Neutrino Oscillation Experiments: Past/Present/Future

Luke Pickering

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

9th of April, 2024

UKRI
Science and Technology Facilities Council
Supported by URF\R1\211661
THE ROYAL SOCIETY

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

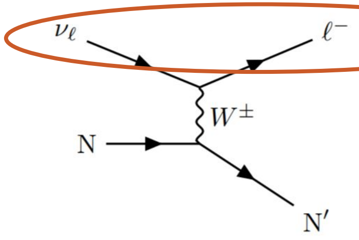
Why Neutrinos Change Flavor

Unknown Properties of Known Neutrinos

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

Unknown Properties of Known Neutrinos

Flavor state defined by paired charged lepton at vertex



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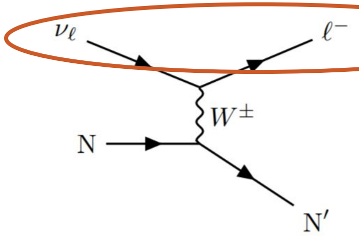

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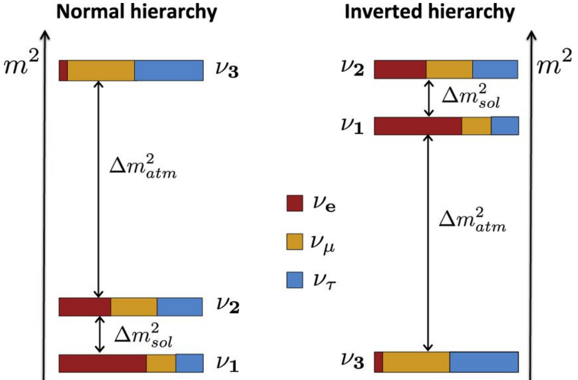

[J. Phys. G: Nucl. Part. Phys. **43** 084001]

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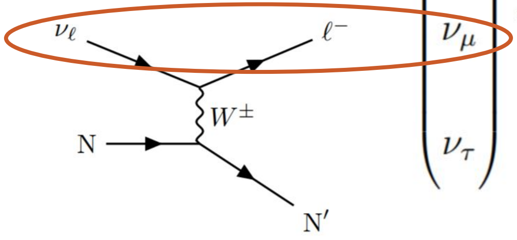

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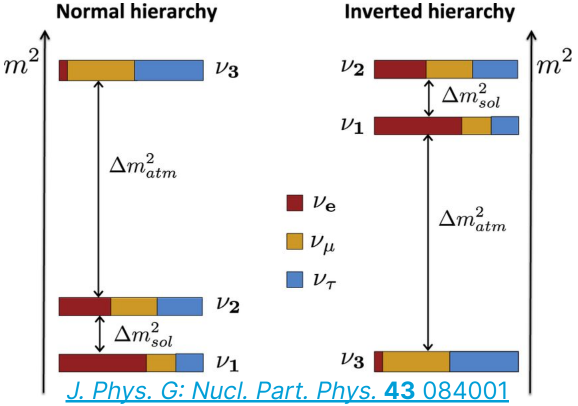

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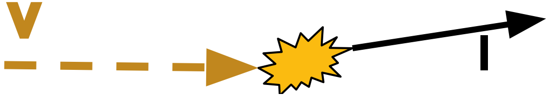

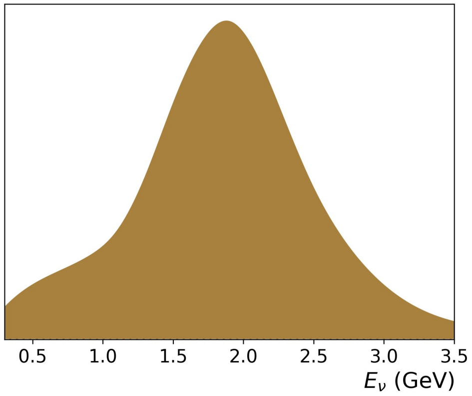

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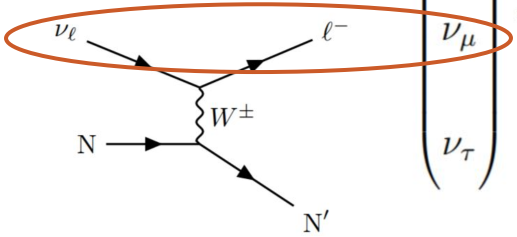

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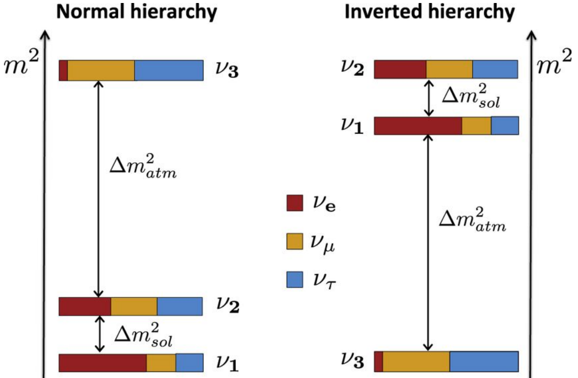

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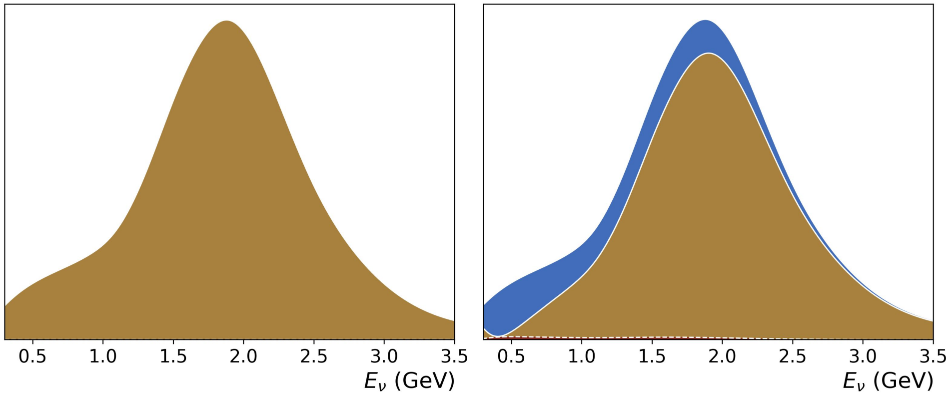

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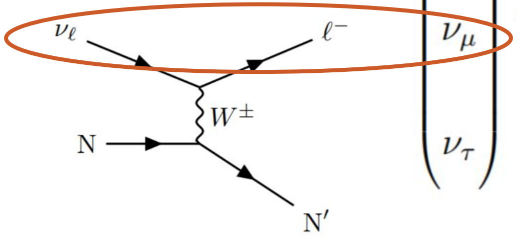

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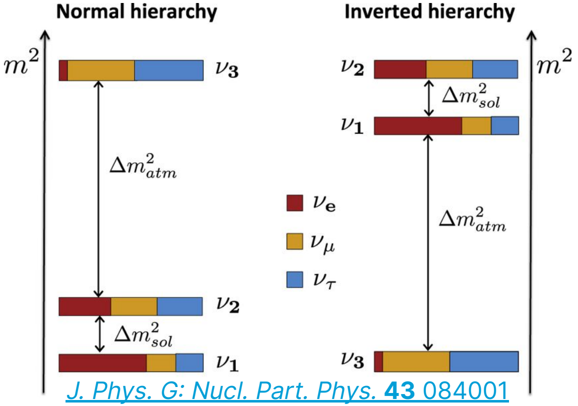

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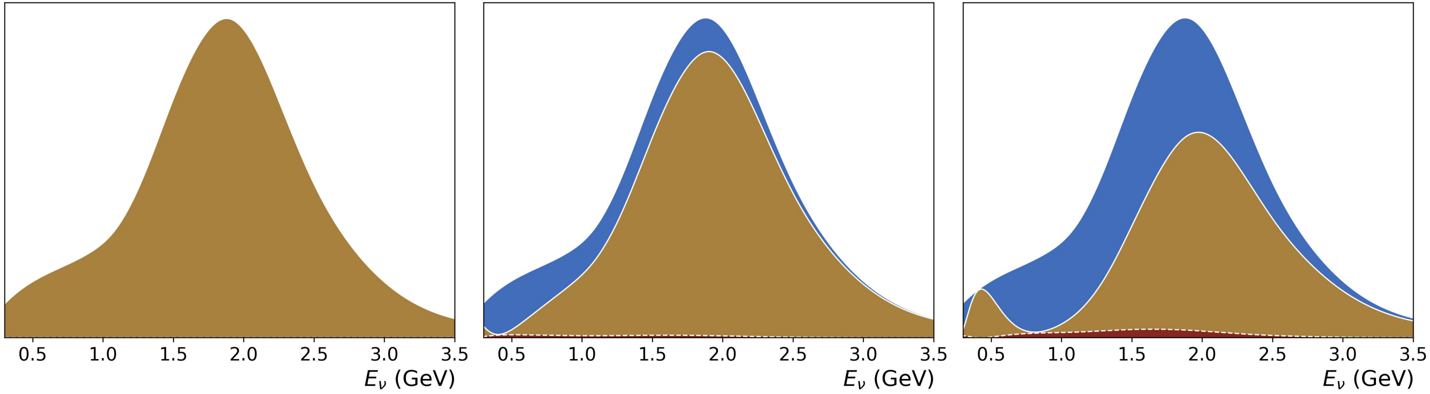

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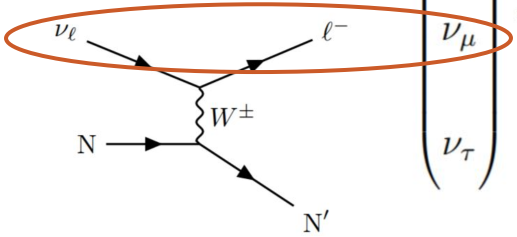

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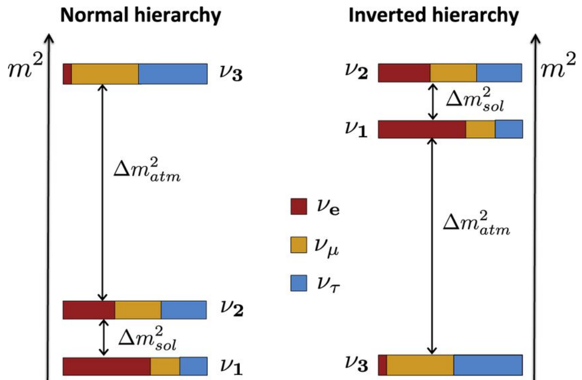

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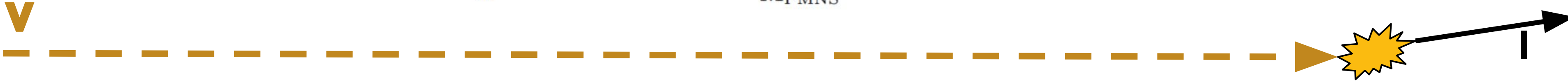

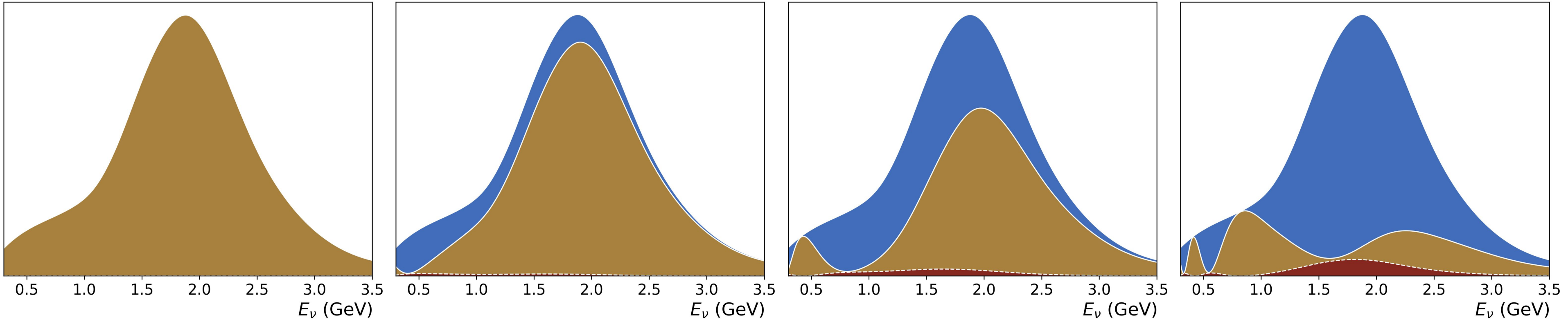

Re-parameterizing the PMNS

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

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

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

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$\mathbf{M}_{\text{PMNS}}$

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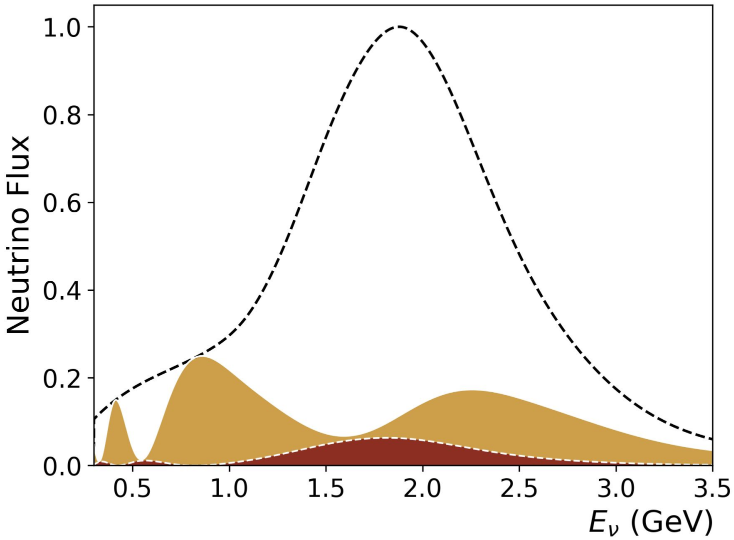
Oscillation Channels

Muon neutrino disappearance

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

Electron neutrino appearance

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



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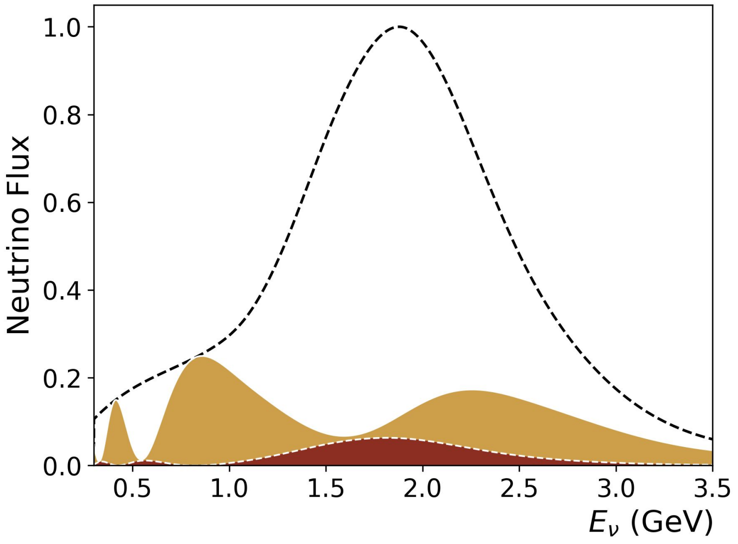
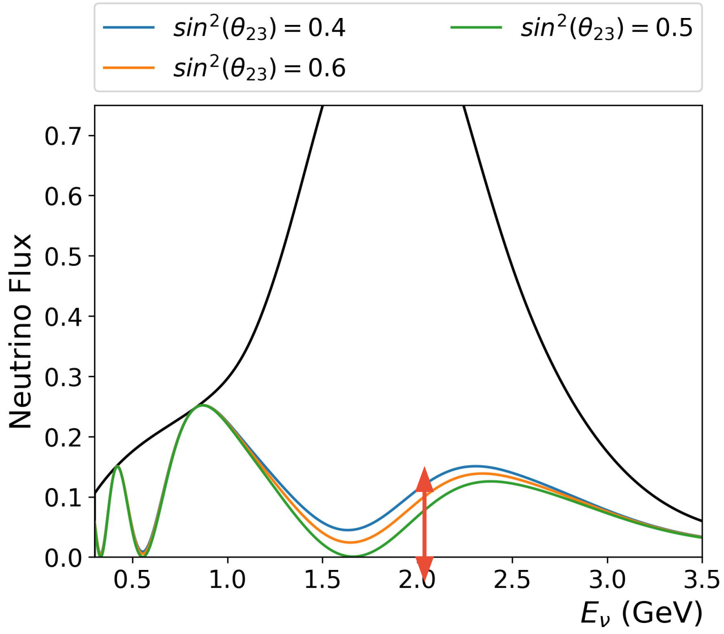


Muon Neutrino Disappearance

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

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



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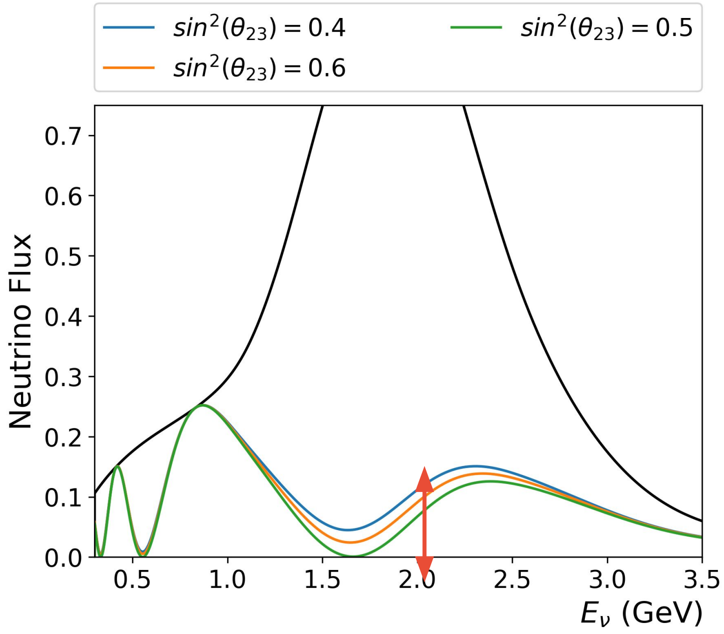

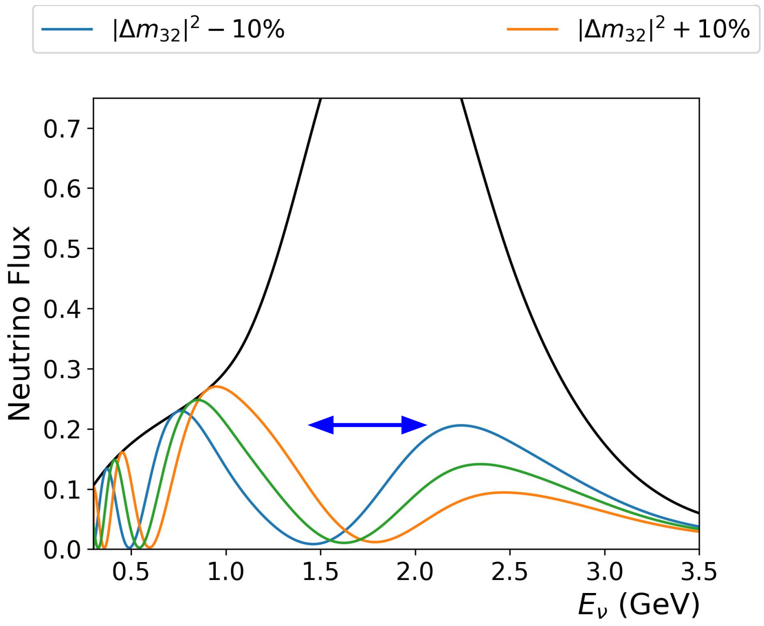

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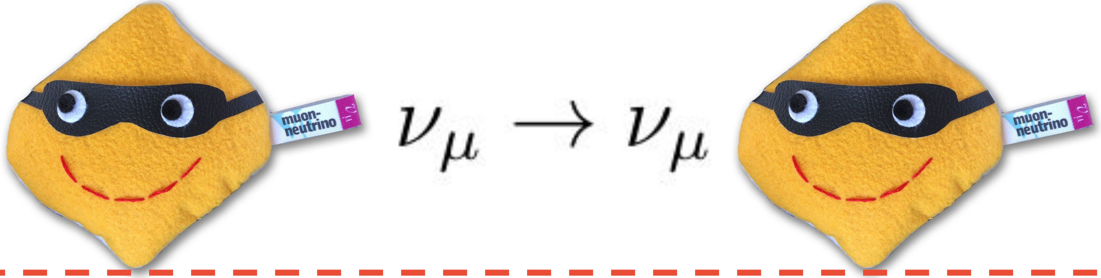
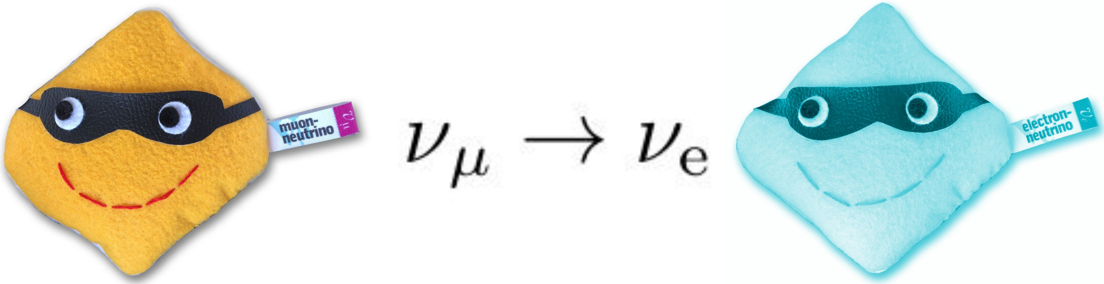


$$\nu_\mu \rightarrow \nu_\mu$$

Electron neutrino appearance



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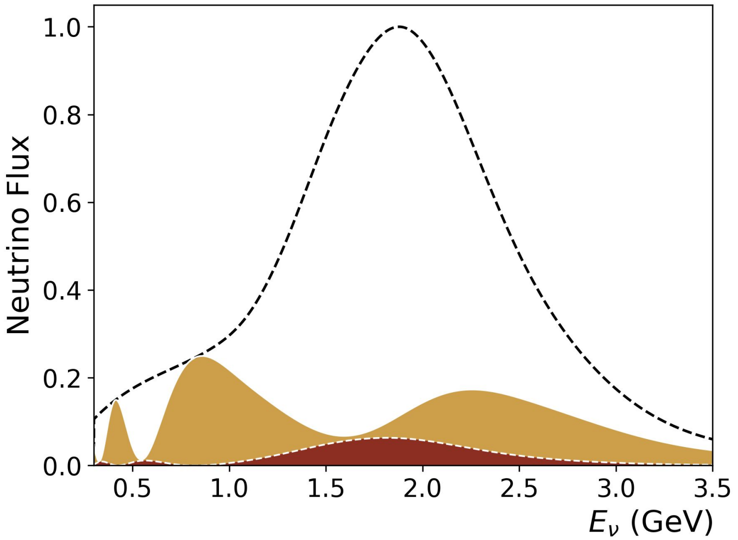


Electron Neutrino Appearance

Appearance probability has '**CP odd**' term.

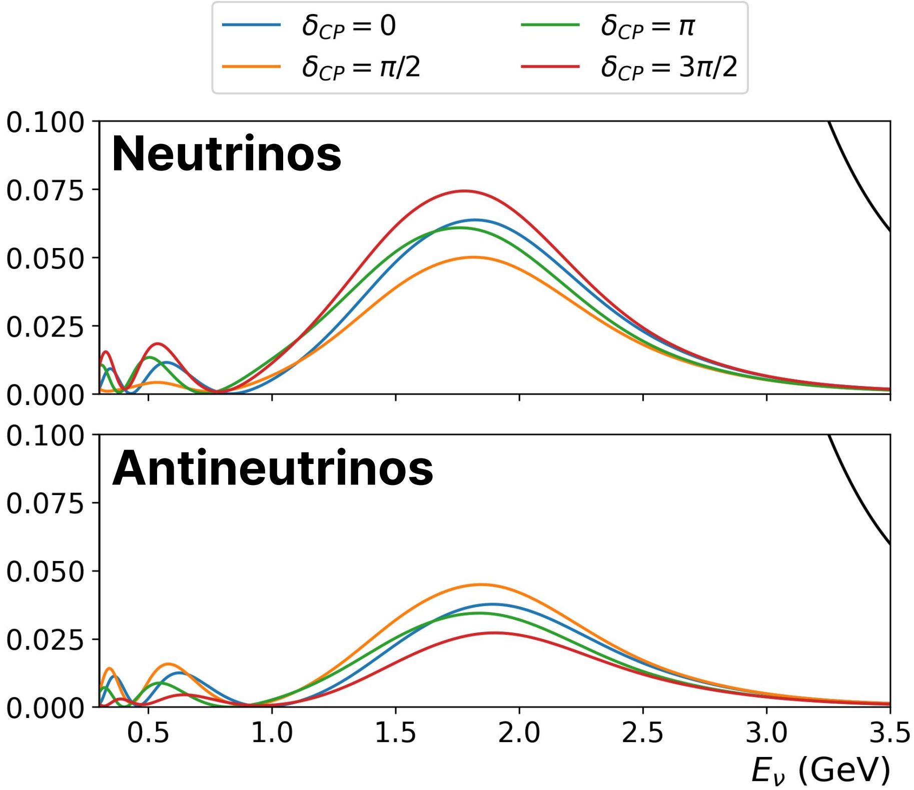
- Sign flip between matter/antimatter

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

$$(+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$

$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big]$$

$$+\text{(CP-even, solar, matter effect terms)}$$



Big Questions

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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?

Is there significant CP violation in the neutrino sector?

Enough to explain matter/antimatter asymmetry?

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

Anatomy of an Oscillation Experiment

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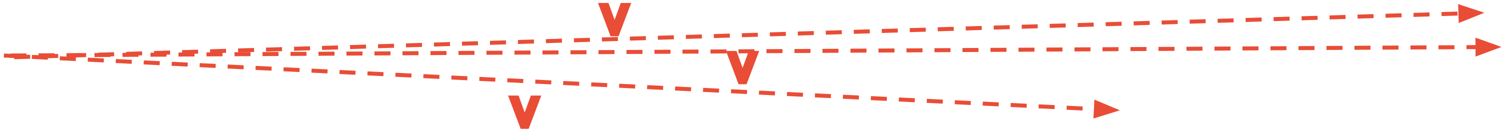
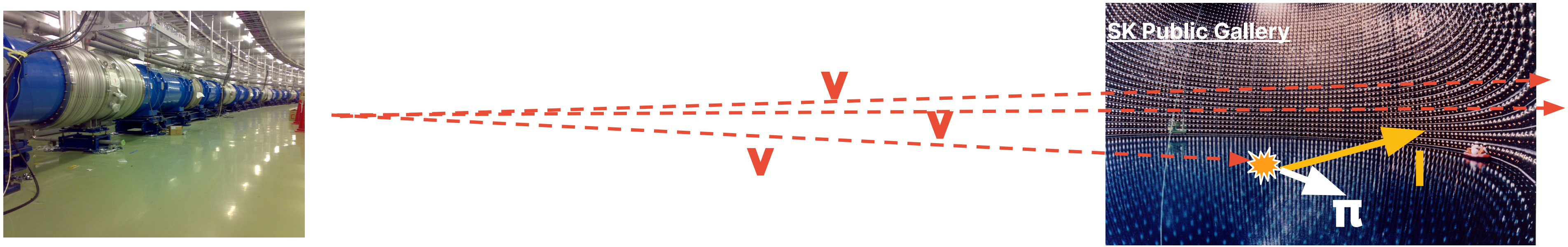


Neutrino Source Φ

1. Find or make a source of neutrinos

Anatomy of an Oscillation Experiment



Neutrino Source Φ

Detector

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

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

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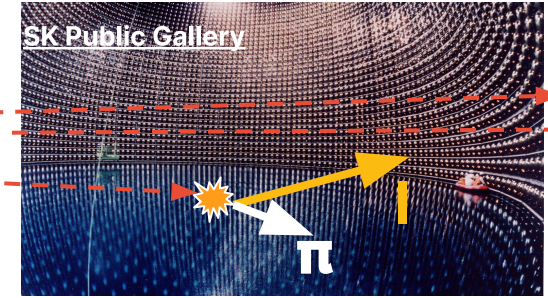
Oscillate!?!?



Detector

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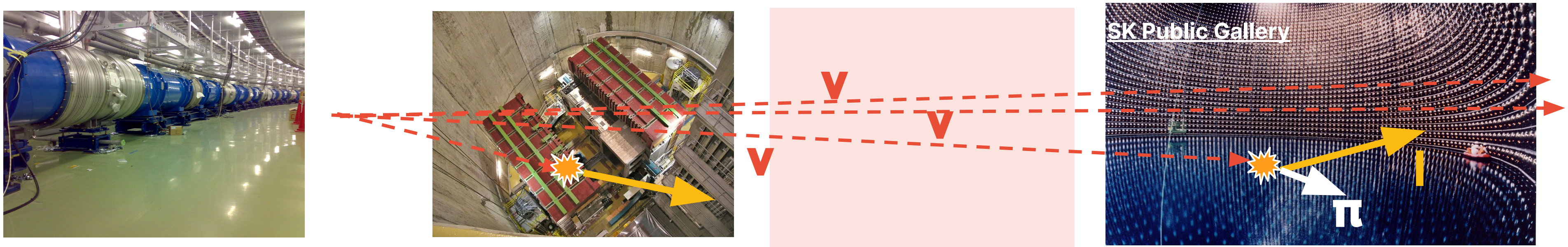
Anatomy of an Oscillation Experiment



Neutrino Source Φ | ***Near* Detector** | **Oscillate!?!?** | ***Far* Detector**

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

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?**

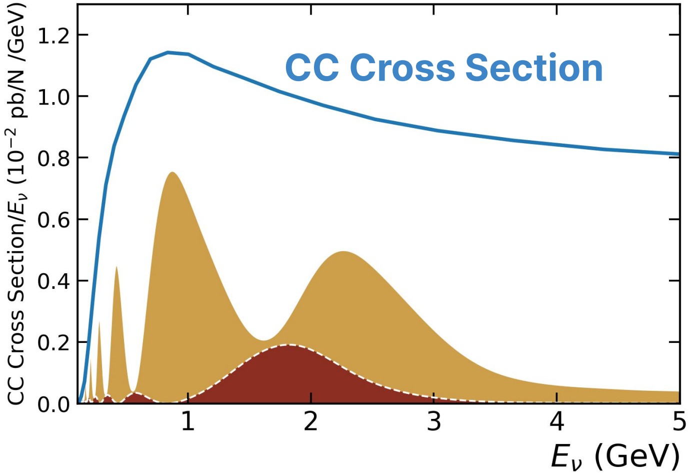
Long Baseline: Current Generation

Energy and Baseline

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

Muon neutrino disappearance

Electron neutrino appearance



Energy and Baseline

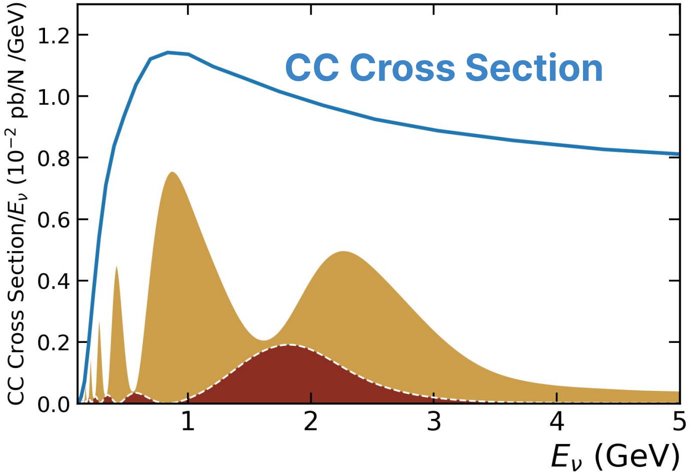
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1-\cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32}L}{4E} + (\text{solar, matter effect terms})$$

Driven by $|\Delta m_{32}|^2 \sim 2\times10^{-3}\ \text{ev}^2$

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

Muon neutrino disappearance

Electron neutrino appearance



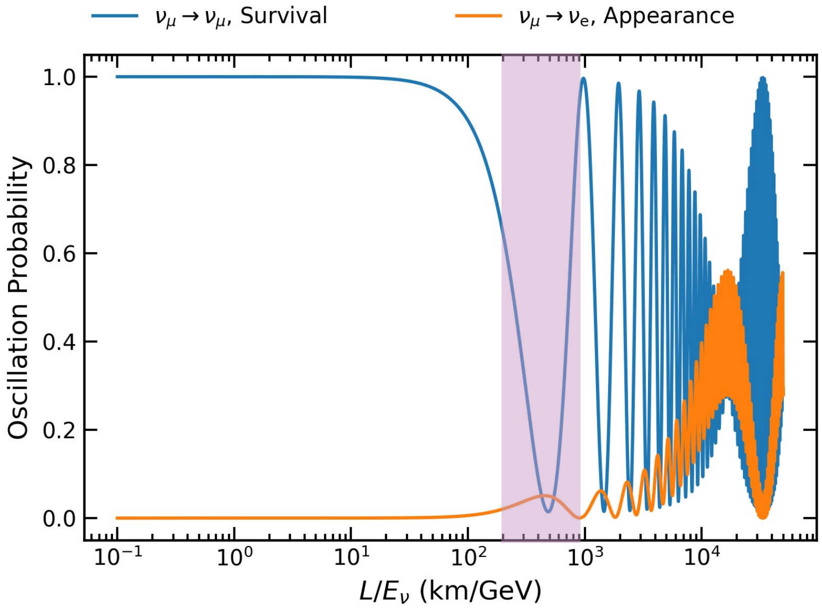
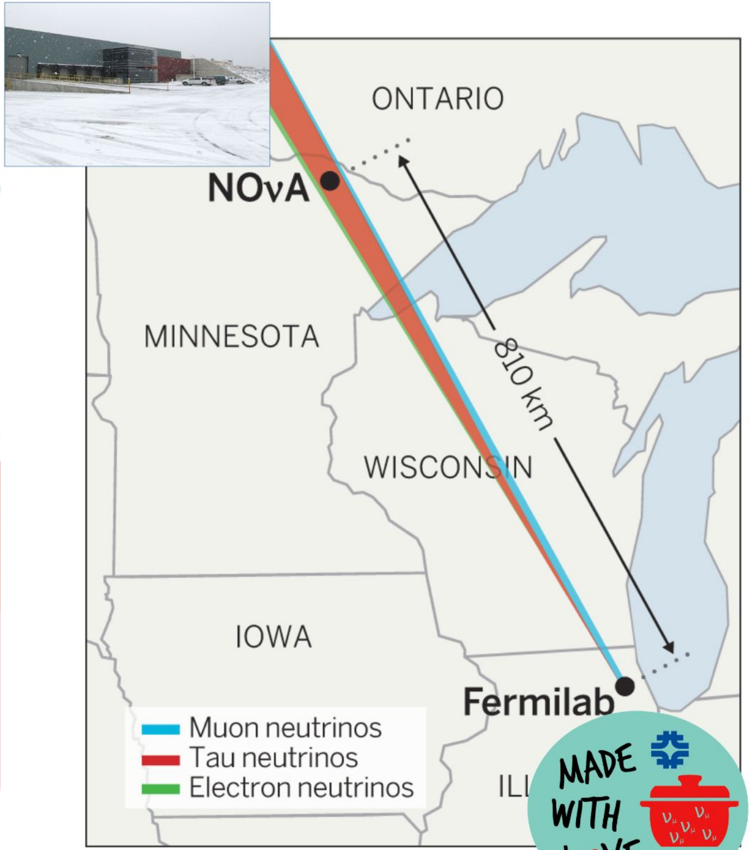


Image credit: t2k-experiment.org



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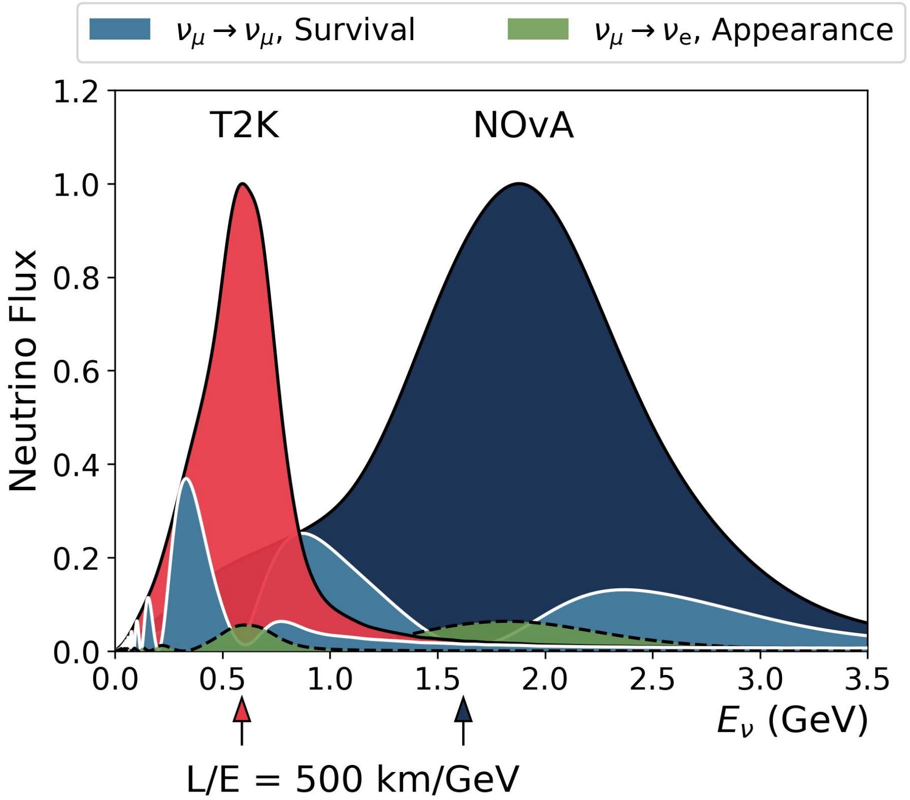


Oscillation parameters: NuFit 5.2 JHEP 2020, 178

T2K

NOvA

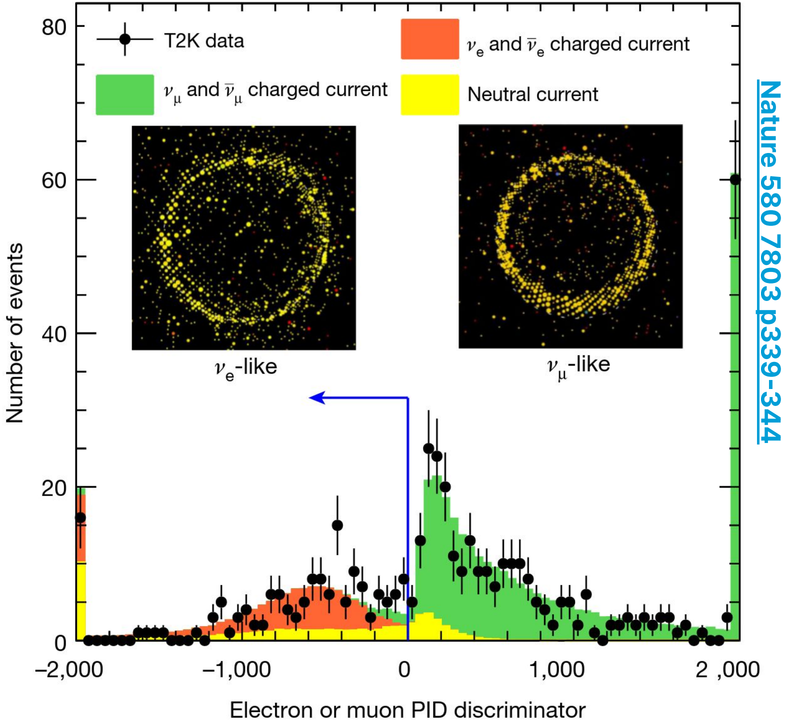
Super Kamiokande

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

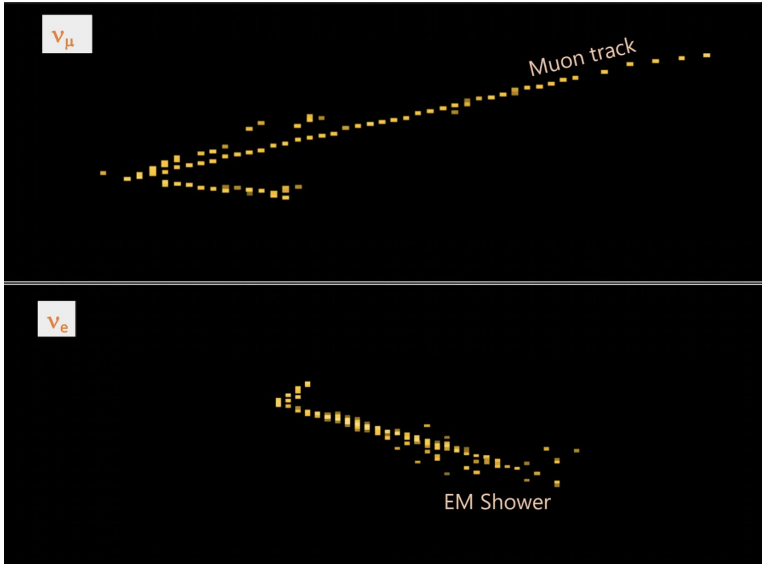
Fiducial Mass:	14 kT
Material:	Liquid scintillator
Detection technique:	Scintillation
Baseline:	810 km
Peak neutrino energy:	1.9 GeV
Location:	Ash River, MN

Far detector event displays



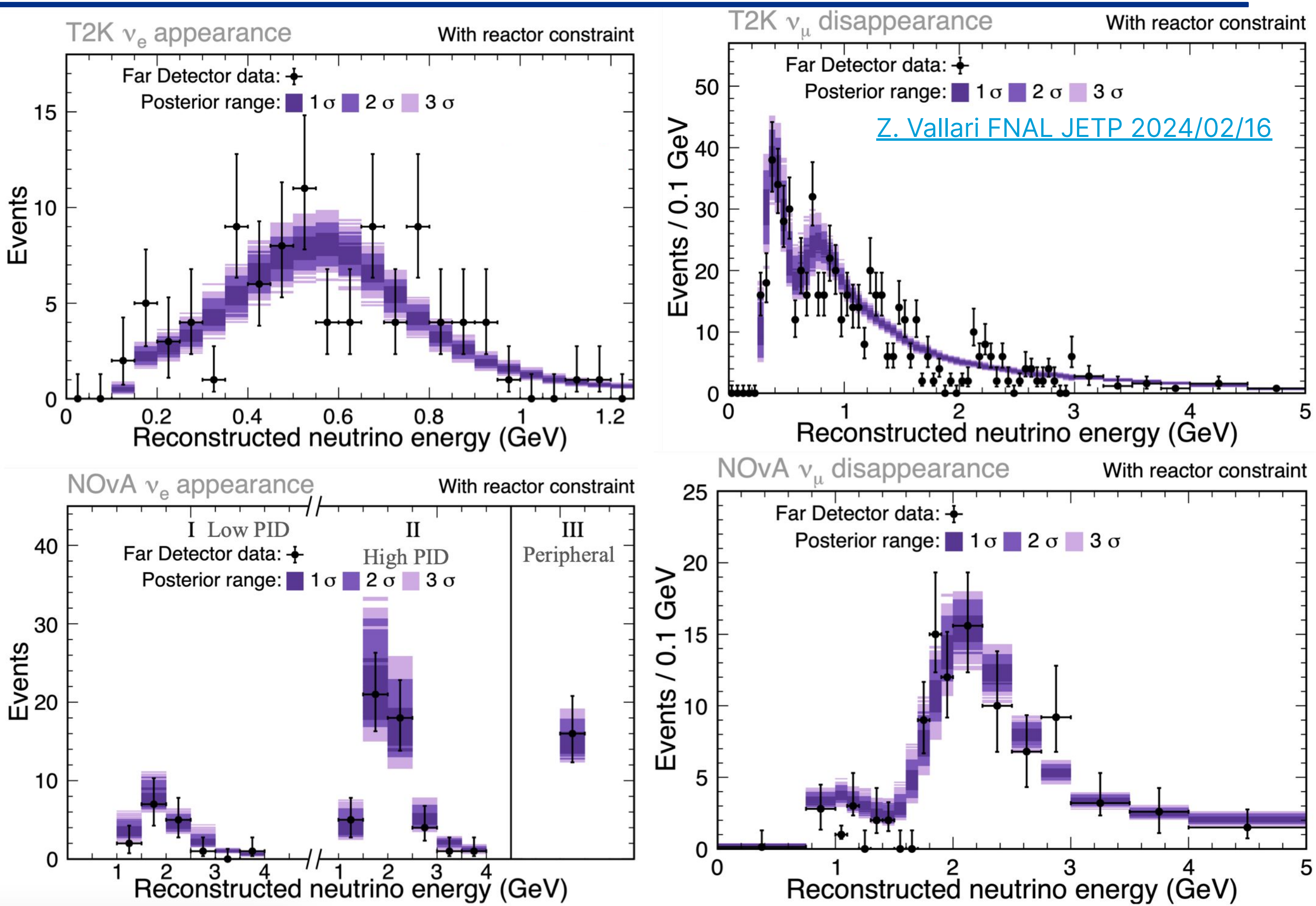
Nature 580 7803 p339-344

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



Z. Vallari FNAL JETP 2024/02/16

Far Detector Samples



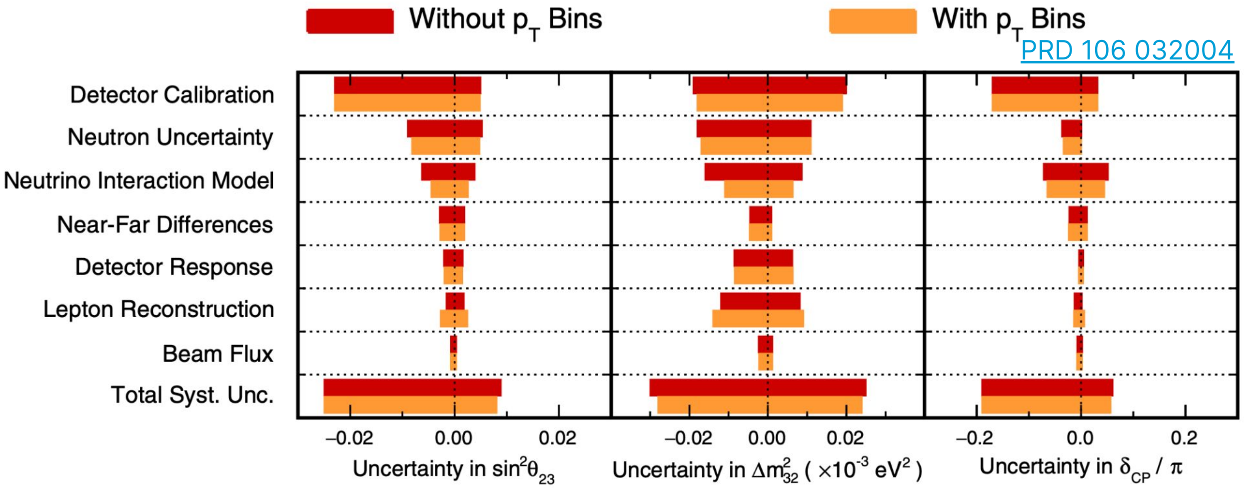
[Z. Vallari FNAL JETP 2024/02/16]

Uncertainties

Eur. Phys. J. C 83, 782 (2023)

Sample		Uncertainty source (%) Flux	Interaction	FD + SI + PN	Flux⊗Interaction (%)	Total (%)
1Rμ	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

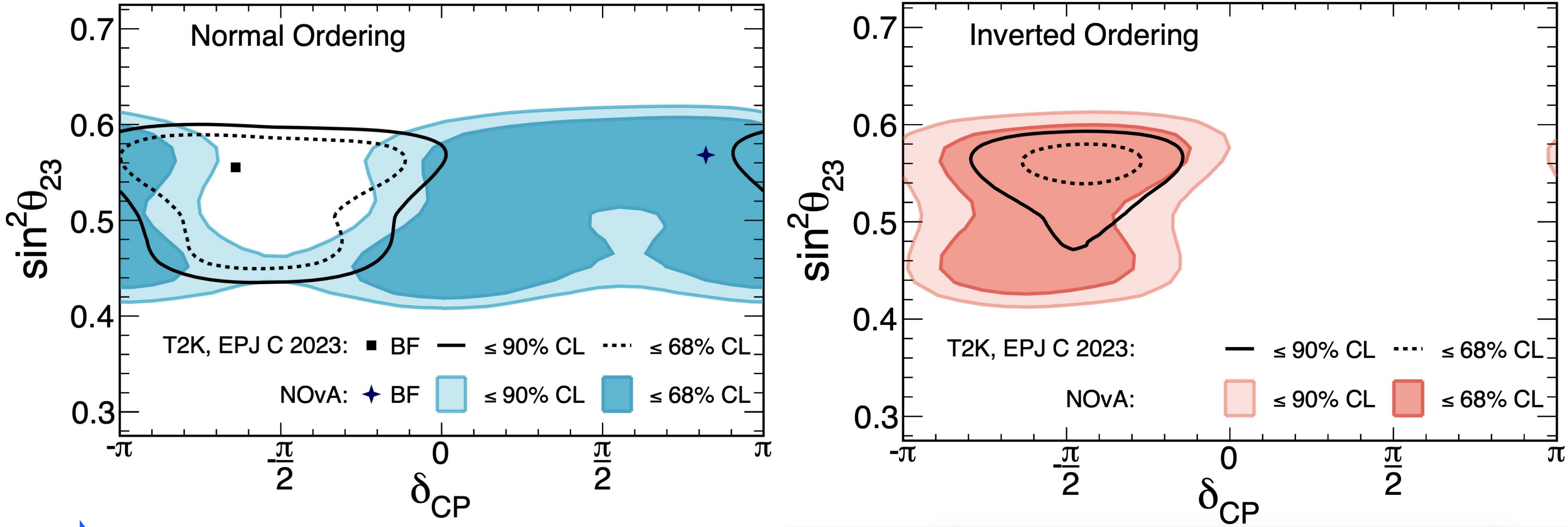


PRD 106 032004

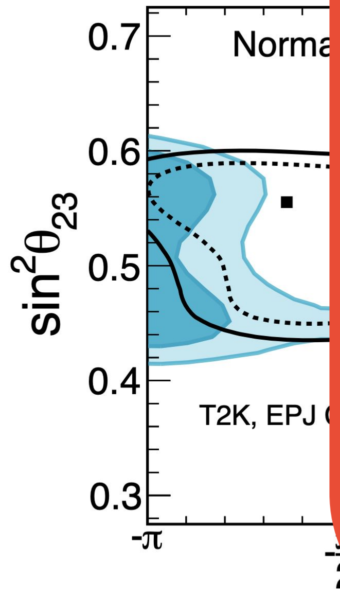
Oscillation parameter uncertainties

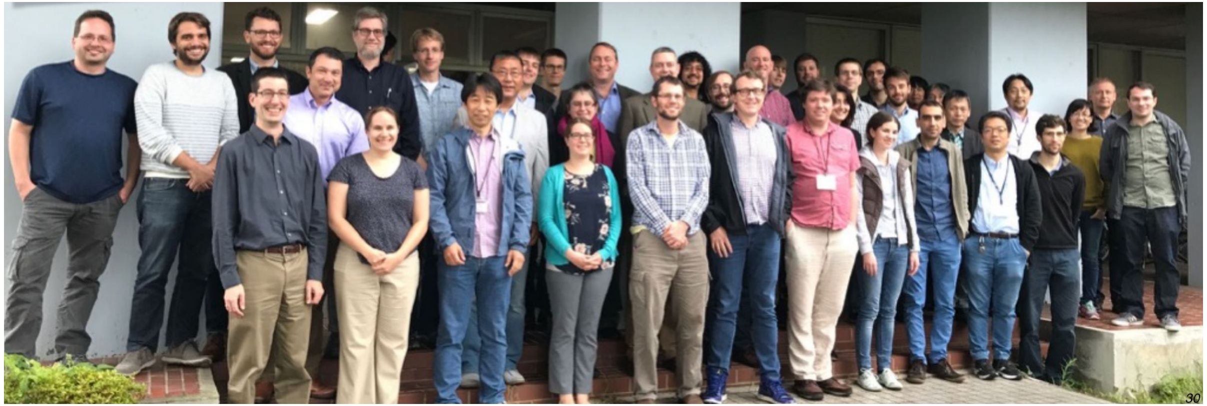
- Overlapping 1σ regions
- Disagree about best fit region for Normal Ordering

Z. Vallari FNAL JETP 2024/02/16

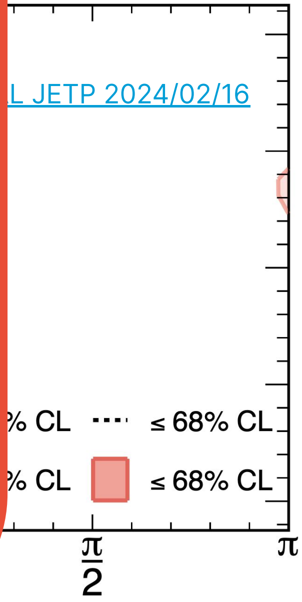


- Overlapp
- Disagre



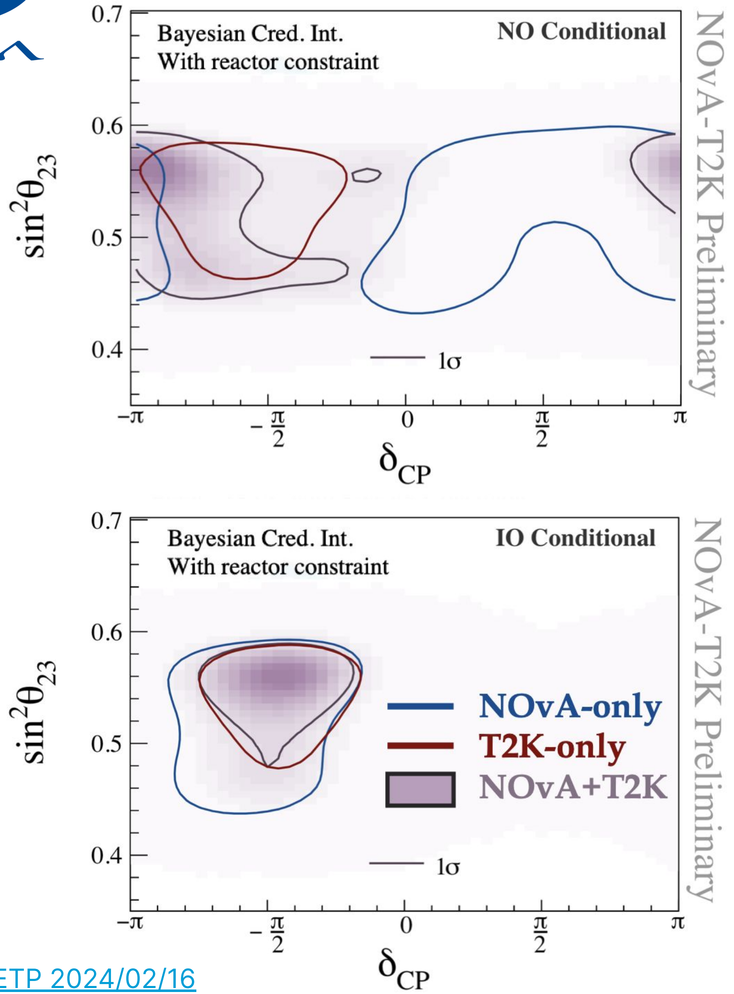


Multiple joint workshops since 2016, only possible thanks to DOE US-Japan and UKRI support.



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

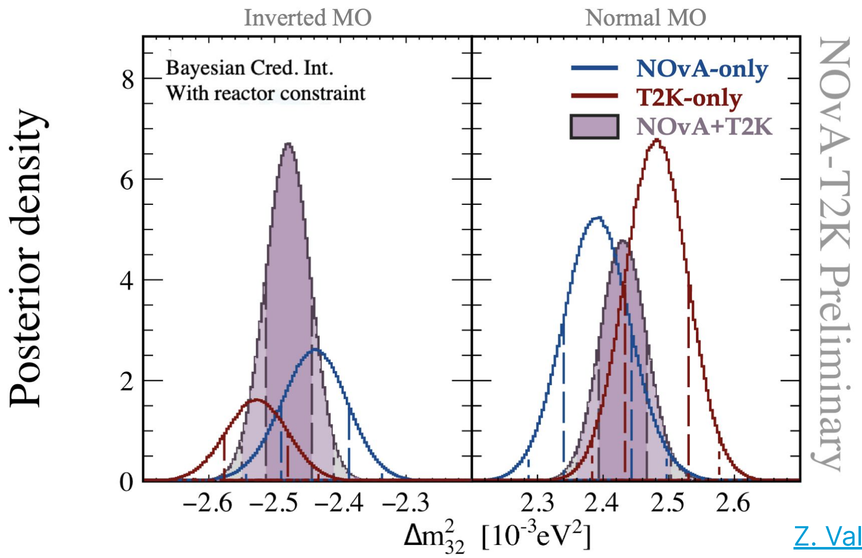


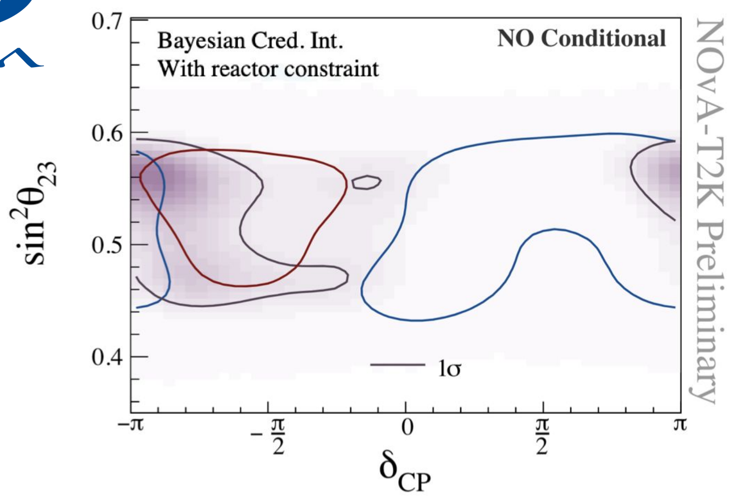
Z. Vallari FNAL JETP 2024/02/16

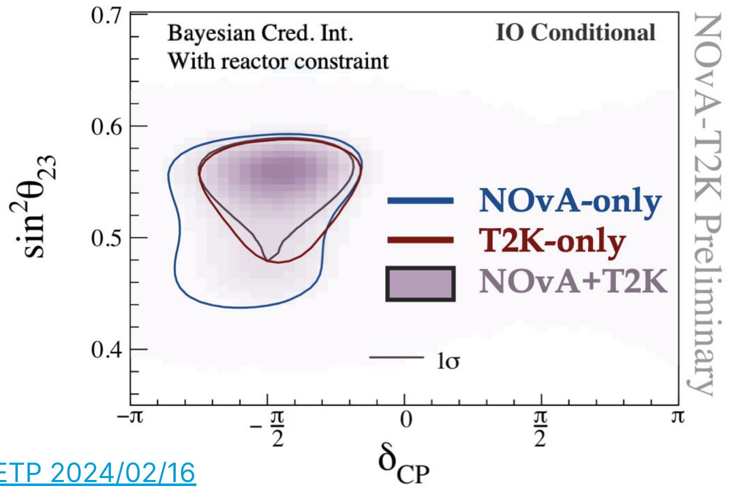
Probe same L/E: ~500 km/GeV

- 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!





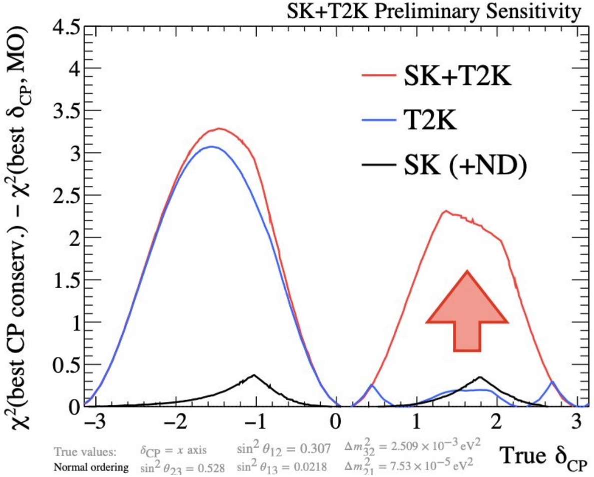


Z. Vallari FNAL JETP 2024/02/16

T2K + Super-K

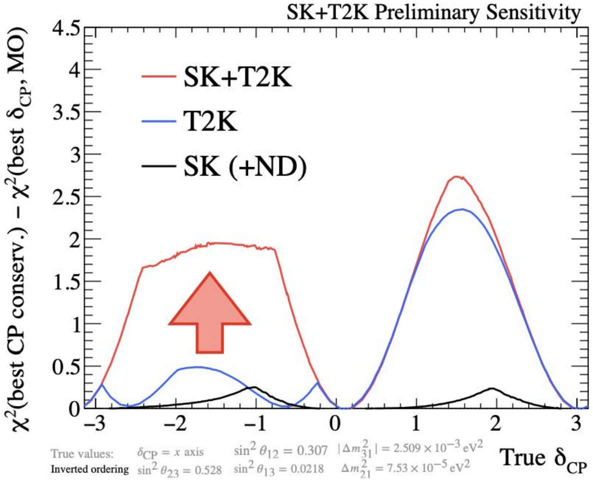
- Inclusion of SK atmospheric data breaks mass ordering degeneracy
- T2K beam data sensitive to $\sin(\delta_{CP})$
- SK atmospheric data sensitive to $\cos(\delta_{CP})$

True NO



L. Berns IPNS Seminar

True IO



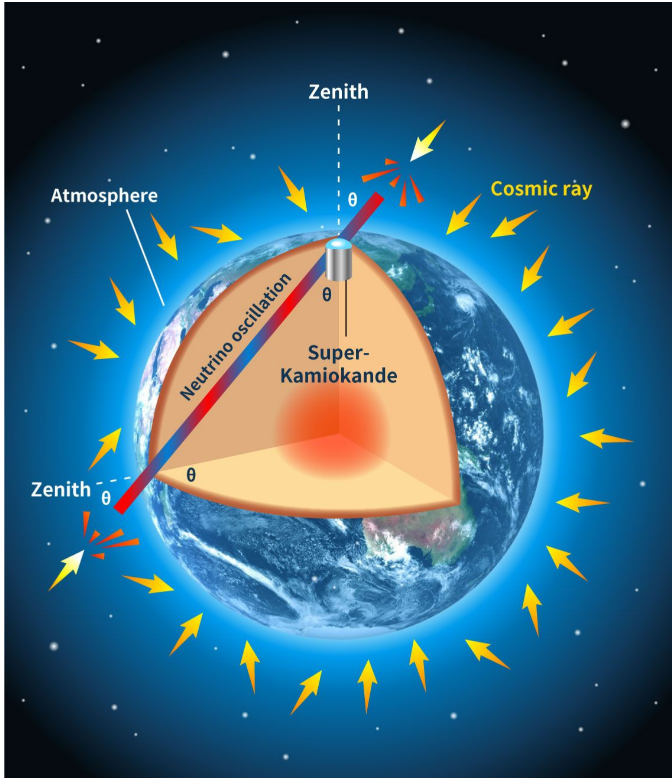
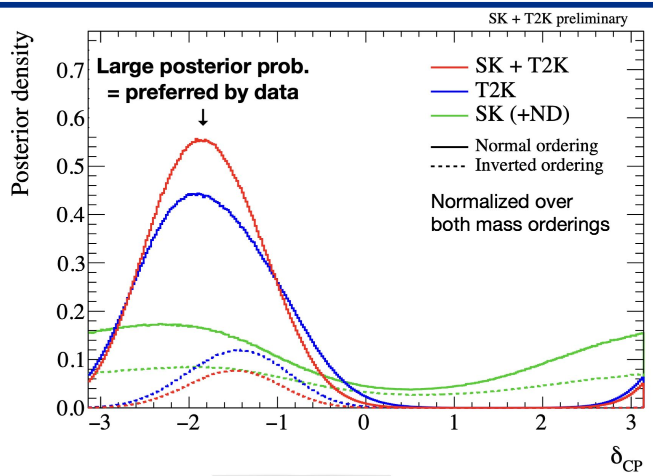
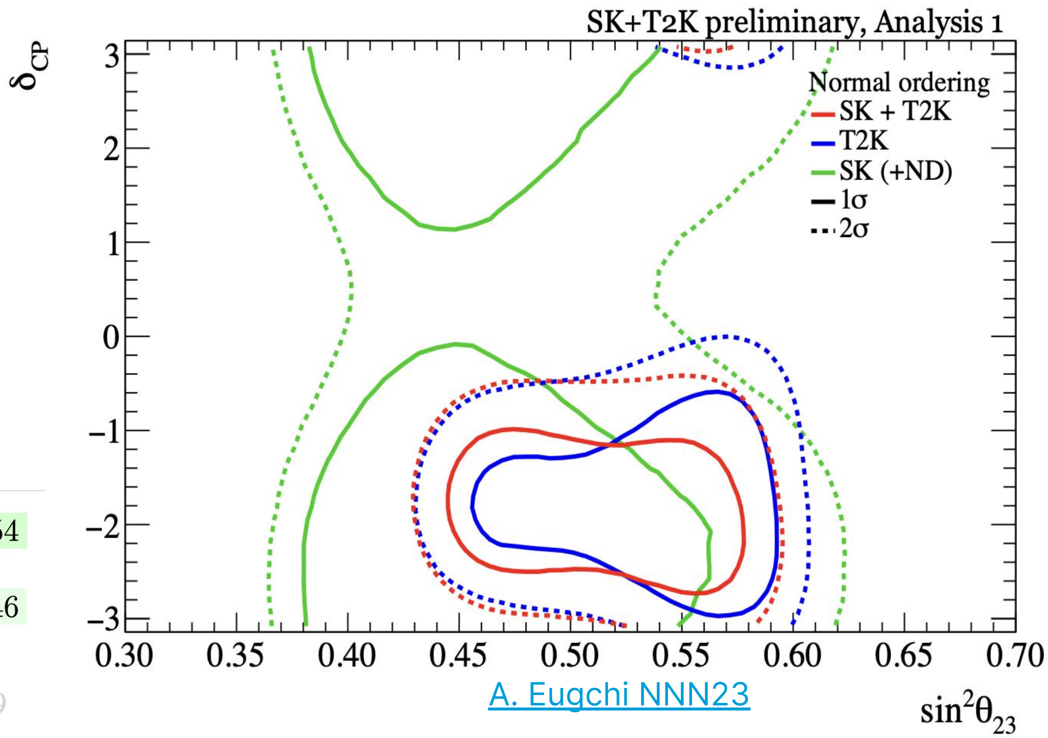


Image credit: Super-K/ICRR

T2K + Super-K



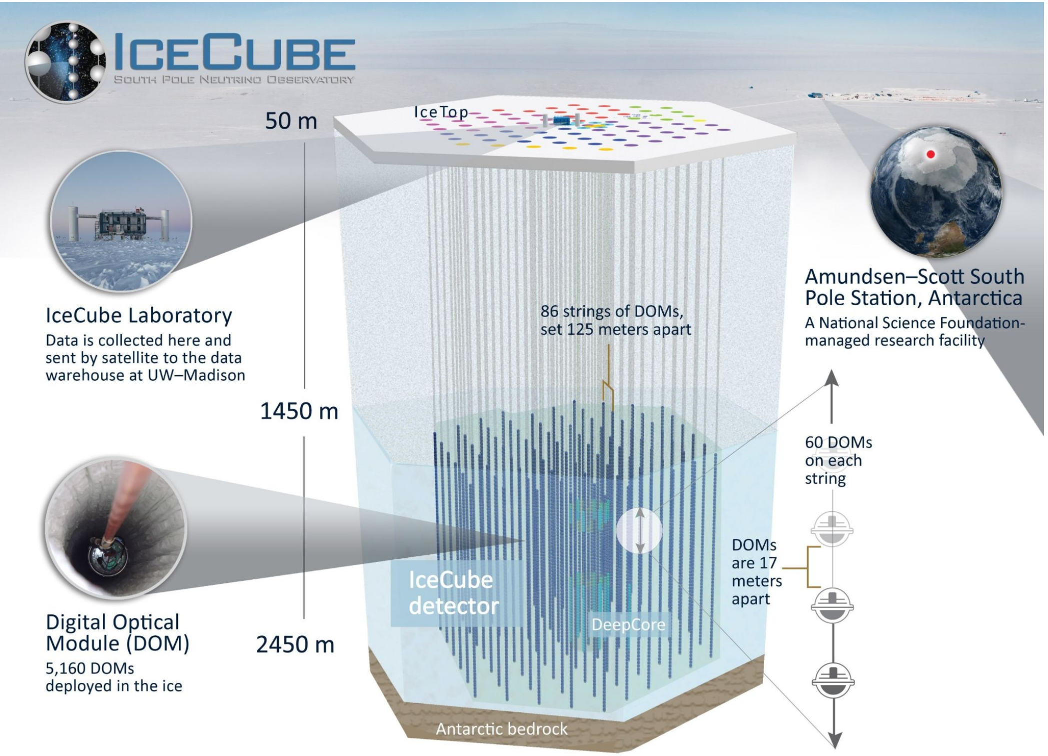
Posterior probability	SK+T2K	T2K	SK
Normal ordering	0.900	0.832	0.654
Inverted ordering	0.100	0.168	0.346
Bayes factor (NO/IO)	9.0	5.0	1.9



A. Eugchi NNN23

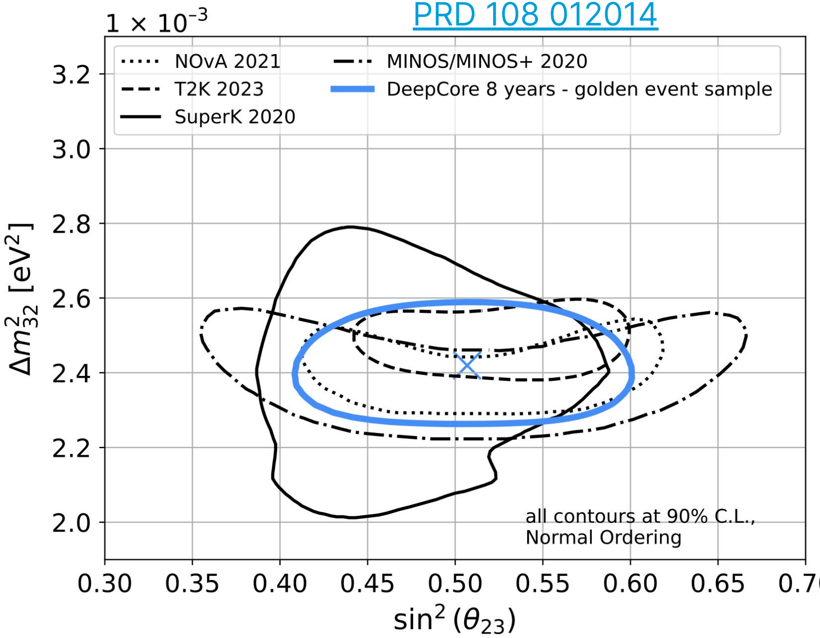
L. Berns IPNS Seminar

IceCube



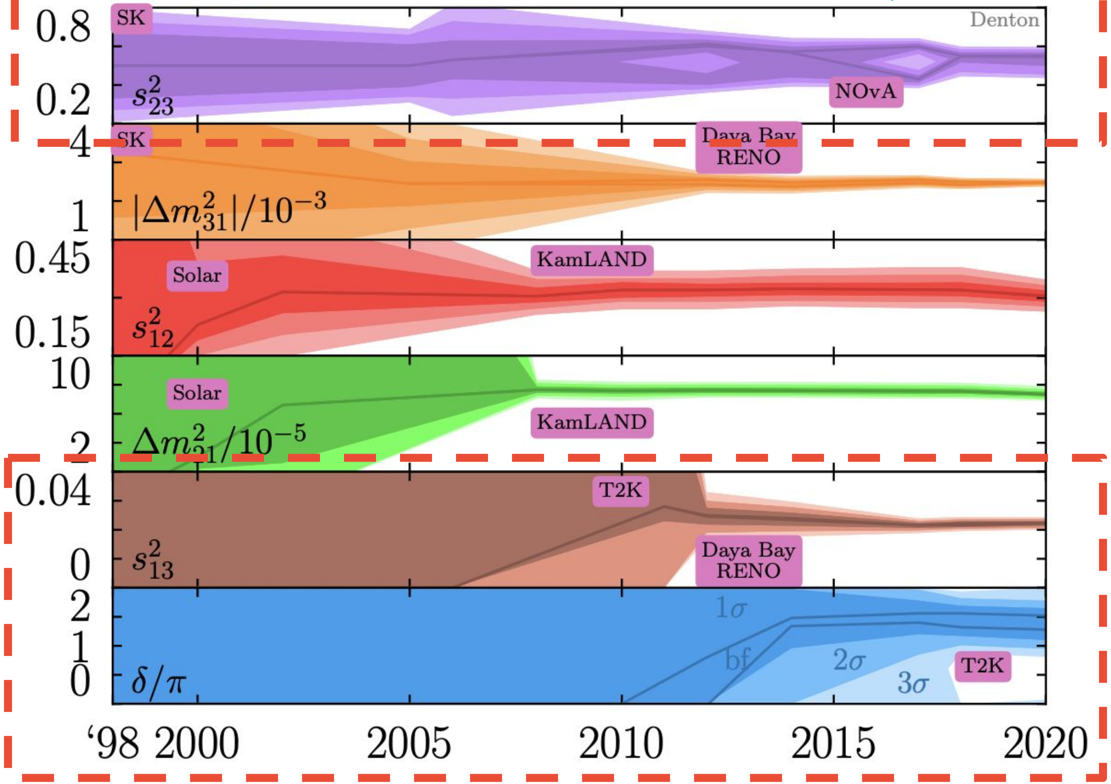
Atmospheric disappearance measurement very consistent with beam-based experiments

PRD 108 012014



State of the ν-tion

[Denton, Neutrino22](#)

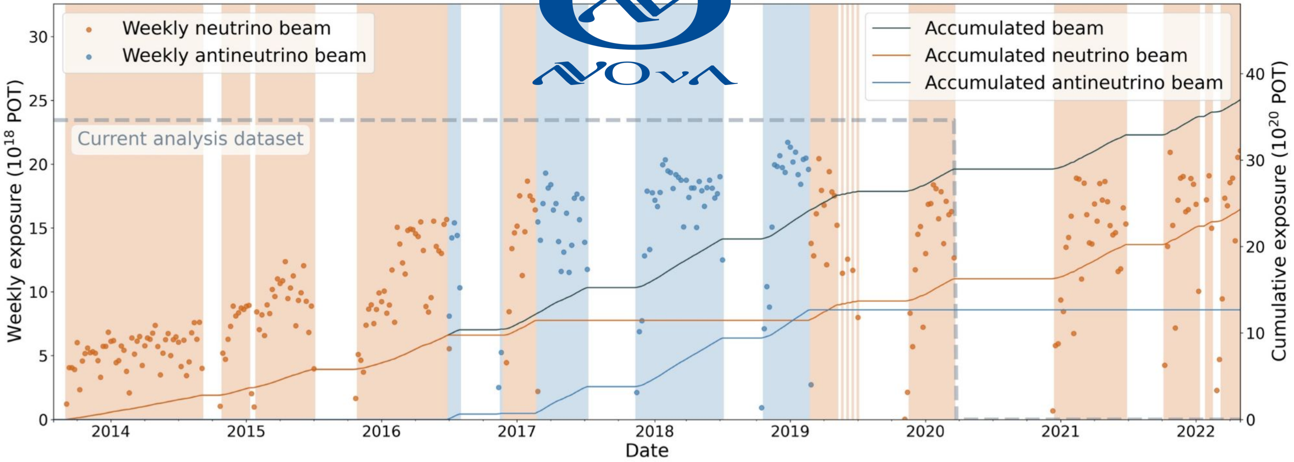


Long Baseline experiments largely sensitive to these parameters

T2K & NOvA

NOvA beam has been running stably at ~1 MW

A. Aurisano NuFact23



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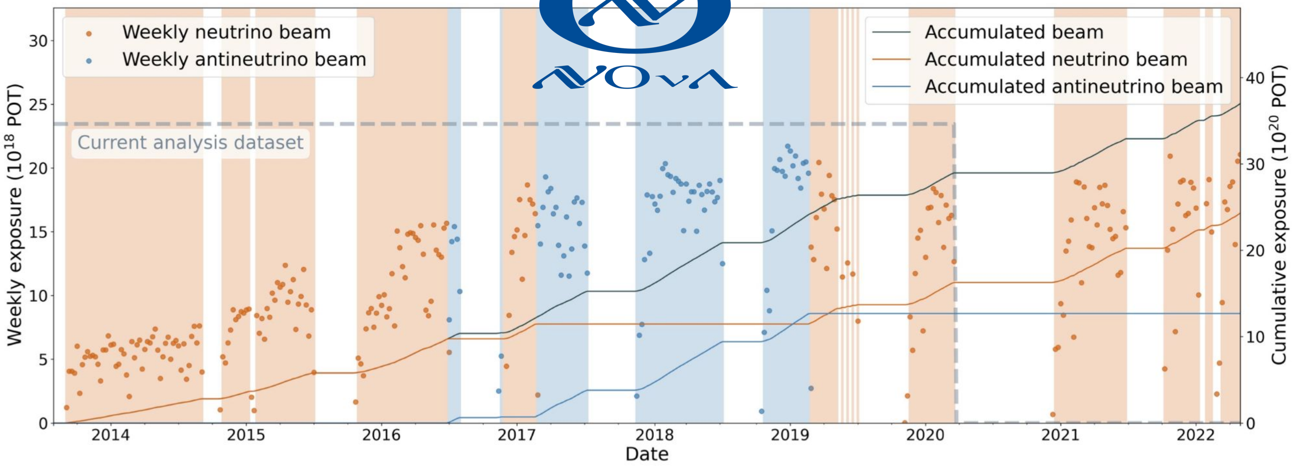

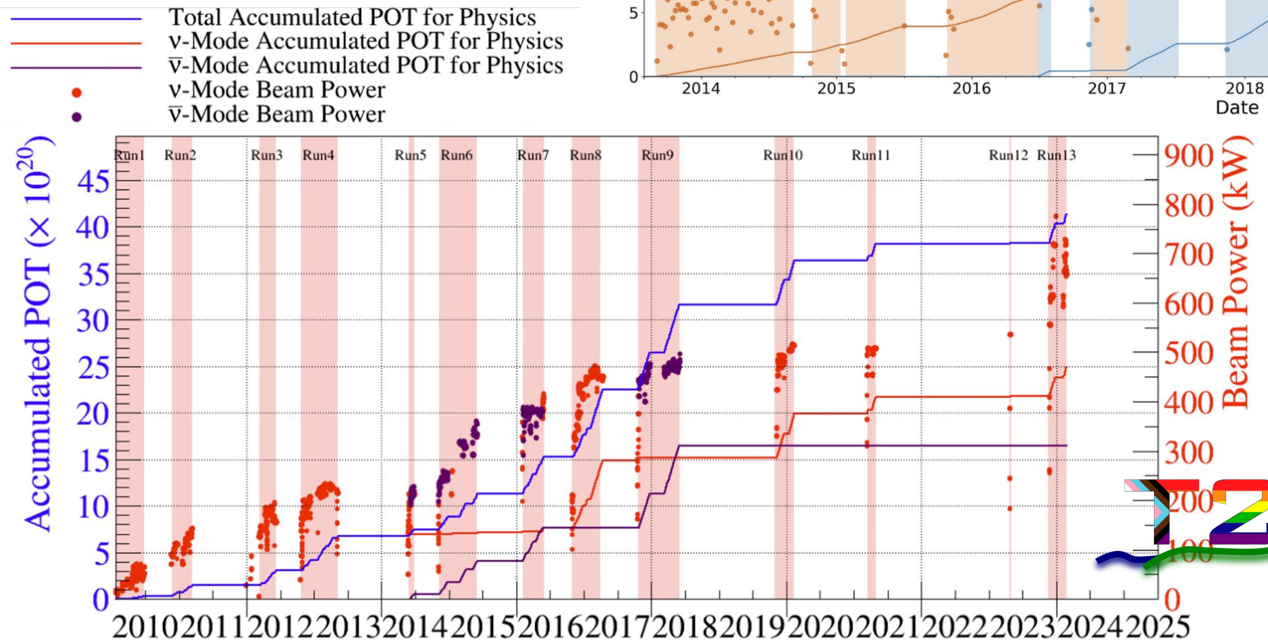

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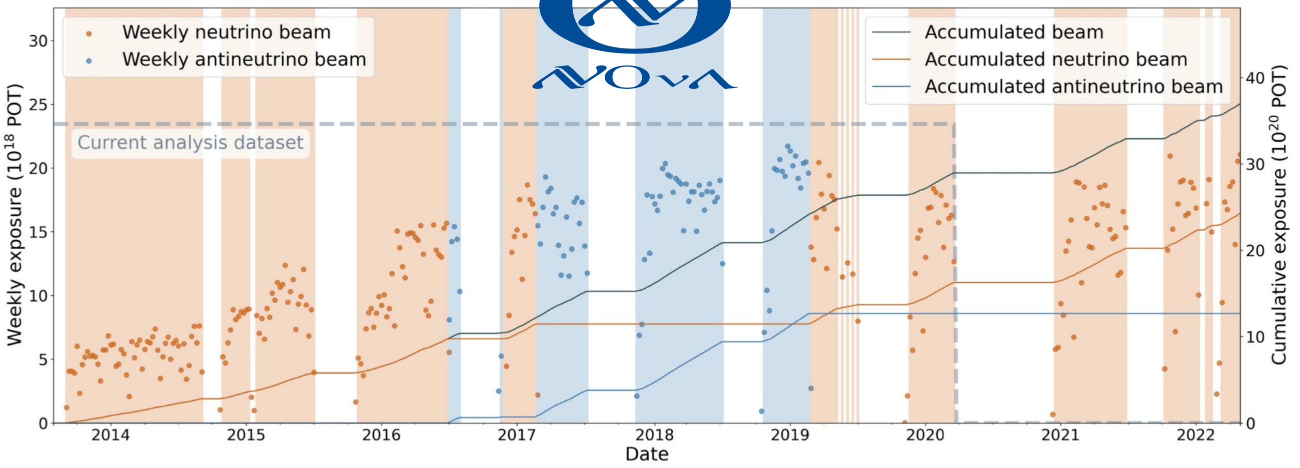
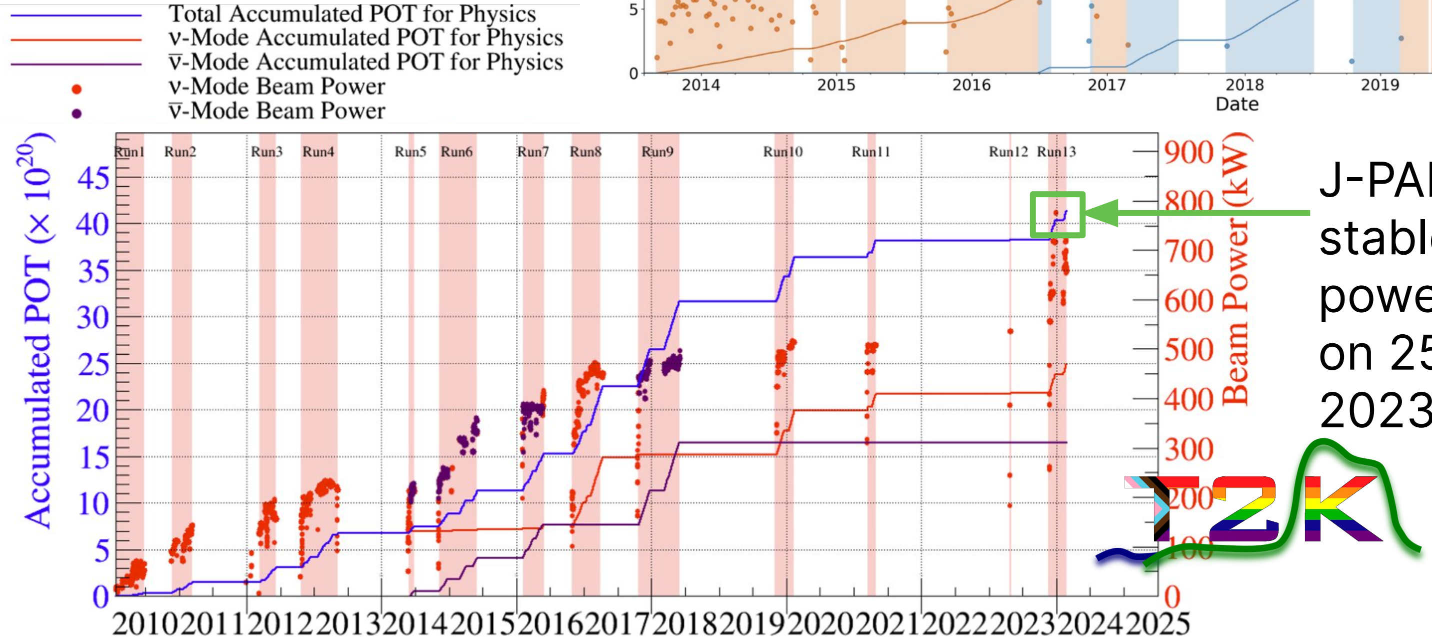
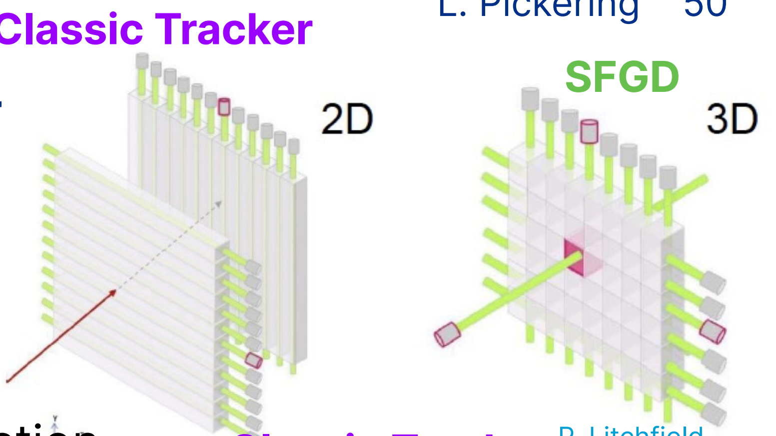


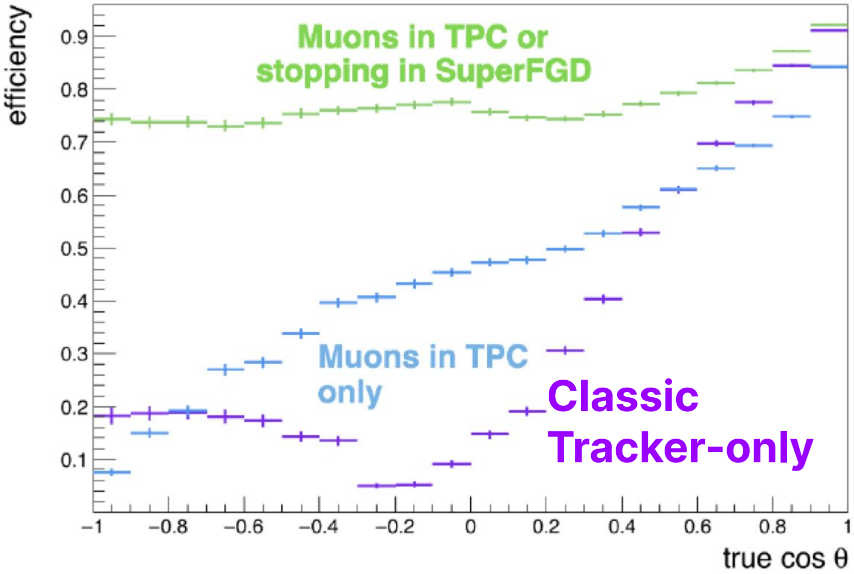


J-PARC Neutrino beam stable at 750 kW design power for the first time on 25th of December 2023!

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

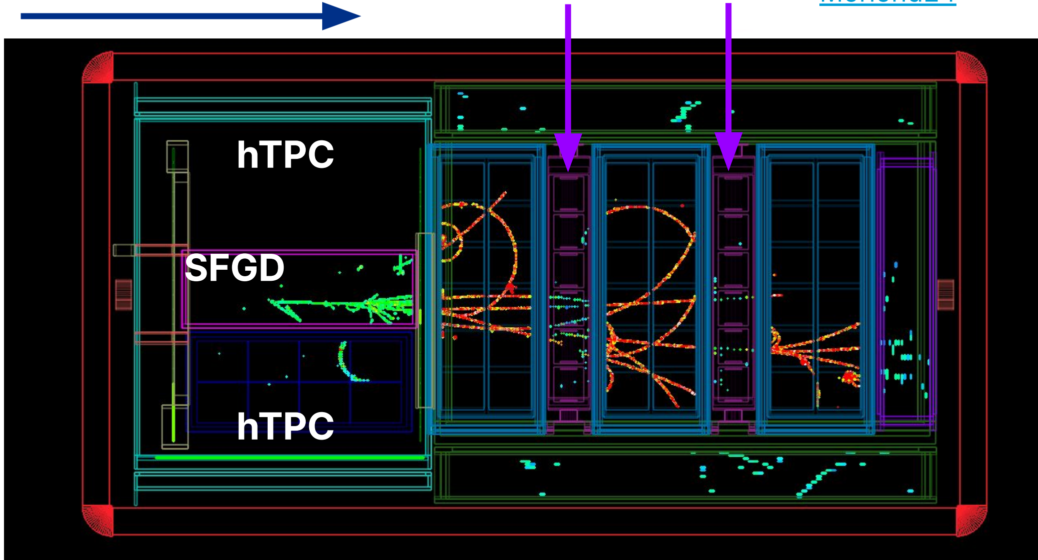




Beam direction

Classic Tracker

P. Litchfield Moriond24



T2K Recent Upgrades

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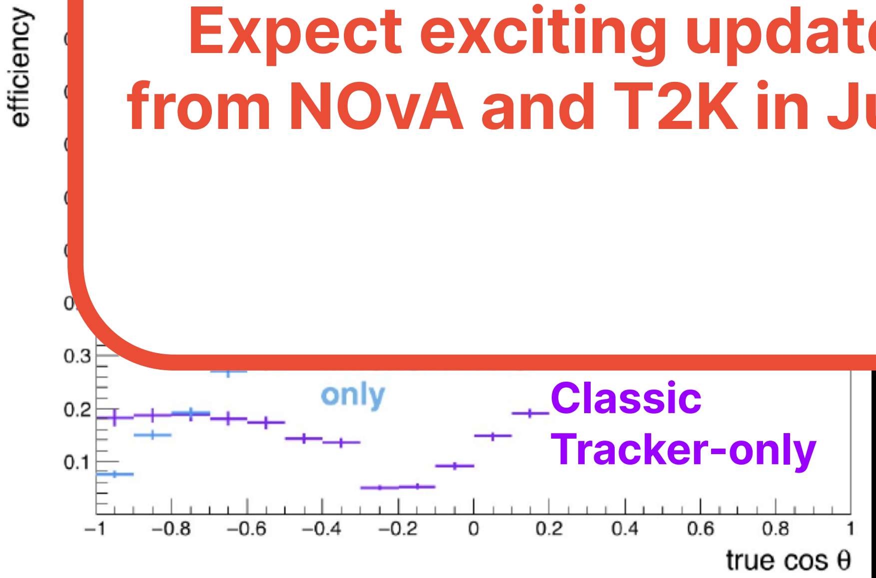
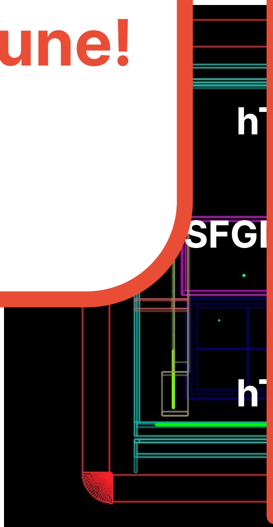
  - SFGD: New, cube-based 3D scintillator tracker

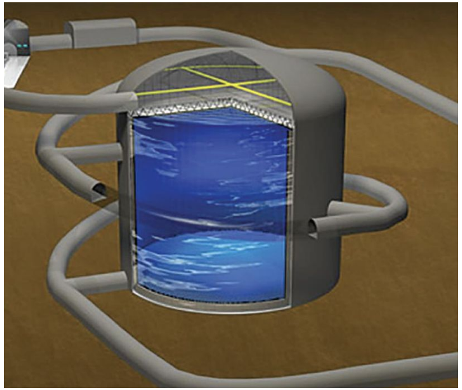
Expect exciting updates from NOvA and T2K in June!





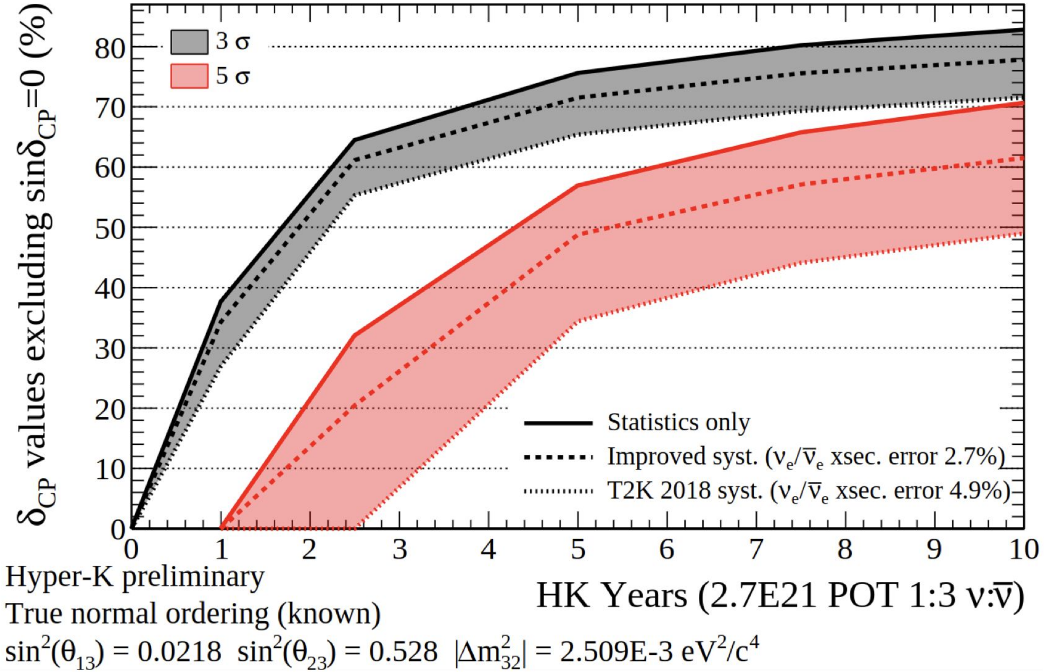
Long Baseline: Next Generation

Hyper-K

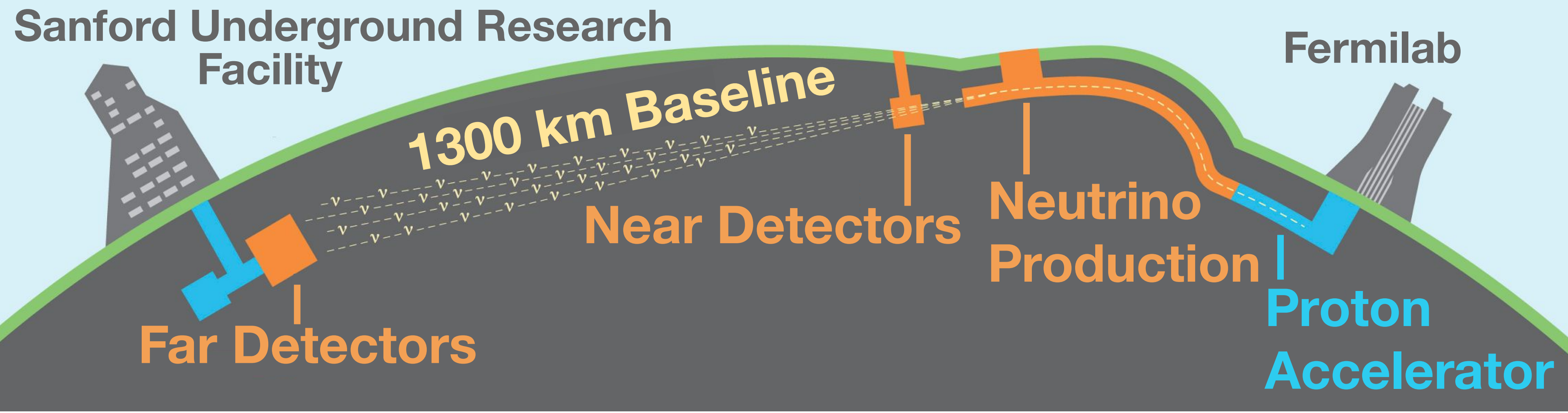


- Builds on successes of SK/T2K
  - **Bigger:** 8x larger fiducial mass than SK
  - **More intense:** beam power ~2x T2K
  - Same baseline: 295 km
  - Similar detector technology
- Data taking from ~2027

C. Naseby NuFact23

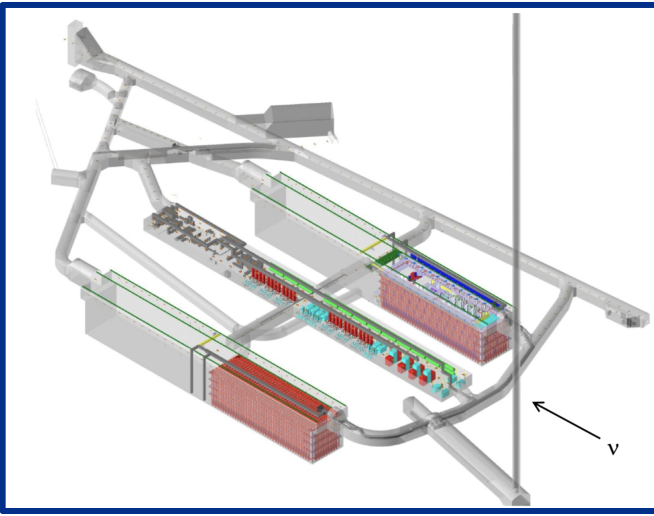


DUNE: Deep Underground Neutrino Experiment



Expect Phase 1 beam data to arrive ~2031

DUNE: Far Detectors

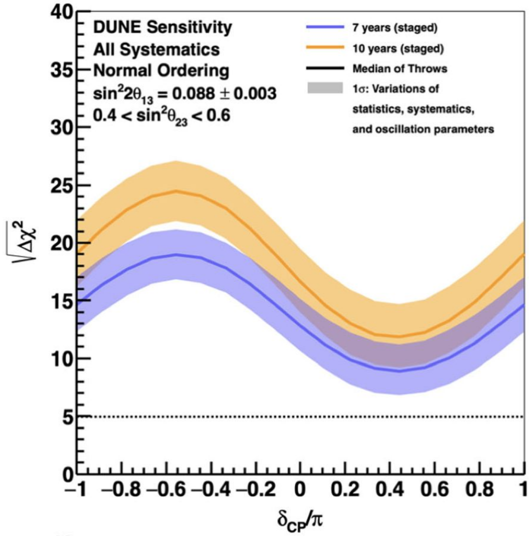


- Four caverns with space for 17 kt LAr TPCs
  - Unprecedented detector resolution for an LBL far detector
- Phase 1: 2x LAr modules
- Rich prototype programme at CERN: ProtoDUNE

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



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[EPJC 80 (2020) 978]

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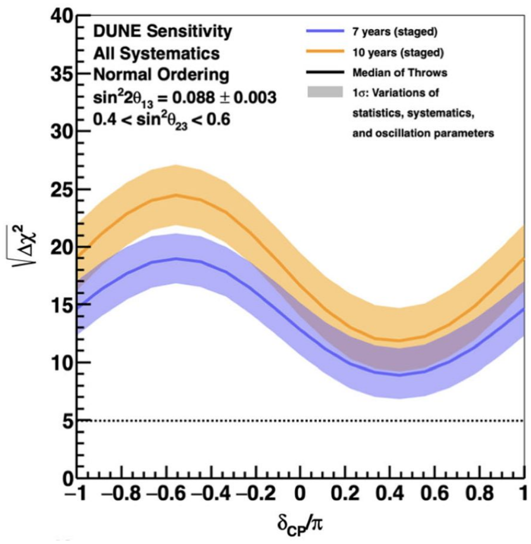
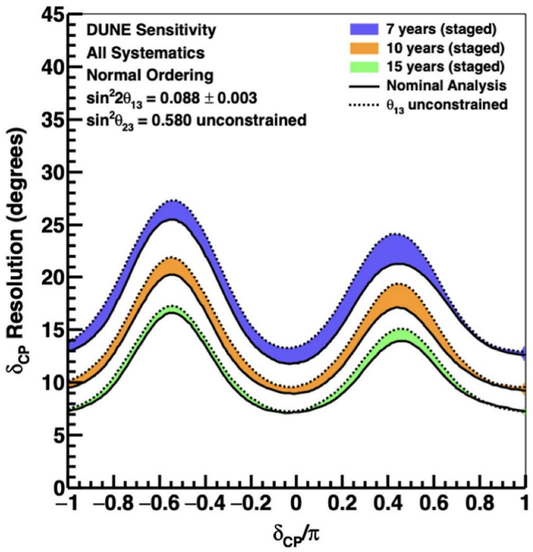




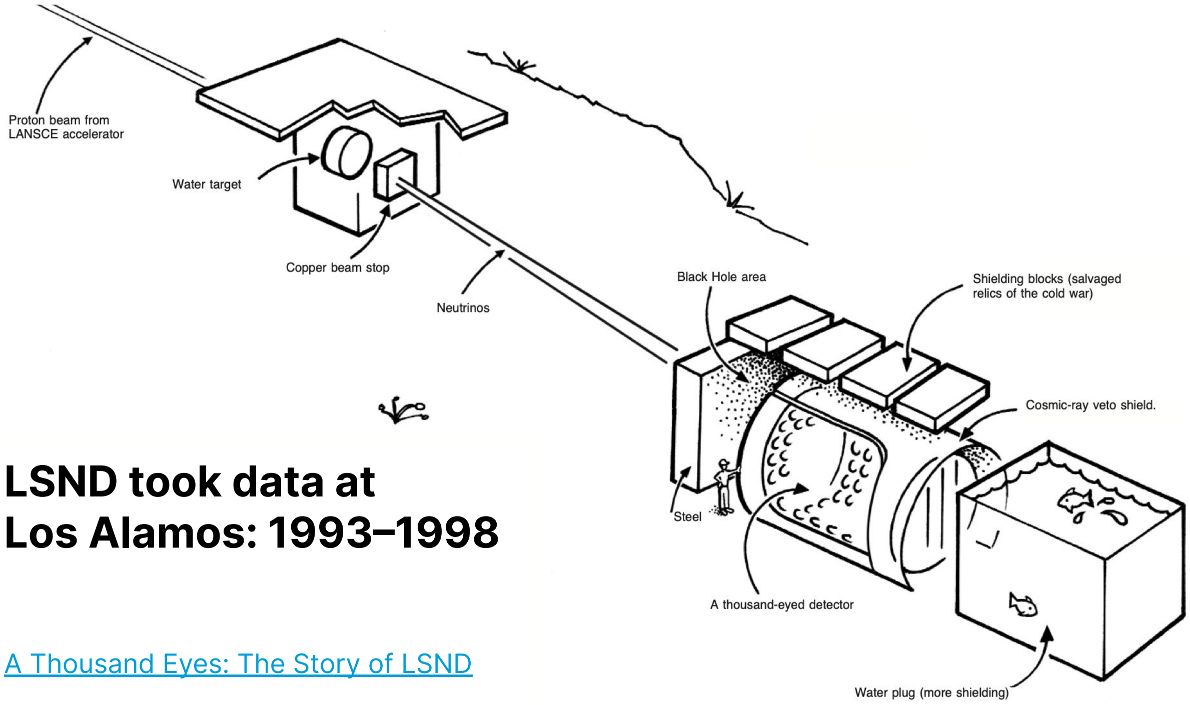
- 7–16° δ_{CP} resolution regardless of true value

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 ~1 km/GeV



LSND took data at Los Alamos: 1993–1998

A Thousand Eyes: The Story of LSND

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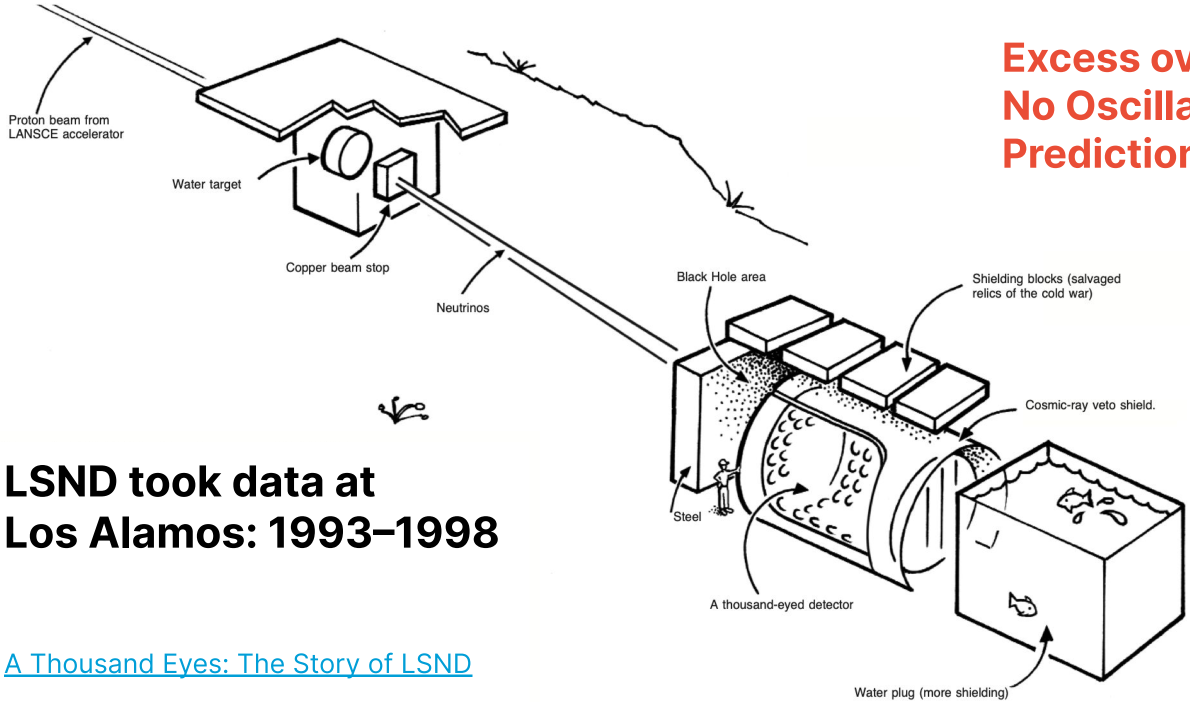
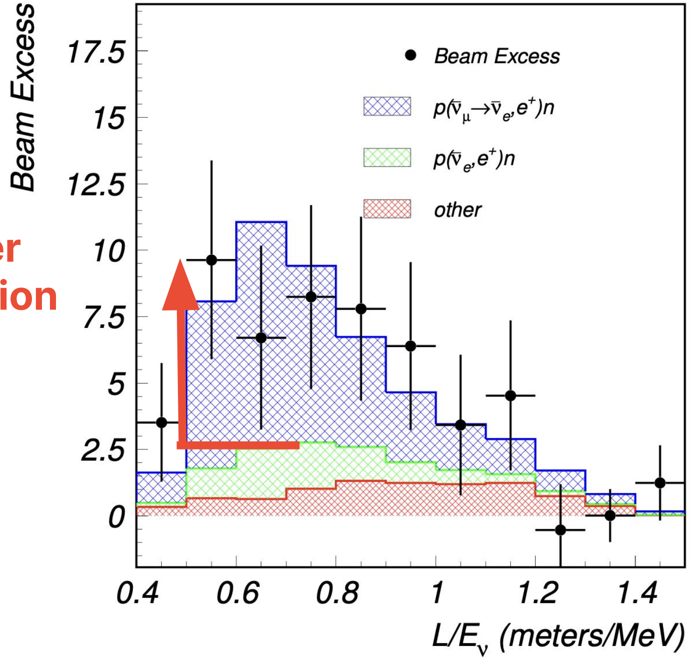


Excess over No Oscillation Prediction



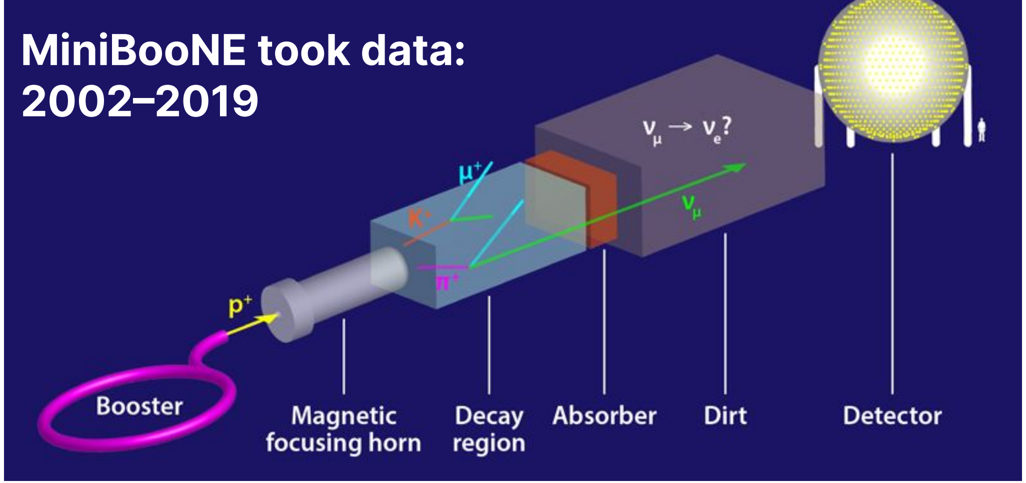
LSND took data at Los Alamos: 1993–1998

A Thousand Eyes: The Story of LSND

LSND and MiniBooNE

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

Image credit: APS/Alan Stonebreaker



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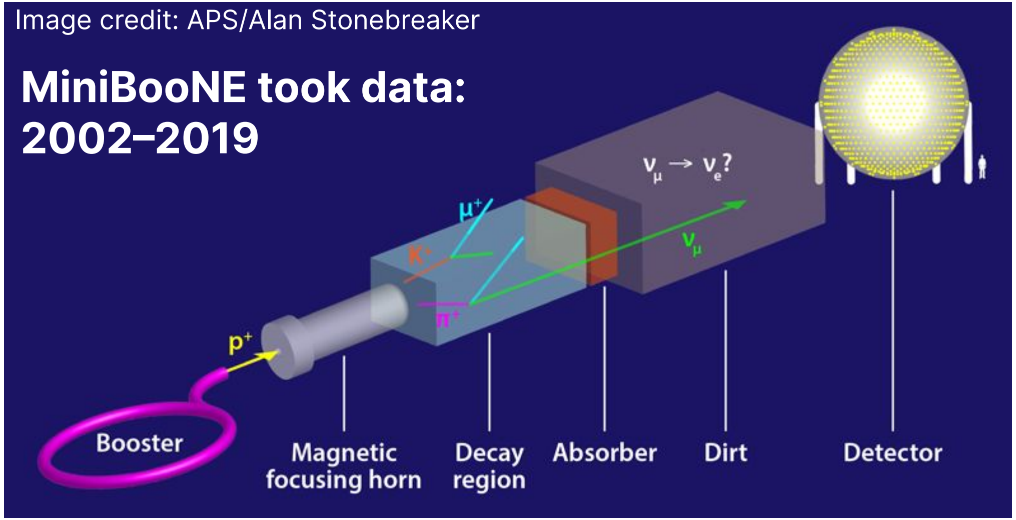
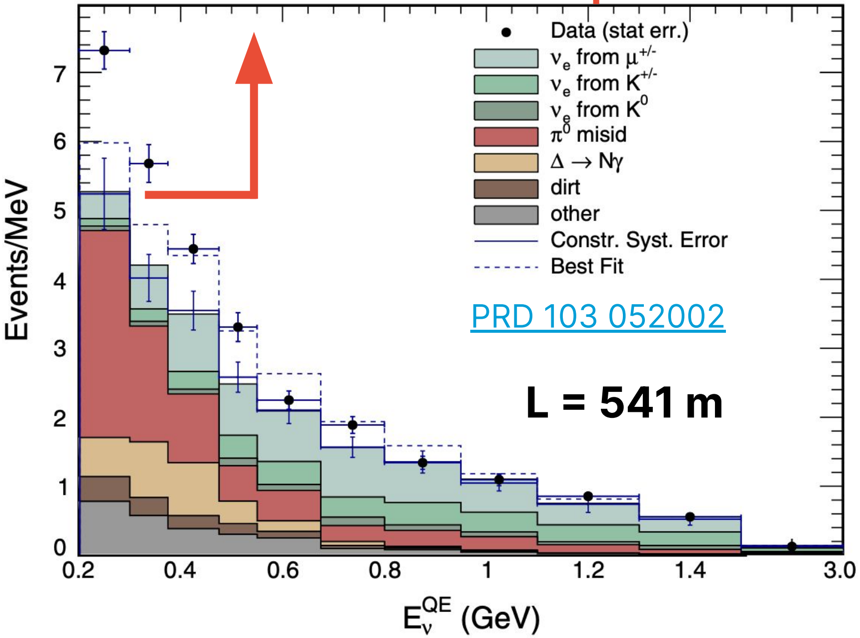


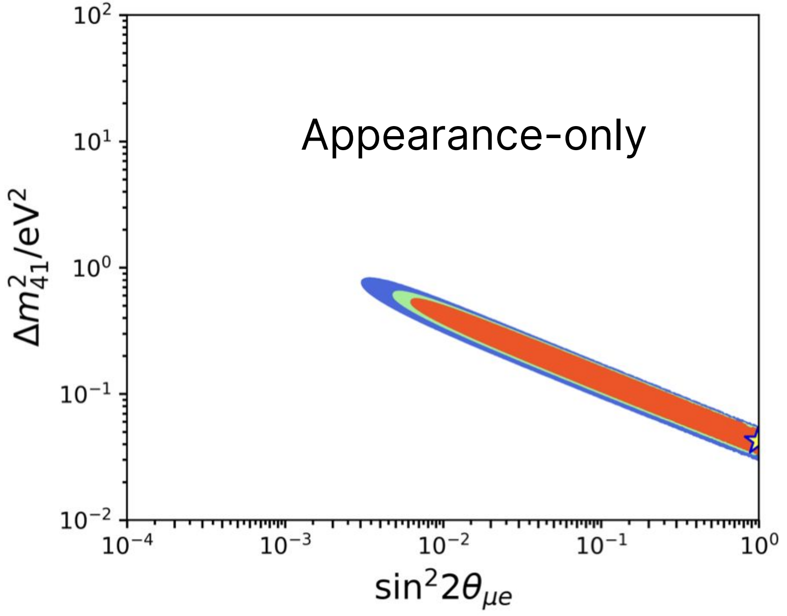
Excess over *no oscillation* prediction

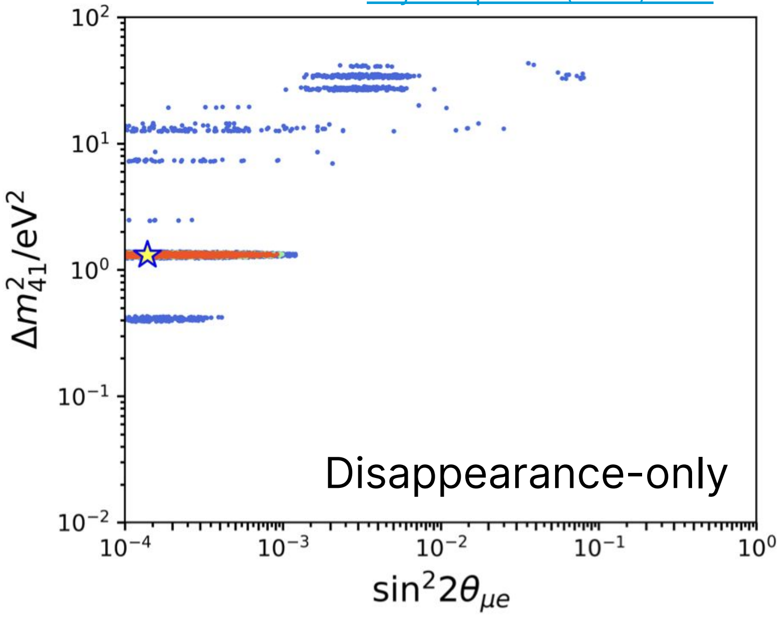


3+1 Tensions

However, difficult to explain global short baseline anomalous observations with just a single additional ~1 ev^2 scale neutrino

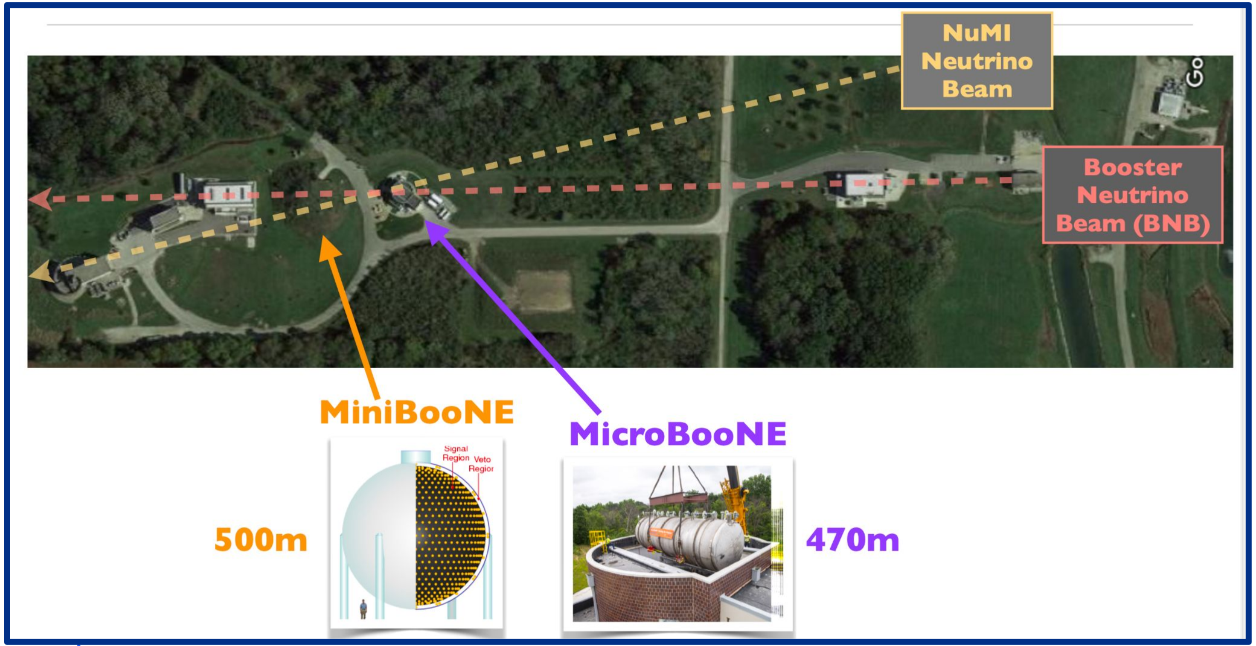
Phys. Rep. 884 (2020) 1-59





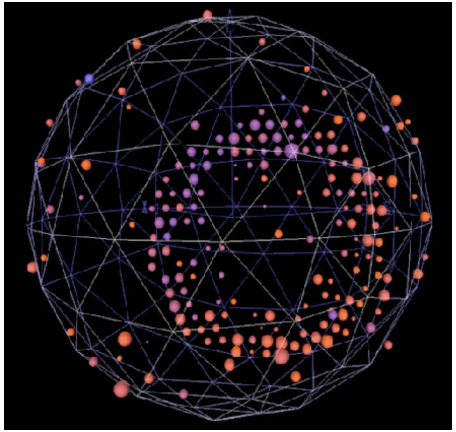
MiniBooNE & MicroBooNE

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



K. Duffy Rencontres de Vietnam22

MiniBooNE: Liquid scintillator + Cherenkov



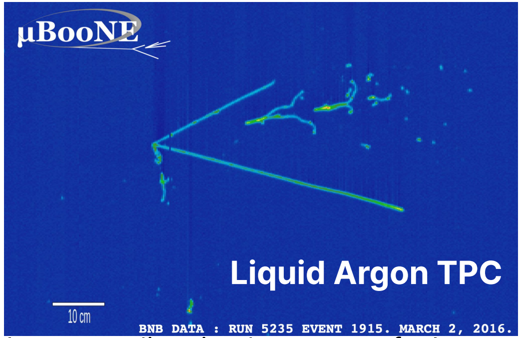
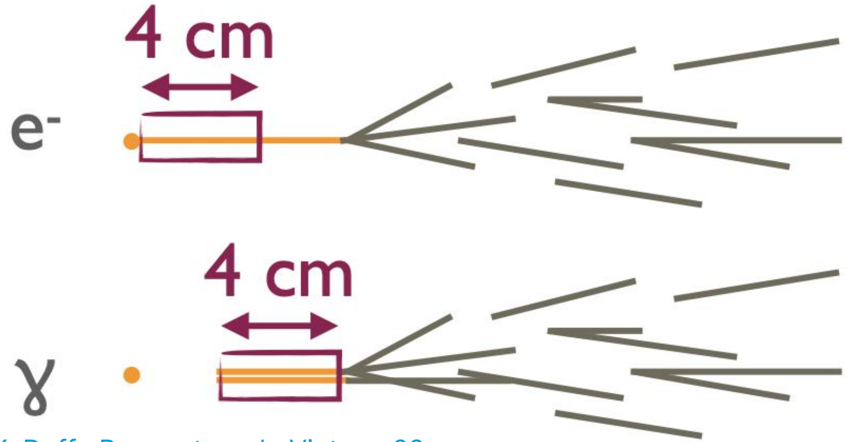


Image credit: microboone-exp.fnal.gov

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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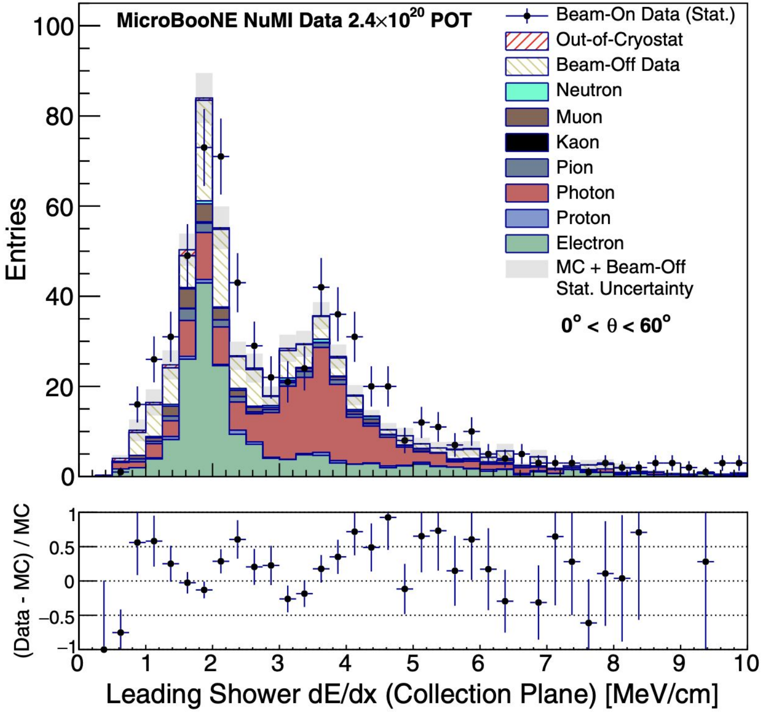
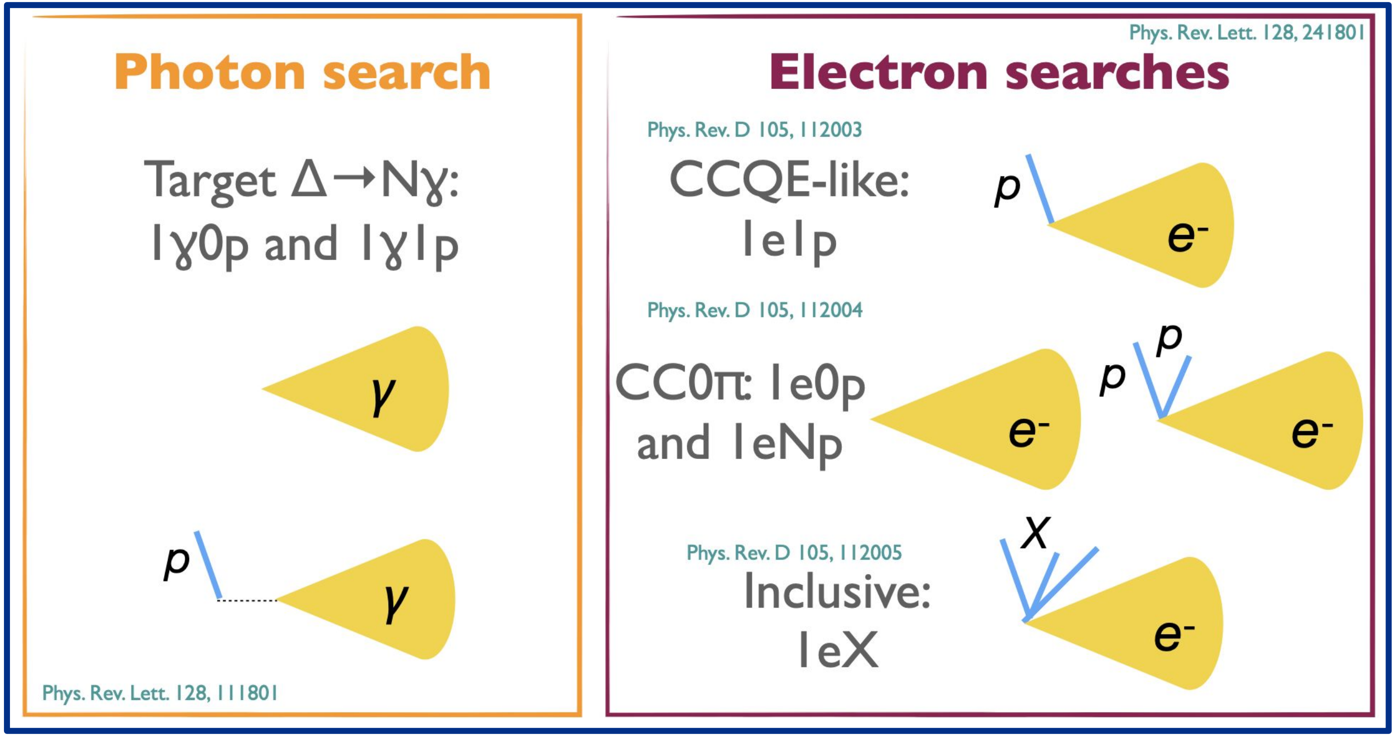


MicroBooNE: First LEE Search



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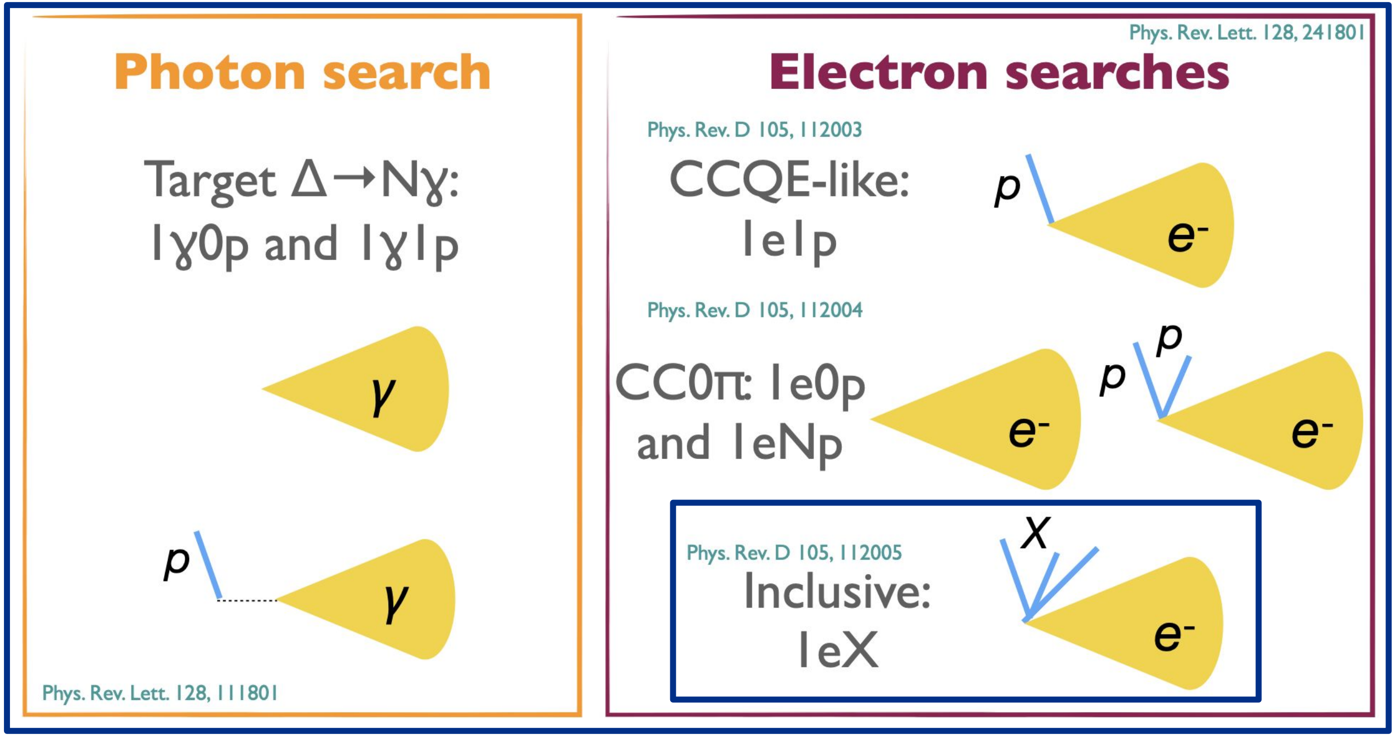
MicroBooNE: First LEE Search



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MicroBooNE: First LEE Search

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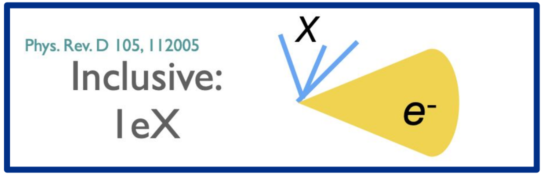
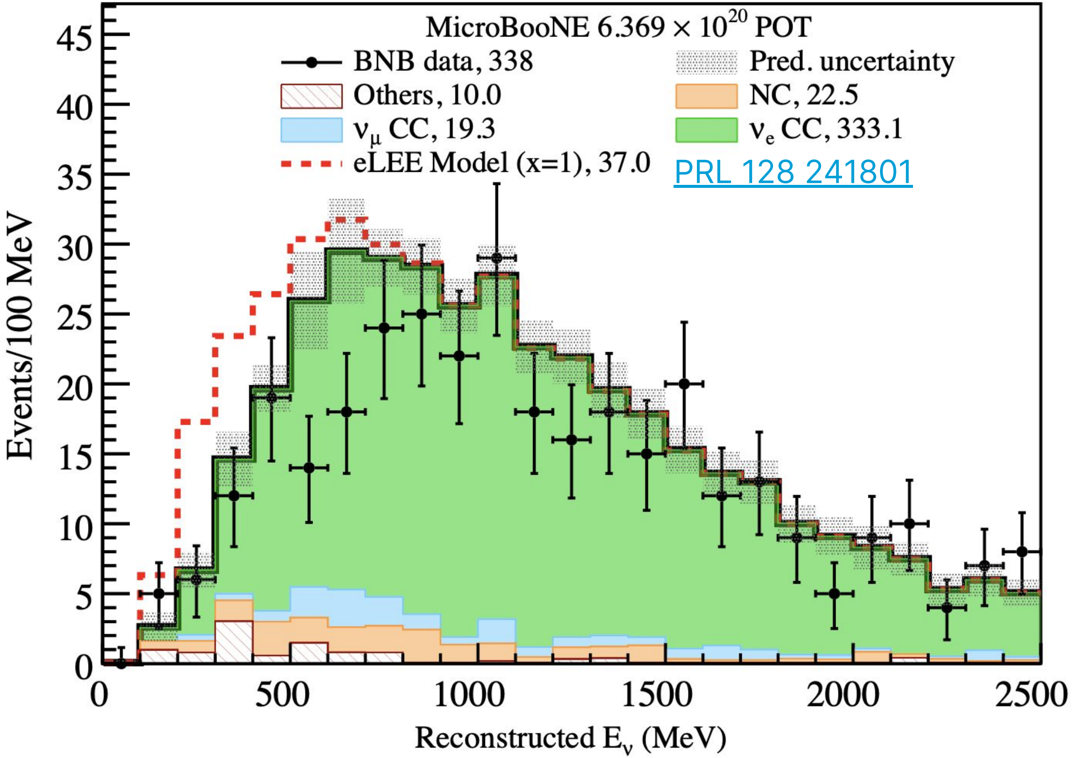


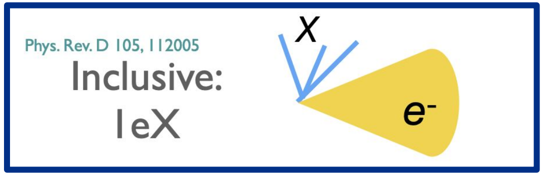
- MicroBooNE sees no evidence of MiniBooNE-like EM excess in channels sampled



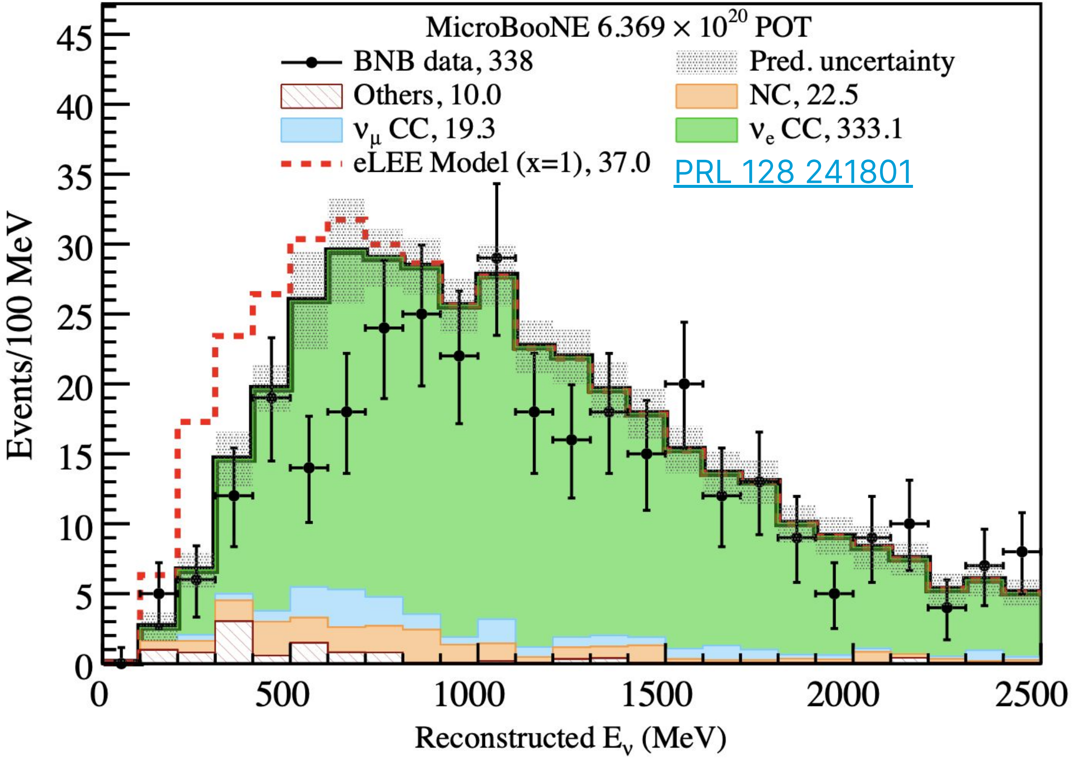
PRL 128 241801

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

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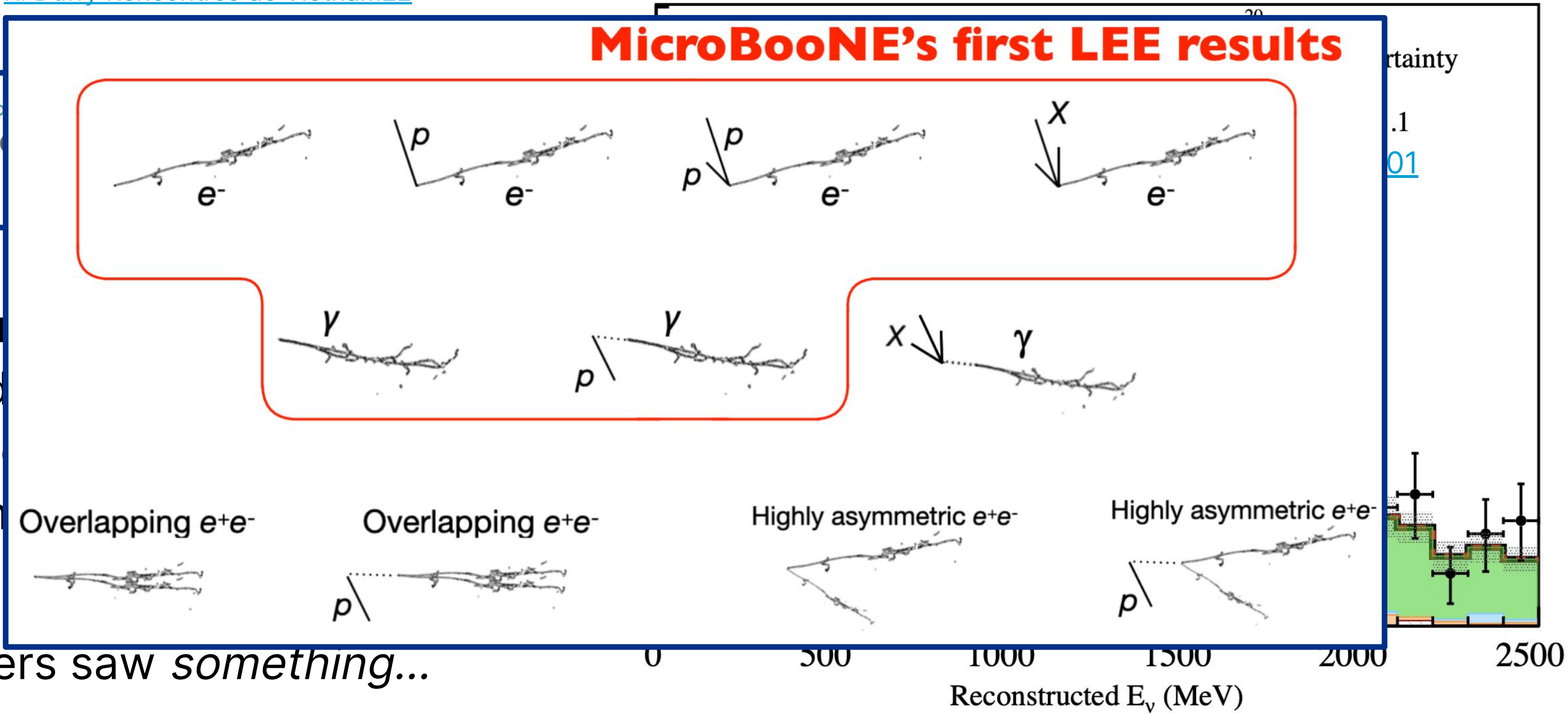
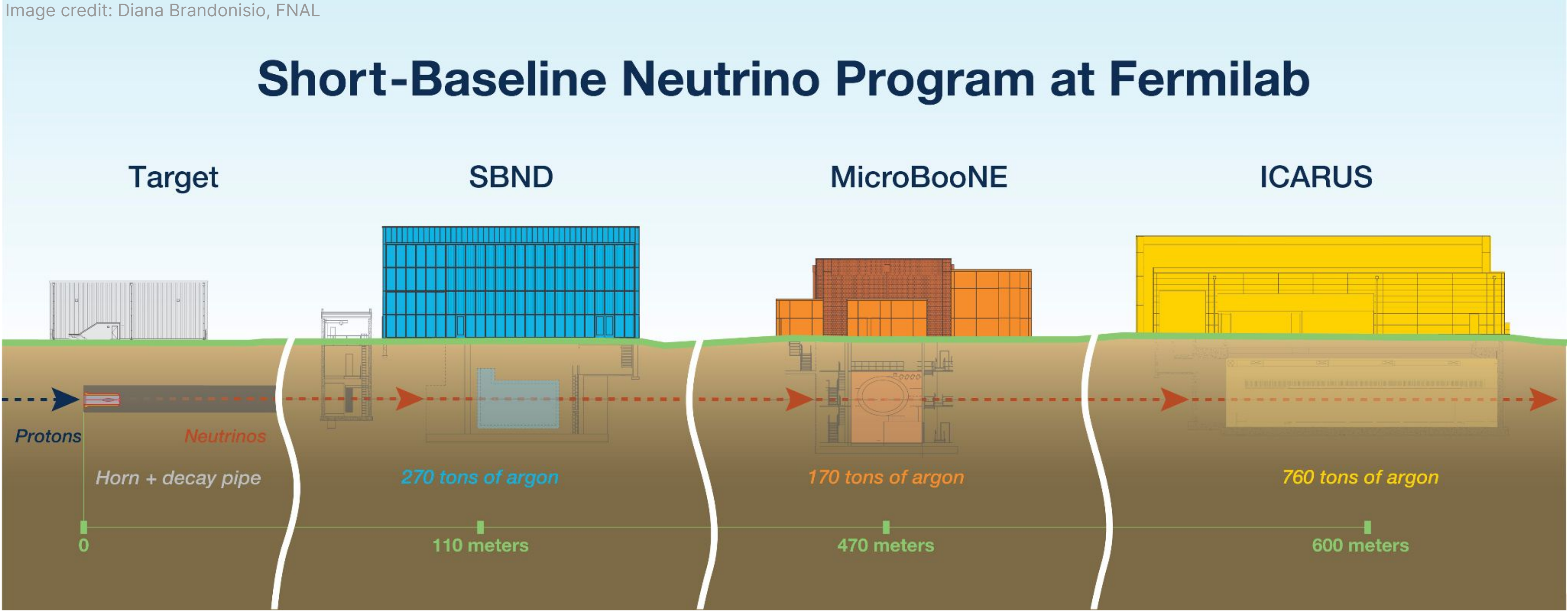


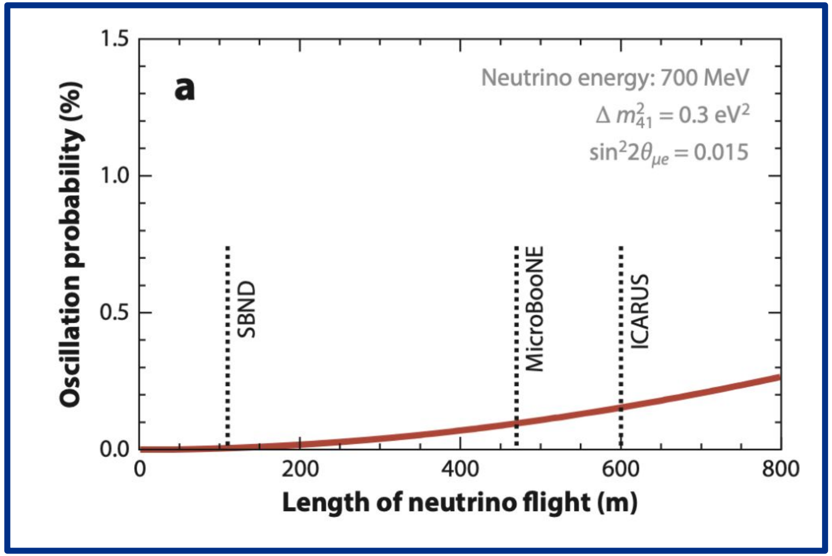
The Search Continues On SBN!



Short Baseline Neutrino

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

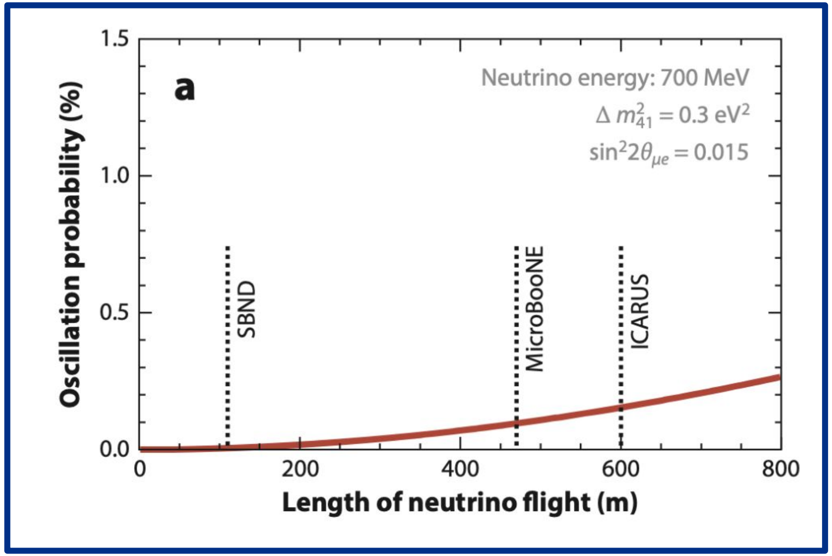
Ann.Rev.Nuc 69 p363-387 (2019)



Short Baseline Neutrino

Ann.Rev.Nuc 69 p363-387 (2019)

- 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!**



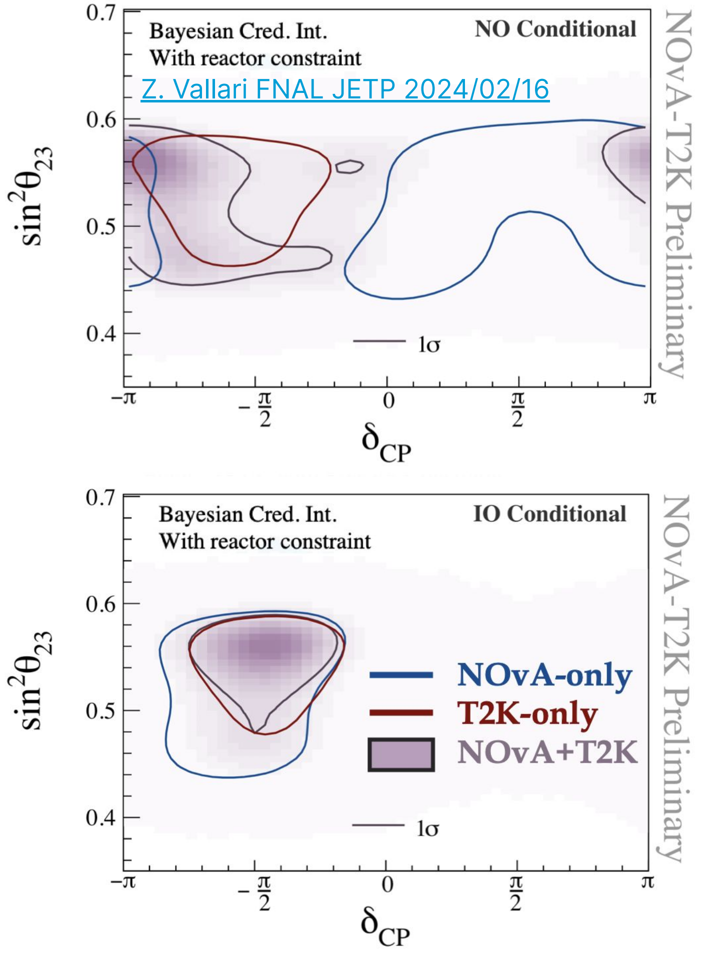
Parting Comments

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 ~1 ev^2 scale sterile neutrinos
- Neutrino beams
- Systematic uncertainty details:
  - Cross section uncertainties and constraint programmes
  - Neutrino flux predictions and uncertainties

Summary

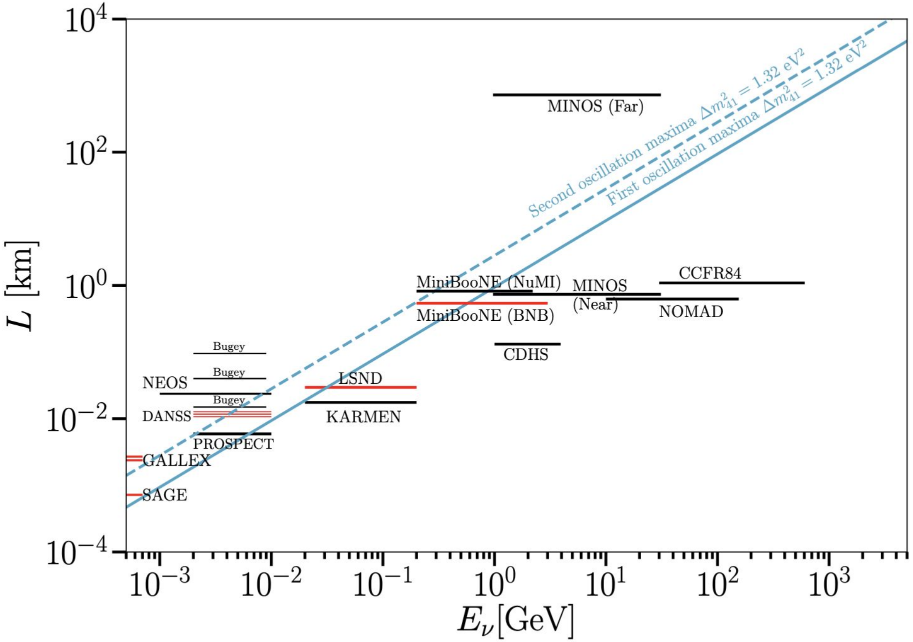
- Neutrino Oscillations are the only confirmed probe of BSM phenomenon:
  - Measured every parameter except δ_{CP}
    - Constraints starting to look exciting for CPV!
  - **Current Gen:** More precise measurements until end of decade. Lots still to learn.
- Next Generation:
  - DUNE/HK will do precision 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!

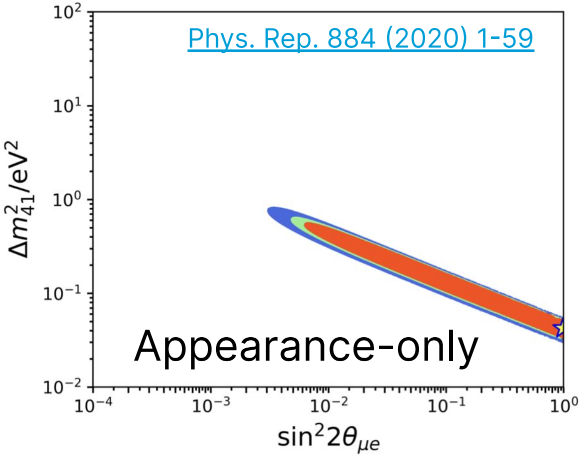


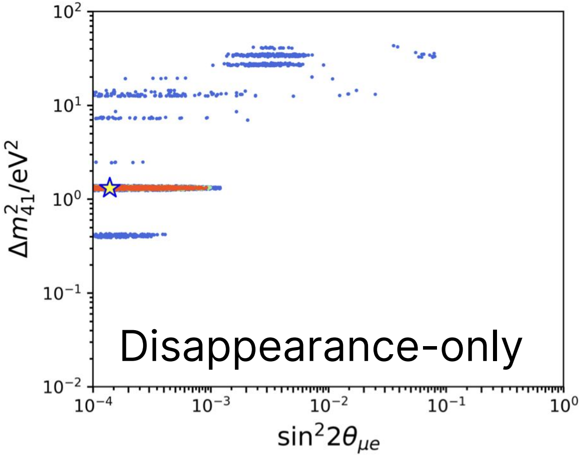
Backups

3+1 Tensions

- However, difficult to explain global data with a single additional ~1 ev^2 scale neutrino

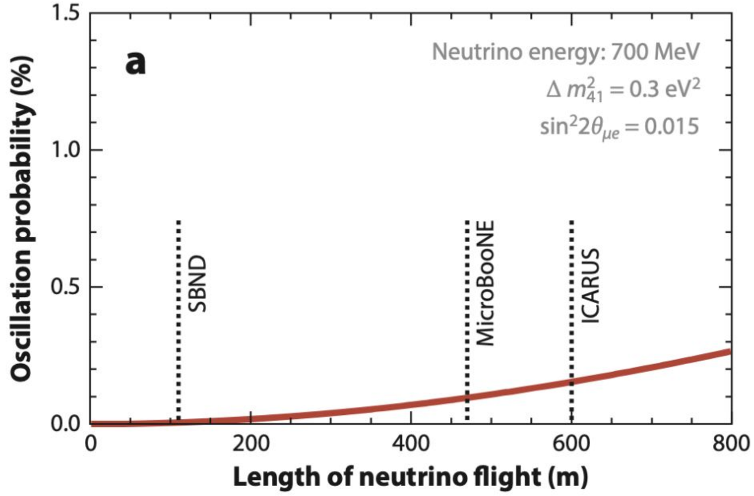






Short Baseline Neutrino

- 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!



SBND Predicted Event Rate

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

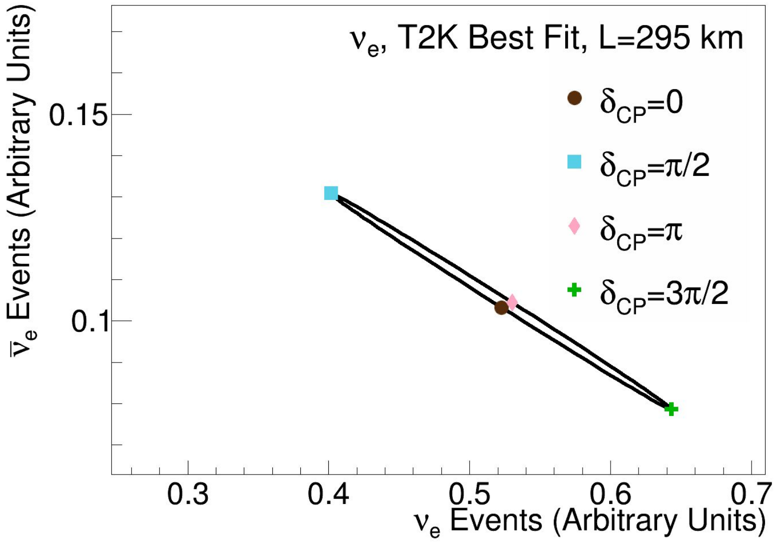
Exciting time ahead for SBL oscillation searches and Ar-target neutrino physics:

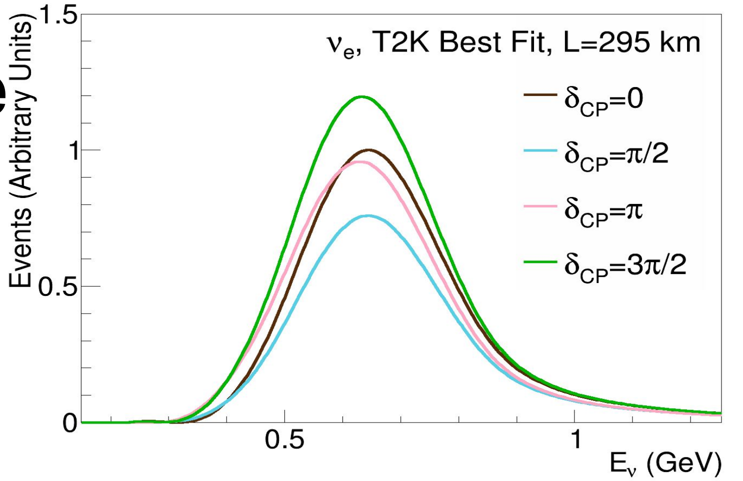
- Important for next-gen Ar-target LBL!

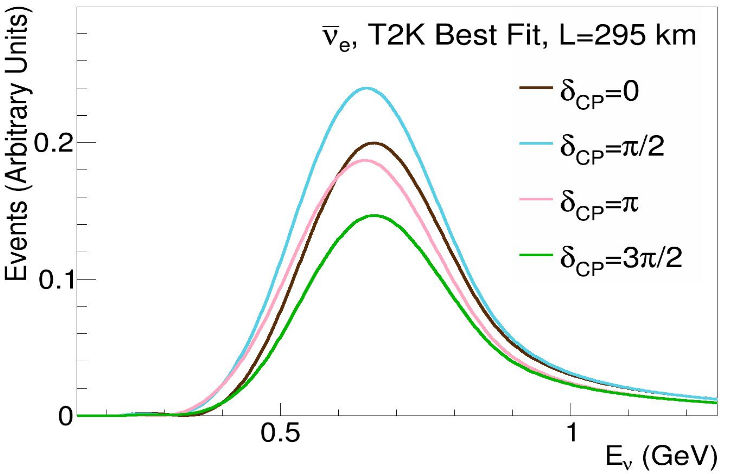
Osc. Details

Electron Neutrino Appearance

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







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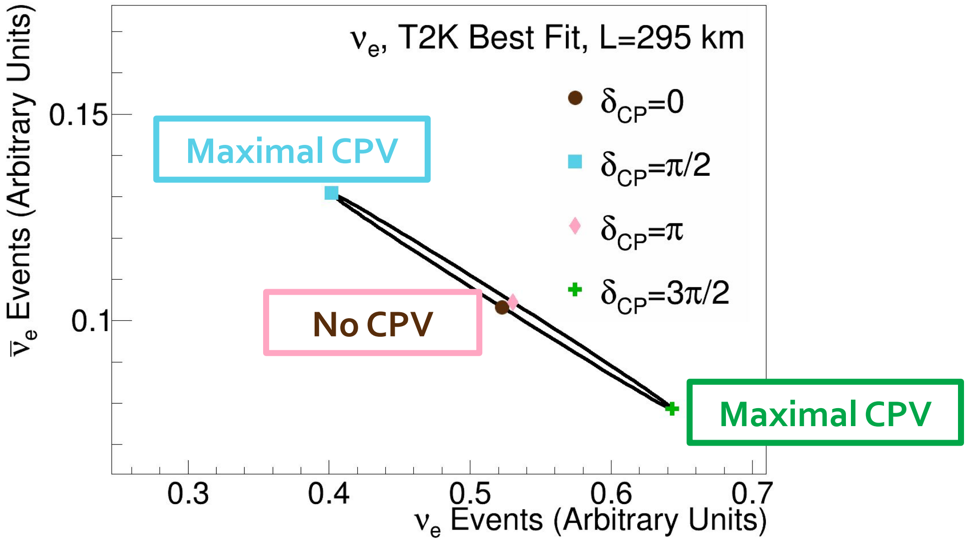
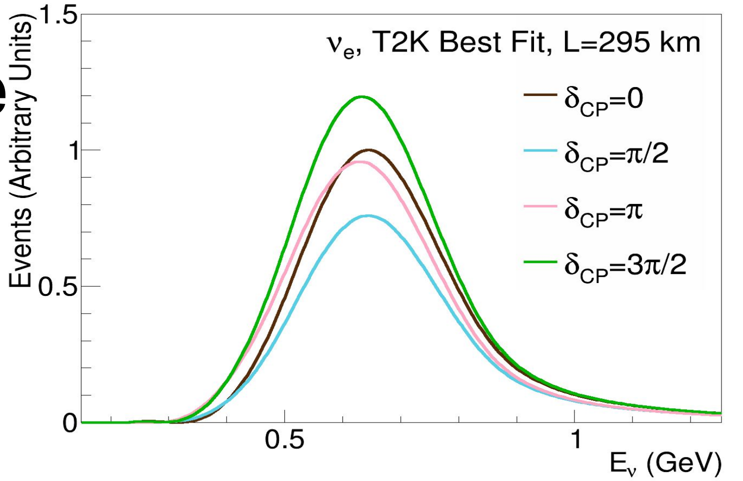
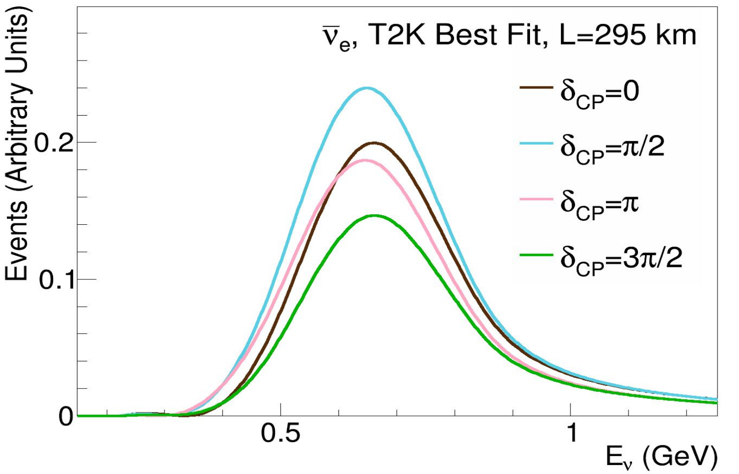
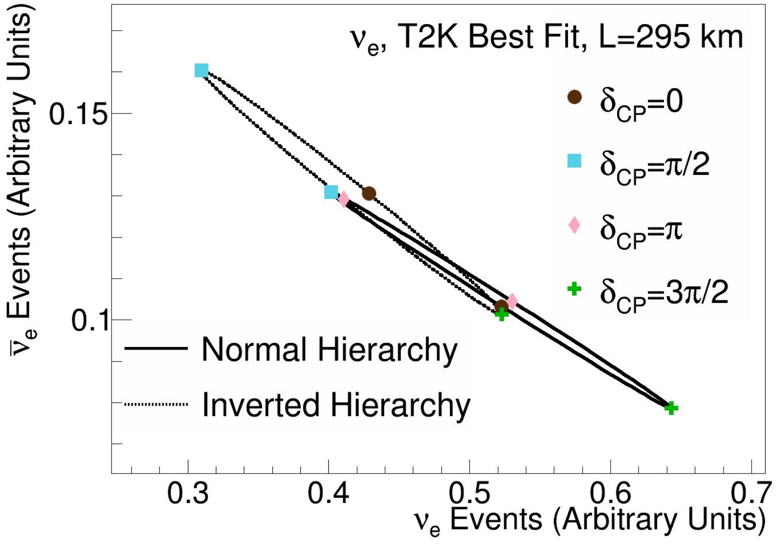


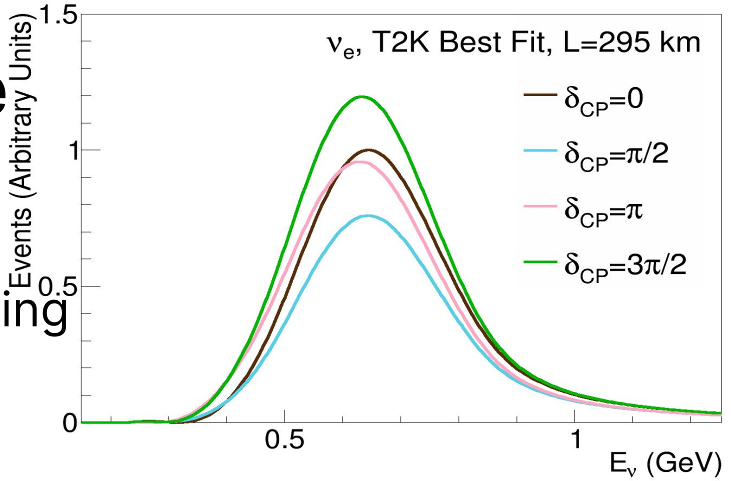


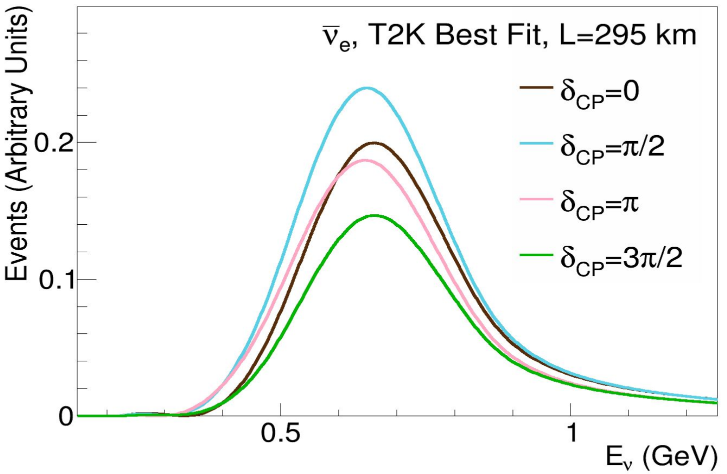


Electron Neutrino Appearance

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







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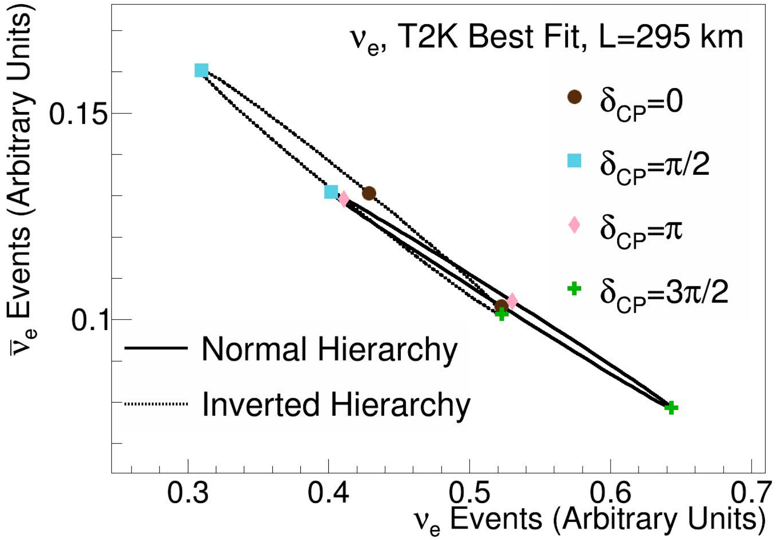
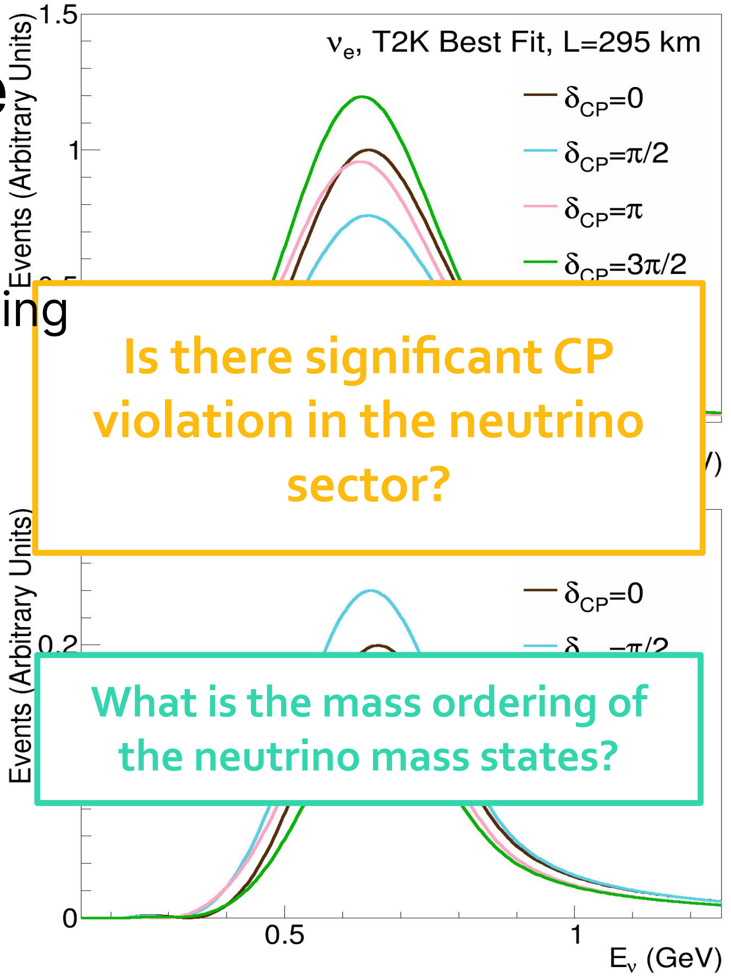




Is there significant CP violation in the neutrino sector?

What is the mass ordering of the neutrino mass states?

Measuring An Oscillation

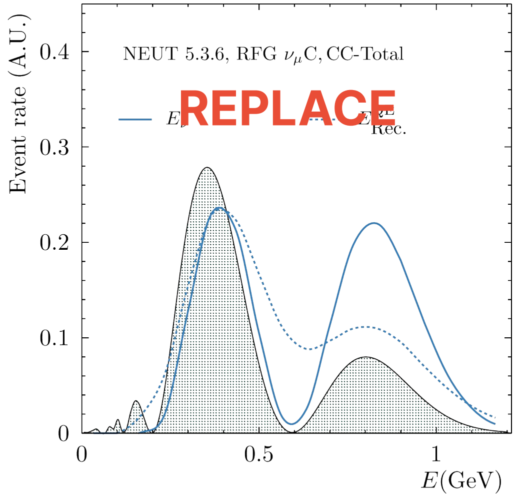
$$N_{\text{near}}(E_{\text{obs}}) = \int dE_\nu \, \Phi_{\text{near}}(E_\nu) \cdot \sigma(E_\nu) \cdot \mathbf{D}_{\text{near}}$$

Want to know

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

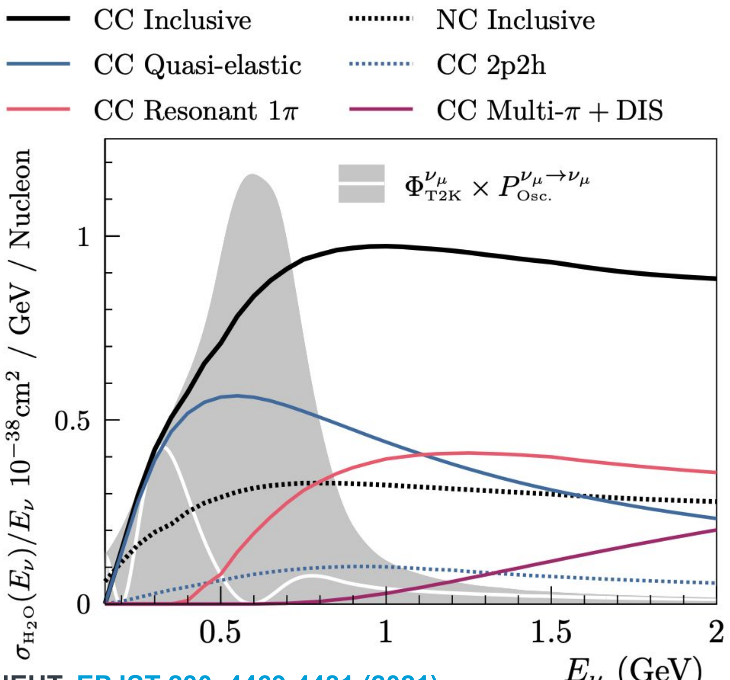
Observe

- 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 → limits on sensitivity
  - Design Near Detector to minimise Flux and Cross Section degeneracy
  - Limited by Detector capability

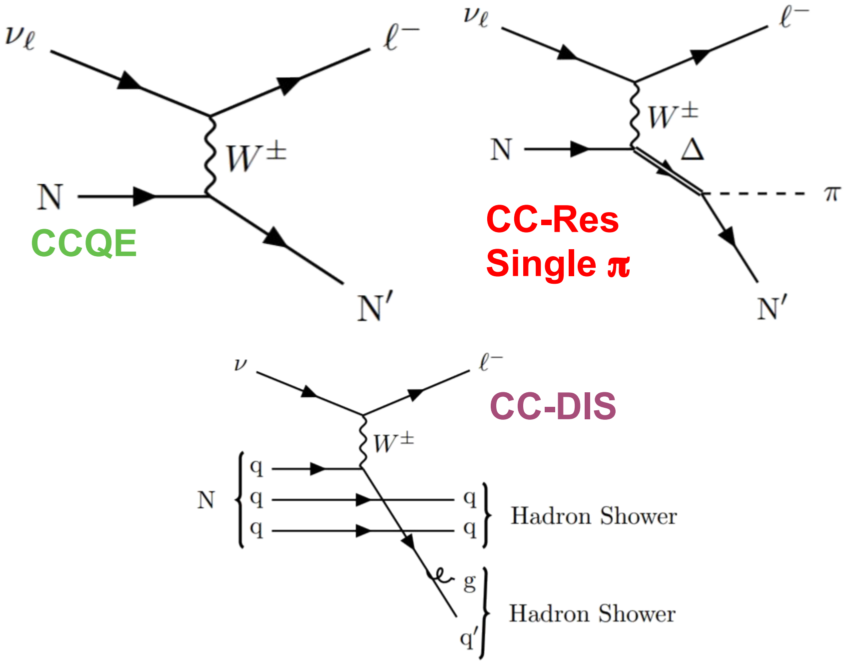


Interacting Neutrinos

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



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



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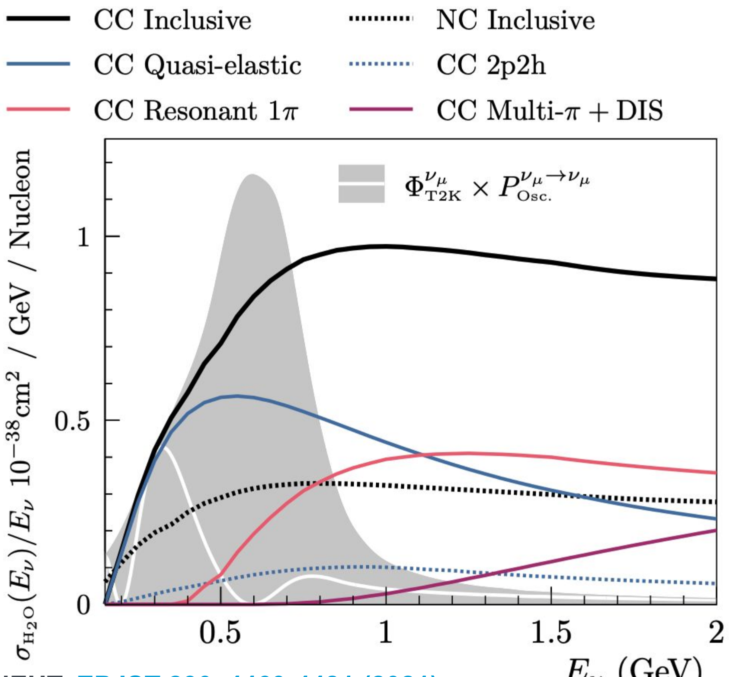
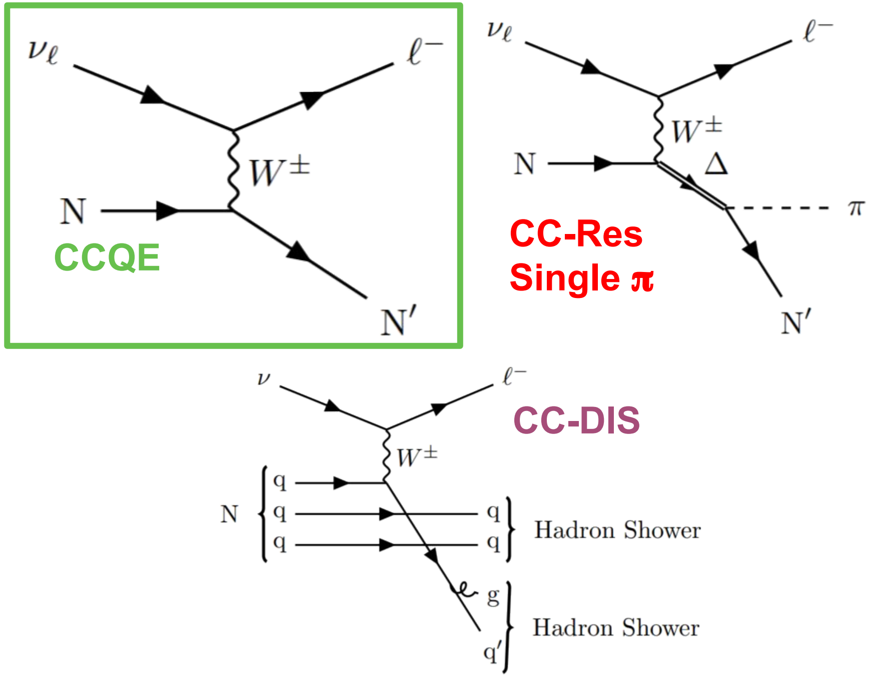
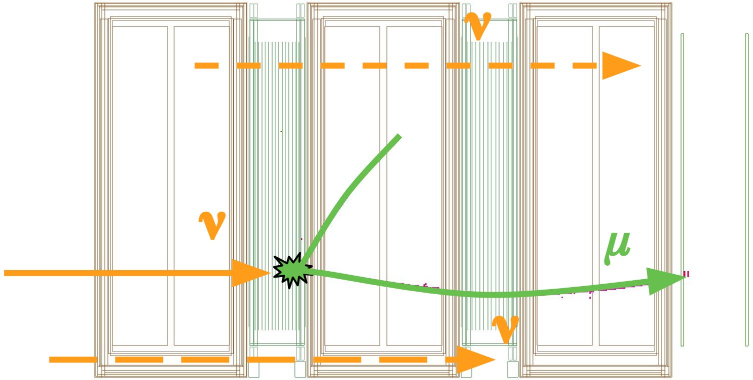


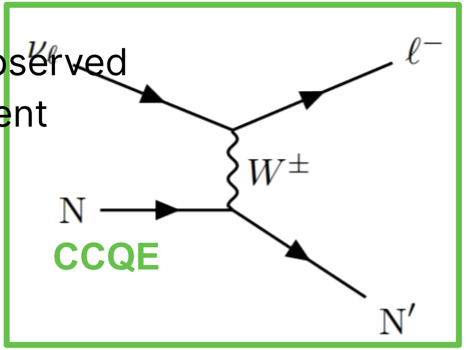
NEUT: EPJST 230, 4469-4481 (2021)



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





$$E_{\mathrm{rec}}^{\mathrm{QE}} = \frac{2M_{\mathrm{N}}E_\ell - M_\ell^2 + M_{\mathrm{N'}}^2 - M_{\mathrm{N}}^2}{2\left(M_{\mathrm{N}} - E_\ell + |\vec{p}_\ell|\cos(\theta_\ell)\right)}$$

Interacting Neutrinos

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

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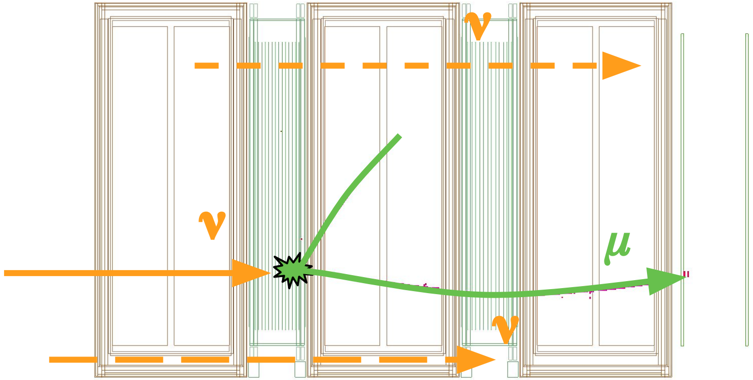
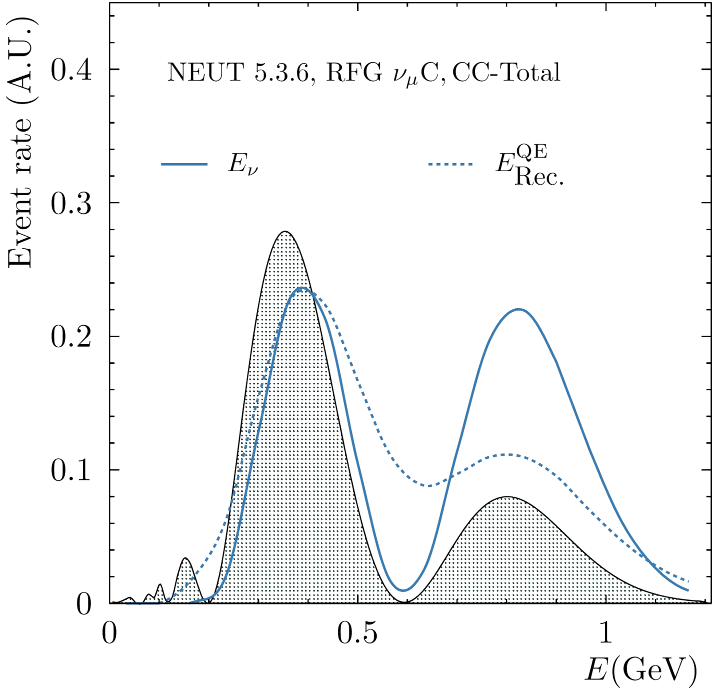
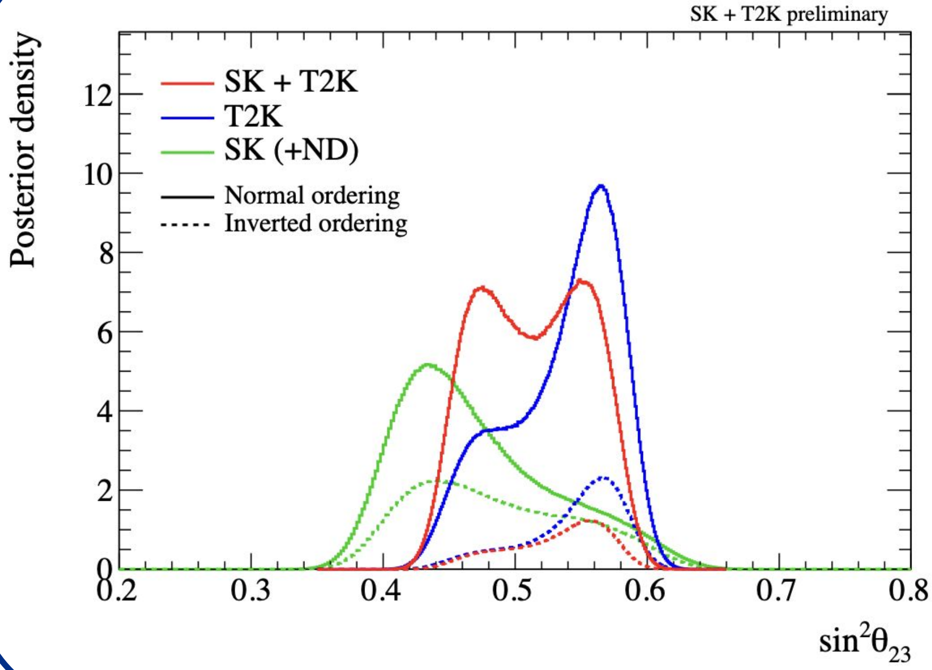




$$E^{\mathrm{QE}}_{\mathrm{rec}} = \frac{2M_{\mathrm{N}}E_\ell - M_\ell^2 + M_{\mathrm{N}'}^2 - M_{\mathrm{N}}^2}{2\left(M_{\mathrm{N}} - E_\ell + |\vec{p}_\ell|\cos\left(\theta_\ell\right)\right)}$$

T2K+SK Octant

L. Berns IPNS Seminar



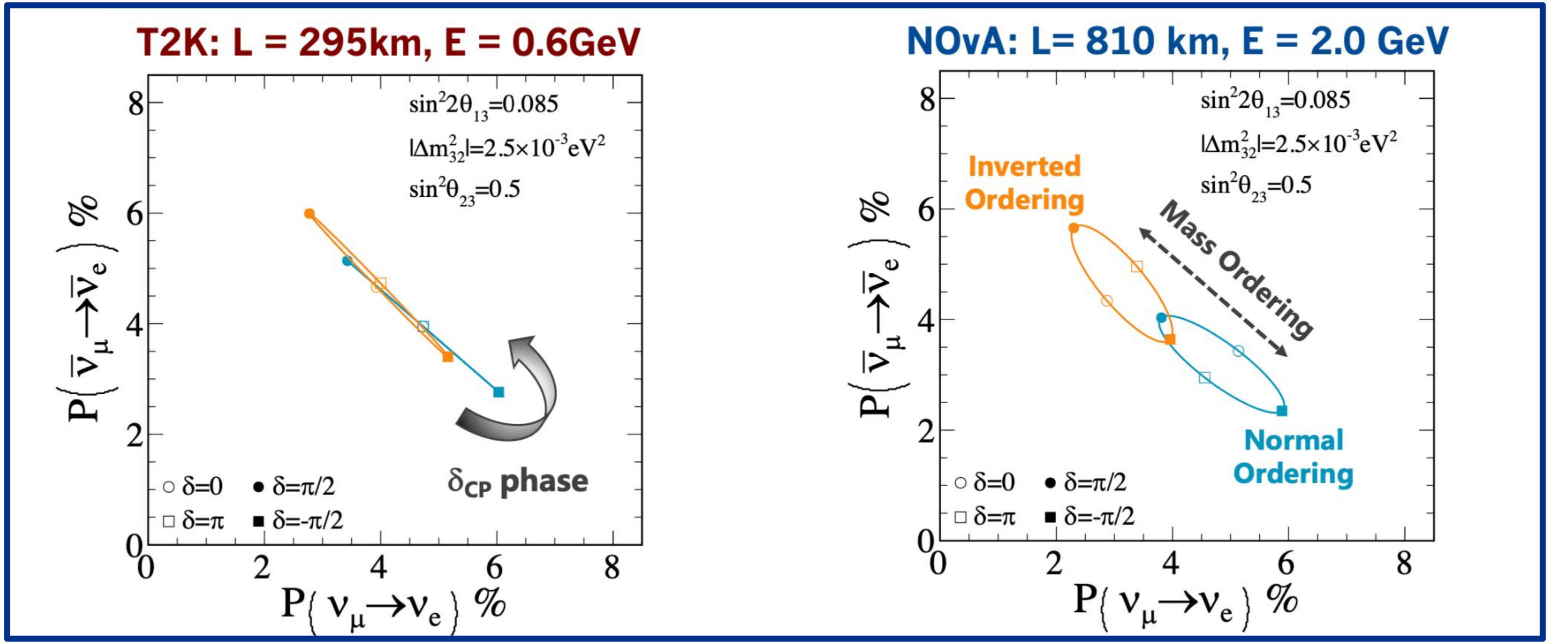
- Different octant preference by each experiment
- As a result, joint fit has no strong octant preference: $P(\text{upper}) = 0.61$

PRISM Details

NOvA Details

Appearance: BiProb

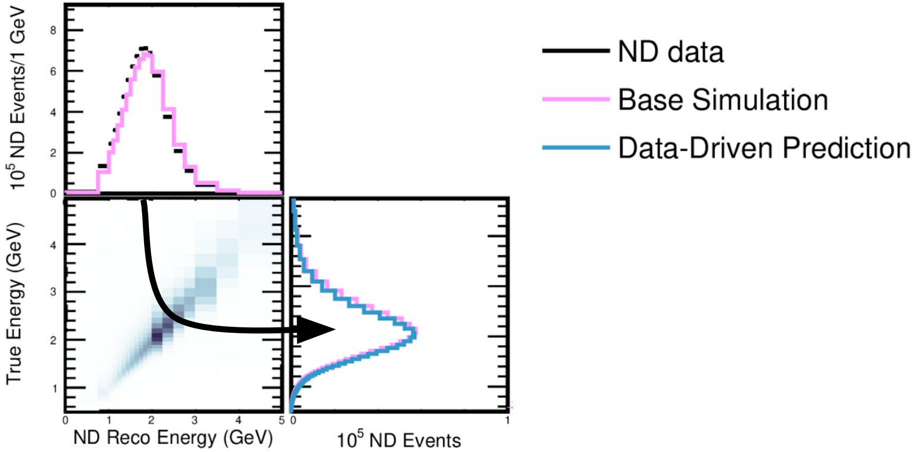
Z. Vallari FNAL JETP 2024/02/16



Near to Far Extrapolation

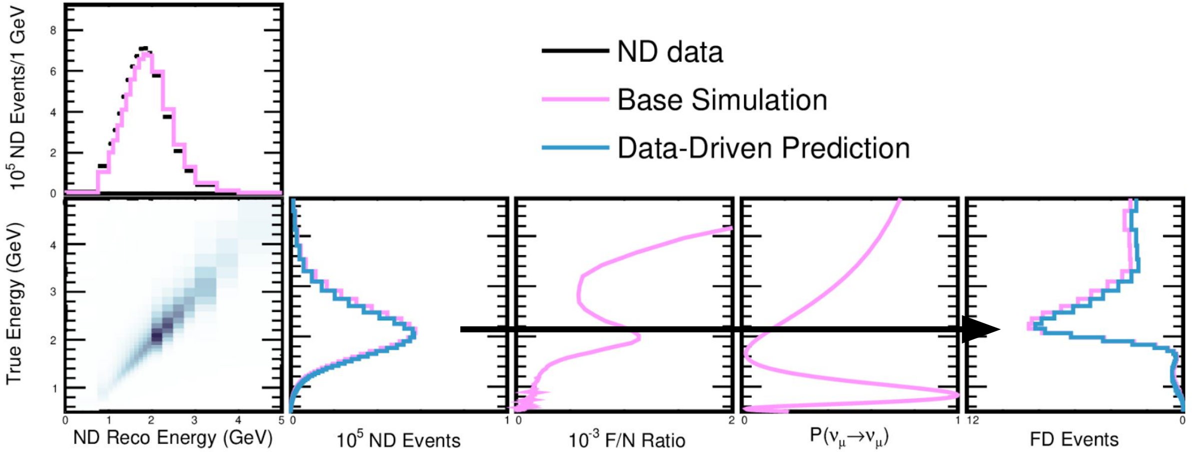
1. **Sample near detector events**

Near to Far Extrapolation



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

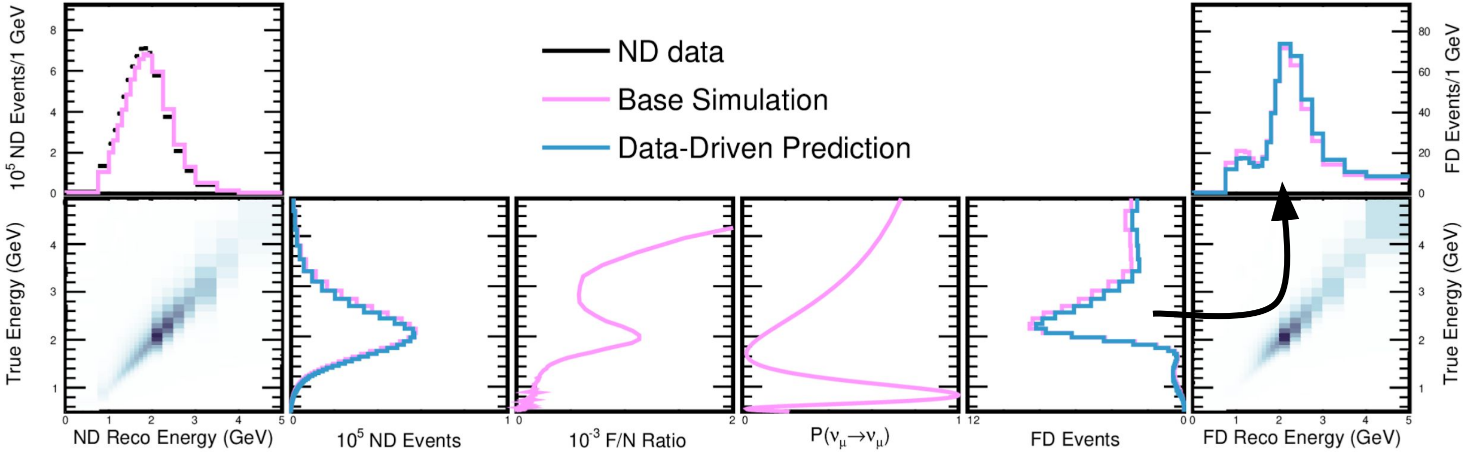
Near to Far Extrapolation



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

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

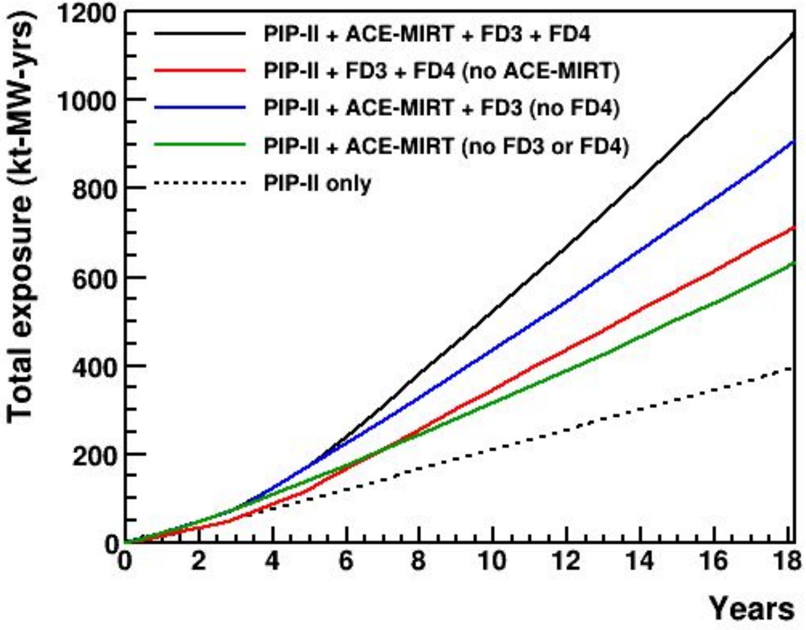
Near to Far Extrapolation



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.**

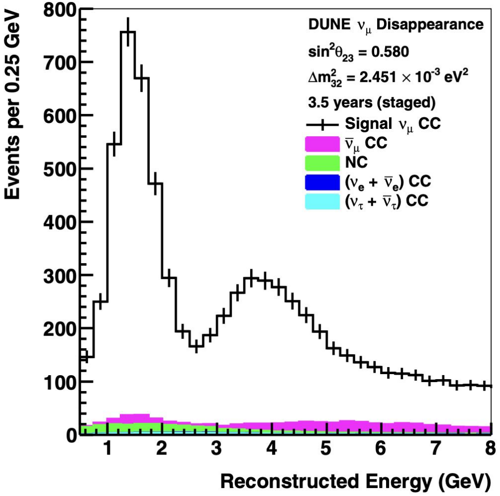
DUNE Details

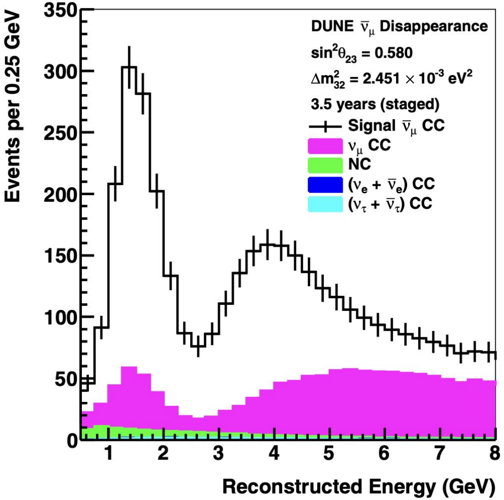
DUNE: Exposure/time

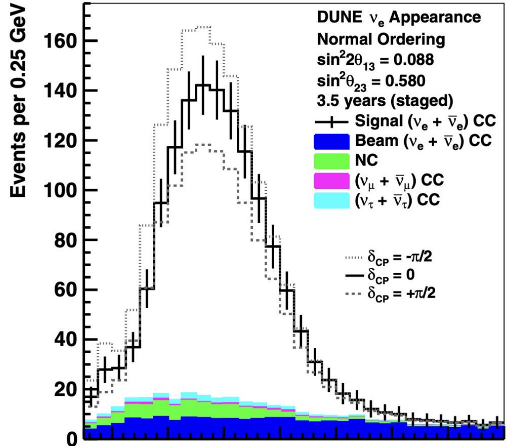


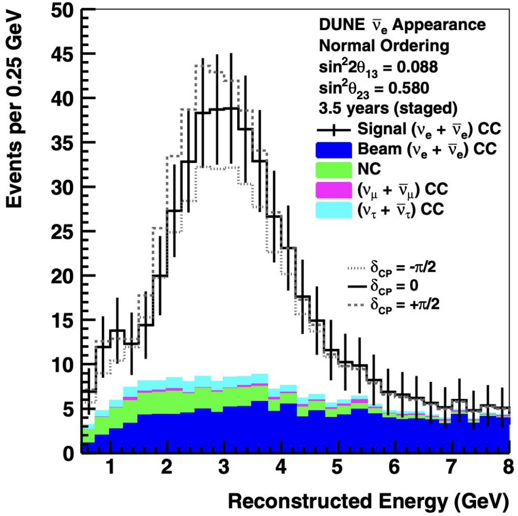
FD Event Samples

EPJC 80 (2020) 978







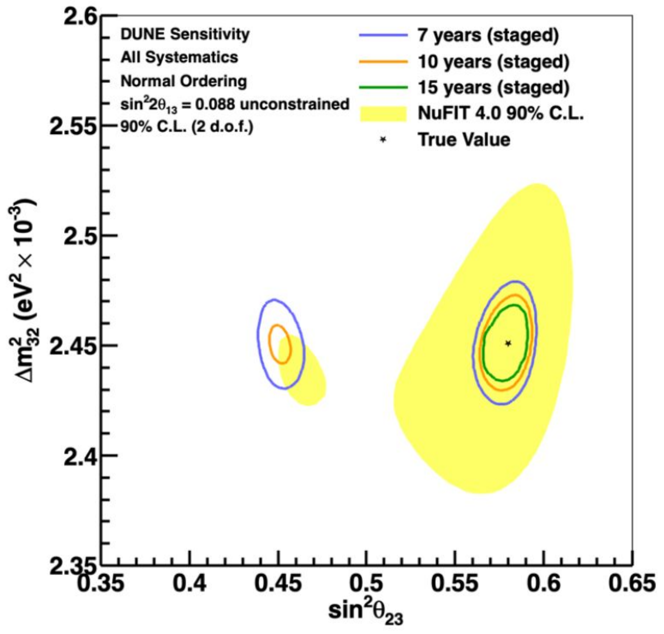


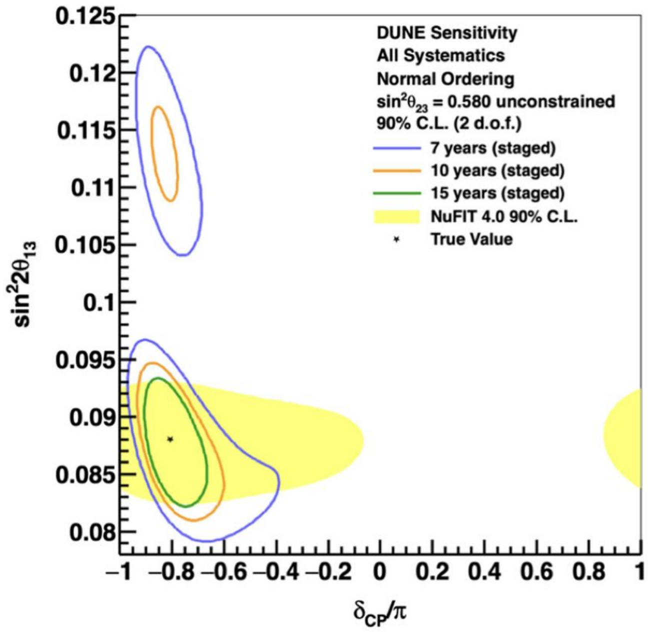
- 2019 Studies:
  - CC-Inclusive, mu- & e-like in nu and nubar mode
- Future:
  - Investigate impact of more granular event selection & projection Near and Far

World-Leading Sensitivities

EPJC 80 (2020) 978

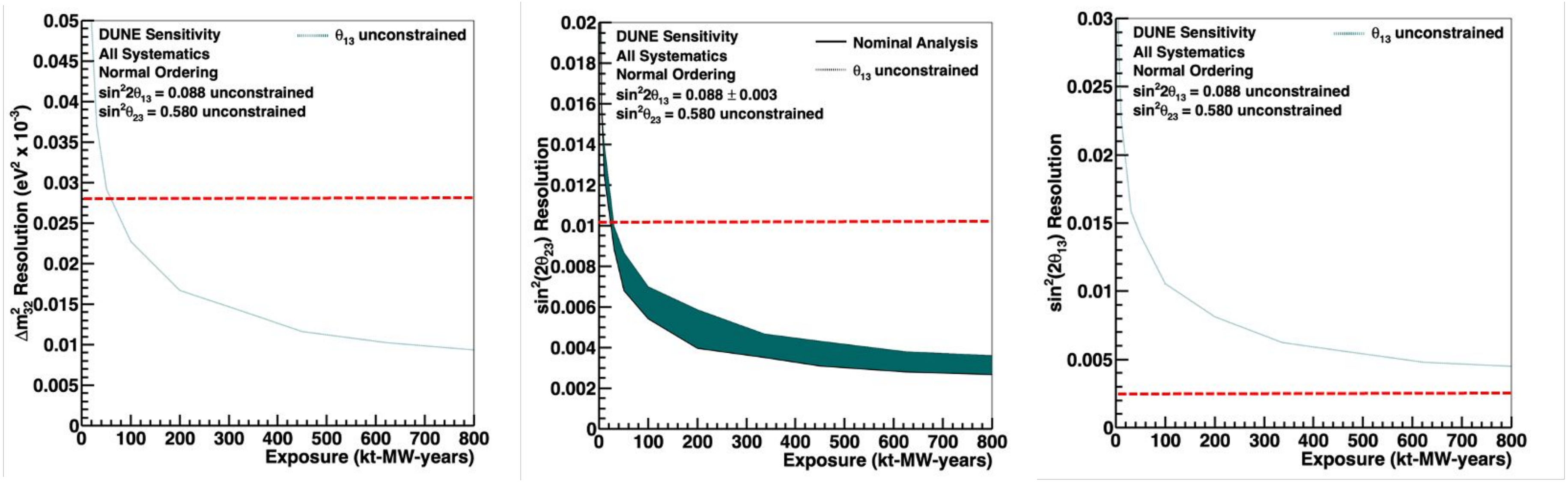
- Assume DUNE-PRISM has been used to minimize and account for significant deviations from interaction model predictions.





Precision Measurements

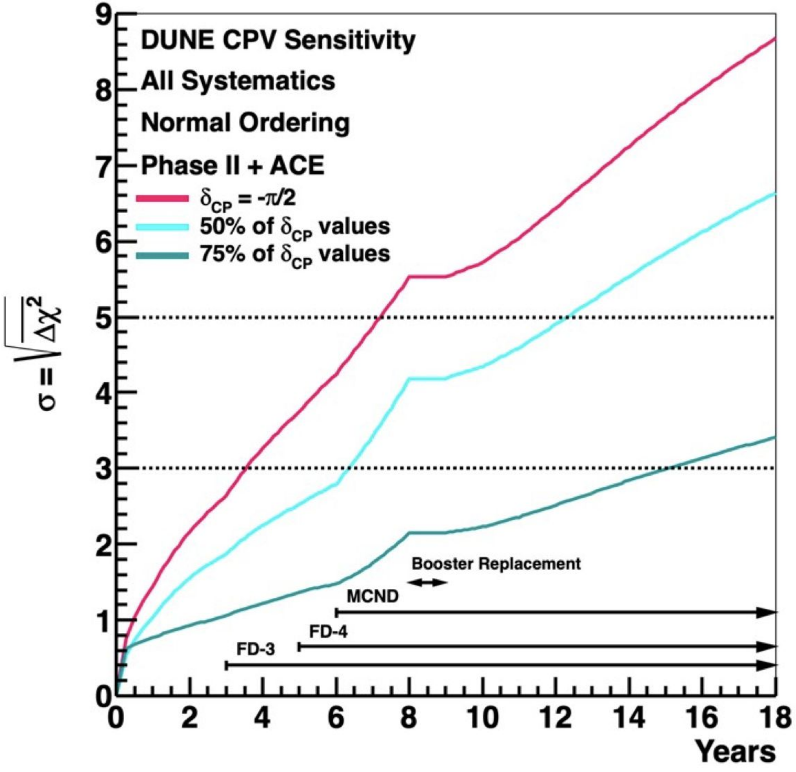
EPJC 80 (2020) 978

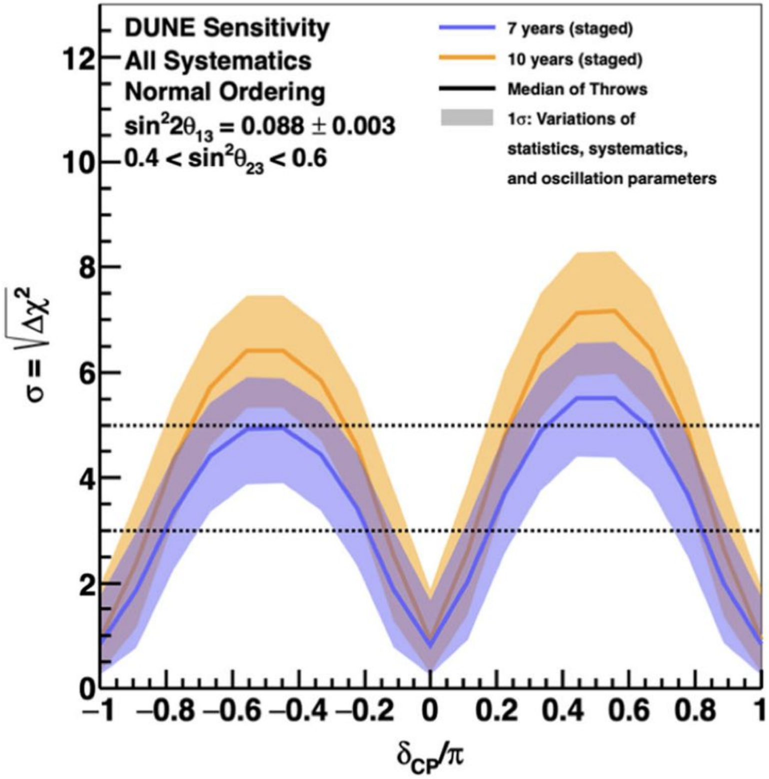


- Expected DUNE sensitivity v.s. current world-averages from NuFit 5.0 (JHEP 09 (2020) 178))
- Ultimate θ_{13} sensitivity approaches reactor constraint
- Precision Osc. measurements, especially joint w/ HK & JUNO, will stress-test PMNS: Different energies/detectors/PMNS matrix elements!

CPV Sensitivity

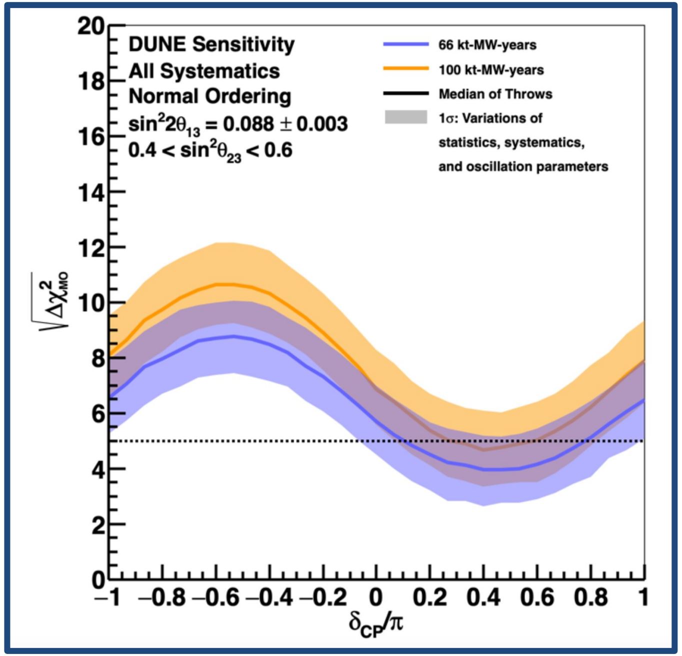
C. Marshall Wednesday Plenary

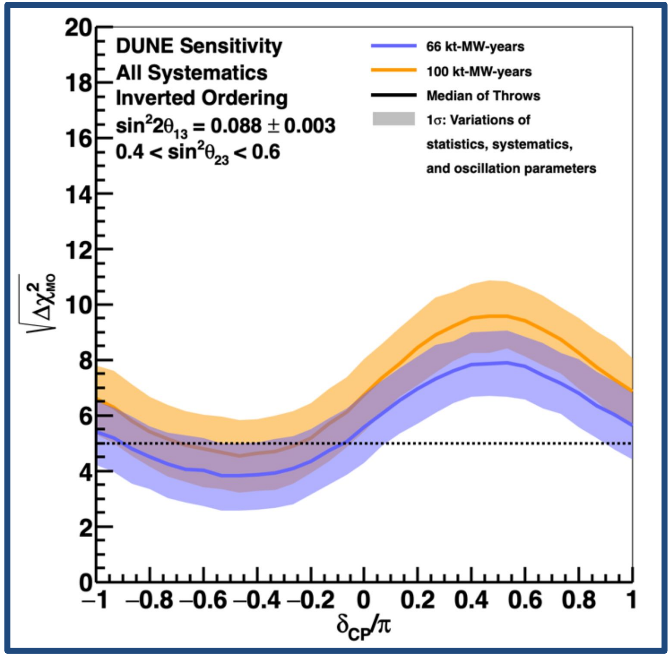




DUNE: Mass Ordering for Short Exposures

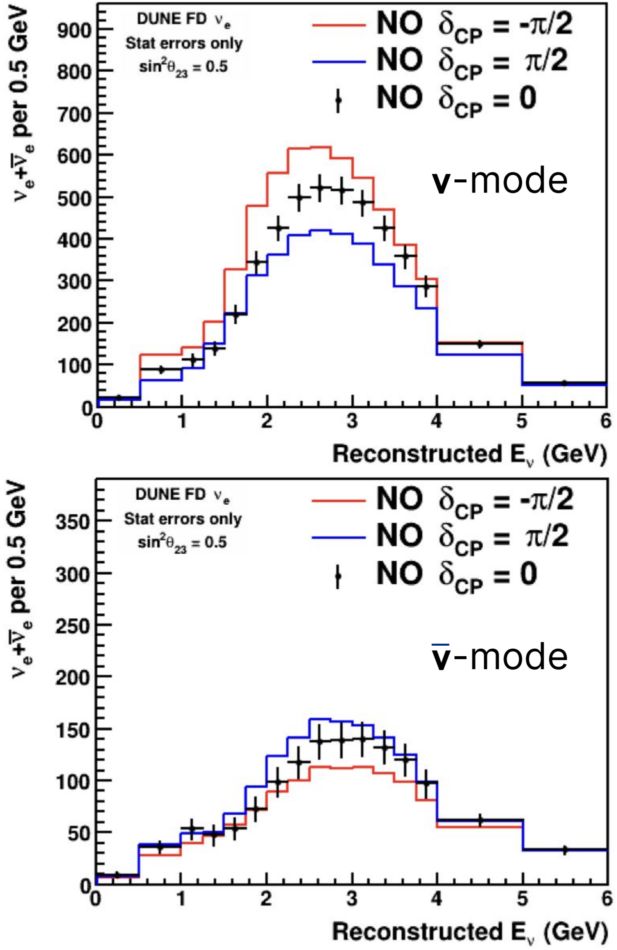
- Strong MO sensitivity, even with short exposures [O(3-5 years)]
  - P < 0.01 to prefer wrong ratio





PRD 105 (2022) 7, 072006

DUNE: δ_{CP} Resolution

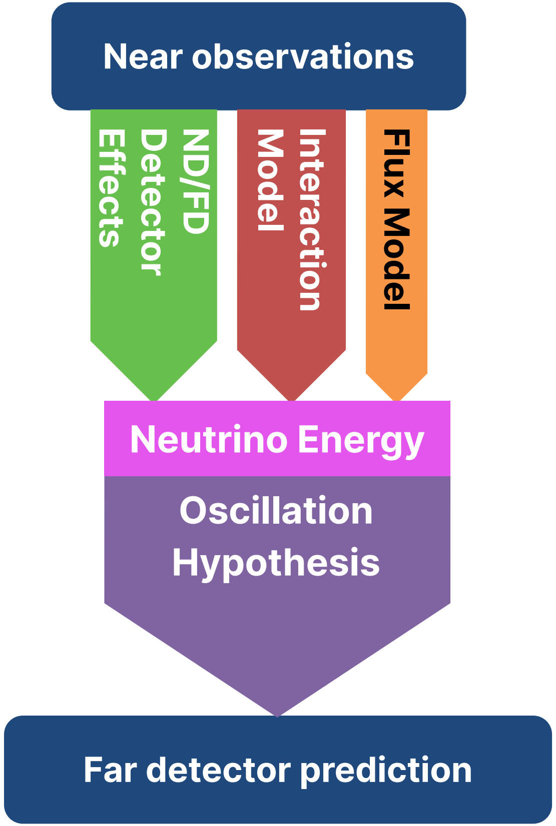


PRISM

Precision Reaction-Independent Spectrum Measurement

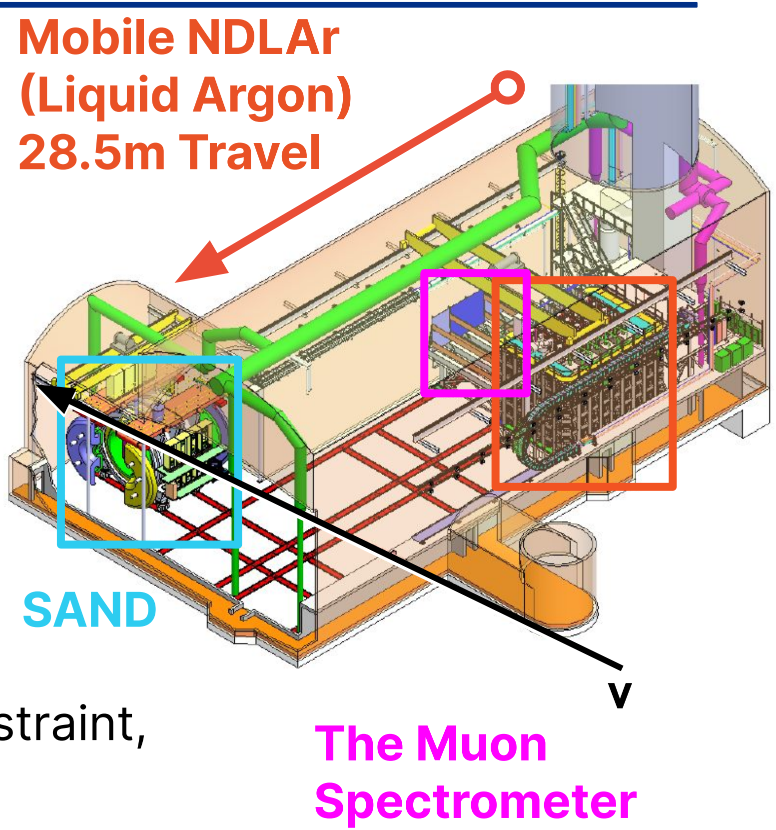
Oscillation Measurements in a Nutshell

- 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

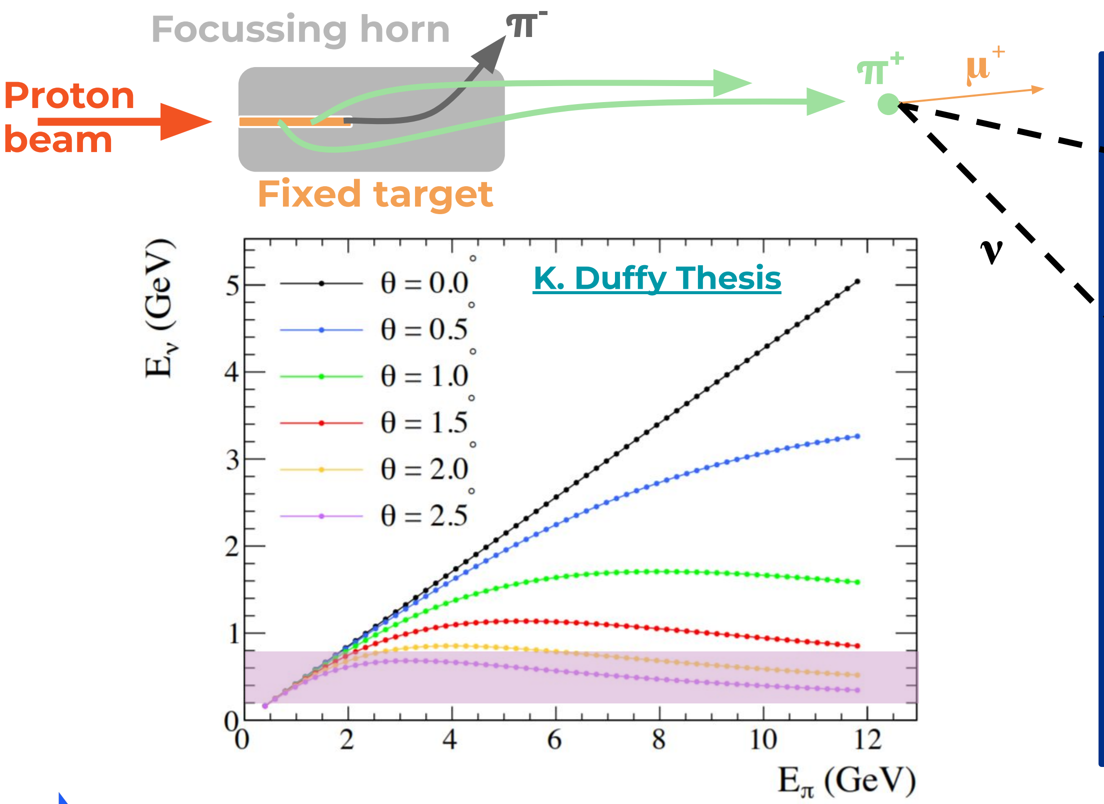


SAND: Beam monitoring and ^{12}C-target physics

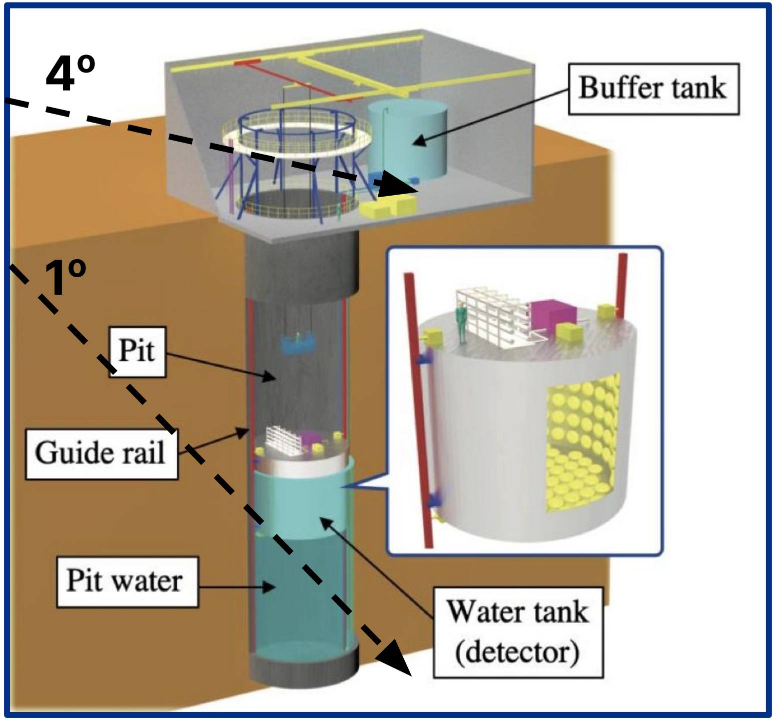
TMS: Muon momentum and sign-selection

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

Off Axis Neutrino Beams



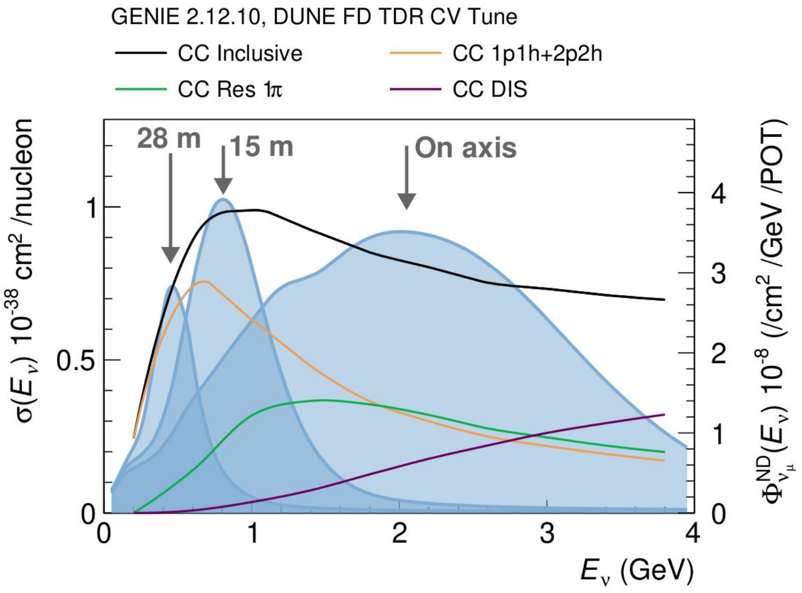
IWCD: Hyper-K Near Detector



C. Naseby NuFact23

DUNE-PRISM and IWCD

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



DUNE-PRISM and IWCD

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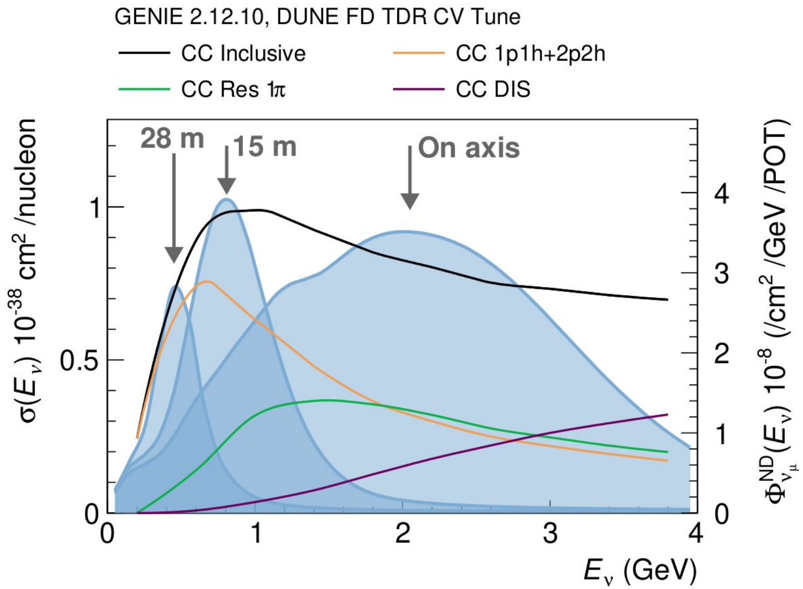
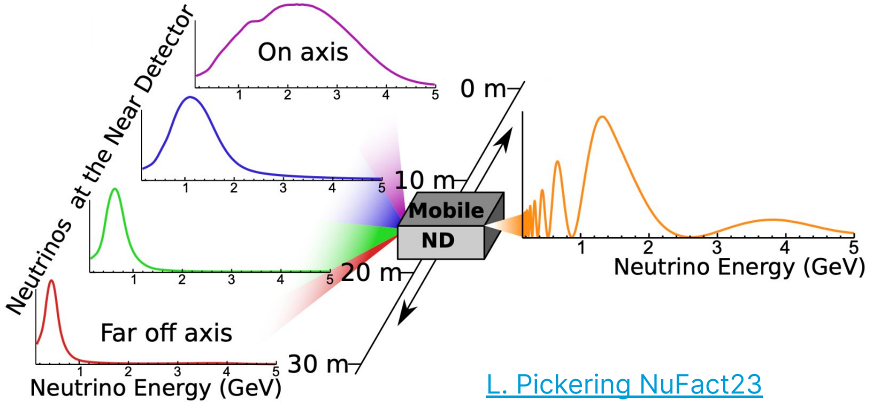


2) Synthesise measurement of an oscillated flux with the near detector

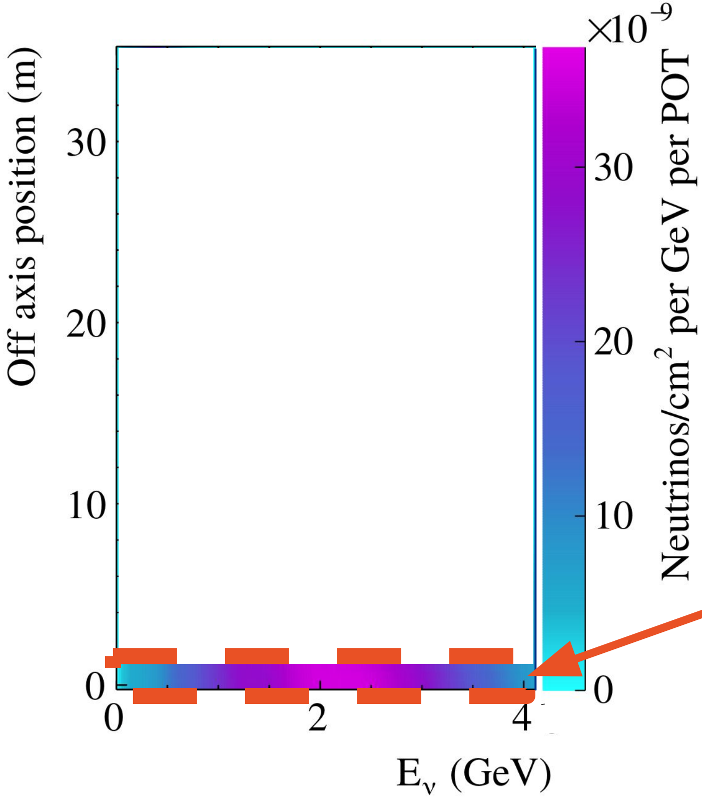
→ More direct extrapolation of near-detector observations

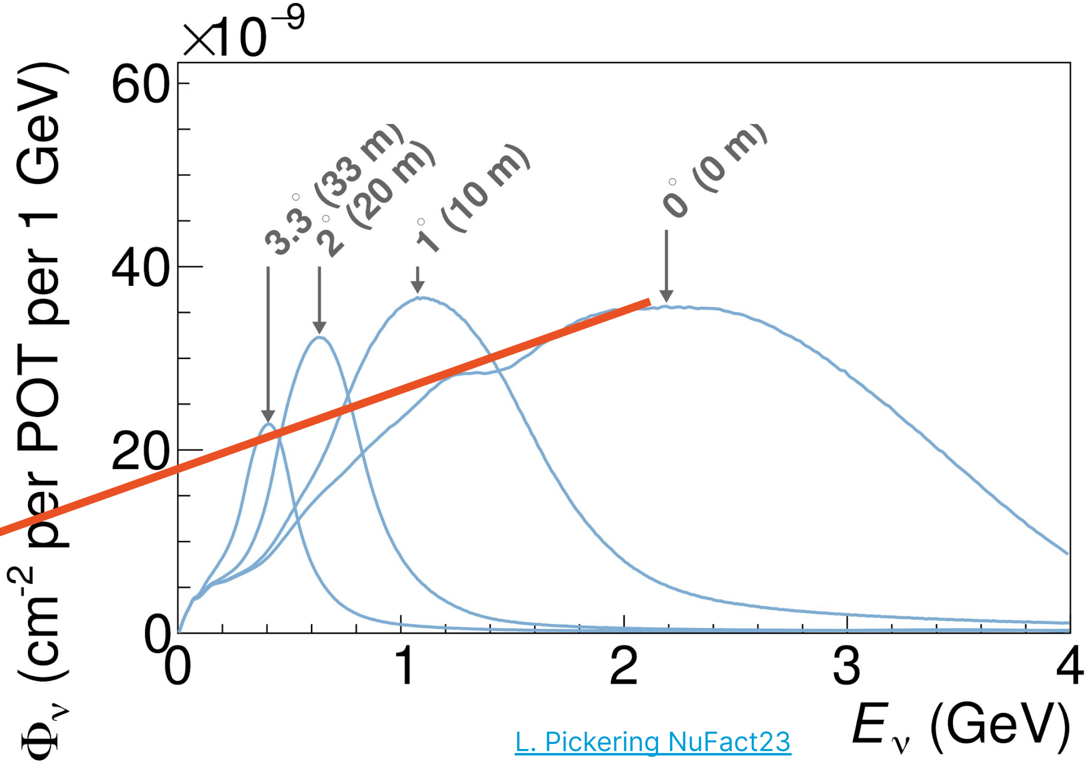
→ Reduce reliance on accuracy of interaction model predictions



L. Pickering NuFact23

Off Axis at the Near Detector





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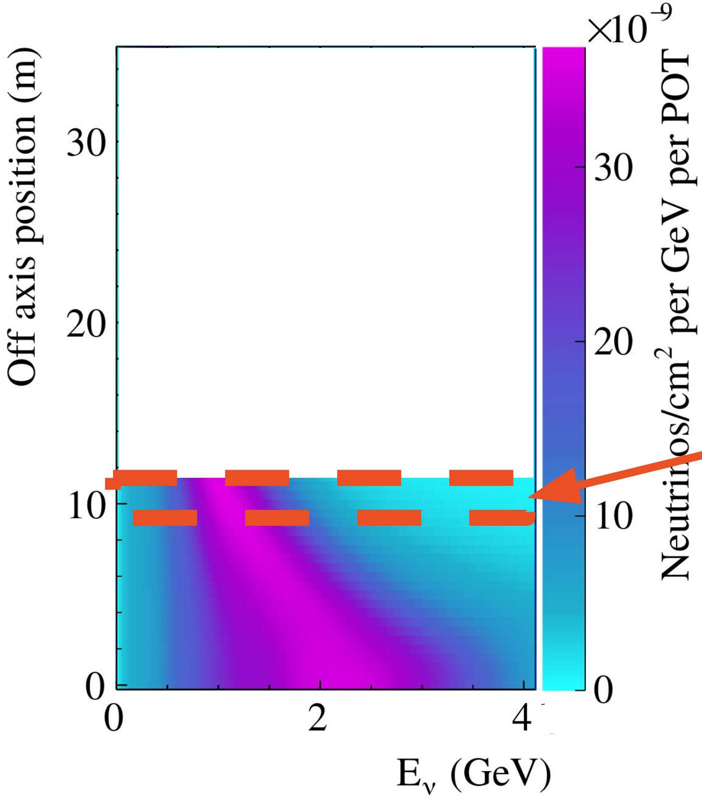

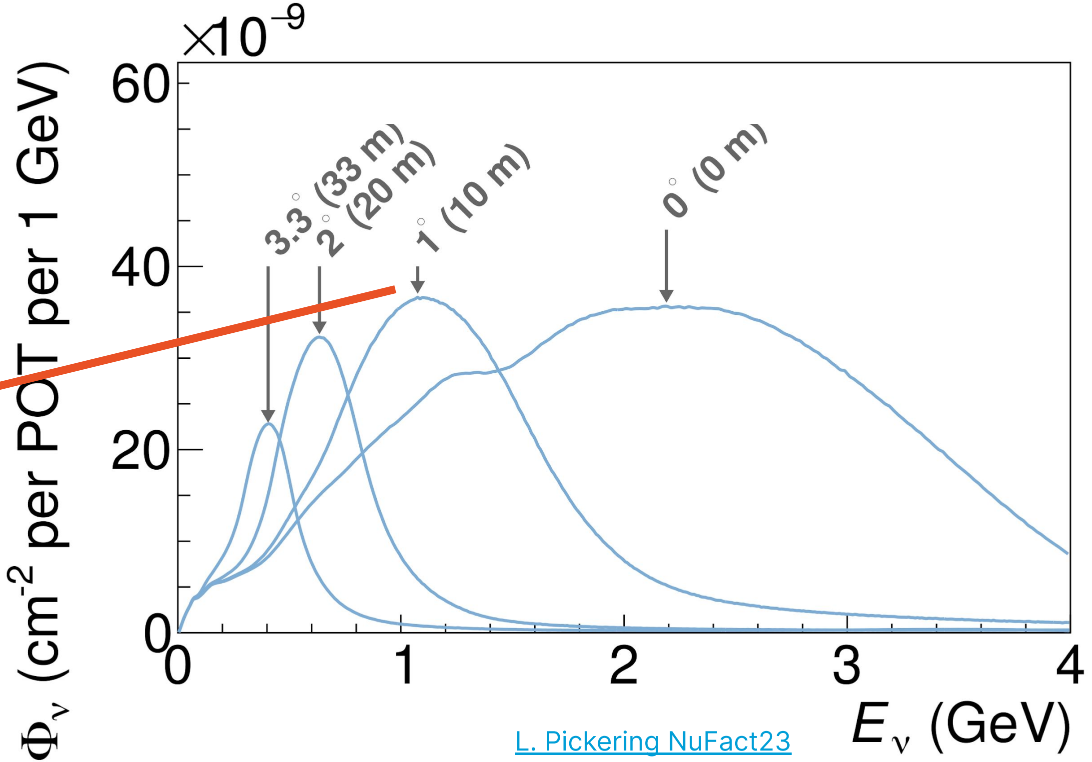

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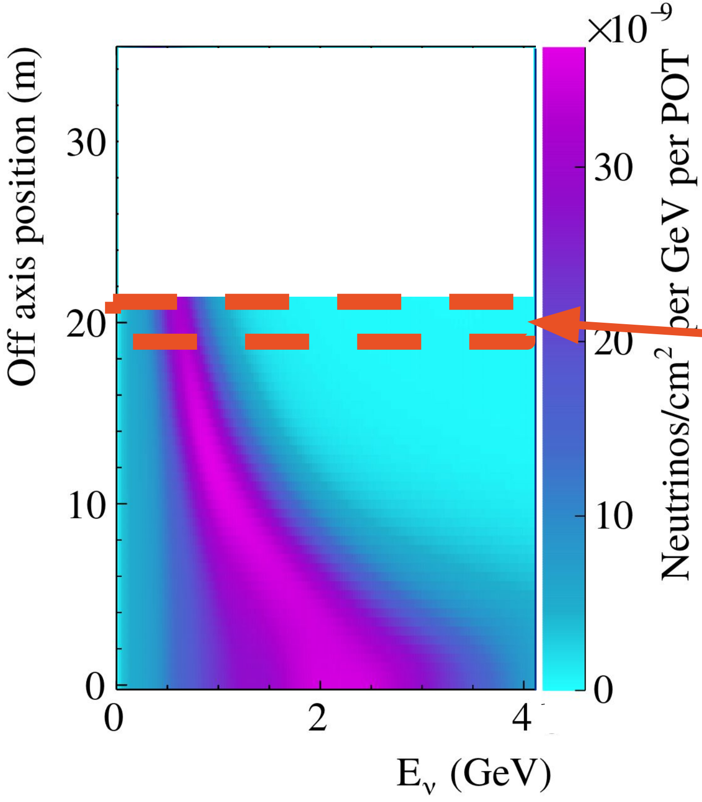

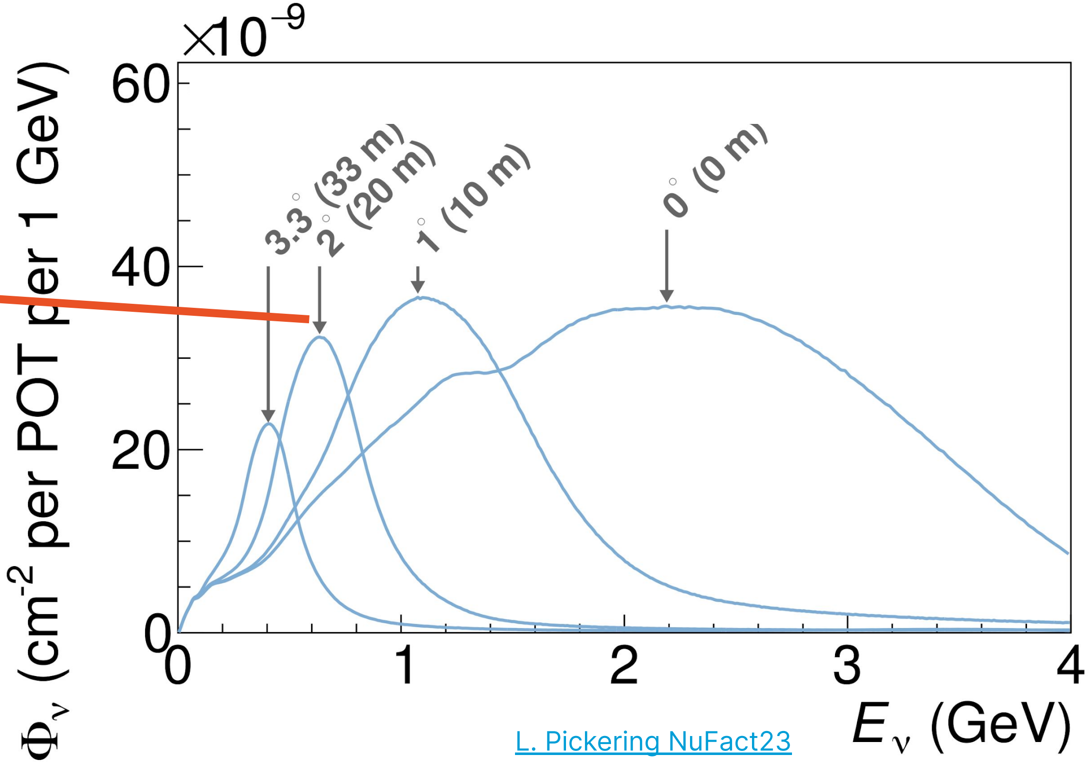

L. Pickering NuFact23

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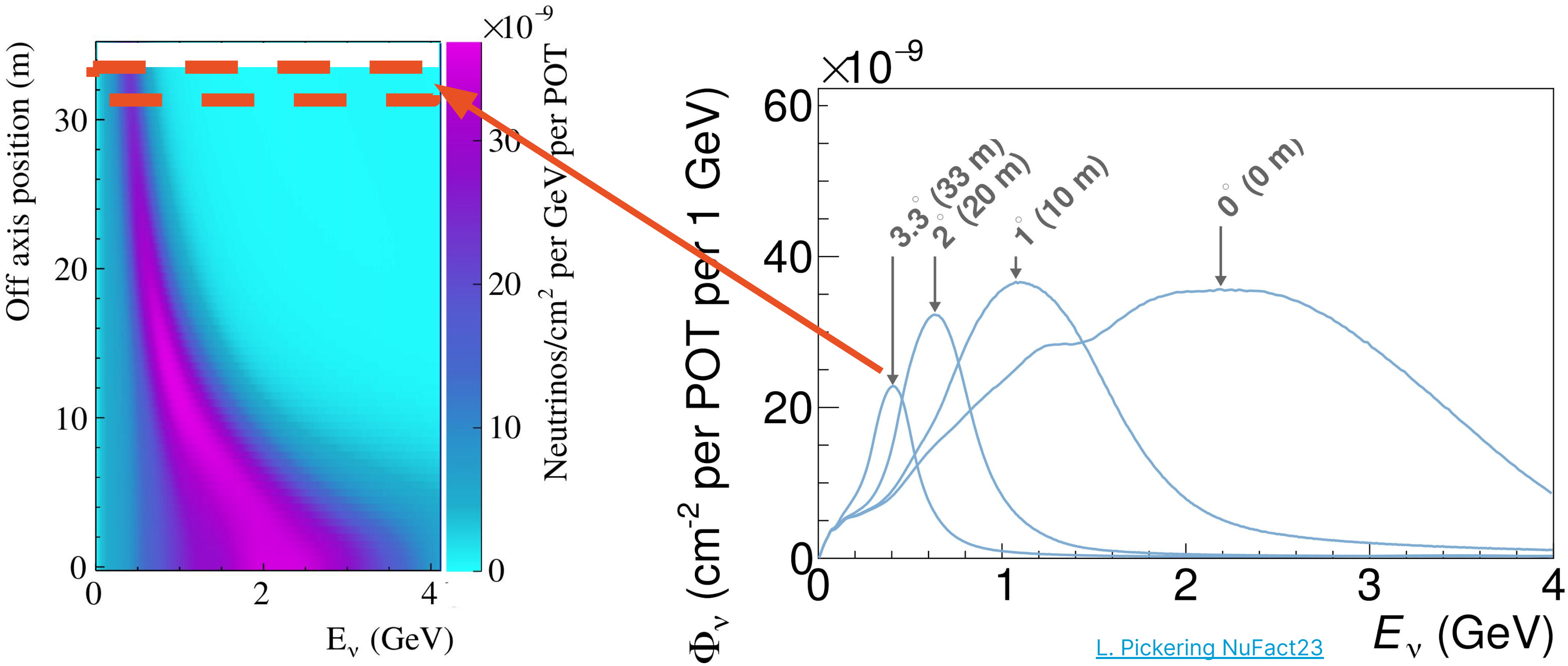
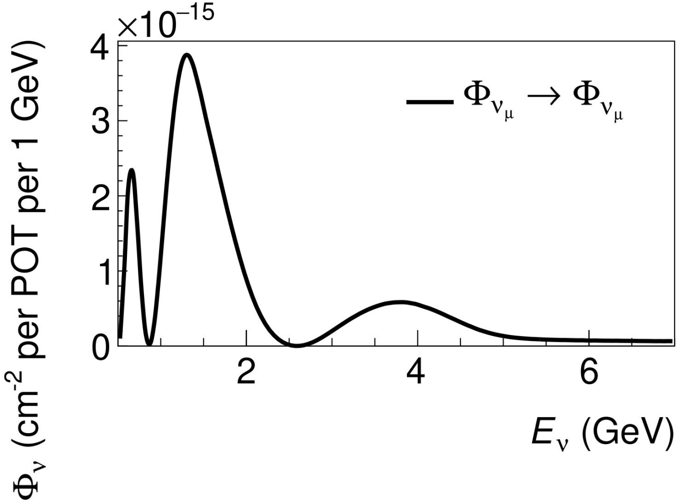


L. Pickering NuFact23

Predicting Oscillations with the Near Detector

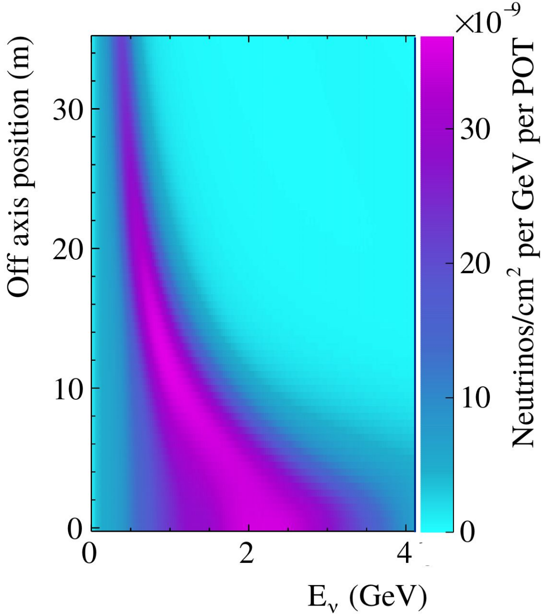
$$\Phi^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$



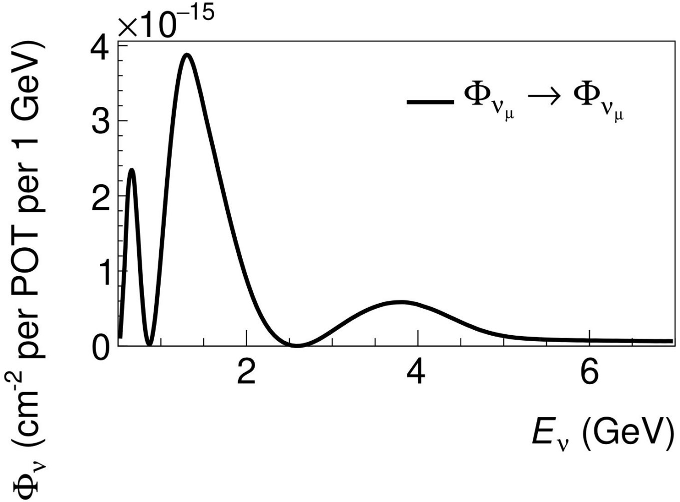
[L. Pickering NuFact23](#)

Predicting Oscillations with the Near Detector

$$\Phi^{\nu}_{\mathrm{Near}}$$



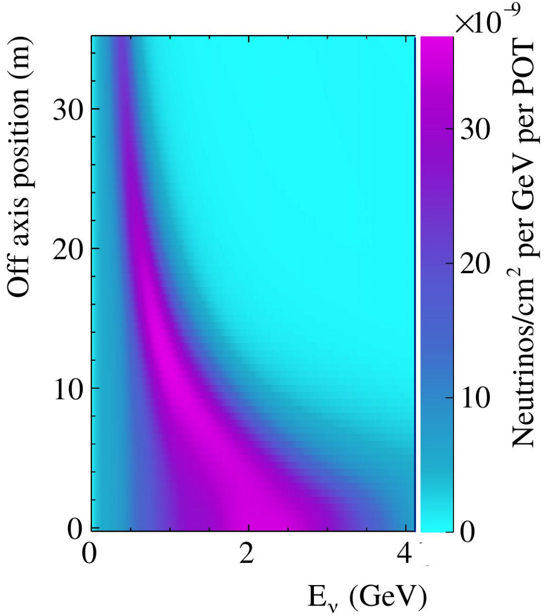
$$\Phi^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$

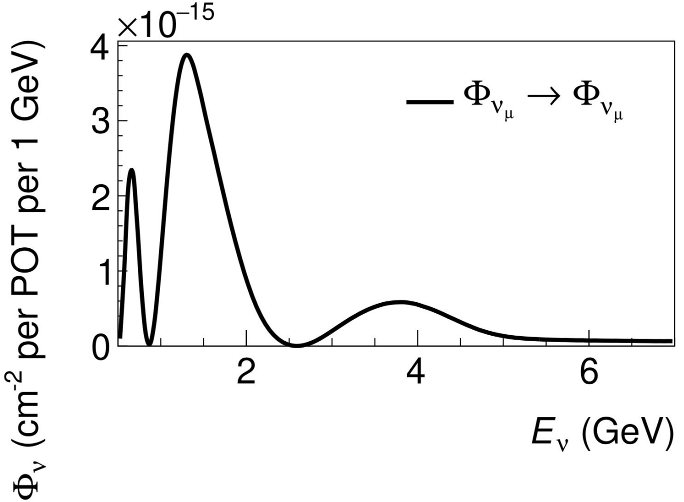


L. Pickering NuFact23

Predicting Oscillations with the Near Detector

$$\Phi^{\nu}_{\mathrm{Near}} \qquad \vec{\Phi}^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$

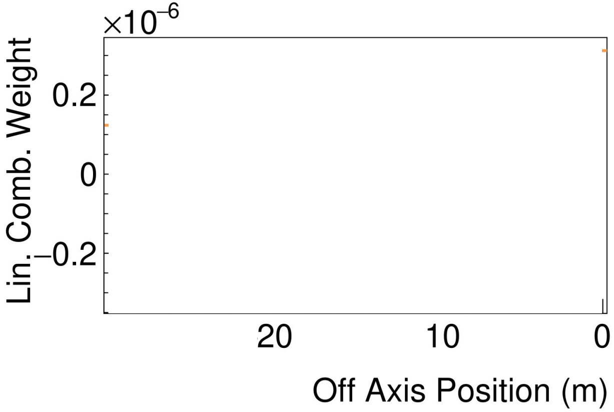


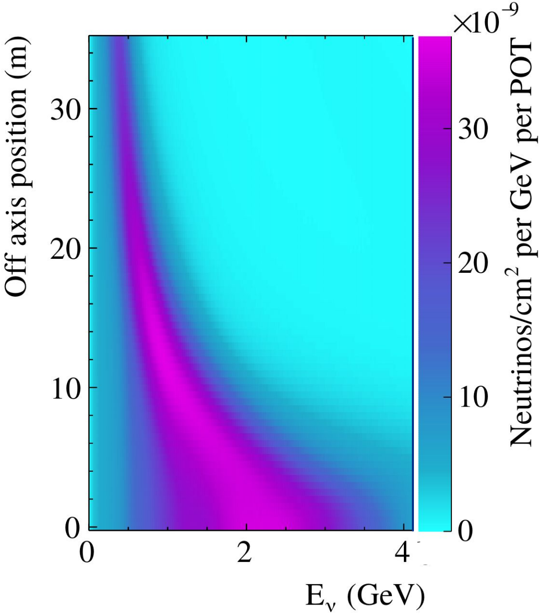


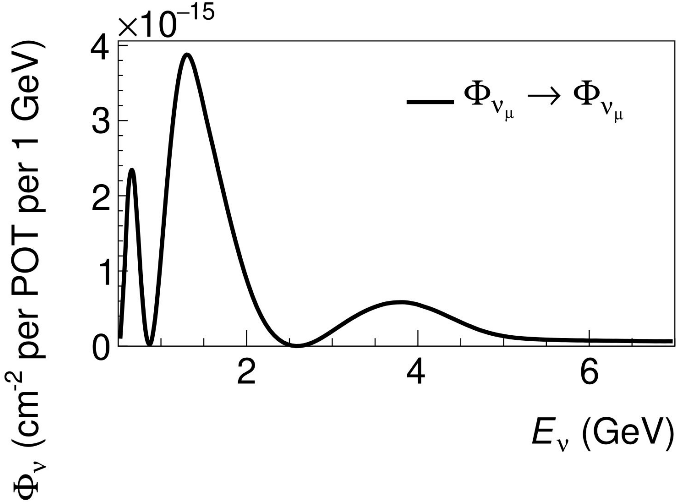
L. Pickering NuFact23

Predicting Oscillations with the Near Detector

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



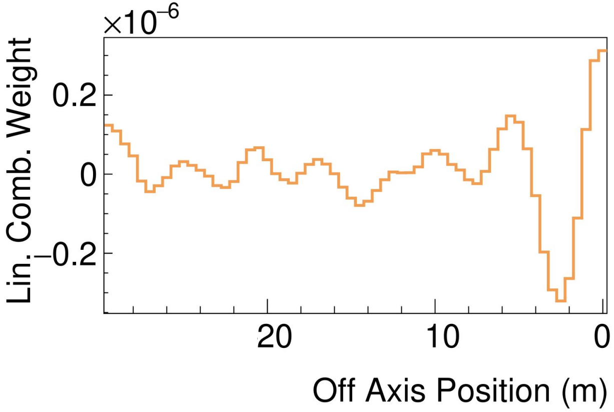


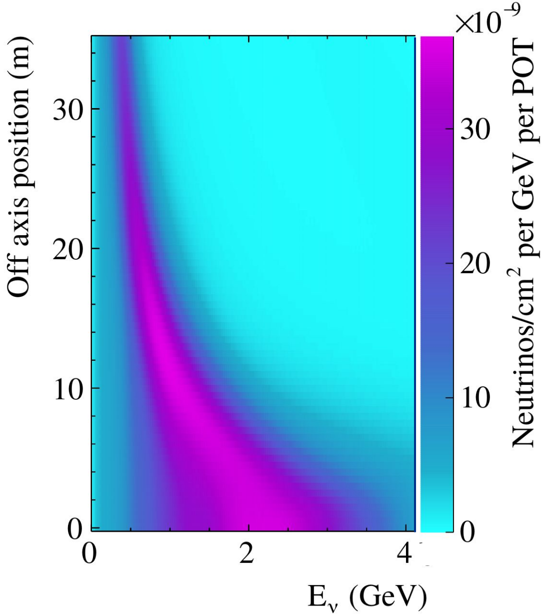


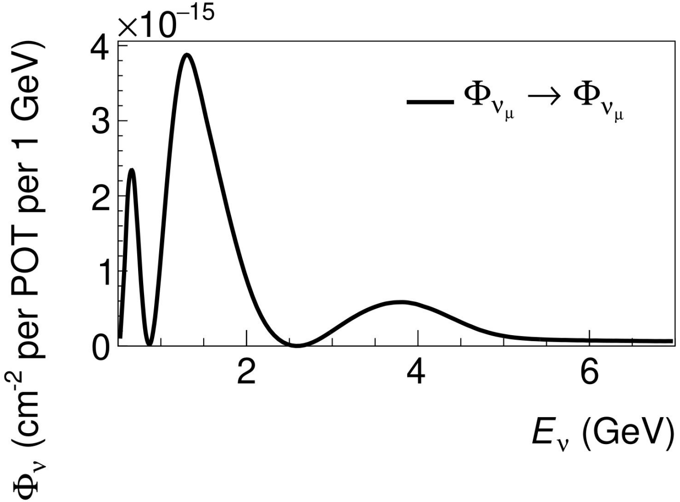
L. Pickering NuFact23

Predicting Oscillations with the Near Detector

$$\vec{\mathcal{C}} \cdot \Phi^{\nu}_{\mathrm{Near}} = \vec{\Phi}^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$



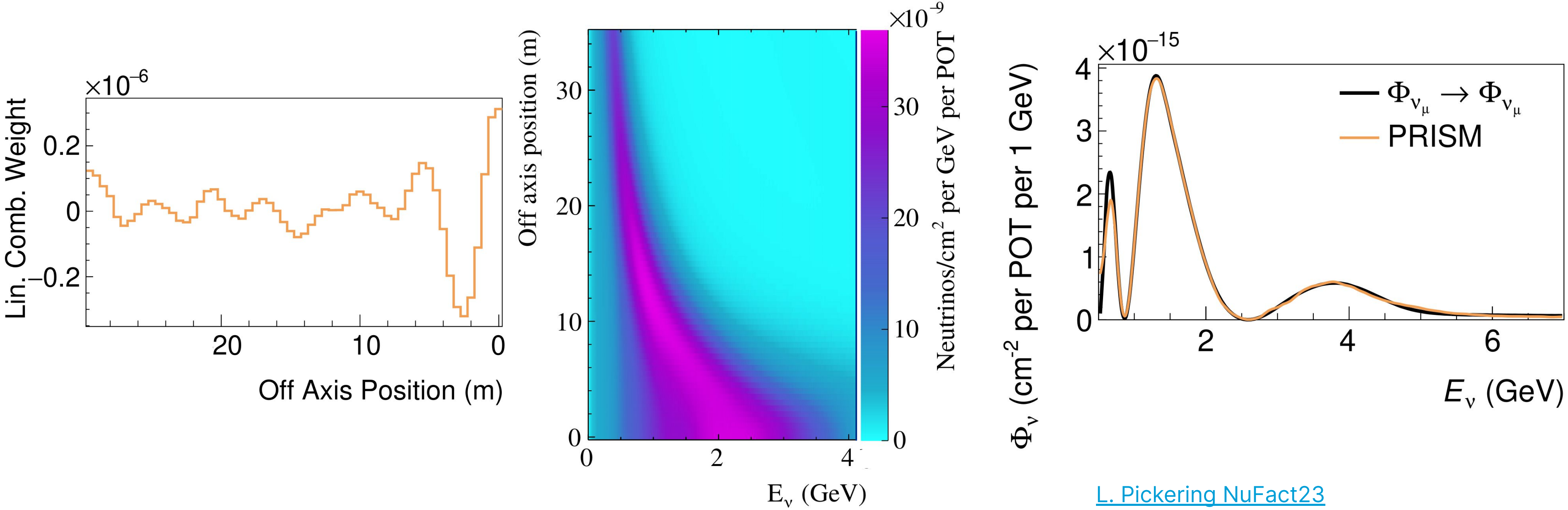




L. Pickering NuFact23

Predicting Oscillations with the Near Detector

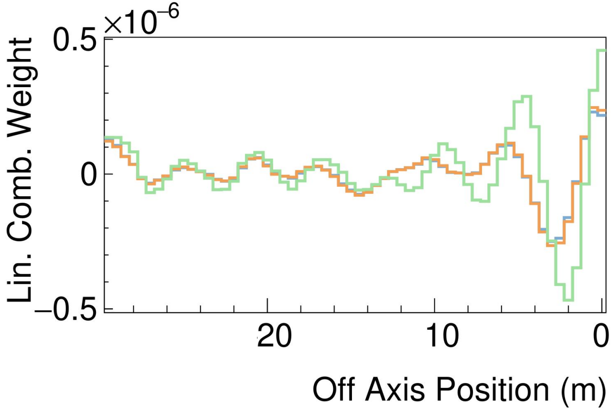
$$\vec{\mathcal{C}} \cdot \Phi^{\nu}_{\mathrm{Near}} = \vec{\Phi}^{\nu}_{\mathrm{Far}} \cdot P^{\mathcal{H}}_{\mathrm{Osc}}$$

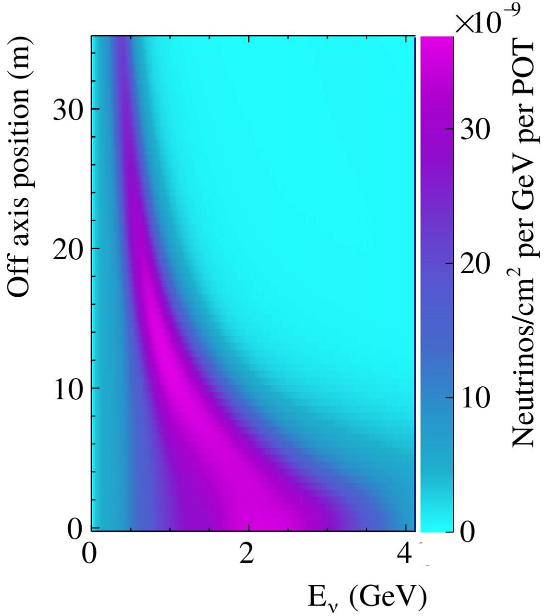


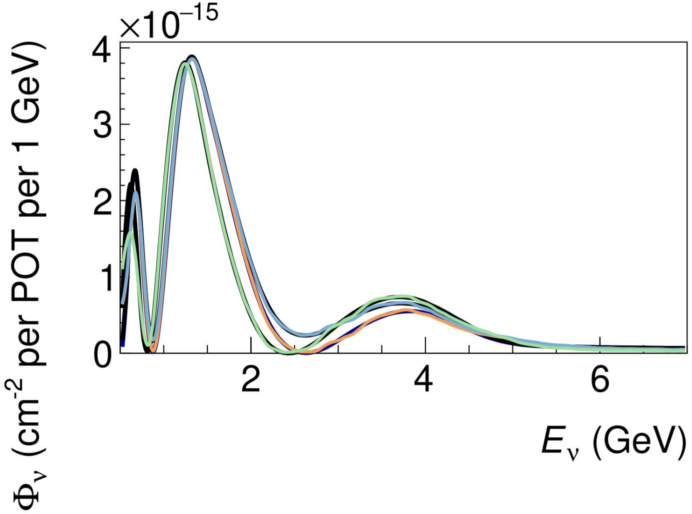
L. Pickering NuFact23

Predicting Oscillations with the Near Detector

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







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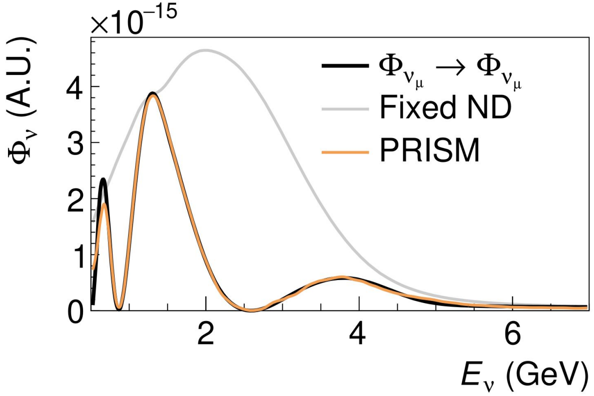
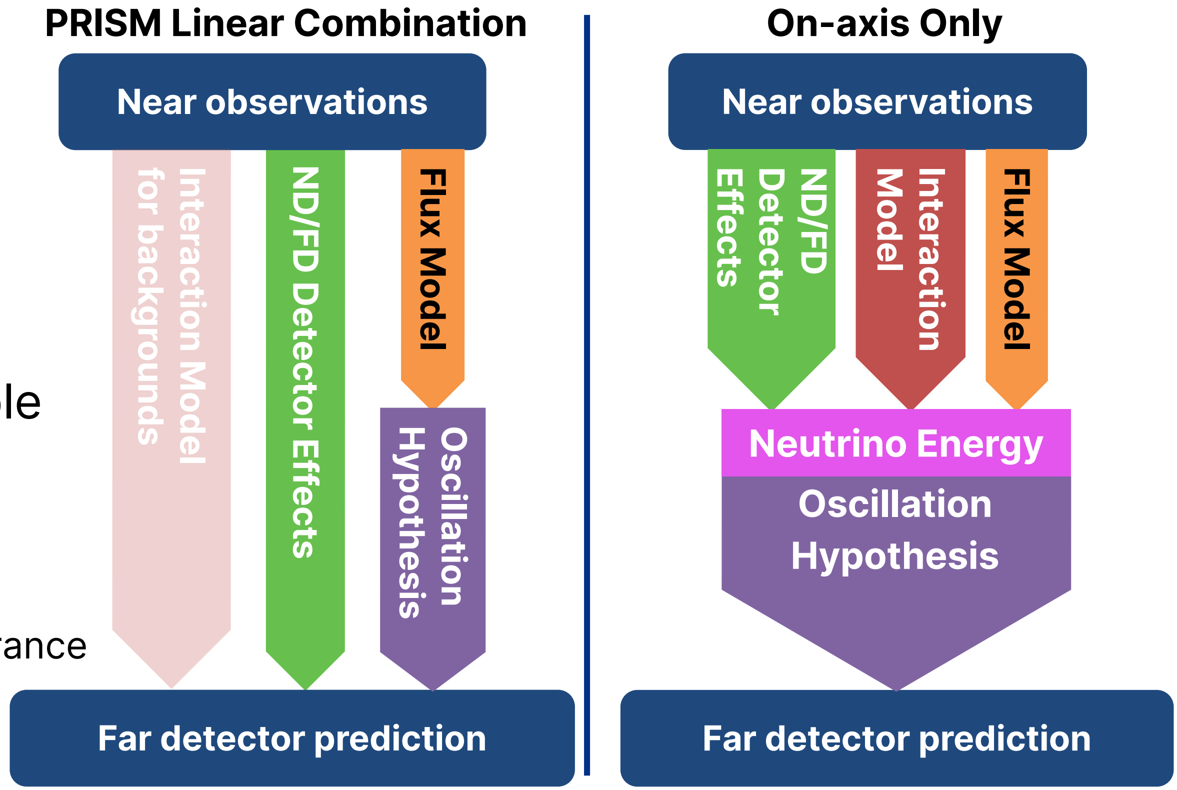
Complementary Approaches





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

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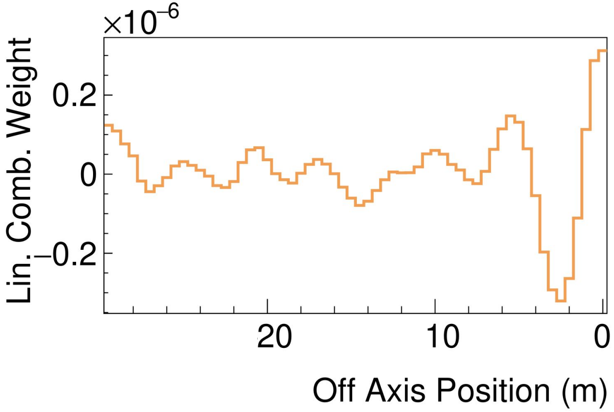
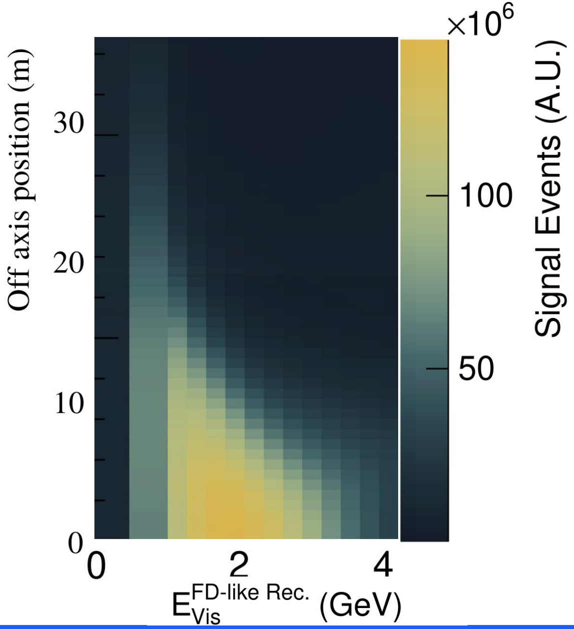
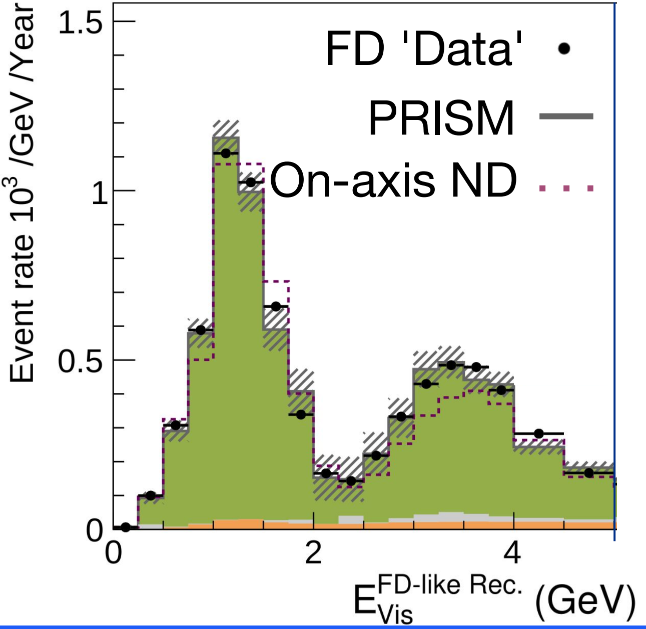
Predicting Oscillations with the Near Detector

$$\vec{\mathcal{C}}\left(P^{\mathcal{H}}_{\mathrm{Osc}}\right) \cdot \underset{\left(=\,\boldsymbol{\Phi}^{\nu}_{\mathrm{Near}}\,\cdot\,\sigma^{\nu}\right)}{\mathbf{R}^{\nu}_{\mathrm{Near}}} = \underset{\left(=\,\vec{\Phi}^{\nu}_{\mathrm{Far}}\,\cdot\,P^{\mathcal{H}}_{\mathrm{Osc}}\,\cdot\,\sigma^{\nu}\right)}{\vec{\mathrm{R}}^{\nu}_{\mathrm{Far}}}$$

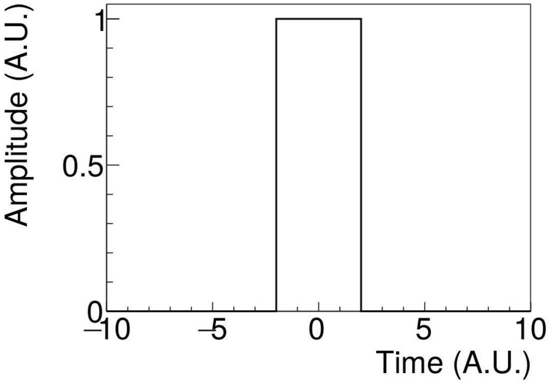






Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines



Discrete Fourier Transforms

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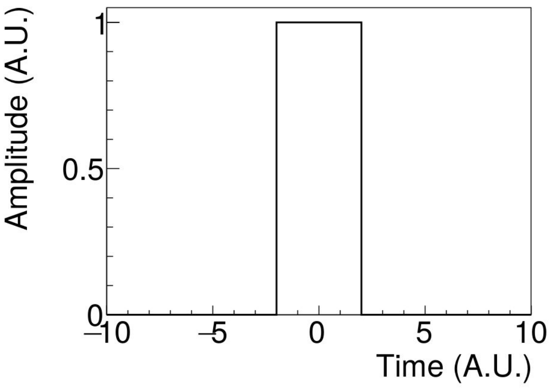
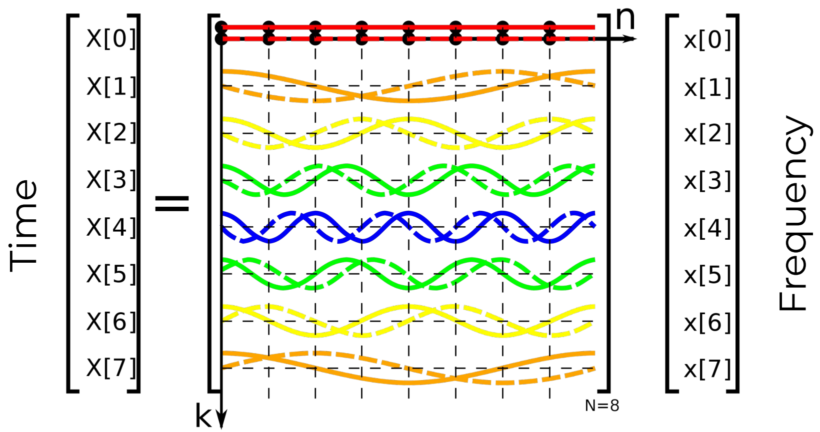
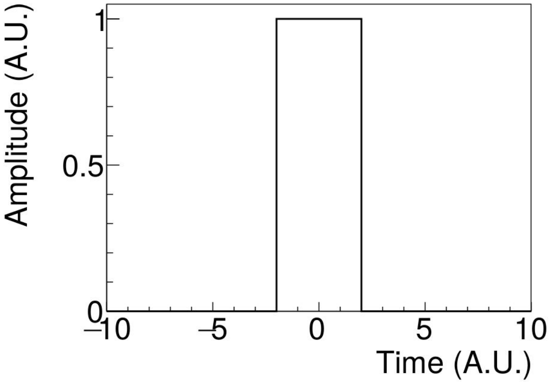
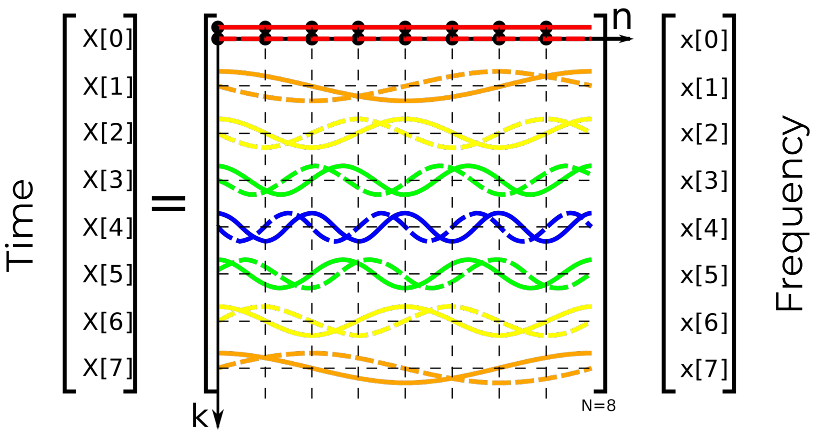


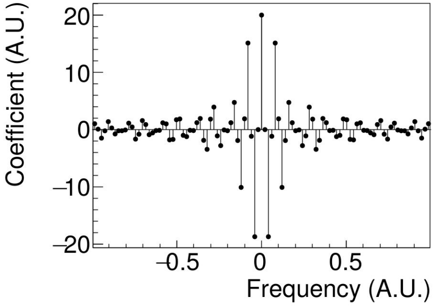


Discrete Fourier Transforms

- Approximate function as a linear sum of sines and cosines







Discrete Fourier Transforms

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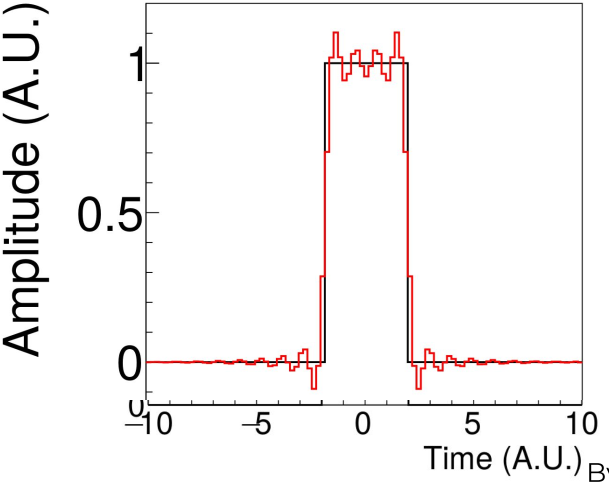

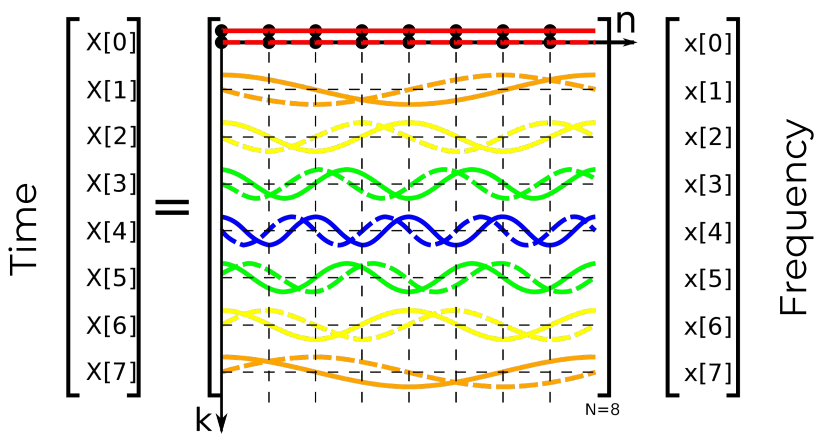

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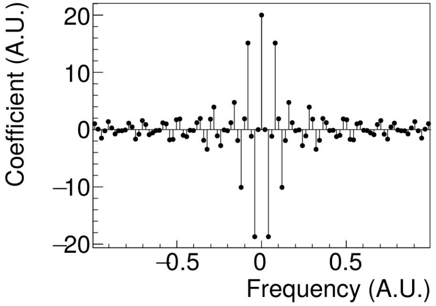

Discrete Fourier Transforms

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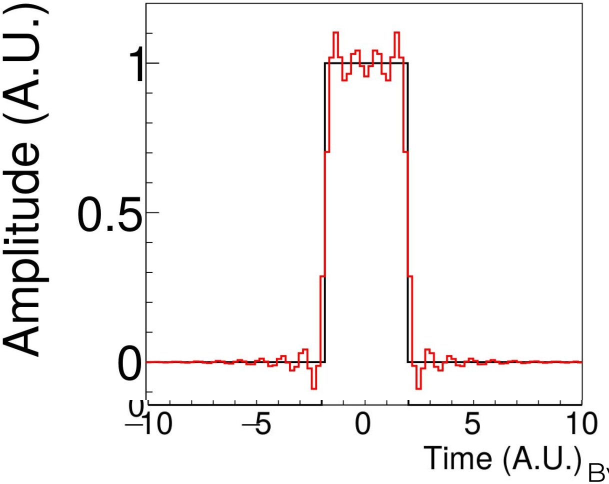
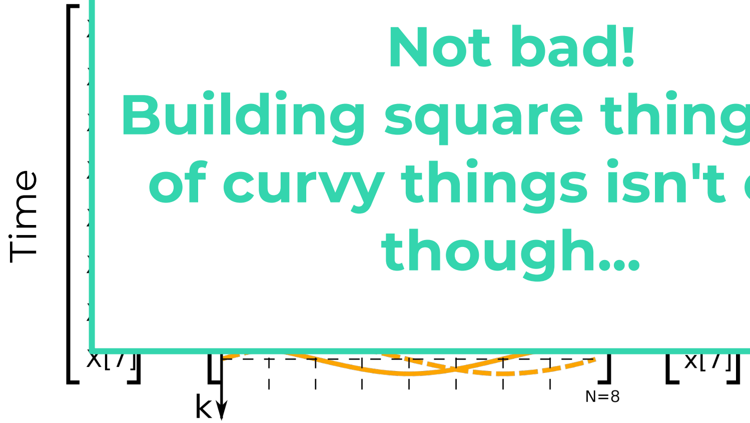
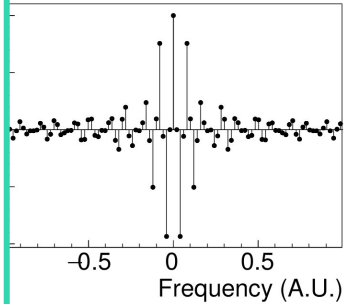


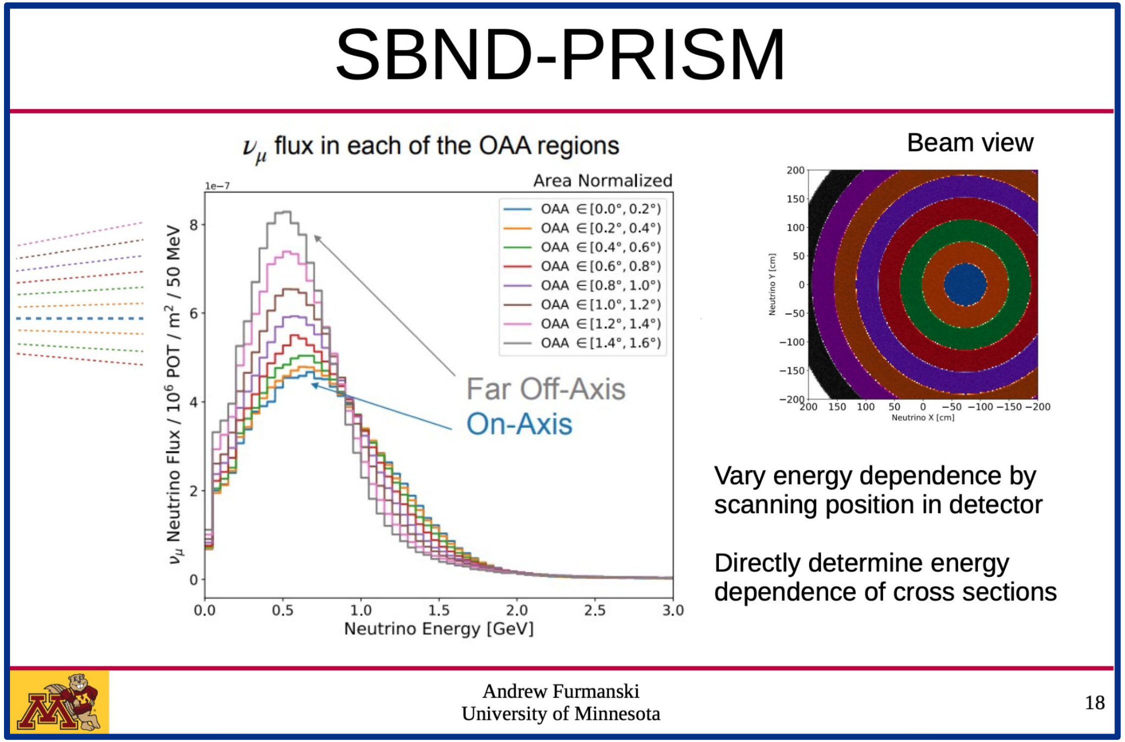


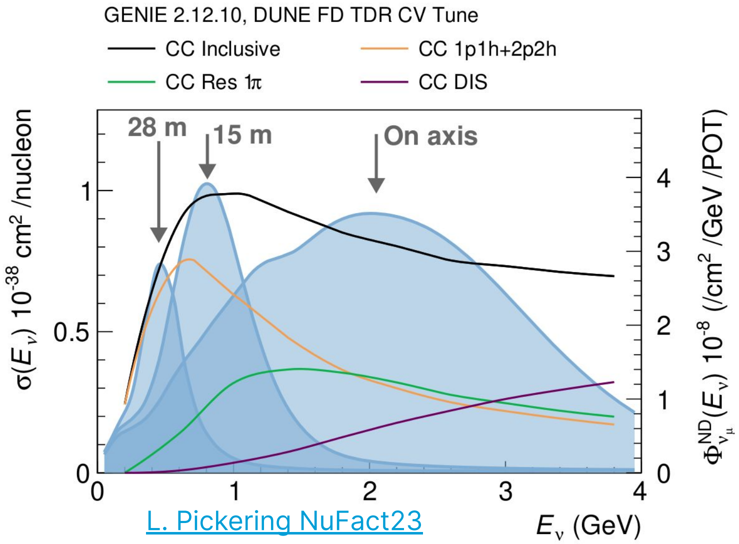


Not bad!
Building square things out of curvy things isn't easy though...

SBND PRISM

A. Furmanski NuFact23





L. Pickering NuFact23