

Current Progress Toward Precision Neutrino Physics: MINERvA, NOvA, & T2K

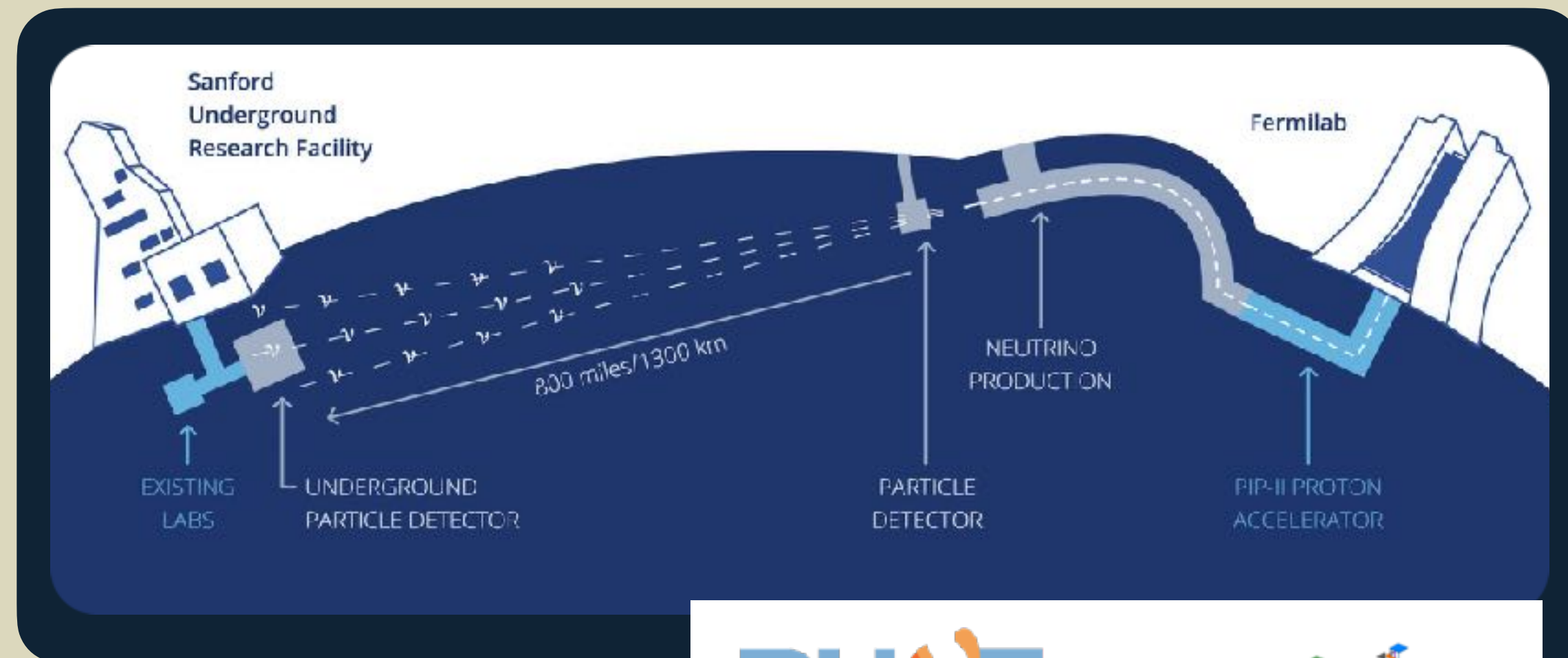
NEUTRINO 2026: XXXII International Conference on
Neutrino Physics and Astrophysics
University of California, Irvine

Bryan Ramson June 24th, 2026

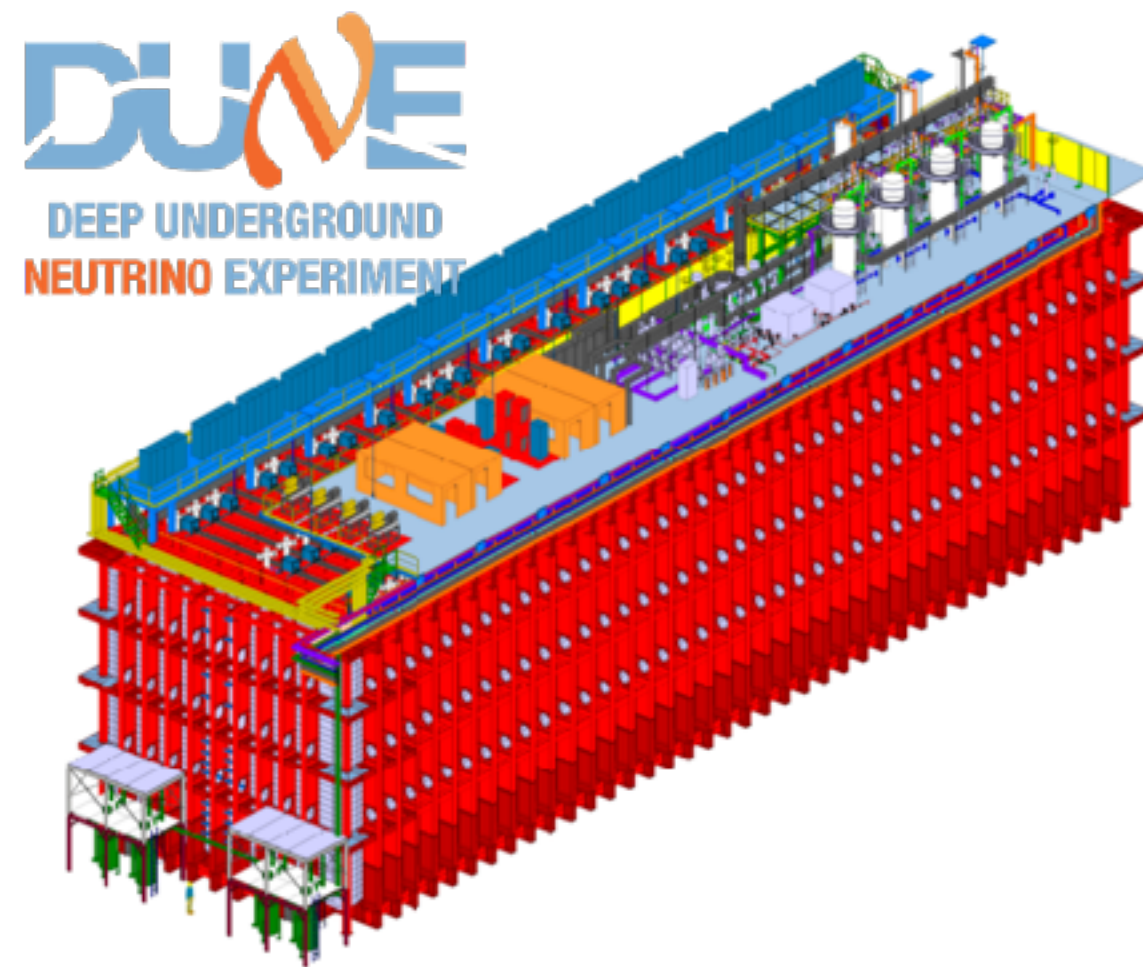


Welcome to the Era of Precision Neutrino Physics

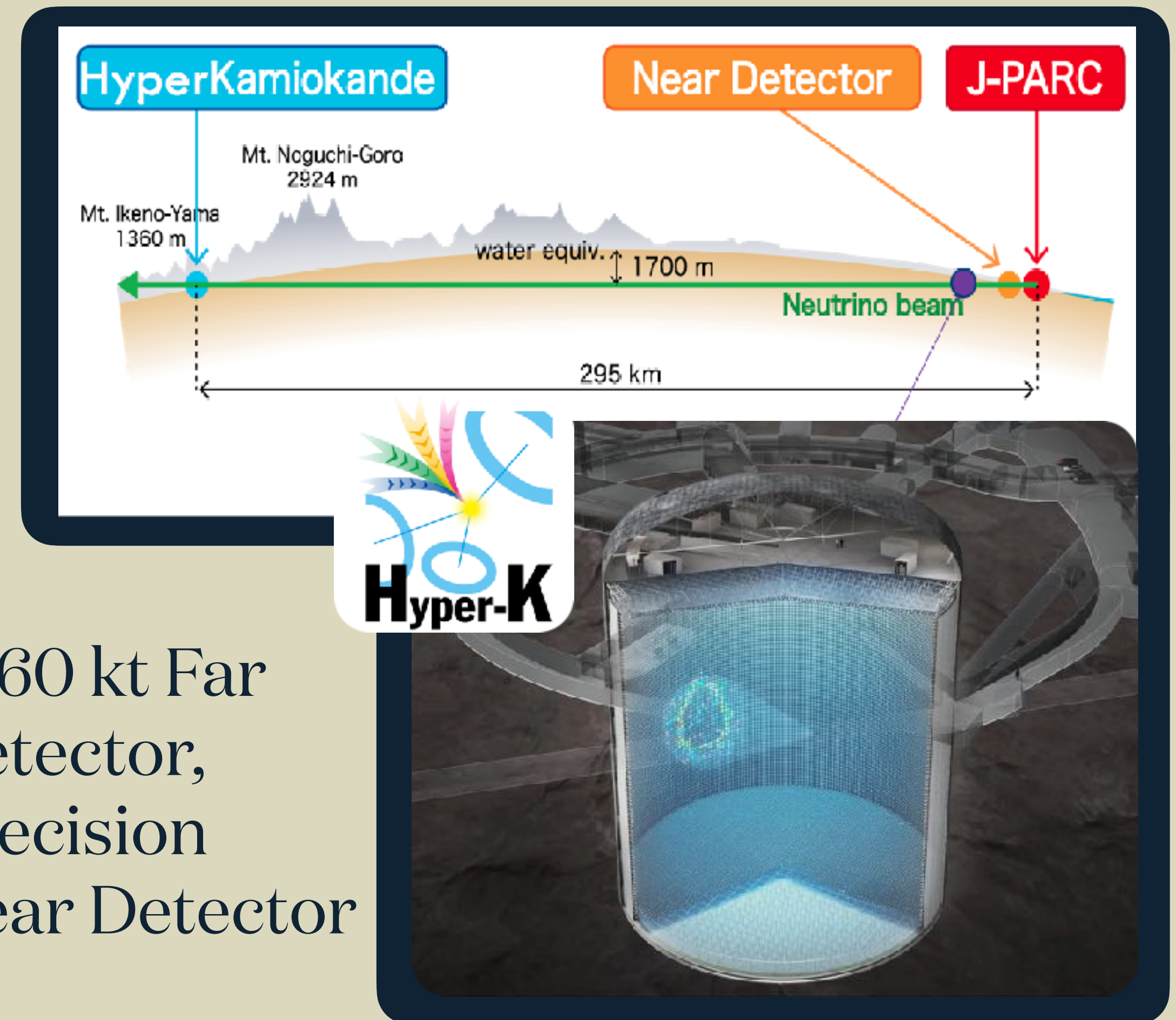
We are entering a new era of physics for neutrinos, characterized by large datasets, gathered with the largest detectors (that will) ever (be) created...



~70kt Far Detector module along with a suite of precision Near Detector Experiments.



~260 kt Far Detector, Precision Near Detector



As a field, we have engaged in *significant* improvements in detector design and technology and computing. Let's examine the contribution of experimental data to our understanding of neutrino cross sections, a critical input into oscillation parameter extraction.

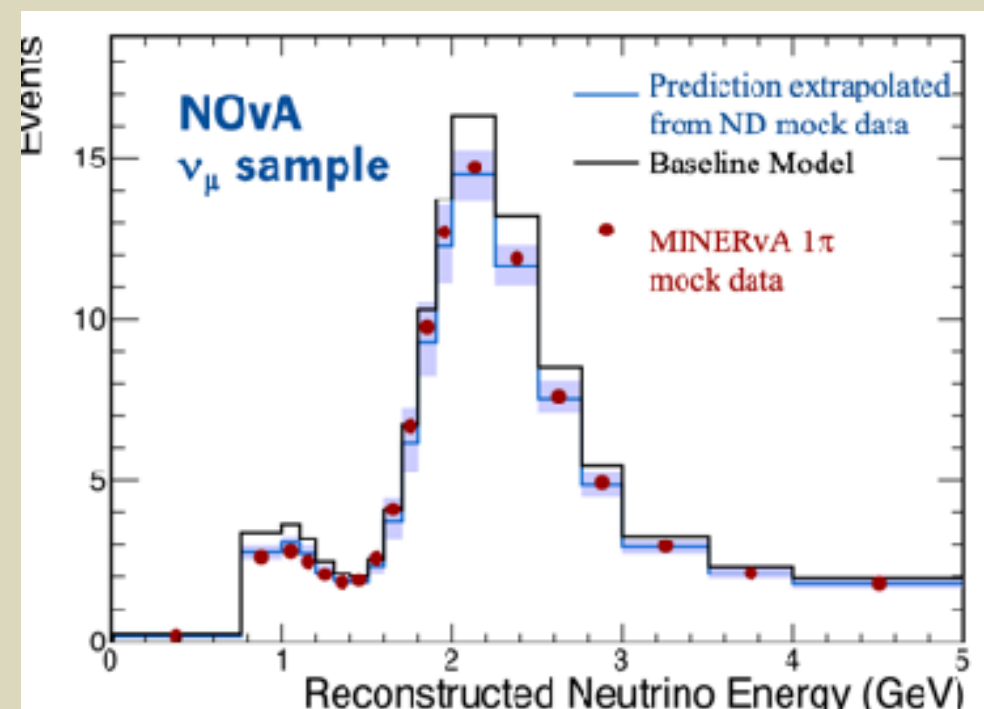
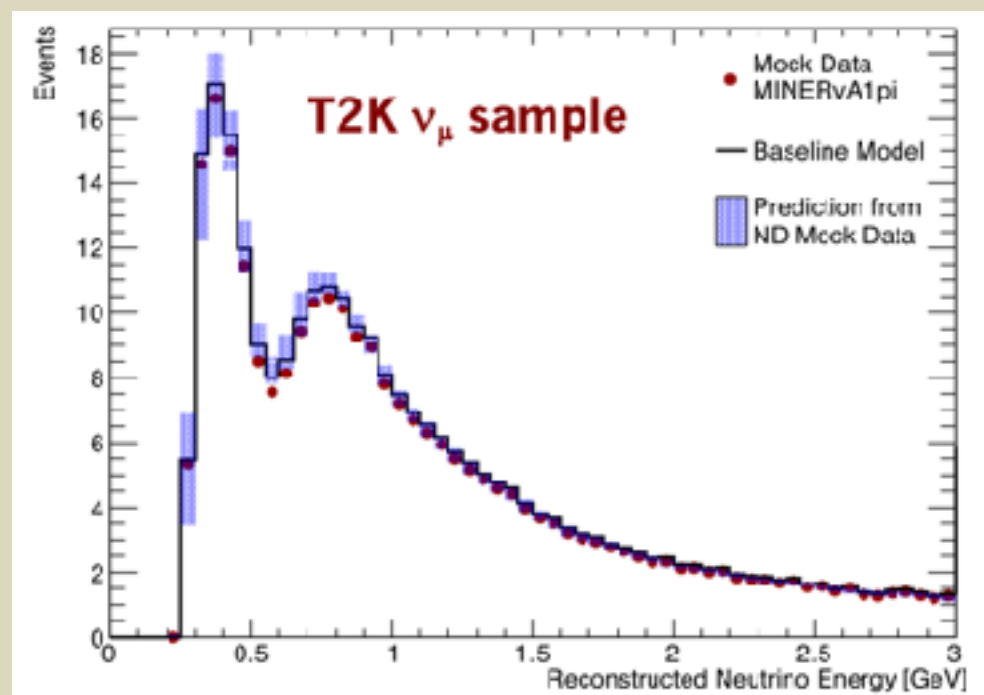
Cross Sections for Experimentalists

Some Background Matter

Flagship measurements for **NOvA** and **T2K** are oscillation focused. Oscillation parameters are inferred from neutrino yields and are defined by the following:

Neutrino Yield

$$N(E_\nu) =$$



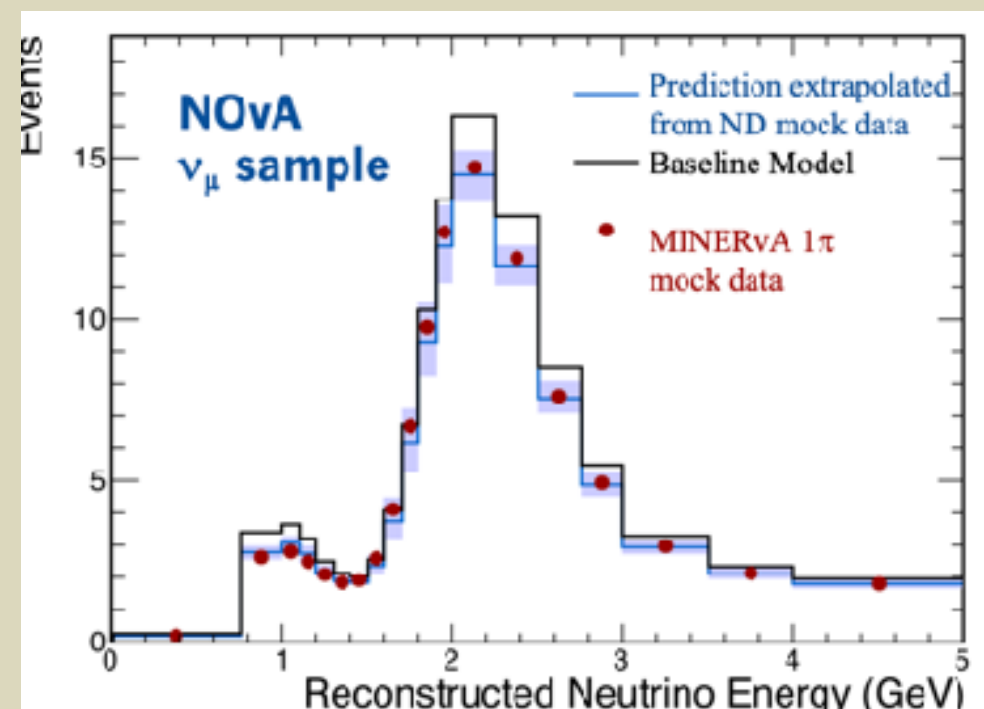
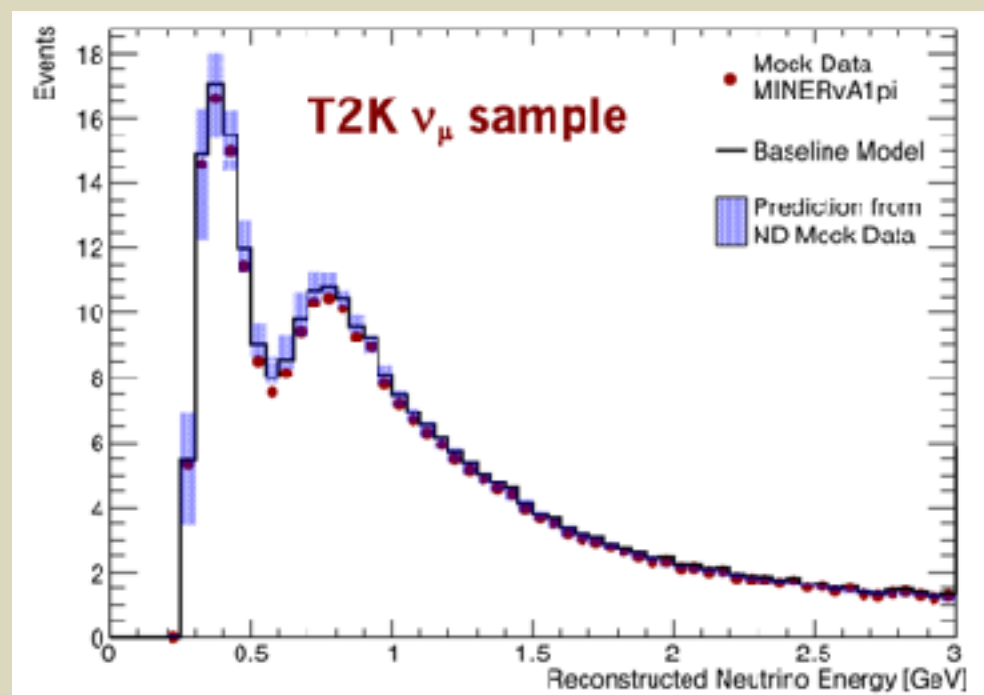
Z. Valleri, JETP Seminar (2024)

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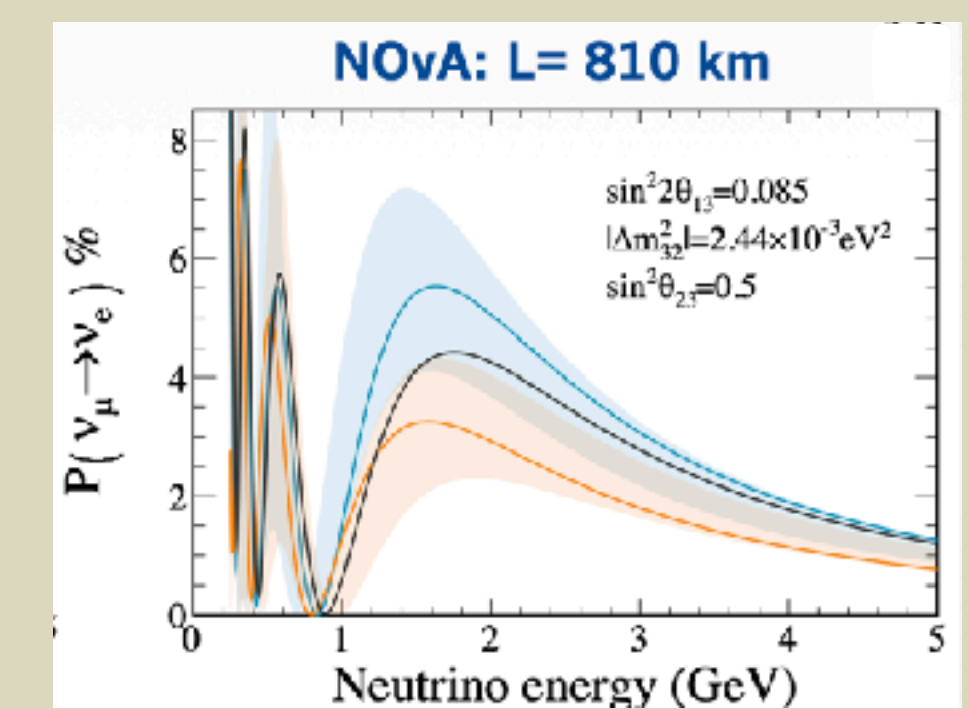
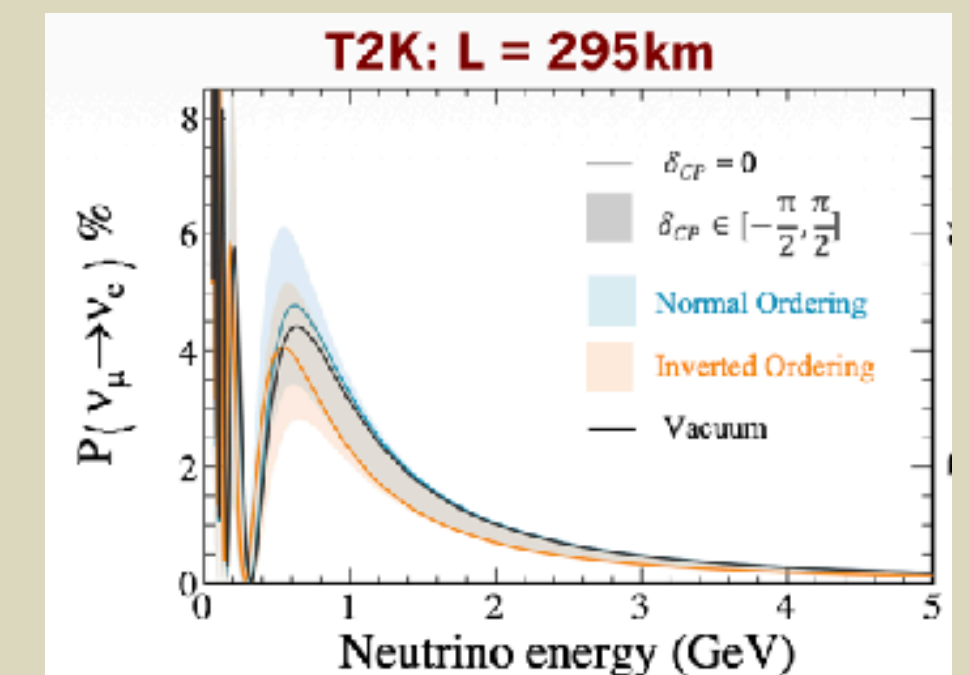
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Oscillation
Probability

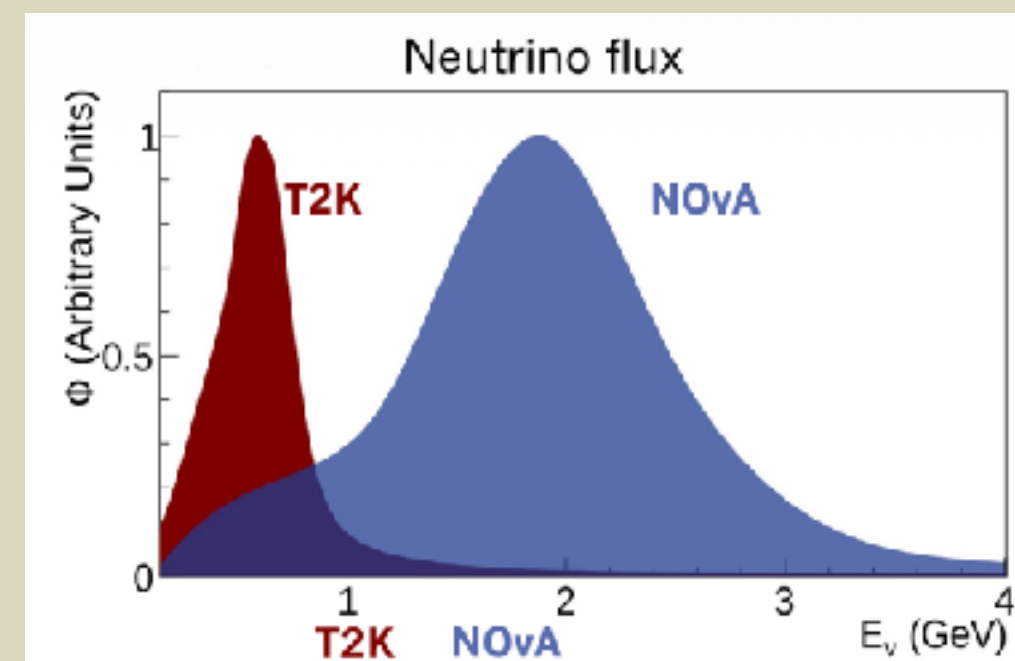
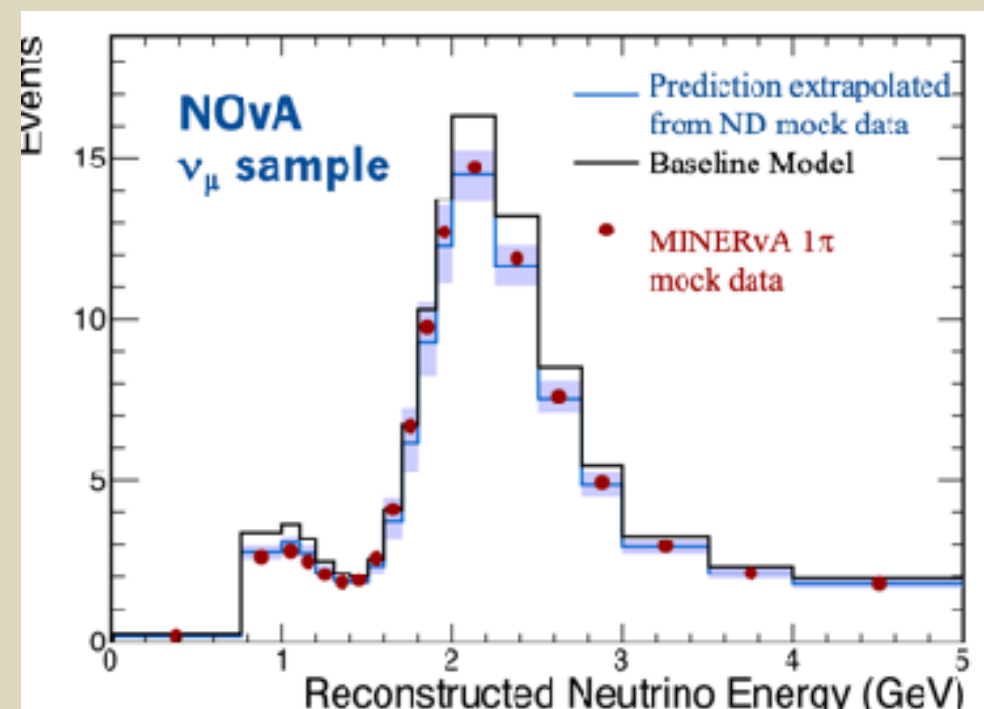
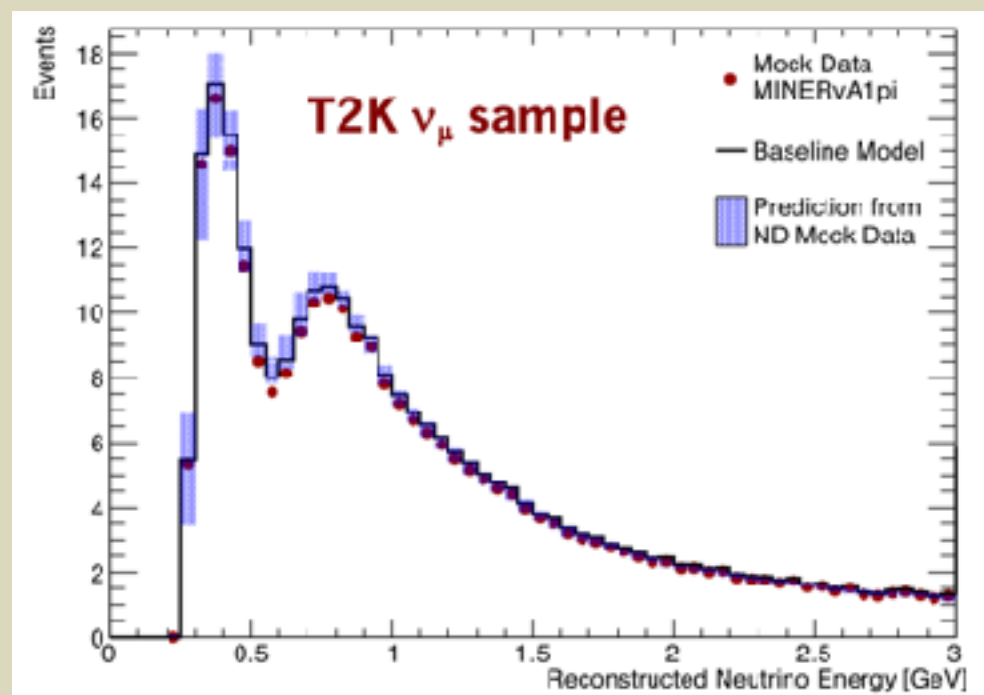
$$P(\nu_A \rightarrow \nu_B)$$



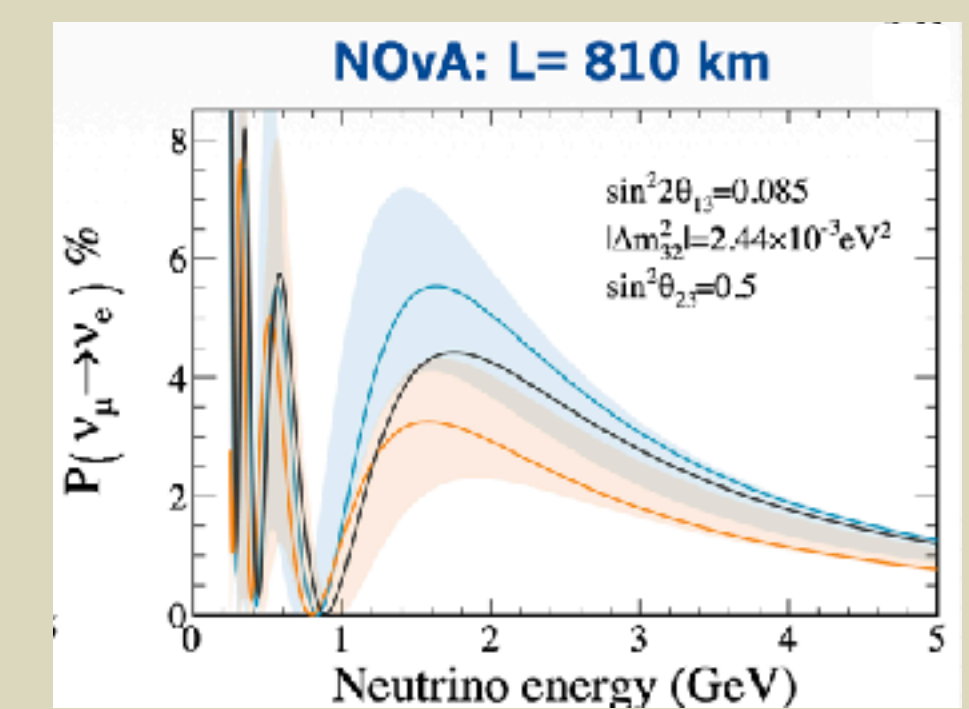
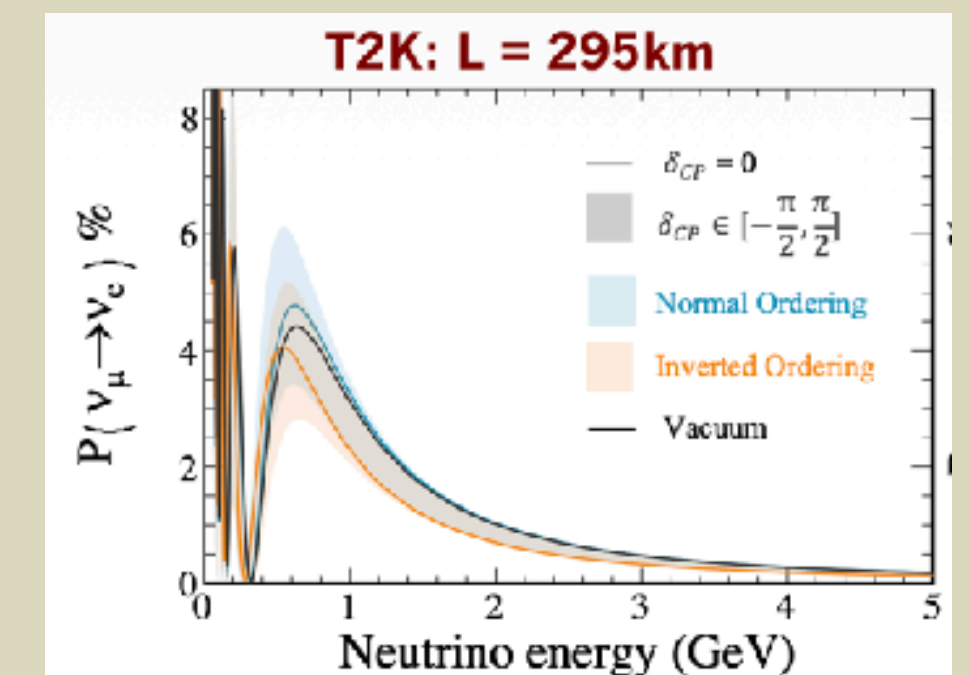
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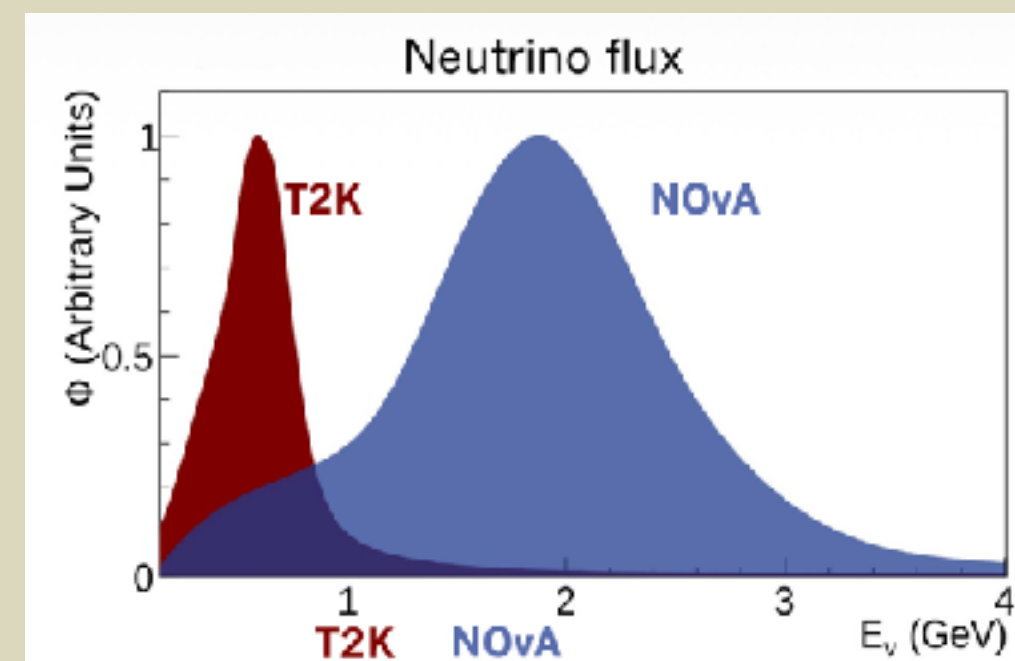
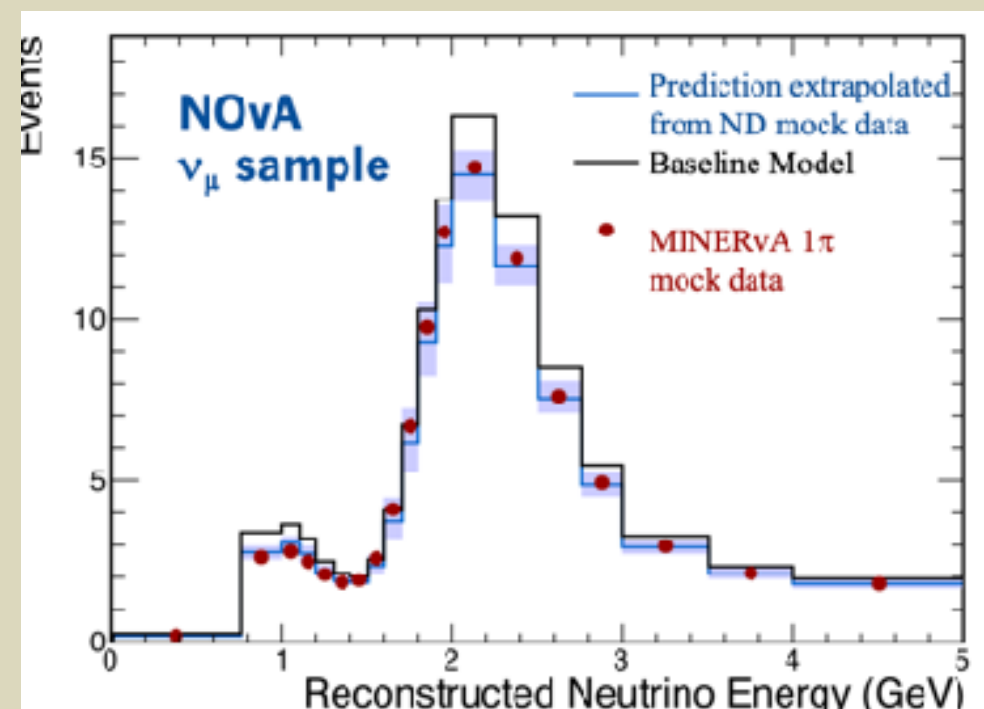
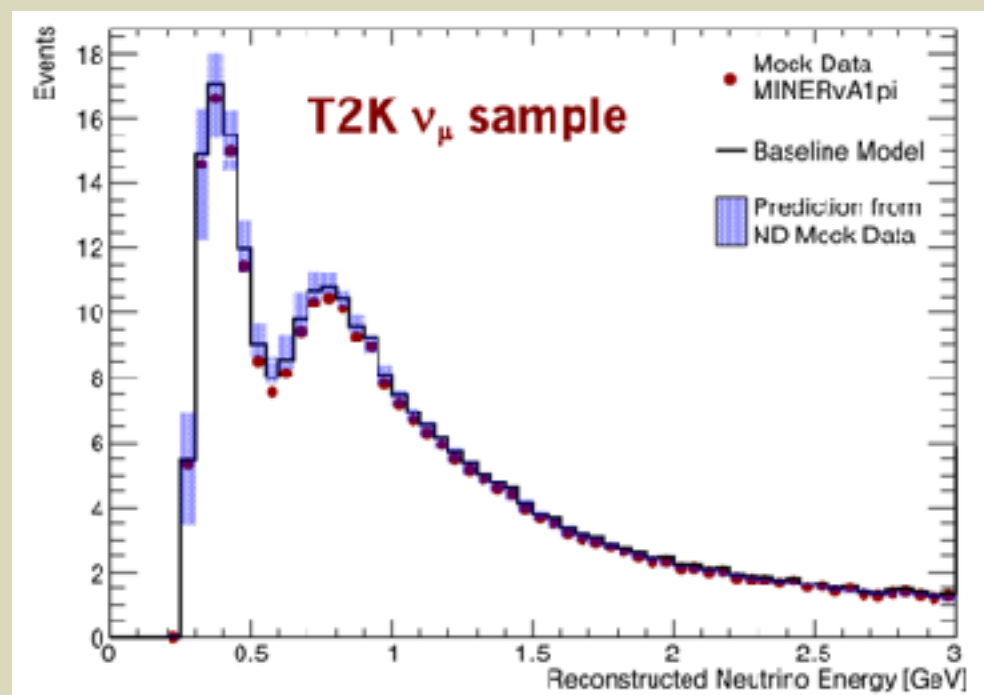
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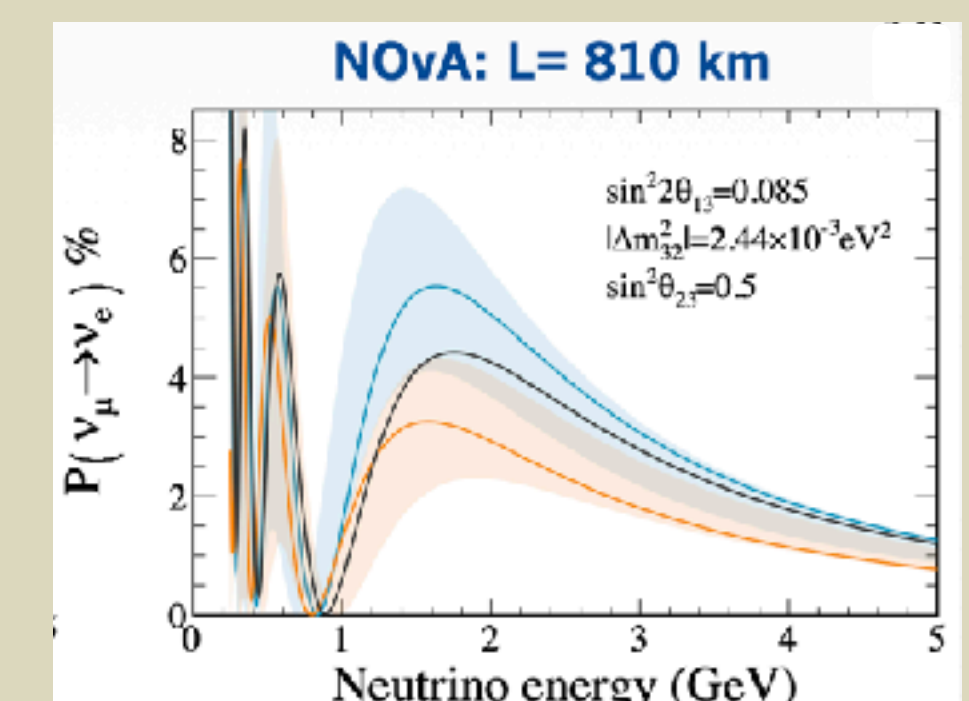
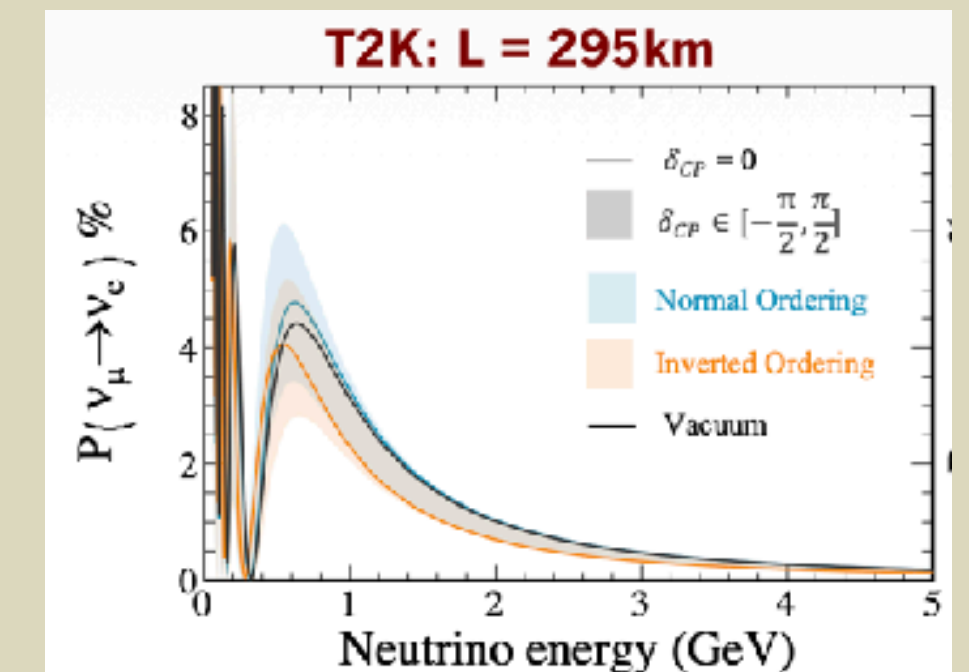
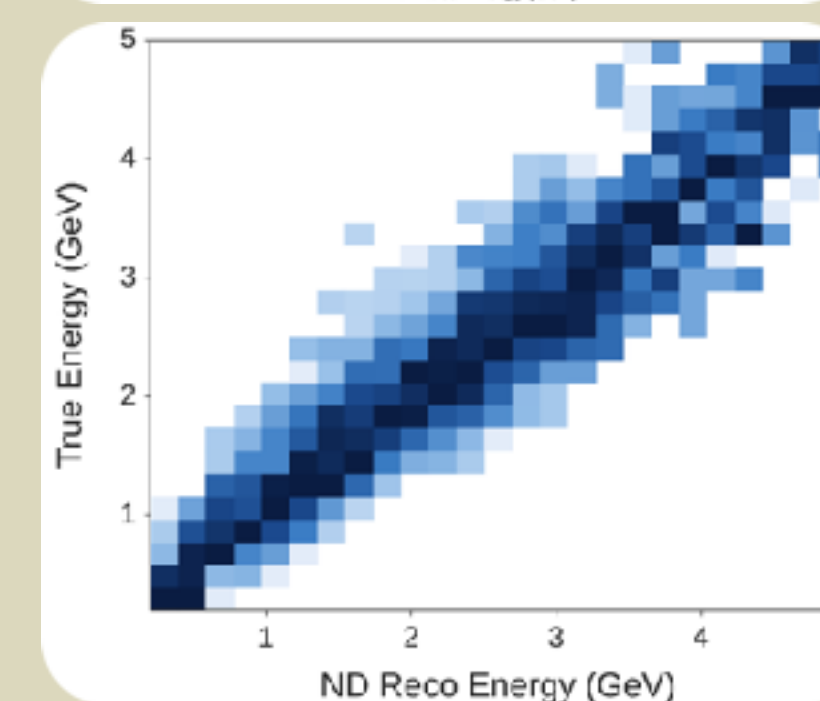
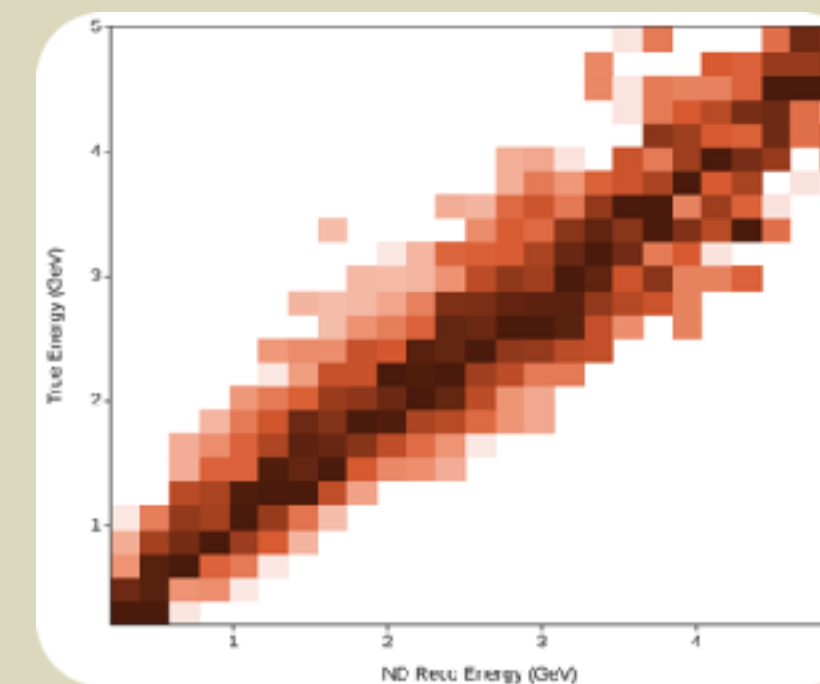
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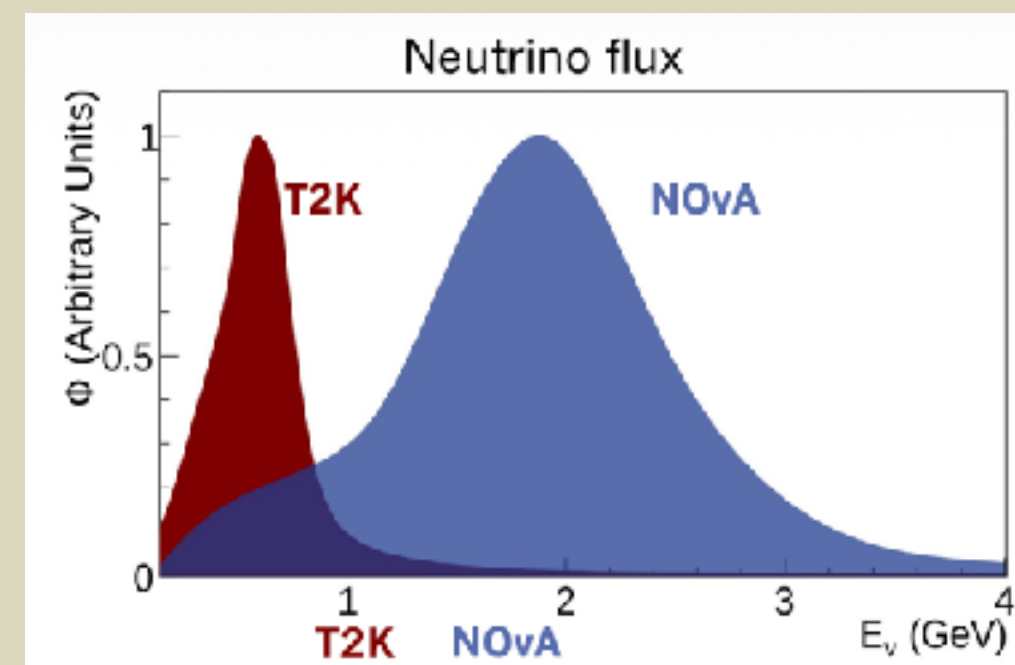
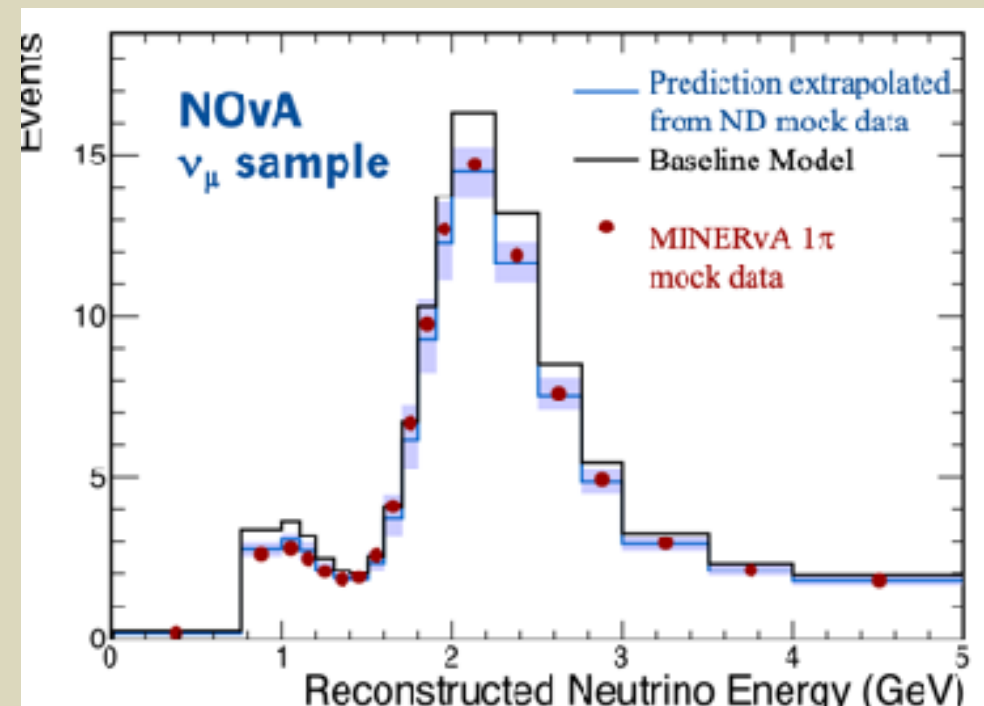
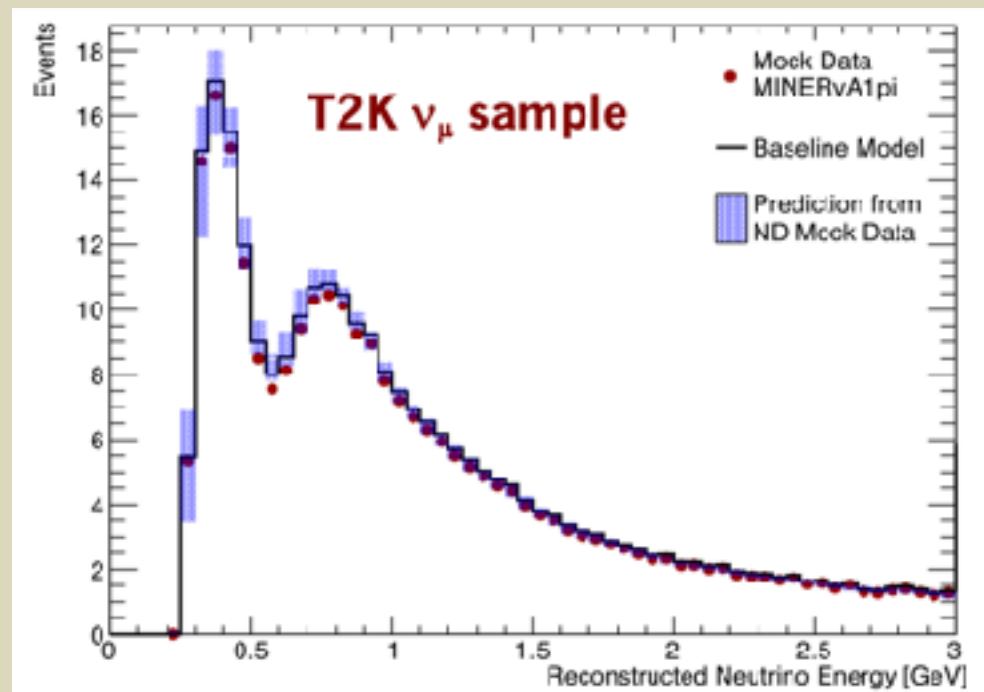
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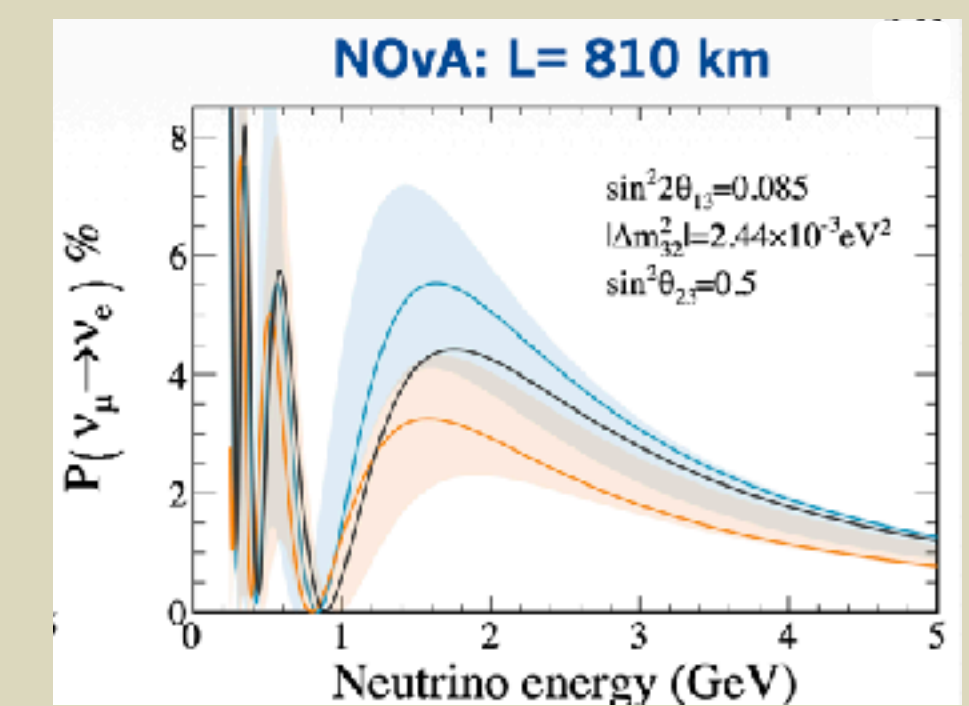
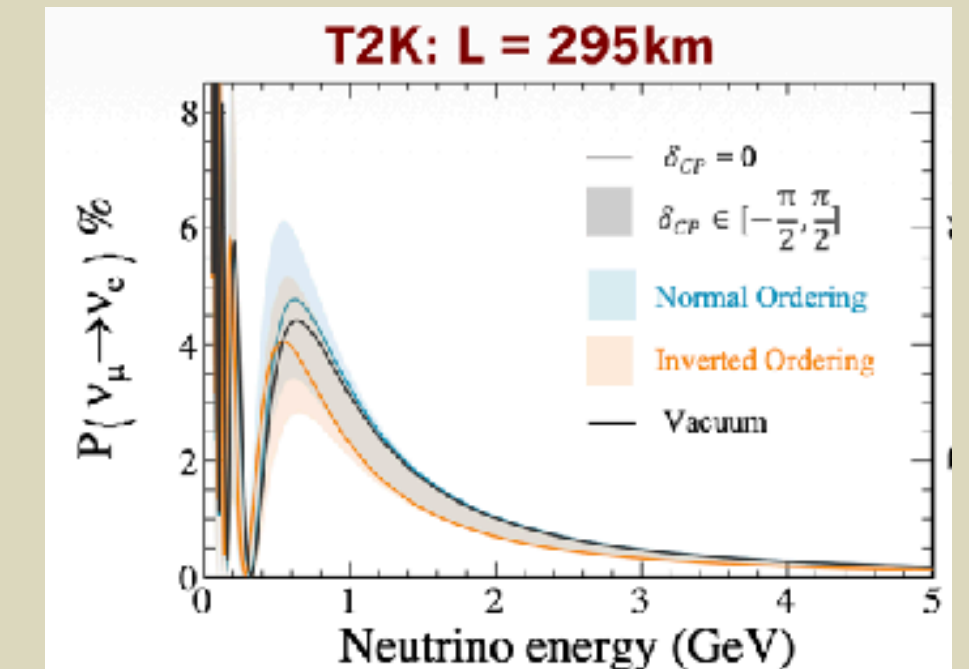
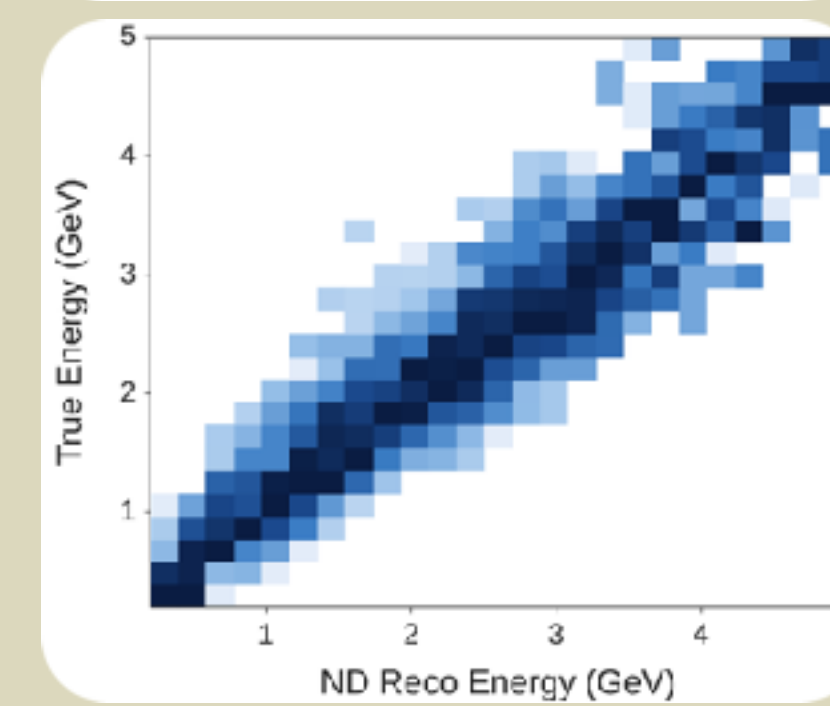
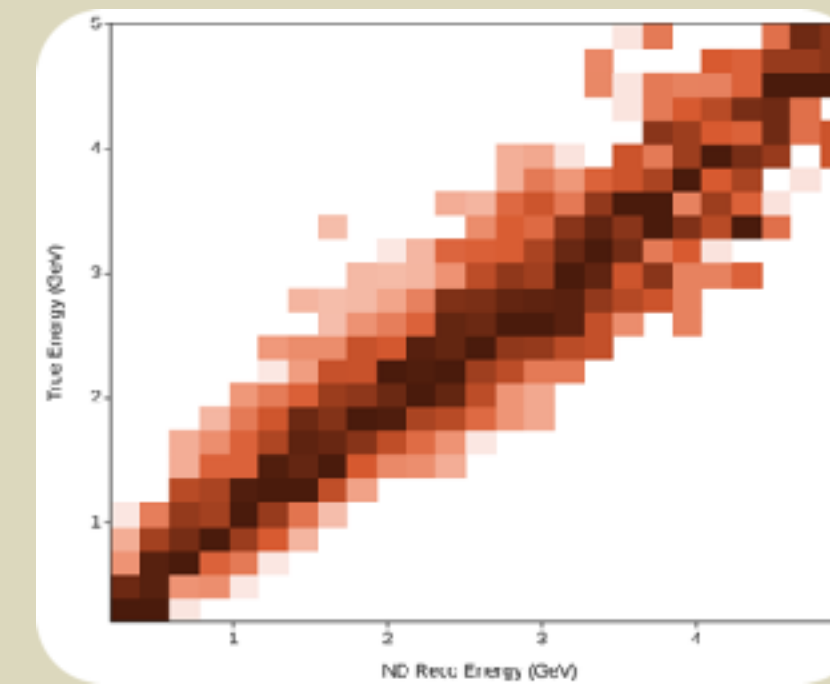
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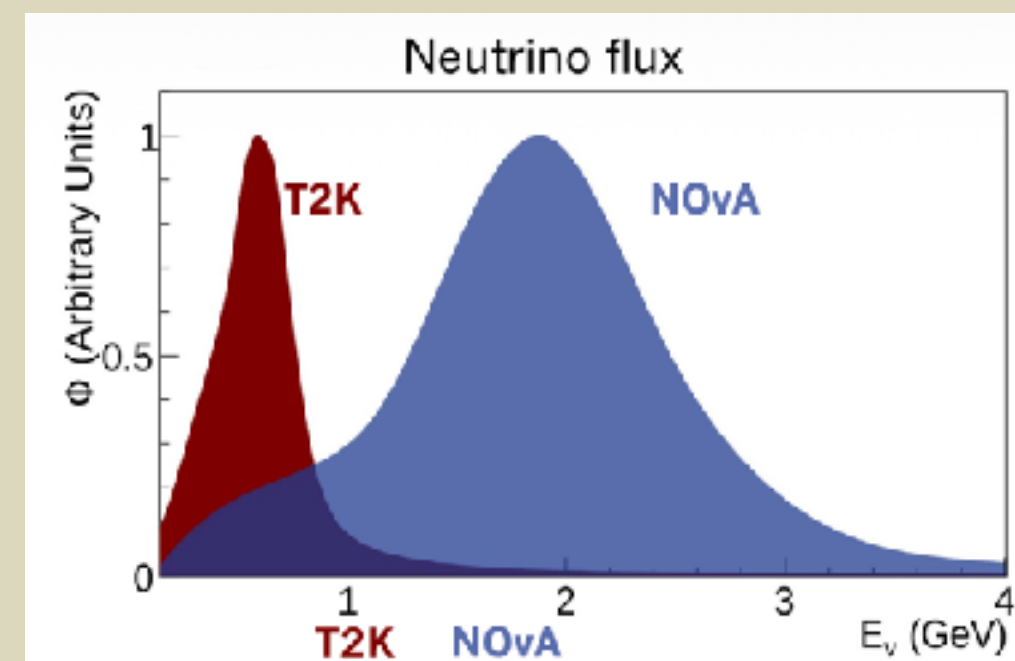
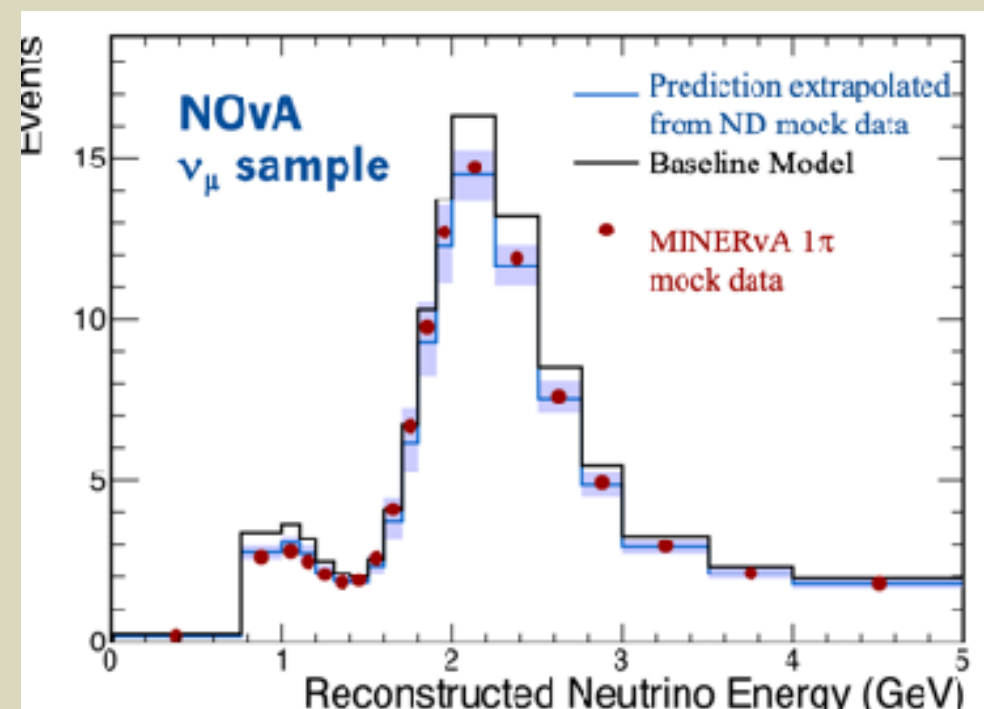
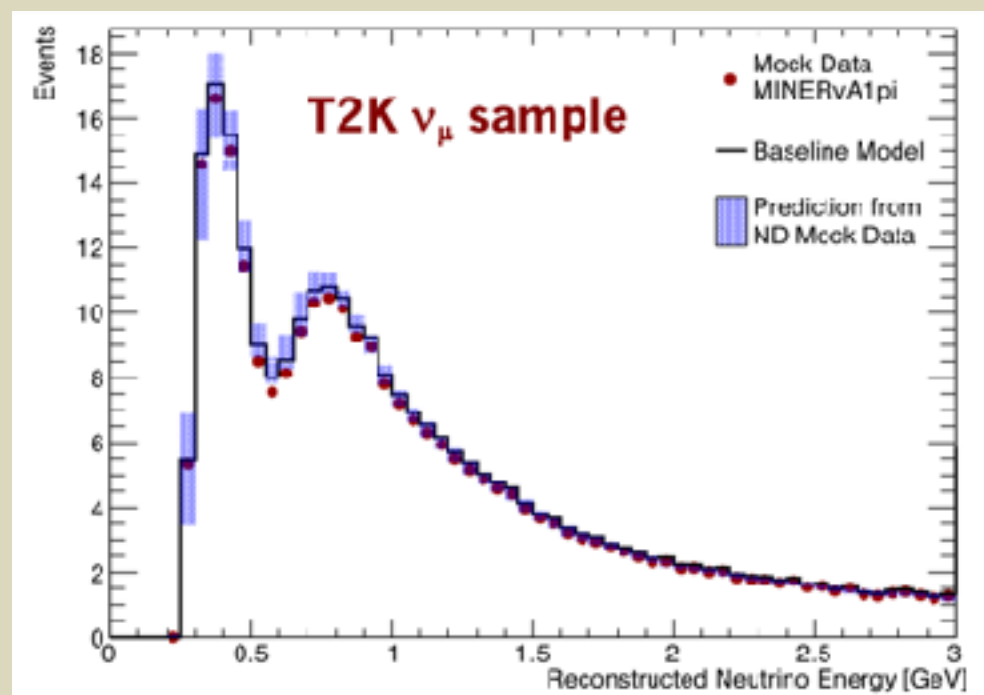
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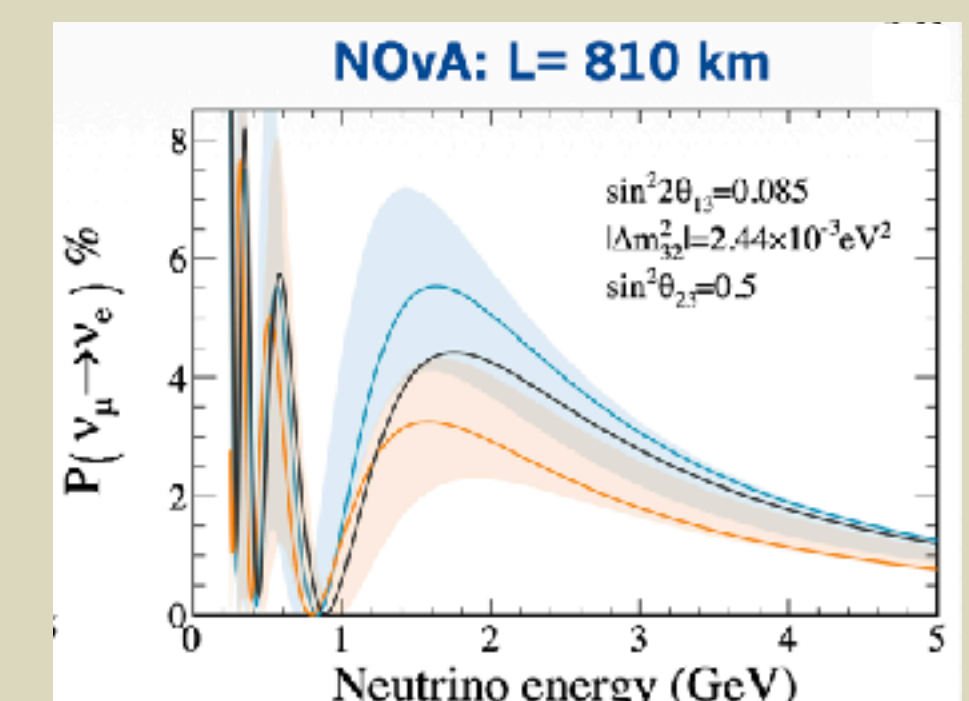
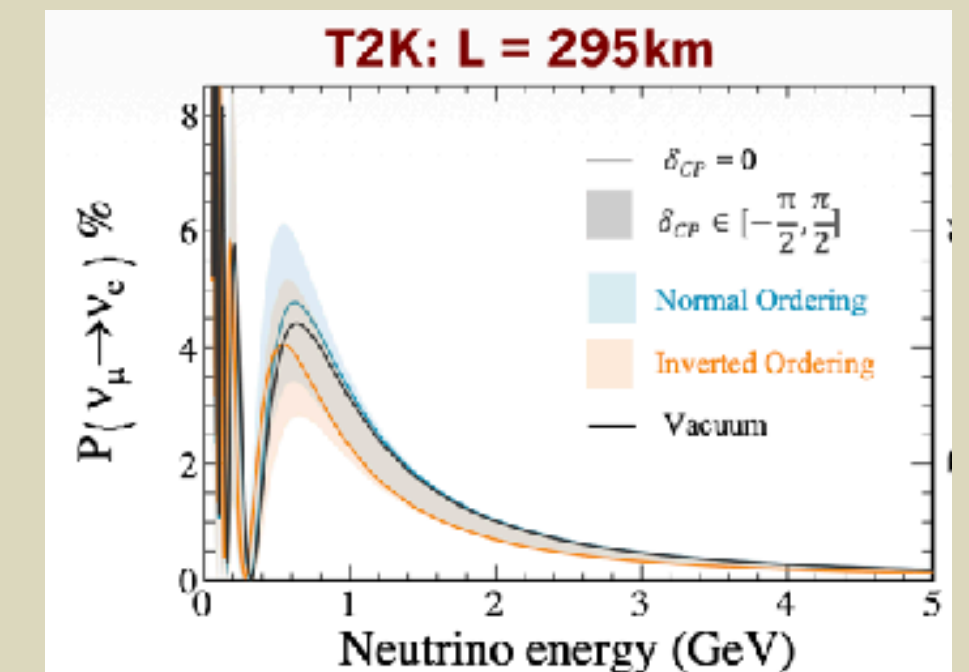
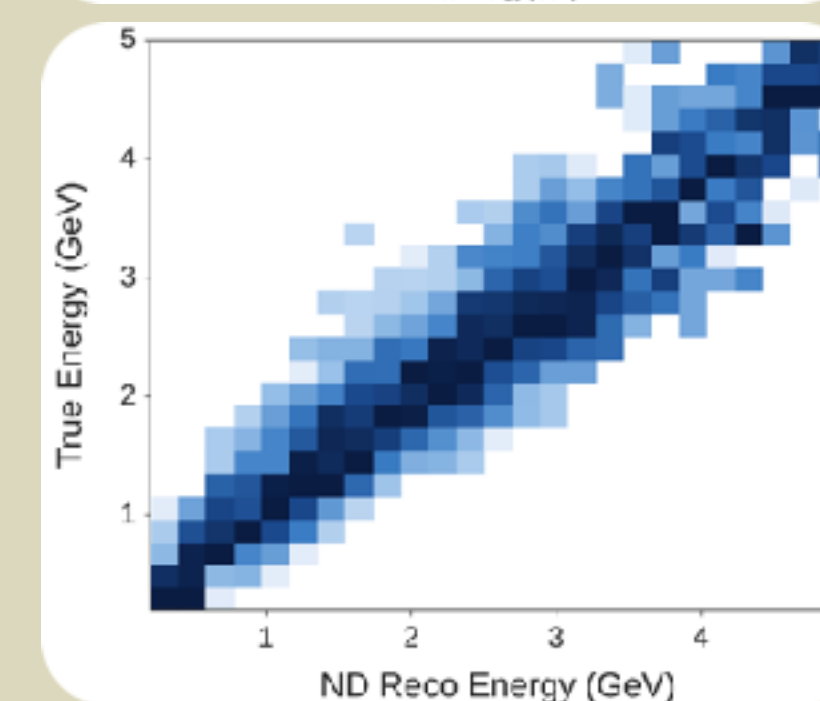
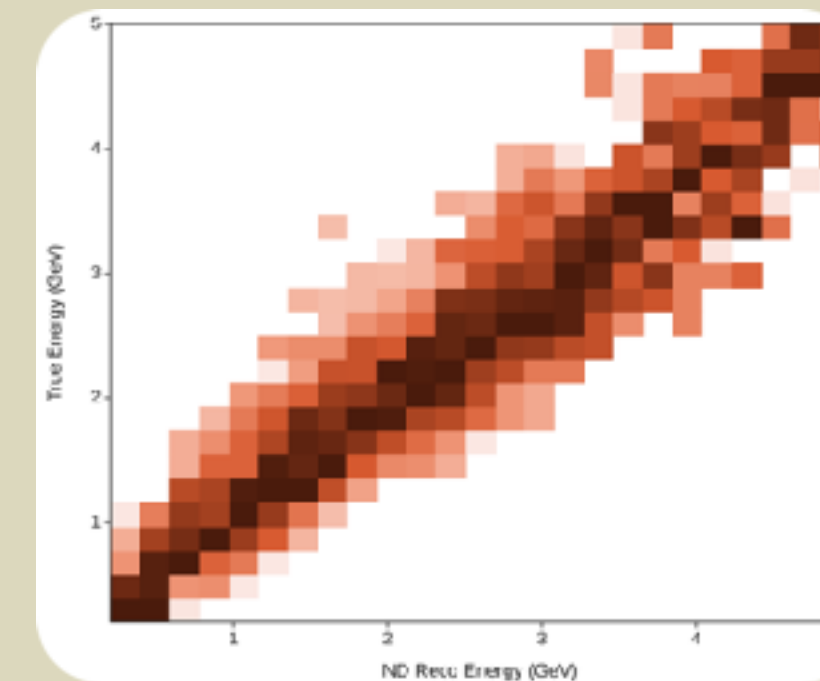
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MINERvA measures cross-sections to directly study neutrino-nucleus interactions! ,

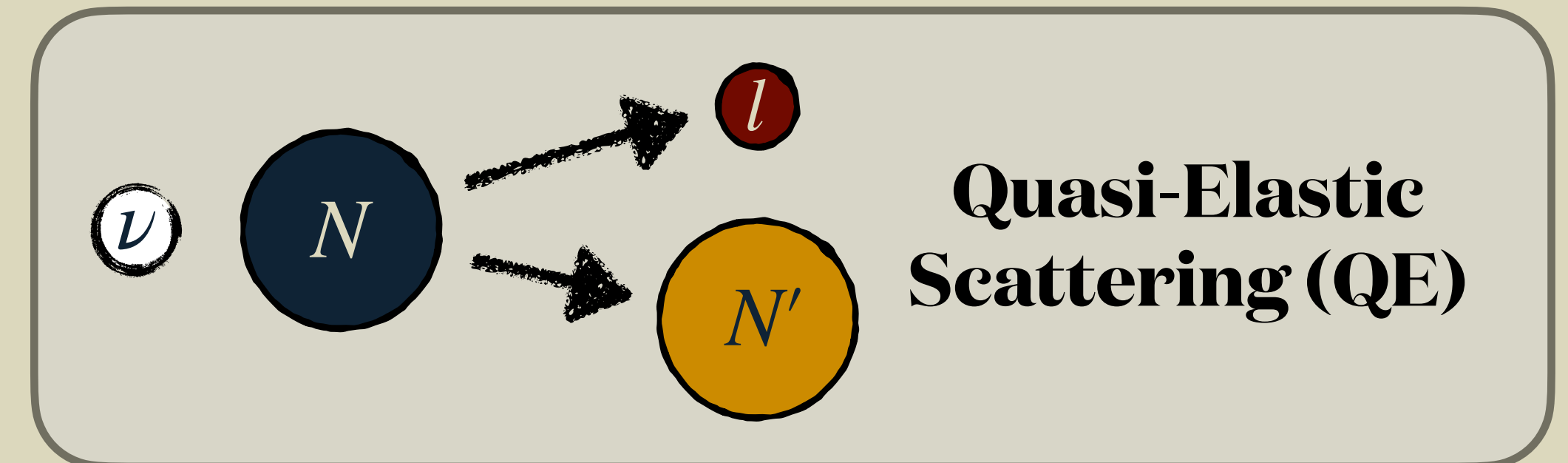
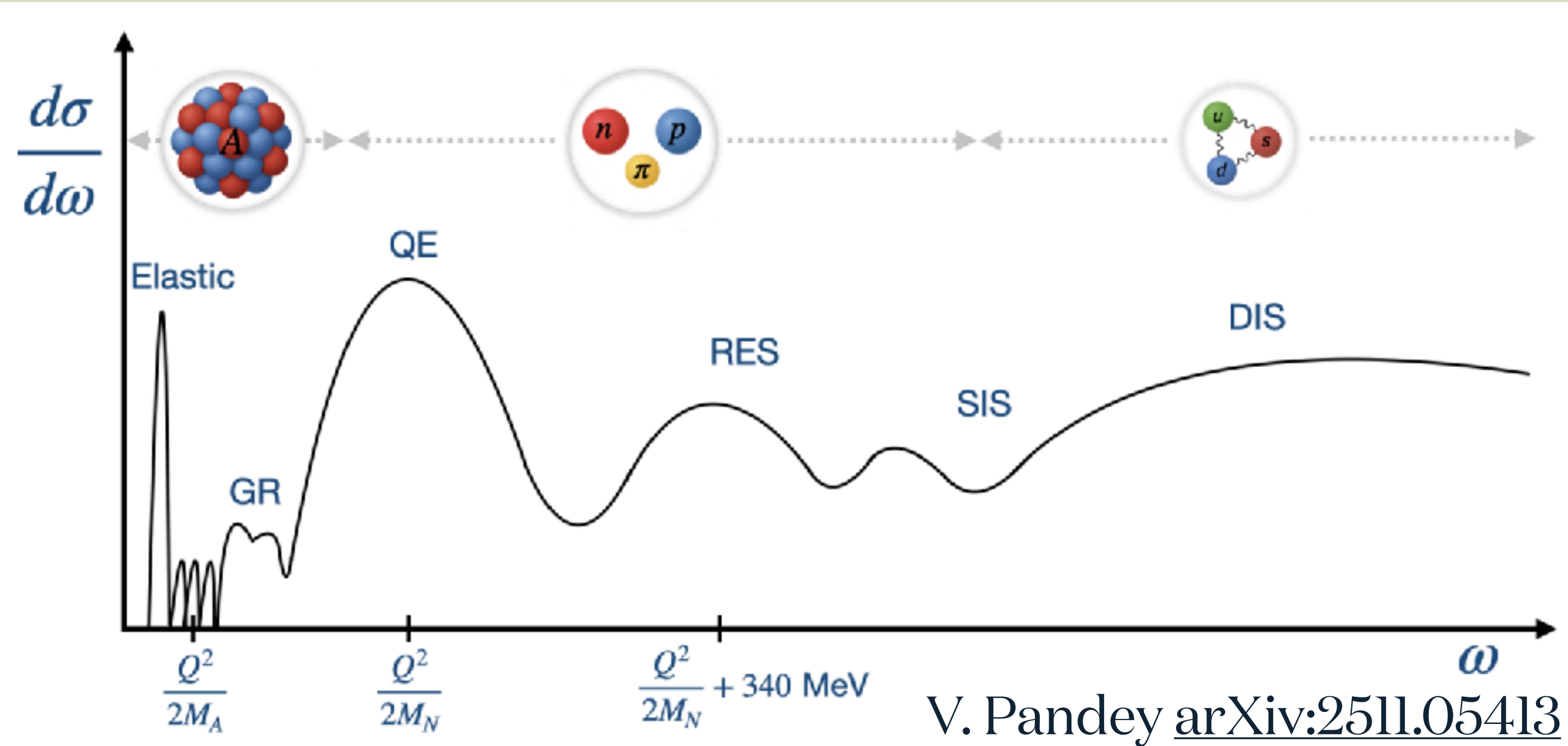
What is a Cross Section?

Cross Sections are maps that encode information about the distribution of structure that we cannot directly see.



Classical treatment used impact parameters, b , and angle, θ , to encode distributed structure in solid angle, $\frac{d\sigma}{d\Omega}$.

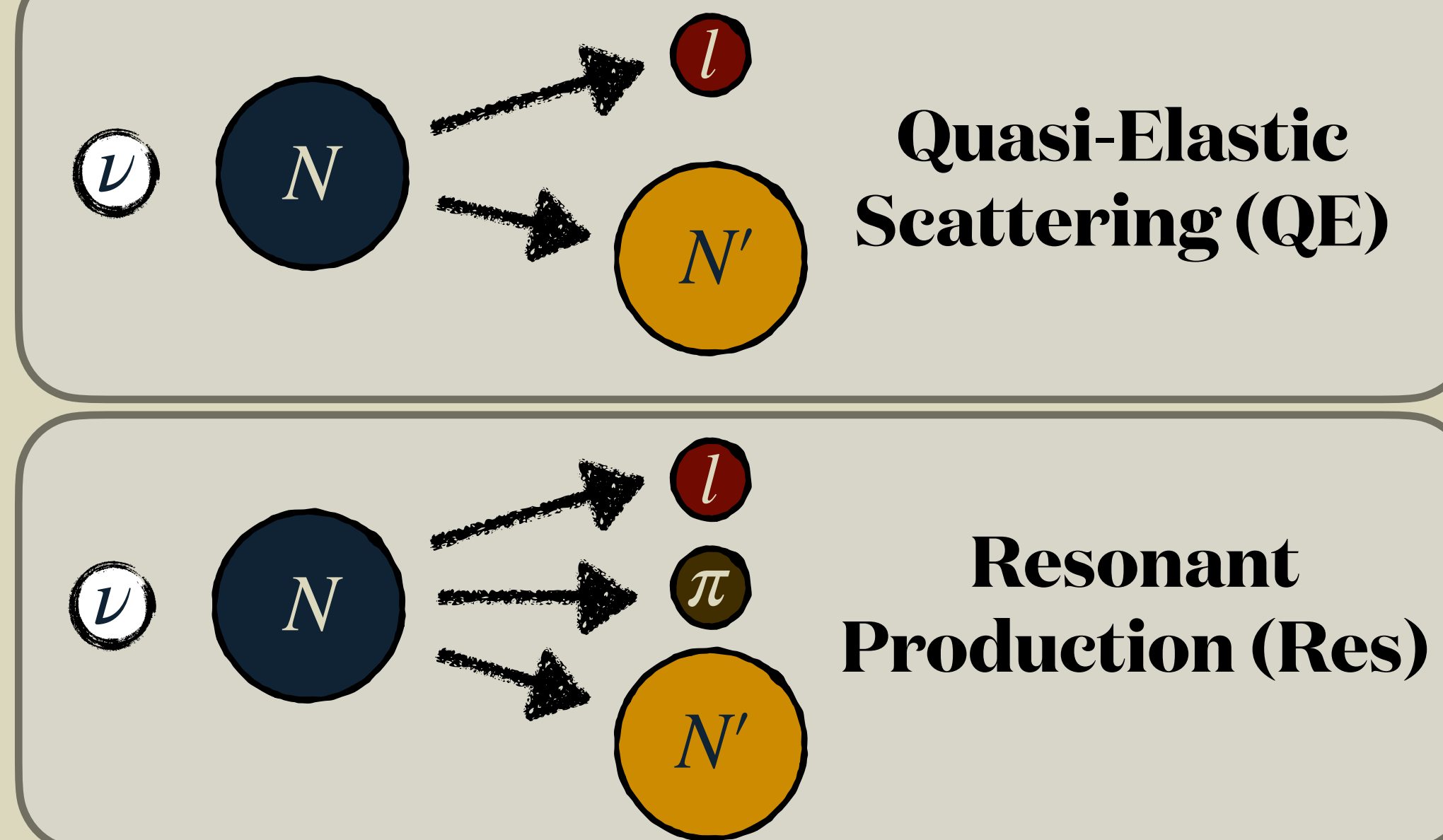
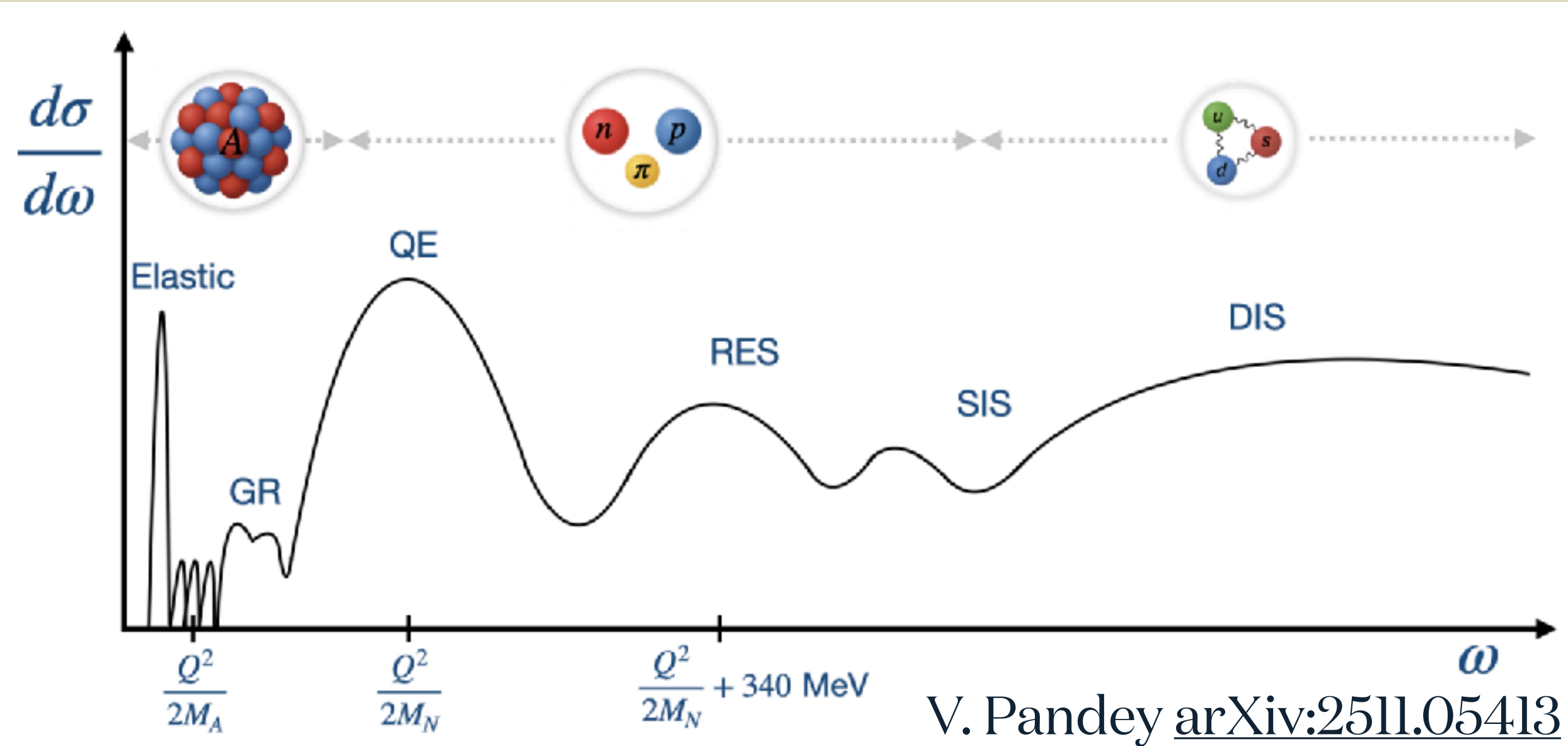
The Neutrino Cross-Section Problem (Part I)



The picture is complicated!

- The dominant process at any particular energy depends on the amount of energy transferred to the nucleus.
- The transition from Res to DIS is essentially the transition from non-perturbative to perturbative QCD

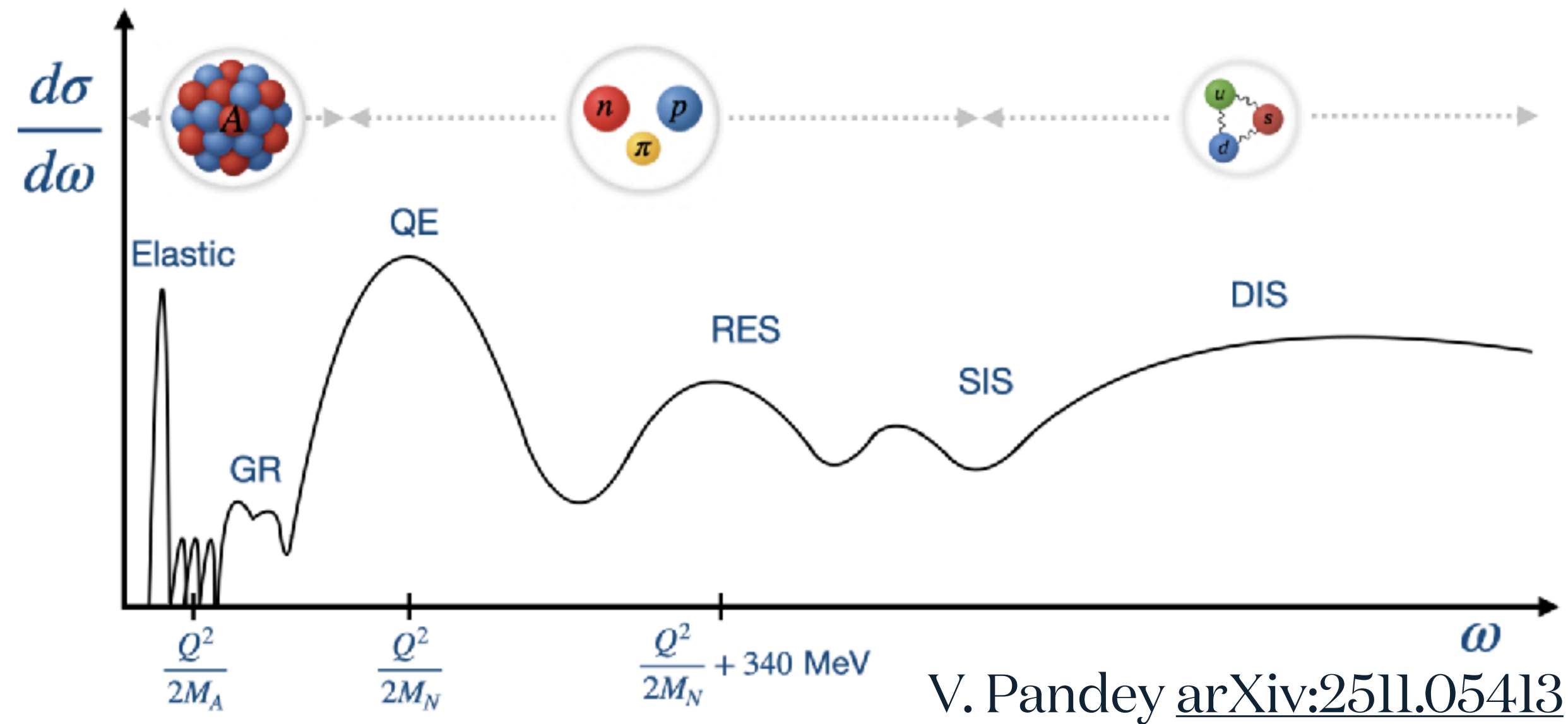
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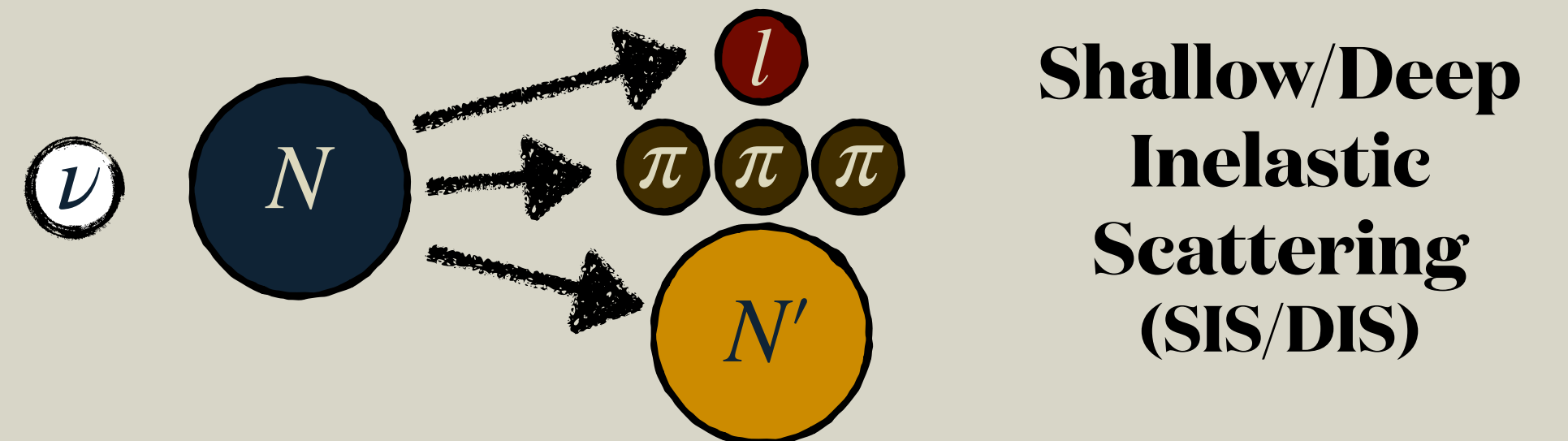
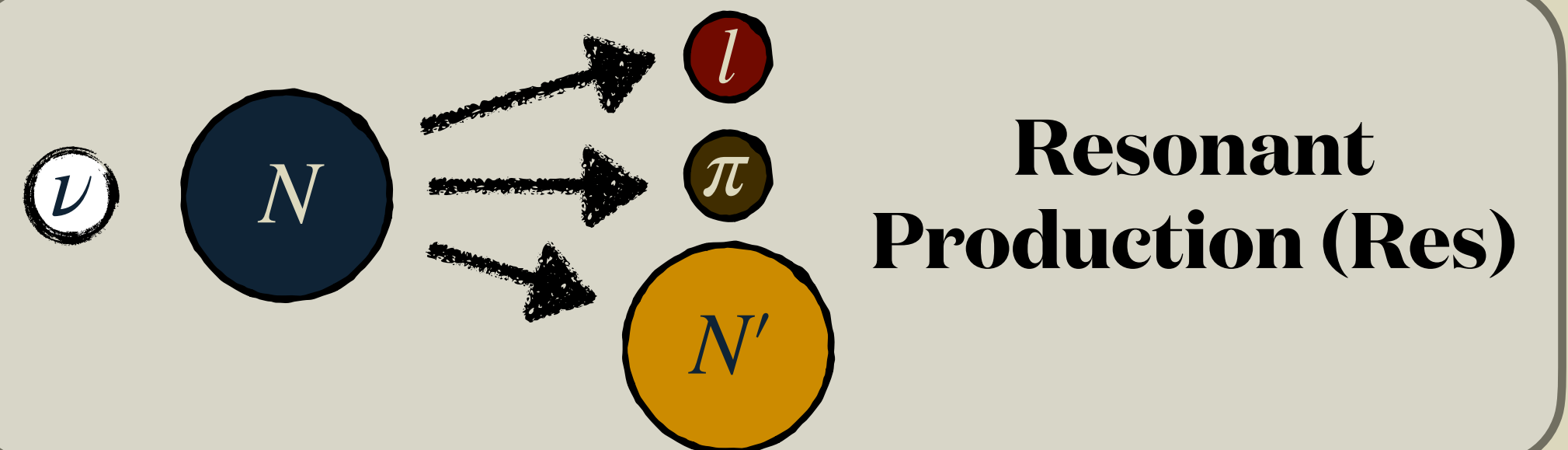
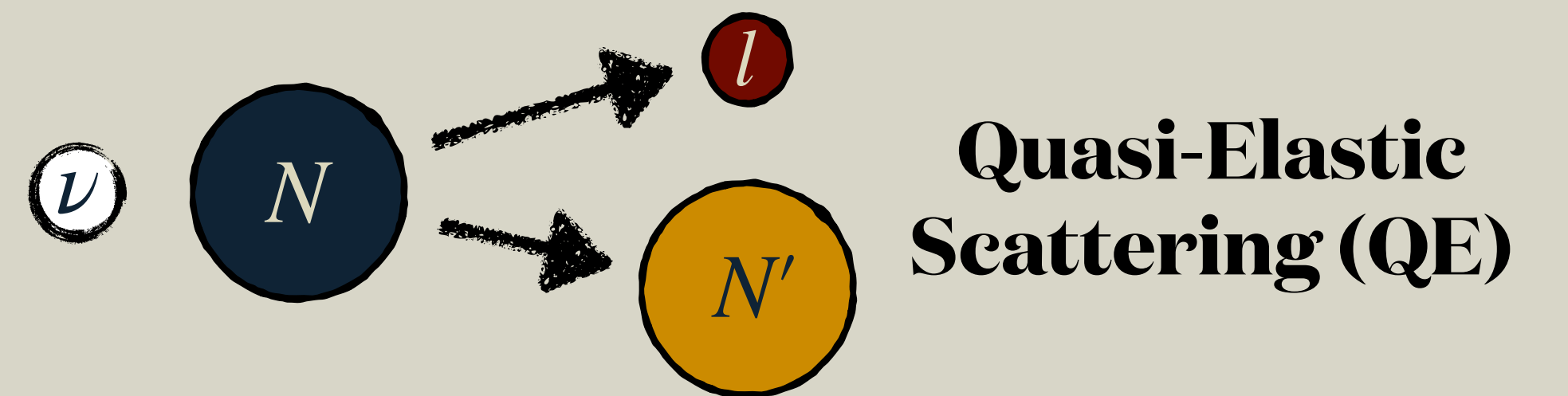
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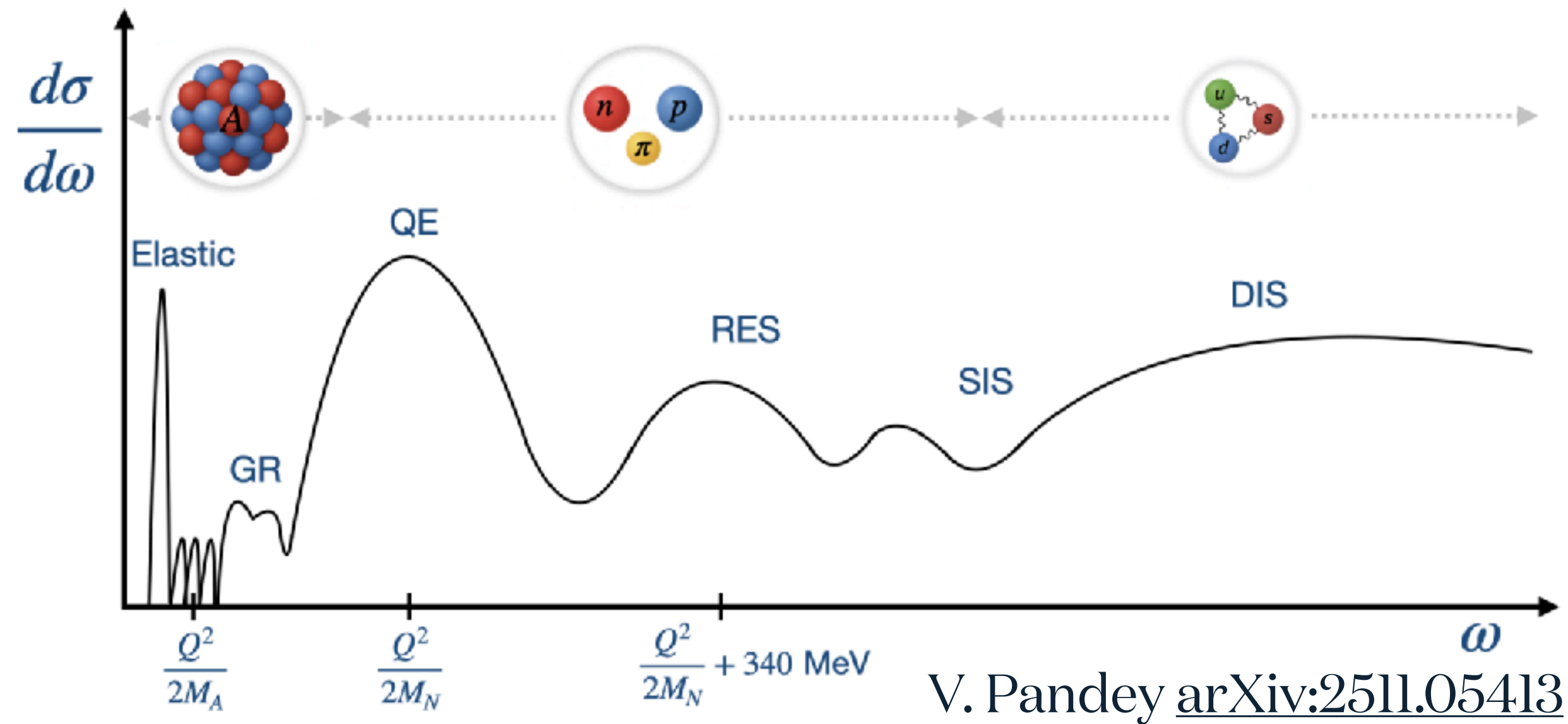


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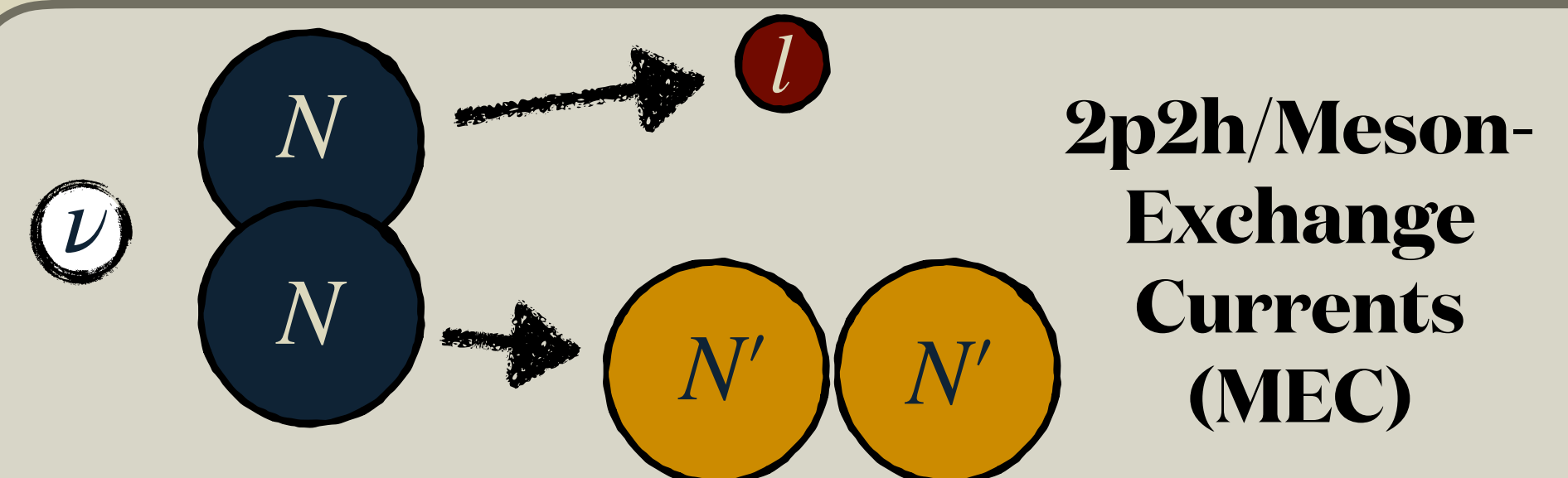
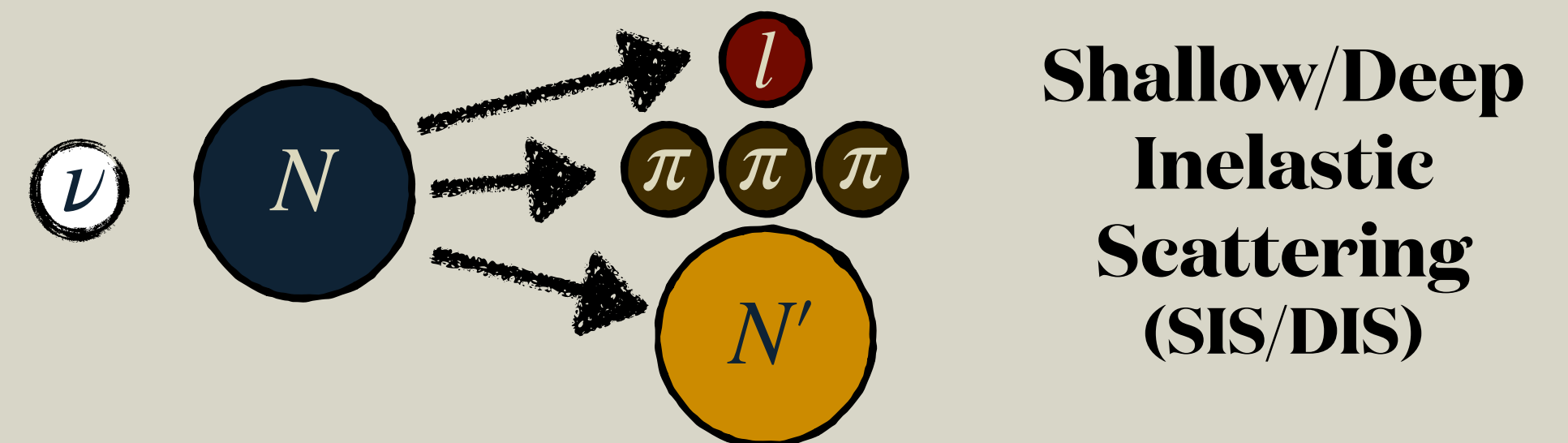
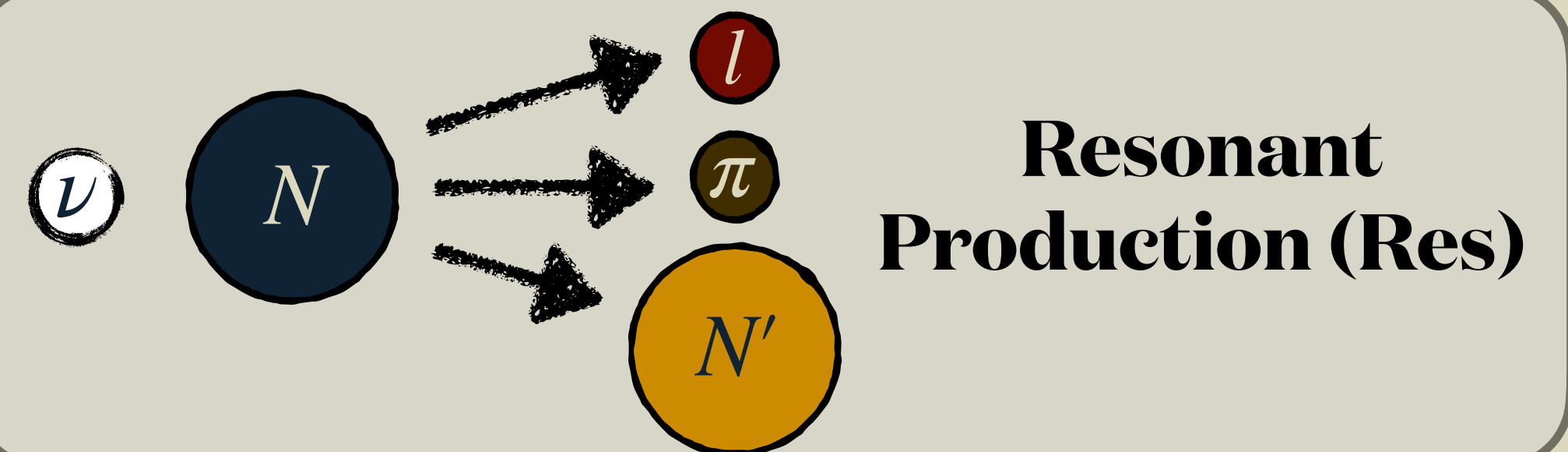
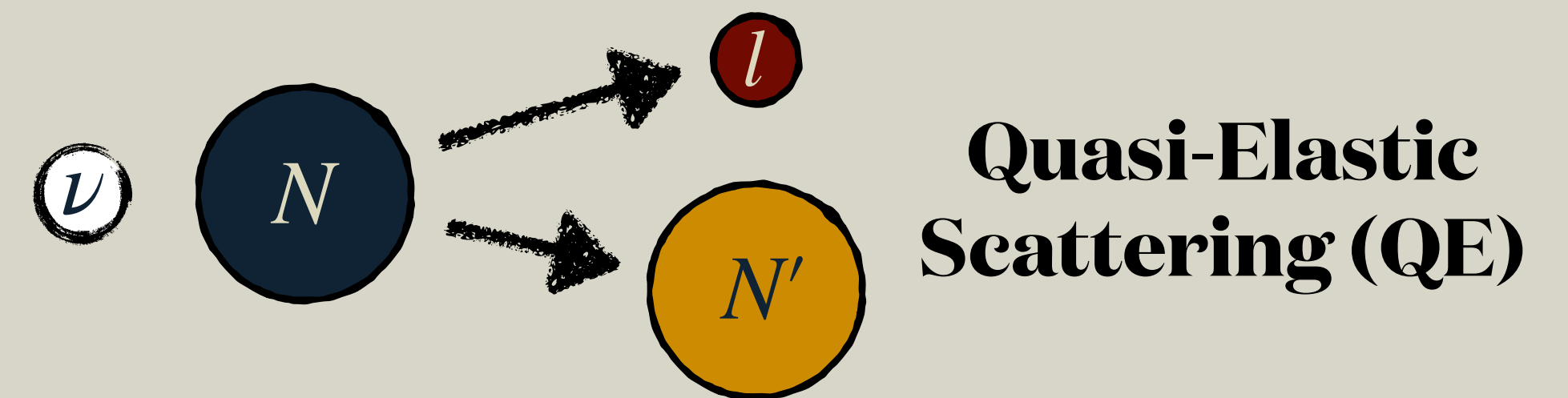


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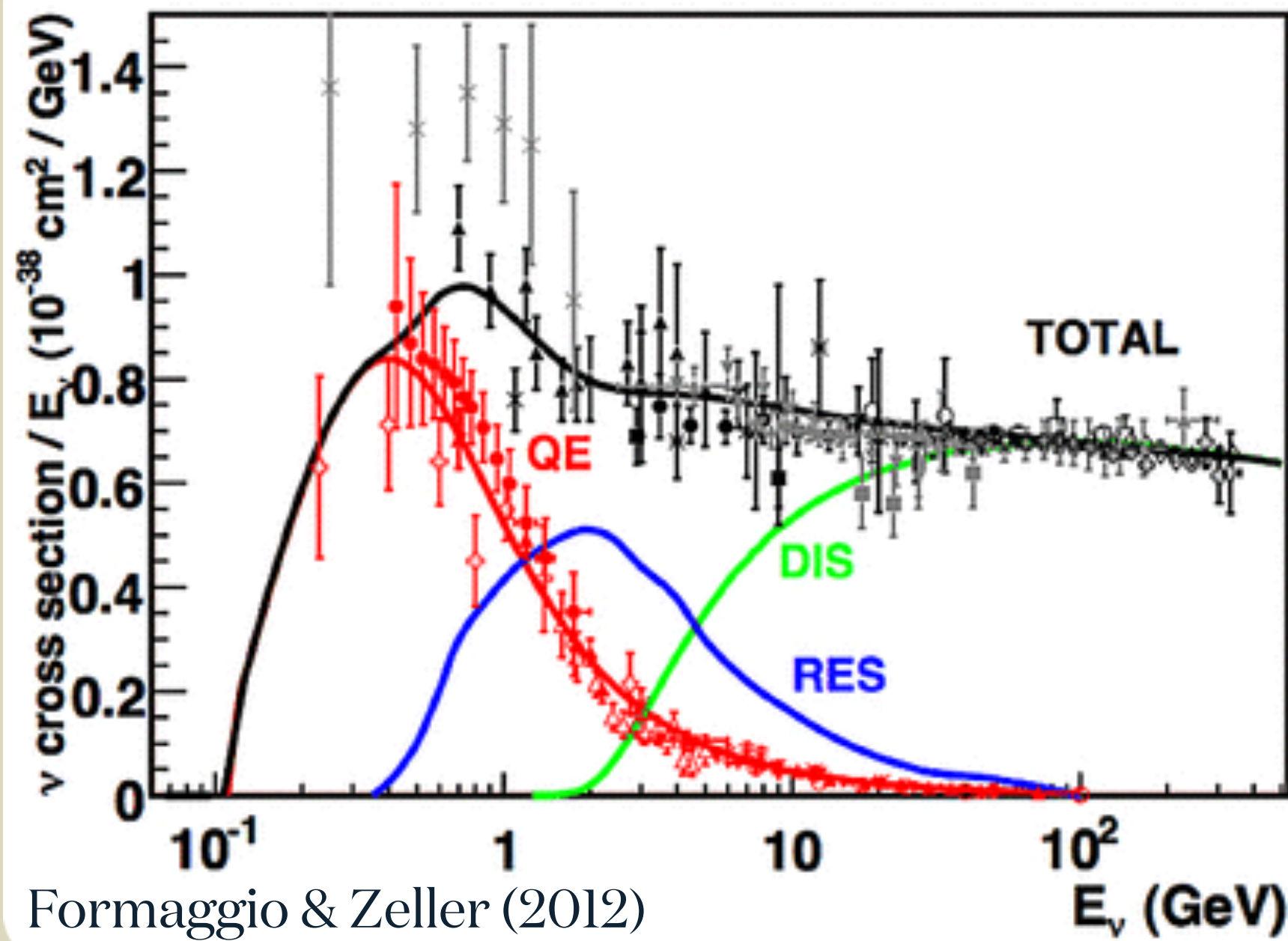
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The Neutrino Cross-Section Problem (Part II)

$\sigma(E_\nu) \propto$
Cross-Section

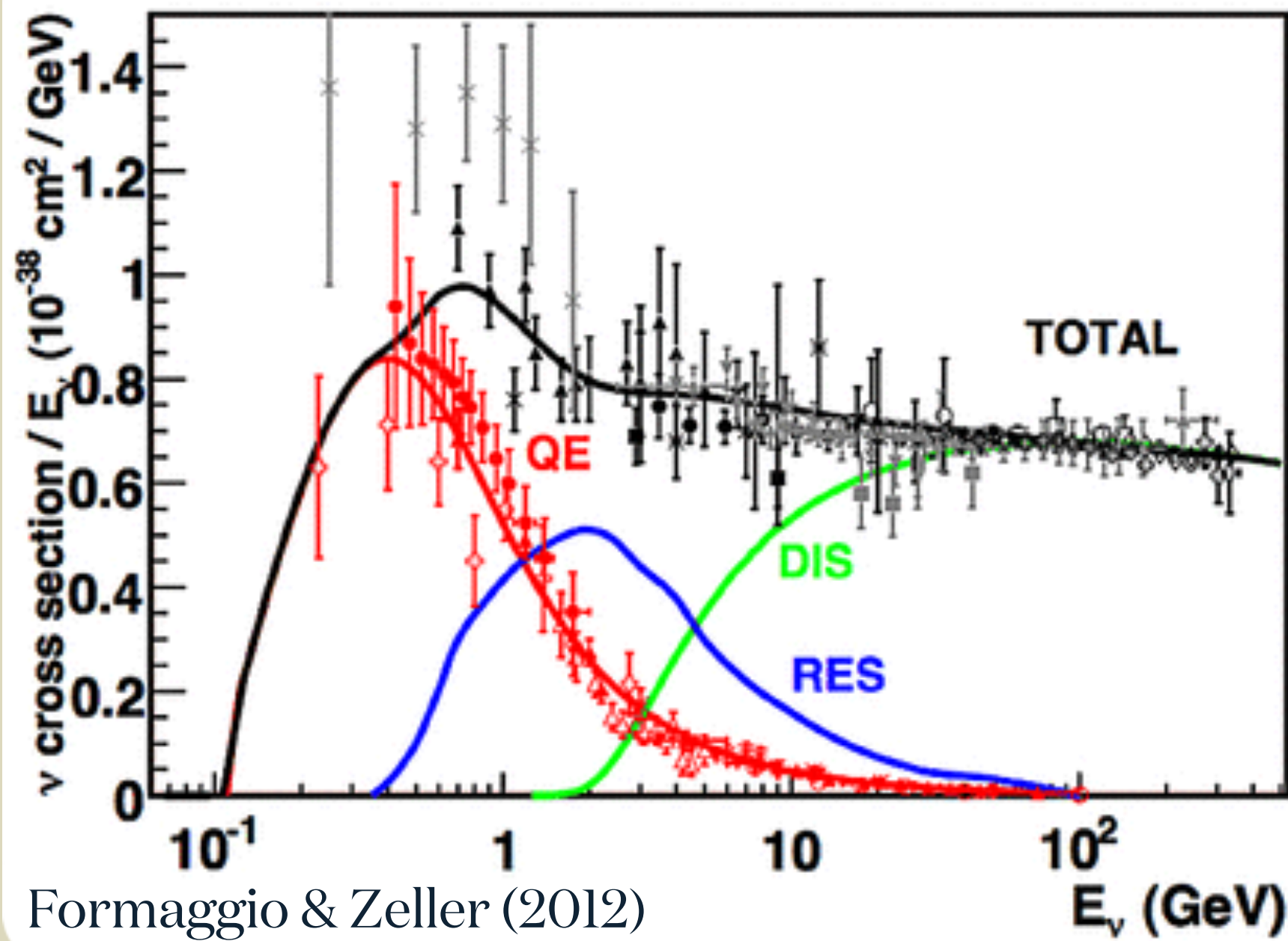


The total cross-section is composed of a linear combination of multiple initial state interaction channels.

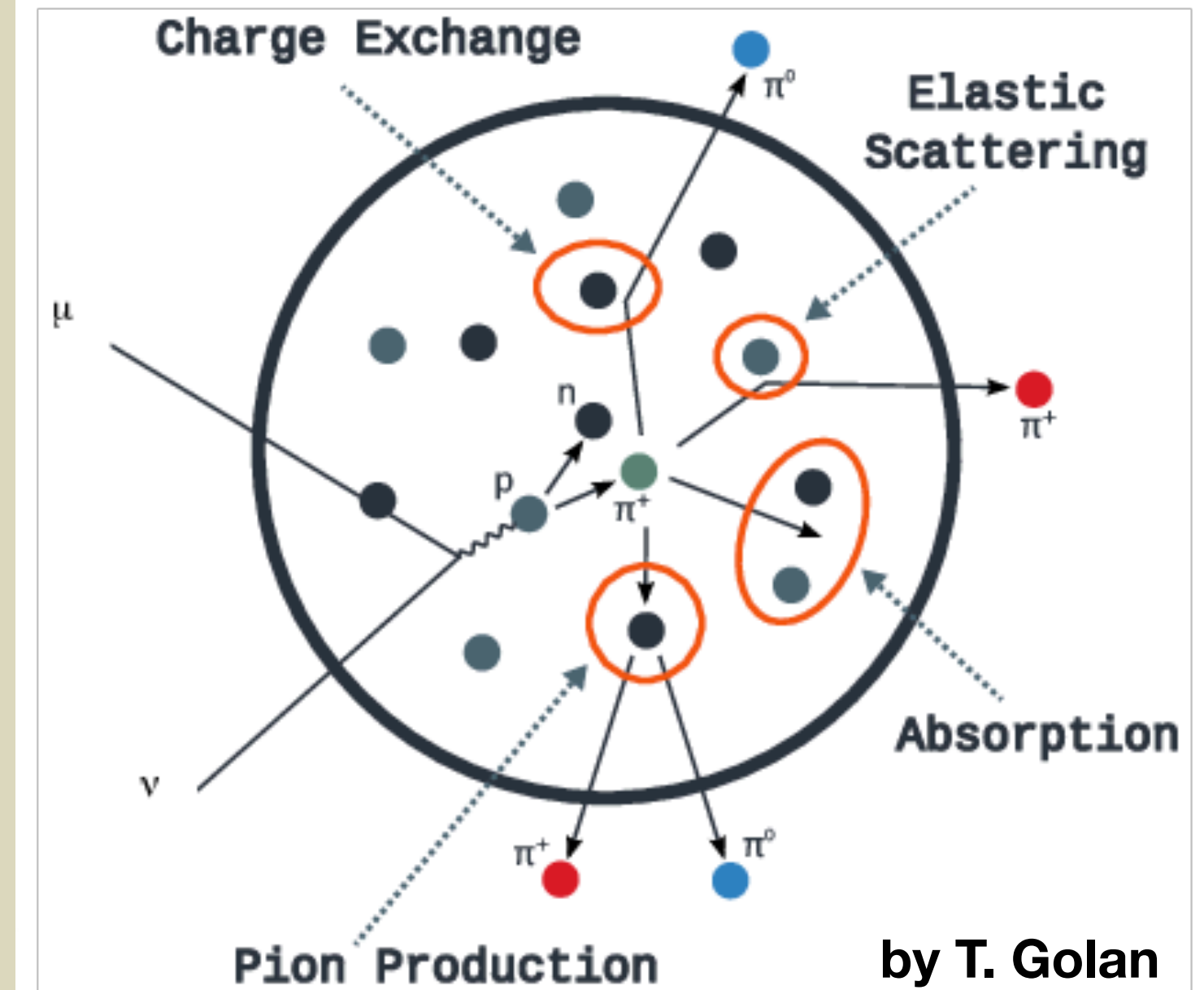
Current cross-section systematic uncertainties on flagship oscillations measurements are around 3-5% of the total values.

The Neutrino Cross-Section Problem (Part II)

$\sigma(E_\nu) \propto$
Cross-Section



Formaggio & Zeller (2012)



The total cross-section is composed of a linear combination of multiple initial state interaction channels.

Final state processes are convolved with initial interaction channels!

Current cross-section systematic uncertainties on flagship oscillations measurements are around 3-5% of the total values.

Very difficult to disentangle.

Measurements & Modeling

Measuring Cross-Sections

Experiments generally measure cross sections as a function of a “signal” process against resolvable background.

$$\sigma = \int \left(\frac{d\sigma}{dx_\alpha} \right) dx_\alpha = \sum_\alpha \left(\frac{\sum_i U_{i\alpha} (N_i^{data} - N_i^{bkgd})}{\Phi_\alpha T \epsilon_\alpha \Delta x_\alpha} \right) \Delta x_\alpha$$

 $U_{i\alpha}$ $N_i^{data} - N_i^{bkgd}$ Φ_α T ϵ_α Δx_α

Unfolding
Matrix

Signal
Estimation

Neutrino
Flux

Nucleon
Targets

Detector
Response

Measurement
Binwidth

Appropriate calculation involves **background estimation** which requires comparison to a **simulated detector** and **available theory**. This is an extended process, sometimes requiring multiple years to evaluate appropriate systematic uncertainties.

'Tuning' Models with Cross-Section Measurements (Part I)

Available theory is approximated in simulation with **model generators**

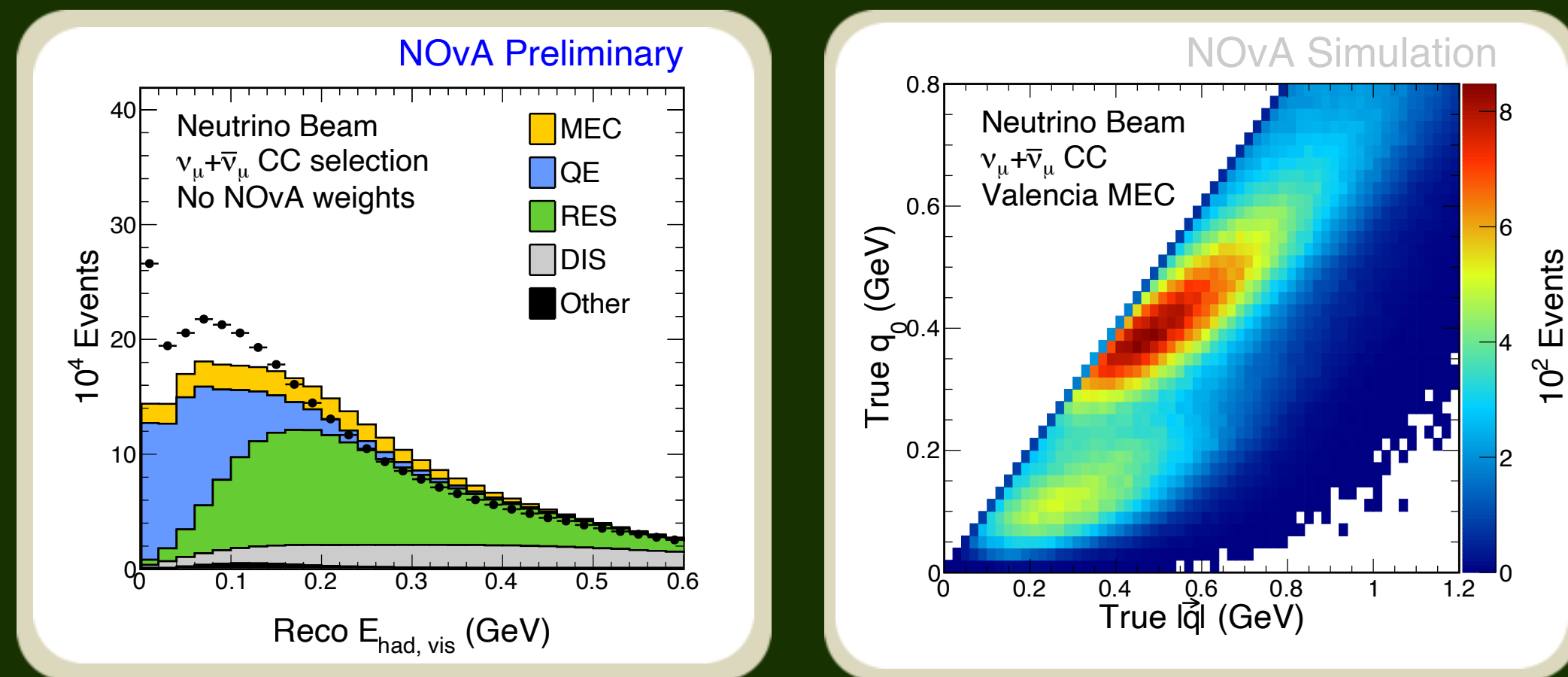


Generators integrate theory for multiple interaction channels into a single product with associated variations interpreted as cross-section uncertainties. Given the piecemeal treatment of multiple models, generators can often accept multiple models for different channels, processes, and effects.

GENIE CMC	Ground State	Quasielastic	2p2h/MEC	Resonant	SIS/DIS	Hadronization	FSI
G18_10i	LFG (Could be RFG, CFG, SF)	Nieves/ Valencia (Could be Llewelyn-Smith, or SuSA)	Nieves/ Valencia (Could be Empirical Model or SuSA)	Berger-Seghal (Could be MK model or DCC or Rein-Seghal)	Bodak-Yang (Tuned)	AGKY (includes different cuts in energy transfer and nuclear recoil)	hA18
G18_10j							hN18
G18_10k							INCL
G18_10i							G4B

‘Tuning’ Models with Cross-Section Measurements (Part II)

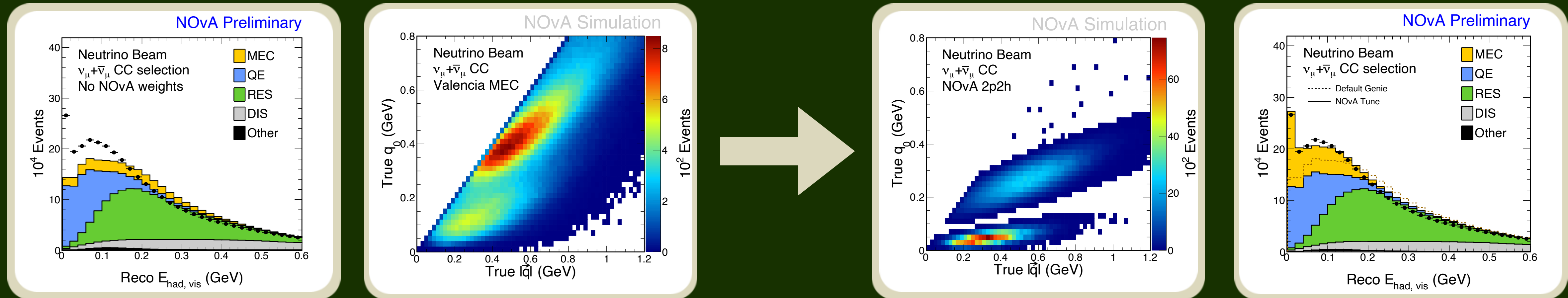
Example of model tuning with MEC in NOvA:



For the last 3Flavor analysis (2024), NOvA began with **Vanilla Nieves/Valencia MEC** as shown in a G18_10j-like starting model. The central value of our model is scaled to match Near Detector observations.

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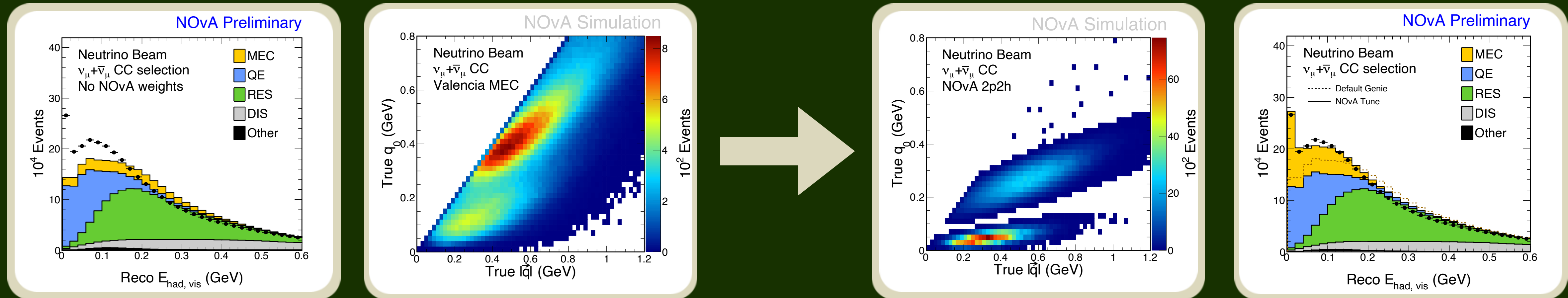
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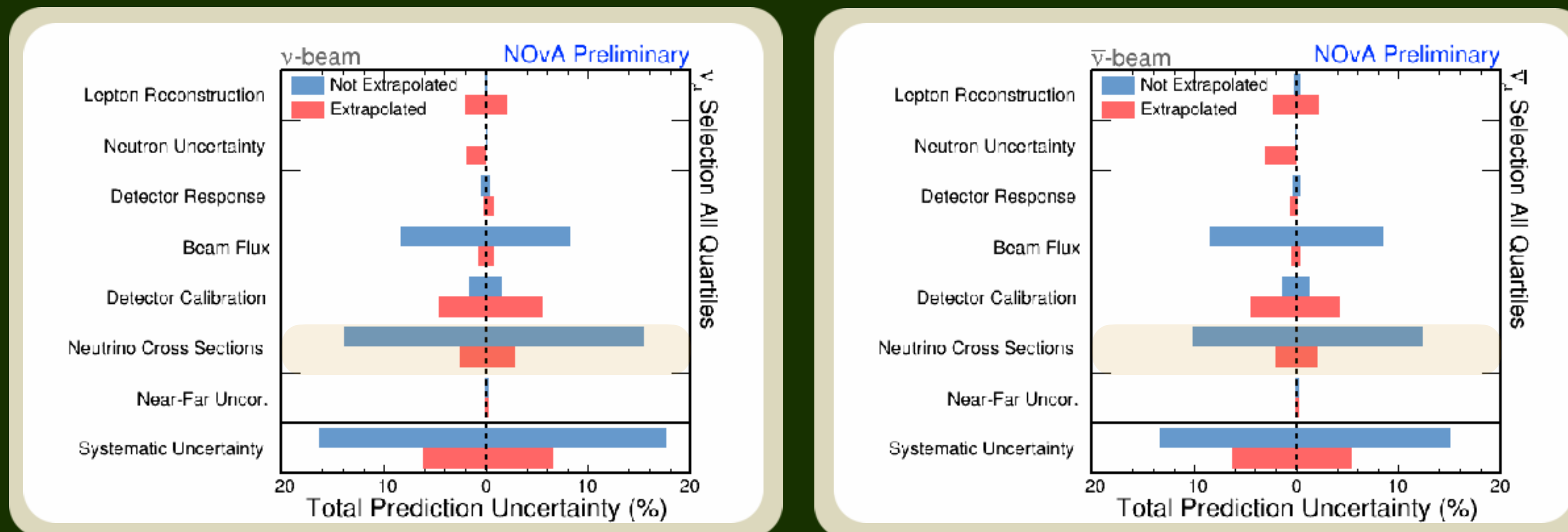
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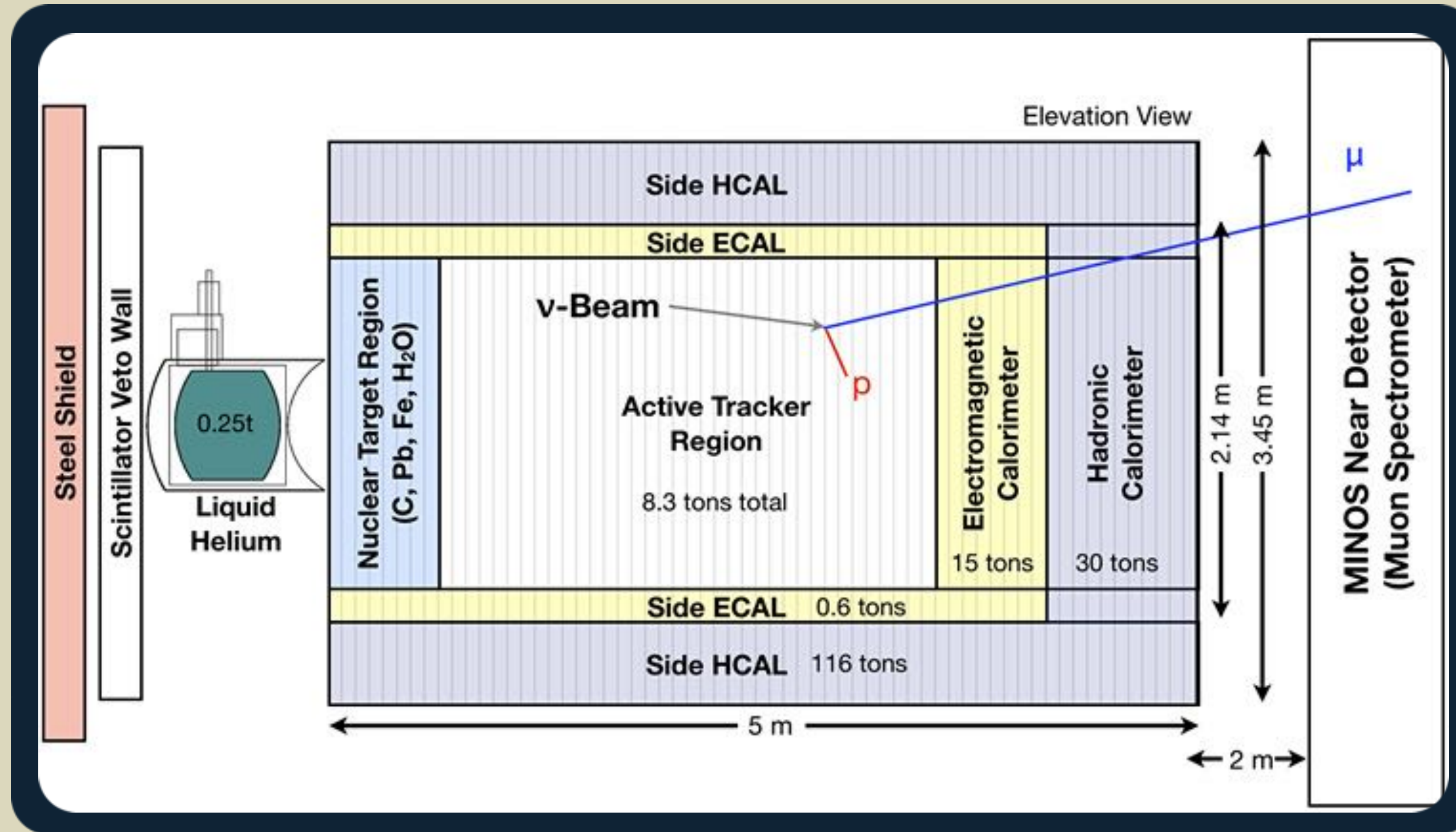
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While not the only thing ‘tuned’ or the only ‘style’ of tuning, some sort of ND adjustment is common for flux characterization (after measurement) and management of cross-section uncertainty in long-baseline oscillation physics.

Current Experiments, Detectors, and Status

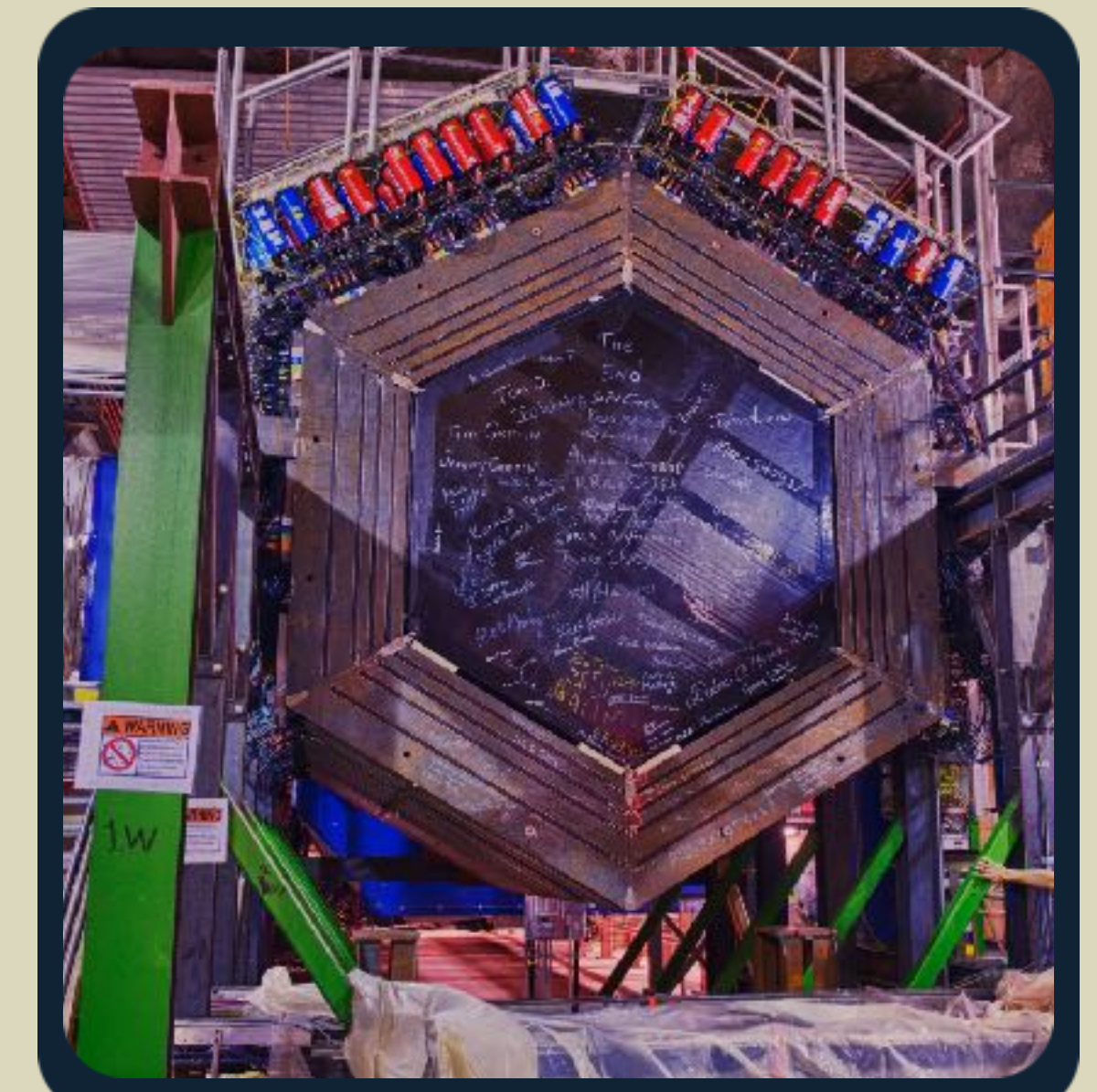
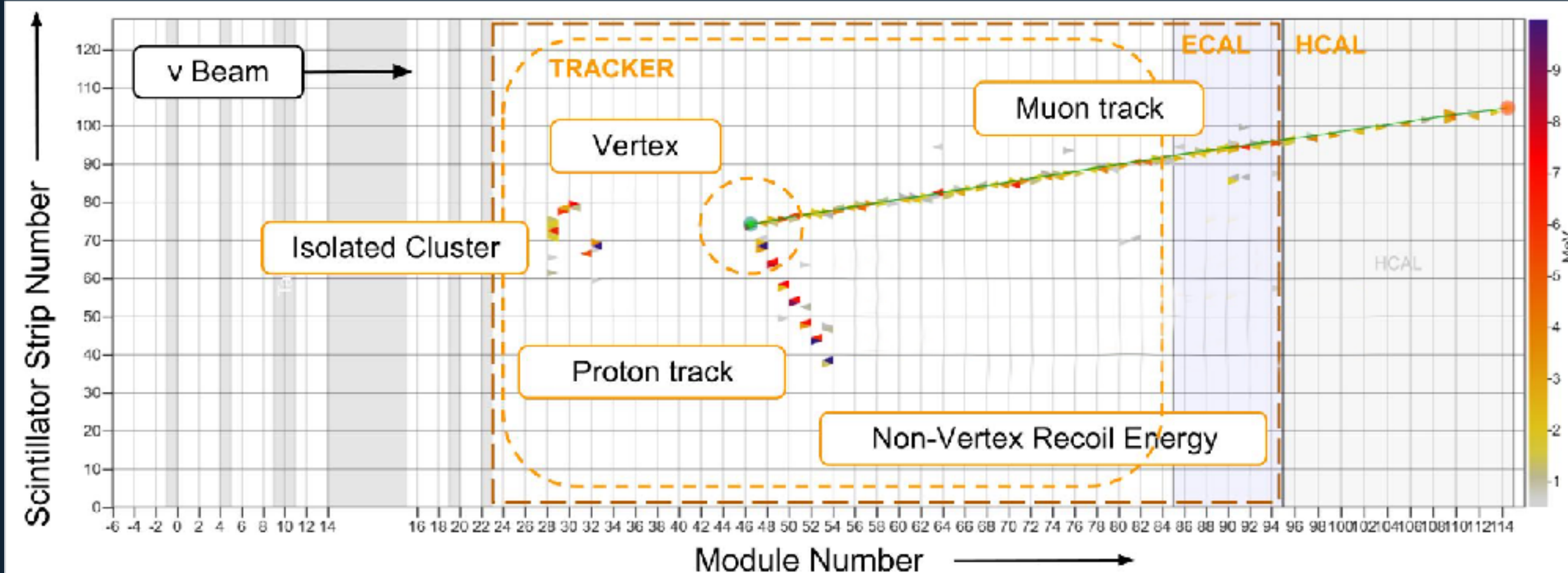
The Current Generation of Experiments: The MINERvA Detector



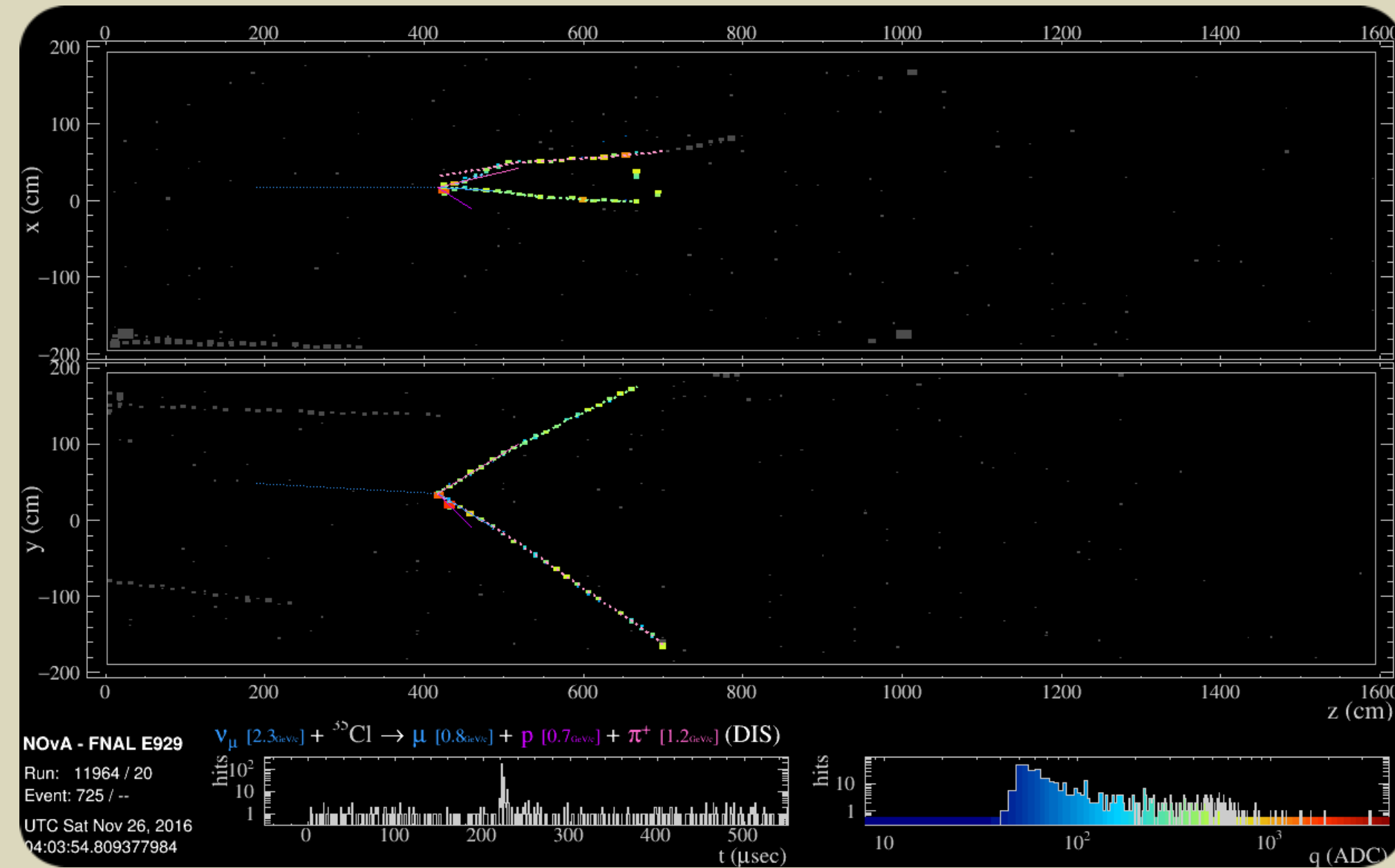
Highly segmented detector with multiple nuclear targets, designed to isolate individual nuclear effects.

- **Central Tracking** with 60 scintillator planes ~8.3 tons
- **ECAL** with Lead and Scintillator
- **HCAL** with Steel and Scintillator
- Carbon, Iron, Lead, Water, Helium targets all less than < 1 ton
- Two on-axis NuMI Beam Configurations

- ~3 GeV Peak
- ~6 GeV Peak

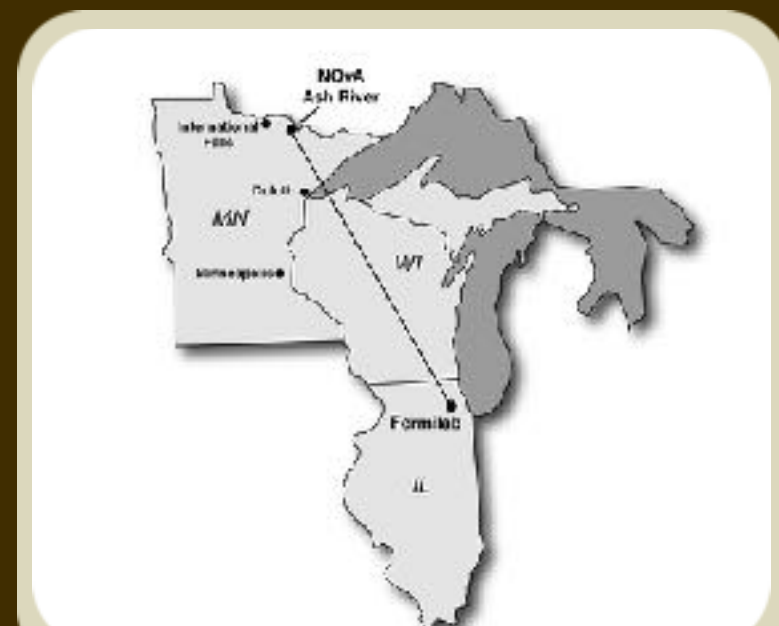
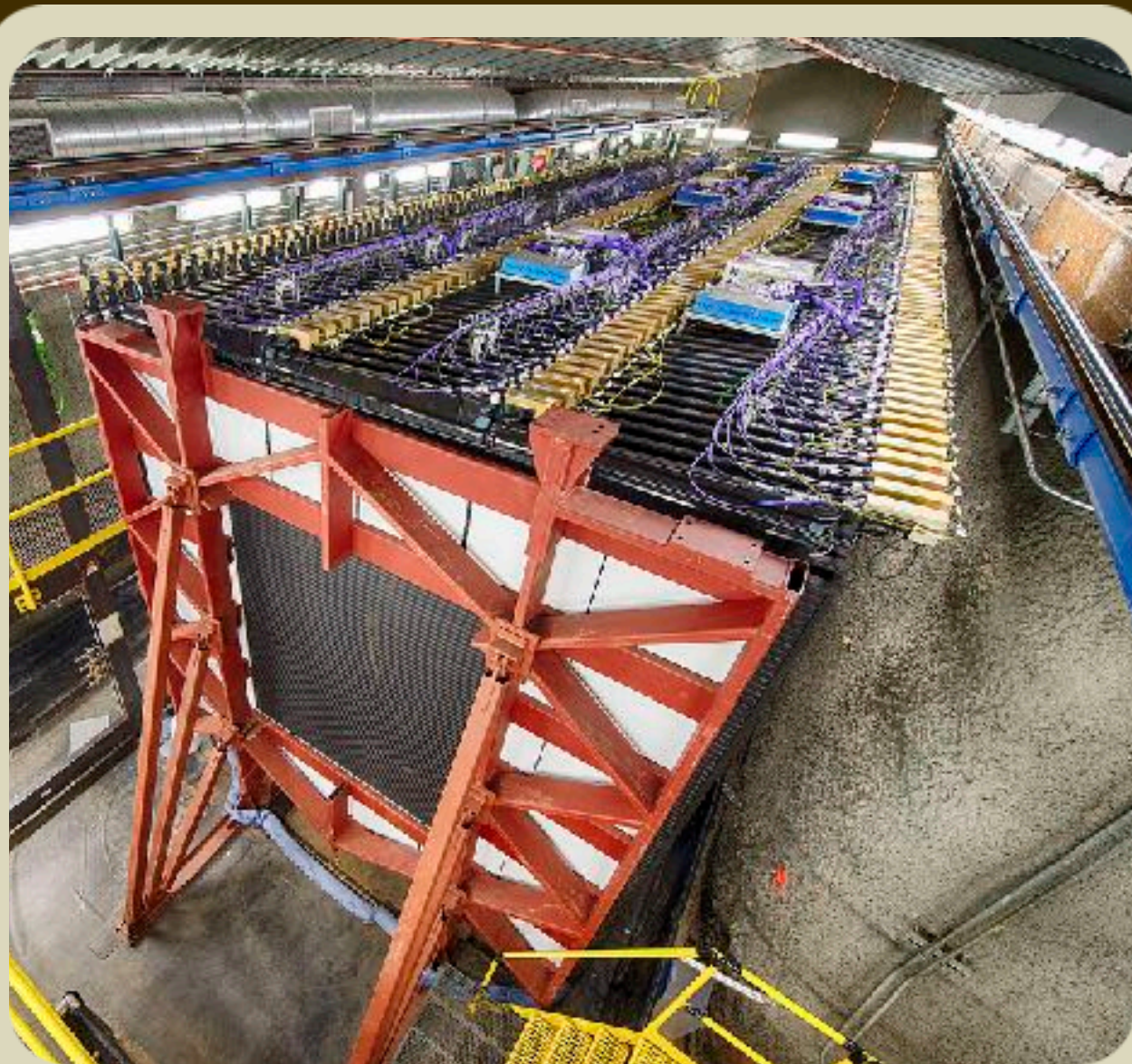


The Current Generations of Experiments: the NOvA Near Detector



Off-axis Near Detector that is functionally identical to the Far Detector, about 300 tons (193 tons fiducial) of liquid scintillator in PVC cells.

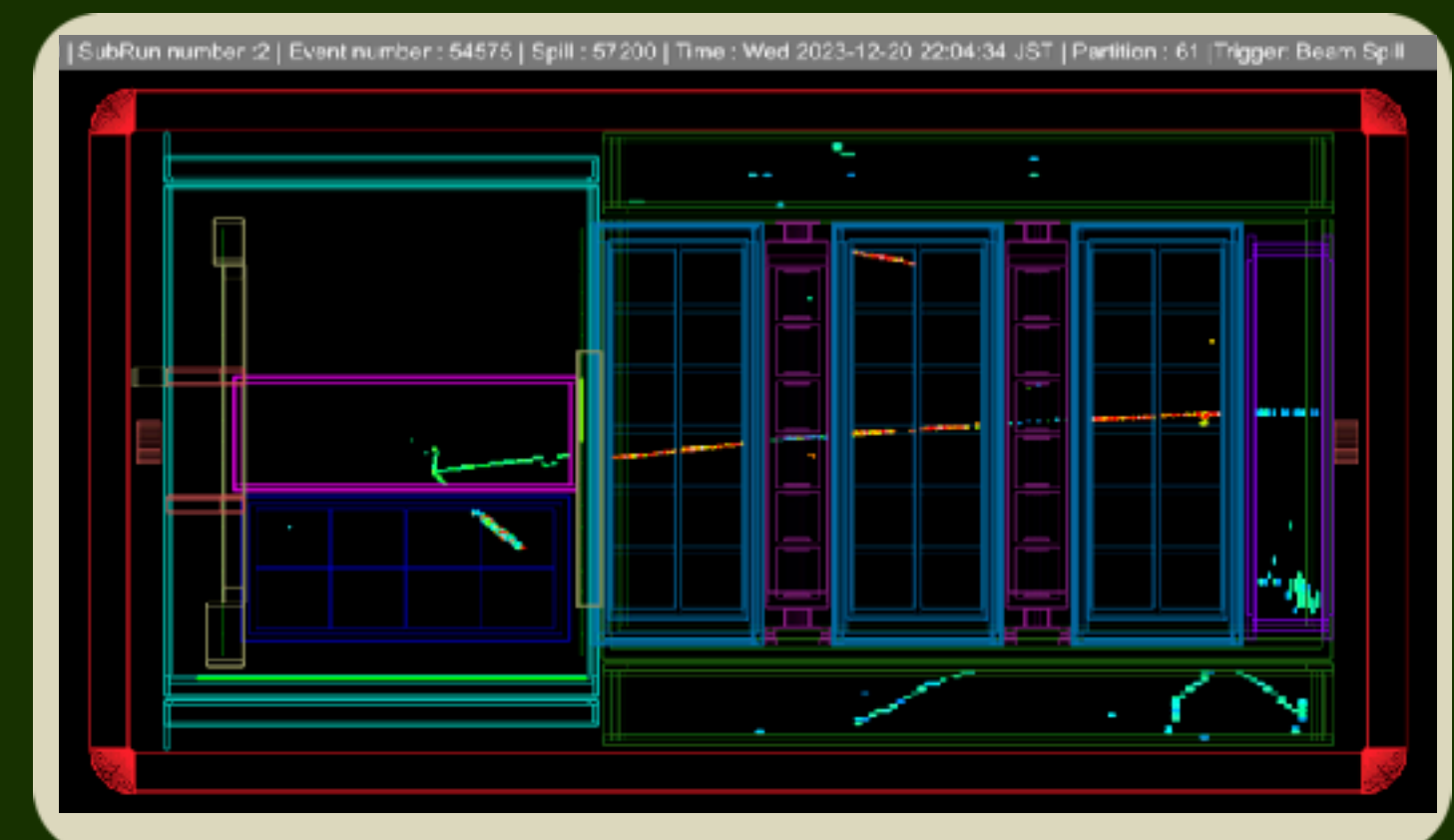
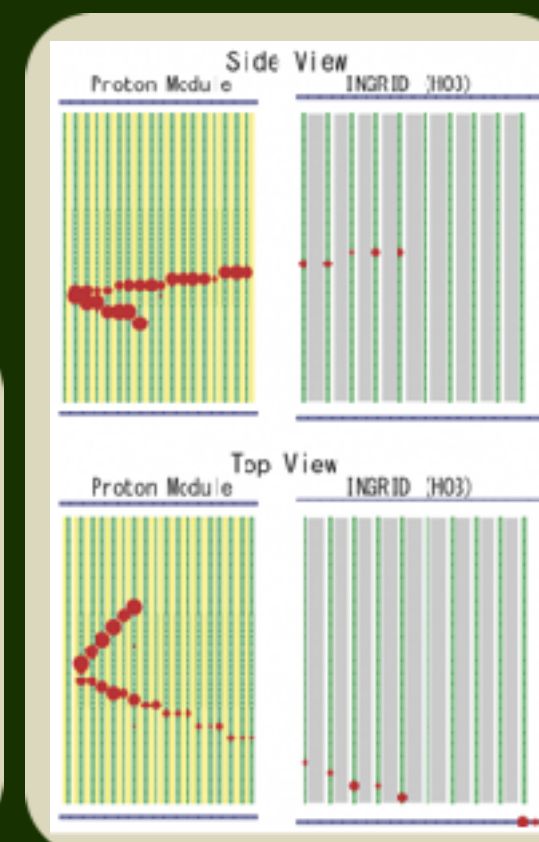
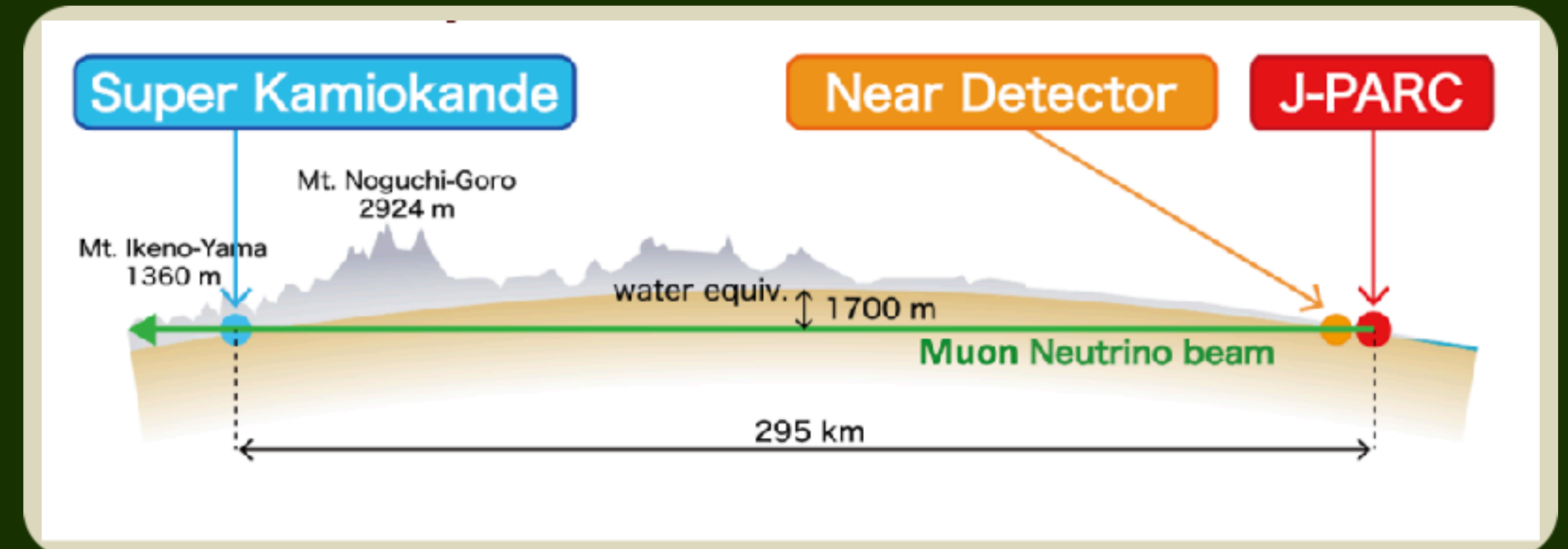
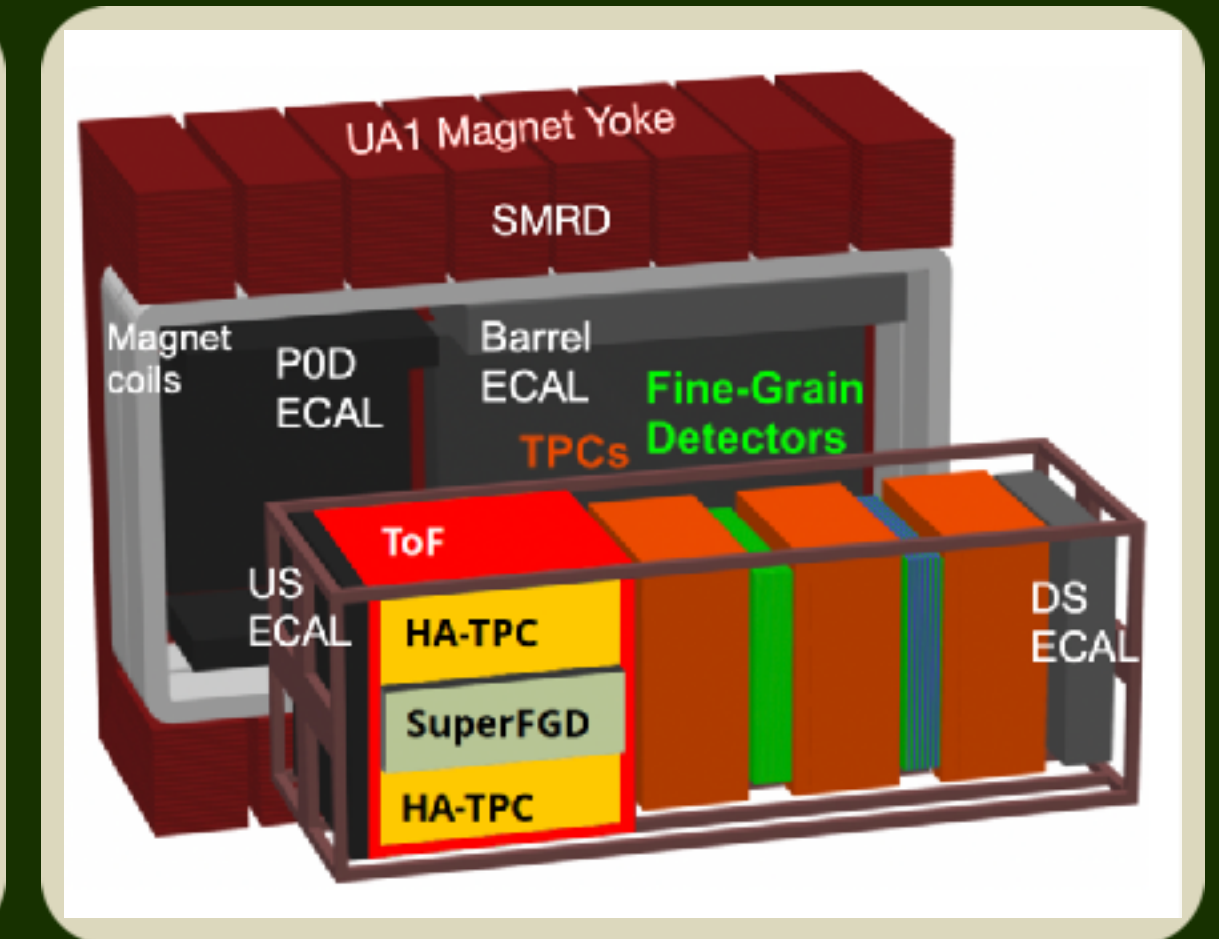
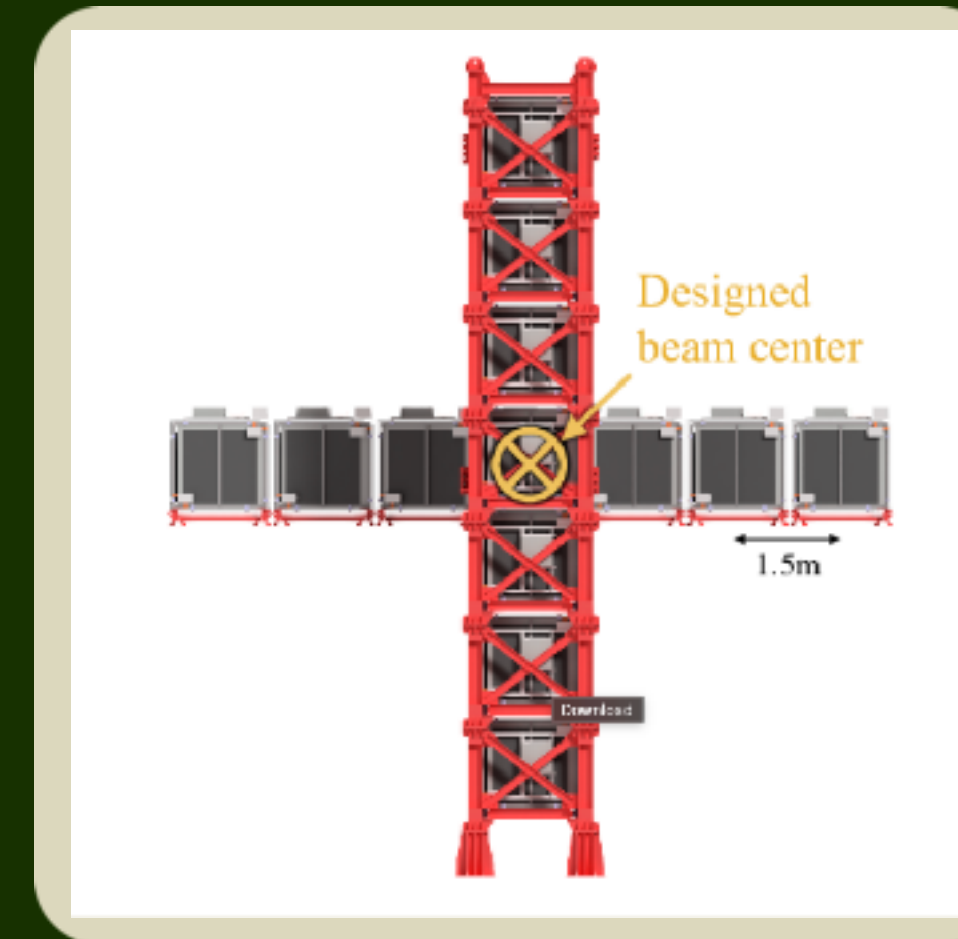
- ND is structurally similar to the FD
 - 4 cm $\times$ 5 cm cell size
- Primarily carbon target (about 60%), also composed of Chlorine, Hydrogen, Oxygen, Titanium
- 14.6 mrad Off-axis Neutrino and Antineutrino Beam, NuMI beam with peak around ~ 2 GeV
- 95% (93%) flux purity in (anti)neutrino mode, $\sim 1\%$ of $\nu_e + \bar{\nu}_e$ in both modes.



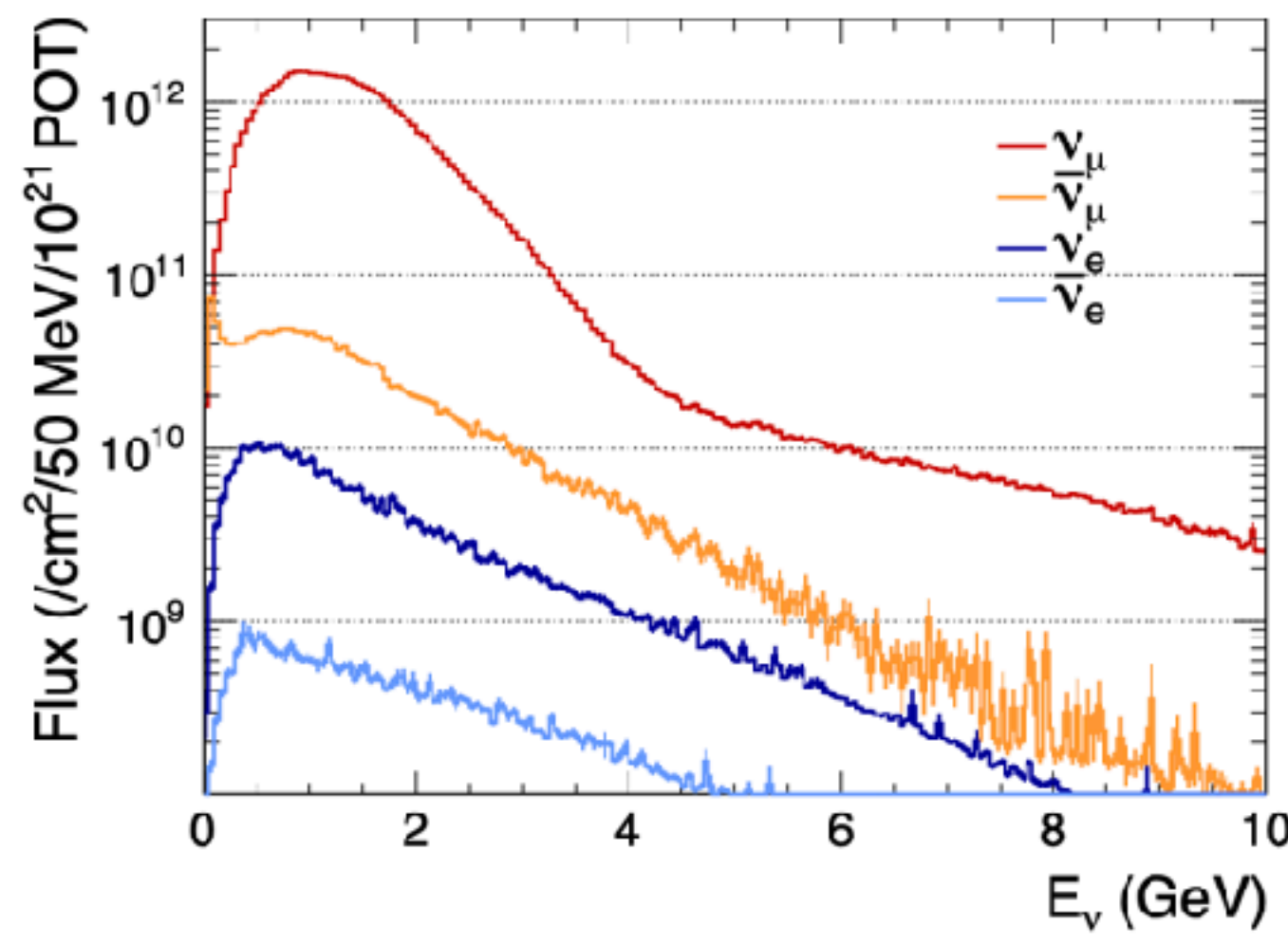
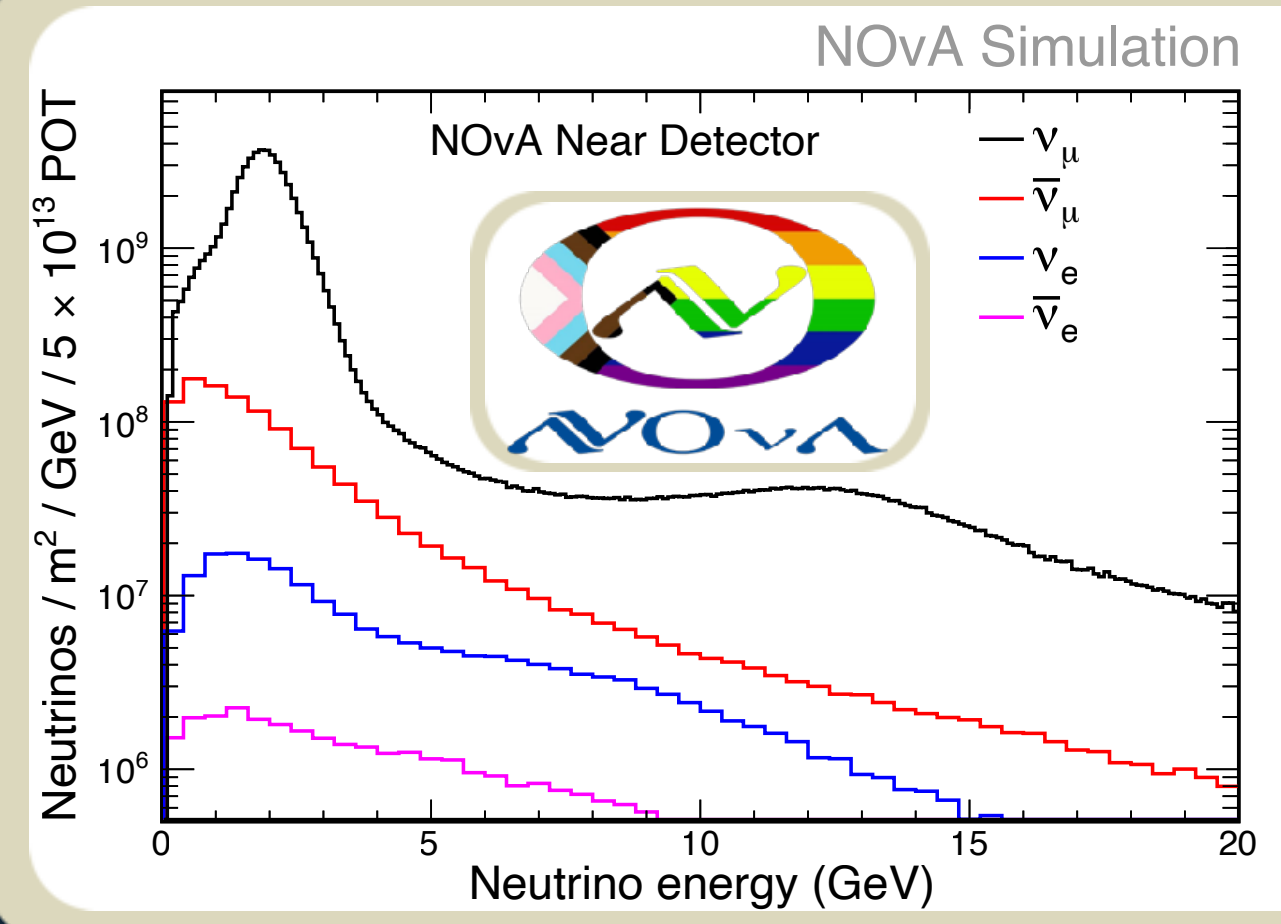
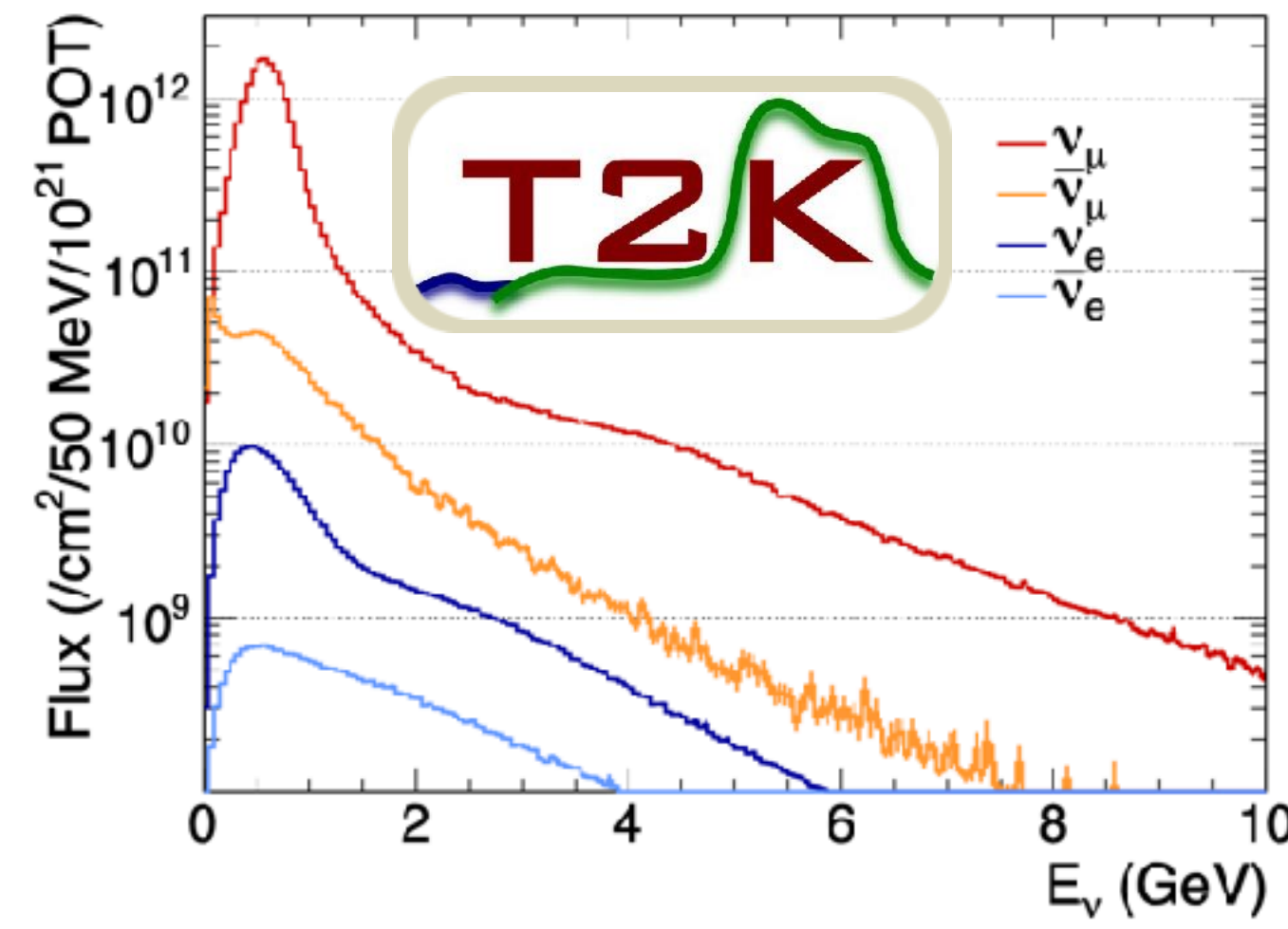
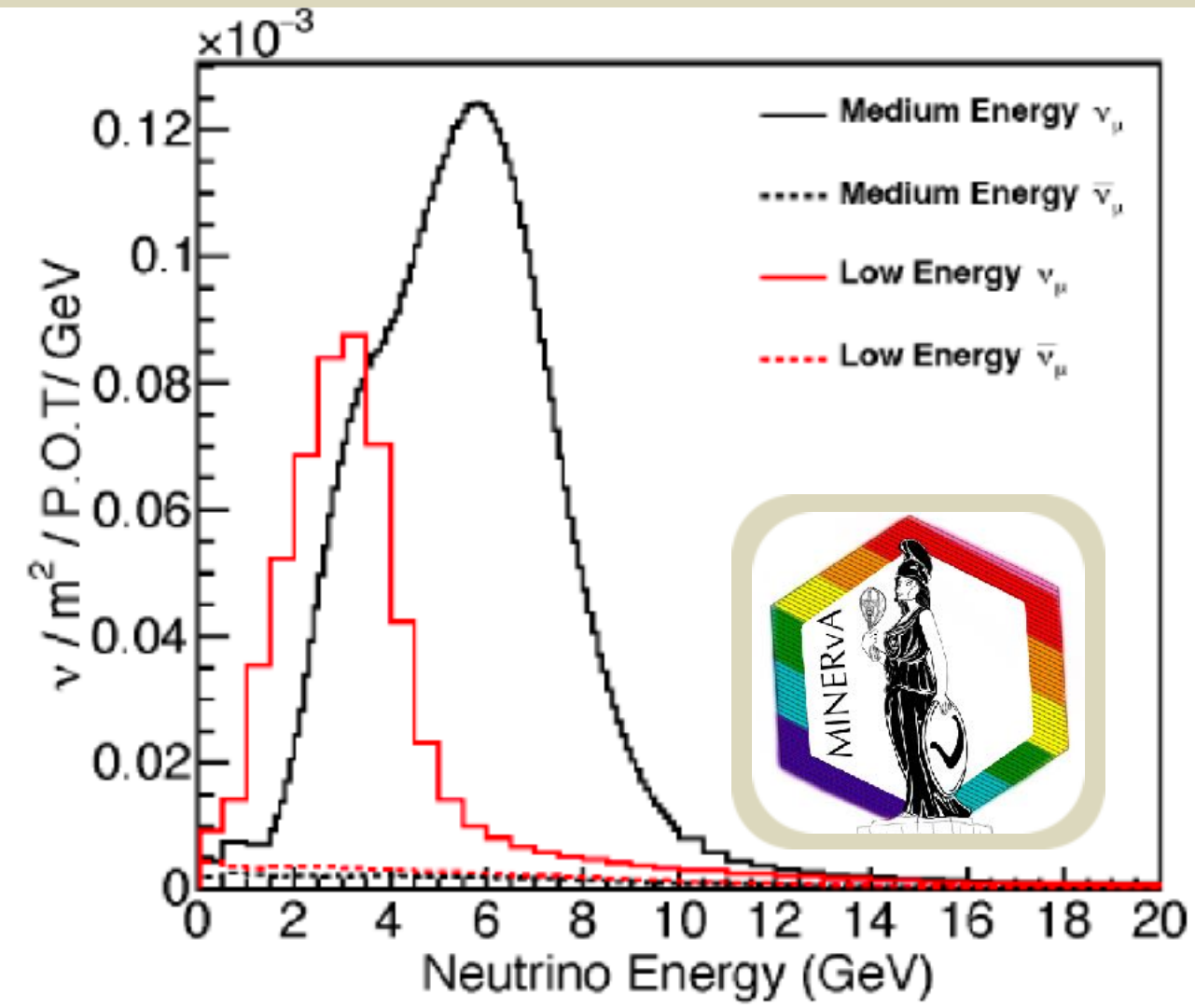
The Current Generation of Experiments: Tokai-to-Kamioka Near Detectors

Multiple Detectors exist:

- **INGRID- On-Axis**
 - 7.1 tons of iron target mass in each module->~100 tons
 - ~300kg in proton add on module full active scintillator
 - Average beam energy of 1.0 GeV
- **ND280 - Off-Axis**
 - Multiple detector subsystems servicing various functions.
 - Only Detector with a magnet
 - Average Beam Energy of 0.6 GeV at 2.5 degrees off axis
 - New Super FGD detector significantly improves tracking.
- **WAGASCI/BabyMIND**



Introducing the Experiments: Considerations of Flux



Flux is the dominant systematic in almost every measurement!

- MINERvA and NOvA share the NuMI beam!
- MINERvA has two independent flux constraints from previous measurements.
- T2K has on-axis and off-axis service, with INGRID serving as a beam monitor.
- JPARC flux onstrained with input from NA61/SHINE

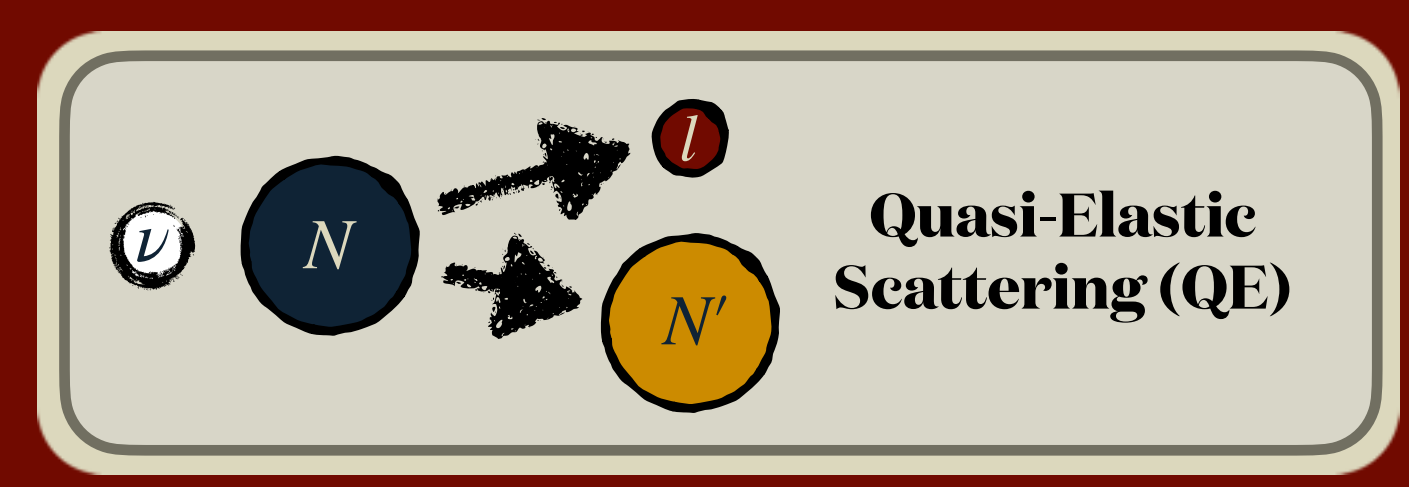
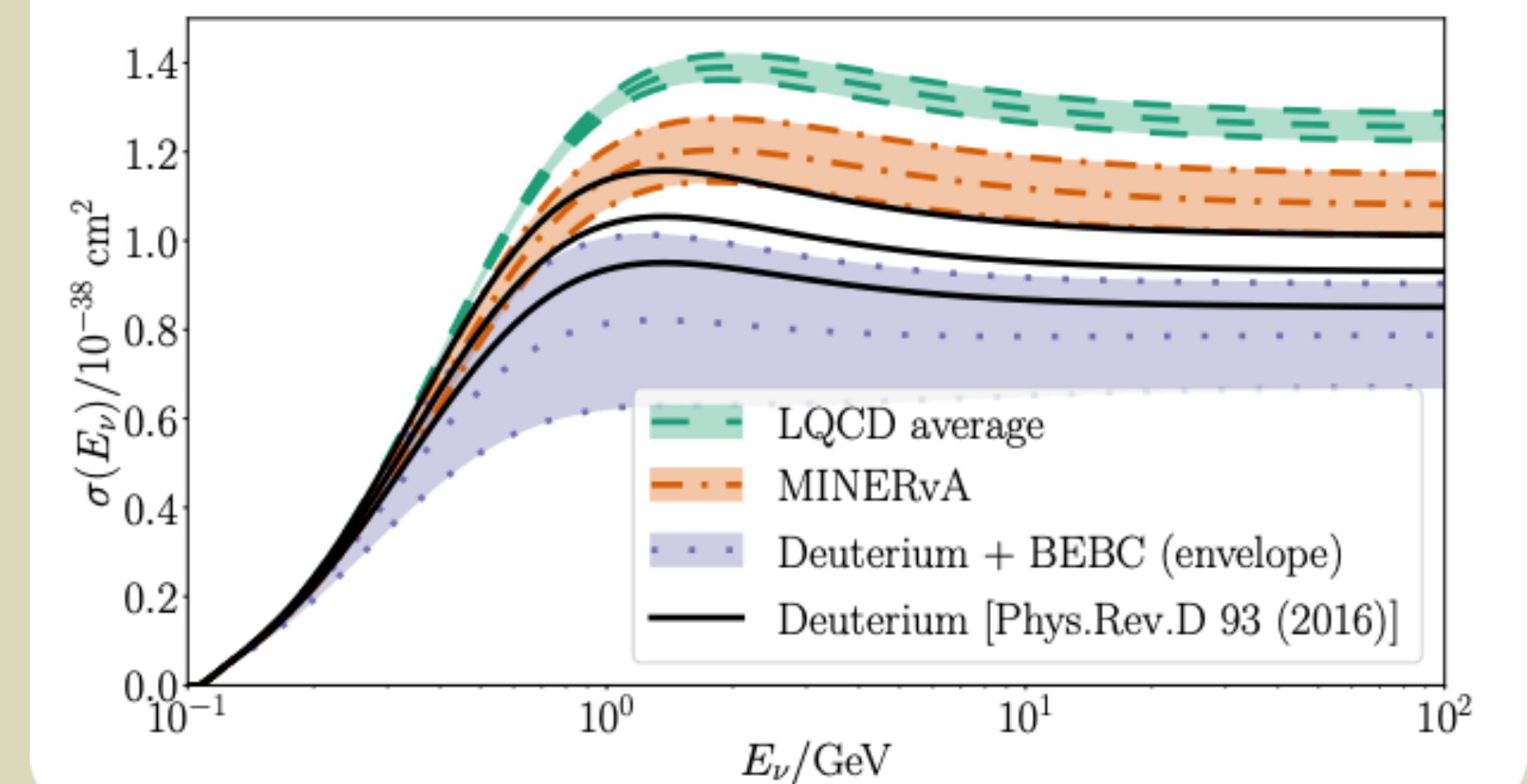
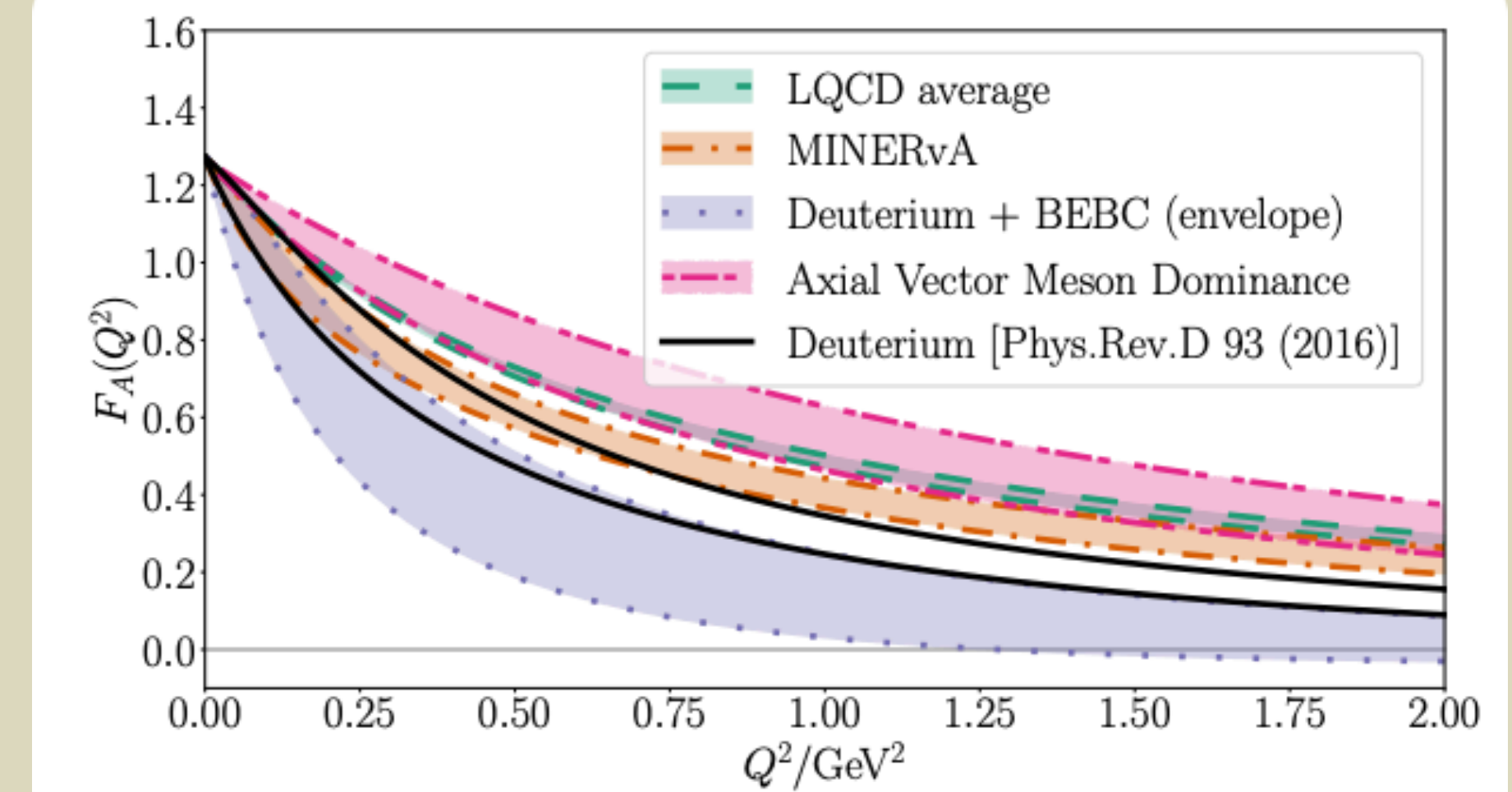
Quasielastic Measurements

New Hydrogen Results from MINERvA

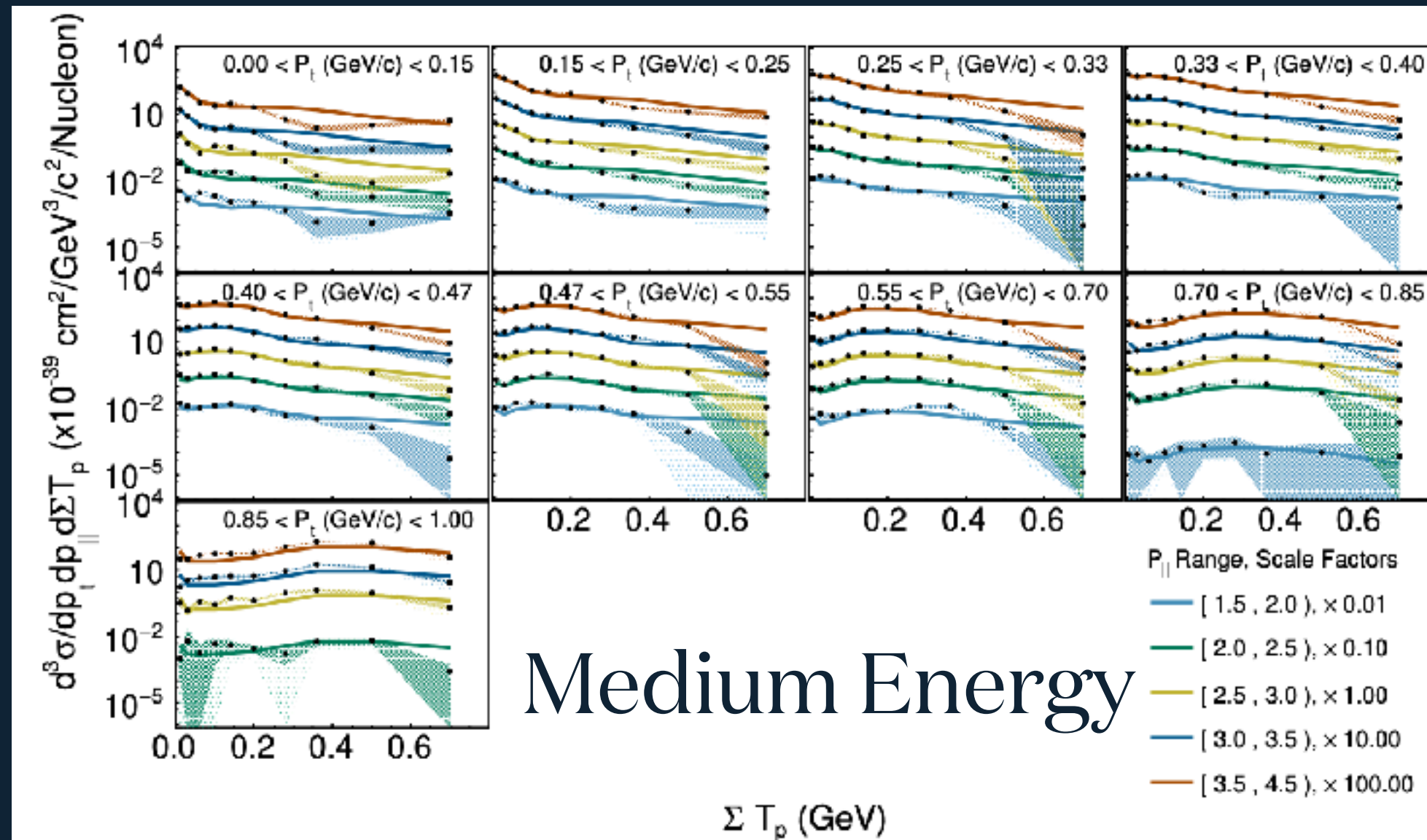
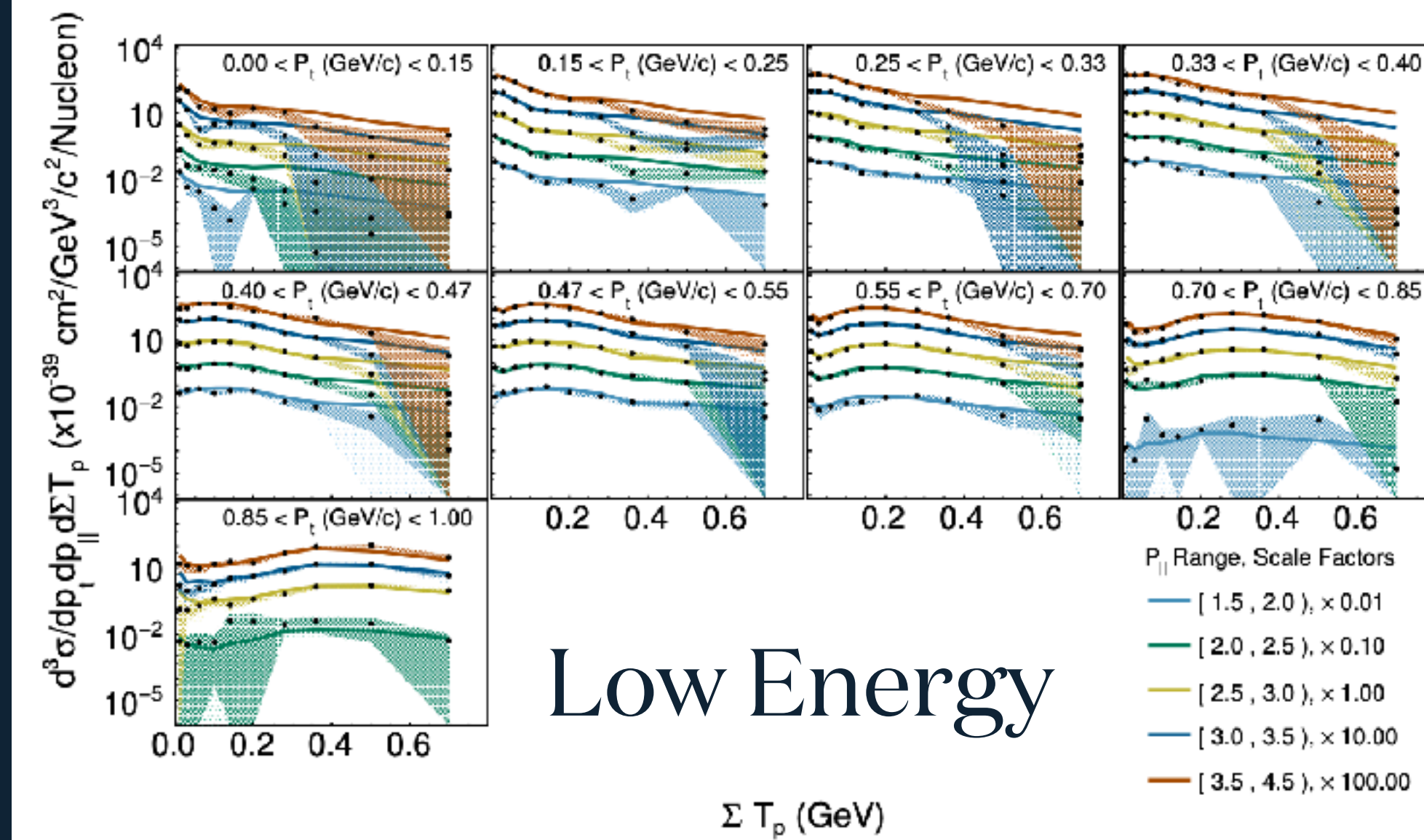
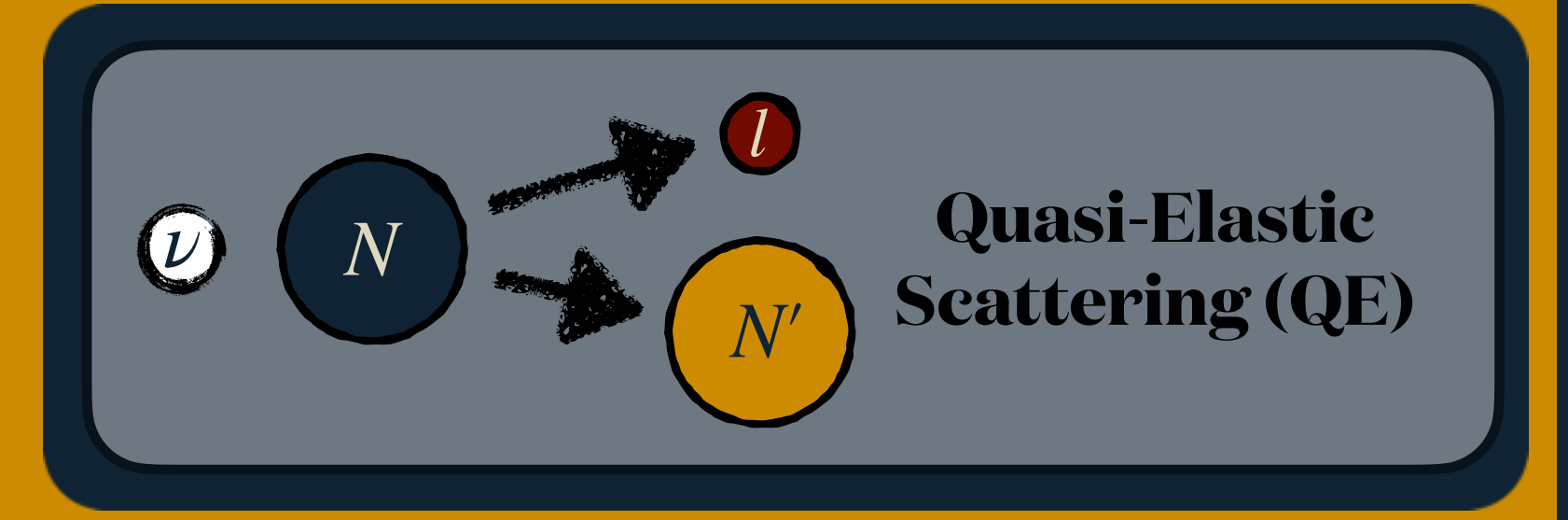
Lattice QCD extension of $\bar{\nu} + H$ measurement from 2023

- Original measurement had calculations for the nuclear axial form factor but used a different form of regularization!
- New calculation extends measurement with Deuterium measurement from old bubble chamber data, LQCD shows **disagreement with old Deuterium Bubble Chamber Data**.
- Critical takeaway here are the comparisons between hydrogen and deuterium, which suggests one cannot comfortably be extended to the other!
- Paper suggests **dropping Deuterium from future tuning exercises!**

Preprint: [arXiv:2512.14097](https://arxiv.org/abs/2512.14097) (Dec 2025)



New Quasi-Elastic-like Scattering Result from MINERvA



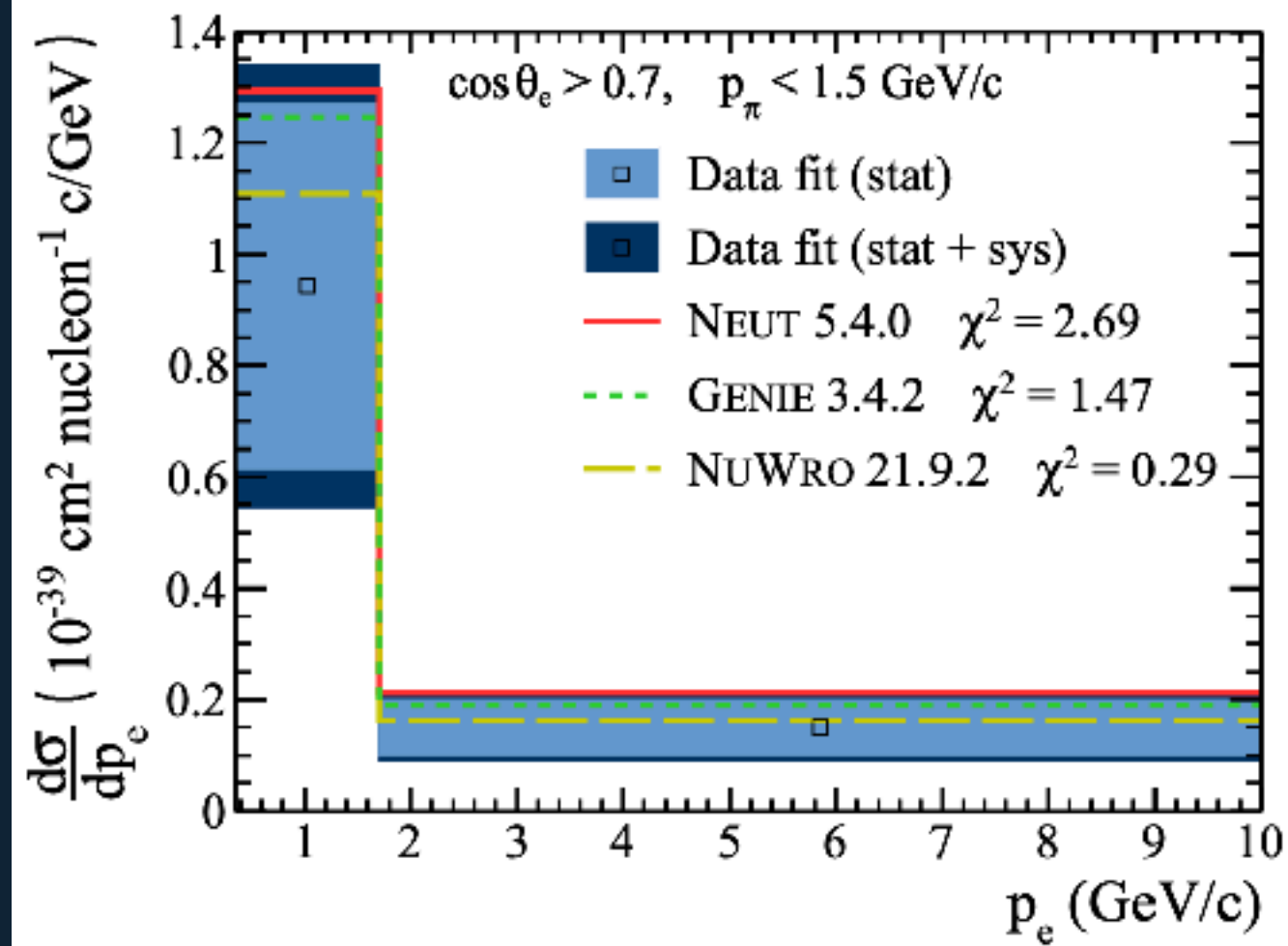
Triple differential cross-section measurement with simple signal topology but across both energy ranges, differential in lepton kinematics and hadronic energy.

- General agreement in the majority of comparisons across both energies despite large discrepancy at high hadronic energy.
- **No generator accurately reproduces the low lepton transverse momentum shape. (Not Shown)**
- Mismodeling persists across beam energy in similar ways as lepton longitudinal energy, suggests mismodeling in energy transfer.

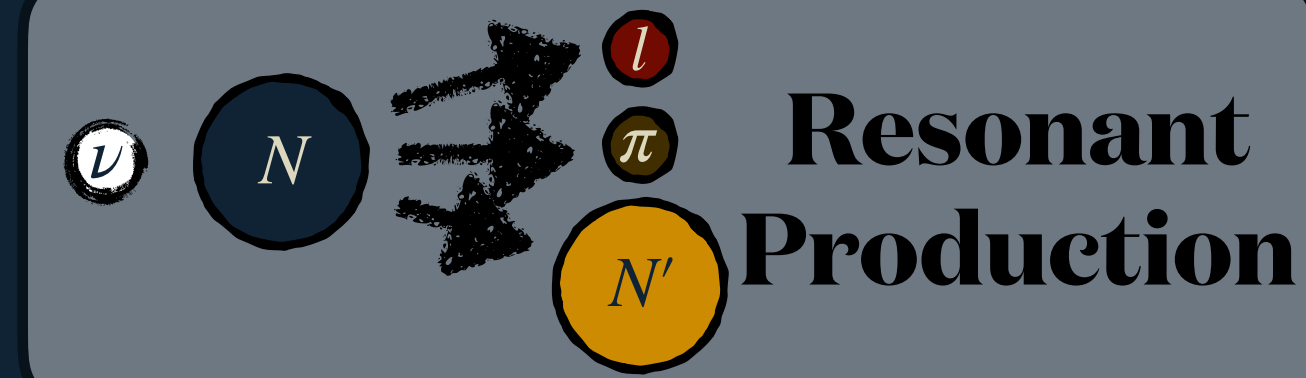
Preprint: [arXiv:2606.00745](https://arxiv.org/abs/2606.00745) (May 2026)

Resonant Production & DIS Measurements

New T2K Results on Charged Single Pion Production From ν_e on Carbon

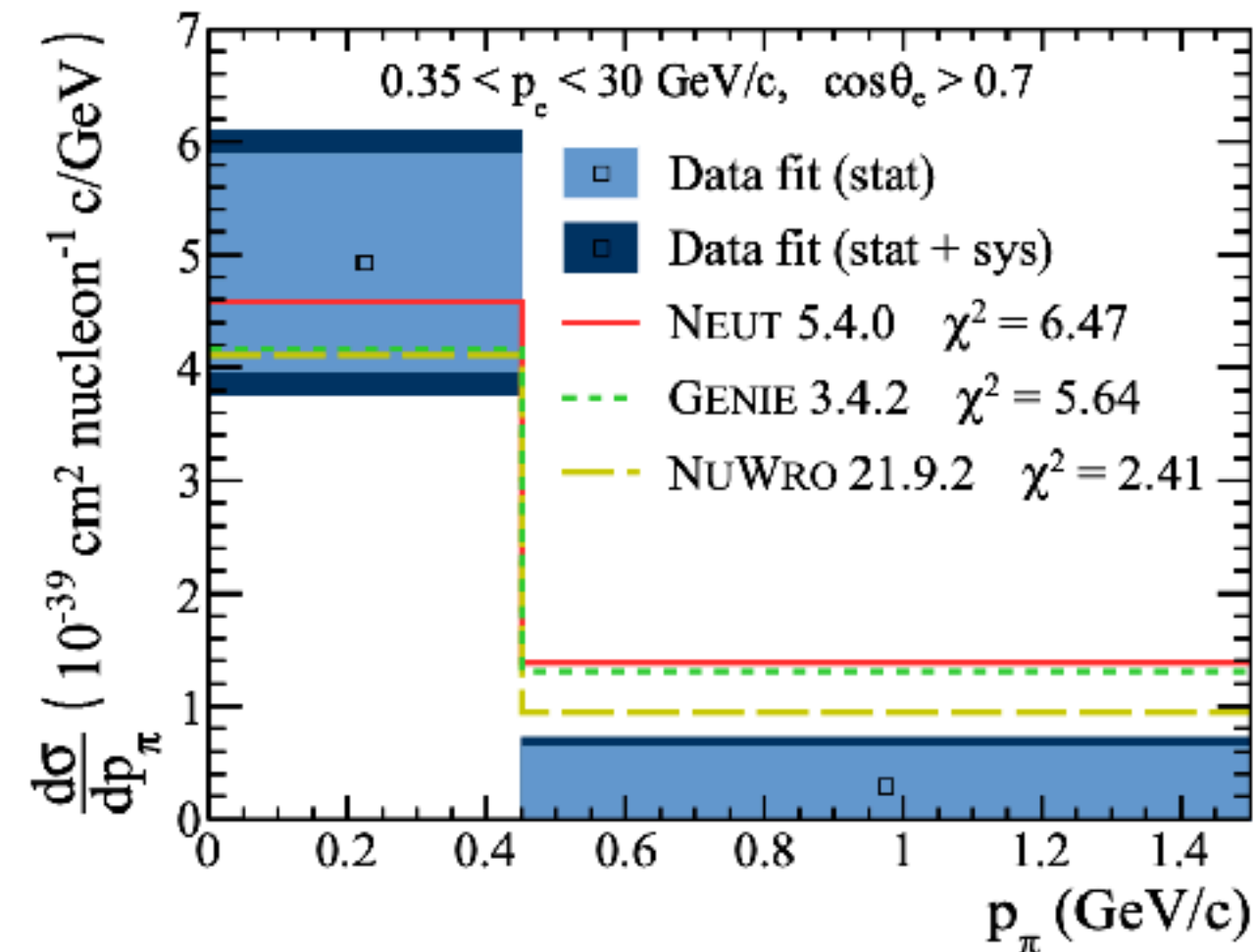
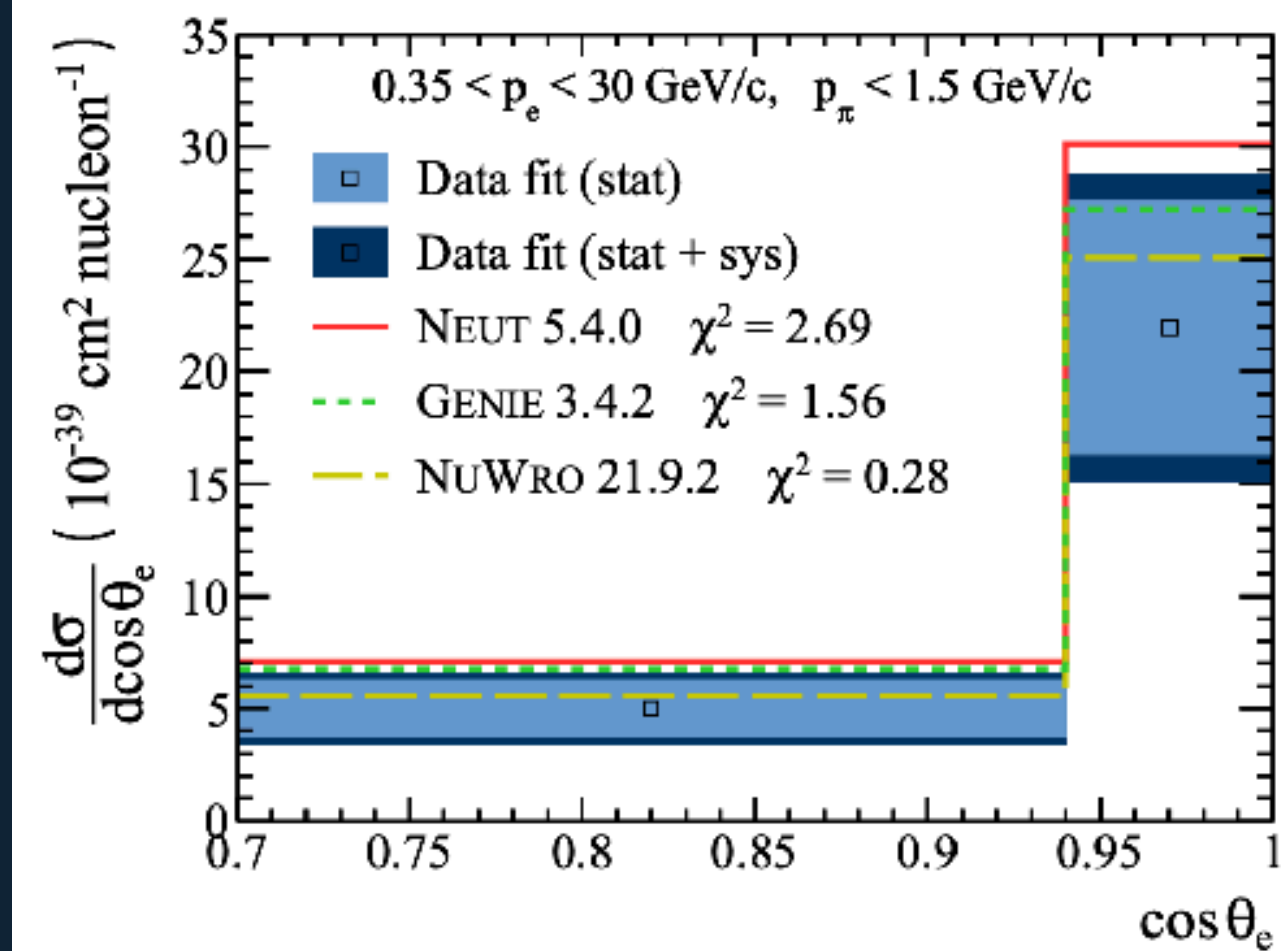


Phys. Rev. Lett. 135, 151802 (Oct, 2025)



First exclusive cross-section with electron-neutrinos on Carbon from T2K on ND280!

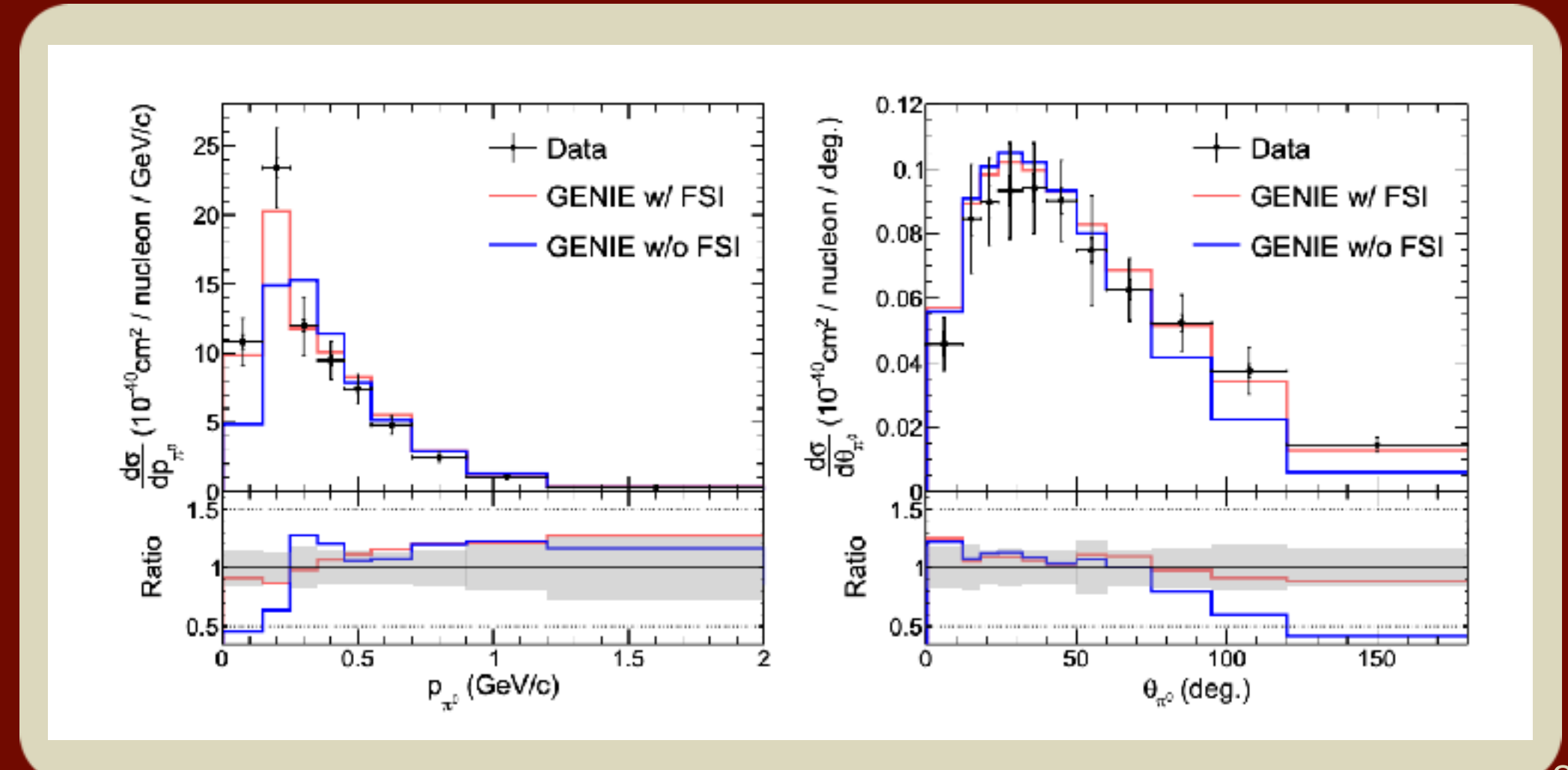
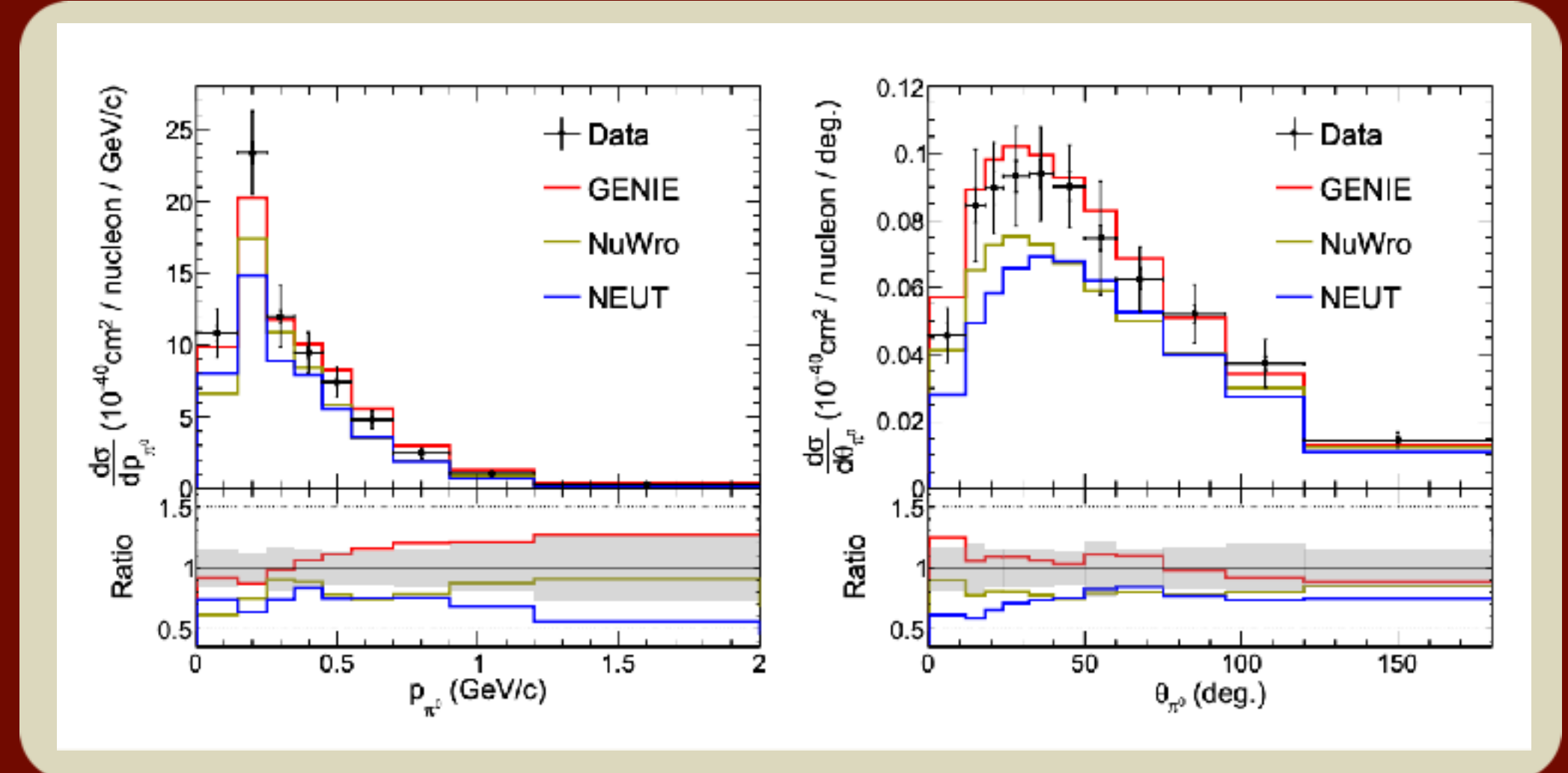
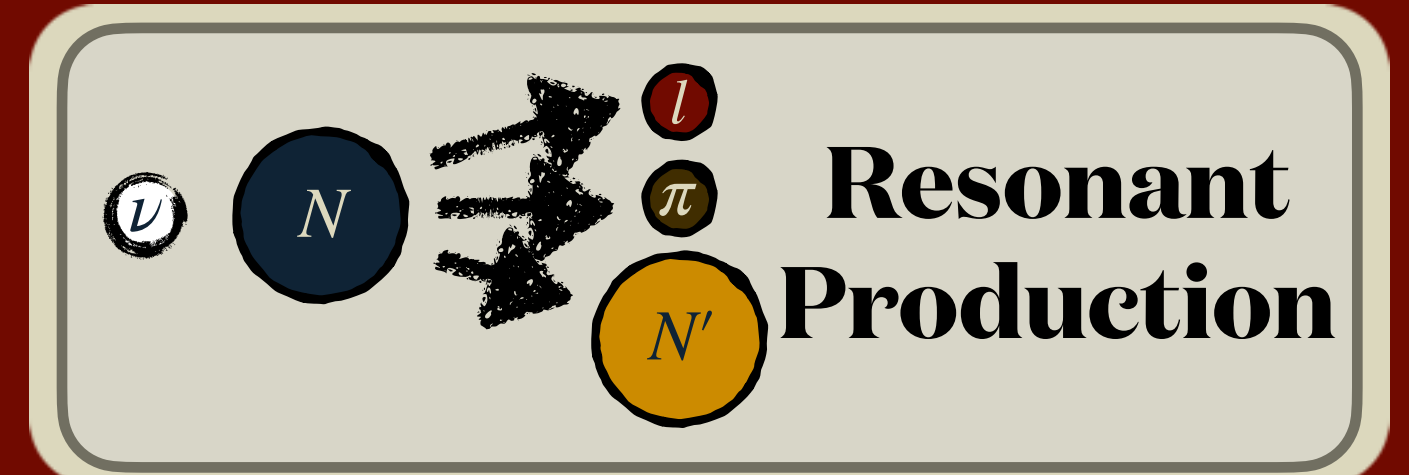
- Phase space is restricted to lepton momentum of $>0.35 \text{ GeV}$ to avoid contamination from neutral pions, **differential in electron and pion momentum and electron angle**
- All tested generators, NEUT, GENIE, and NuWro over predict by $0.5\text{-}1.6\sigma$.
- Biggest source of systematics is multipion contribution, tests of FSI suggests different mechanism from similar measures.



Latest Charged Current Neutral Pion Results from NOvA

The latest of a handful of neutral pion measurements in NOvA, due to ease of observing electromagnetic showers. Differential in muonic and hadronic variables.

- Primarily anti-neutrino beam!
- $6 \times$ improvement on statistics from last MINERvA result on this particular channel.
- Analysis shows good agreement with GENIE, reduced $\chi^2 < 1$ in most regions.
- **Of particular interest is the necessity of good FSI!** Without FSI:
 - Low energy is not well described
 - High angle > 90 degrees is not well described

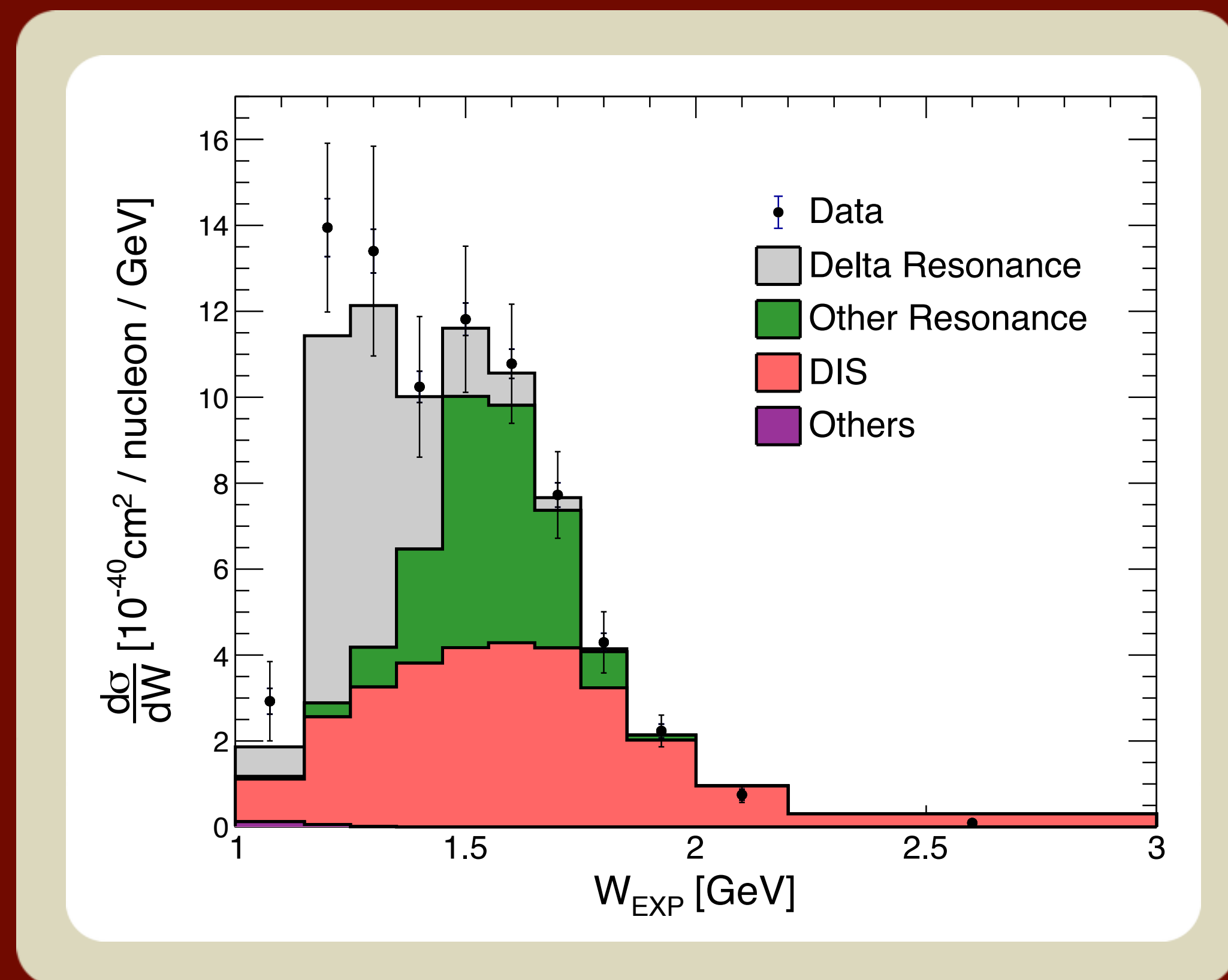
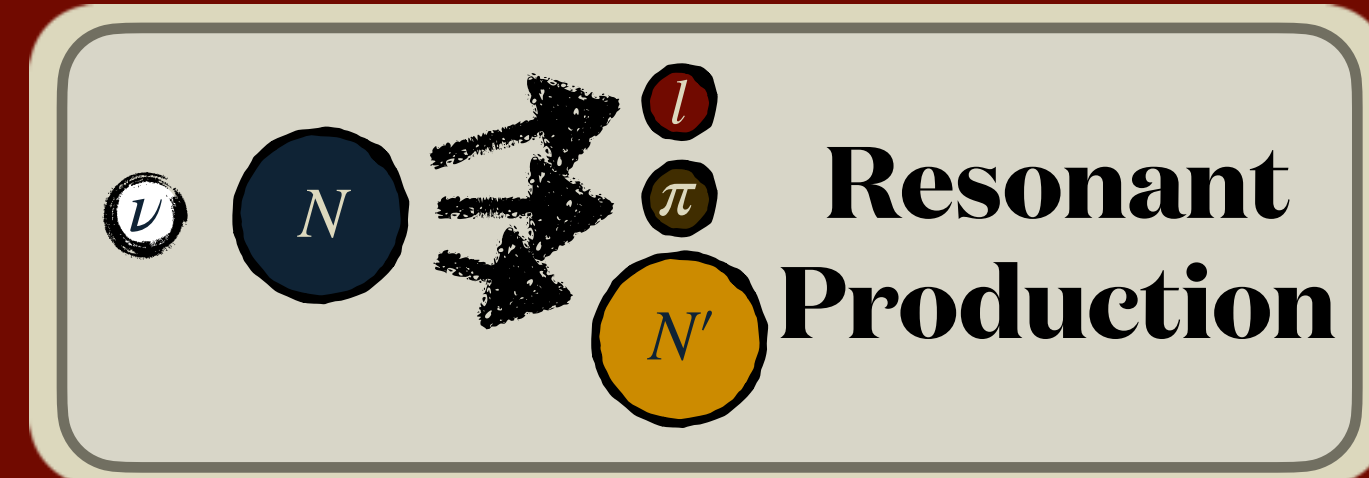


Phys. Rev. D 113, 112008 (June 2026)

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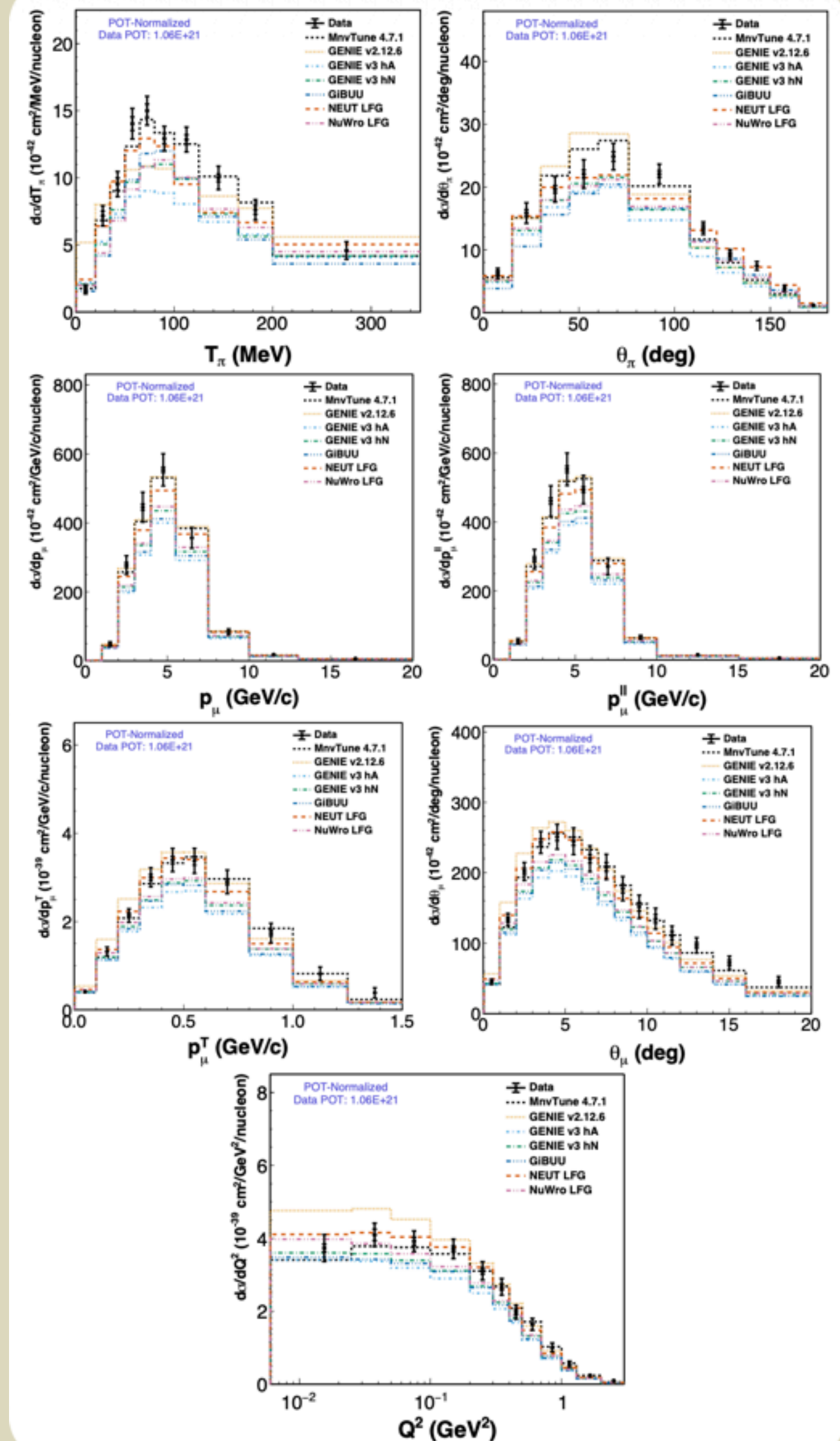


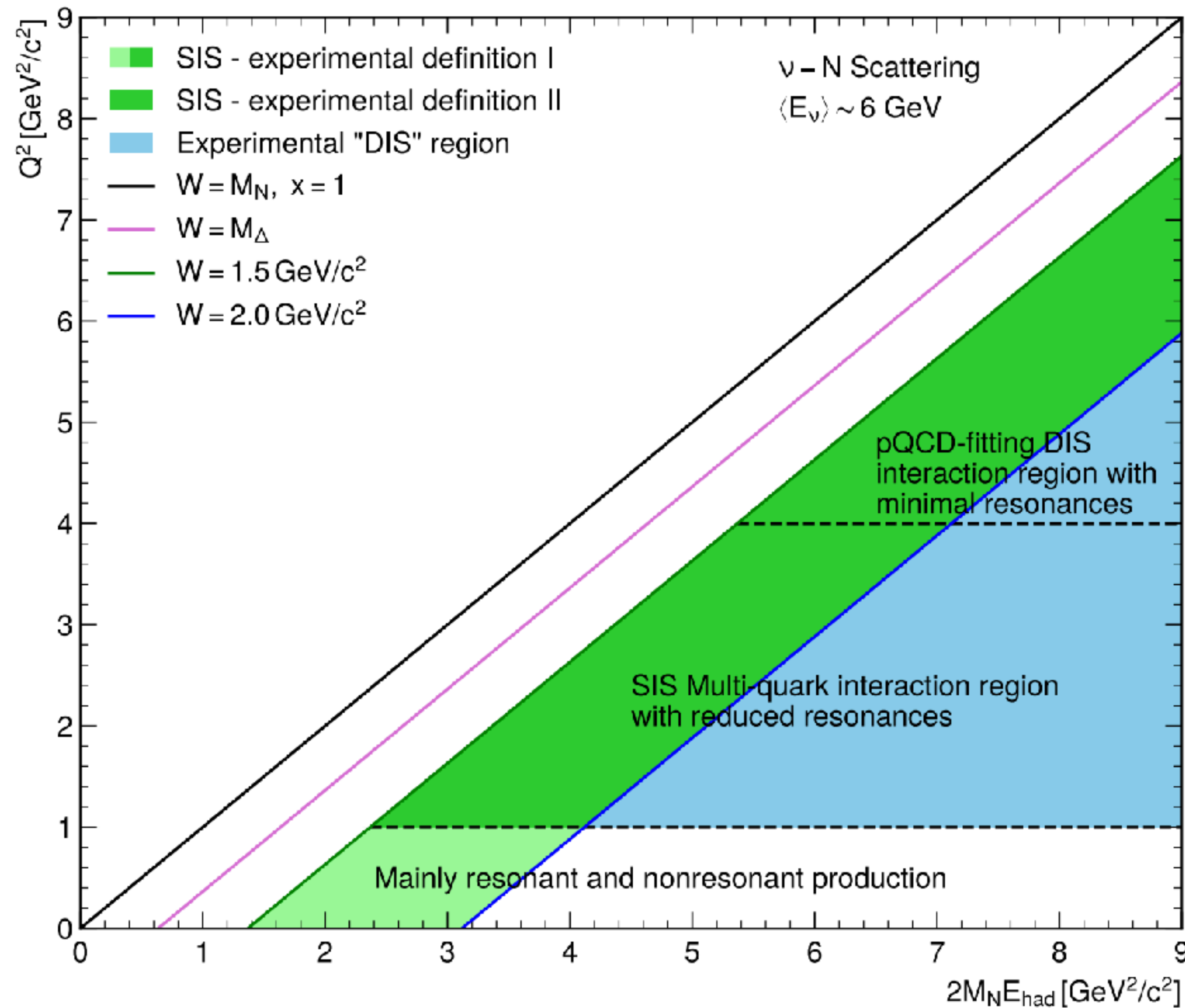
New Results on Charged Single Pion Production From MINERvA

Single differential charged current production of a single pion, *but for first time with no threshold on pion energy!*

- Medium energy beam, GENIEv3 does the best overall but no generator does best overall. ***Required new MINERvA Tune...***
- Sample constructed from track based reconstruction but also includes Michel decays
- General agreement at the edges of phase space, but 10-20% disagreement from modern generators in the bulk.
- Hadronic variables show worse agreement than leptonic.
- All models do okay with Q^2 , but under predict at higher bins.

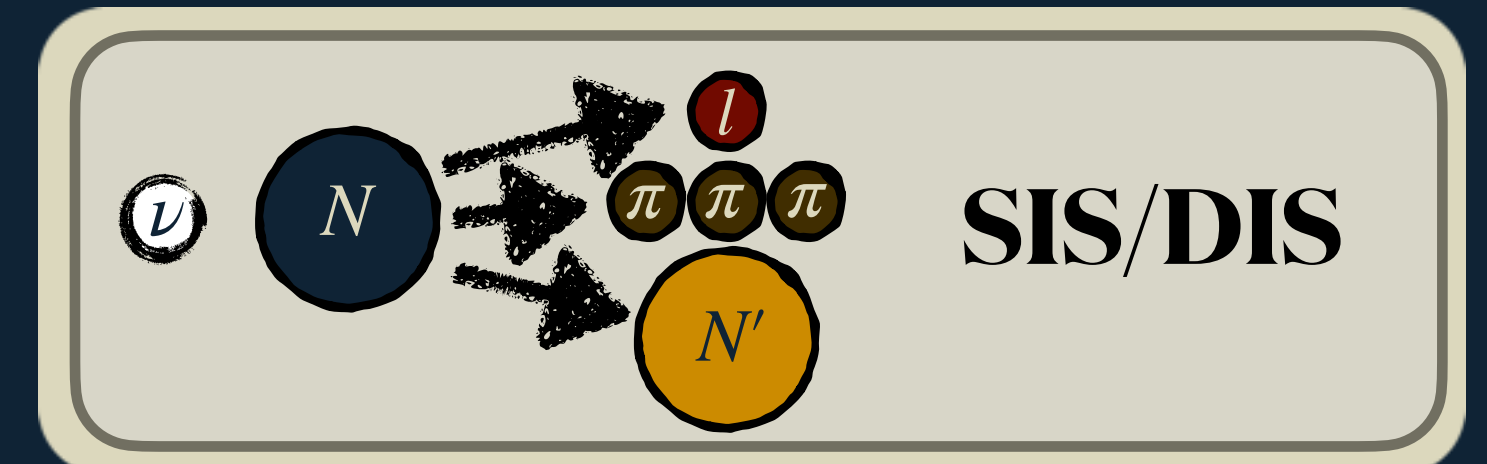
Preprint: arXiv:2605.24224 (May 2026)



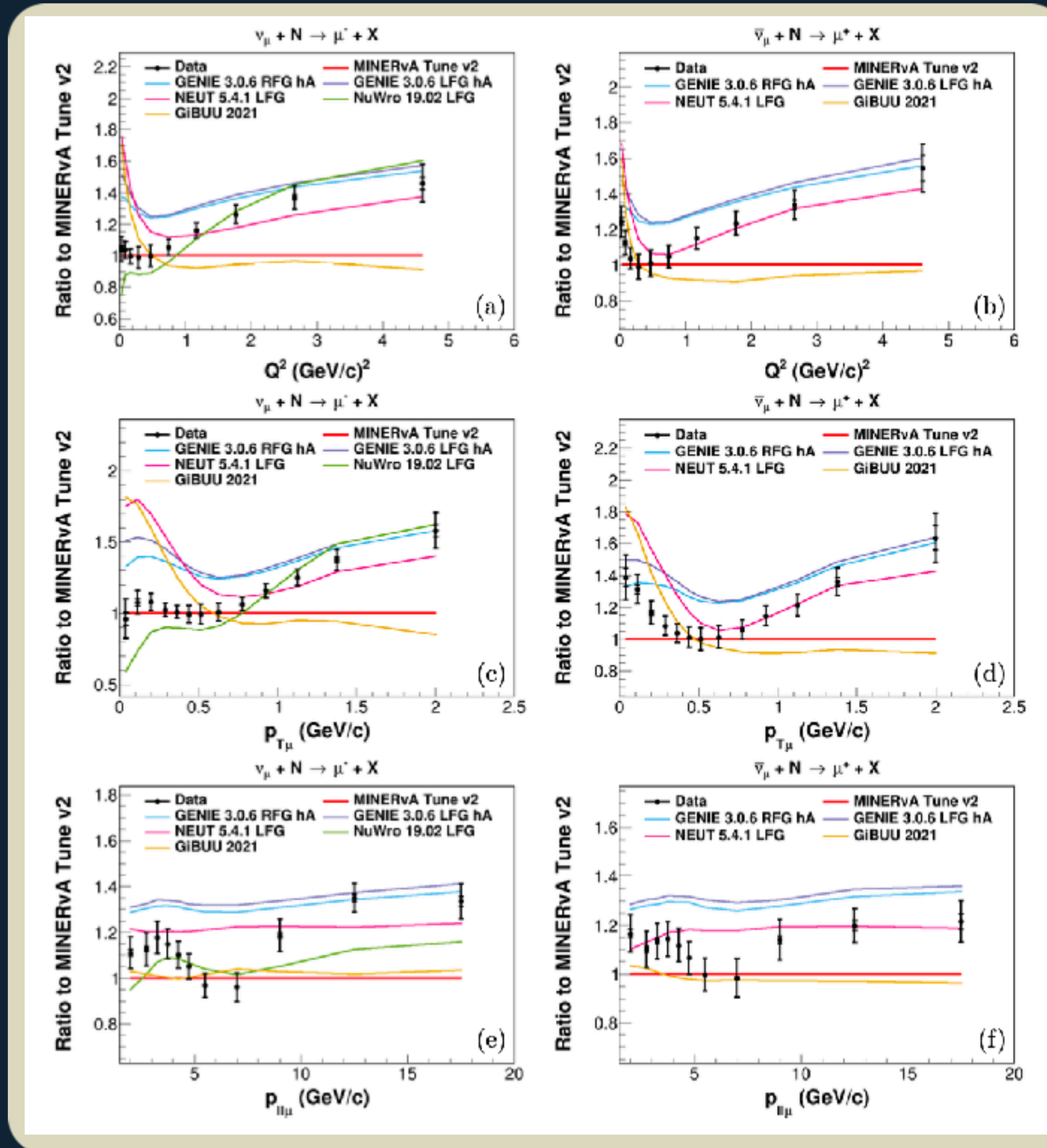
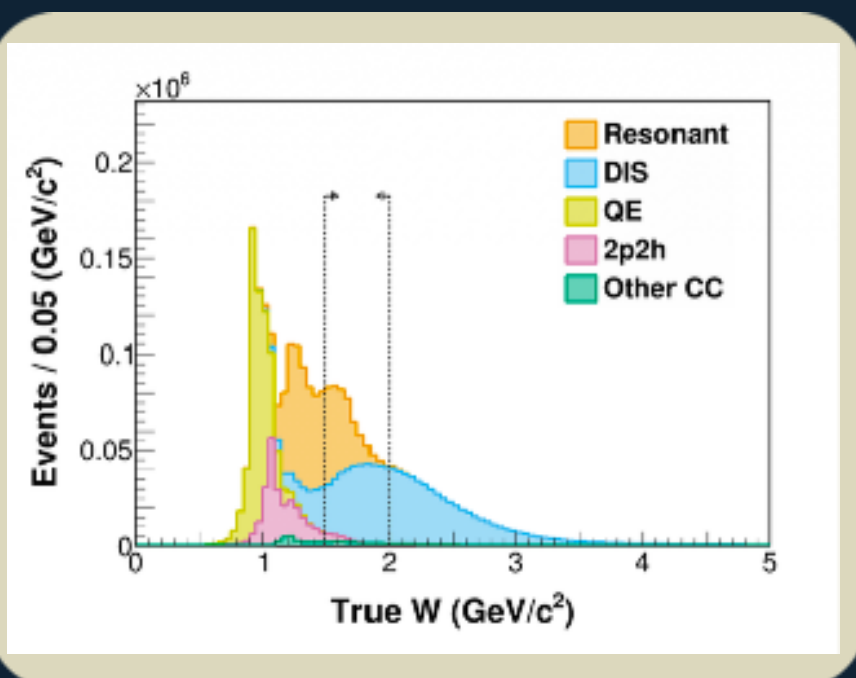
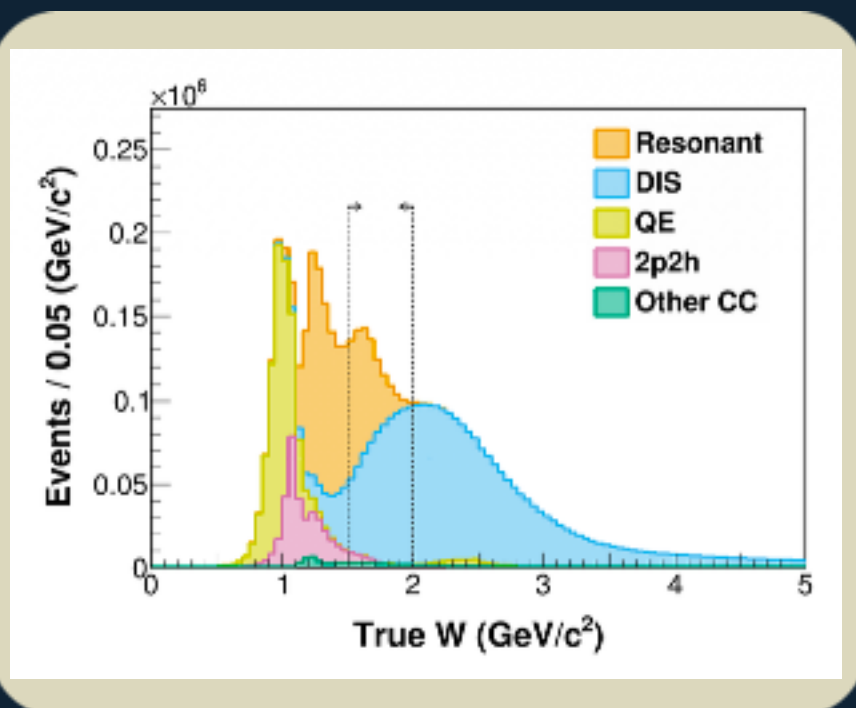


Deliberate probe on transition region from Resonance to DIS *through the SIS transition region. Pioneering Work!*

- Differential in lepton kinematics.
- All signal events have W between 1.5 and 2.0 GeV
- Variations in Q^2 define the more Resonance-like (>0 GeV) or DIS-like (>1 GeV) regions.

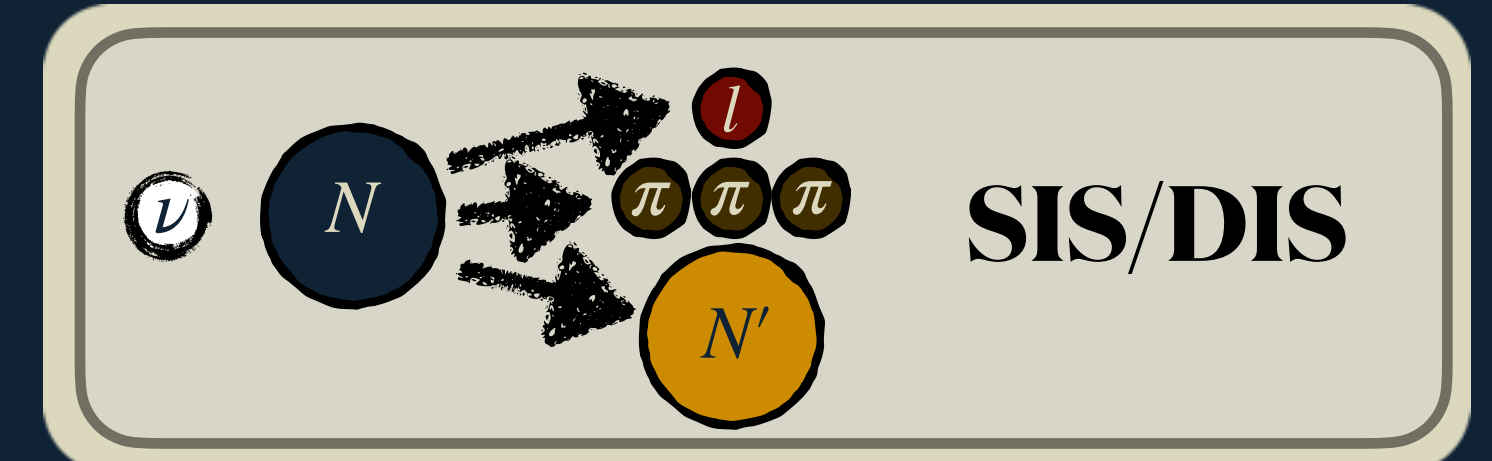


Region I

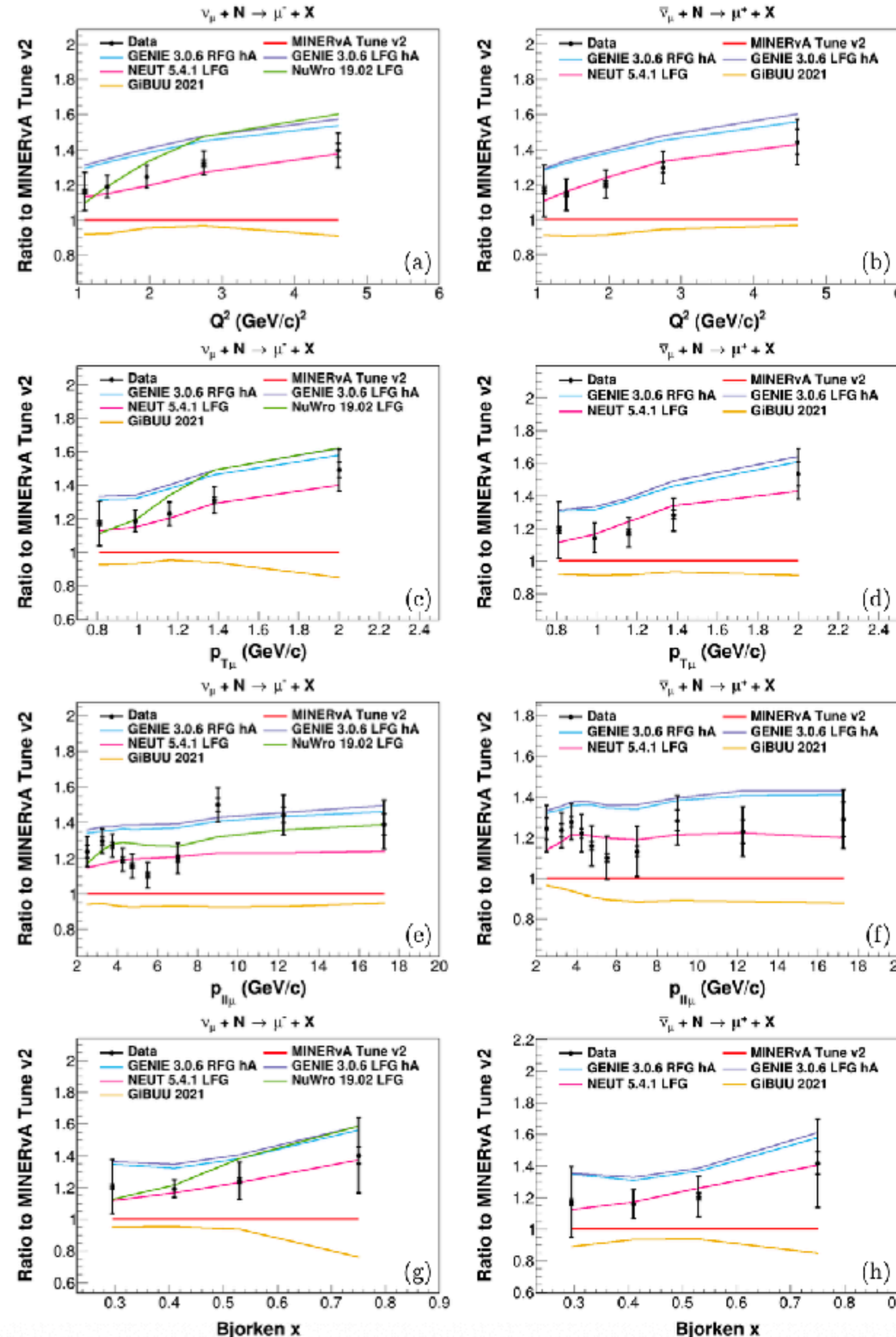
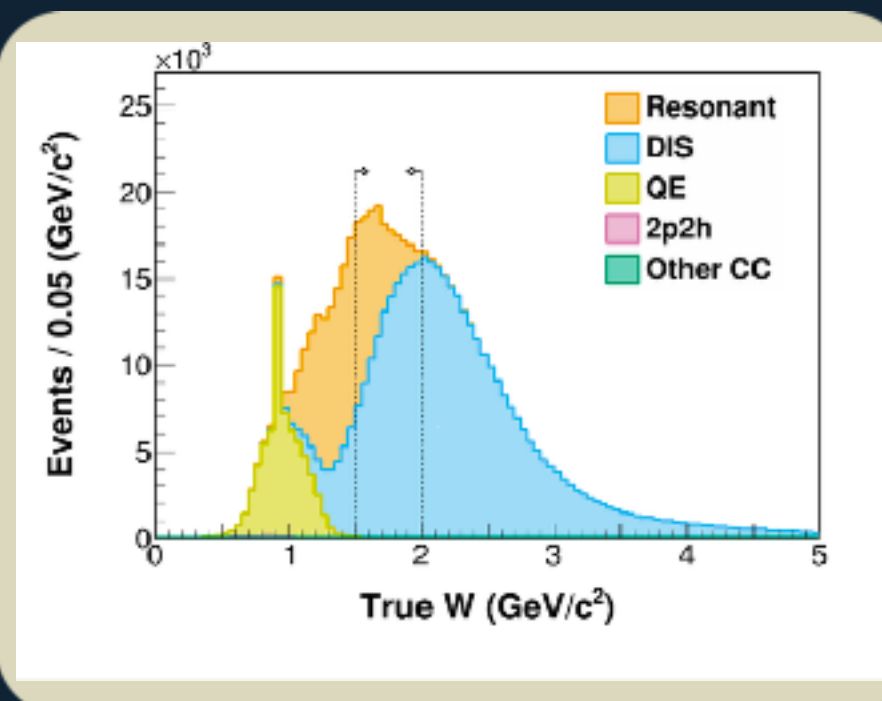
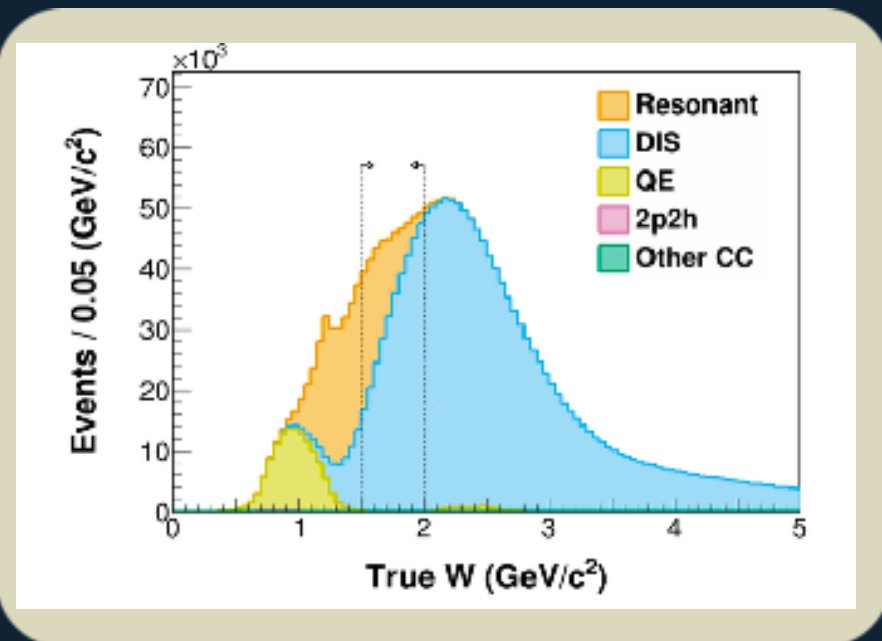


Deliberate probe on transition region from Resonance to DIS *through the SIS transition region. Pioneering Work!*

- Region I ($Q^2 > 0$ GeV) shows no real preference for any particular generator...
- Critical takeaway is that the resonance region with input from other models struggle to define physics at low- Q^2
- Lepton kinematics vary until higher energy/momentum regions

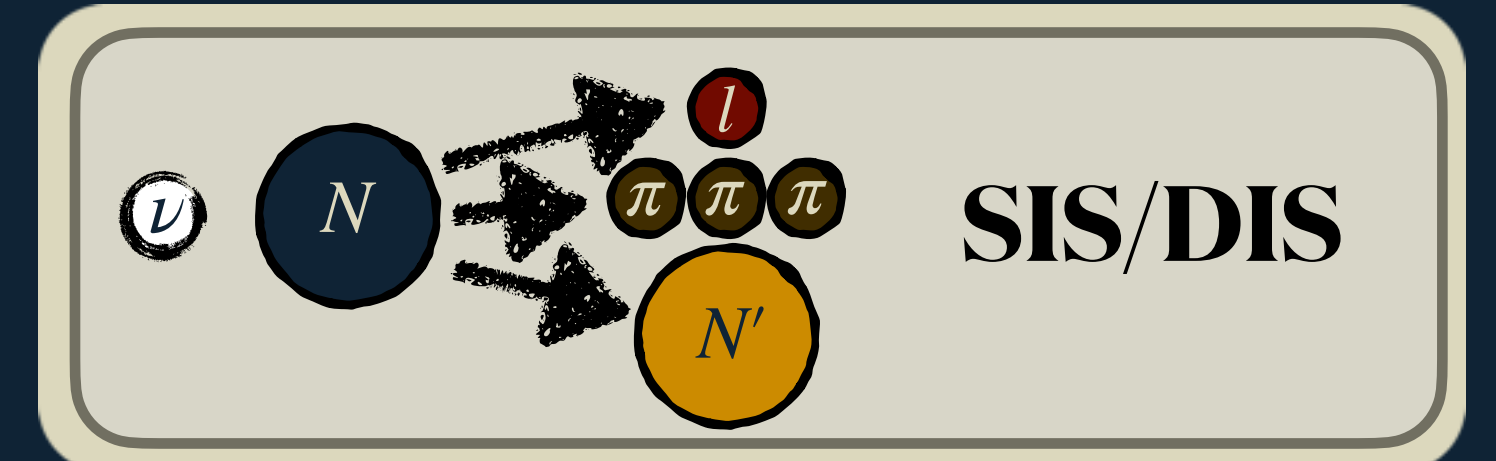


Region II



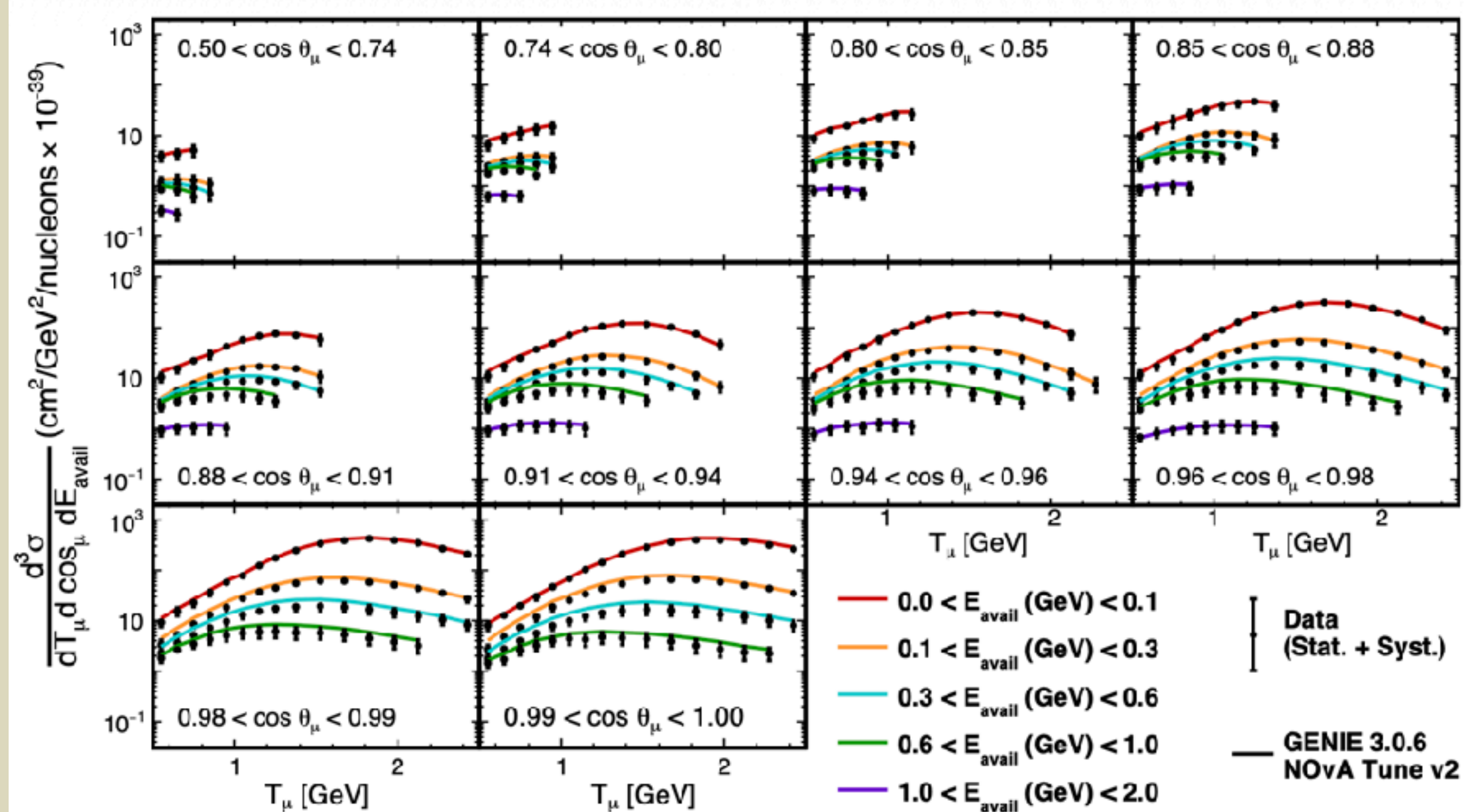
Deliberate probe on transition region from Resonance to DIS *through the SIS transition region. Pioneering Work!*

- Region II ($Q^2 > 1.0$ GeV) has additional differential variable in Bjorken x (!)
- Critical differences are adjustment to non-resonant pion production between the two regions. *Removal hurts Region I but helps Region II!*



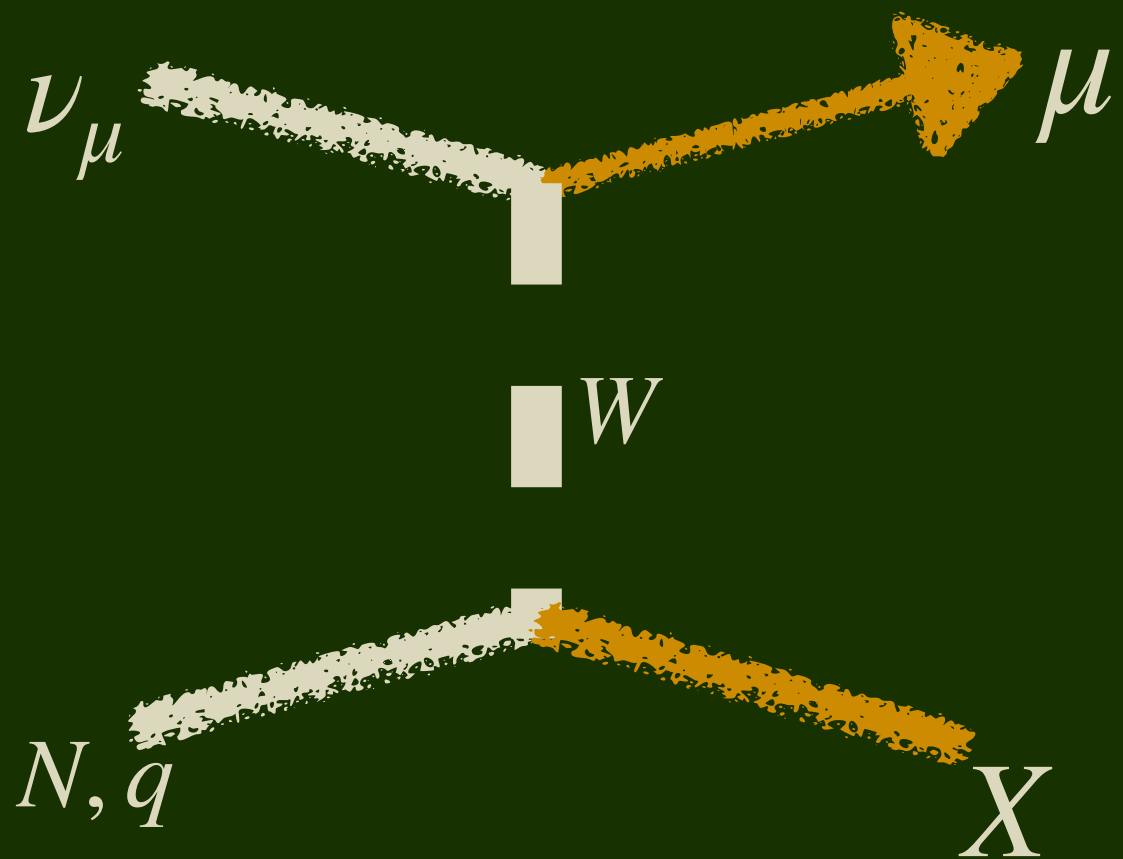
Inclusive Measurements

New Triple-Differential Inclusive Measurement from NOvA



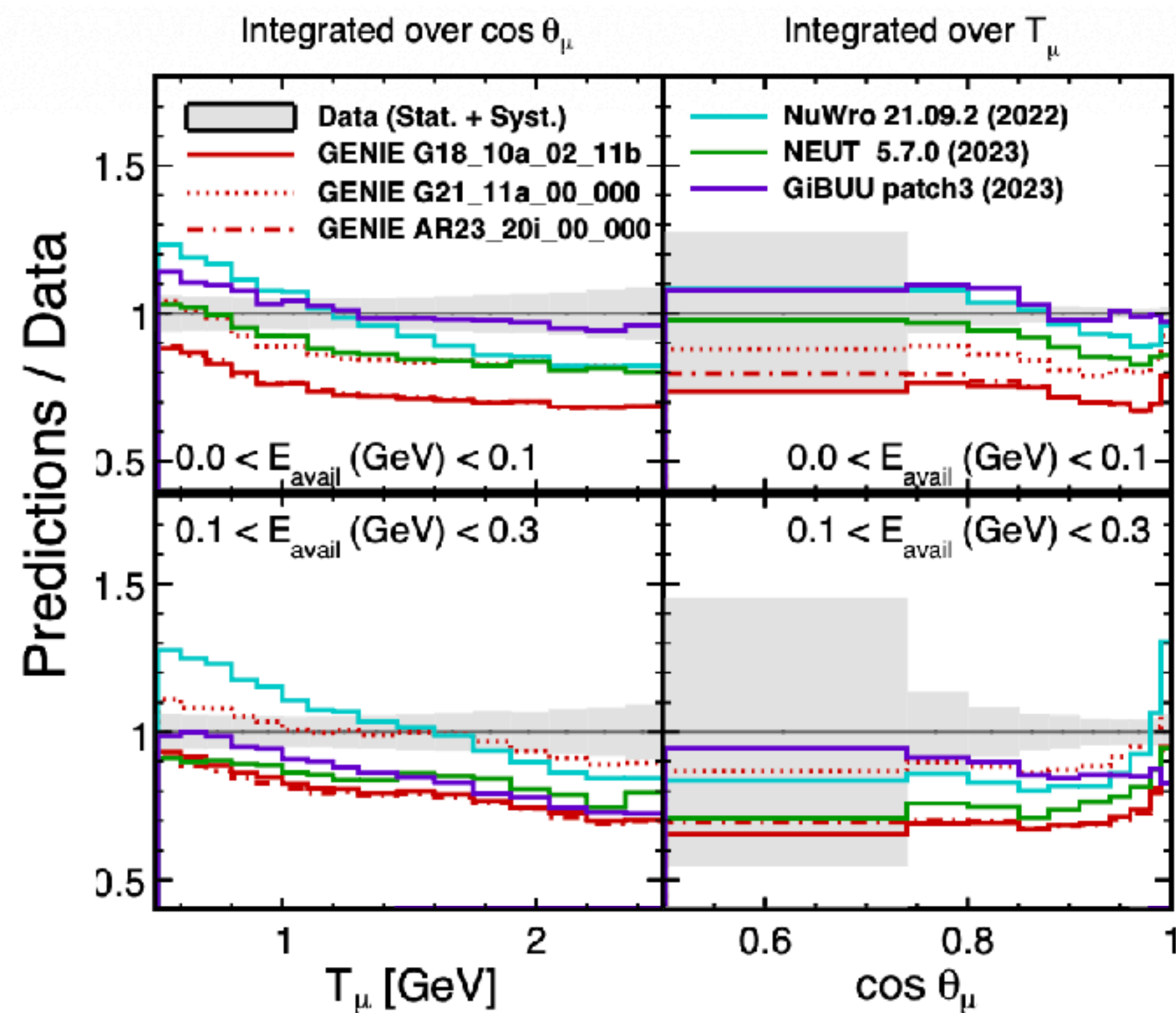
Inclusive triple-differential charged current cross-section measurement primarily with antineutrinos! **Largest antineutrino sample to date!**

- One of the few analyses to observe leptonic and hadronic system simultaneously!
- *Probes entire model configurations in a single measurement!*
- Observations across a broad range of energies, angles, and interaction types.
 - NOvA Tune, Version 2 shows good agreement at low energy indicating QE+MEC models as implemented are appropriate *even for antineutrino data*.
 - Trouble in the forward regions especially at higher hadronic energies.



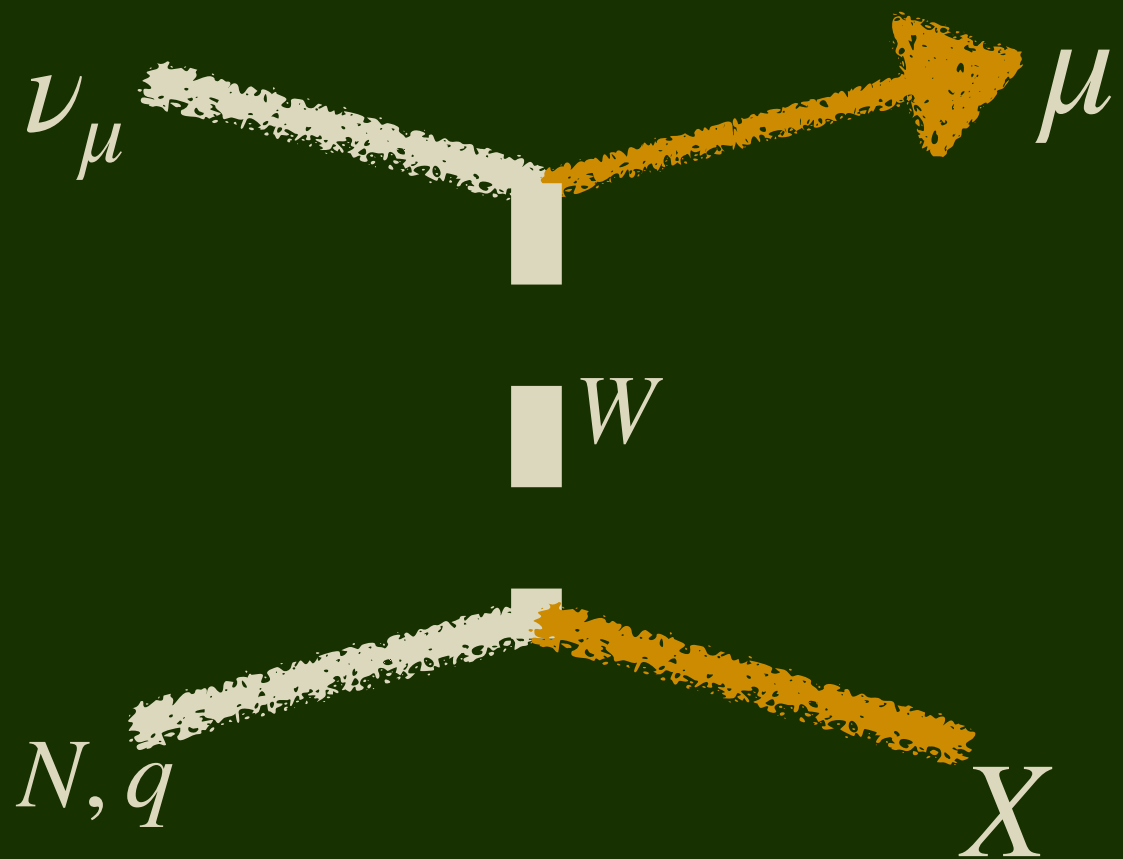
Preprint: [arXiv:2603.06718](https://arxiv.org/abs/2603.06718) (Mar 2026)

New Triple-Differential Inclusive Measurement from NOvA



Inclusive triple-differential charged current cross-section measurement primarily with antineutrinos! **Largest antineutrino sample to date!**

- Observations at hadronic energy < 0.3 GeV
 - Mostly the QE/MEC region with 3 different CMCs for GENIE v3, including the DUNE model(!).
 - Best affinity out of the box is the G21_11a series of models.
 - All models show discrepancy at high angles and high energies.

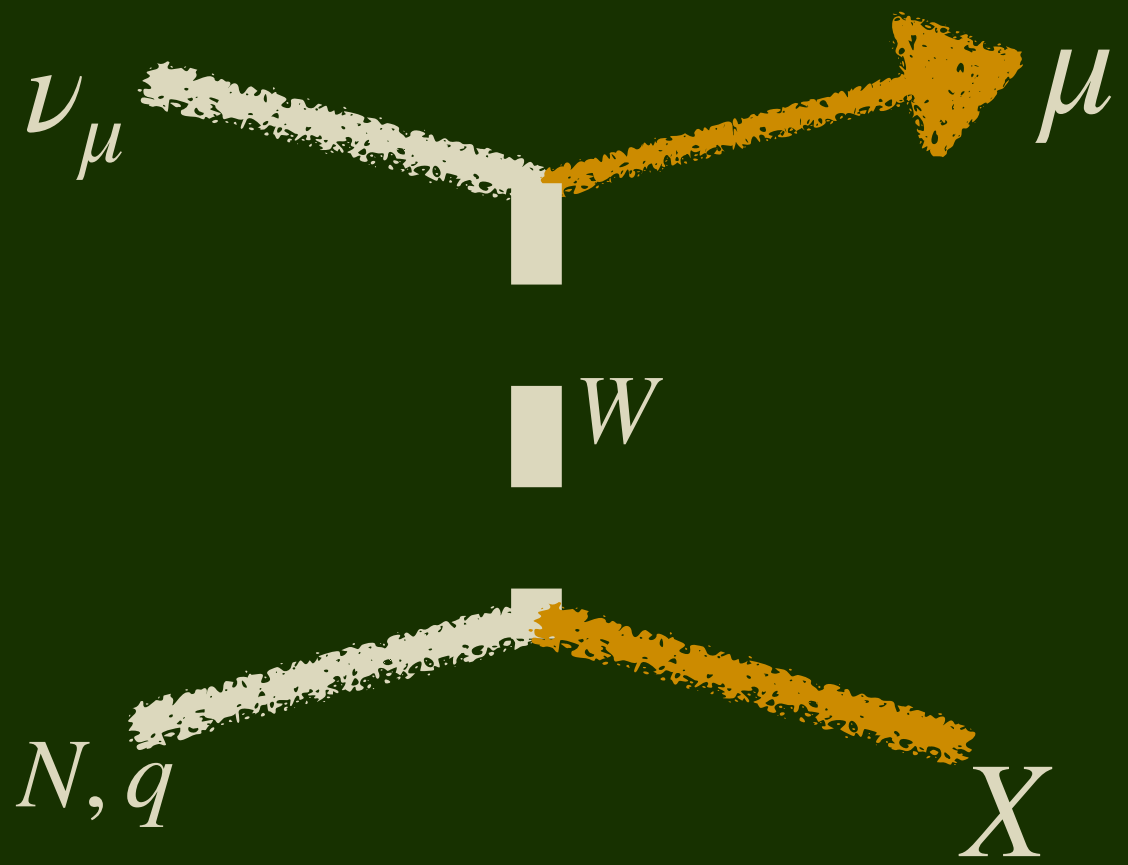
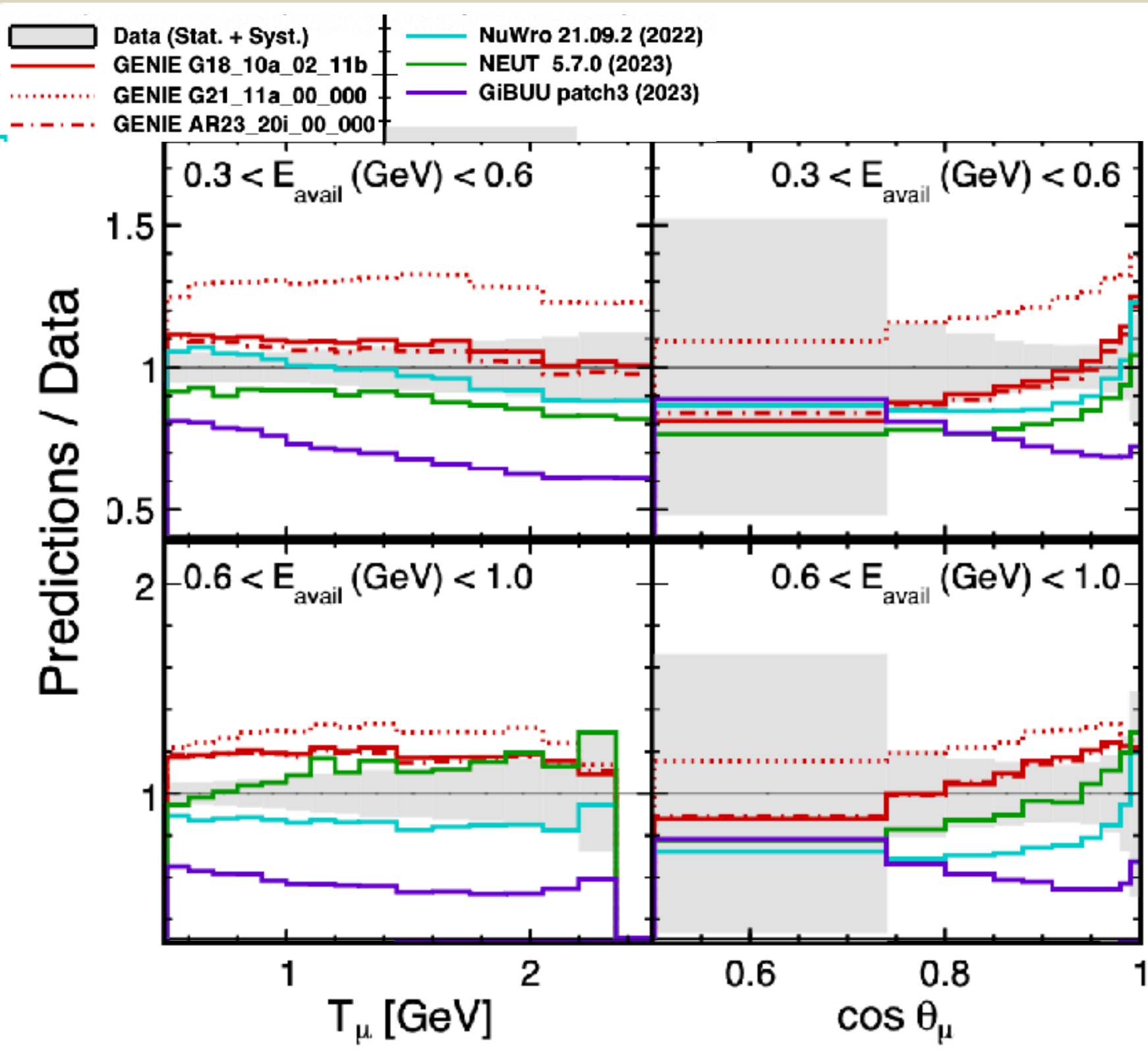


Preprint: [arXiv:2603.06718](https://arxiv.org/abs/2603.06718) (Mar 2026)

New Triple-Differential Inclusive Measurement from NOvA

Inclusive triple-differential charged current cross-section measurement primarily with antineutrinos! **Largest antineutrino sample to date!**

- Observations as a function of hadronic energy 0.3-1.0 GeV:
 - Multiple resonance models probed across generators.
 - Only other differences are treatments of FSI and transition through SIS.

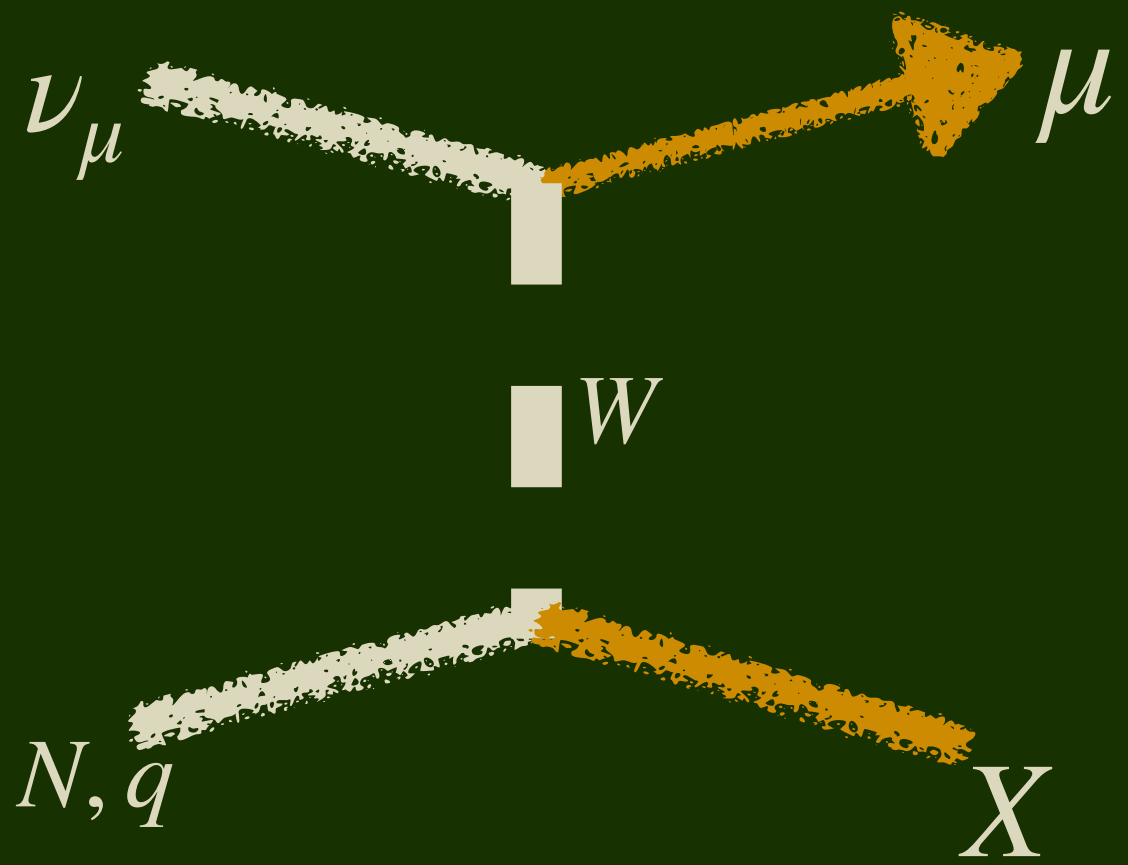
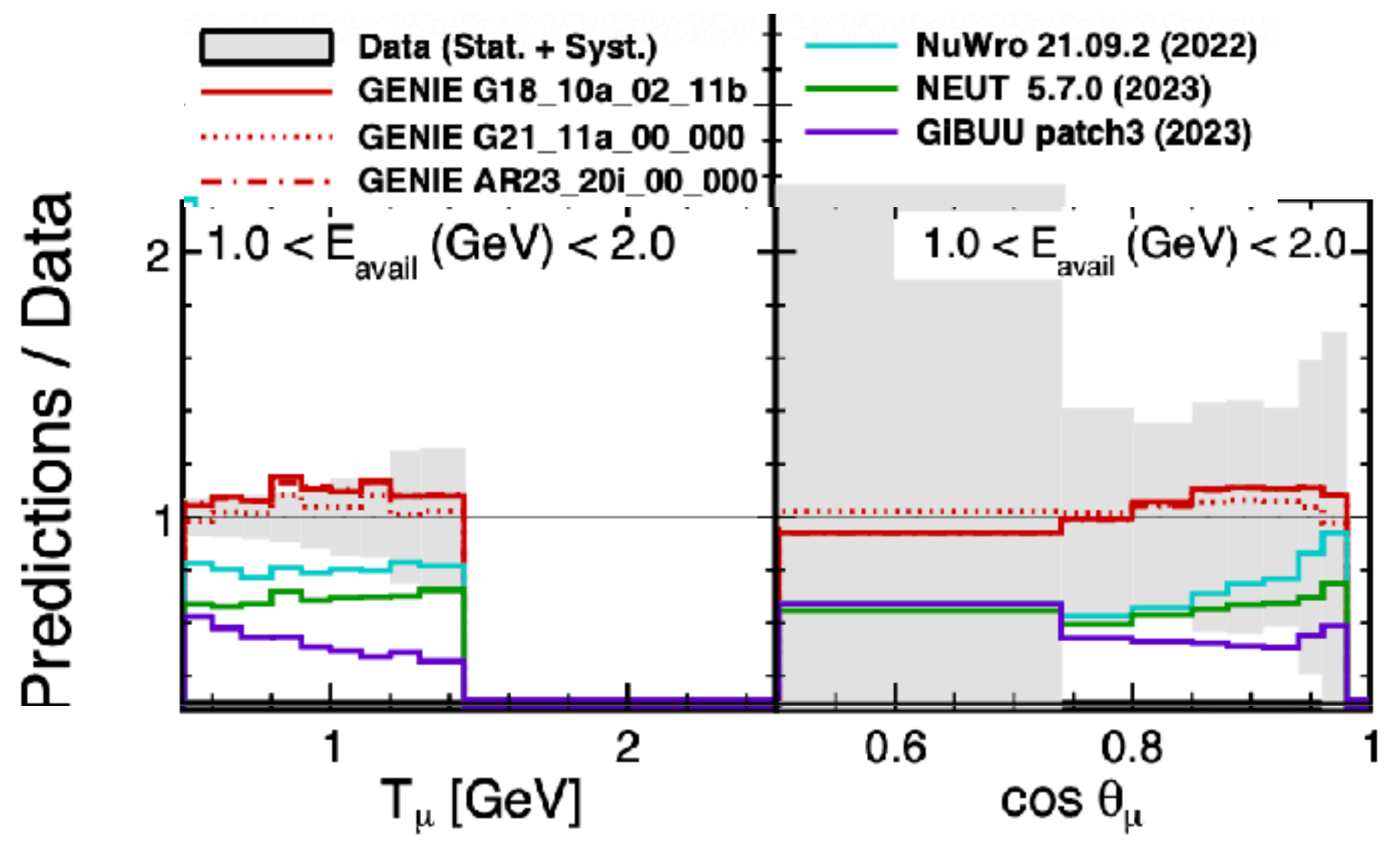


Preprint: [arXiv:2603.06718](https://arxiv.org/abs/2603.06718) (Mar 2026)

New Triple-Differential Inclusive Measurement from NOvA

Inclusive triple-differential charged current cross-section measurement primarily with antineutrinos! **Largest antineutrino sample to date!**

- Observations as a function of hadronic energy > 1.0 GeV:
 - Agreement among all GENIE models in DIS dominated regime.
 - Other models generally show disagreement



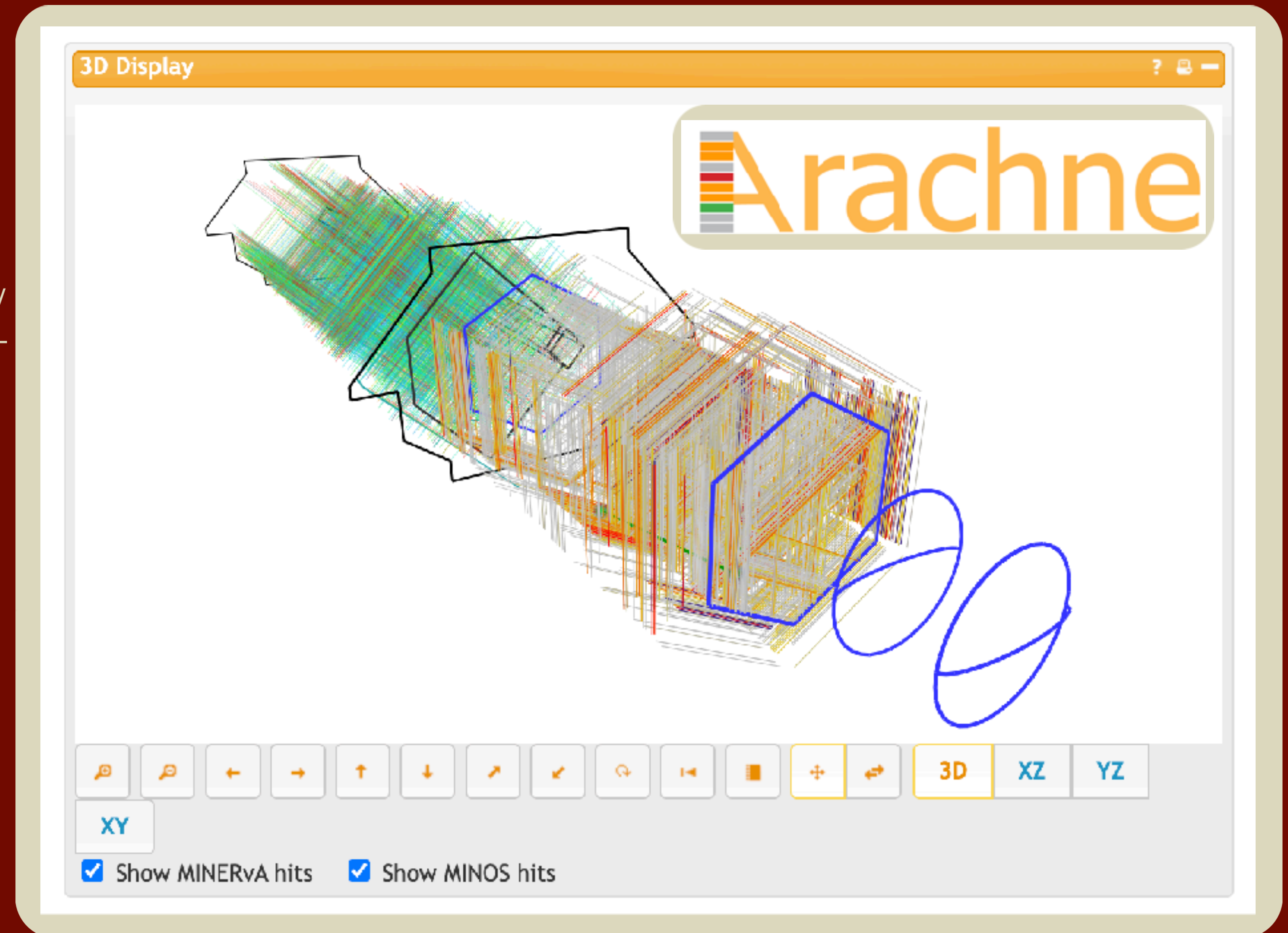
Preprint: [arXiv:2603.06718](https://arxiv.org/abs/2603.06718) (Mar 2026)

On the Horizon

The MINERvA Open Data Product

<https://minerva.fnal.gov/opendata/>

<https://github.com/MinervaExpt>



MINERvA has collected all* experimental data and simulation across both beam configurations along with support products (flux, neutrino interaction, and detector uncertainties).

- Already had two information/training sessions!

Other Completed or Near Term Results

Several completed analyses or near complete analyses across the three experiments!

- Neutron Capture on Oxygen at Super-K (**T2K**) (<https://arxiv.org/abs/2505.22547>)
- Scattering from Helium at **MINERvA**
- Nu-on-e Scattering at **NOvA**

Posters

- Sensitivity to Nuclear Effects in Neutrino–Lead Interactions in MINERvA **MINERvA**
- Deep Inelastic Scattering at the MINERvA Experiment **MINERvA**
- Characterizing an Electron-Neutrino Event Reconstruction Performance Towards Electron-Neutrino Cross Section Measurement in The Upgraded T2K Near Detector **T2K**
- Muon Neutrino $CC0\pi$ Interactions in the Upgraded T2K Near Detector **T2K**
- Improved measurement of the flux-integrated muon neutrino $CC0\pi$ cross section on carbon and oxygen with the FGD1 and FGD2 detectors **T2K**
- Neutrino cross-section results from T2K **T2K**
- QED Radiative Corrections to CC Neutrino Scattering in NOvA **NOvA**
- Charged Pion Production Explorations Using the NOvA Near Detector **NOvA**
- It's Possible: Status of a Single-Differential Cross Section By Charged Pion Kinetic Energy in the NOvA Near Detector **NOvA**
- Measurement of the $\bar{\nu}_\mu$ -Hydrogen Charged-Current Elastic Cross-Section in the NOvA Near Detector **NOvA**
- Measurement of muon antineutrino–nucleus charged current scattering with zero mesons using the NOvA Near Detector **NOvA**
- Towards a muon neutrino charged-current exclusive cross section measurement with one proton and one muon in the final state at the NOvA near detector **NOvA**
- The NOvA Cross-Section Model, Version 3 **NOvA**

Conclusions

- New Cross-Section results from long baseline medium energy experiments are trending toward increasing sophistication!
- Necessary as we prepare for the next generation of experiments!
- Recent developments on
- Resonant interactions, meson production, and DIS has seen some advancement include attempts at disentangling the transition region.
- Triple differential measurements test generator and model configurations holistically.

What a time to be alive!