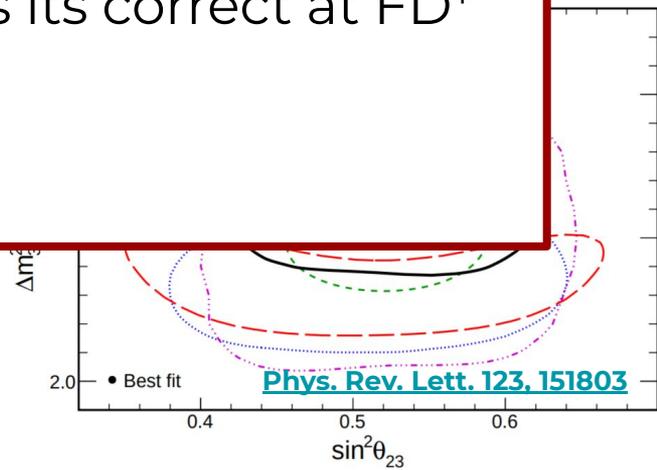


Examples of OA: **T2K**

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

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

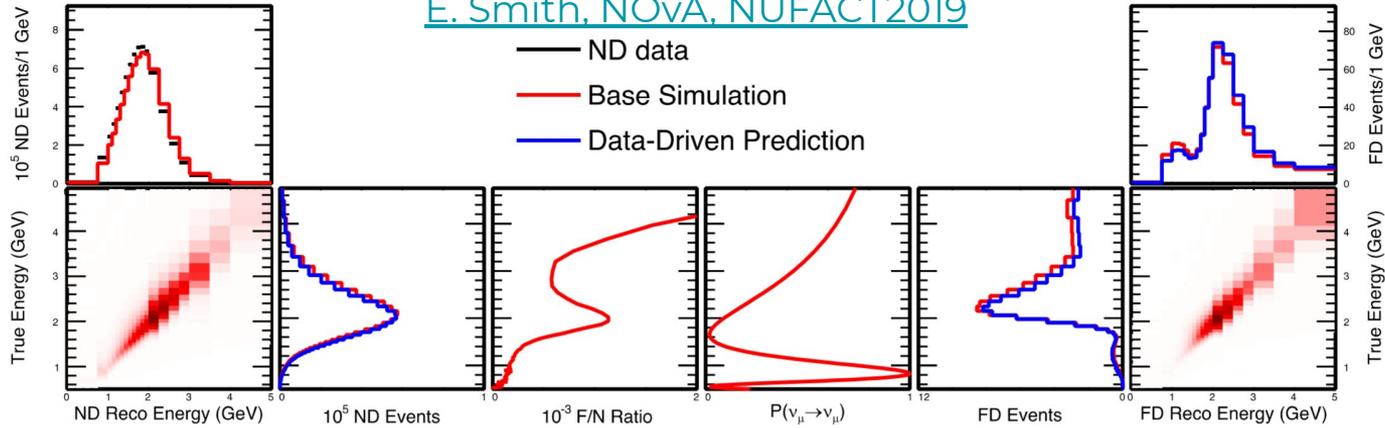
Infer oscillation parameters



Examples of OA:



[E. Smith, NOVA, Nufact2019](#)

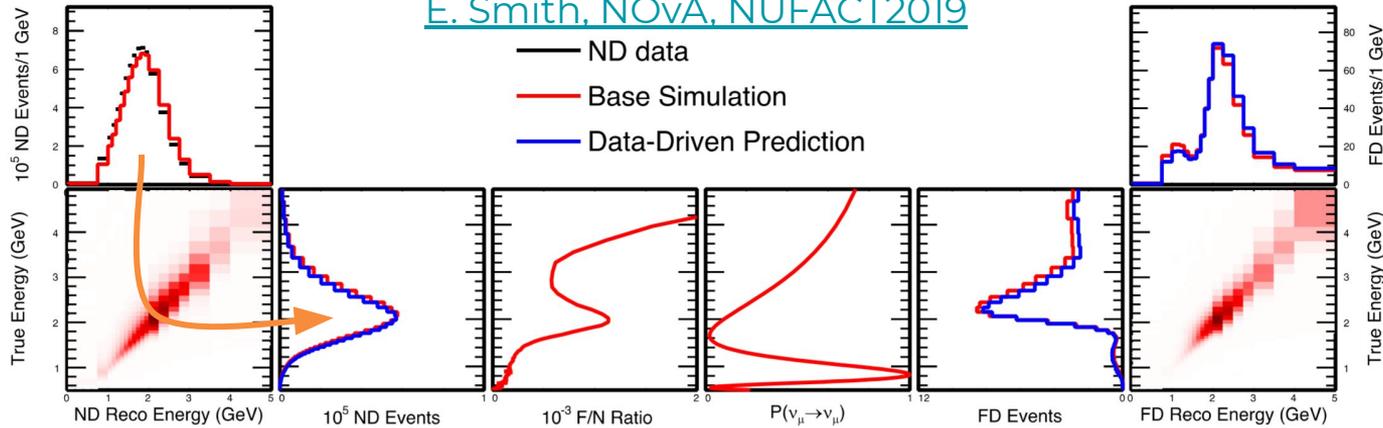


1. Subtract ND backgrounds (WSB, NC, cosmics)

Examples of OA:



[E. Smith, NOVA, Nufact2019](#)

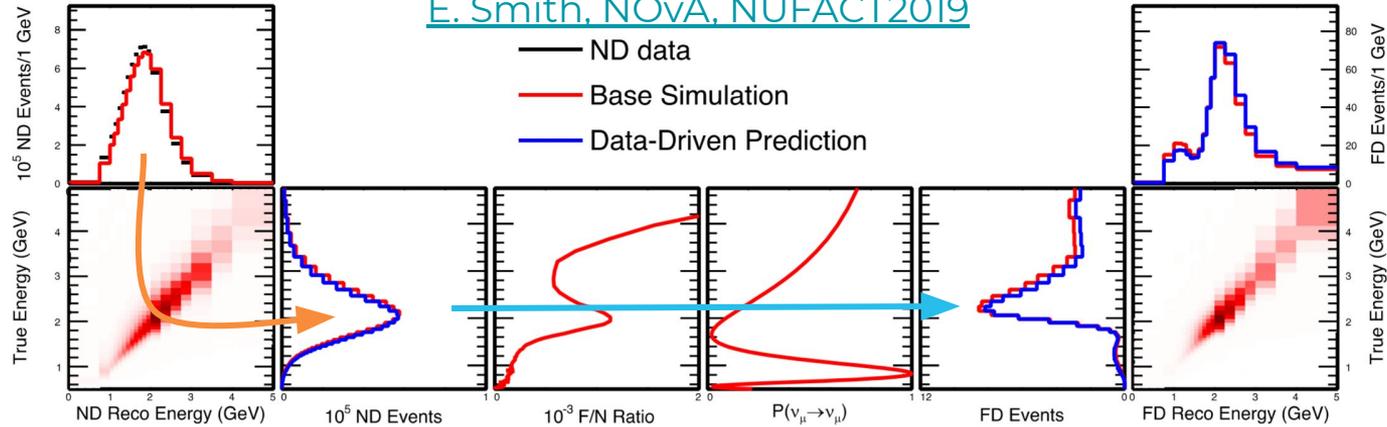


1. Subtract ND backgrounds (WSB, NC, cosmics)
2. Use MC to predict true event rate at ND



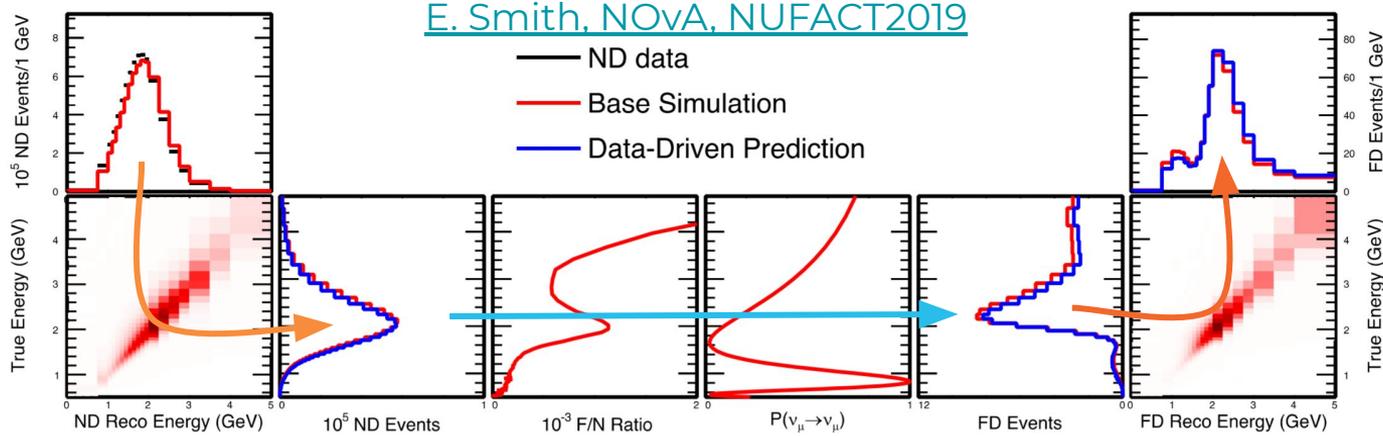
Examples of OA:

[E. Smith, NOVA, Nufact2019](#)



1. Subtract ND backgrounds (WSB, NC, cosmics)
2. Use MC to predict true event rate at ND
3. Oscillate and correct for ND/FD differences

Examples of OA:

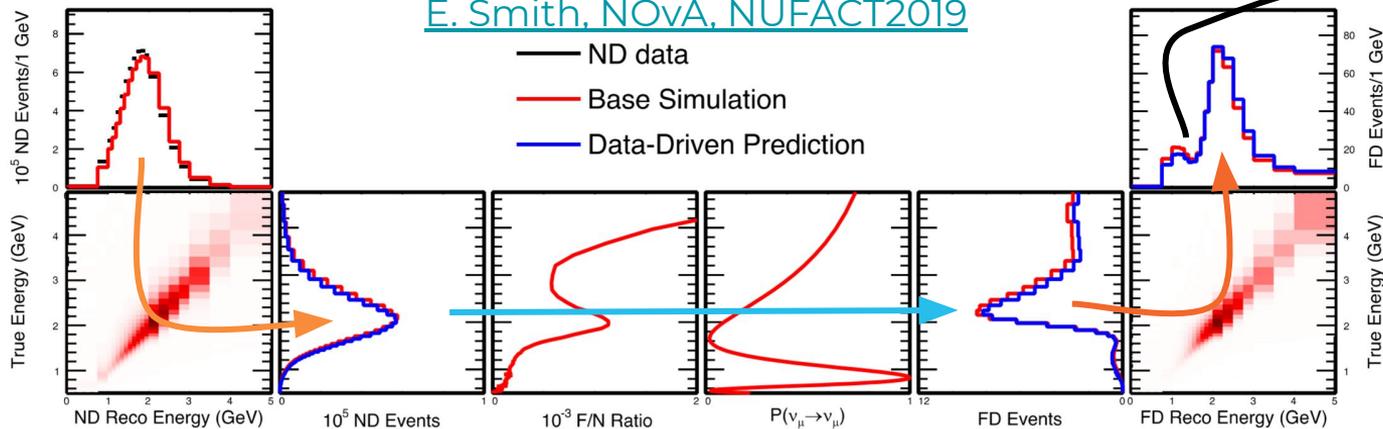


1. Subtract ND backgrounds (WSB, NC, cosmics)
2. Use MC to predict true event rate at ND
3. Oscillate and correct for ND/FD differences
4. Use MC to predict FD observed signal

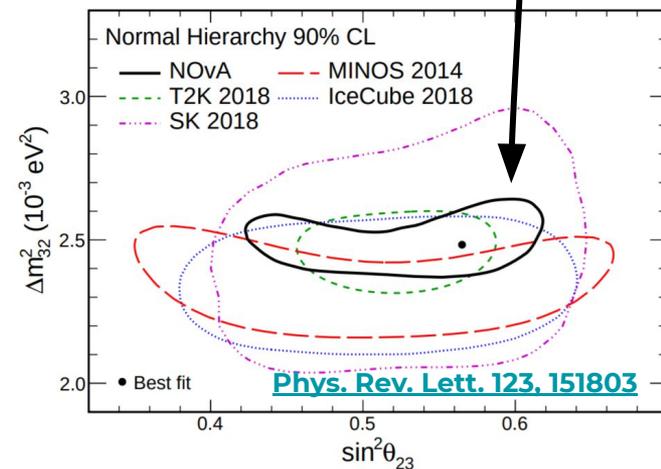
Examples of OA:



E. Smith, NOVA, NUFAC2019

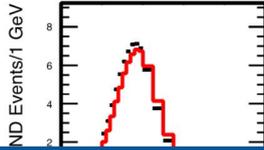


1. Subtract ND backgrounds (WSB, NC, cosmics)
2. Use MC to predict true event rate at ND
3. Oscillate and correct for ND/FD differences
4. Use MC to predict FD observed signal
5. Add MC backgrounds
6. Infer osc. parameters



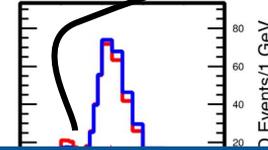


Examples of OA:



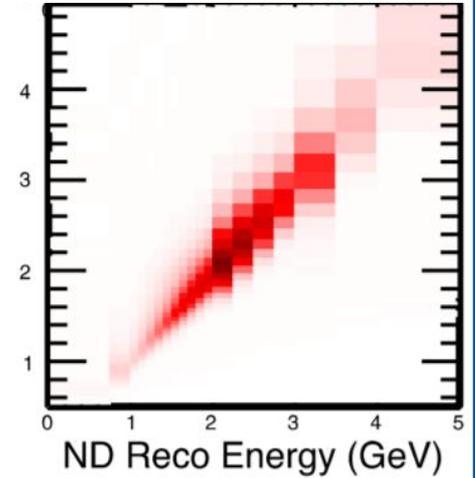
[E. Smith, NOVA, Nufact2019](#)

— ND data
 — Base Simulation
 — Data-Driven Prediction

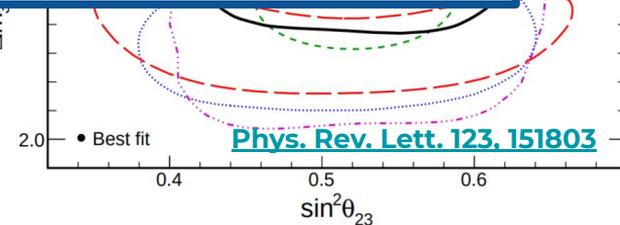


One Line: Extrapolates ND data by assuming model prediction for E_{Obs}^{ν} to E_{True}^{ν} relationship.

True Energy (GeV)



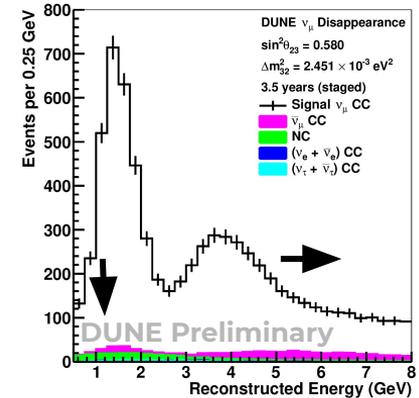
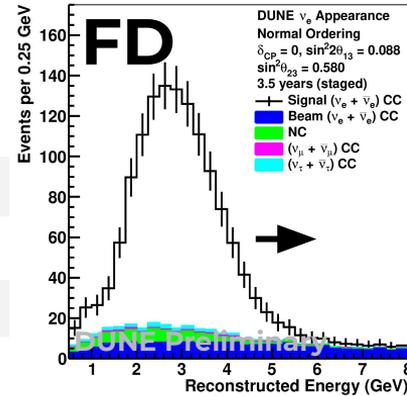
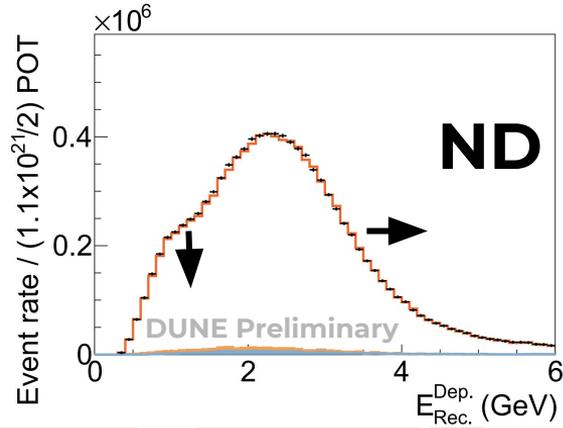
Δm_{21}^2



[Phys. Rev. Lett. 123, 151803](#)

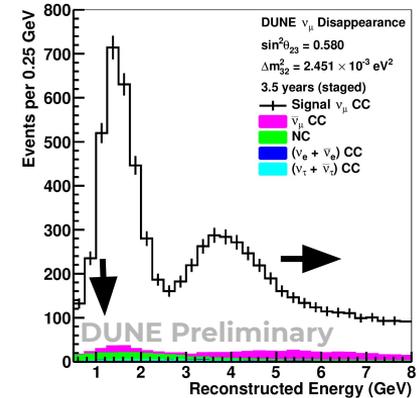
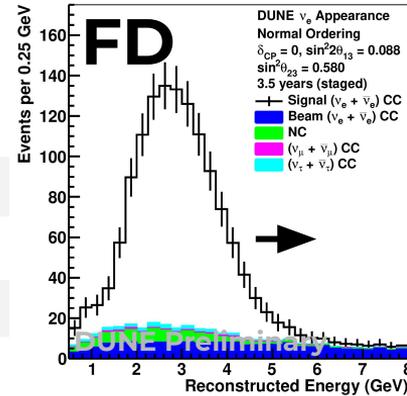
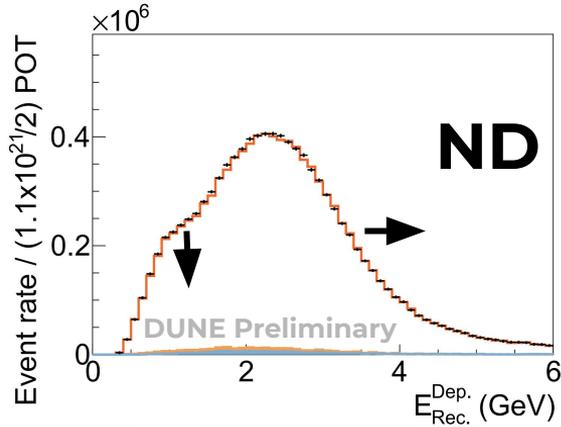
1. S
2. U
3. O
4. Use MC to predict FD observed signal
5. Add MC backgrounds
6. Infer osc. parameters

Examples of OA: DUNE TDR

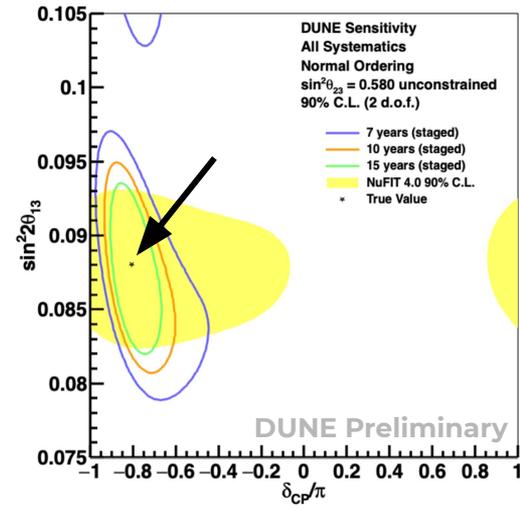


- Wiggle systematics at ND and FD simultaneously

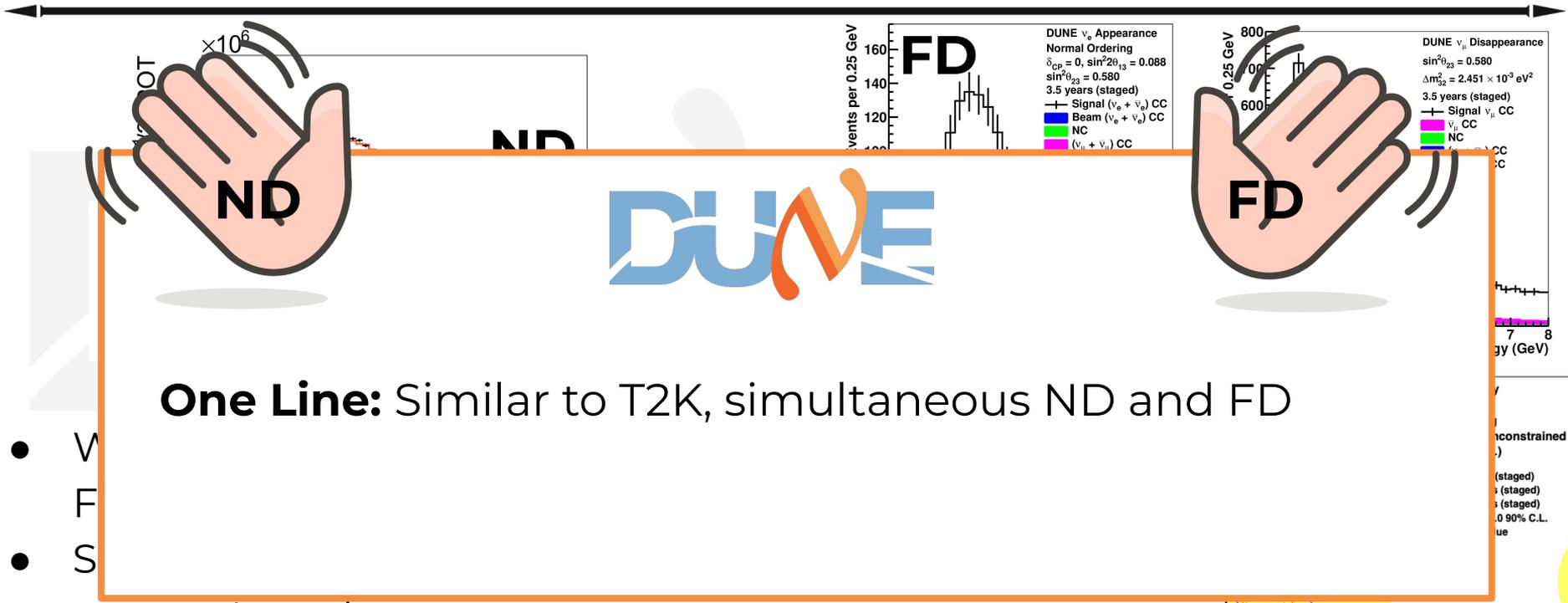
Examples of OA: DUNE TDR



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

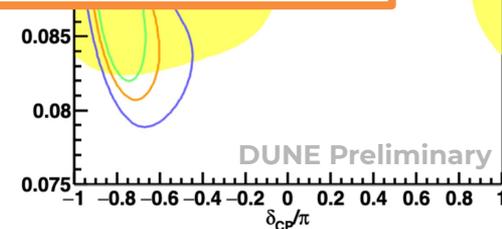


Examples of OA: DUNE TDR

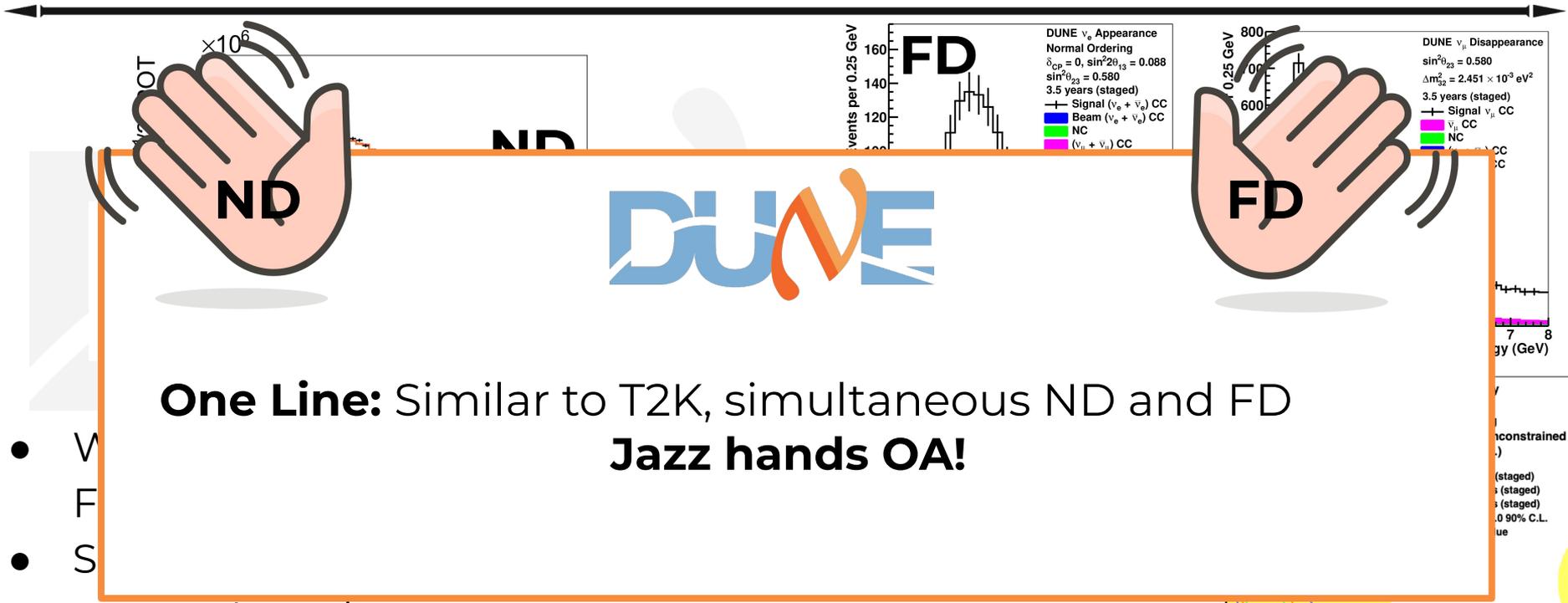


One Line: Similar to T2K, simultaneous ND and FD

- V
 - F
 - S
- parameter values

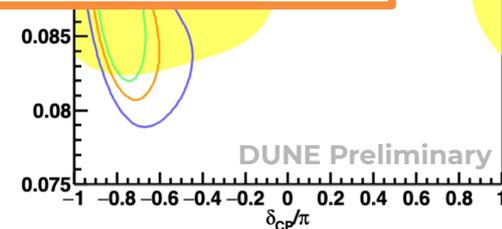


Examples of OA: DUNE TDR



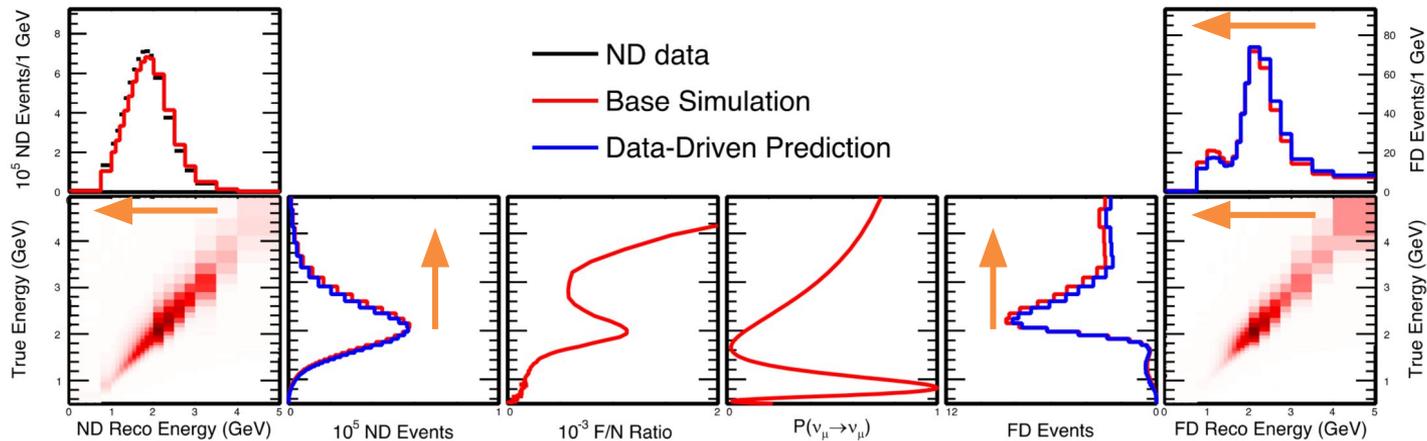
One Line: Similar to T2K, simultaneous ND and FD
Jazz hands OA!

- V
 - F
 - S
- parameter values



Model-driven Extrapolation

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



Model-driven Extrapolation

- Why can we not just look at near/far ratio, even for functionally identical detectors?

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

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

Model-driven Extrapolation

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 - **Fluxes aren't the same**

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- **But what if we could make them the same...**

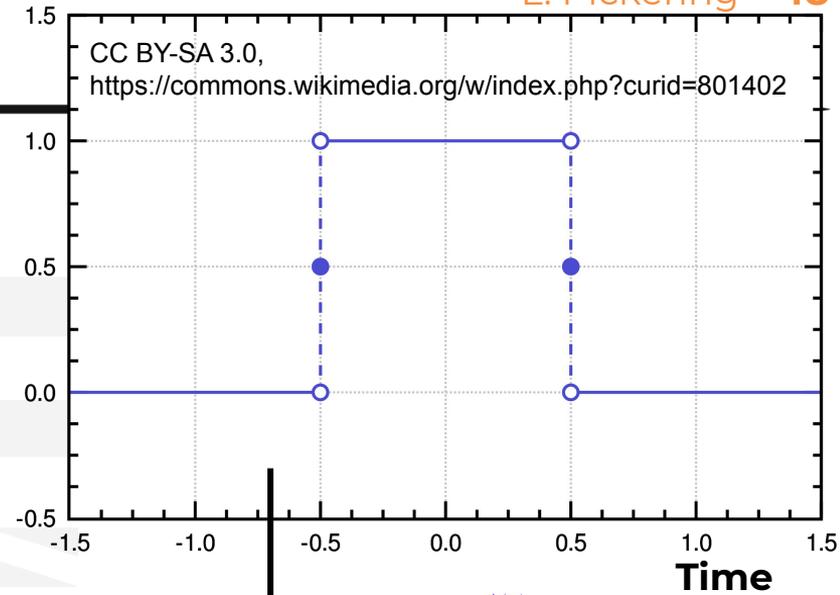


Interlude: Decomposing things into sums of other things with Math(s)

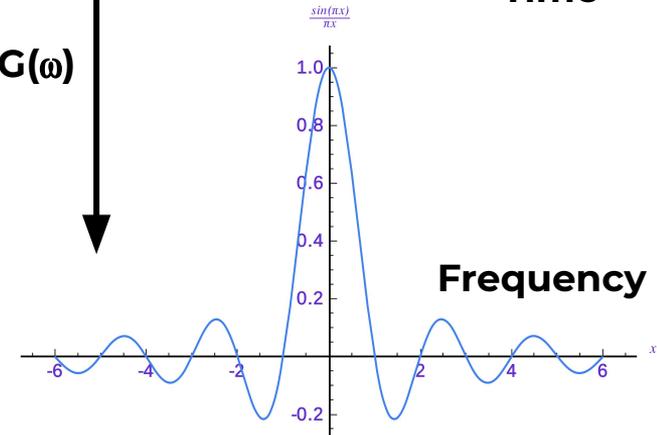


Fourier Transform

- **Complete, orthonormal set of functions:** complex sinusoids.
- Decompose function to integral over frequency components.

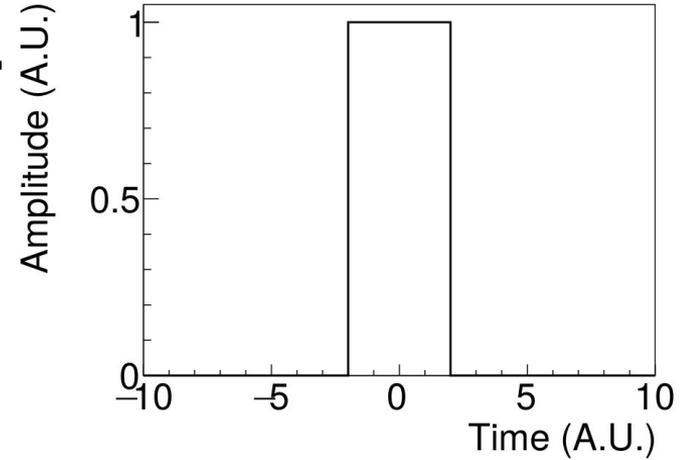


$$F(t) \Rightarrow G(\omega)$$



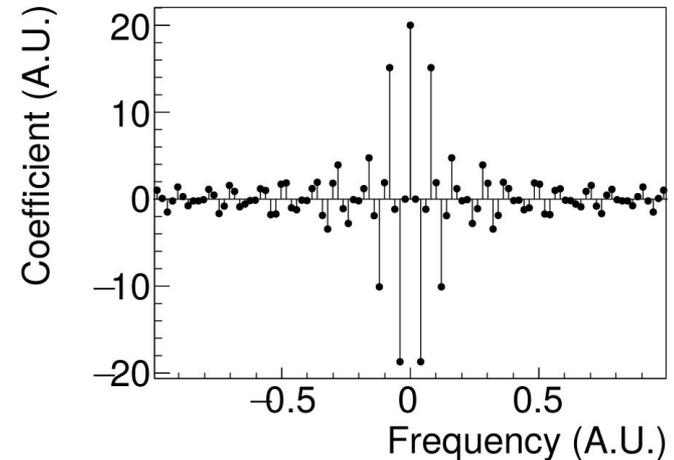
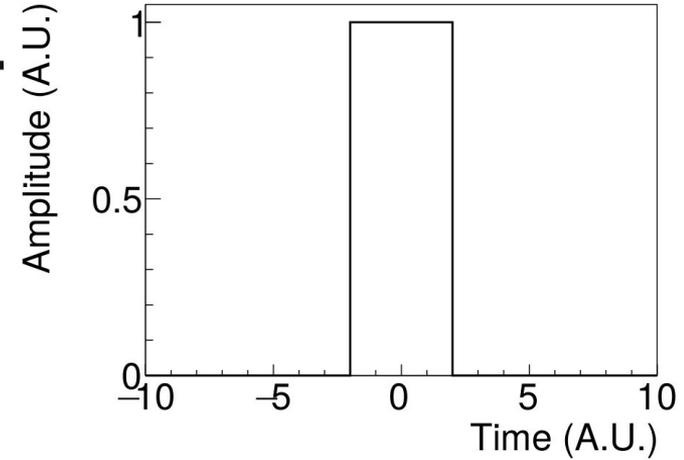
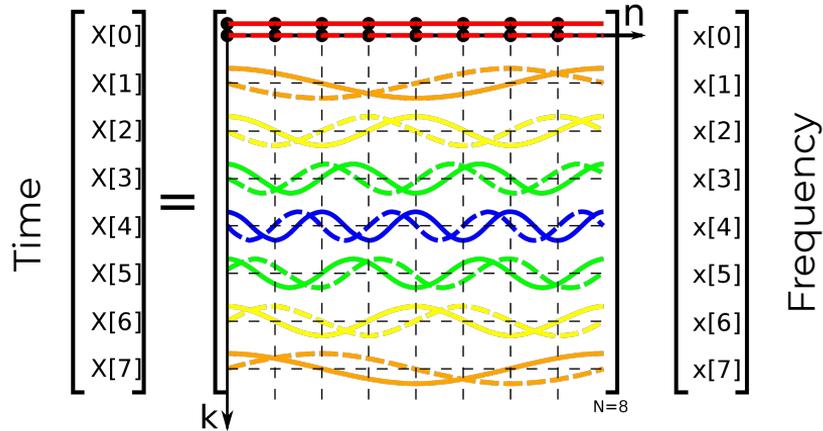
Discrete Fourier Transform

- Practically often use DFT!
- **Don't have complete set:**
 - Available frequencies limited by discreteness
 - Decompose sequence as a linear sum of sines/cosines



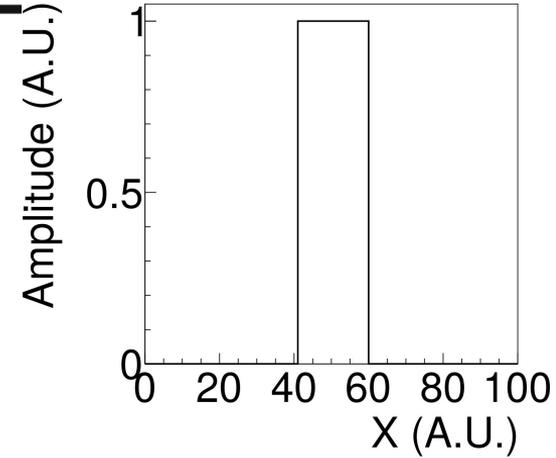
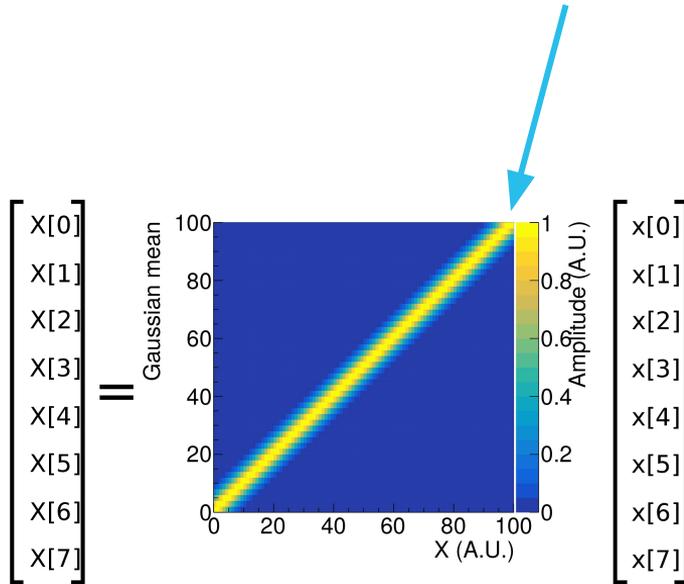
Discrete Fourier Transform

- Practically often use DFT!
- Don't have complete set:
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 - Decompose sequence as a linear sum of sines/cosines
 - **Expressible as a linear algebra problem**



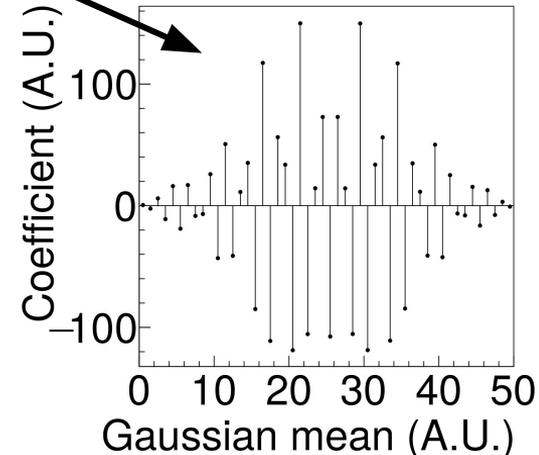
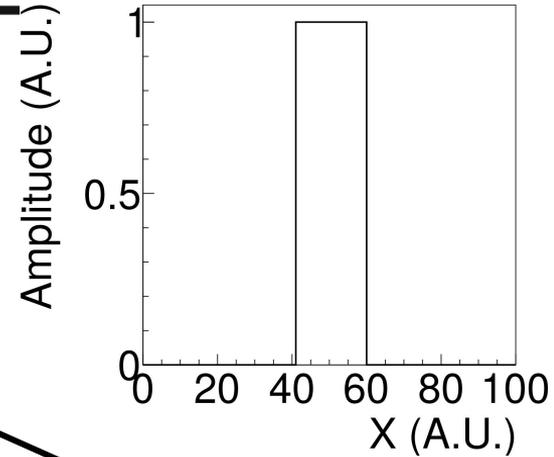
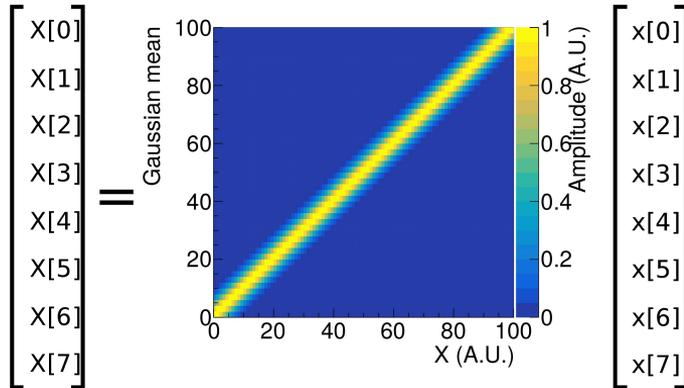
Arbitrary discrete feature analysis

- Okay, what if we don't want to use an orthonormal set: e.g. using gaussians?



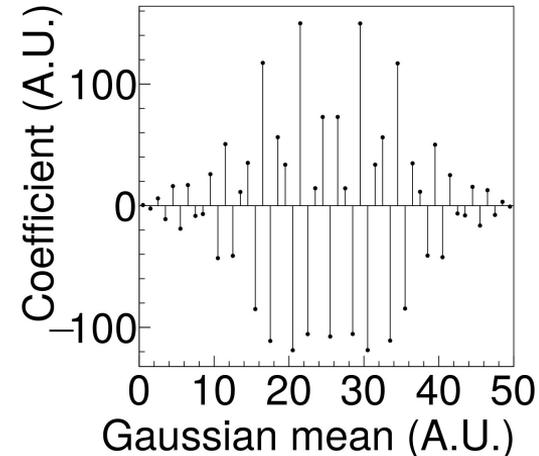
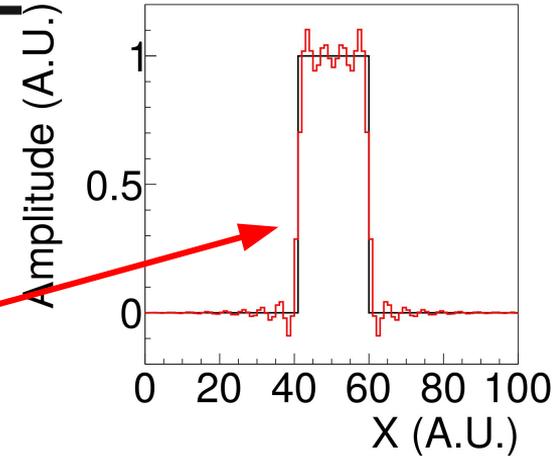
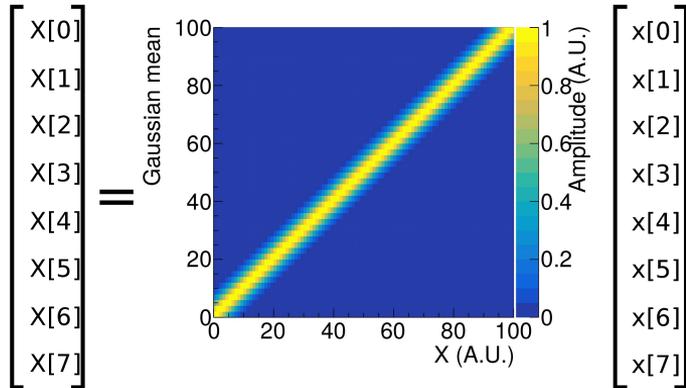
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- **Can still look for near-solutions to the now generally ill-posed linear system**



Arbitrary discrete feature analysis

- Okay, what if we don't want to use an orthonormal set: e.g. using gaussians?
- Can still look for near-solutions to the now generally ill-posed linear system
- **Solution isn't exact, but can be good enough**

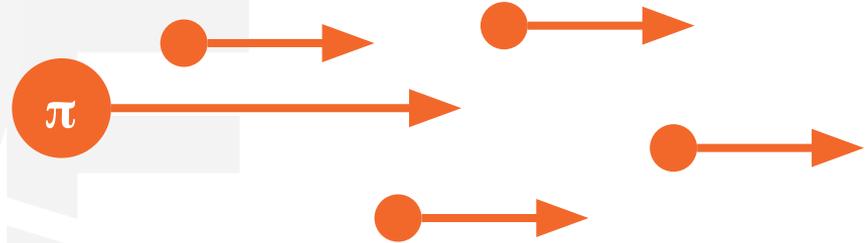


PRISM: Precision Reaction-Independent Spectrum Measurement



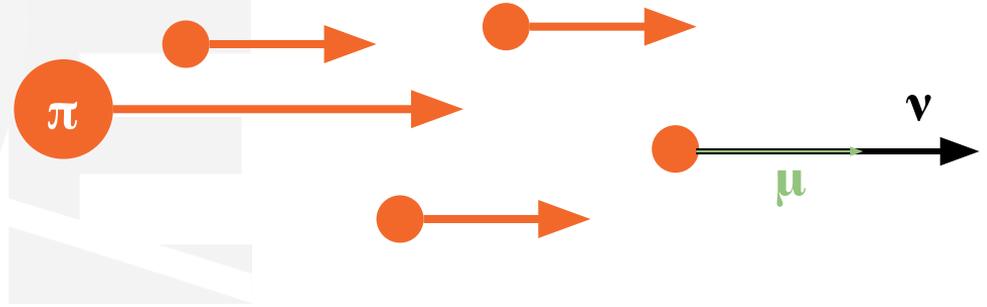
Off Axis Fluxes

- Neutrino beams mostly from decay-in-flight π
 - Boosted decay kinematics result in lower energy neutrinos off beam axis.



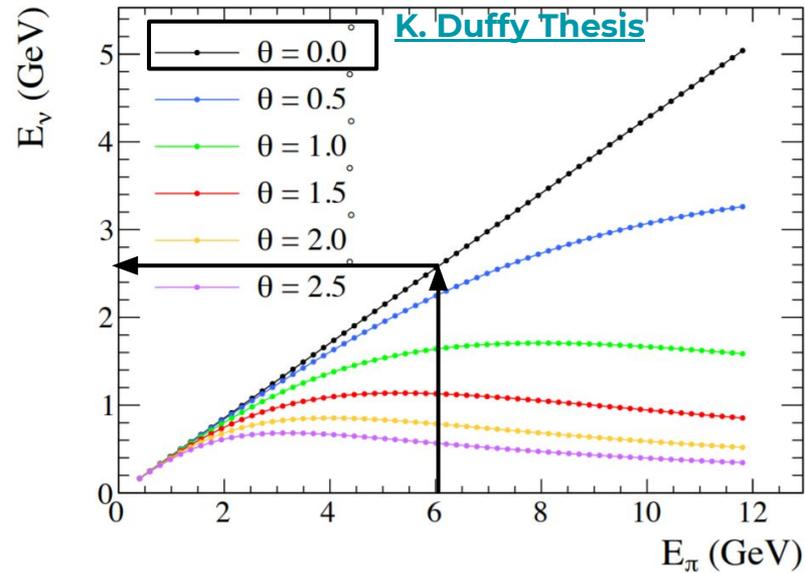
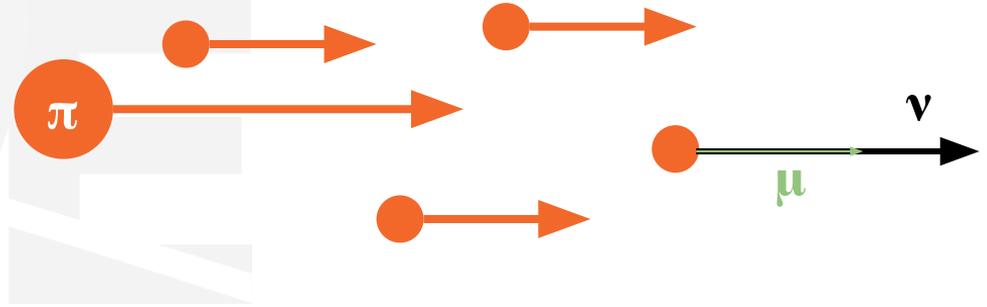
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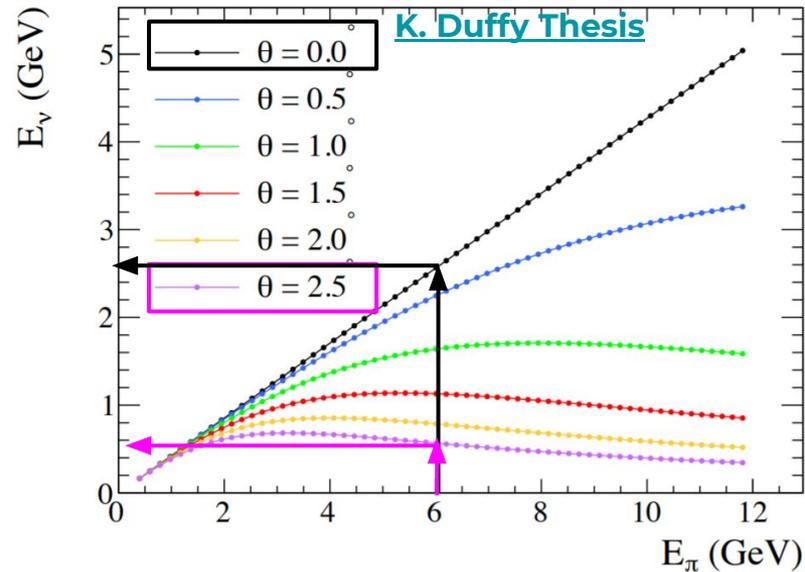
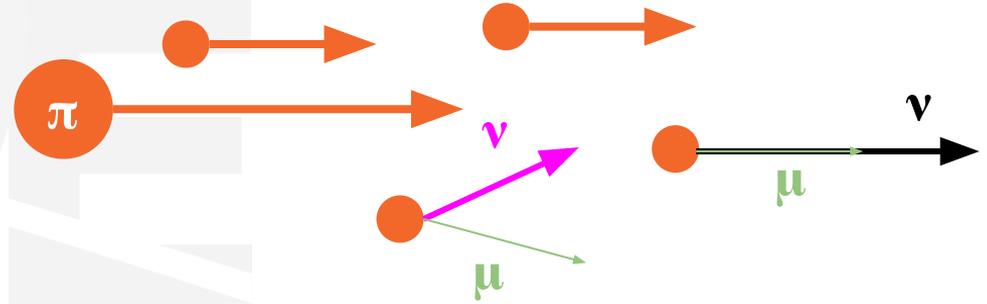
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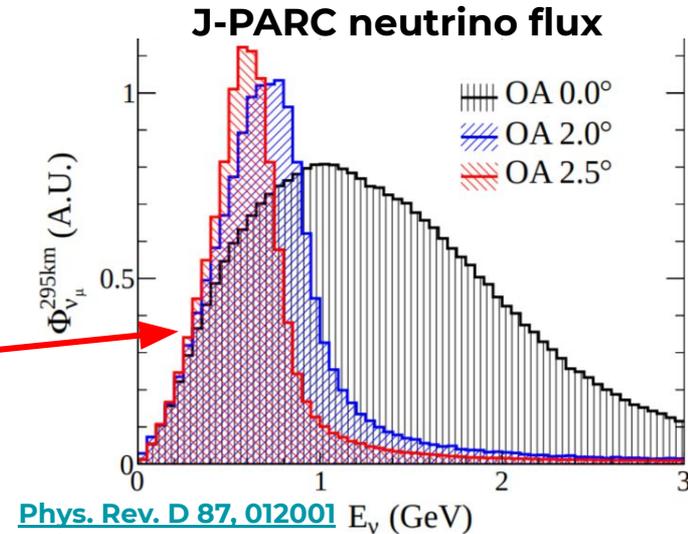
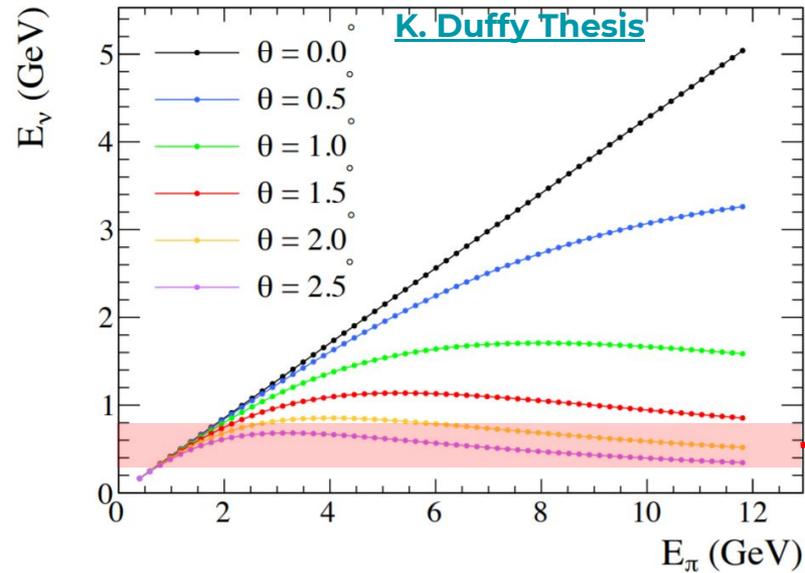
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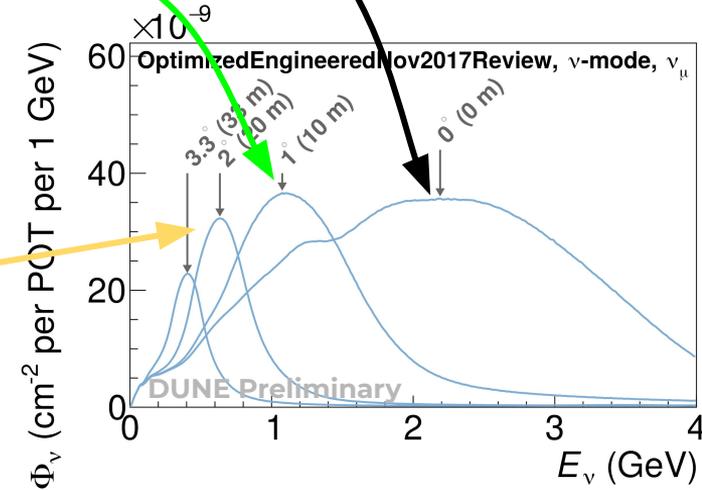
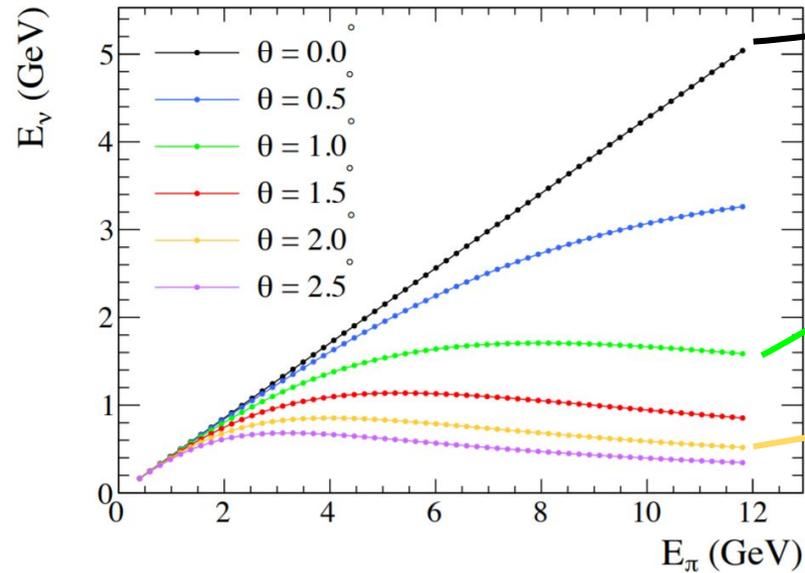
Off Axis Fluxes

- Neutrino beams mostly from decay-in-flight π
 - Boosted 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 maxima



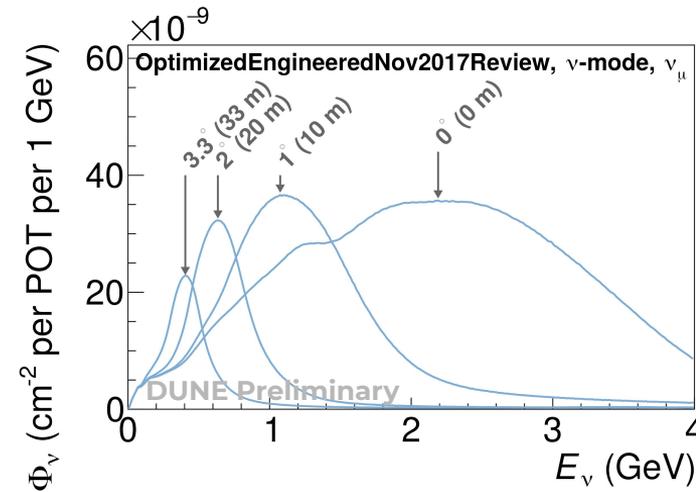
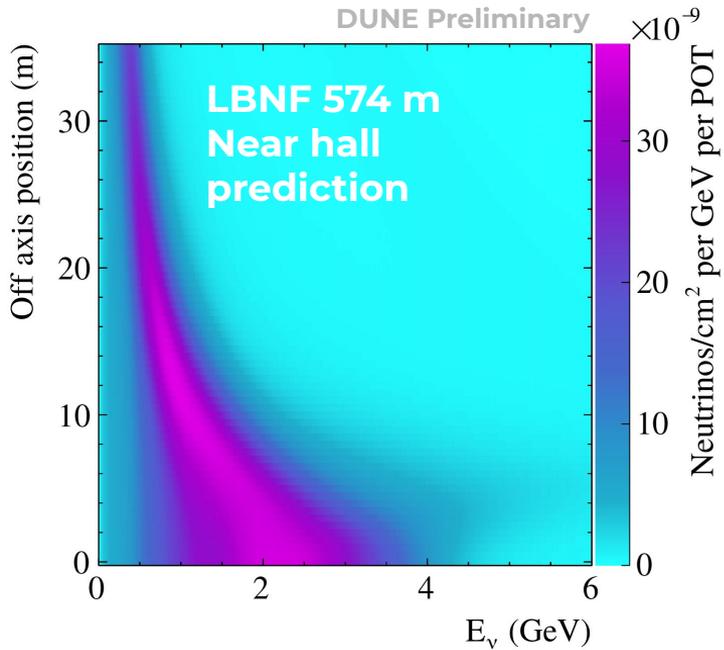
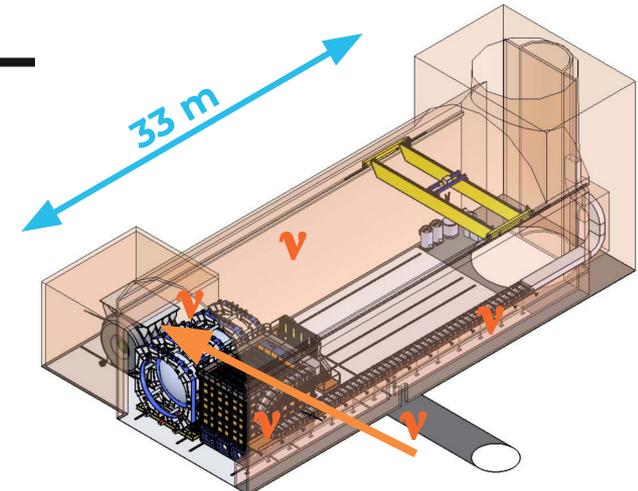
Off Axis ND Fluxes

- Multiple off-axis angles allow sampling of multiple neutrino flux shapes



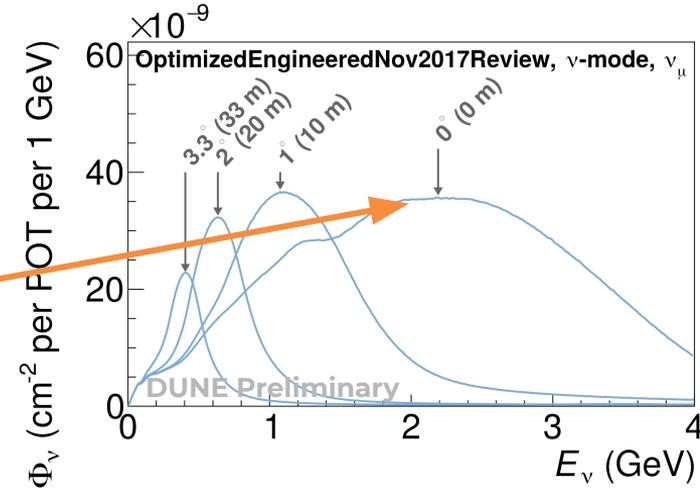
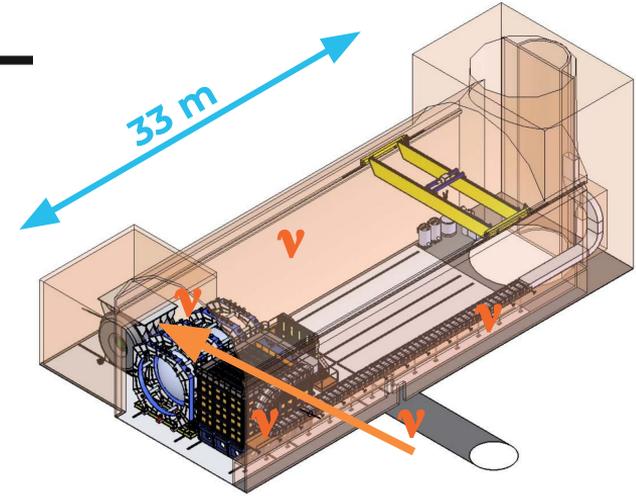
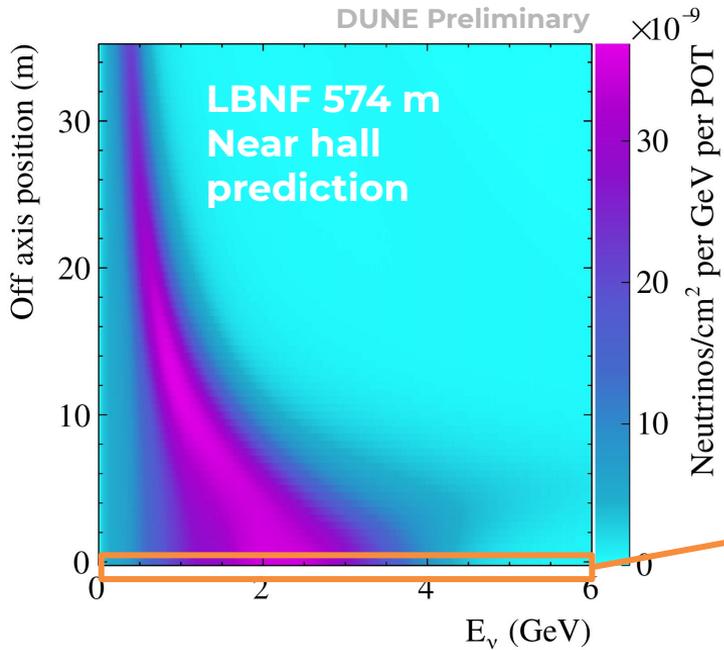
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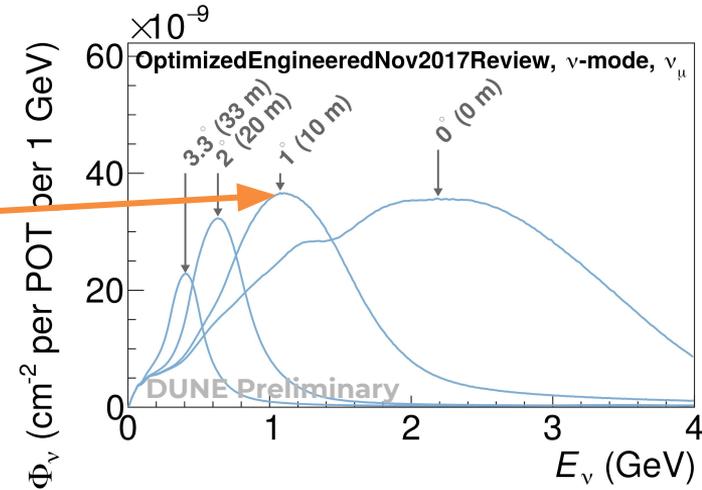
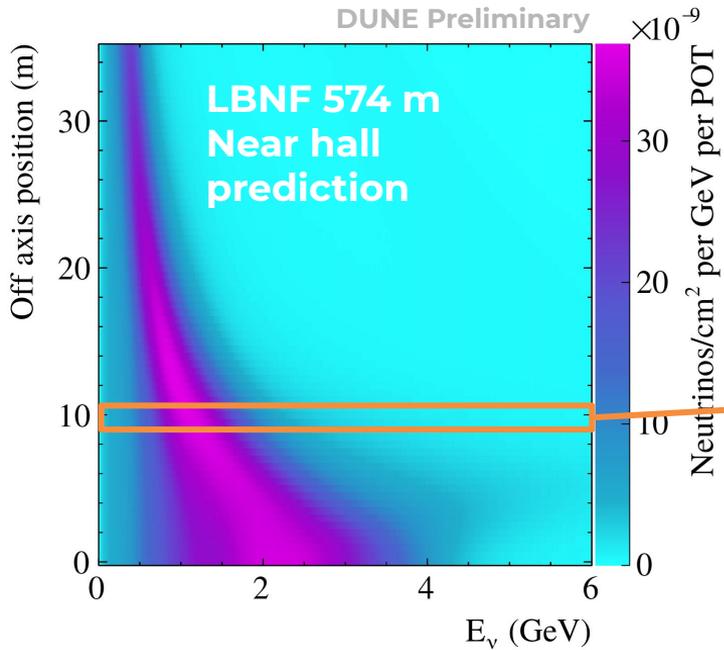
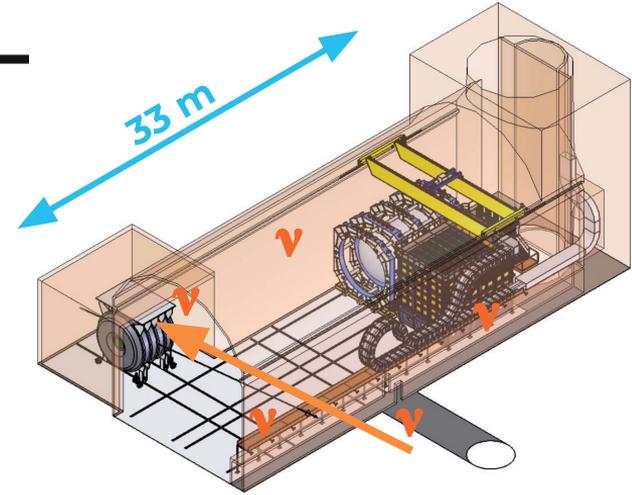
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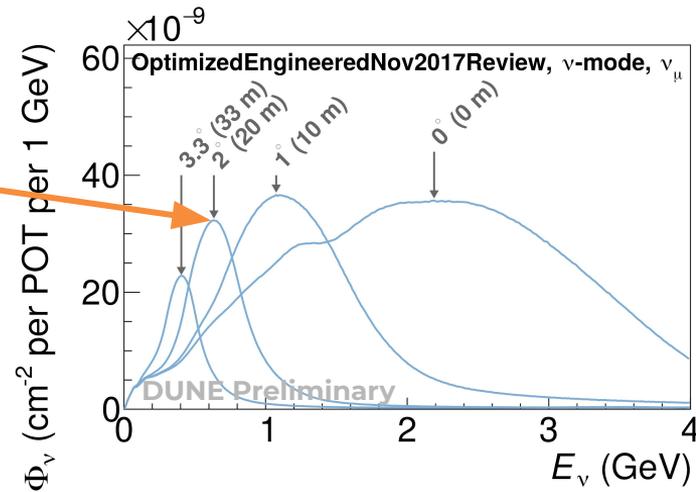
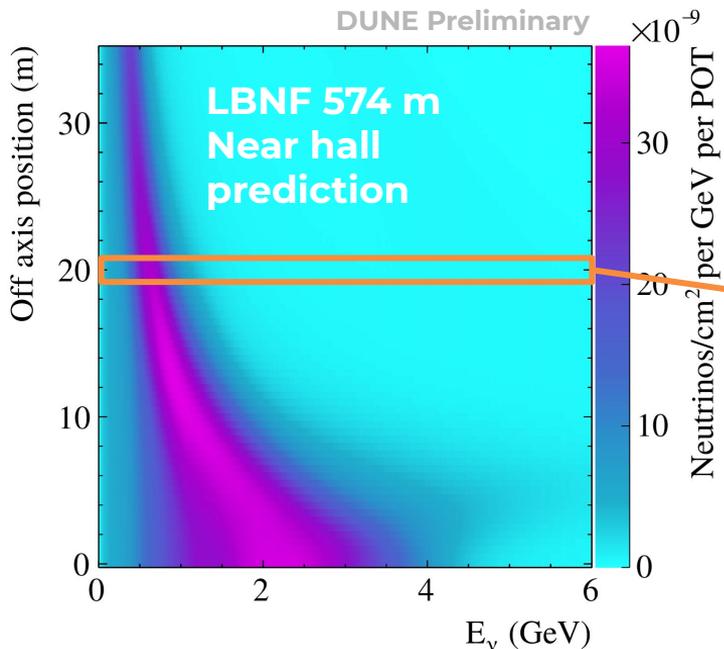
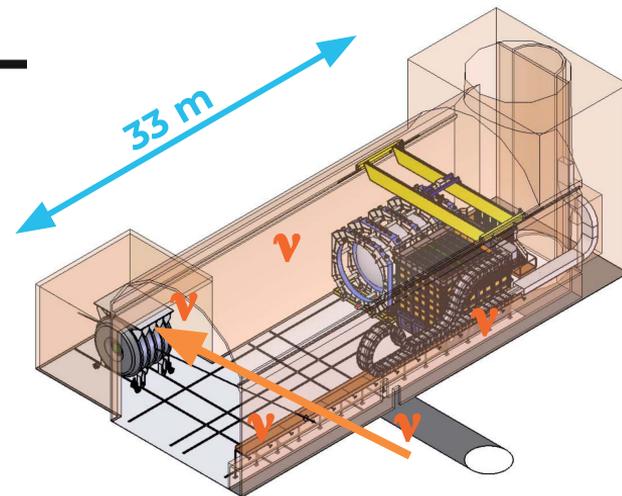
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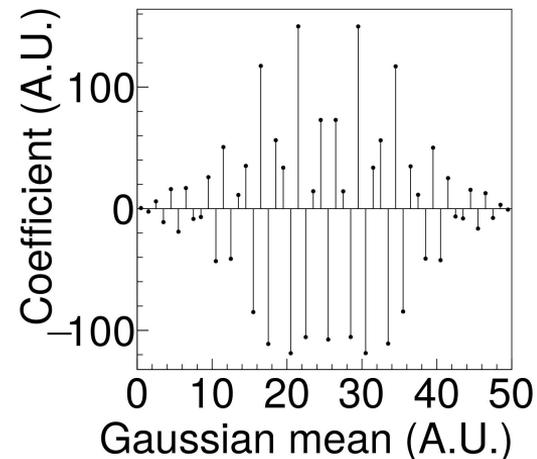
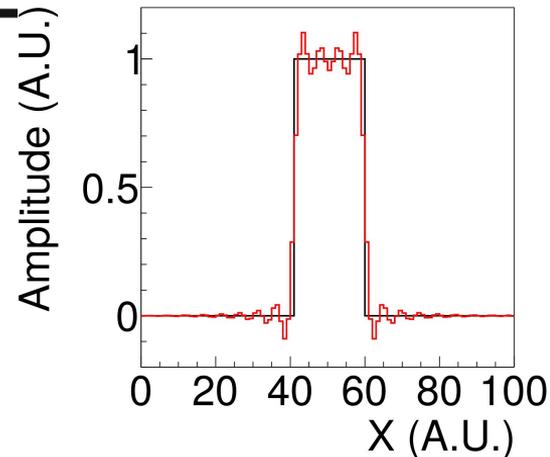
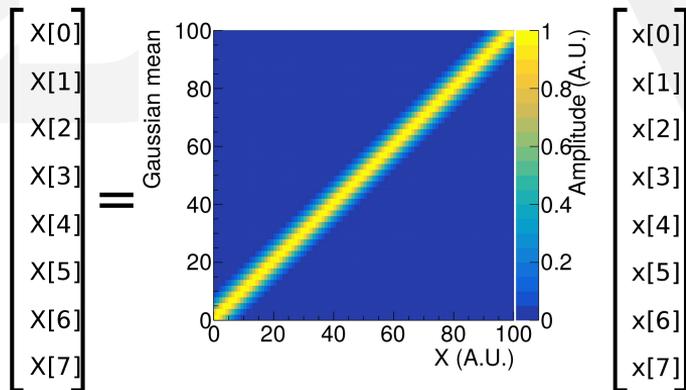
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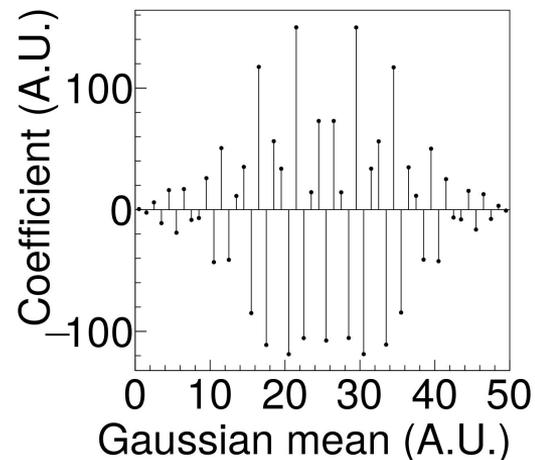
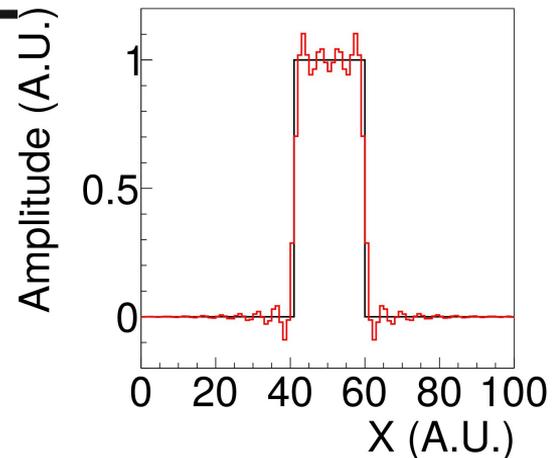
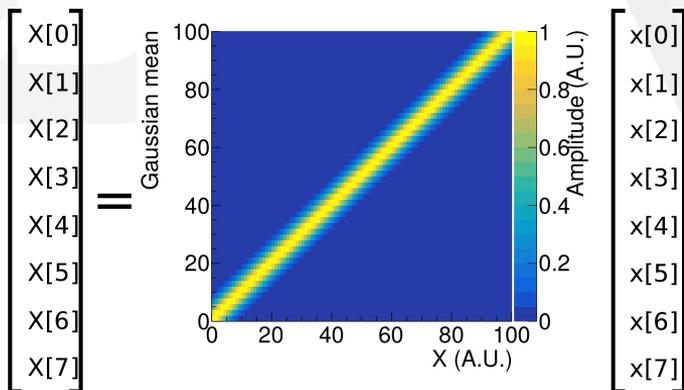
Hmm...

- Those off axis fluxes look almost like gaussians, I wonder...



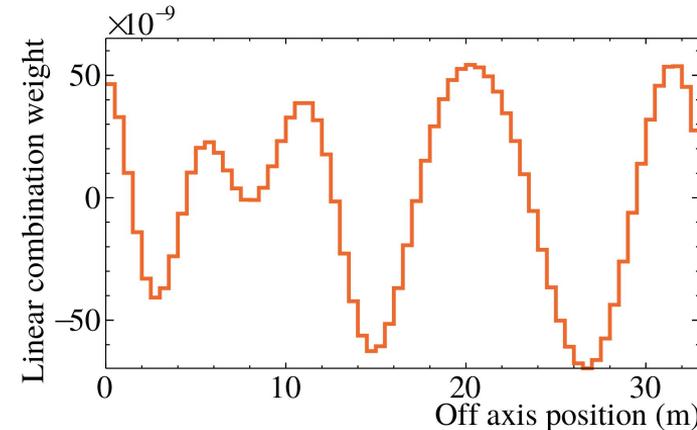
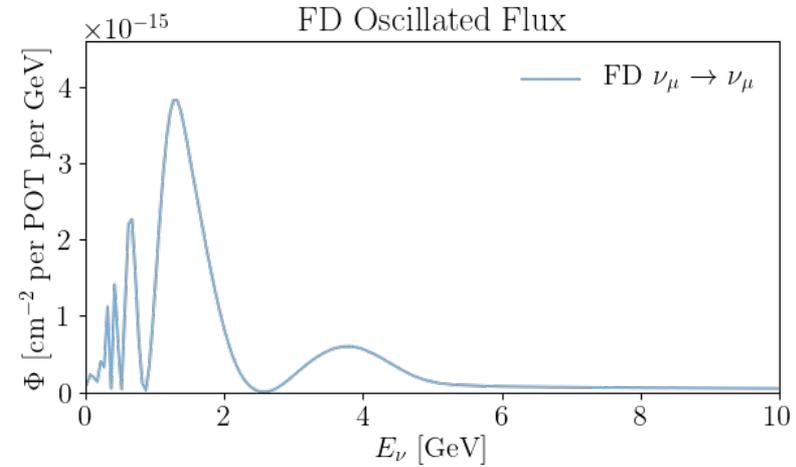
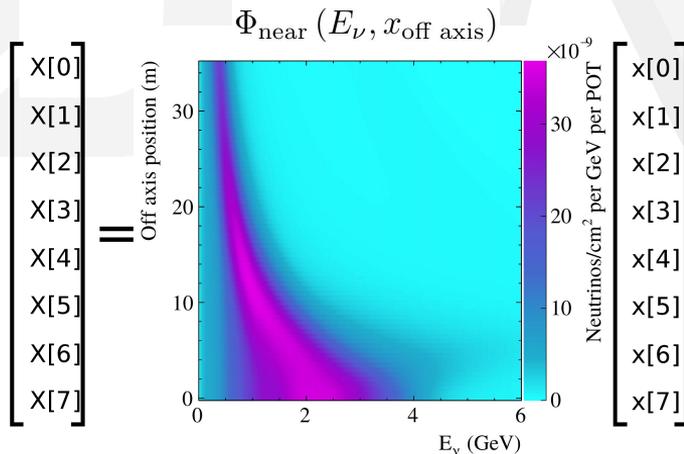
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- Those off axis fluxes look almost like gaussians, I wonder...
- **Now for the bait and switch**



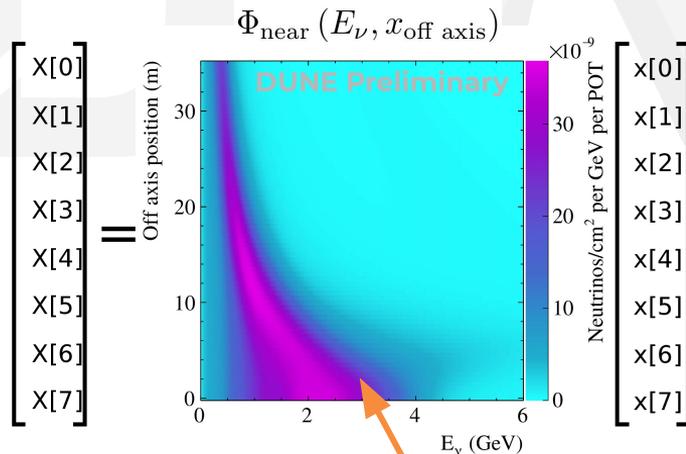
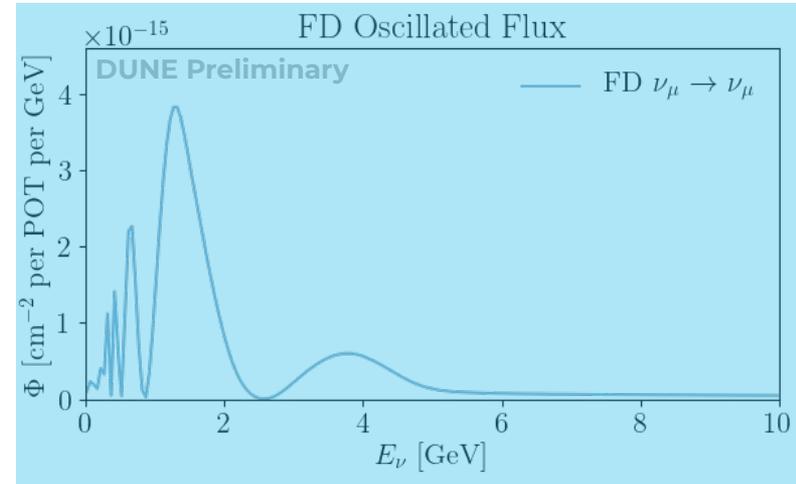
Fitting the FD flux at the ND

- Use the flux distribution at the ND to decompose an oscillated FD flux into a linear combination of ND measurements

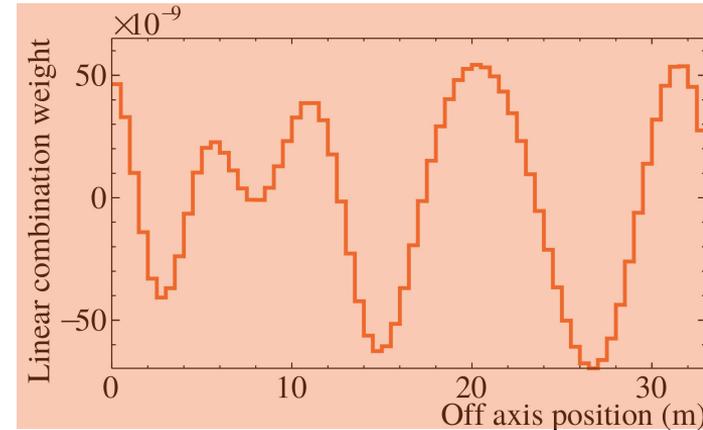


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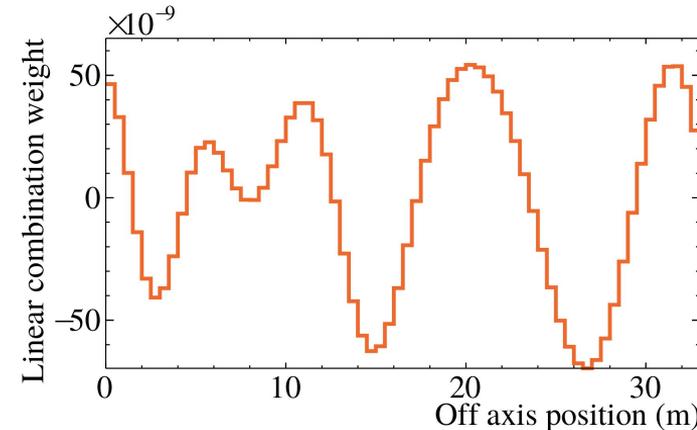
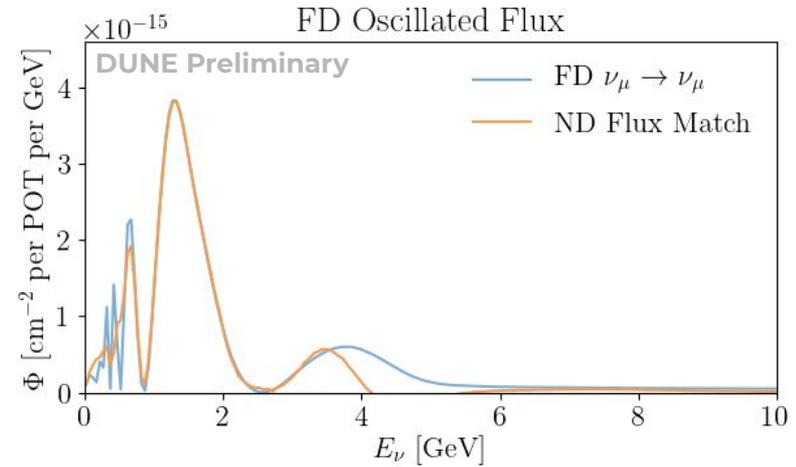
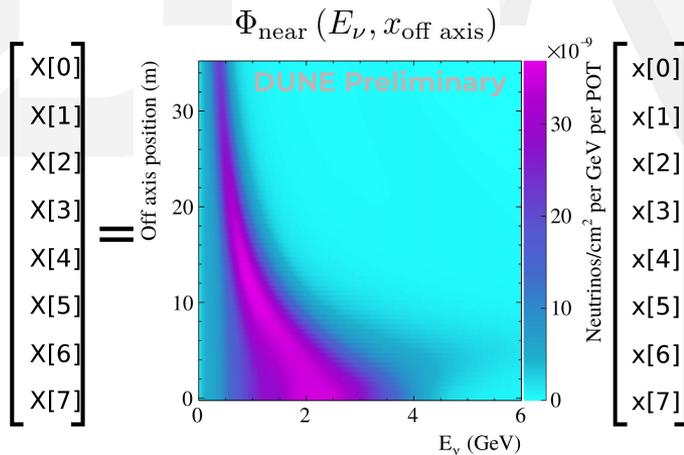


$$\Phi_{\text{far}}(E_\nu) P_{\text{osc}}(E_\nu) = \Phi_{\text{near}}(E_\nu, x_{\text{off axis}}) \times \vec{c}$$



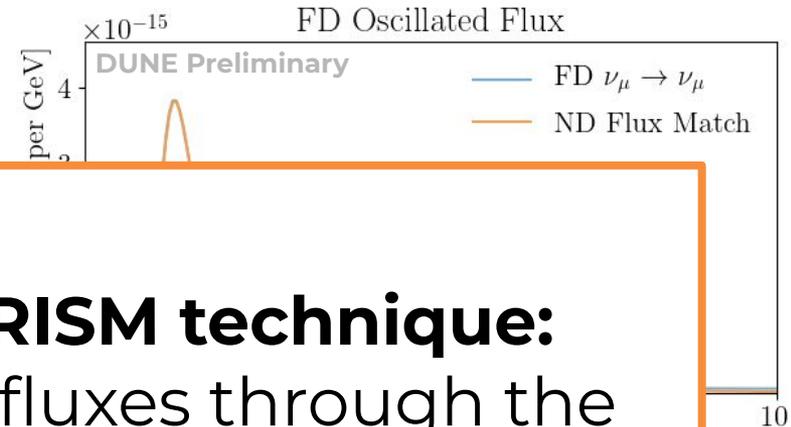
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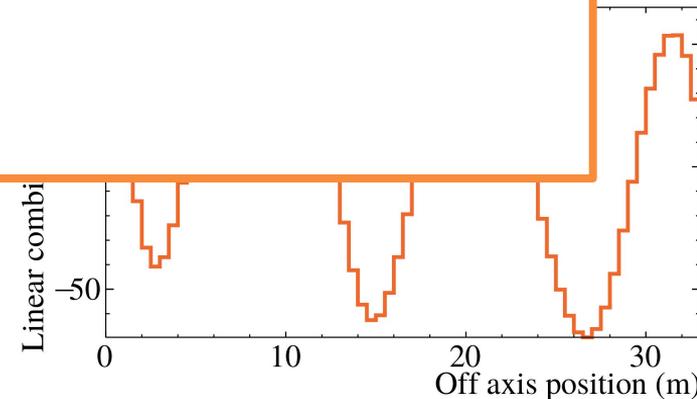


Fitting the FD flux at the ND

- Use the flux distribution at the ND to decompose an oscillated FD flux into



This is the key to the PRISM technique:
Constructing 'interesting' fluxes through the combination of off axis ND fluxes



How does that help?

- If we had truly identical near and far detectors and used the **PRISM method to build**: $\Phi_{\text{near}}(E_\nu, x_{\text{off axis}}) \times \vec{c} = \Phi_{\text{far}}(E_\nu) P_{\text{osc}}(E_\nu)$

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- **Cross-section physics is not position dependent**

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- Cross-section physics is not position dependent
- **Then when we have the right oscillation hypothesis:**
 - **Signal event rate is the same near and far!**

$$N_{\text{near}}(\mathbf{x}_{\text{obs}}) = \int d\mathbf{x}_{\text{true}} \underbrace{\mathbf{D}_{\text{near}}(\mathbf{x}_{\text{obs}}|\mathbf{x}_{\text{true}})}_{\text{Smearing, Eff., Pur.}} \underbrace{N_{\text{targ}}\sigma(\mathbf{x}_{\text{true}})}_{N_{\text{Int}}(\mathbf{x}_{\text{true}})} \underbrace{\Phi_{\text{near}}(E_\nu, x_{\text{off axis}}) \times \vec{c}}_{\text{Flux}}$$

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Remaining complications

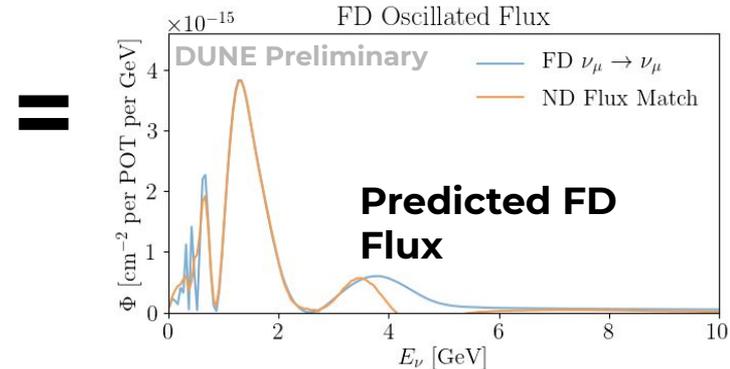
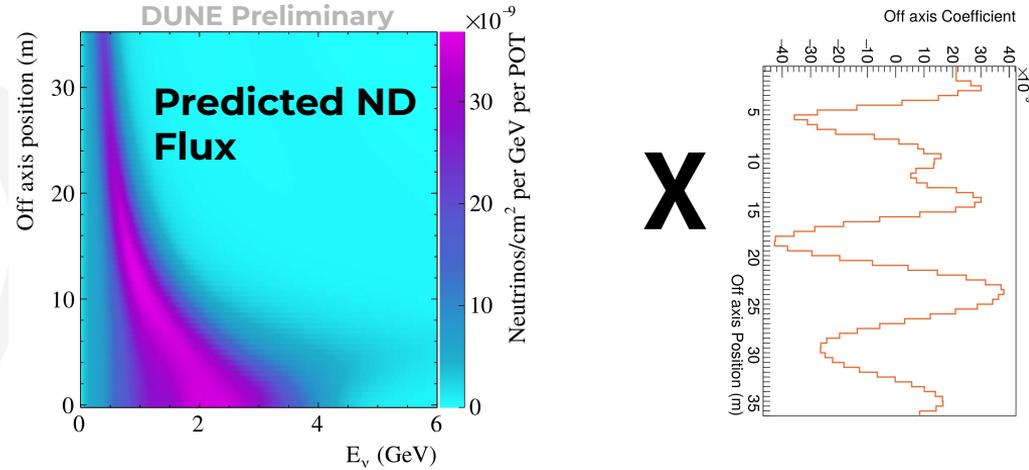
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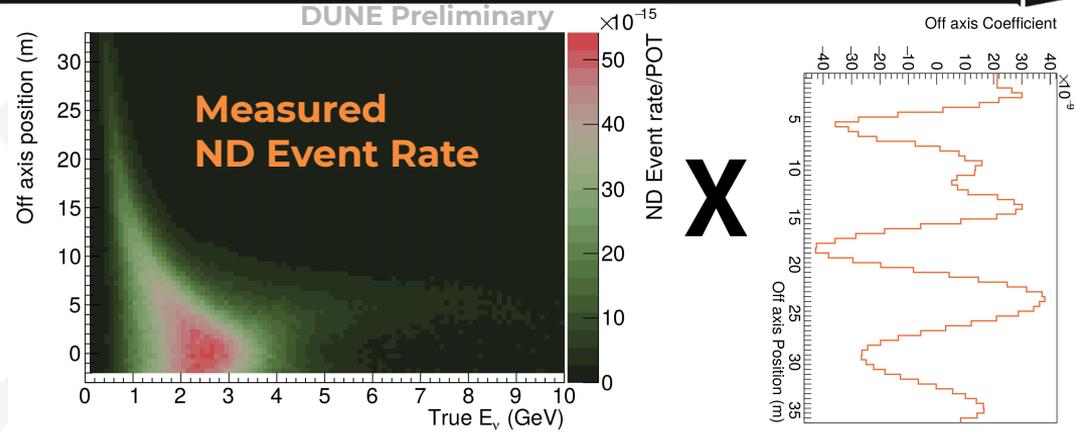
Building a far detector prediction

- **Previously:** Matching flux predictions.

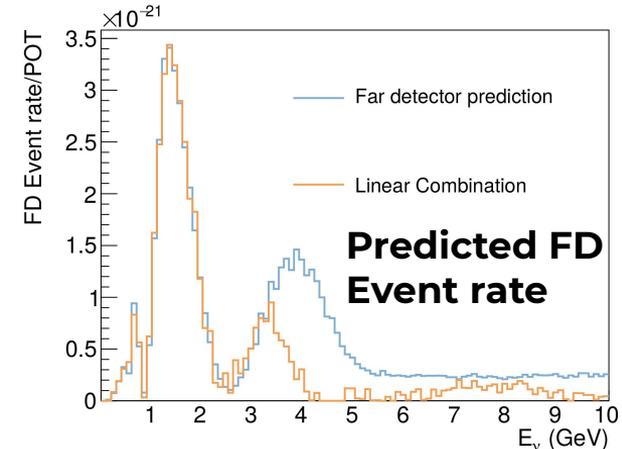


Building a far detector prediction

- Previously: Matching flux predictions.
- **Now: Predicting event rates**
- Combine measurements taken at off axis ND positions with the same coefficients.



==

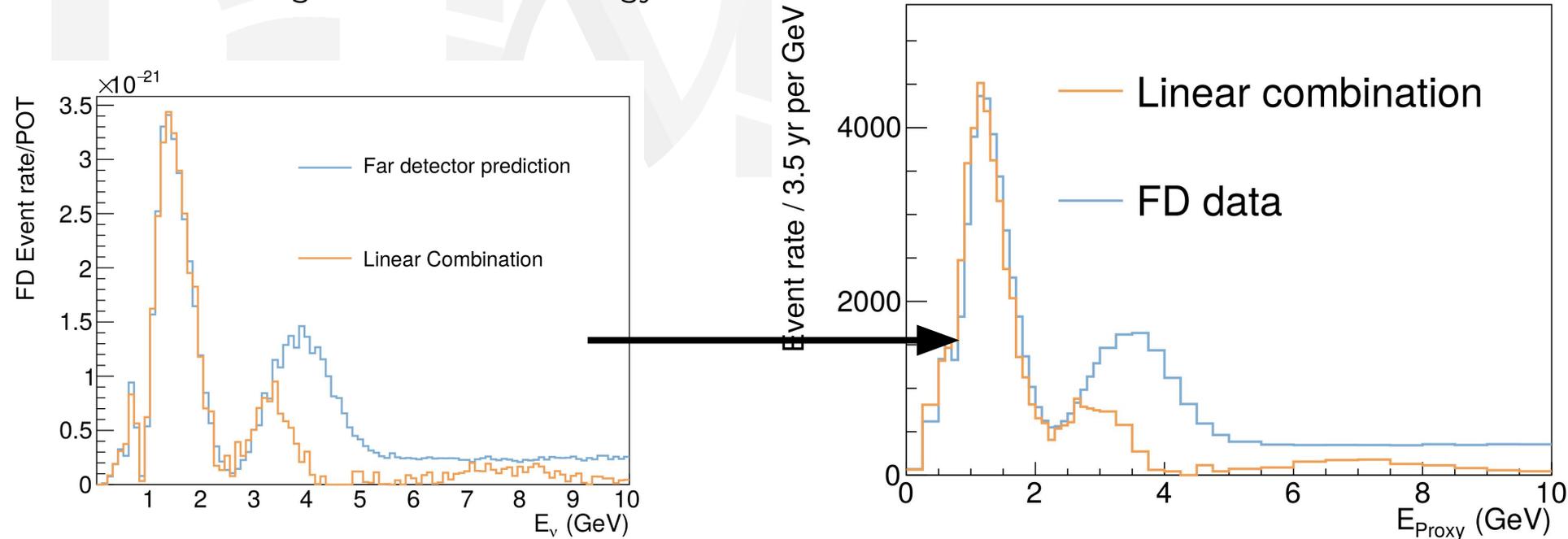


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Which observables?

- Far detector prediction built from combinations of ND data
 - So far, only used positional information to do propagation.
 - **Can build FD prediction in any ND-accessible observables!**
 - e.g. reconstructed energy

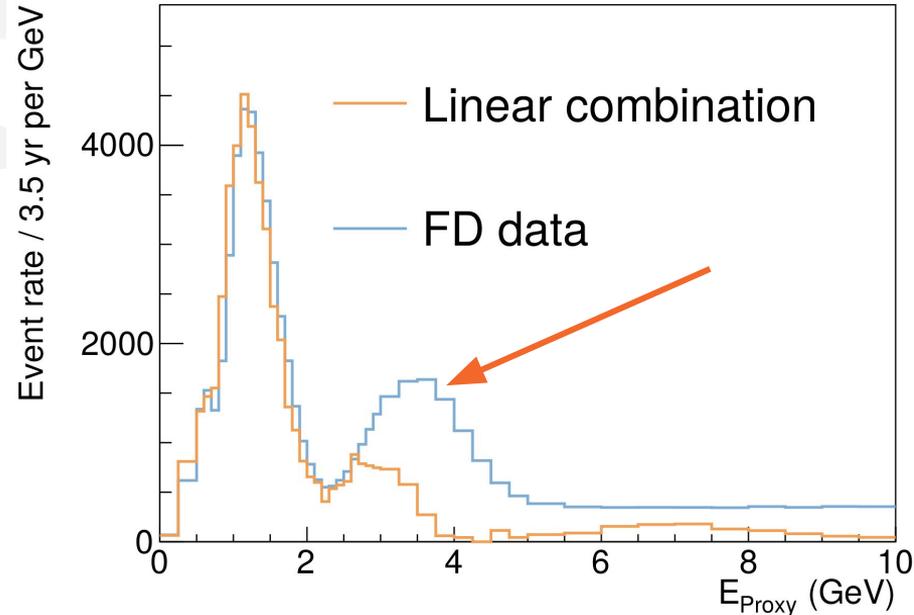


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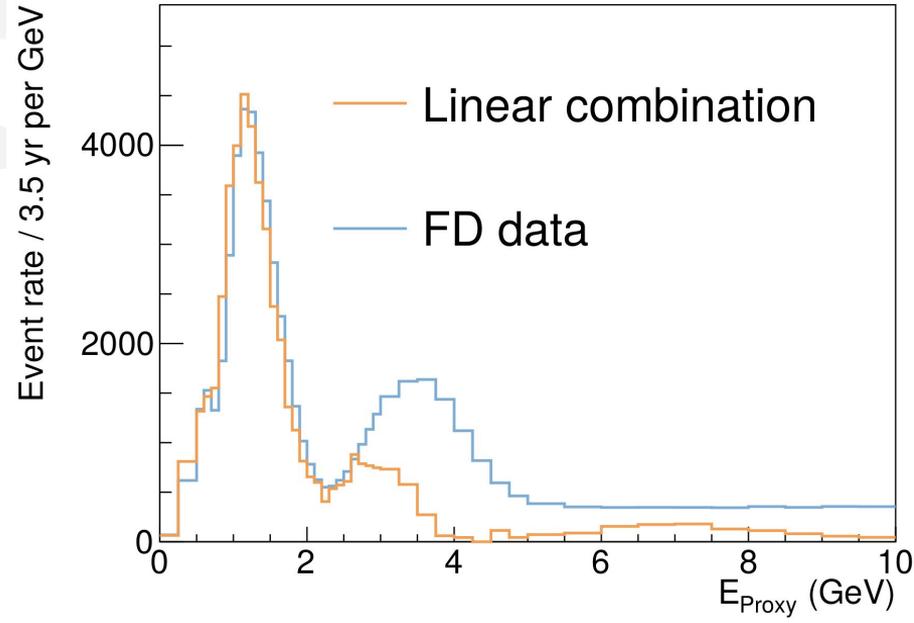
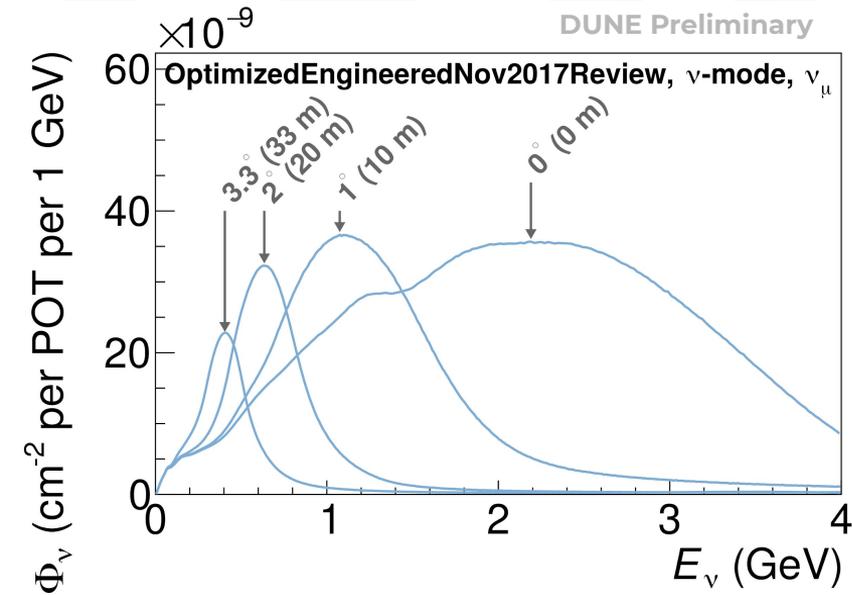
High energy flux match

- Have trouble matching flux much above the on axis peak.



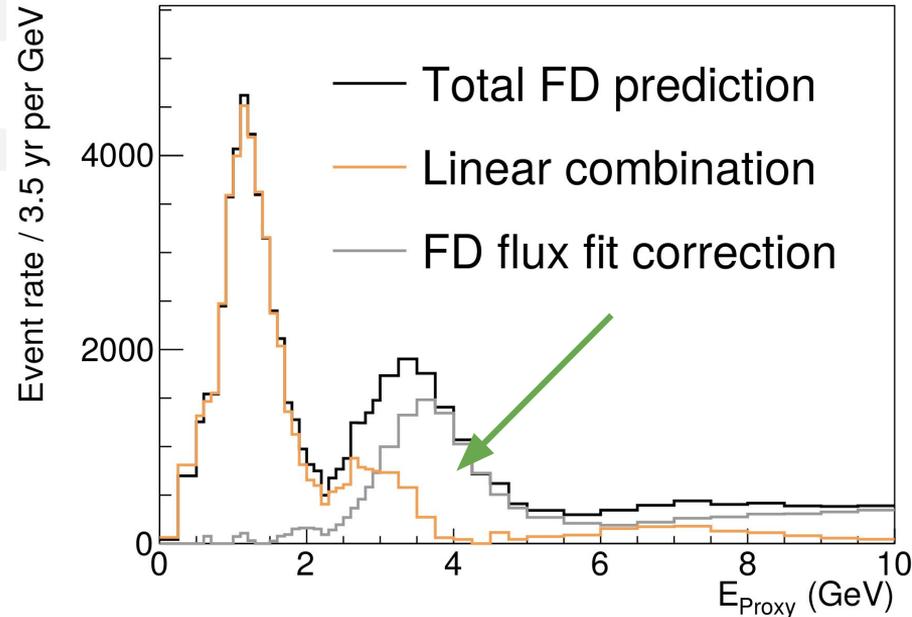
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- Have trouble matching flux much above the on axis peak.
 - **DUNE is on axis**
 - **Moving off axis lowers the peak energy**



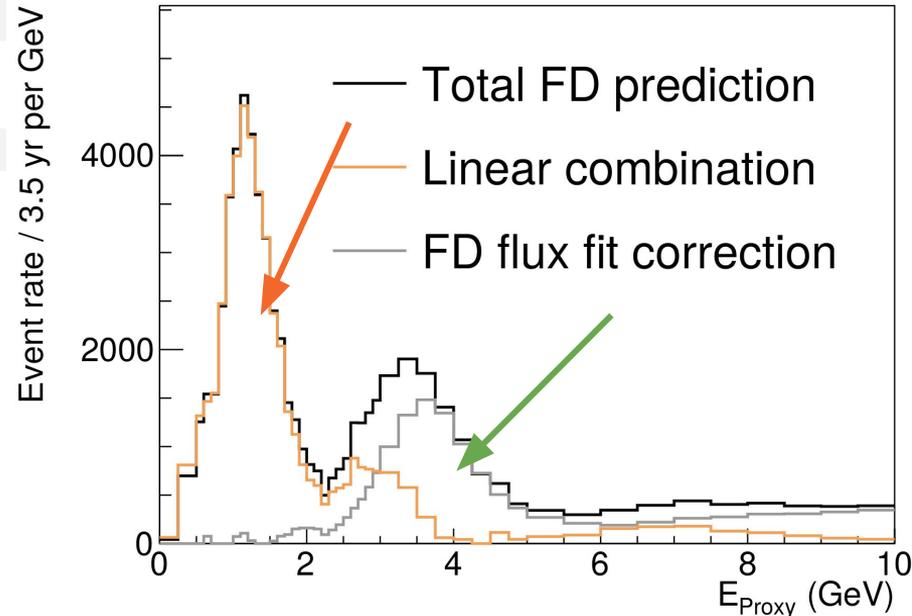
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 - **Fill in the mismatch with FD MC**



High energy flux match

- Have trouble matching flux much above the on axis peak.
 - DUNE is on axis
 - Moving off axis lowers the peak energy
 - Fill in the mismatch with FD MC
 - **Second minimum largely uncorrected**
 - **Most correction above first maximum**

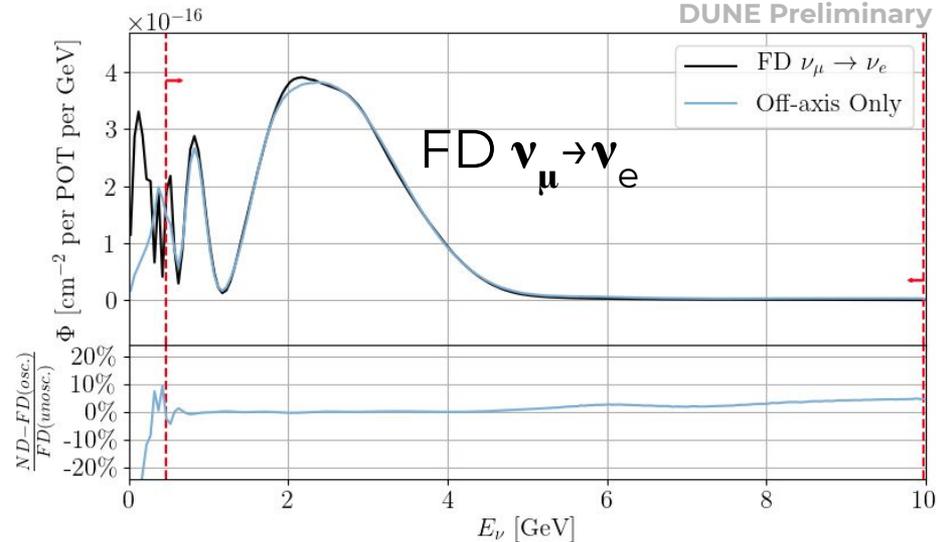
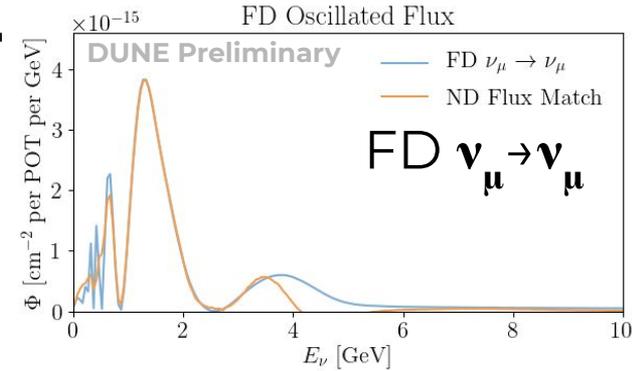


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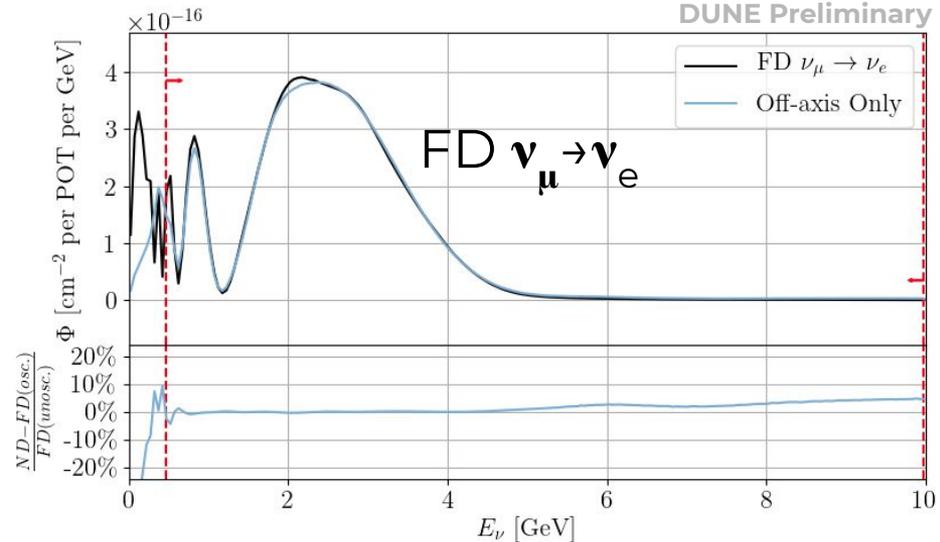
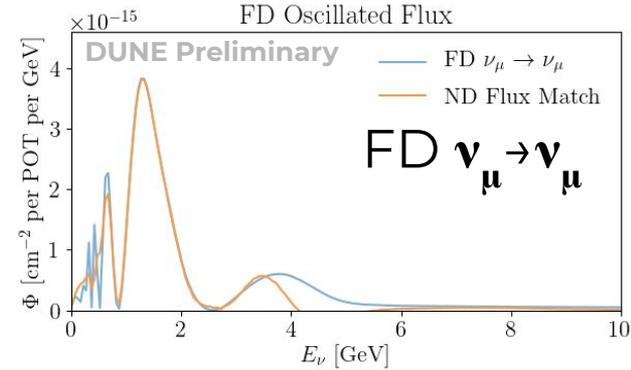
Fixing for an appearance

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



Fixing for an appearance

- For appearance, cannot match ND $\nu_e \Rightarrow$ FD ν_e
- Instead:
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- **More in a few slides...**

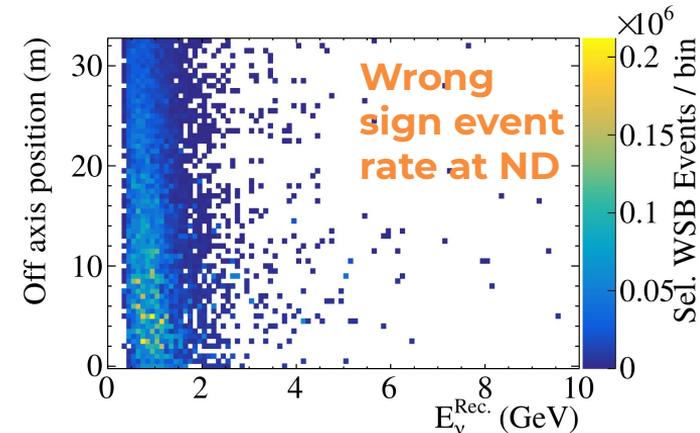
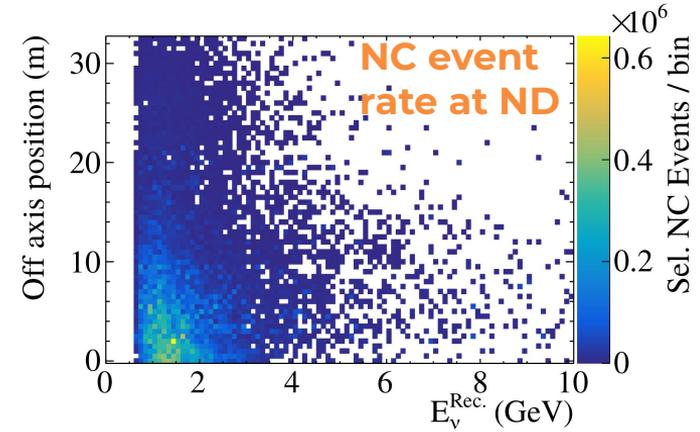


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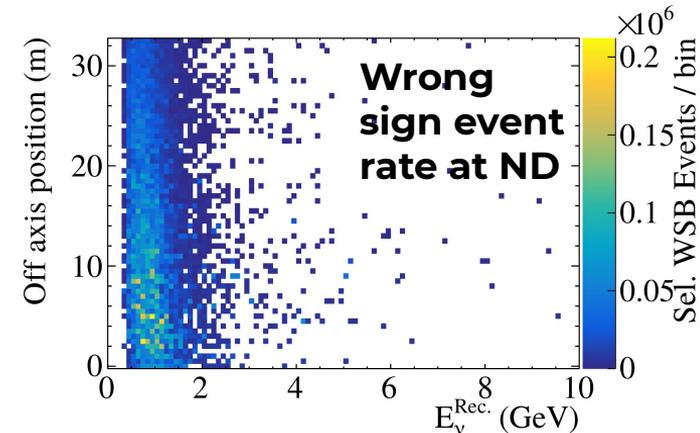
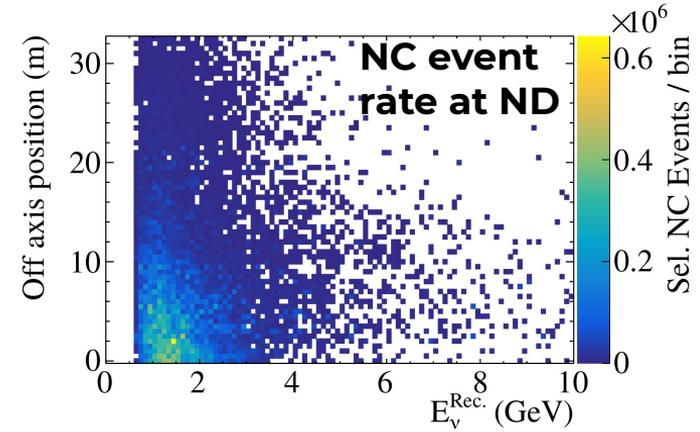
Remaining complications

- So far we have just been talking about signal, and assuming ND and FD are functionally identical.
- Extra steps needed:
 - **Subtract ND backgrounds**
 - Add FD backgrounds
 - ND/FD efficiency differences
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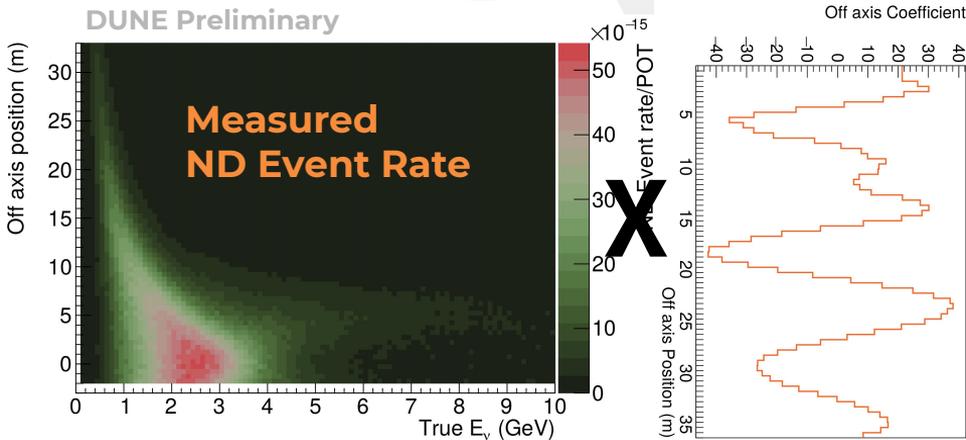
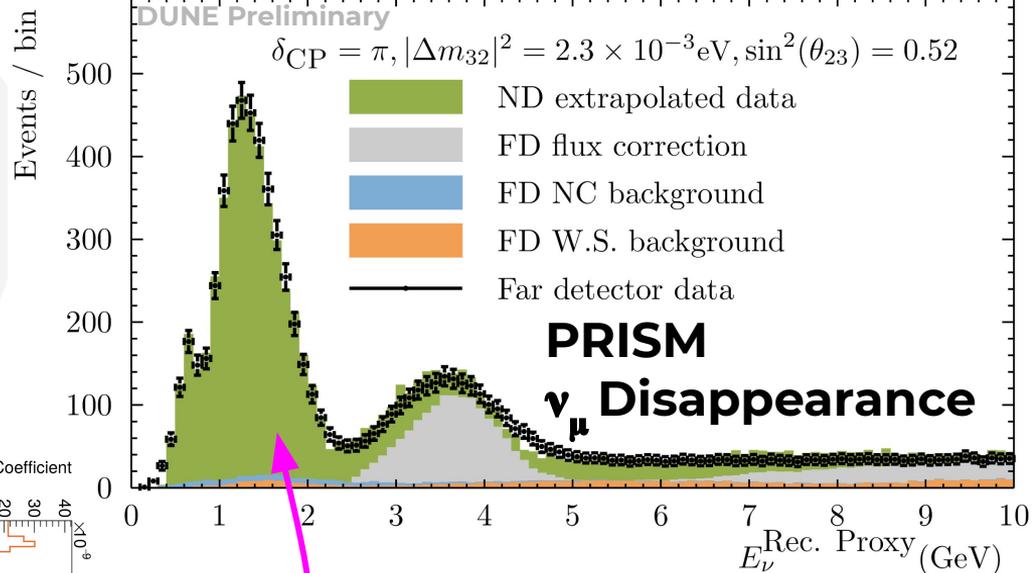
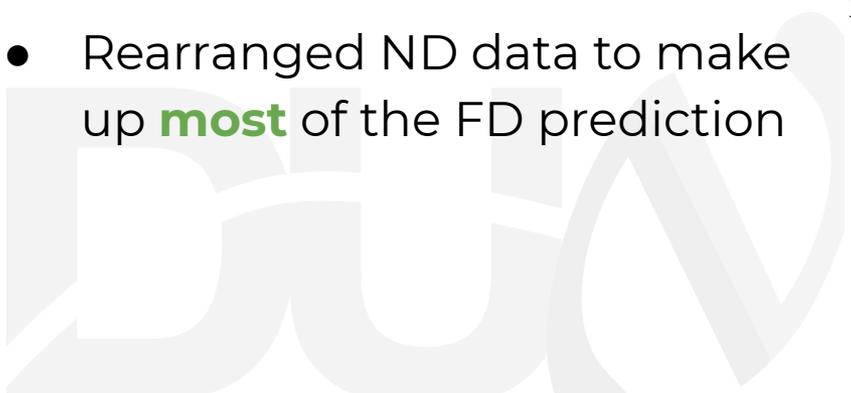
DUNE

PRISMing it all together..



The PRISM prediction

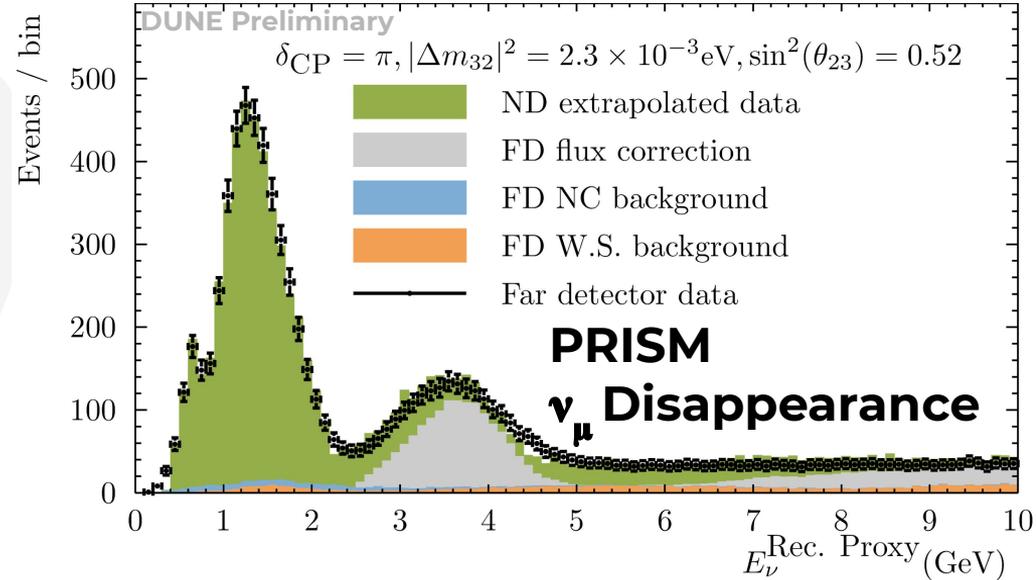
- Rearranged ND data to make up **most** of the FD prediction



≡

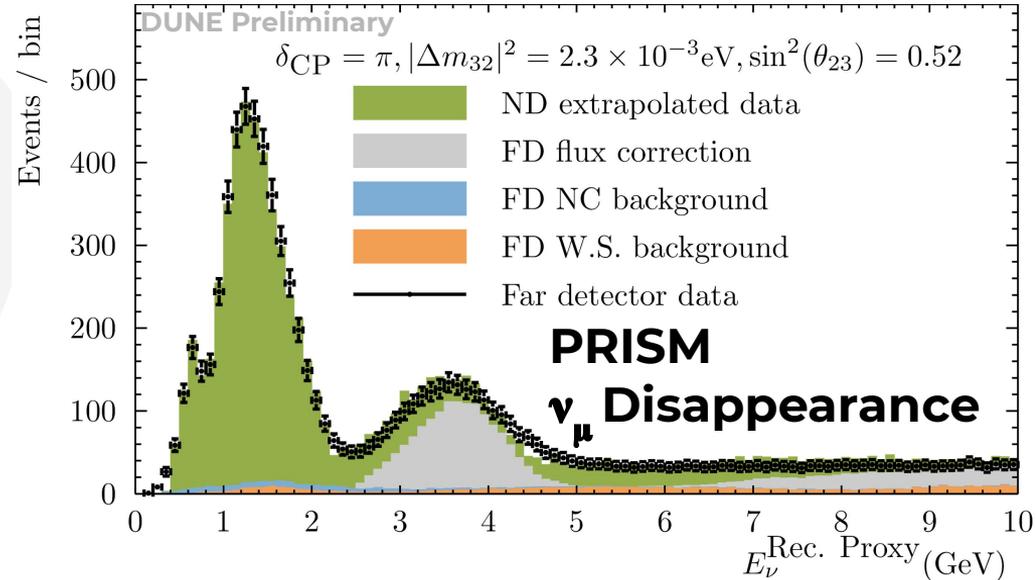
The PRISM prediction

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 - PRISM extrapolation translates unknown modelling errors from ND to FD!
 - Do not require a satisfactory model fit at the ND to do this!



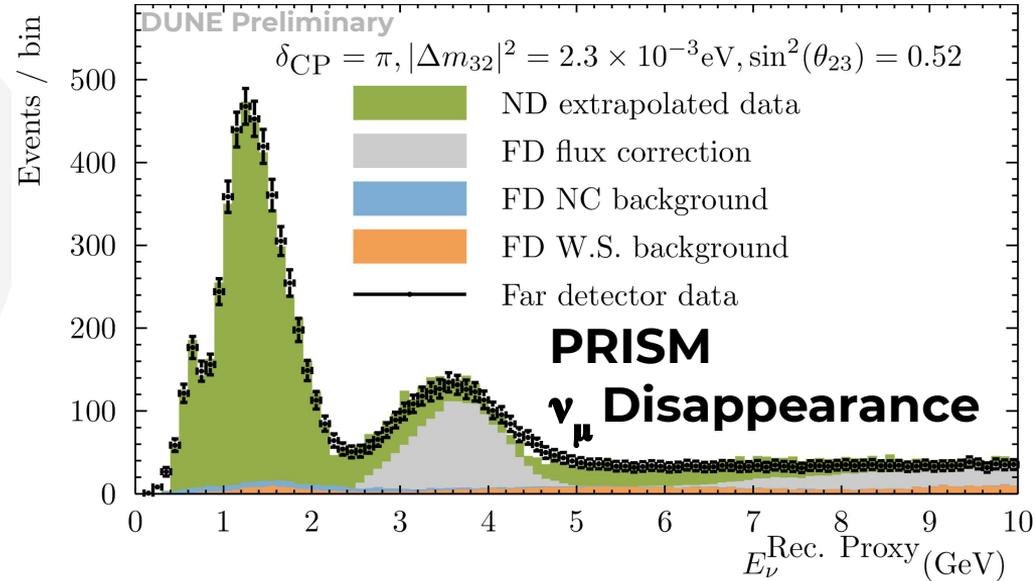
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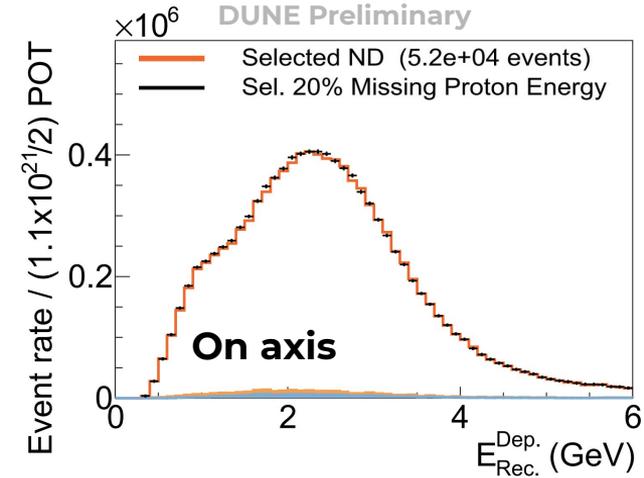
- **We will return to the grey blob in a few slides.**

Okay, so now for the power

- What if the model is wrong and you missed it?
- Can imagine a world where the ND data fits well but $E_{\text{True}}^{\nu} \Rightarrow E_{\text{Obs}}^{\nu}$ is wrong.

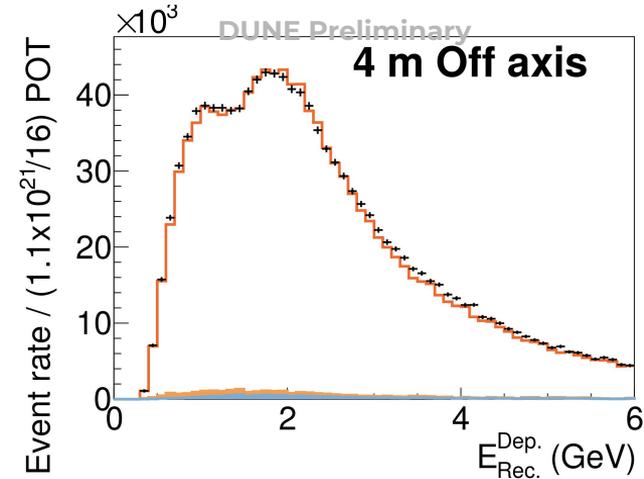
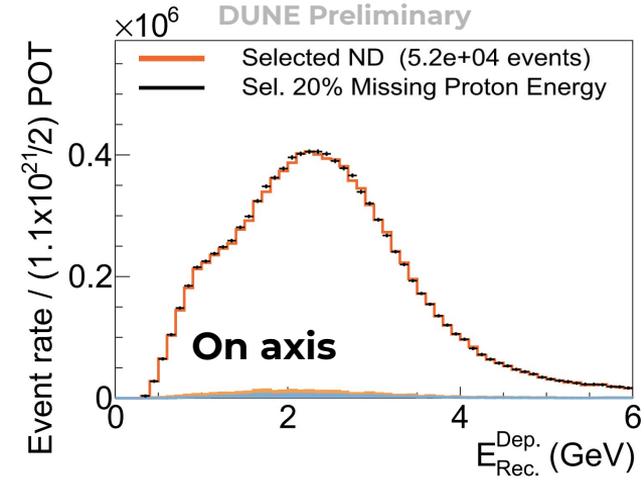
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 - Move 20% of proton KE to neutrons but on-axis ND fit still works well



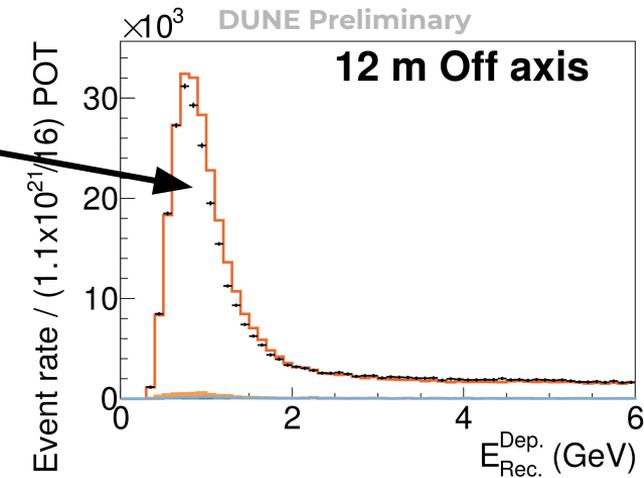
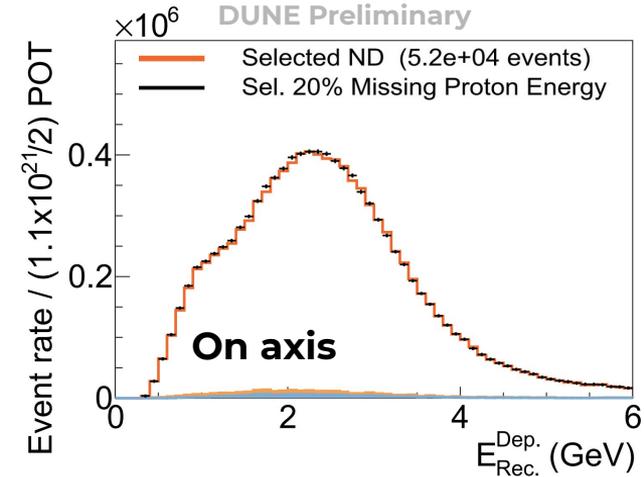
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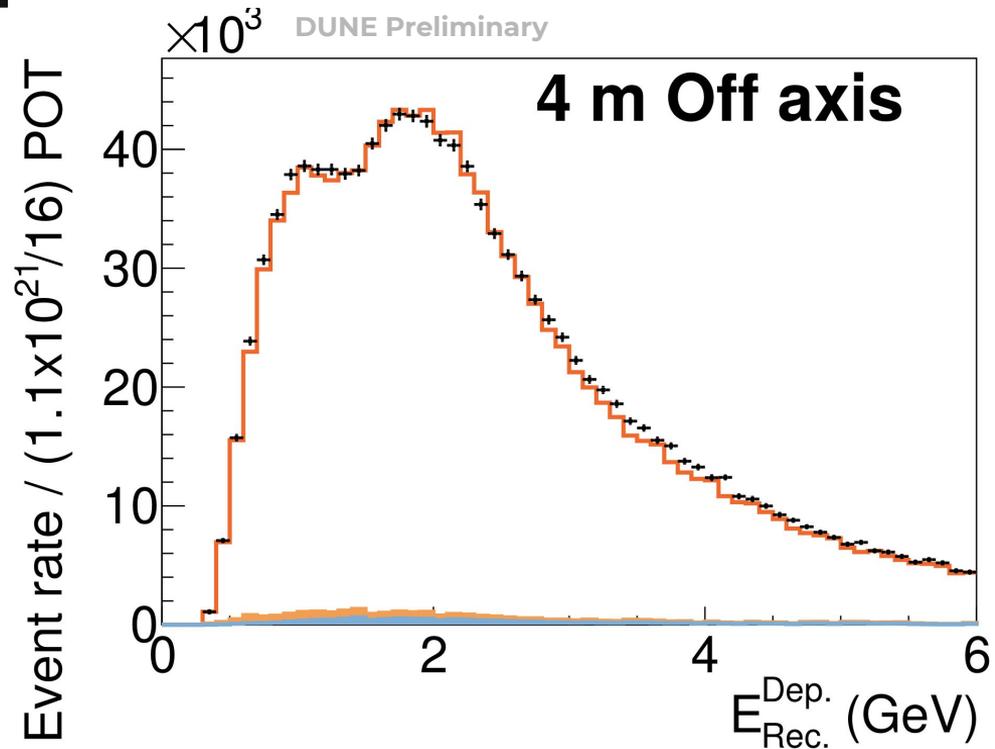
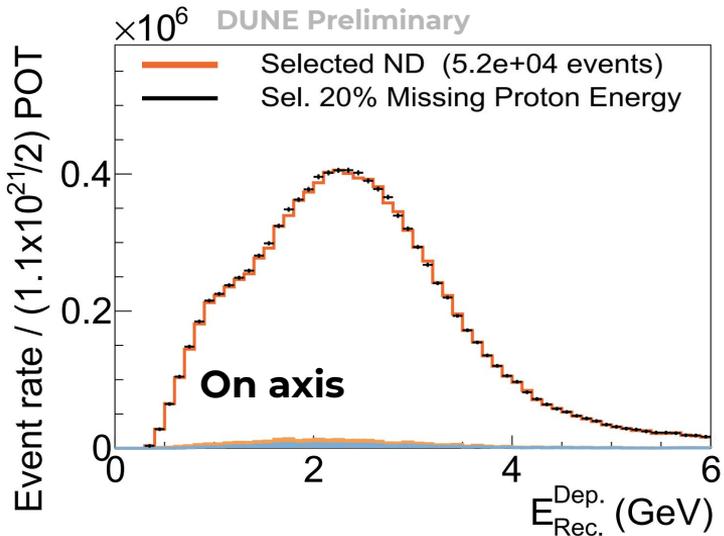


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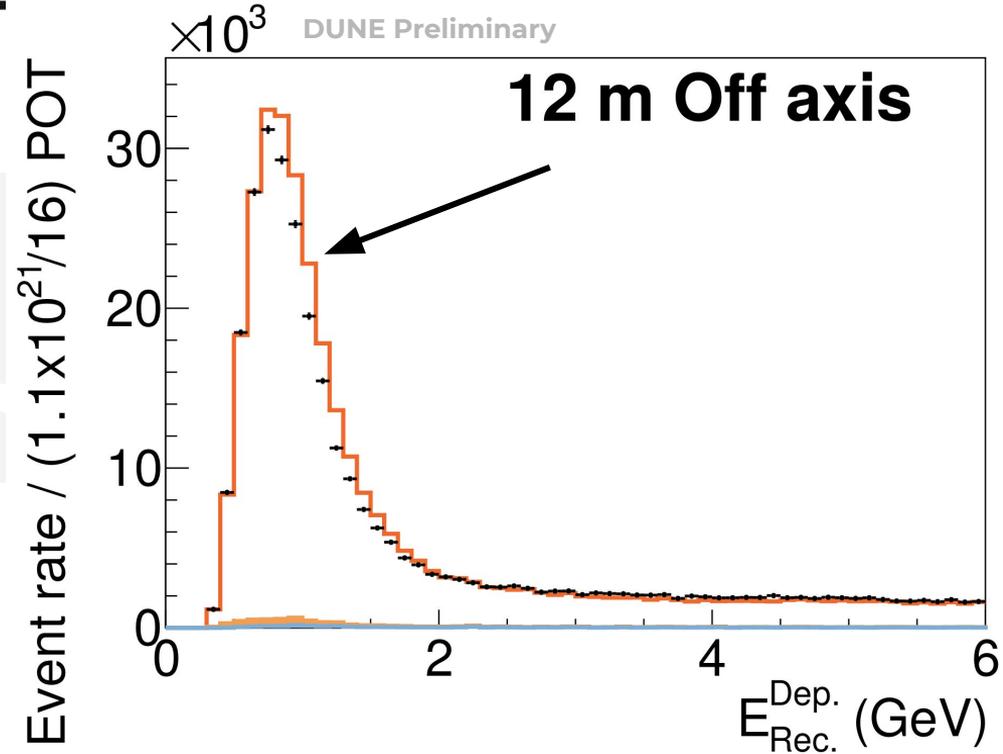
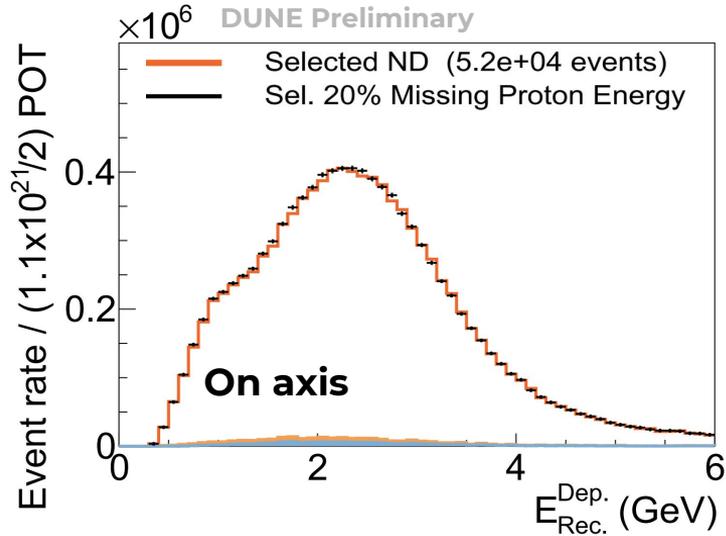
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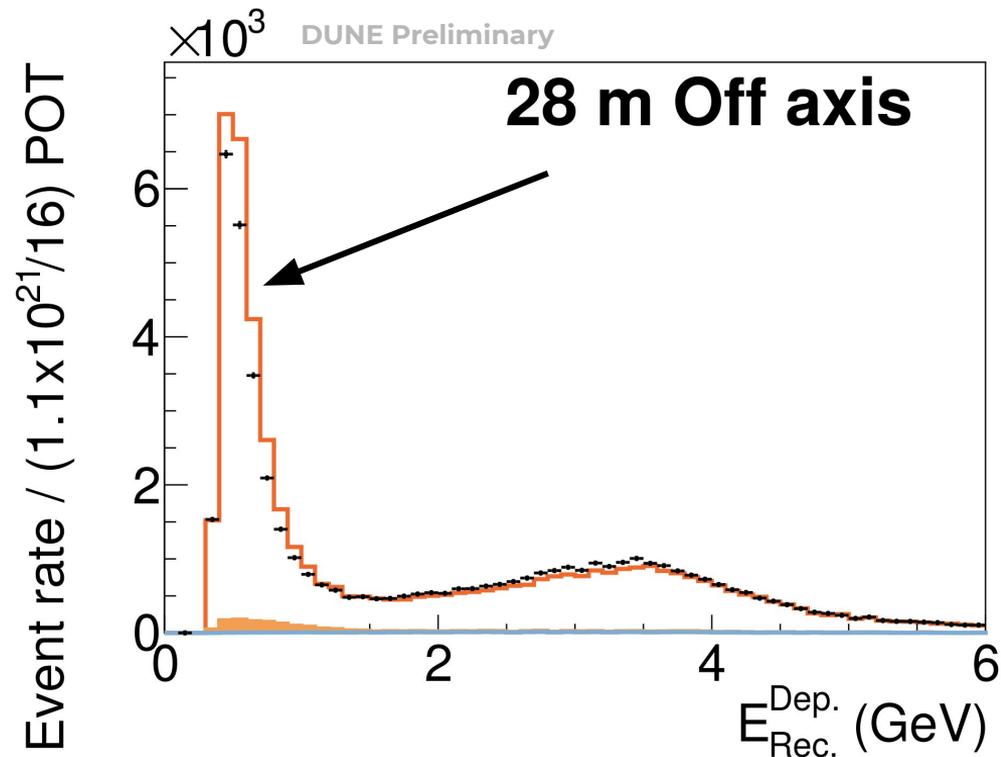
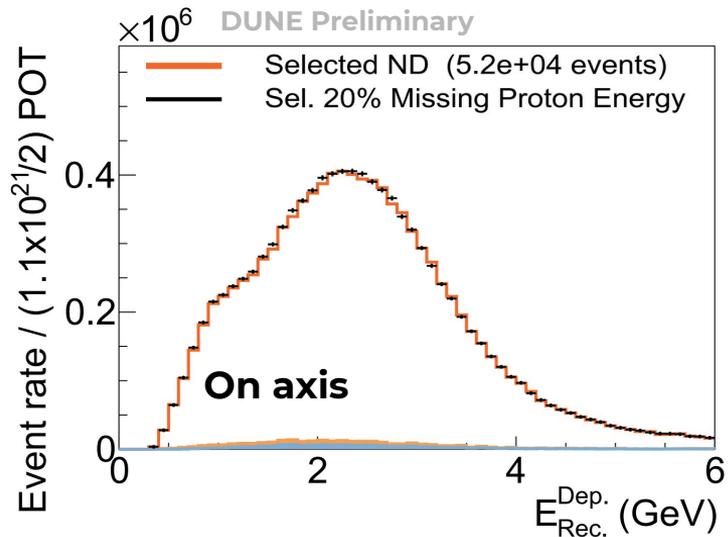
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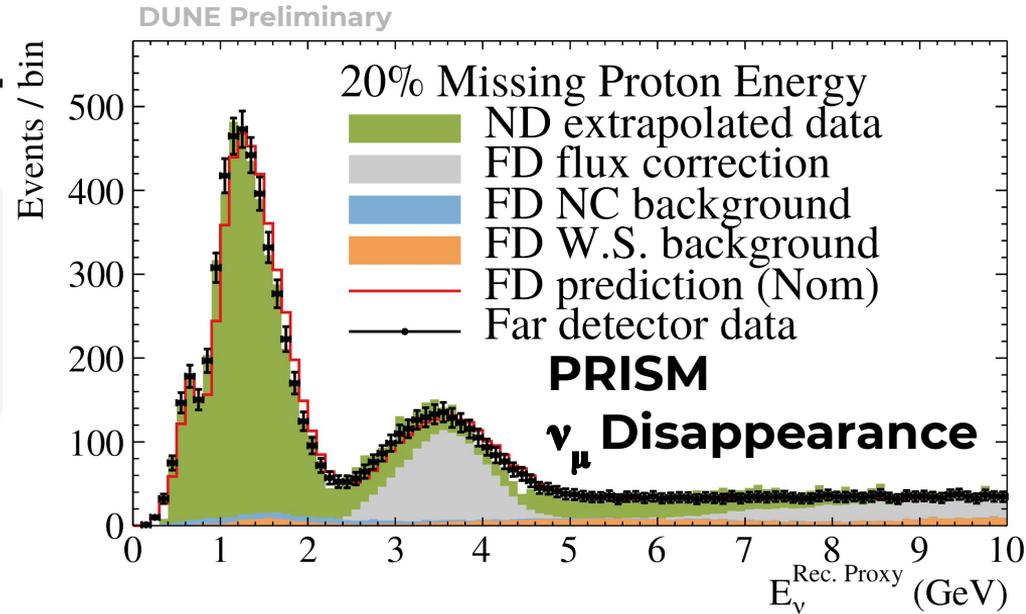


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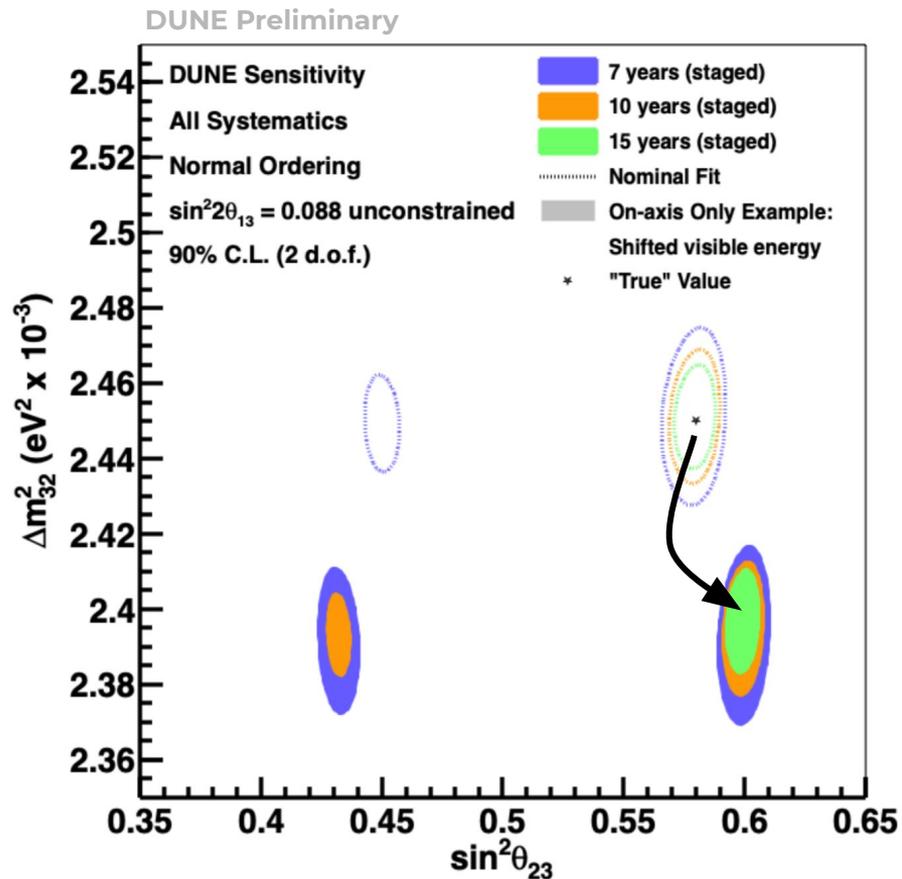
PRISM Prediction

- The ND and FD 'data' has this missing proton energy applied:
 - MC corrections don't
- **PRISM does its job!** Get the feed-down correct by using the ND data!
 - **Without invoking a cross-section model!**



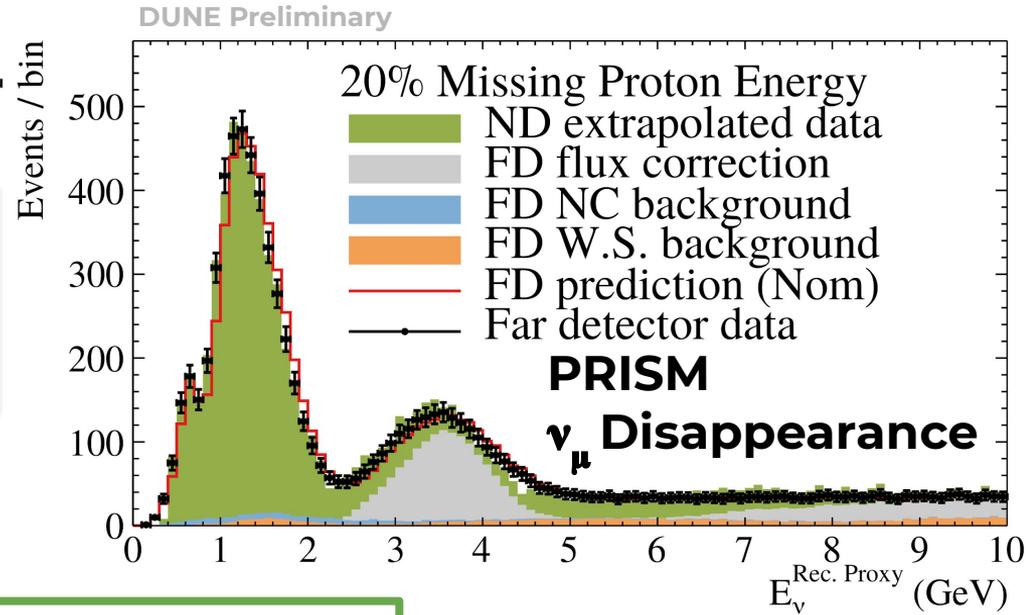
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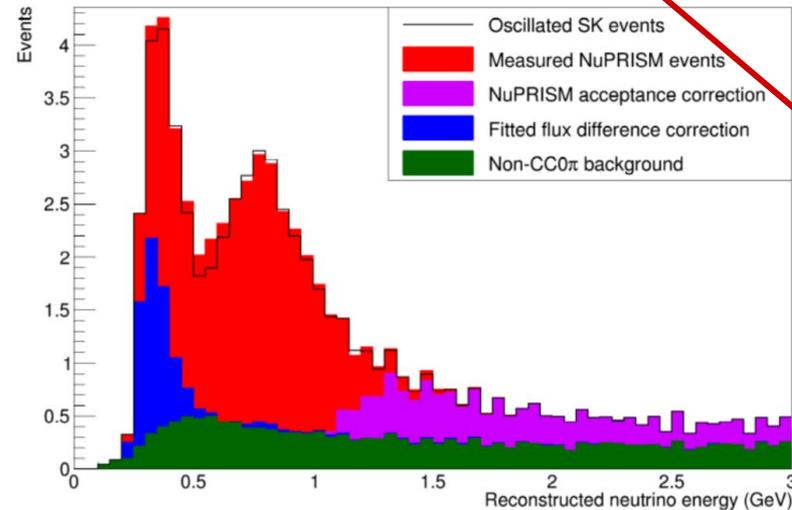
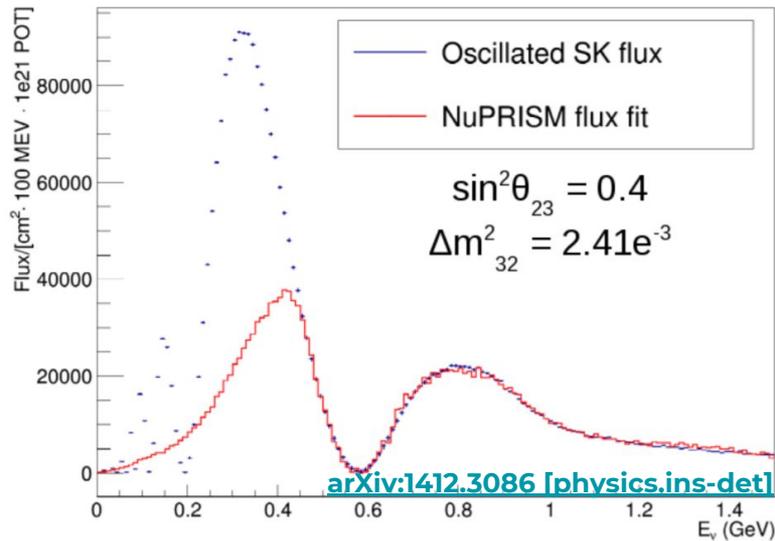
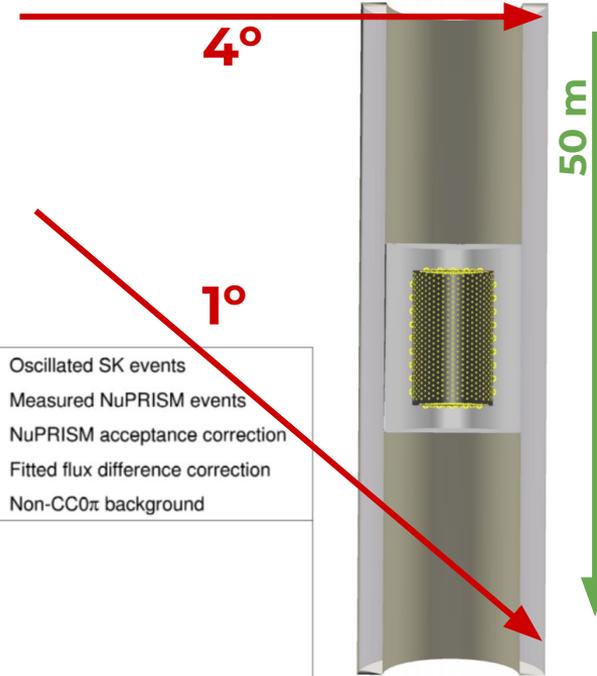


This is why I think PRISM is worth doing!

ν PRISM



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



DUNE

Pre-emptive Answers to Questions



Expected Questions

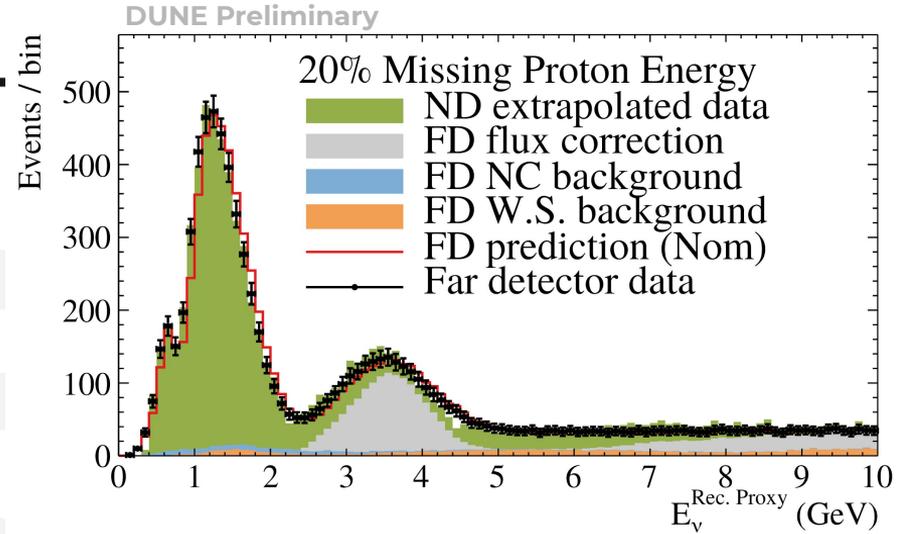
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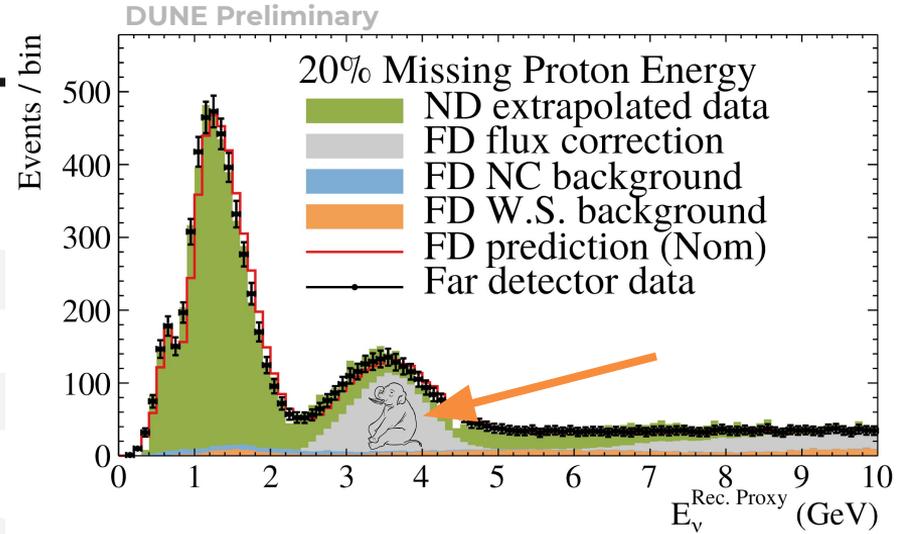
Flux Misfit Correction

- Elephant in the room



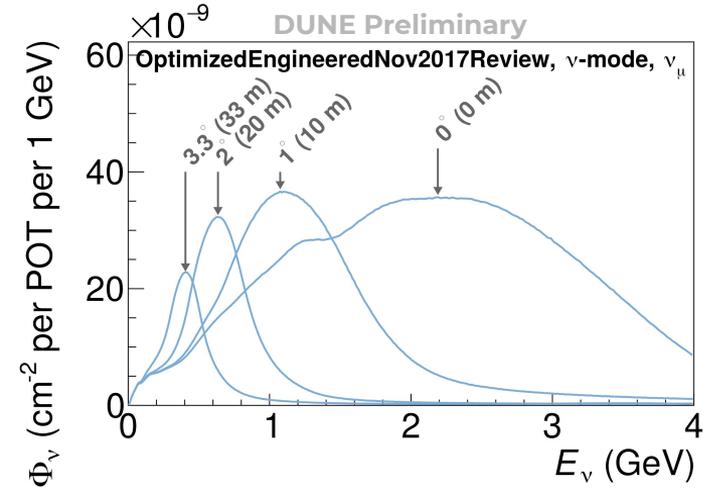
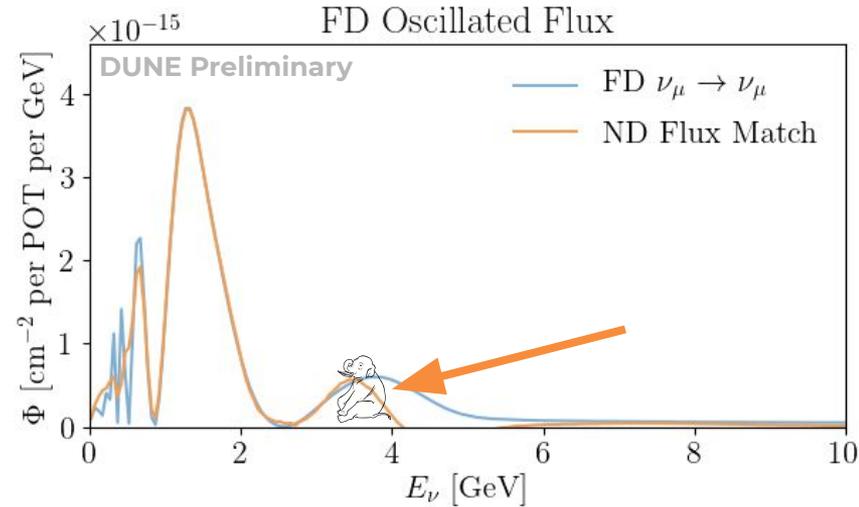
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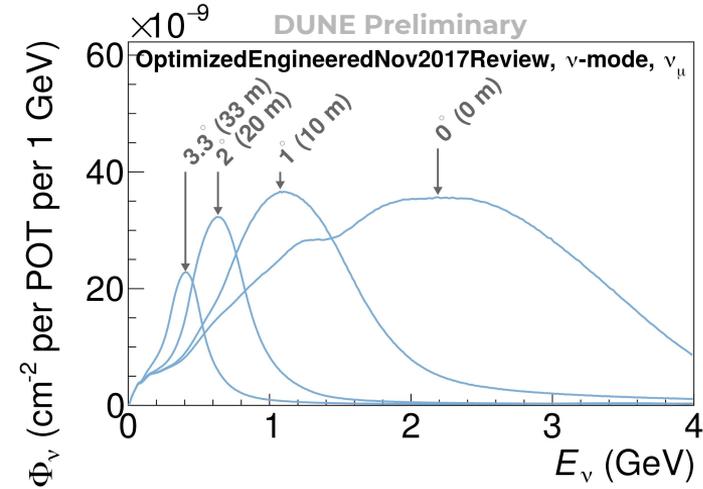
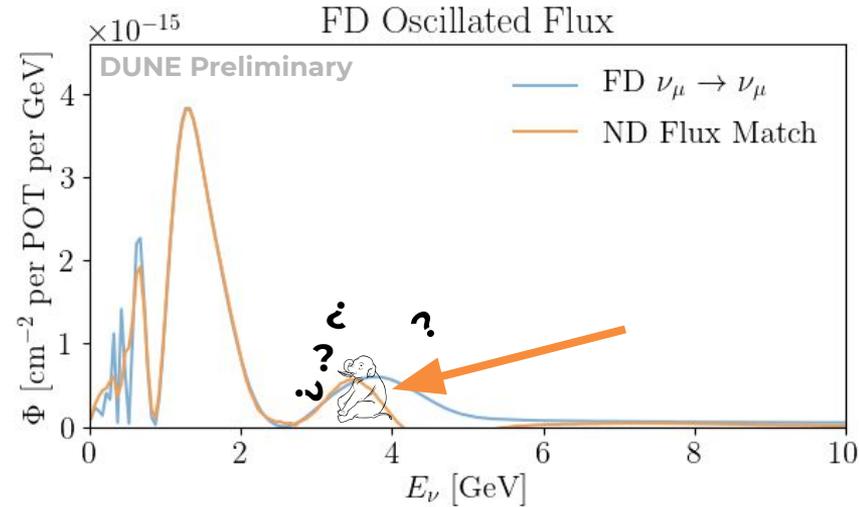
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- **Remember:** This happens because no fluxes peak higher than the on-axis flux



Flux Misfit Correction

- Elephant in the room
- Remember: This happens because no fluxes peak higher than the on-axis flux
- **But what if we used some that did?**



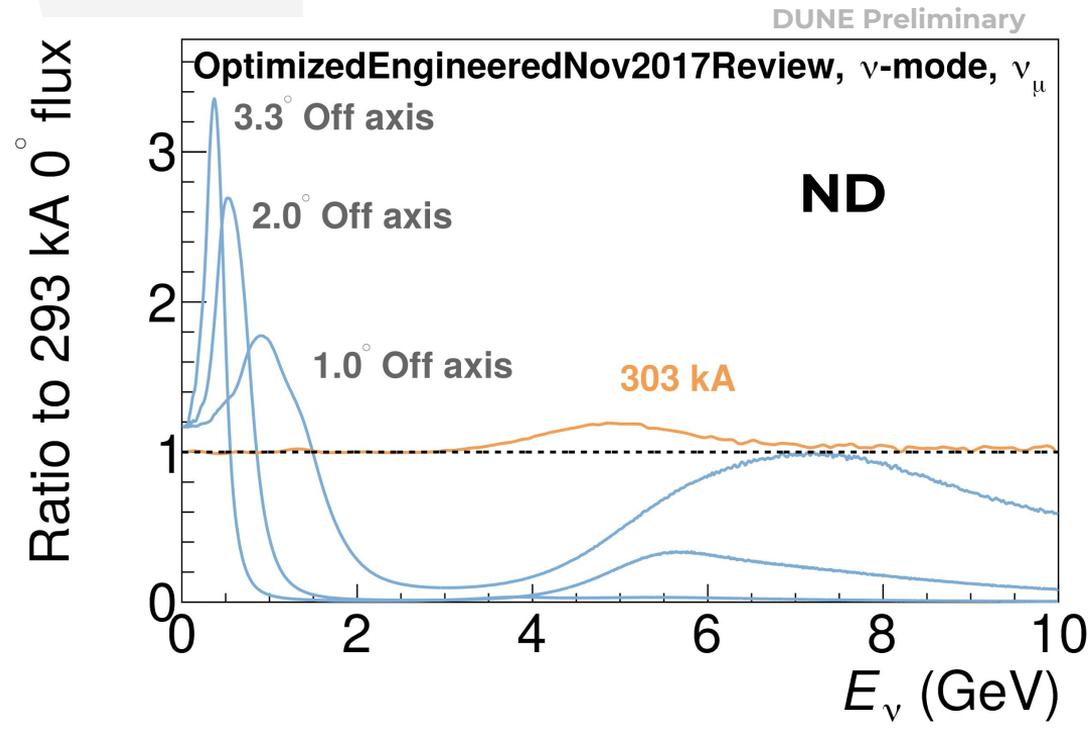
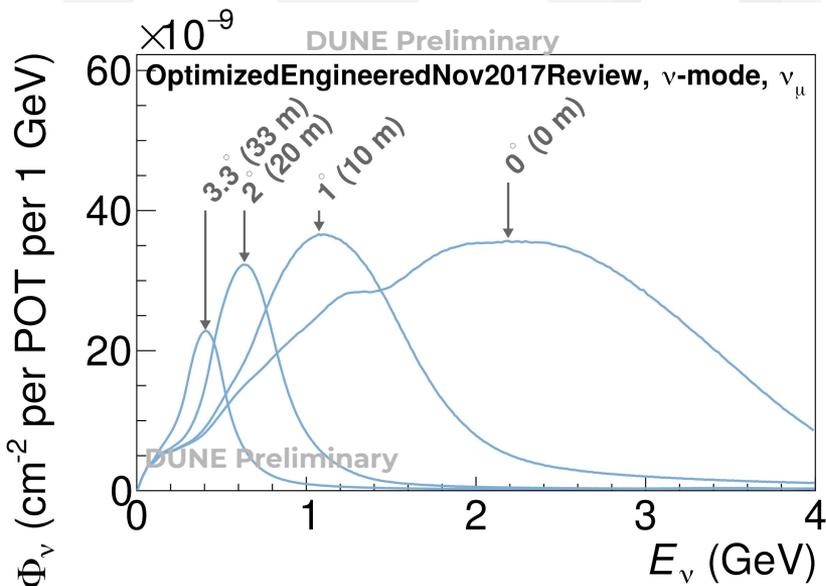
Special Horn Current Runs

- Can make flux predictions under different beam conditions:
 - e.g. Varied horn currents

DUNE

Special Horn Current Runs

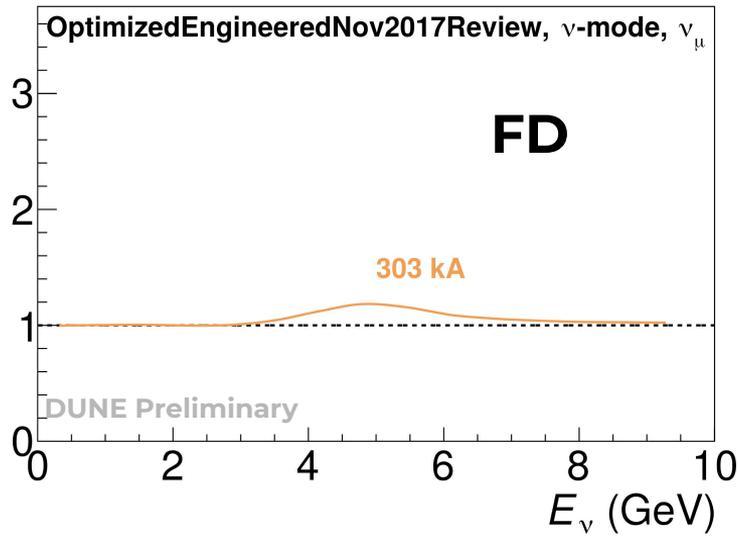
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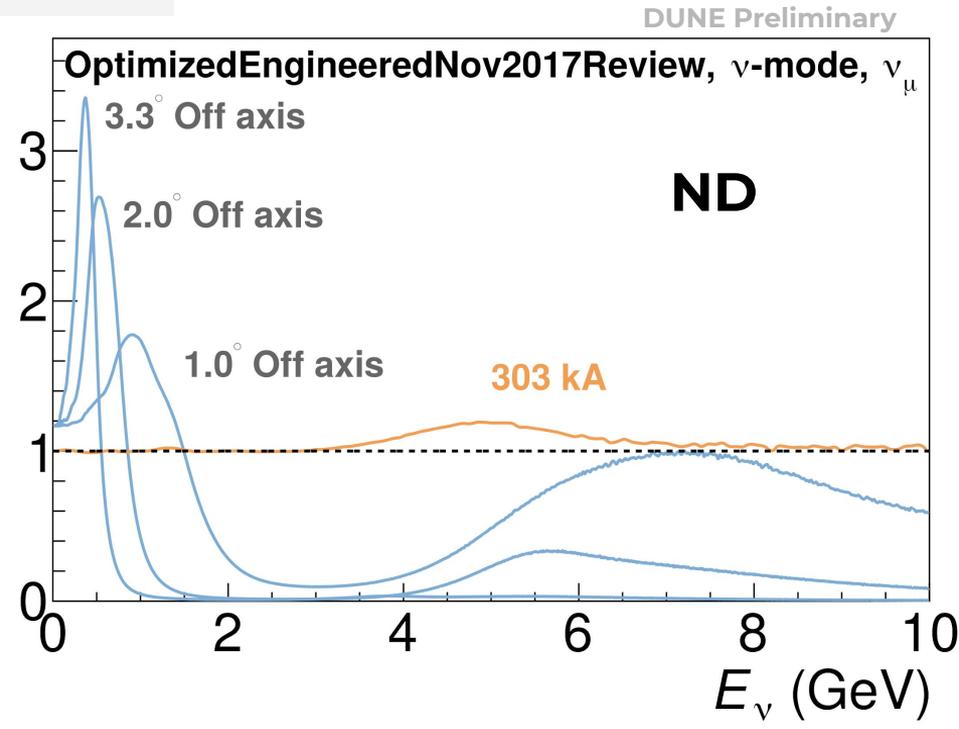
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Ratio to 293 kA FD flux

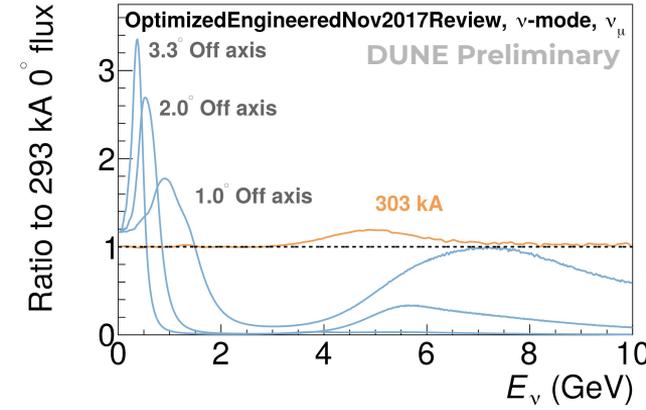
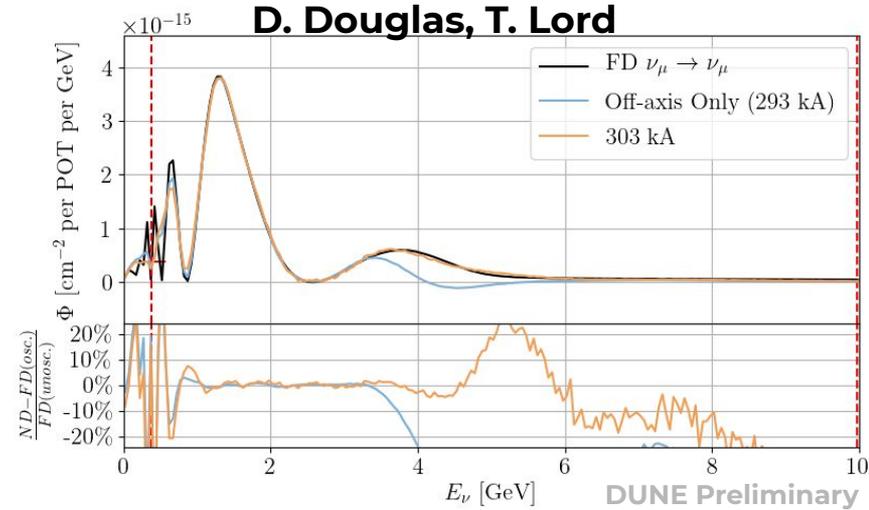


Ratio to 293 kA 0° flux



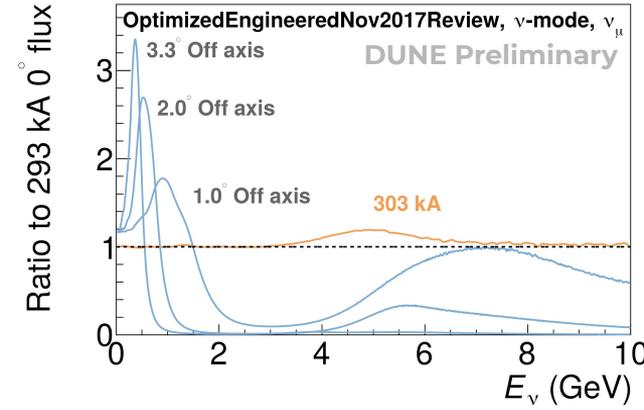
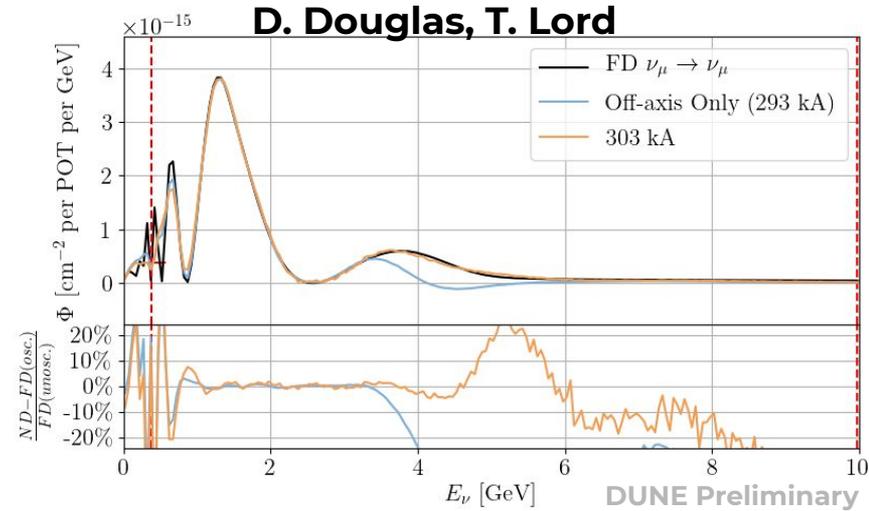
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Special Horn Current Runs

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- Seems to really change the game in terms of reducing the need for FD MC!
- Only need a single extra on-axis sample: **minimal disruption of FD data taking.**

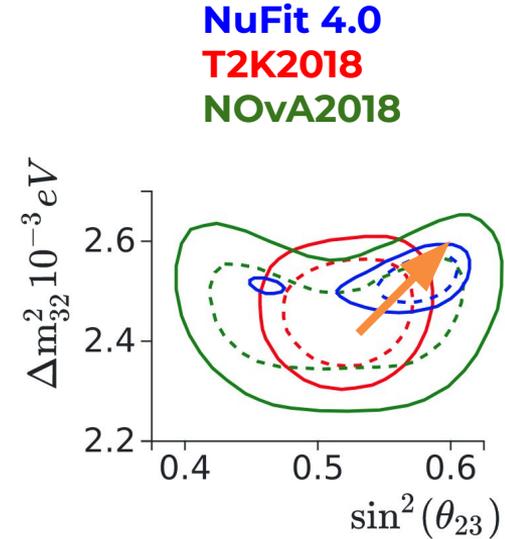
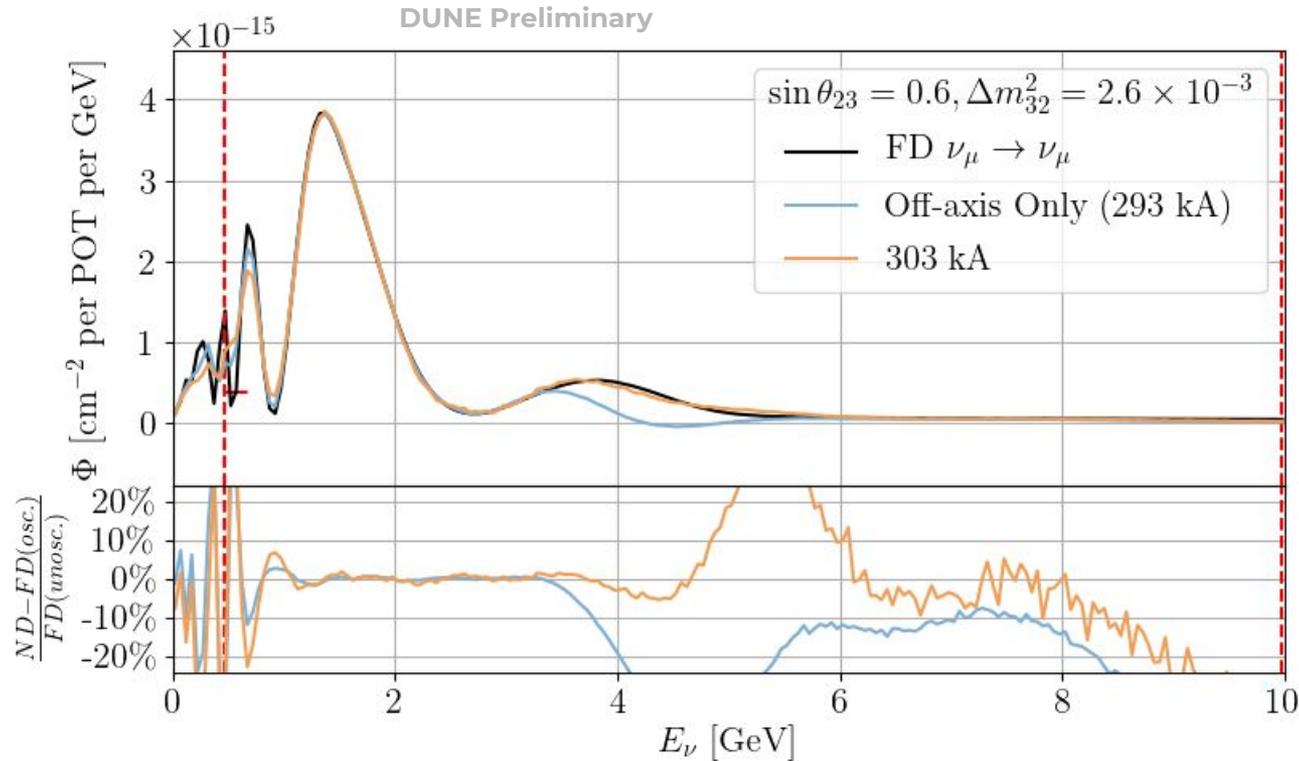


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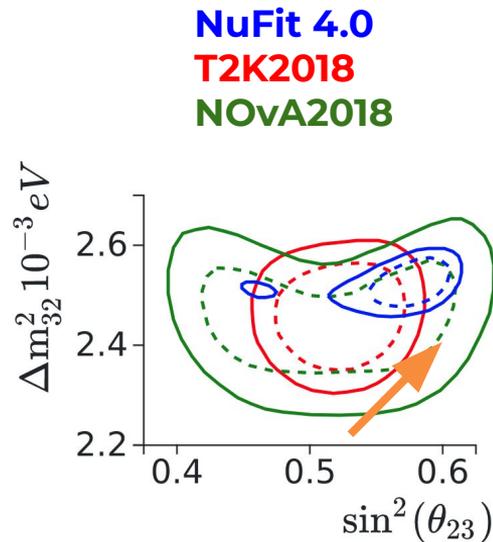
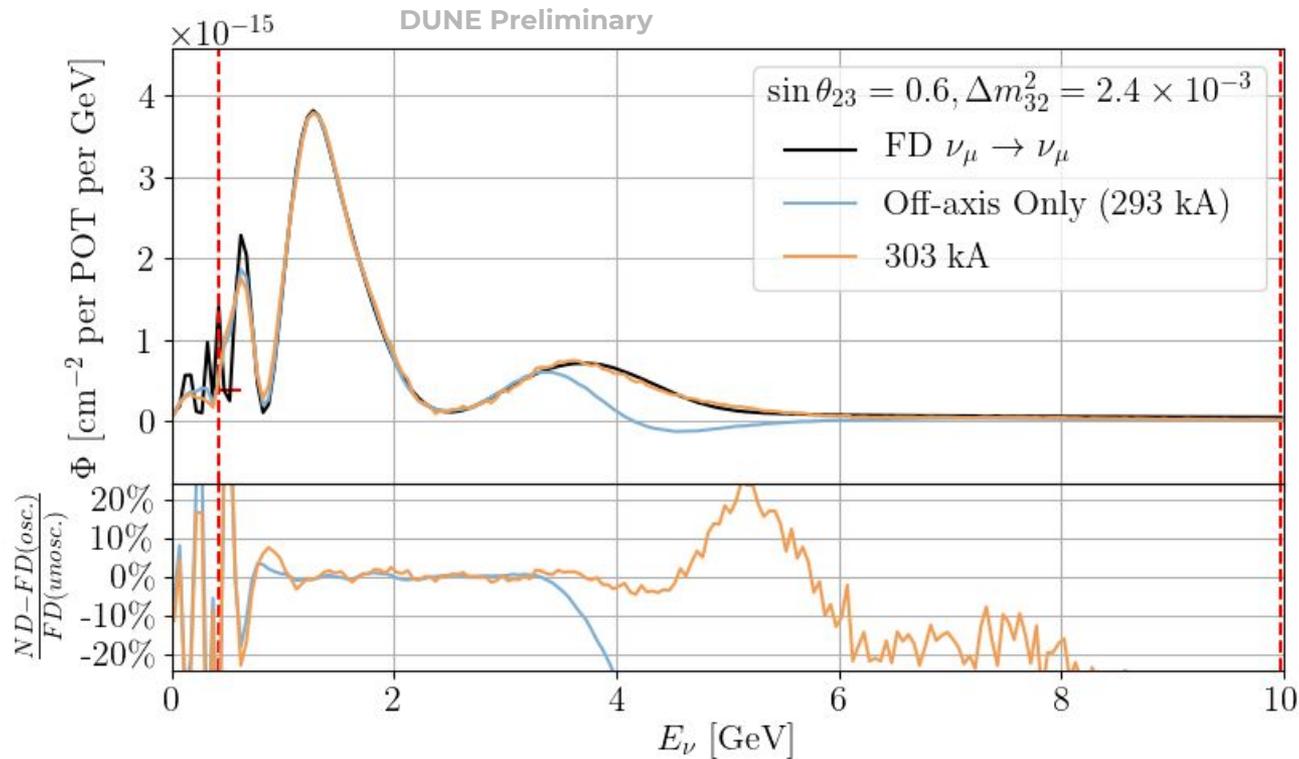
Does it work everywhere?

[Try it yourself!](#)



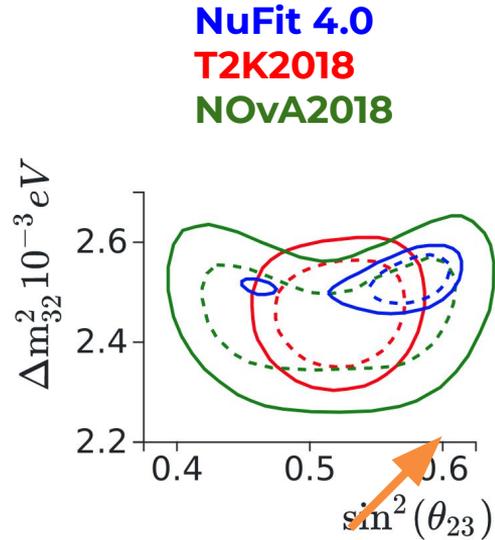
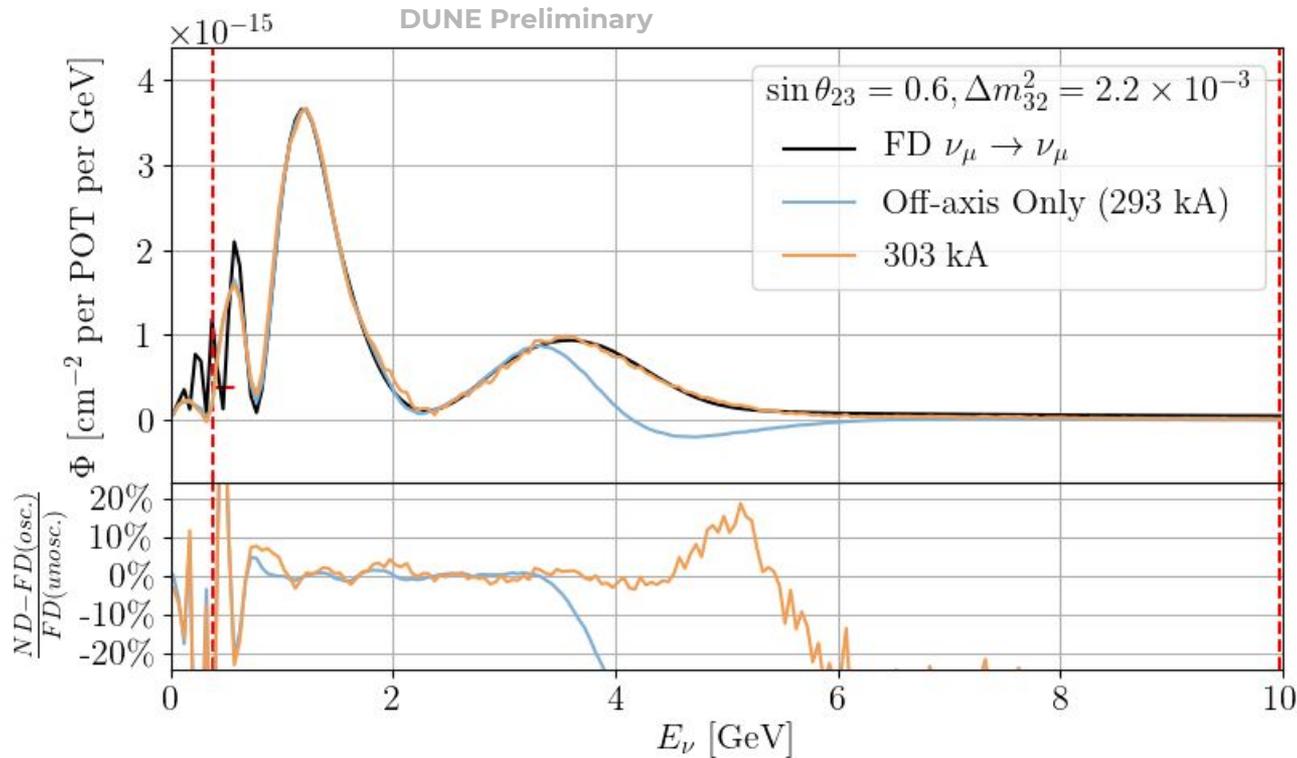
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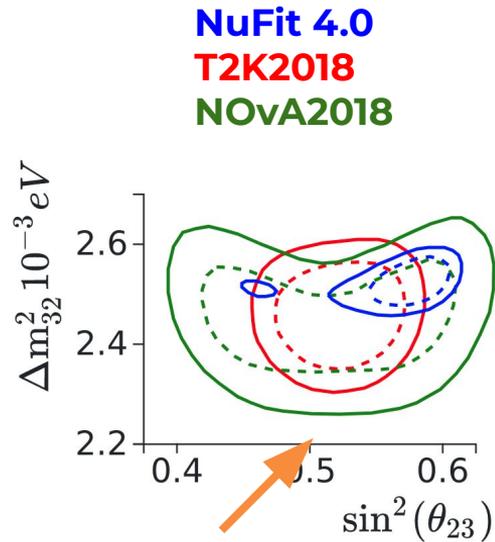
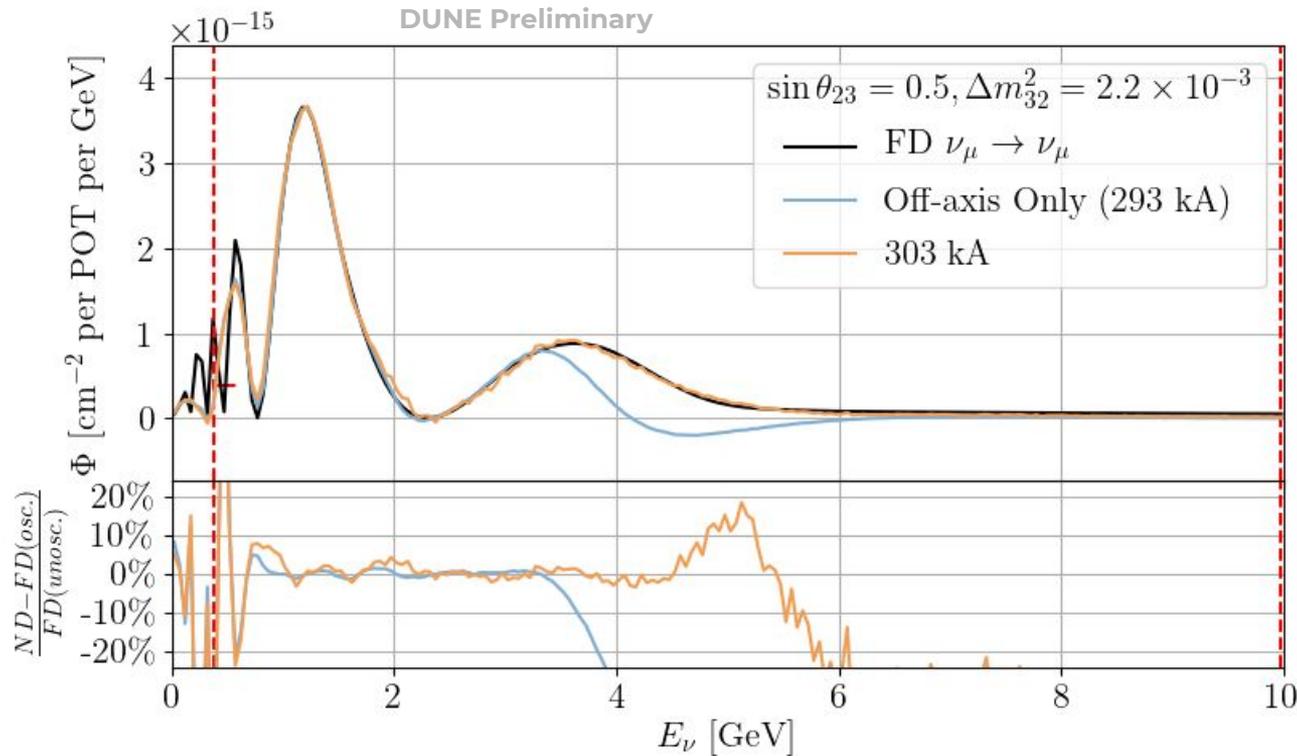
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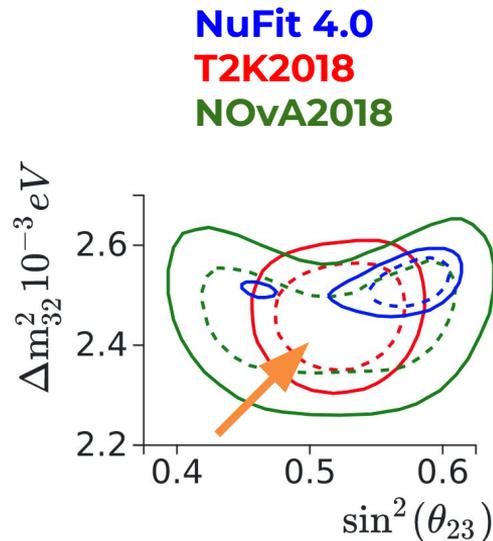
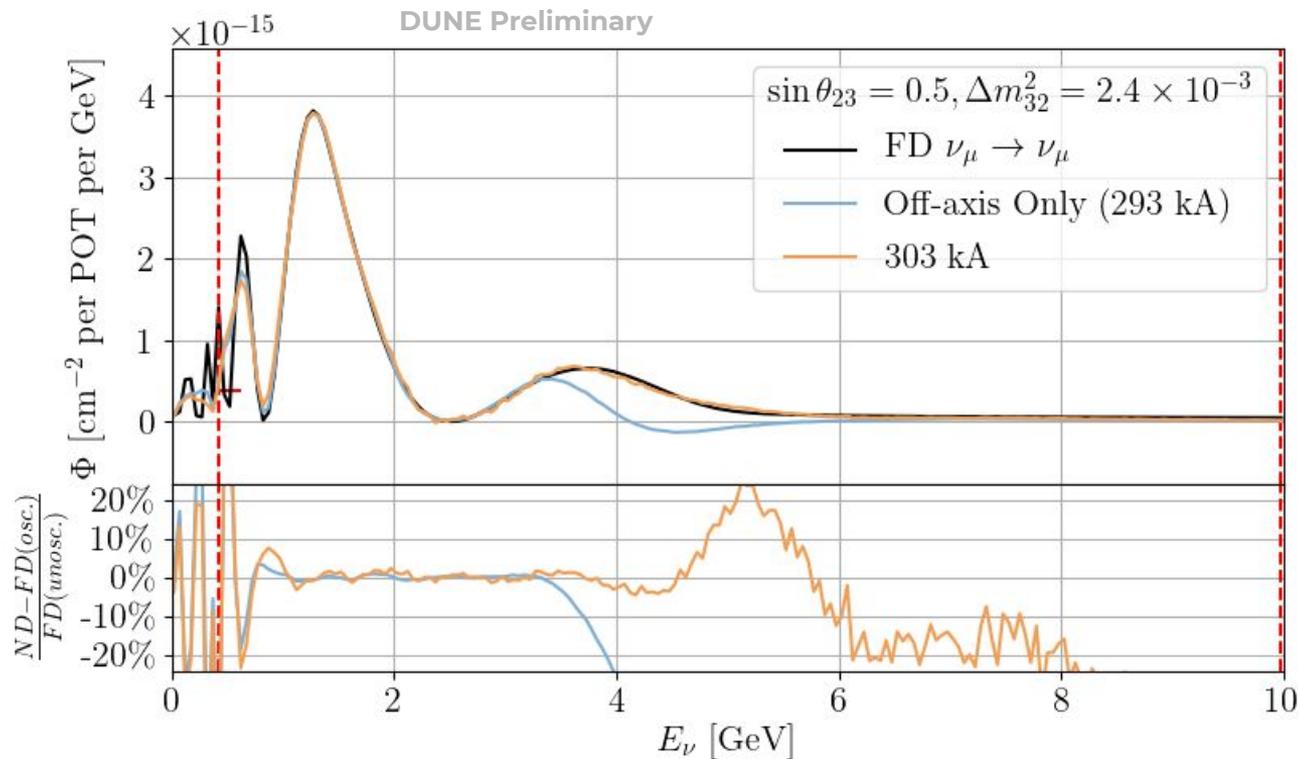
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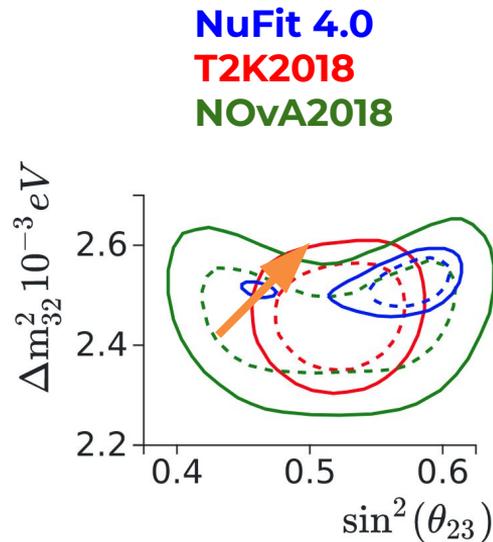
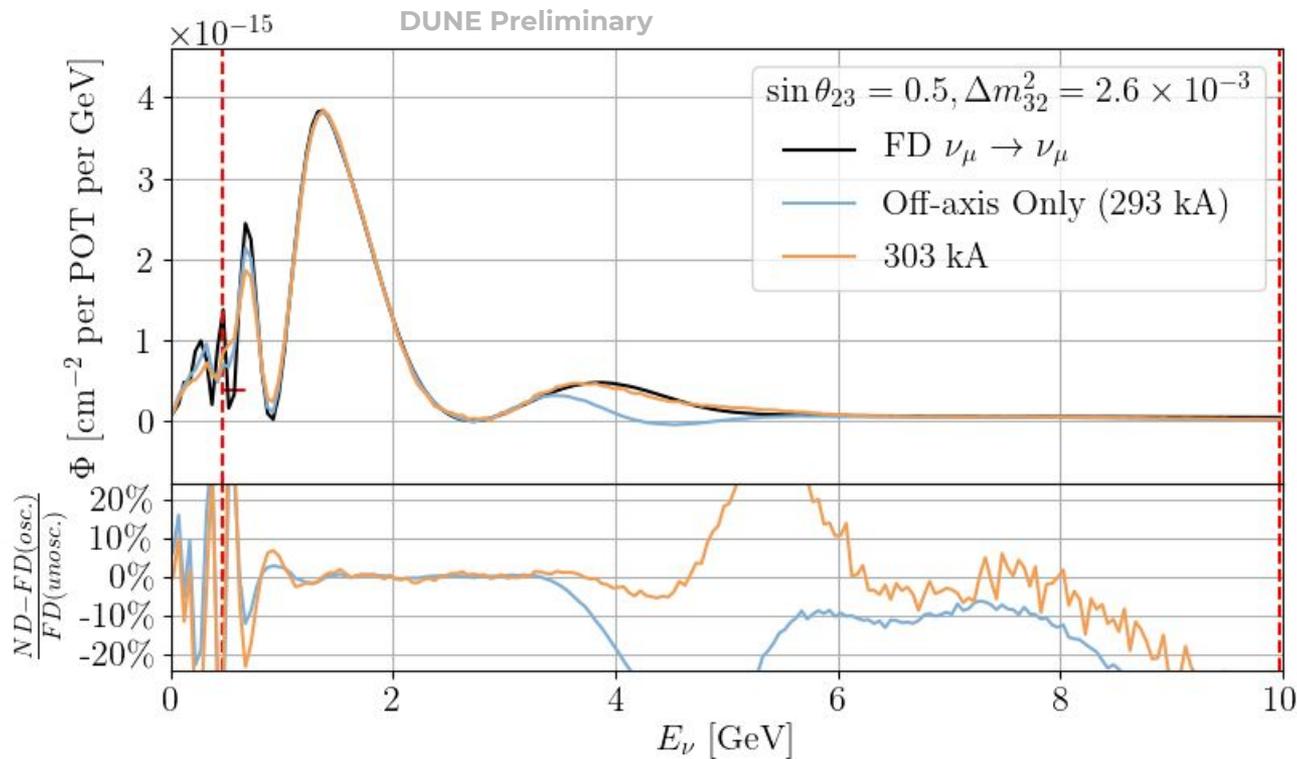
Does it work everywhere?

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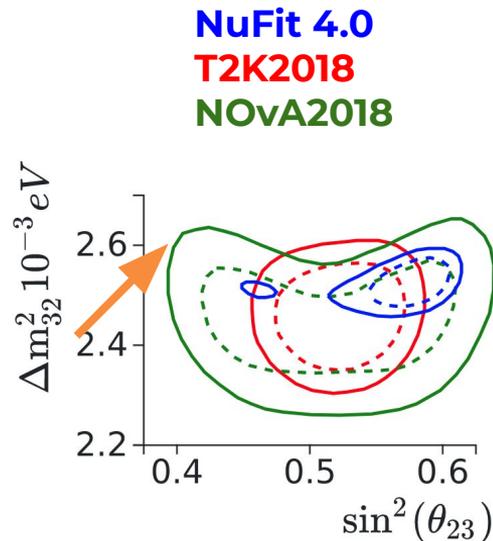
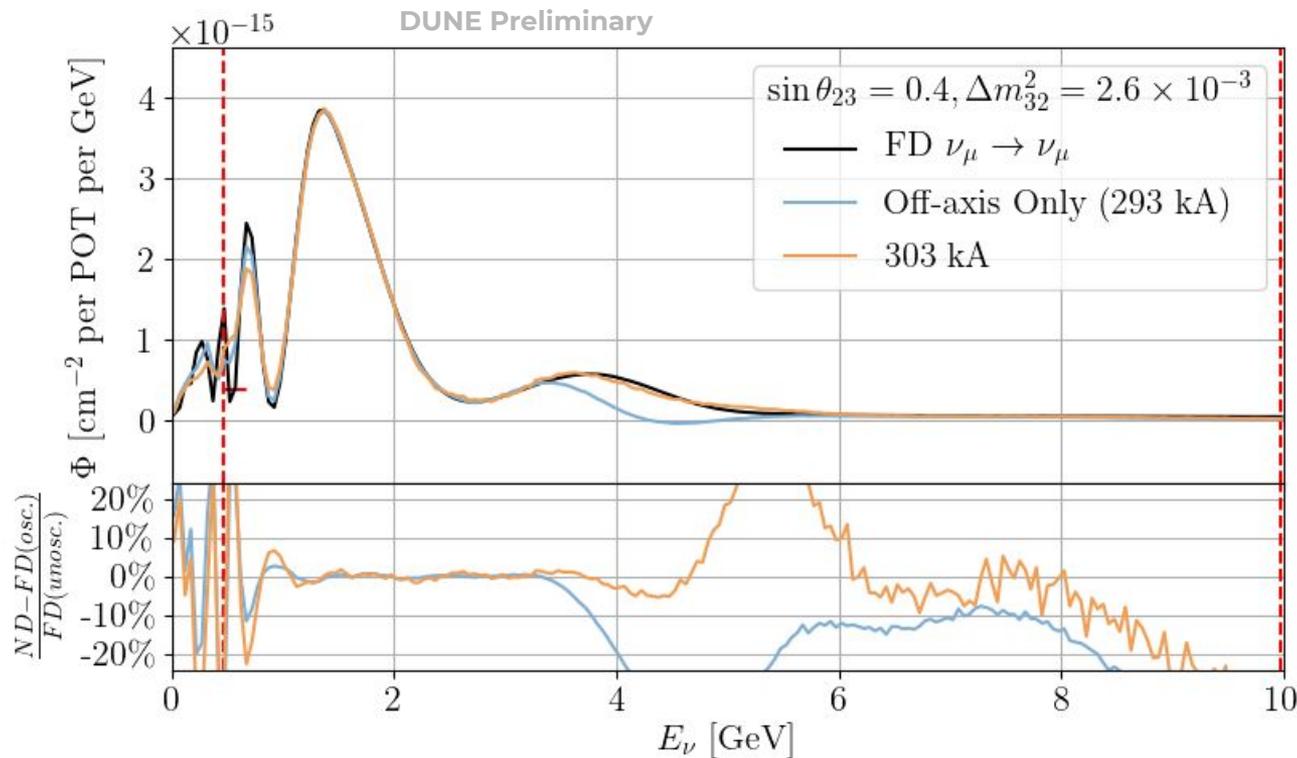
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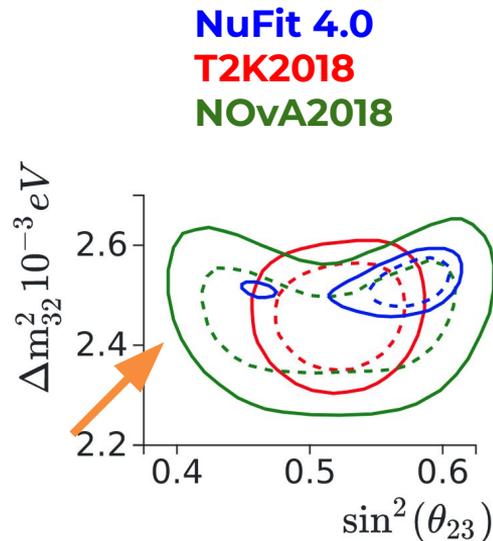
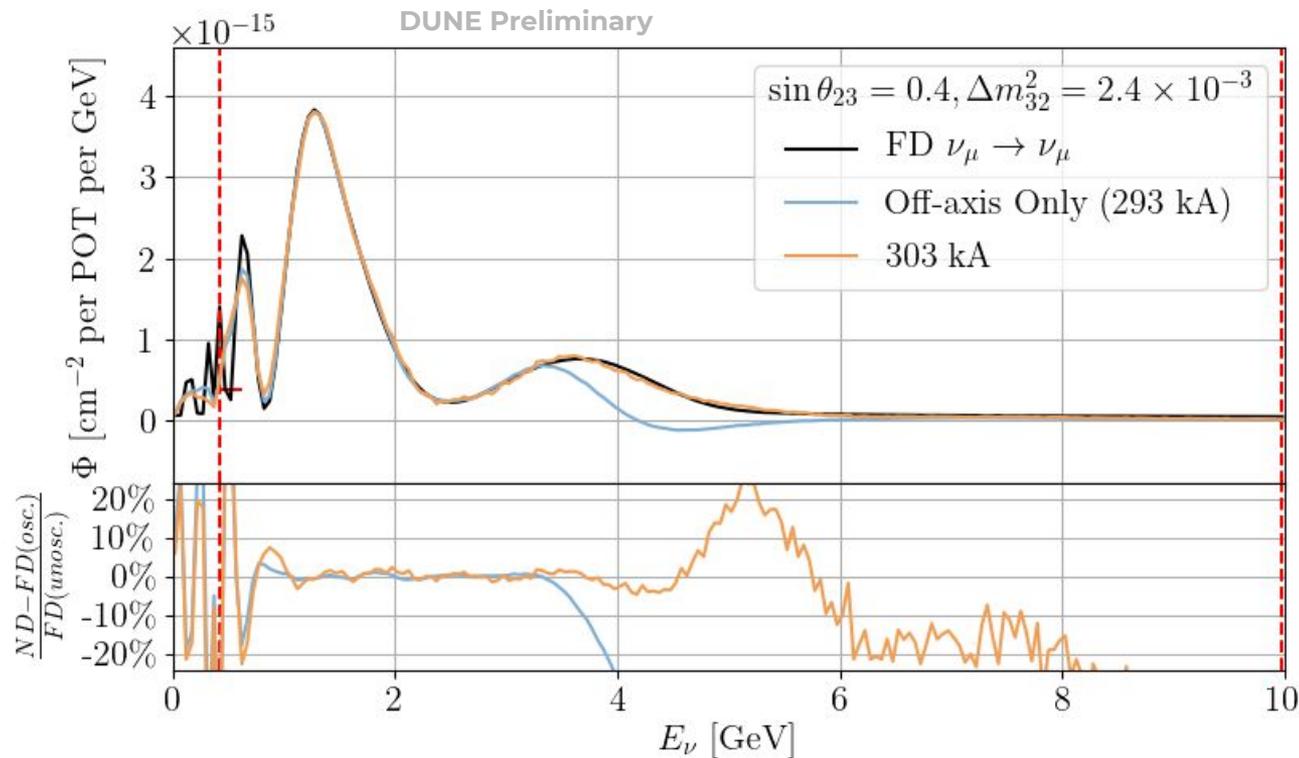
Does it work everywhere?

[Try it yourself!](#)



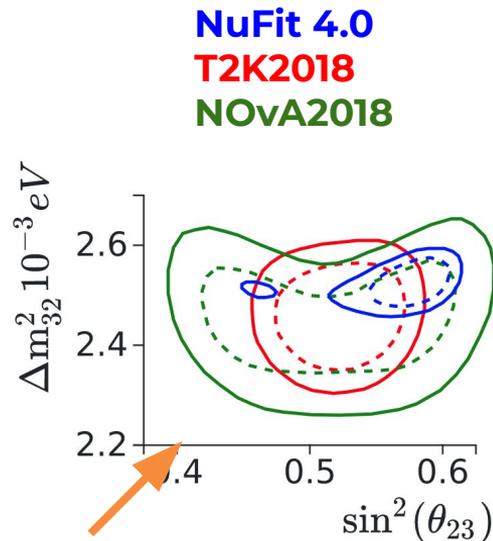
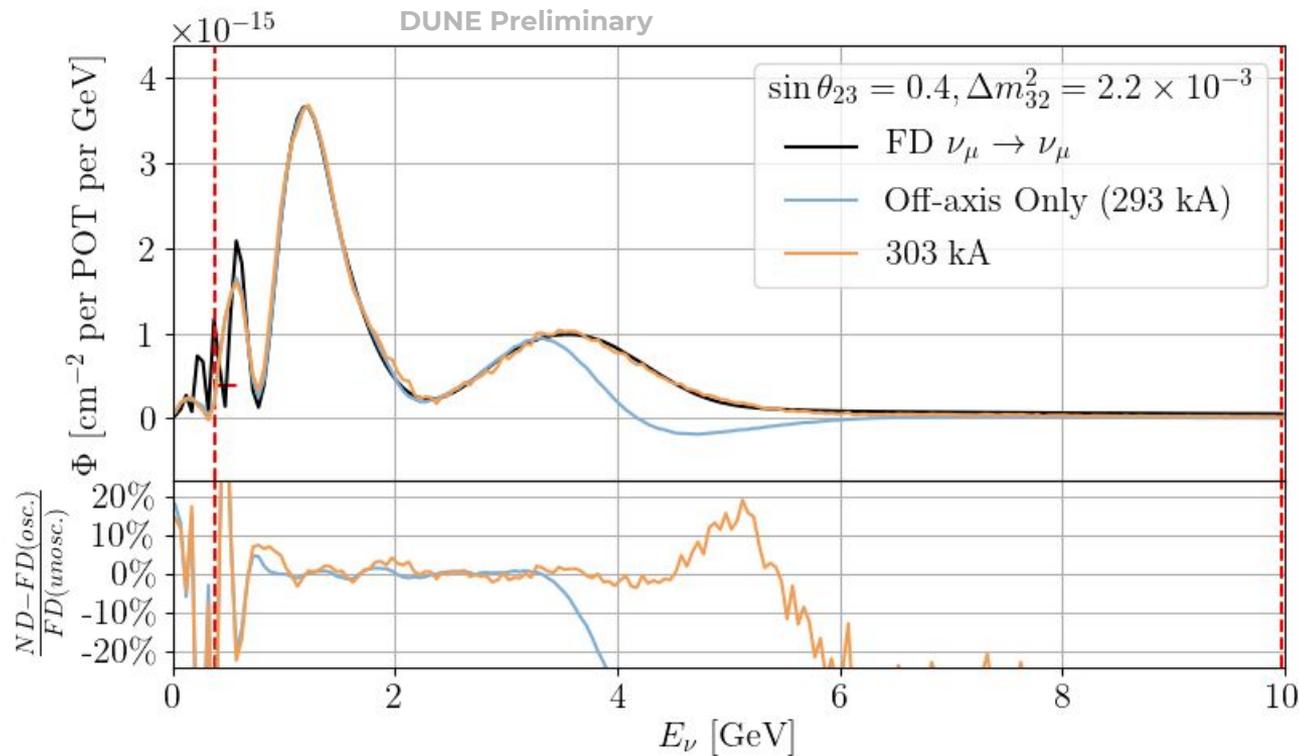
Does it work everywhere?

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Does it work everywhere?

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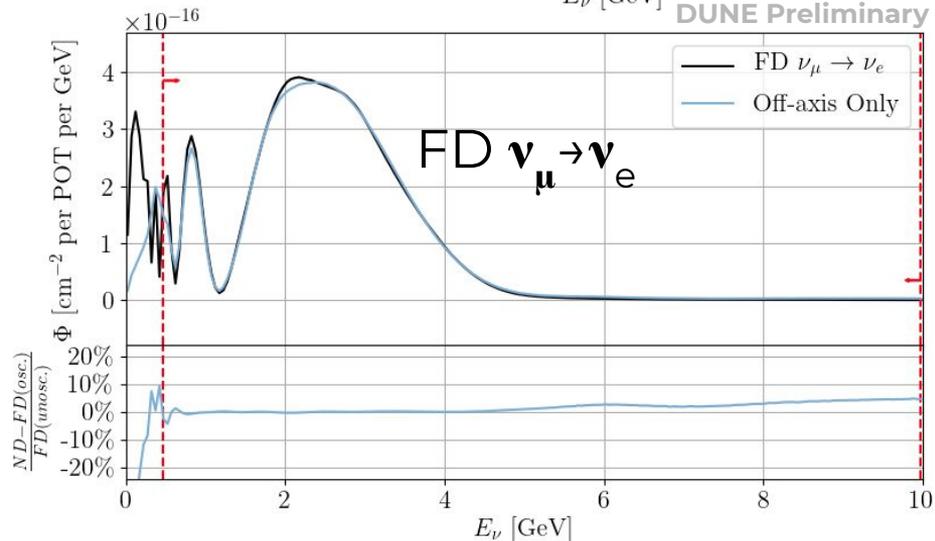
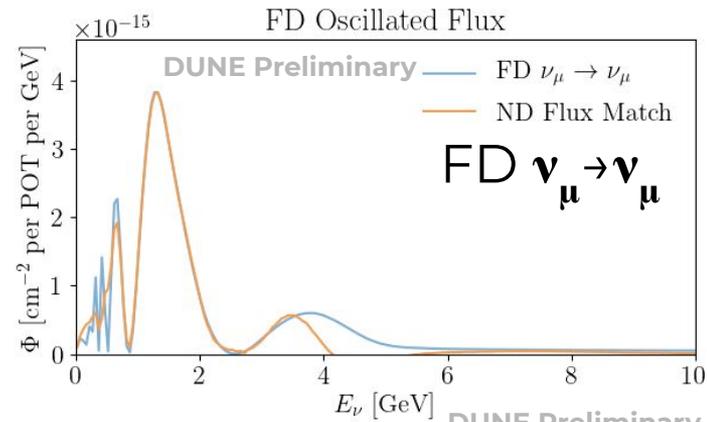


Expected Questions

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- You've only shown one set of oscillation parameters, does it work over the whole allowed space?
- How do you do an appearance analysis...?
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- The ND and FD are functionally un-identical though...
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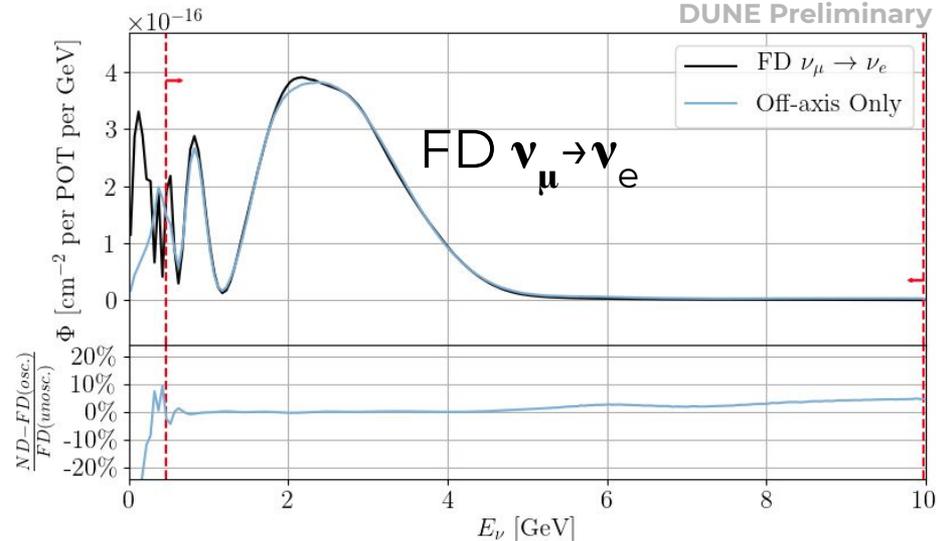
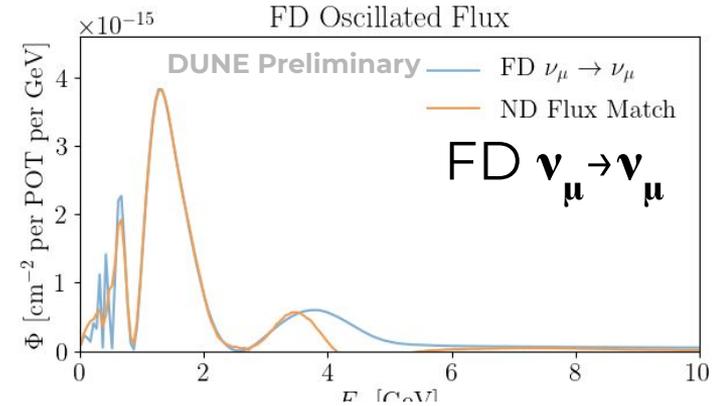
Fixing for an appearance

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



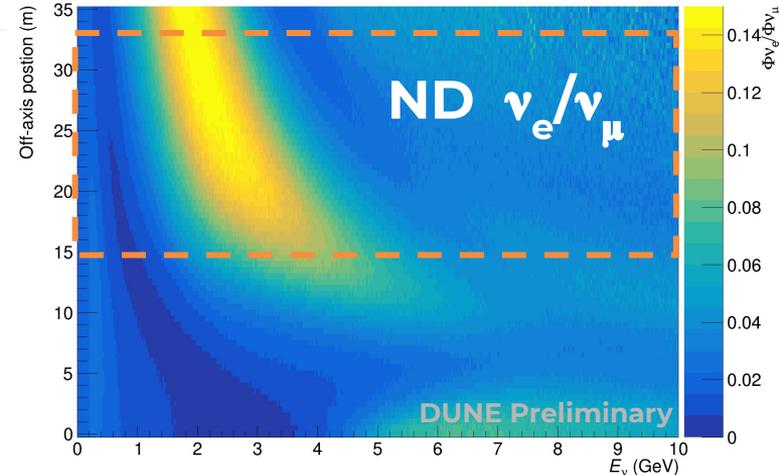
Fixing for an appearance

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



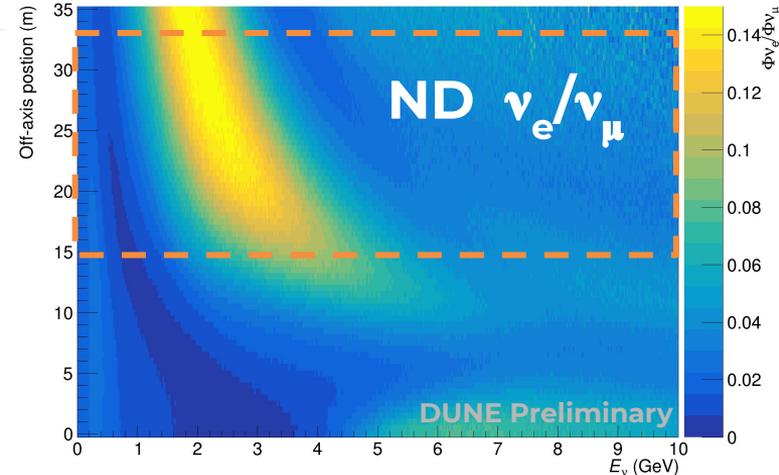
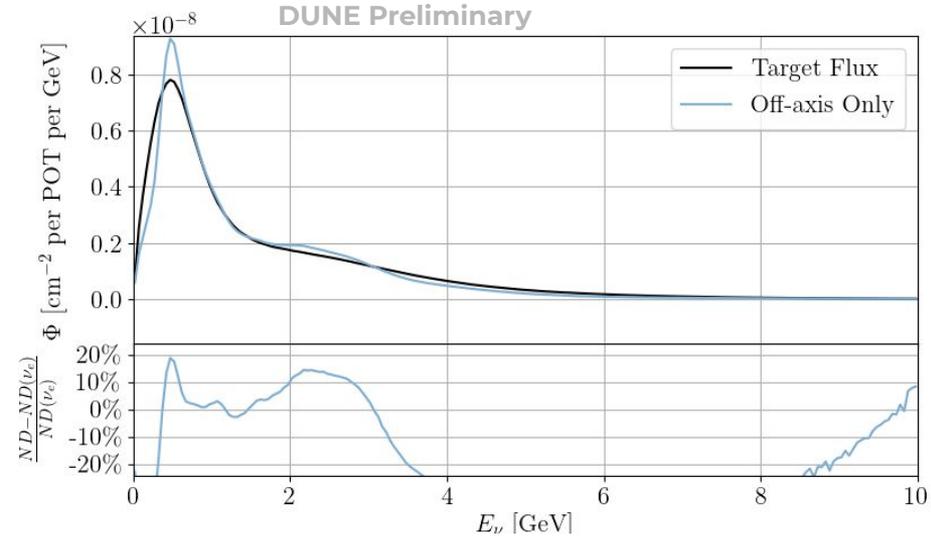
ND nue fits

- 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



ND fits

- Sample ND ν_e flux while scanning off axis angle.
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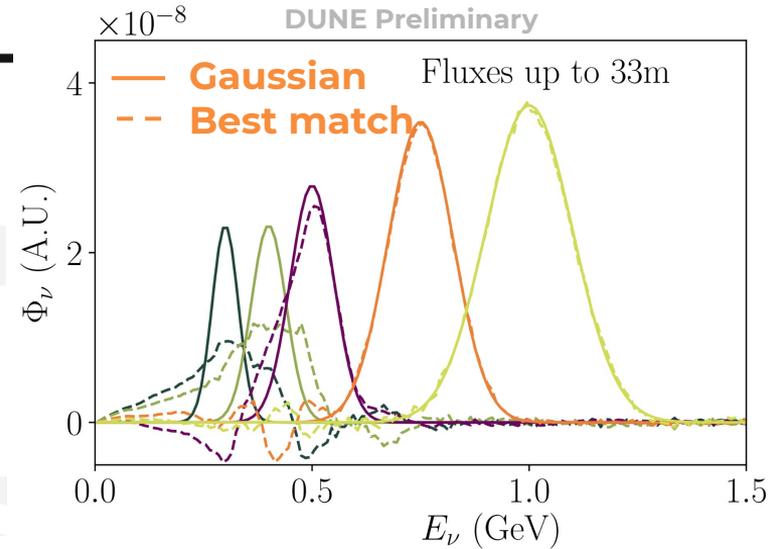


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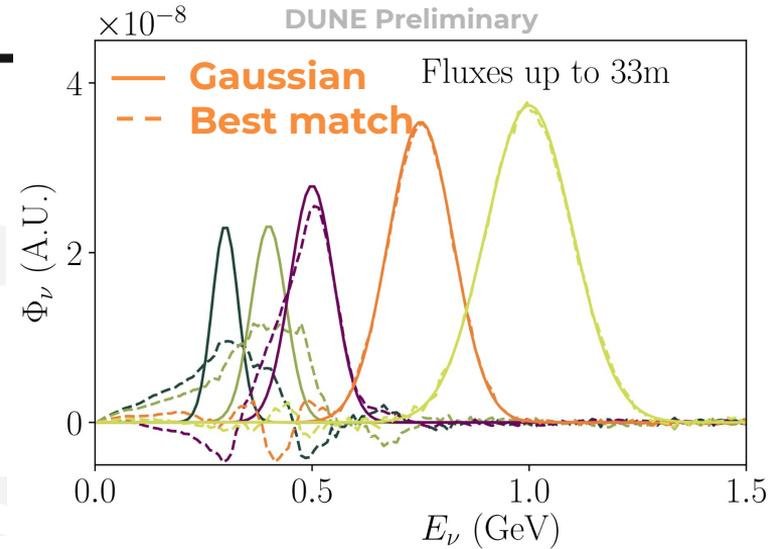
Narrow-band fluxes

- Also of interest to construct narrow band flux measurements.

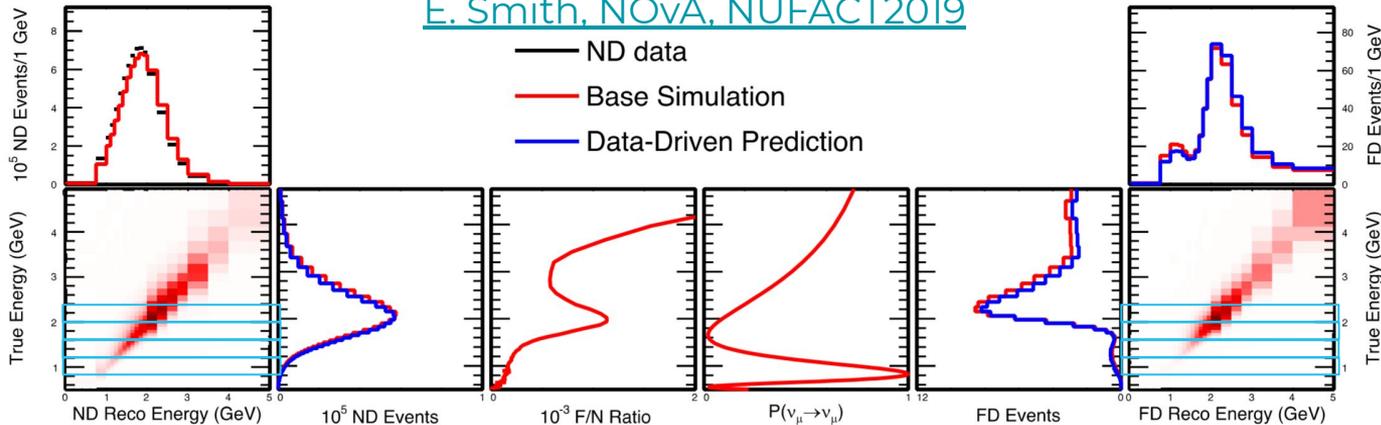


Narrow-band fluxes

- 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](#)

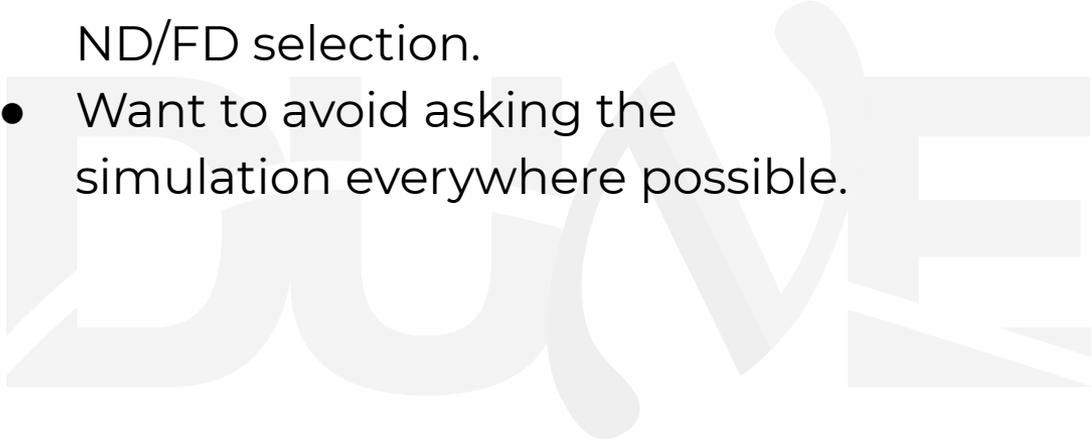


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Near/Far Differences



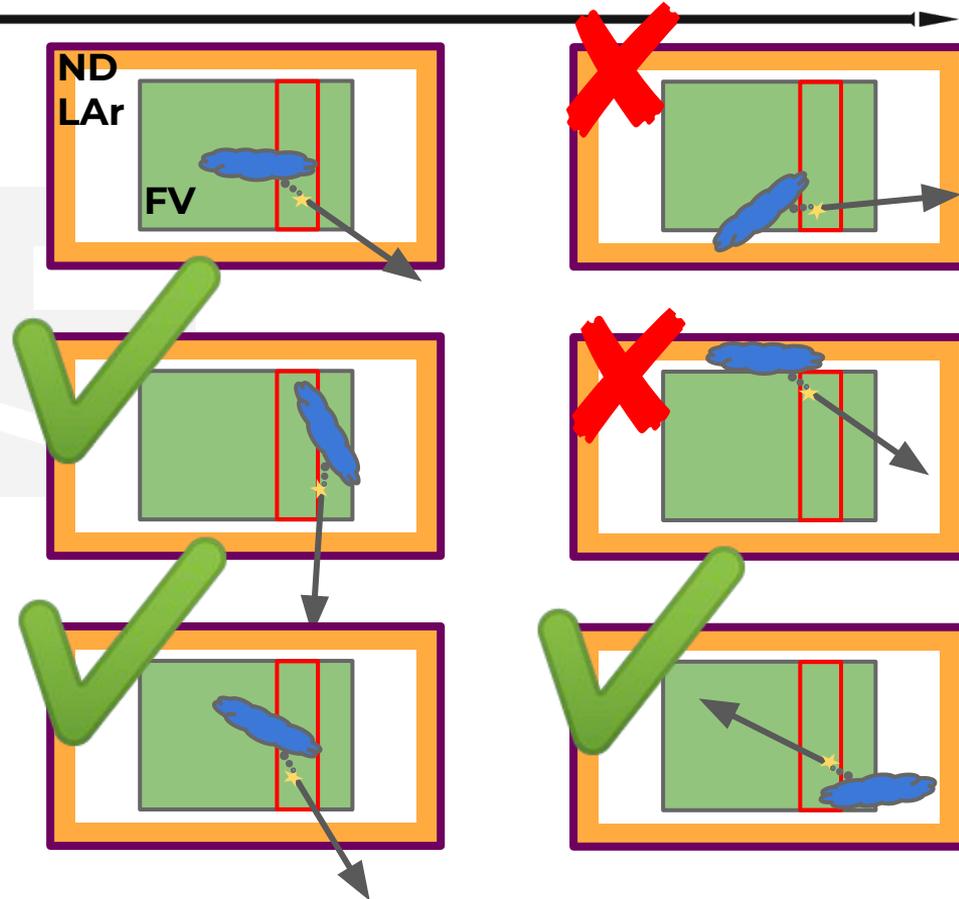
- Must correct for differences in ND/FD selection.
 - Want to avoid asking the simulation everywhere possible.
- 

Near/Far Differences

Hadronic Showers
Muons

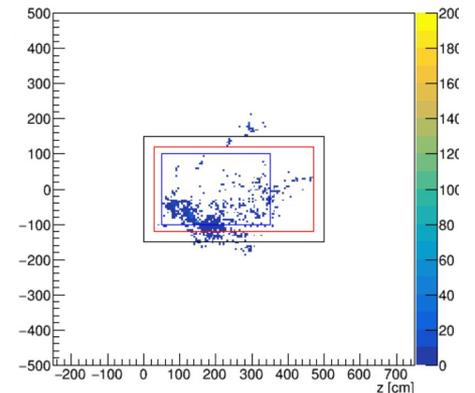
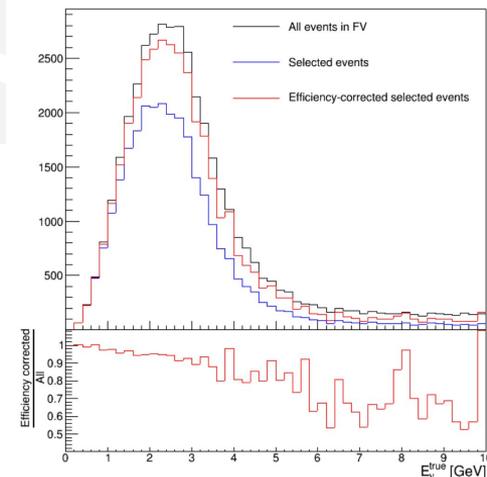
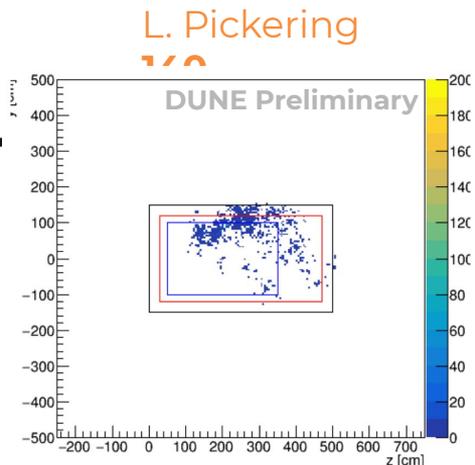
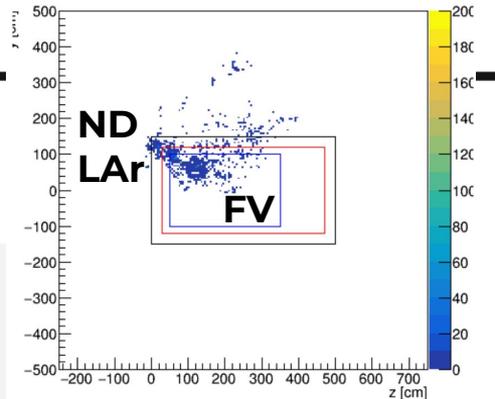
L. Pickering 139

- Must correct for differences in ND/FD selection.
- Want to avoid asking the simulation everywhere possible.
- **An idea:** develop data-driven geometric efficiency correction
 - How often would I have selected this energy deposit under relevant symmetry transformations



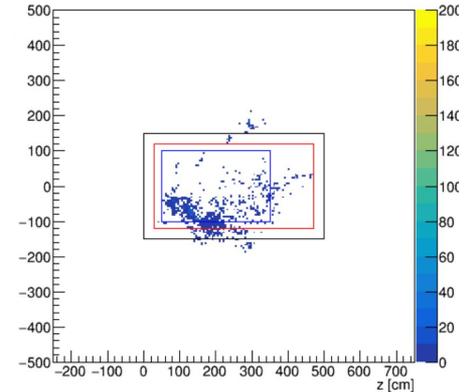
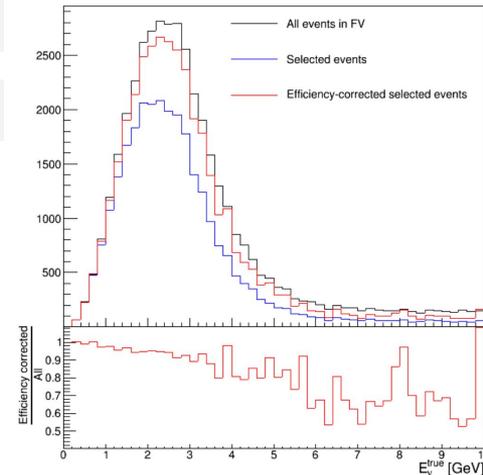
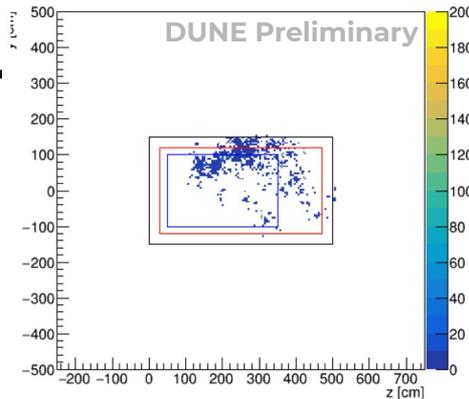
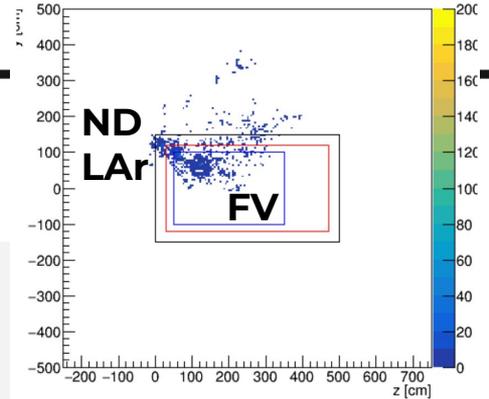
Near/Far Differences

- Must correct for differences in ND/FD selection.
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 - How often would I have selected this energy deposit under symmetry transformations
- **Which events do I select at the FD and never see at the ND?**



Near/Far Differences

- Must correct for differences in ND/FD selection.
- Want to avoid asking the simulation everywhere possible.
- An idea: develop data-driven geometric efficiency correction
 - How often would I have selected this energy deposit under symmetry transformations
- Which events do I select at the FD and never see at the ND?
- **Also have to account for resolution difference ND/FD.**



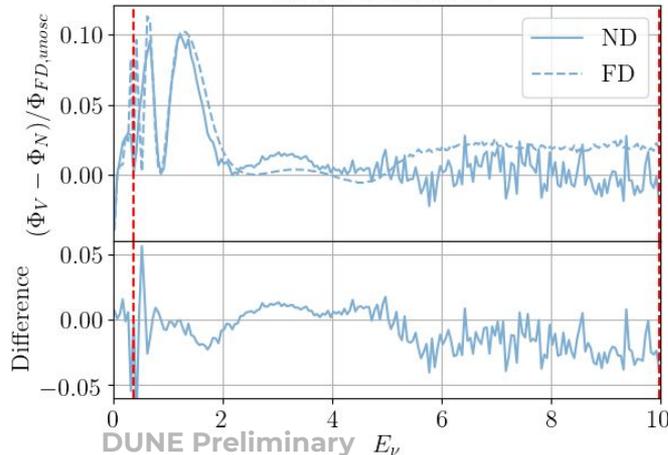
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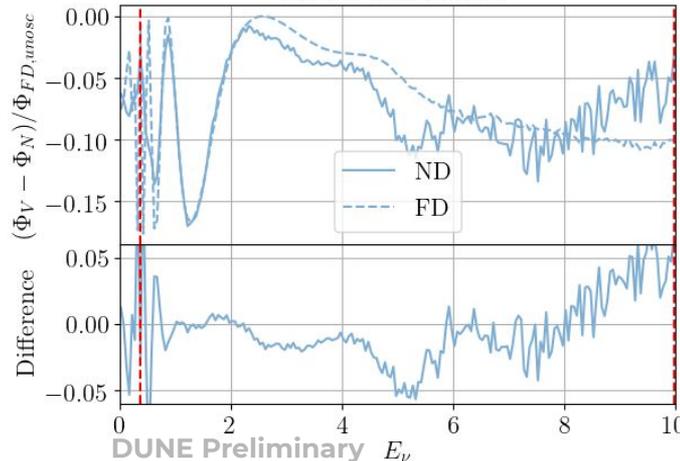
Flux Uncertainties

- 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

PPFX Universe 20

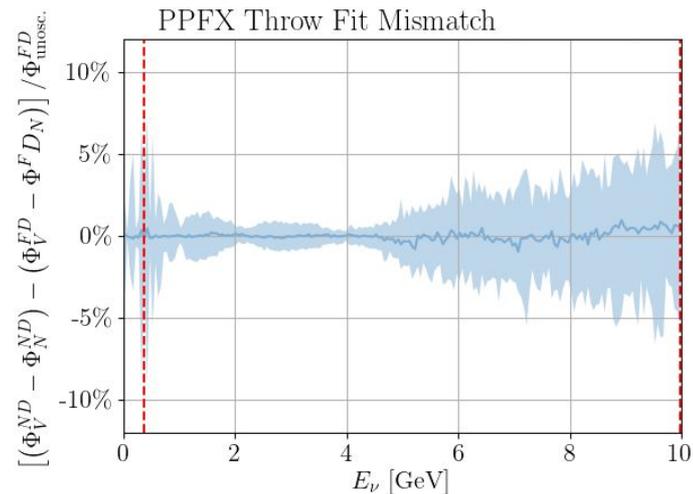


PPFX Universe 25



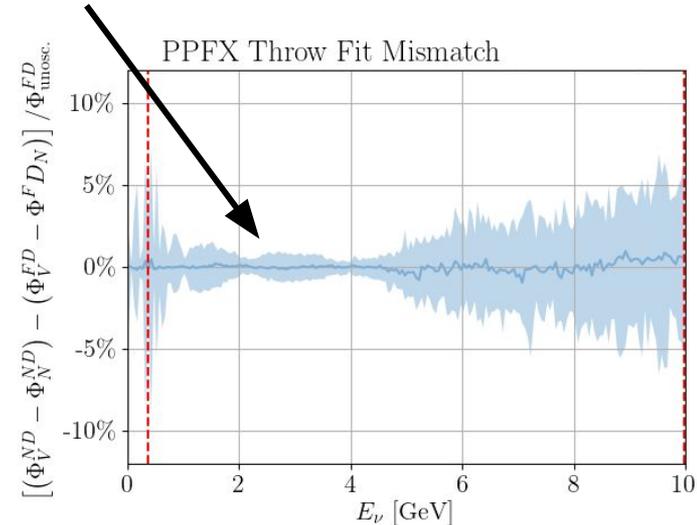
Flux Uncertainties

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- **Here: 100 universes used in the TDR analysis**



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: 100 universes used in the TDR analysis**
 - **Cancellations down to a few percent still observed!**



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



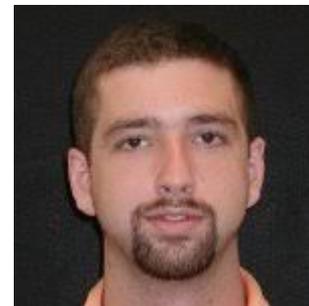
D. Douglas



C. Vilela



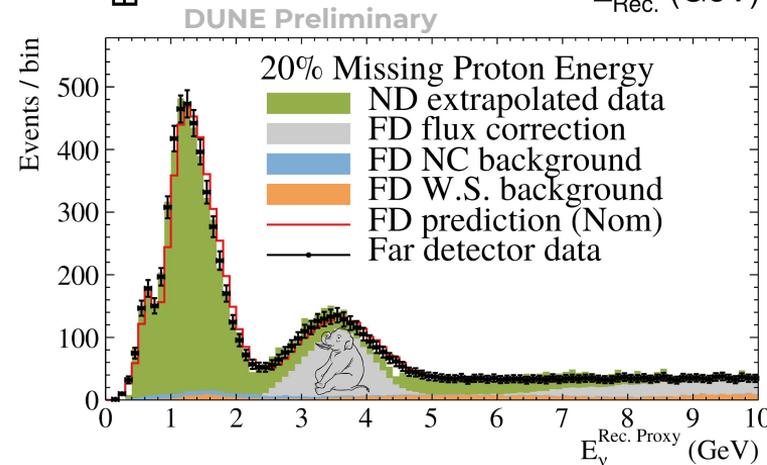
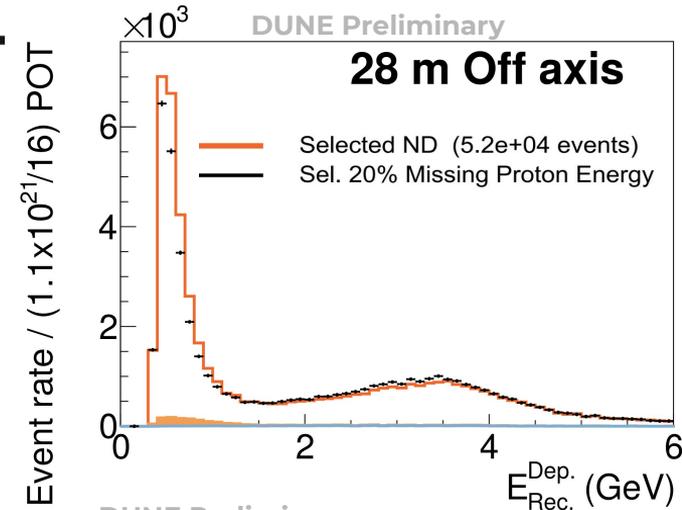
T. Lord



M. Wilking

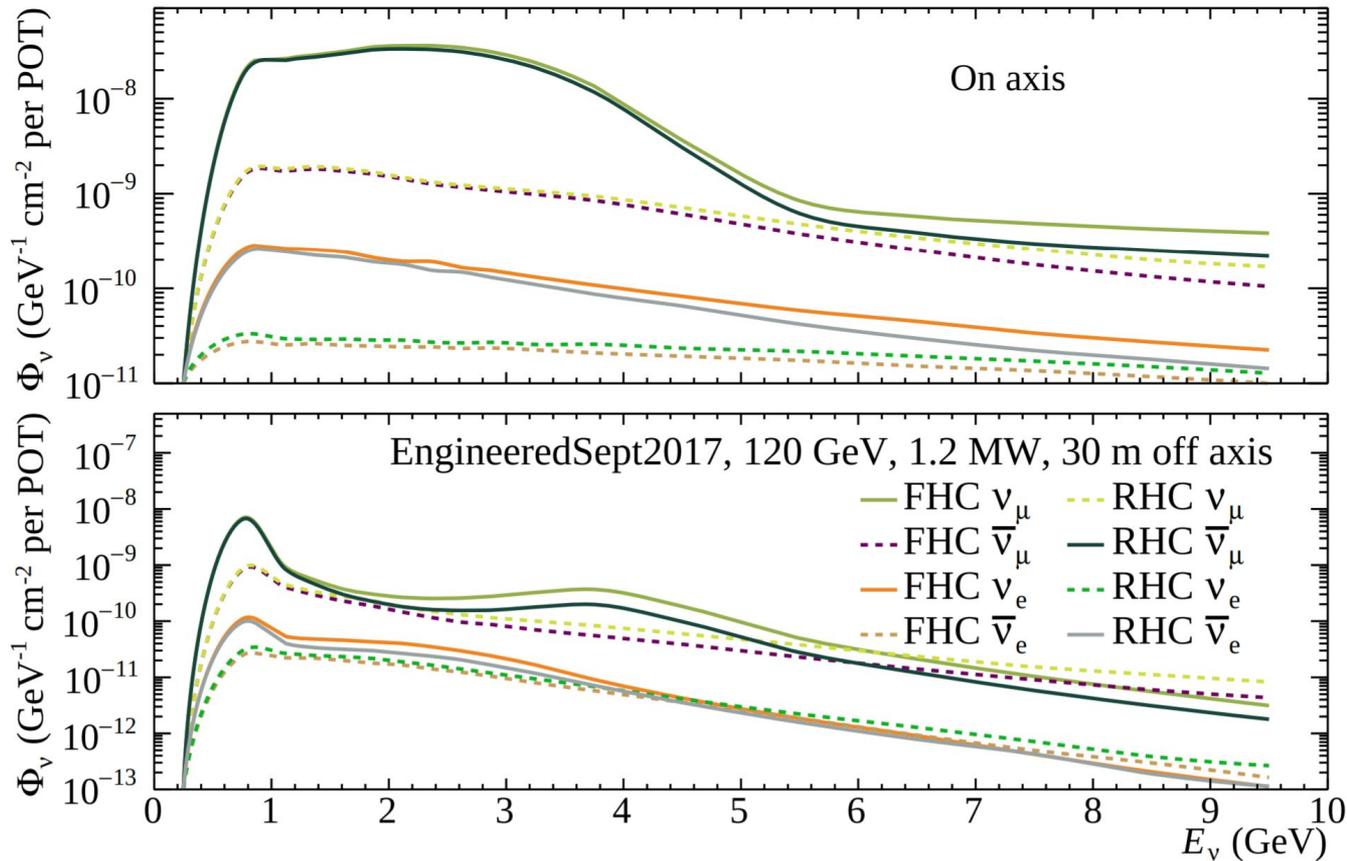
Summary

- **Having measurements off axis is very powerful:** very hard for a wrong model to predict high stats measurements over such a range of energies consistently
- The PRISM technique uses that power to build an OA that is robust **even to things you don't know are wrong!**



Thanks for listening

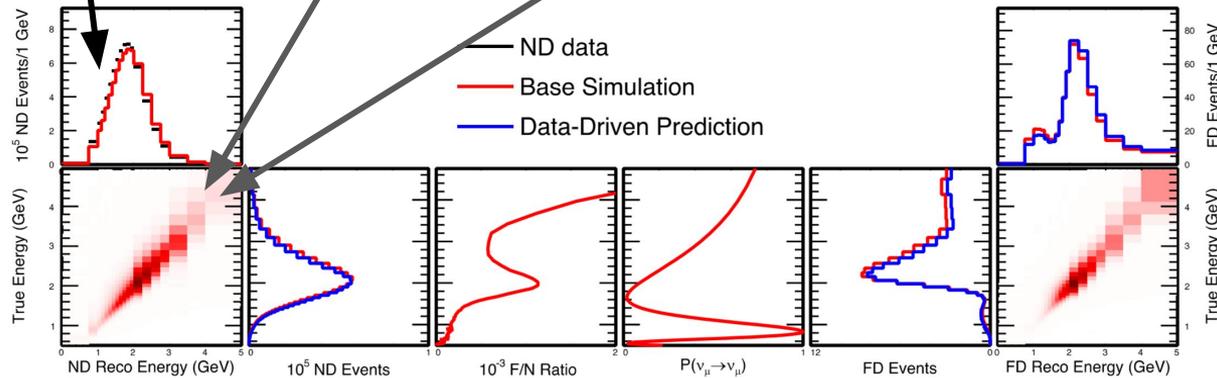
Parent Species Off axis.



Concrete Example: NOvA

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

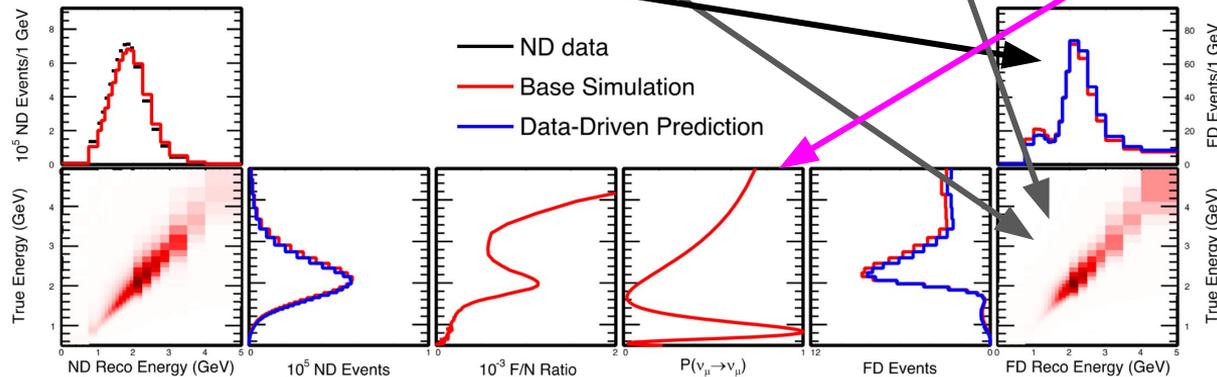
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Concrete Example: NOvA

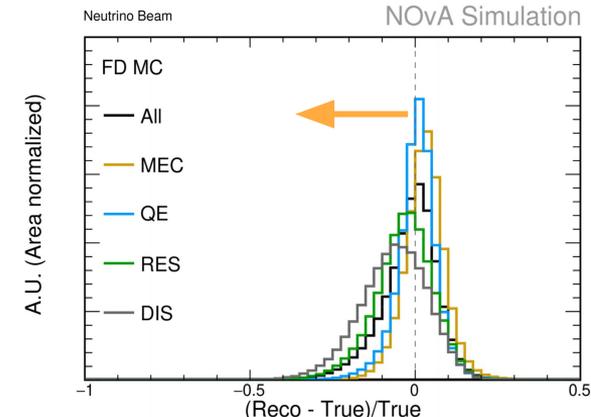
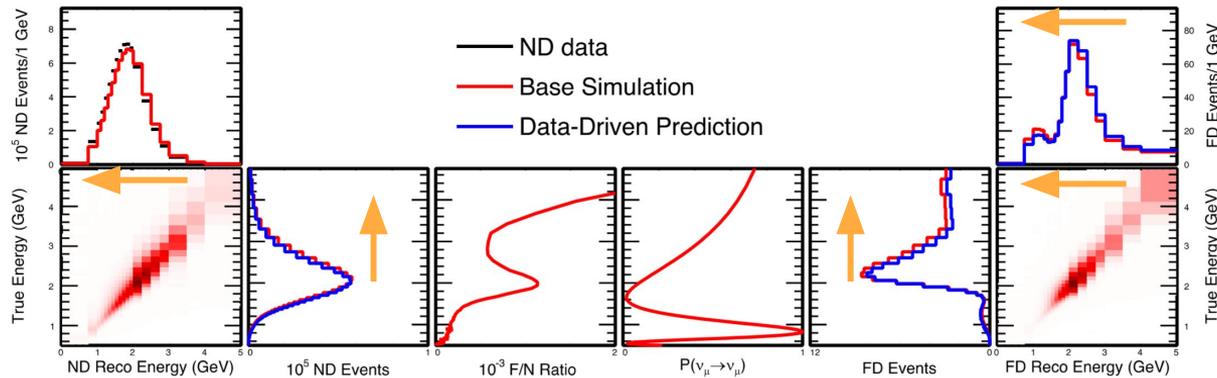
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Concrete Example: NOvA

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



Hand Picked Fake Data

INTRODUCTION

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

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

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

Sum over knock-out nucleons:

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

Sum over mesons:

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

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



Multivariate ReWeighting

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

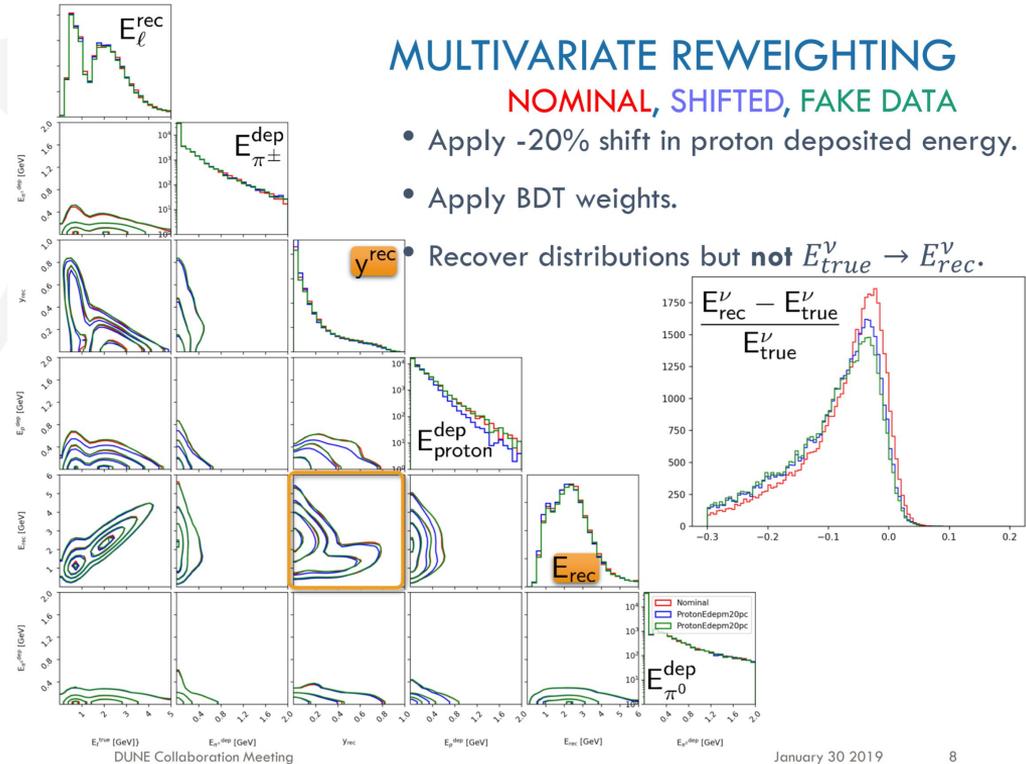
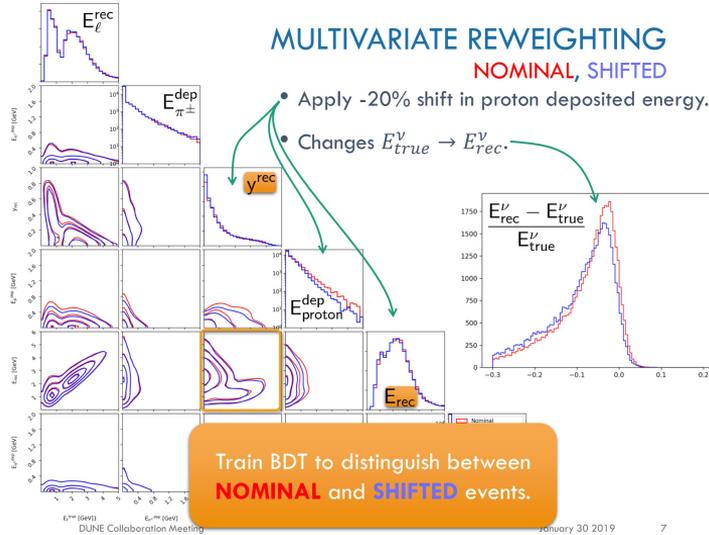
- Reweighting/Fake data technique that is being used more on T2K and DUNE (originated in Collider land).
- Get BDT to give you event weights that make your nominal MC look like something else in many distributions at once (but get the correlations correct).

MULTIVARIATE REWEIGHTING

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

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

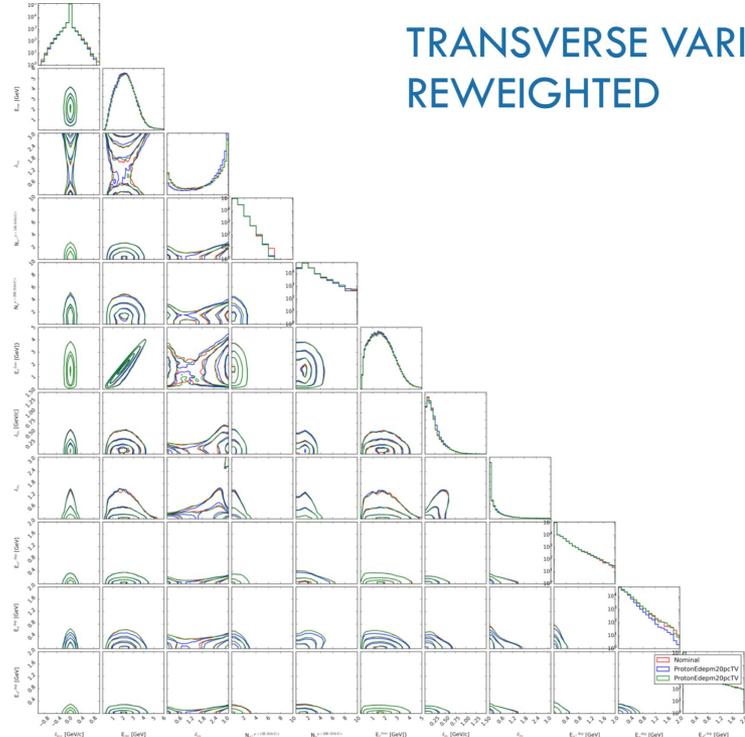
Missing Proton Fake Data

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

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 noisy.

TRANSVERSE VARIABLES,
REWEIGHTED



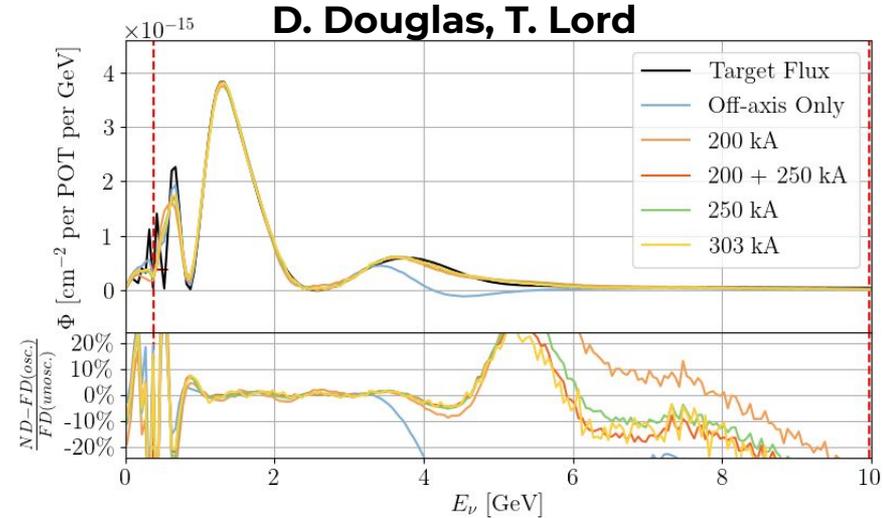
NE Collaboration Meeting

January 30 2019

21

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.**



Model-driven Extrapolation

- If model isn't correct:
 - \Rightarrow Attribute data/MC discrepancy to the wrong energy range at the ND
 - \Rightarrow 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.