

Neutrino Oscillation Experiments: Past/Present/Future

Luke Pickering

IOP: Joint APP, HEPP and NP Conference
The Spine, Liverpool

9th of April, 2024

My Perspective (Bias)



- Neutrino Interactions WG



- Long Baseline Oscillations
- DUNE-PRISM

**Focus more on: LBL with beam
& DUNE vs. Hyper-K**

This Talk

- Why Neutrinos Change Flavor
- Anatomy of an Oscillation Experiment
- Long Baseline: Current Generation
- Long Baseline: Next Generation
- Short Baseline Recent Results and Prospects

Why Neutrinos Change Flavor

Unknown Properties of Known Neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}}_{\mathbf{M}_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Unknown Properties of Known Neutrinos

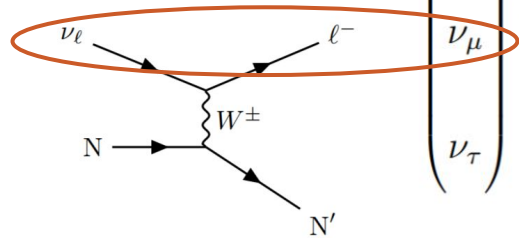
Flavor state defined by paired charged lepton at vertex

The diagram shows a Feynman vertex where a neutrino line (N) and a charged lepton line (l⁻) meet at a vertex labeled W[±]. The neutrino line is labeled ν_ℓ and the charged lepton line is labeled ℓ⁻. The neutrino line is circled in orange. The diagram is followed by an equals sign and a matrix equation:

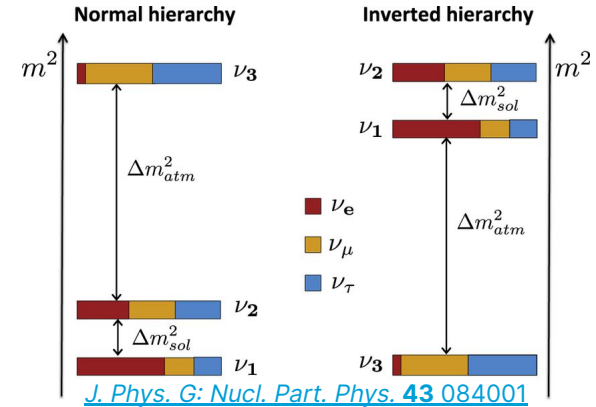
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}}_{\mathbf{M}_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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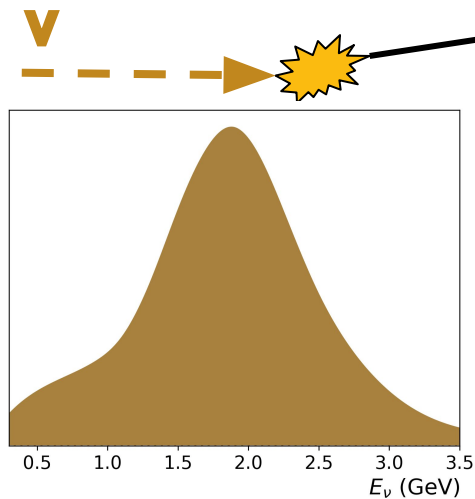
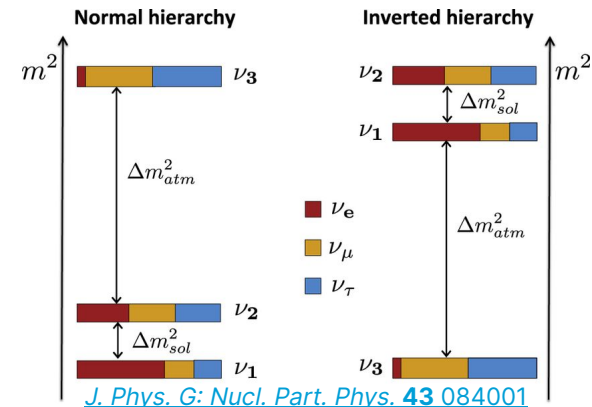
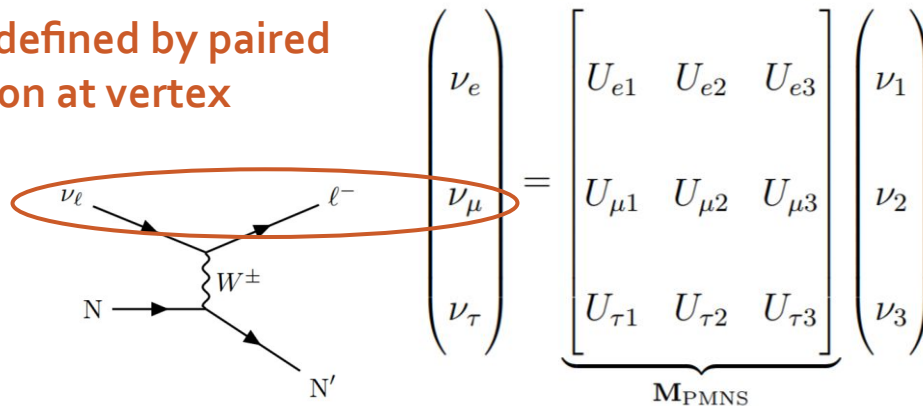


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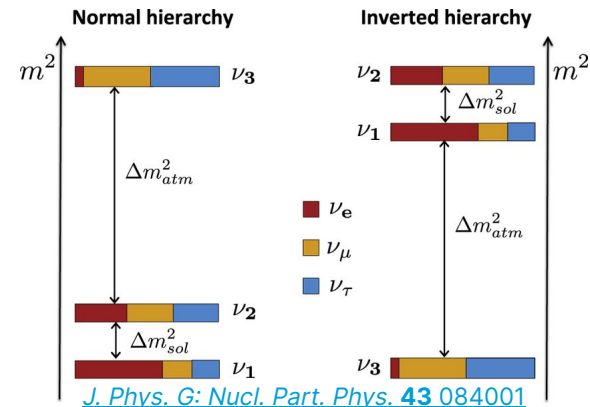
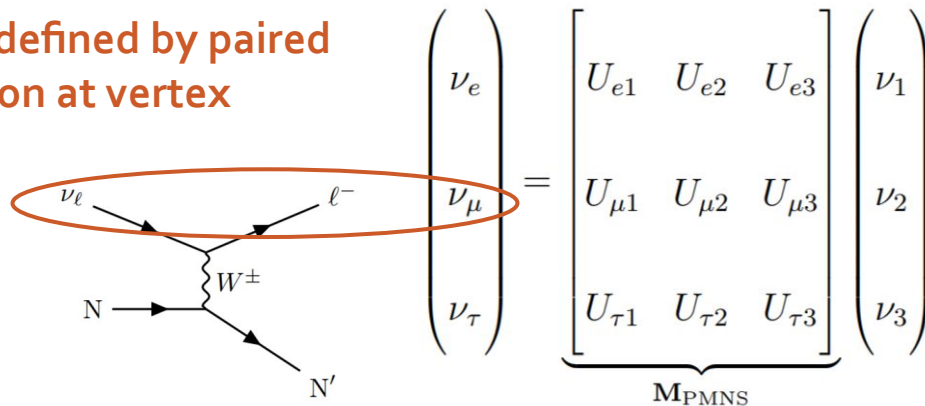
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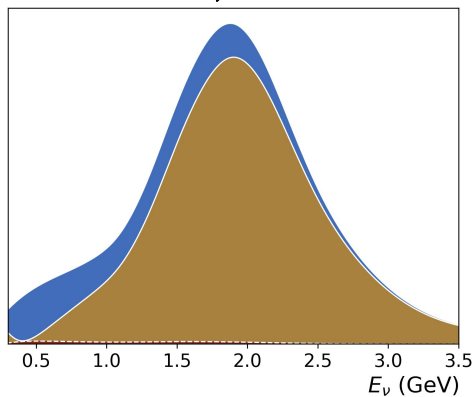
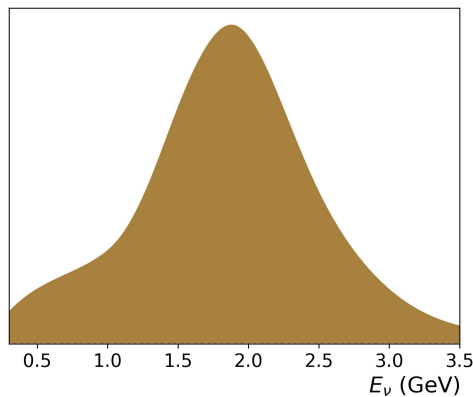


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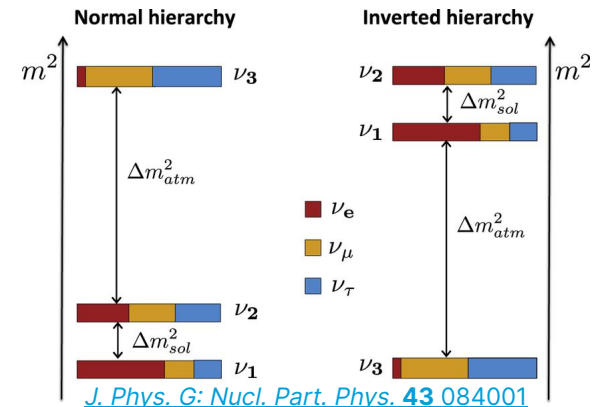
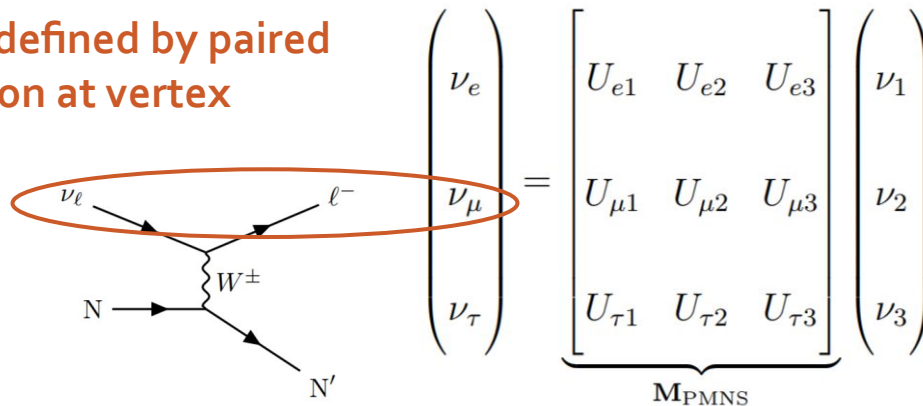


V

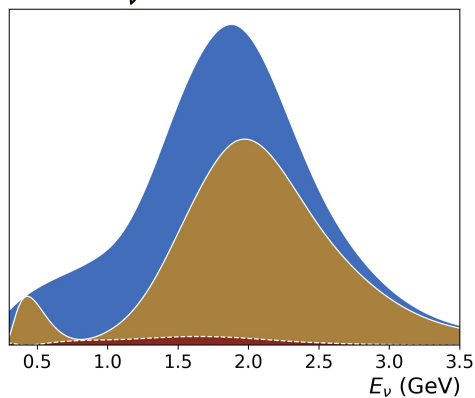
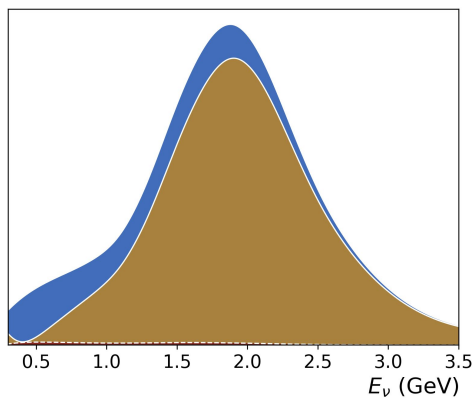
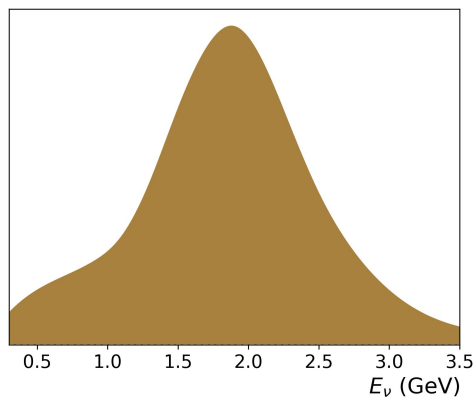


Unknown Properties of Known Neutrinos

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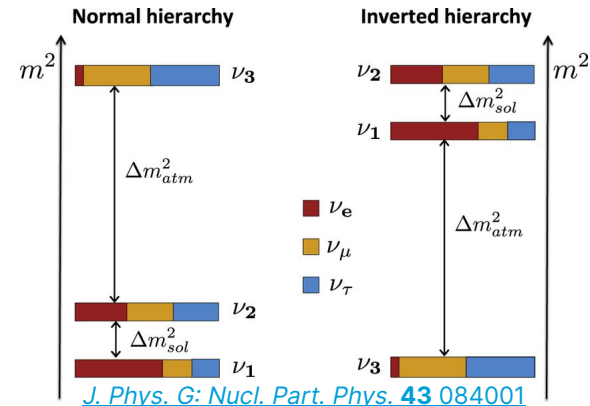
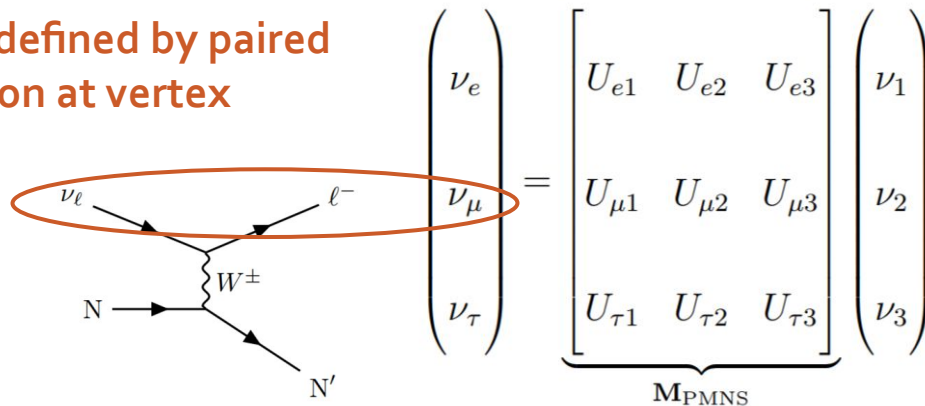


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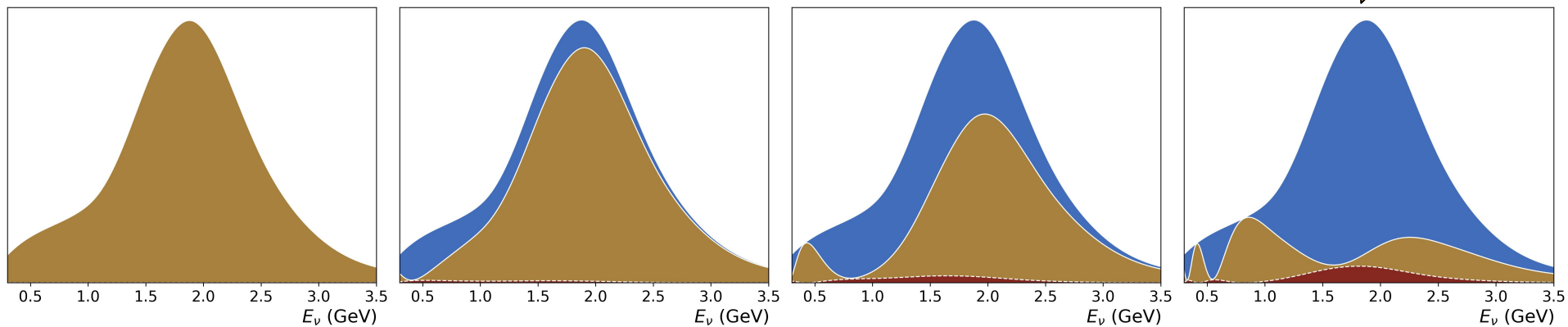


Unknown Properties of Known Neutrinos

Flavor state defined by paired charged lepton at vertex




V



Re-parameterizing the PMNS

$$\begin{array}{c} \text{Atmospheric/} \\ \text{Accelerator} \end{array} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{array}{c} \text{Reactor} \end{array} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{array}{c} \text{Solar} \end{array} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



 \mathbf{M}_{PMNS}

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

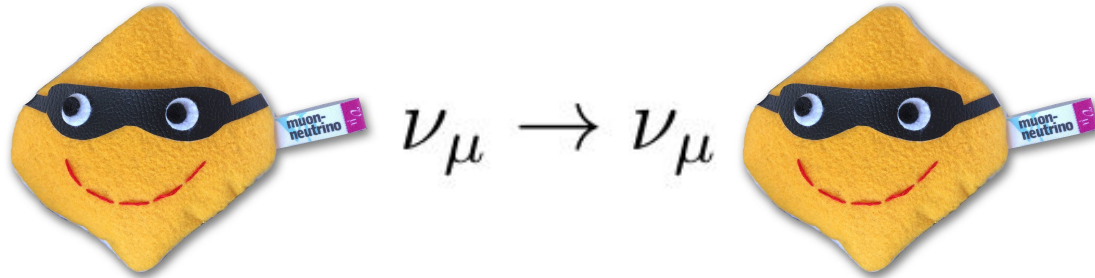
Re-parameterizing the PMNS

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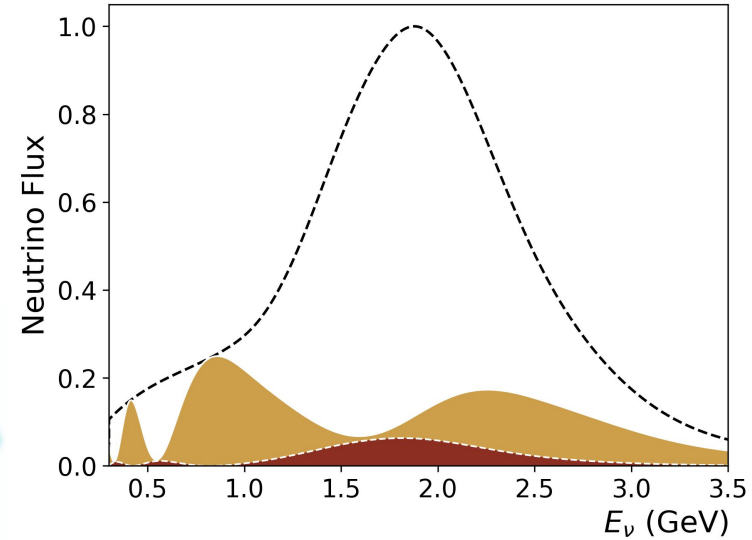
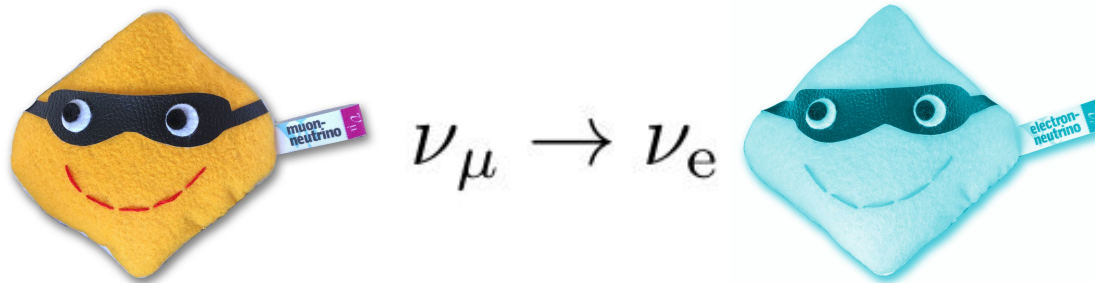
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Oscillation Channels

Muon neutrino disappearance

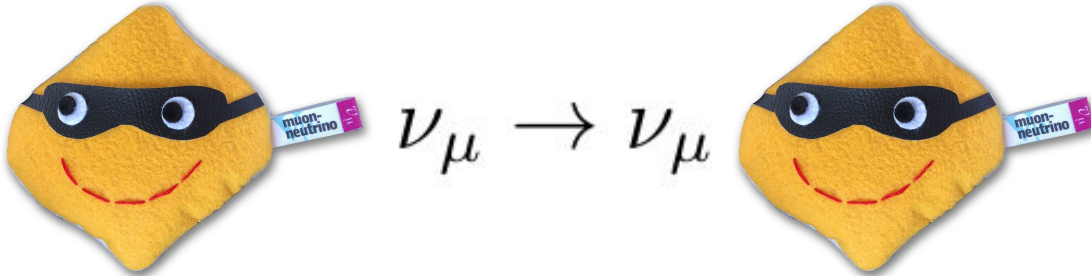


Electron neutrino appearance

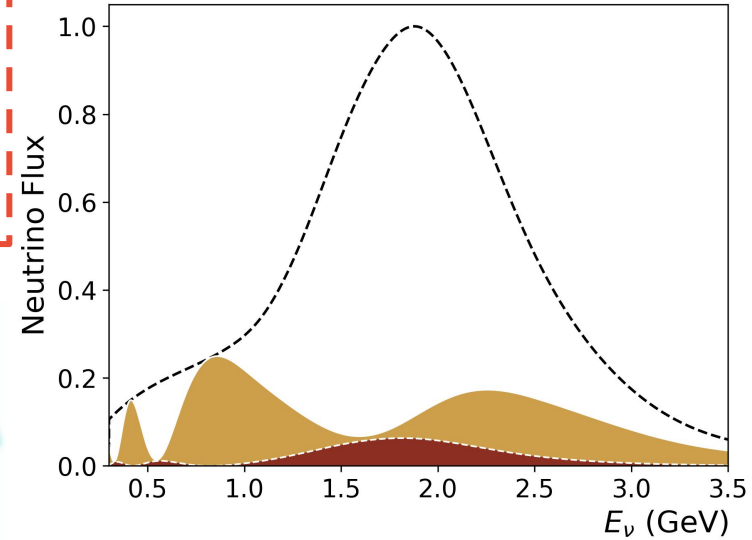
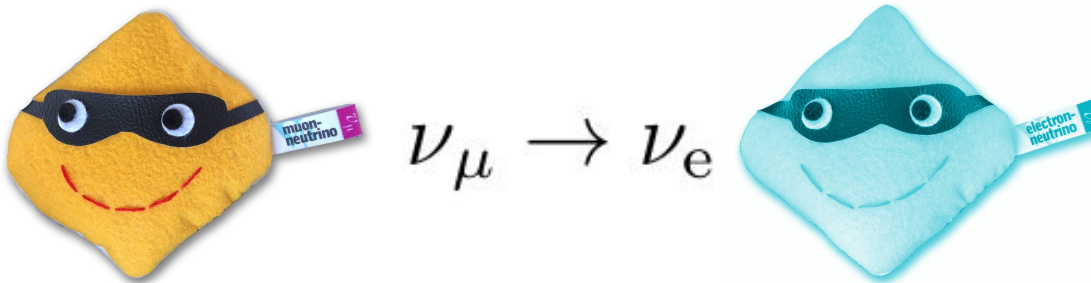


Oscillation Channels

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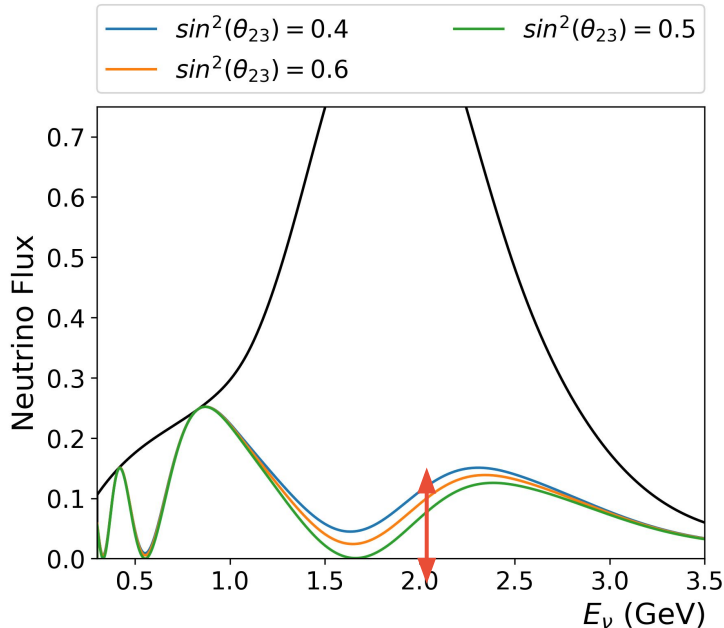
Electron neutrino appearance



Muon Neutrino Disappearance

Muon neutrino survival probability depends on **mixing angles**, and **mass-squared splittings**.

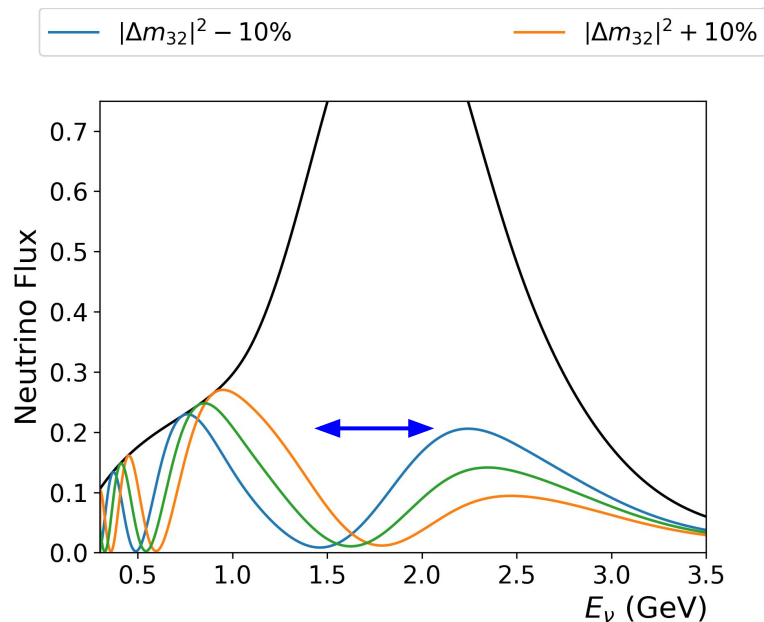
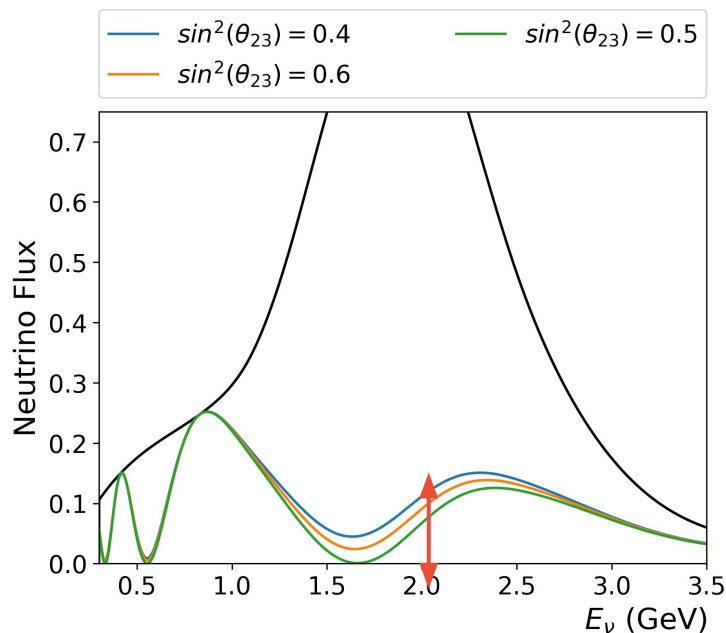
$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4\cos^2 \theta_{13}\sin^2 \theta_{23} \times [1 - \cos^2 \theta_{13}\sin^2 \theta_{23}] \sin^2 \frac{\Delta m_{32}^2 L}{4E} + (\text{solar, matter effect terms})$$



Muon Neutrino Disappearance

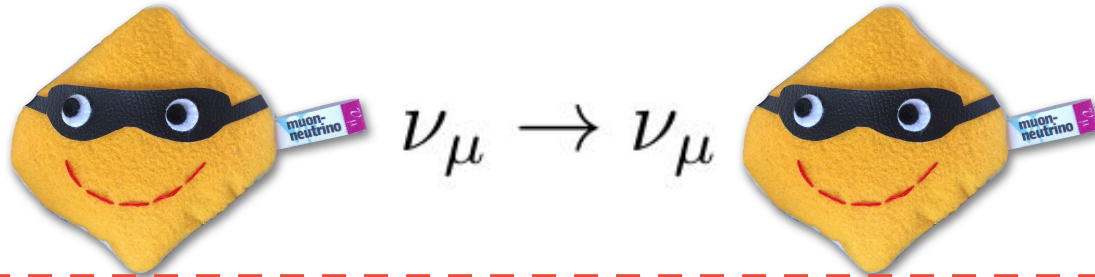
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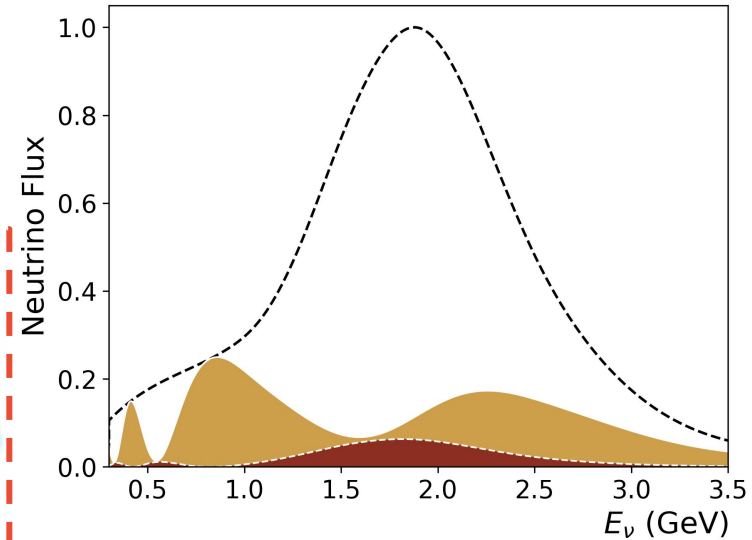
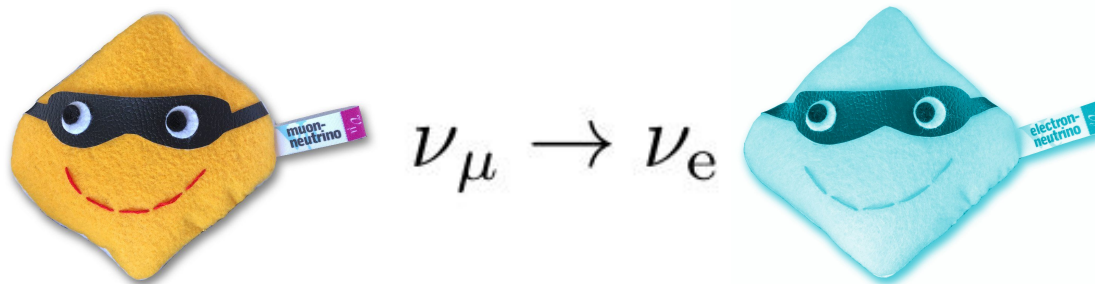


Oscillation Channels

Muon neutrino disappearance



Electron neutrino appearance



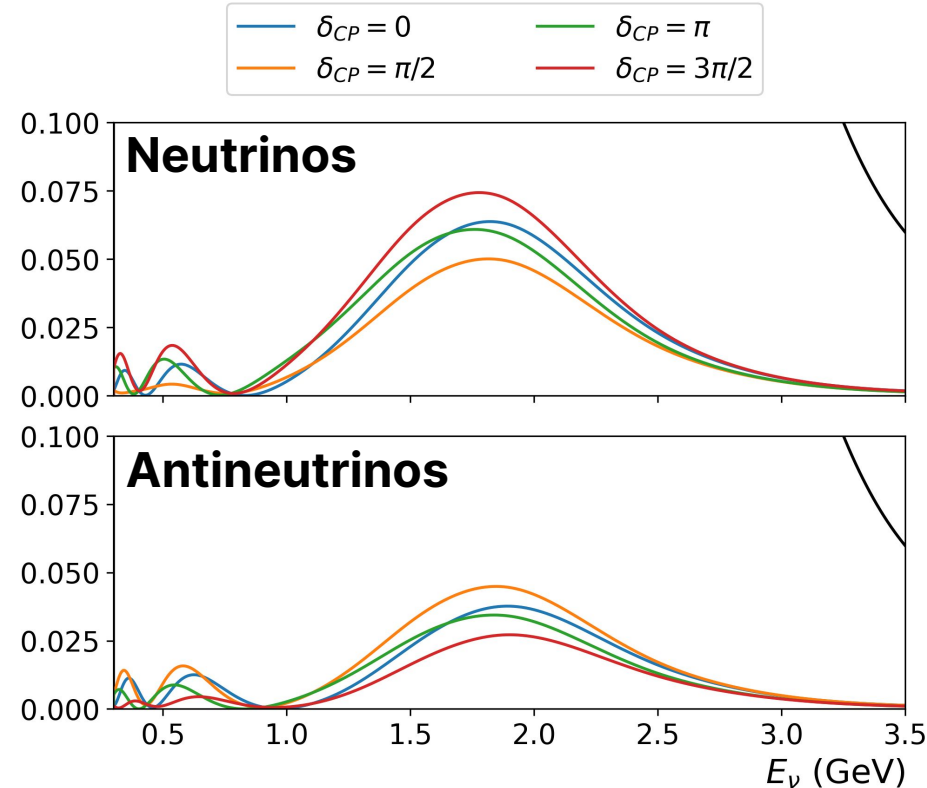
Electron Neutrino Appearance

Appearance probability has 'CP odd' term.

- Sign flip between matter/antimatter

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4E}$$

$$\begin{aligned}
 & \left[\begin{array}{l} (+) - \\ \times \sin \frac{\Delta m_{21}^2 L}{4E} \sin^2 \frac{\Delta m_{32}^2 L}{4E} \sin \delta_{CP} \end{array} \right] \\
 & + (\text{CP-even, solar, matter effect terms})
 \end{aligned}$$



Big Questions

**Is there significant
CP violation in the
neutrino sector?**

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What is the mass ordering of the neutrino mass states?

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Are standard 3-flavour PMNS oscillations able to explain observations?

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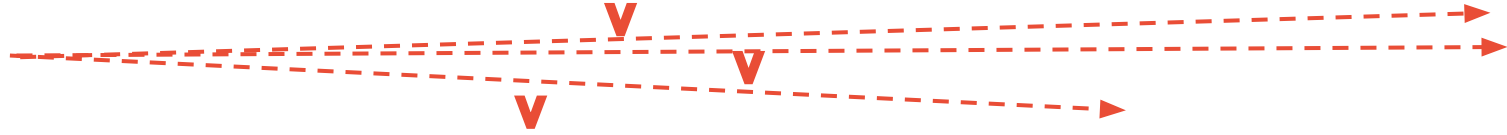
What are the precise values of the neutrino oscillation parameters?

Enough to explain matter/antimatter asymmetry?

Are standard 3-flavour PMNS oscillations able to explain observations?

Anatomy of an Oscillation Experiment

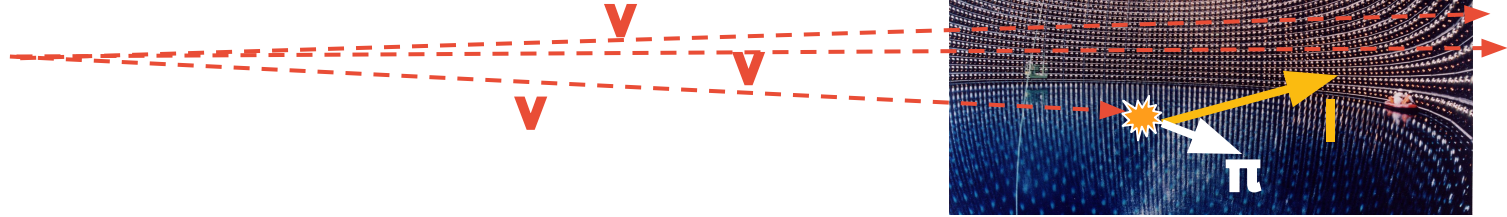
Anatomy of an Oscillation Experiment



Neutrino Source Φ

1. Find or make a source of neutrinos

Anatomy of an Oscillation Experiment



Neutrino Source Φ

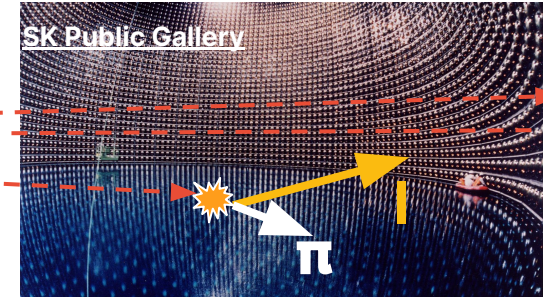
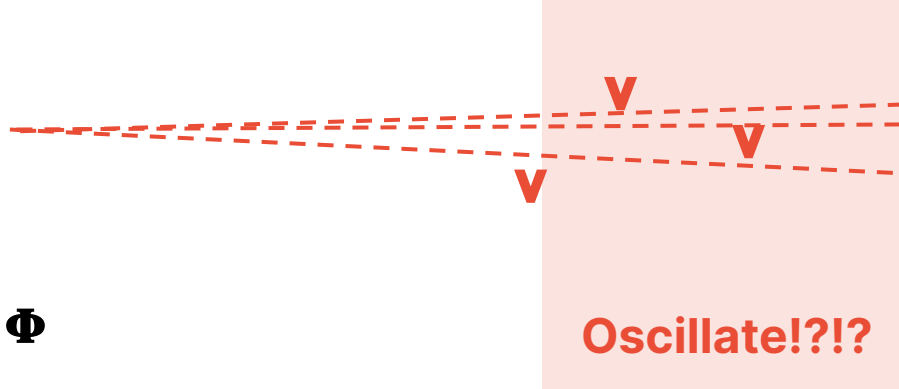
Detector

$$N(E_{\text{obs}}) = \int dE_{\nu} \Phi(E_{\nu}) \cdot$$

$$\sigma(E_{\nu}) \cdot D$$

1. Find or make a source of neutrinos
2. ...
3. Predict the expected rate with a **flux/cross-section/detector** model
4. Look in your detector/box...

Anatomy of an Oscillation Experiment



Neutrino Source Φ

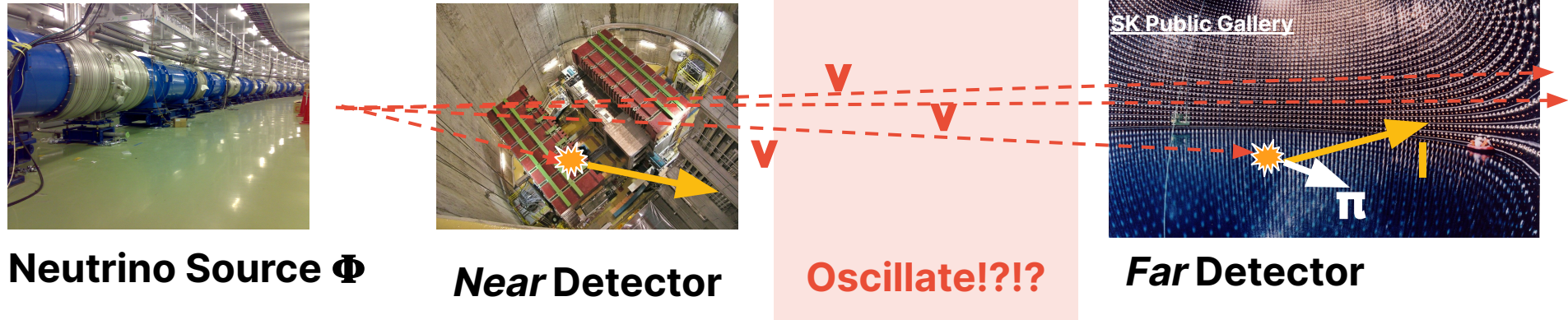
Oscillate!?!?

Detector

$$N(E_{\text{obs}}) = \int dE_{\nu} \Phi(E_{\nu}) \cdot P_{\text{osc}}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot D$$

1. Find or make a source of neutrinos
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Anatomy of an Oscillation Experiment



$$N(E_{\text{Obs}}) = \int dE_{\nu} \Phi(E_{\nu}) \cdot P_{\text{osc}}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot D$$

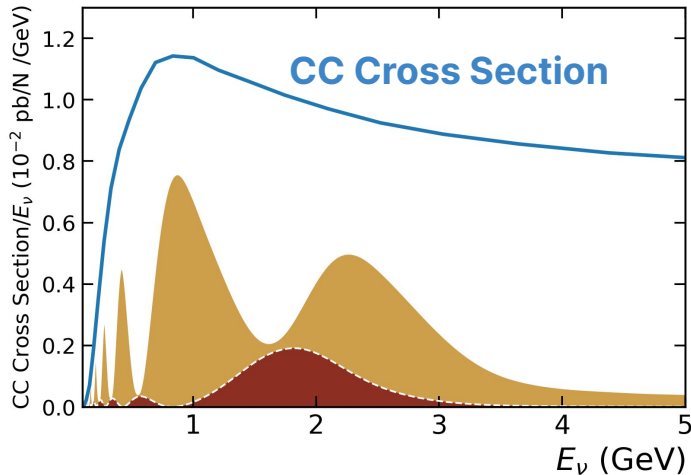
1. Find or make a source of neutrinos
2. **Constrain model uncertainties before oscillation with *Near Detector***
3. Predict the expected rate with a **flux/cross-section/detector** model
4. Look in your detector/box... **See appearance/disappearance?**

Long Baseline: Current Generation

Energy and Baseline

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

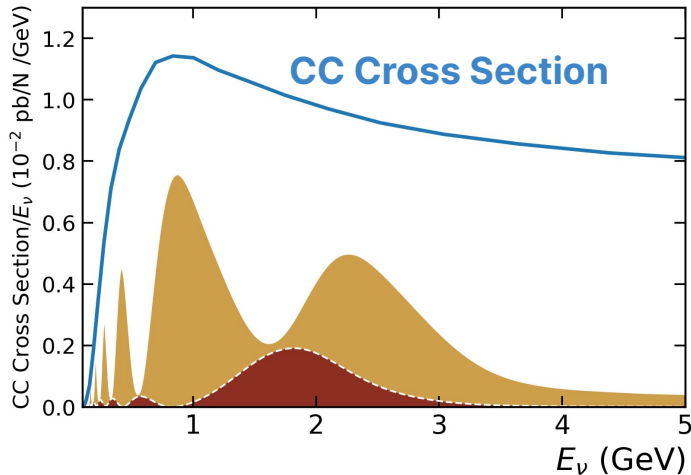
Muon neutrino disappearance
Electron neutrino appearance



Energy and Baseline

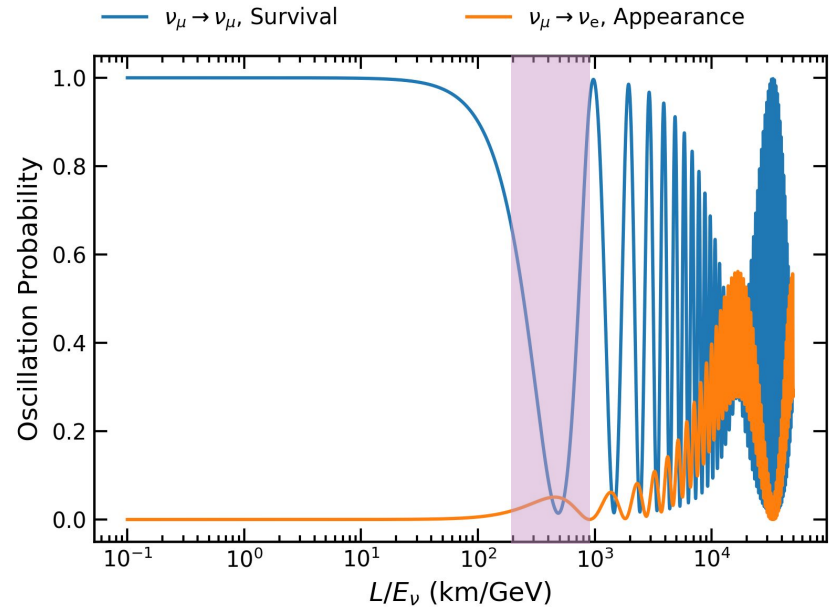
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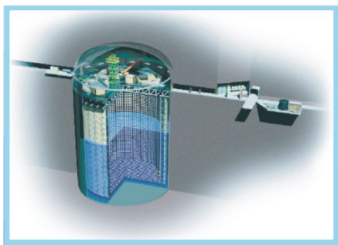
Muon neutrino disappearance
Electron neutrino appearance



Driven by $|\Delta m_{32}|^2 \sim 2 \times 10^{-3} \text{ eV}^2$

For energy O(GeV), first oscillation maximum at baseline O(500 km)





Super-Kamiokande (ICRR, Univ. Tokyo)

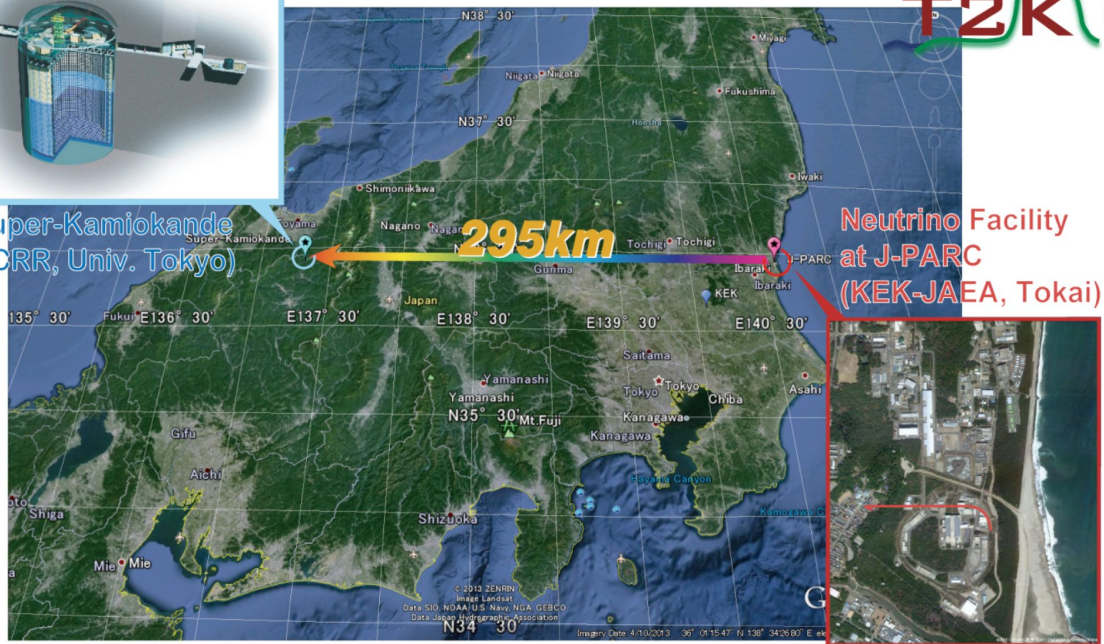
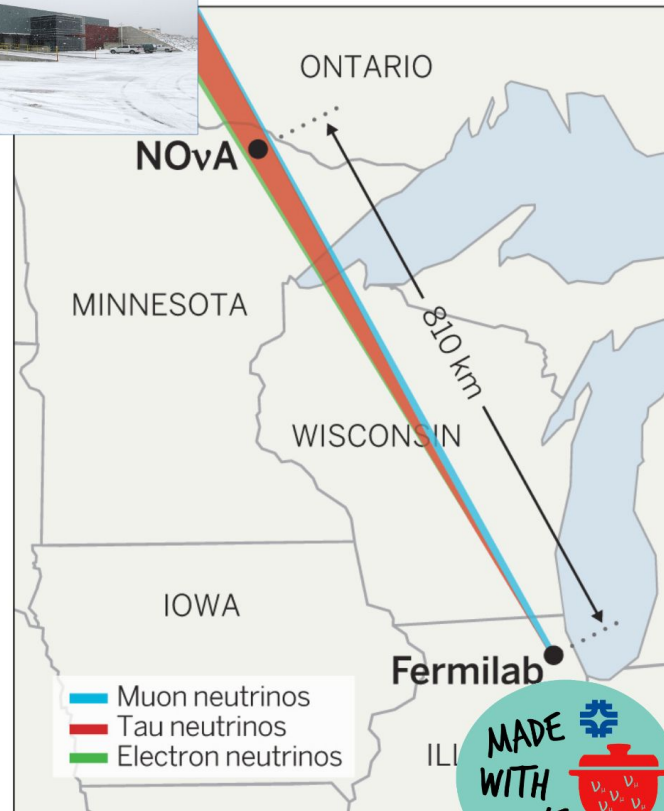
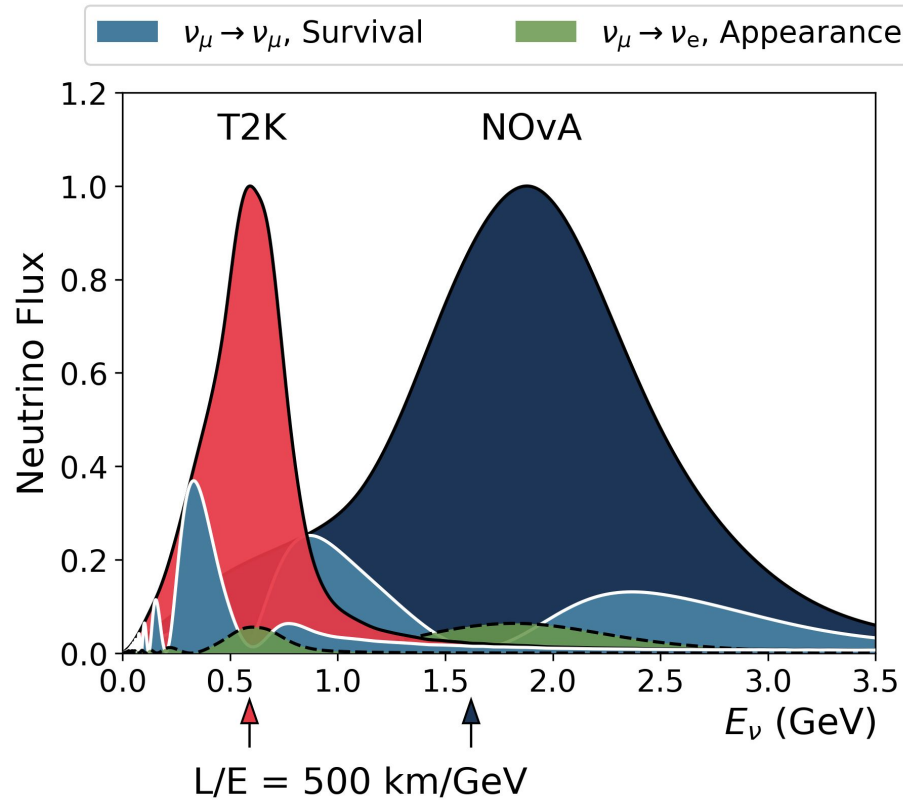


Image credit: t2k-experiment.org





Oscillation parameters: [NuFit 5.2](#)
[JHEP 2020, 178](#)

Super Kamiokande



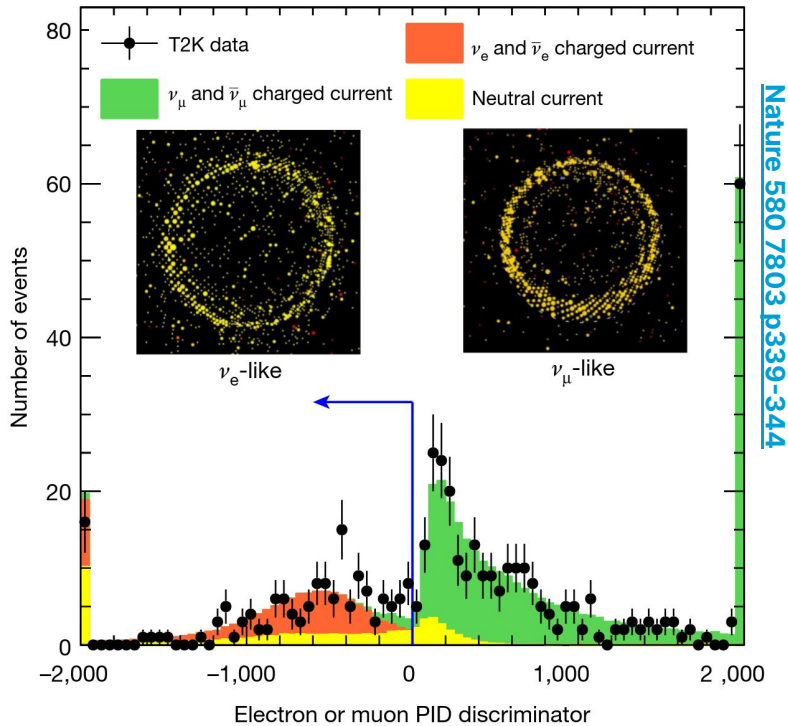
Fiducial mass:	~22.5 kT
Material:	Ultrapure Water
Detection technique:	Cherenkov
Baseline:	295 km
Peak neutrino energy:	0.6 GeV
Location:	Mozumi Mine, Gifu, Japan

NOvA Far Detector

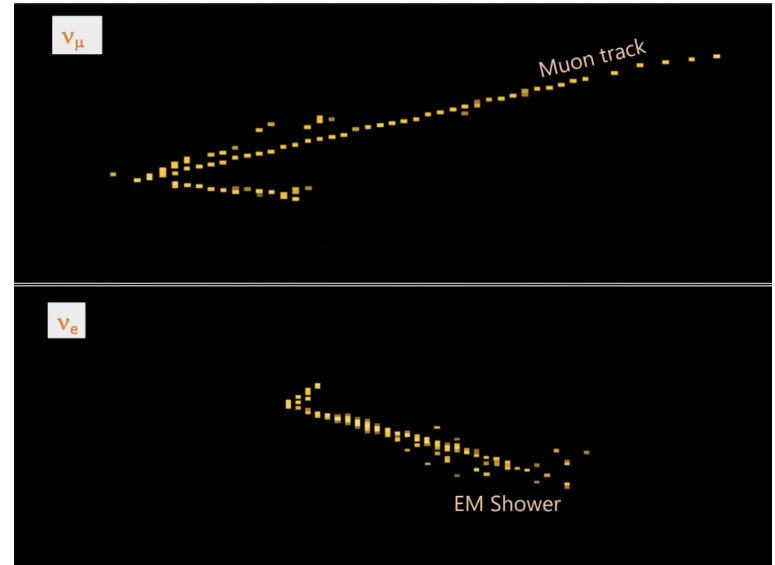


Fiducial Mass:	14 kT
Material:	Liquid scintillator
Detection technique:	Scintillation
Baseline:	810 km
Peak neutrino energy:	1.9 GeV
Location:	Ash River, MN

Far detector event displays

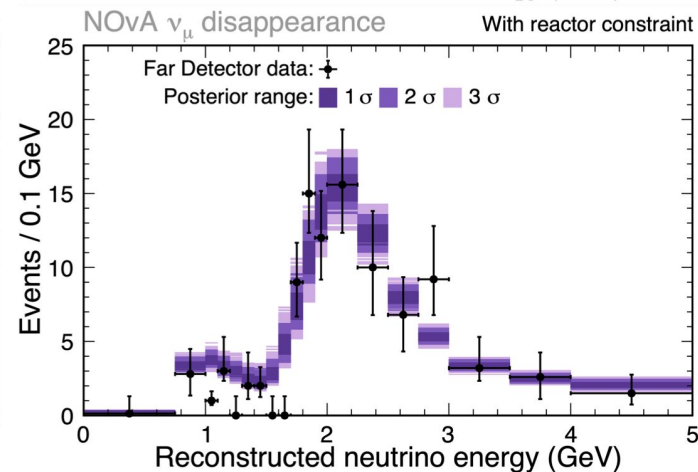
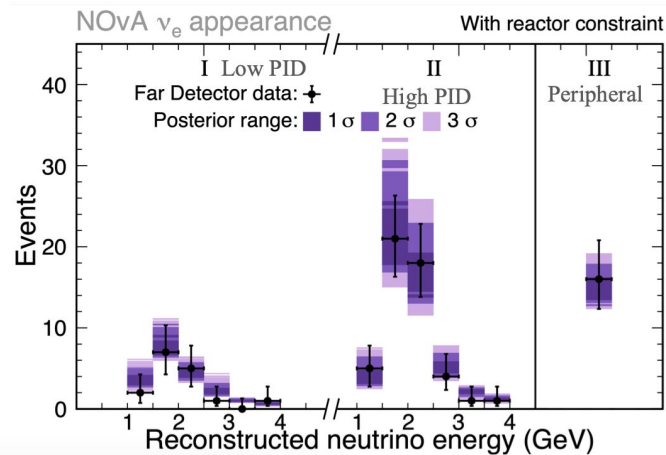
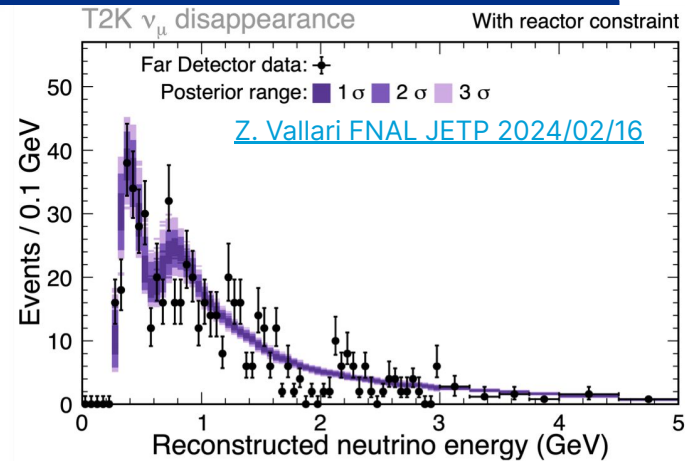
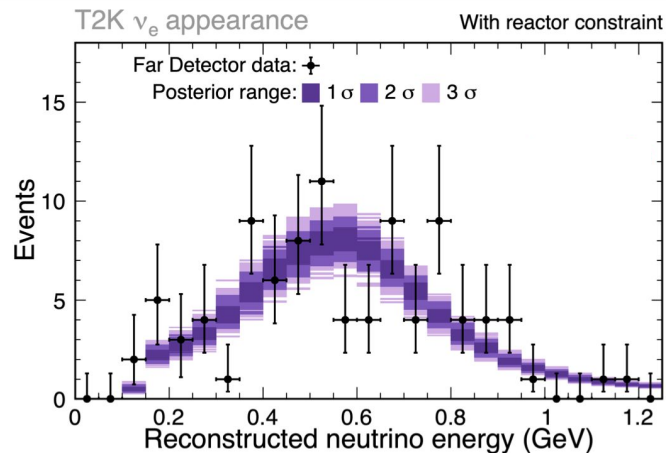


Both experiments analyse muon-like and electron-like events at near and far detectors



Z. Vallari FNAL JETP 2024/02/16

Far Detector Samples



Uncertainties

[Eur. Phys. J. C 83, 782 \(2023\)](#)

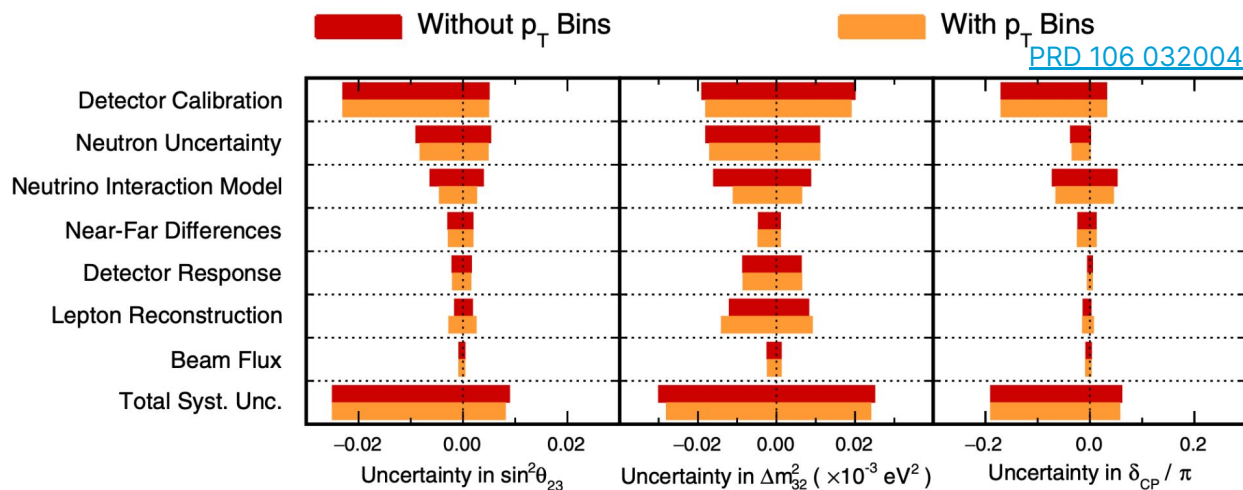
Sample		Uncertainty source (%)			Flux \otimes Interaction (%)	Total (%)
		Flux	Interaction	FD + SI + PN		
1R μ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)



FD predicted event rate
uncertainties

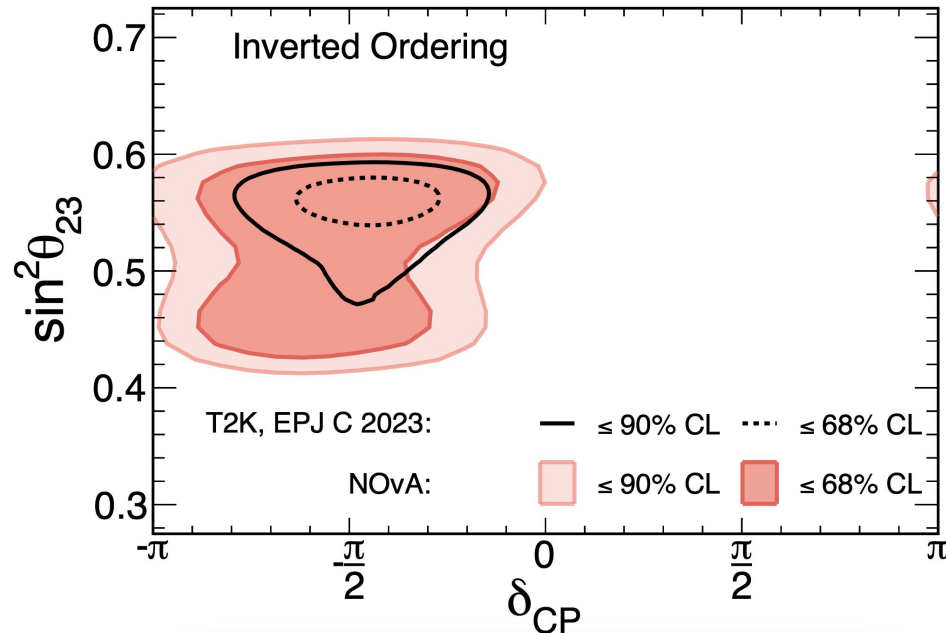
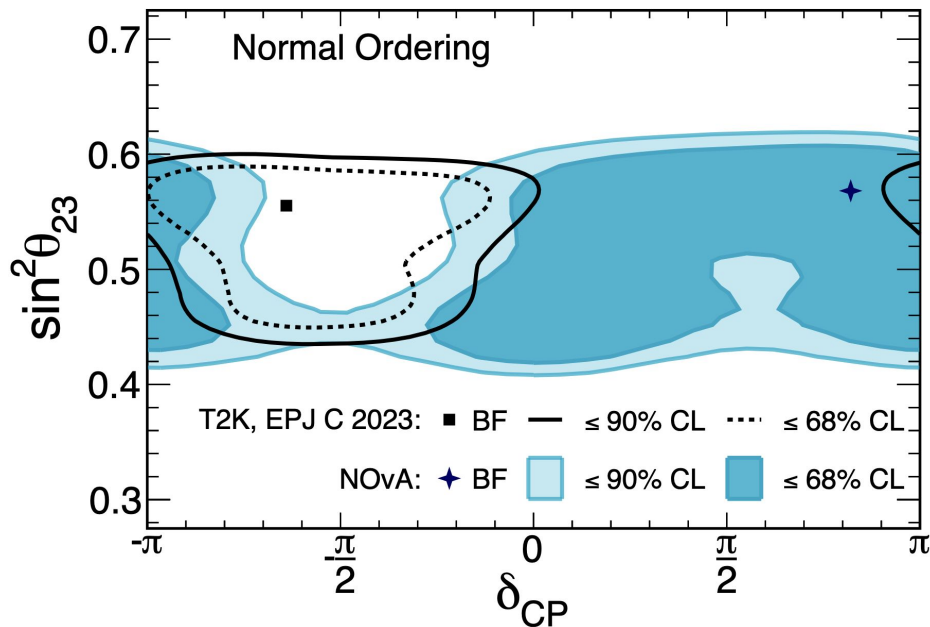


Oscillation parameter
uncertainties

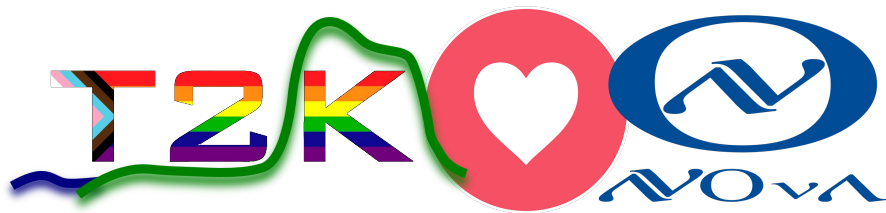


- Overlapping 1σ regions
- Disagree about best fit region for Normal Ordering

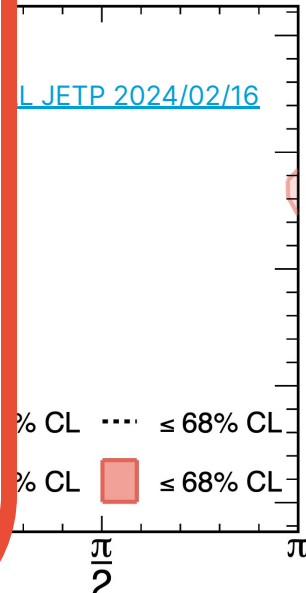
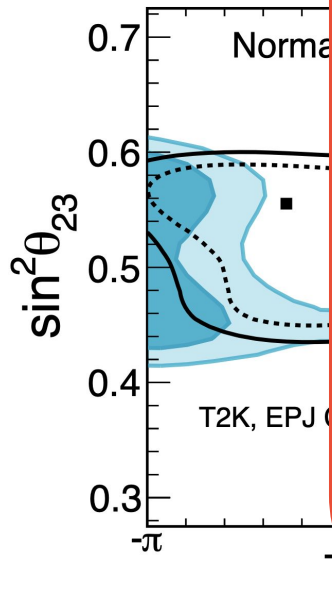
[Z. Vallari FNAL JETP 2024/02/16](#)



- Overlap
- Disagreement



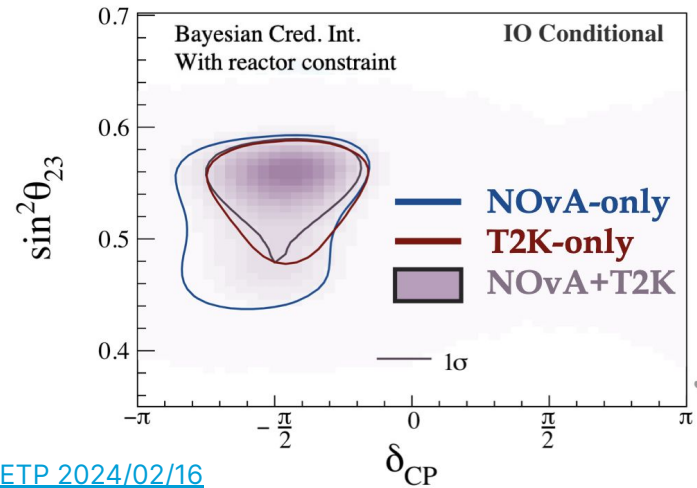
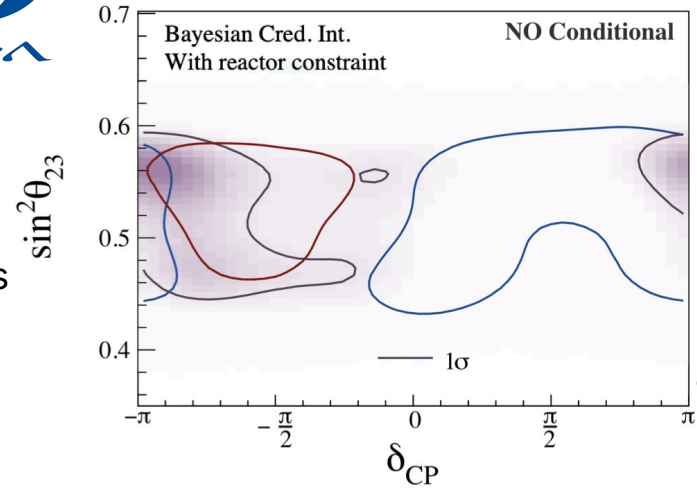
Multiple joint workshops since 2016, only possible thanks to DOE US-Japan and UKRI support.





Probe same L/E: ~ 500 km/GeV

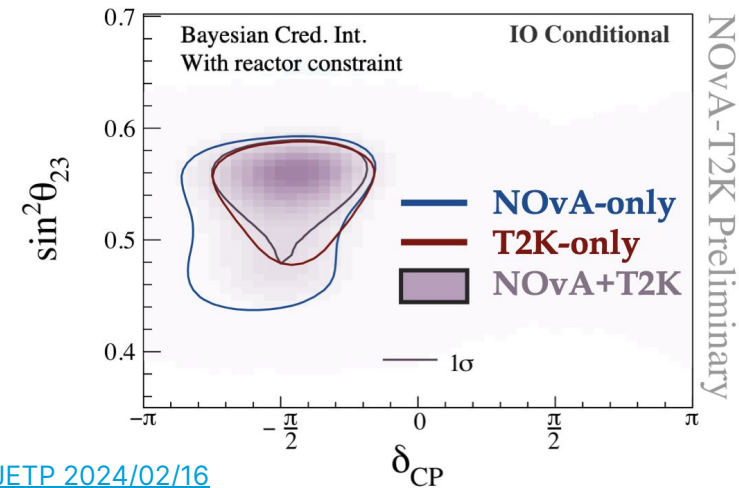
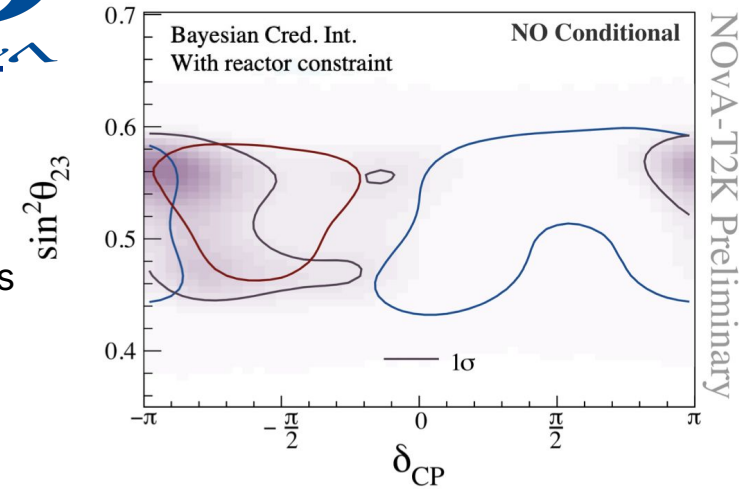
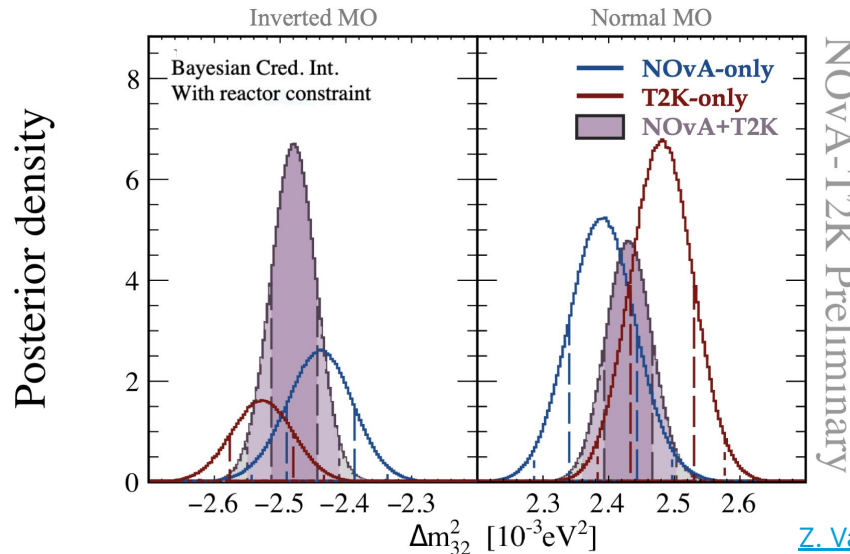
- Measurements are statistically limited
- Different L and different E
- Potential to break degeneracies in both signal physics and with different dominant systematic uncertainties



Probe same L/E: ~ 500 km/GeV

- Measurements are statistically limited
- Different L and different E
- Potential to break degeneracies in both signal physics and with different dominant systematic uncertainties

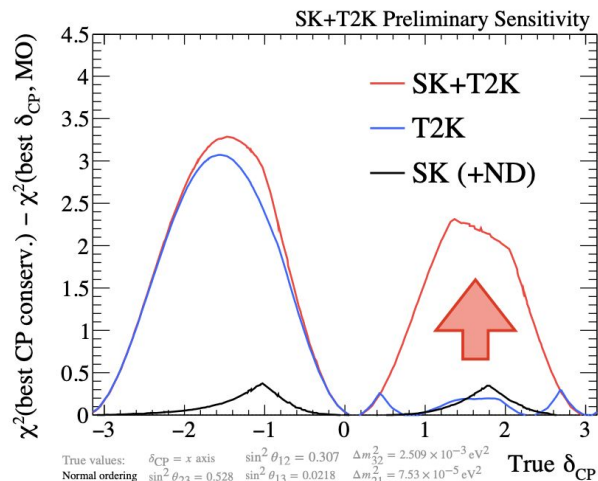
Joint fit (very) weakly prefers Inverted Mass Ordering!



T2K + Super-K

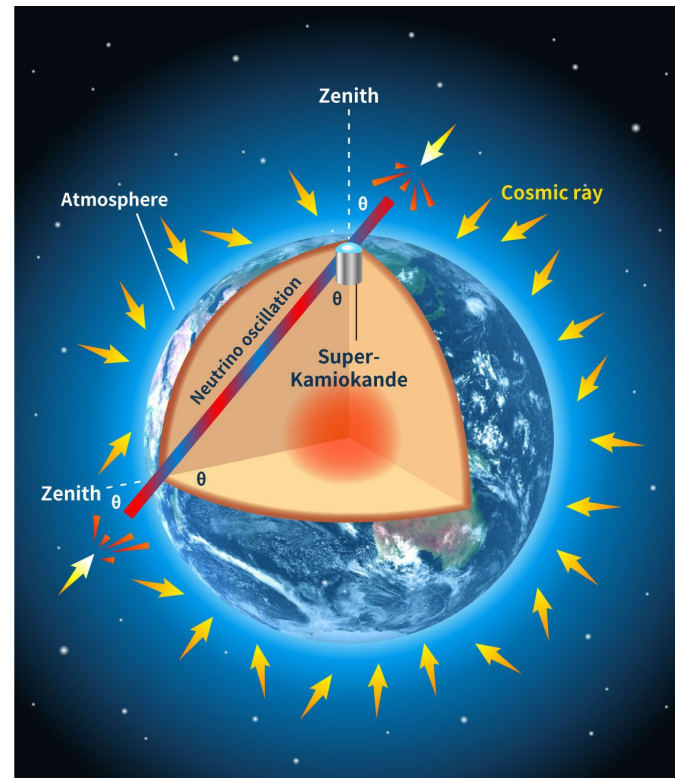
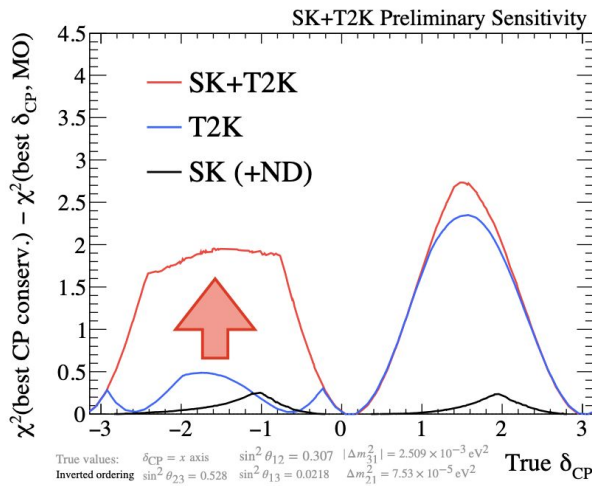
- Inclusion of SK atmospheric data breaks mass ordering degeneracy
- T2K beam data sensitive to $\sin(\delta_{CP})$
- SK atmospheric data sensitive to $\cos(\delta_{CP})$

True NO



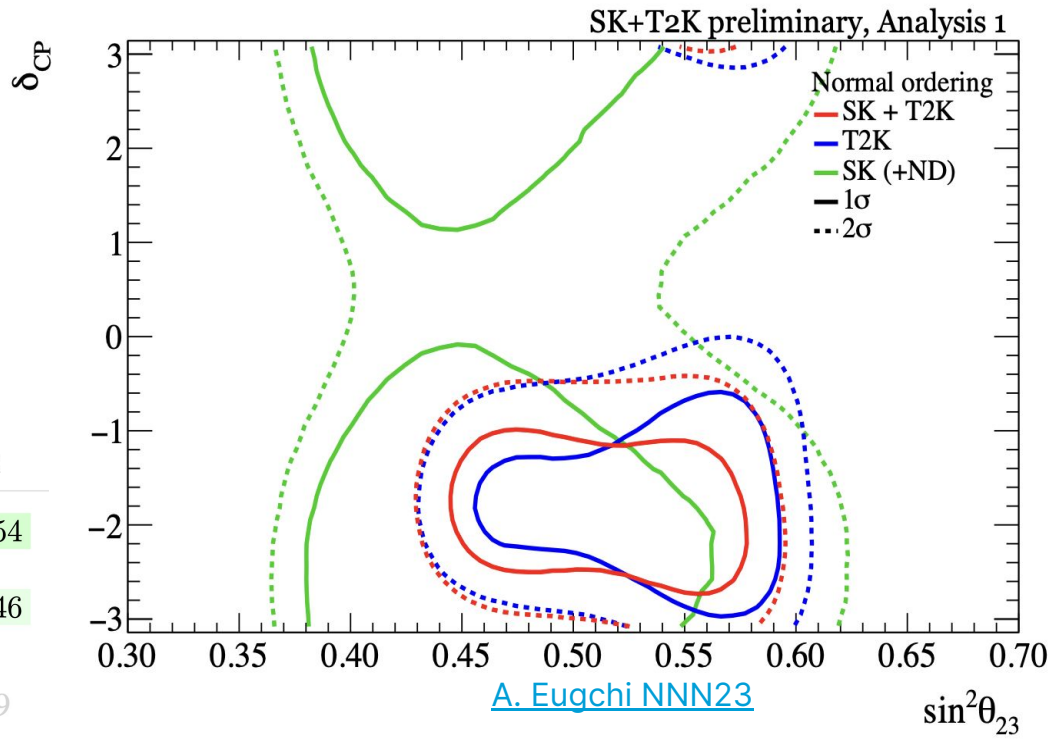
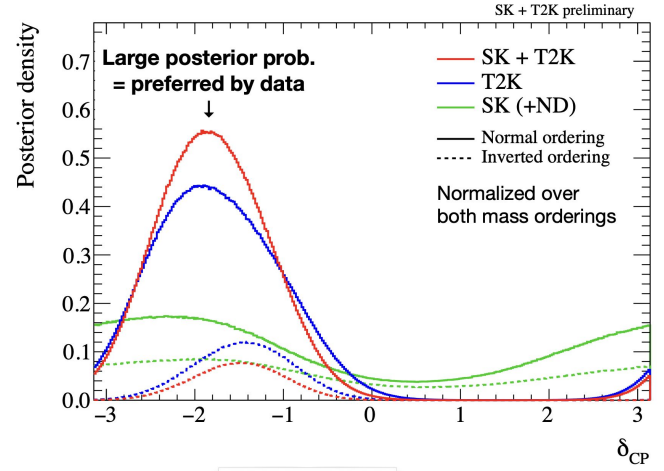
[L. Berns IPNS Seminar](#)

True IO



[Image credit: Super-K/ICRR](#)

T2K + Super-K



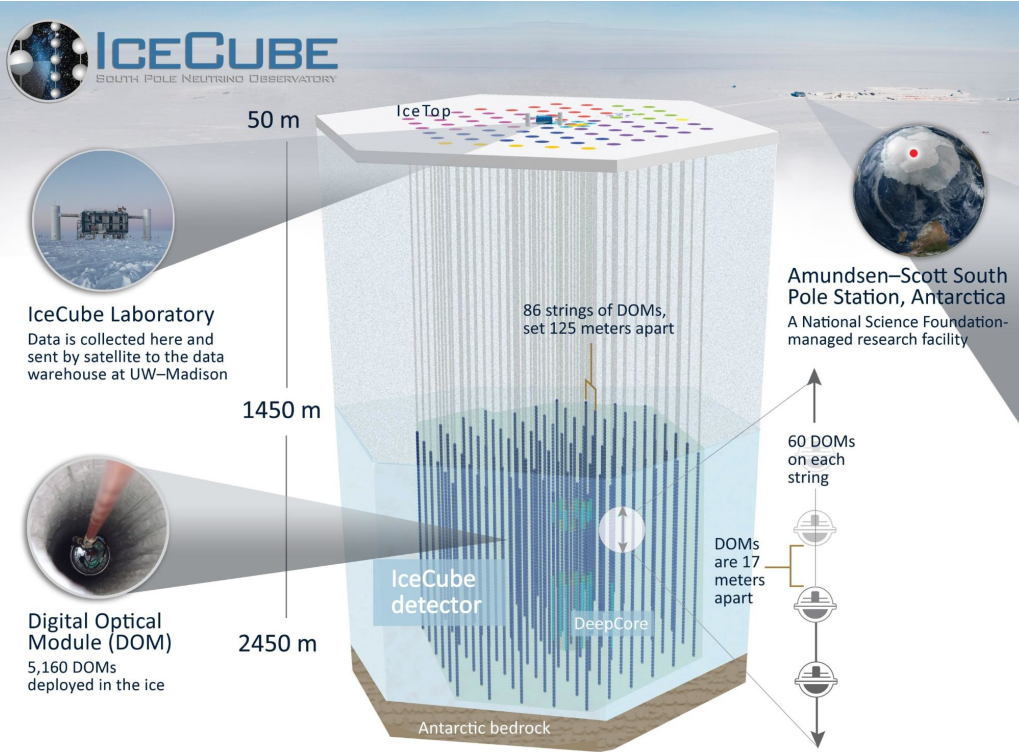
Posterior probability	SK+T2K	T2K	SK
Normal ordering	0.900	0.832	0.654
Inverted ordering	0.100	0.168	0.346
Bayes factor (NO/IO)	9.0	5.0	1.9

[L. Berns IPNS Seminar](#)

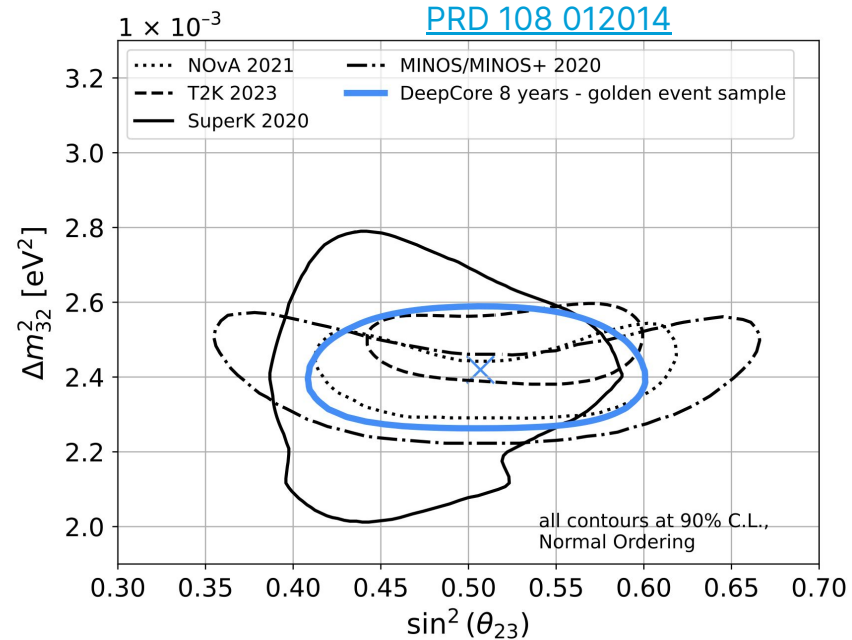
[A. Eugchi NNN23](#)



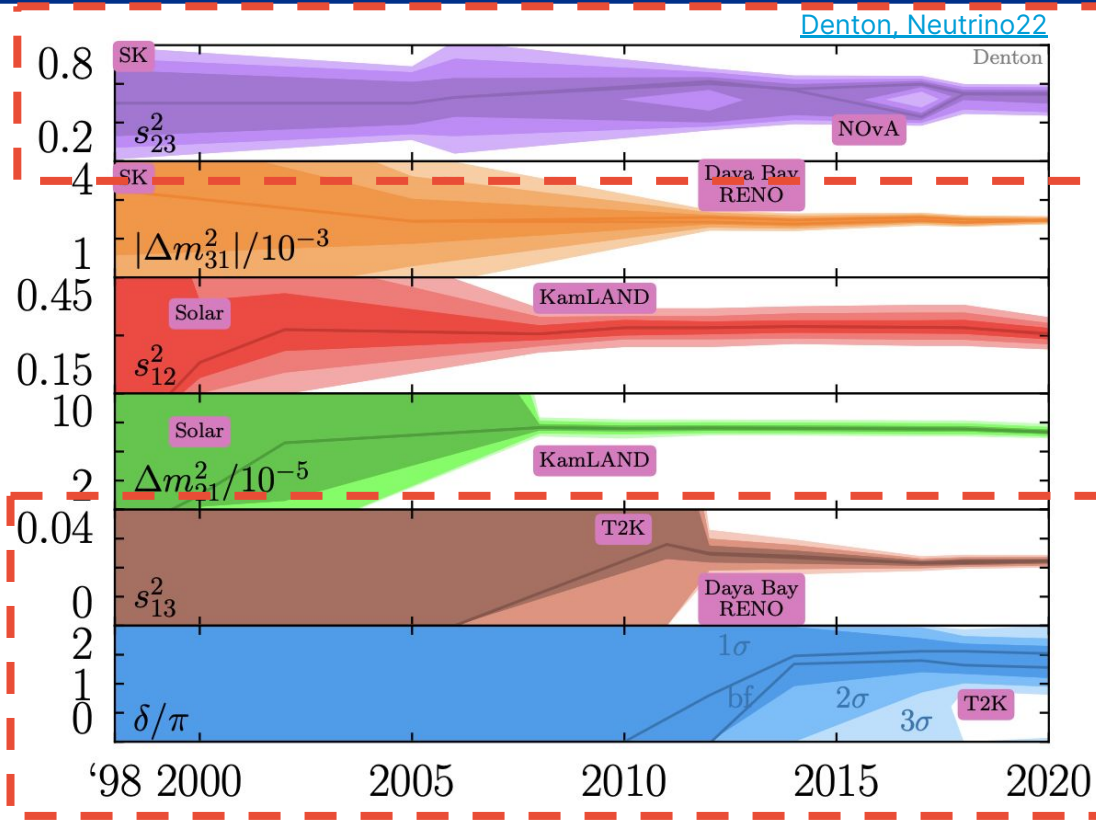
IceCube



Atmospheric disappearance measurement very consistent with beam-based experiments



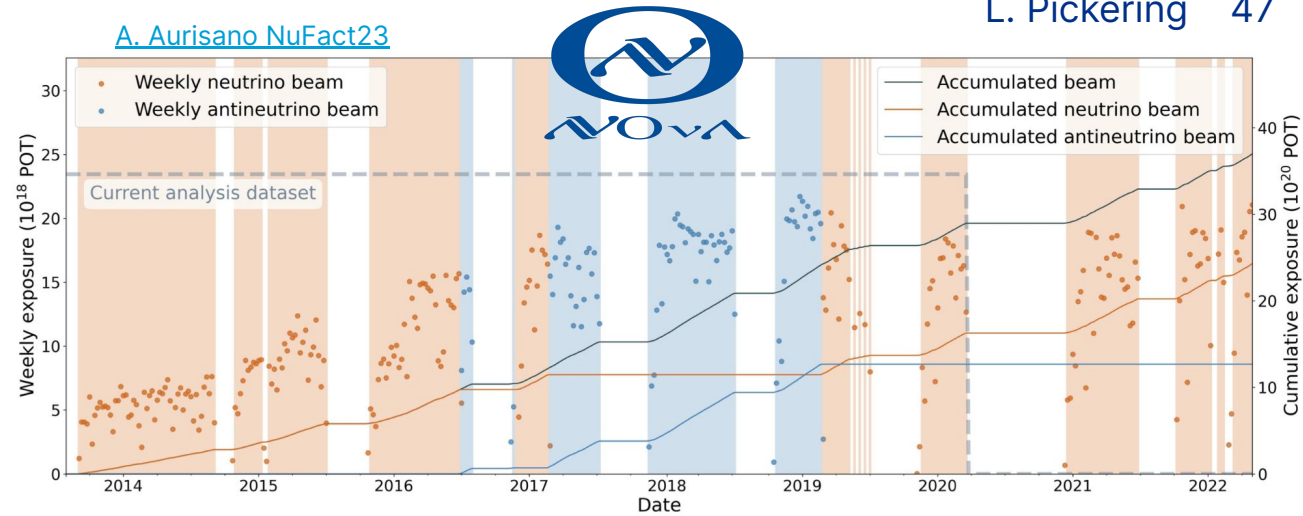
State of the ν -tion



Long Baseline experiments largely sensitive to these parameters

T2K & NOvA

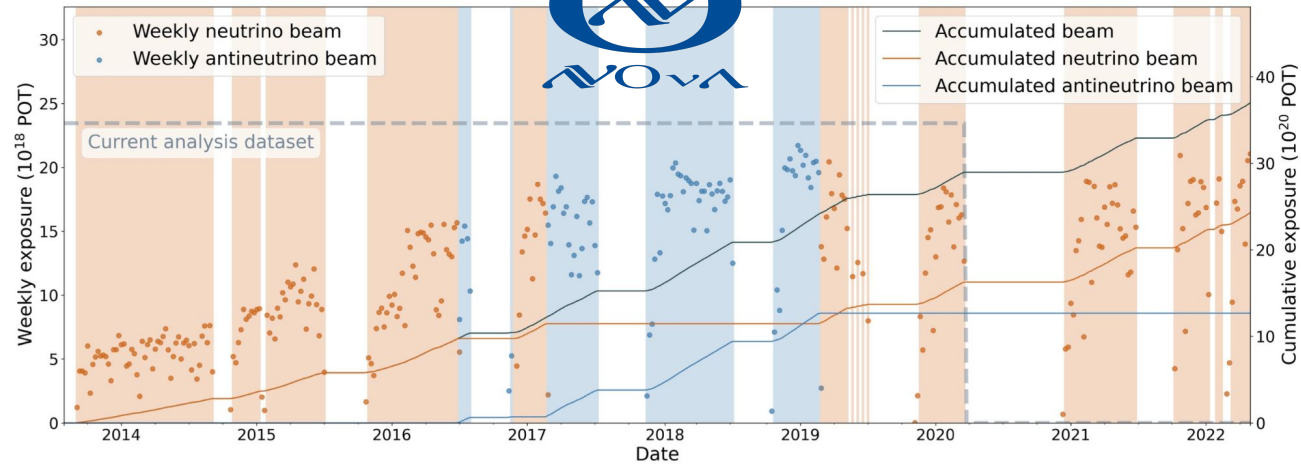
NOvA beam has been running stably at ~1 MW



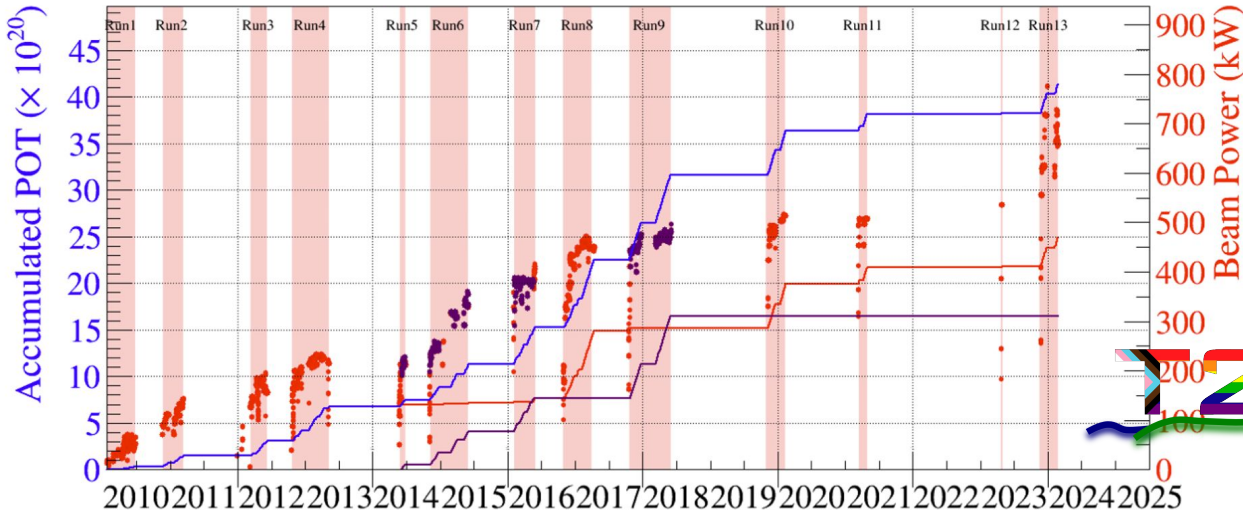
T2K & NOvA

NOvA beam has been running stably at ~1 MW

A. Aurisano NuFact23



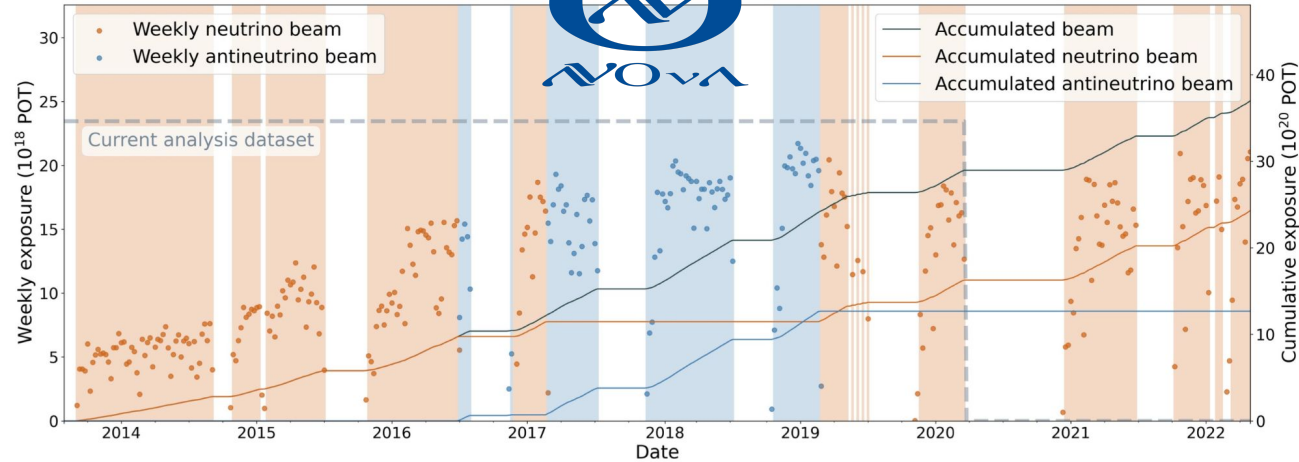
- Total Accumulated POT for Physics
- ν -Mode Accumulated POT for Physics
- $\bar{\nu}$ -Mode Accumulated POT for Physics
- ν -Mode Beam Power
- $\bar{\nu}$ -Mode Beam Power



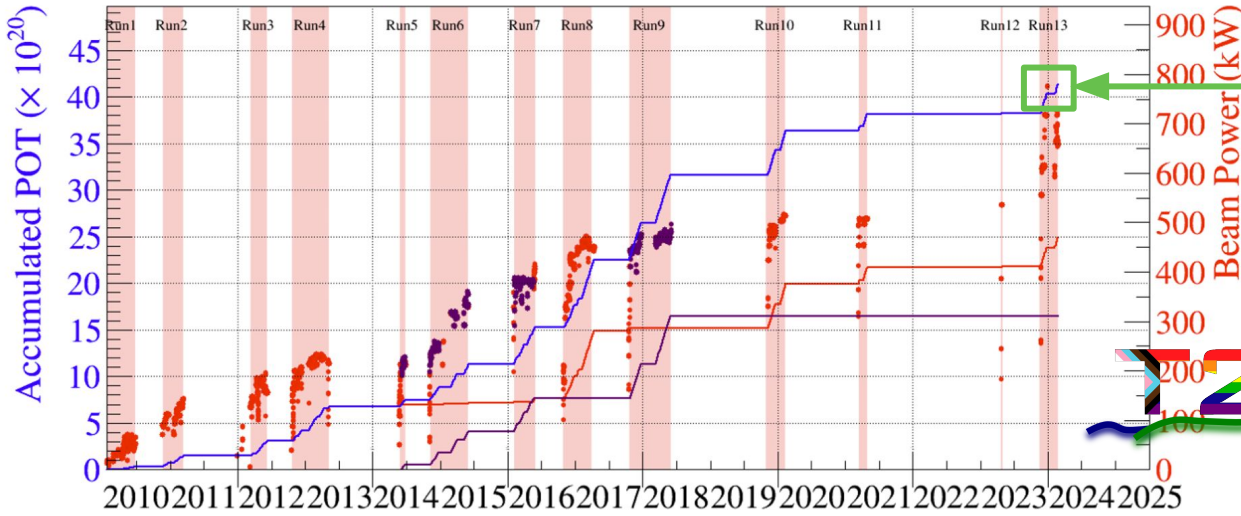
T2K & NOvA

NOvA beam has been running stably at ~1 MW

A. Aurisano NuFact23



- Total Accumulated POT for Physics
- ν -Mode Accumulated POT for Physics
- $\bar{\nu}$ -Mode Accumulated POT for Physics
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- $\bar{\nu}$ -Mode Beam Power



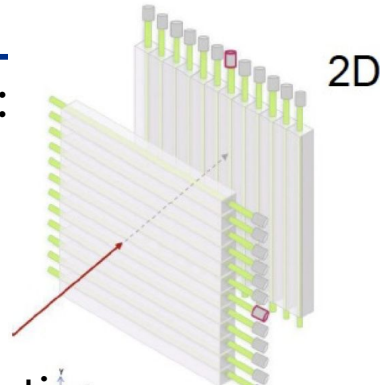
J-PARC Neutrino beam stable at 750 kW design power for the first time on 25th of December 2023!



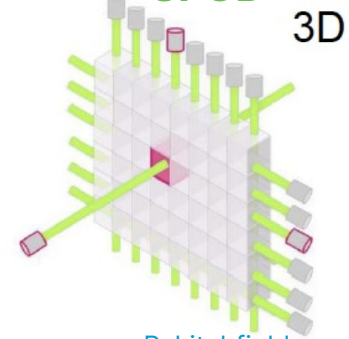
T2K Recent Upgrades

- Near detector upgrade commissioning ongoing:
 - SFGD: New, cube-based 3D scintillator tracker
 - 2 new horizontal TPCs
 - SFGD+hTPCs have significantly improved acceptance

Classic Tracker



SFGD

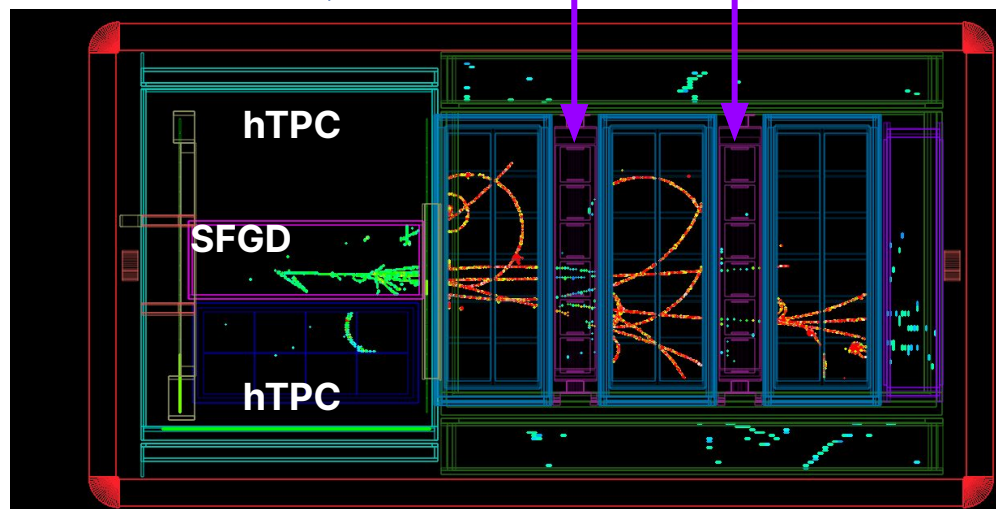


Beam direction

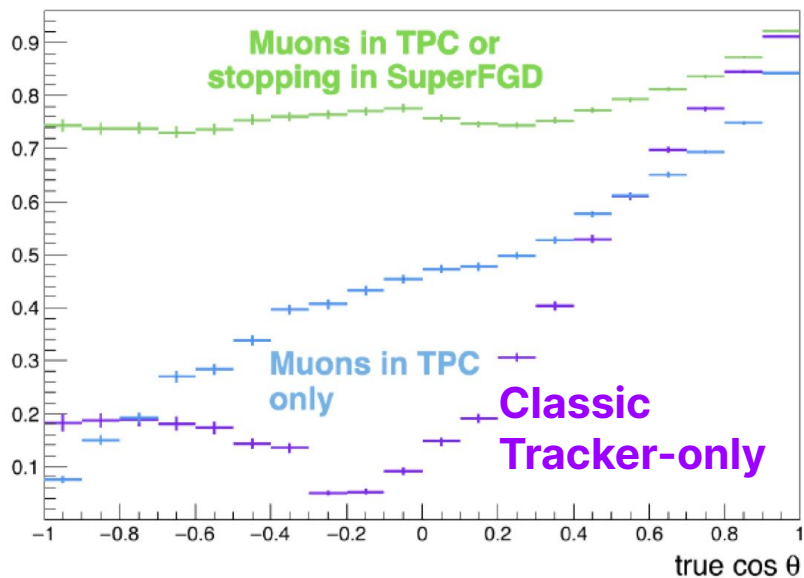


Classic Tracker

[P. Litchfield](#)
[Moriond24](#)



efficiency

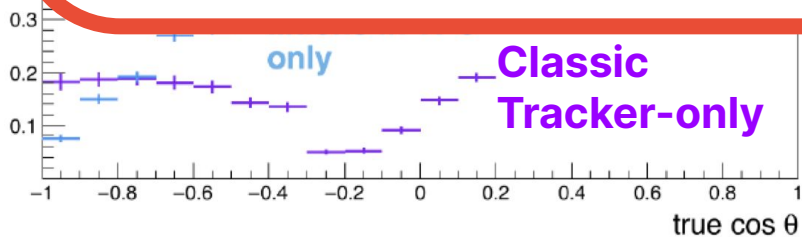


T2K Recent Upgrades

- Near detector upgrade commissioning ongoing:

- SFGD: New cube-based 3D scintillator tracker

Expect exciting updates from NOvA and T2K in June!



NEUTRINO 2024

XXXI International Conference on Neutrino Physics and Astrophysics

Milano (Italy) - June 16-22, 2024

Topics

Neutrino oscillations	Supernova neutrinos
Neutrino mass	Astrophysical neutrinos
Neutrinoless Double Beta Decay	Geoneutrinos
Neutrino interactions	Neutrino role in cosmology
Accelerator neutrinos	Sterile neutrinos
Reactor neutrinos	Theory of neutrino masses and mixing, Leptogenesis
Atmospheric neutrinos	Beyond Standard Model searches in the neutrino sector
Solar neutrinos	New technologies for neutrino physics

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<https://neutrino2024.org>

<https://agenda.infn.it/event/37867>

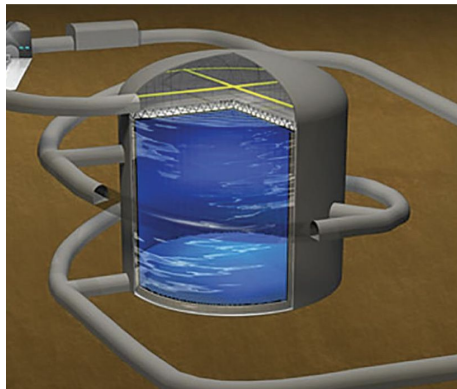
Organizing Secretariat: secretariat@neutrino2024.org

Scientific Secretariat: scientific@neutrino2024.org

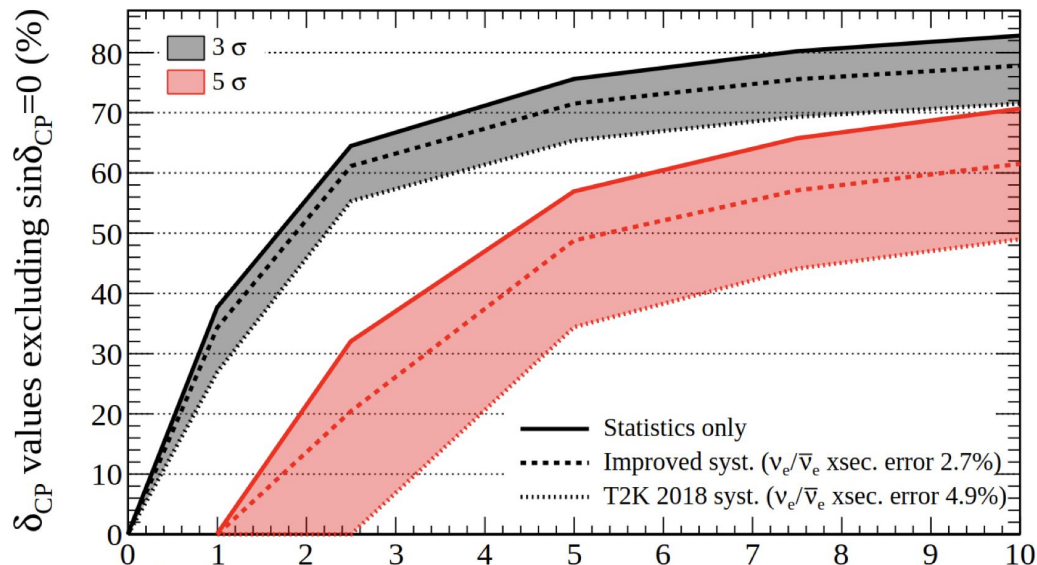


Long Baseline: Next Generation

Hyper-K



C. Naseby NuFact23



Hyper-K preliminary

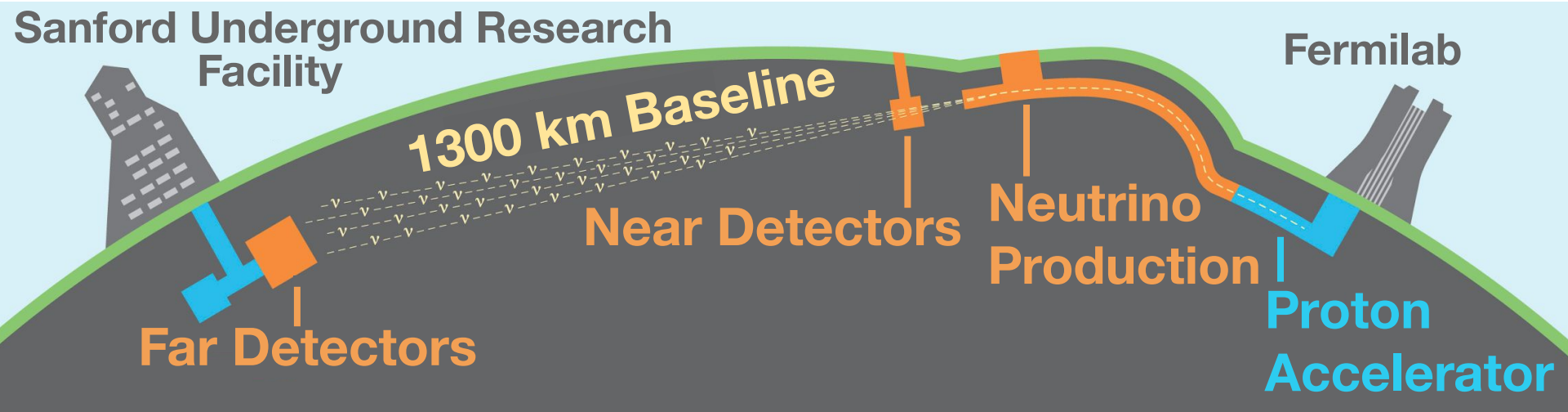
True normal ordering (known)

$$\sin^2(\theta_{13}) = 0.0218 \quad \sin^2(\theta_{23}) = 0.528 \quad |\Delta m_{32}^2| = 2.509\text{E-}3 \text{ eV}^2/c^4$$

HK Years (2.7E21 POT 1:3 $\nu:\bar{\nu}$)

- Builds on successes of SK/T2K
 - **Bigger:** 8x larger fiducial mass than SK
 - **More intense:** beam power $\sim 2x$ T2K
 - Same baseline: 295 km
 - Similar detector technology
- Data taking from ~ 2027

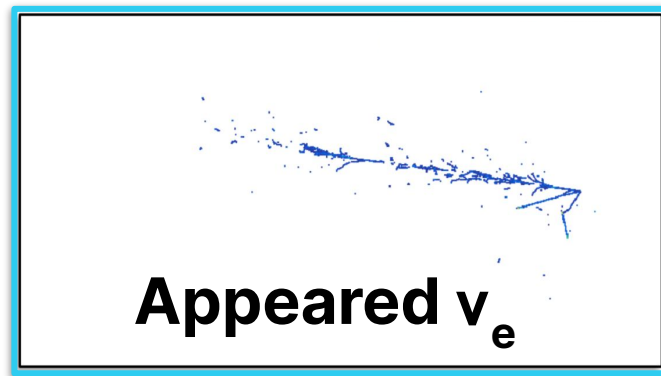
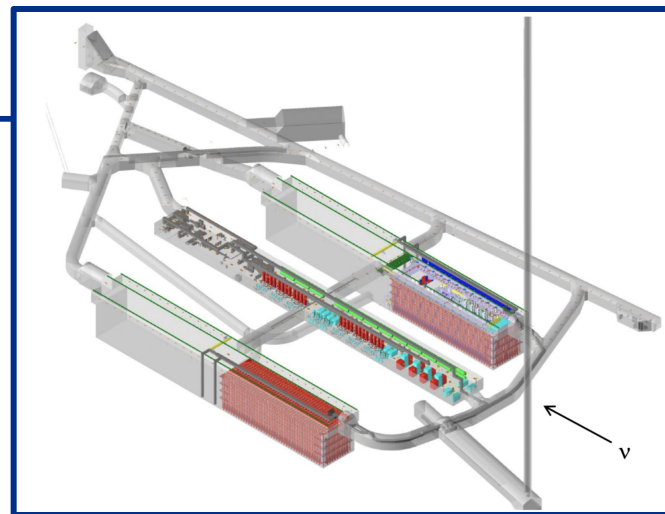
DUNE: Deep Underground Neutrino Experiment



Expect Phase 1 beam data to arrive ~2031

DUNE: Far Detectors

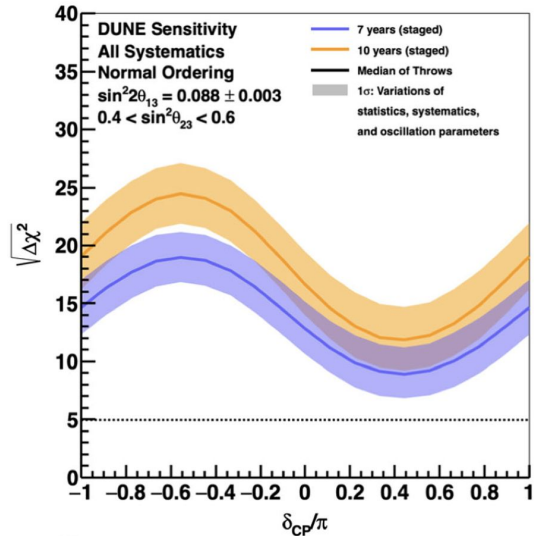
- Four caverns with space for 17 kt LAr TPCs
 - Unprecedented detector resolution for an LBL far detector
- Phase 1: 2x LAr modules
- Rich prototype programme at CERN: ProtoDUNE



DUNE: Long-term Sensitivity

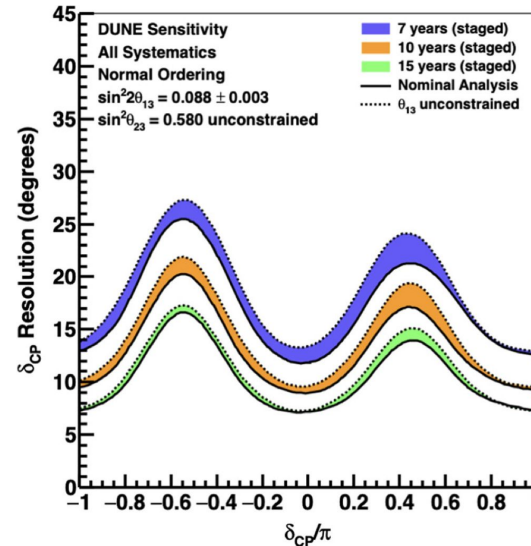
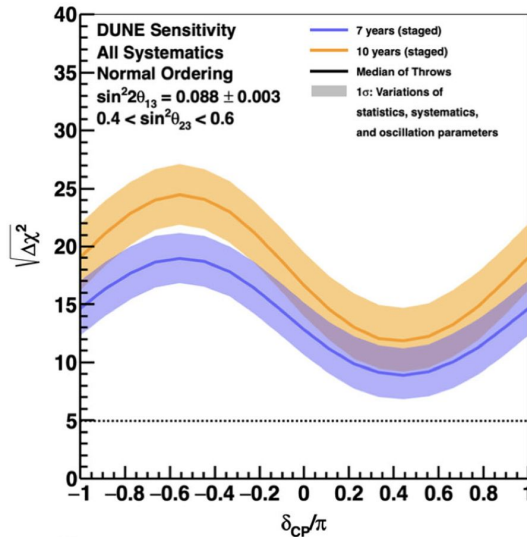
[EPJC 80 \(2020\) 978](#)

- Ultimate MO determination is unambiguous
 - Not dependent on precision measurement of other oscillation parameters
 - Requires no external oscillation parameter input



DUNE: Long-term Sensitivity

- Ultimate MO determination is unambiguous
 - Not dependent on precision measurement of other oscillation parameters
 - Requires no external oscillation parameter input



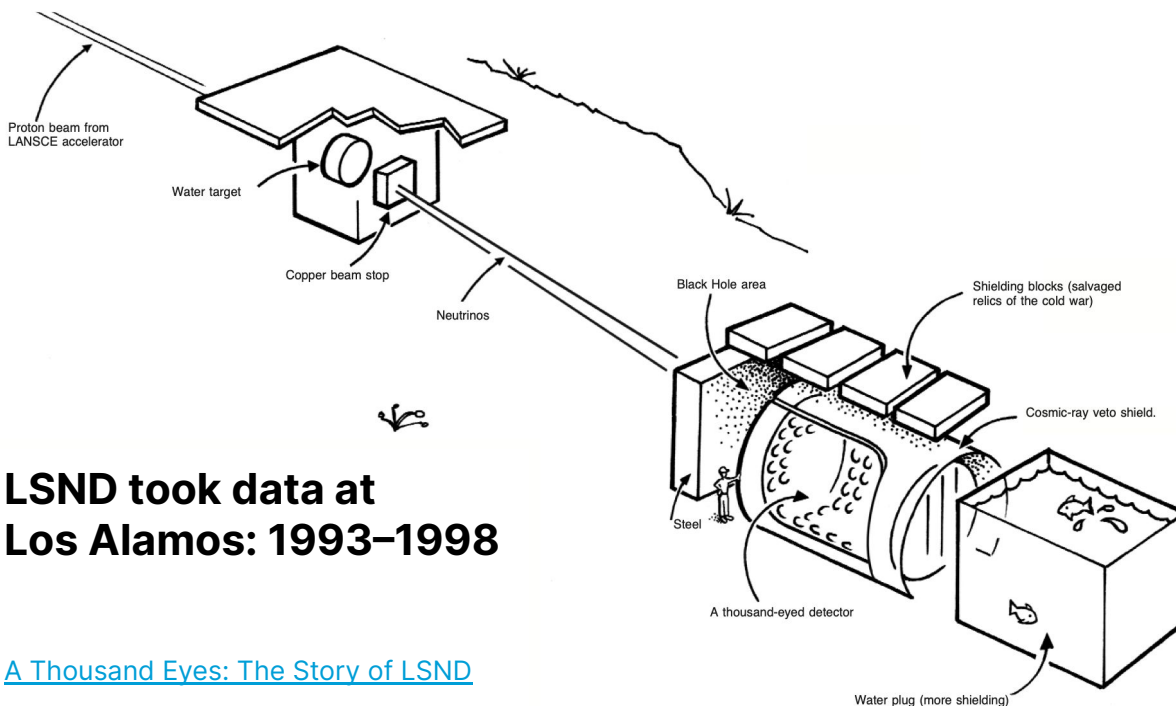
- 7–16° δ_{CP} resolution regardless of true value

Short Baseline (brief) History, Recent Results, and Prospects

Liquid Scintillator Neutrino Detector

In 90s, did not have a clear picture of three known neutrino mass-splittings:

- LSND looked for oscillation at: $L/E \sim 1 \text{ km/GeV}$

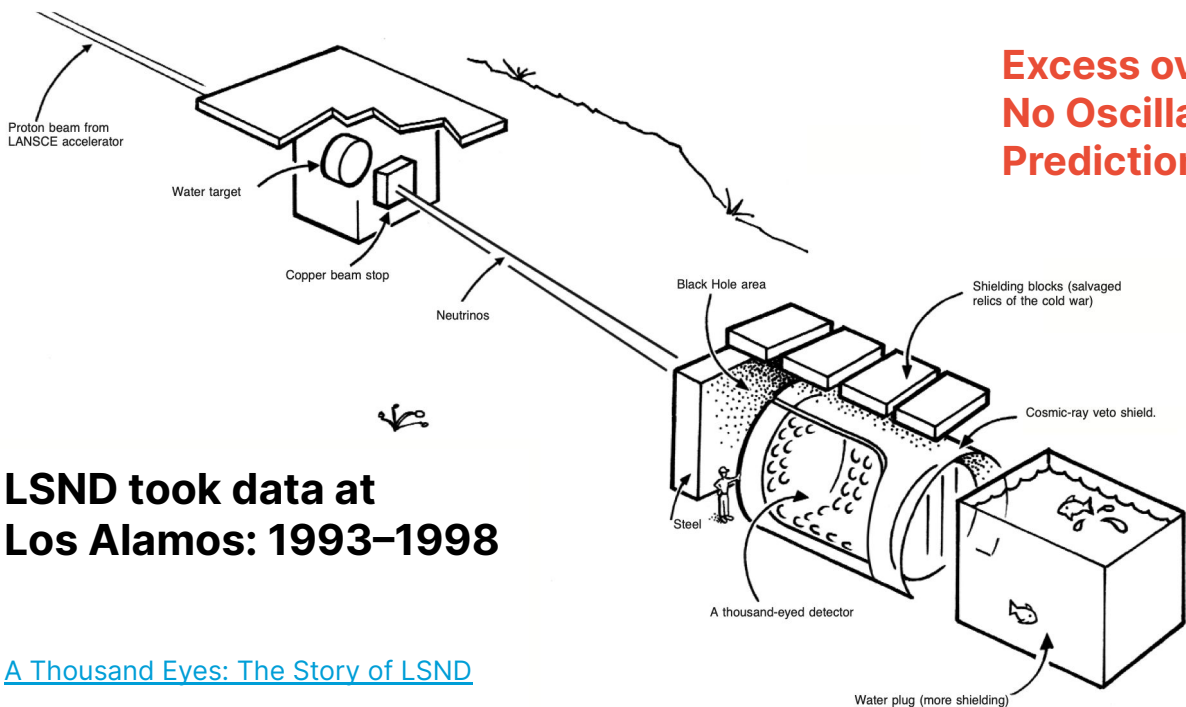


**LSND took data at
Los Alamos: 1993–1998**

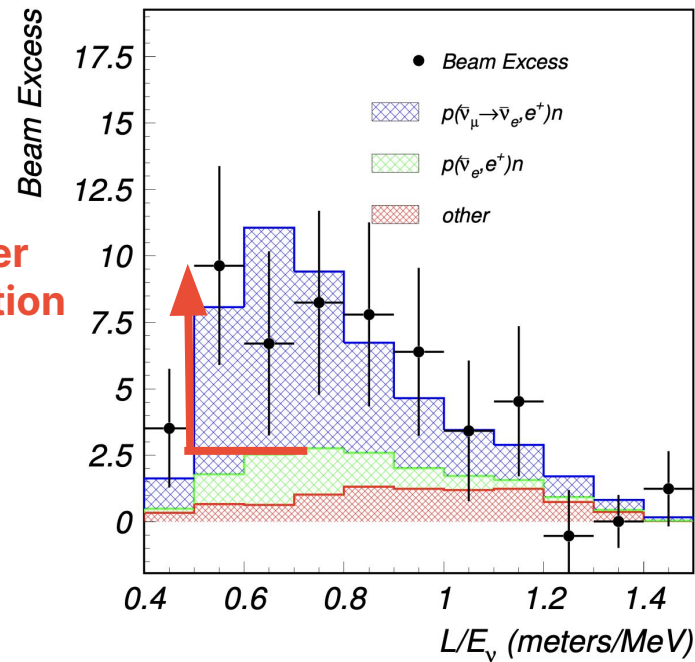
Liquid Scintillator Neutrino Detector

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**Excess over
No Oscillation
Prediction**



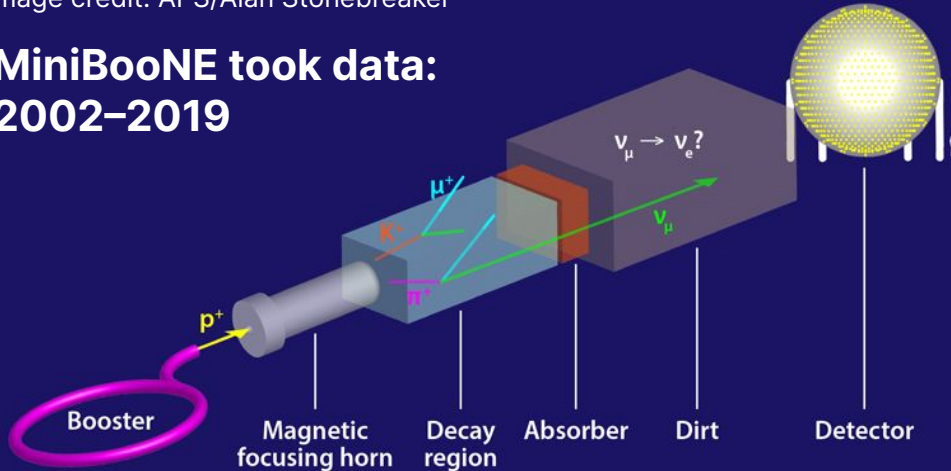
**LSND took data at
Los Alamos: 1993–1998**

LSND and MiniBooNE

- MiniBooNE commissioned to investigate LSND excess:
 - ~same L/E
 - Different L and E
 - Similar detector technology

Image credit: APS/Alan Stonebreaker

**MiniBooNE took data:
2002–2019**

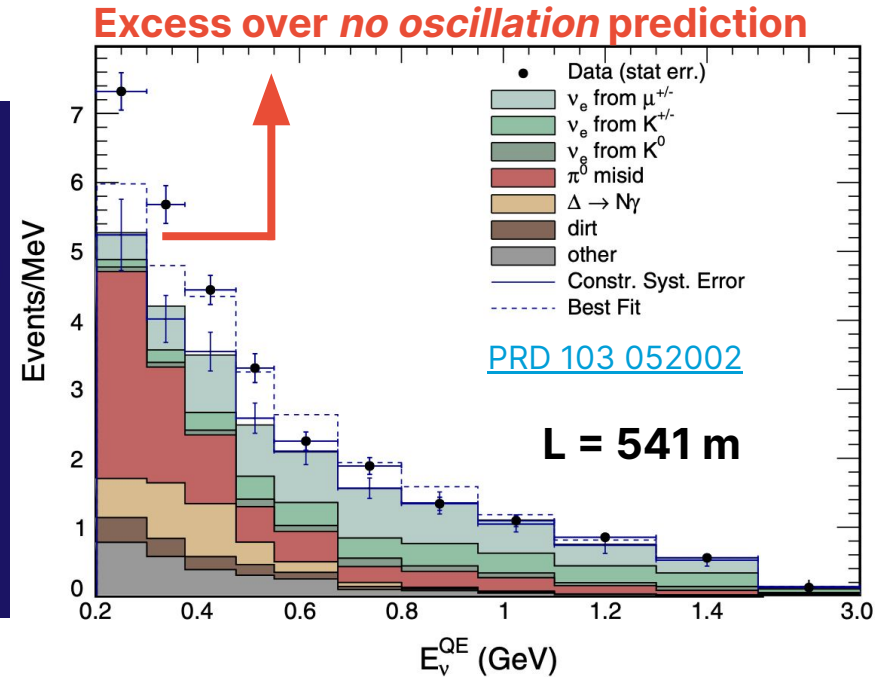
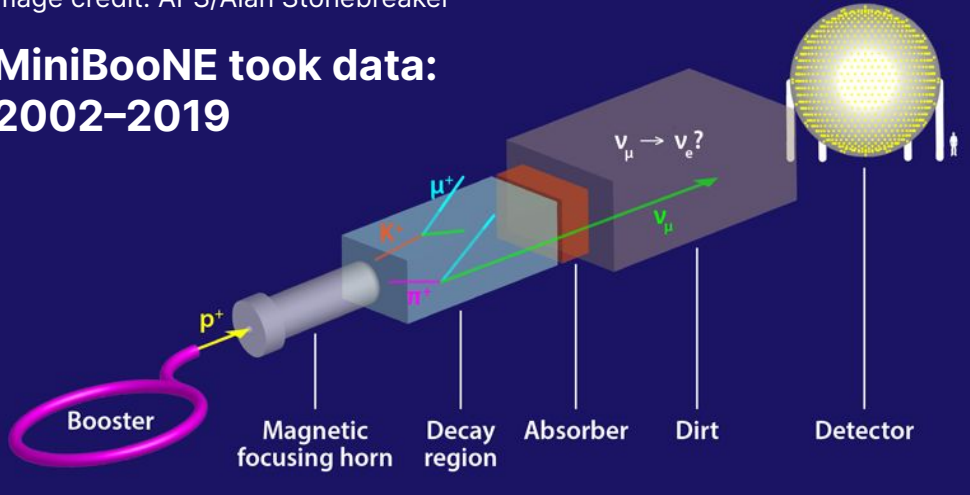


LSND and MiniBooNE

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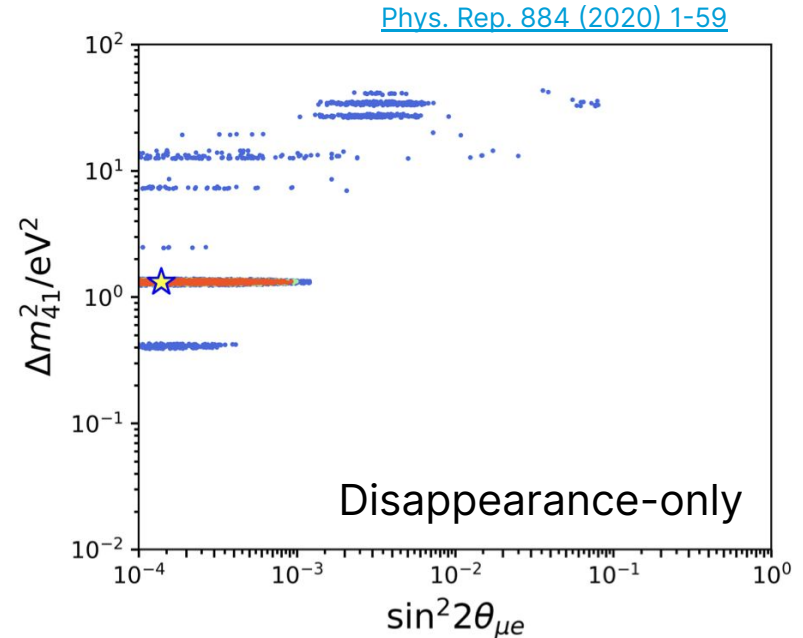
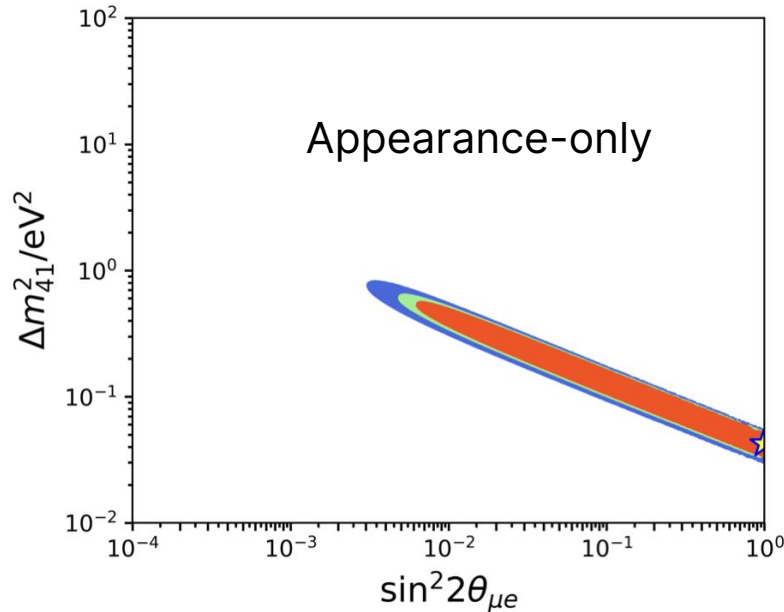
Image credit: APS/Alan Stonebreaker

**MiniBooNE took data:
2002–2019**



3+1 Tensions

However, difficult to explain global short baseline anomalous observations with just a single additional $\sim 1 \text{ eV}^2$ scale neutrino

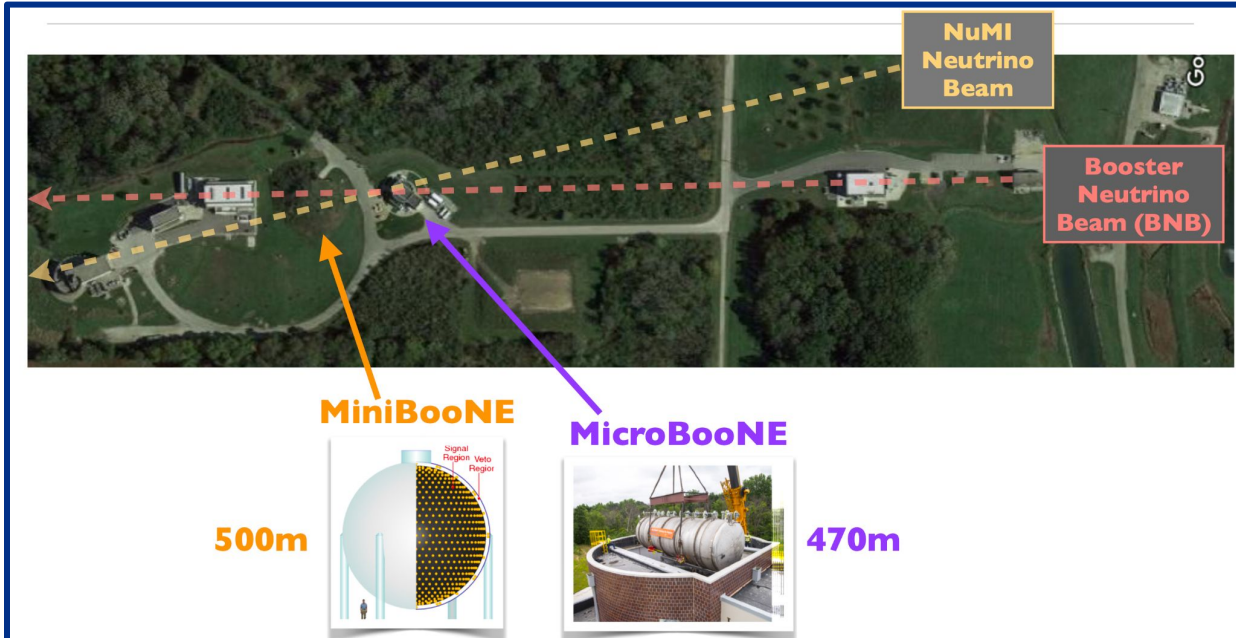
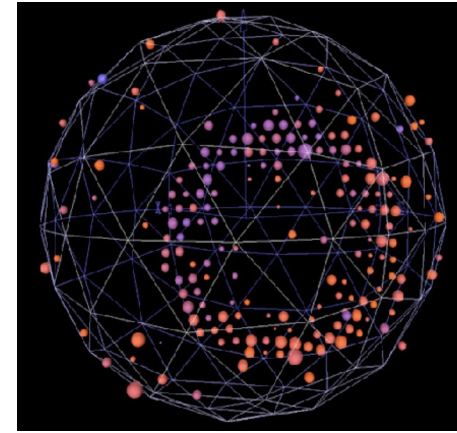


[Phys. Rep. 884 \(2020\) 1-59](#)

MiniBooNE & MicroBooNE

MiniBooNE: Liquid scintillator + Cherenkov

- Commissioned to investigate MiniBooNE's observed excess
 - In the same beam: ~same L and same E
 - Very different detector technology: LAr vs. LS+Cherenkov



K. Duffy Rencontres de Vietnam22

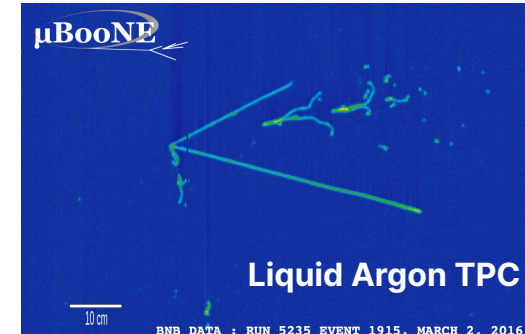
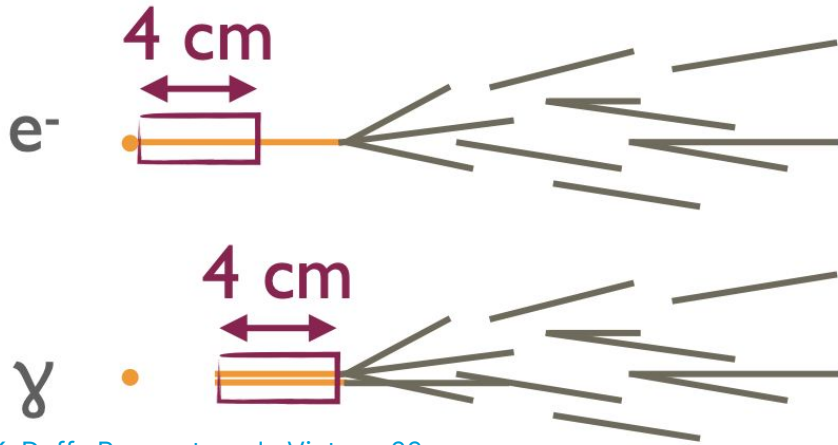


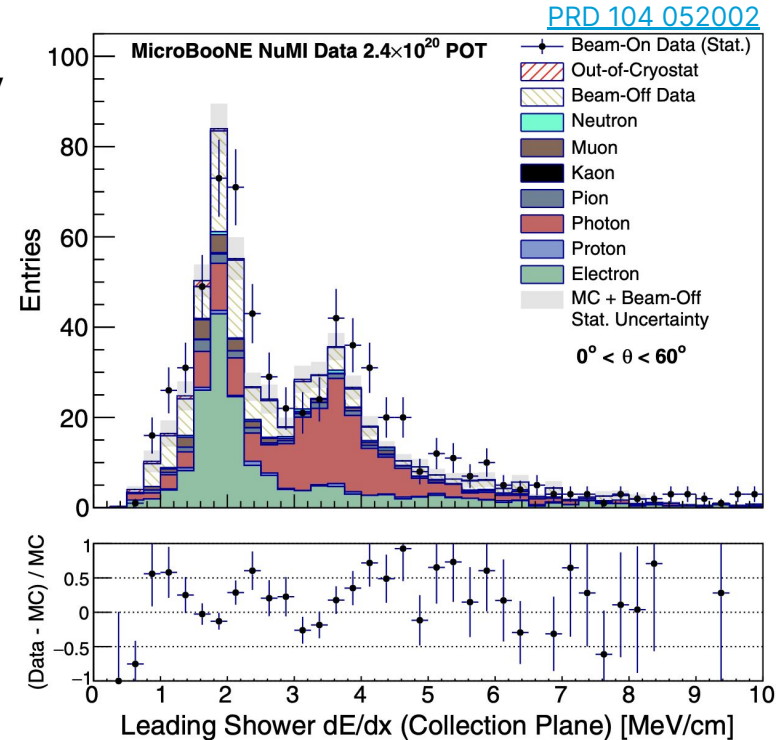
Image credit: microboone-exp.fnal.gov

MiniBooNE & MicroBooNE

- Commissioned to investigate MiniBooNE's observed excess
 - In the same beam: ~same L and same E
 - Very different detector technology: LAr vs. LS+Cherenkov
 - **Most important: Can separate electrons from photons:**
 - Energy deposit at the start of the shower



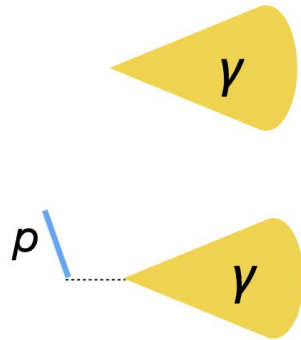
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MicroBooNE: First LEE Search

Photon search

Target $\Delta \rightarrow N\gamma$:
 $|\gamma_0 p$ and $|\gamma| p$



Phys. Rev. Lett. 128, 111801

Phys. Rev. Lett. 128, 241801

Electron searches

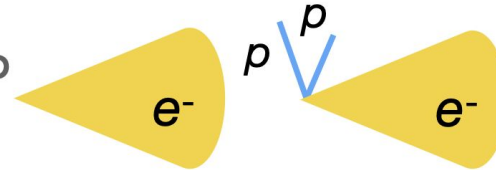
Phys. Rev. D 105, 112003

CCQE-like:
 $|e| p$



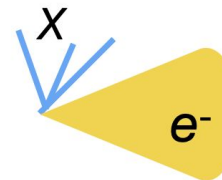
Phys. Rev. D 105, 112004

CC0π: $|e_0 p$
 and $|e N p$



Phys. Rev. D 105, 112005

Inclusive:
 $|e X$

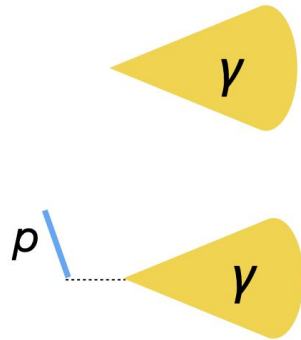


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MicroBooNE: First LEE Search

Photon search

Target $\Delta \rightarrow N\gamma$:
 $|\gamma_0 p$ and $|\gamma| p$



Phys. Rev. Lett. 128, 111801

Phys. Rev. Lett. 128, 241801

Electron searches

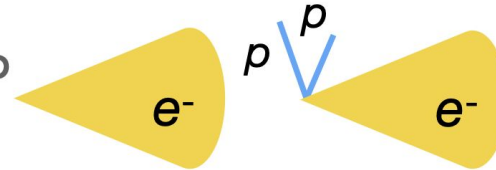
Phys. Rev. D 105, 112003

CCQE-like:
 $|e| p$



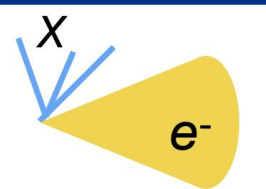
Phys. Rev. D 105, 112004

CC0π: $|e_0 p$
 and $|e N p$



Phys. Rev. D 105, 112005

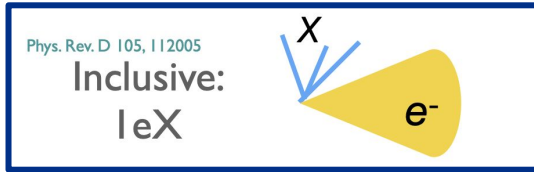
Inclusive:
 $|e X$



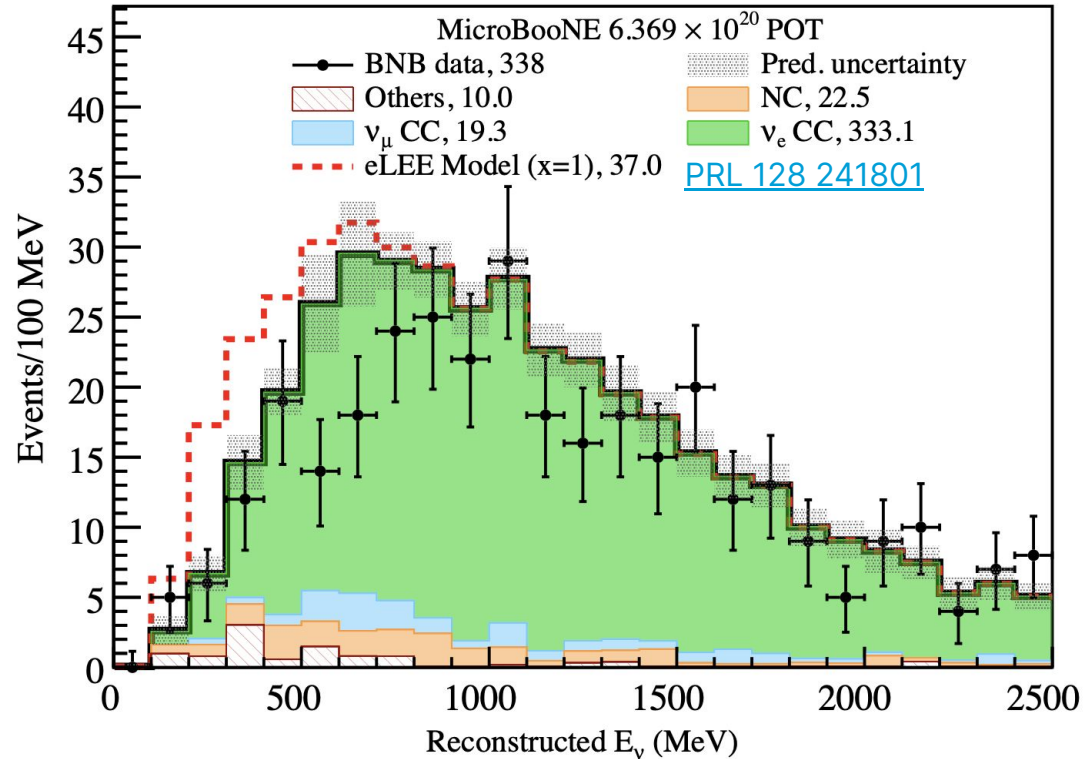
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MicroBooNE: First LEE Search

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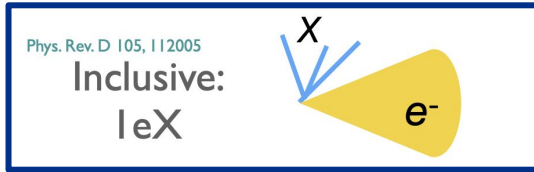


- MicroBooNE sees no evidence of MiniBooNE-like EM excess in channels sampled

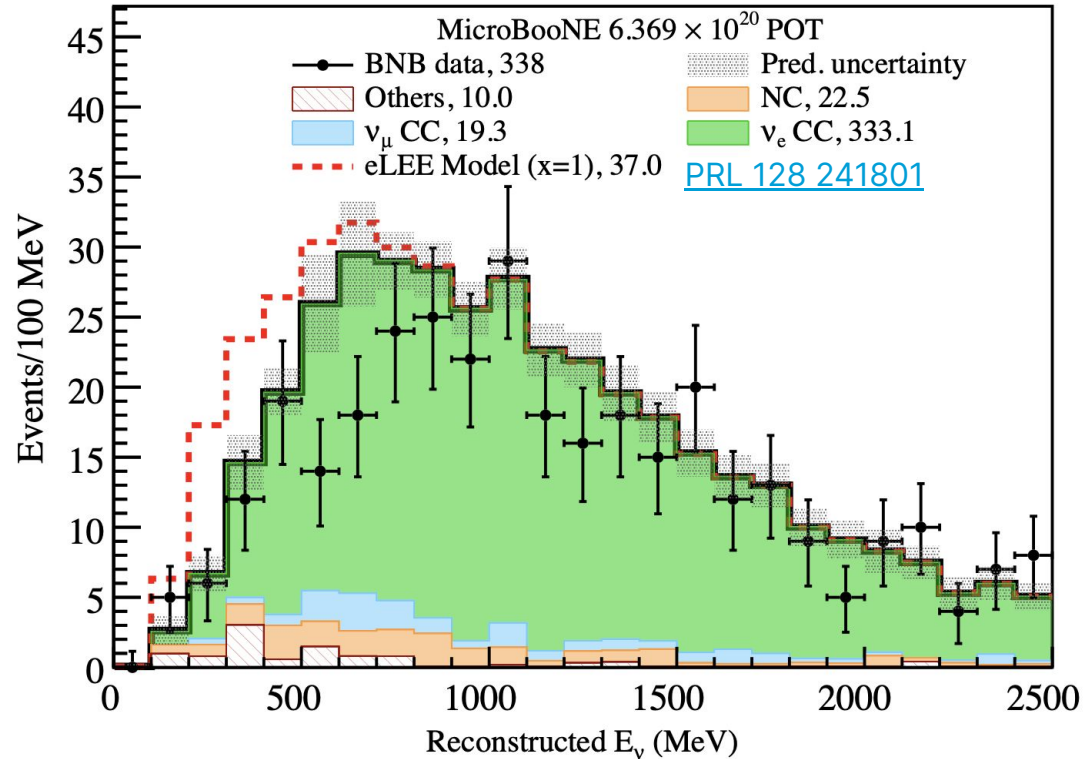


MicroBooNE: First LEE Search

[K. Duffy Rencontres de Vietnam22](#)



- MicroBooNE sees no evidence of MiniBooNE-like EM excess in channels sampled
- But LSND, MiniBooNE, and others saw *something*...

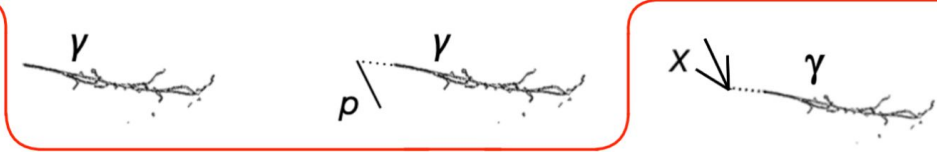
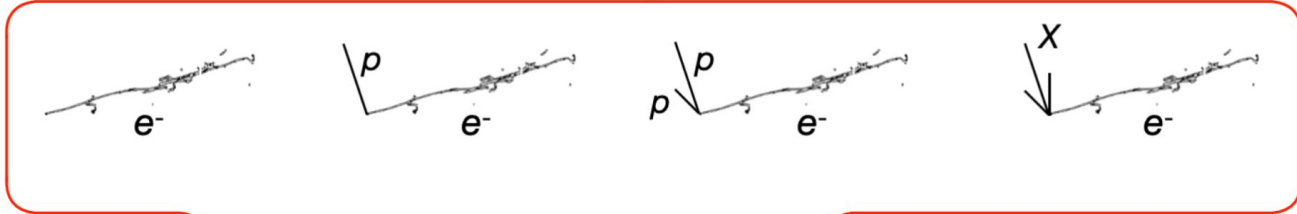


MicroBooNE: First LEE Search

K. Duffy Rencontres de Vietnam22

Phys. Rev. D
In

MicroBooNE's first LEE results

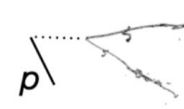


Overlapping e^+e^-

Overlapping e^+e^-

Highly asymmetric e^+e^-

Highly asymmetric e^+e^-

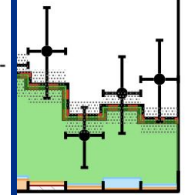


others saw *something...*

0 500 1000 1500 2000

Reconstructed E_ν (MeV)

uncertainty
.1
01

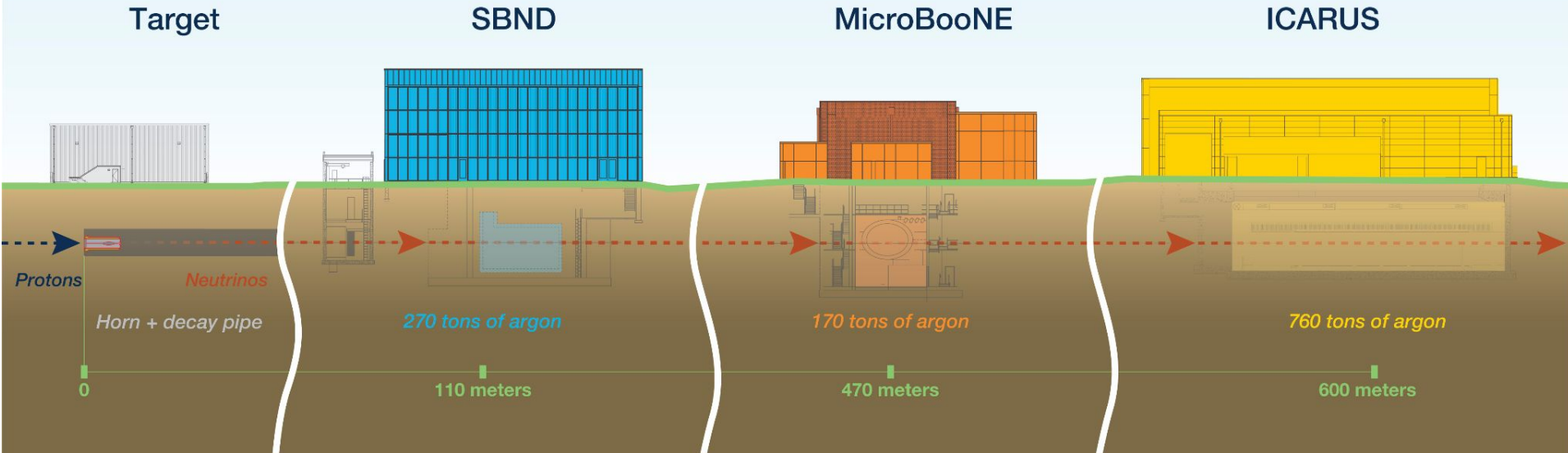


- MicroBooNE evidence for EM
- But others saw something...

The Search Continues On SBN!

Image credit: Diana Brandonisio, FNAL

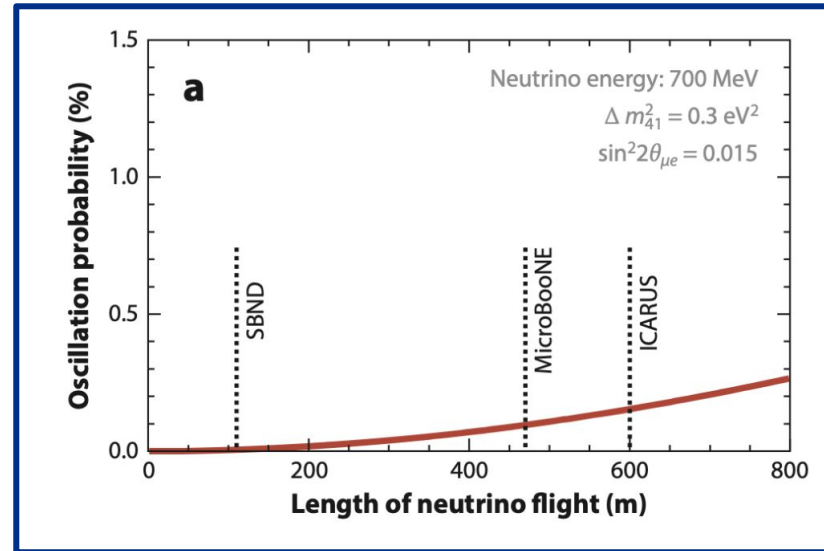
Short-Baseline Neutrino Program at Fermilab



Short Baseline Neutrino

- Near Detector to constrain unoscillated rate
- Look for appearance/disappearance in MicroBooNE and ICARUS data
- ICARUS taking data since 2021

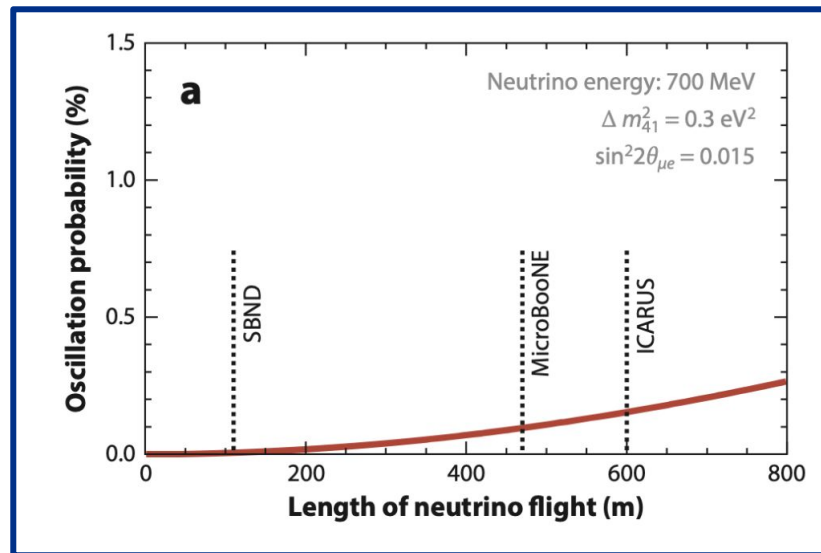
[Ann.Rev.Nuc 69 p363-387 \(2019\)](#)



Short Baseline Neutrino

- Near Detector to constrain unoscillated rate
- Look for appearance/disappearance in MicroBooNE and ICARUS data
- ICARUS taking data since 2021
- **SBND is full of liquid argon**
 - **Commissioning phase beginning now!**

[Ann.Rev.Nuc 69 p363-387 \(2019\)](#)



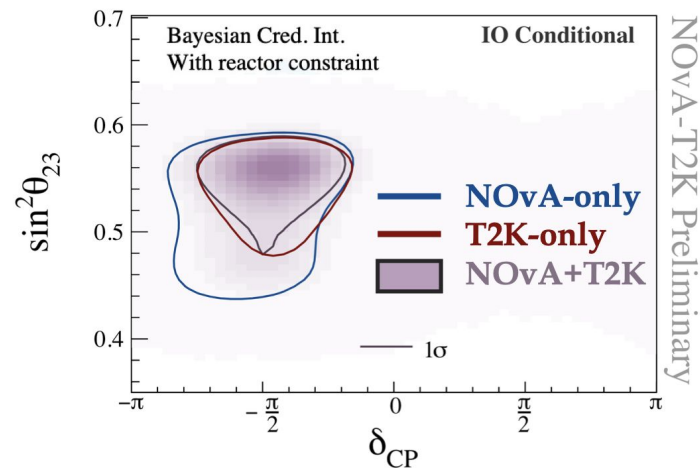
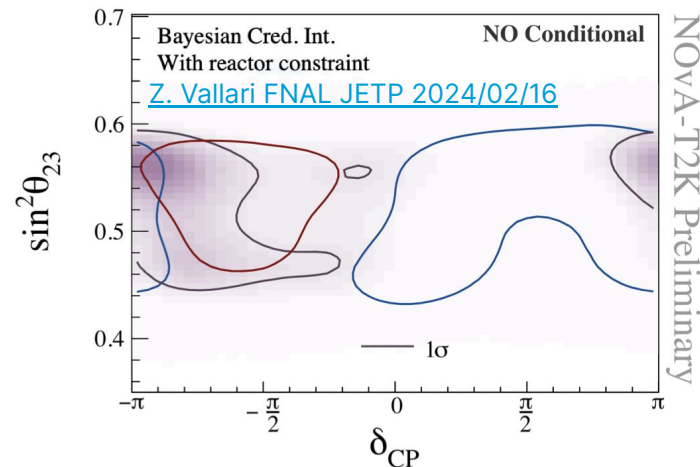
Parting Comments

Things That I Didn't Mention

- Future atmospheric neutrino experiments:
 - IceCube Gen-2, KM3NeT: ORCA and ARCA
- Current or future atmospheric programmes on LBL experiments that also have beams
- Reactor experiments and anomalies
- Extensive BSM programmes in addition $\sim 1 \text{ eV}^2$ scale sterile neutrinos
- Neutrino beams
- Systematic uncertainty details:
 - Cross section uncertainties and constraint programmes
 - Neutrino flux predictions and uncertainties

Summary

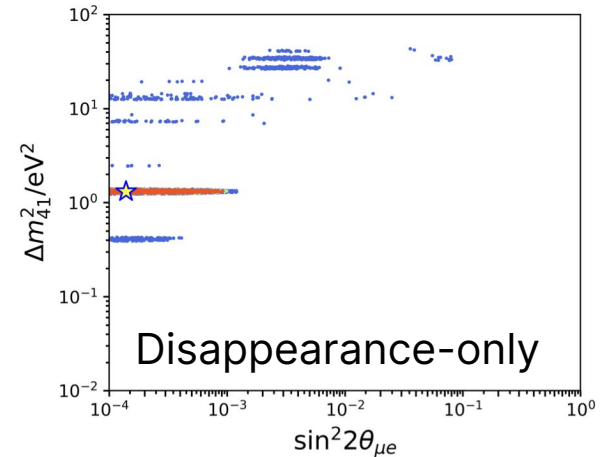
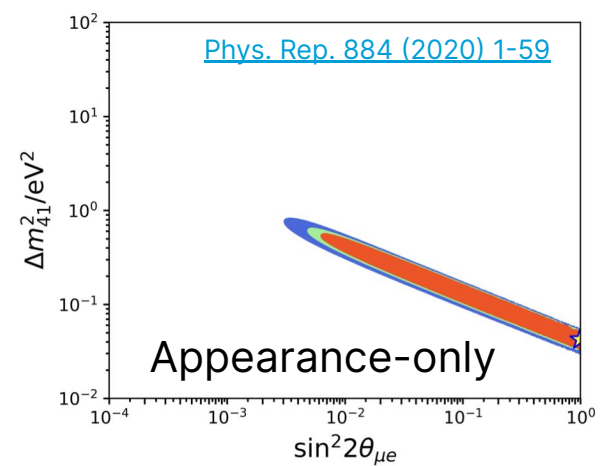
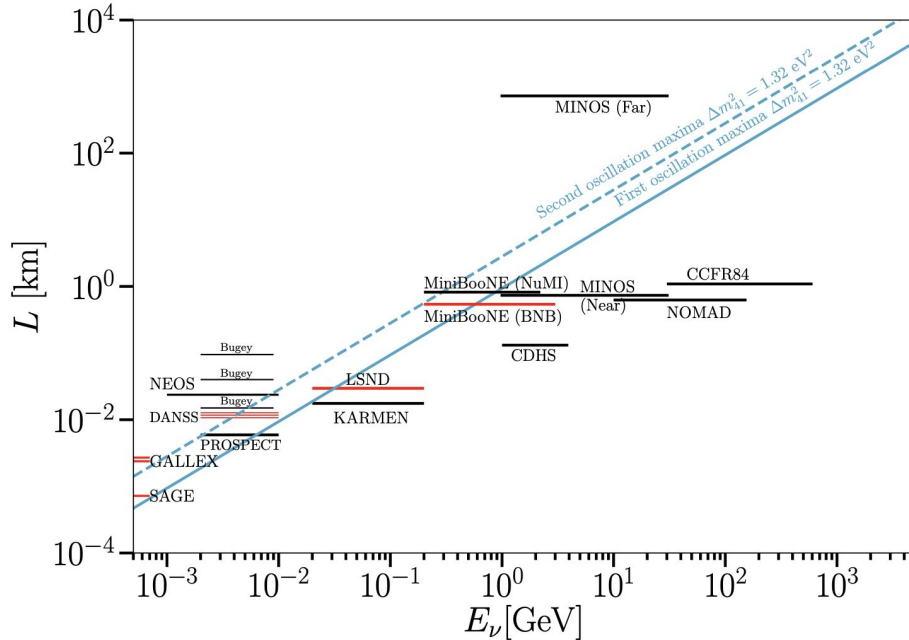
- Neutrino Oscillations are the only confirmed probe of BSM phenomenon:
 - Measured every parameter except δ_{CP}
 - Constraints starting to look exciting for CPV!
 - **Current Gen:** More precise measurements until end of decade. Lots still to learn.
- Next Generation:
 - DUNE/HK will do precision physics and unambiguously measure fundamental symmetry parameters:
 - Mass ordering and δ_{CP}
- Short baseline:
 - Anomalies may motivate extra neutrinos
 - First multi-detector beam-based experiment entering final commissioning as we speak!



Backups

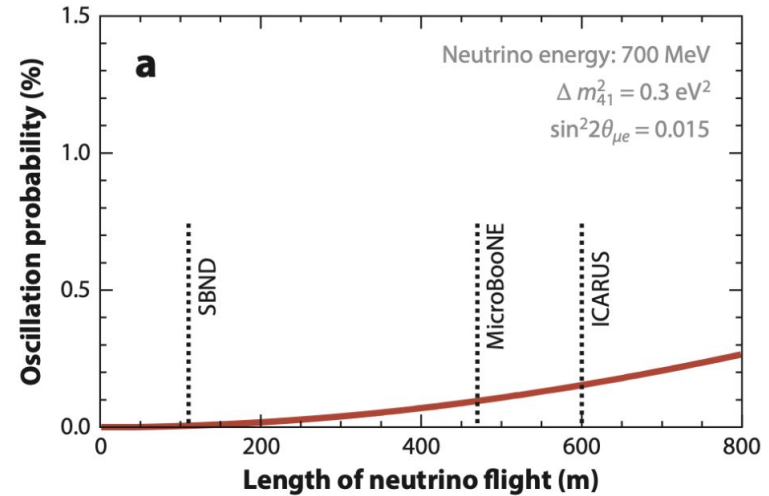
3+1 Tensions

- However, difficult to explain global data with a single additional $\sim 1 \text{ eV}^2$ scale neutrino



Short Baseline Neutrino

- Near Detector to constrain unoscillated rate
- Look for appearance/disappearance in MicroBooNE and ICARUS data
- ICARUS taking data since 2021
- SBND is filling/full of liquid argon
 - Commissioning phase beginning now!



Process	SBND Predicted Event Rate	No. Events
	ν_μ Events (By Final State Topology)	
CC Inclusive		5,212,690
CC 0π	$\nu_\mu N \rightarrow \mu + Np$	3,551,830
	· $\nu_\mu N \rightarrow \mu + 0p$	793,153
	· $\nu_\mu N \rightarrow \mu + 1p$	2,027,830
	· $\nu_\mu N \rightarrow \mu + 2p$	359,496
	· $\nu_\mu N \rightarrow \mu + \geq 3p$	371,347
CC $1 \pi^\pm$	$\nu_\mu N \rightarrow \mu + \text{nucleons} + 1\pi^\pm$	1,161,610
CC $\geq 2\pi^\pm$	$\nu_\mu N \rightarrow \mu + \text{nucleons} + \geq 2\pi^\pm$	97,929
CC $\geq 1\pi^0$	$\nu_\mu N \rightarrow \mu + \text{nucleons} + \geq 1\pi^0$	497,963

[A. Furmanski NuFact23](#)

30x MicroBooNE stats

5M ν_μ CC per year
 2M NC per year
 12k ν_e CC per year

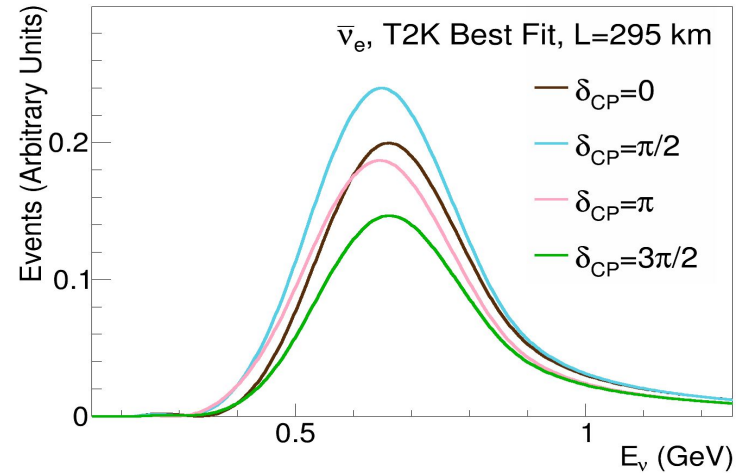
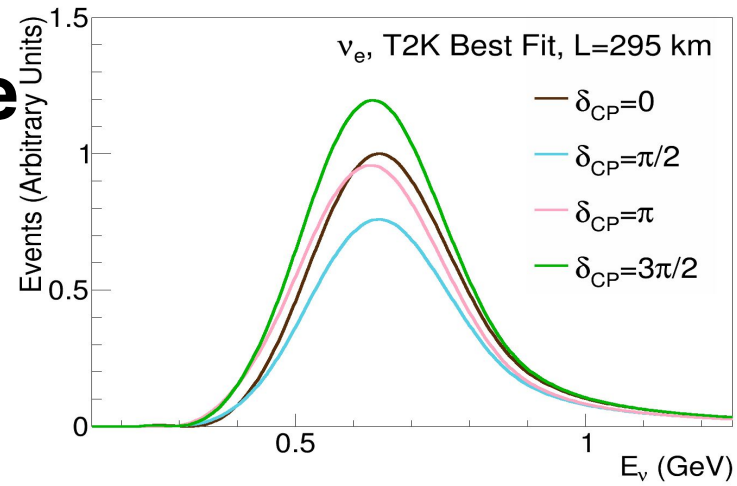
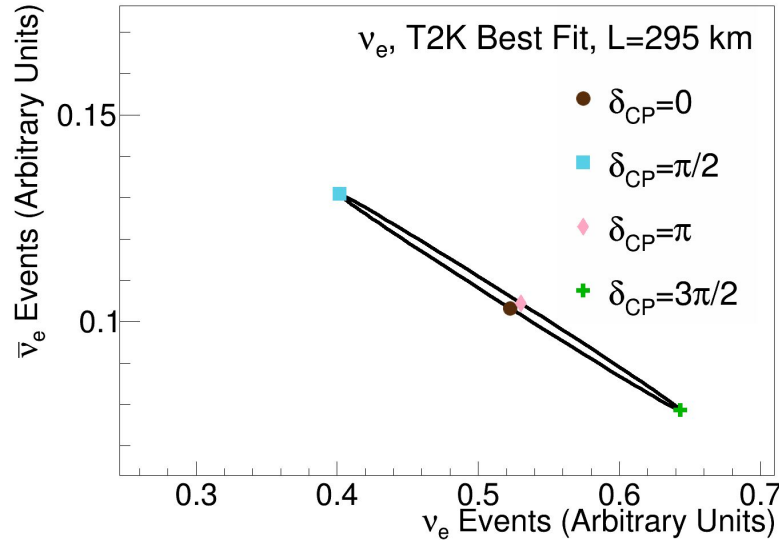
Exciting time ahead for SBL oscillation searches and Ar-target neutrino physics:

- Important for next-gen Ar-target LBL!

Osc. Details

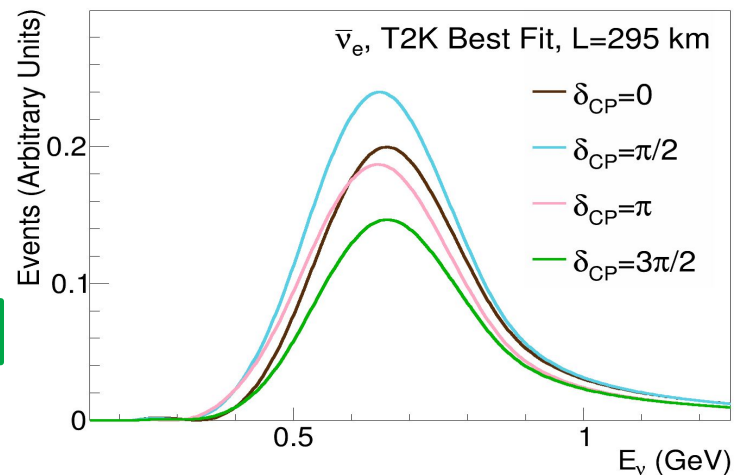
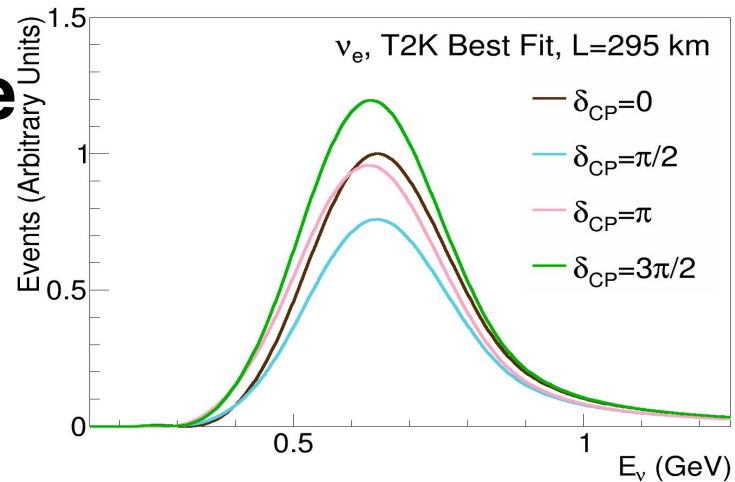
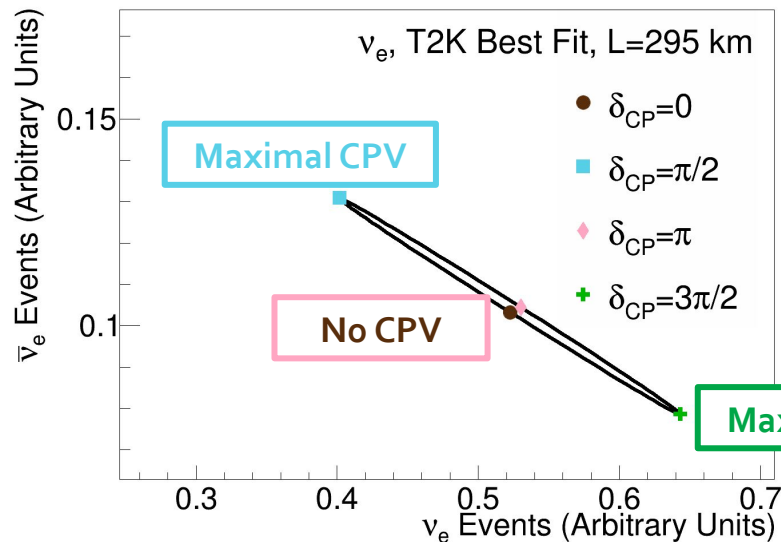
Electron Neutrino Appearance

- Appearance probability has 'CP odd' term.
 - Sign flip between matter and antimatter



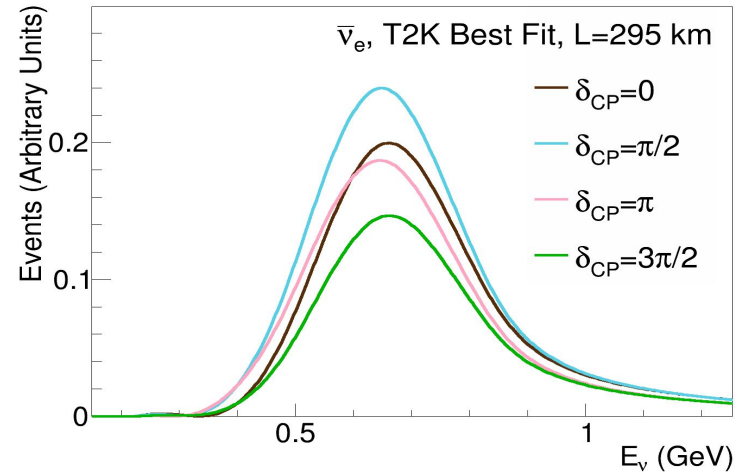
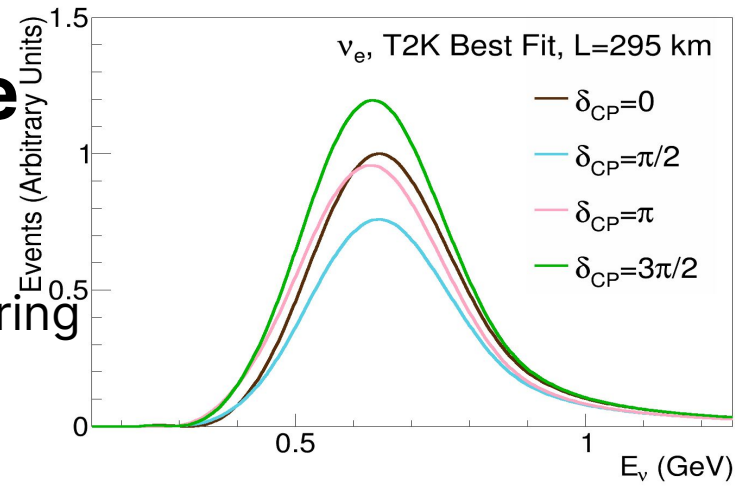
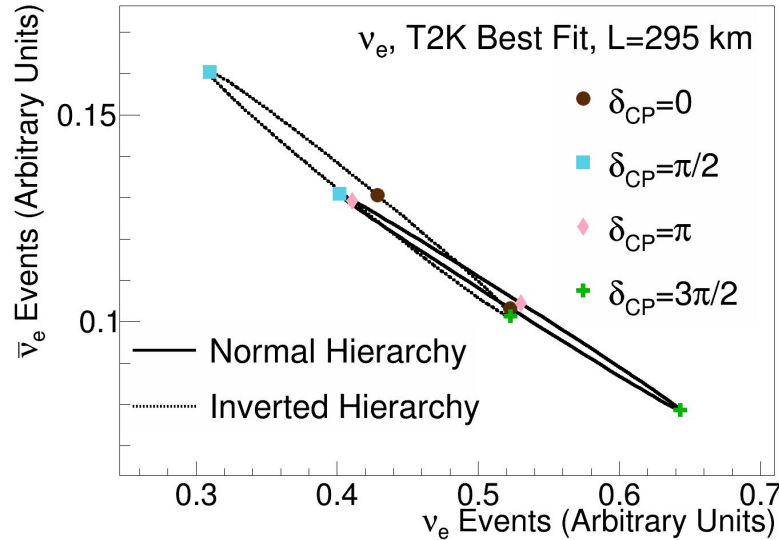
Electron Neutrino Appearance

- Appearance probability has 'CP odd' term.
 - Sign flip between matter and antimatter



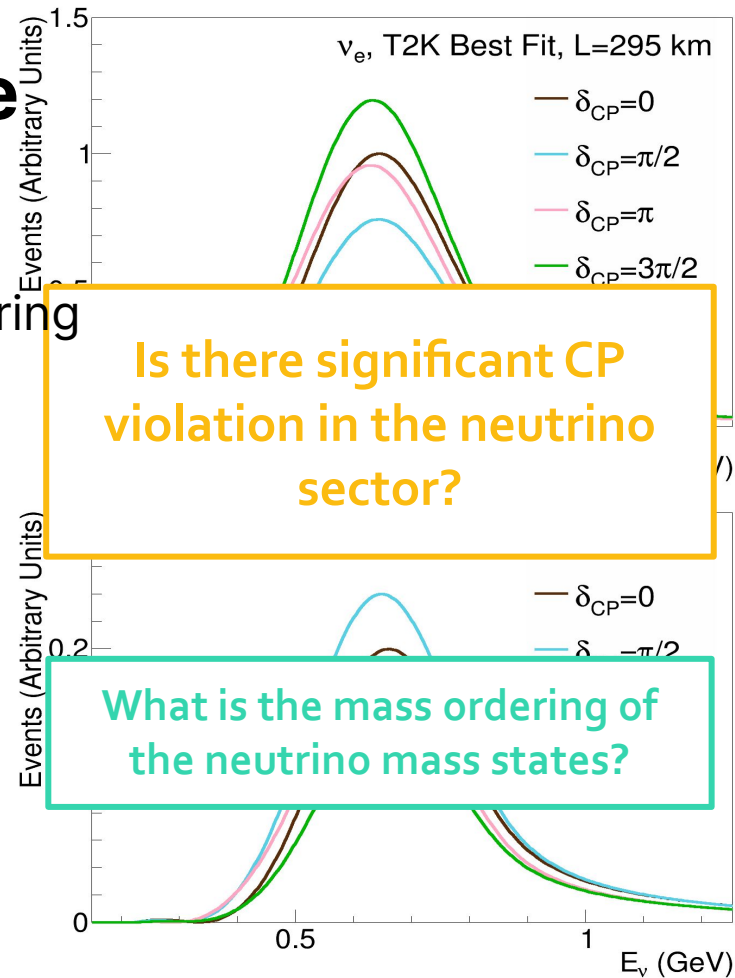
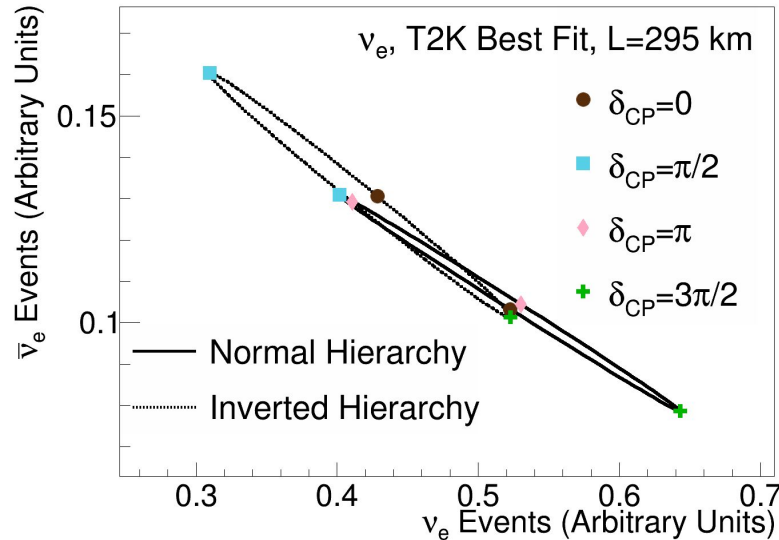
Electron Neutrino Appearance

- Appearance probability has 'CP odd' term.
 - Sign flip between matter and antimatter
 - Matter-effect induces modest mass ordering dependence



Electron Neutrino Appearance

- Appearance probability has 'CP odd' term.
 - Sign flip between matter and antimatter
 - Matter-effect induces modest mass ordering dependence



Is there significant CP violation in the neutrino sector?

What is the mass ordering of the neutrino mass states?

Measuring An Oscillation

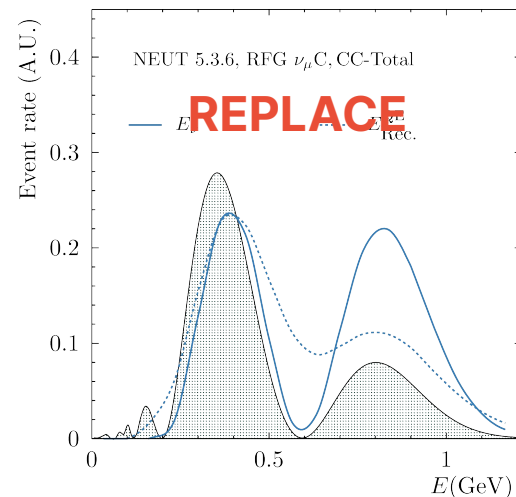
$$N_{\text{near}}(E_{\text{obs}}) = \int dE_{\nu} \Phi_{\text{near}}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot D_{\text{near}}$$

Want to know

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

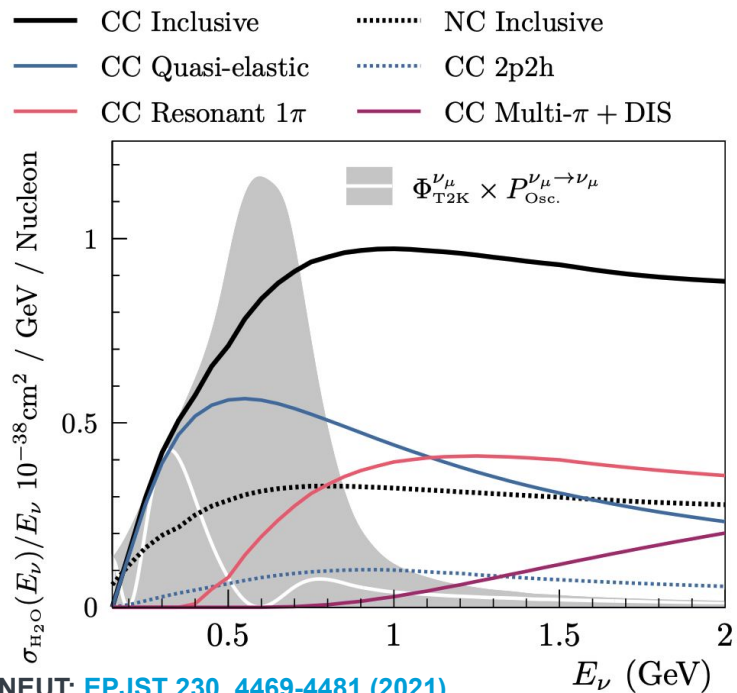
Observe

- Oscillation measurements are **not** just near-to-far ratio:
 - Oscillation is not a function of observed energy, E_{obs}
- Must use models to infer P_{osc} from observations
- Degeneracies inside the integral \rightarrow limits on sensitivity
 - Design Near Detector to minimise **Flux** and **Cross Section** degeneracy
 - Limited by **Detector** capability

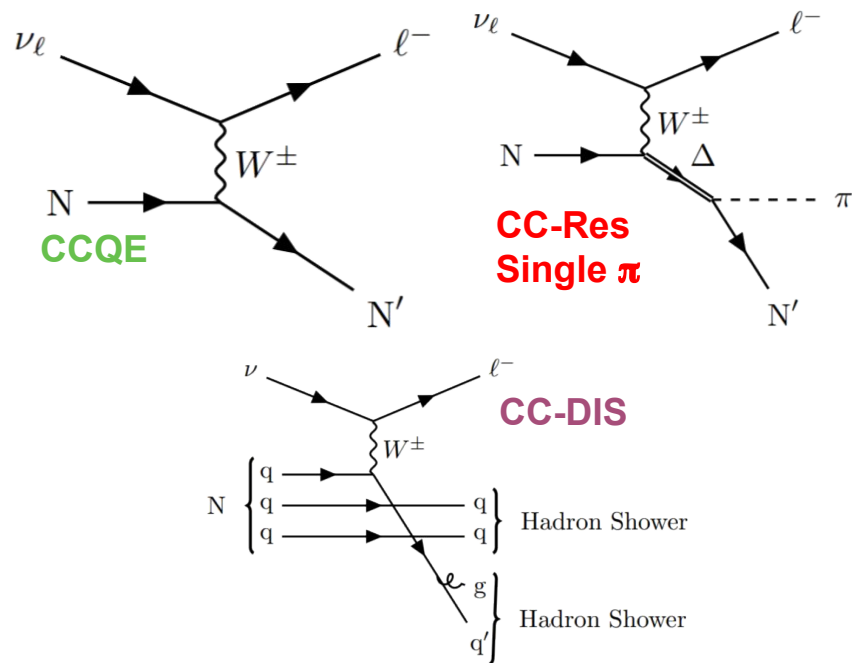


Interacting Neutrinos

- Measuring oscillation is complicated by:
 - Oscillation depends on unknowable neutrino energy
 - Multiple interaction channels, rates only known to $\sim 10\%$

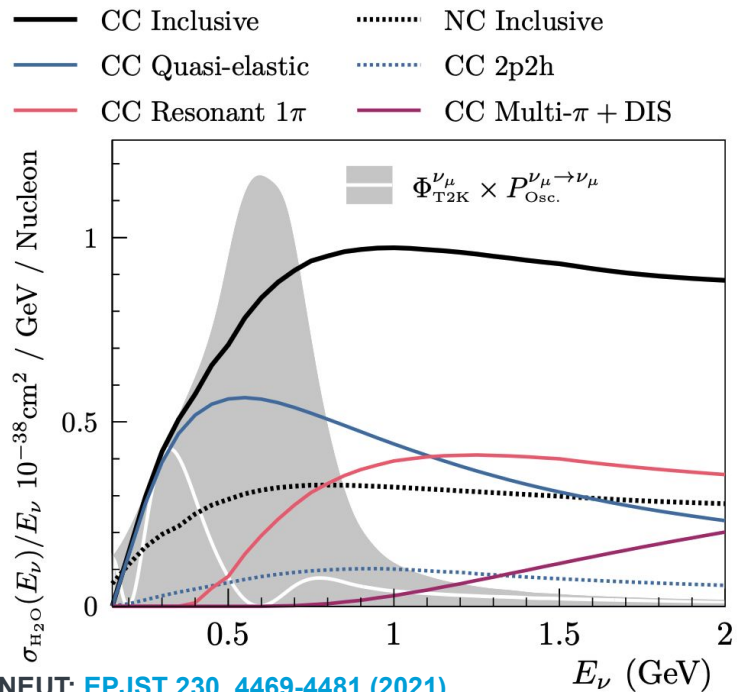


NEUT: [EPJST 230, 4469-4481 \(2021\)](#)

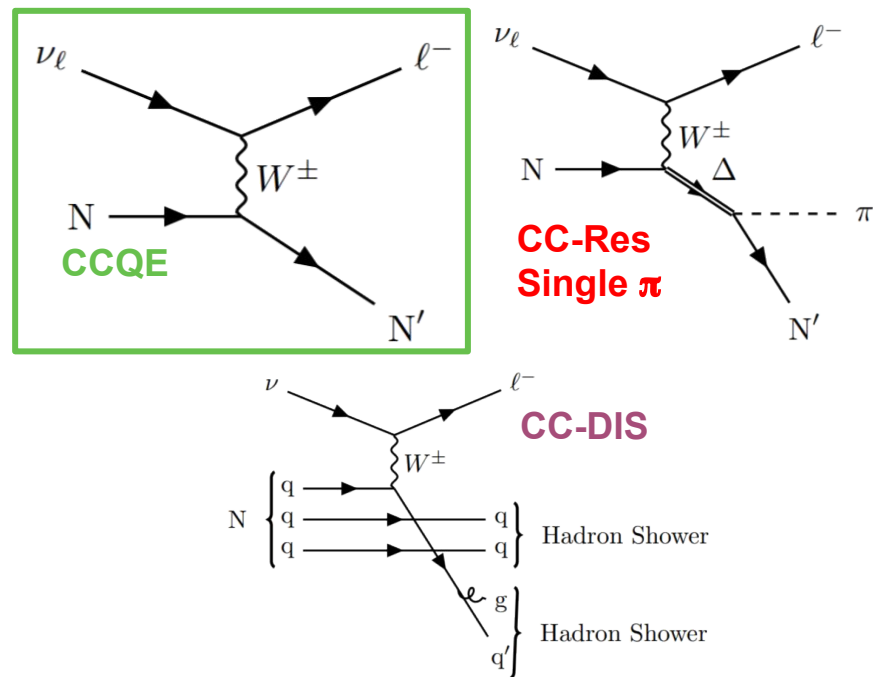


Interacting Neutrinos

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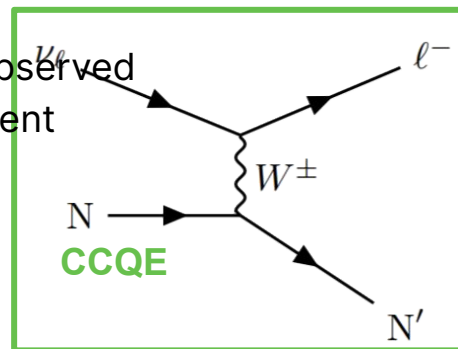
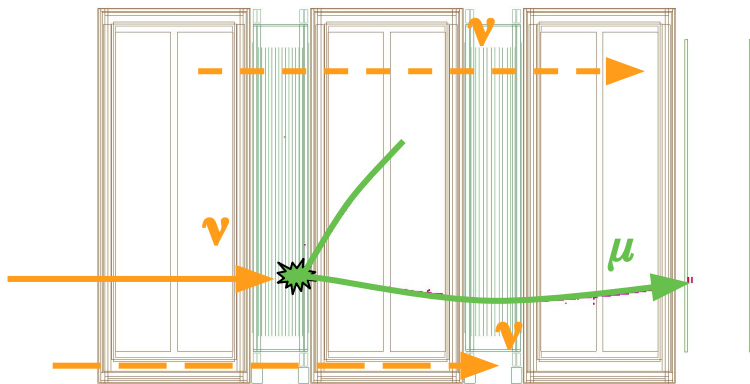


NEUT: [EPJST 230, 4469-4481 \(2021\)](#)



Interacting Neutrinos

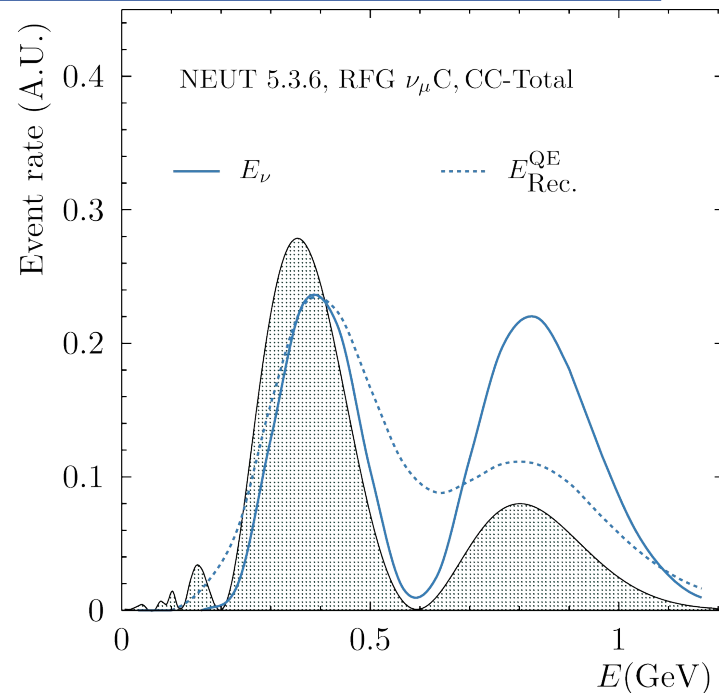
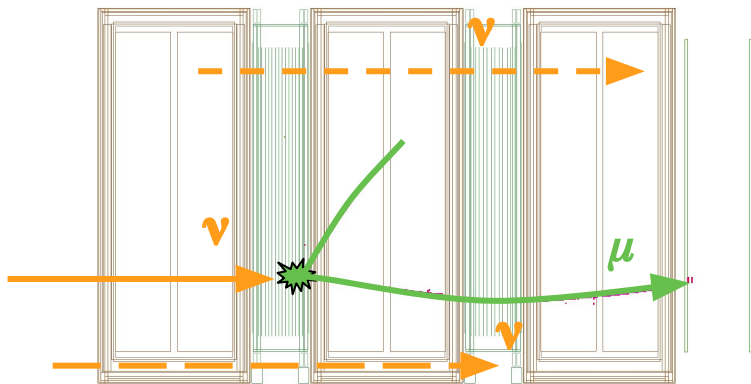
- Measuring oscillation is complicated by:
 - Oscillation depends on unknowable neutrino energy
 - Multiple interaction channels, rates only known to ~10%
 - Reconstructing the neutrino energy from observed final state particles is highly model dependent



$$E_{\text{rec}}^{\text{QE}} = \frac{2M_N [E_\ell] - M_\ell^2 + M_{N'}^2 - M_N^2}{2(M_N - [E_\ell] + [\vec{p}_\ell] \cos(\theta_\ell))}$$

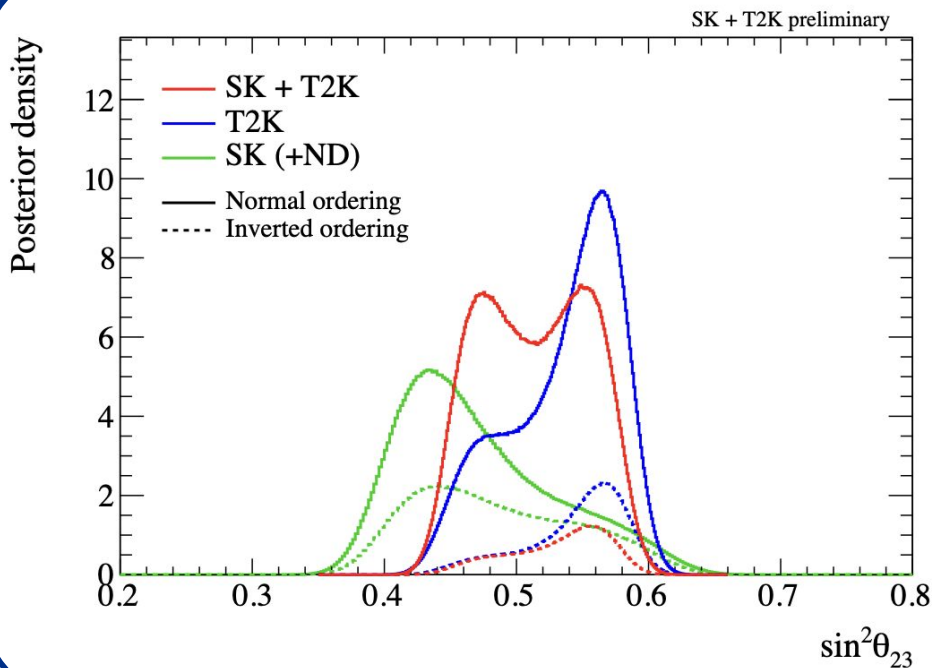
Interacting Neutrinos

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T2K+SK Octant



[L. Berns IPNS Seminar](#)

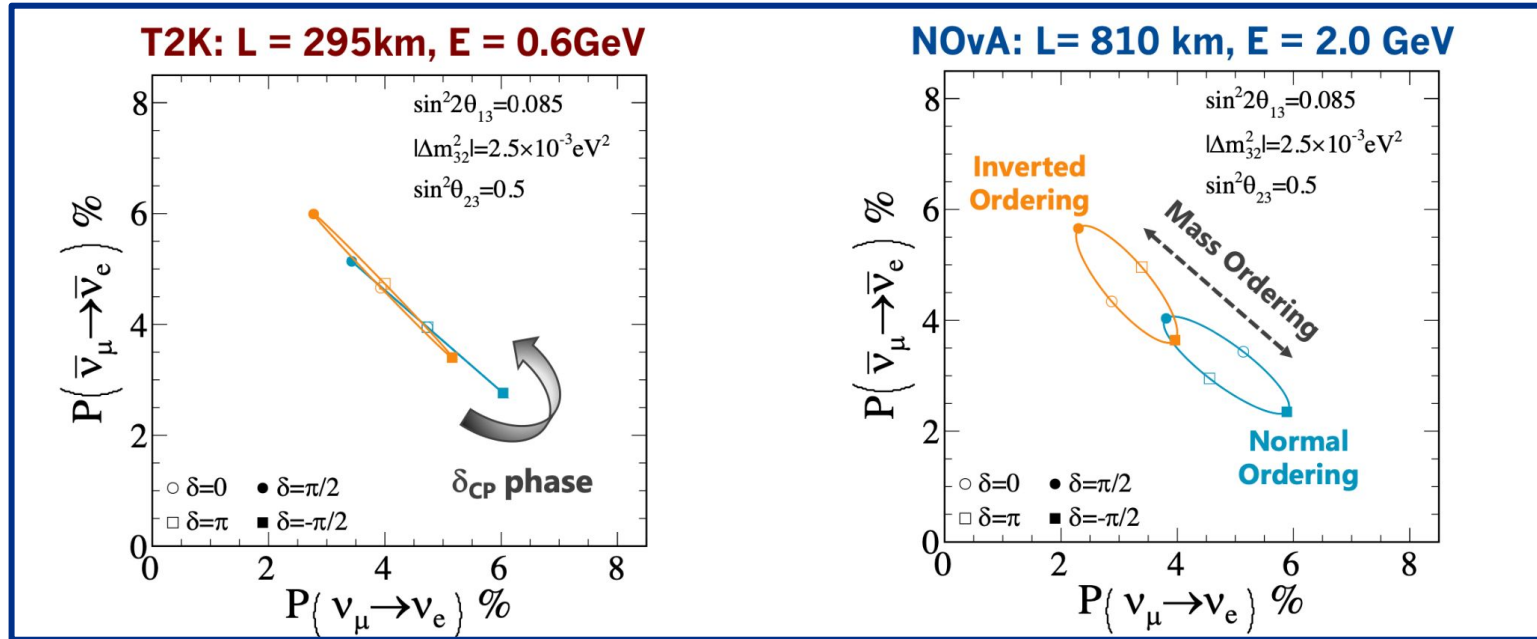
- Different octant preference by each experiment
- As a result, joint fit has no strong octant preference: $P(\text{upper}) = 0.61$

PRISM Details

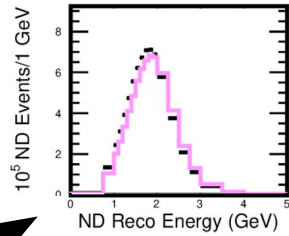
NOvA Details

Appearance: BiProb

Z. Vallari FNAL JETP 2024/02/16



Near to Far Extrapolation

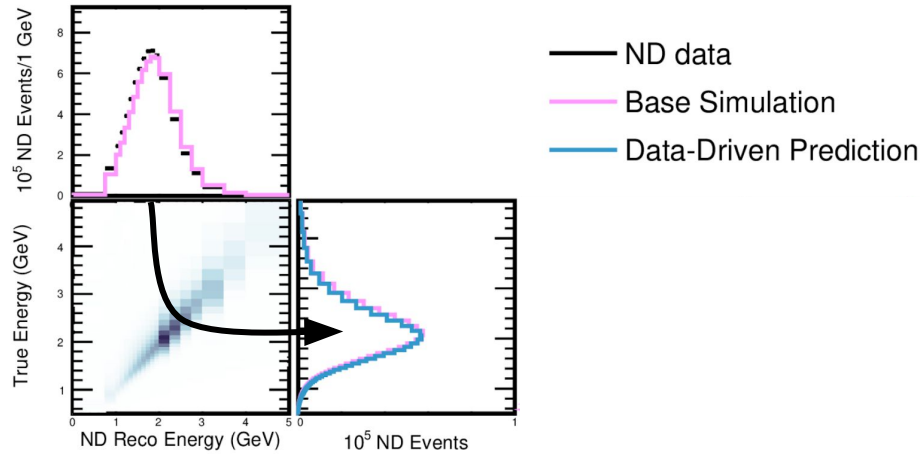


— ND data
— Base Simulation

1. Sample near detector events

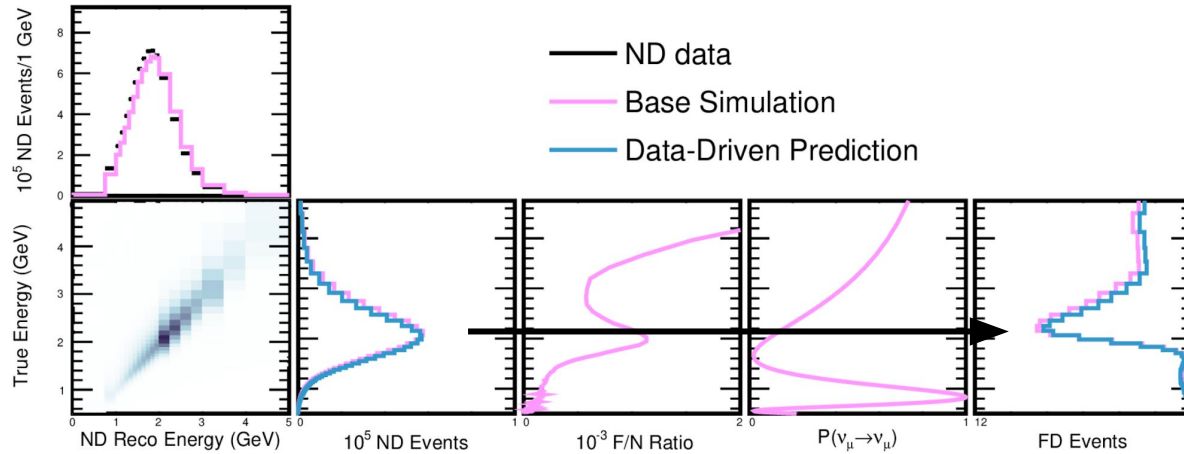


Near to Far Extrapolation



1. Sample near detector events
2. **Estimate true neutrino energy spectrum with interaction model**

Near to Far Extrapolation

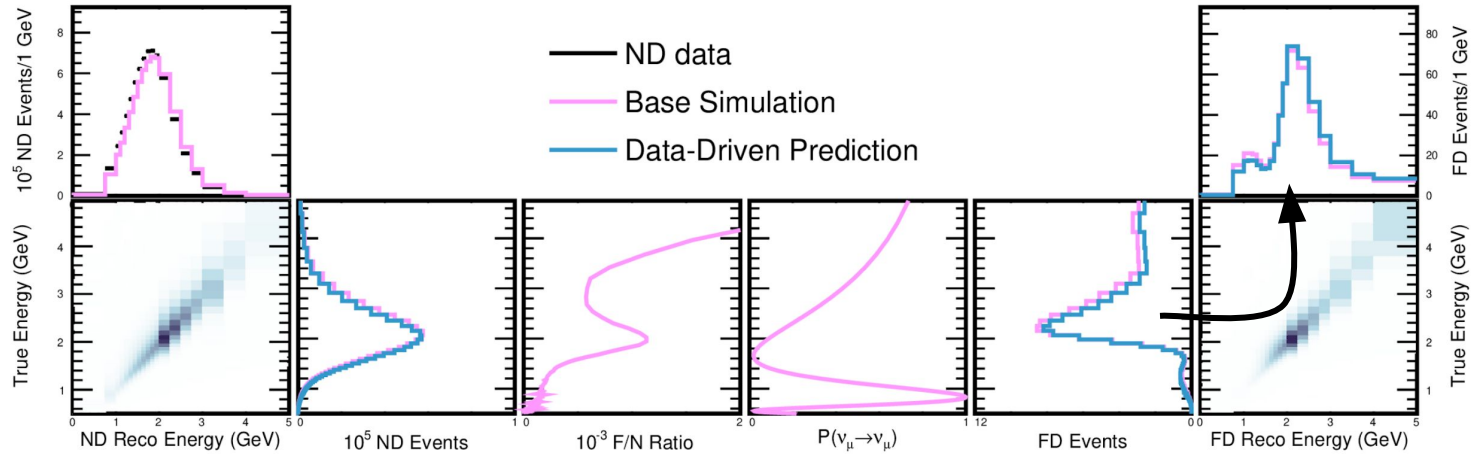


1. Sample near detector events
2. Estimate true neutrino energy spectrum with interaction model

3. **Account for far/near differences and oscillate true spectrum**



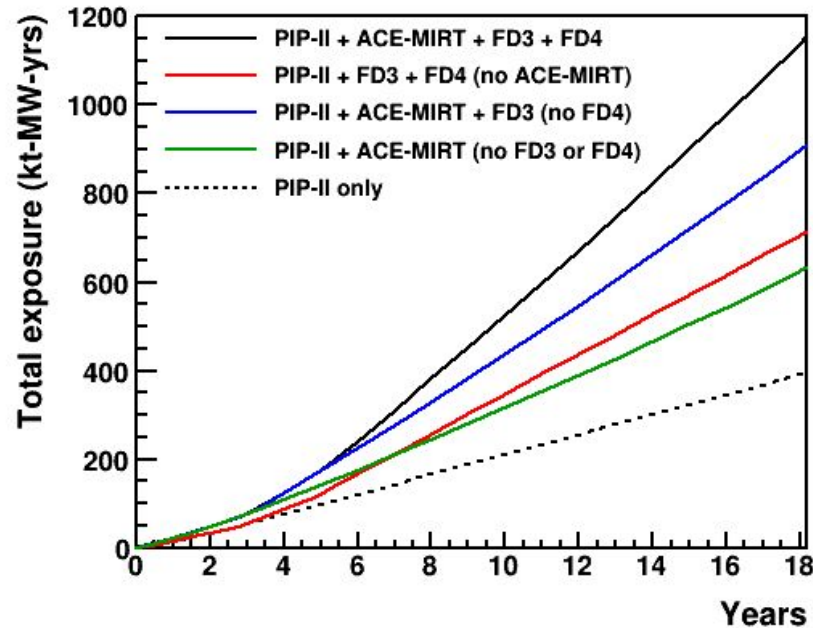
Near to Far Extrapolation



1. Sample near detector events
2. Estimate true neutrino energy spectrum with interaction model
3. Account for far/near differences and oscillate true spectrum
4. **Predict observed oscillated spectrum and compare for goodness of fit.**

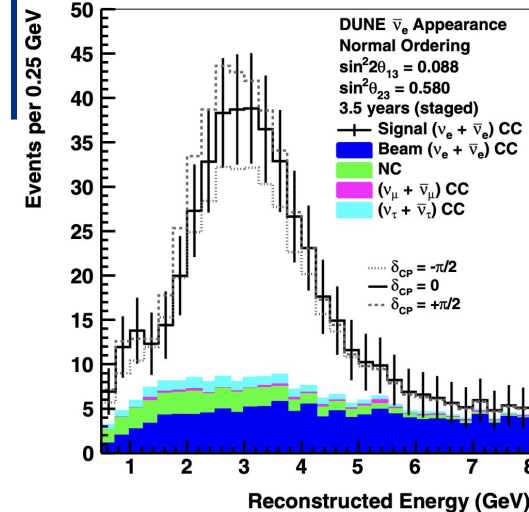
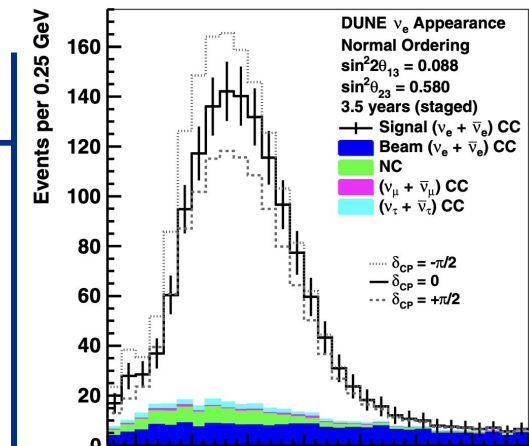
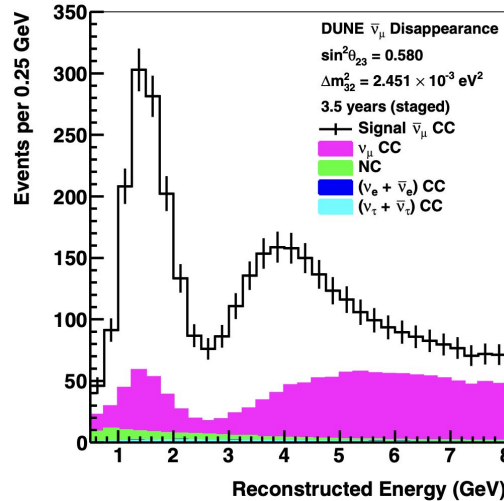
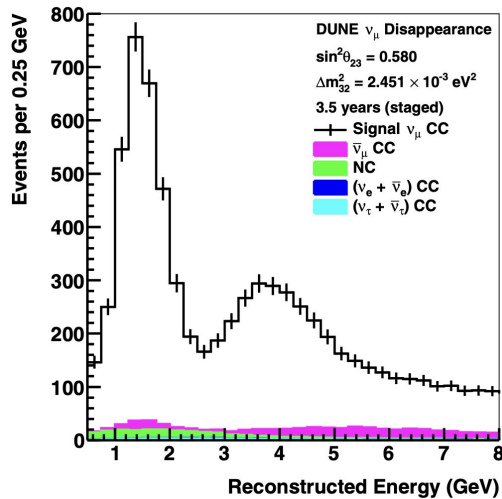
DUNE Details

DUNE: Exposure/time



FD Event Samples

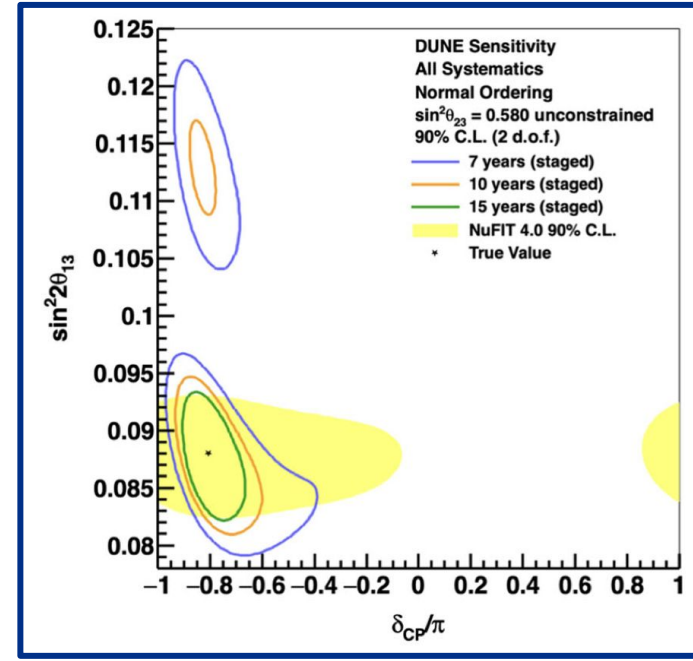
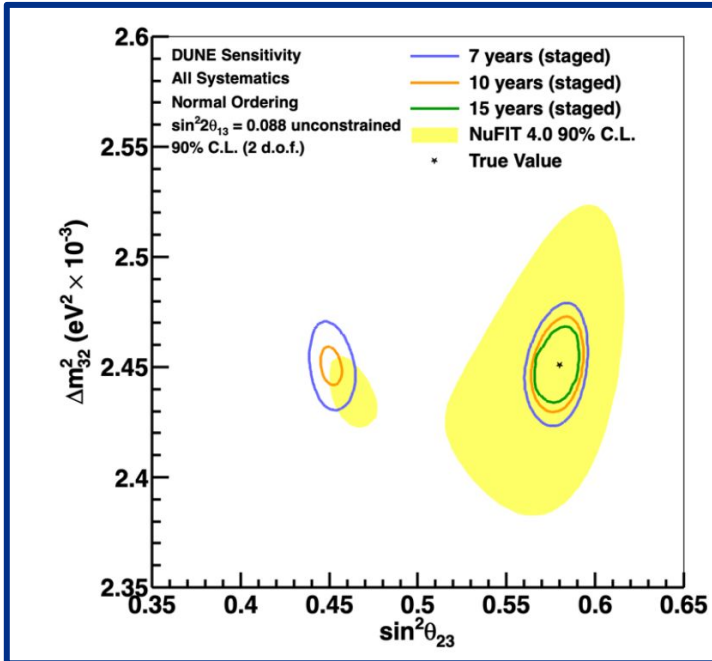
EPJC 80 (2020) 978

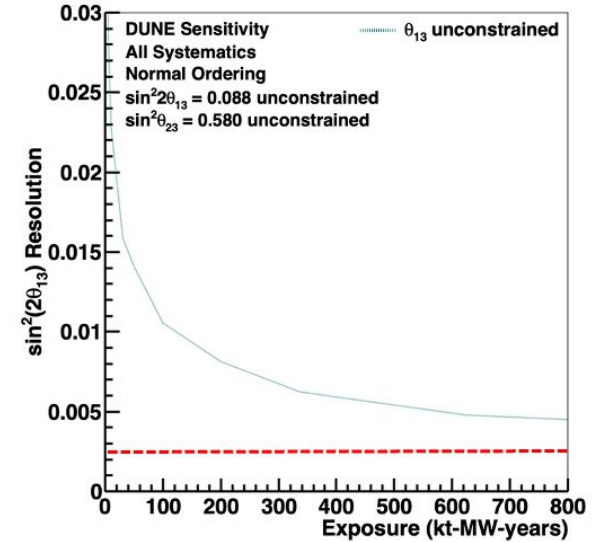
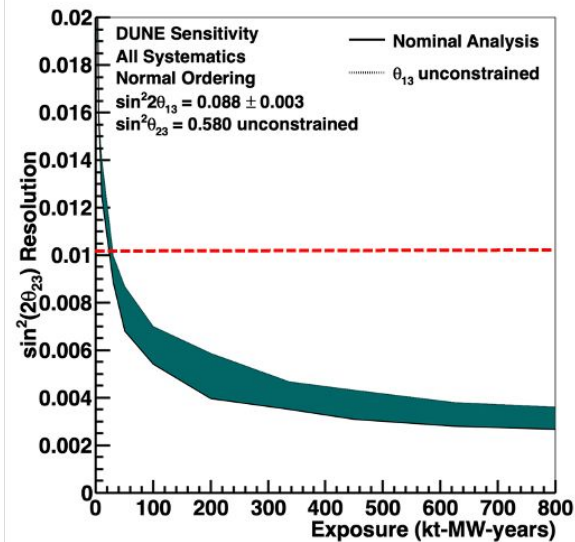
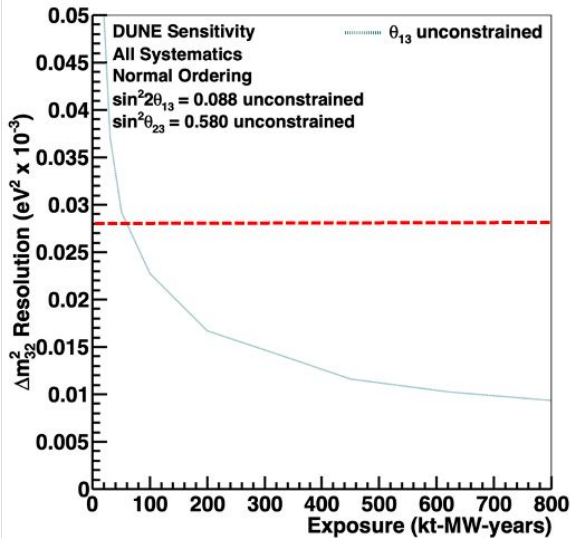


- 2019 Studies:
 - CC-Inclusive, mu- & e-like in nu and nubar mode
- Future:
 - Investigate impact of more granular event selection & projection Near and Far

World-Leading Sensitivities

- Assume DUNE-PRISM has been used to minimize and account for significant deviations from interaction model predictions.

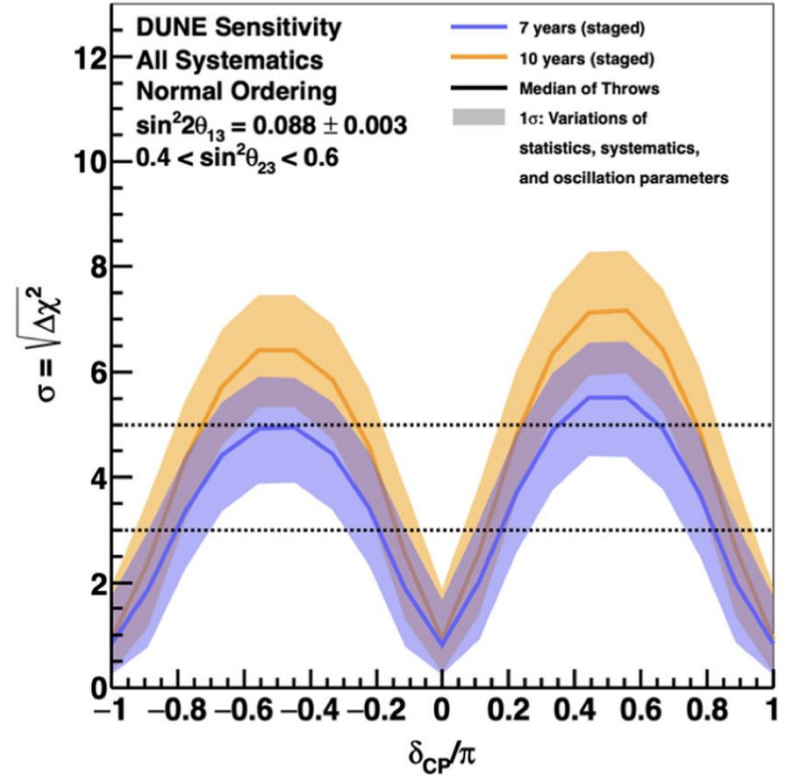
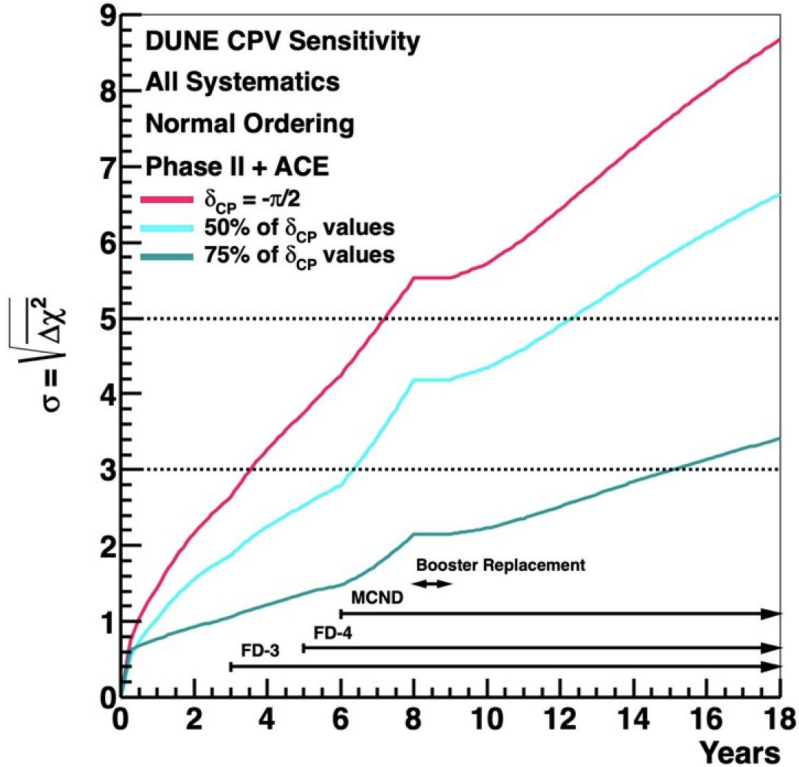




- Expected DUNE sensitivity v.s. **current world-averages** from NuFit 5.0 (JHEP 09 (2020) 178))
- Ultimate θ_{13} sensitivity approaches reactor constraint
- Precision Osc. measurements, especially joint w/ HK & JUNO, will stress-test PMNS: Different energies/detectors/PMNS matrix elements!

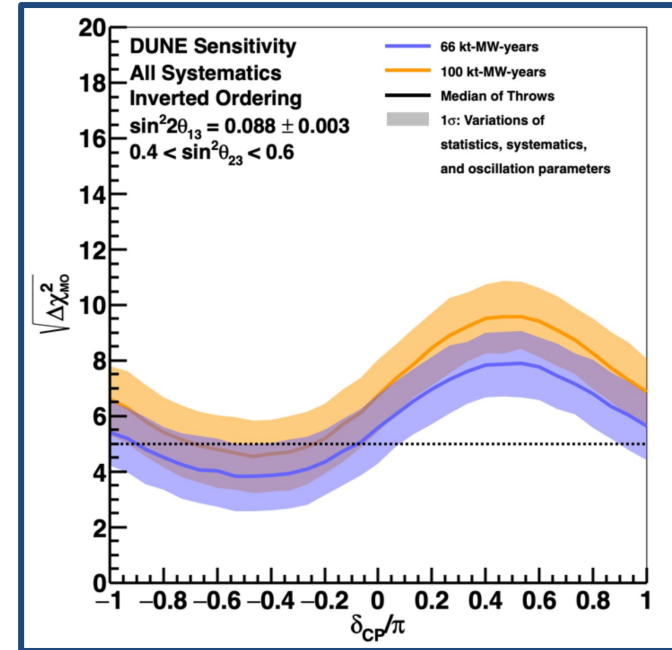
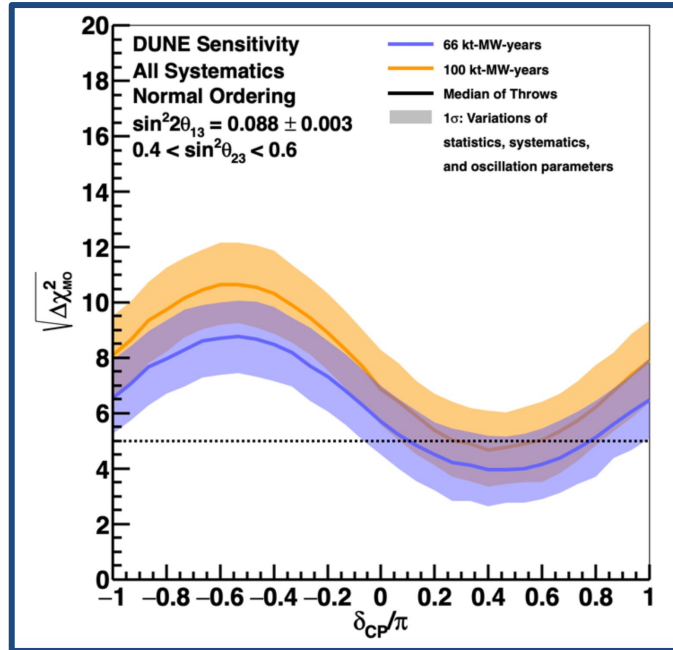
CPV Sensitivity

[C. Marshall Wednesday Plenary](#)



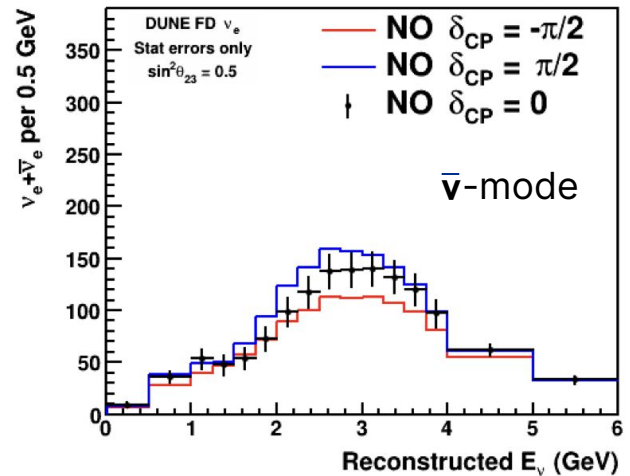
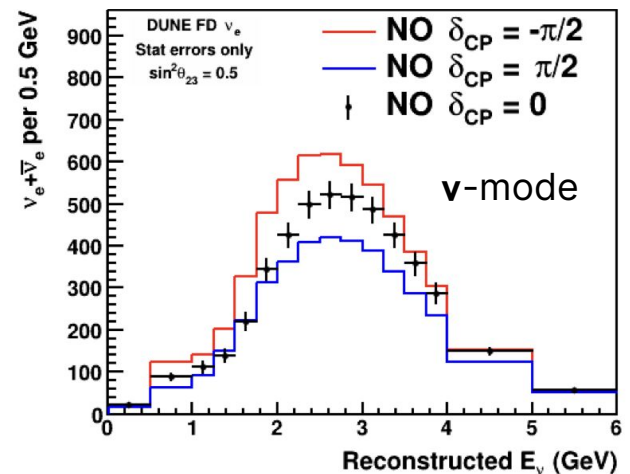
DUNE: Mass Ordering for Short Exposures

- Strong MO sensitivity, even with short exposures [O(3-5 years)]
 - $P < 0.01$ to prefer wrong ratio



PRD 105 (2022) 7, 072006

DUNE: δ_{CP} Resolution

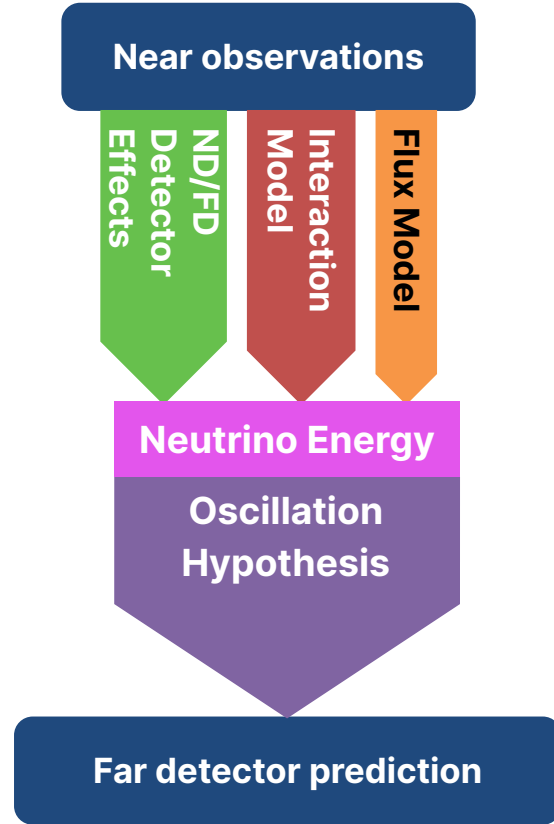


PRISM

Precision Reaction-Independent Spectrum Measurement

Oscillation Measurements in a Nutshell

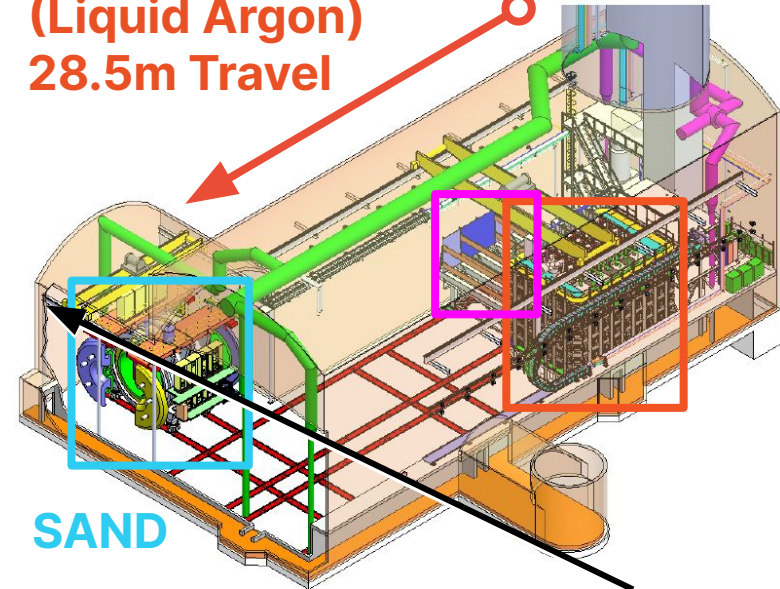
- Existing LBL oscillation analyses:
 - Use models to 'unfold' near detector observations to a neutrino energy spectrum (implicit or explicit)
 - Apply oscillation hypothesis
 - Compare to far detector observations
- What happens if the model is wrong?
 - Predict oscillation features at the wrong place
 - Inflate errors → degrade sensitivity
 - and/or bias measurements
- Current generation experiments are still largely statistically limited
 - The next generation hope not to be limited at the ' 5σ ' level
 - Need to actively design the experimental programme to minimize systematic uncertainty in flux and interaction models



DUNE: Near Detectors

- Constrain systematic uncertainties
 - Neutrino Beam
 - Neutrino–Ar interactions in few GeV region
- Monitor beam stability
- Function in high-rate environment

**Mobile ND_LAr
(Liquid Argon)
28.5m Travel**



SAND

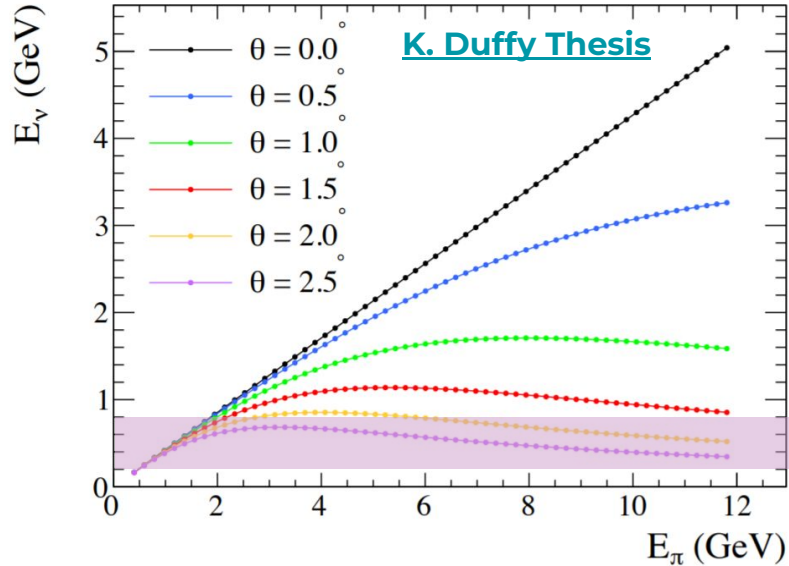
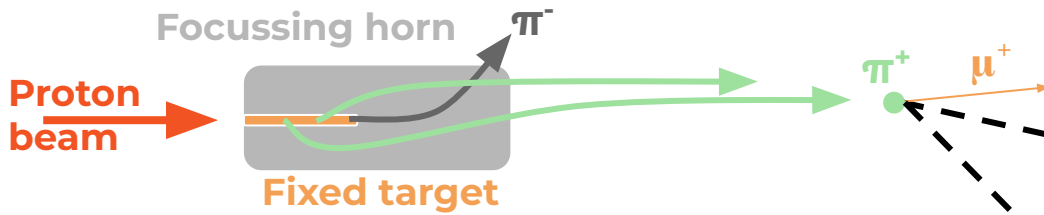
**The Muon
Spectrometer**

SAND: Beam monitoring and ^{12}C -target physics

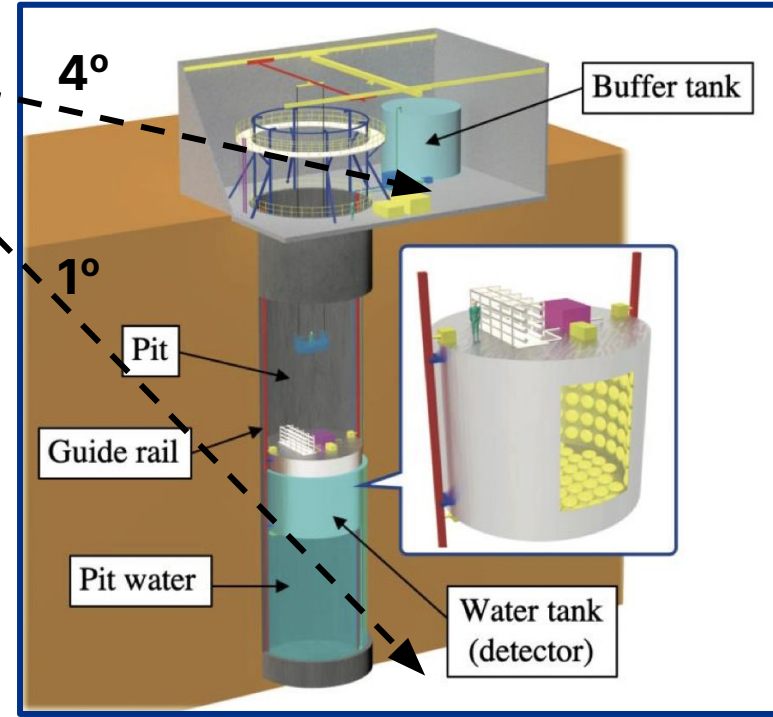
TMS: Muon momentum and sign-selection

ND_LAr: ^{40}Ar -target physics, unoscillated rate constraint, moveable 28.5m in/out of beam spot

Off Axis Neutrino Beams



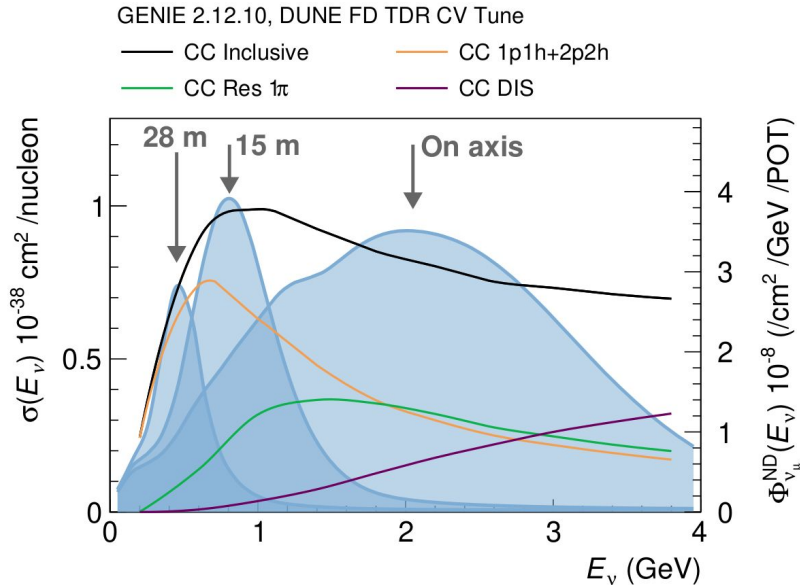
IWCD: Hyper-K Near Detector



[C. Naseby NuFact23](#)

DUNE-PRISM and IWCD

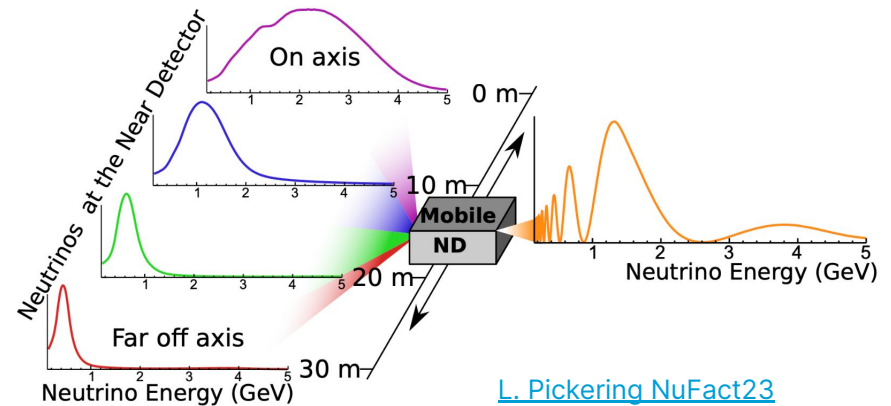
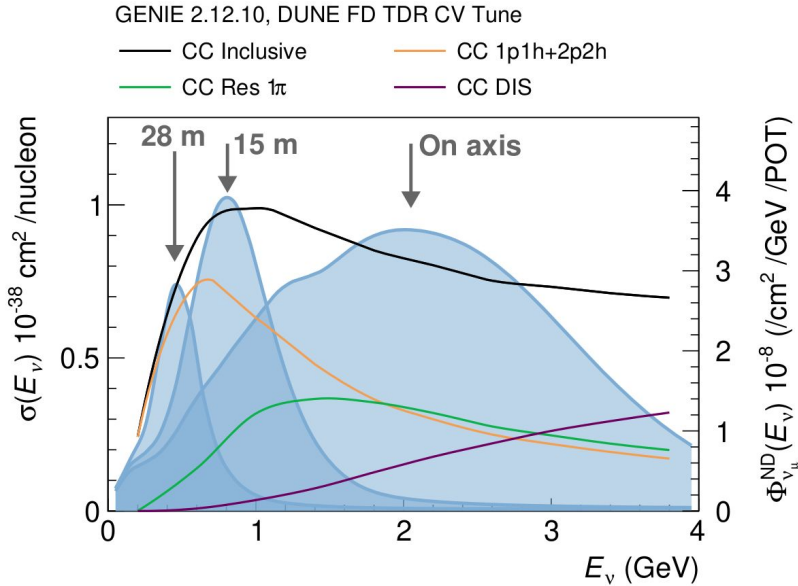
1) Over-constrain interaction model with on- and off-axis observations



DUNE-PRISM and IWCD

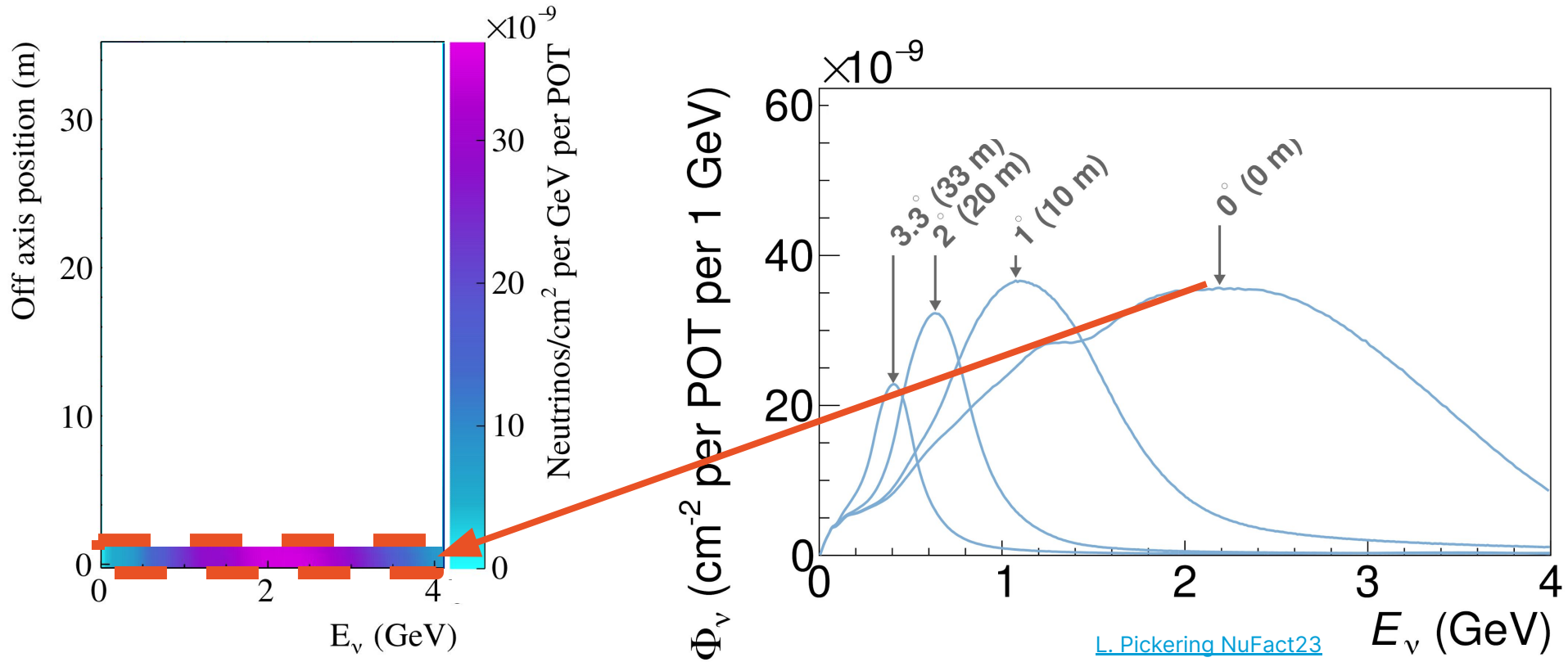
1) Over-constrain interaction model with on- and off-axis observations

2) Synthesise measurement of an oscillated flux with the near detector
 → More direct extrapolation of near-detector observations
 → Reduce reliance on accuracy of interaction model predictions



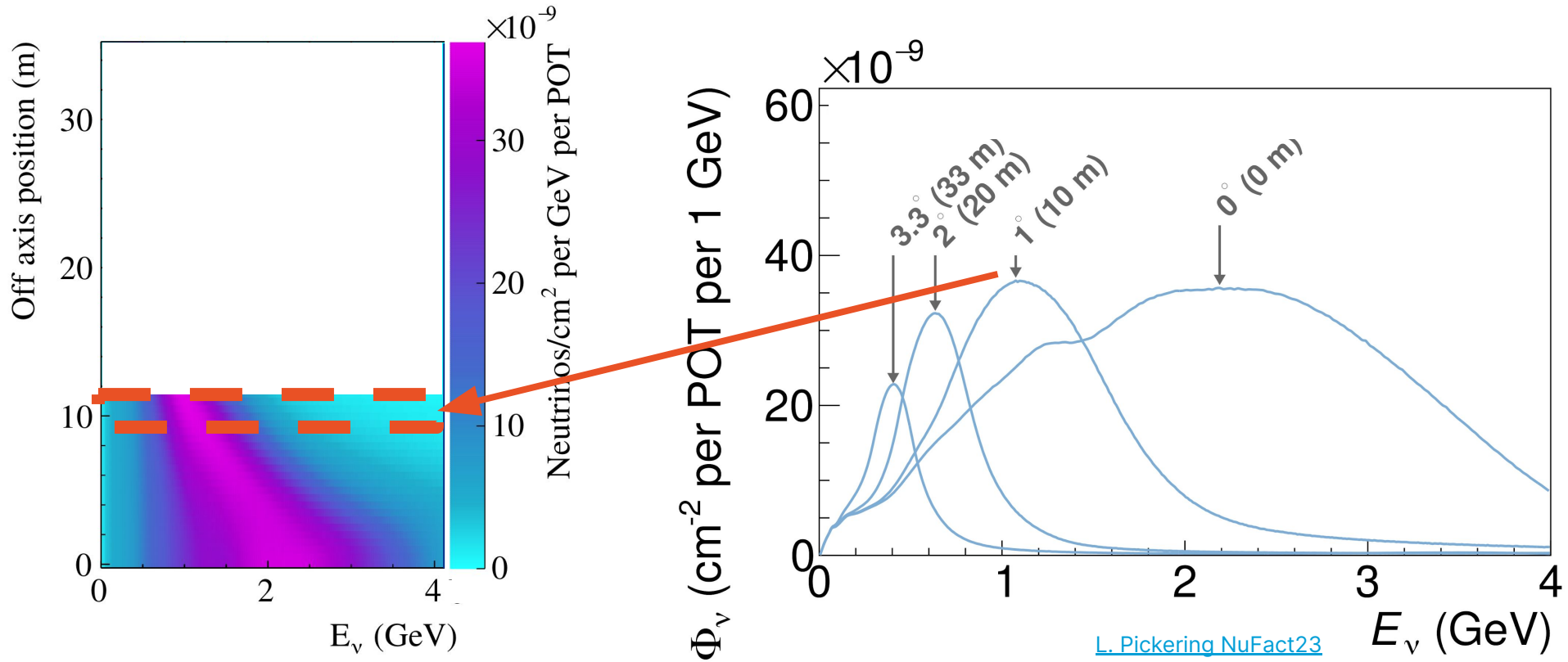
[L. Pickering NuFact23](https://arxiv.org/abs/2308.10000)

Off Axis at the Near Detector



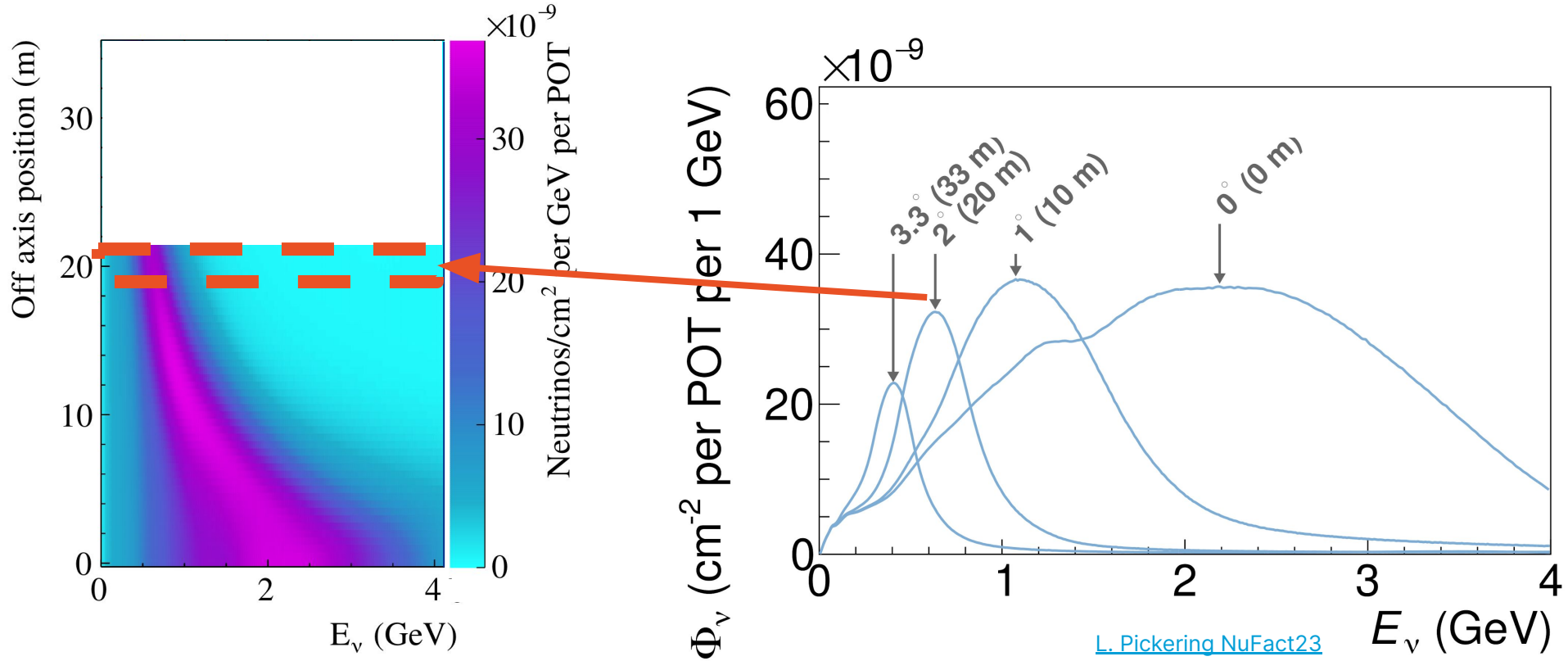
[L. Pickering NuFact23](#)

Off Axis at the Near Detector



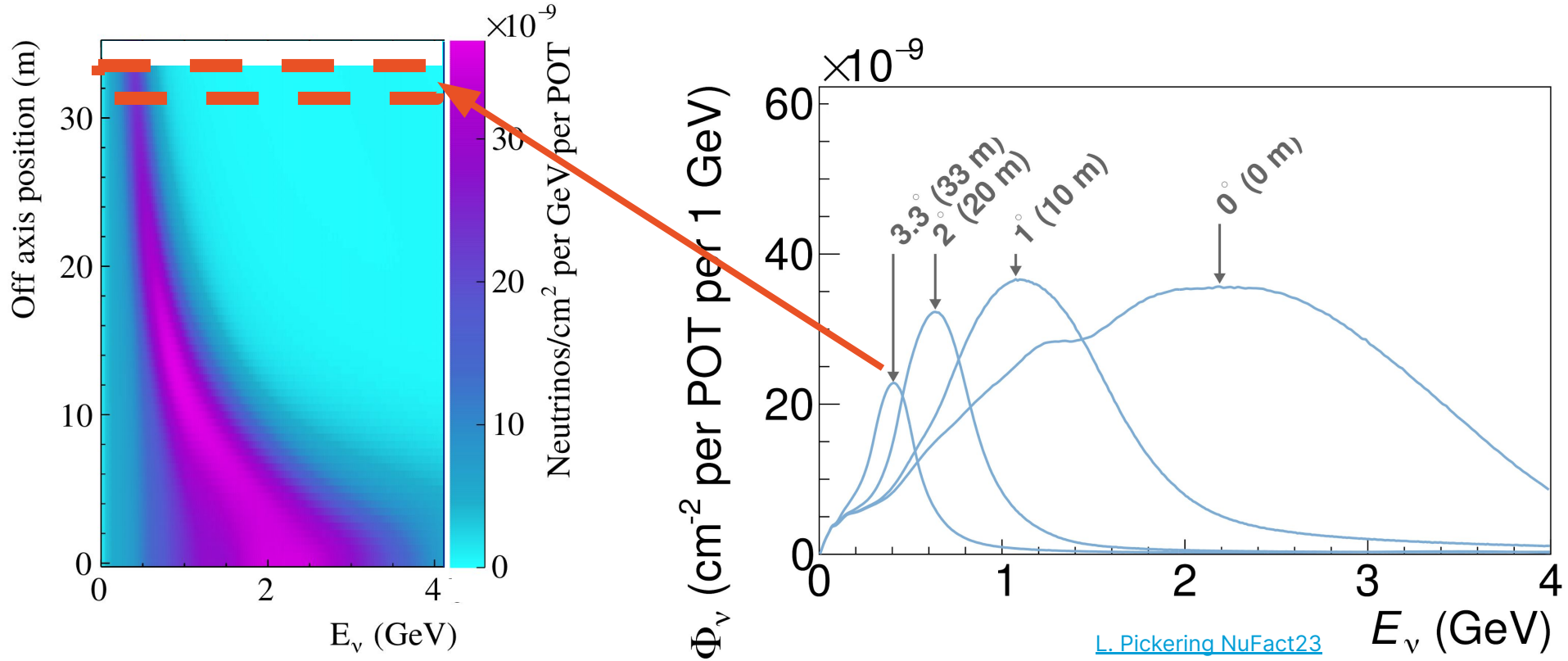
[L. Pickering NuFact23](#)

Off Axis at the Near Detector



[L. Pickering NuFact23](#)

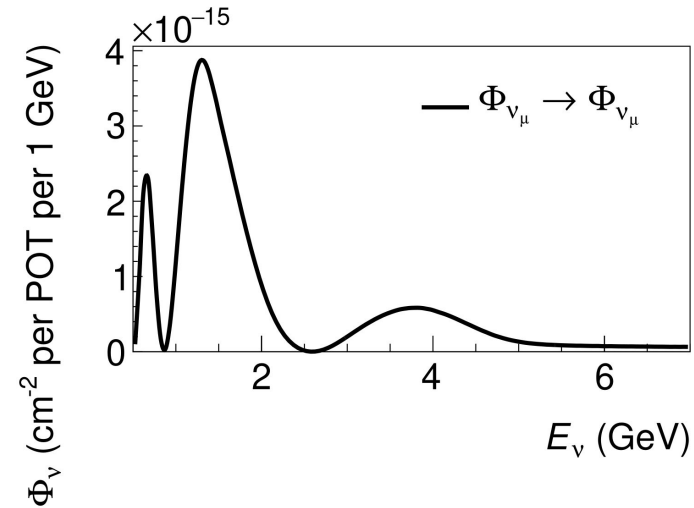
Off Axis at the Near Detector



[L. Pickering NuFact23](#)

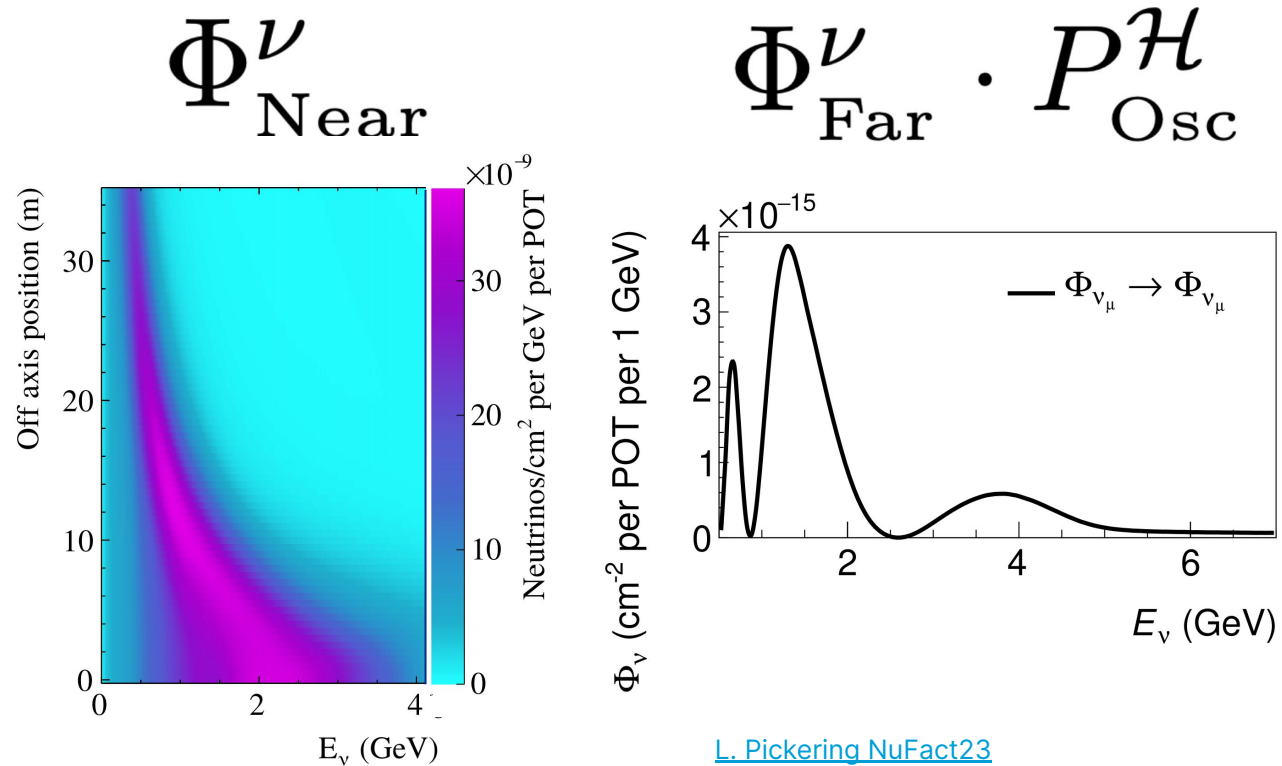
Predicting Oscillations with the Near Detector

$$\Phi_{\text{Far}}^{\nu} \cdot P_{\text{Osc}}^{\mathcal{H}}$$



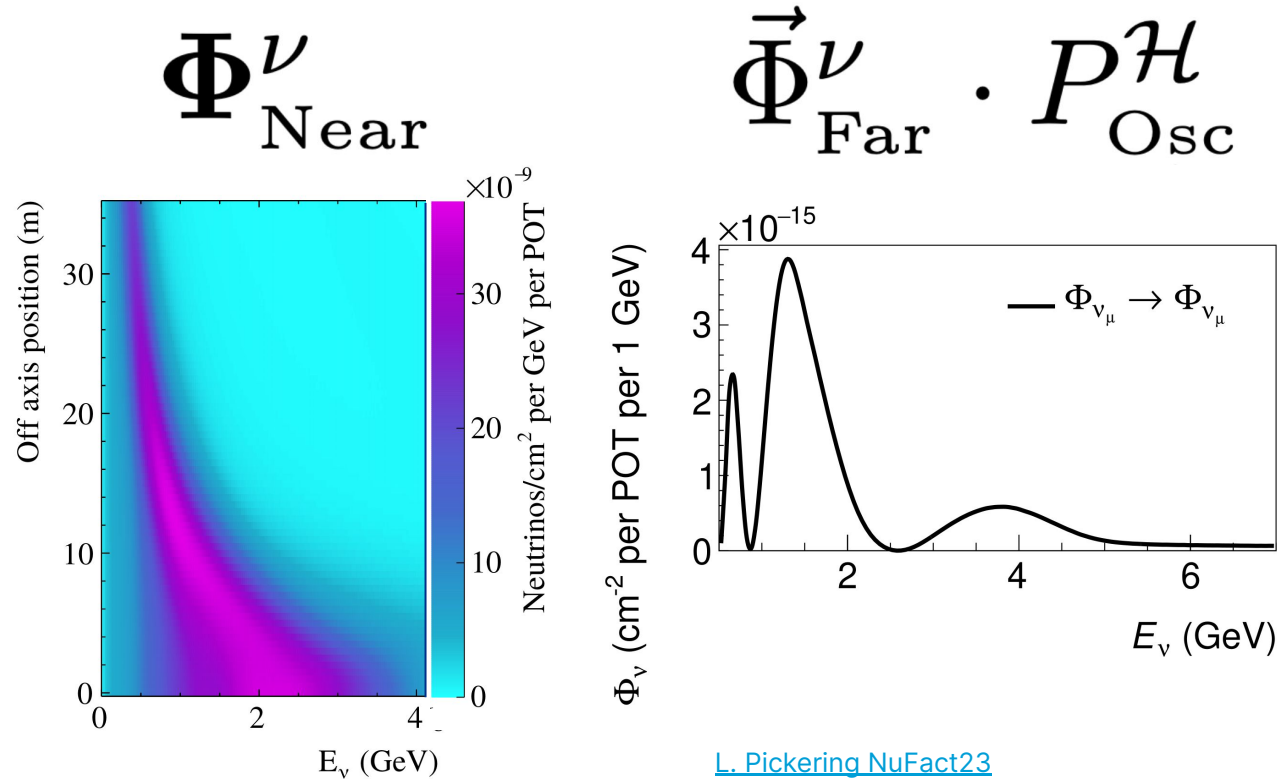
[L. Pickering NuFact23](#)

Predicting Oscillations with the Near Detector



[L. Pickering NuFact23](#)

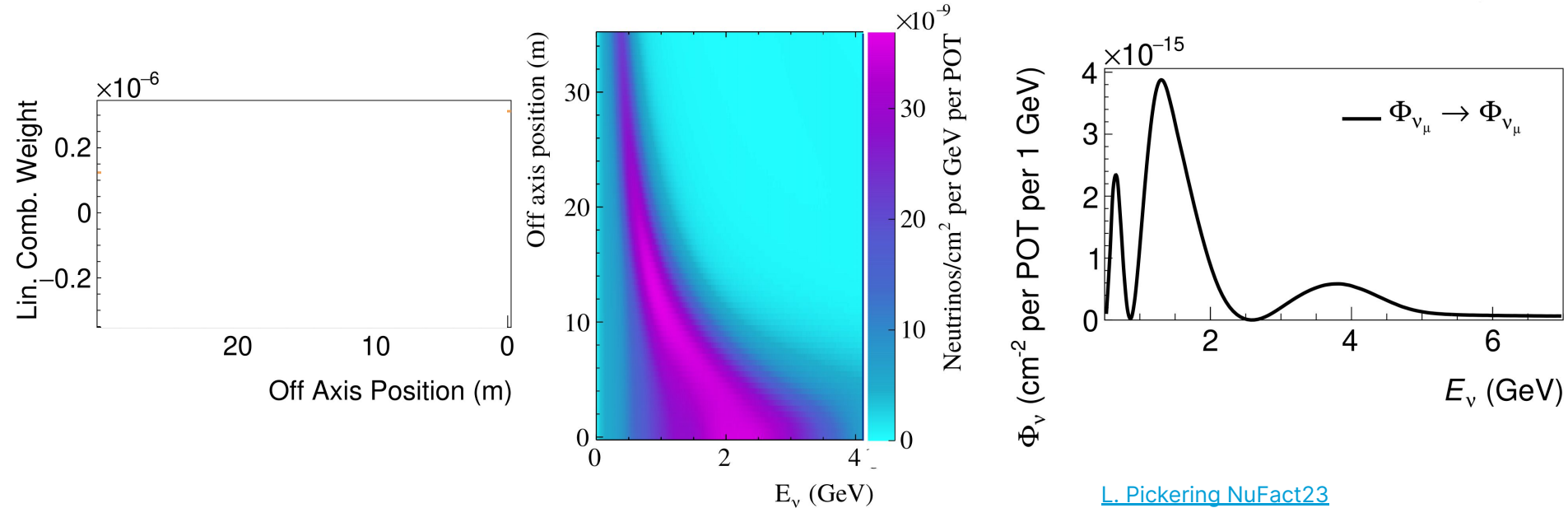
Predicting Oscillations with the Near Detector



[L. Pickering NuFact23](#)

Predicting Oscillations with the Near Detector

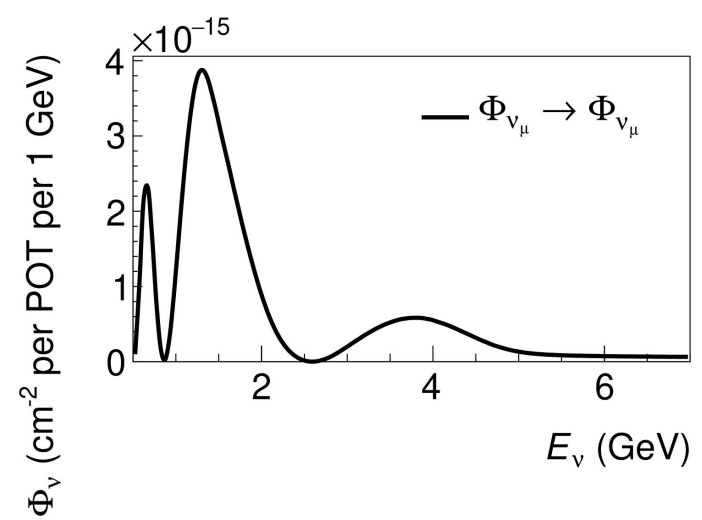
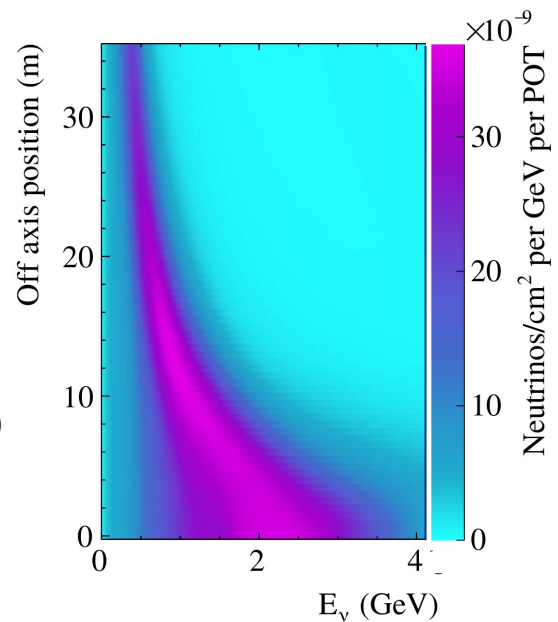
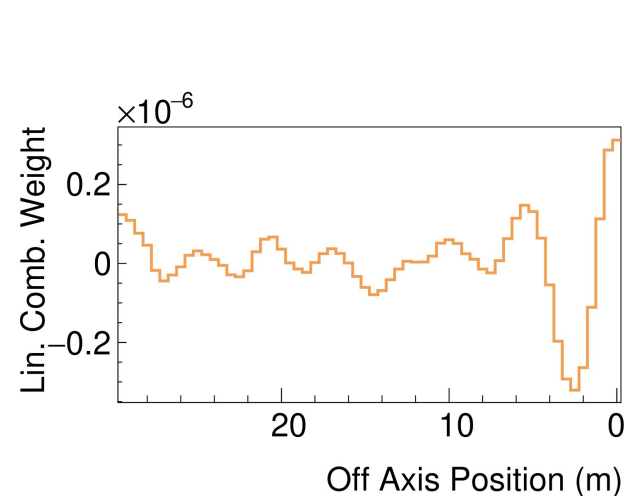
$$\vec{C} \cdot \Phi_{\text{Near}}^{\nu} = \vec{\Phi}_{\text{Far}}^{\nu} \cdot P_{\text{Osc}}^{\mathcal{H}}$$



[L. Pickering NuFact23](#)

Predicting Oscillations with the Near Detector

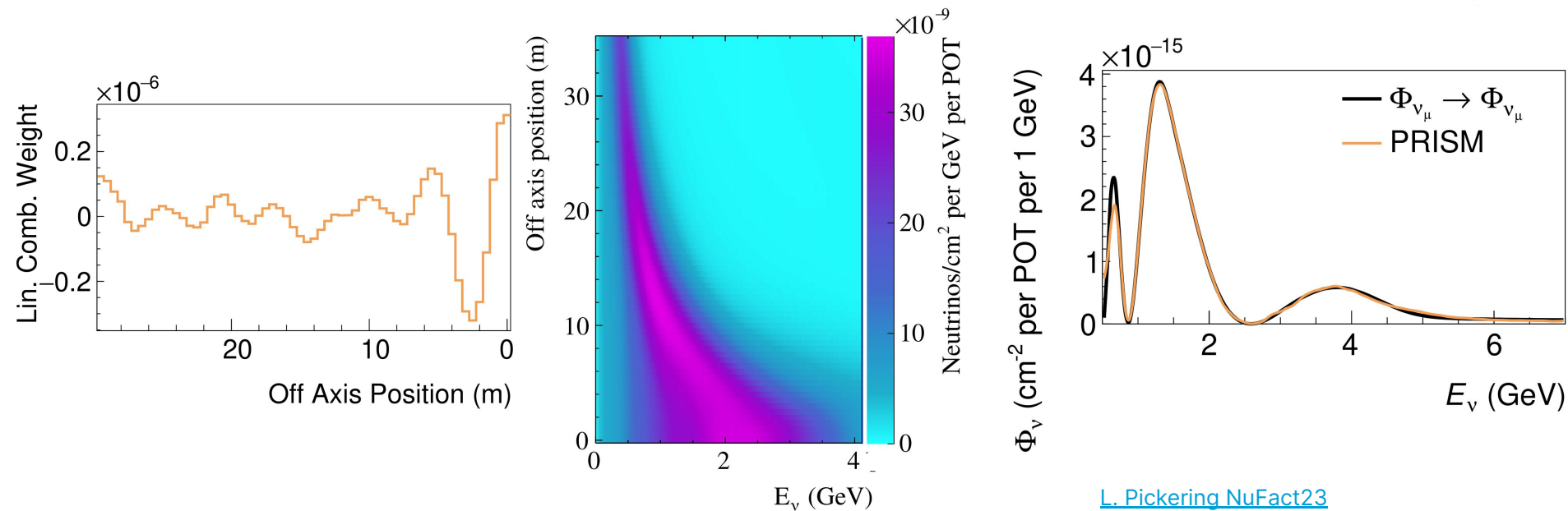
$$\vec{c} \cdot \Phi_{\text{Near}}^{\nu} = \vec{\Phi}_{\text{Far}}^{\nu} \cdot P_{\text{Osc}}^{\mathcal{H}}$$



[L. Pickering NuFact23](#)

Predicting Oscillations with the Near Detector

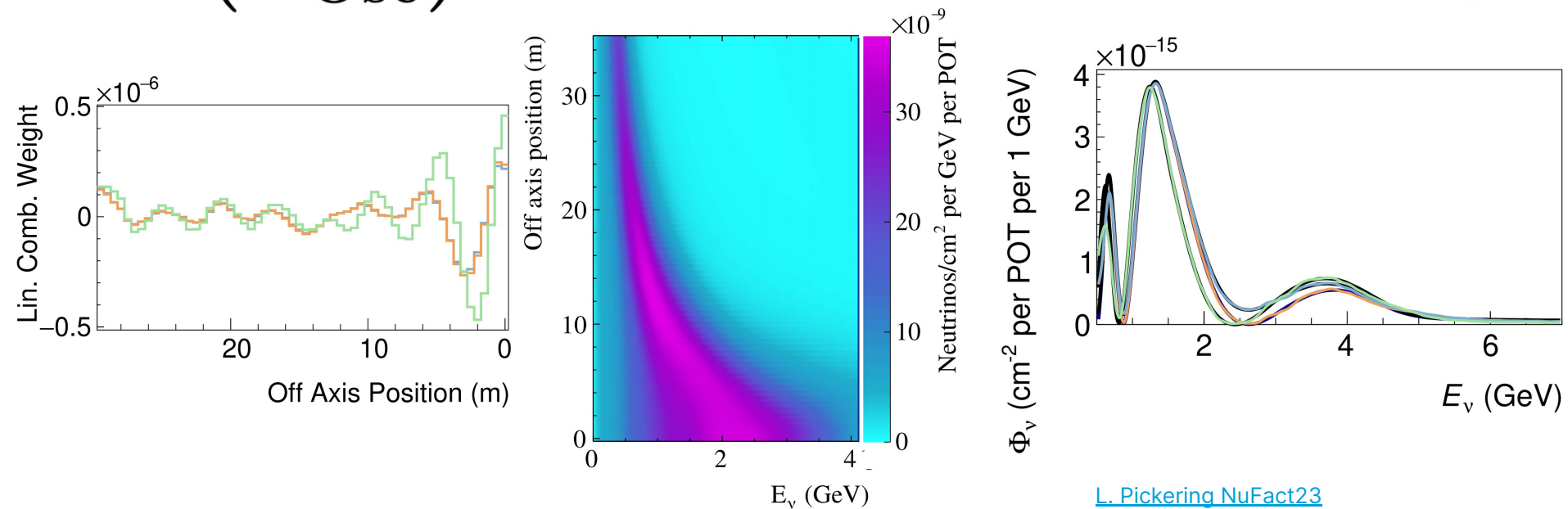
$$\vec{C} \cdot \Phi_{\text{Near}}^{\nu} = \vec{\Phi}_{\text{Far}}^{\nu} \cdot P_{\text{Osc}}^{\mathcal{H}}$$



[L. Pickering NuFact23](#)

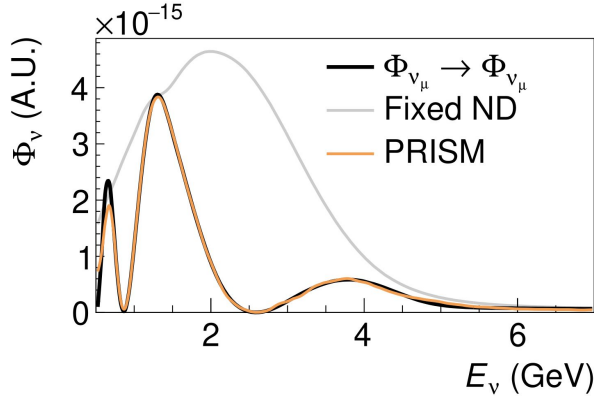
Predicting Oscillations with the Near Detector

$$\vec{C} \left(P_{\text{Osc}}^{\mathcal{H}} \right) \cdot \Phi_{\text{Near}}^{\nu} = \vec{\Phi}_{\text{Far}}^{\nu} \cdot P_{\text{Osc}}^{\mathcal{H}}$$



[L. Pickering NuFact23](#)

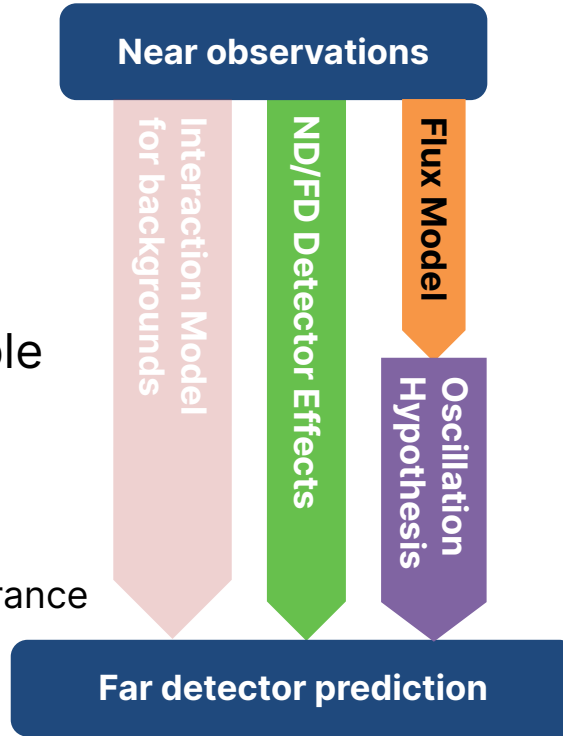
Complementary Approaches



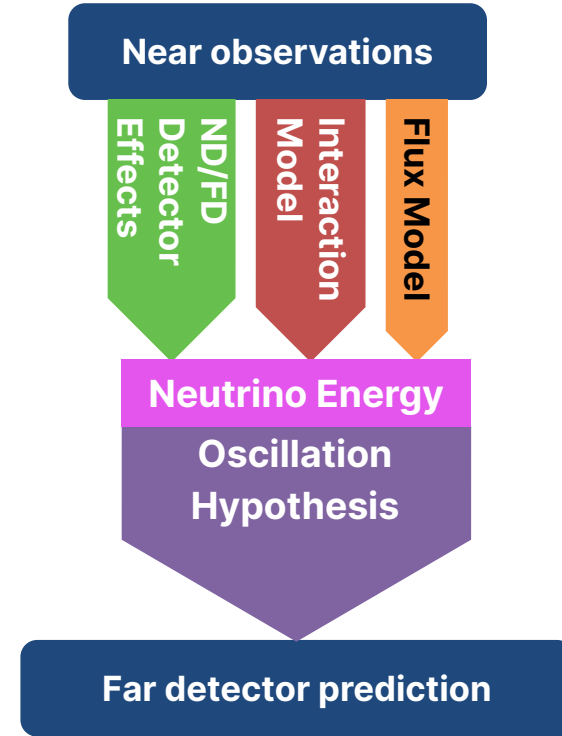
- Off axis measurements enable more-direct near-to-far extrapolation
 - Reduce dependence on signal interaction model for disappearance

[L. Pickering NuFact23](#)

PRISM Linear Combination

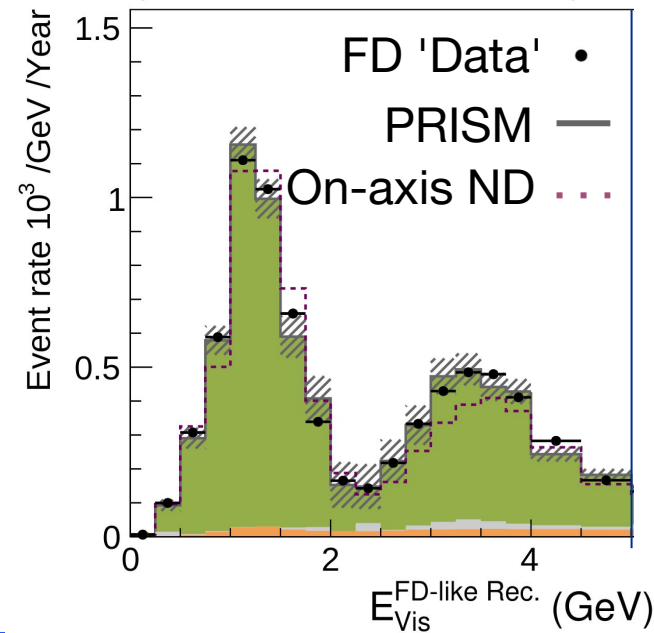
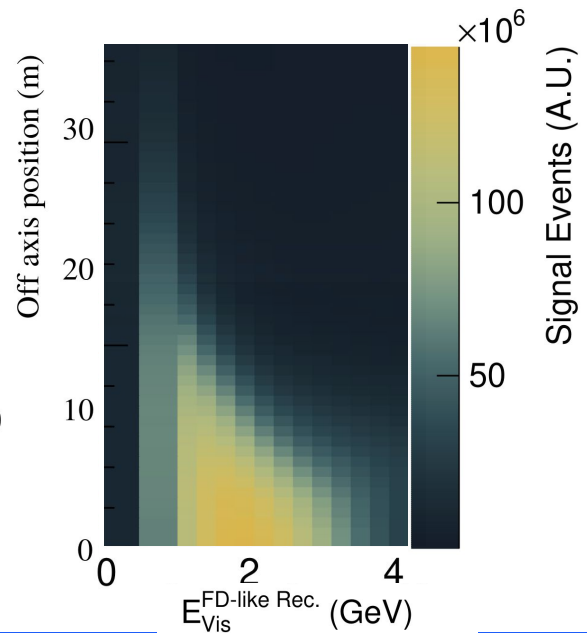
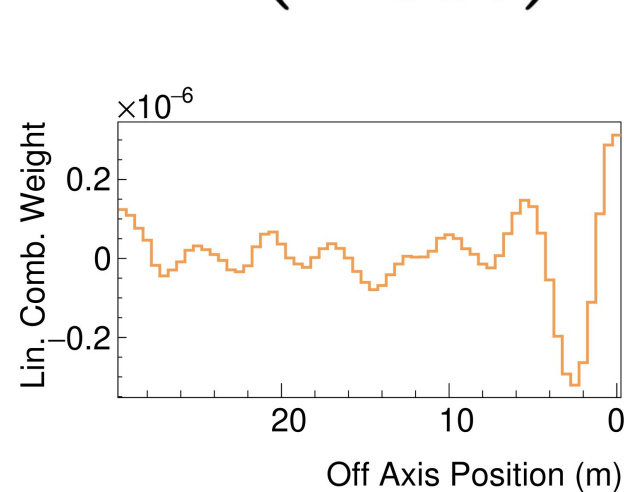


On-axis Only



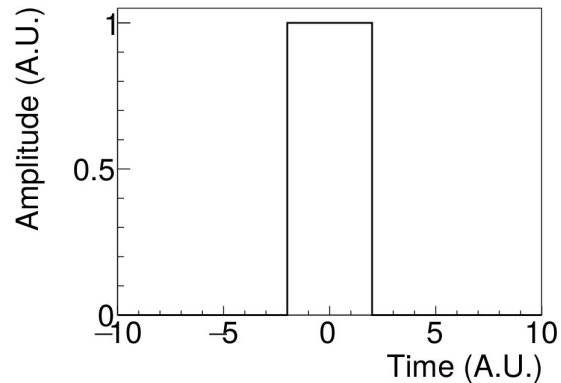
Predicting Oscillations with the Near Detector

$$\vec{C} \left(P_{\text{Osc}}^{\mathcal{H}} \right) \cdot \left(= \Phi_{\text{Near}}^{\nu} \cdot \sigma^{\nu} \right) = \left(= \vec{R}_{\text{Far}}^{\nu} \cdot P_{\text{Osc}}^{\mathcal{H}} \cdot \sigma^{\nu} \right)$$



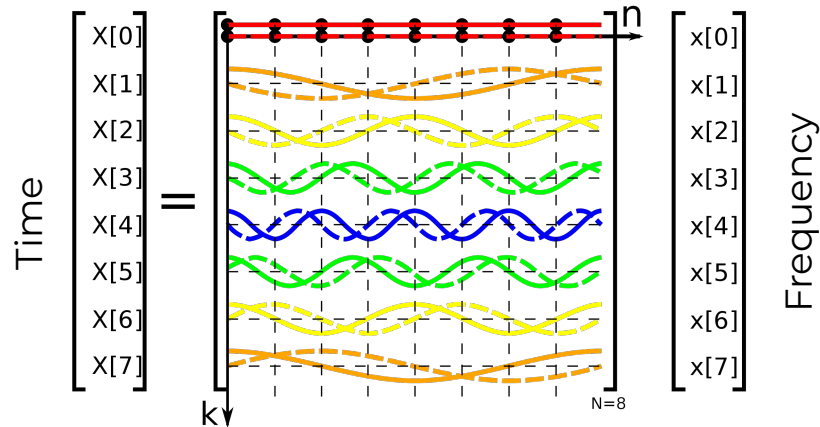
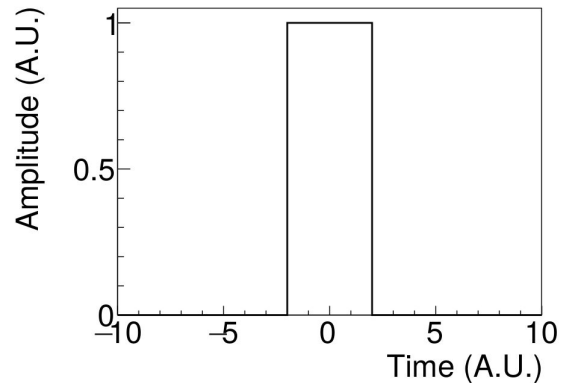
Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines



Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines

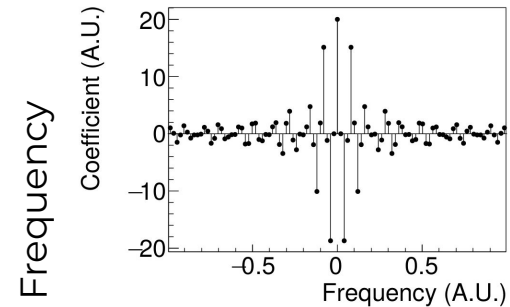
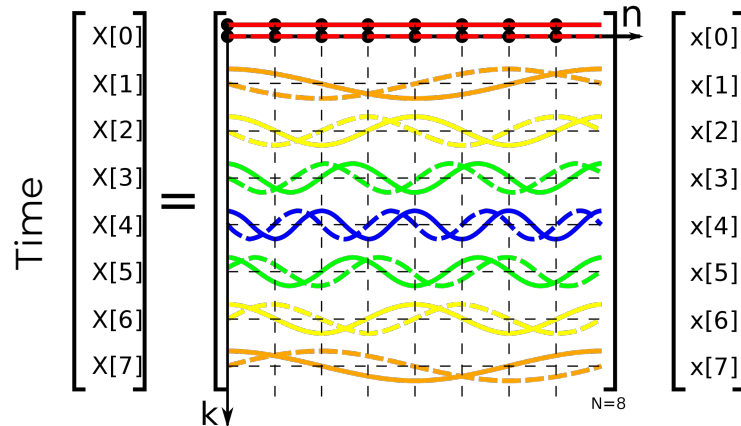
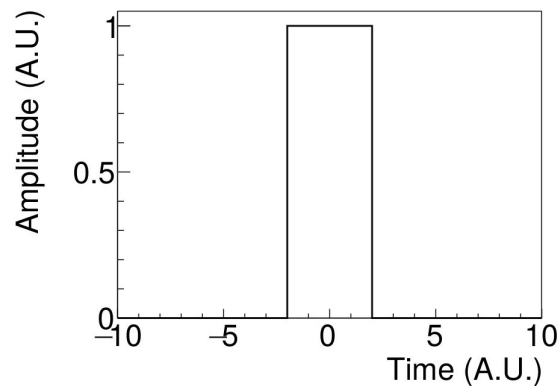


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Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines

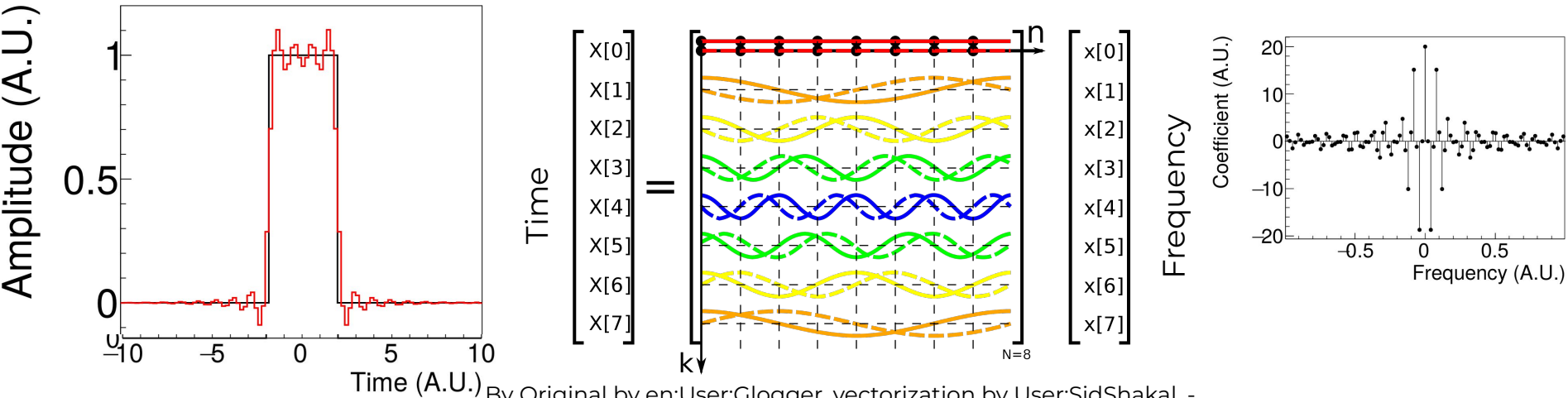


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 Hand-traced in Inkscape, based on
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Discrete Fourier Transforms

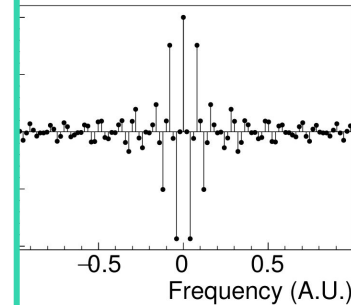
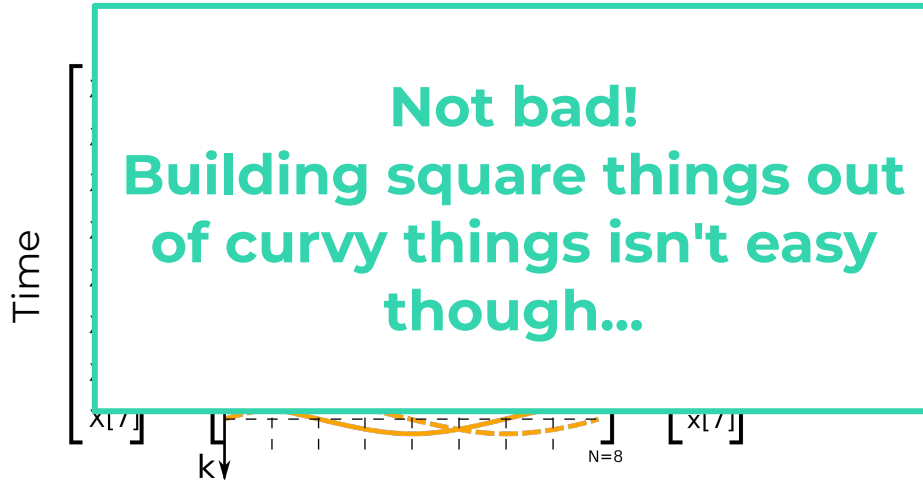
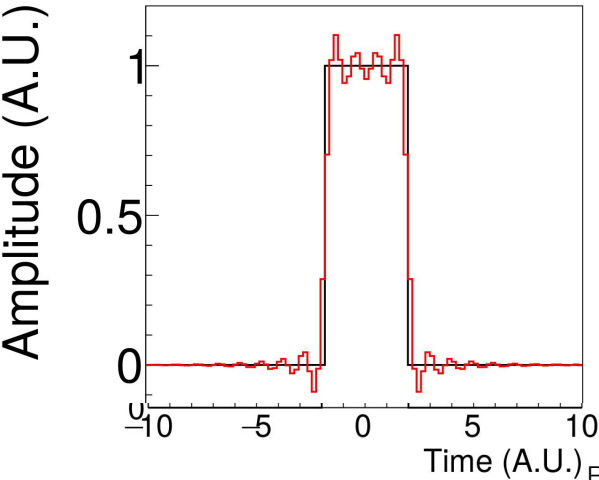
- Approximate function as a linear sum of sines and cosines



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Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines



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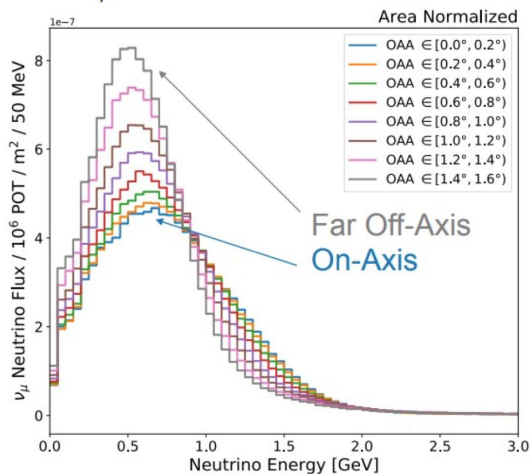


SBND PRISM

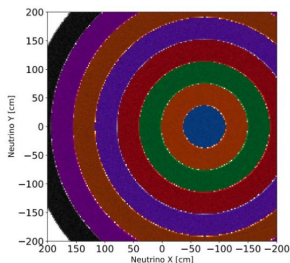
A. Furmanski NuFact23

SBND-PRISM

ν_μ flux in each of the OAA regions



Beam view

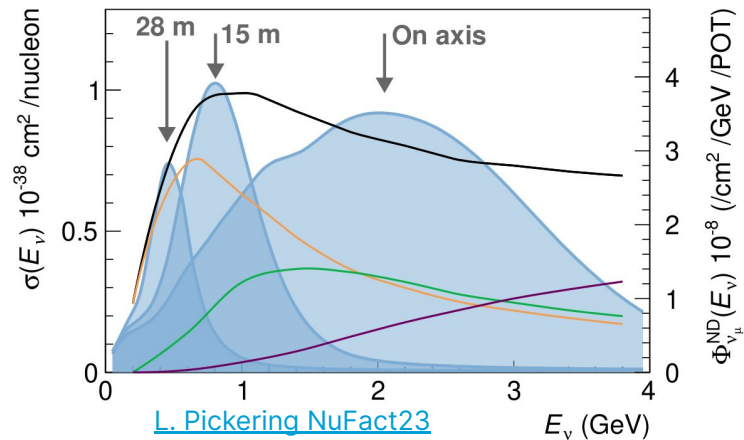


Vary energy dependence by scanning position in detector

Directly determine energy dependence of cross sections

GENIE 2.12.10, DUNE FD TDR CV Tune

— CC Inclusive — CC 1p1h+2p2h
— CC Res π — CC DIS



Andrew Furmanski
University of Minnesota

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