Near Detector Analyses with DUNE PRISM

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DUNE Neutrino Interaction School 2021

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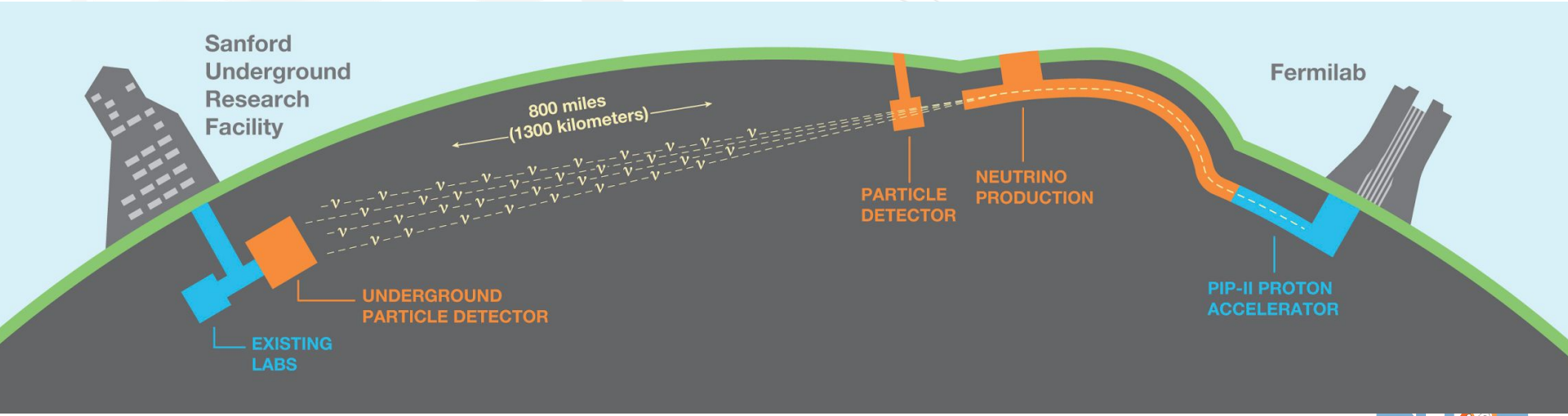
MICHIGAN STATE UNIVERSITY

This Talk

- DUNE Oscillation Physics Reminder
- The LBNF Beam
- Motivating DUNE-PRISM
- DUNE-PRISM as an analysis machine



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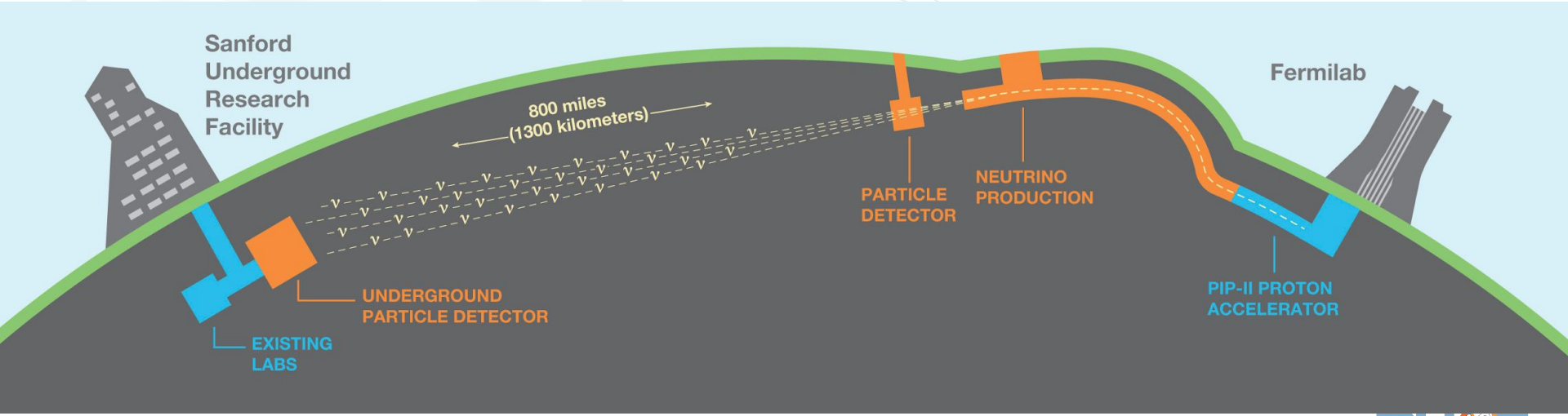
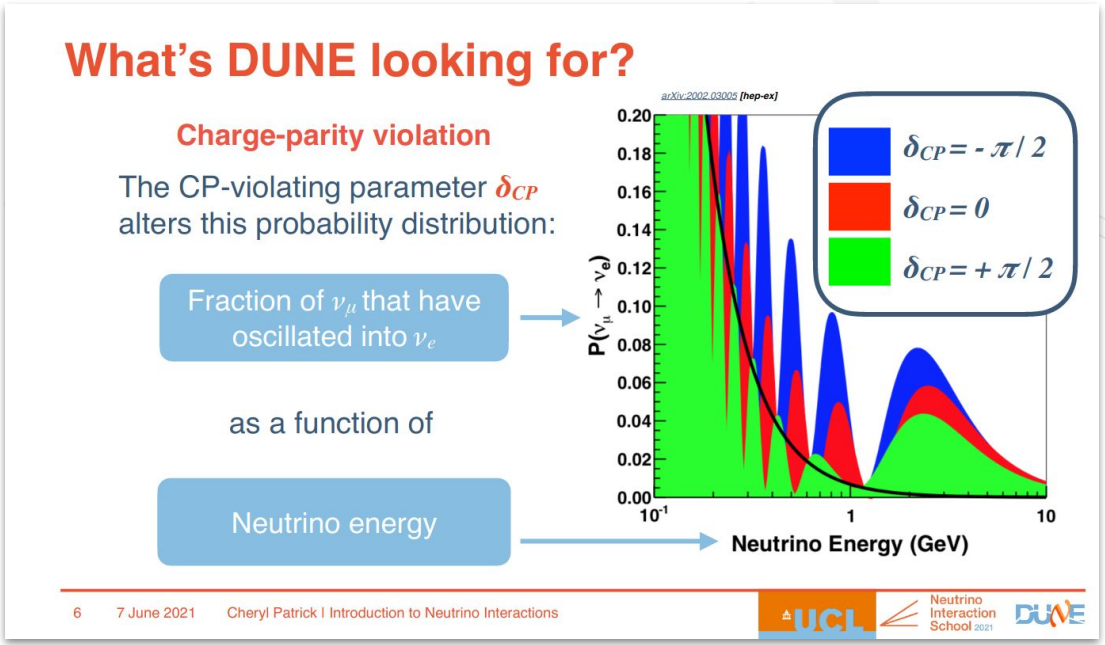


DUNE Oscillation Goals



- Heard from Cheryl a few weeks ago
- Look for signature oscillation wiggles in Far detector data
- Measure oscillations precisely enough to answer pressing fundamental physics questions.

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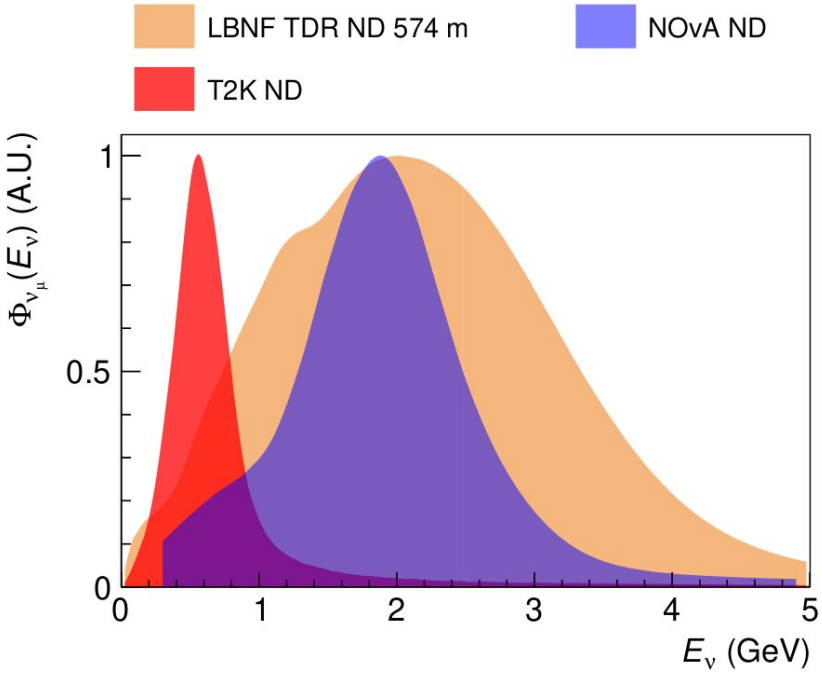
DUNE PRISM

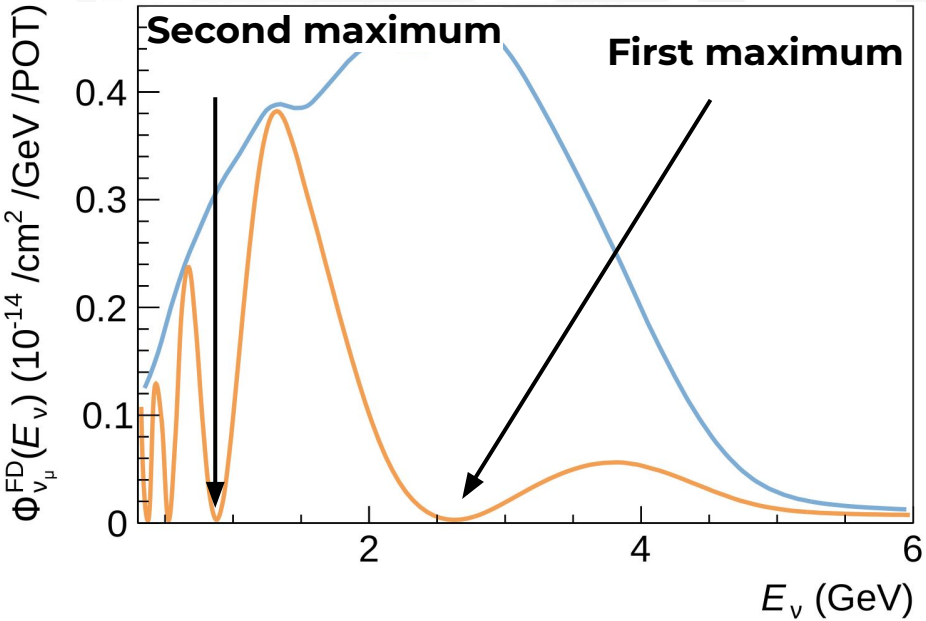
The DUNE Neutrino Flux

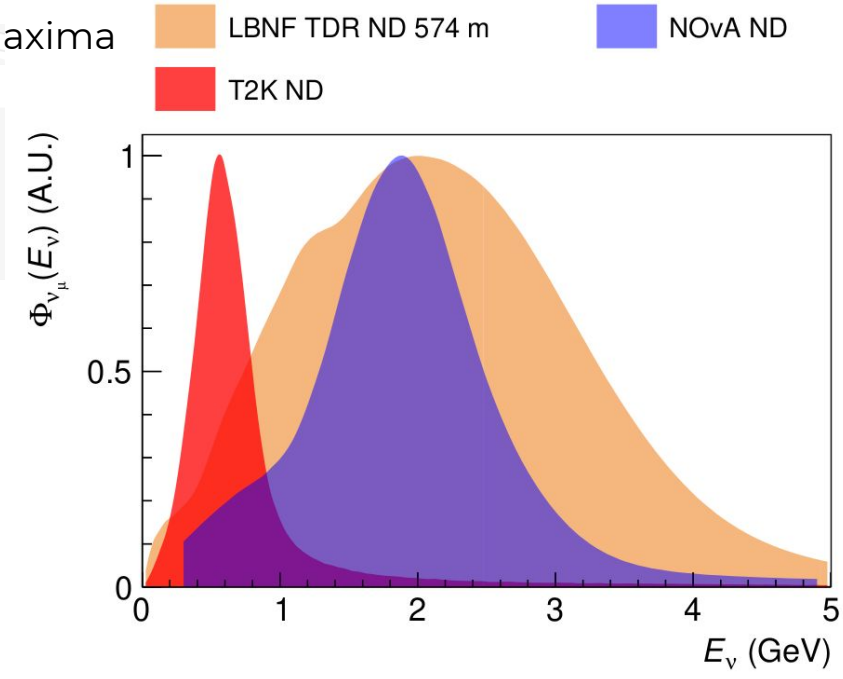
- Current generation experiments use narrow-band beams
  - Relatively narrow unknown neutrino-by-neutrino energy distribution
  - Smaller energy range to constrain interaction physics



The DUNE Neutrino Flux

- Current generation experiments use narrow-band beams
  - Relatively narrow unknown neutrino-by-neutrino energy distribution
  - Smaller energy range to constrain interaction physics
- DUNE will use an wide band beam:
  - Access to physics at higher order oscillation maxima

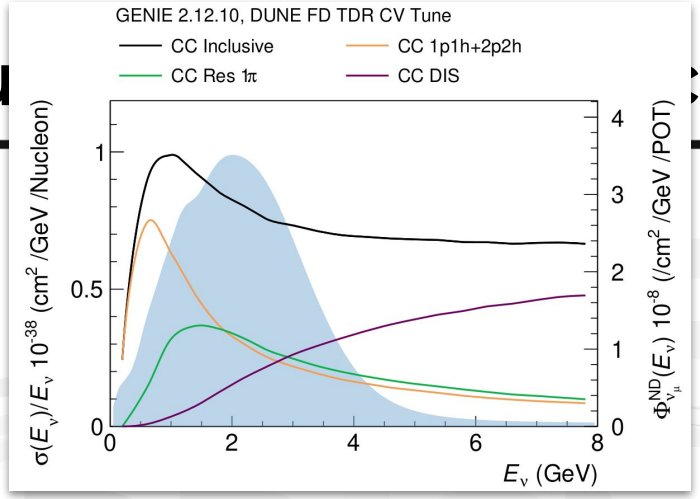


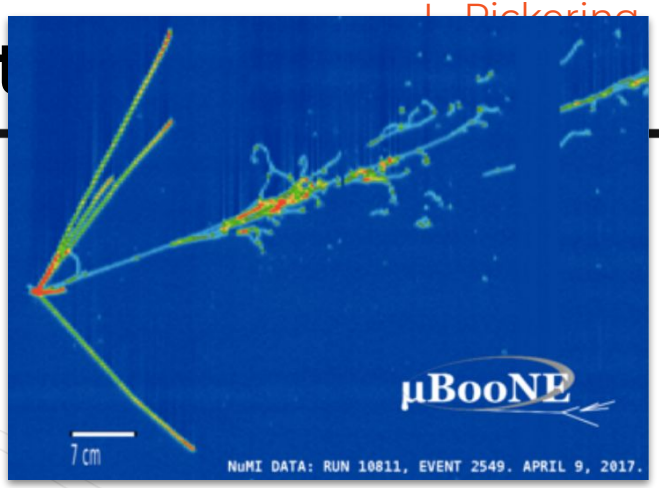


Oscillations at the Far Detector

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

Measu…cillat…





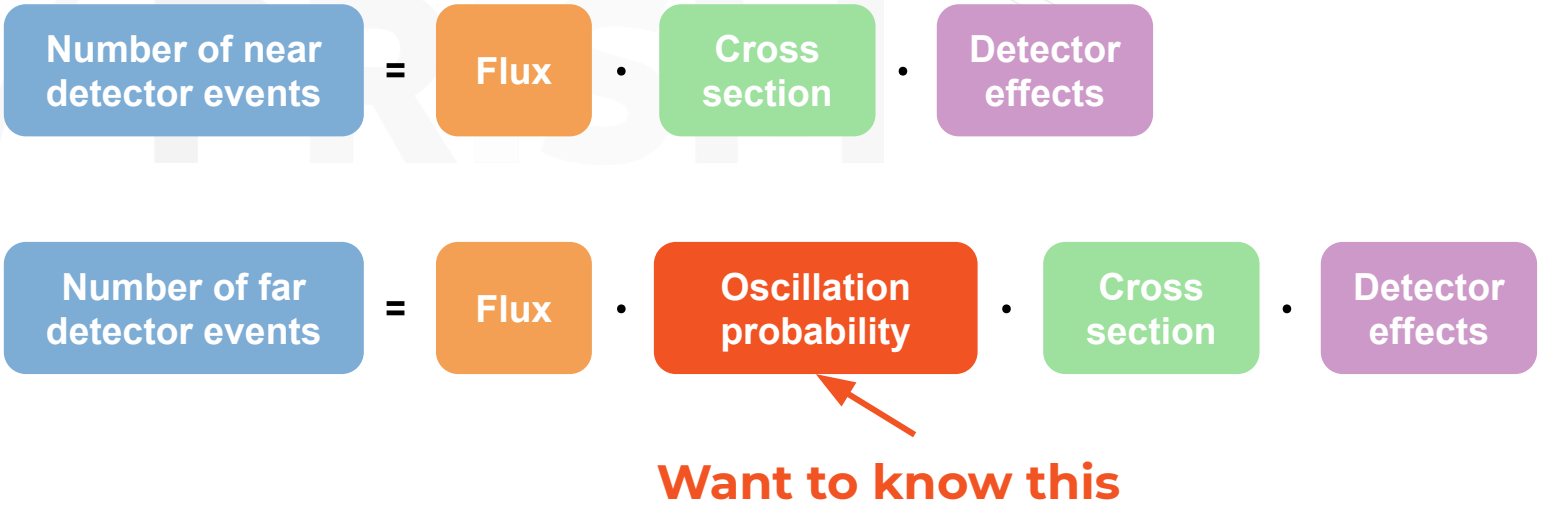
Number of near detector events = **Flux** • **Cross section** • **Detector effects**

Measuring Neutrino Oscillations

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

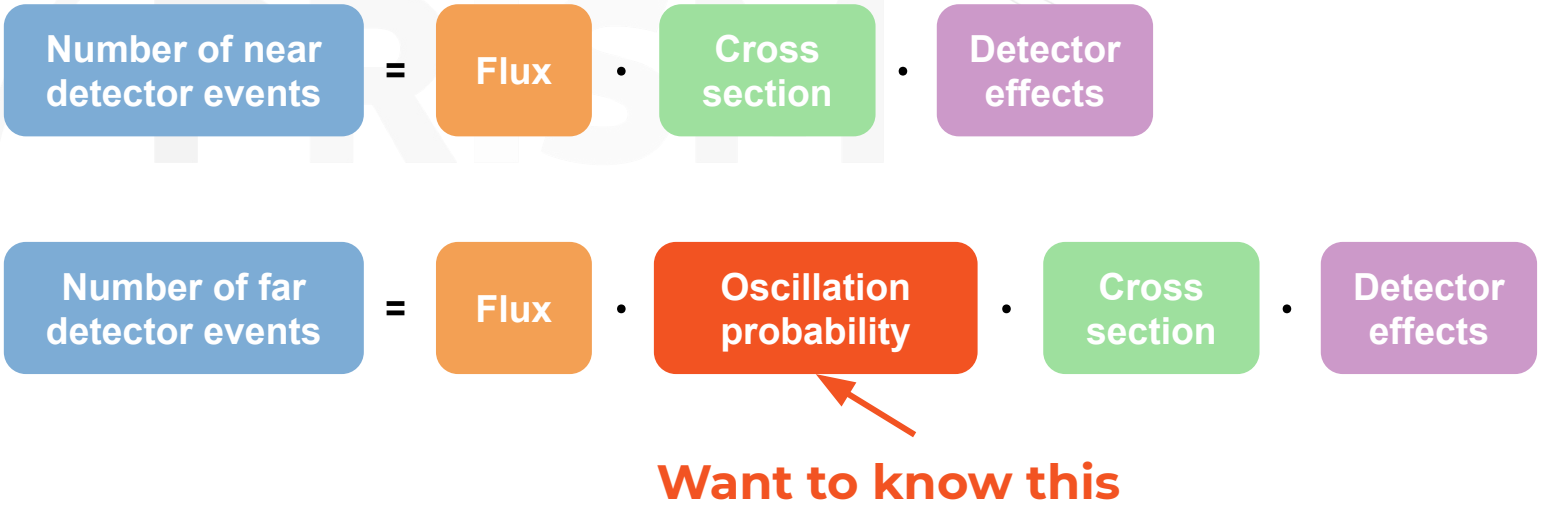
Number of far detector events = Flux · Oscillation probability · Cross section · Detector effects

Measuring Neutrino Oscillations



Measuring Neutrino Oscillations

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



Measuring Neutrino Oscillations

- Can we not just look at near/far ratio?
  - It isn't quite that simple...

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

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

Want to know this

Measuring Neutrino Oscillations

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

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

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Want to know this

Measuring Neutrino Oscillations

- Can
  - E
  - C
  - C

Possible Dream Scenario: Make near detector measurements in an oscillated flux

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

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

Want to know this

Oscillations at the Far Detector

- Can
  - E
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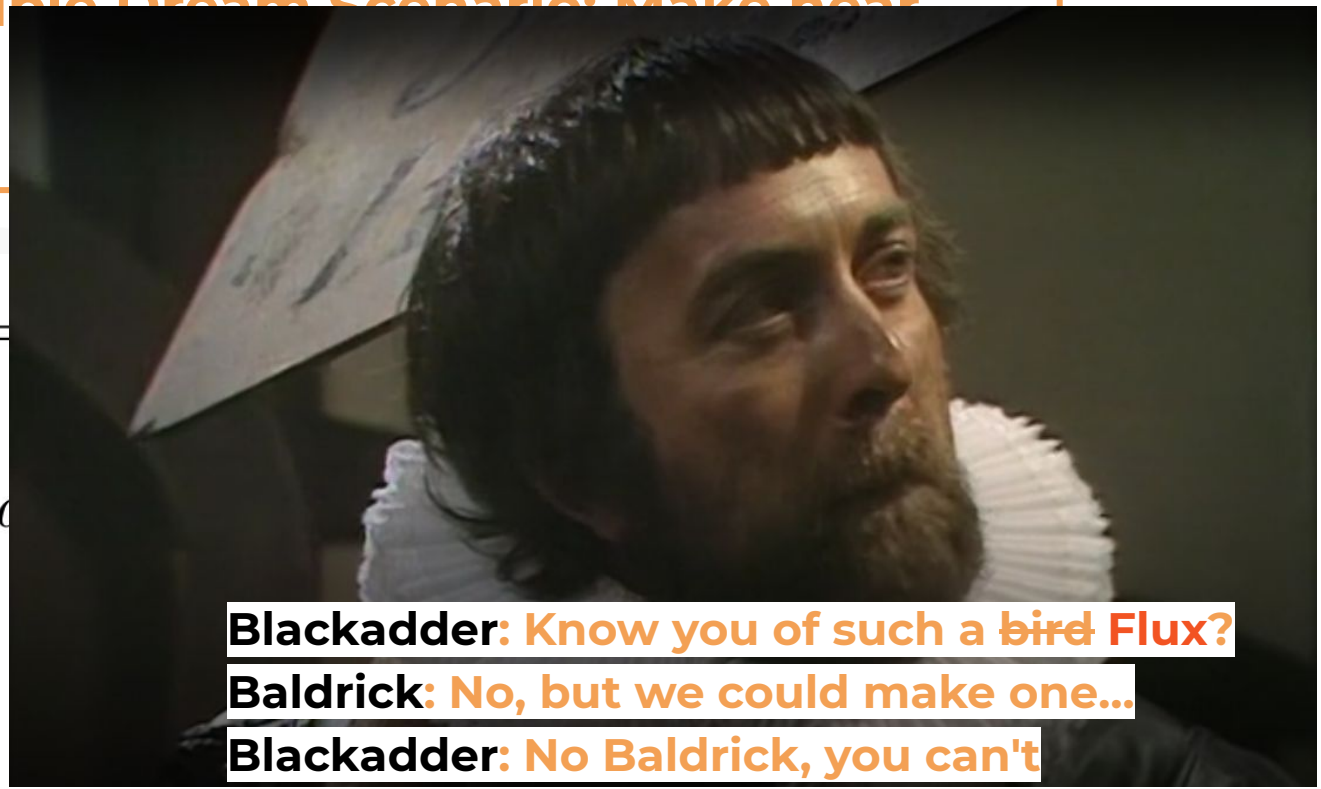
  - C

Possi… detector

$$N_{\text{near}}\left(E_{\text{obs}}\right) =$$

$$N_{\text{far}}\left(E_{\text{obs}}\right) = \int$$



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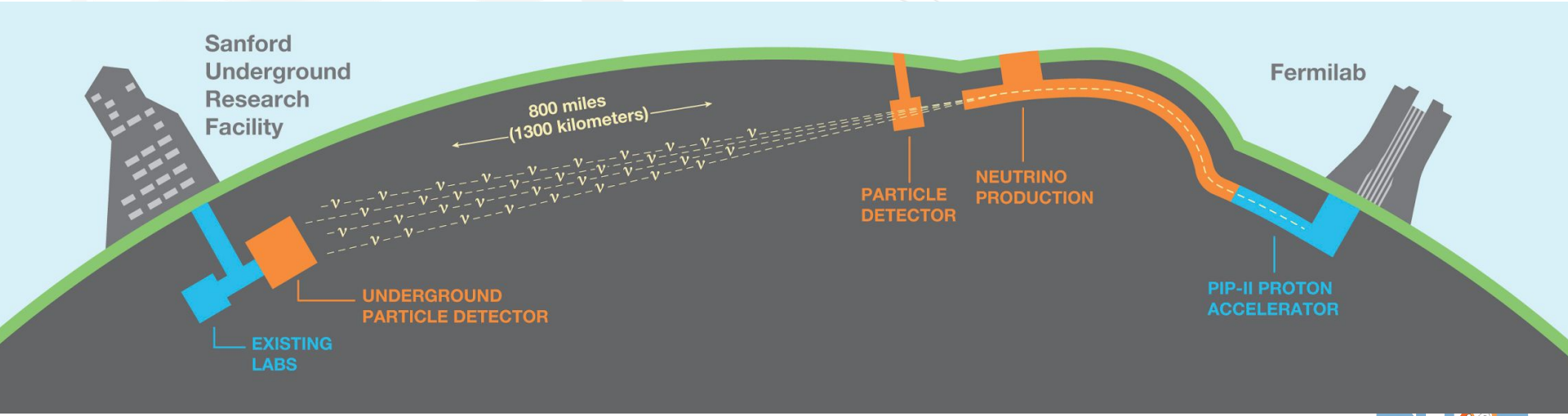

Producing a Beam of Neutrinos

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

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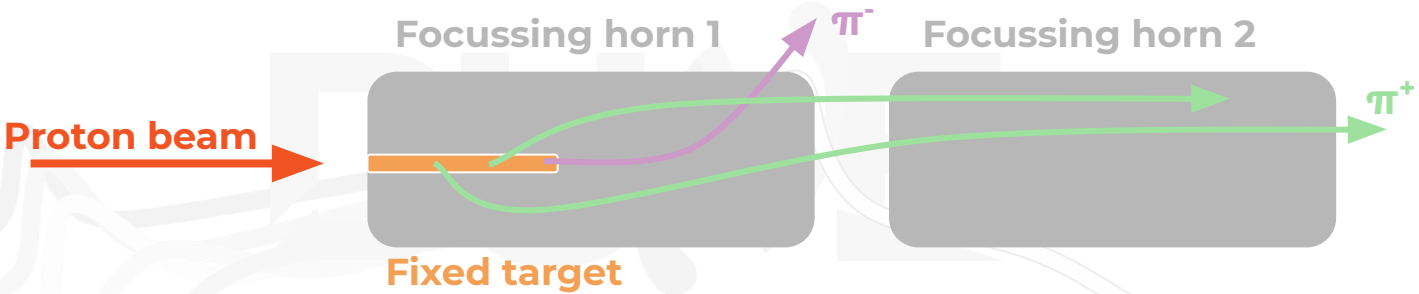

- Proton beam strikes a fixed target producing secondary hadrons: mostly pions and kaons
- These are sign-selected and focussed by one or more magnetic horns.

Producing a [illegible]s

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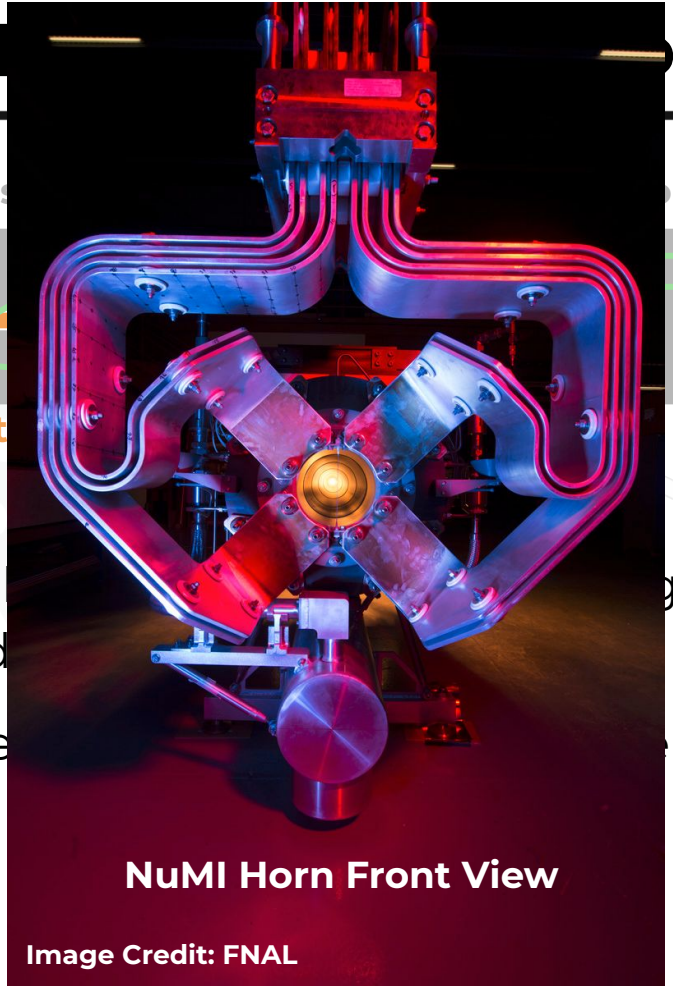

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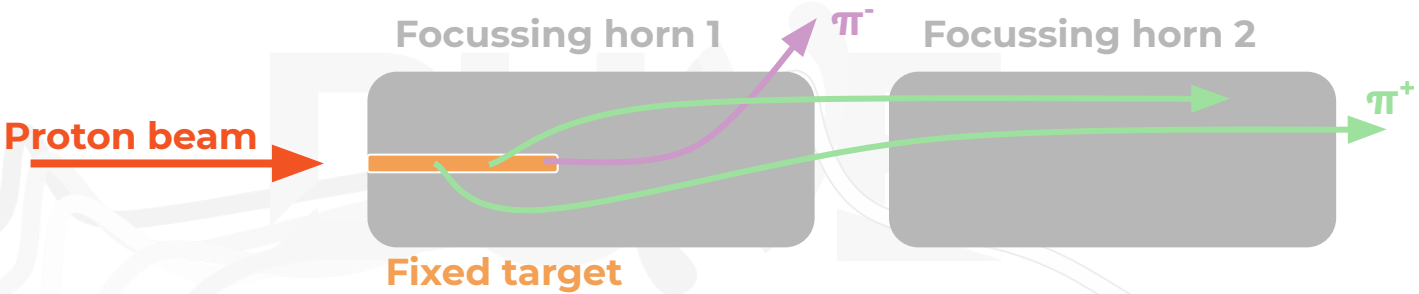

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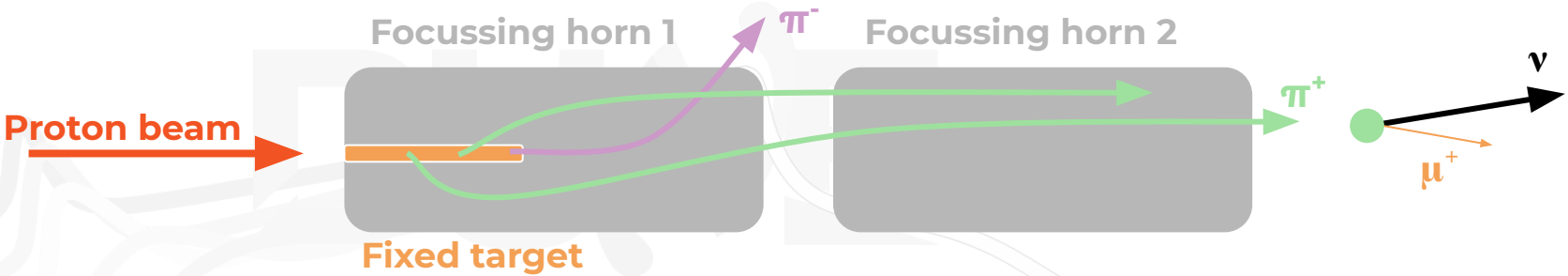

- Proton beam strikes a fixed target producing secondary hadrons: mostly pions and kaons
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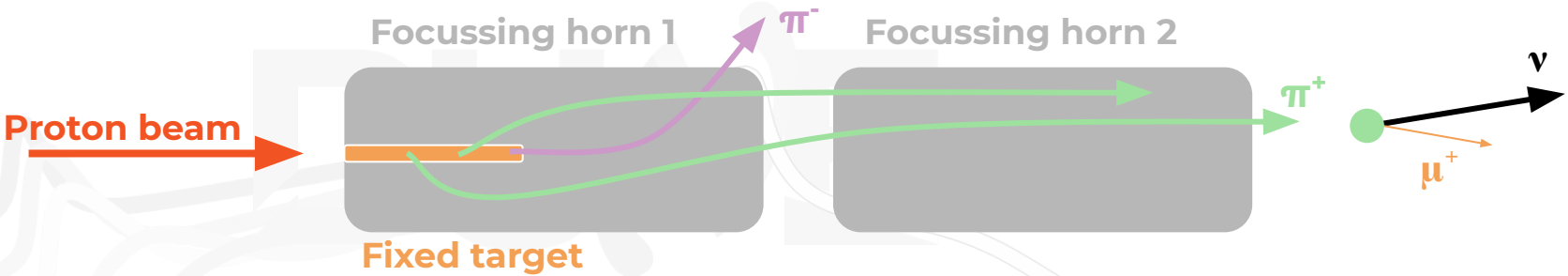
- This secondary beam of particles decays to produce neutrinos.

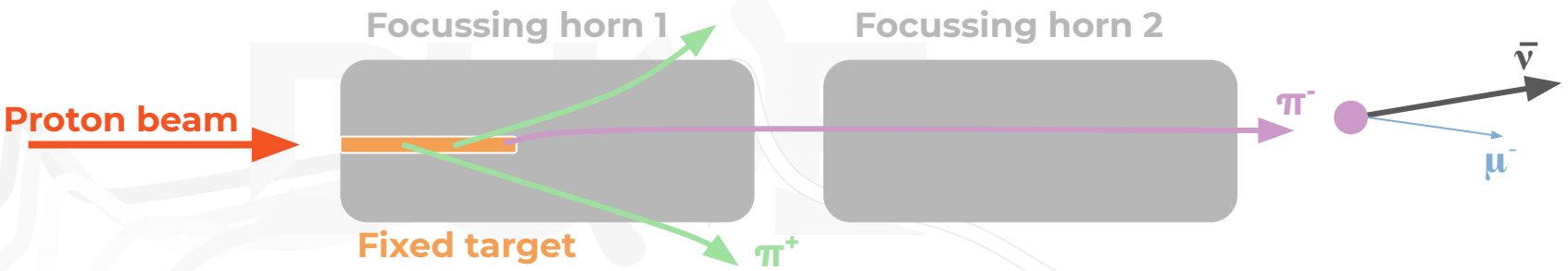
Producing a Beam of Neutrinos



Neutrino mode, focussing positive particles

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

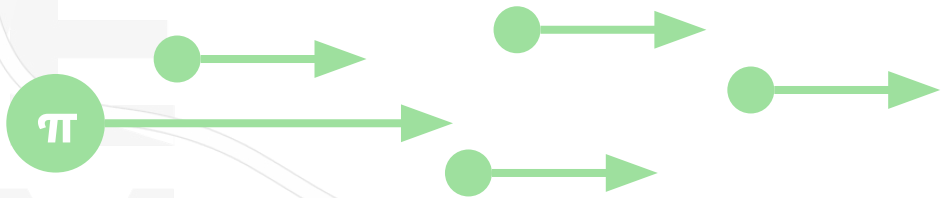
Producing a Beam of Neutrinos



Anti-neutrino mode, focussing negative particles

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

Neutrinos On their Way



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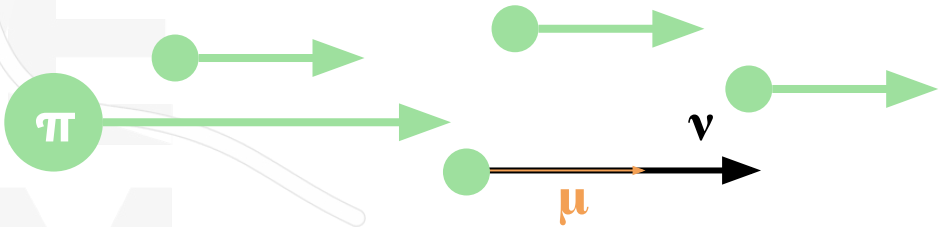

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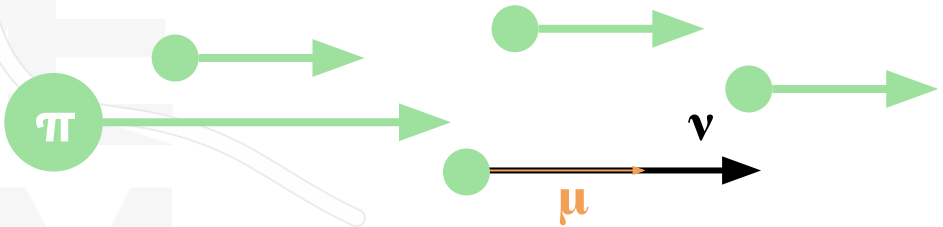
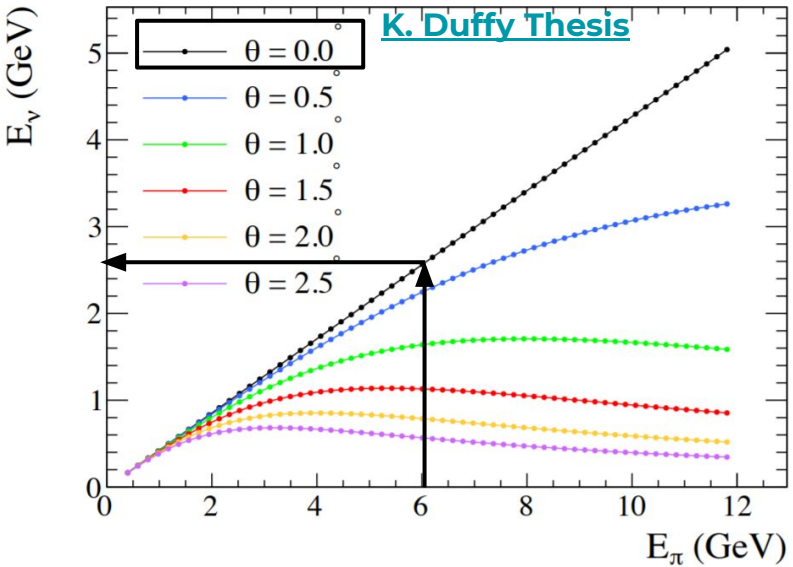
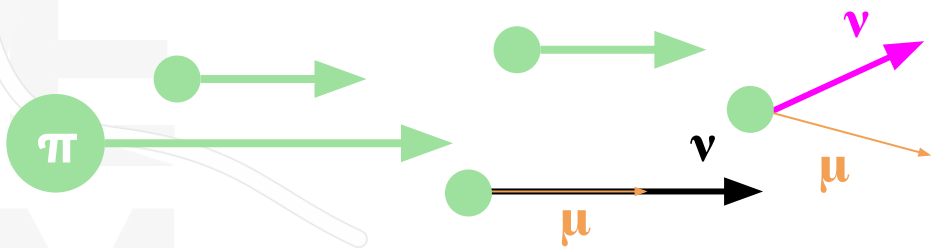
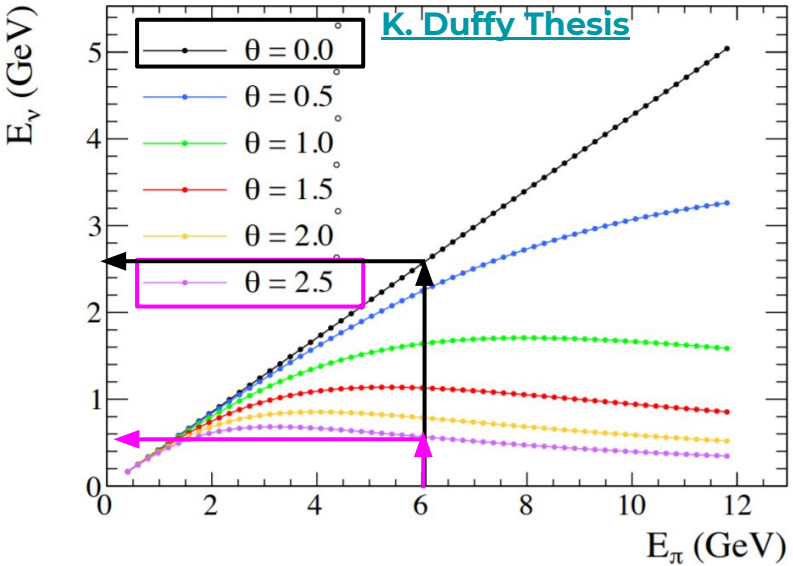




Neutrinos On their Way Off Axis

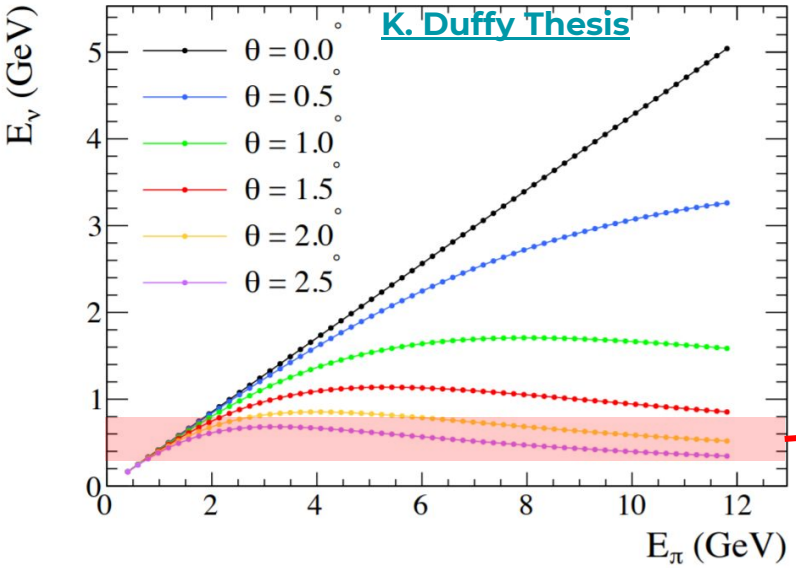
- Boosted π decay kinematics result in lower energy neutrinos off beam axis.

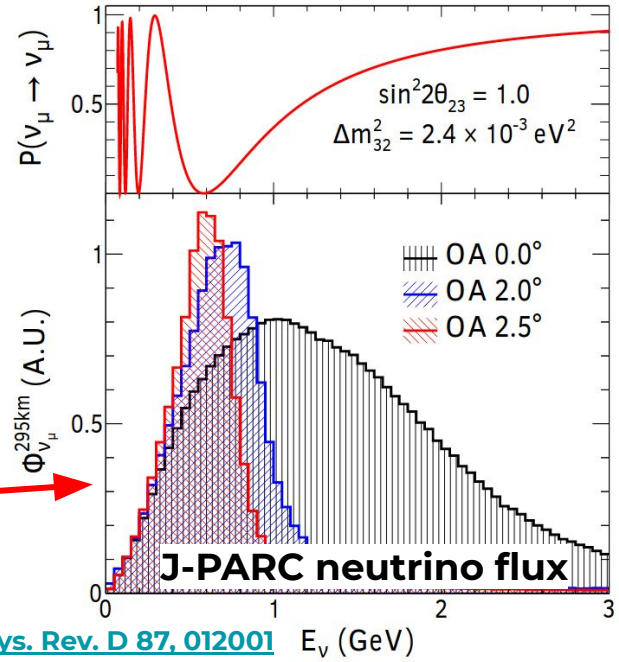




Neutrinos On their Way Off Axis

- 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

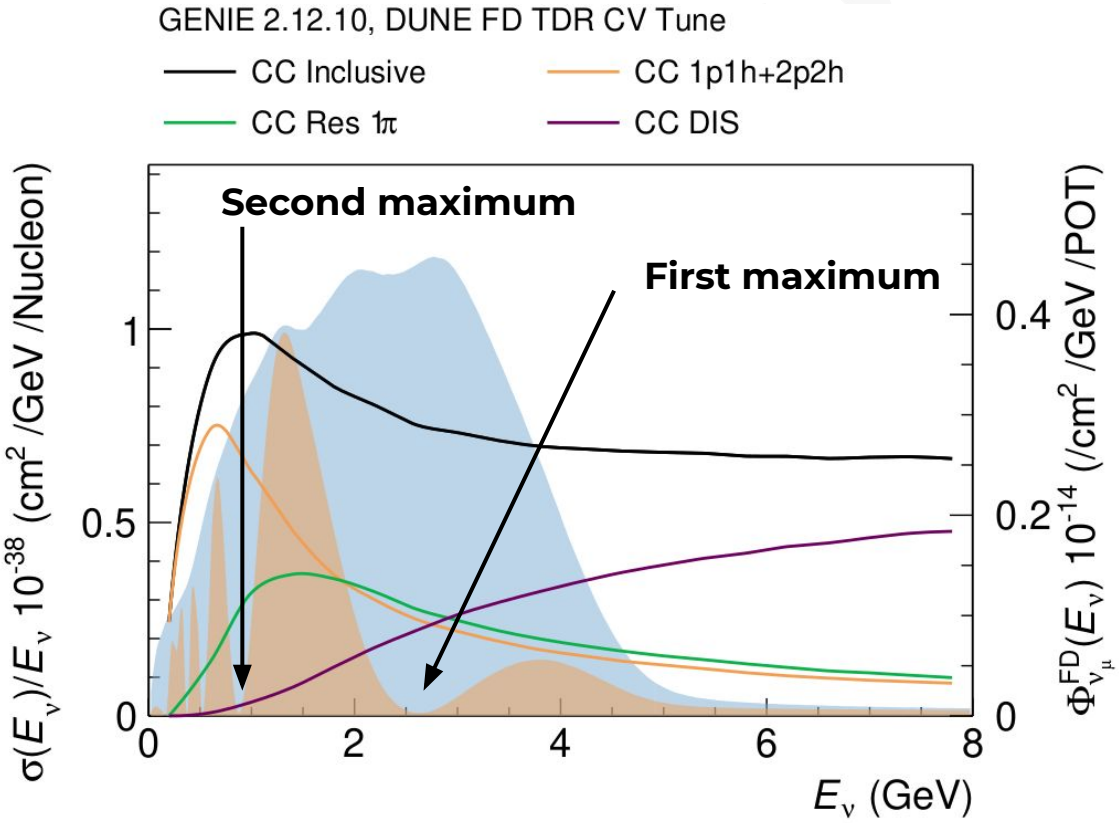


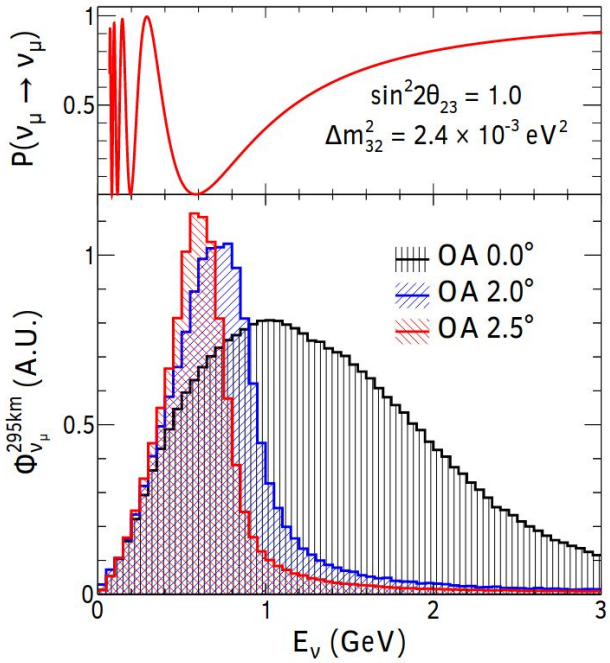


Phys. Rev. D 87, 012001

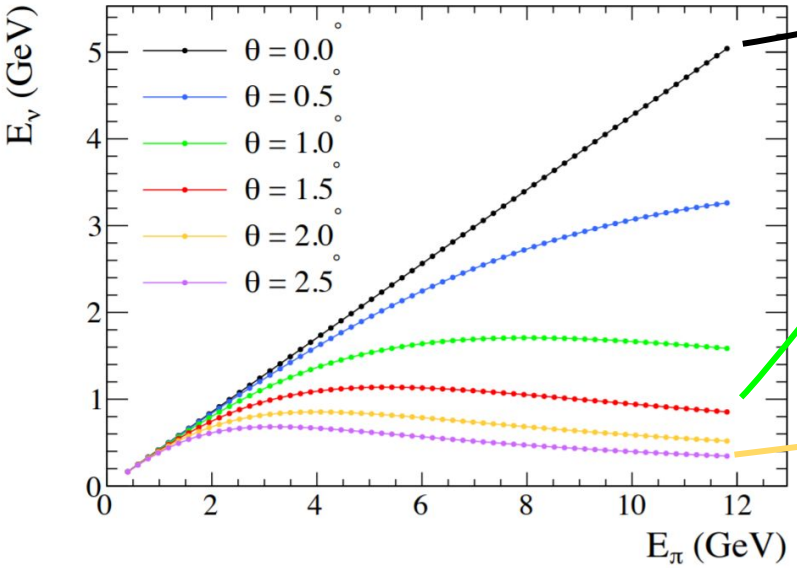
On-axis Beams

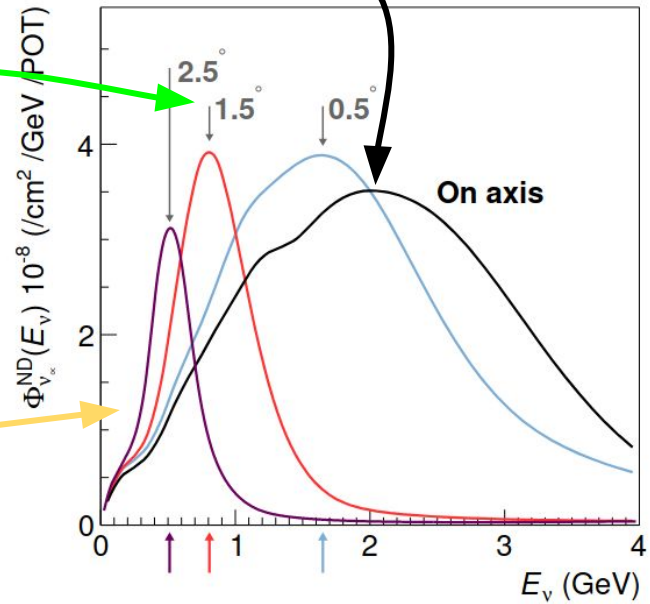
The DUNE far detectors will sit on axis to be exposed to the wide band beam





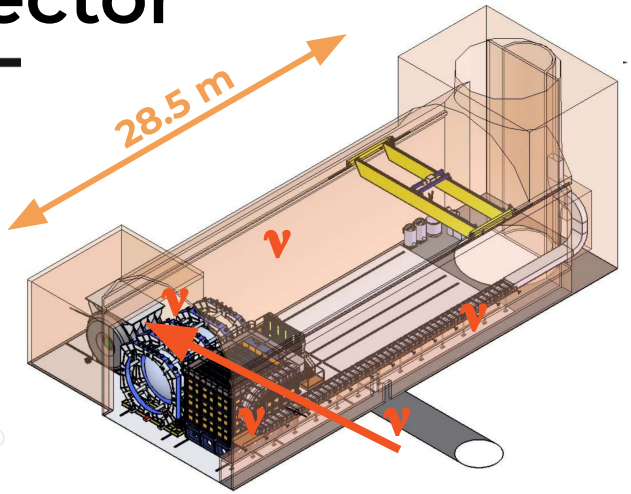
Off Axis at the DUNE Near Detector

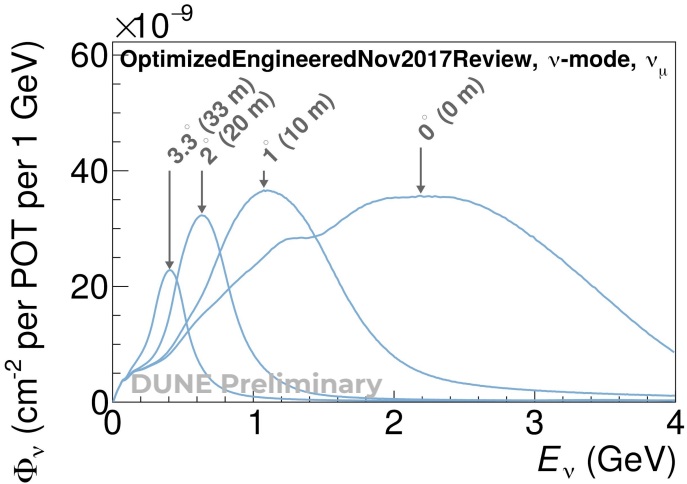




Off Axis at the DUNE Near Detector

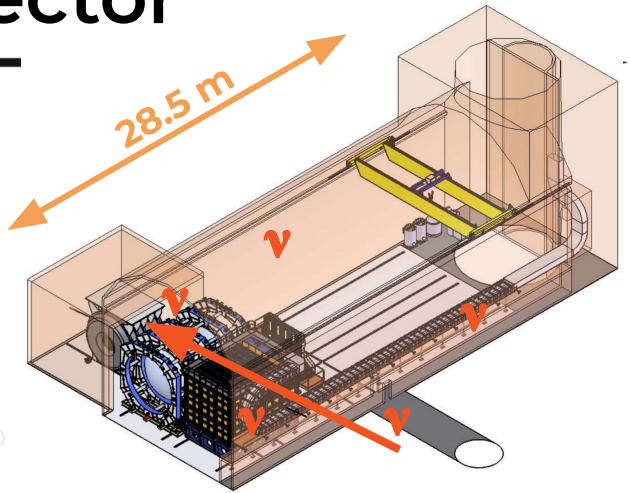
- Use a mobile Near Detector
  - Sample different neutrino energy spectra at different positions

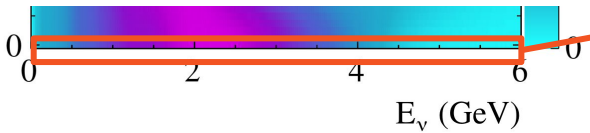


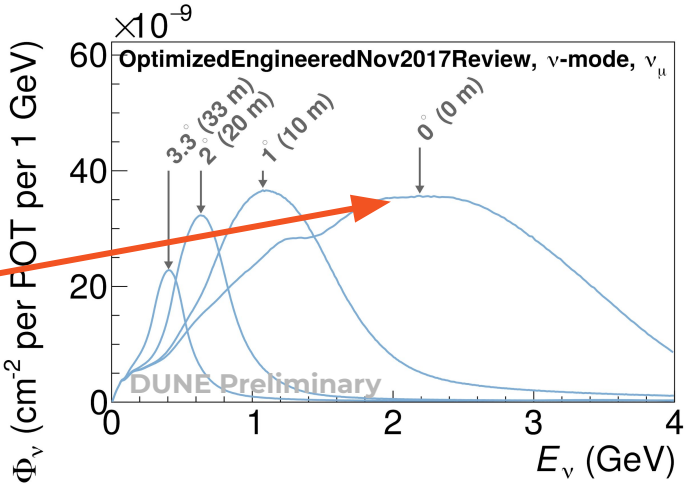


Off Axis at the DUNE Near Detector

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







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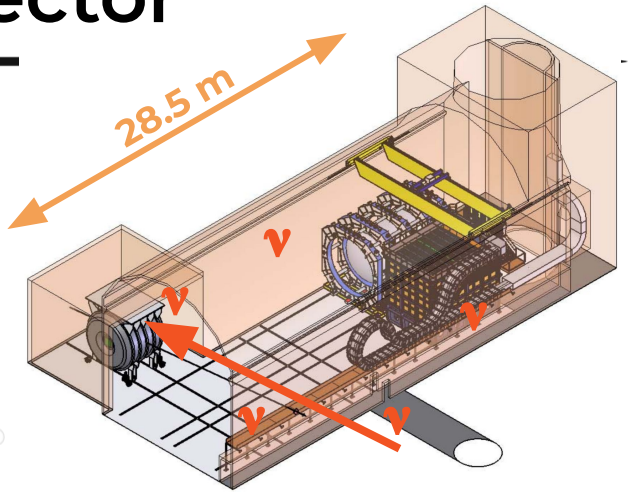

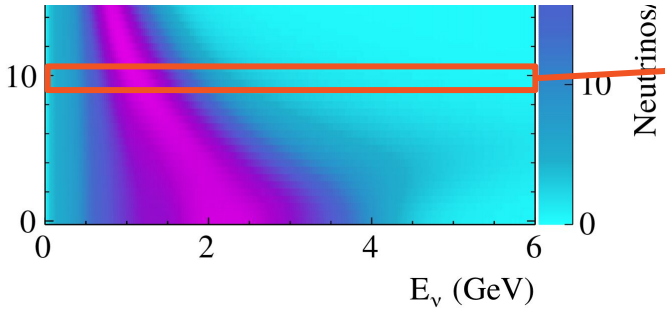

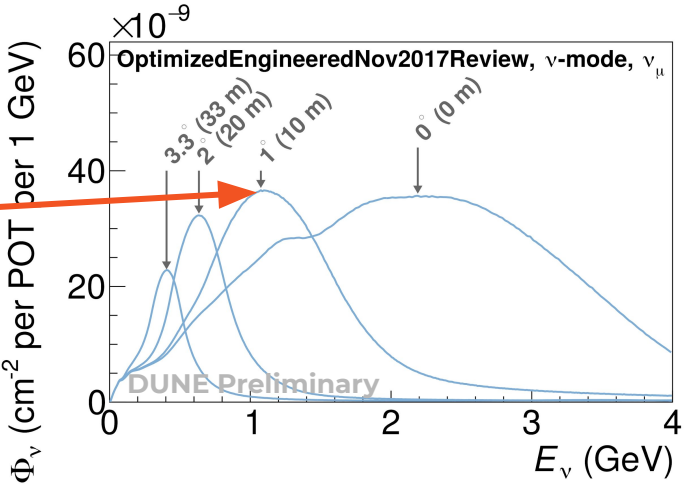

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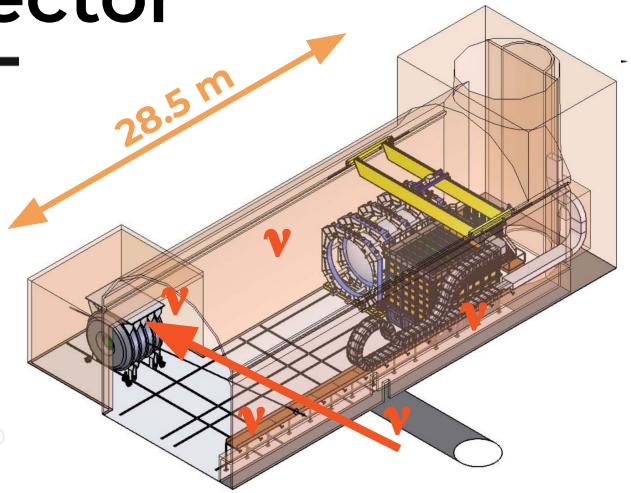

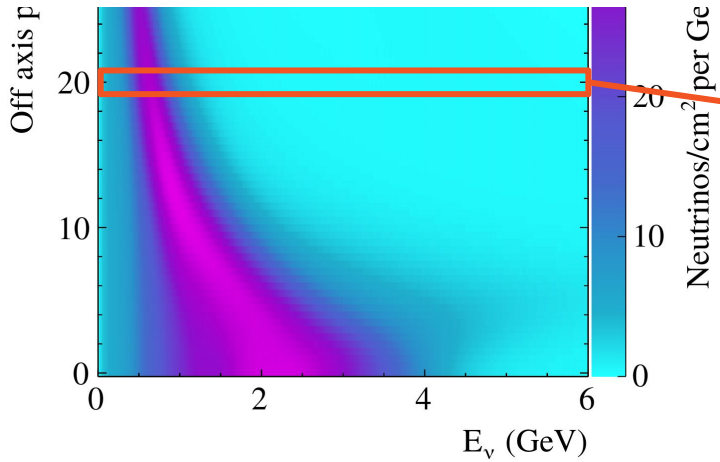

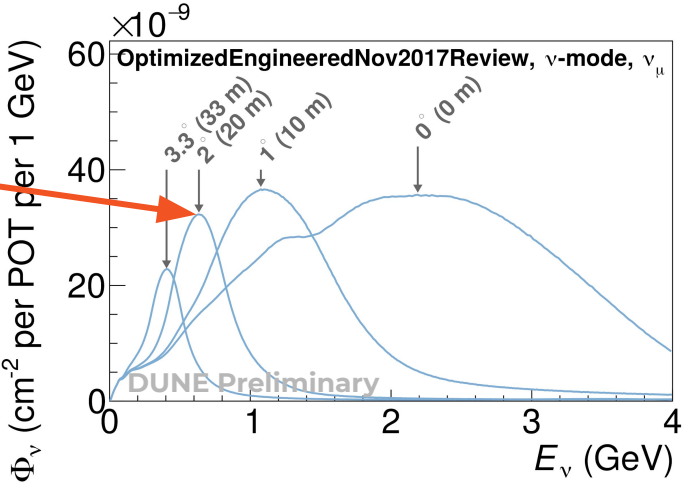

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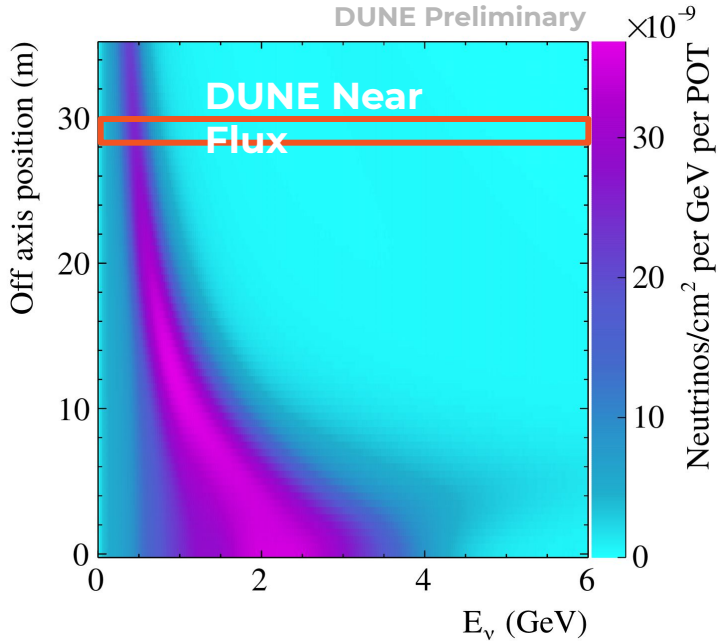
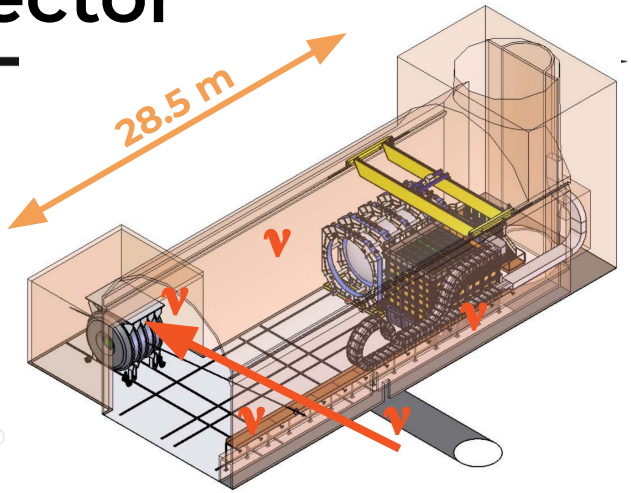
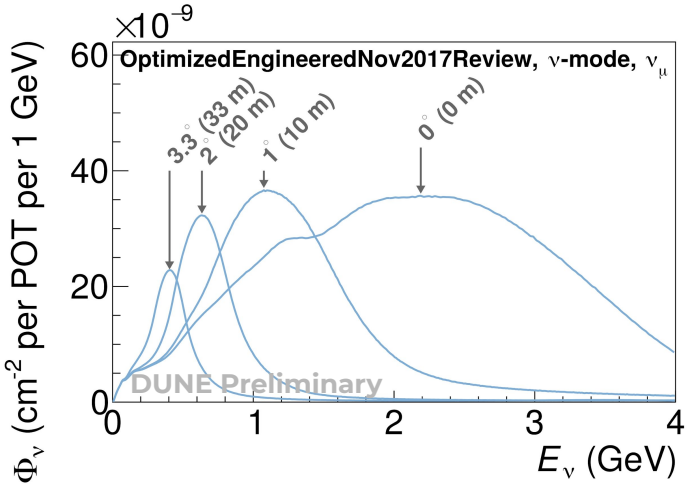
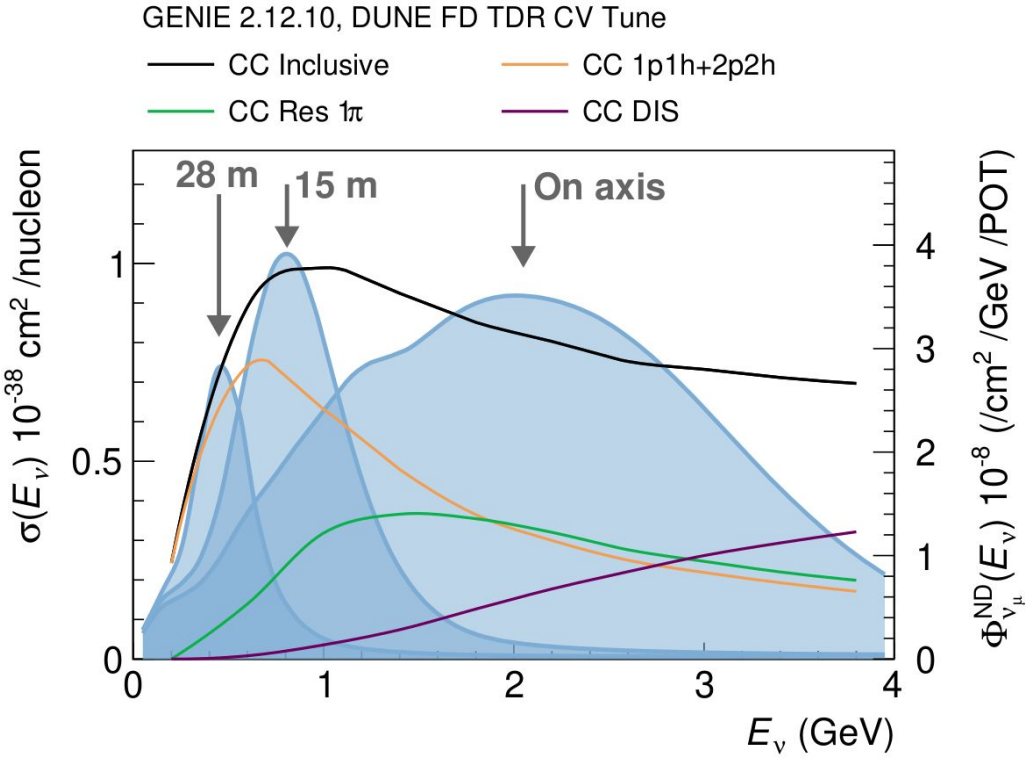






Off Axis Near Detector Measurements

- Mobile near detector allows us to make cross-section measurements in different energy distributions:
  - same detector
  - same target material as FD
- DUNE's mobile near detector opens up a new degree of freedom never before used in a cross-section measurement programme.

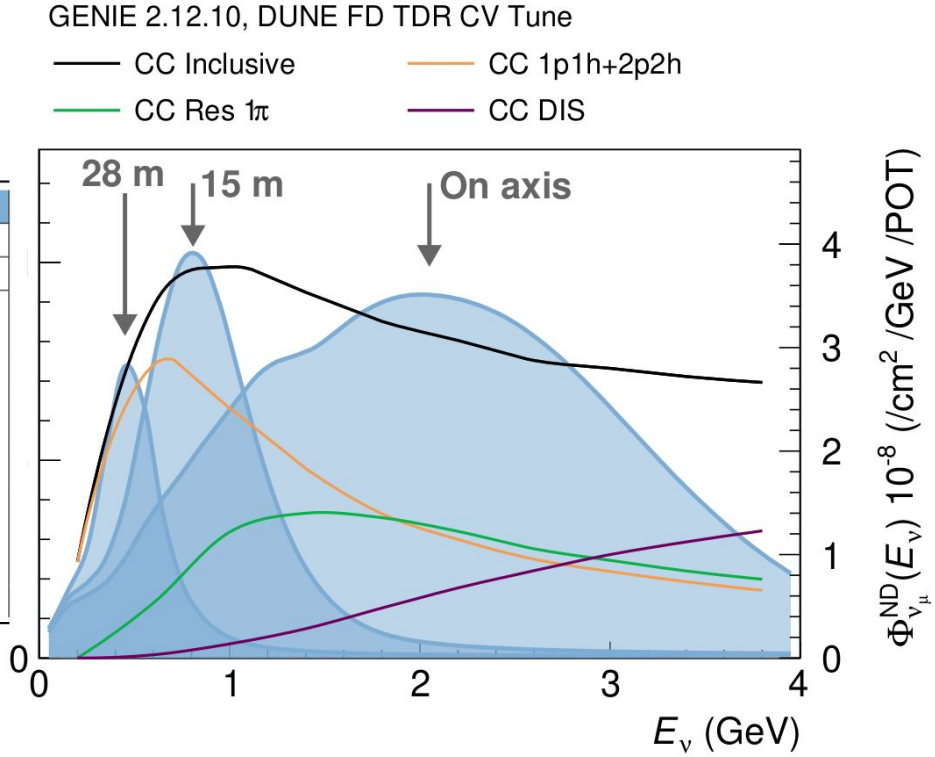


Off Axis Near Detector Measurements

- Mobile near detector allows us to make cross-section

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

cross-section measurement programme.



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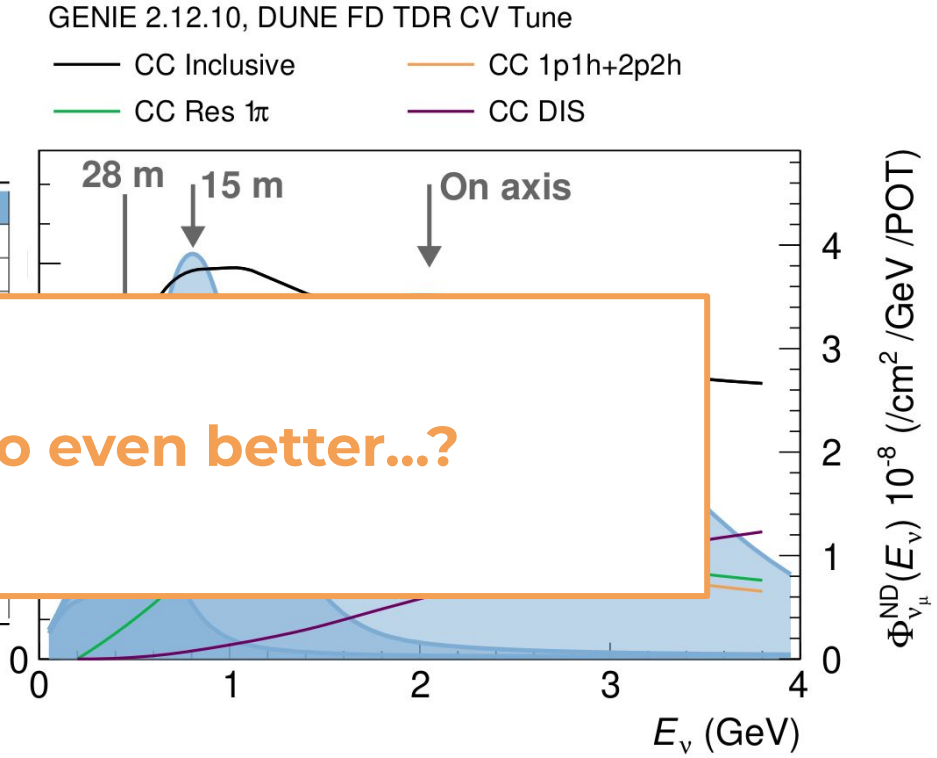
Off Axis Near Detector Measurements

- Mobile near detector allows us to make cross-section

		ND-LAr				ND-GAr
		All int.	Selected			All int.
Stop	Run duration	$N_{\nu_\mu CC}$	N_{Sel}	WSB	NC	$N_{\nu_\mu CC}$
On axis (293 kA) m						
On axis (280 kA) m						
4 m off axis m						
8 m off axis m						
12 m off axis m						
16 m off axis m						
20 m off axis m						
24 m off axis m						
28 m off axis m						
30.5 m off axis m	12 dys.	87,000	39,000	2.5%	0.7%	2,500



But can we do even better...?

cross-section measurement programme.

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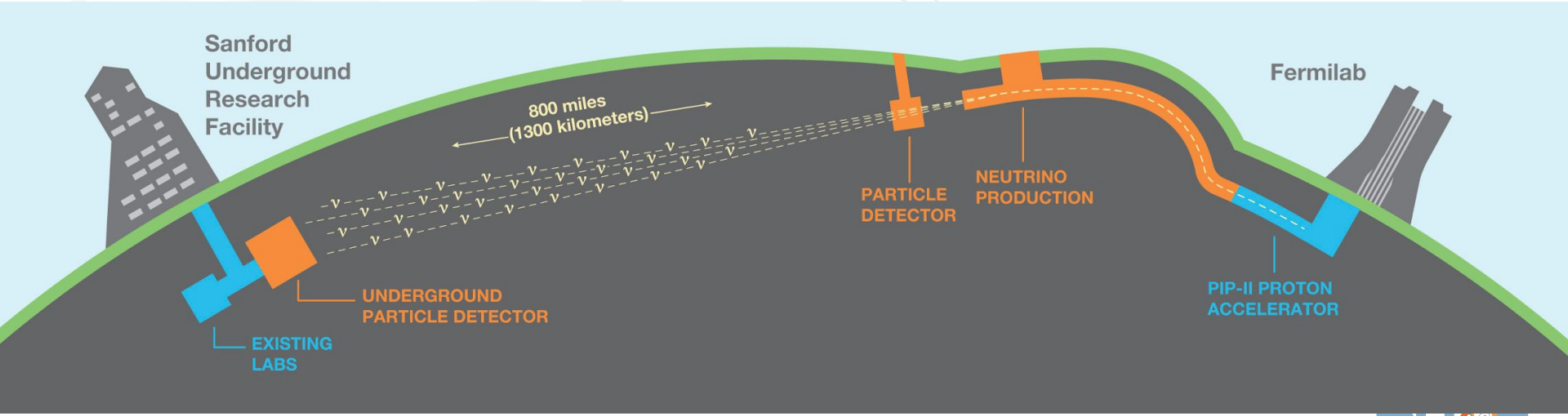
DUNE PRISM

This Talk

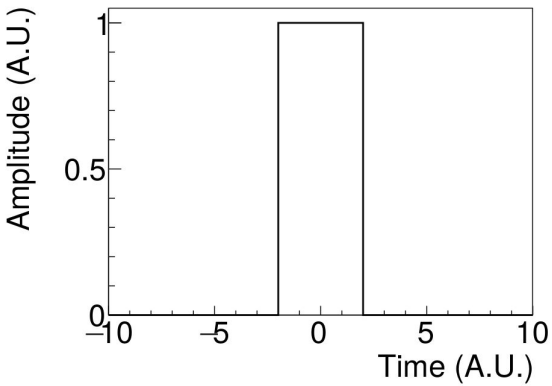
- **DUNE Oscillation Physics Reminder**
- **The LBNF Beam**
- **Motivating DUNE-PRISM**
- DUNE-PRISM as an analysis machine



A Quick Aside

Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines



Discrete Fourier Transforms

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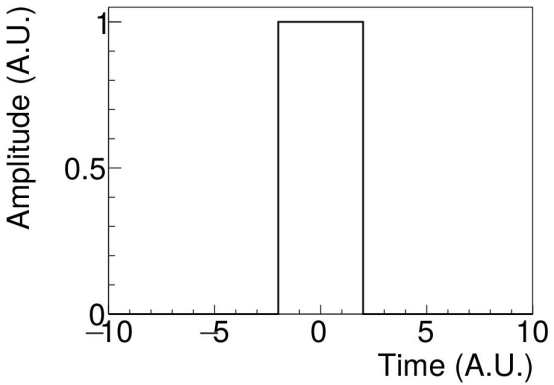

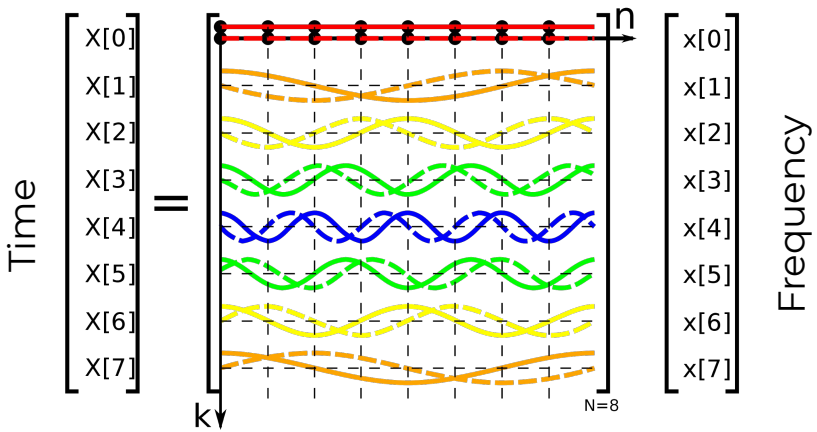

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Discrete Fourier Transforms

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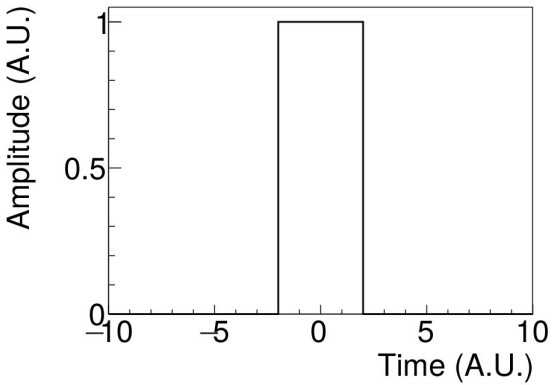

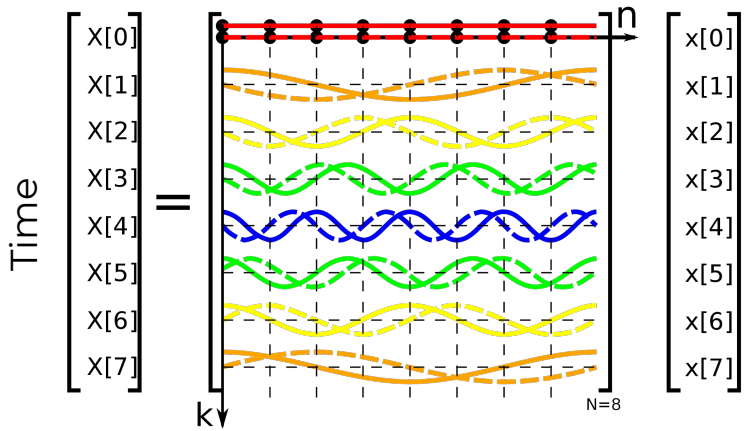

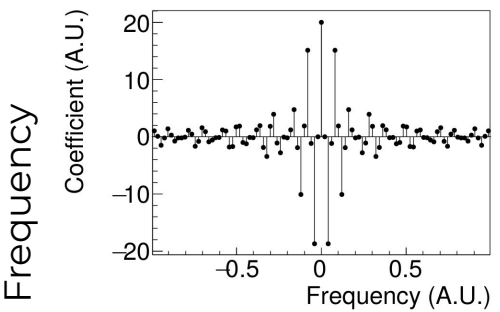

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Discrete Fourier Transforms

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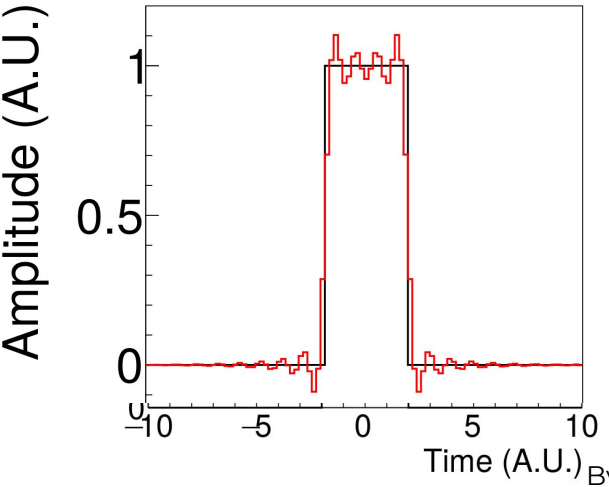

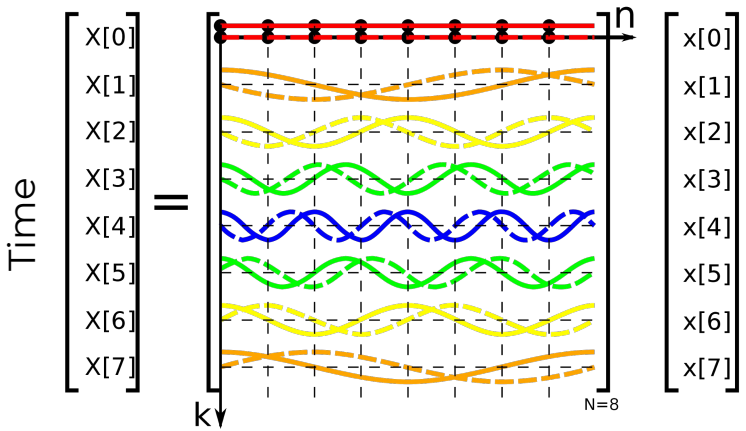

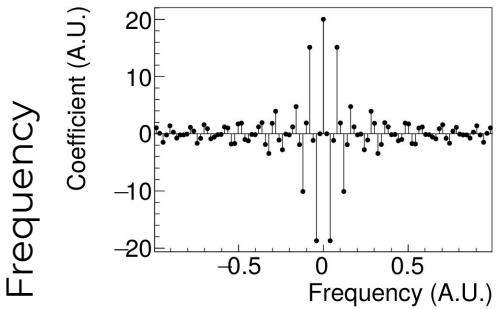

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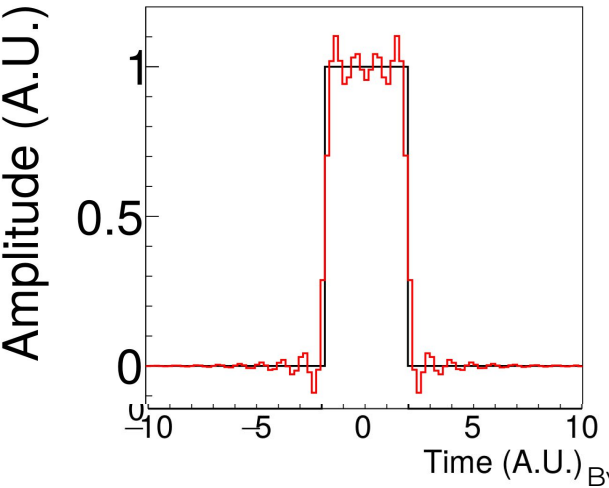
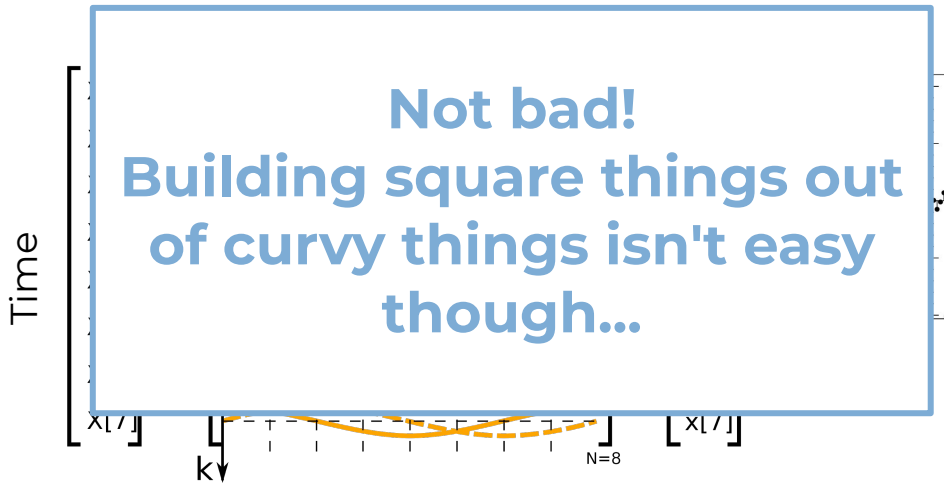
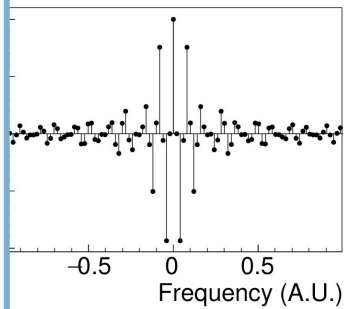
Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines







Not bad!
Building square things out of curvy things isn't easy though...

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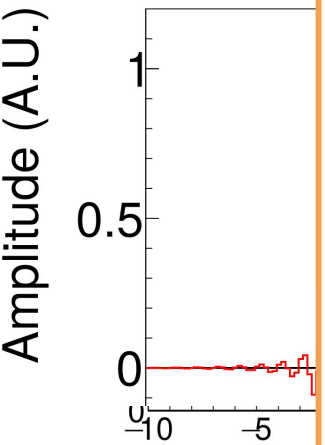
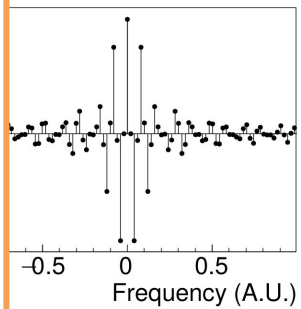
Discrete Fourier Transforms

- 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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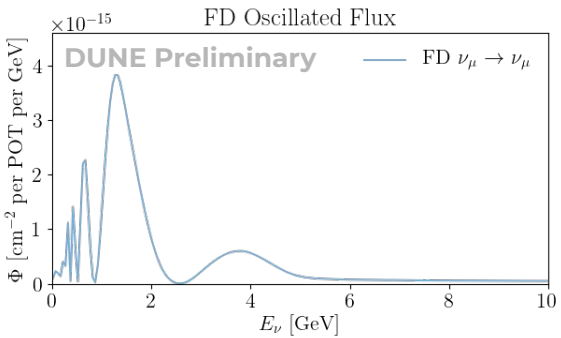
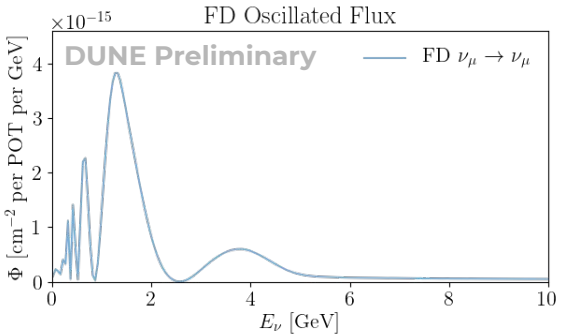
Building an Oscillated Flux

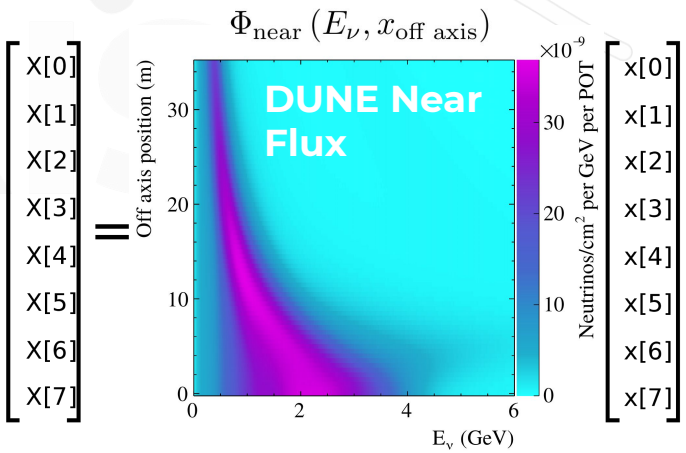
- Want to measure oscillated flux at the near detector



Building an Oscillated Flux

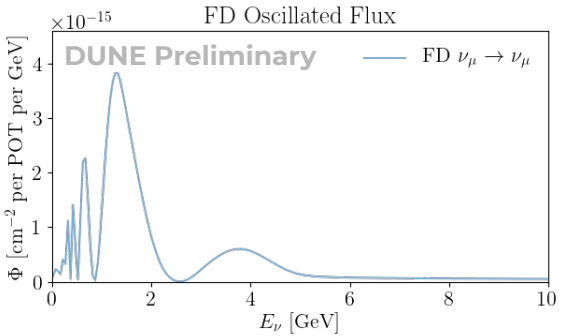
- Want to measure oscillated flux at the near detector
  - **Try to decompose into a linear sum of off-axis near detector fluxes (*c.f.* Discrete FT)**

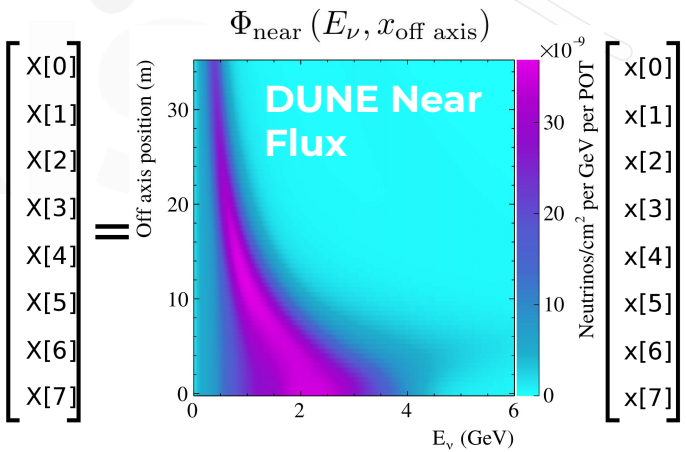


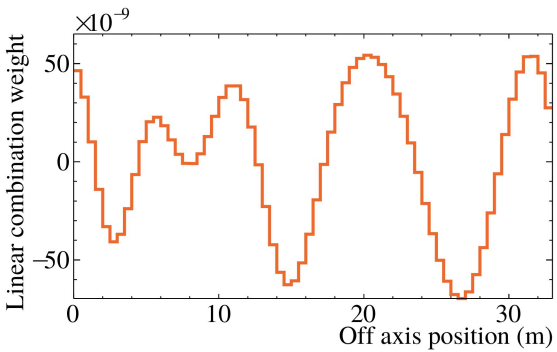


Building an Oscillated Flux

- 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**

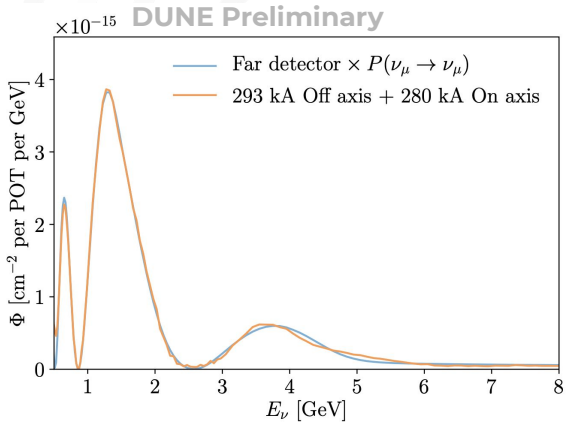


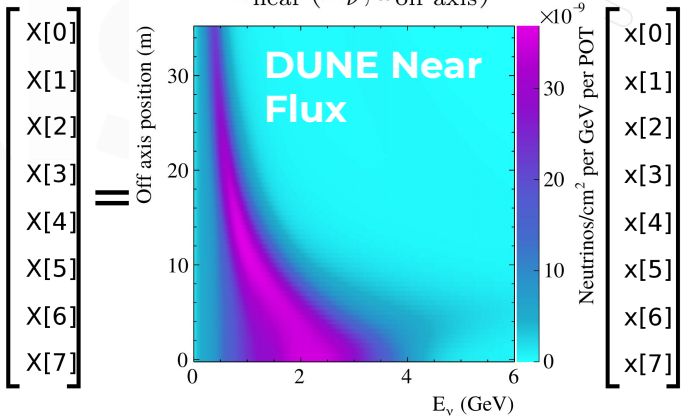


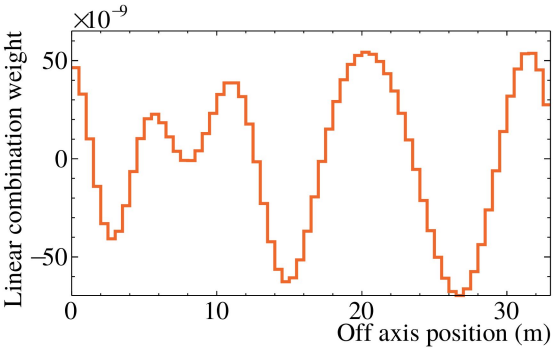


Building an Oscillated Flux

- 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?**



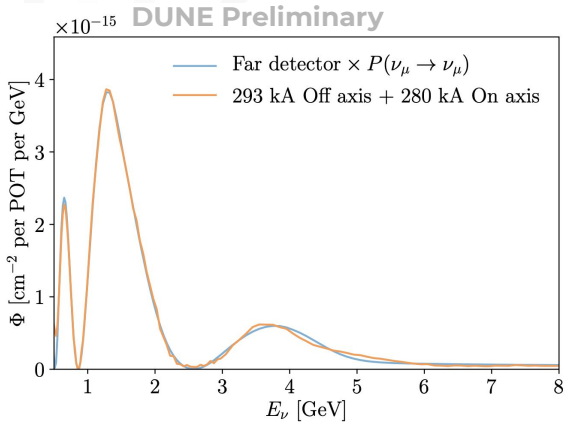


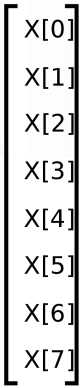


Building a

- Want to meas
  - Try to decon
  - Solve for wei
  - How good is

Discrete FT)





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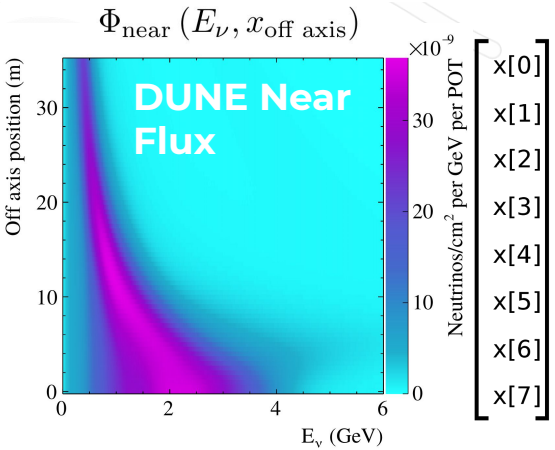
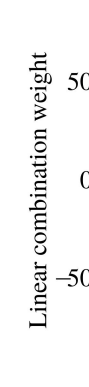
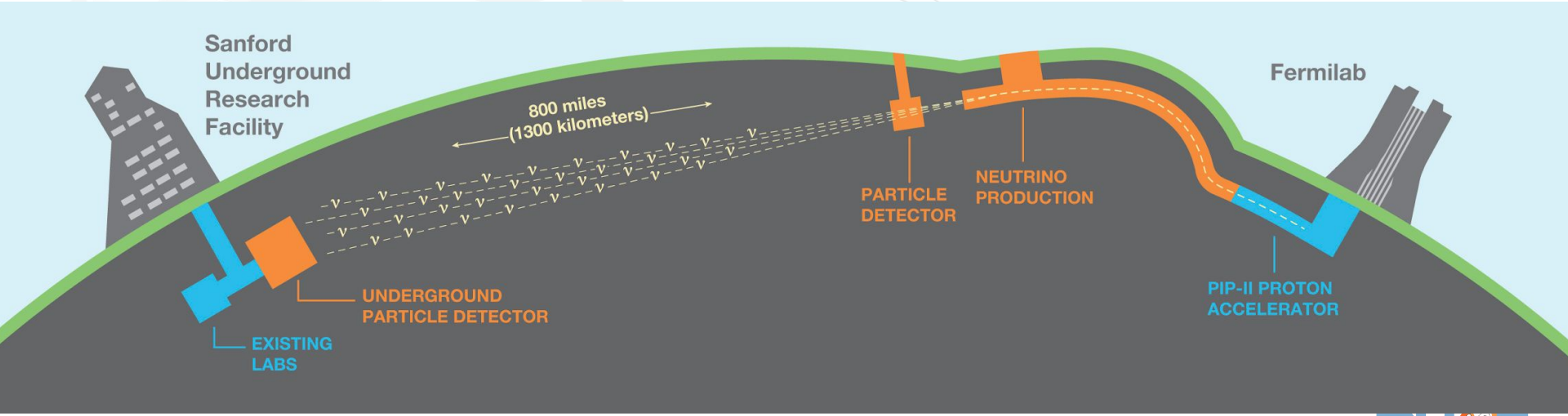




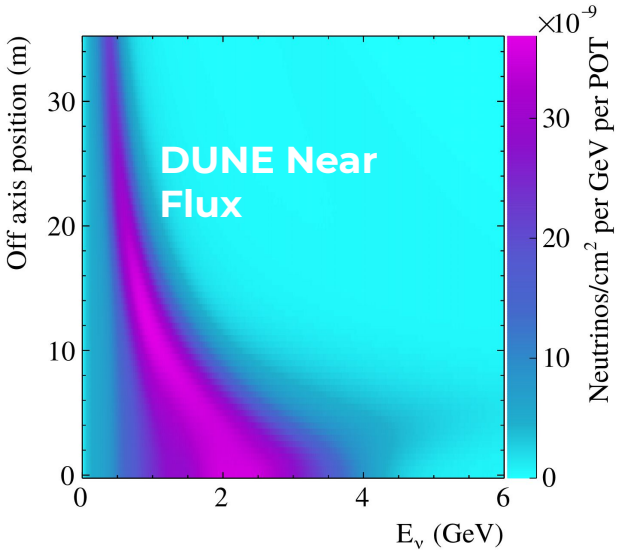
This Talk

- DUNE Oscillation Physics Reminder
- The LBNF Beam
- Motivating DUNE-PRISM
- DUNE-PRISM as an analysis machine

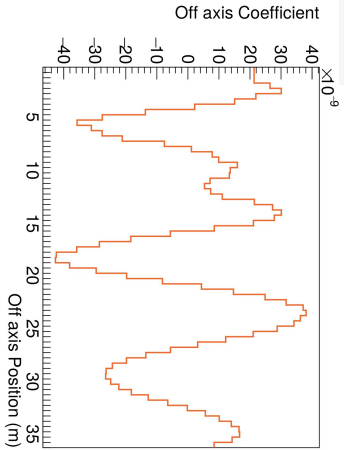


Building a Far Detector prediction

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



X



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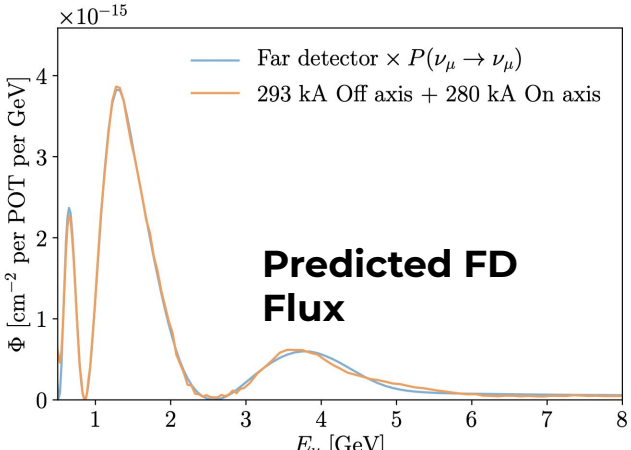

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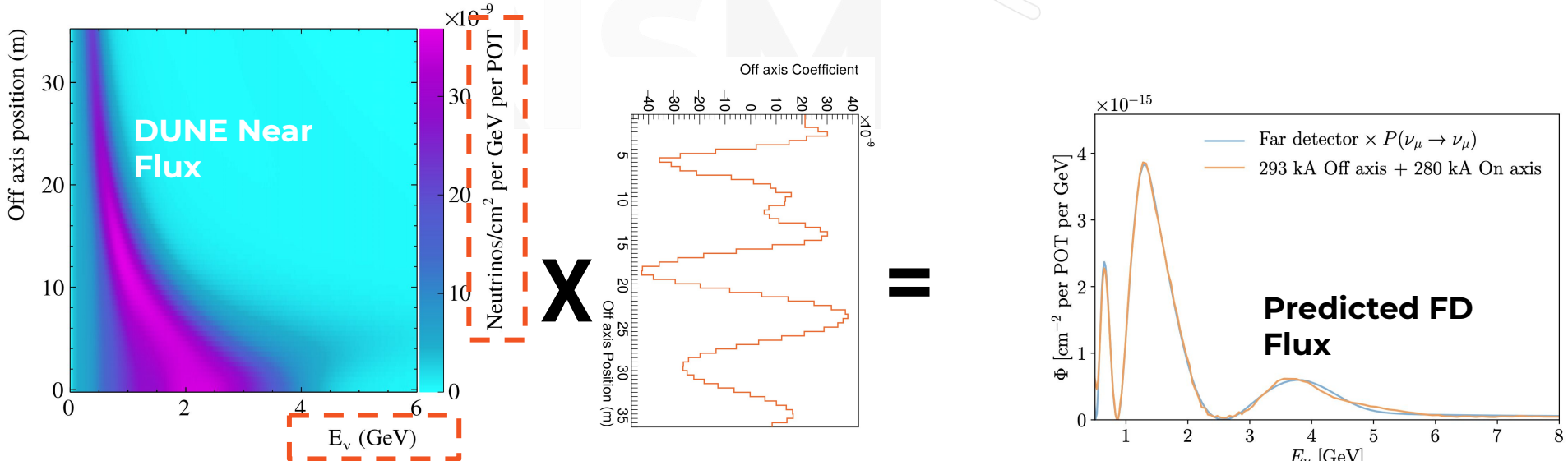

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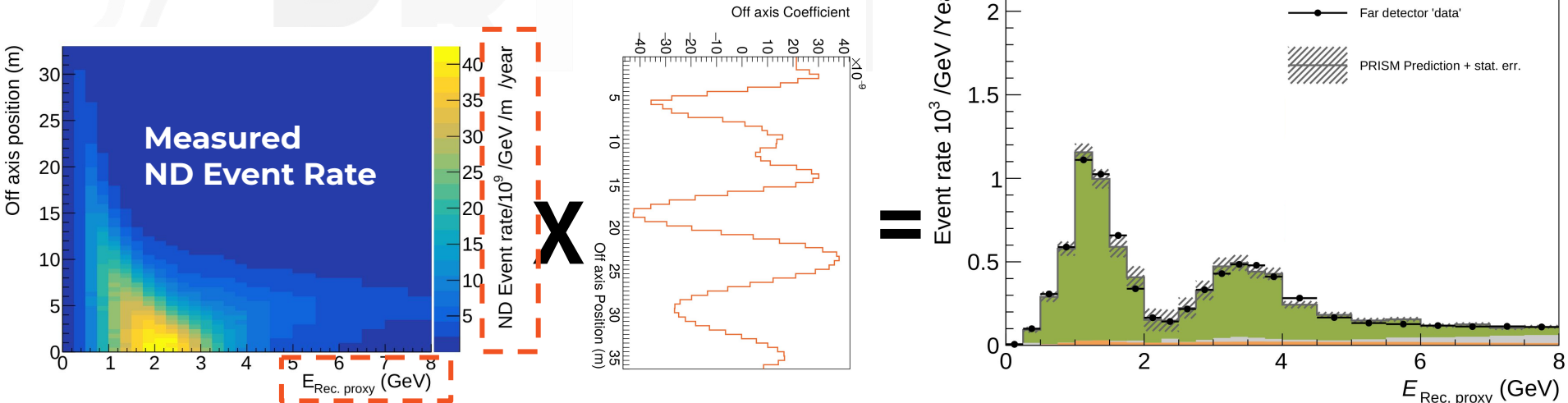

Other Linear Combinations

- So far have used the linear combinations to make measurements in an oscillated flux.
  - Not particularly useful for making cross-section measurements.

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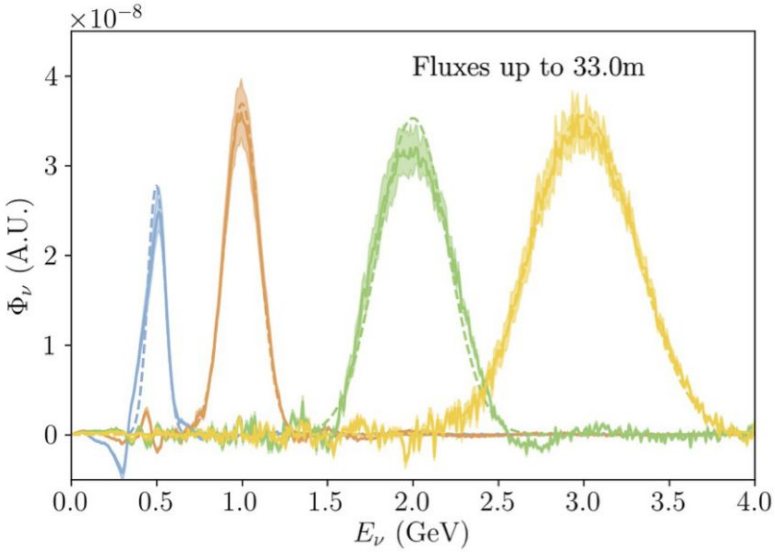
  - Most useful is to build narrow-band 'gaussian' fluxes



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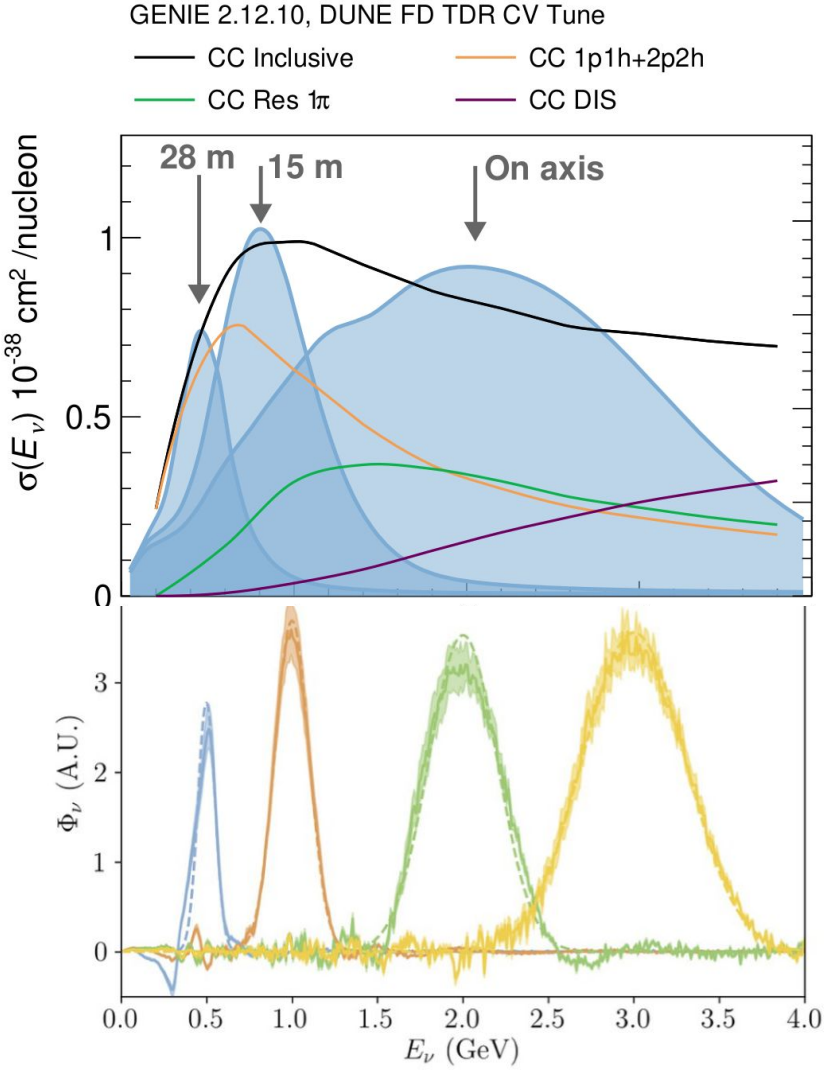
- So far have used the linear combinations to make measurements in an oscillated flux.
  - Not particularly useful for making cross-section measurements.
- Can linearly combine measurements in other ways:
  - Most useful is to build narrow-band 'gaussian' fluxes
  - Significantly finer spectrum than obtained by sampling at a single off axis position.



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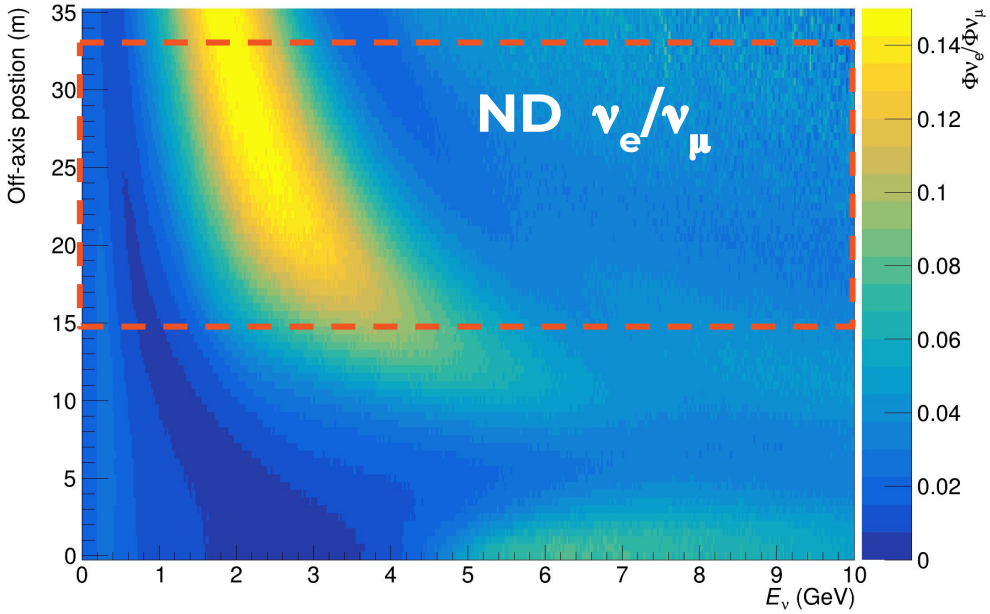
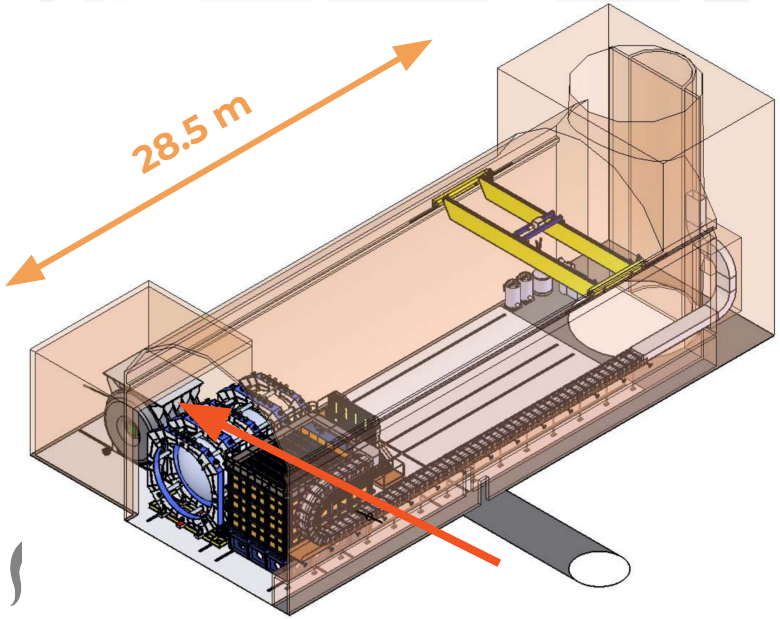
Capturing Some Nues

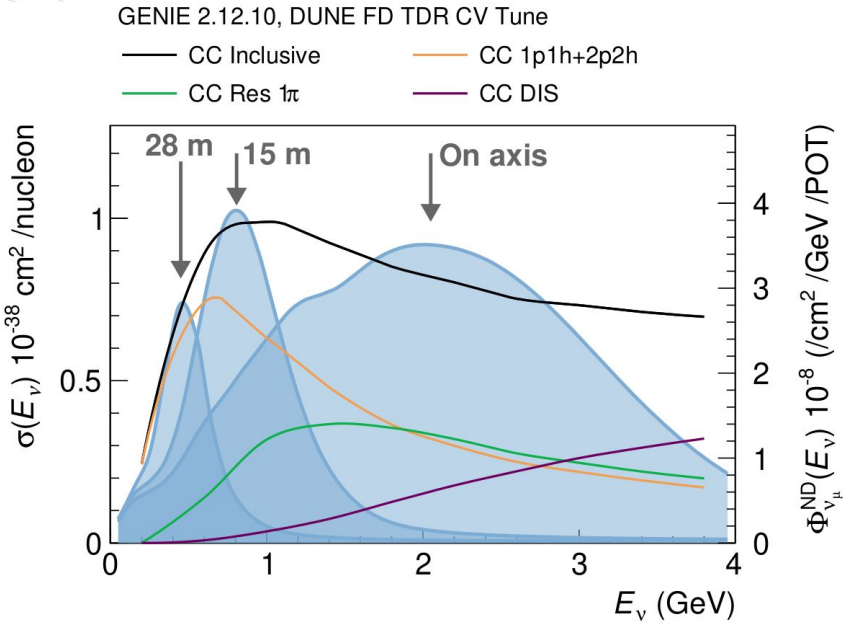
- Because of the different tertiary meson beam decays that produce muon and electron neutrinos, we expect a higher proportion of electron neutrinos off axis:
  - Rates are low, but purity is significantly higher
  - Combine with on-axis measurements to obtain nue/numu cross-section constraint that is vital for CPV measurements!



Summary

- Mobile near detector opens up a new degree of freedom that is strongly correlated with neutrino energy.
- Moving giant liquid argon detectors is fun and cool.





Thanks for listening

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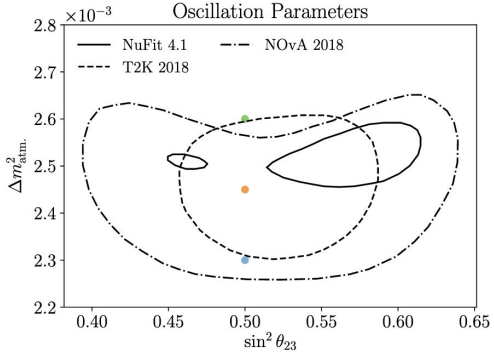
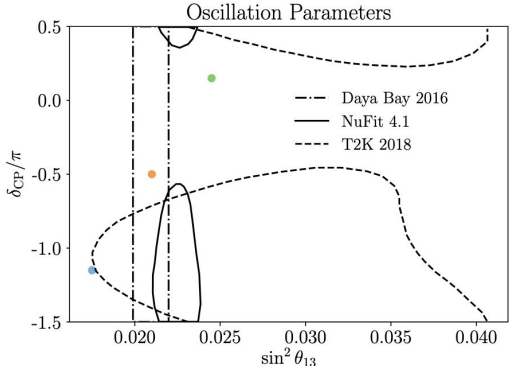
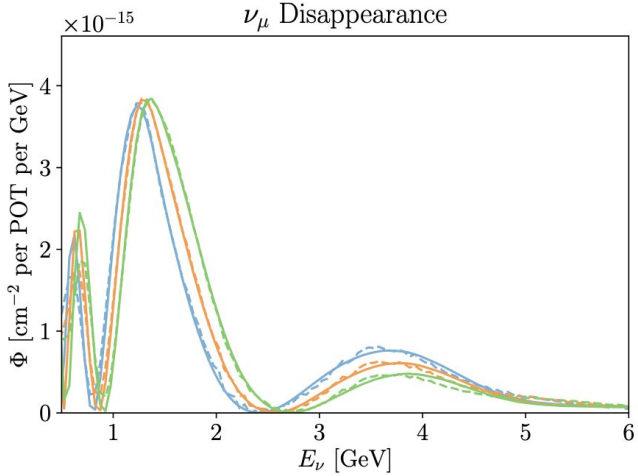
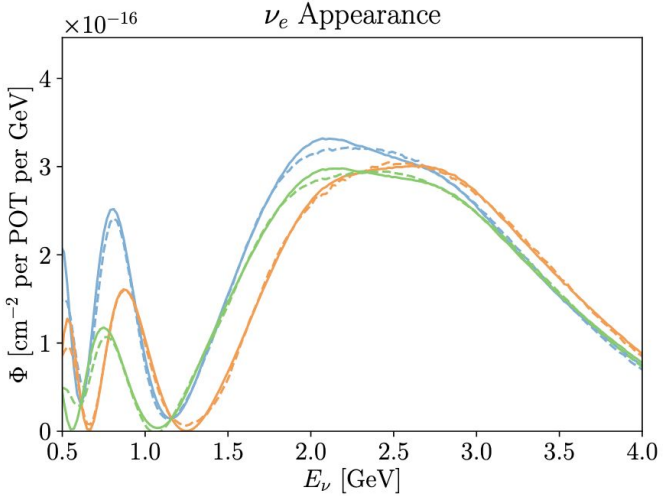
Is this the only Game we can Play?



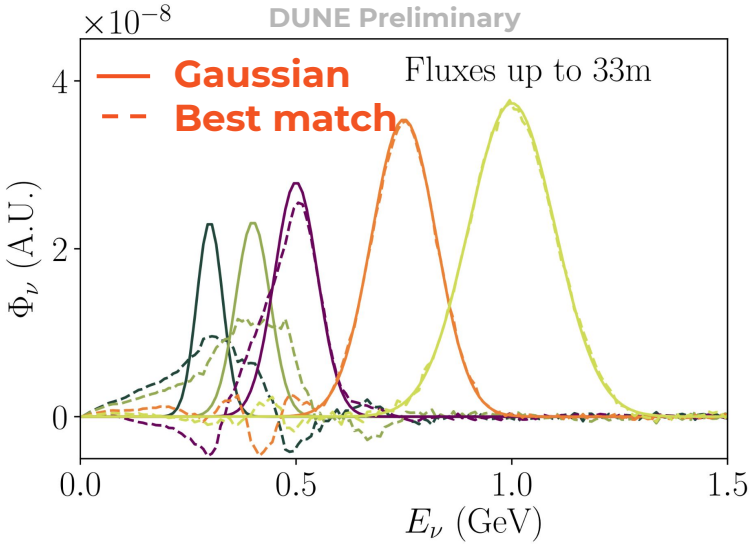




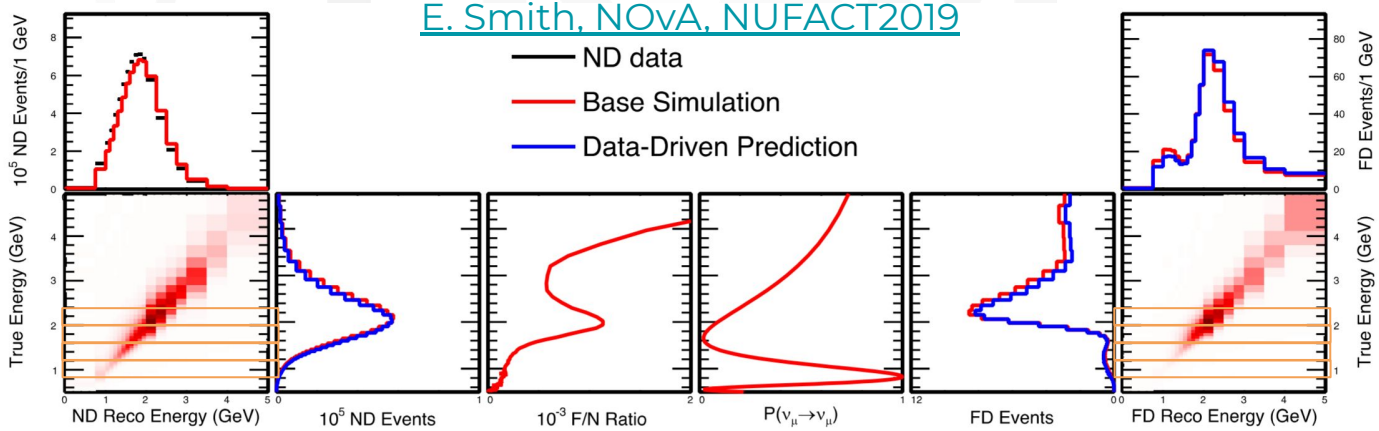


Narrow-band fluxes

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

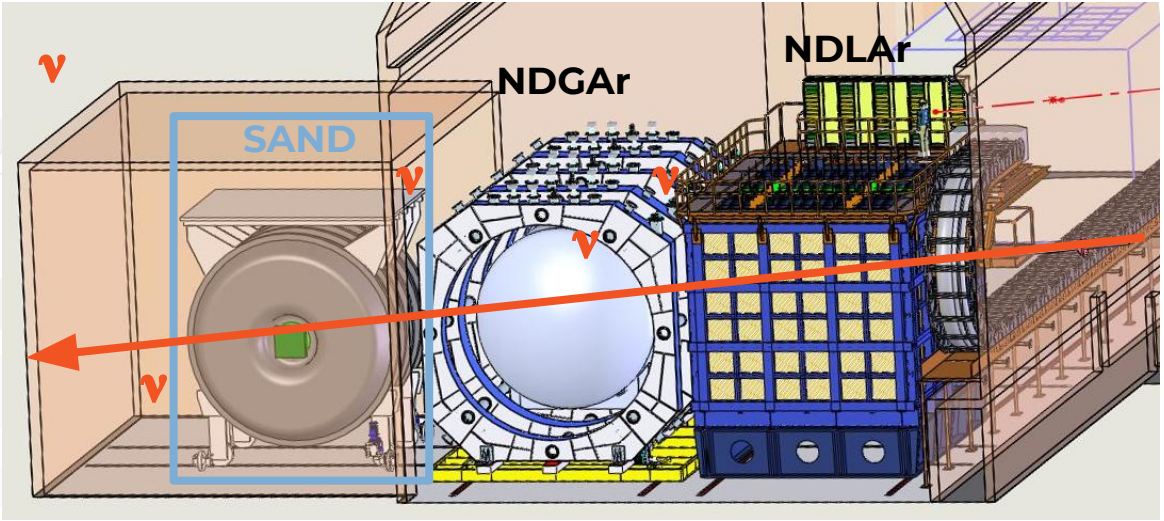


E. Smith, NOvA, NUFACT2019



DUNE Near Detector Concept

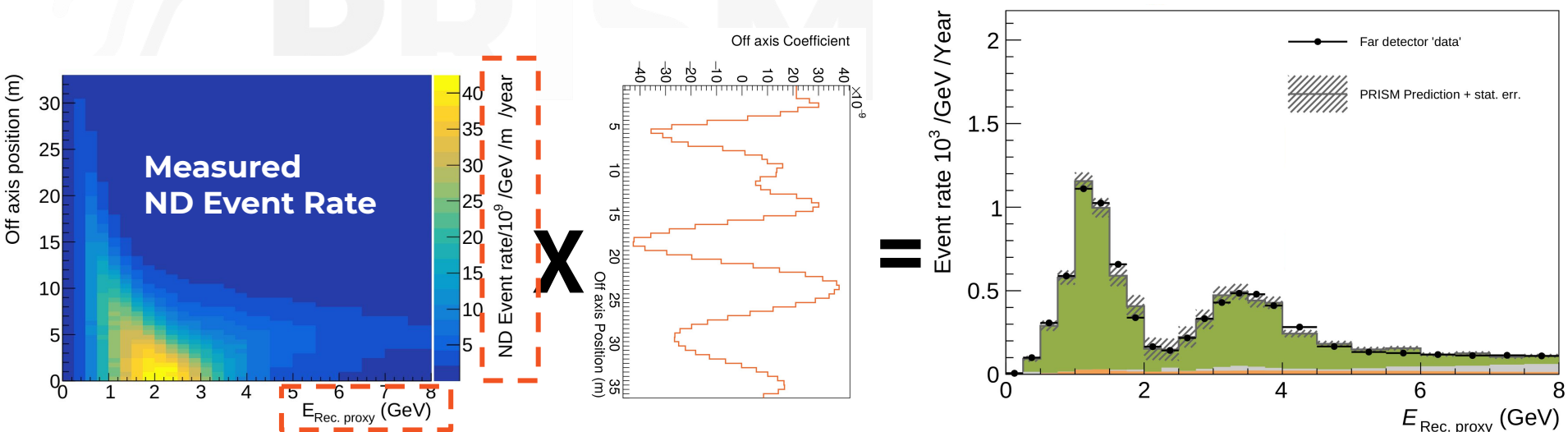
- **ArgonCube**: LAr TPC
  - Primary target, similar to FD
- **MPD**: GAr TPC + ECal + Low mass magnet
  - Charge/momentum/PID
  - Low threshold neutrino target
- **SAND**: 3D plastic scintillator detector inside a superconducting solenoid:
  - Beam monitor
  - Neutrino interaction physics



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

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!



How does that help?

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

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

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

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

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How does that help?

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

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

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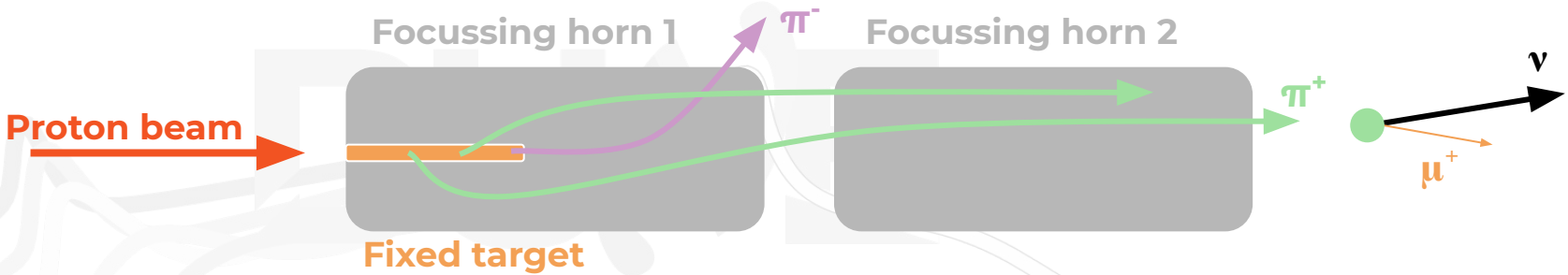
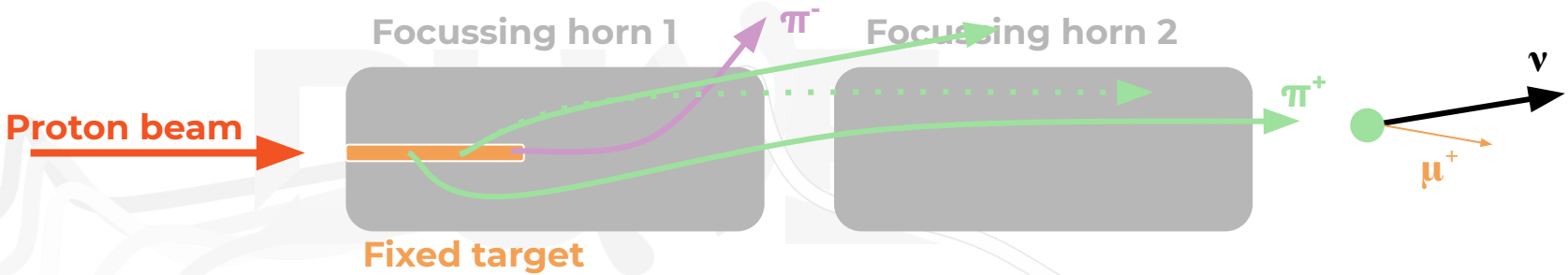
Special Horn Current Runs



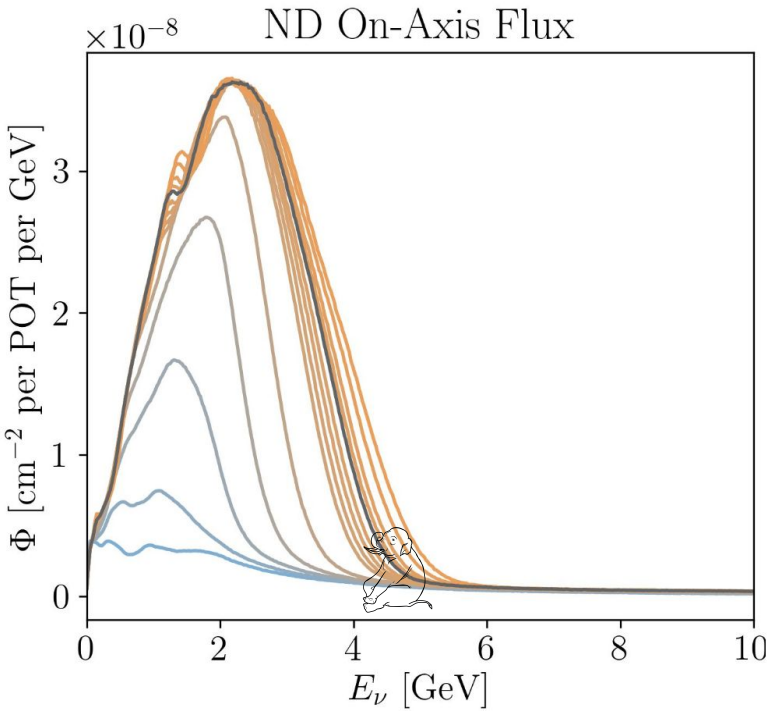
- If we vary the current in the magnetic horns, we change their momentum acceptance

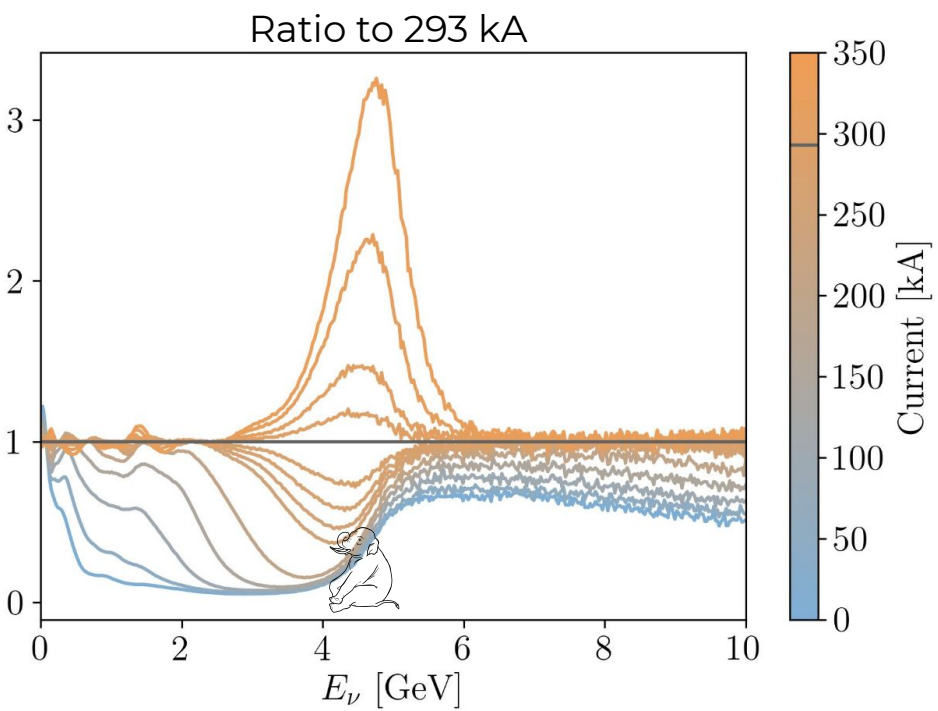
Special Horn Current Runs



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

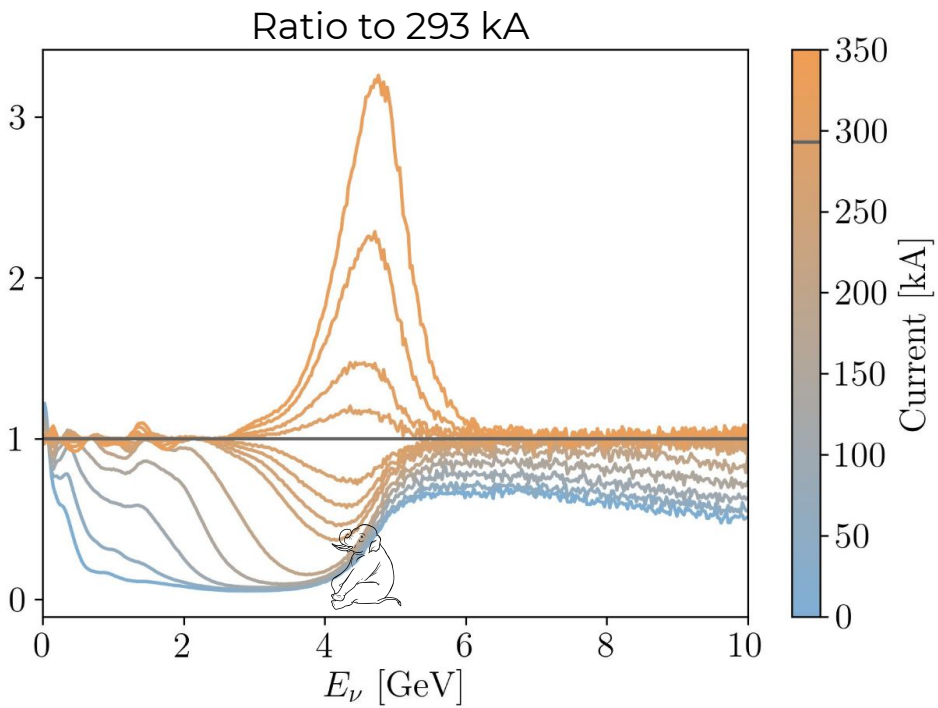
Special Horn Current Runs





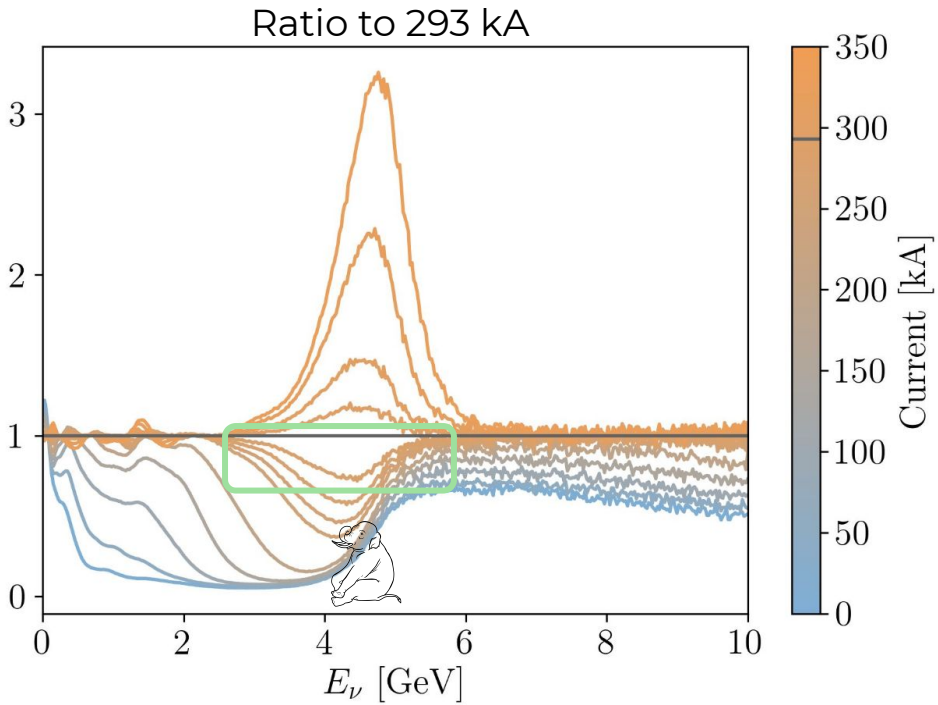
Special Horn Current Runs

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



Special Horn Current Runs

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



Special Horn Current Runs

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