Neutrinos are a high-energy (nuclear) particle physic

Neutrino Interactions Lecture 2

Hampton University Graduate Studies (HUGS) Program 2024
Week 2 — June 6th, 2024

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Neutrinos are weird and awesome (Whoo! Cowboys)

Last time on our program!

We briefly touched on neutrino properties, why they're important, and how they fit into the standard model

We explored the fundamental fermion known as the neutrinos, starting with its initial postulation in a last ditch attempt to conserve energy in beta decay.

We then talked about its first observation and the discovery of different neutrinos flavors.

We talked about a deficit in neutrinos which were measured by multiple experiments and the confirmation of neutral current processes.

Eventually we got the confirmation of neutrino oscillations!

We then reviewed the current generation and the future generation of *long baseline* neutrino oscillation experiments and their corresponding physics programs.

Now we get into the fun stuff!

Neutrinos and Oscillation Physics (Part Two)

Paths to Beyond the Standard Model Physics

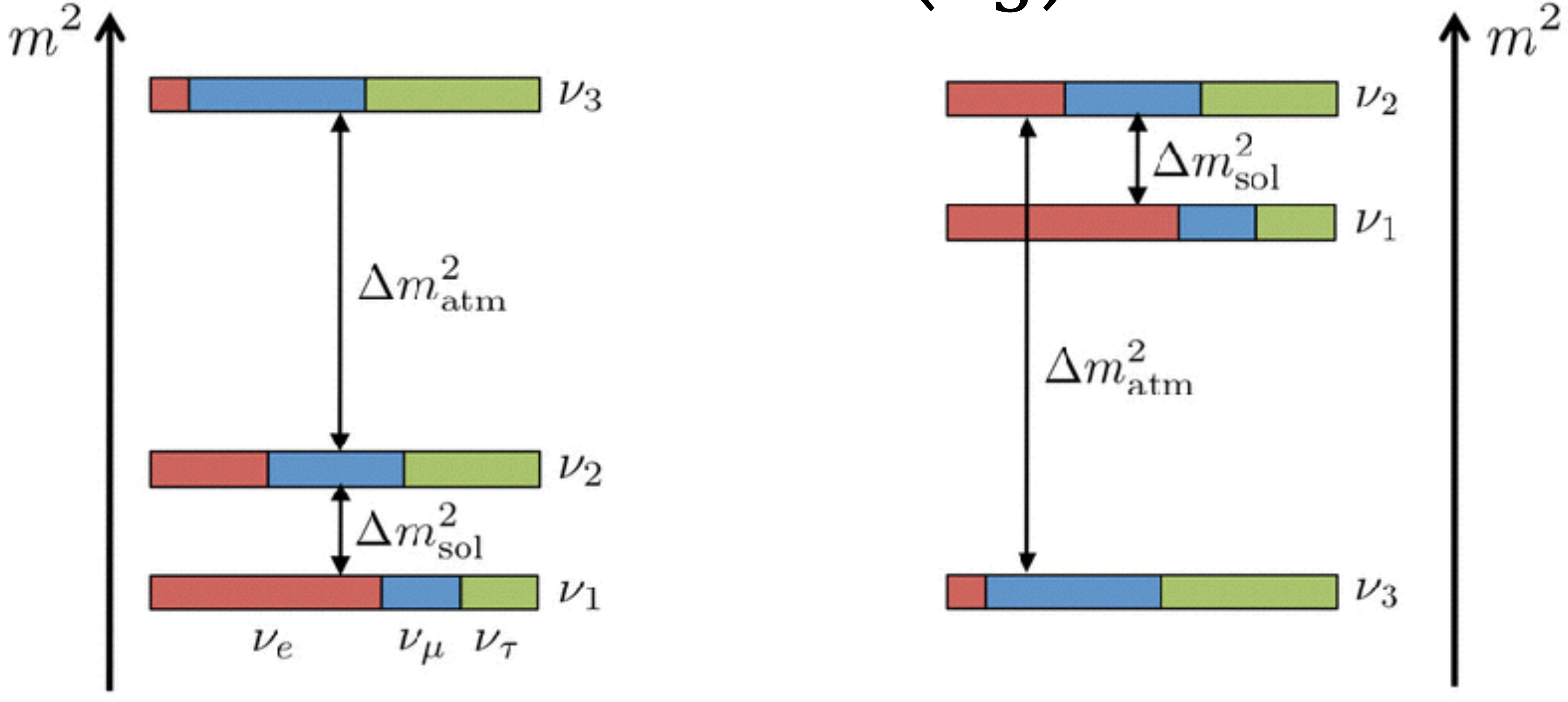
$$\mathcal{L}_{\mathrm{CC}} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L} \gamma^\mu \nu_{\alpha L} + \text{h.c.} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L} \gamma^\mu \sum_{i=1,2,3} U_{\alpha i}\, \nu_{iL} + \text{h.c.}$$

$$|U| = \overset{\text{PMNS Matrix}}{\begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu 1} & |U|_{\mu 2} & |U|_{\mu 3} \\ |U|_{\tau 1} & |U|_{\tau 2} & |U|_{\tau 3} \end{bmatrix}} = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \overset{\text{Reactor}}{\begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix}} \overset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$$U_{\alpha i}\colon \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathcal{R}_{Atmos}(\theta_{23}) \cdot \mathcal{R}_{React}(\theta_{13}, \delta_{CP}) \cdot \mathcal{R}_{Solar}(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

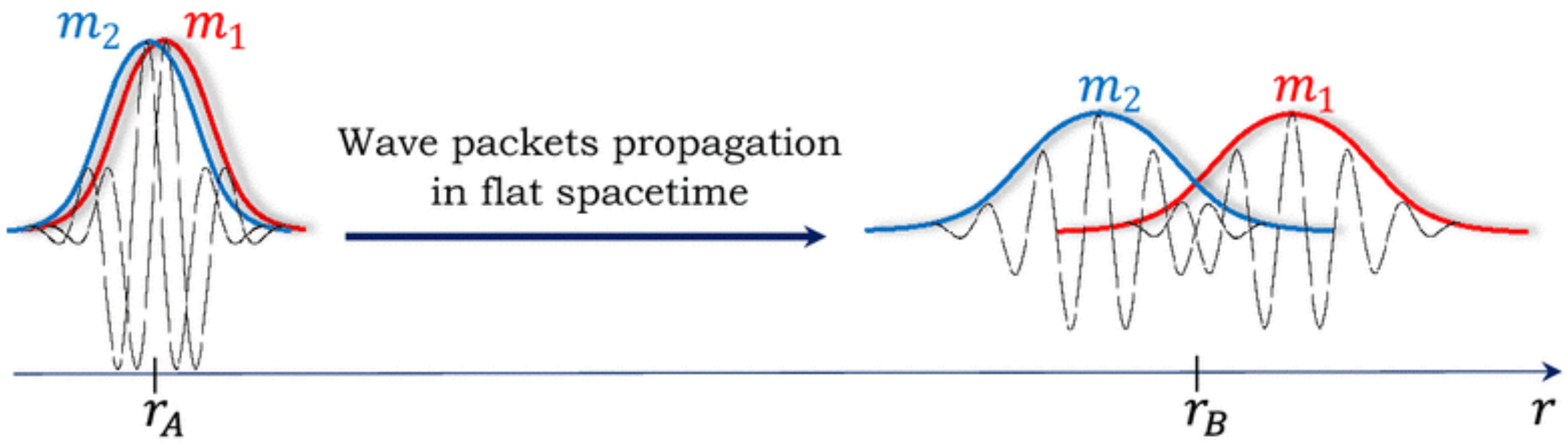
The neutrino mixing matrix has parameters and coefficients directly describing the splitting of the mass states and asymmetry between neutrino and anti-neutrinos!

Leptonic CP-violation serves as a proof of concept for the matter-antimatter asymmetry!



Neutrinos and Oscillation Physics (Part Five)

Derivation of Oscillations



Let's start by assuming two unique bases exist for describing neutrinos (in 3 flavors). The translation between the two is described by the unitary PMNS matrix:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}\,|\nu_i\rangle\,,$$

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$|\nu_i\rangle = \sum_\alpha U^*_{\alpha i}\,|\nu_\alpha\rangle\,,$$

Now for the mass states, we can propagate the neutrino through space-time as a plane wave:

$$|\,\nu_j(t)\,\rangle = e^{-i\left(E_j t - \vec{p}_j \cdot \vec{x}\right)}\,|\,\nu_j(0)\,\rangle\ ,$$

And in the ultrarelativistic limit (assume m<<p):

$$E_j = \sqrt{p_j^2 + m_j^2} \simeq p_j + \frac{m_j^2}{2\,p_j} \approx E + \frac{m_j^2}{2\,E}\,, \quad |\,\nu_j(L)\,\rangle = e^{-i\left(\frac{m_j^2\,L}{2\,E}\right)}\,|\,\nu_j(0)\,\rangle\ .$$

All math is seriously from wikipedia

Neutrinos and Oscillation Physics (Part Six)

Derivation of Oscillations

Now, examining the probability of changing flavor as a neutrino propagates:

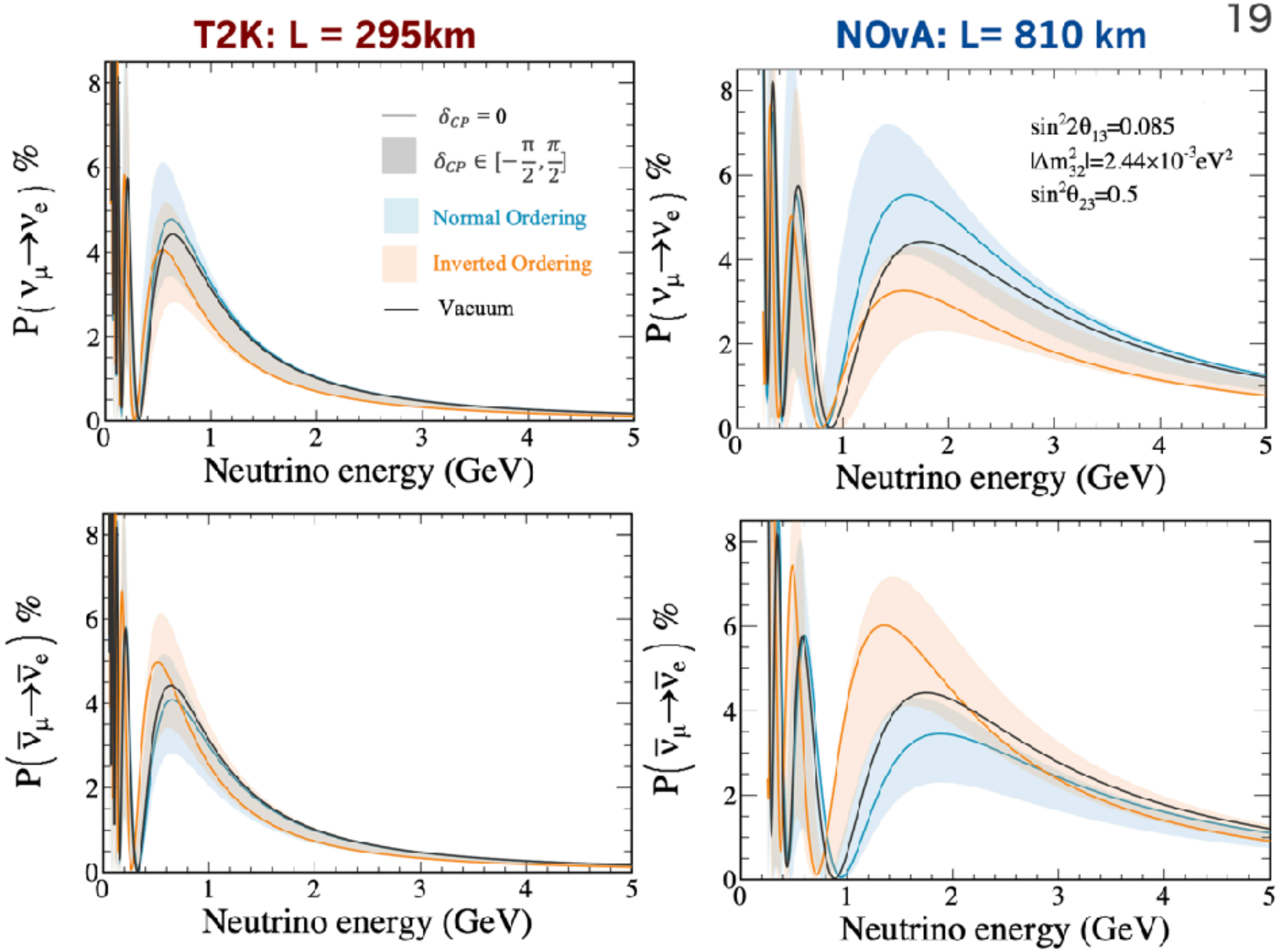
$$P_{\alpha\to\beta} = \left| \langle \nu_\beta \,|\, \nu_\alpha(L) \rangle \right|^2 = \left| \sum_j U^*_{\alpha j}\, U_{\beta j}\, e^{-i\frac{m_j^2\, L}{2E}} \right|^2 .$$

Which with $\Delta_{jk} m^2 \equiv m_j^2 - m_k^2$:

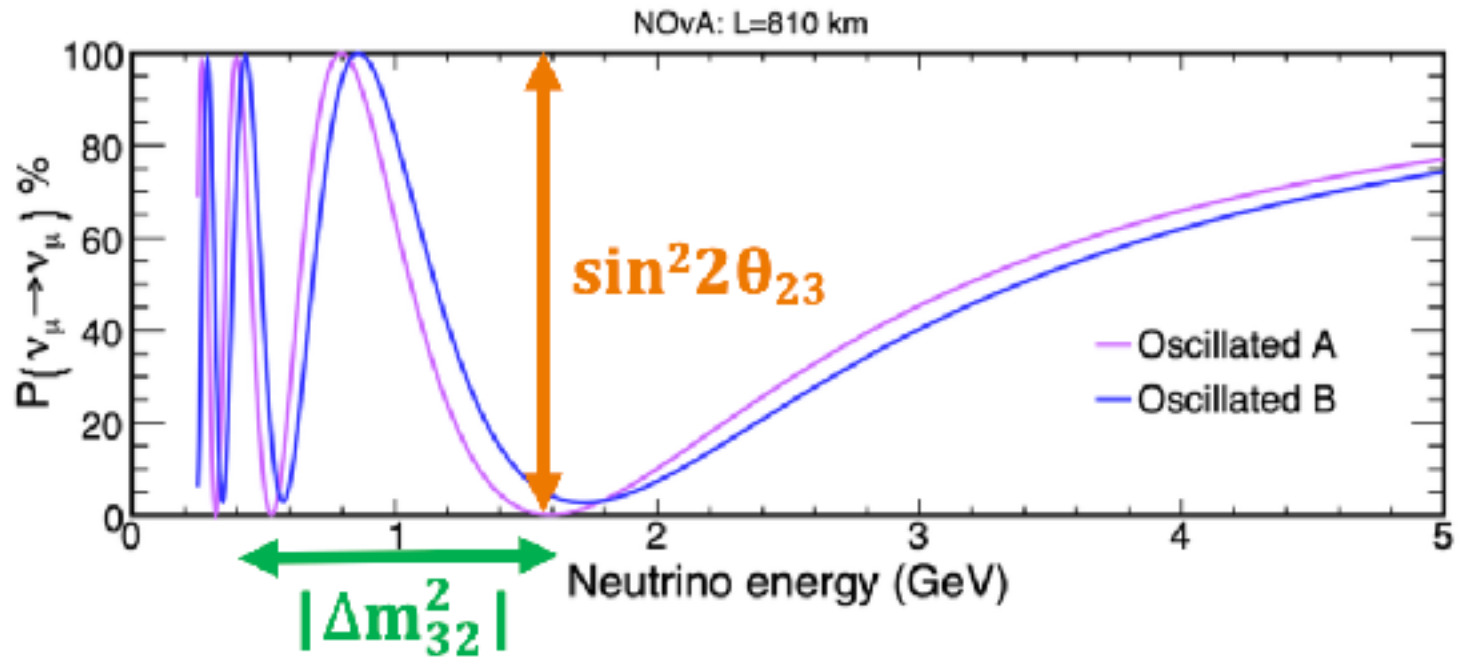
$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4 \sum_{j>k} \mathcal{R}_e \left\{ U^*_{\alpha j}\, U_{\beta j}\, U_{\alpha k}\, U^*_{\beta k} \right\} \sin^2\left(\frac{\Delta_{jk} m^2\, L}{4E} \right)$$
$$+\, 2 \sum_{j>k} \mathcal{I}_m \left\{ U^*_{\alpha j}\, U_{\beta j}\, U_{\alpha k}\, U^*_{\beta k} \right\} \sin\left(\frac{\Delta_{jk} m^2\, L}{2E} \right) ,$$

and:

$$\frac{\Delta_{jk}(mc^2)^2\, L}{4\hbar c\, E} = \frac{\text{GeV fm}}{4\hbar c} \times \frac{\Delta_{jk} m^2}{\text{eV}^2} \frac{L}{\text{km}} \frac{\text{GeV}}{E} \approx 1.27 \times \frac{\Delta_{jk} m^2}{\text{eV}^2} \frac{L}{\text{km}} \frac{\text{GeV}}{E} ,$$



(Z. Vollari, NOvA-T2K JETPS, ’24)



Neutrinos and Oscillation Physics (Part Seven)

Derivation of Oscillations

Finally:

$$A_{\mathsf{CP}}^{(\alpha\beta)} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = 4 \sum_{j>k} \mathcal{I}_m \left\{ U^*_{\alpha j}\, U_{\beta j}\, U_{\alpha k}\, U^*_{\beta k} \right\} \sin\left(\frac{\Delta_{jk} m^2\, L}{2E} \right)$$

with:

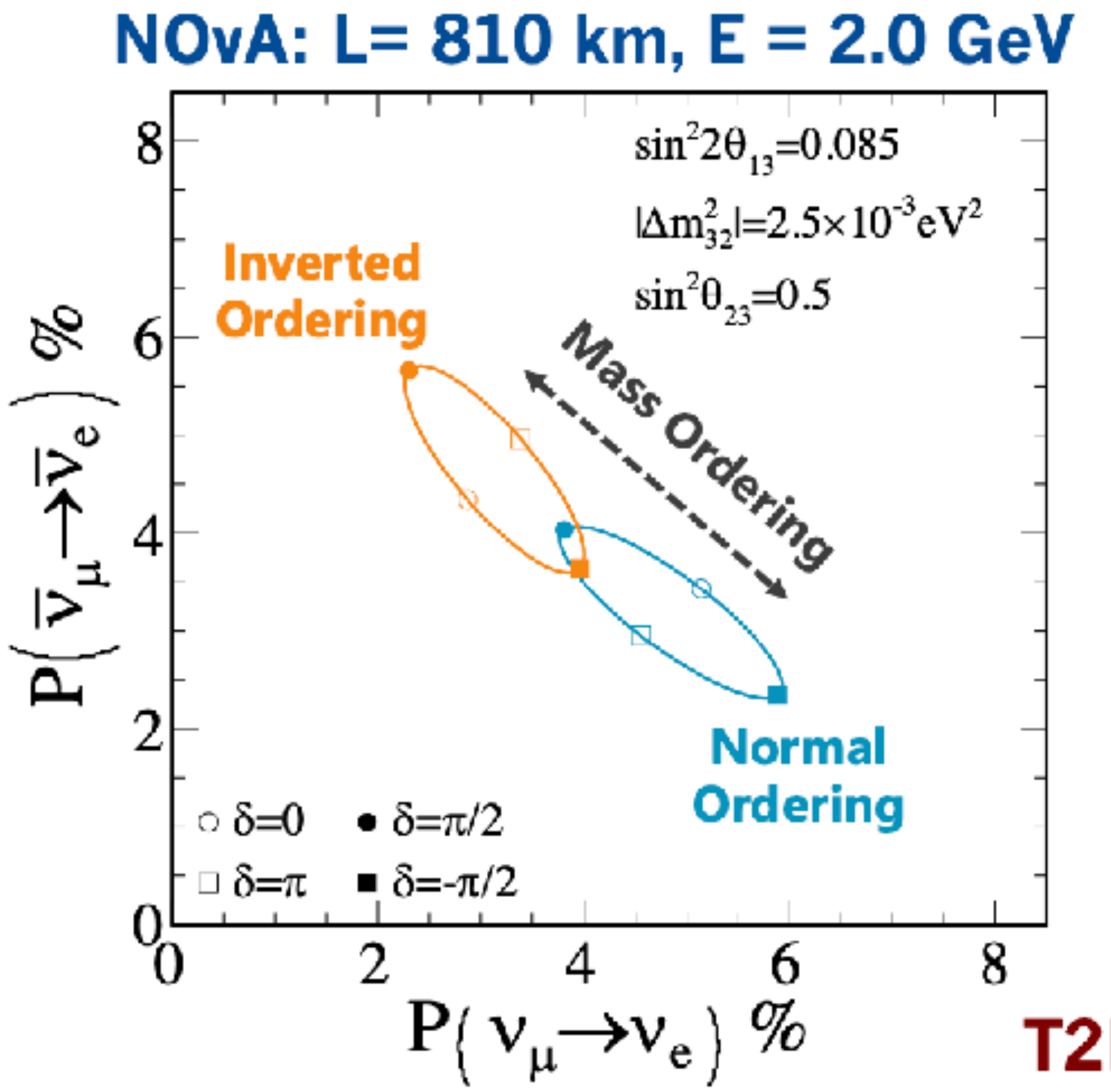
$$\mathcal{I}_m \left\{ U^*_{\alpha j}\, U_{\beta j}\, U_{\alpha k}\, U^*_{\beta k} \right\} = J \sum_{\gamma,\ell} \varepsilon_{\alpha\beta\gamma}\, \varepsilon_{jk\ell} \ ,$$

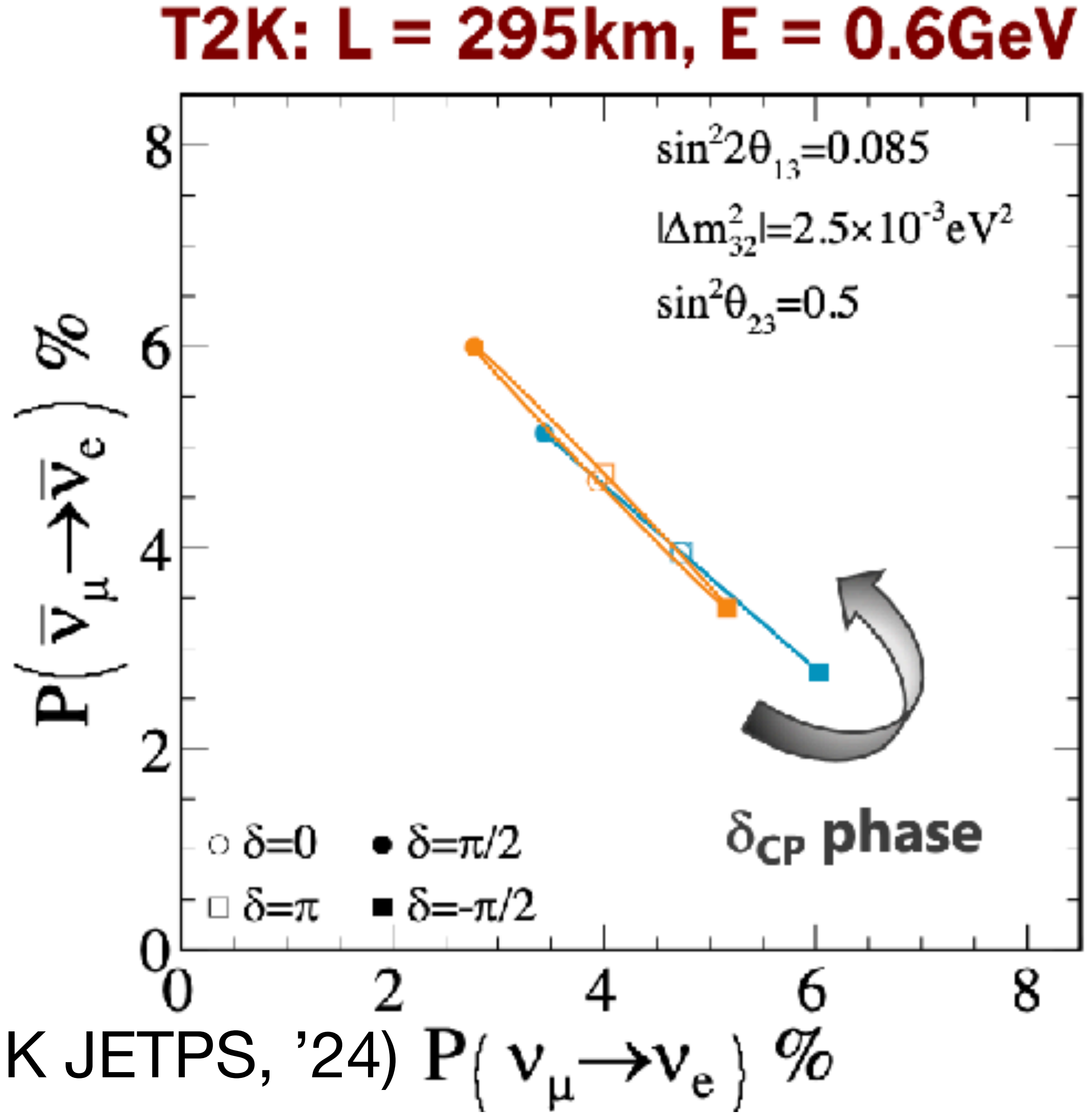
gives:

$$A_{\mathsf{CP}}^{(\alpha\beta)} = 16 \sin\left(\frac{\Delta_{21} m^2\, L}{4E} \right) \sin\left(\frac{\Delta_{32} m^2\, L}{4E} \right) \sin\left(\frac{\Delta_{31} m^2\, L}{4E} \right) J \sum_{\gamma} \varepsilon_{\alpha\beta\gamma}$$

The last expression for the amplitude of the asymmetry as we move from neutrino flavor α to β illustrates the degeneracy that comes with the mass splitting!

NOvA has a longer baseline and is at higher energy allowing for the degeneracy in mass ordering to be resolved.

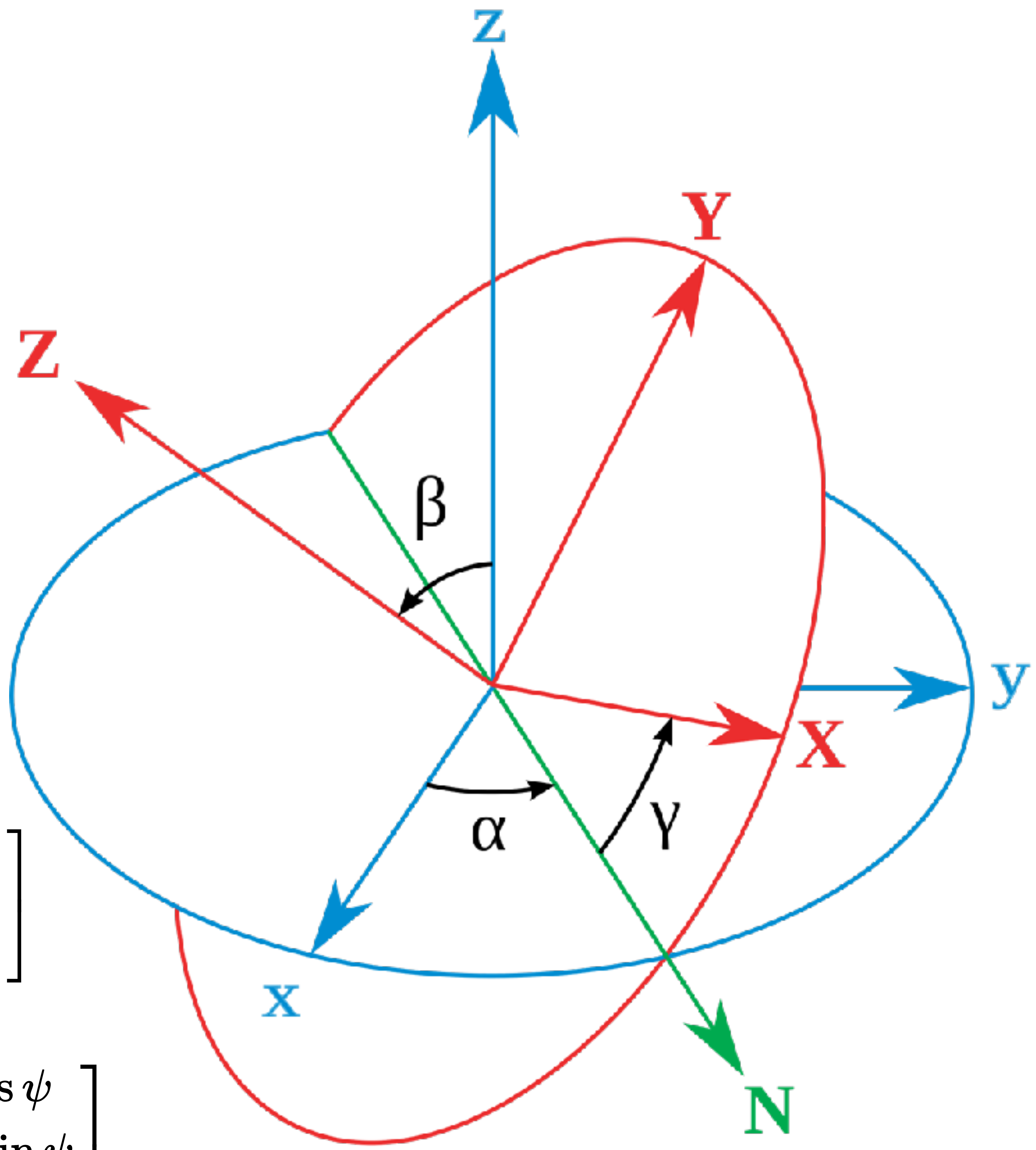

NOvA: L= 810 km, E = 2.0 GeV


T2K: L = 295km, E = 0.6GeV

(Z. Vollari, NOvA-T2K JETPS, '24)

Neutrinos and Oscillation Physics (Part Eight)

Angular Decomposition by Inspection



Comparing the decomposed PMNS matrix:

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

$$= \begin{bmatrix}c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta}\\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}\\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}\end{bmatrix}$$

to the generalized form describing any arbitrary rotation in 3-dimensions presents some interesting similarities:

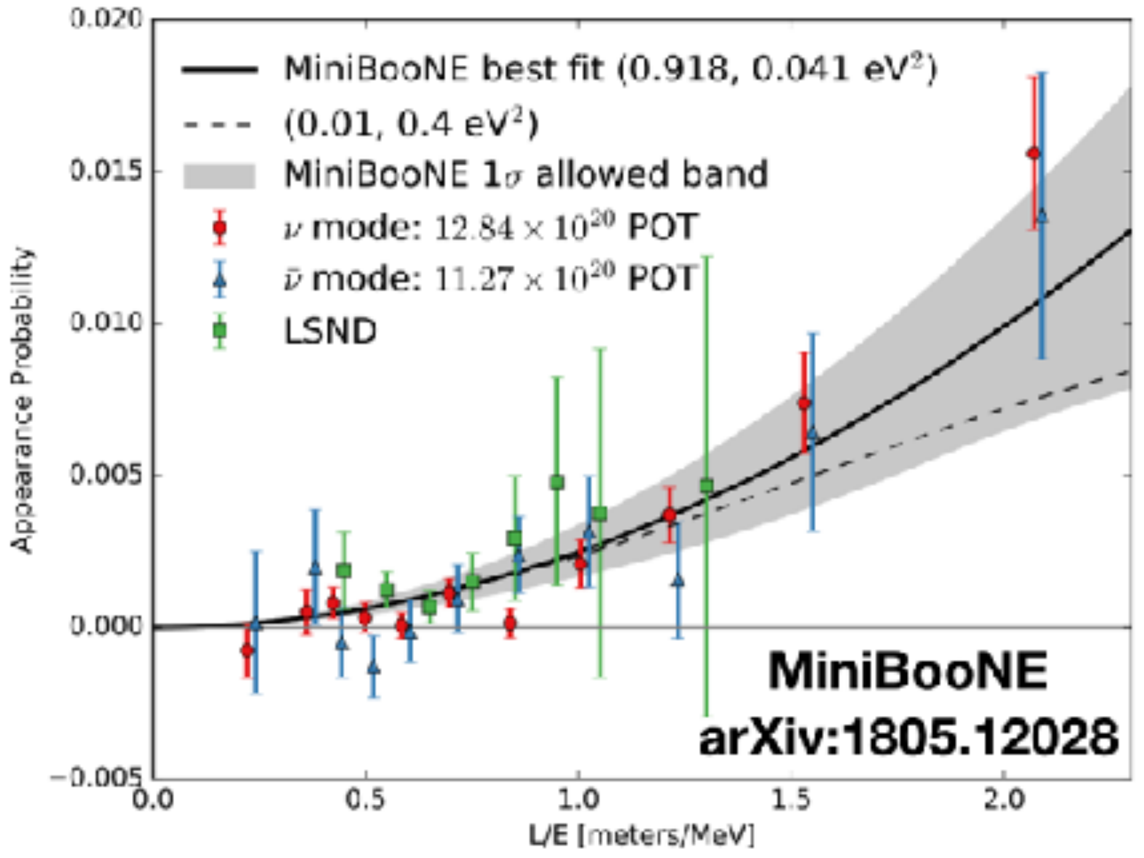
$$\mathbf{A}_X = \begin{bmatrix}1 & 0 & 0\\ 0 & \cos\phi & -\sin\phi\\ 0 & \sin\phi & \cos\phi\end{bmatrix} \quad \mathbf{A}_Y = \begin{bmatrix}\cos\theta & 0 & \sin\theta\\ 0 & 1 & 0\\ -\sin\theta & 0 & \cos\theta\end{bmatrix} \quad \mathbf{A}_Z = \begin{bmatrix}\cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}$$

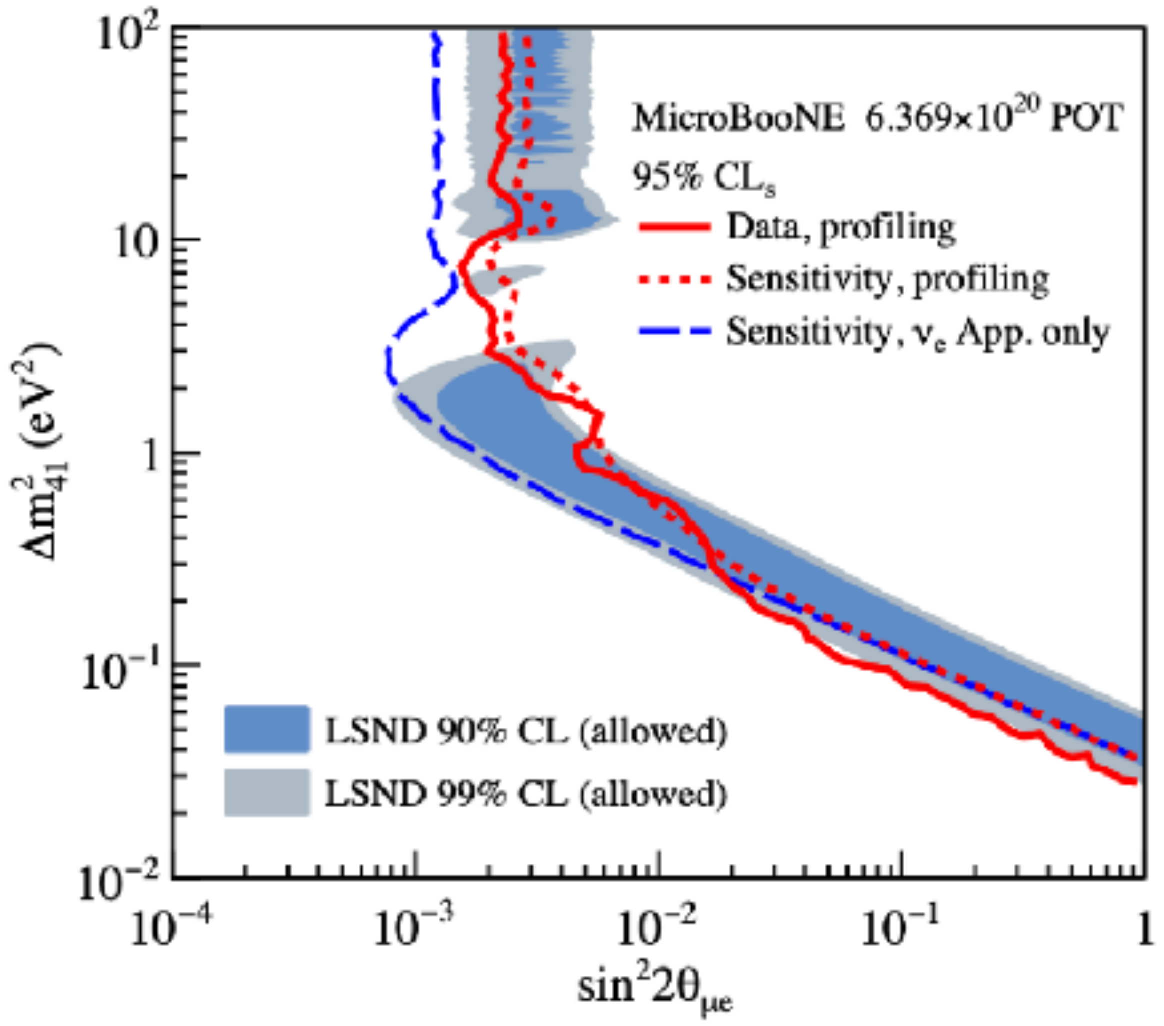
$$\mathbf{A} = \begin{bmatrix}\cos\theta\cos\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi\\ \cos\theta\sin\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi\\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta\end{bmatrix}$$

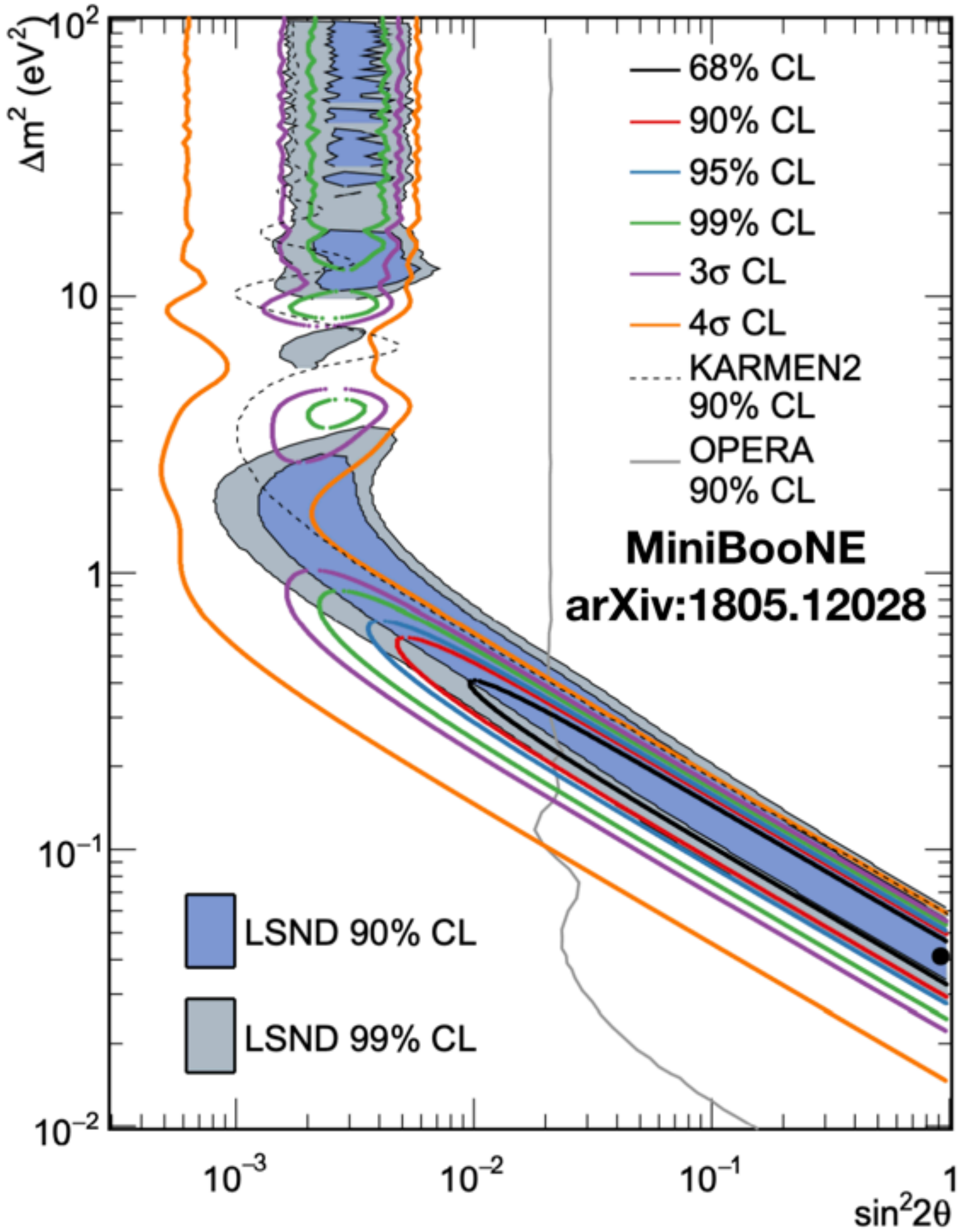
Neutrinos and Oscillation Physics (Part Nine)

Sterile Neutrinos as a path to BSM Physics

The inclusion of a possible fourth neutrino requires the expansion of the 3x3 PMNS matrix to a 4x4 lepton mixing matrix implying an additional mass eigenstate, additional mass splittings, and *dimensions* of CP violation:

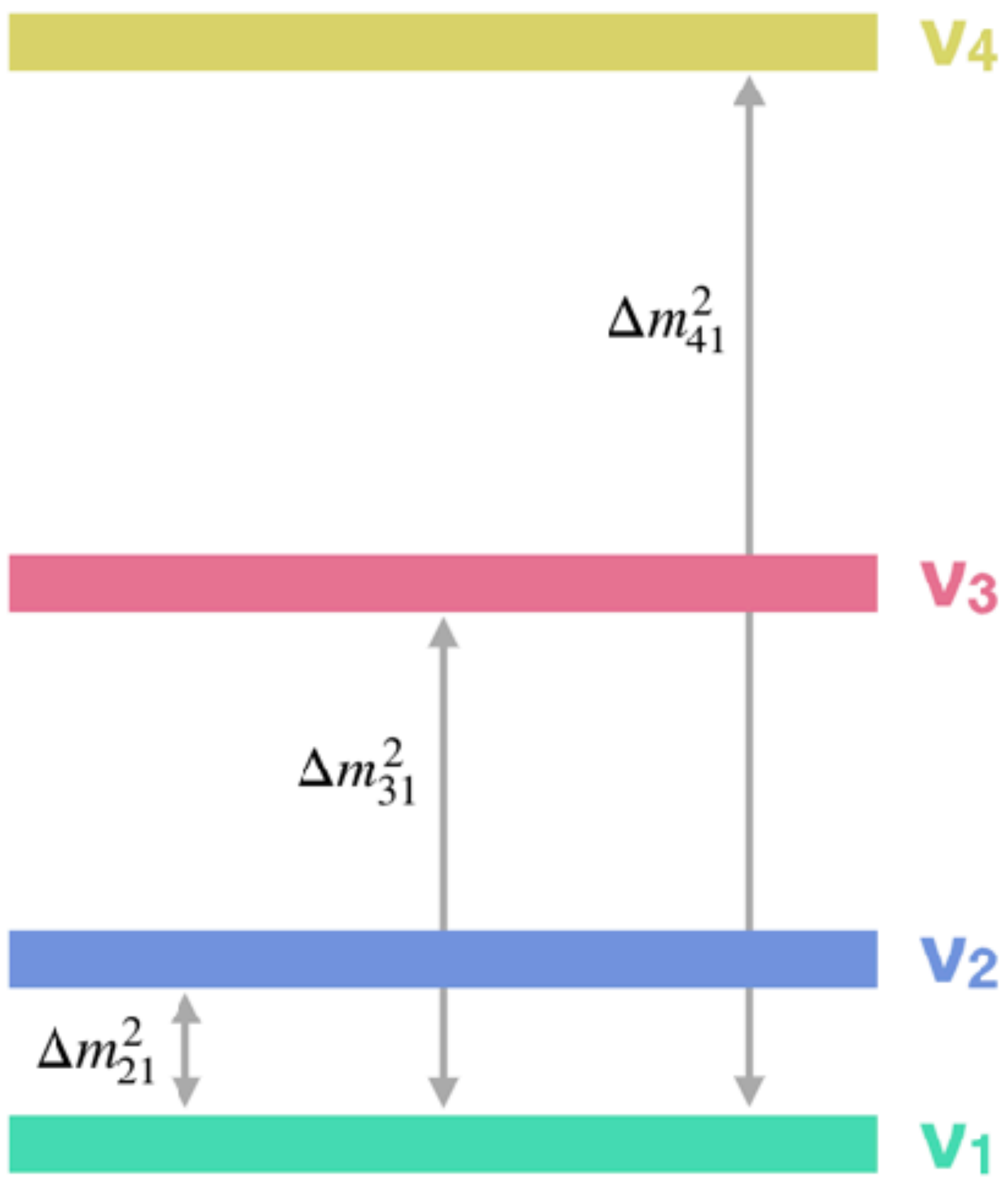






$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

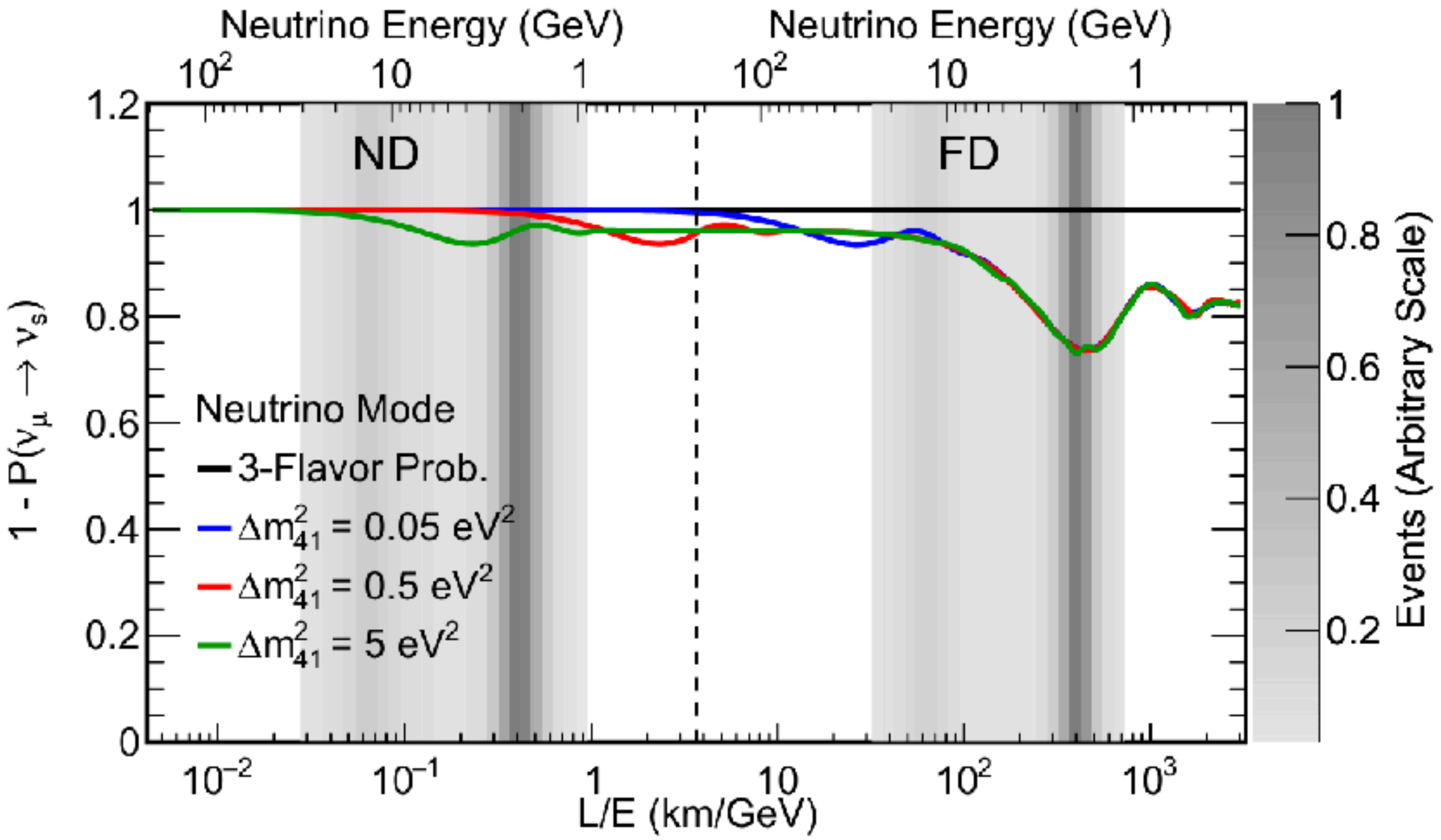
(V. Hewes, Sterile JETPS, ’23)



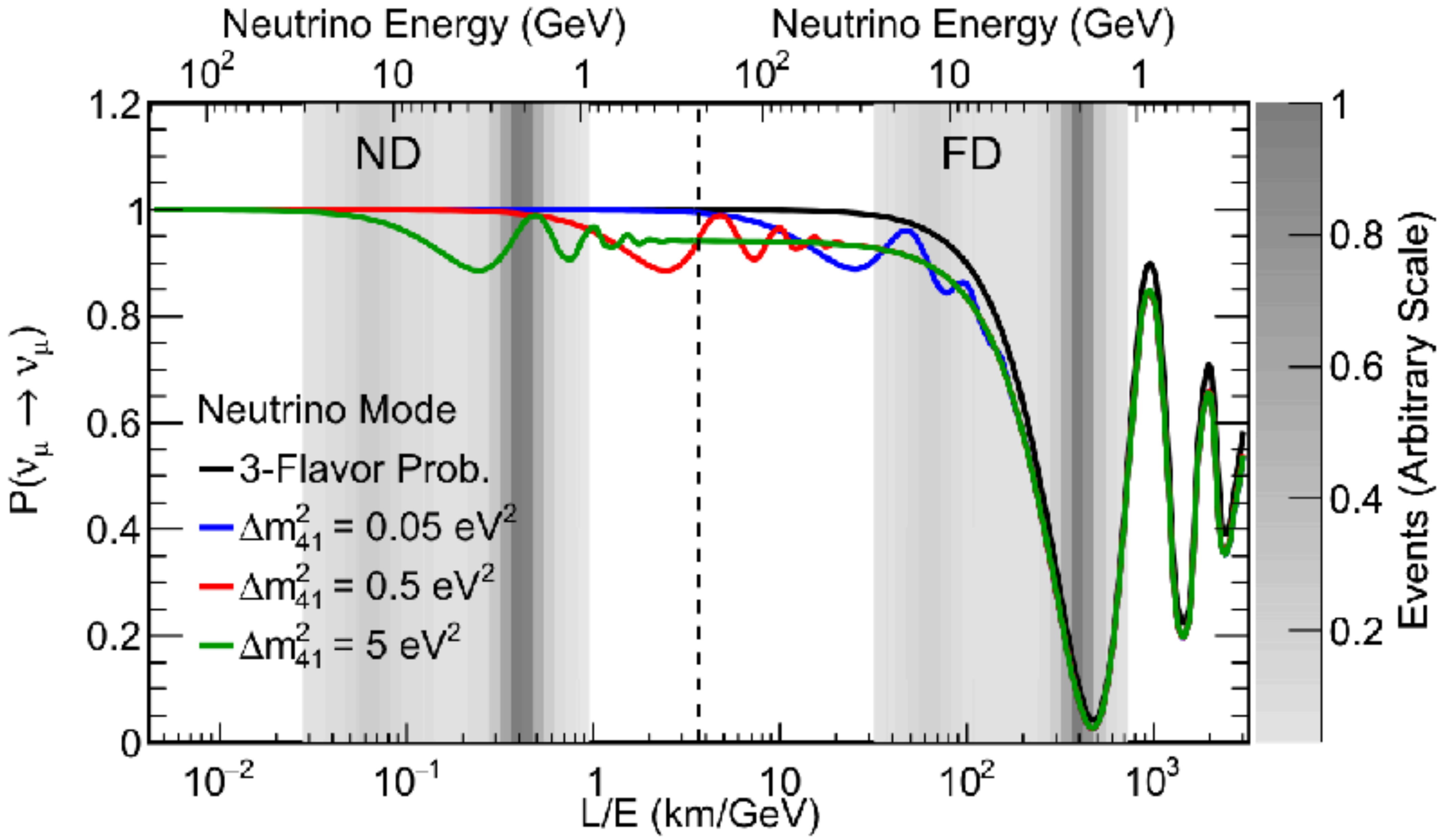
Neutrinos and Oscillation Physics (Part Ten)

Sterile Neutrinos as a path to BSM Physics

Sensitivity to sterile neutrinos depends greatly on the new mass but oscillations are on a much shorter baseline! Hence, **Short Baseline** *Neutrino Oscillation Experiments.*



$$1 - P(\nu_\mu \rightarrow \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41} - \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31} + \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin\Delta_{31},$$



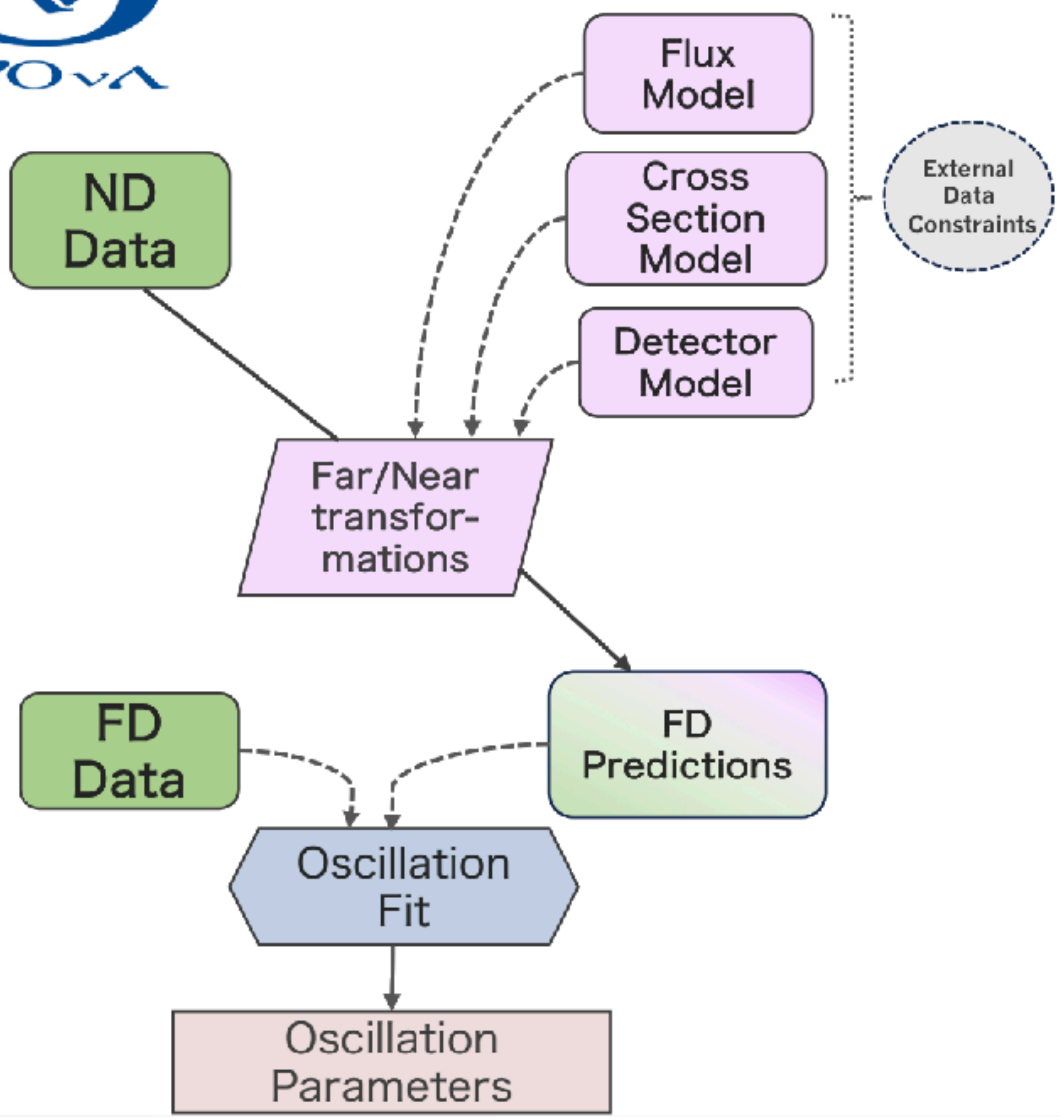
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{24}\sin^2\Delta_{41} + 2\sin^2 2\theta_{23}\sin^2\theta_{24}\sin^2\Delta_{31} - \sin^2 2\theta_{23}\sin^2\Delta_{31},$$

Big news *in the past few years regarding the existence of the* ***Low Energy Excess.***

How to do a 3-Flavor Oscillations Analysis

A brief conceptual overview of how to do an oscillations extraction for T2K and NOvA

(Z. Vollari, NOvA-T2K JETPS, ’24)



Flux Model

Cross Section Model

Detector Model

External Data Constraints

ND Data

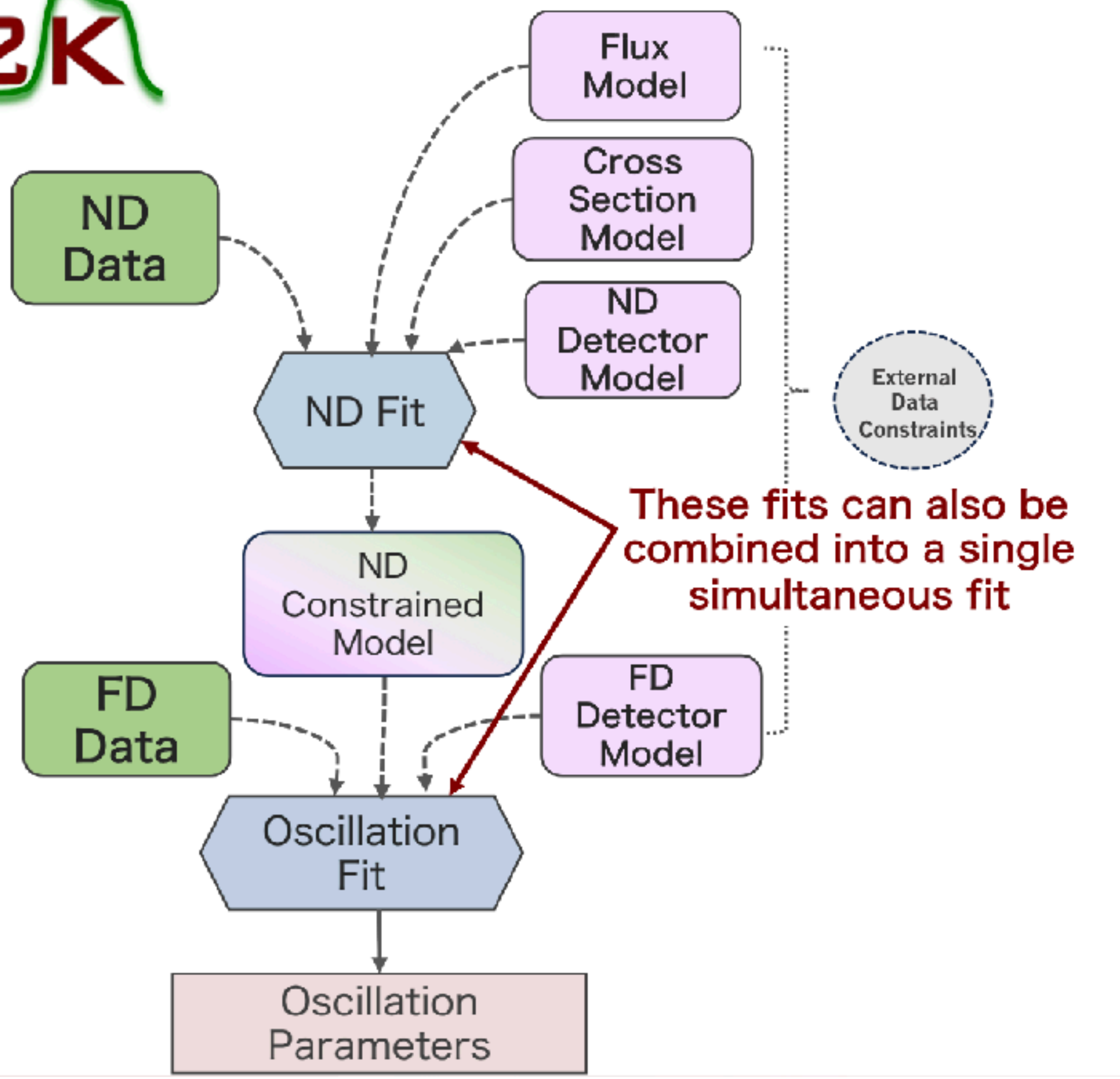
Far/Near transfor-mations

FD Data

FD Predictions

Oscillation Fit

Oscillation Parameters



Flux Model

Cross Section Model

ND Detector Model

External Data Constraints

ND Data

ND Fit

These fits can also be combined into a single simultaneous fit

ND Constrained Model

FD Data

FD Detector Model

Oscillation Fit

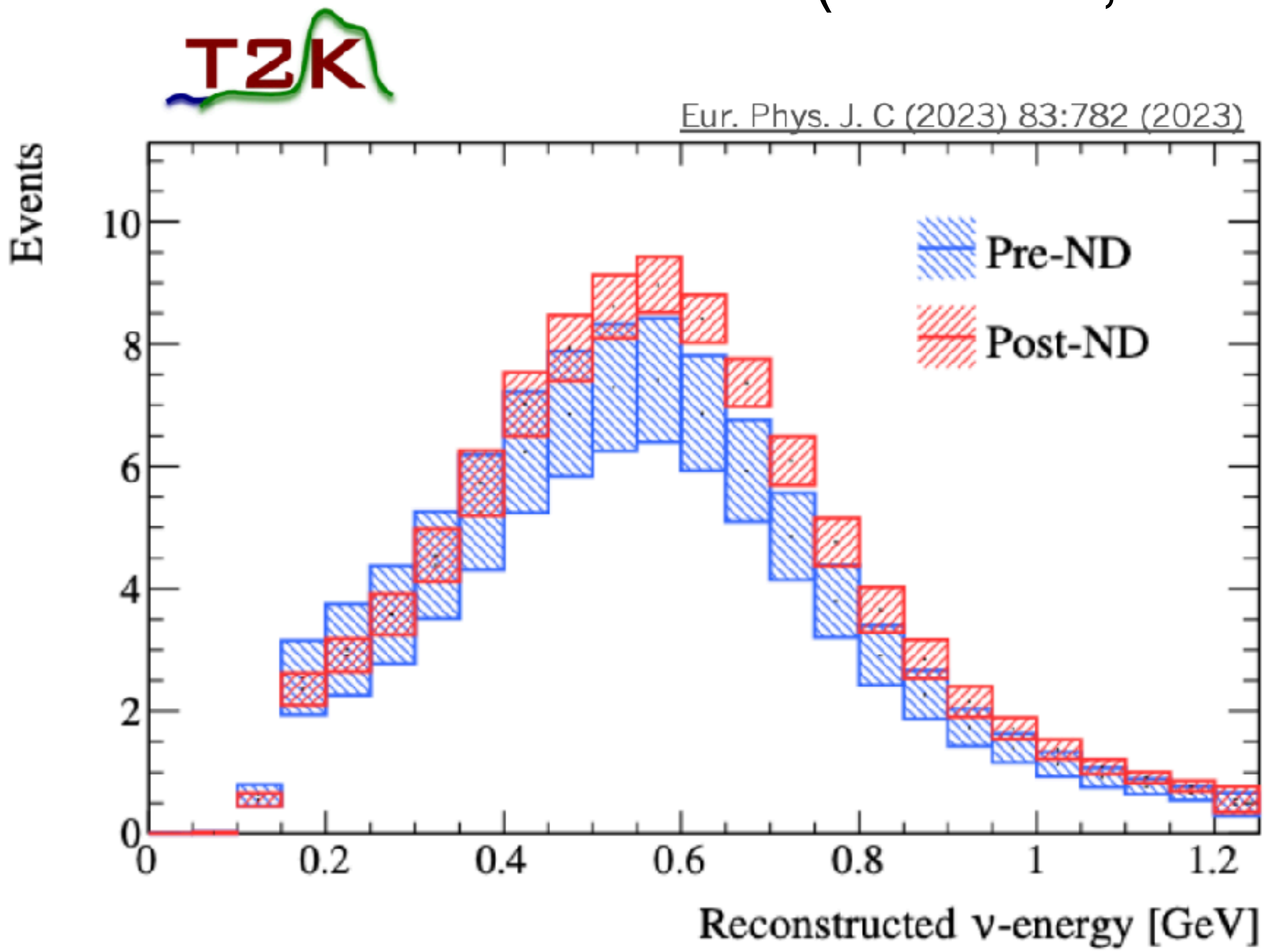
Oscillation Parameters

Numerous advantages and disadvantages to using these competing ways of extracting the oscillation parameters. Requires initial investment but in different ways with different tradeoffs.

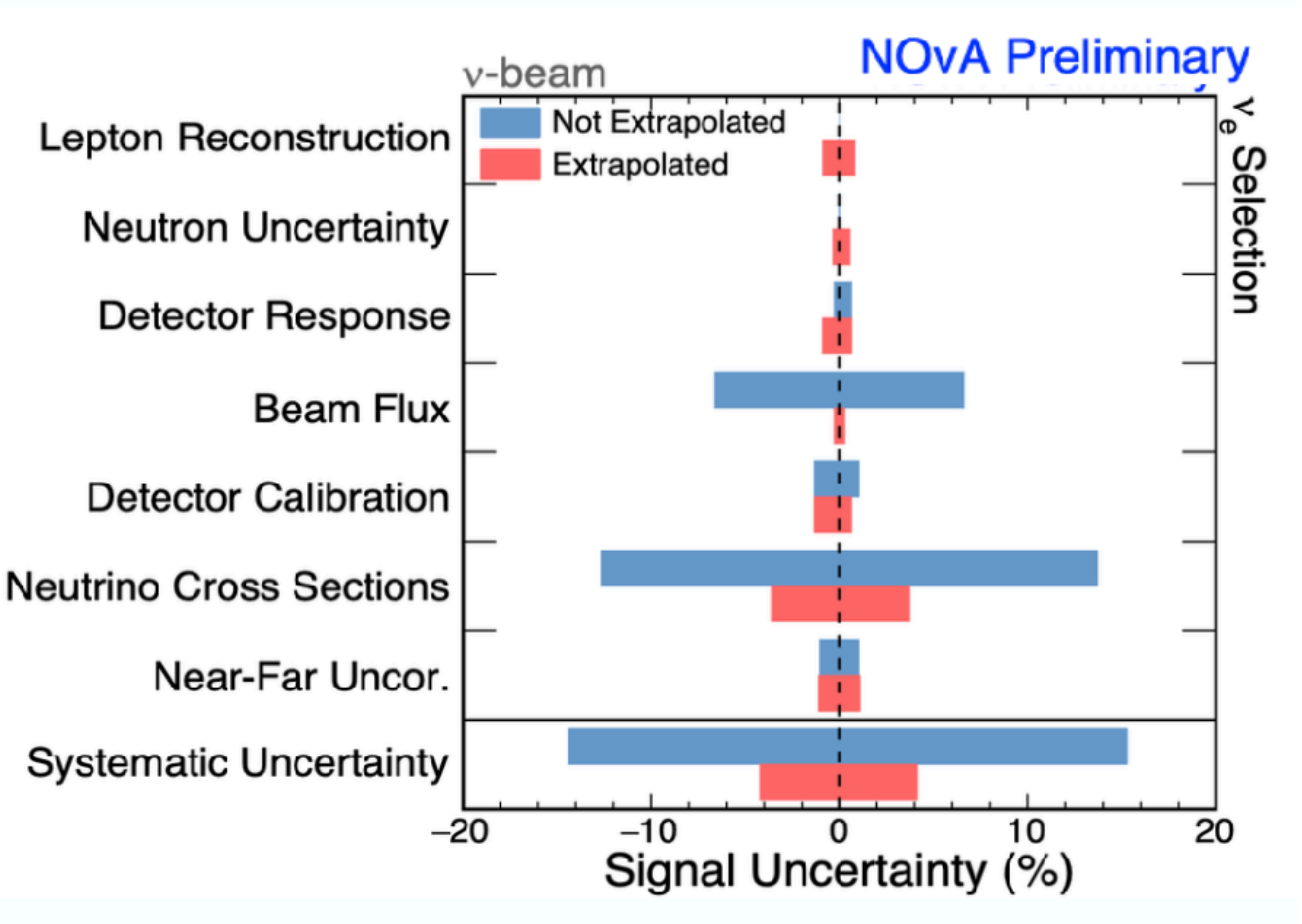
The Effect of the Near Detector on Oscillations

The Advantages of Characterizing the Flux Pre-Oscillation

(Z. Vollari, NOvA-T2K JETPS, ’24)



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



The Near Detector reduces uncertainties from around 15% to around 5% for systematic uncertainties in both experiments.

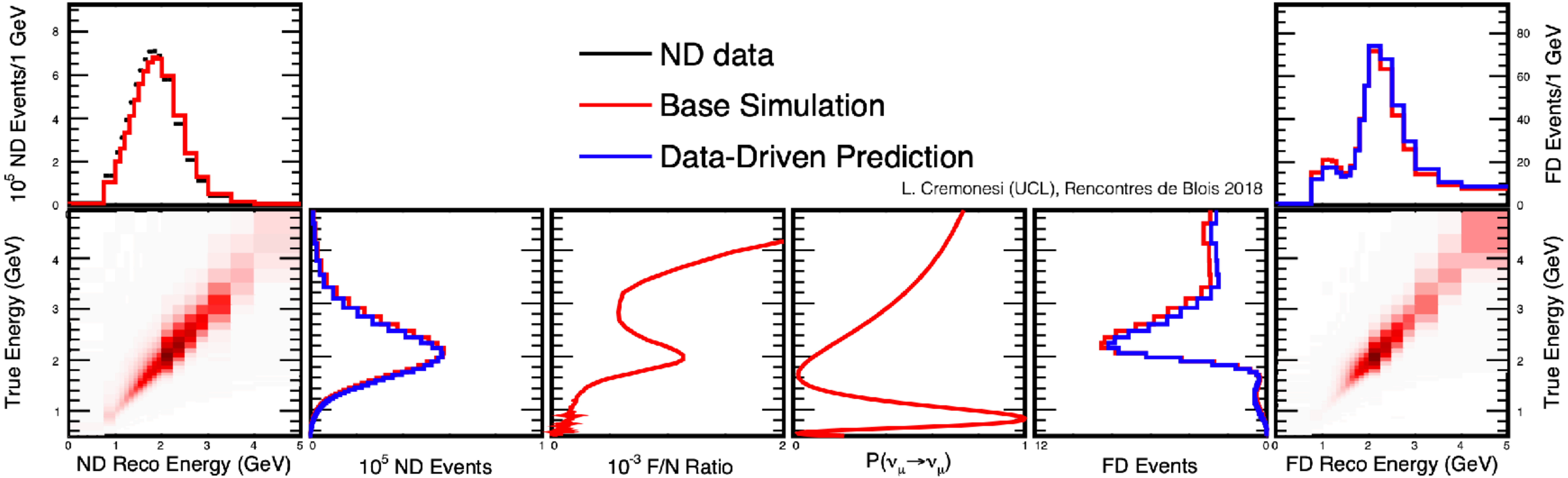
How to do an (Extrapolation Based) 3-Flavor Oscillations Analysis

A brief conceptual overview for experiments like NOvA and DUNE

$$N_{\mu/e}(E_\nu) = P(\nu_\mu \rightarrow \nu_{\mu/e})\sigma(E_\nu)\Phi(E_\nu)\epsilon(E_\nu)$$

$\Phi_{ND}(E_\nu)\ \sigma(E_\nu)$

$\Phi_{FD}(E_\nu)\ \sigma(E_\nu)$



$\epsilon_{ND}(E_\nu)$

$$\frac{\Phi_{FD}(E_\nu)\epsilon_{FD}(E_\nu)}{\Phi_{ND}(E_\nu)\epsilon_{ND}(E_\nu)}$$

$\epsilon_{FD}(E_\nu)$

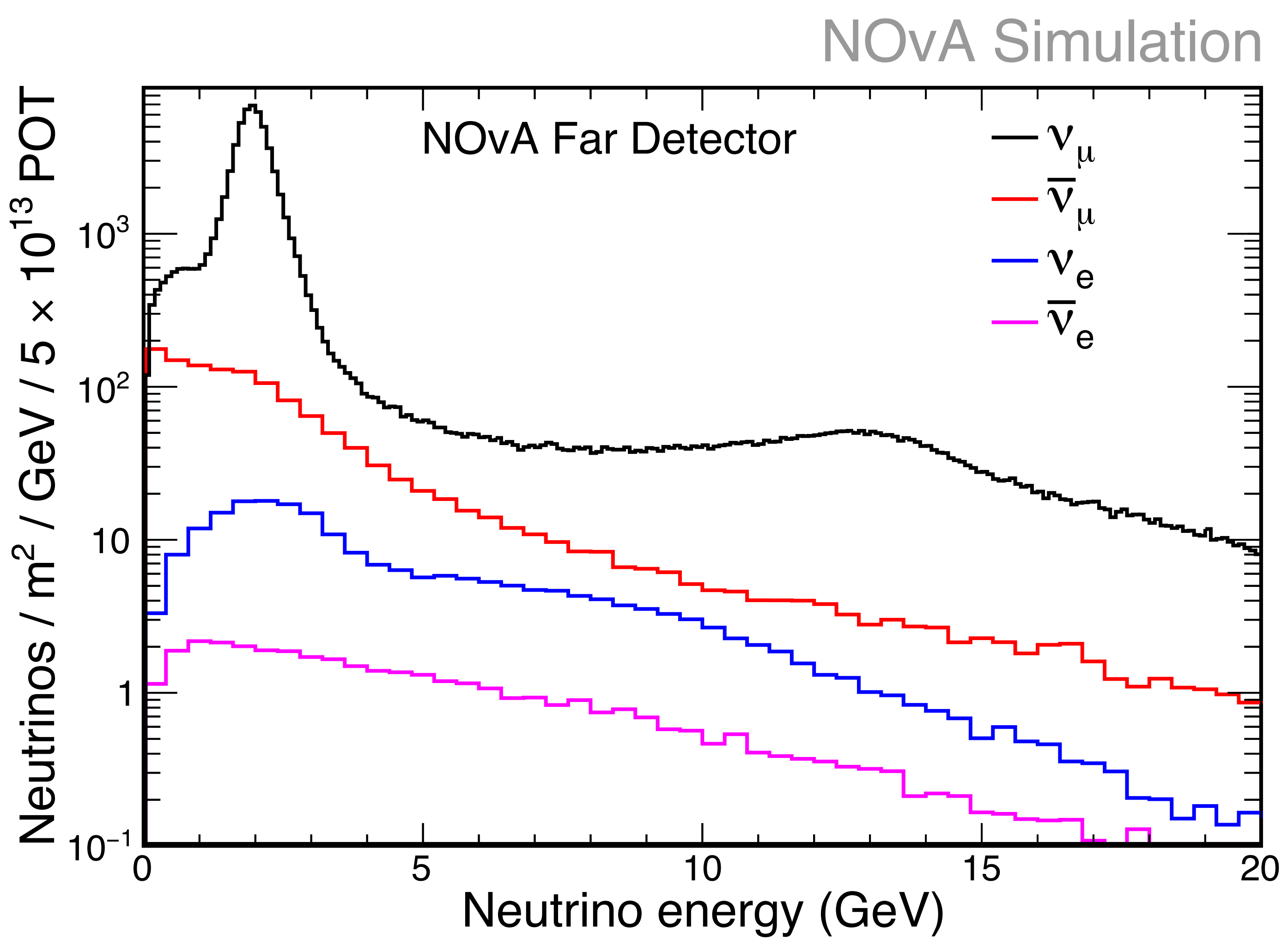
Major questions about whether uncertainties on flux, acceptance, and efficiency can be tightly controlled across **all** *long baseline* experiments.

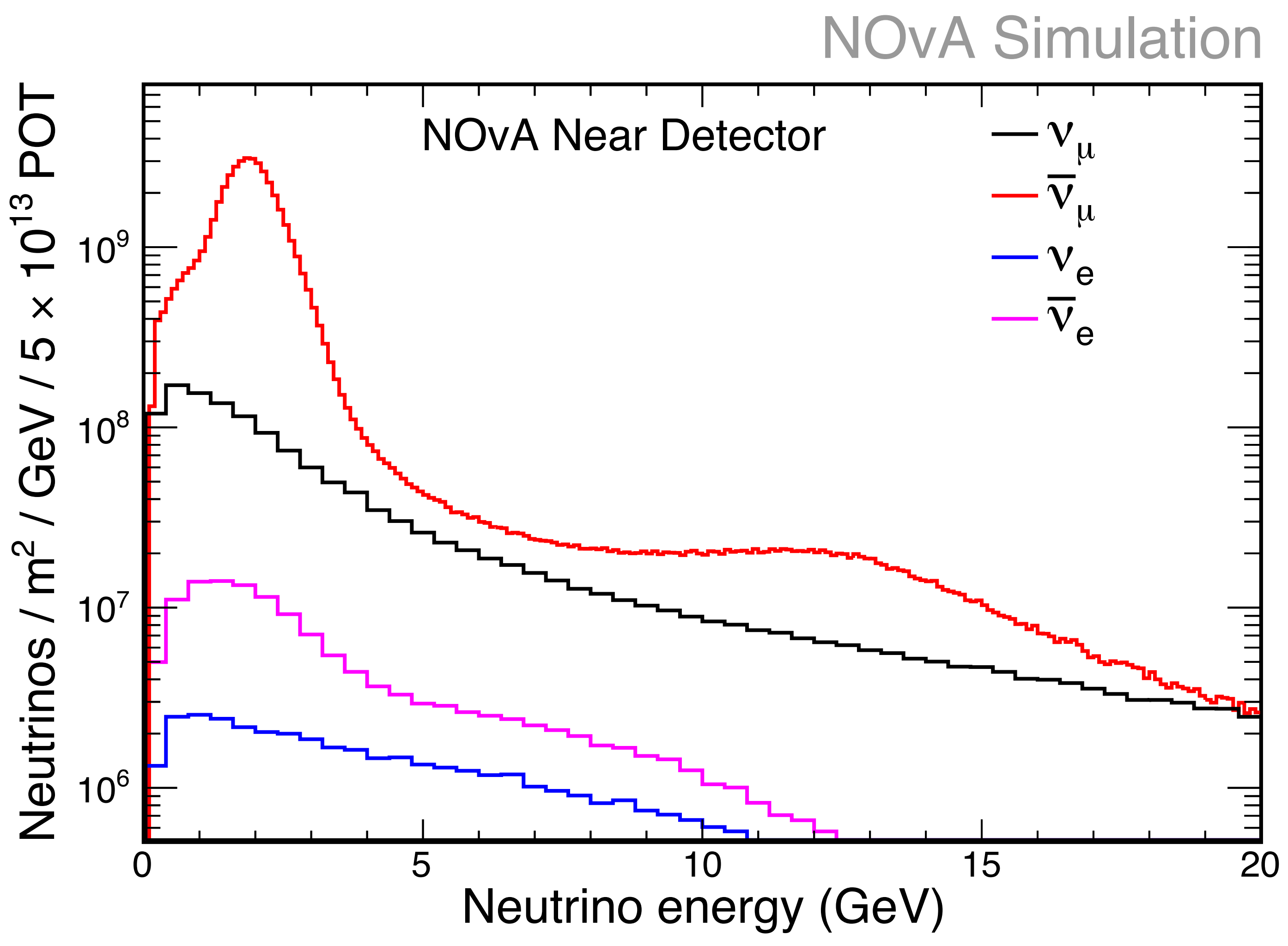
How Neutrino Beams Work

The expansion of the muon-neutrino beam discovery

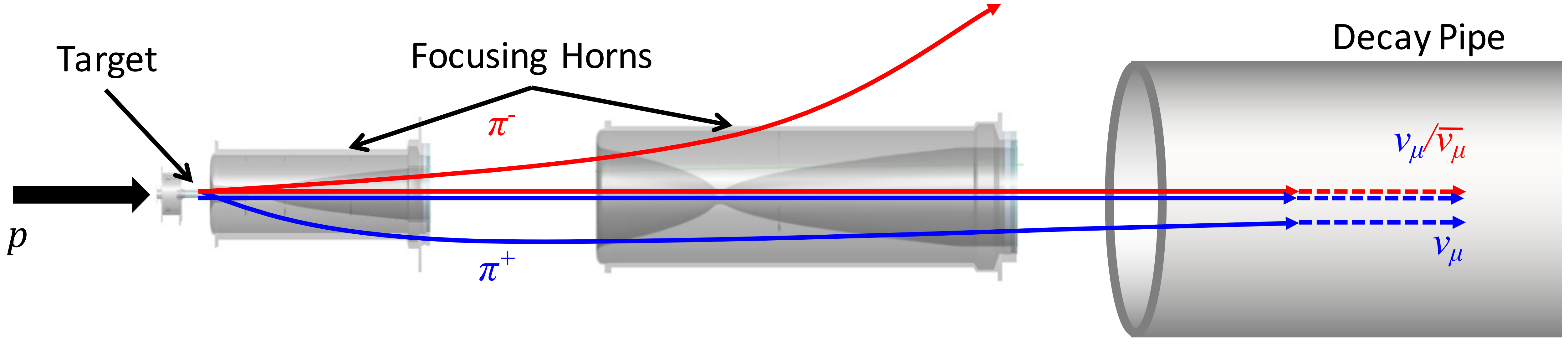
Neutrino Beams at NOvA

How to Produce Neutrinos & Antineutrinos



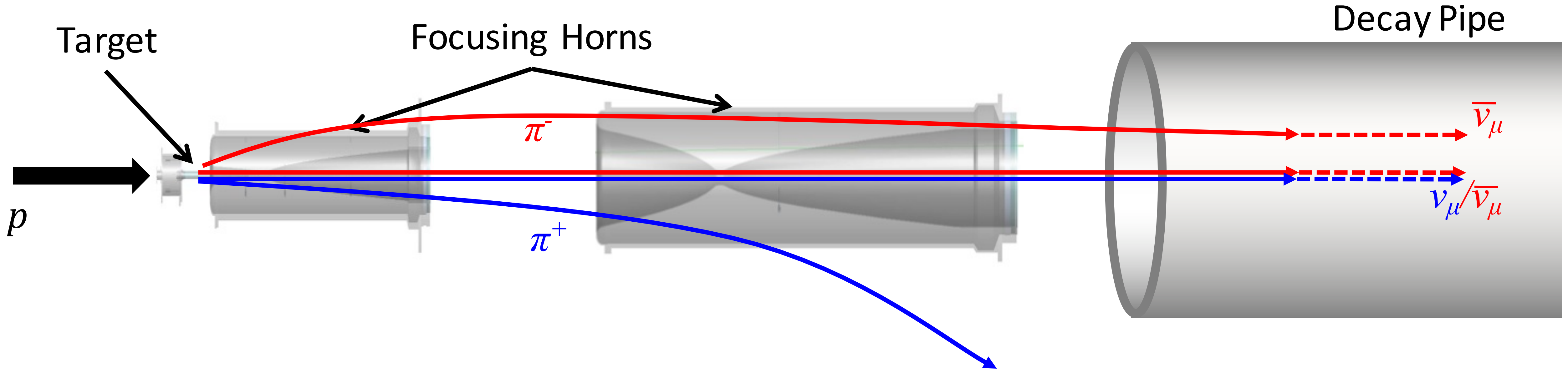


Forward Horn Current



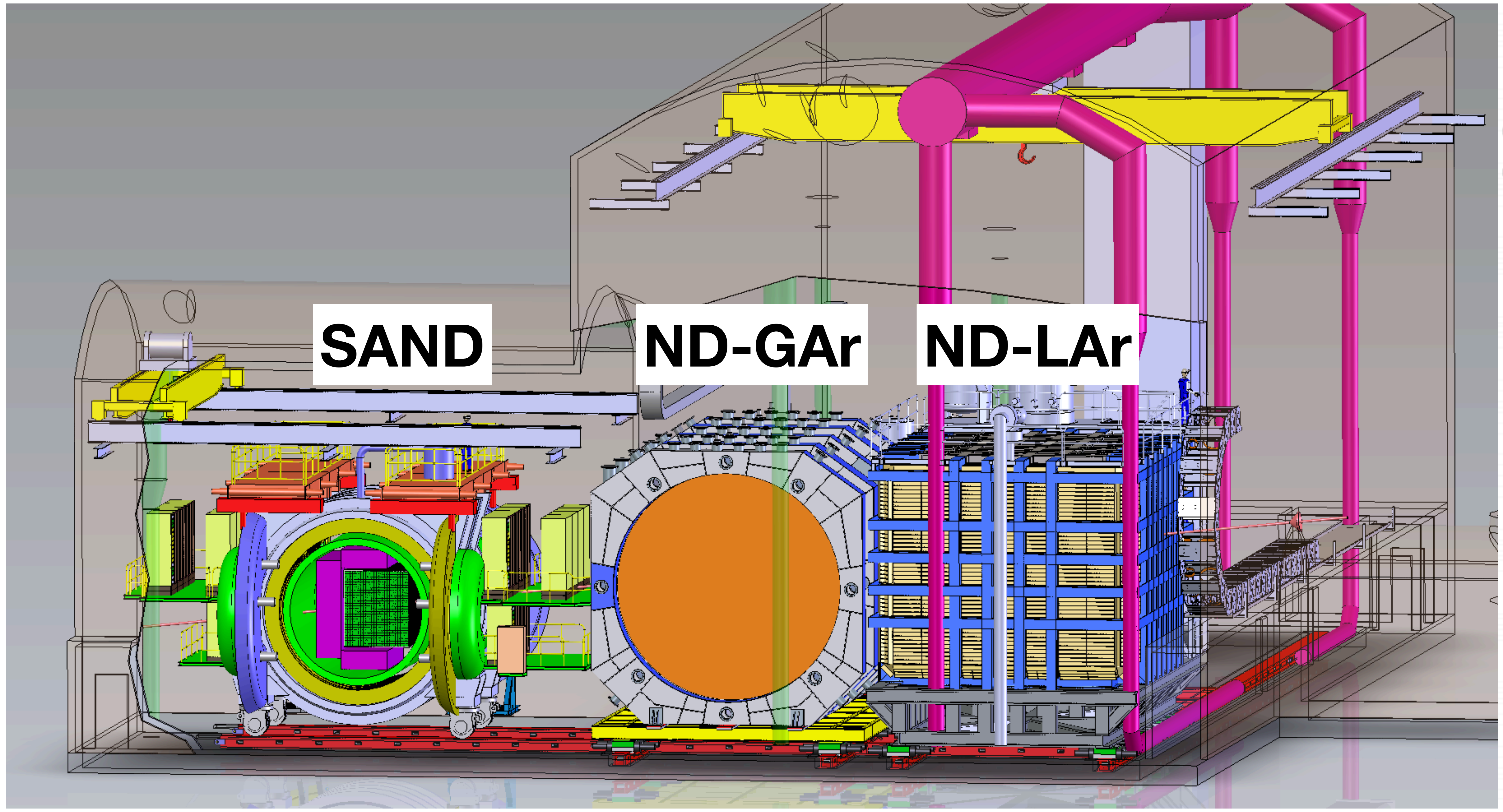
NOvA is served by the NuMI (Neutrinos from the Main Injector) beam, energy peaksaround 2 GeV, but of critical importance is that NOvA is slightly off-axis! Intensity of ~ 10^{22}POT exposures.

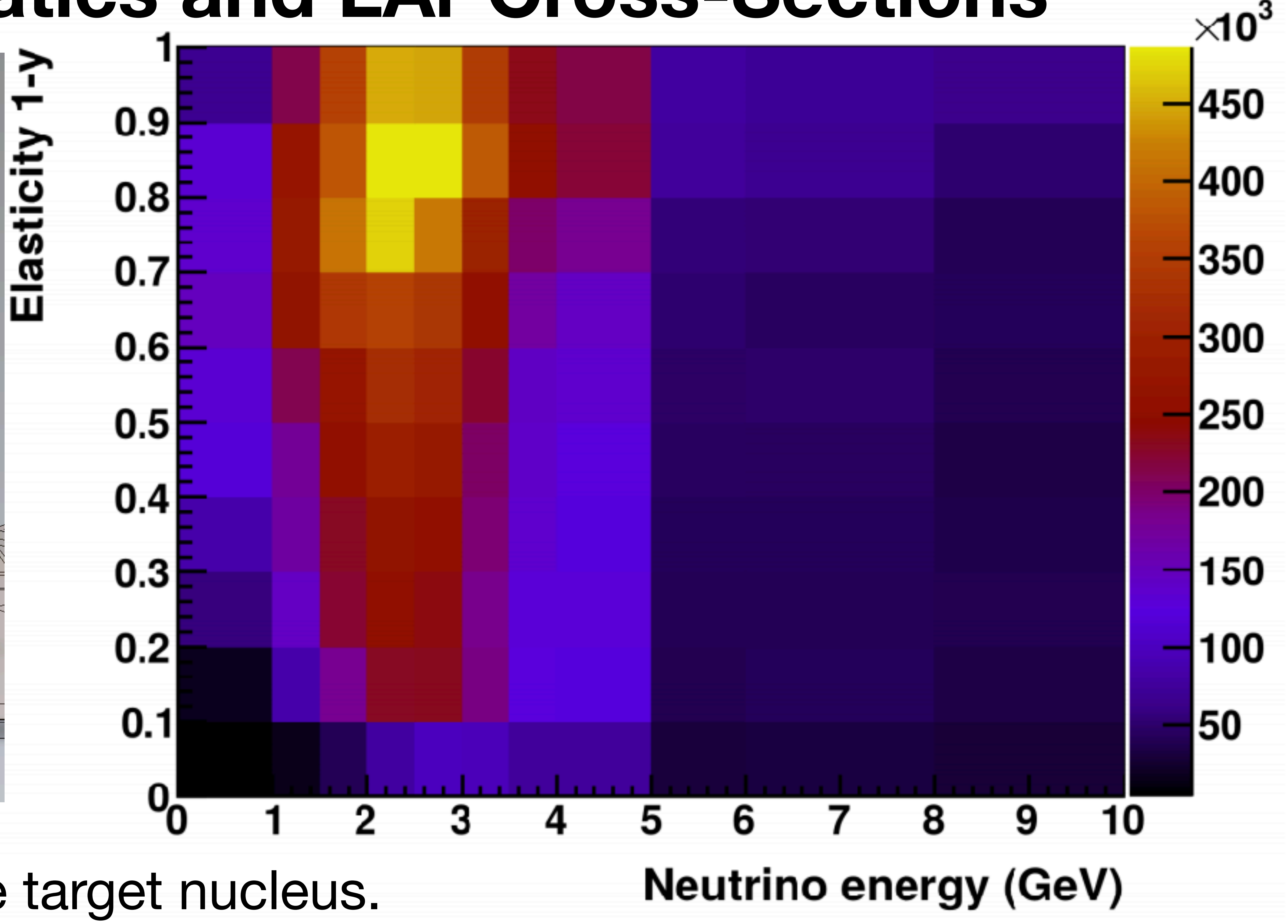
Reverse Horn Current



The DUNE Near Detector (Phase 2)

Necessary to Constrain Beam Systematics and LAr Cross-Sections





ND-LAr functionally similar to FD modules with the same target nucleus.

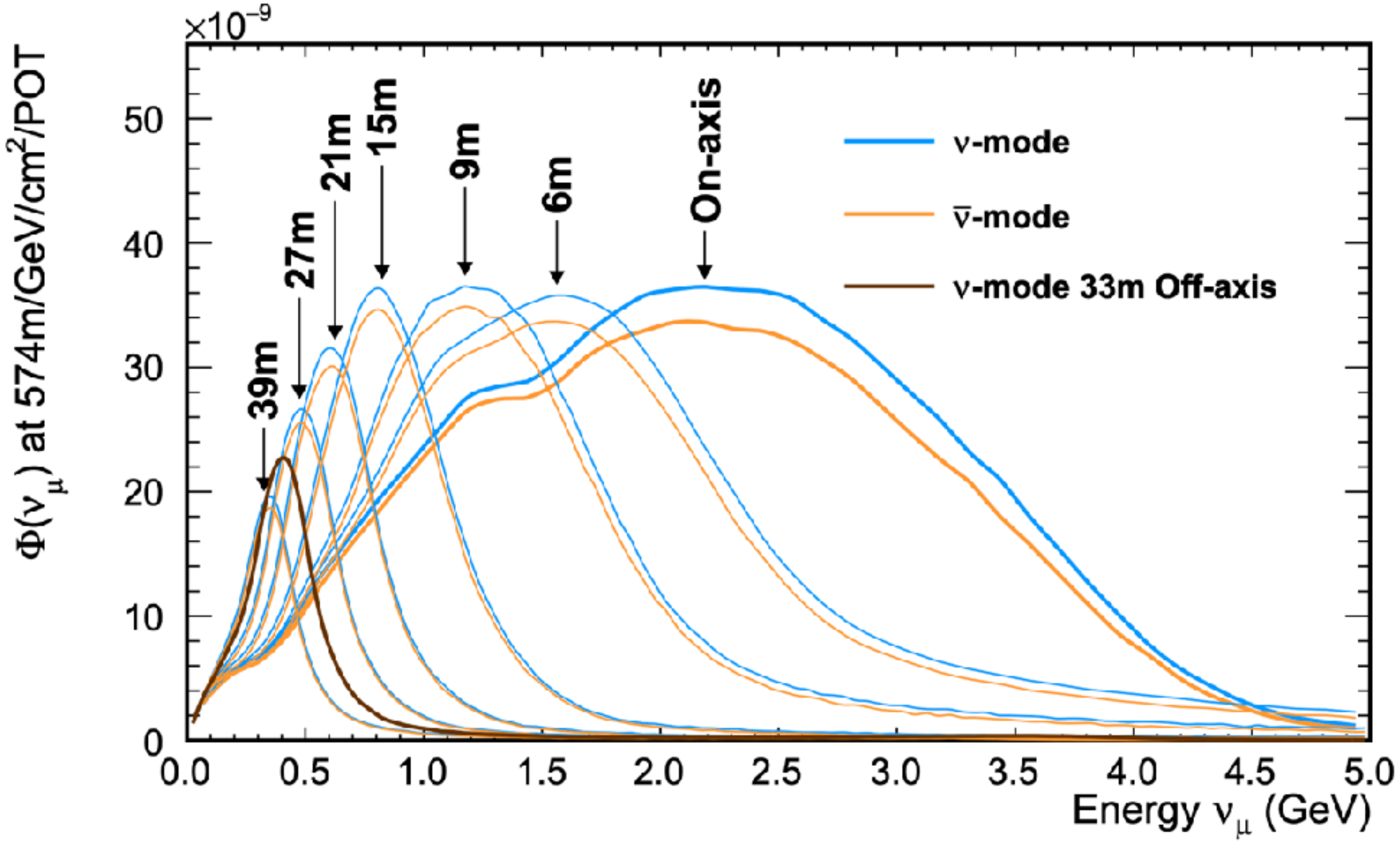
ND-GAr gives charge separation and some analysis of secondary interactions with the same target nucleus.

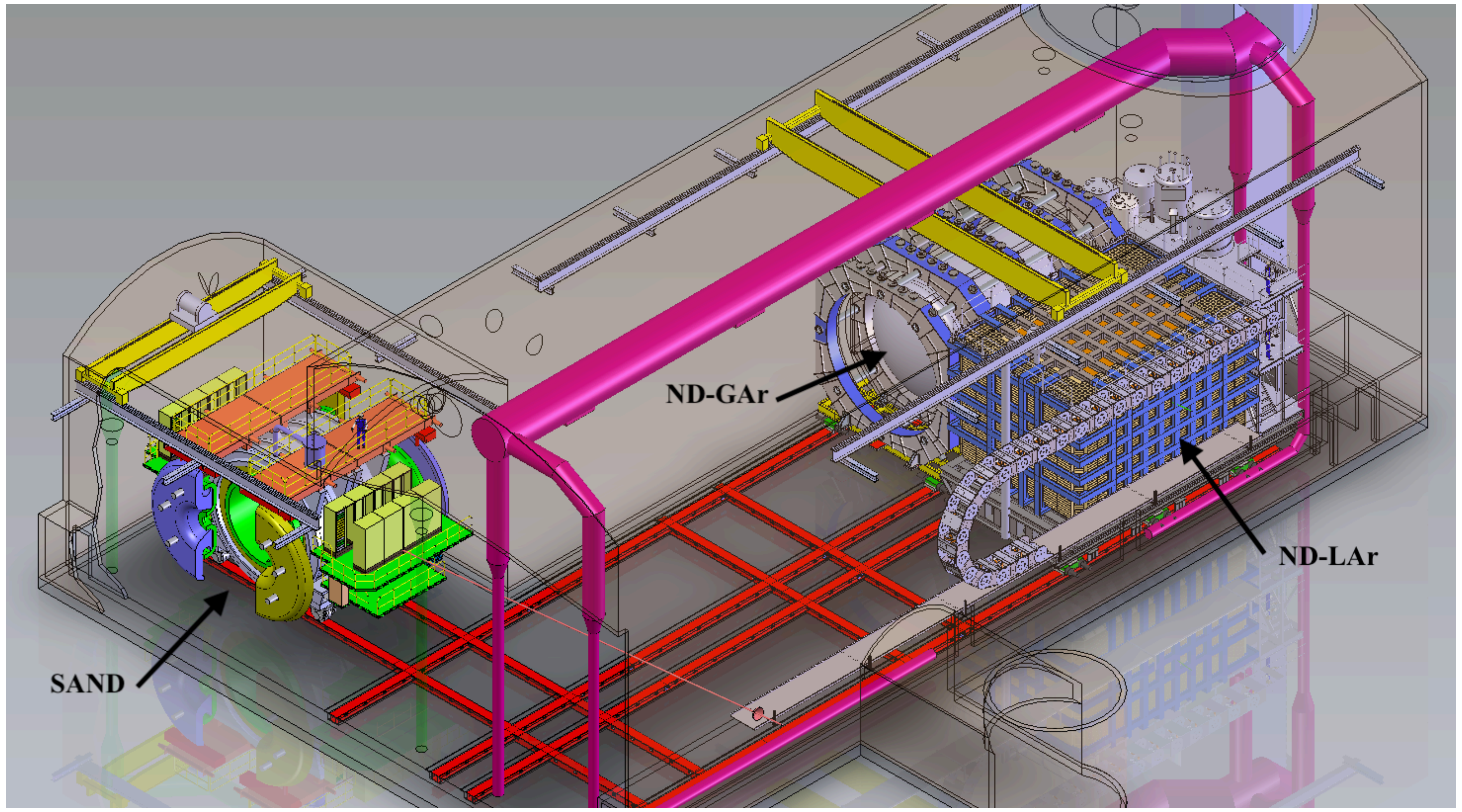
System for on-Axis Neutrino Detection (SAND) serves as always on beam monitoring system with polypropylene CH2 and separate C target

From the ND CDR, 50 tons of LAr at 1.2 MW neutrino beam should yield about **59 million ν_μCC events per *year***.

The LBNF/DUNE Beam

The Next Generation of Flux Characterization





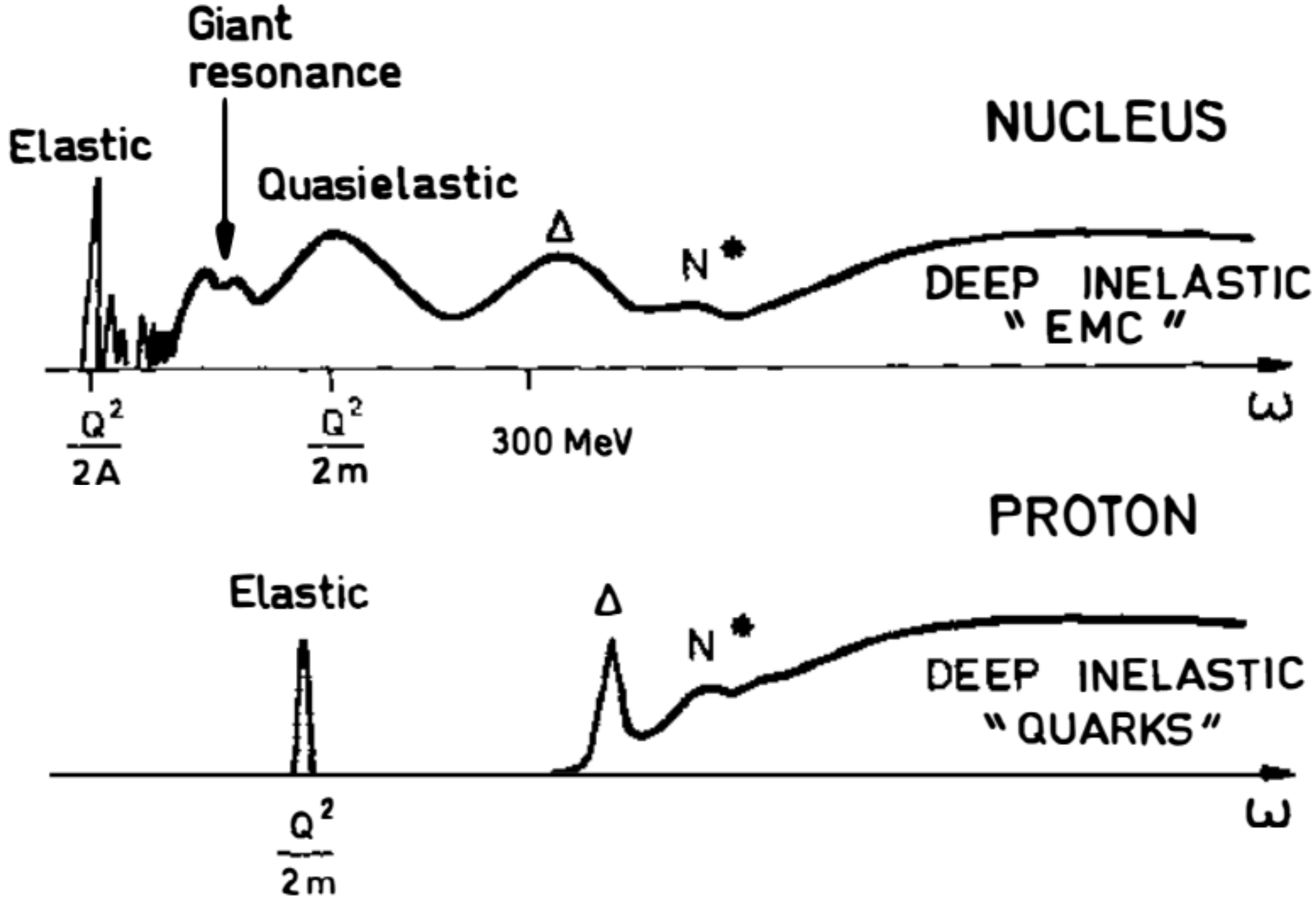
DUNE-PRISM will have the Argon detectors move in order to deconvolve the flux from the cross sections.

Will constrain beam flux shape and normalization to ~1%!

Outside possibility of moving to higher energies!

Lepton-Nuclear Scattering

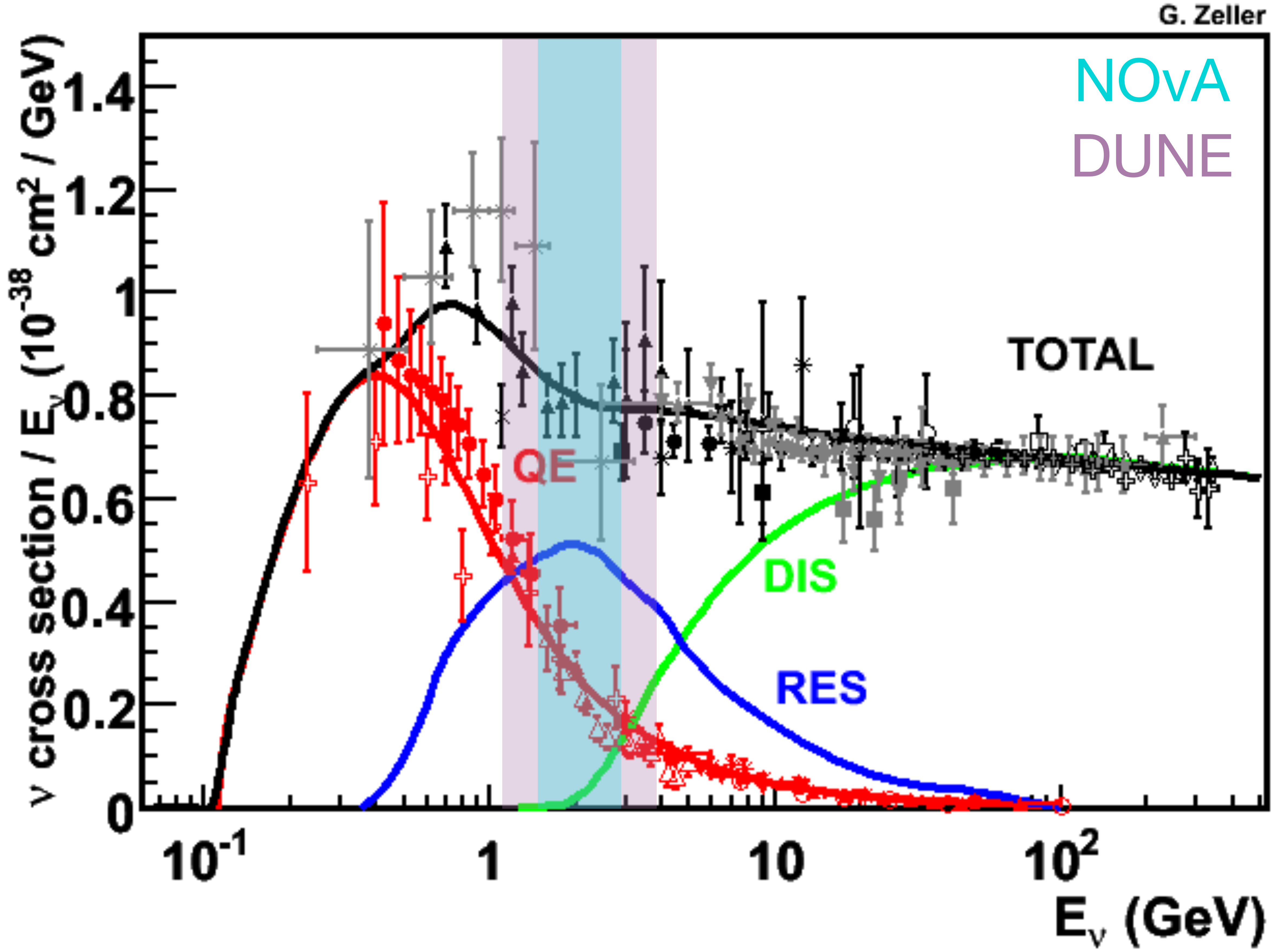
Hints from ep/eA scattering

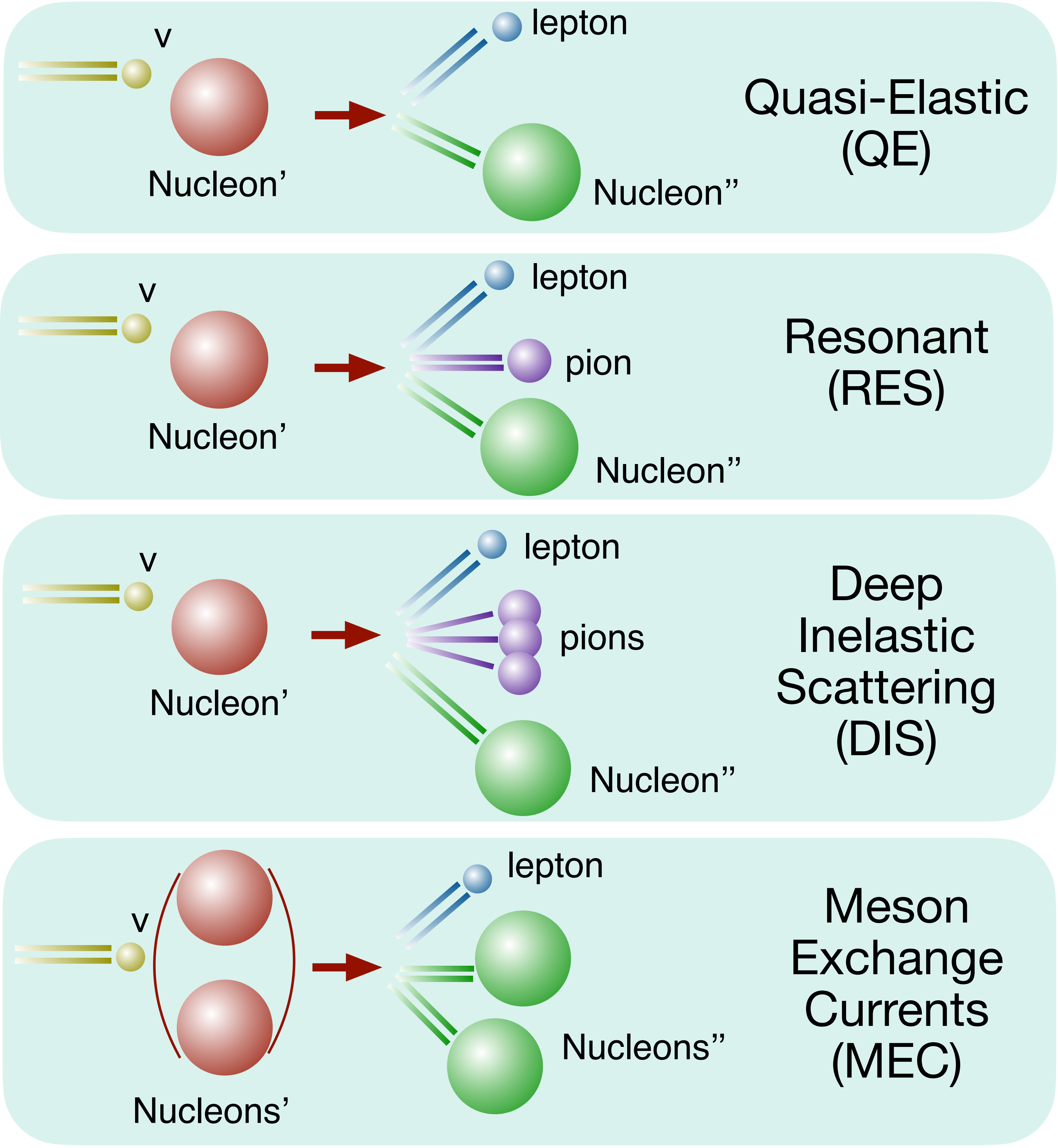


This mostly describes lepton-nucleus interactions in energy from the hundreds of MeV to tens on GeV.

The Neutrino-Nucleus Cross Section Problem (Part One)

Defining a Wayward Source of Uncertainty



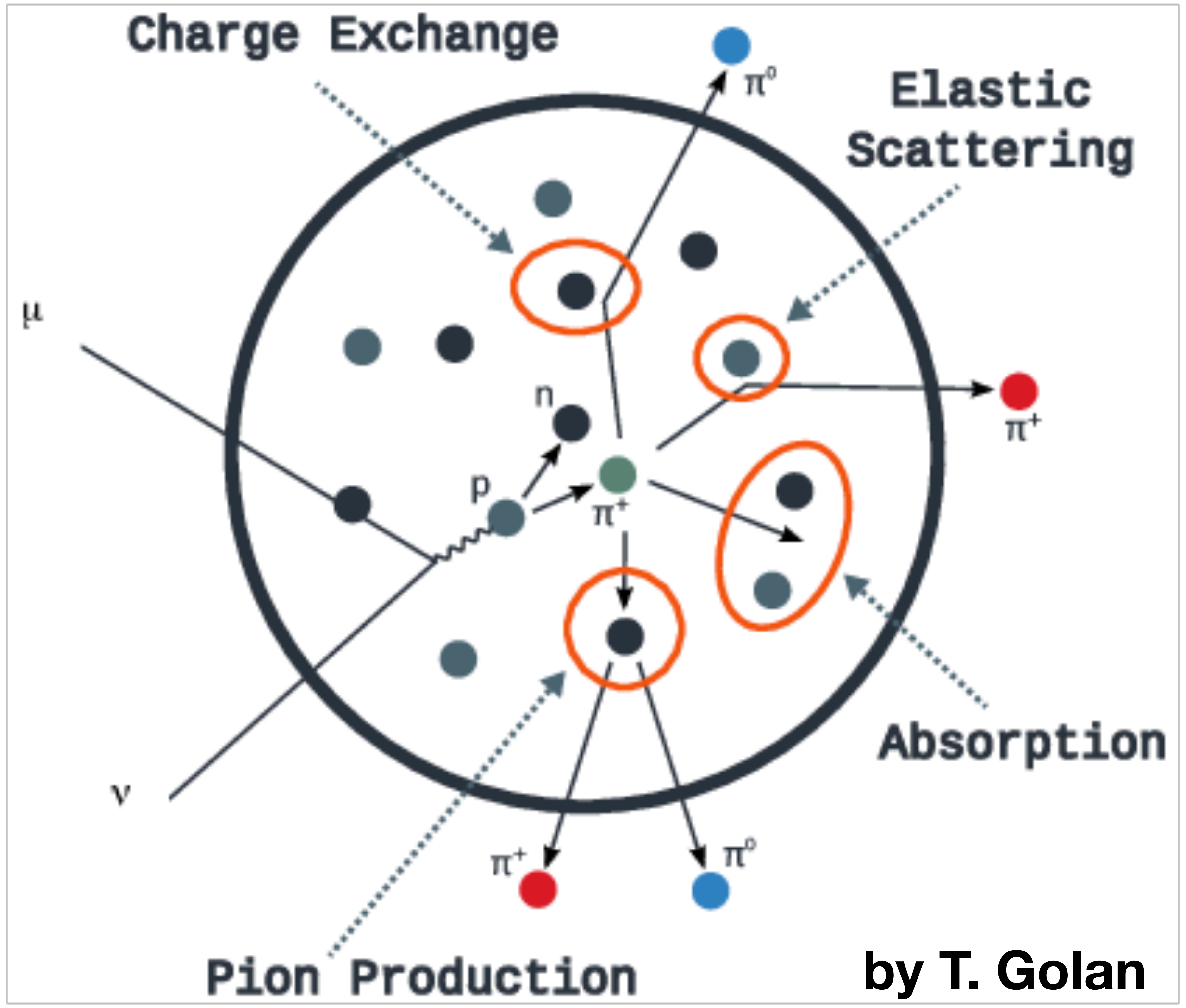


Many Neutrino scattering measurements but to first order must understand interplay between four different types of scattering (QE/Elastic, RES, DIS, MEC).

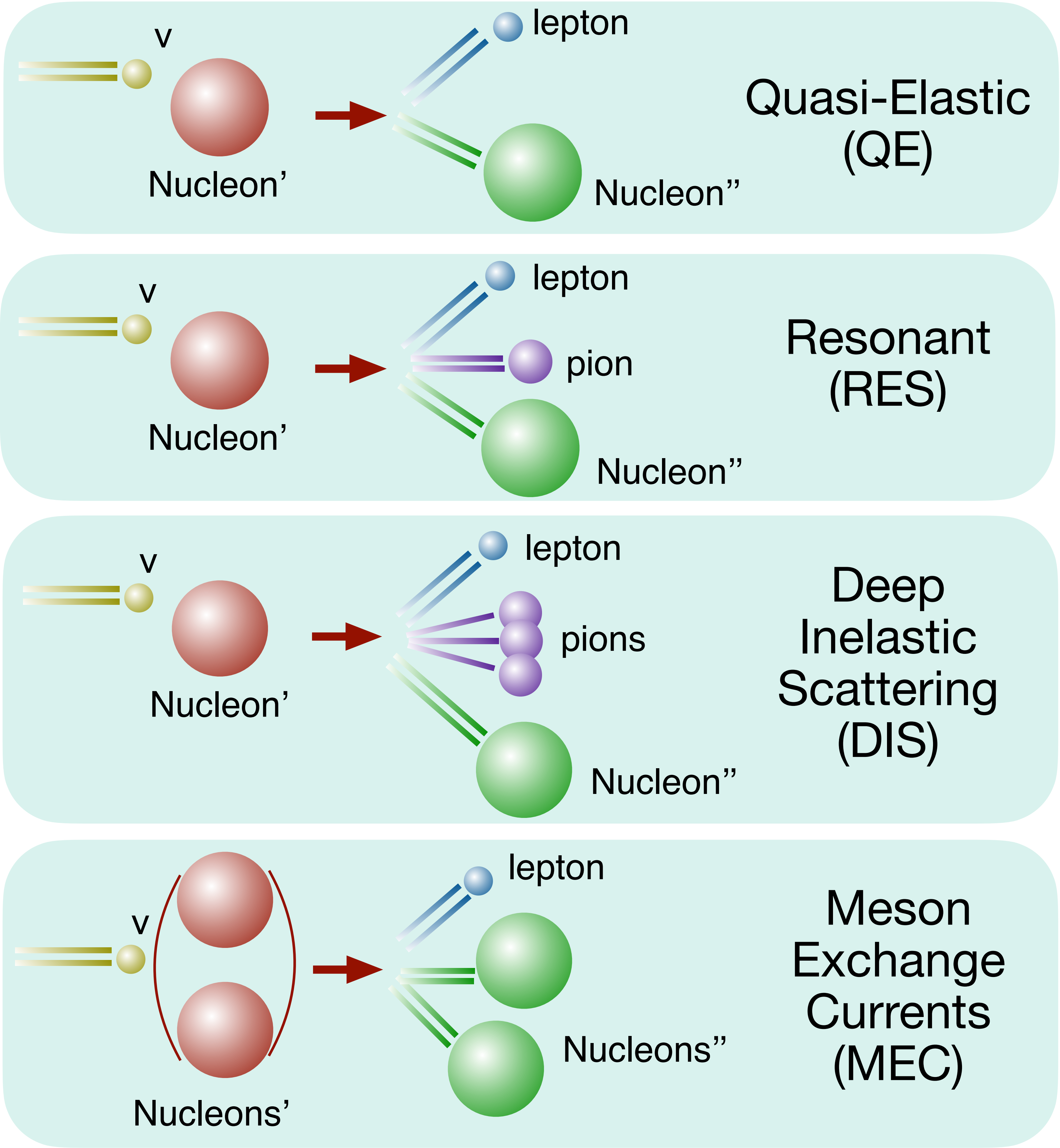
To second order, must also deal with initial state and FSI effects (nuclear matter effects, absorption, interaction with cold nuclear matter)!

The Neutrinos-Nucleus Cross Section Problem (Part Two)

Defining a Wayward Source of Uncertainty



by T. Golan



Many neutrino scattering measurements but to first order must understand interplay between four different types of scattering (QE/Elastic, RES, DIS, MEC).

To second order, must also deal with initial state and FSI effects (nuclear matter effects, absorption, interaction with cold nuclear matter)!

Application of Cross-Section Models

The Work of Neutrino Generators

What was shown so far is an analysis of world data in aggregate. Those data still need to be approximated with models and applied in generators.

NuWro

Wroclaw Neutrino Event Generator

NEUT

Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

```
Version: {:56}|
Authors: Joshua Isaacson, William Jay, Alessandro Lovato,
    Pedro A. Machado, Noemi Rocco

Undergraduate Student Contributions:
    Diego Lopez Gutierrez, Sherry Wang, Russell Farnsworth
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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

All generators compete to describe physics but each generator is more or less experiment specific and also “tuned” to describe data from each experiment.

How Generators Work

An Exercise in Piecewise Functions with GENIE

Models are applied piecewise with dozens of individual parameters.

It’s necessary to rigorously vet and understand models before applying to data.

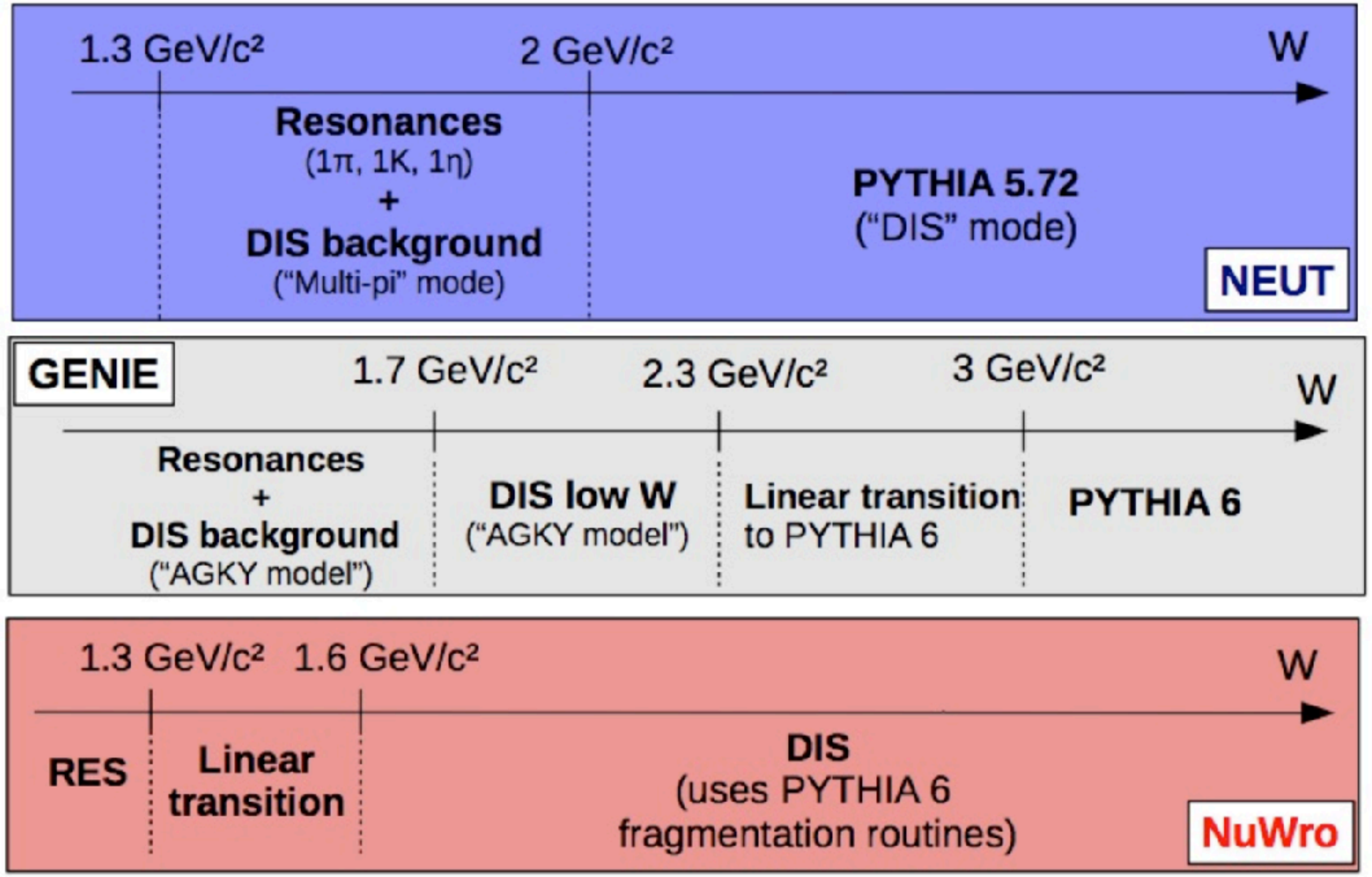
CMC	Initial State	QE	Res	MNI/MEC	DIS	FSI	Tune
N18_10j_02_11a (3.0.6)	LFG	Valencia	Berger-Seghal	Valencia	Bodek-Yang*	ItraNuke hN	Free-Nuke
N18_10j_02_11a (3.2)	LFG	Valencia	Berger-Seghal	Valencia	Bodek-Yang*	ItraNuke hN	Free-Nuke
N18_10j_02_11a * (3.4)	LFG	Valencia*	Berger-Seghal	Valencia	Bodek-Yang*	ItraNuke hN	Free-Nuke
N21_11b_02_11b* (3.2)	LFG	SuSAv2 1p1h	Berger-Seghal	SuSav2 2p2h	Bodek-Yang*	ItraNuke hN	Free-Nuke
N18_12j_02_11a	Correlated Fermi Gas	Valencia	Berger-Seghal	Valencia	Bodek-Yang*	ItraNuke hN	Free-Nuke
N18_10k_02_11b	LFG	Valencia	Berger-Seghal	Valencia	Bodek-Yang*	INCL++	Free-Nuke
GPRD18_10a_02_11b	LFG	Valencia	Berger-Seghal	Empirical	Bodek-Yang*	ItraNuke hN	Julia-Tune
AR23_20i_00_000 (3.4)	LFG*	Valencia	Berger-Seghal	SuSAv2 2p2h*	Bodek-Yang*	hA2018*	Free-Nuke

How Generators Work

An Example of Piecewise Functions in Other Models with SIS/DIS

Other generators may make different decisions when it comes to model but they should all agree!

Major tension between models and experiments in many cases…



J. Morfin, NuSTEC Workshop 2019

NEUT

Genie
UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

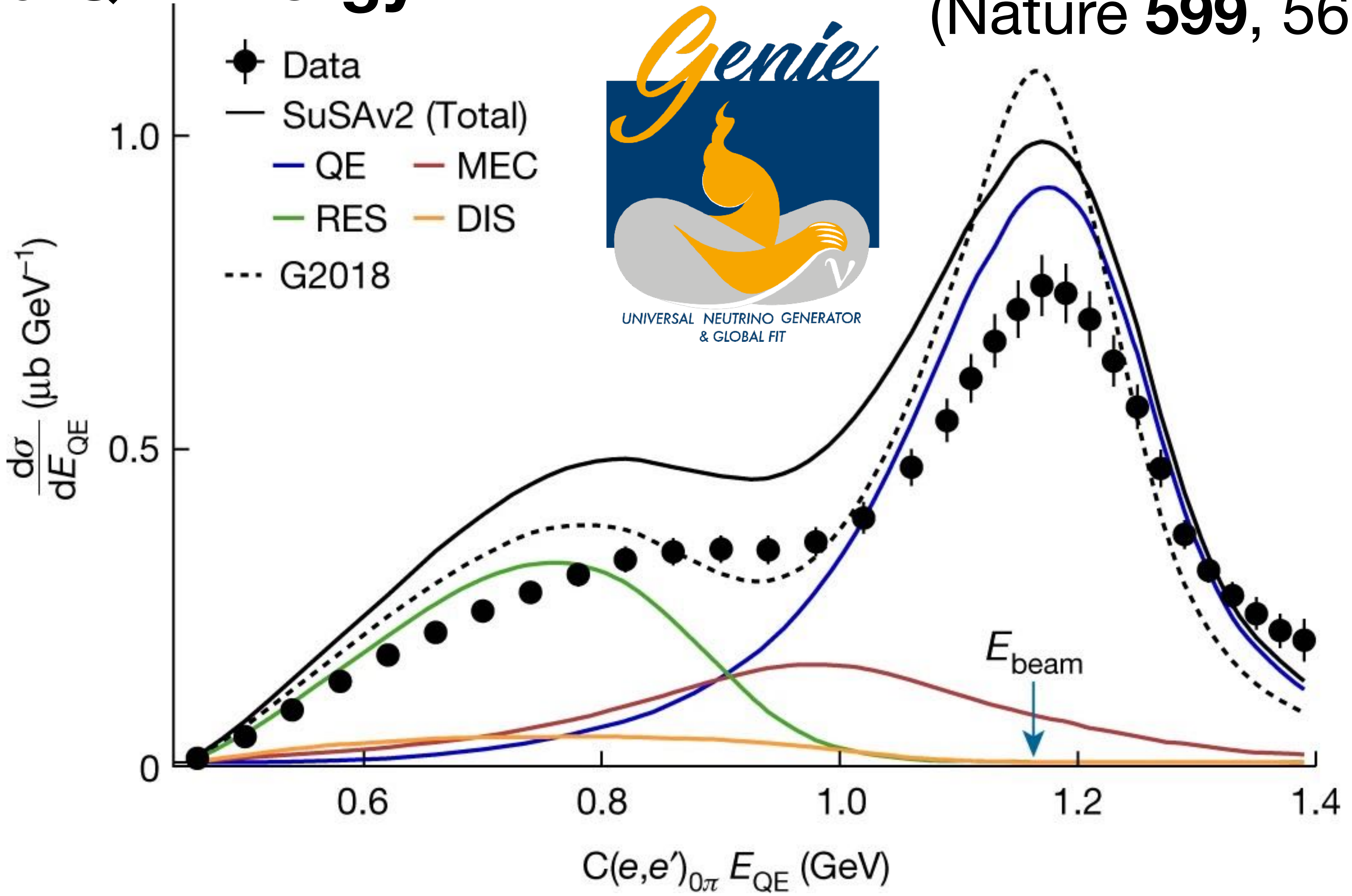
NuWro
Wroclaw Neutrino Event Generator

Generator (GENIE) Output

Validating Output from Neutrino Event Generators

Reconstructed QE Energy

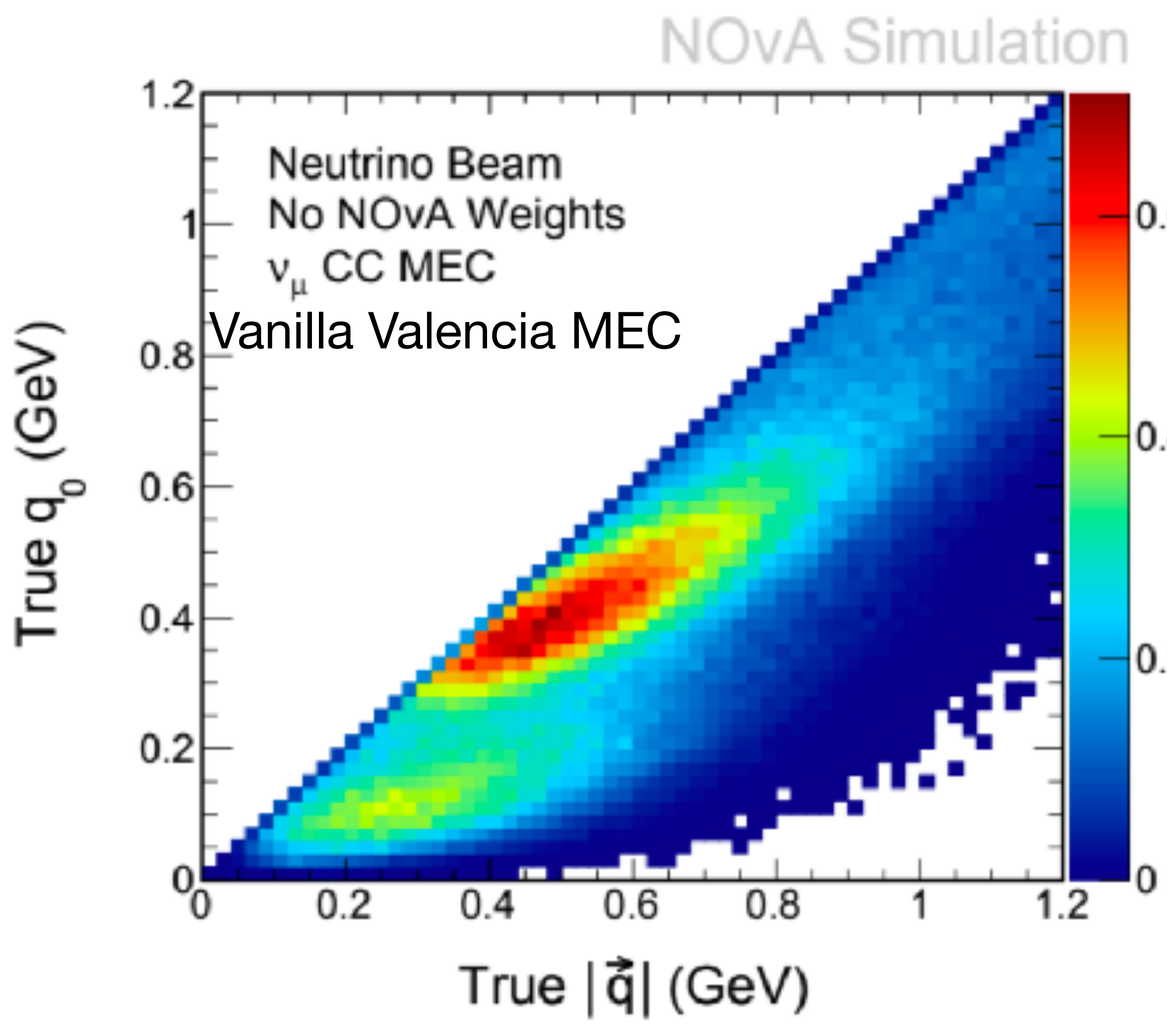
(Nature **599**, 565–570 2021)

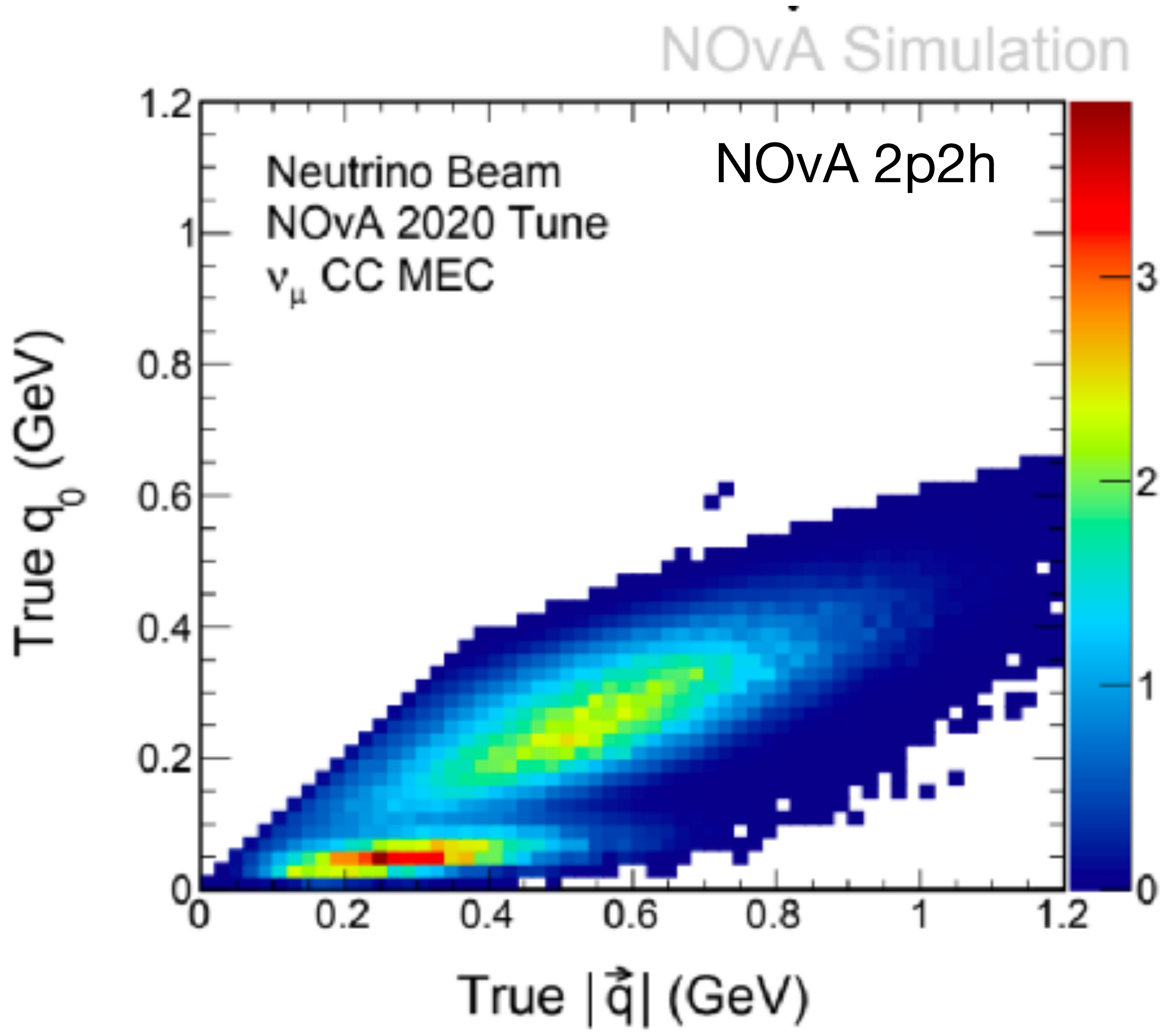


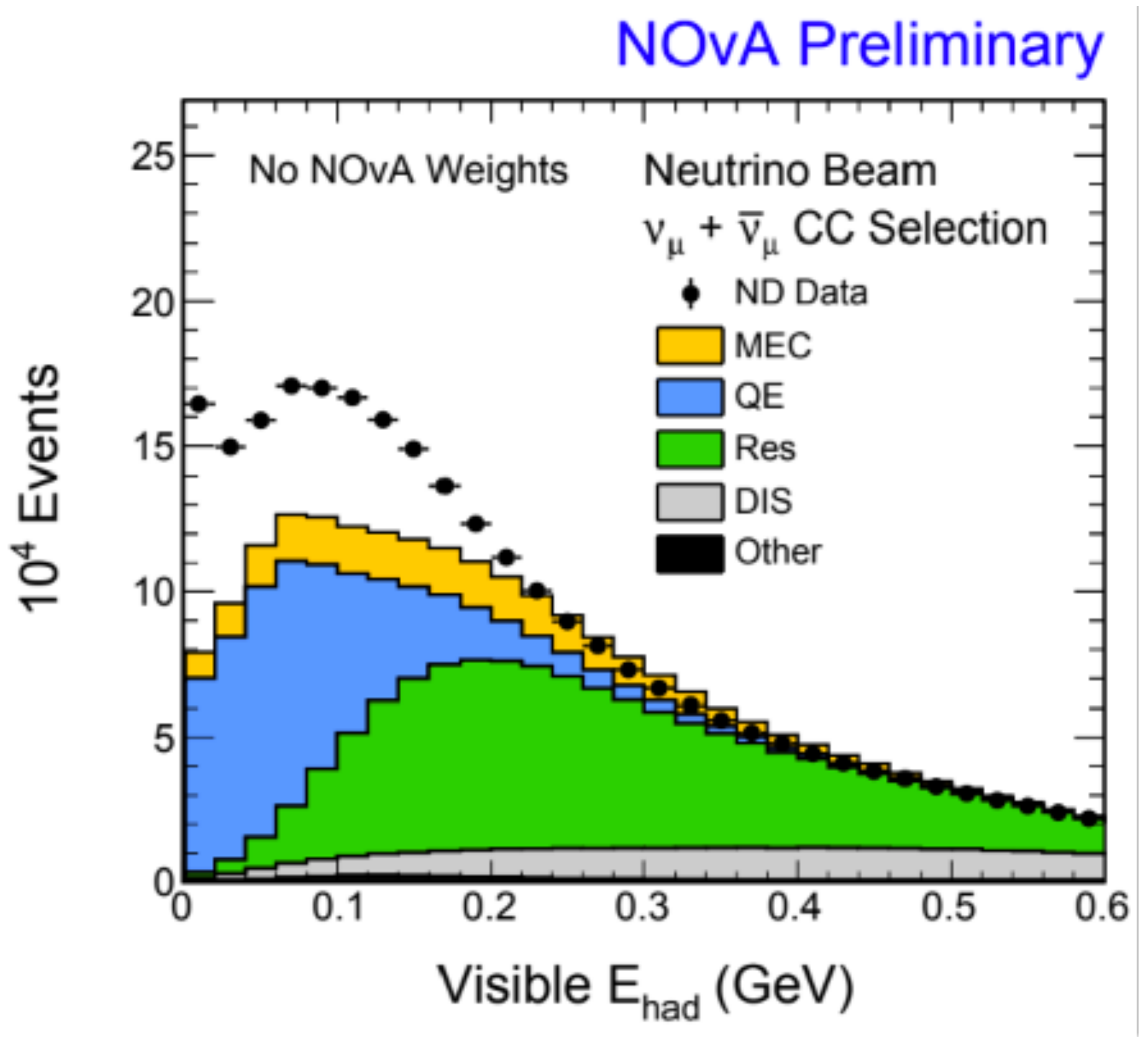
Popular MIT/JLab Group involved in GENIE development has compared neutrino generator output to electron scattering from Carbon. These results should be simple to reproduce.

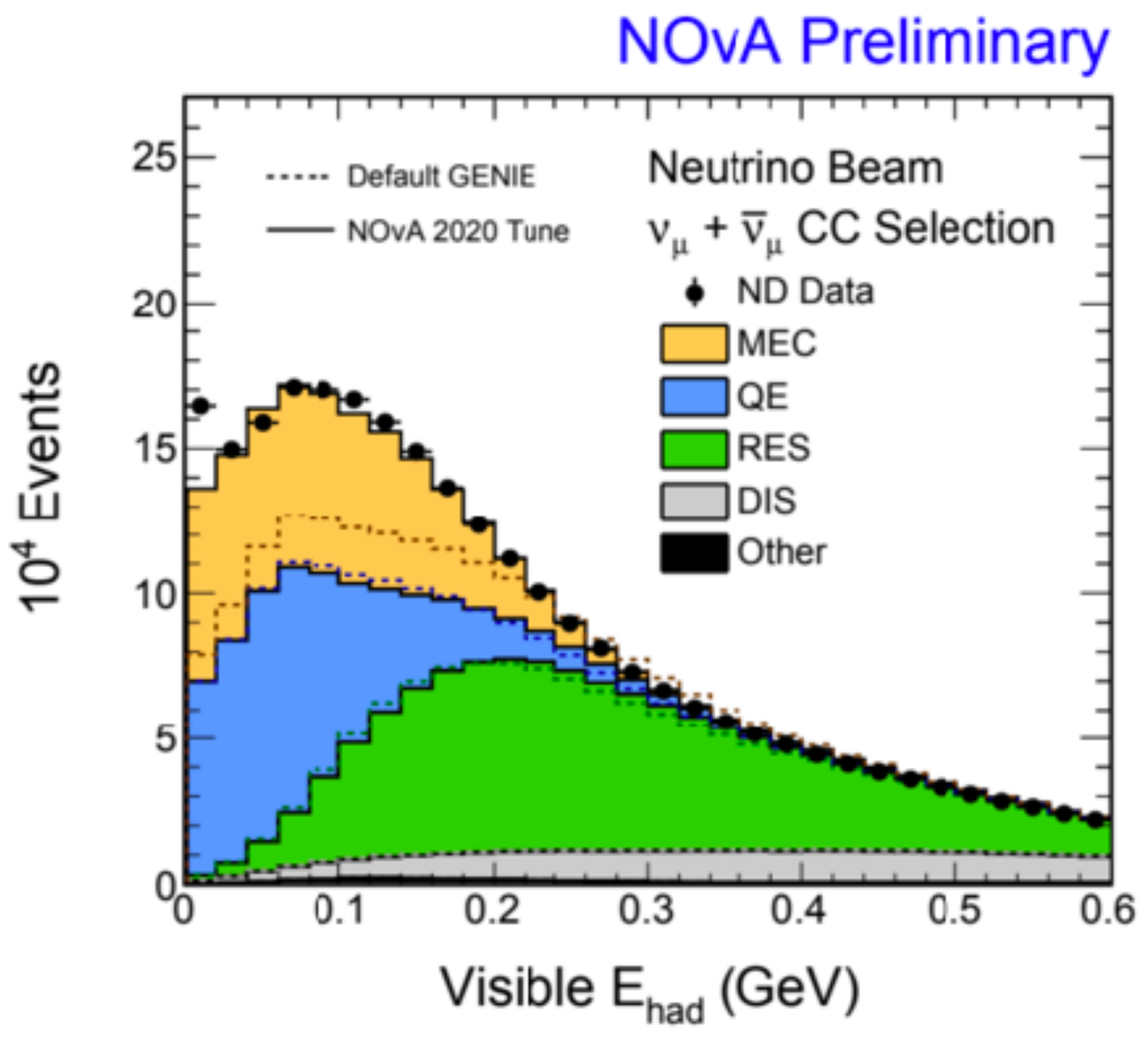
Application of Generators to Data

An example with MEC in GENIE on NOvA









NOvA uses GENIE to model neutrino interactions, but no 'vanilla' model describes excess data in the NOvA ND.

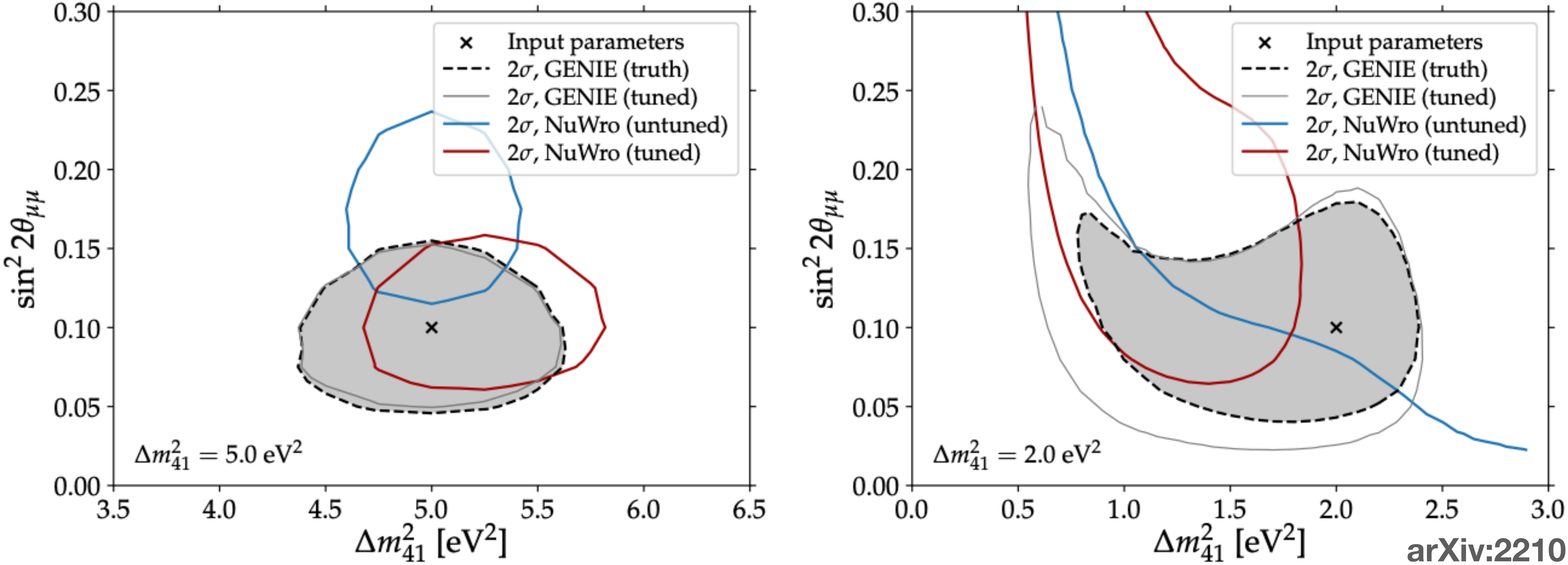
Custom '2p2h' tune does not perfectly describe low energy bins.

MEC exists (!) but no older neutrino experiments around to bound the effect.

Each neutrinos experiment *requires* significant *tunes* to match any given generator and tunes bring experiments out of agreement with each other!

Application of Modeling to New Physics Searches

An example with the NOvA Tune in Sterile Searches



arXiv:2210.03753

Tuning from public release of first NOvA oscillations analysis, but broad strokes are similar even if large changes in underlying model and treatment of systematics have changed.

Near Detector model tuning is a reasonable stop-gap in, but parameter sensitivity to tuning can not be estimated *a-priori*. **Will we know when we are wrong?**

Conclusions and Summary

Yeehaw!

Neutrino Oscillations are a well understood phenomenon with significant international effort and numerous extensions

The business of performing parameter estimation for observable lepton oscillation phenomena is technically challenging.

Neutrino focused event generators are an active field of development and ripe for improvement.

The next generation of *long baseline* oscillation experiments will increase statistics by orders of magnitude but are potentially limited by our current understanding of neutrino-nucleus scattering.

The next generation of *long baseline* oscillation experiments will also have state-of-the-art beam and Near Detectors to exploit such beam.

This environment is fertile for creative young scientists!