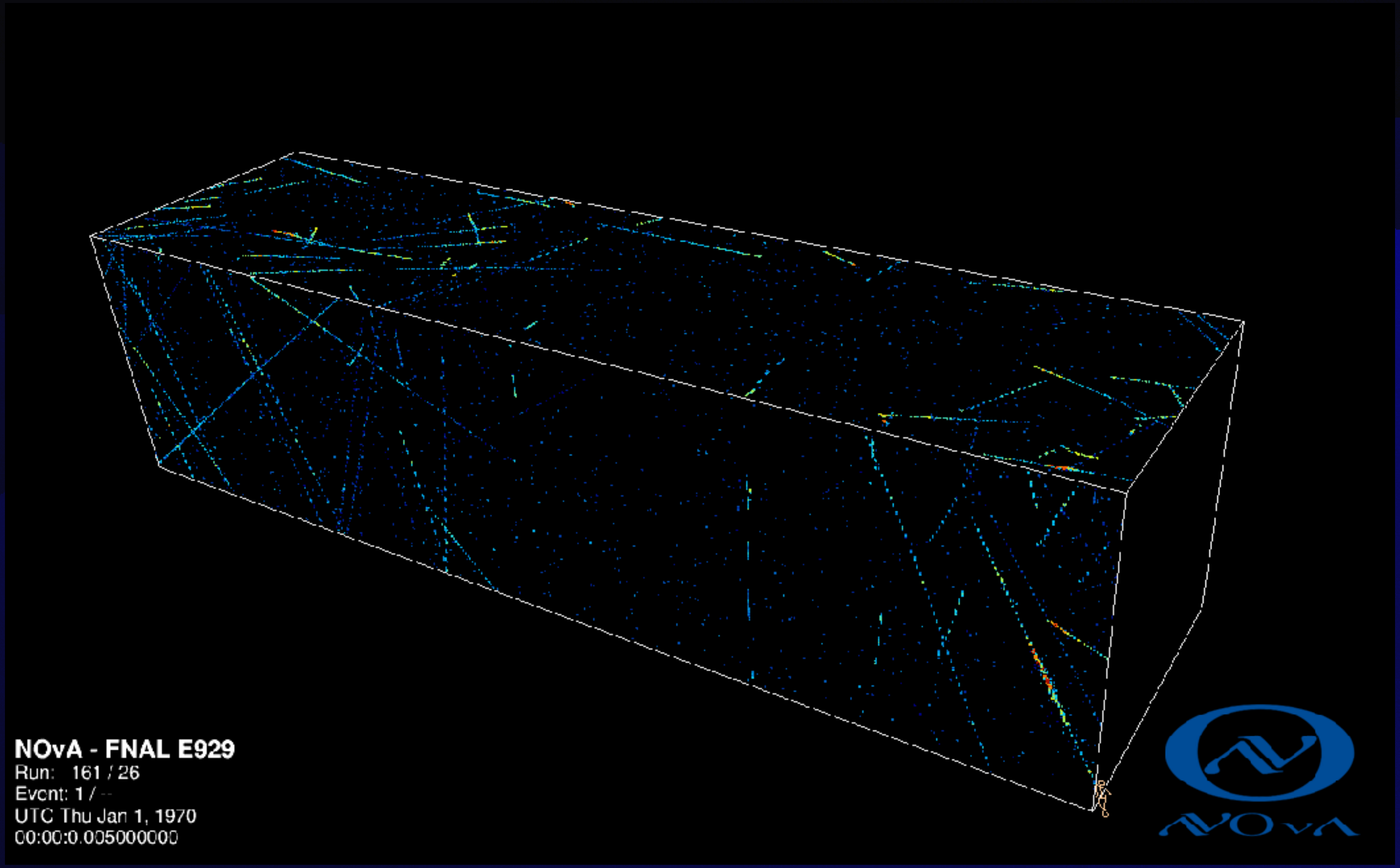
Cross-Section Modeling on the NOvA Experiment

NuFact 2023: The 24th International Workshop on Neutrinos From Accelerators
Seoul National University, Seoul, Korea
August 22nd, 2023

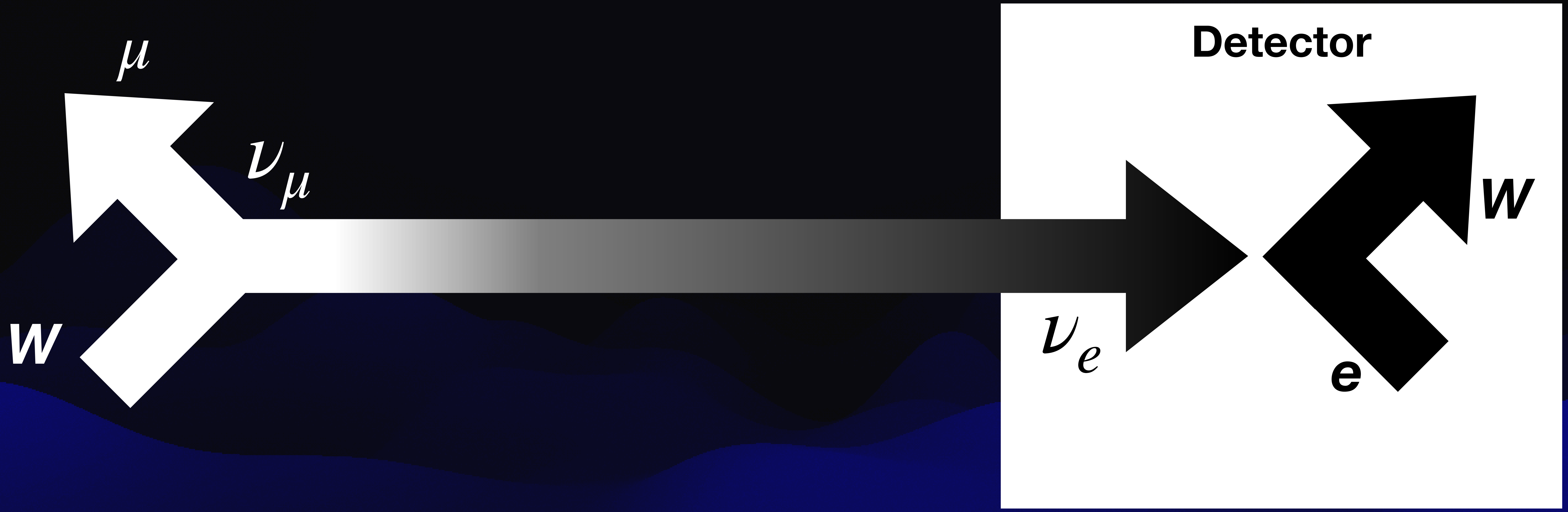


Bryan Ramson, Mat Muether, & Kirk Bays, on behalf of the NOvA Collaboration

Fermilab

Introduction to Neutrinos and Oscillations Physics

Paths to Beyond-the-Standard-Model Physics



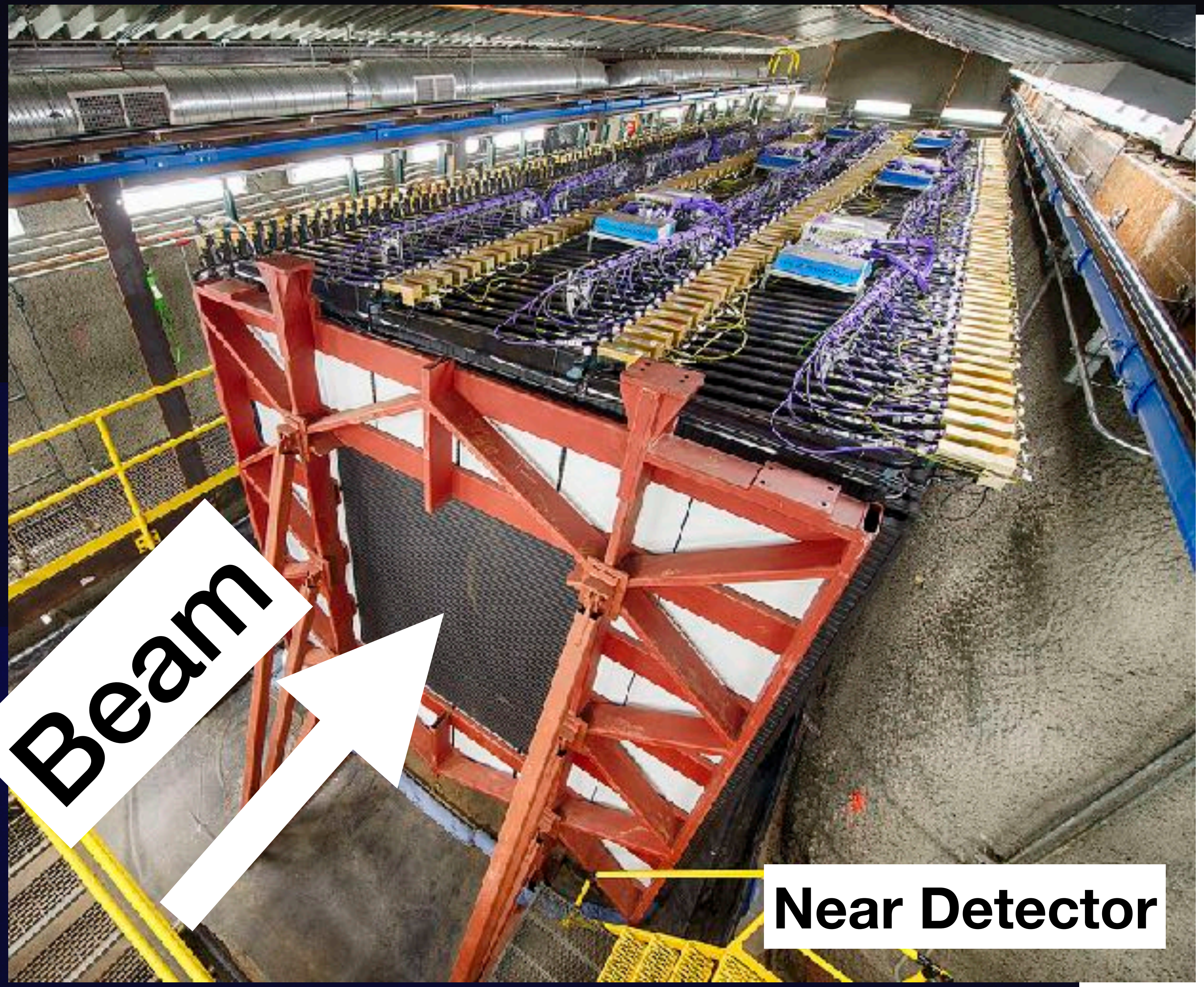
$$|U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu 1} & |U|_{\mu 2} & |U|_{\mu 3} \\ |U|_{\tau 1} & |U|_{\tau 2} & |U|_{\tau 3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}}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

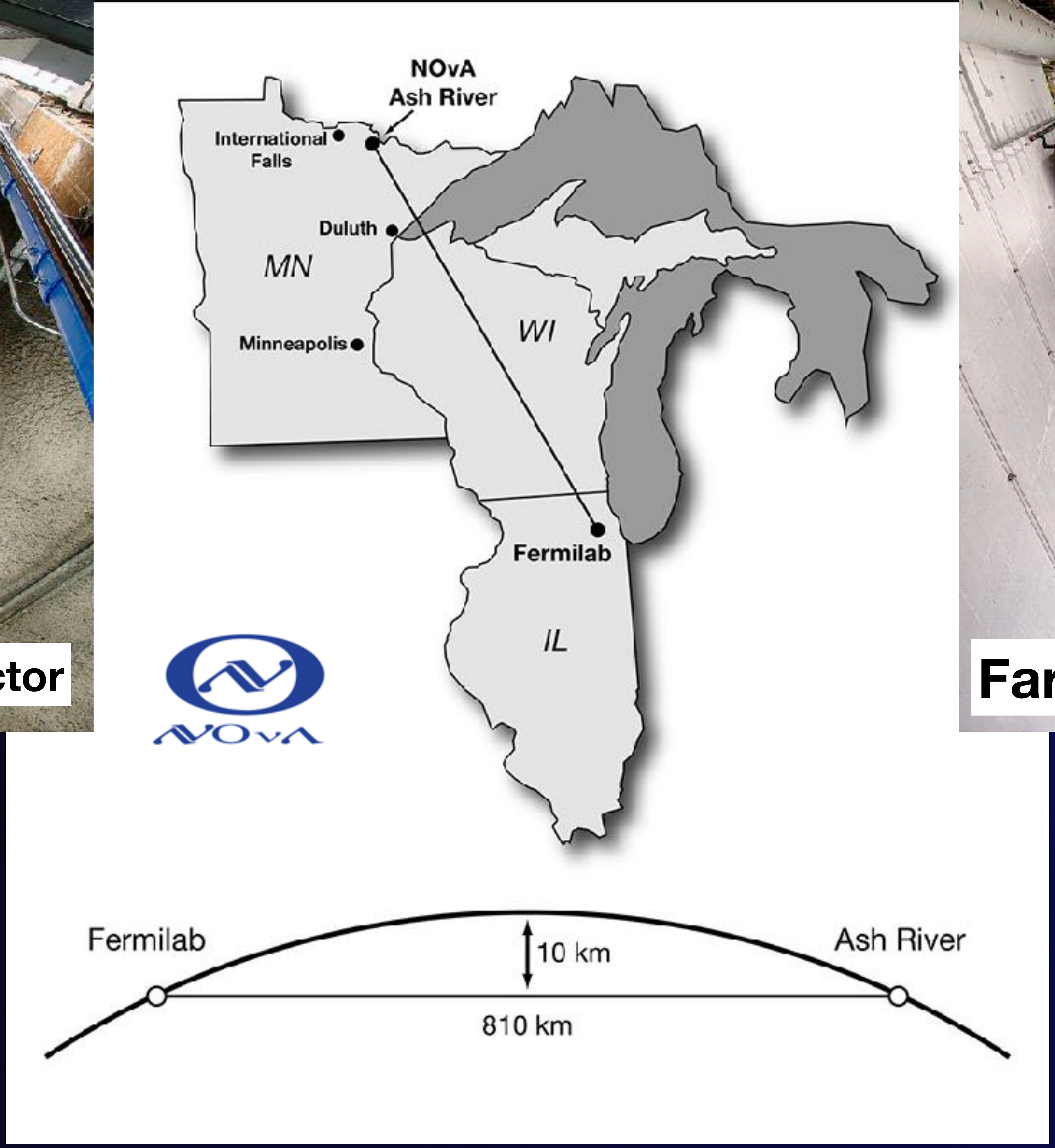
PMNS matrix depends on four independent parameters and resolution of all the three Euler angles gives access to CP-violating term. Mass hierarchy is tied into measurements of oscillation probability.

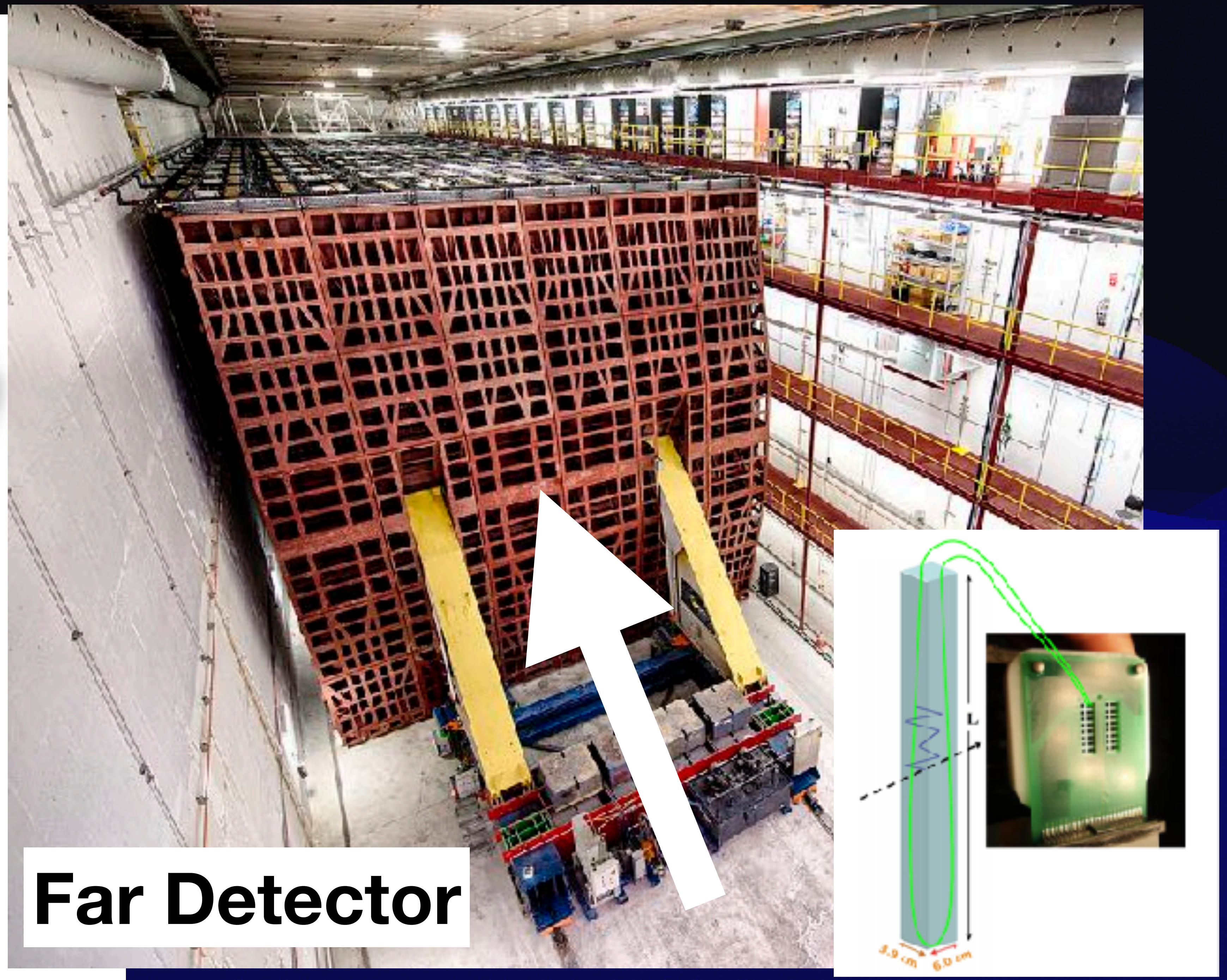
Introduction to the NOvA Experiment

The NuMI Off-Axis ν_e Appearance Experiment

Long-baseline neutrino oscillation experiment







Two functionally equivalent detectors, differ only in size, acceptance, and distance from beam.

14.6 mrad Off-axis ν_μ beam gives narrow peak around 2 GeV for (anti)neutrinos.

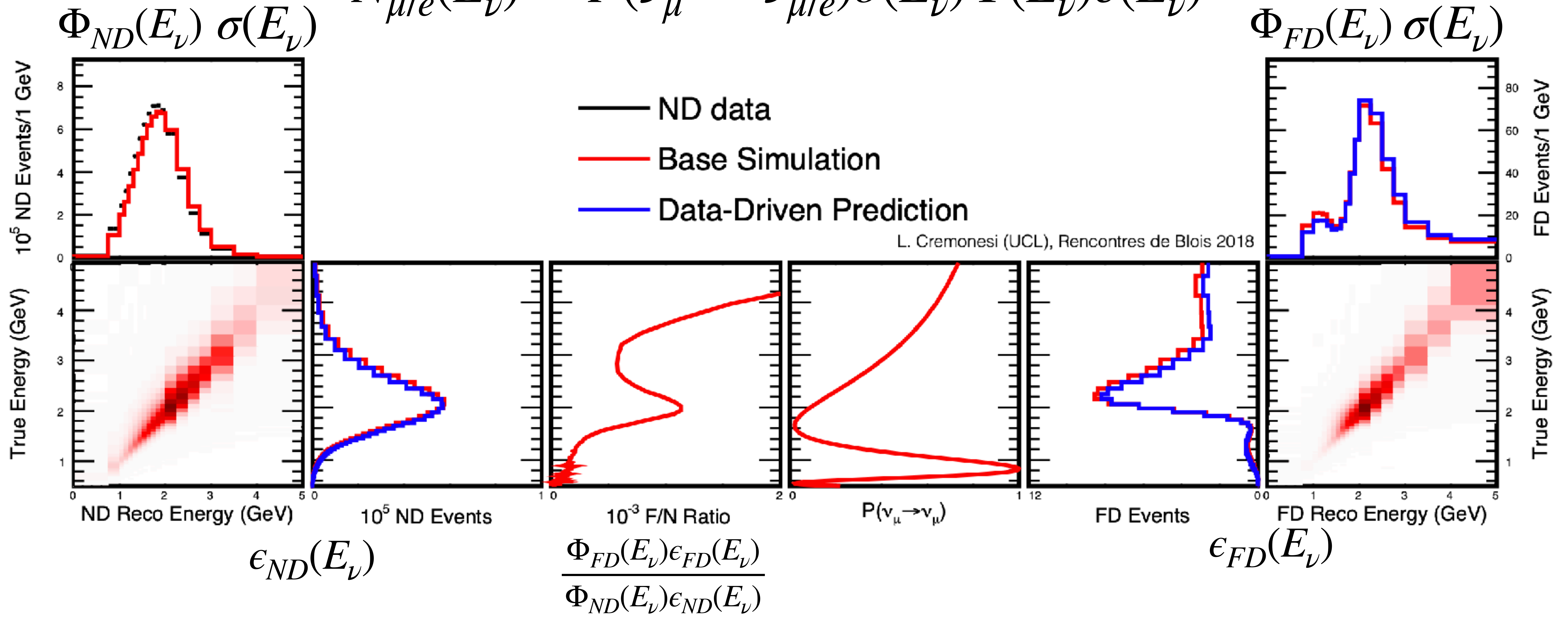
Tracking calorimeter made of PVC cells filled with a liquid scintillator and a plastic scintillating light guide connected to an APD, each about 4cm x 6cm x 15.5m.

C	Cl	H	O	Ti
65.9%	16.1%	10.7%	3.0%	2.4%

How to Do an Oscillations Analysis

A Brief Conceptual Overview for Extrapolative Oscillations Measurements

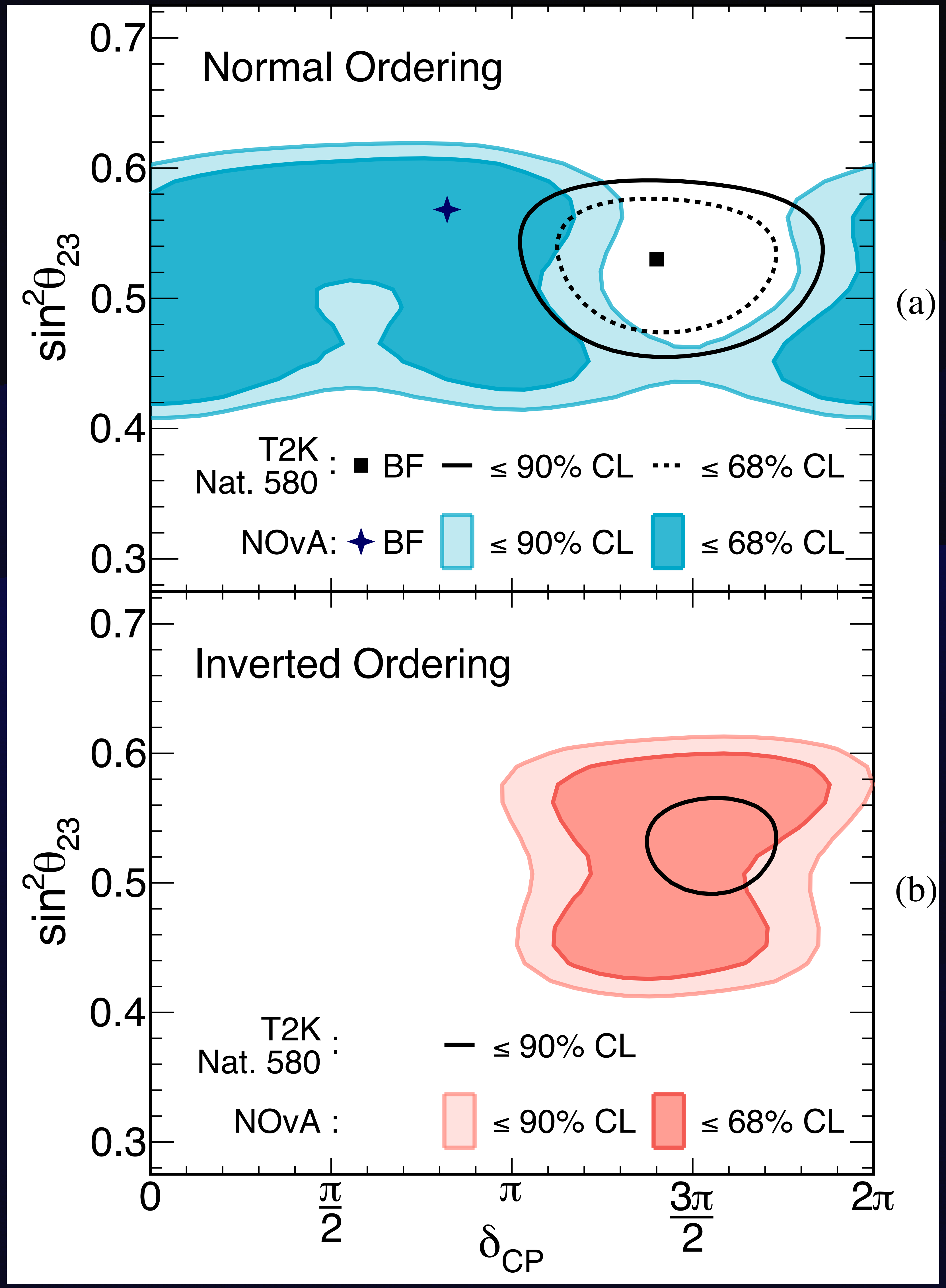
$$N_{\mu/e}(E_\nu) = P(\nu_\mu \rightarrow \nu_{\mu/e})\sigma(E_\nu)\Phi(E_\nu)\epsilon(E_\nu)$$

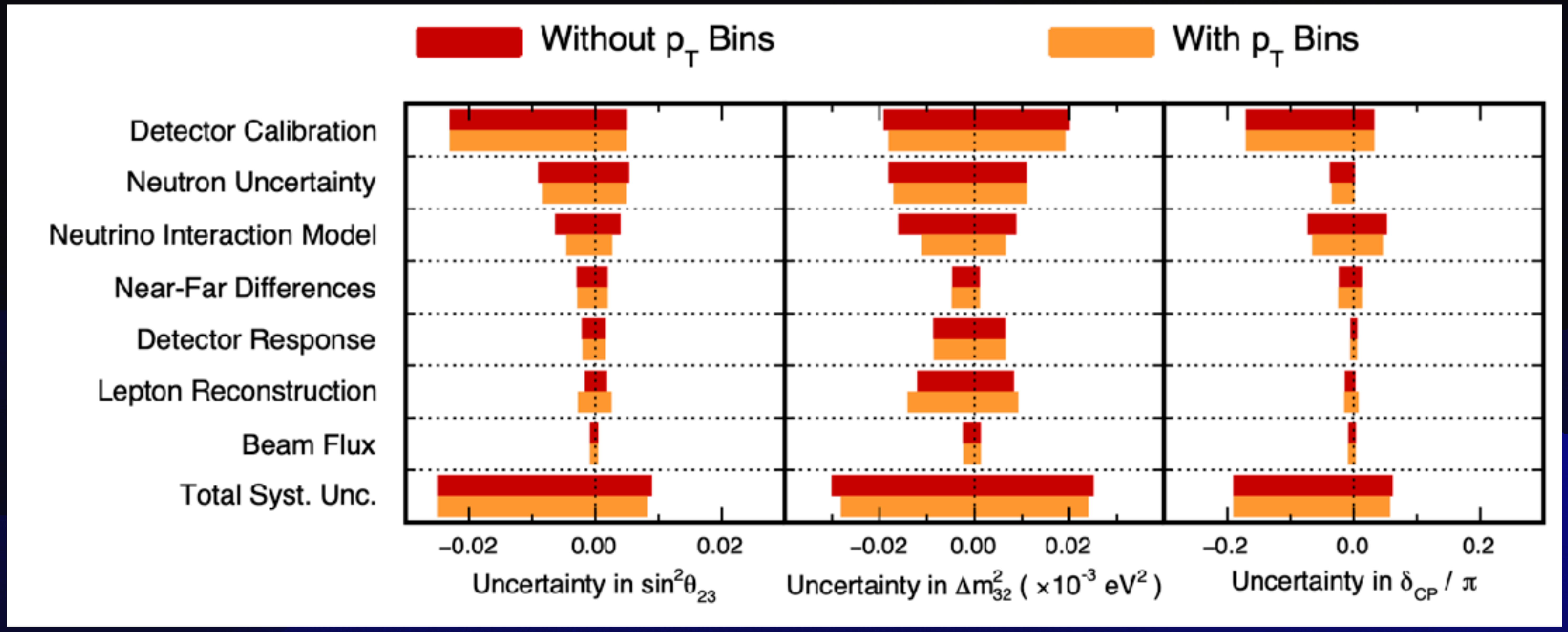


NOvA extrapolative style analysis exploits the similarity of detectors to propagate systematic uncertainties through the analysis. Extrapolative style makes evident the tolerance of results relative to systematic uncertainties within the analysis.

Current Generation of Long-Baseline Experiments

Current State-of-the-Art Measurements



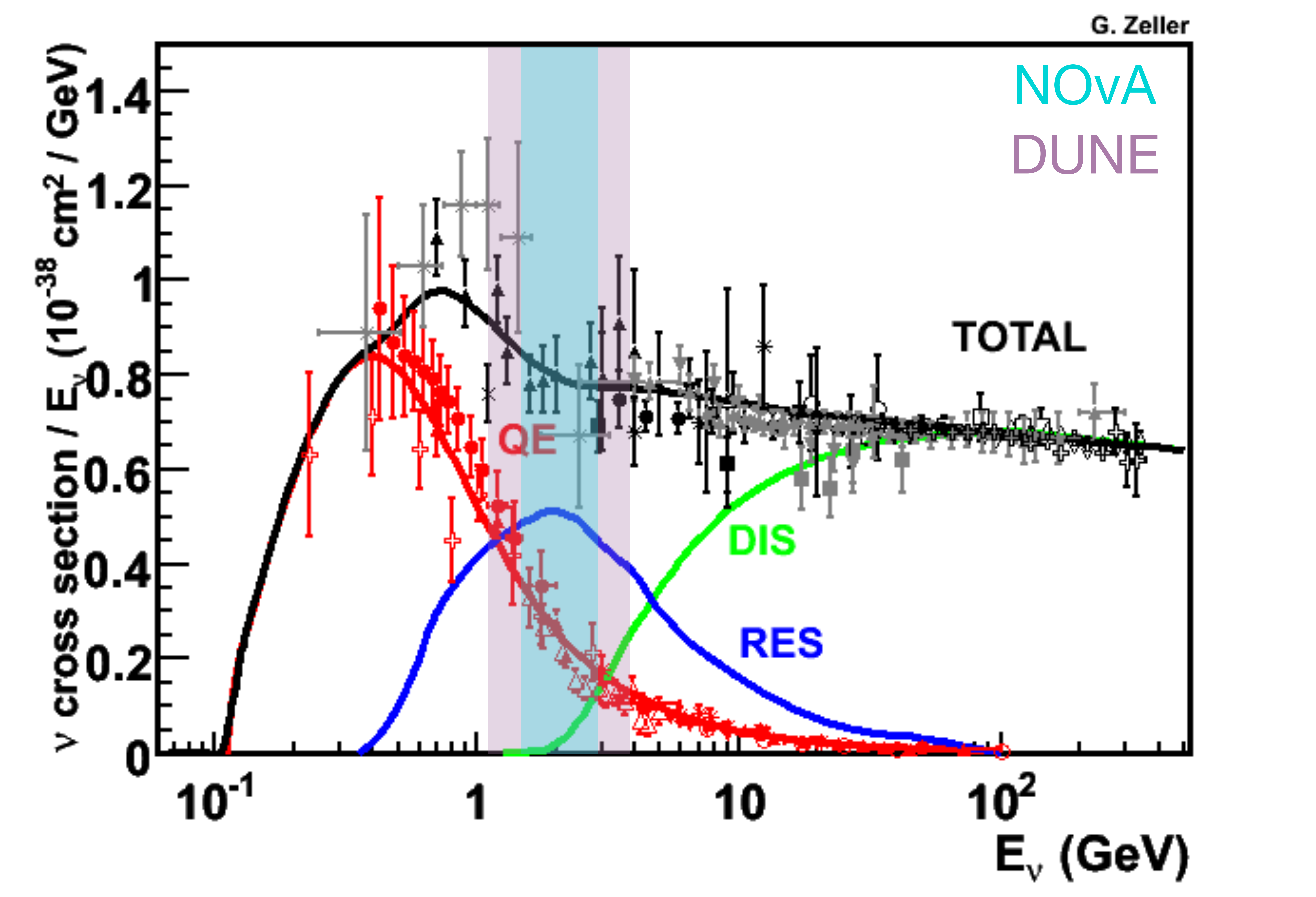


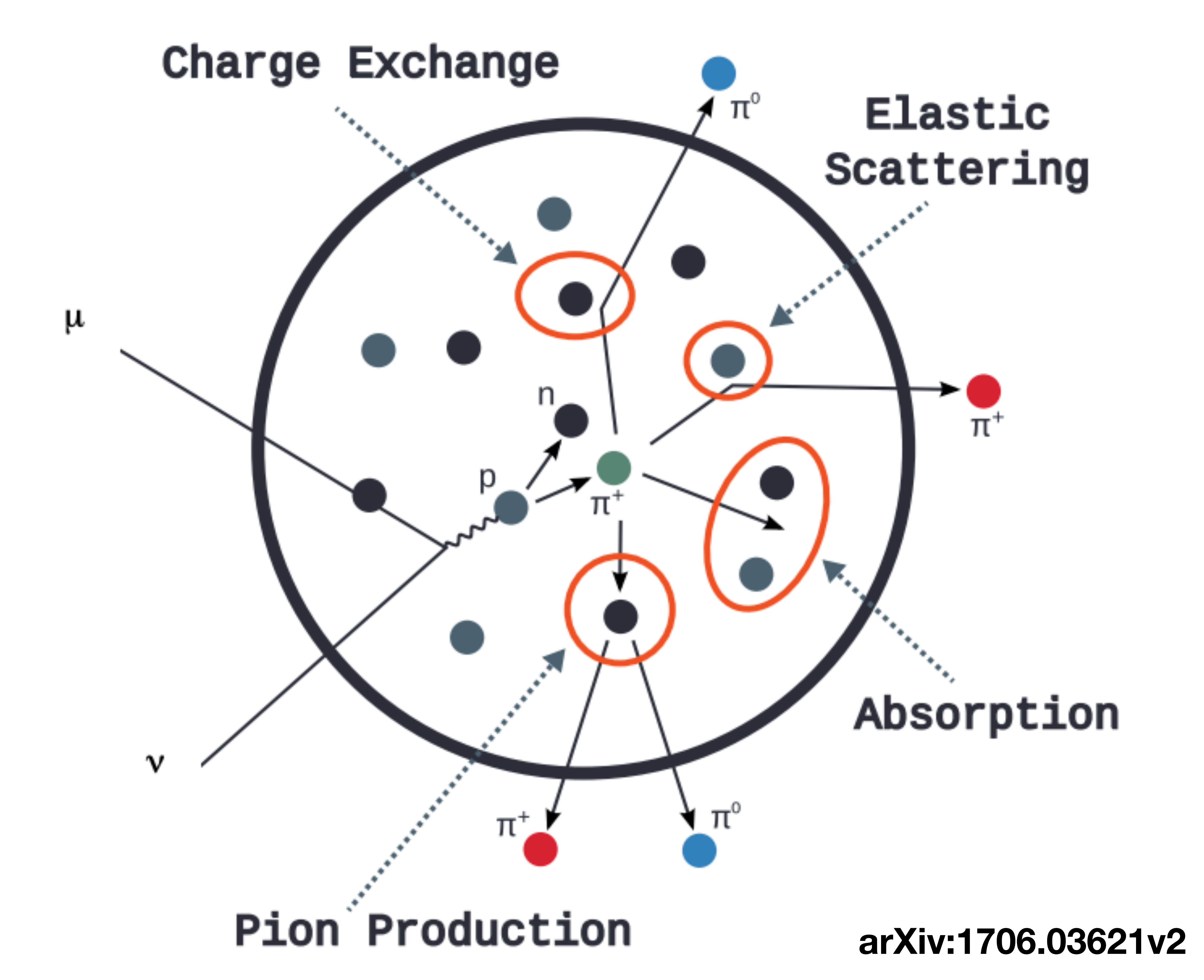
Latest 3-flavor results from NEUTRINO 2022 show large uncertainties on measurement on the atmospheric neutrino angle (θ_{23}) and CP-Violating parameter.

Largest uncertainties are controllable because of analysis style however, interaction model systematic will become more important as other sources are reduced.

The Neutrino-Nucleus Cross Section Problem

Where is the Problem?



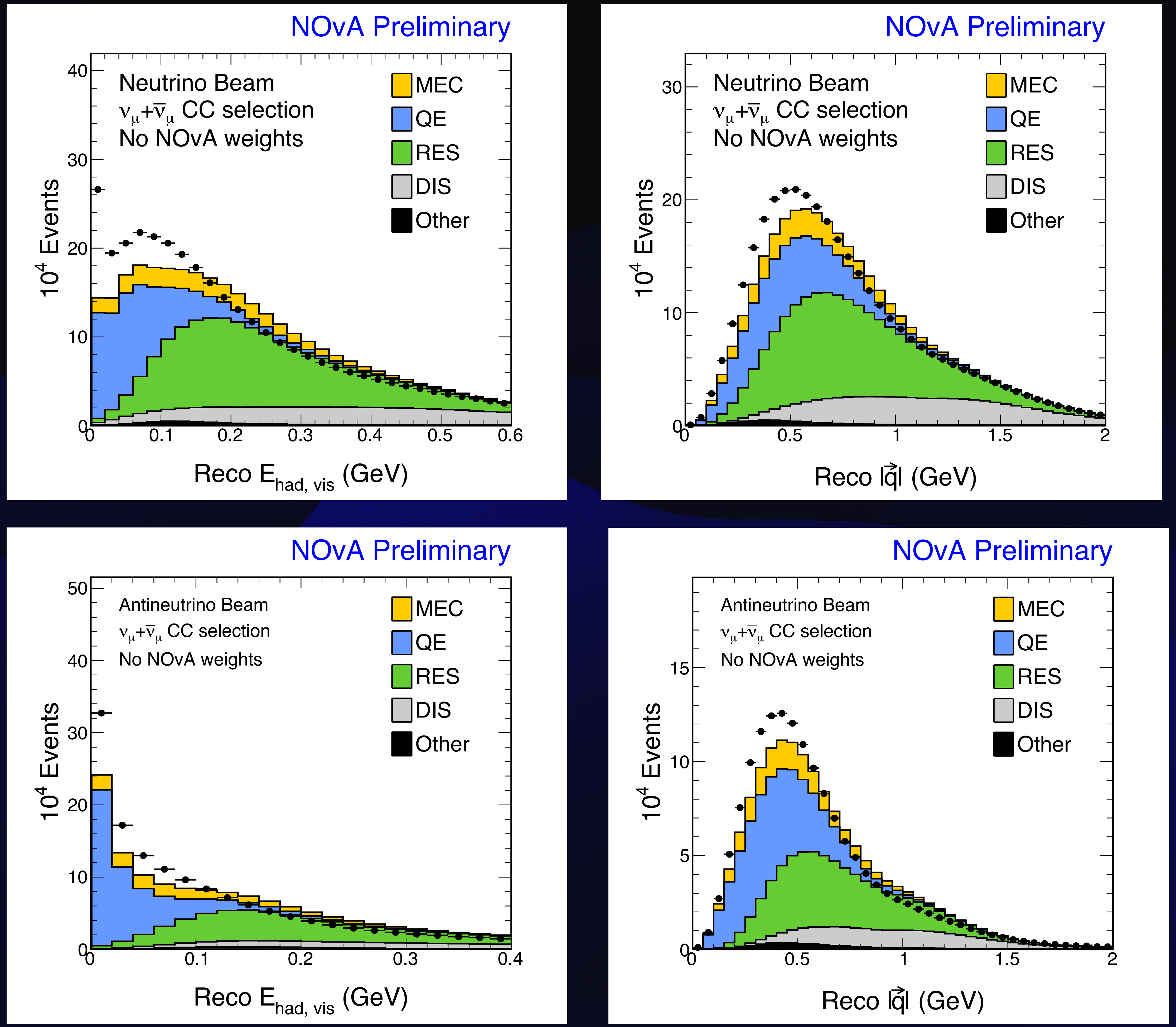


To first order must understand interplay between four different types of scattering (QE/Elastic, RES, DIS, MEC).

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

Starting Point for the 2020 3-Flavor Analysis

Strategy and Initial Impressions



Approach is broken into two parts: **Central Value** and **Systematics** over the initial state, final state, and four processes:

Initial State	QE	MEC	Res	DIS	Final State

Tuning Philosophy

- Are there external data or theory explanations for our choices?
- How much do the data agree with the model?
- Do our systematics cover differences?

Initial comparisons show consistent underprediction of data.

Definition of Simulation

Descriptions of GENIE Configuration

We choose GENIE v3.0.6 as was the most up to date as of the last model freeze and included considerable fixes over GENIE 2.12 (2018 Analysis).

CMC	Initial State	QE	MEC	Res	DIS	Final State	Tune
N18_10j_02_11a	Local Fermi Gas	Valencia	Valencia	Berger-Seghal	Bodek-Yang	IntraNuke-hN2018	Free-Nucleon

Initial State: Local Fermi Gas, traditionally well motivated but not perfect.

QE: Valencia 1p1h suitable Central Value model, slight updates (N18_10j) include the use of the z-expansion formalism. Uncertainties treated with RPA knobs, and Z-Expansion knobs (Axial Mass and coefficients of the expansion).

Res/DIS: Berger-Seghal and Bodek-Yang well understood, 02_11a tune sets central value to bubble chamber data.

Final State Interactions and MEC are challenges in modeling for NOvA!

Final State Interactions for 2020 3F Analysis

Semi-Classical Intranuclear Cascade model

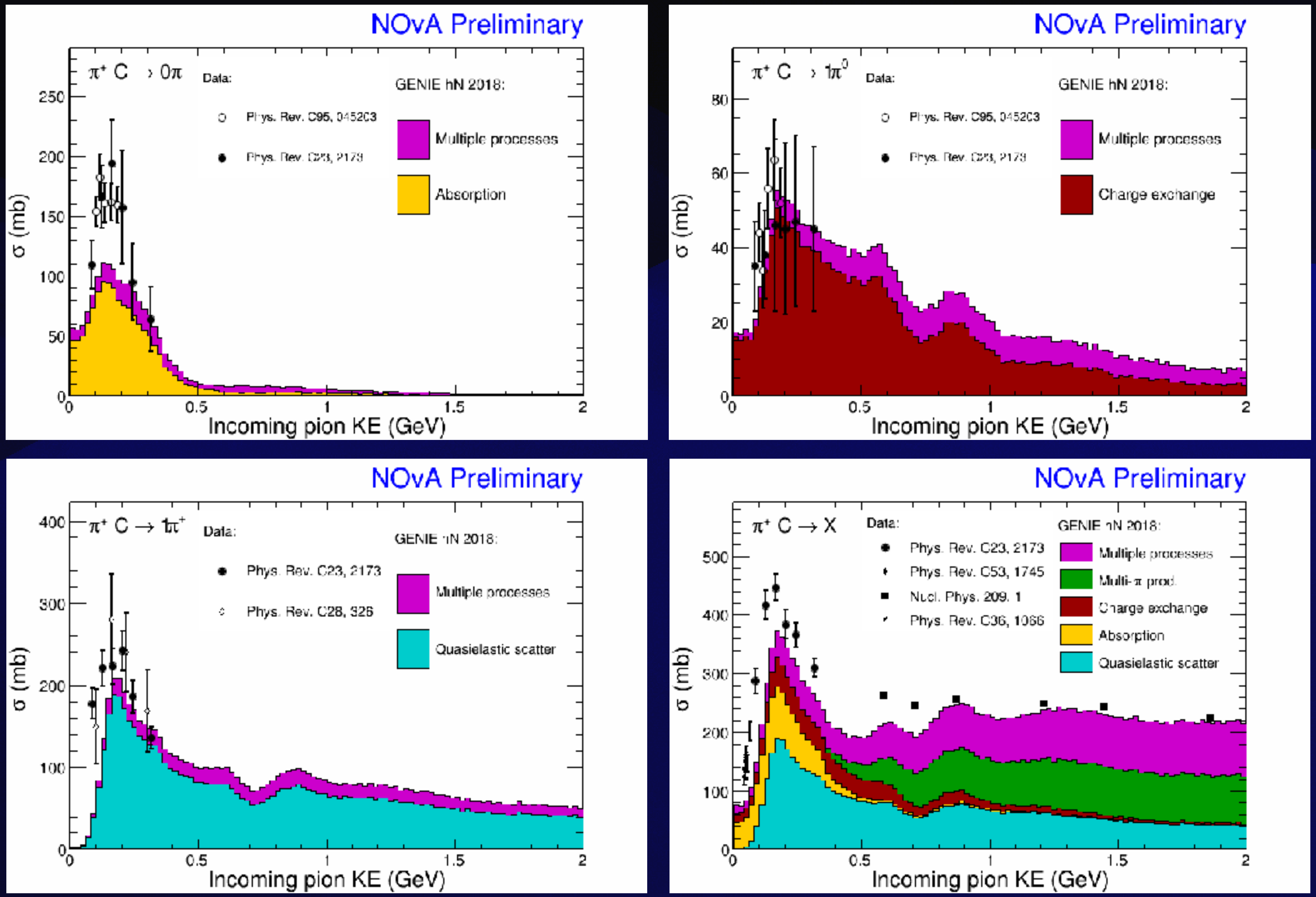
Choice between empirical “effective” cascade model IntraNuke hA2018 or semi-classical model, hN2018. We chose the latter.

First we developed the central value tune.

Divided reactive pion cross-section into three topological processes, charge exchange, absorption, and quasi-elastic.

Tune fate fractions to better match available data.

40% decrease in absorption with 40% increase in mean free path based on reaction channel.



Final State Interactions for 2020 3F Analysis

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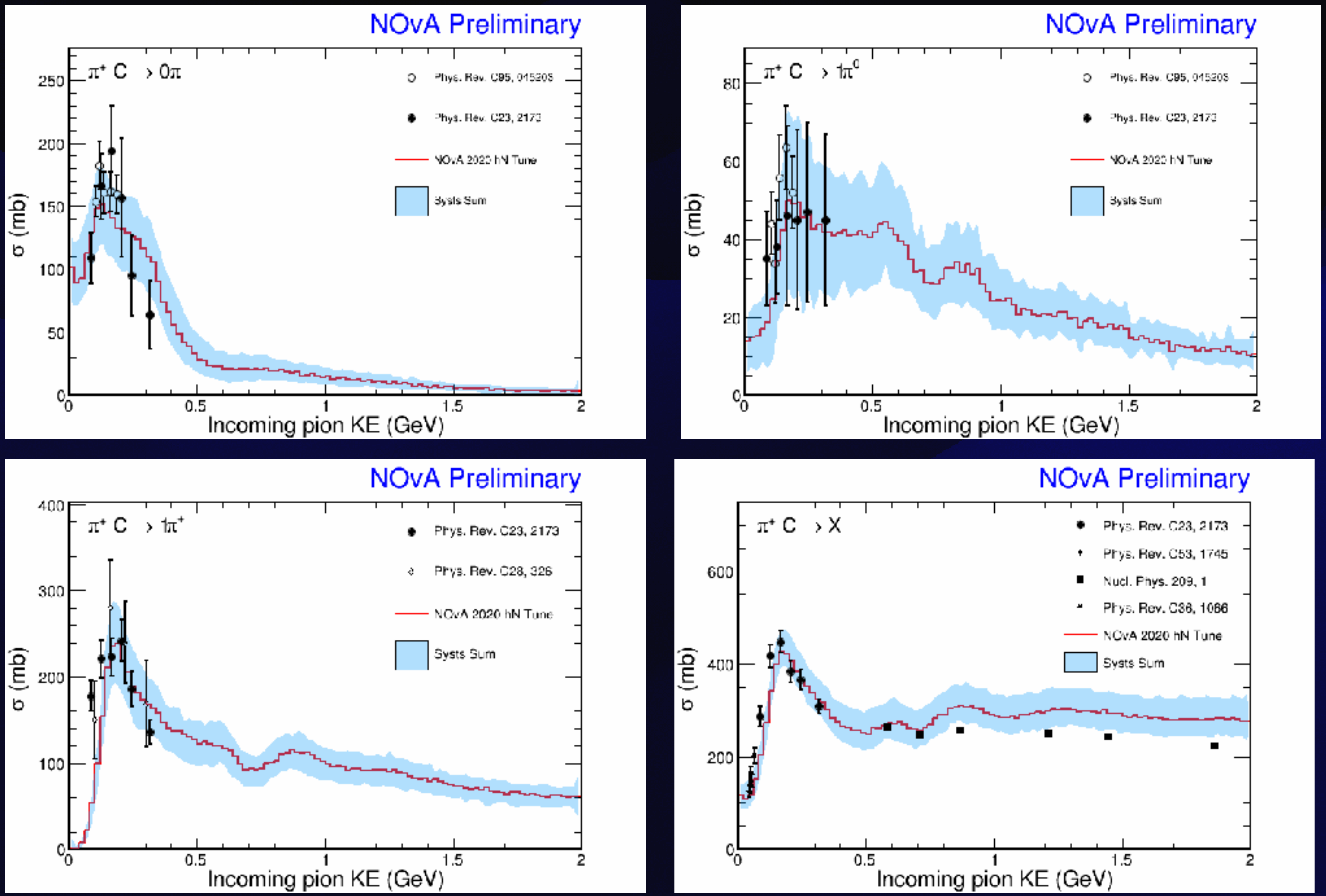


Reweightable uncertainties had not been properly implemented and systematics had to be developed.

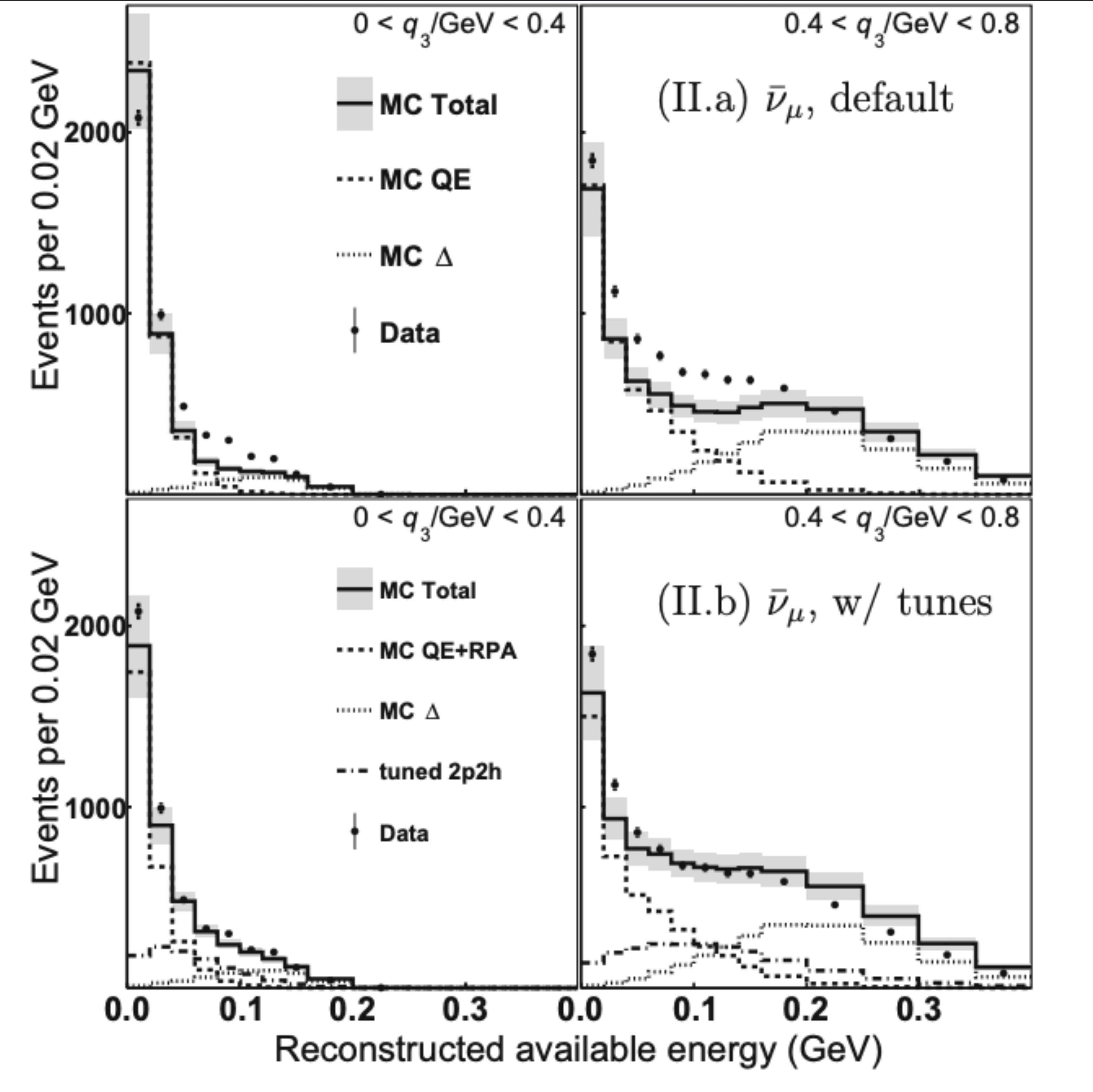
We use T2Ks fate fractions along with a mean free path scan to bracket uncertainties in the data. Reweighting implemented using a BDT.

https://doi.org/10.1103/PhysRevD.99.052007

Meson Exchange Currents/2p2h for 2020 3F Analysis

Central Value Tuning Method Explanation

MEC model is a large source of uncertainty in neutrino scattering; generally not well understood for neutrinos.



A. Filkins *et al.* (MINERvA Collaboration)
Phys. Rev. D **101**, 112007 (2020)

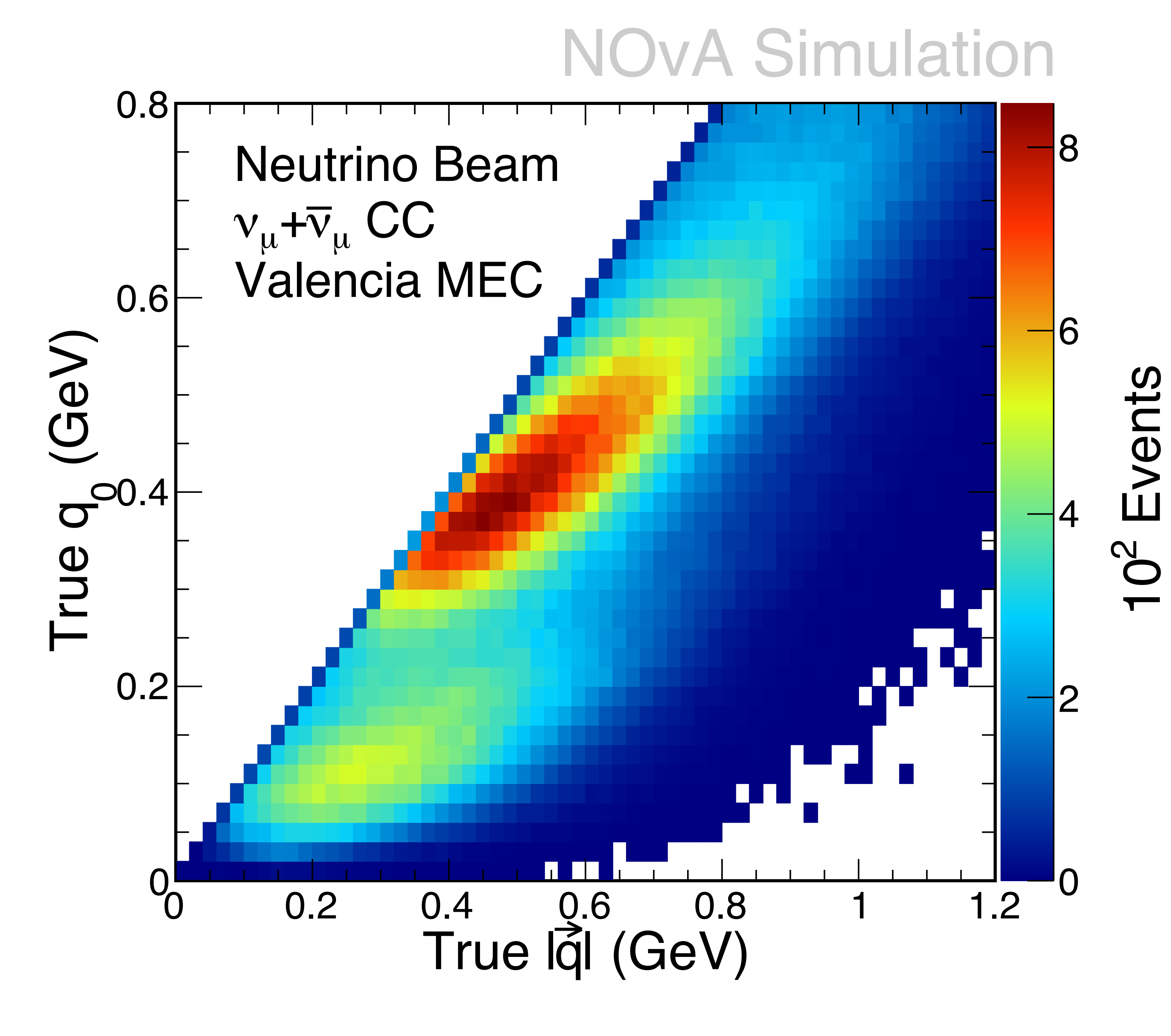
Approach: save MEC tuning for last and *assume* all leftover differences between data and simulation are due to MEC.

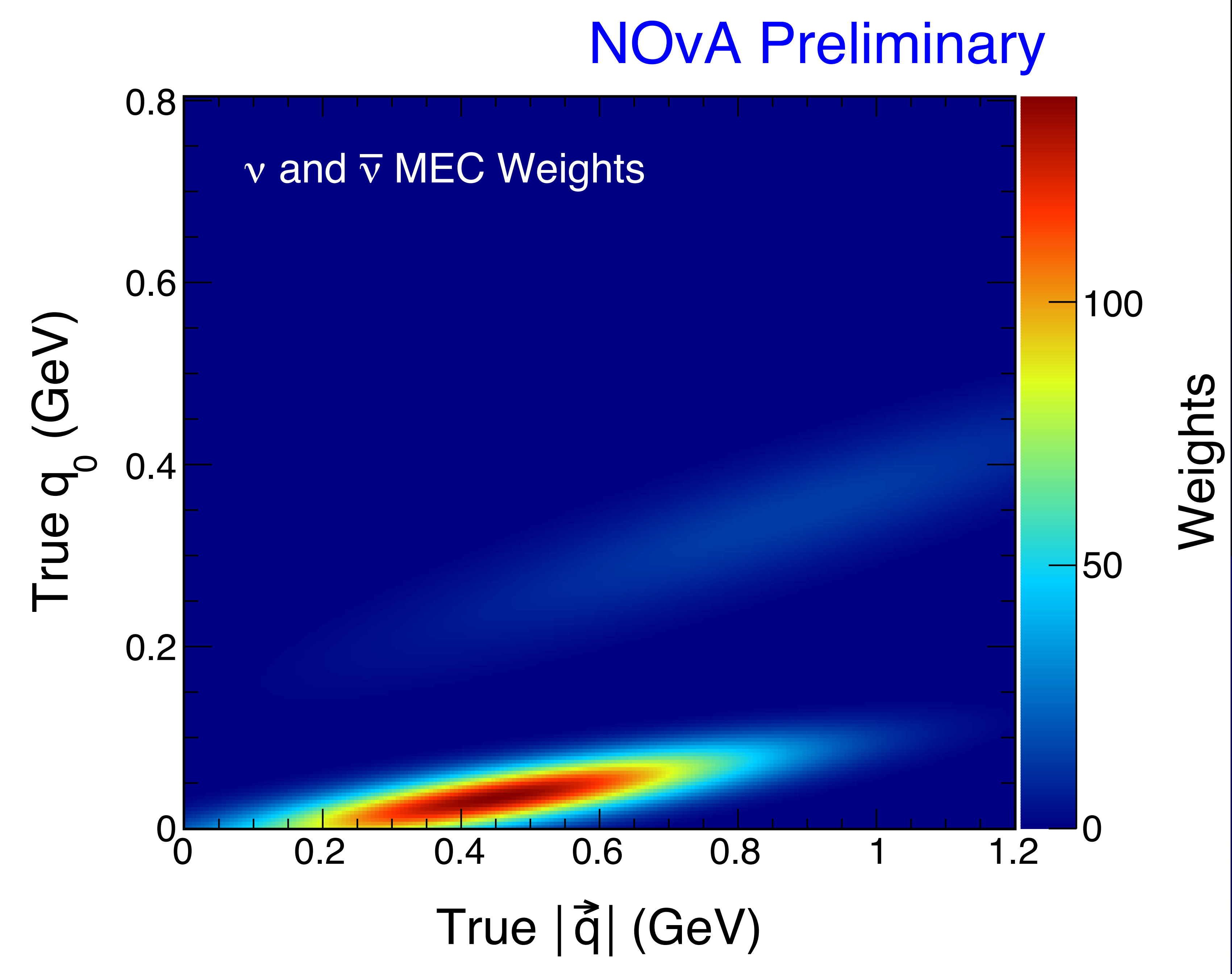
Apply purely empirical adjustments to Valencia model; better supported theoretically.

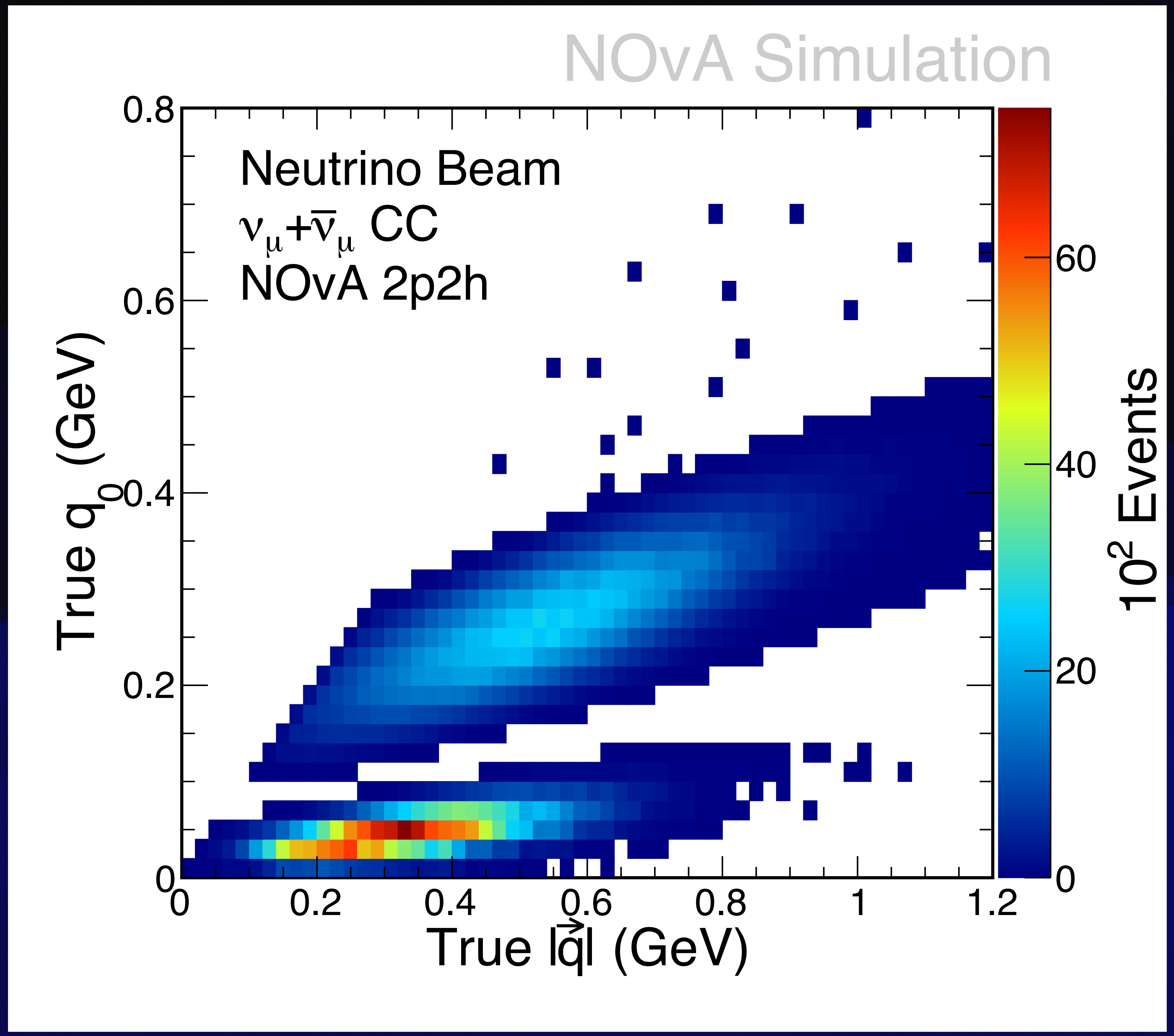
Method inspired by MINERvA's approach.

Meson Exchange Currents/2p2h for 2020 3F Analysis

Central Value Tuning Method Application







Fit is performed to Near Detector data using dual 2D-Gaussians in energy and momentum transfer space.

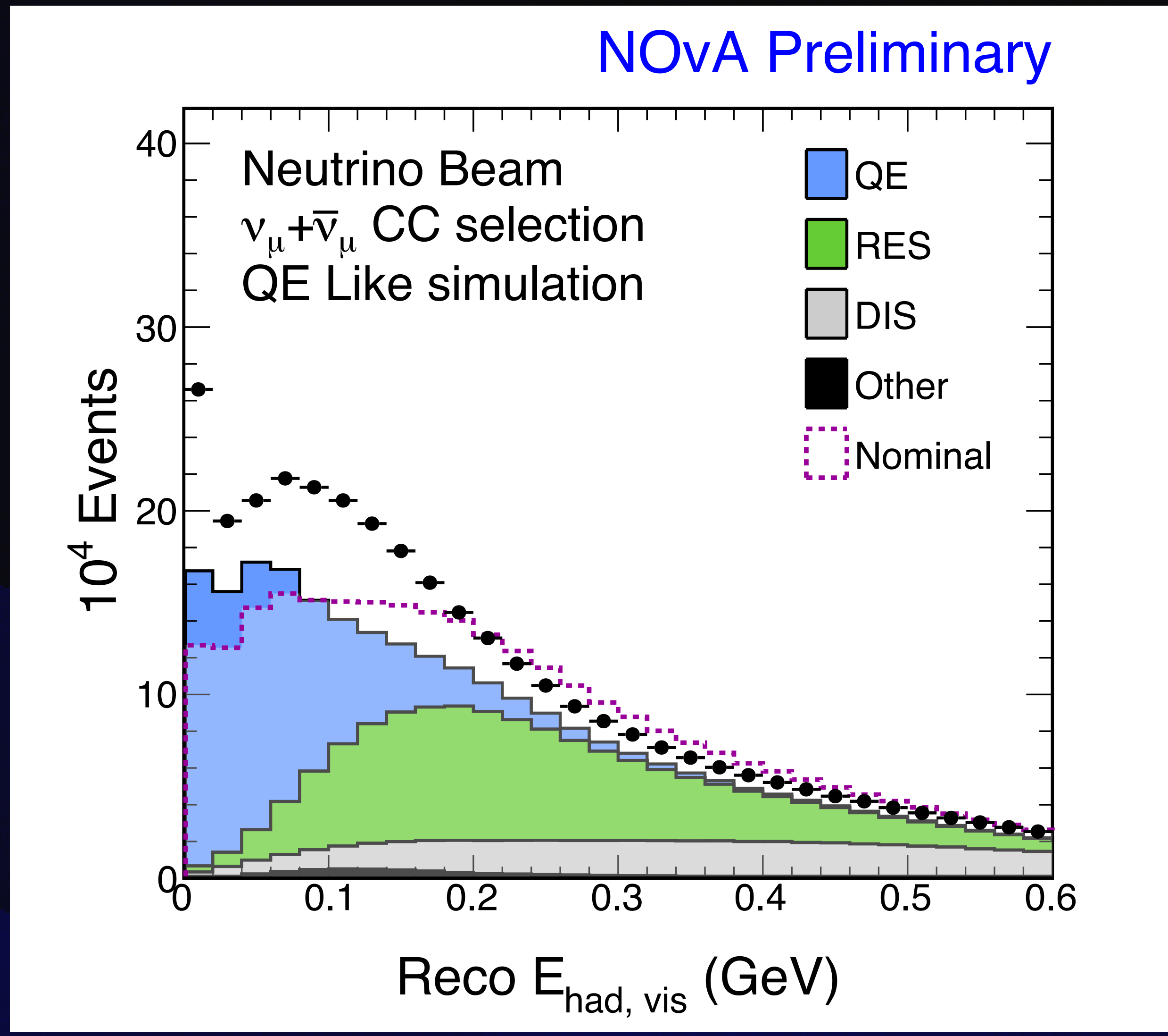
Central Value shifted upwards by about 50%.

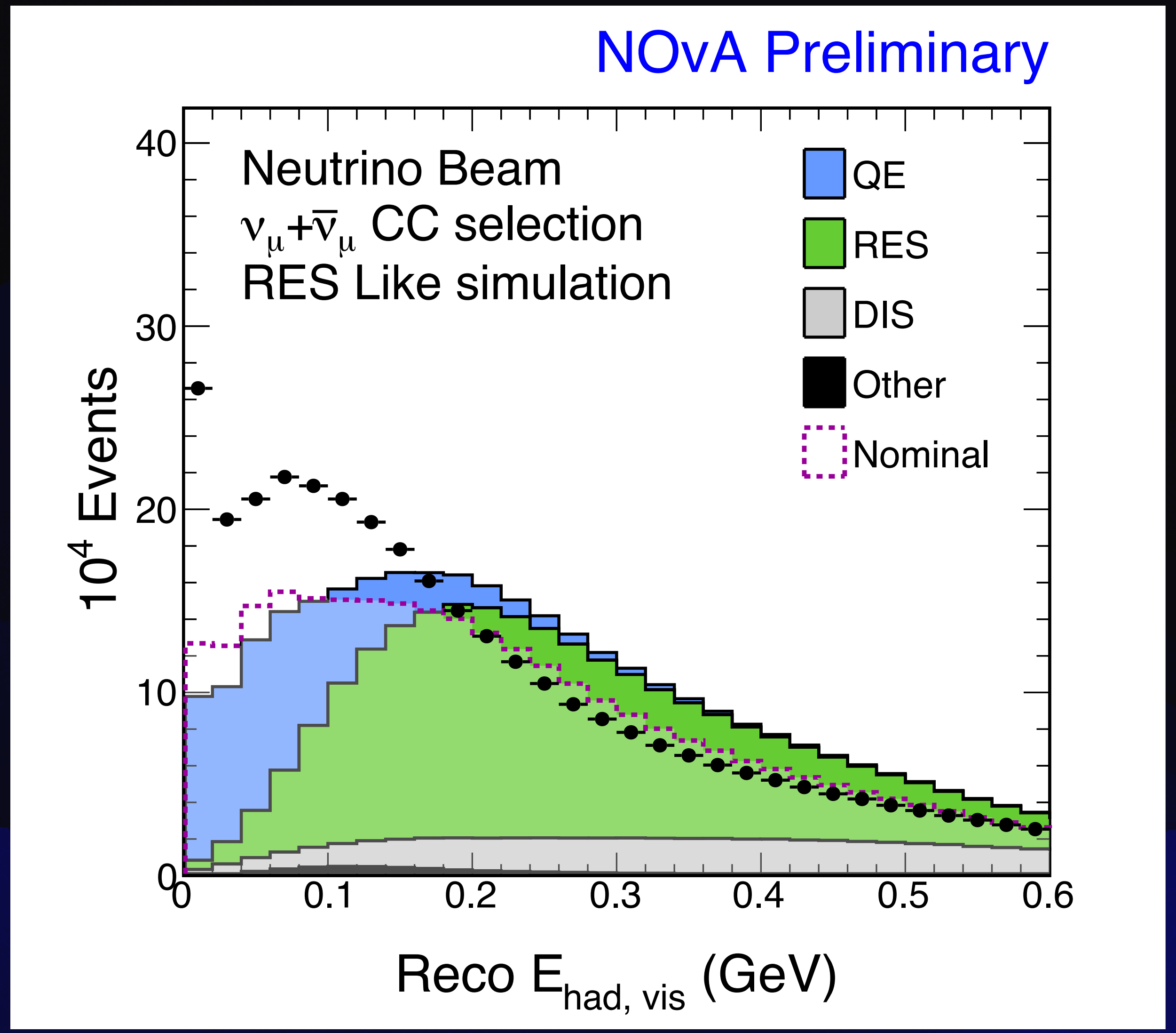
Robust systematics are applied to assess remaining differences.

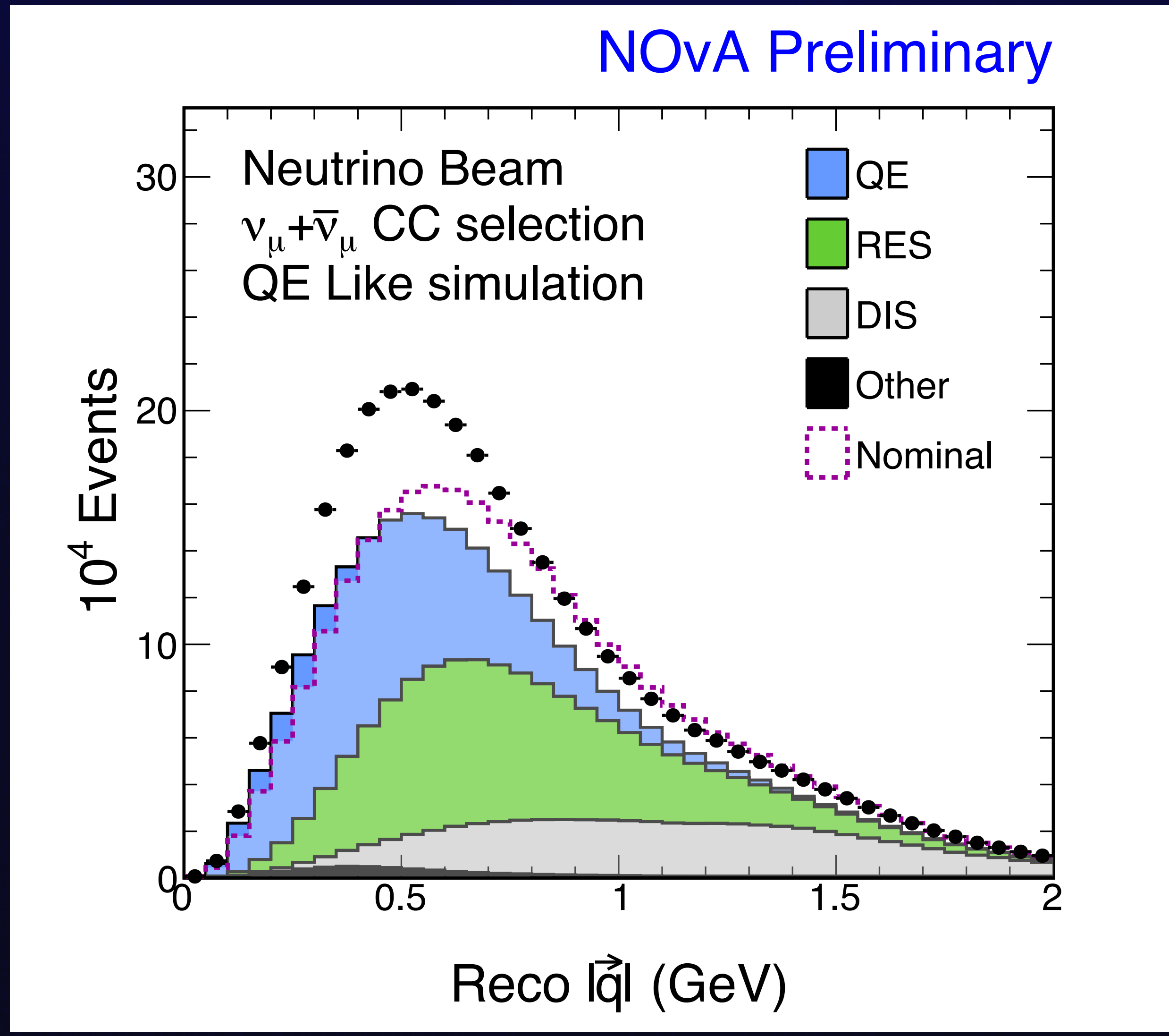
Component	Parameter	Fitted value
Gaussian 1	Normalization	14.85
	Mean q_0	0.36
	Mean $\lvert\vec{q}\rvert$	0.86
	Sigma q_0	0.13
	Sigma $\lvert\vec{q}\rvert$	0.35
	Correlation	0.89
Gaussian 2	Normalization	42.0
	Mean q_0	0.034
	Mean $\lvert\vec{q}\rvert$	0.45
	Sigma q_0	0.044
	Sigma $\lvert\vec{q}\rvert$	0.31
	Correlation	0.75
Base model	Normalization	-0.08

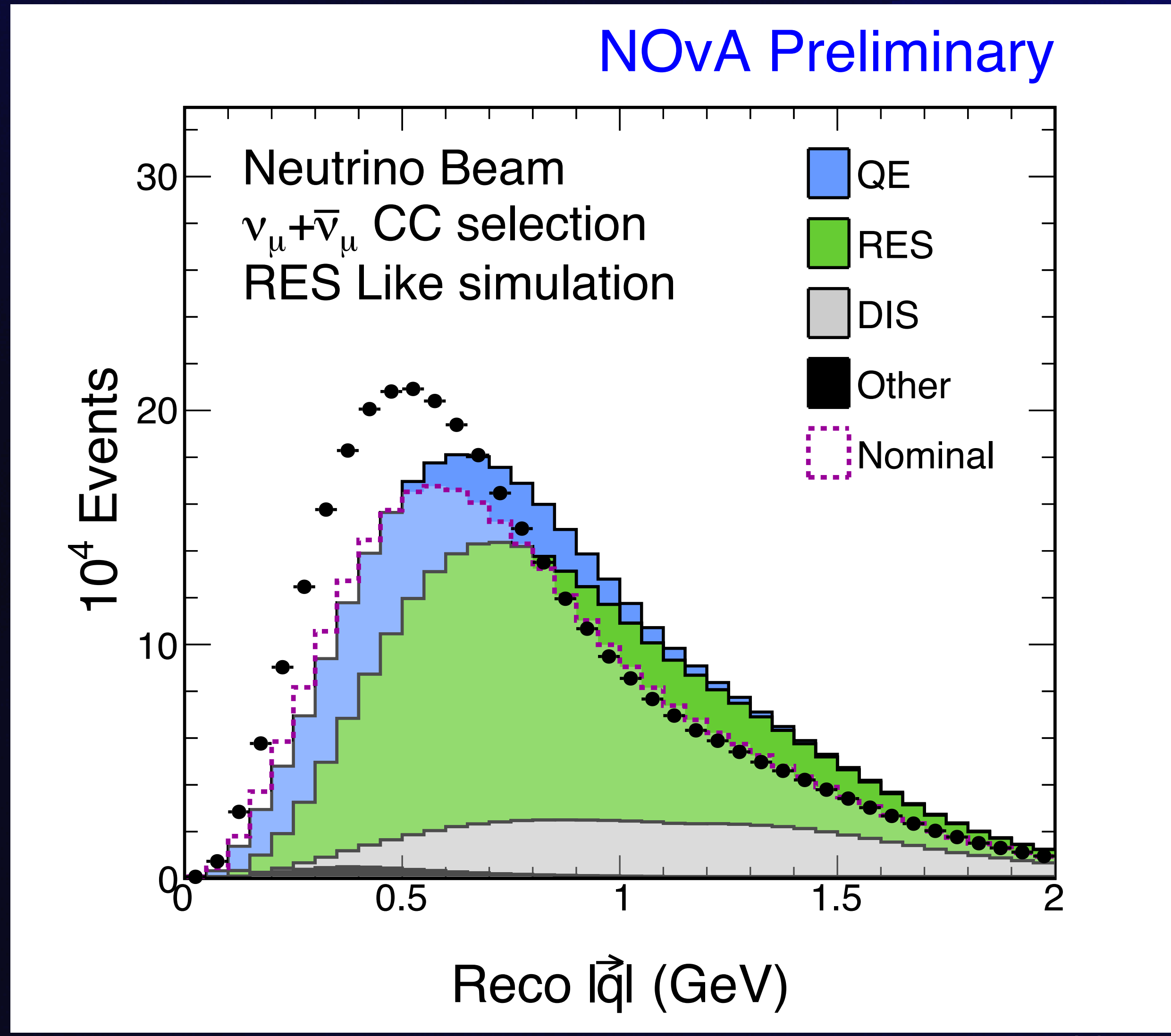
Meson Exchange Currents/2p2h for 2020 3F Analysis

Shape Tune and Struck Pair Composition









Systematic 1: We use a set of GENIE knobs (Z-Expansion norm and coefficients, CCQE RPA, and Resonant Production Axial/Vector Mass and Suppression) to create a RES-like and QE-like template.

Systematic 2: We add a model spread systematic based on struck nucleon pairs, expanding on previous work done in the last analysis.

$$\frac{np}{np+nn} = 0.69 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases}$$

$$\frac{np}{np+pp} = 0.66 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases}$$

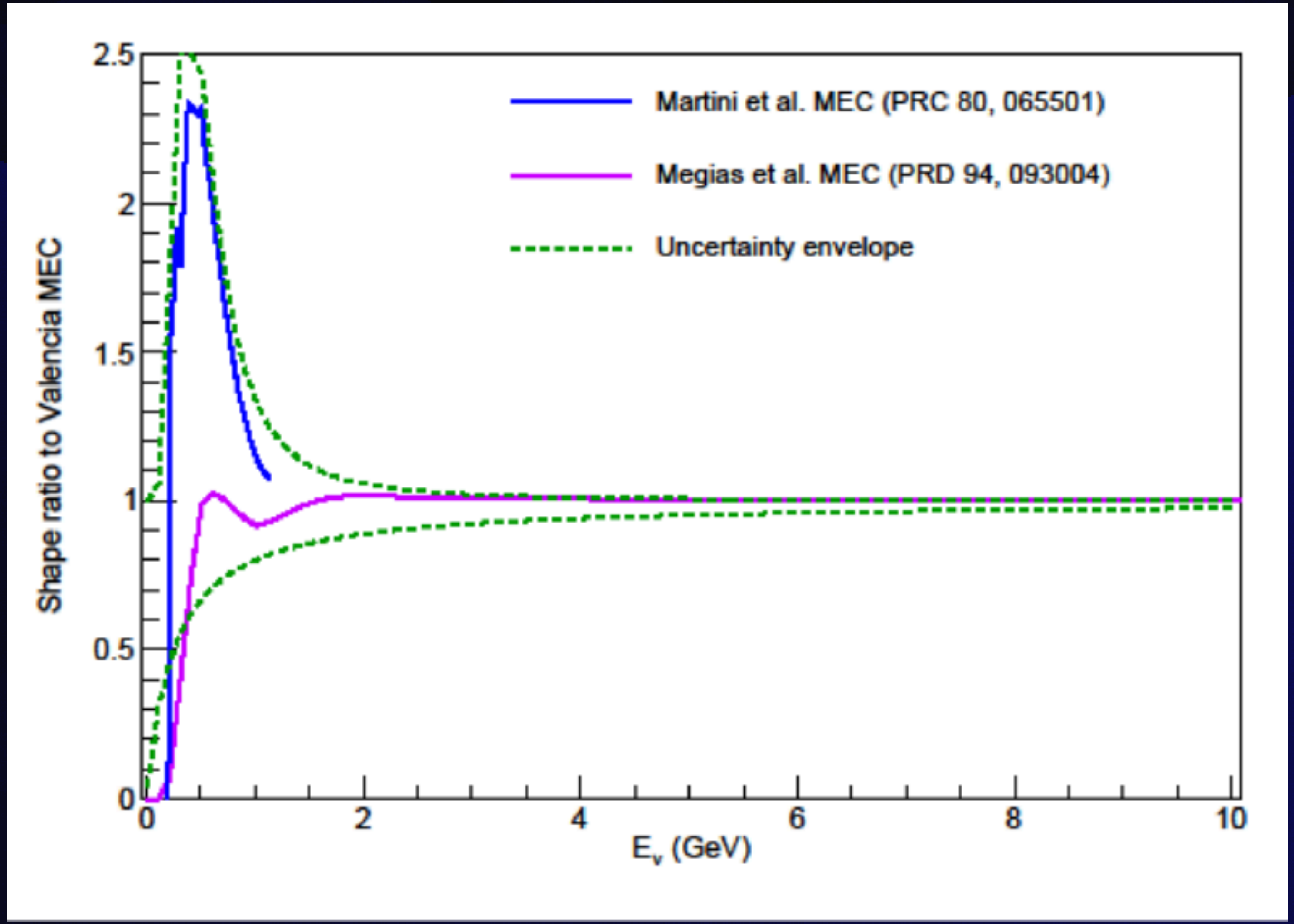
Meson Exchange Currents/2p2h for 2020 3F Analysis

Neutrino Cross-Section/Hadronic Energy Scale

Systematic 3: We scale the Martini and SuSA predictions to the Valencia model at 10 GeV

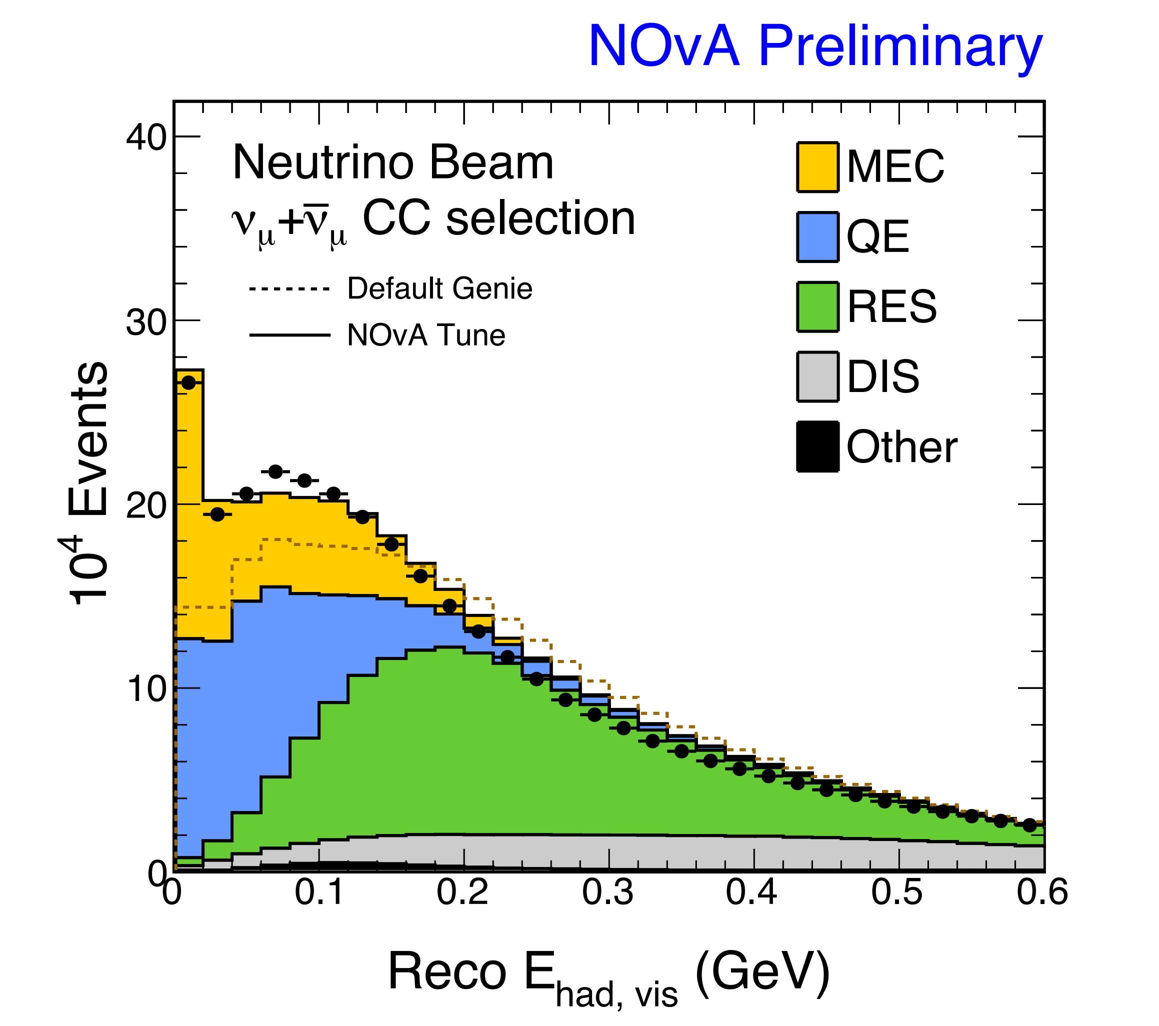
Finally, we construct an envelope to bound the model spread.

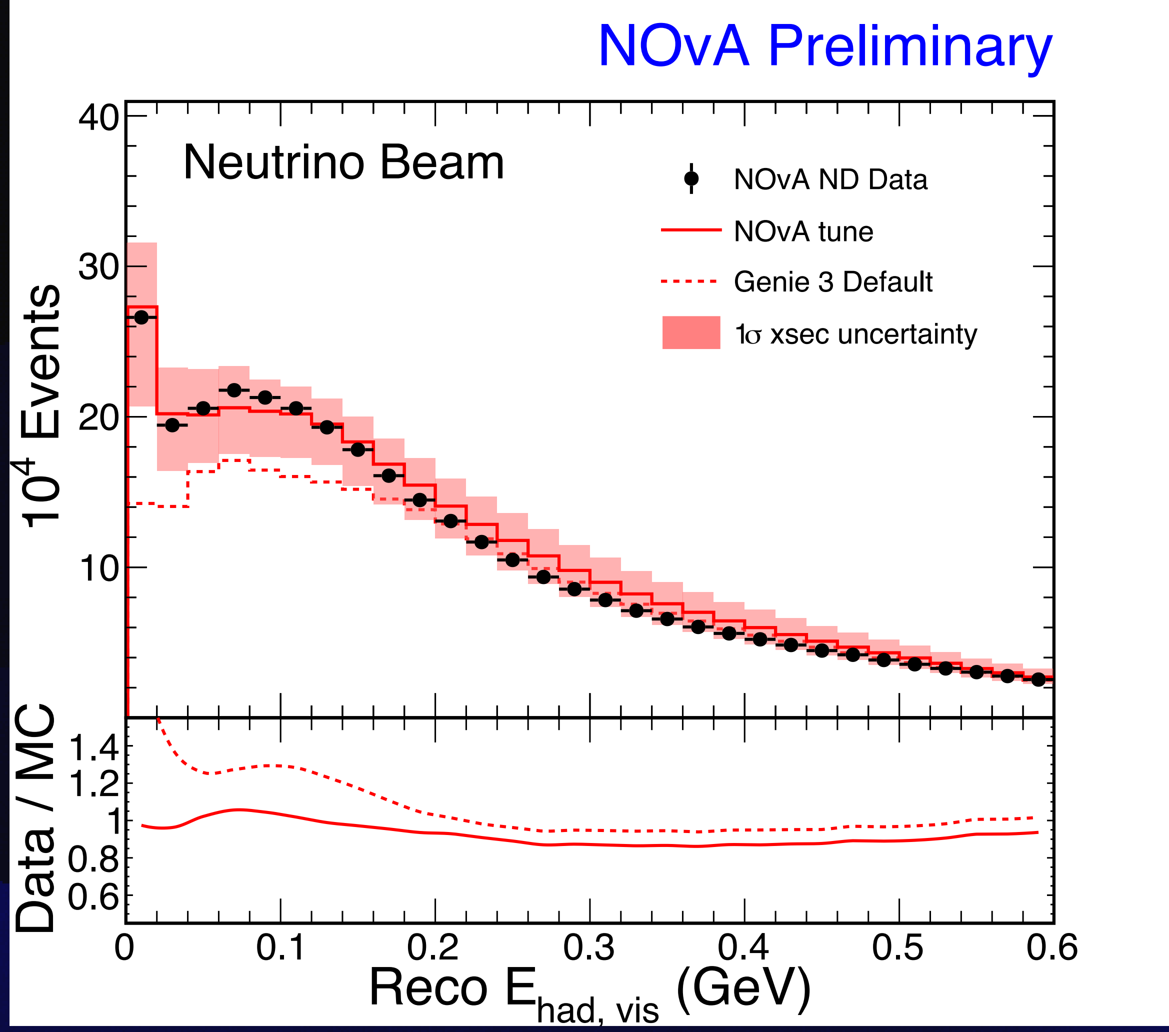
$$f(E_\nu) = \frac{0.5}{1 + 2(E_\nu - 0.25)}$$

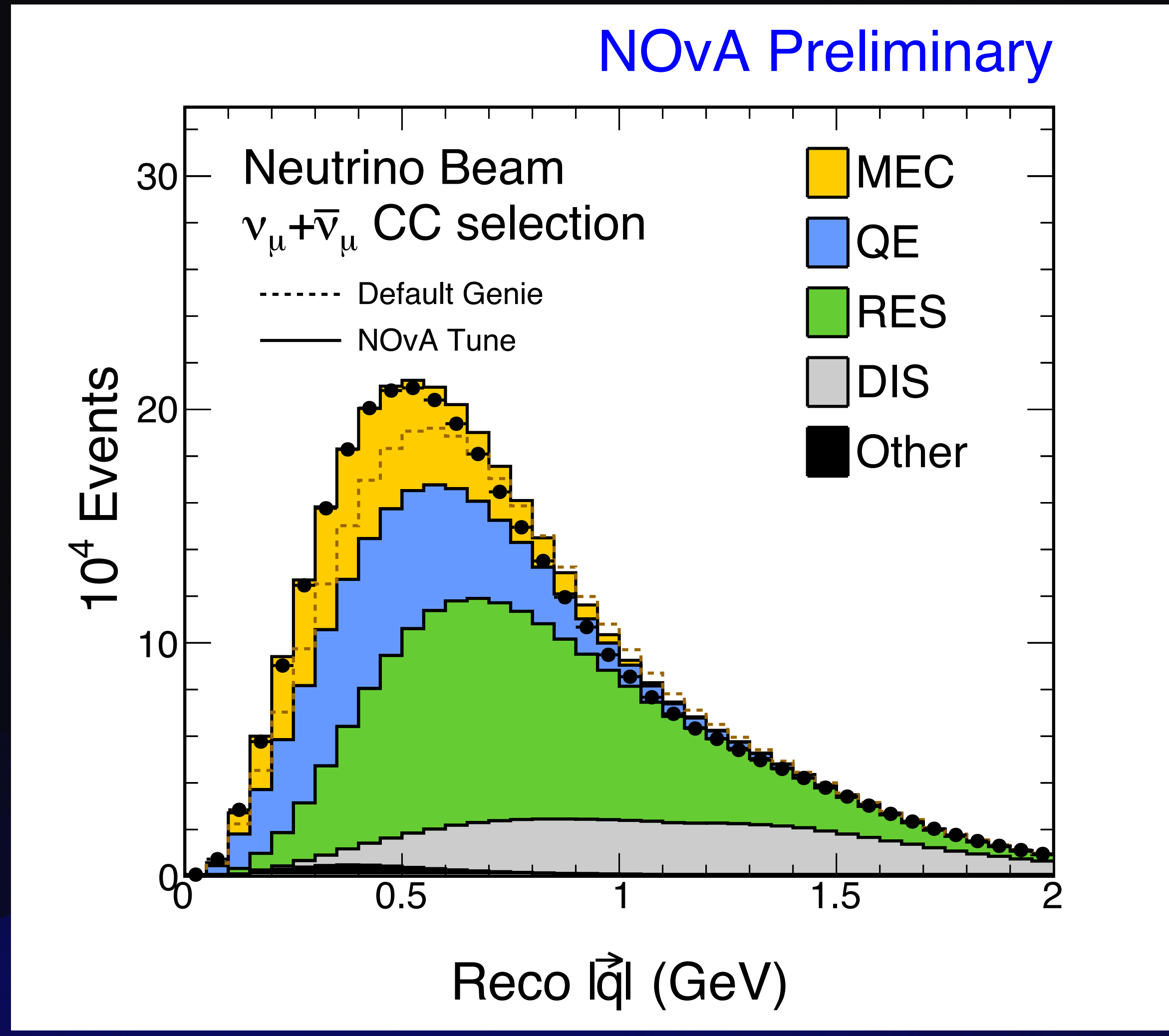


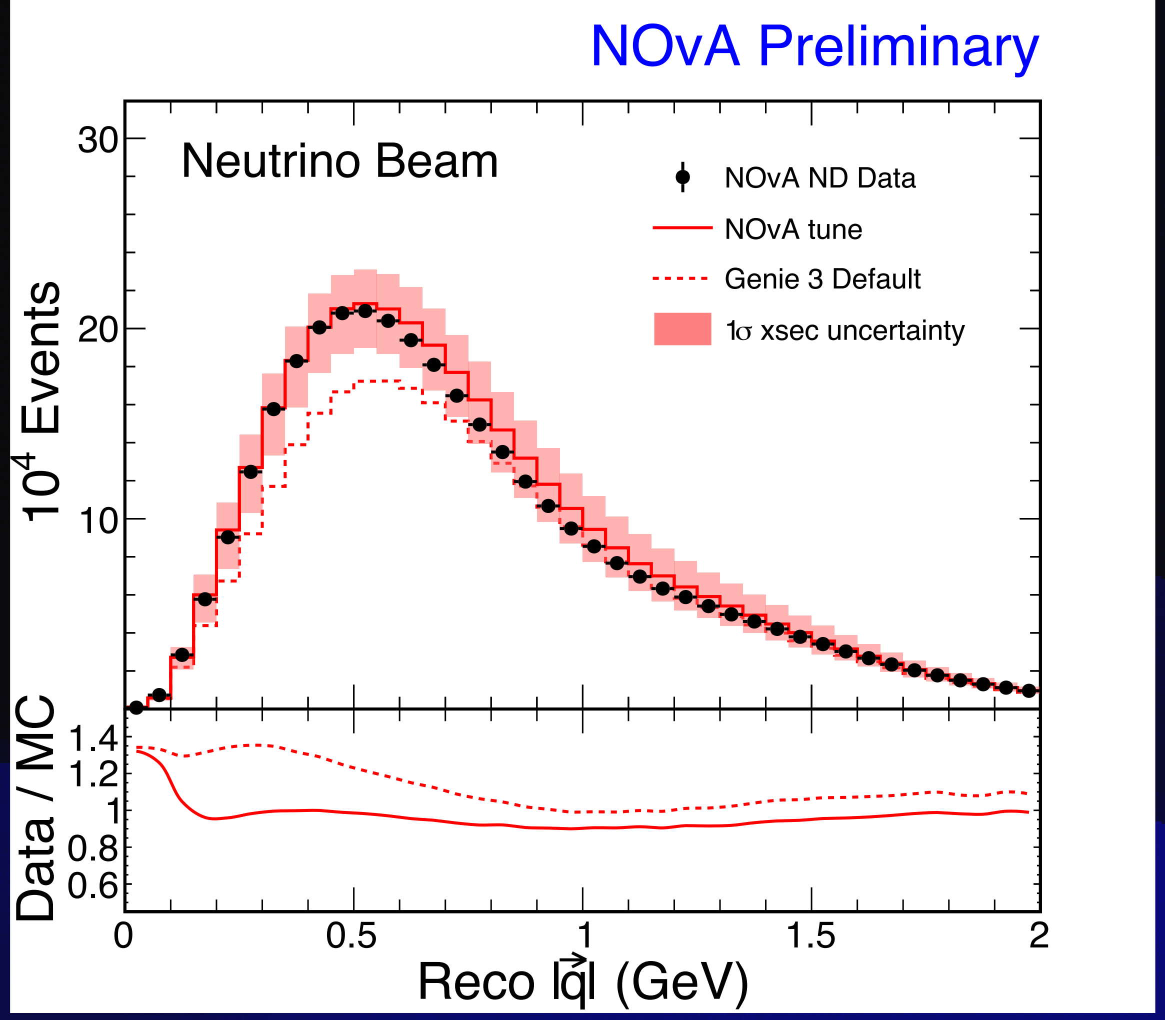
Meson Exchange Currents/2p2h for 2020 3F Analysis

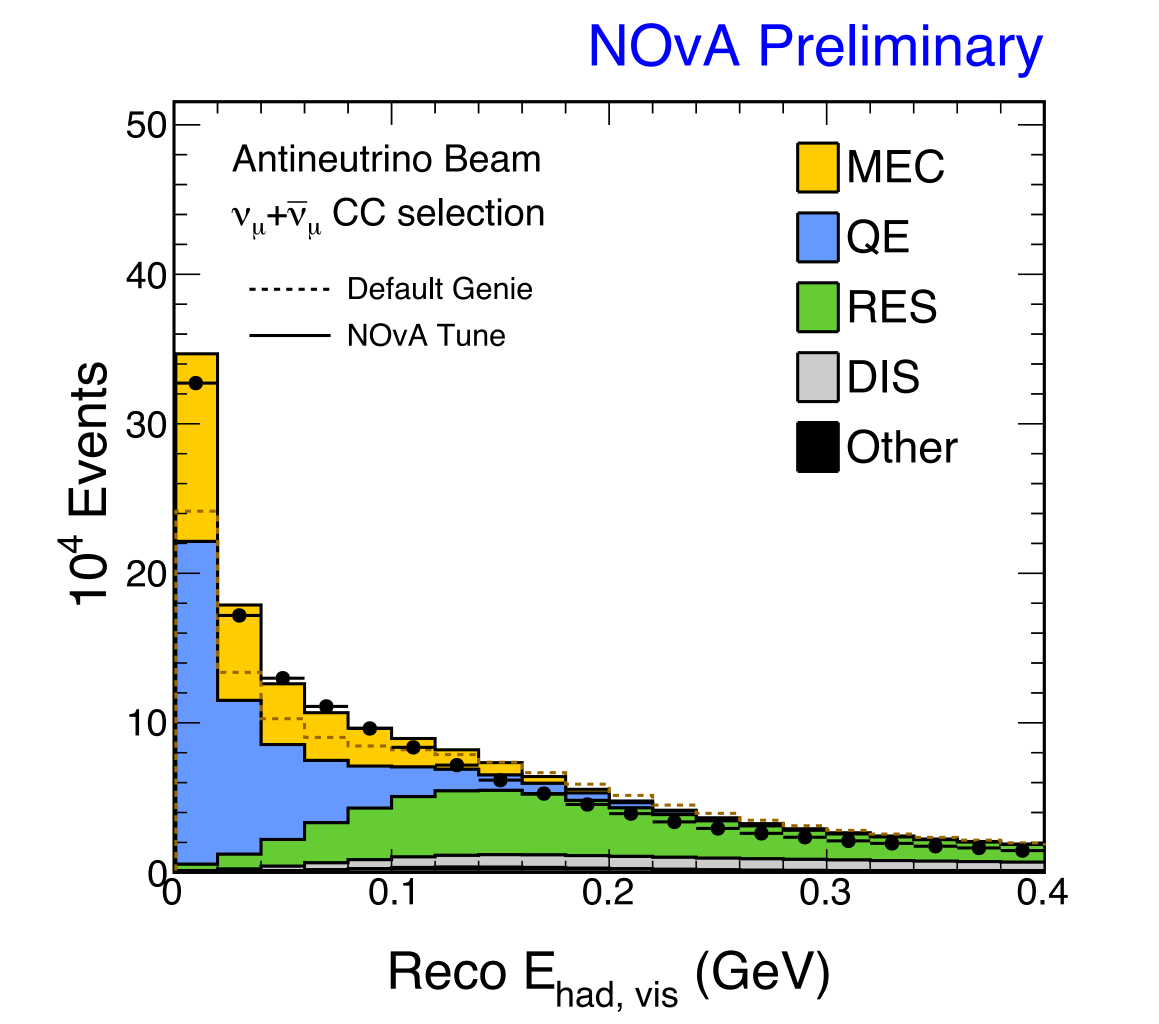
Final Tune and Systematics

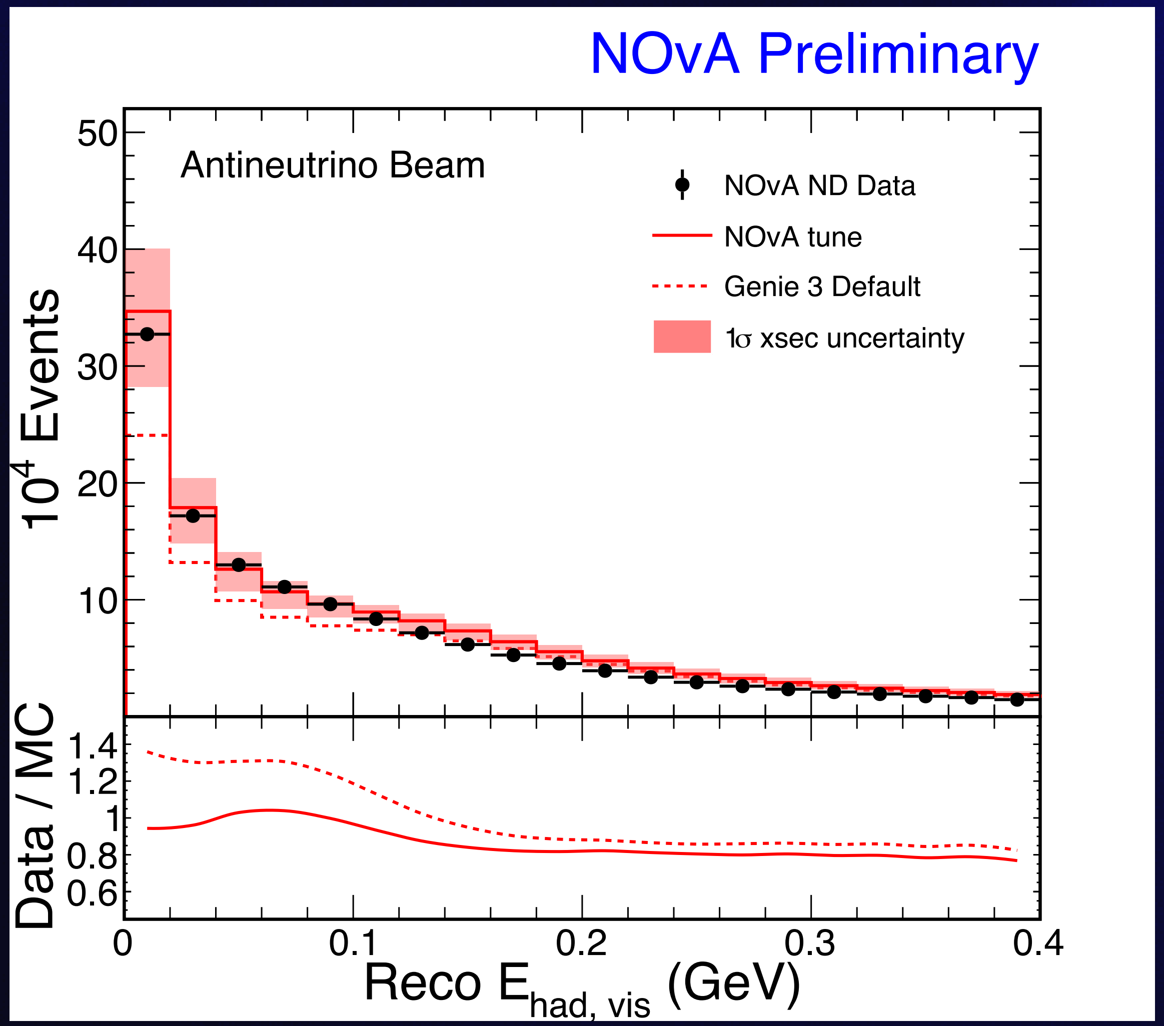


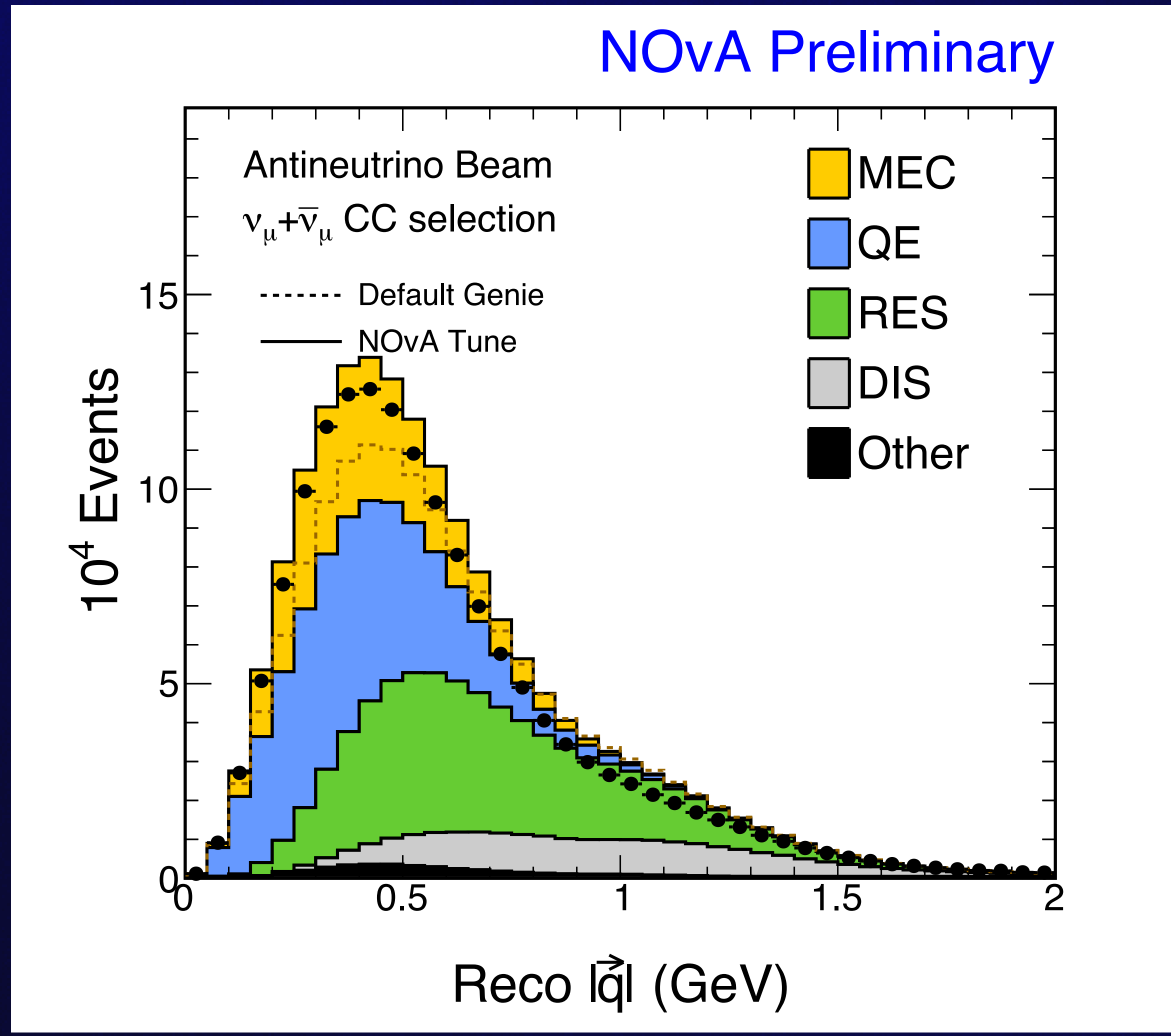


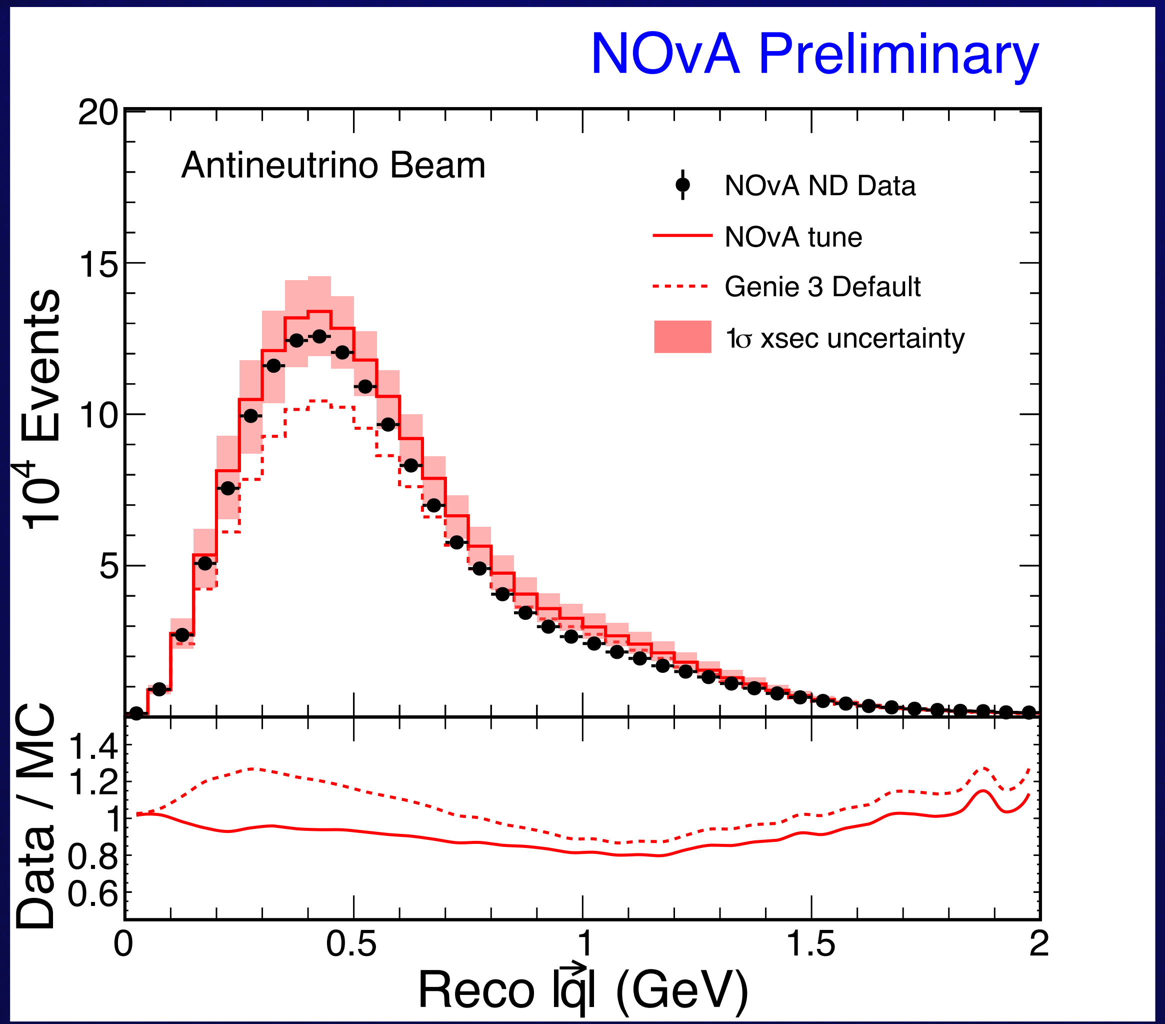








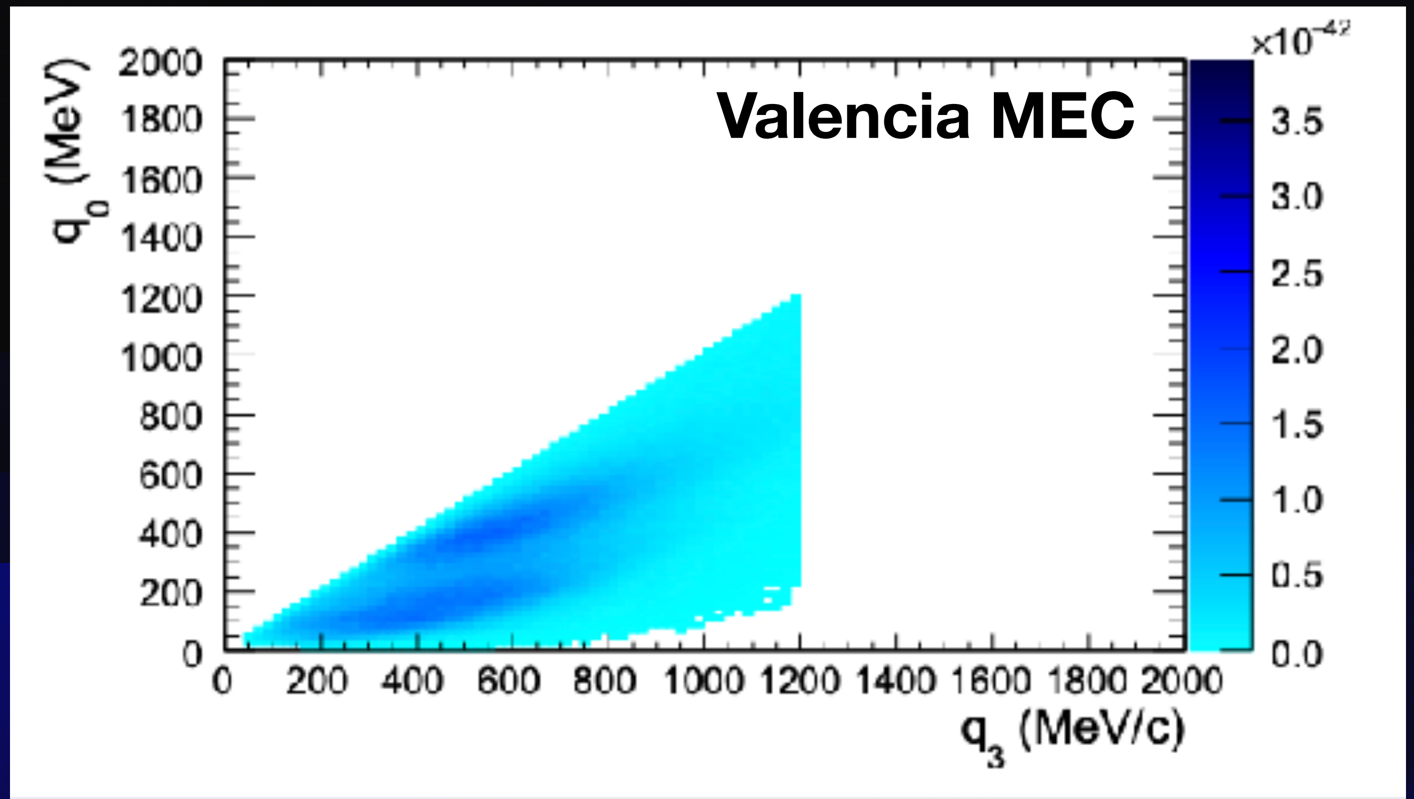


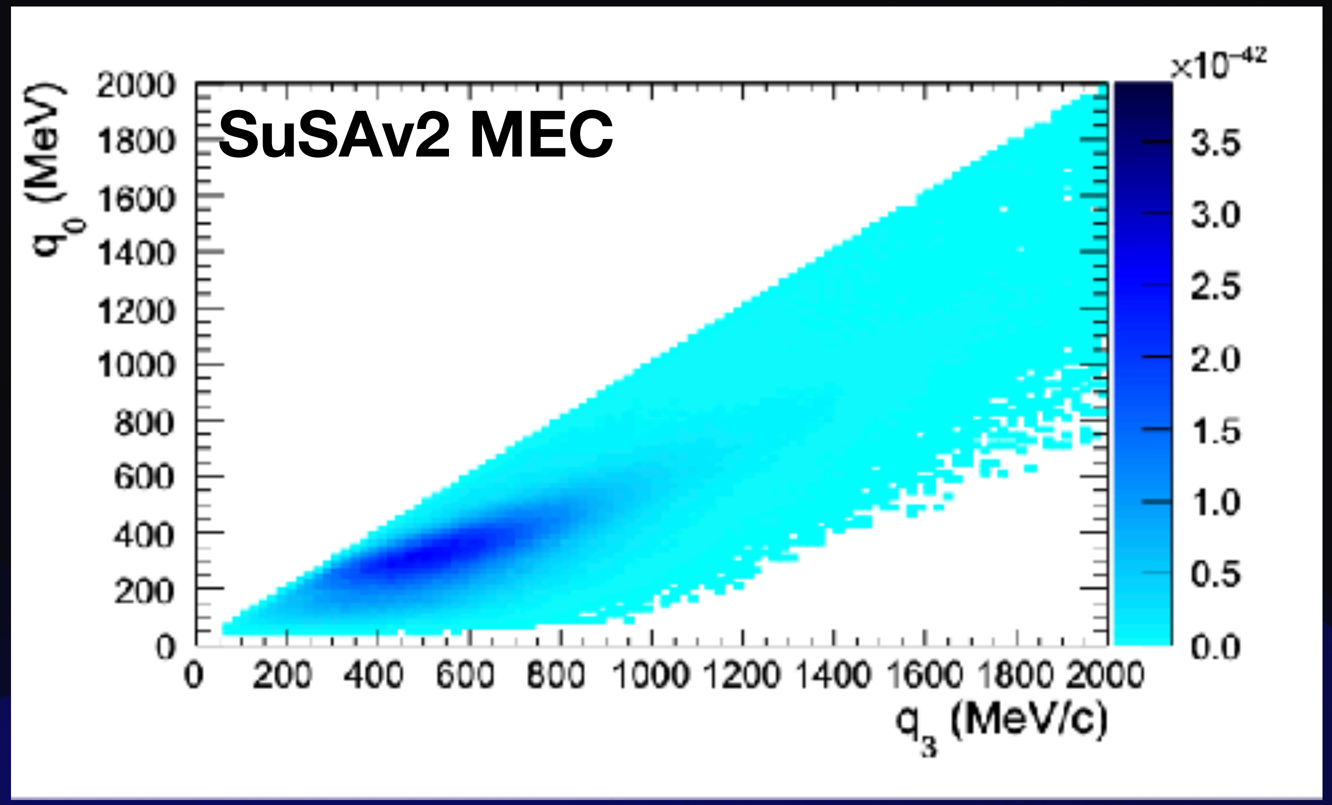


Developments in GENIE Since 2020

Relevant Updates Since the 2020 Analysis

New developments in Meson Exchange Currents/2p2h Modeling! arXiv:1905.08556v3



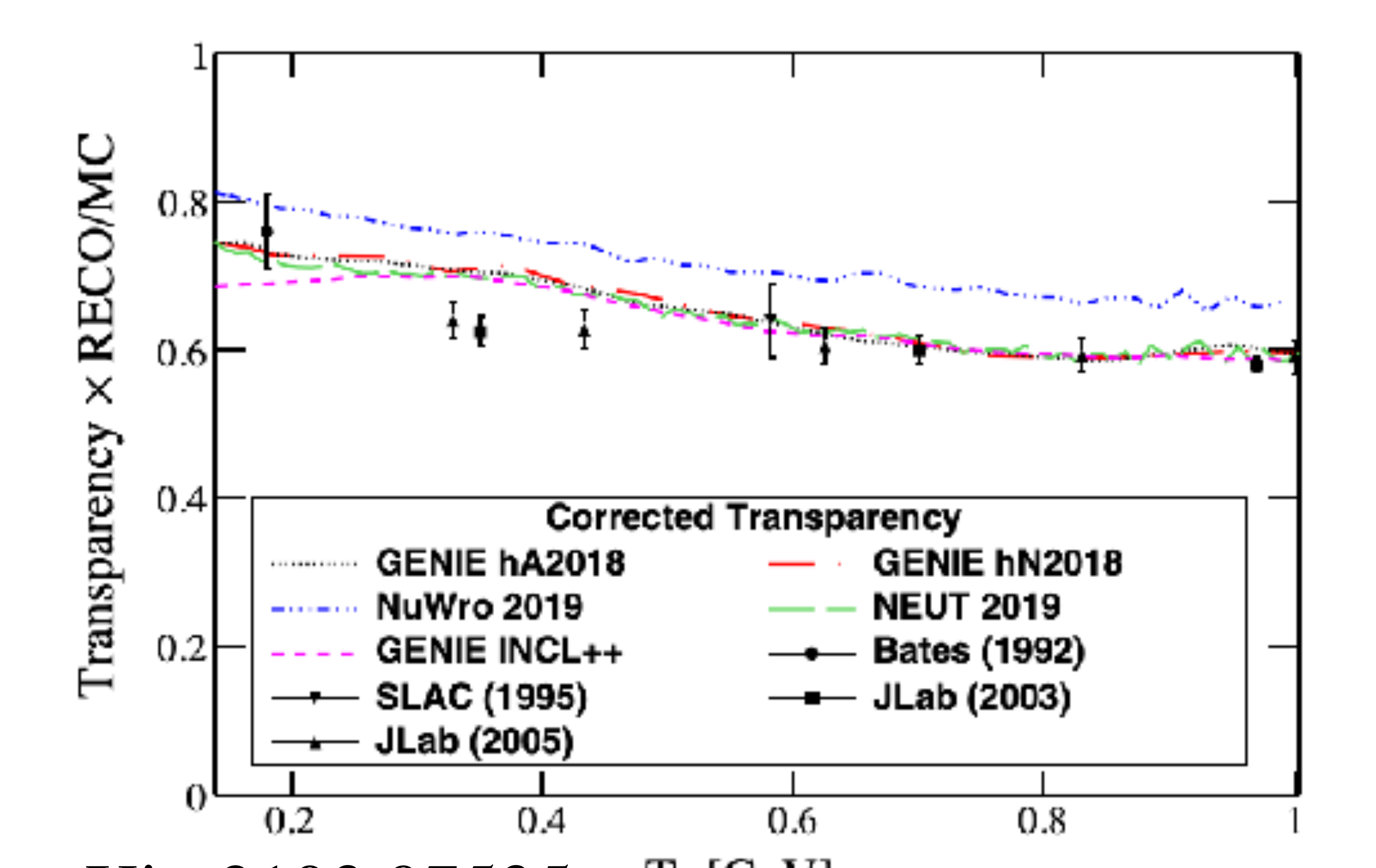


SuSAv2 is well motivated theoretically and has larger coverage in our tuning phase space!

Implementation of Short Range Correlations in Initial State.

Full Quantum Cascade FSI model, INCL++ available and implemented in GENIE.

Would like to use in NOvA, but unlikely because of effort to provide adequate systematic uncertainty treatment.



arXiv:2103.07535

Future Model Selection Strategy

Moving to New Models for Future Analyses

Engaging in first part of prepping new models for **deciding on a Central Value configuration.**

Two goals here for Central Value: choices must be **accurate** (close to or motivated by physics) *and* **future-proof** (large coverage of phase space).

These two goals may not align but we can improve accuracy later.

We have a two part approach:

1. Compare simulated truth information of different models to judge applicability to experiment.

2. Generate a new fully reconstructed test configuration and assess coverage.

Possible Future NOvA Productions

Models Considered for Future Analyses

Final comparison reduces total list to core short list of models we consider seriously for “miniproduction". Model will be fully validated in fully reconstructed test sample.

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
N21_11b_02_11b* (3.2)	LFG	SuSAv2 1p1h	Berger-Seghal	SuSav2 2p2h	Bodek-Yang*	ItraNuke hN	Free-Nuke
AR23_20i_00_000 (3.4)	LFG*	SuSAv2 1p1h*	Berger-Seghal	SuSAv2 2p2h*	Bodek-Yang*	hA2018	Free-Nuke

DUNE model is a welcome addition and comes with many benefits besides the central value tuning and systematics options.

Models Considered for Future Analyses

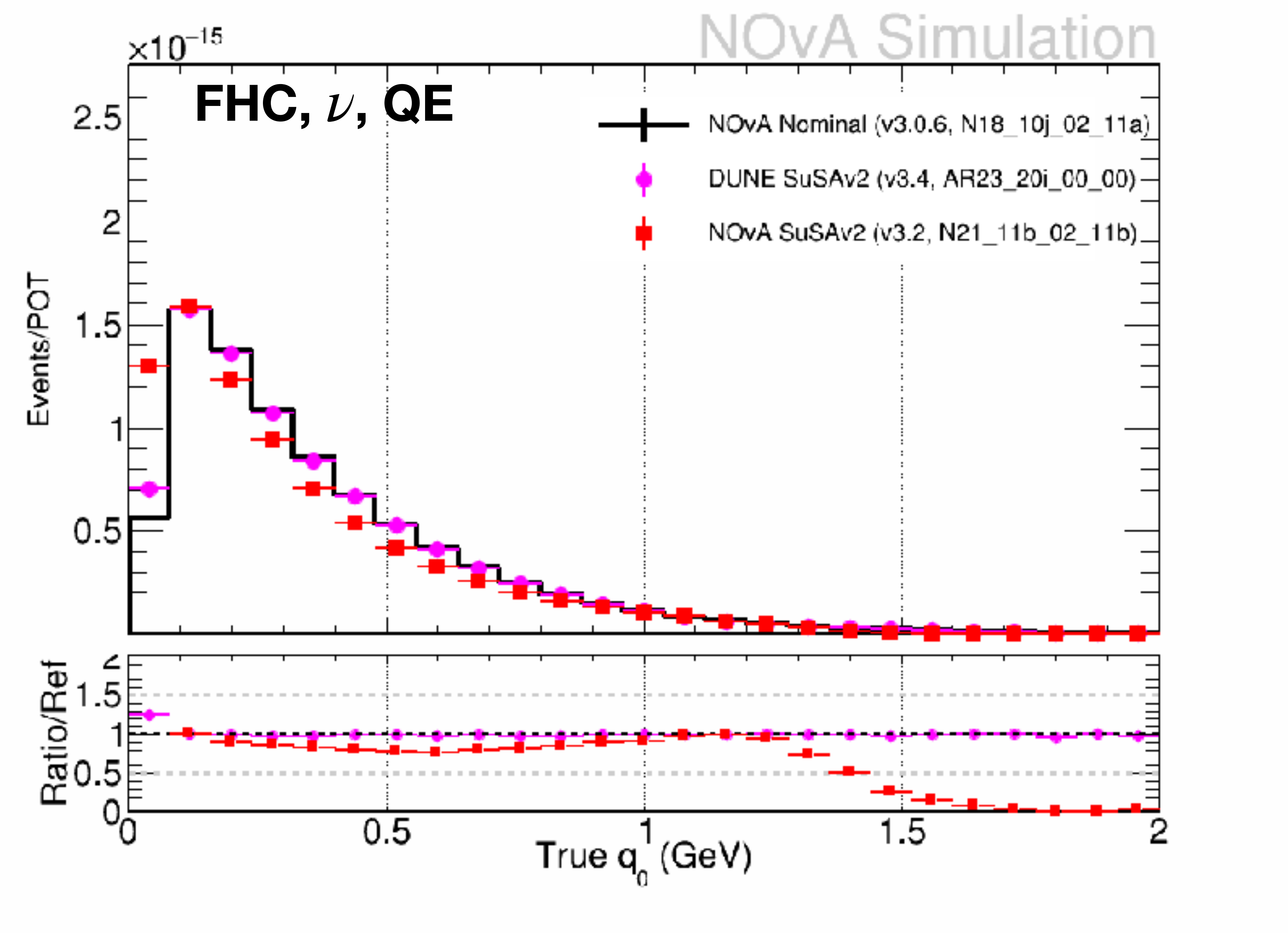
Considerations for Initial State and QE

CMC	Initial State	QE	MEC	Res	DIS	Final State	Tune
AR23_20i_00_000 (3.4)	LFG*	SuSAv2 1p1h*	SuSAv2 2p2h*	Berger-Seghal	Bodek-Yang*	hA2018*	Free-Nuke

Quasi Elastic Scattering in SuSAv2 is similar to the Valencia model!

Above 1.2 GeV model behaves somewhat differently.

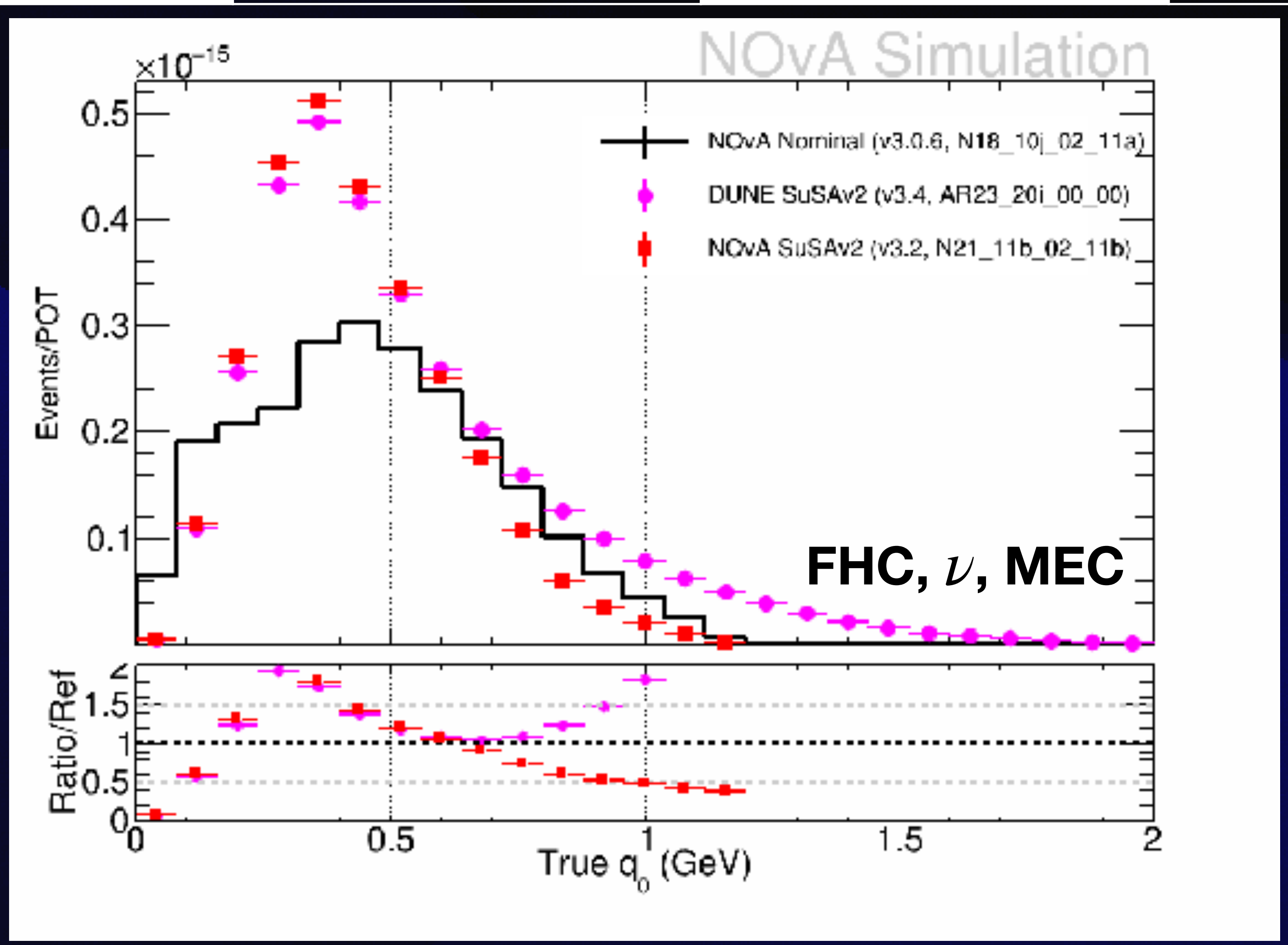
Actively considering the effect of the initial state on low energy transfer regions.

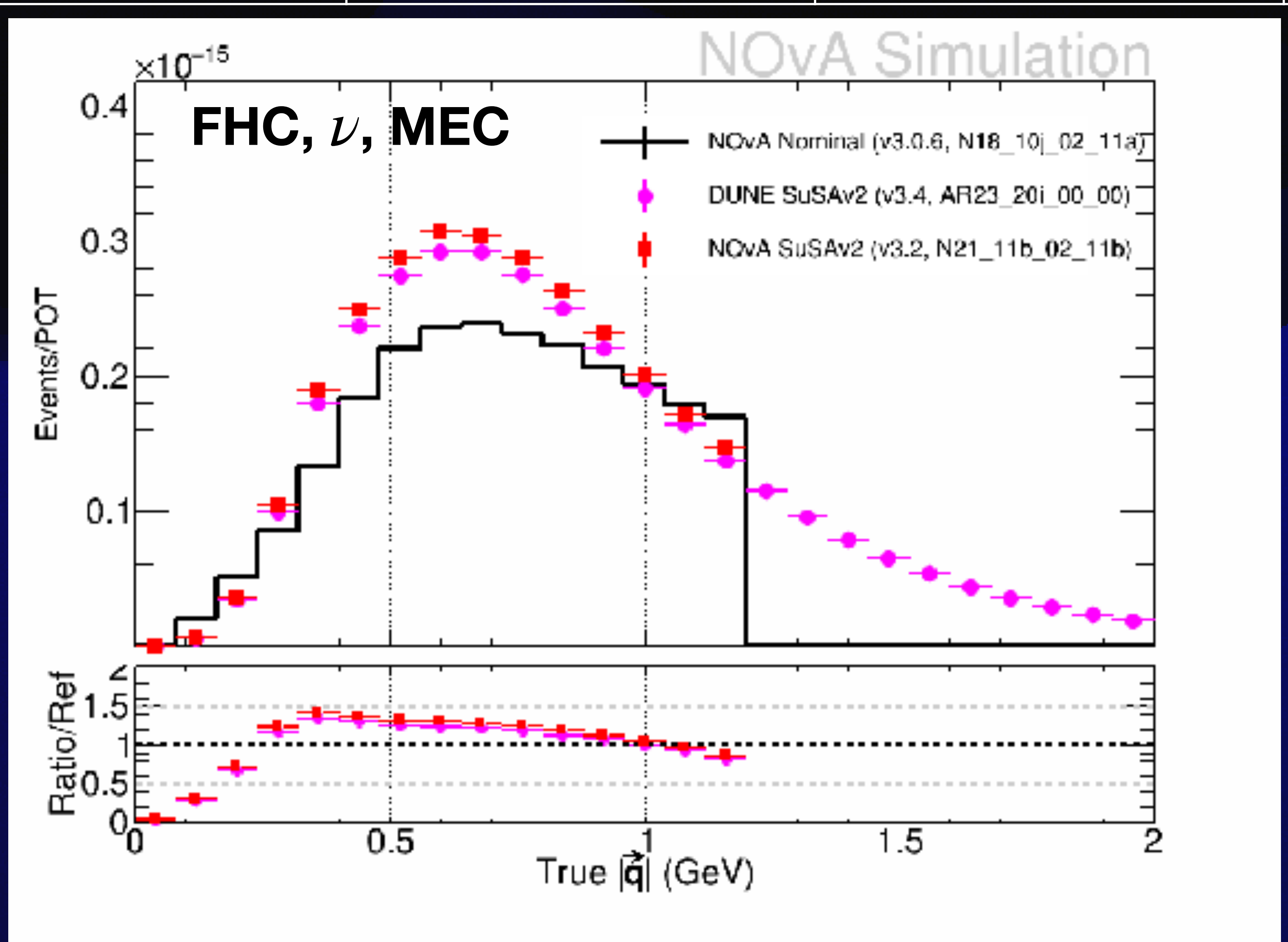


Models Considered for Future Analyses

Considerations for Meson Exchange Currents

CMC	Initial State	QE	MEC	Res	DIS	Final State	Tune
AR23_20i_00_000 (3.4)	LFG*	SuSAv2 1p1h*	SuSAv2 2p2h*	Berger-Seghal	Bodek-Yang*	hA2018*	Free-Nuke





Significant adjustment of MEC over the entire range, **expansion** of the phase space in momentum transfer!

Significant reduction of events in the lowest MEC bins for energy and momentum transfer. ***Active discussion in NOvA about approach.***

Summary & Conclusions

Effective cross-section modeling is a complex but necessary input for the current generation of long baseline oscillation experiments. Likely to remain a source of intense activity into the DUNE Era.

NOvA used **GENIE v3.0.6, N18_10j_02_11a** for its last 3F Flavor analysis, did significant surgery on the MEC and FSI tunes to enhance applicability to NOvA data. Used methods established by other experiments for most difficult work.

Final results established robust uncertainties with central value tune, but improvements are possible.

Next iteration of modeling for future analysis definitely moving toward **GENIE v3.4.** Front runner CMC for our purposes is **AR23_20i_00_000**.

Assuming no show stoppers we intend to work closely with **DUNE** in in tuning our model. Possibility for a robust **Fermilab Tune for AR23_20i_00_000 with SBN?**

Backup

Possible Future NOvA Productions

Models Considered for Future Analyses

NOvA considered new models (GENIE CMCs) for our next production. List is extensive!

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*	SuSAv2 1p1h*	Berger-Seghal	SuSAv2 2p2h*	Bodek-Yang*	hA2018*	Free-Nuke