NSTAR 2026

CP-violation or Nuclear Excitation

The Role of Neutrino Interaction Model Uncertainties on Accelerator-Based Neutrino Oscillation Measurements

Stephen Dolan

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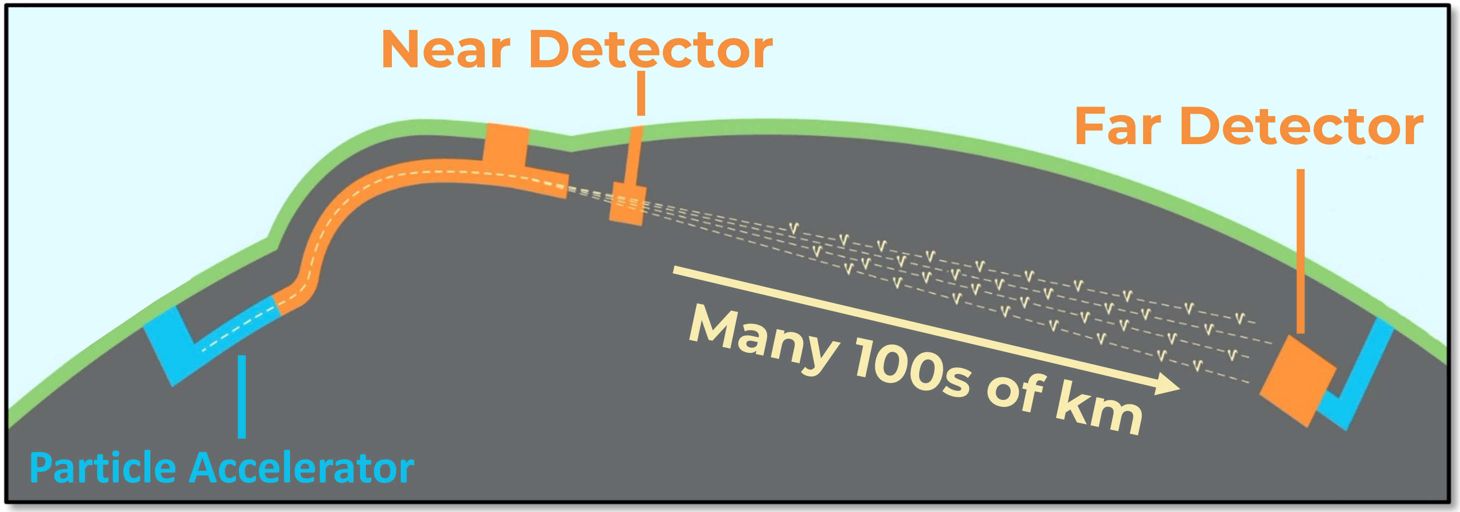
Based on the content of a new review paper: arXiv:2605.28671

Collaborators: L. Pickering, P. Stowell, C. Wilkinson, C. Wret

And on a submission for JPhysG Emerging Leaders: arXiv:2605.28696

Collaborators: J. McKean, L. Munteanu

Accelerator-Based Experiments



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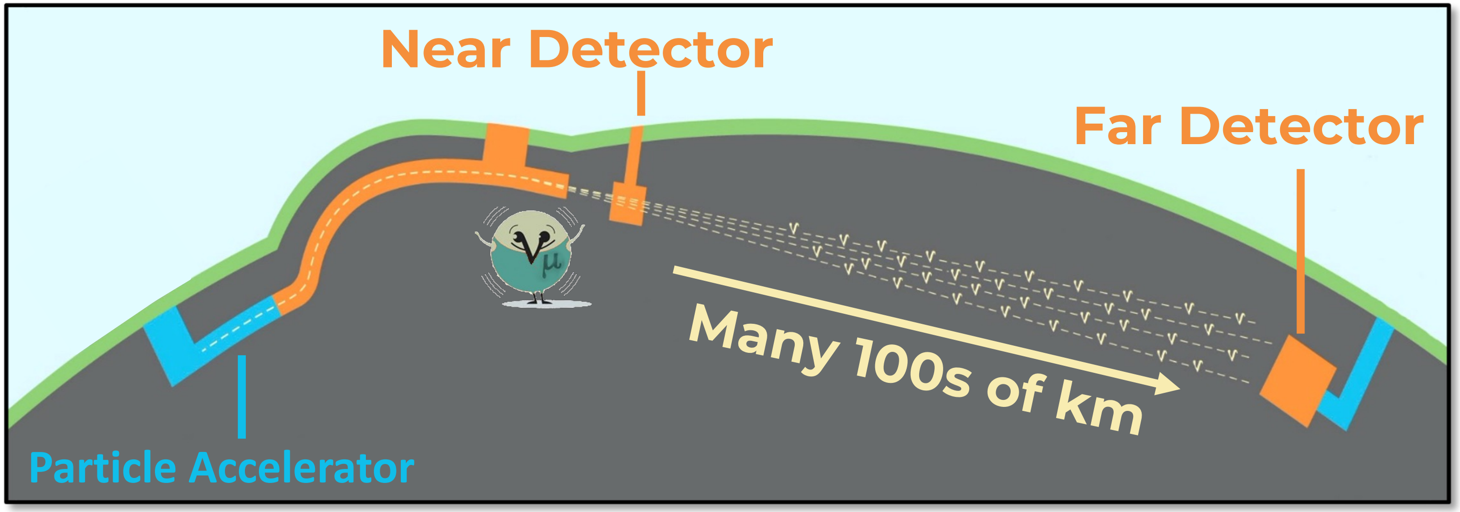

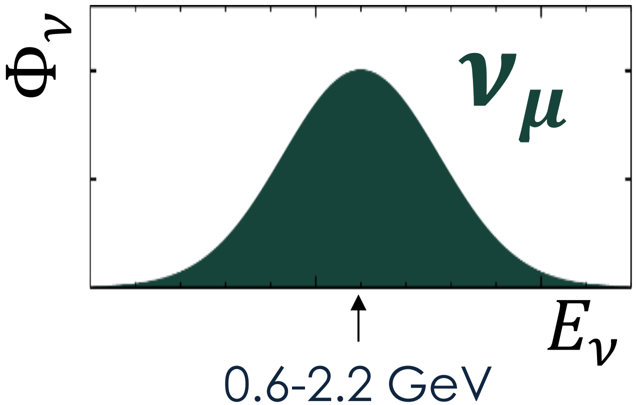

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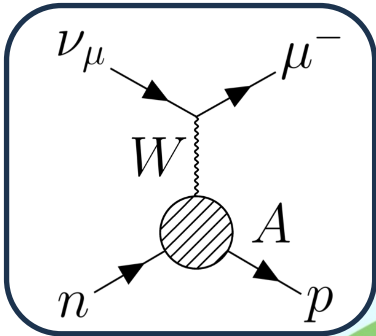
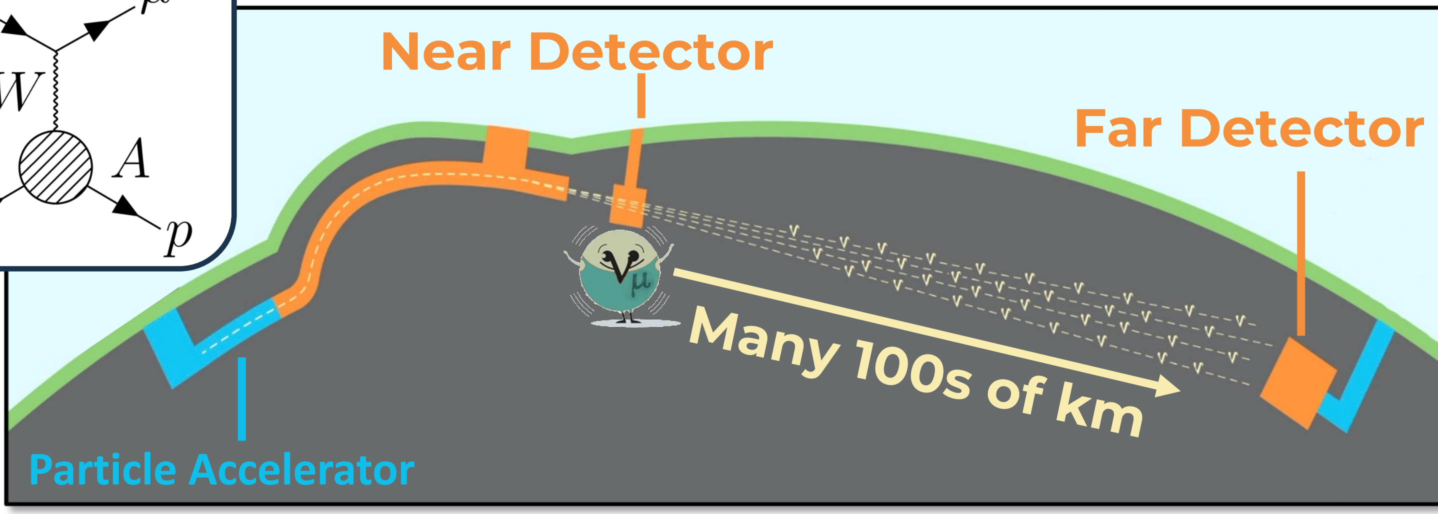
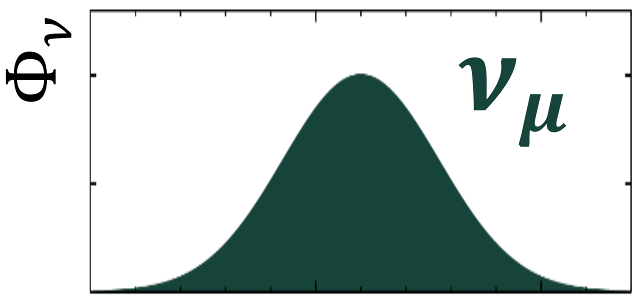






E_ν

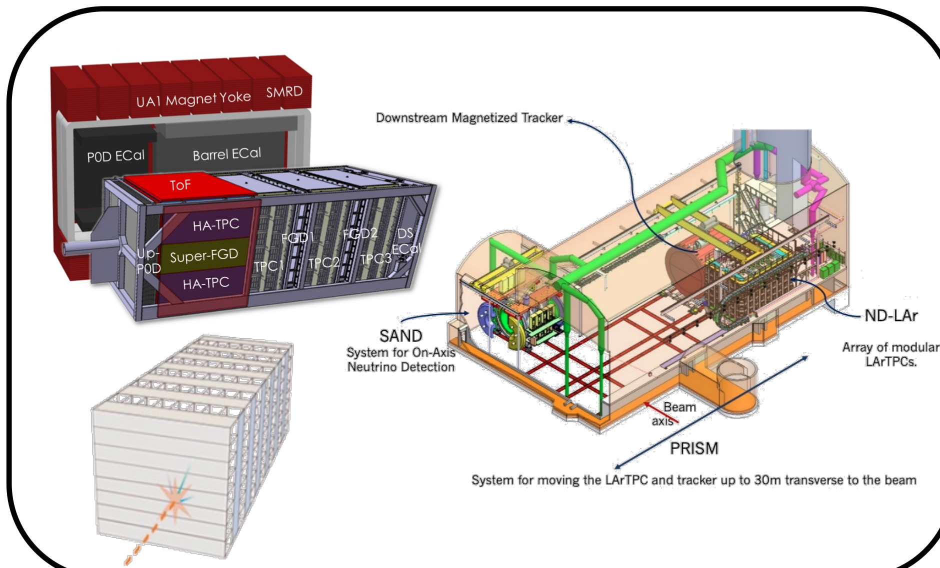
At the near detector

$$N_\mu(E_\nu) \propto \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects



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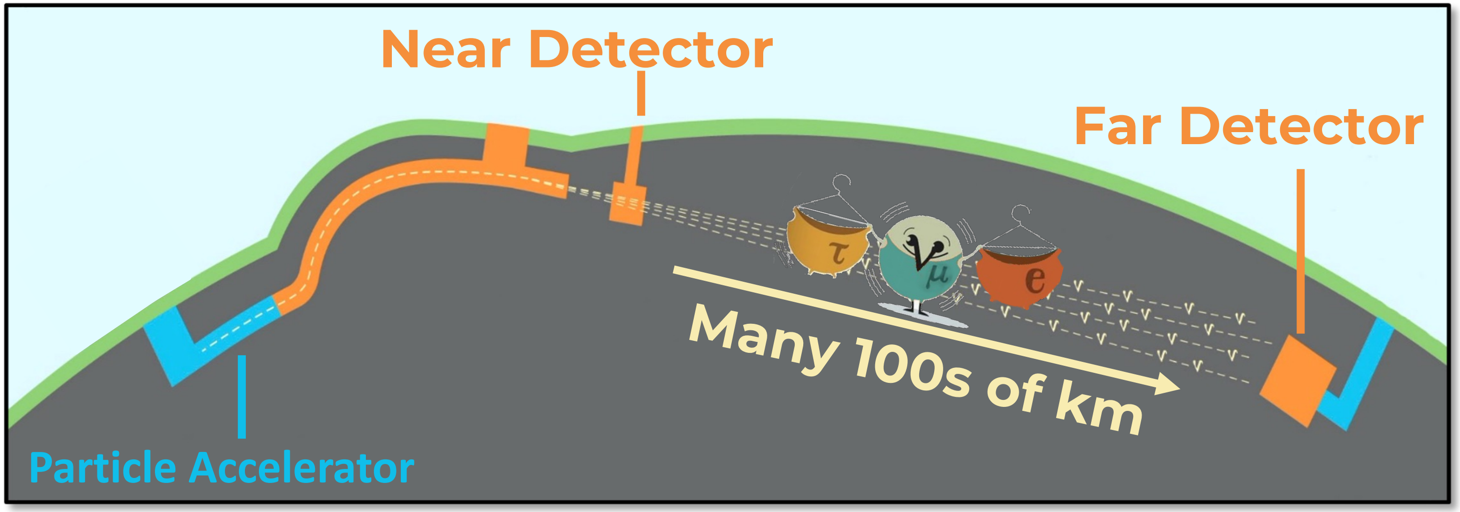

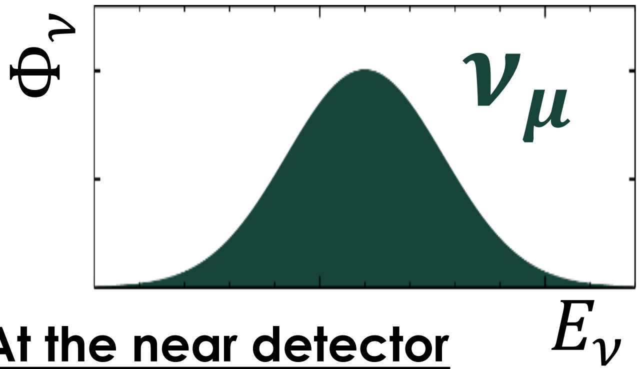

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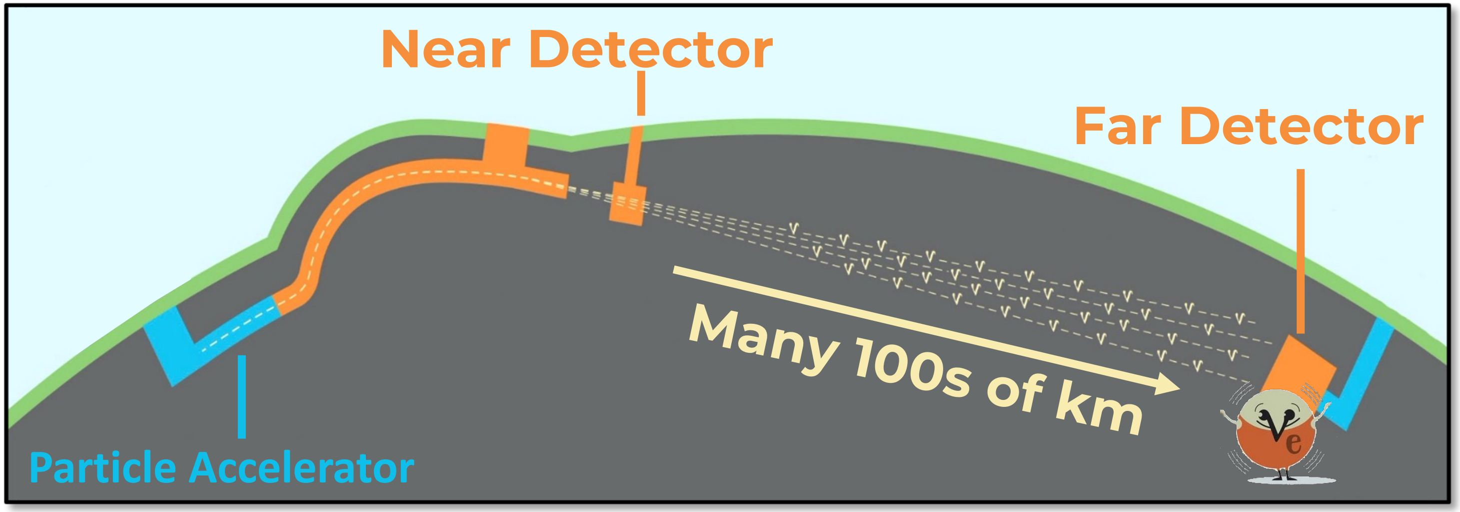

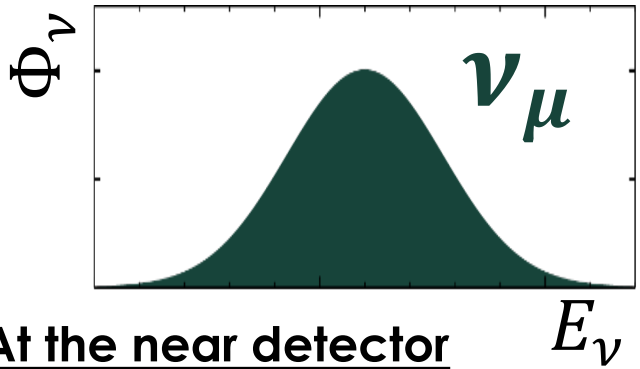

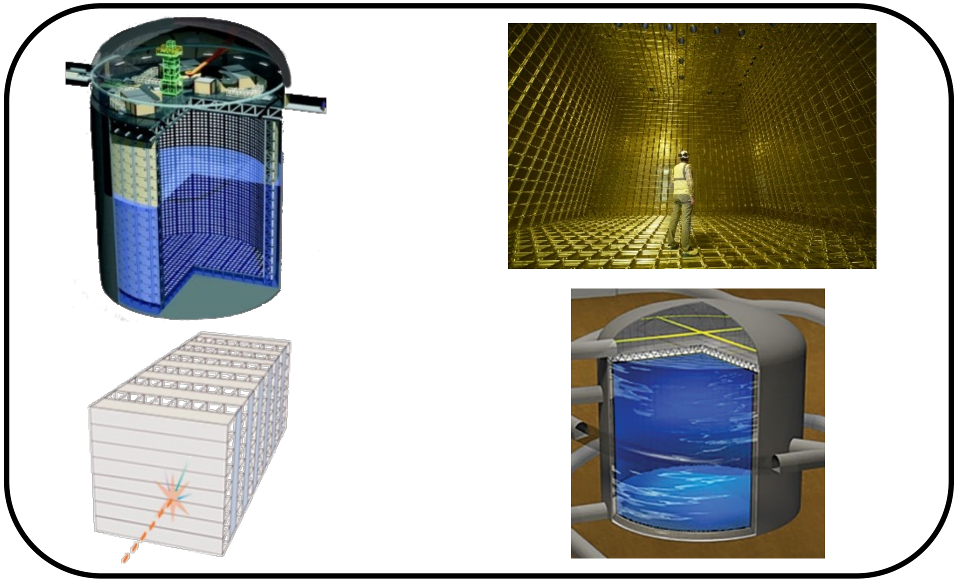

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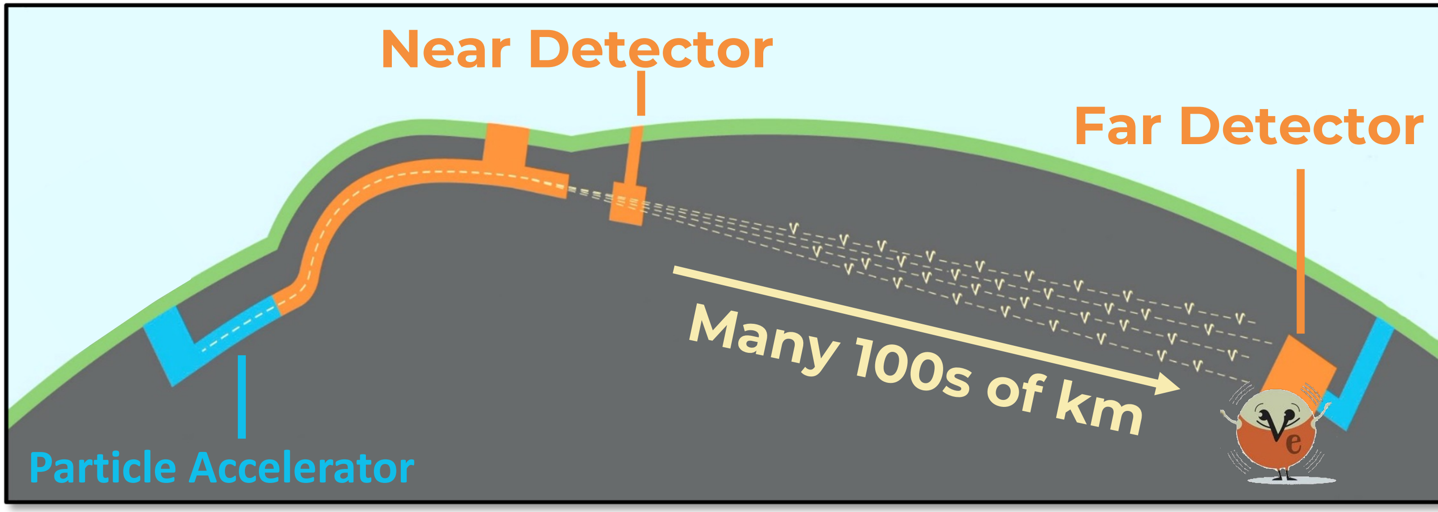

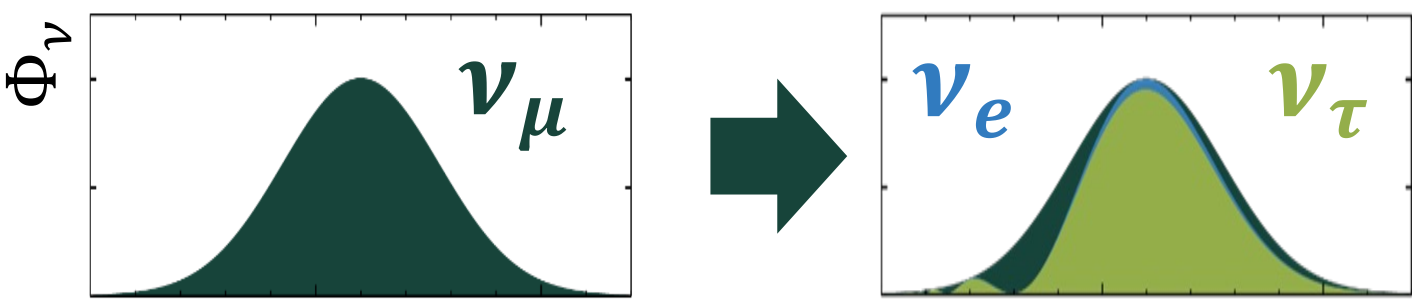

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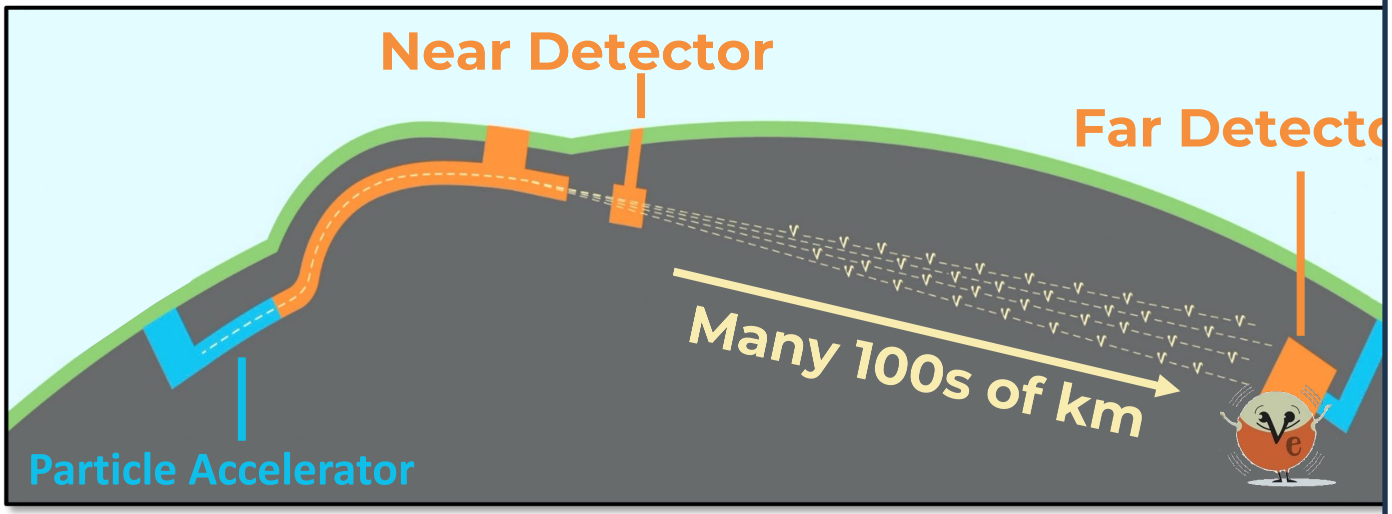
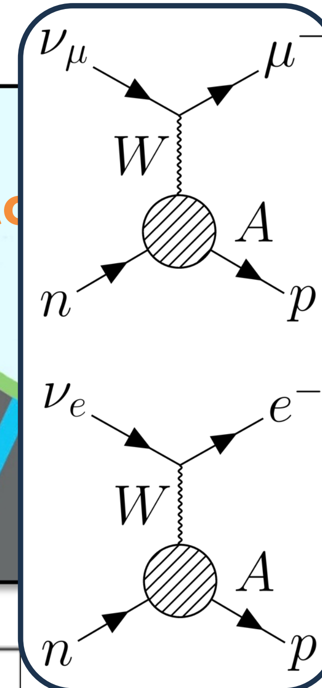
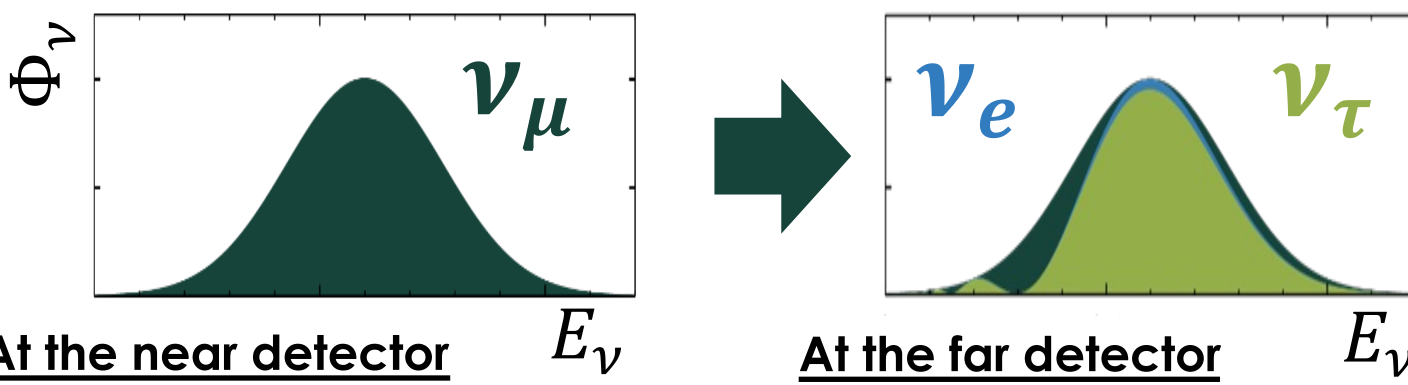






At the near detector

$$N_\mu(E_\nu) \propto \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

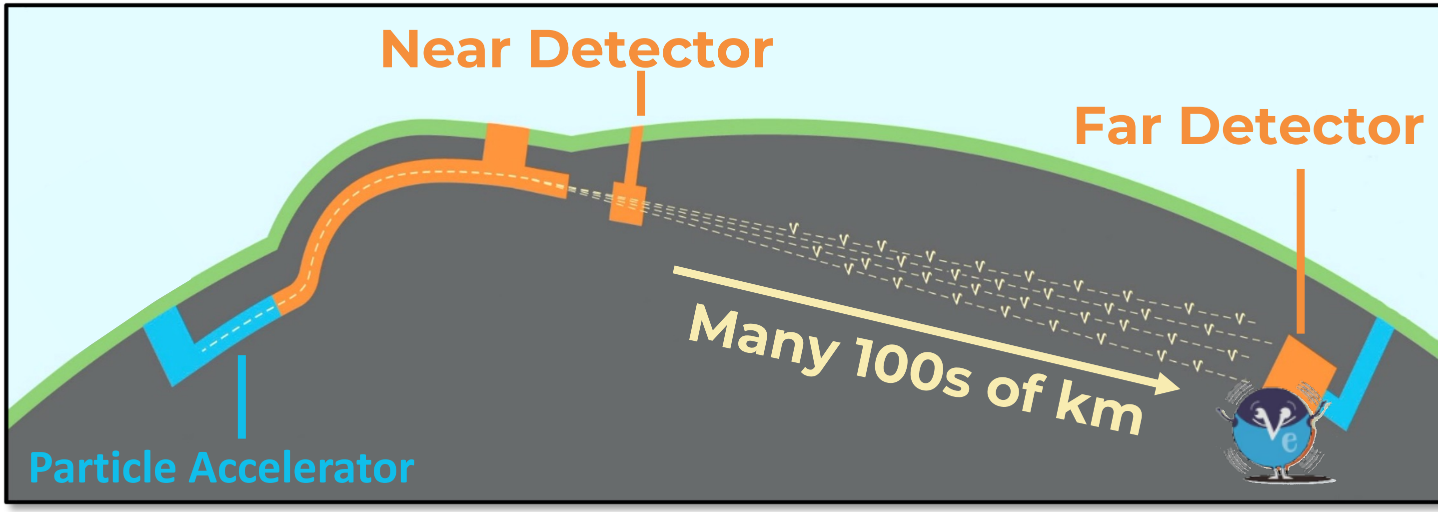
At the far detector

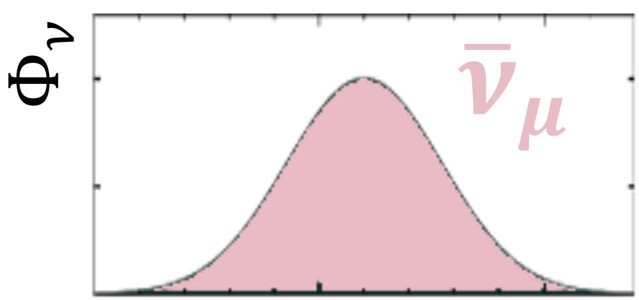
$$N_\mu(E_\nu) \propto P(\nu_\mu \rightarrow \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

$$N_e(E_\nu) \propto P(\nu_\mu \rightarrow \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Oscillation probability

Accelerator-Based Experiments





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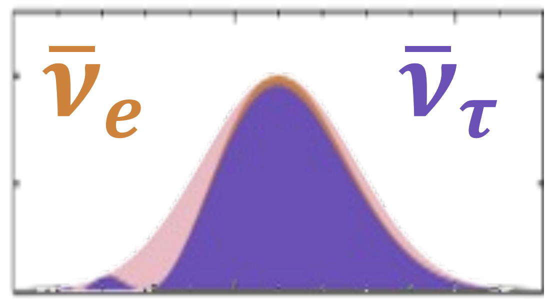

E_ν

At the near detector

$$N_\mu(E_{\bar{\nu}}) \propto \sigma(E_{\bar{\nu}})\Phi_{\bar{\nu}}(E_{\bar{\nu}})\epsilon(E_{\bar{\nu}})$$

Interaction cross section

Neutrino flux

Detector effects

At the far detector

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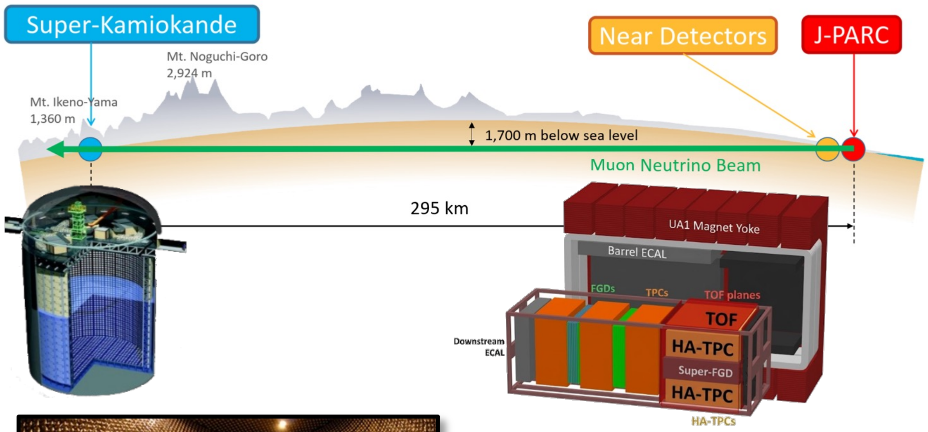
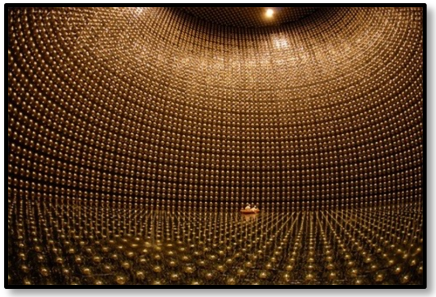
Oscillation probability

Current results: T2K, NOvA

T2K





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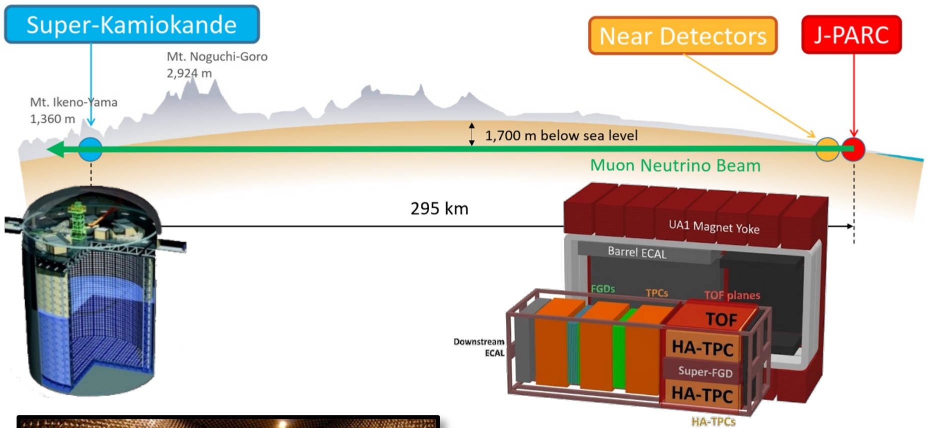

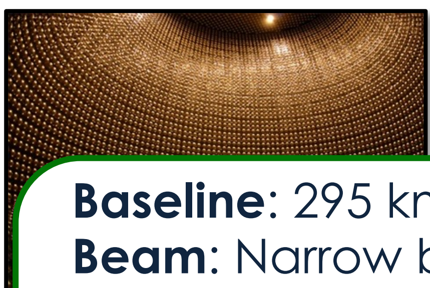

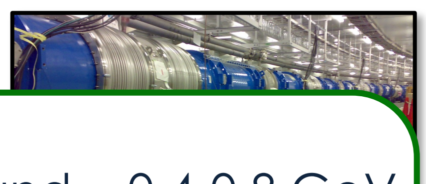

Baseline: 295 km
Beam: Narrow band, ~0.4-0.8 GeV
Far detector: Water Cherenkov
Far detector mass (FV): ~23 kt
Observed $N_{\nu_e+\bar{\nu}_e}$: ~150
Observed $N_{\nu_\mu+\bar{\nu}_\mu}$: ~450

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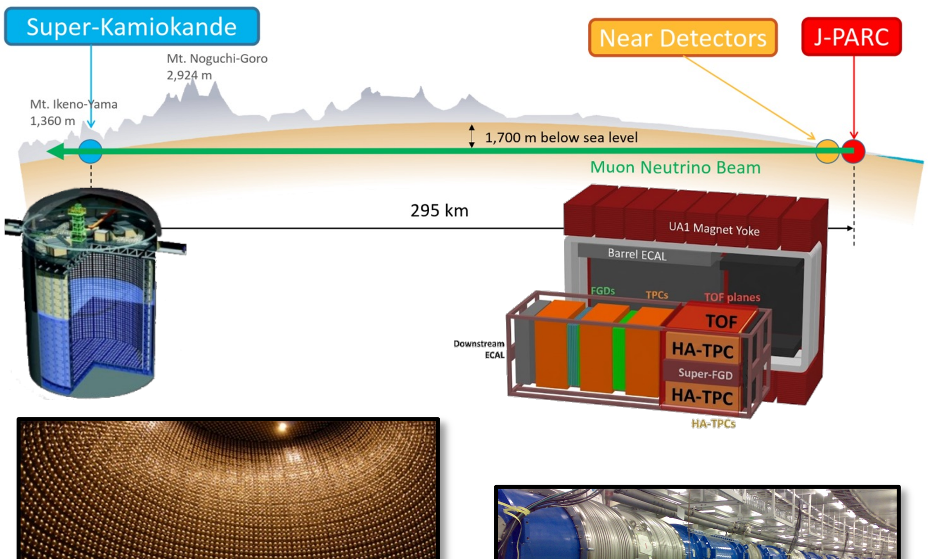

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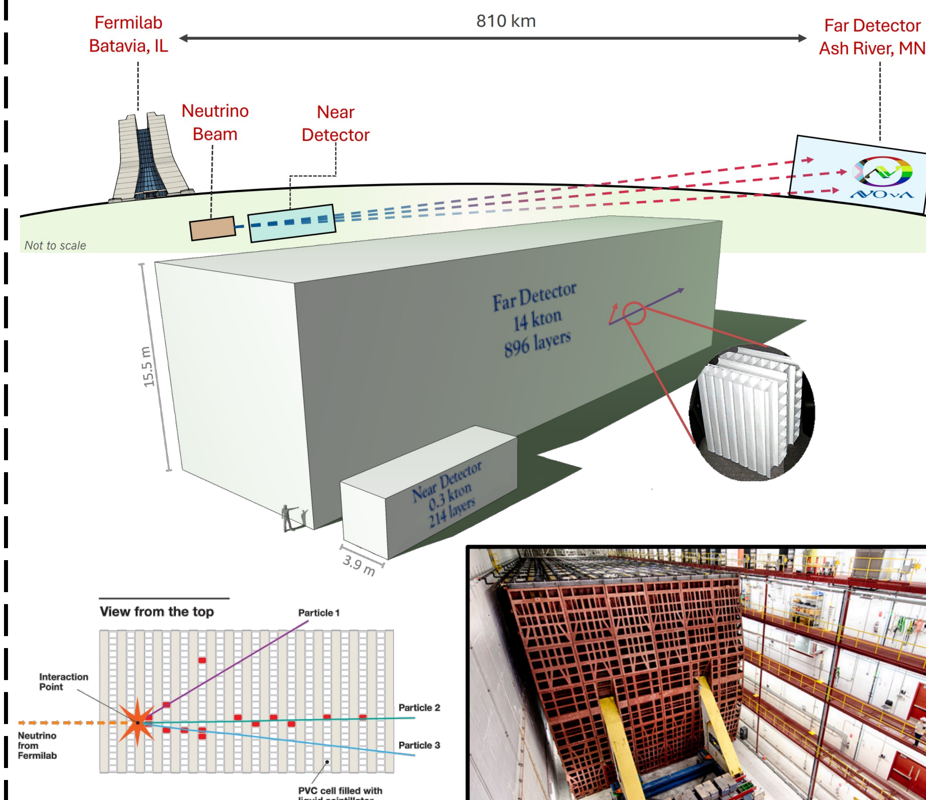

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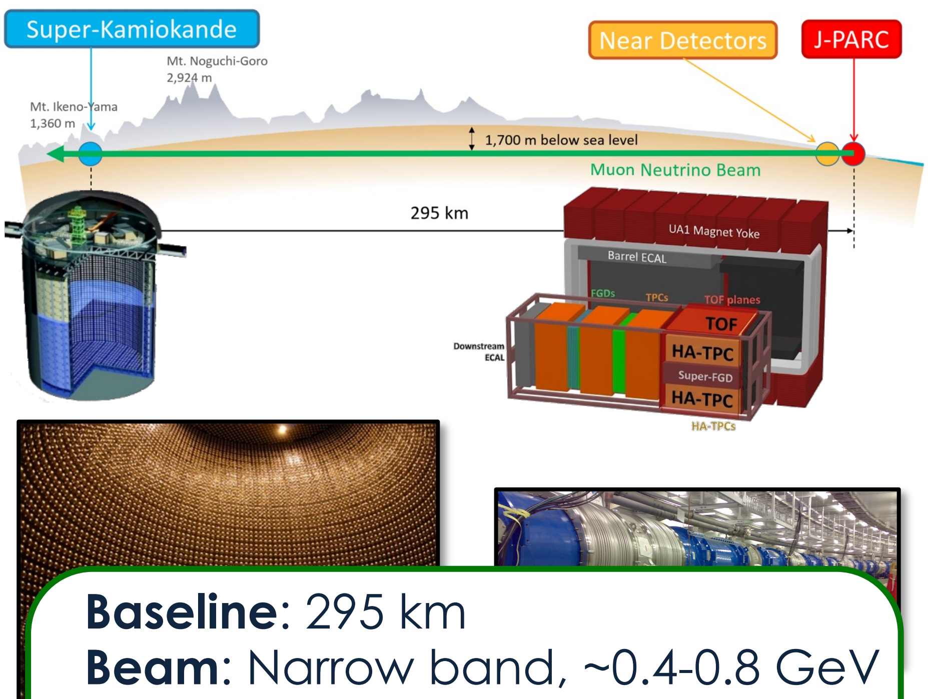

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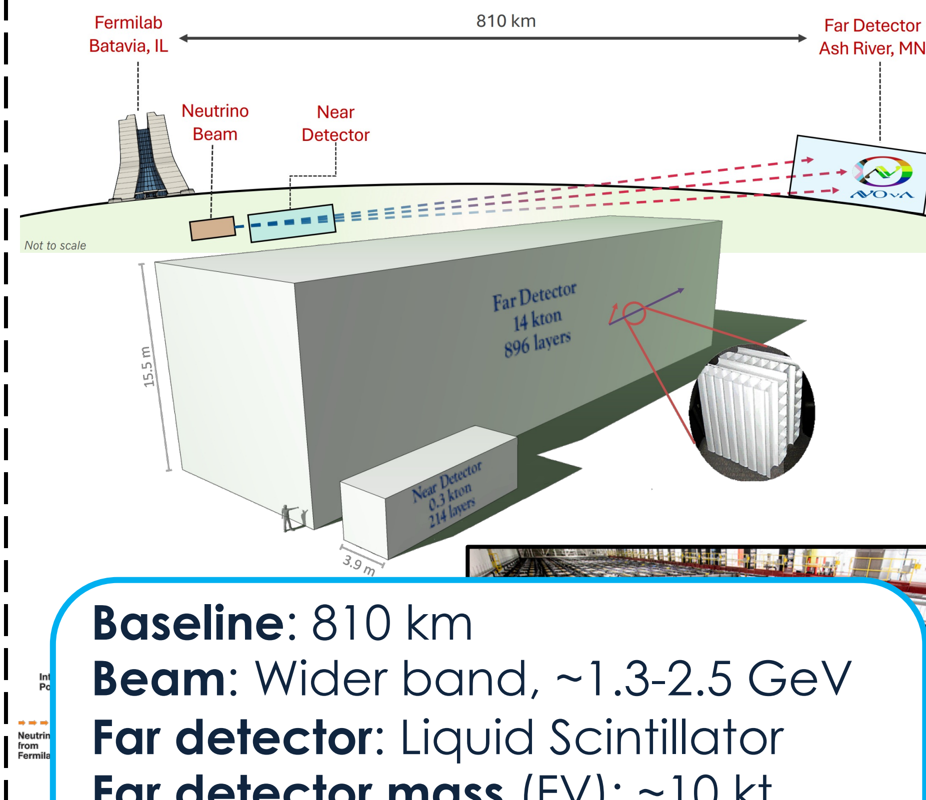
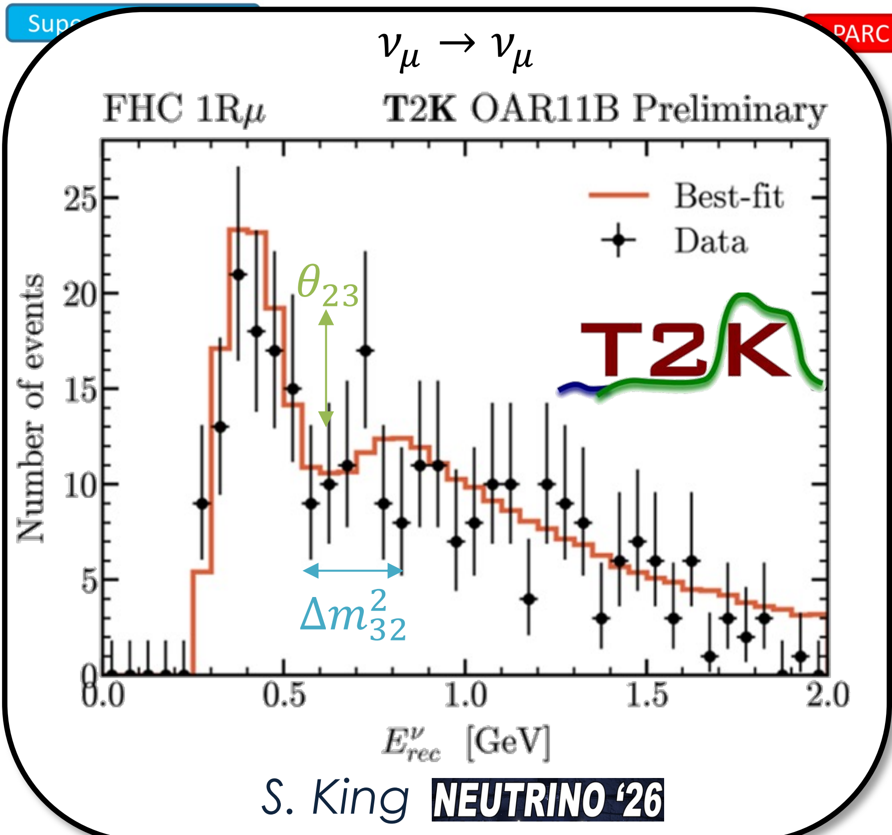
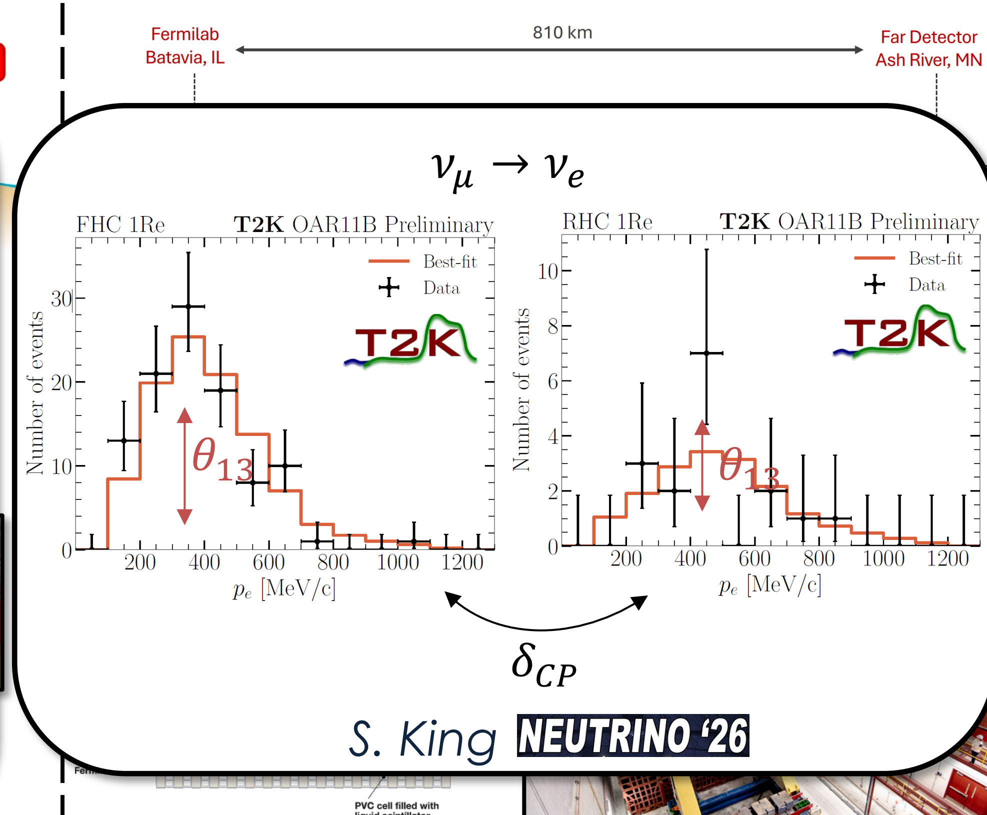


Baseline: 810 km
Beam: Wider band, ~1.3-2.5 GeV
Far detector: Liquid Scintillator
Far detector mass (FV): ~10 kt
Observed $N_{\nu_e+\bar{\nu}_e}$: ~200
Observed $N_{\nu_\mu+\bar{\nu}_\mu}$: ~490

Current results: T2K, NOvA

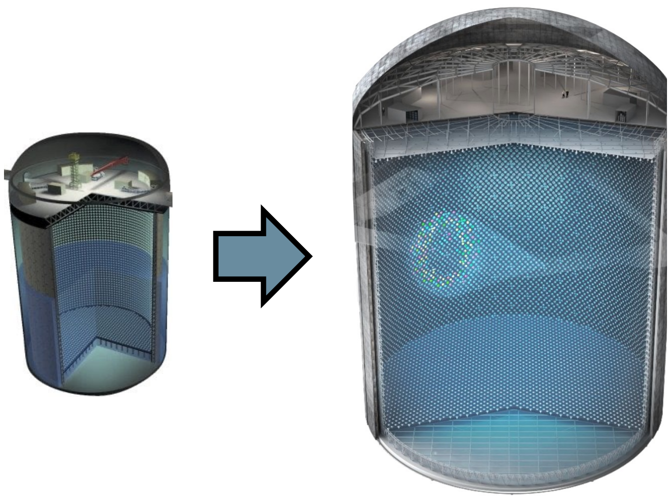




Coming soon for LBL neutrinos

What? T2K is evolving!

T2K evolved into Hyper-K!



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T2K

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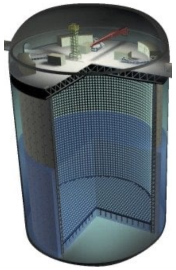
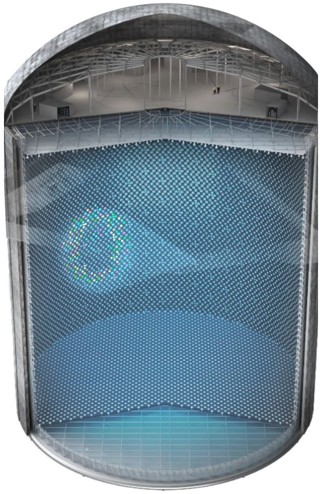
Hyper-K

T2K evolved into Hyper-K!

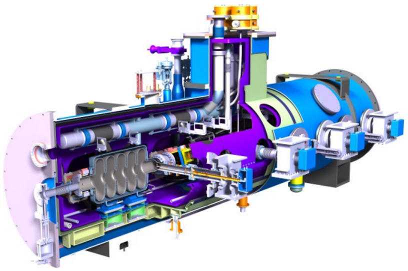




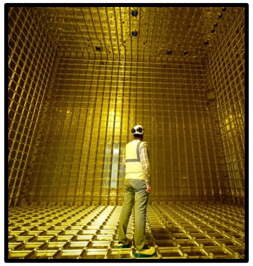
DUNE

A wild DUNE appears!

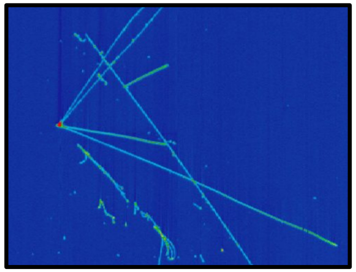
New beam



New detectors



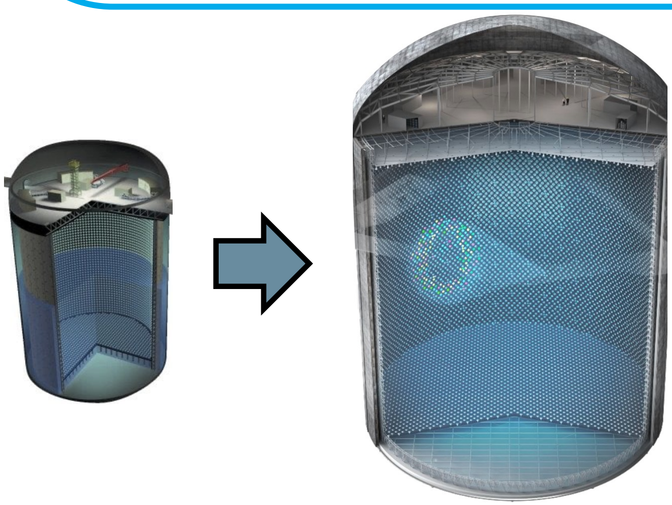
New technology



Coming soon for LBL neutrinos

Baseline: 295 km
Beam: Narrow band, ~0.4-0.8 GeV
Far detector: Water Cherenkov
Far detector mass (FV): ~190 kt
Projected $N_{\nu_e+\bar{\nu}_e}$: ~4500
Projected $N_{\nu_\mu+\bar{\nu}_\mu}$: ~21000
First beam: ~2028

Baseline: 1300 km
Beam: Broad band, ~0.8-3.5 GeV
Far detector: Liquid Argon TPC
Far detector mass (FV): ~4x10 kt
Projected $N_{\nu_e+\bar{\nu}_e}$: ~4100
Projected $N_{\nu_\mu+\bar{\nu}_\mu}$: ~23000
First beam: ~2031



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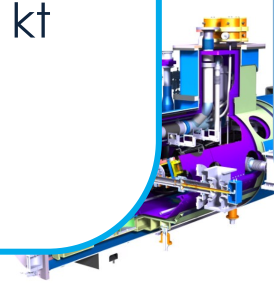

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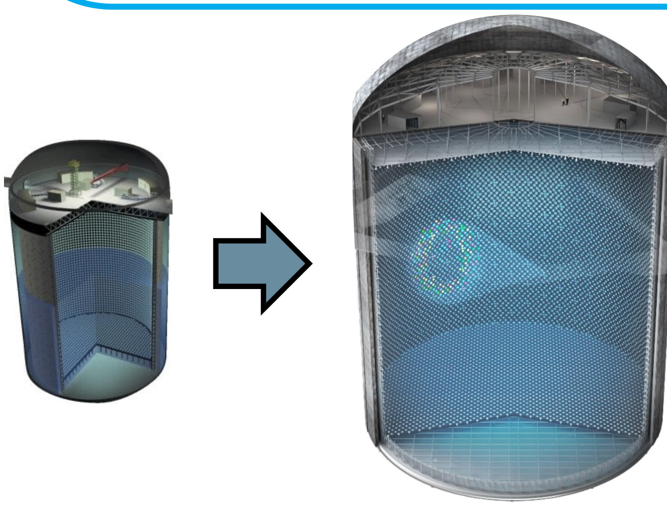
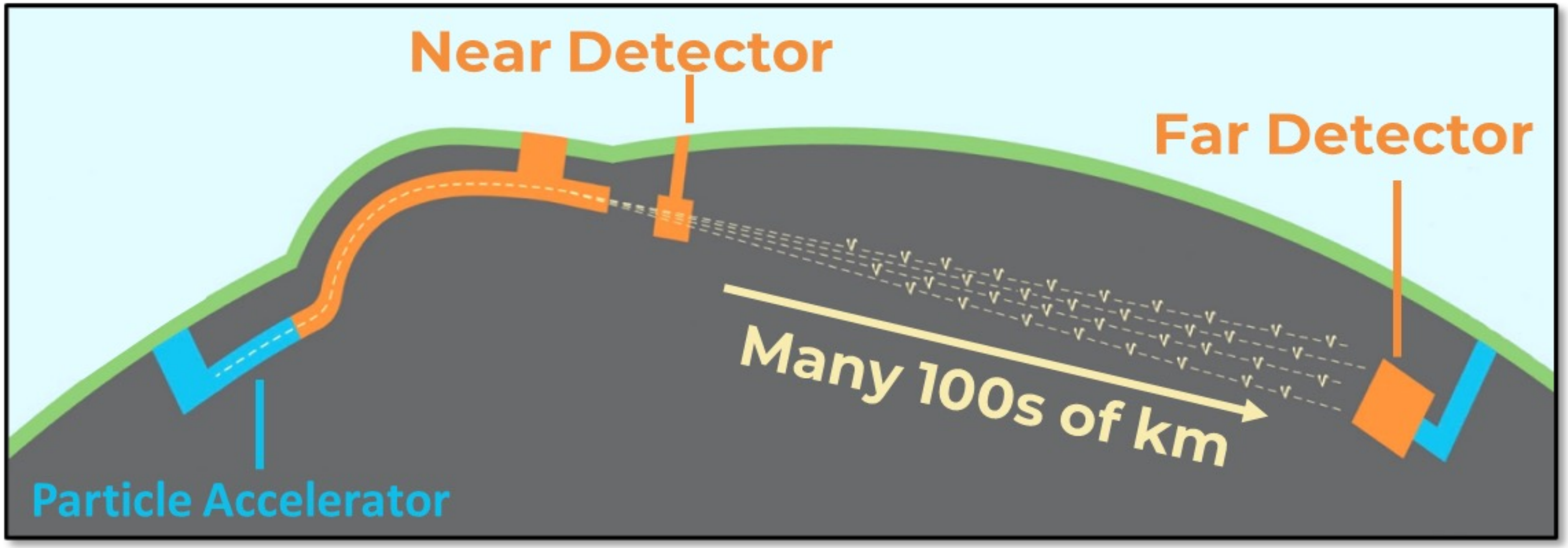


Projected statistics in far-detector samples arXiv:2605.28671

Experiment	T2K	NOvA	Hyper-K	DUNE
$N^{FD}_{\nu_\mu}$ (ν-mode)	318	384	≈8800	≈15000
$N^{FD}_{\bar{\nu}_\mu}$ ($\bar{\nu}$-mode)	137	106	≈12000	≈8100
$N^{FD}_{\nu_e}$ (ν-mode)	108	181	≈2800	≈3300
$N^{FD}_{\bar{\nu}_e}$ ($\bar{\nu}$-mode)	16	32	≈1500	≈900

What about systematics?



$$N_\ell(E_\nu) \propto P(\nu_\mu \rightarrow \nu_\ell)(E_\nu)\, \sigma(E_\nu)\, \Phi_\nu(E_\nu)\, \epsilon(E_\nu)$$

- $N_\ell(E_\nu)$: **Far detector event rate**
- $P(\nu_\mu \rightarrow \nu_\ell)(E_\nu)$: **Oscillation Probability**
- $\sigma(E_\nu)$: **Interaction Cross Section**
- $\Phi_\nu(E_\nu)$: **Incoming neutrino flux**
- $\epsilon(E_\nu)$: **Detector Efficiency**

What about systematics?

Current long-baseline experiments

Uncertainty on N_ℓ	T2K	NOvA
Stat. Uncertainty	6-10%	5-7%
All Syst.	**~5%**	**~3.5%**

$$N_\ell(E_\nu) \propto P(\nu_\mu \to \nu_\ell)(E_\nu)\,\sigma(E_\nu)\,\Phi_\nu(E_\nu)\,\epsilon(E_\nu)$$

Far detector event rate

Oscillation Probability

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What about systematics?

Current long-baseline experiments

Uncertainty on N_ℓ	T2K	NOvA
Stat. Uncertainty	6-10%	5-7%
Cross Sections	$\sim$**4%**	$\sim$**3.5%**
All Syst.	$\sim$**5%**	$\sim$**3.5%**

$$N_\ell(E_\nu) \propto P(\nu_\mu \rightarrow \nu_\ell)(E_\nu)\, \boldsymbol{\sigma}(\boldsymbol{E_\nu})\, \Phi_\nu(E_\nu)\, \epsilon(E_\nu)$$

Far detector event rate

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😱 Large contribution to syst. uncertainties from cross-section modelling

😅 Syst. uncertainties remains small compared to stat. uncertainties

What about systematics?

Current long-baseline experiments

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Future experiments

Uncertainty on N_ℓ	Hyper-K	DUNE
Stat. Uncertainty	1-2%	1-3%

What about systematics?

Current long-baseline experiments

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Future experiments

Uncertainty on N_ℓ	Hyper-K	DUNE
Stat. Uncertainty	1-2%	1-3%

- 😱 Likely large contribution to syst. uncertainties from cross-section modelling
- 😱 Current syst. uncertainties are larger than projected stat. uncertainties

➡ Improved understanding of neutrino interactions is necessary to avoid being prematurely limited by systematic uncertainties

Plenty of details: arXiv:2605.28671

Where are we so far?

- Current neutrino oscillation experiments are mostly **statistics limited**
- Systematic uncertainties related to neutrino-nucleus interactions are often dominant and **are unacceptably large for the next generation of experiments**

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- Current neutrino oscillation experiments are mostly **statistics limited**
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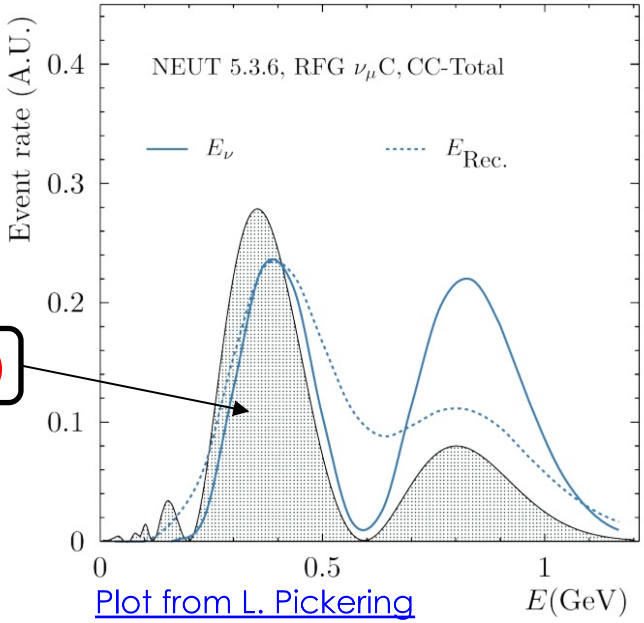
Key question:

What do we need to better understand to reduce uncertainties on oscillation measurements?

Event rates to oscillation parameters

Our physics of interest

$P(\nu_\mu \to \nu_\ell)(E_\nu)\ \Phi_\nu(E_\nu)$

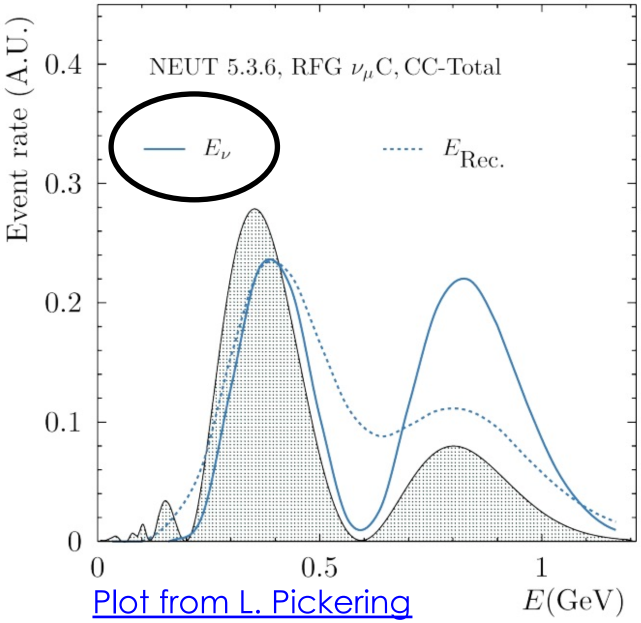


Plot from L. Pickering

Event rates to oscillation parameters

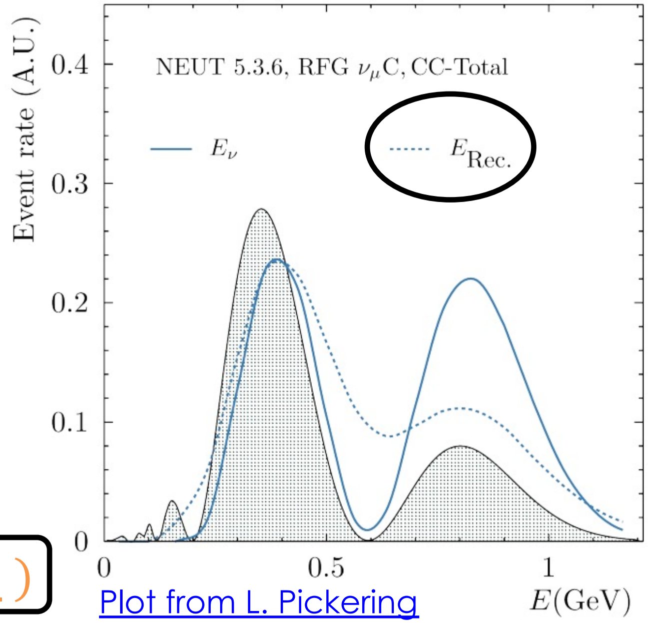
What we would like to measure

$$N_\ell(E_\nu) = P(\nu_\mu \rightarrow \nu_\ell)(E_\nu)\, \sigma(E_\nu)\, \Phi_\nu(E_\nu)\, \epsilon(E_\nu)$$



Plot from L. Pickering

Event rates to oscillation parameters



Plot from L. Pickering

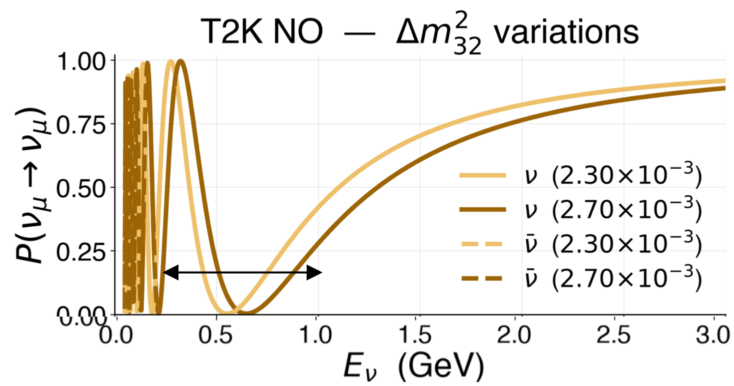
What we can actually measure

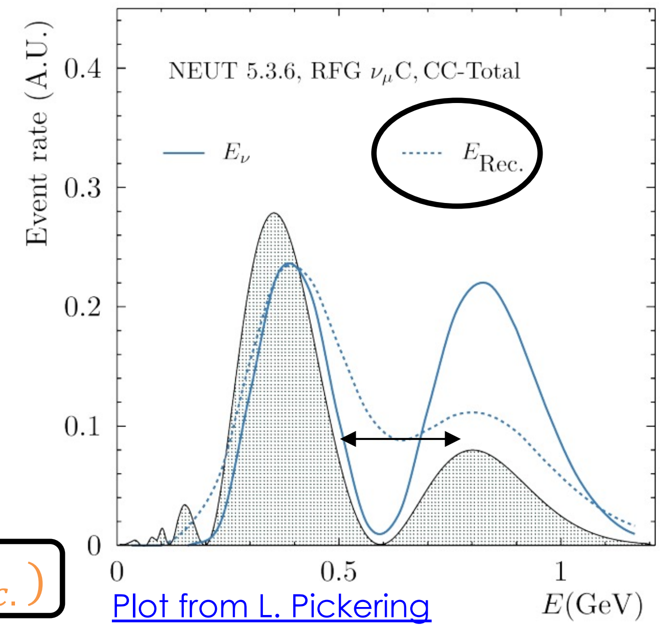
$$N_\ell(E_{Rec.}) = P(\nu_\mu \to \nu_\ell)(E_\nu)\ \sigma(E_\nu)\ \Phi_\nu(E_\nu)\ \epsilon(E_\nu)\ S(E_\nu, E_{Rec.})$$

Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial

Plot from L. Munteanu





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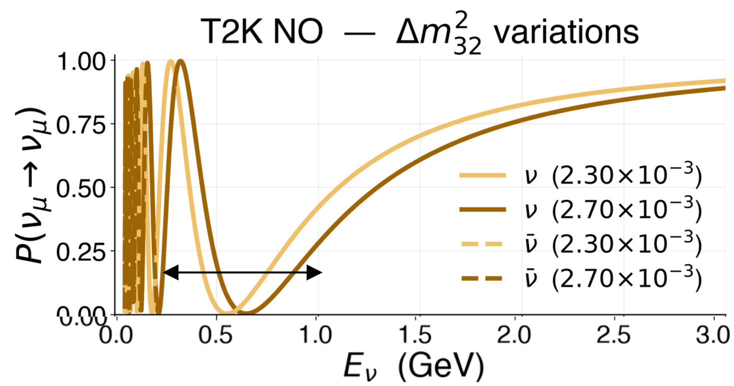
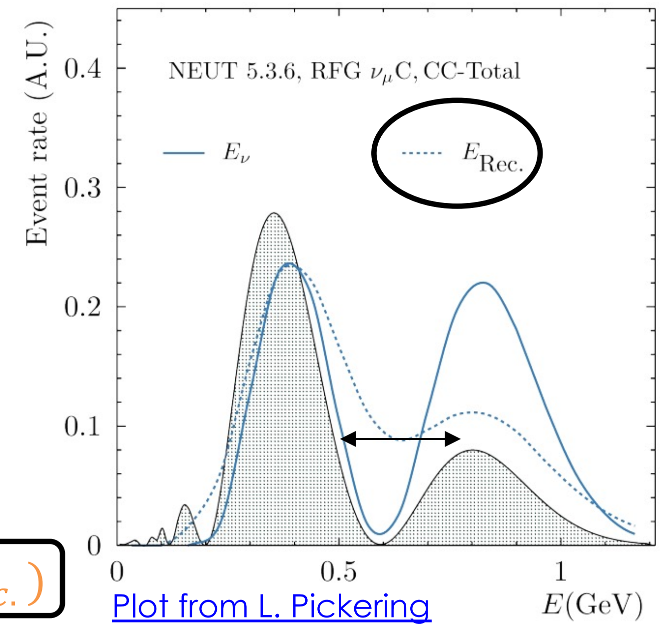
Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial
- **Require a good control over cross section energy dependence and energy reconstruction!**

Plot from L. Munteanu





Plot from L. Pickering

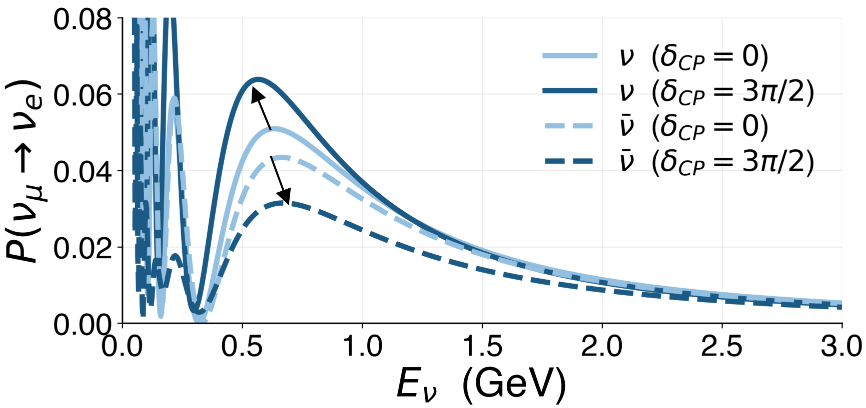
What we can actually measure

$$N_\ell(E_{Rec.}) = P(\nu_\mu \to \nu_\ell)(E_\nu)\,\sigma(E_\nu)\,\Phi_\nu(E_\nu)\,\epsilon(E_\nu)\,S(E_\nu, E_{Rec.})$$

Event rates to oscillation parameters

Animations from L. Munteanu

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial
- **Require a good control over cross section energy dependence and energy reconstruction!**
- Constraints on δ_{CP} rely on differences between electron neutrino and anti-neutrino appearance
- But we mainly measure muon neutrino interactions at the near detector



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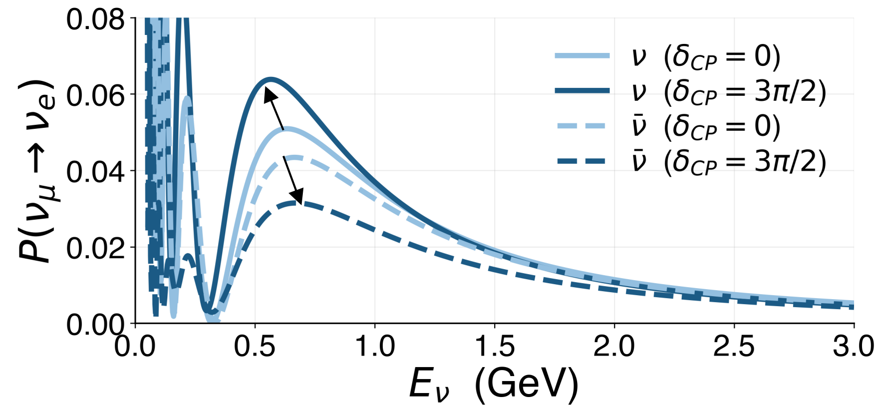
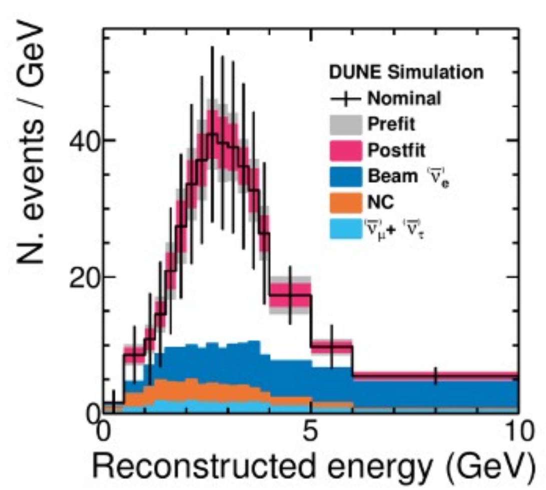
- But we mainly measure muon neutrino interactions at the near detector
- **A good modelling of ν_e/ν_μ and $\boldsymbol{\nu/\bar{\nu}}$ cross section ratio is essential**



Event rates to oscillation parameters

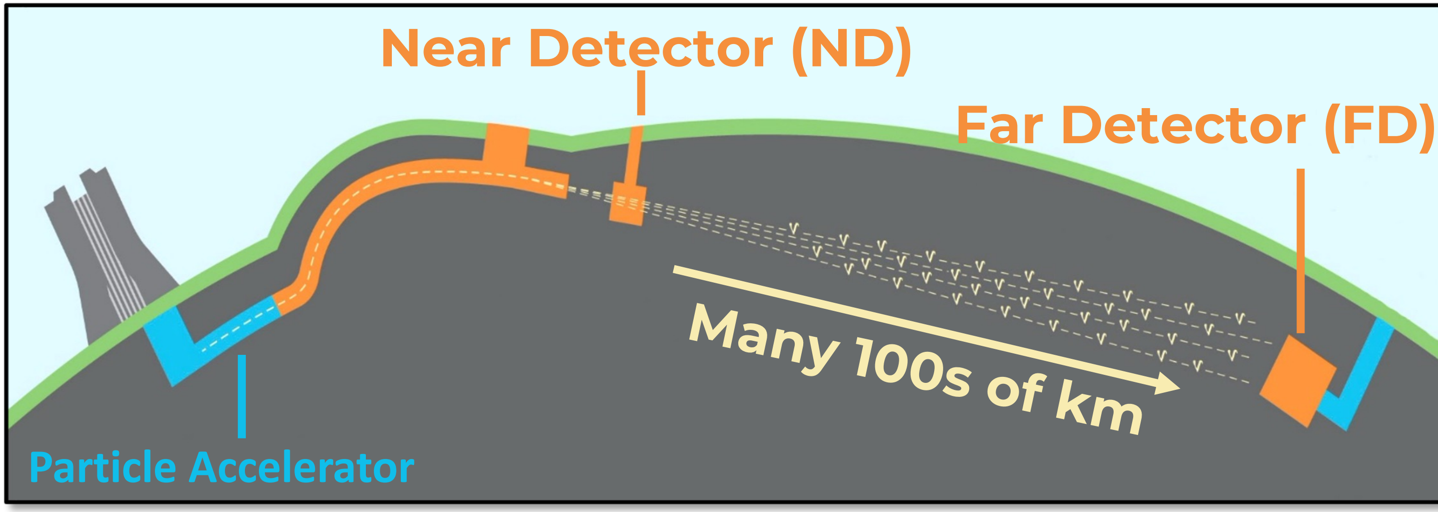
- **Another challenge:** not all events are signal events



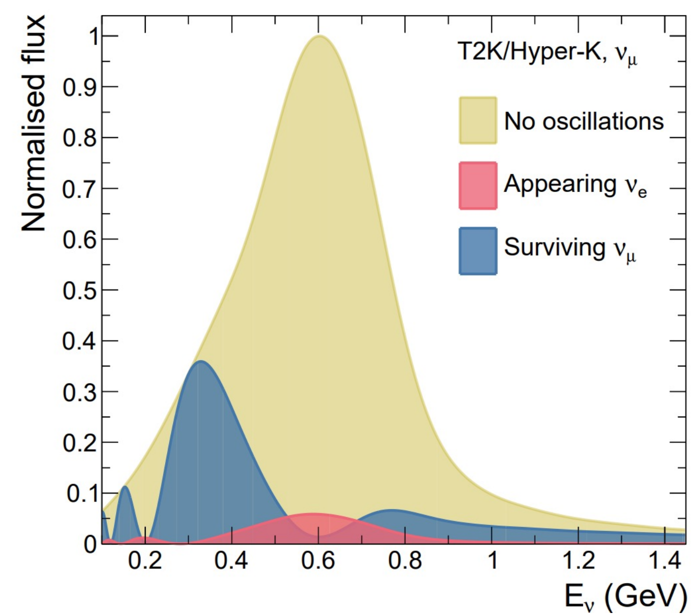
Experiment	Selection	NC	Wrong sign	Wrong flavour	Beam $\overset{(-)}{\nu}_e$	Total bkgd.
DUNE	$\nu_\mu \to \nu_\mu$	2.6%	6.7%	0.8%	N/A	10.1%
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	2.5%	36.2%	0.8%	N/A	39.5%
	$\nu_\mu \to \nu_e$	4.7%	0.8%	2.8%	12.8%	21.2%
	$\bar{\nu}_\mu \to \bar{\nu}_e$	8.4%	20.0%	5.9%	30.5%	64.8%
Hyper-K	$\nu_\mu \to \nu_\mu$	3.5%	5.3%	0.03%	N/A	8.8%
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	2.6%	34.3%	0.01%	N/A	36.9%
	$\nu_\mu \to \nu_e$[1]	5.9%	0.5%	0.3%	12.2%	18.9%
	$\bar{\nu}_\mu \to \bar{\nu}_e$	9.8%	14.9%	0.6%	23.4%	48.6%

Can we constrain all this with the near detector?

Near detector constraints



The flux of seen by ND **is very different** from the oscillated ν_μ or ν_e at the FD



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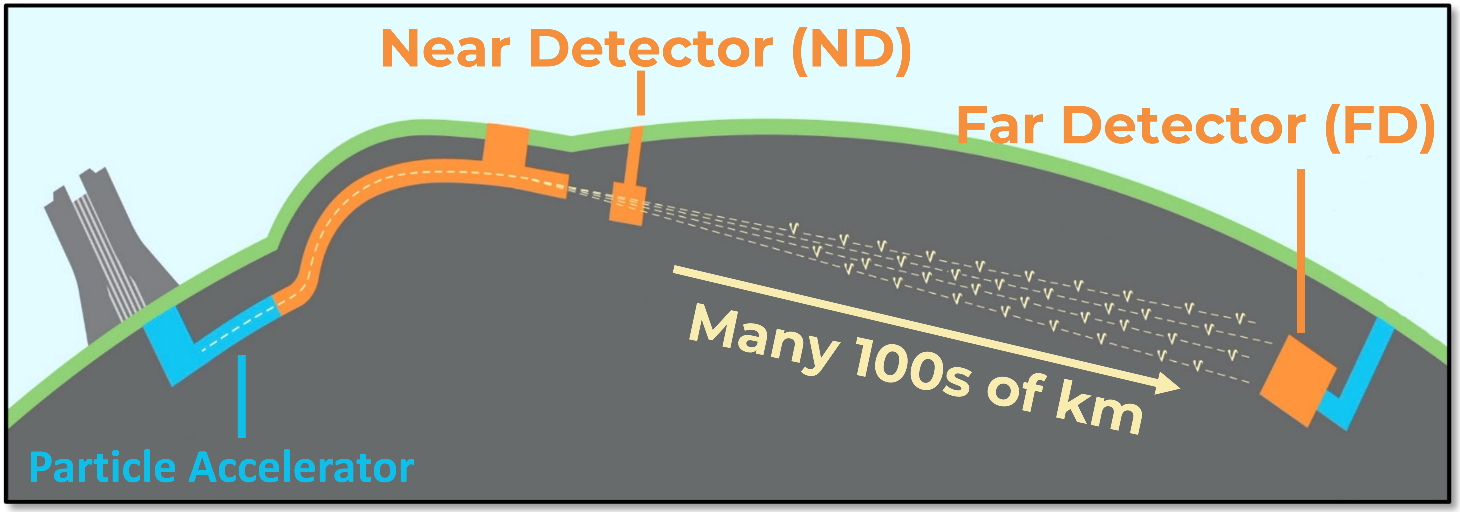

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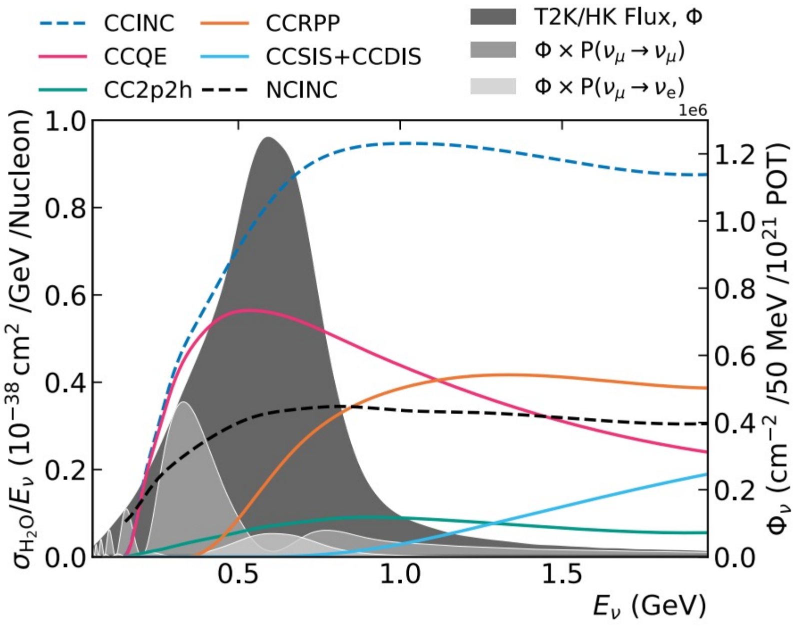
Since we do not know E_ν for every interaction, the ND constrains the **cross section averaged over the ND flux**



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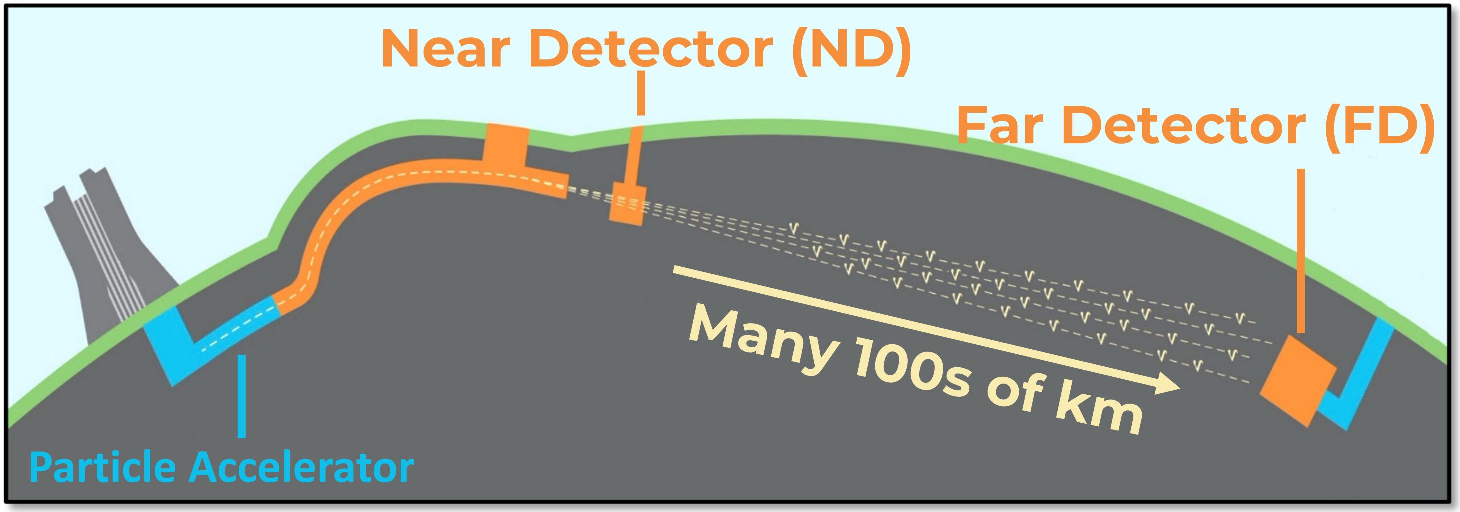

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This can be **very different** than the cross section averaged over the **FD flux**

Channel		Hyper-K/T2K (CC0π)		DUNE (CCINC)	
		w/o osc.	w/ osc.	w/o osc.	w/ osc.
ν_μ	CCQE	74.8%	68.1%	18.4%	16.1%
	CC2p2h	14.4%	14.8%	5.0%	4.3%
	CCRPP	10.1%	14.9%	38.6%	29.9%
	CCSIS/DIS	0.3%	0.7%	36.3%	48.5%

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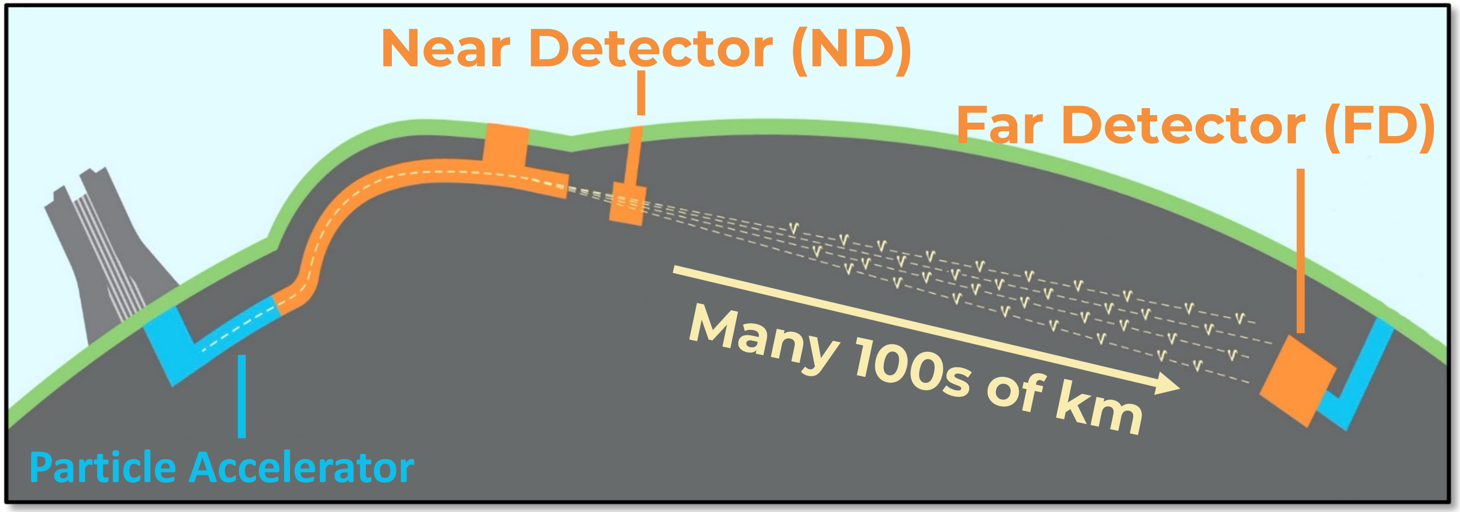

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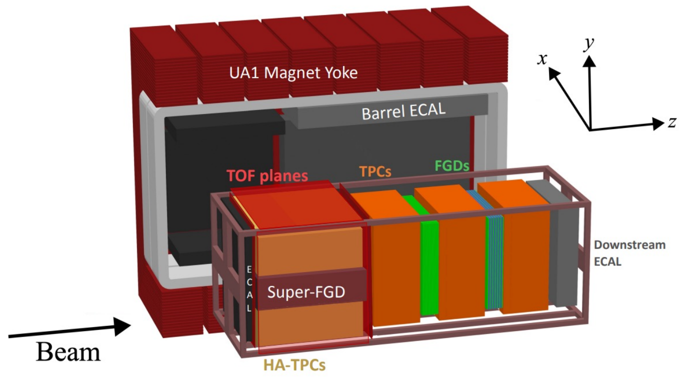
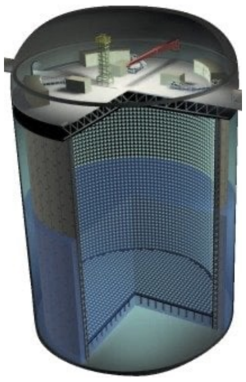


T2K ND: ND280 - mostly carbon

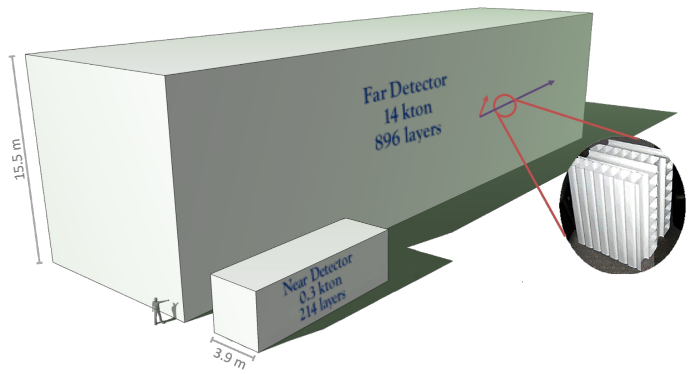


T2K FD: Super-K - water

Further complications in extrapolating from ND to FD

- The ND and FD targets are not always the same → We rely on modelling the **target dependence** of cross sections

Near detector constraints

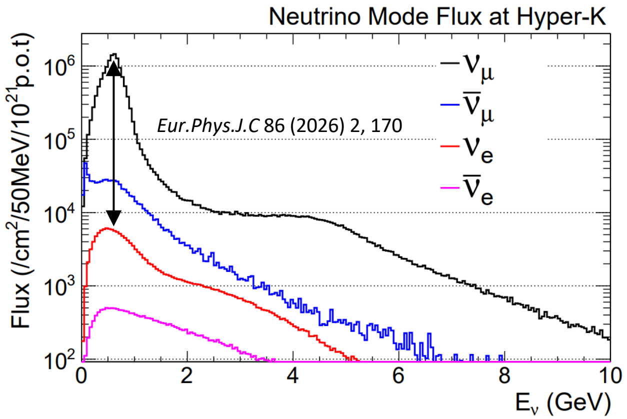


Small ND vs large FD

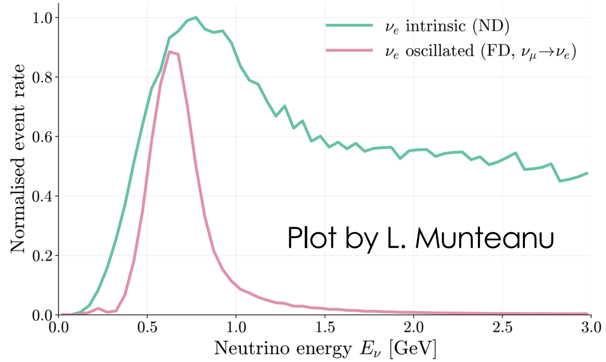
Further complications in extrapolating from ND to FD

- The ND and FD targets are not always the same → We rely on modelling the **target dependence** of cross sections
- The ND and FD acceptance are not always the same → We rely on modelling the **angular dependence** of cross sections

Near detector constraints



ν_e flux is more than100x less than ν_μ
(low stats + challenging backgrounds)



ν_e event rate shape at ND is very different to that expected at FD

Further complications in extrapolating from ND to FD

- The ND and FD targets are not always the same → We rely on modelling the **target dependence** of cross sections
- The ND and FD acceptance are not always the same → We rely on modelling the **angular dependence** of cross sections
- We do not have many ν_e at the ND and they do not match the flux of ν_e at the FD → We rely on modelling the **flavour dependence** of cross sections

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(a non exhaustive list)

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Where are we so far?

- Current neutrino oscillation experiments are mostly **statistics limited**
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Another key question:

How well do we control these specific aspects of neutrino interaction modelling?

Answering with model spread

How well do we control these specific aspects of neutrino interaction modelling?

To answer this, we would ideally

1. Choose one robust model that **describes global data**
2. Vary a **comprehensive set of parameters** within their **theory+data driven limits**
3. See the uncertainty band in e.g. neutrino energy dependence

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- For existing incomplete parameterisations, there're often not well-defined limits

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Alternative fall-back approach: **model spread**

1. Choose many models that span current theory models
2. See their spread in how they predict in e.g. neutrino energy dependence

Neutrino energy reconstruction

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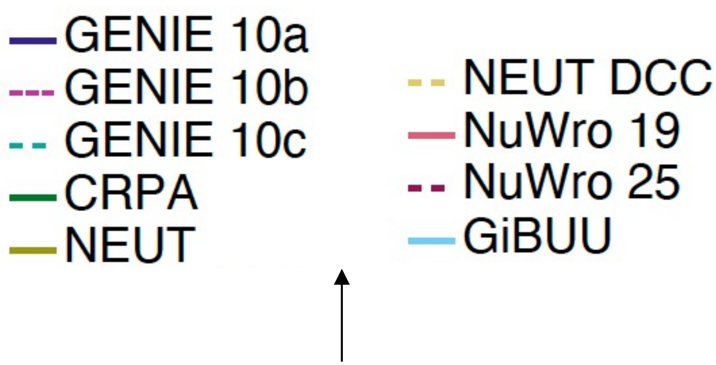

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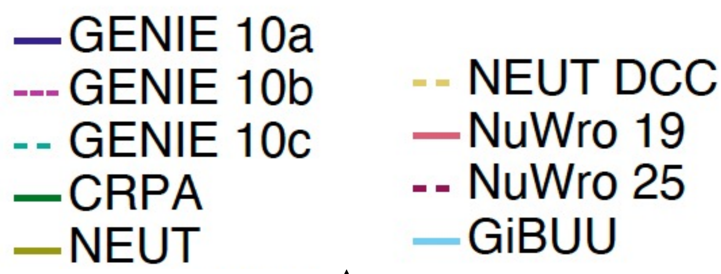
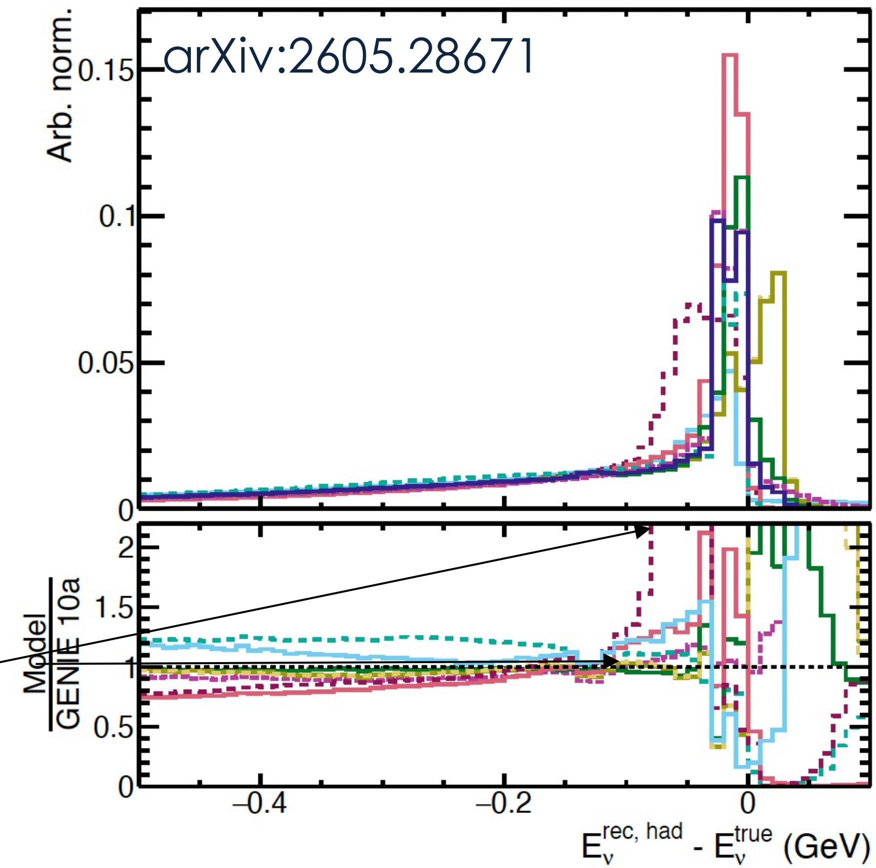


Model spread

Proportion of E_ν reconstructed **within 200 MeV** of the true E_ν differs by **more than 100%**



Energy dependence

We need to know:

2. The energy dependence of neutrino cross sections
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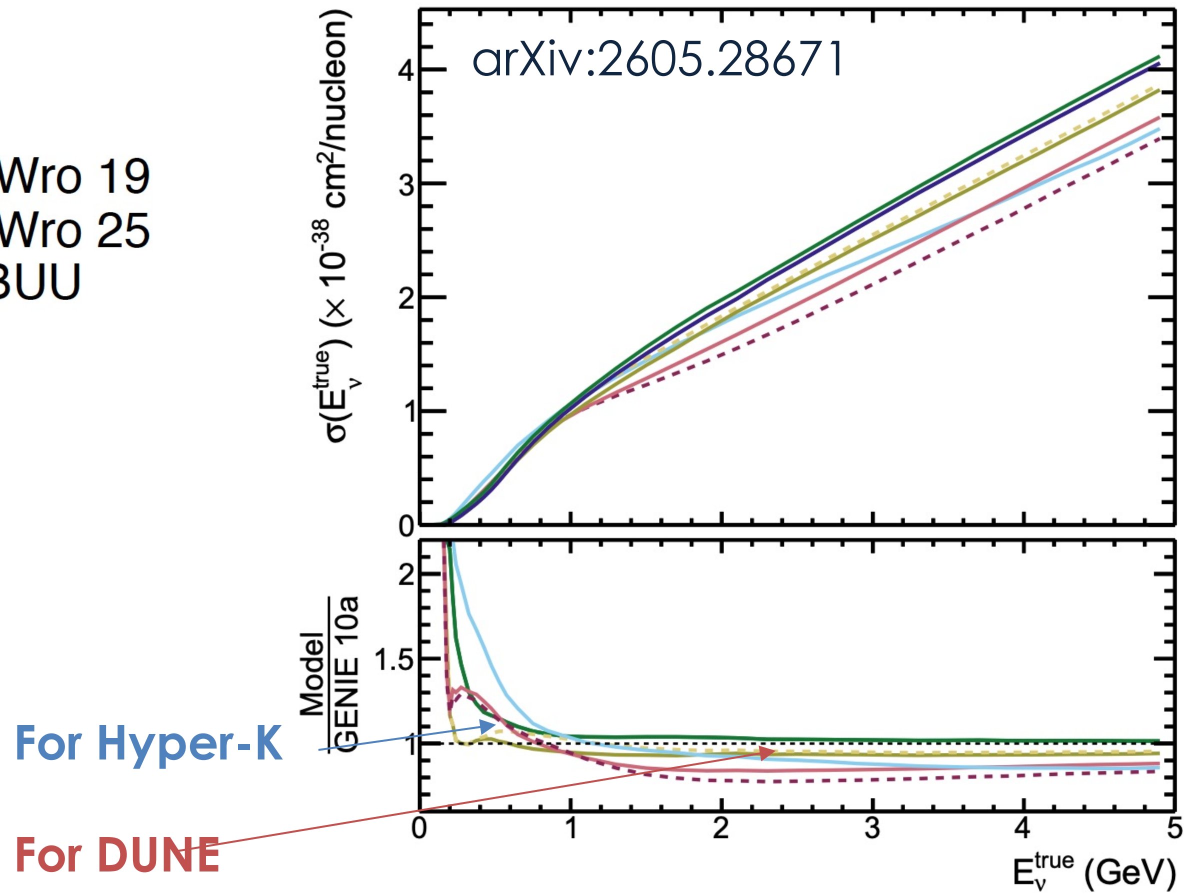
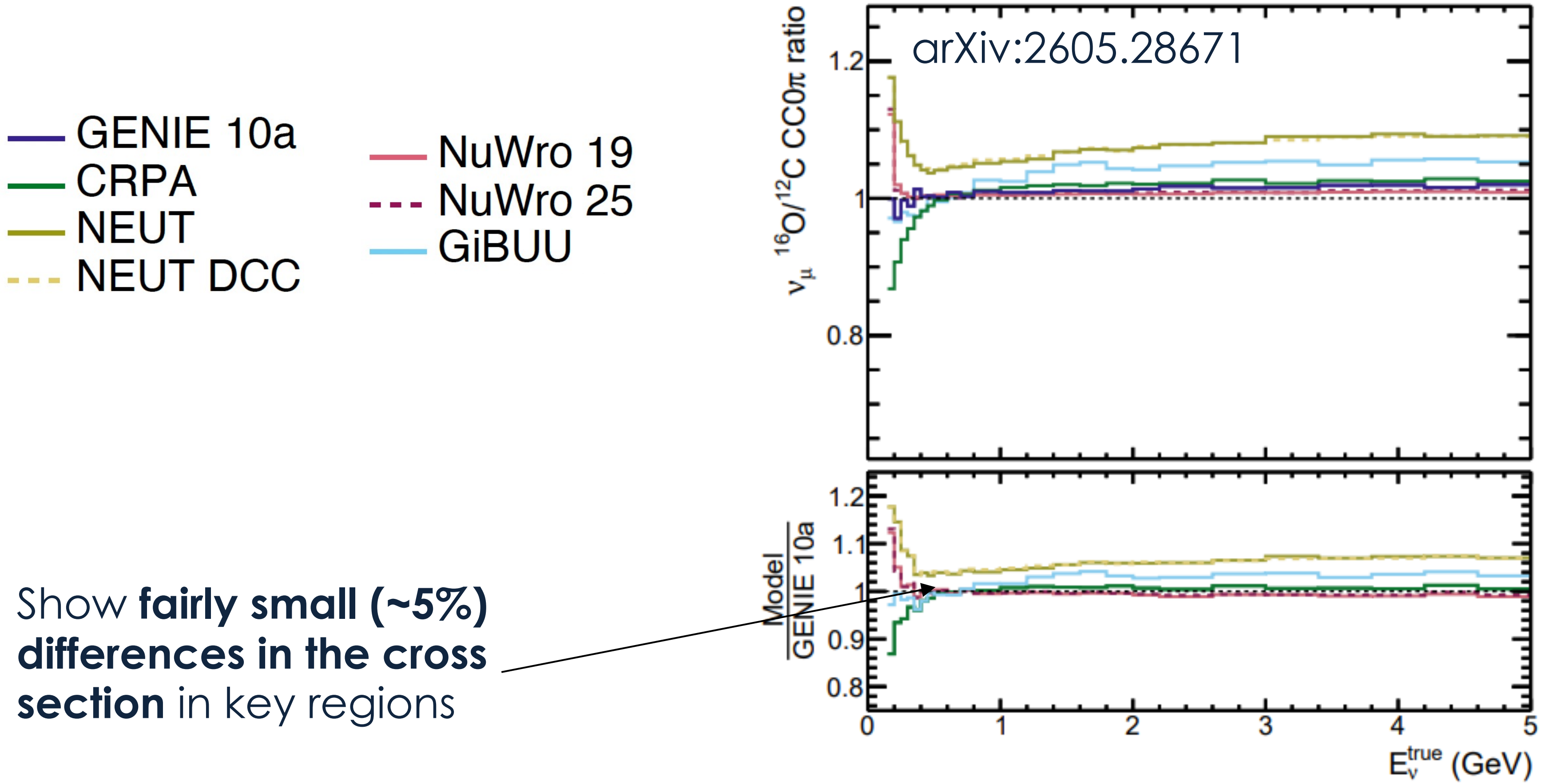


Show **significant (~20%) differences in the cross section** in key regions and on its evolution with E_ν

Target dependence

We need to know:

3. The target dependence of neutrino cross sections
   - *So we can use the full power of near detector constraints*

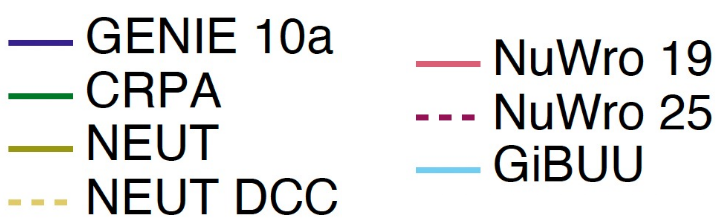


Show **fairly small (~5%) differences in the cross section** in key regions

Angular dependence

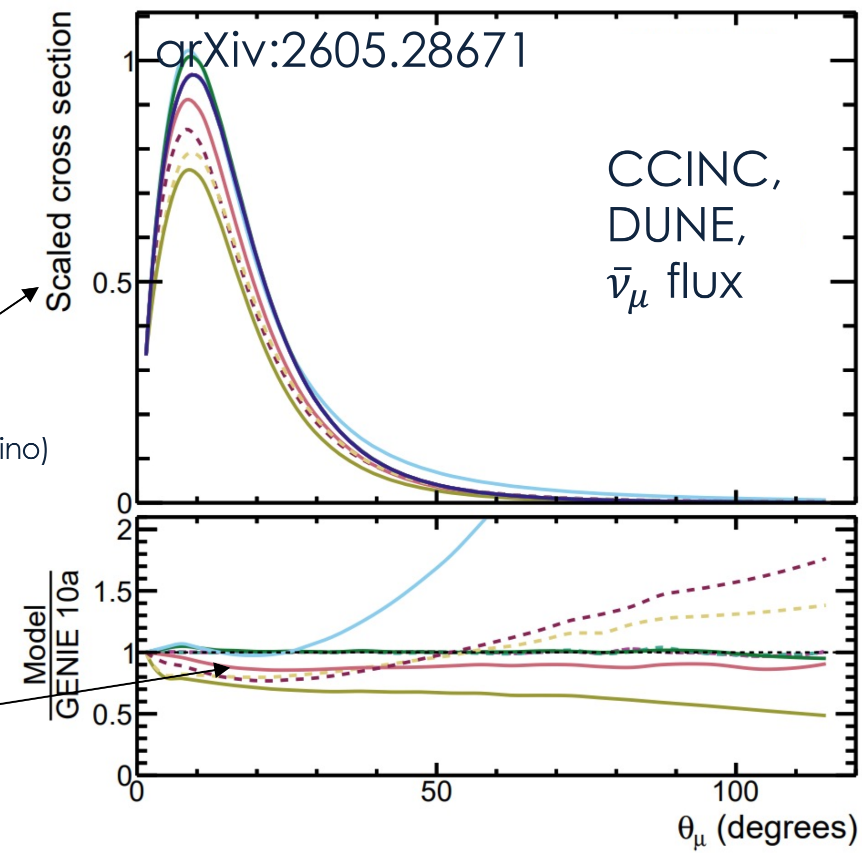
We need to know:

4. The angular dependence of neutrino cross sections
   - *So we can use the full power of near detector constraints*



Cross section relative to $\theta_\mu = 0$

(θ_μ is the angle between the outgoing muon and the incoming neutrino)



Show **significant (~30%) differences in the cross section** in key regions

ν_e/ν_μ differences

We need to know:

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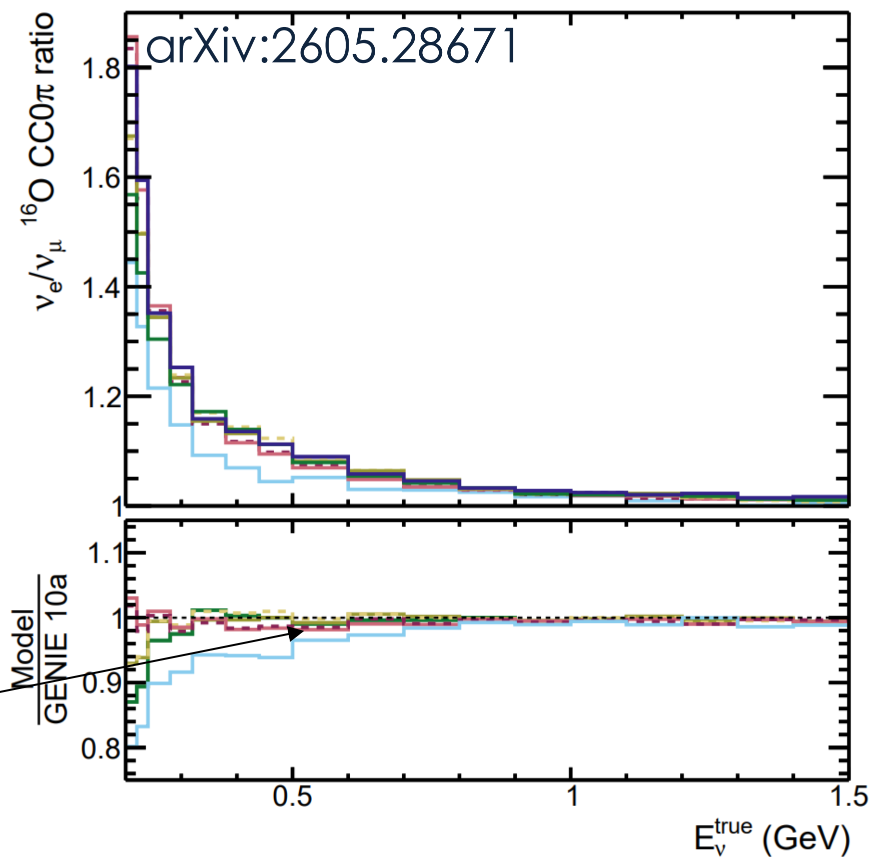

Show **fairly small (~3-5%) differences in the cross-section ratio** in key regions

$\nu/\bar{\nu}$ differences

We need to know:

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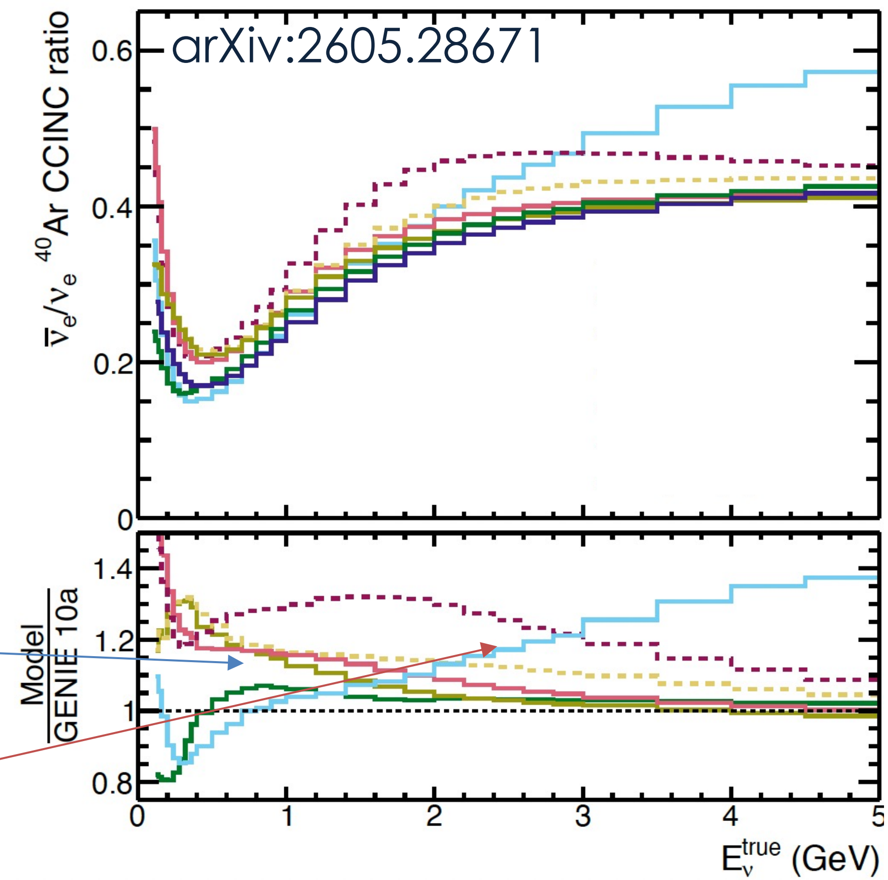

Show **significant (~30%) differences in the cross section** at Hyper-K and DUNE peak energies!

For Hyper-K

For DUNE

Background contirbutions

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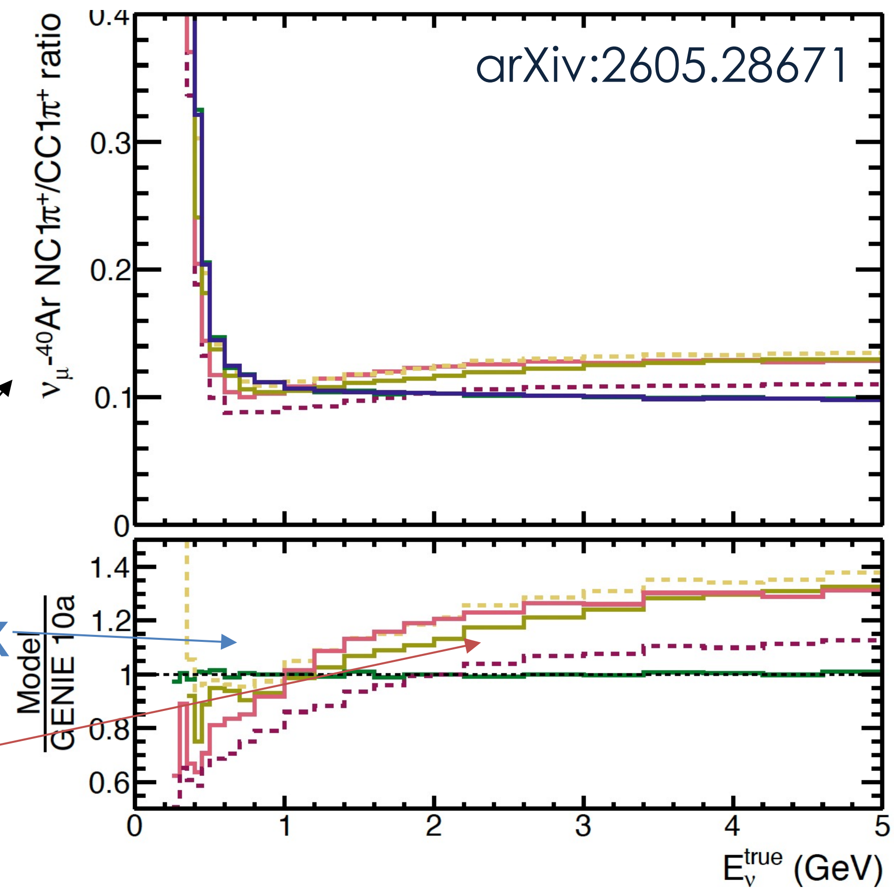
Ratio of NC background cross section to the CC cross section we try to constrain at the ND



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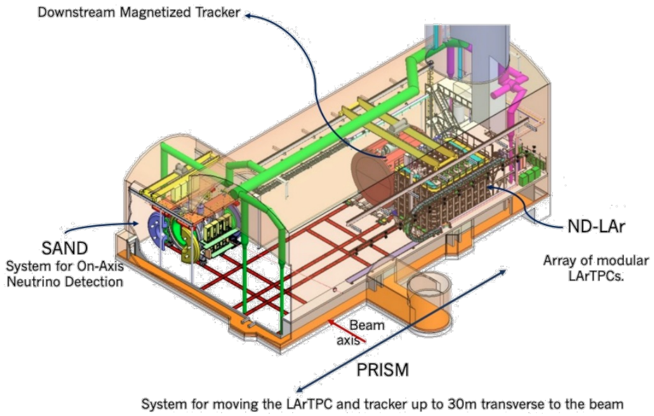
- Current models **differ substantially** in their predictions of some of the cross sections that matter most for neutrino oscillation experiments

Confronting the challenge

Improved near detector capabilities



Engagement with the nuclear theory community

GiBUU

NuWro Wroclaw Neutrino Event Generator

Genie UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Dedicated lepton-nucleus cross-section measurement programs

SBN Program

MINERvA

e4V

nuSCOPE neutrino SPS COmplex for Precision Experiments

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(a non exhaustive list of my own thoughts)

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  - Covering fundamental model ingredients
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- Help with **hadronization**
  - We're already well past the point where PYTHIA is enough
- More means to **benchmark FSI cascade models**
  - Comparing microscopic QE to cascades is great, can we go further?
  - More internally consistent "hard scatter" + FSI models like GiBUU

Summary

- Next-generation neutrino oscillation experiments have unique potential to **push back the frontiers of particle physics**
- Their ability to do this hinges on the extent to which we can **model certain aspects of neutrino interactions**
  - Near detector data ***does not*** remove the need for accurate modelling
- Current neutrino interaction models **are likely not sufficient** for DUNE or Hyper-K to reach their ultimate sensitivity
  - The current uncertainty parameterisations are **definitely not sufficient**
- Developing the models we need for the future relies on **close collaboration between experimentalists and theorists**

Backups

What can we measure: PMNS

Pontecorvo-**M**aki-**N**akagawa-**S**akata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Three-flavour mixing

$$P_{\alpha\rightarrow\beta} = |\langle\nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

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The **phase of the oscillation** depends on:
- The difference in neutrino mass state masses
- The distance travelled (L) over the neutrino energy (E)

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$$U_{PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$ $c_{ij} = \cos\theta_{ij}$

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- The difference in neutrino mass state masses
- The distance travelled (L) over the neutrino energy (E)

The **amplitude of the oscillation** depends on:
- The PMNS neutrino mixing matrix elements

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Pontecorvo-**M**aki-**N**akagawa-**S**akata

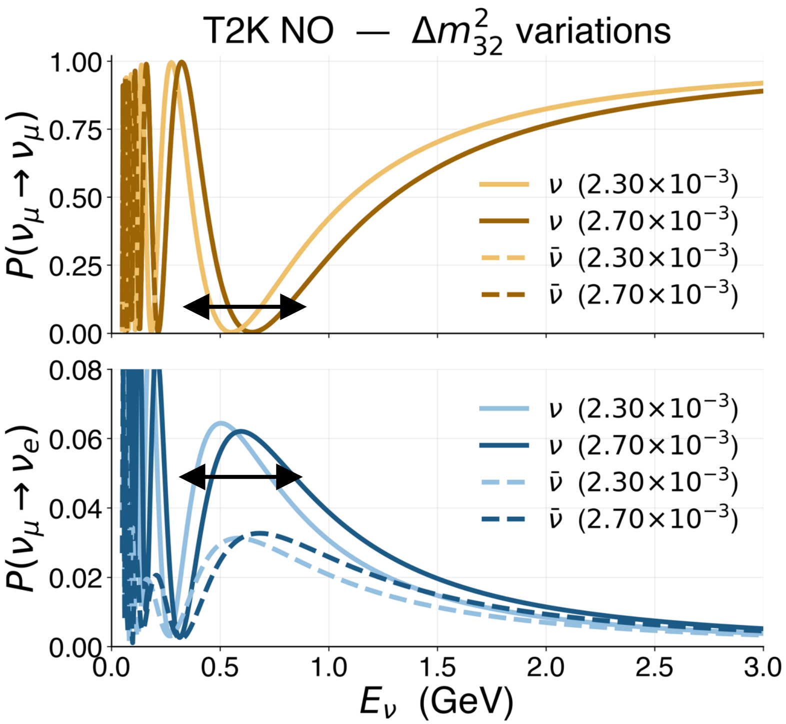
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \updownarrow \Delta m^2_{32} \qquad U_{PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{+i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix} 1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$ $\quad c_{ij} = \cos\theta_{ij}$

(See PPTX upload for animated version)

<u>What long-baseline experiments can measure</u>

One of the mass splittings: Δm^2_{32}



Note the difference in y-axis scale!

What can we measure: PMNS

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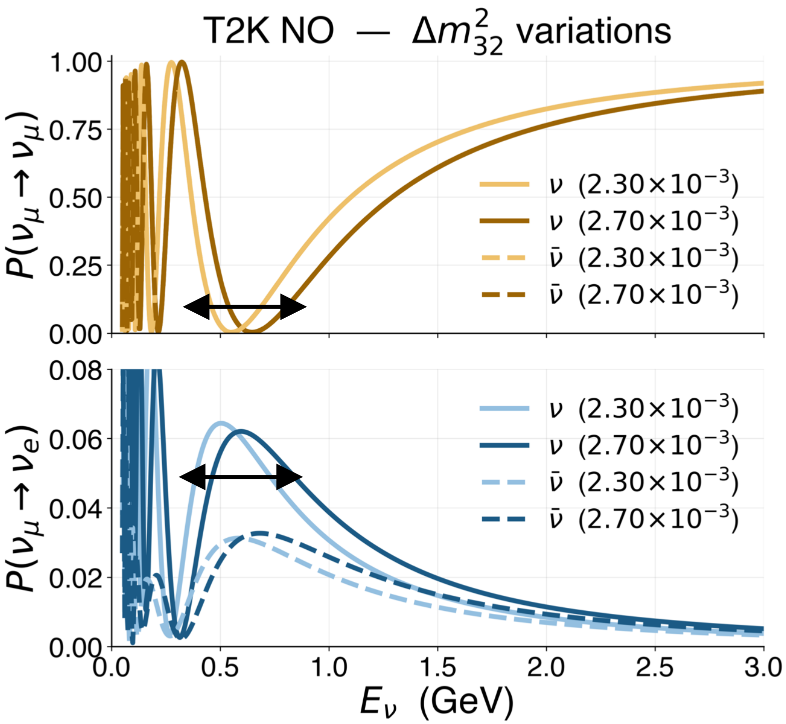
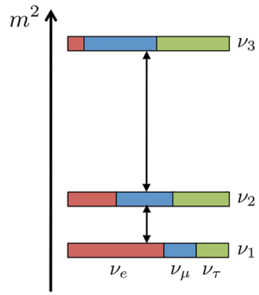
What long-baseline experiments can measure

One of the mass splittings: Δm^2_{32}

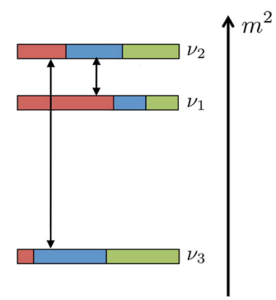
Including its sign!

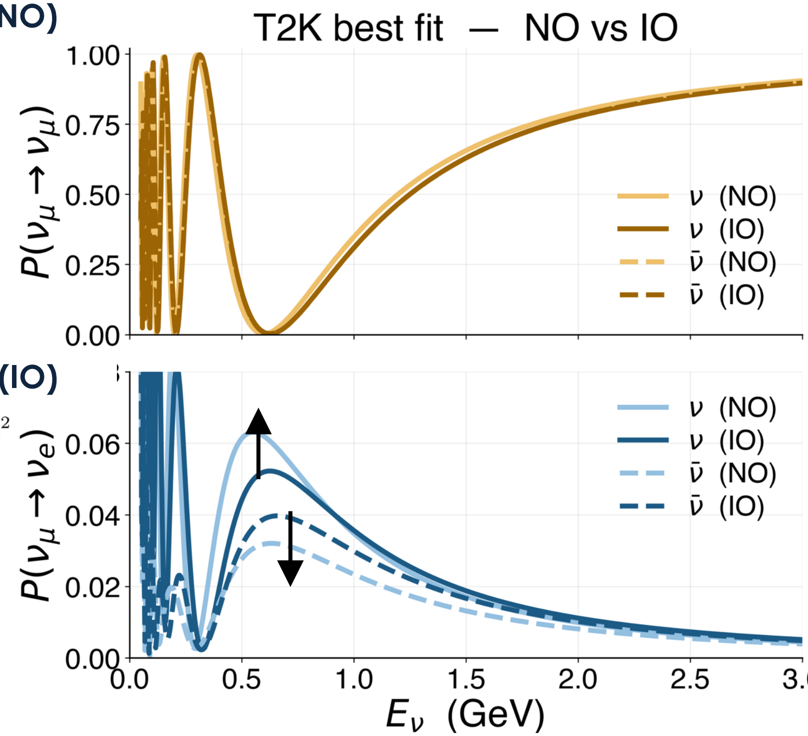


Normal Ordering (NO)



Inverted Ordering (IO)





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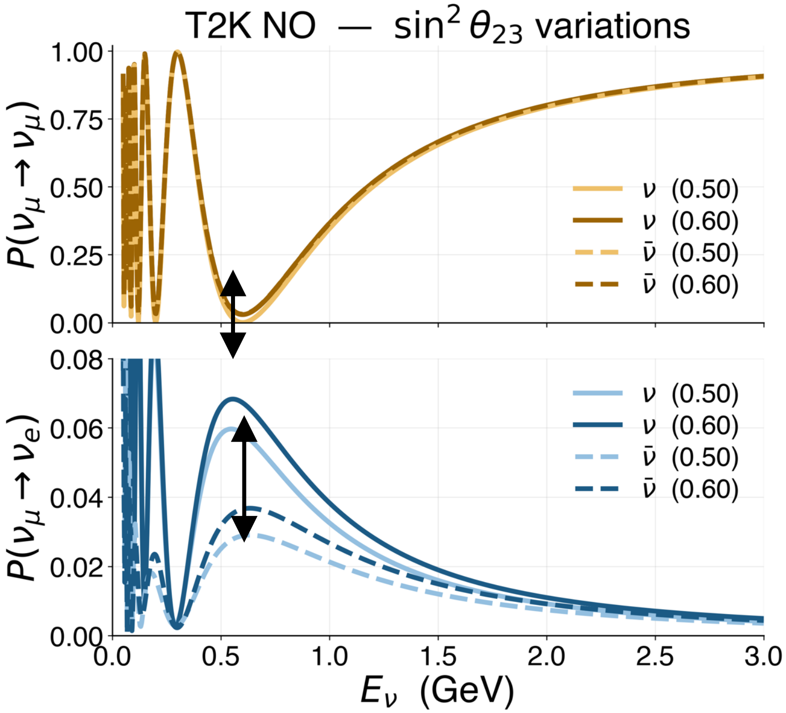
(See PPTX upload for animated version)

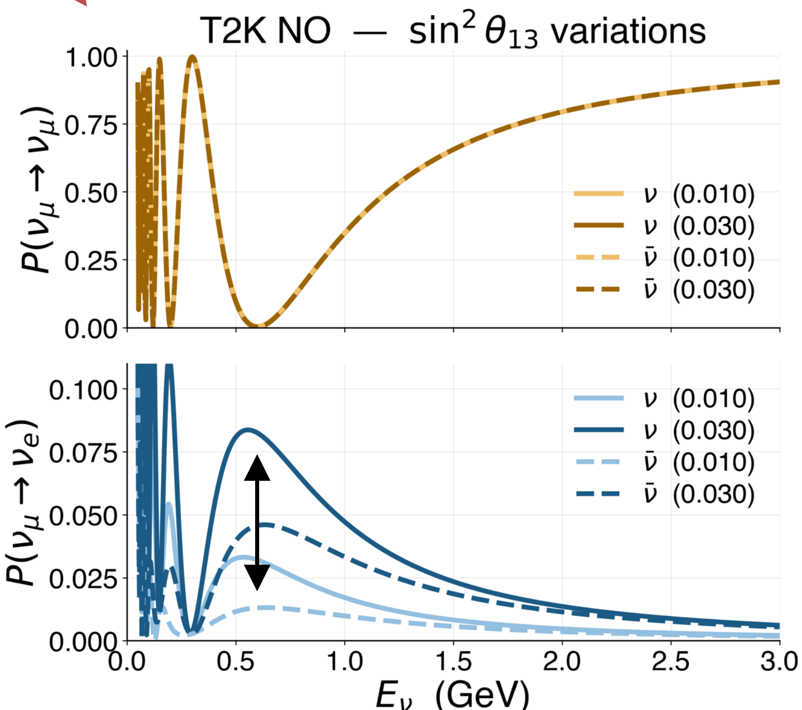
What long-baseline experiments can measure

One of the mass splittings: Δm^2_{32}

Two of the mixing angles: θ_{23}, θ_{13}*

*Accelerator-based experiments typically use external constraints on θ_{13} from reactor measurements. This helps to break degeneracies with other parameters.





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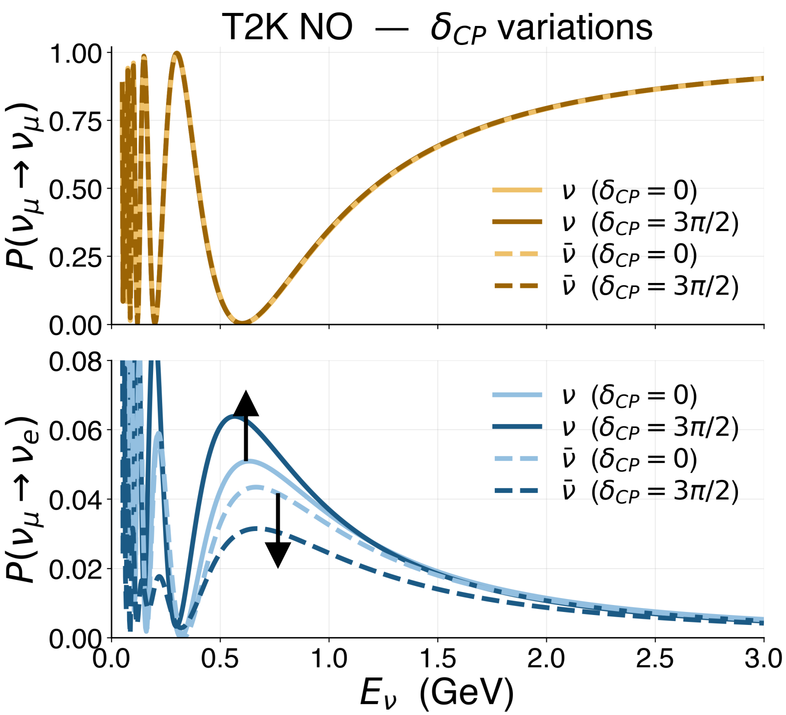
What long-baseline experiments can measure

One of the mass splittings: Δm^2_{32}

Two of the mixing angles: θ_{23}, θ_{13}

One CP-Violating phase: δ_{CP}



A possible timeline

2029 – Combinations of experiments provide 3σ determination of neutrino mass ordering 🎉

2030 – Hyper-K provides 5σ evidence for CP-violation 🎉

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2039 – DUNE and Hyper-K inferences of $P(\nu_\mu \rightarrow \nu_\ell)$ disagree with no clear explanation …

Conclusions

Long-baseline neutrino oscillation measurements are confronting some of the primary open questions in HEP

Next years: *To precision PMNS measurements …*

- What is the neutrino mass ordering?
- Is there CP-violation in the lepton sector? How much (via δ_{CP})?
- Are there symmetries in the PMNS parameters (e.g. μ, τ in ν_3)

Next decades: … *and beyond*

- Is the PMNS 3ν paradigm sufficient to describe global data?
- If not, what kind of deviations do we see?

What this needs

- Successful realisation of DUNE *and* Hyper-K
- Their consideration alongside global oscillation data
- A dedicated effort to confront potentially limiting systematics