

Neutrino–nucleus interactions as the limiting systematic for next-generation oscillation experiments

Why understanding the nucleus matters for measuring δ_{CP}

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Outline

- PART I — The Precision Frontier & Systematic Challenges
- PART II — Microscopic Theory of Neutrino-Nucleus Interactions
- PART III — Experimental Benchmarking & Generator Tensions
- PART IV — Mitigation Strategies & Experimental Infrastructure
- PART V — Synthesis, Outlook & Conclusions

Neutrino Oscillations

- There is a non-zero probability of detecting a different neutrino flavor than that produced at the source:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

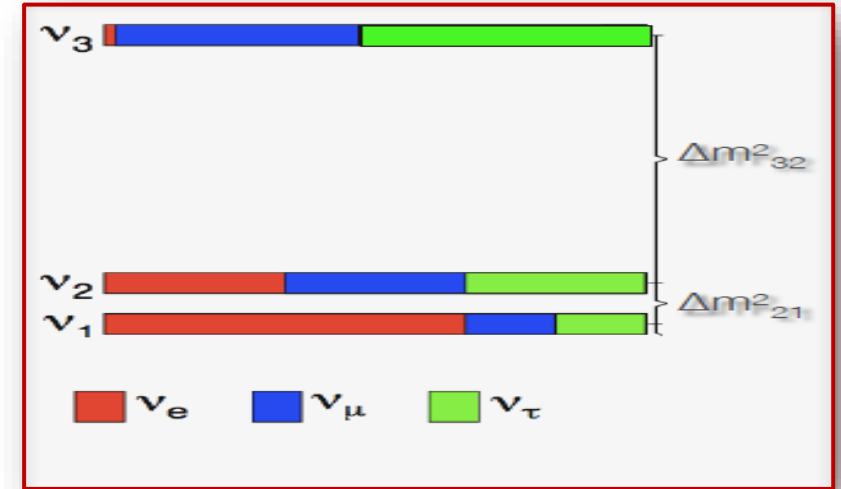
Atmospheric + Accelerator L/E 500 km/GeV	Reactor + Accelerator L/E 500 km/GeV	Solar + Reactor L/E 15,000 km/GeV
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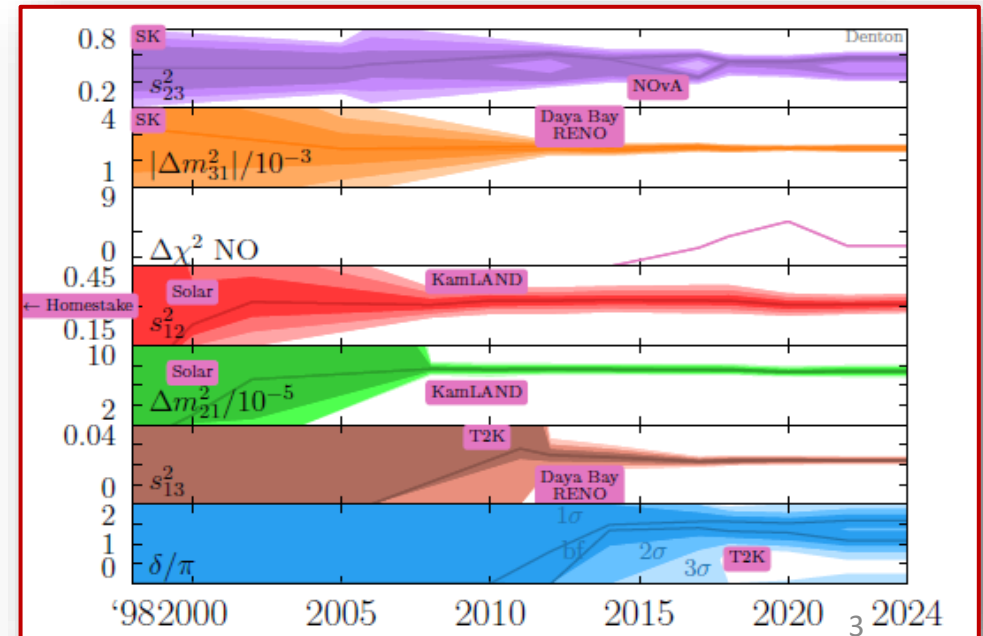
- As in the quark case, the CP phase can be non-zero if all 3 angles are non-zero.

- Mass ordering is NOT known for atmospheric neutrinos but known for the solar mass scale.
- The octant of the large mixing angle is not known!
- CP violation in the lepton sector has NOT been measured.

- Measuring the elements of the matrix with more than one technique is essential to paint the full picture of oscillations



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Experimental Framework & Discovery Thresholds

1. Baseline Configurations

DUNE (Deep Underground Neutrino Experiment)

- 1300 km baseline from Fermilab to SURF.
- High-intensity wide-band beam.
- 40 kt fiducial Liquid Argon Time Projection Chamber (LArTPC).
- Primary observables:
 - $\nu_e/\bar{\nu}_e$ appearance
 - $\nu_\mu/\bar{\nu}_\mu$ disappearance spectra.

Hyper-Kamiokande (HK)

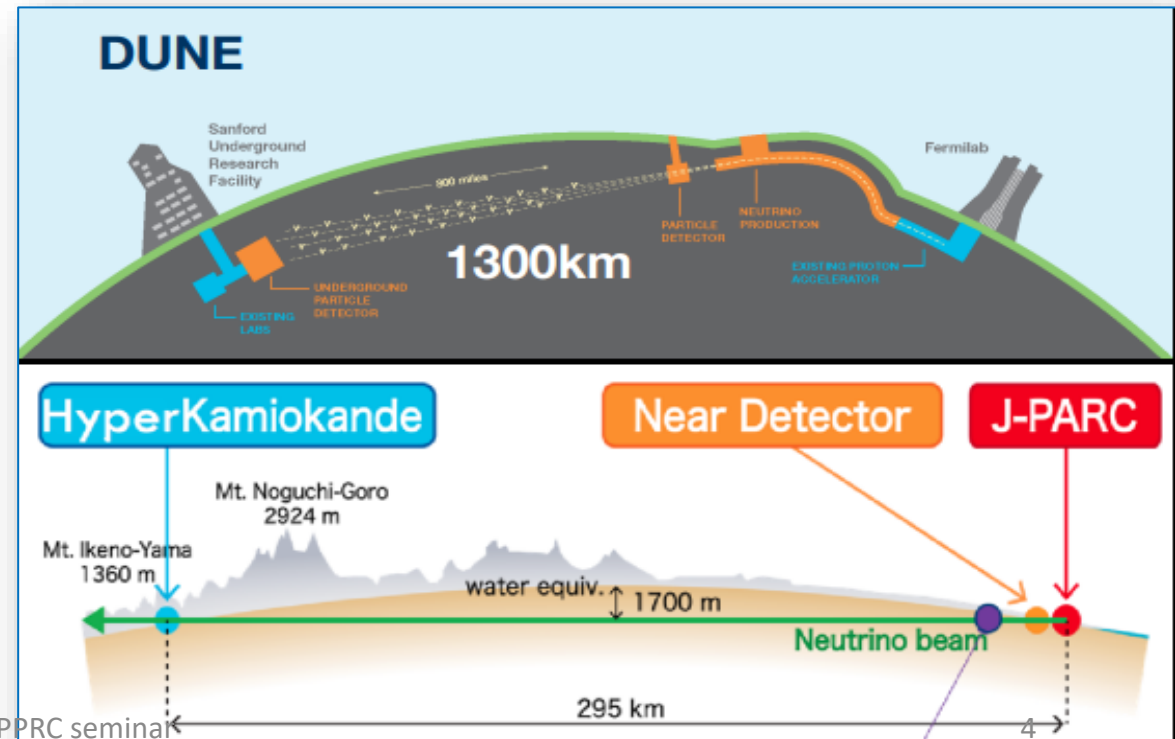
- 295 km baseline from J-PARC to Kamioka.
- Narrow-band off-axis beam (2.5°) with peak energy around 0.60 GeV.
- 187 kt fiducial Water Cherenkov detector (H₂O+Gd).
- High-statistics reconstruction with rejection and neutron tagging.

The Systematic Imperative

- Transition from the statistics-limited era (T2K/NOvA) to a systematics-dominated precision regime.
- Discovery sensitivity is critically dependent on reducing the total systematic uncertainty budget below the 2–3% level.
- The precision frontier is now fundamentally limited by neutrino–nucleus interaction modeling.

Physics Targets & Discovery Reach

- 5σ sensitivity to leptonic CP violation for $\sim 50\%$ of possible δ_{CP} values
- Mass Ordering determination through combined DUNE + JUNO analyses.
- Precision measurement of:
 - θ_{23} octant
 - atmospheric oscillation parameters.



Physics Objectives: The Energy Scale Constraint

1. Precision Targets for Oscillation Parameters

- δ_{CP} Resolution:**
 Target sensitivity between 6° and 20° , depending on the true value of δ_{CP} .
 Achieving this goal requires highly stable spectral reconstruction.
- Atmospheric Mass Splitting ($|\Delta m^2_{31}|$):**
 Sub-percent precision on atmospheric oscillation parameters is required to stabilize global oscillation fits and strengthen mass-ordering sensitivity.
- Mixing Angle θ_{23} :**
 Determination of the octant ($> 45^\circ$ or $< 45^\circ$) with significance exceeding 3σ over a large fraction of parameter space.

2. The Critical Link: Energy Scale & Parameter Bias

- Linear Propagation of Bias:**
 A systematic shift of only 1% in the reconstructed energy scale (E_{rec}) can induce shifts of 15° – 20° in the extracted value of δ_{CP} .
- Spectral Distortion:**
 Nuclear effects such as 2p2h interactions and Final State Interactions (FSI) distort the oscillation dip. If incorrectly modeled, the oscillation fit compensates by shifting Δm^2_{31} and toward biased solutions.
- Systematic Threshold:**
 To preserve 5σ discovery sensitivity, the absolute energy-scale uncertainty must be constrained below the 1% level.

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3. Multi-Channel Convergence Strategy

- ν_e Appearance vs. ν_μ Disappearance:**
 Joint fits are required to disentangle the CP phase from atmospheric oscillation parameters.
- Reactor/Atmospheric Synergy:**
 External constraints from JUNO and atmospheric neutrino data provide complementary information on Δm^2_{31} and the Mass Ordering, reducing degeneracies in long-baseline oscillation analyses.

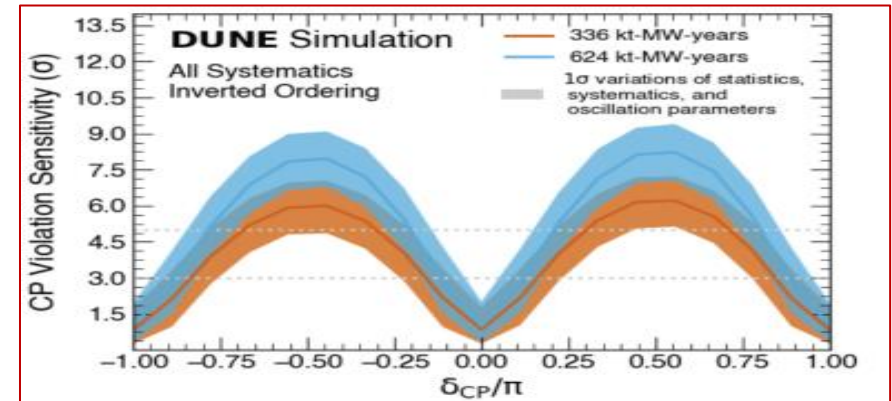


Figure 2.1: DUNE CPV Sensitivity for Inverted Mass Ordering.

arXiv:2505.15019

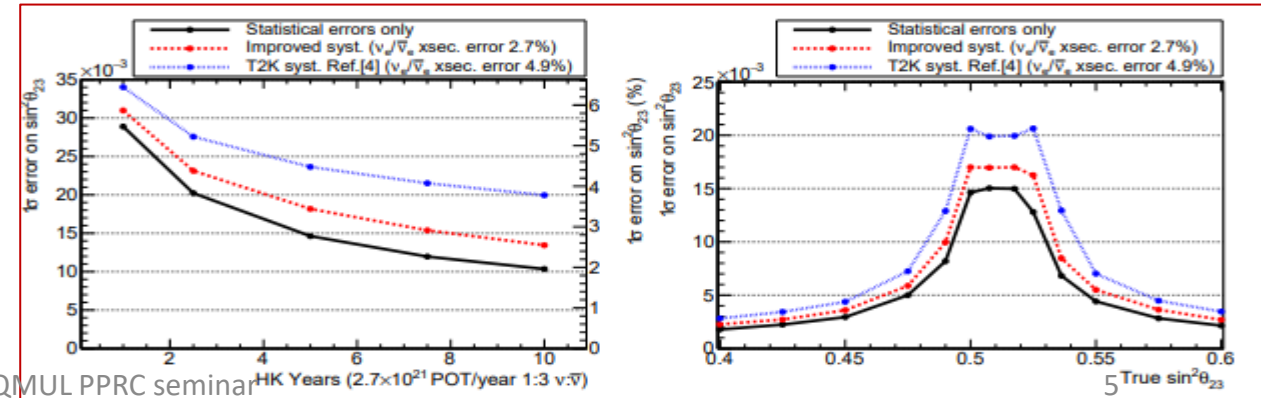


Figure 2.2: Atmospheric Mixing Parameter Constraints ($\sin^2 \theta_{23}$).

The Systematic Floor: From Statistics to Precision Systematics

The Statistical Paradigm Shift (2020 → 2030)

- **Legacy Era (Statistics-Limited):**
Experiments such as T2K and NOvA operated with $O(10^3)$ signal events, where statistical fluctuations dominated the total uncertainty budget.
- **DUNE / Hyper-K Era (Systematics-Limited):**
Future exposures exceeding 600 kt·MW·yr will produce $O(10^5)$ events, reducing statistical uncertainties to the $\sim 1\%$ level.
- **Consequence:**
Discovery sensitivity is now fundamentally limited by systematic uncertainties rather than event statistics.

Systematic Uncertainty Budget

- **Current Status:**
Total systematic error currently fluctuates between 5% and 8% dominated by neutrino interaction modeling and flux normalization.
- **Discovery Requirement:**
A robust 5σ measurement of leptonic CP violation requires reducing the total uncertainty budget below 2–3%.
- **Dominant Contributions:**
 - Flux normalization and spectral shape
 - Nuclear effects: 2p2h, MEC, FSI
 - Hadronic energy reconstruction and detector response

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3. The Discovery Ceiling

- **Sensitivity Saturation:**
Without systematic reduction, increasing beam exposure produces only diminishing returns in CPV sensitivity.
- **Precision Frontier:**
Mastering neutrino–nucleus interactions is now the central requirement for precision oscillation physics.

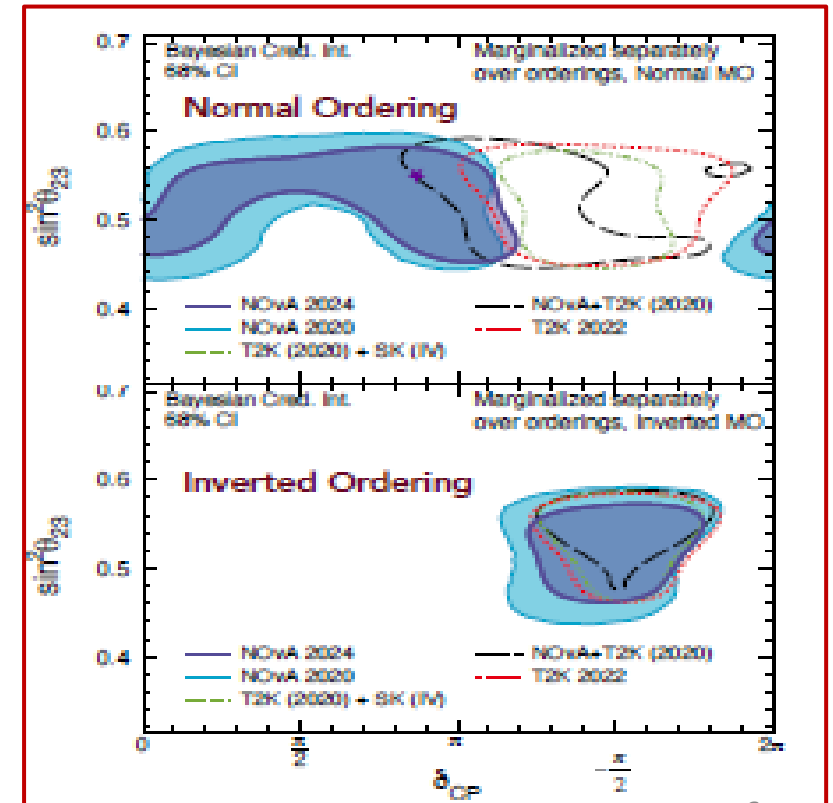


Figure T2K and NOvA Joint Oscillation Analysis Contours

Flux Constraints : Hadron Production & Extrapolation

1. Neutrino Flux Determination: $\Phi(E\nu)$

- **Source:** The neutrino flux is an inferred quantity derived from the interaction of high-energy protons (120 GeV/c at Fermilab, 30 GeV/c at J-PARC) on graphite targets.
- **Primary Uncertainties:** Dominated by the differential cross-sections of secondary hadron production ($p + A \rightarrow \pi^\pm, K^\pm, K_L^0$), the focusing horn magnetic field stability, and target degradation.
- **Spectral Feature:** The flux is characterized by a "wide-band" or "narrow-band" energy spread, where the ν_e "intrinsic" beam contamination (at the O(1%)) represents a critical irreducible background for appearance searches

2. External Data Constraints: NA61/SHINE & EMPHATIC

- **Hadron Benchmarking:** Auxiliary experiments provide measurements of hadron yields to reduce the "a priori" flux uncertainty.
 - **NA61/SHINE (CERN):** Provides high-precision (θ, p) phase space coverage using replica targets to account for secondary re-interactions within the target geometry.
- **EMPHATIC (Fermilab):** Targeted measurements of low-energy hadron production to constrain the low-energy tail and K/ π ratios

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3. The Near-to-Far Extrapolation Limitation

- **Measurement Covariance:** Near Detectors measure the convolution of flux and cross-section: $M_{ND} \approx \Phi \otimes \sigma$
- **Non-Cancellation:** The assumption that flux uncertainties cancel in the Far/Near ratio is limited
 - **Geometric Acceptance:** Different angular acceptance between ND (extended source) & FD (point source).
 - **Nuclear Response:** Variations in interaction rate between different detector materials (Plastic vs. Argon).

Phys.Rev.D 108 (2023) 072013

Hadron Production Benchmarking
(NA61/SHINE data vs models)

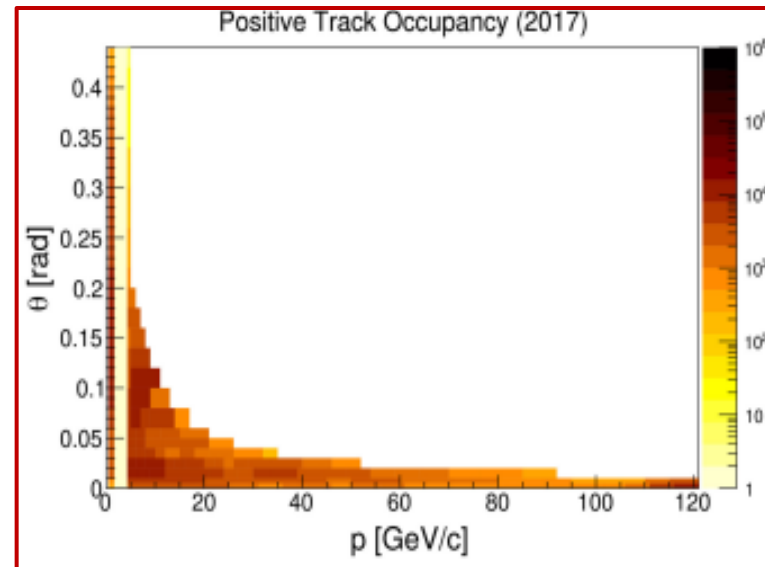


Figure 4.2 : Phase space coverage (p, θ) by NA61/SHINE, ensuring a flux prediction constrained by direct hadronic measurements

Total DUNE Flux Prediction Correlations

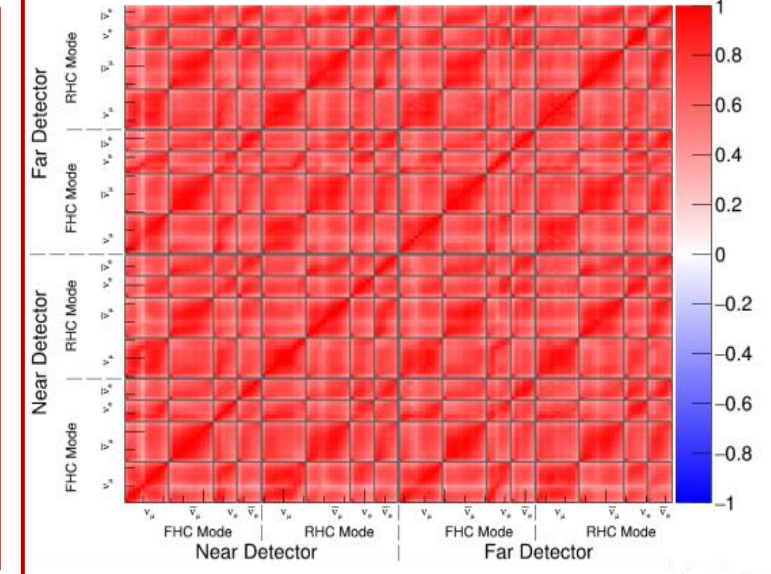


Figure 4.1 : Total DUNE flux correlation illustrating the structure of systematic uncertainties

Analytical Framework: Convolution Model & Energy Mapping

1. Mathematical Representation

The observed event distribution in reconstructed energy space, $N(E_{rec})$ is the result of a multi-dimensional convolution of the flux, the nuclear response, and the detector performance:

$$N(E_{rec}) = \int \Phi(E_\nu) \sigma(E_\nu, A) \epsilon(E_{rec}) R(E_\nu, E_{rec}) dE_\nu \quad \text{With } \epsilon(E_{rec})$$

- **$\Phi(E_\nu)$ (Spectral Flux):** The incoming neutrino energy distribution, integrated over the beam spill.
- **$\sigma(E_\nu, A)$ (Interaction Cross-Section):** The probability of interaction on a complex nucleus of mass A. This term is highly dependent on the underlying nuclear model (e.g., RPA, 2p2h, SF).
- **$R(E_\nu, E_{rec})$ (Migration Matrix):** The detector response function representing the probability that a neutrino with true energy E_ν is observed at E_{rec}

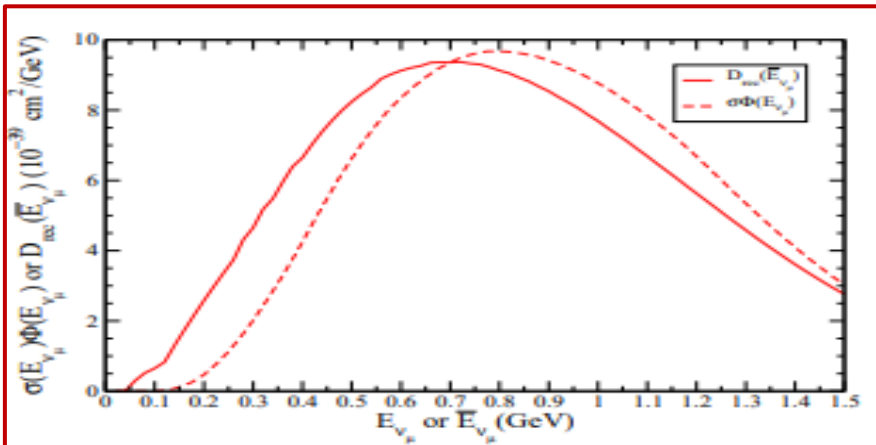


Figure 5.2: Neutrino Energy Feed-down and Reconstruction Bias (Martini et al. Model).

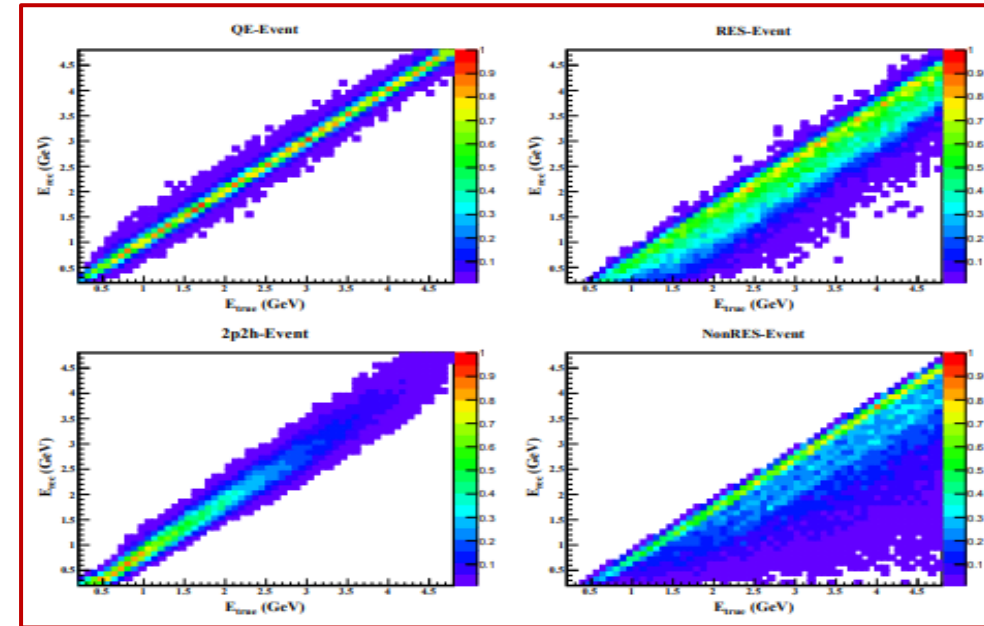


Figure 5.1: Two-Dimensional Migration Matrices for Argon Target (GiBUU Simulation).

arXiv:1906.02190

- **Degeneracy:** The Near Detector measures the product $(\Phi \cdot \sigma)$. Without an independent constraint, an overestimation of the flux can be masked by an underestimation of the cross-section.
- **Missing Energy Component:** The R matrix is not diagonal. Nuclear effects such as **2p2h** and **Pion Absorption** shift events from the peak toward the "low-energy tail" (**energy feed-down**).
- **Systematic Uncertainties:** If the migration matrix R is built using an incorrect nuclear model, the reconstructed oscillation parameters $(\delta_{CP}, \Delta m^2_{31})$ will exhibit a model-dependent bias.

Nuclear Target Complementarity: Argon vs Oxygen

1. Comparative Physics: Argon vs. Oxygen

- **Isospin Asymmetry (N/Z):**
 - **^{40}Ar (DUNE):** $N/Z \approx 1.22$ Large neutron excess; complex shell structure; sensitive to neutron-rich multinucleon currents.
 - **^{16}O (Hyper-K):** $N/Z = 1.0$. Isoscalar nucleus; simpler shell structure; with a larger relative contribution from quasi-elastic topologies in the sub-GeV regime
- **Detector Specificity:**
 - **LArTPC (Argon):** High-resolution imaging of the hadronic final state (protons, charged pions); lower thresholds.
 - **Water Cherenkov (Oxygen):** High statistics; optimized for sub-GeV rings; sensitive to π^0 and neutron-capture photons.

2. Strategy for Systematic Mitigation

- **Model Universality:** A consistent nuclear model must describe interactions on both targets consistently. Divergences between DUNE and Hyper-K datasets would signal a failure in the underlying nuclear theory.
- **Vector/Axial Separation:** The different N/Z ratios provide complementary sensitivity to the vector and axial structure of the nuclear response.
- **Cross-Validation:** Leveraging ^{12}C data (from MINERvA/T2K) as a bridge to validate the scaling from light to heavy nuclei

Cross-Target Validation: Argon vs. Oxygen".

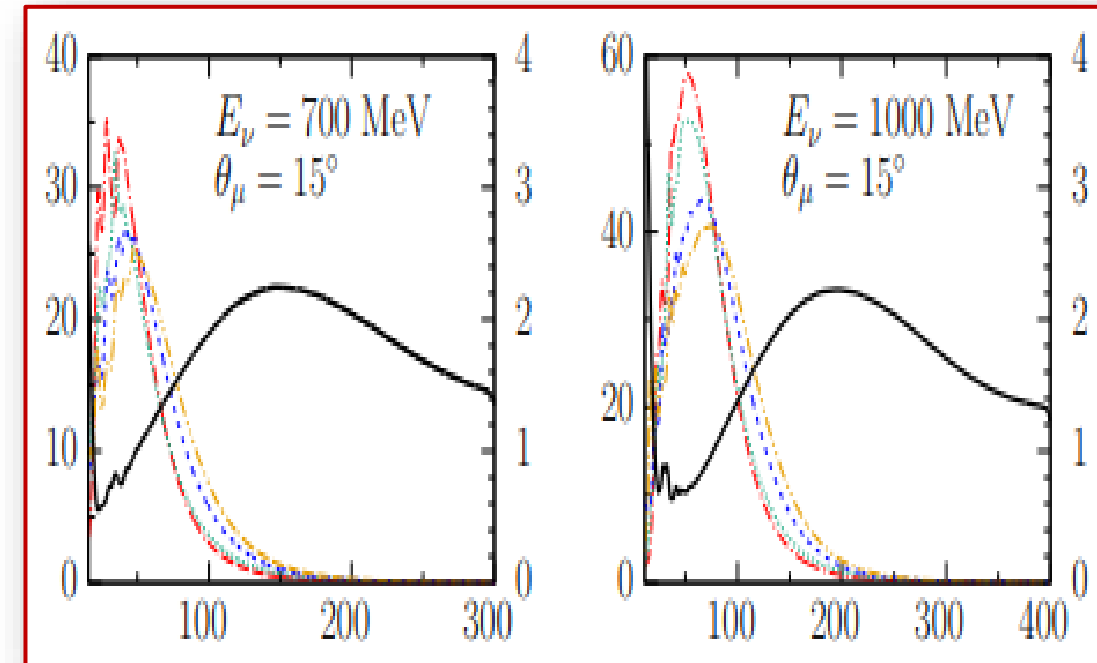


Figure 6.1: Differential cross-section comparison between ^{16}O (dotted) and ^{40}Ar (dashed) at 700 MeV and 1000 MeV

<https://arxiv.org/pdf/1704.07817>

The Hadronic Tensor & Nuclear Response Functions

1. Formalism: The Leptonic-Hadronic Decomposition

The double-differential cross-section is factorized into a leptonic tensor $L_{\mu\nu}$ (precisely known from Electroweak theory) and a hadronic tensor $W^{\mu\nu}$ (encoding the complex nuclear dynamics):

$$d^2\sigma / (d\Omega dE') = (G_F^2 \cos^2\theta_c) / (2\pi^2) \cdot k' E' \cos^2(\theta/2) \cdot [L_{\mu\nu} W^{\mu\nu}]$$

$W^{\mu\nu}$ Structure: Encapsulates the transition from a correlated nuclear ground state $|\Psi_0\rangle$ to a continuum final state $|\Psi_f\rangle$ under the action of the weak current operator J^μ

2. Response Functions: R_L and R_T

In the inclusive regime, $\langle W^{\mu\nu} \rangle$ is decomposed into two primary response functions:

- **Longitudinal Response R_L** : Associated with the charge density and the vector component of the current.
- **Transverse Response R_T** : Associated with the current density and both vector and axial-vector components.
- **Significance:** Most multinucleon effects (2p2h) and Meson Exchange Currents (MEC) manifest as an enhancement in the **Transverse** channel, directly impacting neutrino E_{rec} .

3. The Many-Body Challenge

- **Completeness:** The calculation requires a consistent treatment of nuclear correlations, requiring approximations such as the **Random Phase Approximation (RPA)** to account for long-range collective behaviors.

The Hadronic Tensor & Nuclear Response Functions

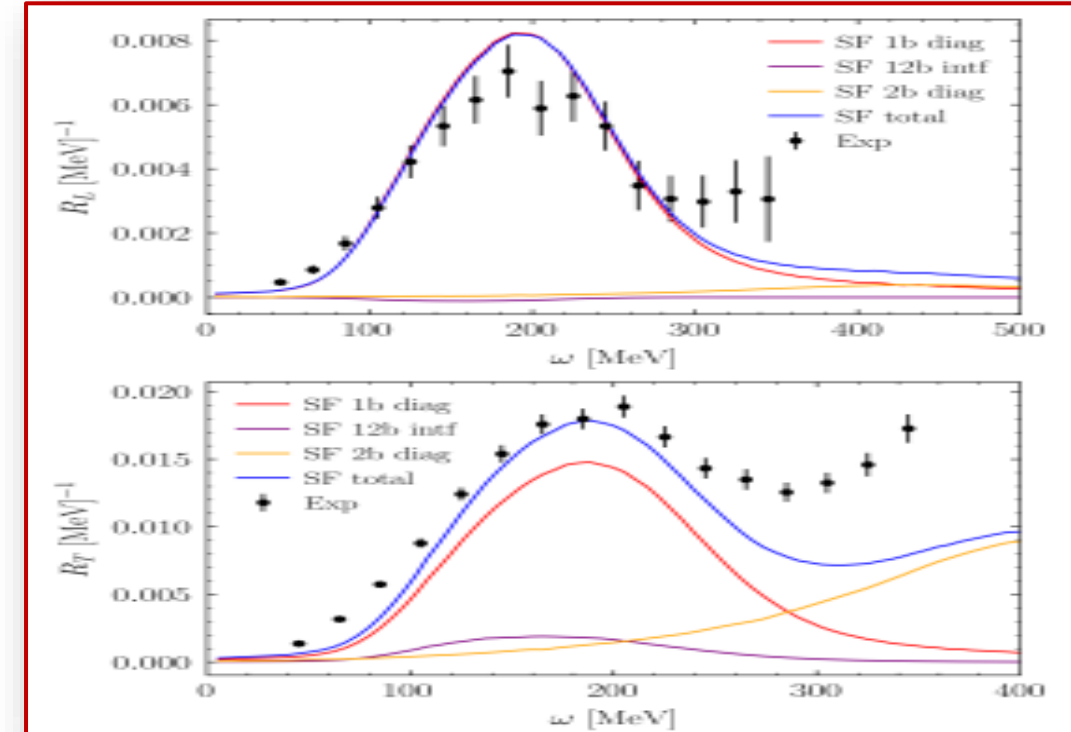


Figure 7.1 (Top) : Longitudinal Response (R_L). Constrained by the vector current and electron scattering data. Figure 7.2 (Bottom) : Transverse Response (R_T). Enhanced by 2p2h and Meson Exchange Currents (MEC), shown by the orange curve

Limitations of the Impulse Approximation & RPA Effects

1. The Impulse Approximation (IA) Framework

- **Definition:** The IA assumes that the neutrino scatters off a single, independent nucleon, with the remaining nucleus acting as a spectator (valid for high momentum transfer Q^2)
- **Limitations:** This approach neglects collective nuclear behaviors and the screening of the weak charge, which become dominant at the low momentum transfers ($Q^2 \lesssim 0.2 \text{ GeV}^2$) relevant for oscillation experiments.

2. Long-Range Correlations: Random Phase Approximation (RPA)

- **Mechanism:** The nucleus acts as a polarized medium. The RPA accounts for the collective excitation of multiple nucleons, leading to a redistribution of the strength in the nuclear response.
- **Phenomenology :**
 - **Suppression:** Significant reduction of the cross-section at low Q^2 compared to the free-nucleon prediction.
 - **Enhancement:** Potential enhancement at intermediate kinematics due to the attractive/repulsive nature of the nucleon-nucleon interaction in different channels.

3. Impact on Oscillation Analysis

- **Event Rate Bias:** Neglecting RPA effects can lead to **order-10% distortions** in the predicted event rate near the oscillation maximum
- **Energy Reconstruction:** Since RPA affects the shape of the Q^2 distribution, its omission introduces non-linear distortions in the migration matrix, biasing the extraction of Δm^2_{31} and θ_{23}

Differential Q^2 cross-section and RPA suppression.

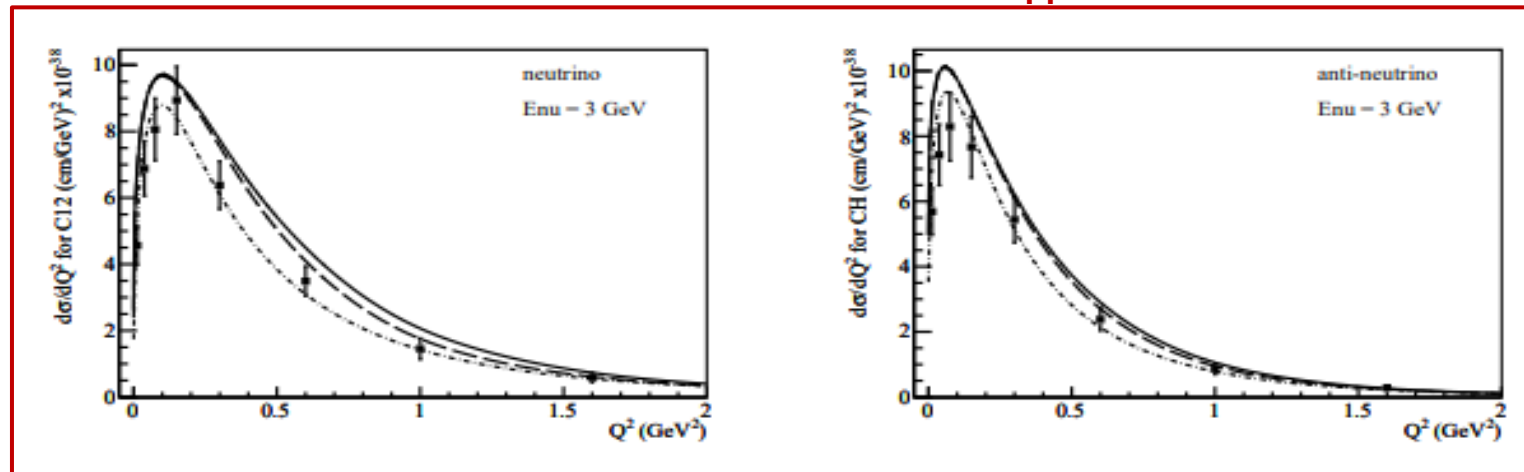


Figure 8.1: Comparison between MINERvA data (points) and the Valencia model at $(E_{\nu} = 3) \text{ GeV}$. The suppression at low (Q^2) (difference between the dot-dashed and solid lines) illustrates the impact of RPA collective effects on the nuclear response

The Nuclear Ground State: From RFG to Spectral Functions

1. Limitations of the Relativistic Fermi Gas (RFG)

- Model:** Assumes nucleons are non-interacting particles moving within a global potential well with a rigid momentum cut-off k_F

- Limitations:** Fails to account for the detailed shell structure and the high-momentum components observed in experimental data. It lacks the complexity required to model energy-momentum correlations accurately.

Validation: Spectral Functions for Argon have been validated using electron-scattering data (e, e'p) from **Jefferson Lab (Experiment E12-14-012)**.

3. Impact on Precision Physics

- Energy Balance:** SF provide a more accurate distribution of the binding energy, which is a direct input for neutrino energy reconstruction.

- Systematic Improvement:** Moving from RFG to SF reduces the "a priori" modeling uncertainty of the initial state from $\approx 10\%$ to $< 4\%$, providing a more robust foundation for oscillation analyses.

2. Spectral Functions $P(\mathbf{p}, E)$

- Definition:** Represents the joint probability density of finding a nucleon with a specific momentum \mathbf{p} and a removal energy E .

- Advantages:** Incorporates the shell model structure and accounts for **Short-Range Correlations (SRC)**—pairs of nucleons with high relative momentum k_F and low center-of-mass momentum.

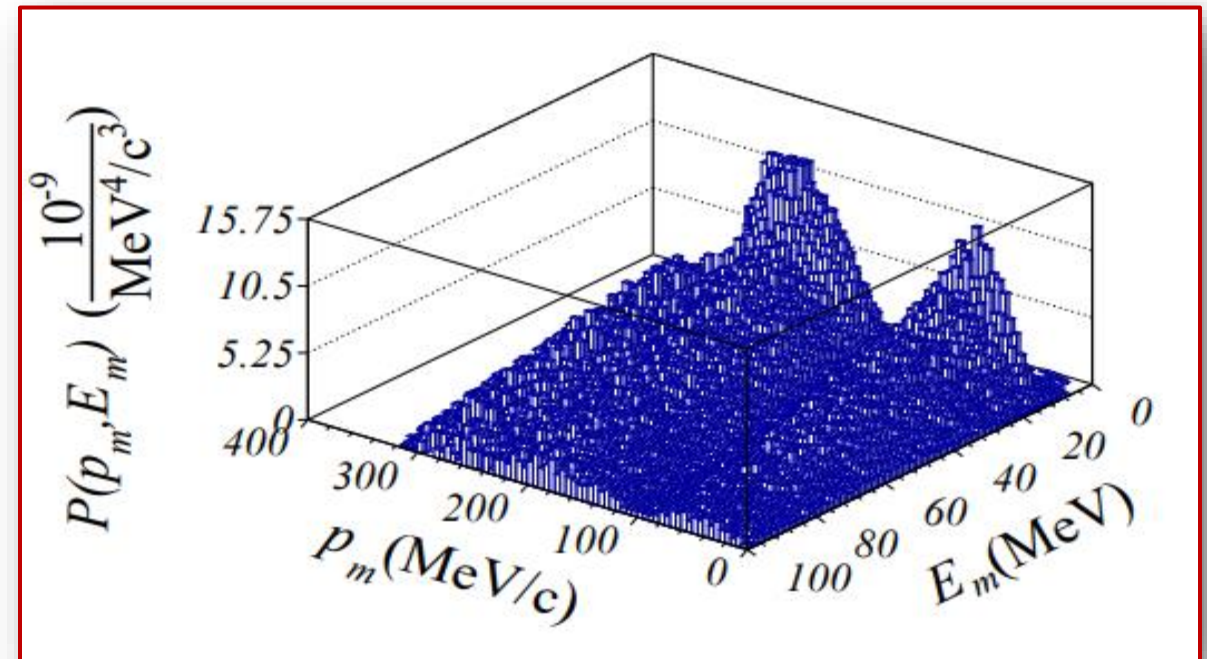


Figure 9.1: Joint probability distribution of nucleon removal energy and momentum. The peaks represent the nuclear shell structure, while the broad strength at high p_m and E_m

incorporates Short-Range Correlations (SRC).
Figure 9.1: The Spectral Function $P(\mathbf{p}_m, E_m)$ of ^{40}Ar

<https://doi.org/10.1103/PhysRevD.105.112002>

Multinucleon Currents: 2p2h & Meson Exchange Currents

1. Physical Mechanism: Beyond the Independent-Particle Model

- **Definition:** Neutrino coupling to a correlated nucleon pair (np or pp) mediated by **MEC**
- **Kinematic Impact:** These 2p2h (2-particle, 2-hole) excitations populate the "**Dip Region**"—the energy transfer space between the Quasielastic (QE) and Delta (Δ) resonance peaks

2. The Challenge of "Energy Feed-down"

- **Topological Mimicry:** 2p2h events often produce a **CC0 π** (no pion) final state, mimicking a standard QE interaction.
- **Missing Energy:** A portion of E_ν is transferred to a second nucleon. If this nucleon is below the detection threshold, the reconstructed energy (E_{rec}) is systematically underestimated.
- **Impact:** This shift distorts the oscillation dip, biasing the extraction of oscillation parameters, including δ_{CP} or a shift in Δm^2_{31}

Electron-Scattering Benchmarking of the "Dip Region"

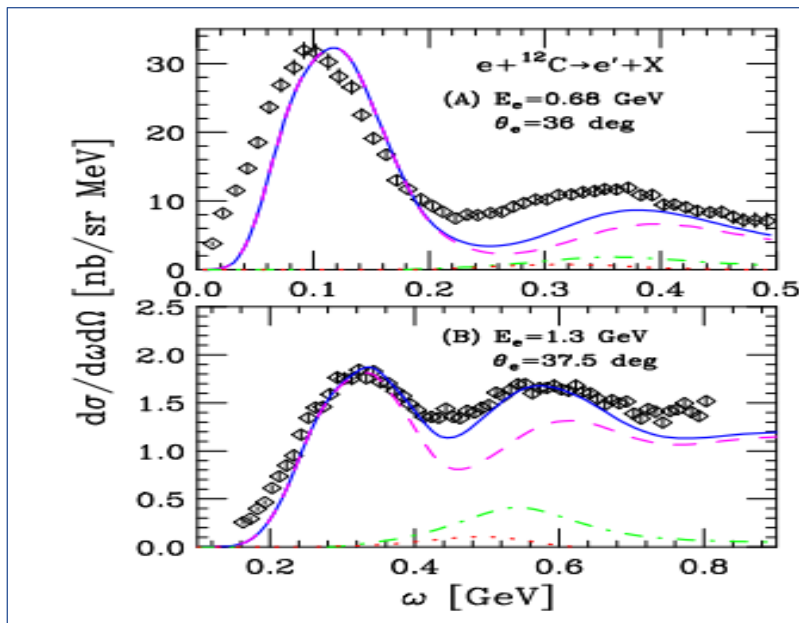


Figure 1: Double differential cross-section on ^{12}C showing the Quasielastic and Δ peaks. The solid line includes Meson Exchange Currents (MEC), which fill the kinematic "dip" (valley) between the peaks, while the dashed line neglects them

3. Statistical Weight

- **Contribution:** Accounts for up to 25% of the inclusive cross-section in the 1–3 GeV range.
- **Requirement:** Accurate 2p2h modeling is essential for percent-level energy scale calibration and to avoid biases in δ_{CP} extraction

Experimental Validation and Statistical Weight of 2p2h Currents Left

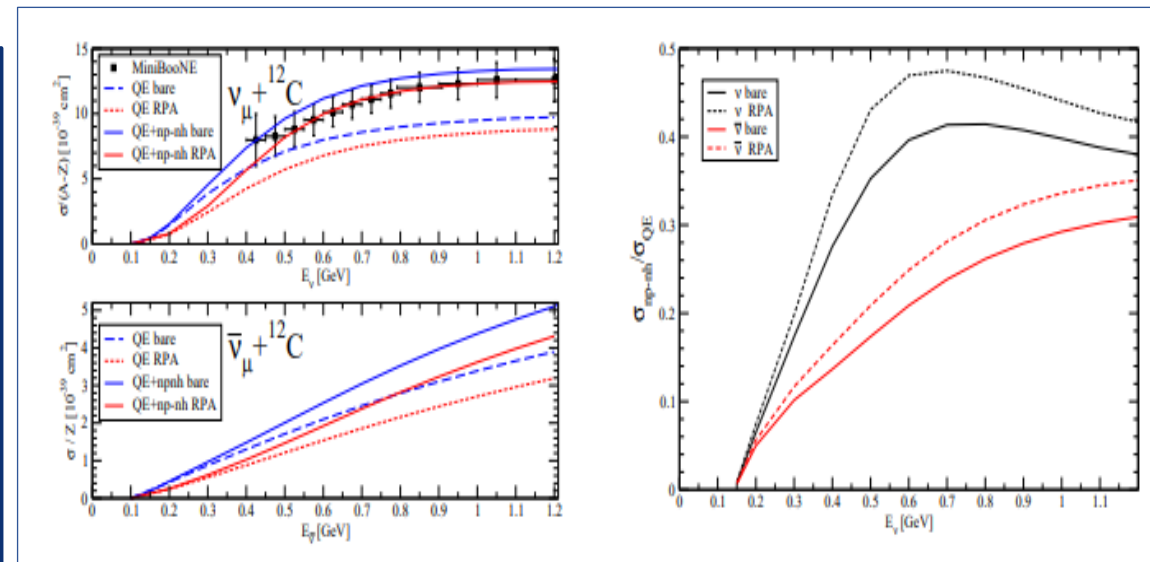


Figure 2: (Left) Comparison of the Valencia model with MiniBooNE data. The inclusion of multinucleon currents (np–nh) solid red line) is essential to describe the observed cross-section enhancement. (Right): Ratio of the 2p2h (multinucleon) component to the single-nucleon cross-section. At DUNE/T2K energies, this contribution represents 30% to 40% of the total CC0 π signal

Theoretical Model Divergence: Martini vs. Nieves

1. Structural Comparison of Leading Frameworks

- **Martini et al. (Lyon Model):** Relativistic RPA approach based on the Local Fermi Gas, predicting a significant transverse enhancement from 2p2h currents.
- **Nieves et al. (Valencia Model):** Also based on a Local Fermi Gas but incorporates a different treatment of Δ -hole excitations and nucleon self-energies, historically predicting a **lower 2p2h contribution** compared to the Martini framework.
- **Kinematic Coverage:** Both models are primarily validated in the Quasielastic (QE) and 2p2h regions but exhibit different extrapolation behaviors as energy transfer (ω) increases toward the resonance region

3. Path Toward Convergence

- **Recent Developments:** Integration of improved nucleon self-energies and consistent treatment of the axial sector are reducing the tension between these frameworks.
- **Experimental Role:** External data from **MINERvA** and **T2K** are currently being used to benchmark these models, though a universal preference has not yet been established

2. Impact on Oscillation Parameter Extraction

- **Parameter Sensitivity:** The choice between these two validated models can induce a shift of approximately **O(5%)** in the extracted value of $\sin^2\theta_{23}$.
- **Atmospheric Mass Splitting:** Discrepancies in the predicted energy "feed-down" lead to systematic variations in the reconstructed $|\Delta m^2_{31}|$, often exceeding the projected statistical uncertainty of next-generation experiments.
- **Model Dependence:** The absence of a unique theoretical consensus on the magnitude of 2p2h enhancement represents a leading source of model-dependent uncertainty in joint fits.

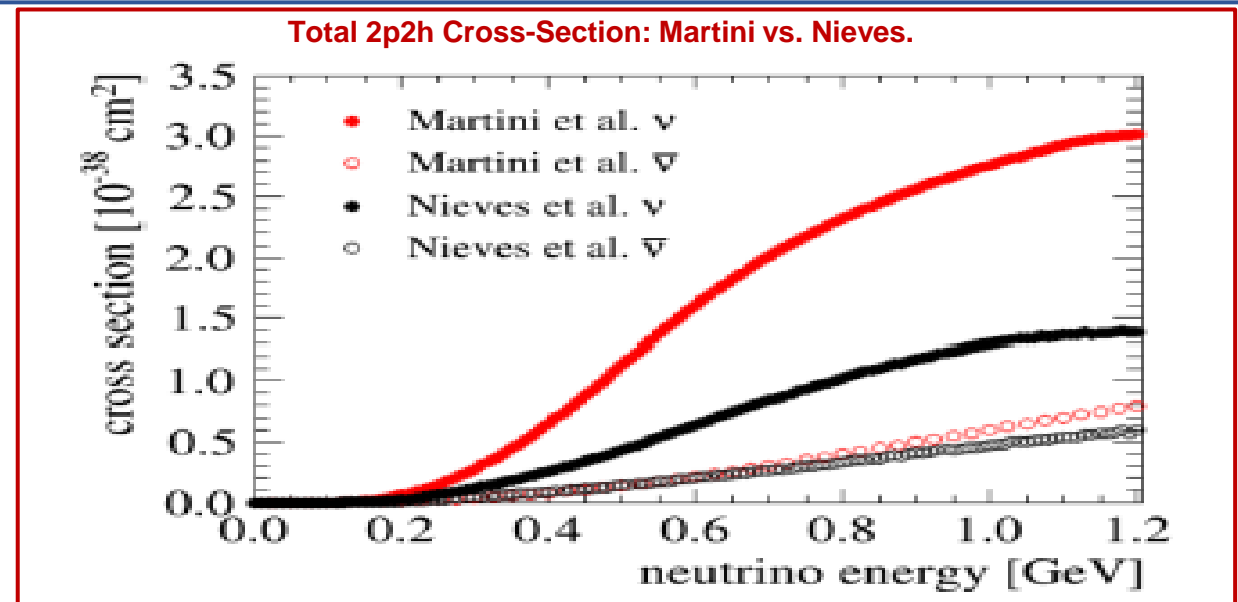


Figure: Comparison of multinucleon (2p2h) cross-section predictions as a function of neutrino energy. The significant discrepancy in normalization between the Martini (red) and Nieves (black) models represents a leading source of model-dependent uncertainty.

Final State Interactions (FSI) & Hadronic Transport

1. Mechanism: Post-Interaction Transport

- **Definition:** Produced hadrons (p , n , π) must traverse the dense nuclear medium before detection. FSI represent the re-scattering, absorption, or charge exchange of these particles within the residual nucleus.
- **Primary Processes:**
 - **Pion Absorption:** A pion produced at the vertex is absorbed, leading to a $CC1\pi \rightarrow CC0\pi$ topology migration.
 - **Charge Exchange:** Modification of the particle charge (e.g., $\pi^+ \rightarrow \pi^0$) altering the observed final state.

Nucleon Knock-out: Secondary nucleons are ejected through re-scattering, increasing the apparent hadronic multiplicity

3. Systematic Floor

- **Constraint:** Uncertainties in pion absorption cross-sections remain a significant contributor to the ν_e appearance systematic budget, as they directly affect the background-to-signal ratio.

2. Impact: Topology Migration & Energy Feed-down

- **Reconstruction Bias:** If a pion is absorbed, its rest mass and kinetic energy are partially lost to the nuclear system (transferred to undetected nuclear excitation energy).
- **Migration Matrix Distortion:** FSI smear the correlation between the true interaction type and the observed topology. This "energy feed-down" systematically shifts the reconstructed energy E_{rec} toward lower values, mimicking oscillation effects.
- **Modeling Frameworks:** FSI are typically simulated using **Intranuclear Cascade (INC)** models or transport equations (e.g., GiBUU), requiring precise benchmarking against hadron-nucleus scattering data.

Schematic Representation of Final State Interactions (FSI)

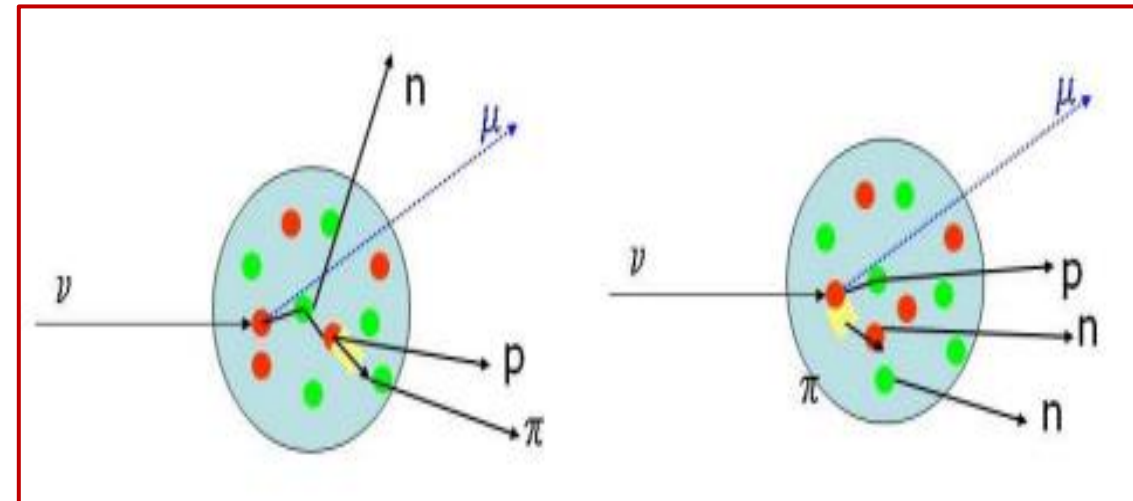


Figure: (Left): Typical FSI process where produced hadrons undergo re-scattering before exiting the nucleus. (Right): Pion absorption process, where a produced pion is thermalized within the nuclear medium, leading to a $CC1\pi \rightarrow CC0\pi$ topology migration and energy feed-down.

The Transition Regime: Shallow to Deep Inelastic Scattering (SIS/DIS)

1. Kinematic Context: Beyond the Resonance Peak

- **Definition:** The transition from discrete nucleon resonances (e.g., $\Delta(1232)$) to the continuum of **Deep Inelastic Scattering (DIS)**, typically occurring in the invariant mass range $1.7 < W < 2.0$ GeV.
- **Shallow Inelastic Scattering (SIS):** A region where perturbative QCD is not yet fully applicable and resonant descriptions become overly complex due to the high density of states.

2. Modeling Challenges & Hadronization

- **Non-Perturbative nPDFs:** Uncertainties in nuclear Parton Distribution Functions (nPDFs) at low Q^2 and the x-Bjorken transition region.
- **Hadronization Models:** Dependence on phenomenological frameworks (e.g., the **Lund string model** in PYTHIA) to describe the transition from partons to observable hadrons.

Duality: The requirement for "Quark-Hadron Duality" to ensure a smooth transition between the sum of resonances and the smooth DIS scaling curve.

3. Impact on DUNE & Background Predictions

• **Neutral Current (NC) Backgrounds:** SIS/DIS interactions are a primary source of high-multiplicity Neutral Current events, which can mimic ν_e appearance signals through π^0 production.

• **Energy Reconstruction:** Mismodeling the hadronic multiplicity and energy fraction in the DIS tail introduces non-linearities in the calorimetric energy scale, affecting the sensitivity to δ_{CP} .

Transition from Resonance Region to DIS Scaling

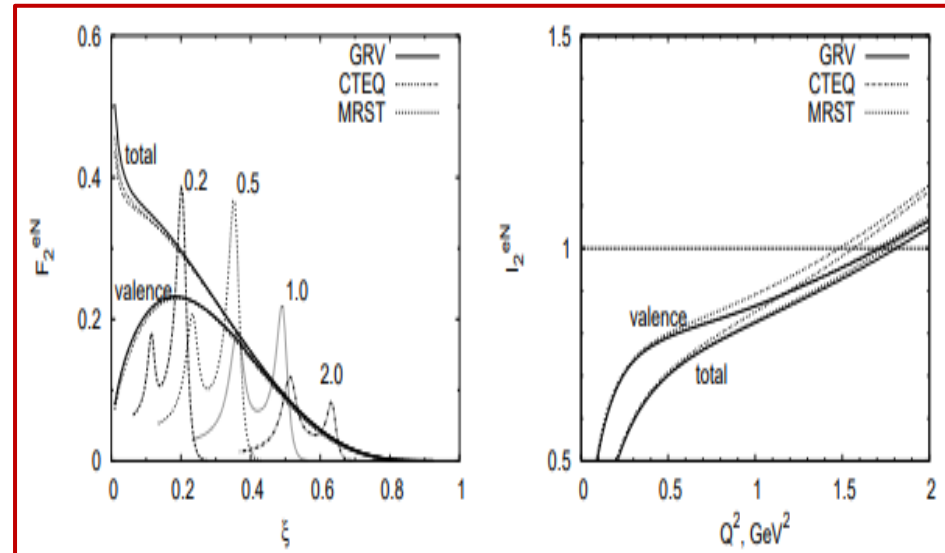
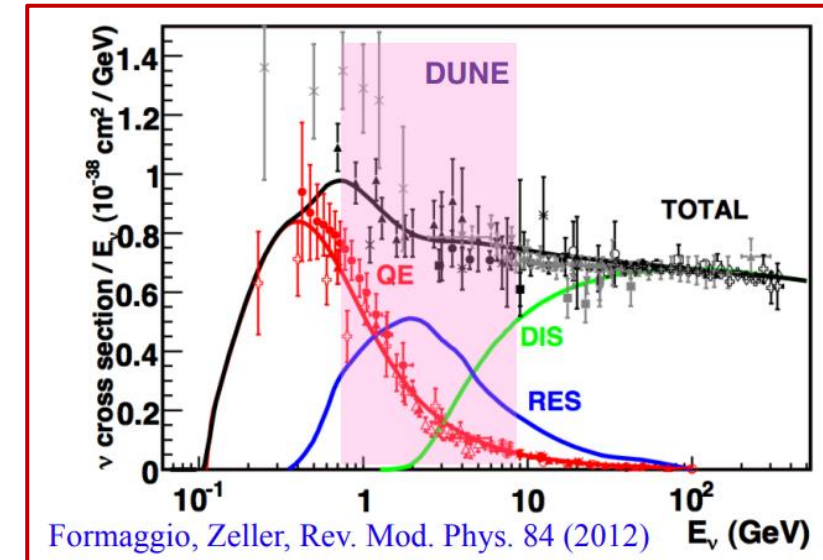


Figure 1: Left) Comparison of resonance-region F_2 data (peaks) and the DIS scaling limit (smooth curve) for $0.2 < Q^2 < 2.0$ GeV². (Right): Integrated ratio $I_2(Q^2)$ illustrating the onset of duality as the ratio approaches 1.0 at higher momentum transfer

Decomposition of the Neutrino Cross-Section in the DUNE Energy Regime



Formaggio, Zeller, Rev. Mod. Phys. 84 (2012)

Figure 2 Neutrino-nucleon cross-section components vs. DUNE flux. The shaded region indicates the DUNE energy envelope, showing the maximum overlap between Quasi-Elastic (red), Resonant (blue), and DIS (green) processes.

Transition toward Ab Initio Methods & First-Principles Theory

1. Limitations of Empirical Tuning

- **Legacy Approach:** Dependence on "ad hoc" parameters (e.g., axial mass M_A , 2p2h scaling factors) tuned to fit specific experimental datasets (MiniBooNE, T2K).
- **The Risk of Circularity:** Tuning models to current data may mask underlying physics deficiencies, leading to a loss of predictive power when extrapolated to different energy regimes or target nuclei $C \rightarrow Ar$.

3. Many-Body Ab Initio Frameworks

- **Green's Function Monte Carlo (GFMC) & VMC:** Solving the Schrödinger equation for nuclei $A \leq 12$ using high-precision nucleon-nucleon potentials.
- **Chiral Effective Field Theory χ EFT :** A systematic expansion providing consistent one- and two-body currents, now being extended to heavier systems like ^{40}Ar via Coupled-Cluster or In-Medium SRG methods.
- **Goal:** Transitioning toward **ACHILLES** and other next-generation generators that implement these parameter-free response functions.

2. Lattice QCD: Benchmarking the Axial Sector

- **Sub-percent Precision:** Lattice QCD calculations of the **nucleon axial form factor $g_A(Q^2)$** have achieved a precision level of $\approx 1\%$

Impact: This reduces the historical reliance on phenomenological dipole parameterizations provides a parameter-free frameworks for the axial-vector current at the nucleon level

Precision gain via Lattice QCD integration

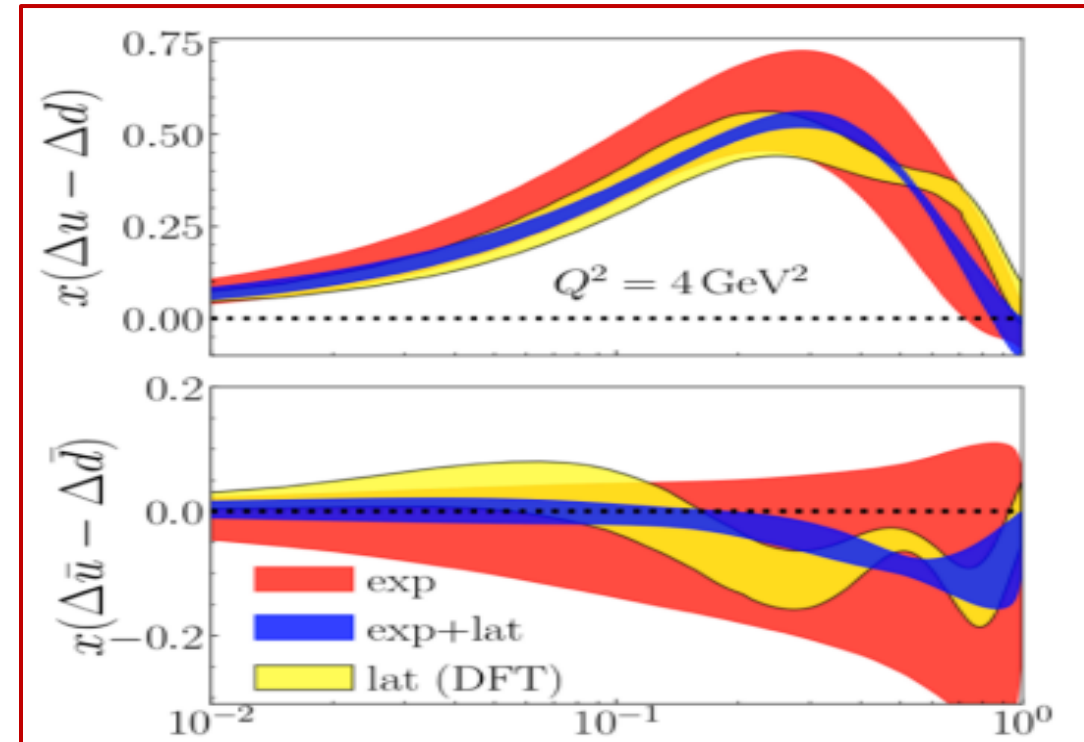


FIGURE Comparison of nucleon structure uncertainties using experimental data alone (red) versus the inclusion of first-principles Lattice QCD constraints (blue). The reduction in the error bands validates the transition toward a parameter-free theoretical foundation for neutrino-nucleus interactions.

The Event Generator Landscape: Bridging Theory & Data

1. Operational Role of Generators

- **Interface:** Generators translate microscopic nuclear cross-sections into fully differential final-state particle vectors (p , n , π) leptons) within detector simulations (Geant4).
- **The Factorization Assumption:** Most generators factorize the interaction into:
 1. **Initial Interaction:** Primarily Quasielastic (QE), Resonance (RES), or DIS.
 2. **Intranuclear Cascade (INC):** Semiclassical transport of hadrons through the nuclear medium.
- **Irreducible Uncertainty:** The choice of generator and its internal model configuration (tunes) represents a leading source of model-dependent systematic uncertainty. [1]

2. Core Generators in the 2026 Landscape

- **GENIE (Standard Framework):** High modularity and extensive experimental interfaces. Utilizes "Global Fits" (Tunes) such as G18_10a to merge disparate nuclear models into a continuous energy range.
- **GiBUU (Transport Theory):** Replaces the cascade approximation with a consistent solution of the **Boltzmann-Uehling-Uhlenbeck (BUU)** equation. Ensures that the initial interaction and final-state transport occur within the same consistent nuclear potential.
- **NuWro (Spectral Function Focus):** A research-oriented framework emphasizing the implementation of advanced Spectral Functions (SF) and $2p2h$ current updates (Valencia/Martini models). [1, 2]

3. Impact on Oscillation Systematics

- **Topological Inconsistency:** Discrepancies in predicted proton multiplicities and pion absorption rates between GENIE and GiBUU lead to diverging estimates of the "energy feed-down," impacting the δ_{CP} discovery potential. [1]

GENIE vs GiBUU: Topology Predictions on Argon

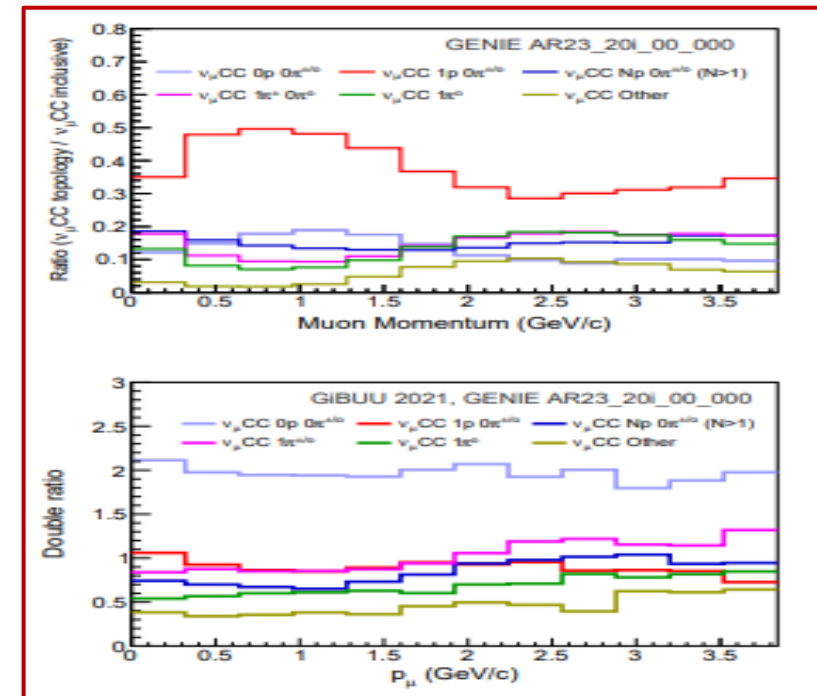


Figure: Predicted topological fractions for ν_μ CC interactions on Argon. The top panel shows the ratios of exclusive topologies (e.g., $0p0\pi$, $1p0\pi$) to the inclusive cross-section for GENIE AR23, respectively. The bottom panel displays the double ratio, revealing discrepancies of up to 100% in certain channels (notably $0p0\pi$). This highlights the significant model dependence in predicting event topologies and hadronic multiplicities

Global Benchmarking: Cross-Experimental Validation

1. Comparative Physics Framework

- **Decoupling Degeneracies:** Single-experiment analyses are intrinsically limited by the flux-cross-section convolution. Global benchmarking across different beams and targets is required to break these degeneracies.
- **Sensitivity to Target & Energy:**
 - **T2K vs. MicroBooNE:** Comparative study of Carbon (^{12}C) and Argon (^{40}Ar) at similar energies ($E_\nu \sim 0.6$ GeV) to isolate **A-dependence** of nuclear effects.
 - **T2K vs. MINERvA:** Comparison of narrow-band vs. wide-band flux responses on hydrocarbon targets to probe the **energy dependence** of 2p2h and resonance modeling

3. Next-Generation Standards: nuSCOPE

- **Status:** A CERN-based initiative (merged from ENUBET/NuTag) submitted to the **2026 ESPPU** (European Strategy for Particle Physics Update).
- **Objective:** Deployment of monitored and tagged neutrino beams to achieve **percent-level flux monitoring**, providing a flux-independent benchmark for neutrino-nucleus scattering. [1, 2]

13/05/2026

<https://arxiv.org/pdf/2503.21589>

2. Benchmarking via Transverse Kinematic Imbalance (TKI)

- **The TKI Probe:** Observables such as δp_t and $\delta \alpha_t$ provide a direct diagnostic of Fermi motion and Intranuclear Cascade (INC) physics.
- **Model Failure Identification:** Benchmarking reveals that while models (GENIE, NEUT) can fit inclusive data, they frequently fail to describe the correlated hadronic-leptonic phase space across disparate experiments

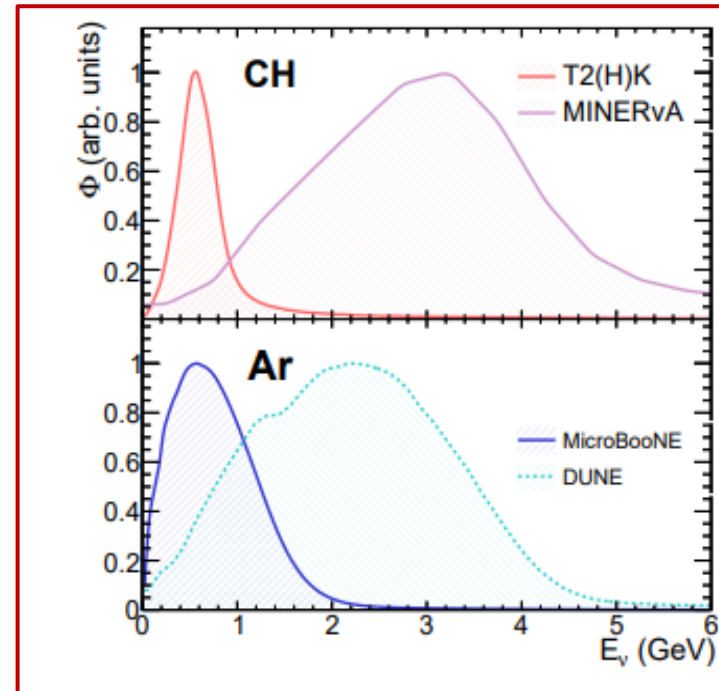


Figure 1: Neutrino Flux Landscape. Comparison of incoming flux shapes for CH (T2K, MINERvA) and Argon (MicroBooNE, DUNE) targets across the 0.5-5 GeV regime.

Figure 1: Neutrino Flux Landscape.

Comparison of incoming flux shapes for CH (T2K, MINERvA) and Argon (MicroBooNE, DUNE) targets

I. El Atmani -- QMUL PRPC Series 10

<https://arxiv.org/pdf/2407.10962>

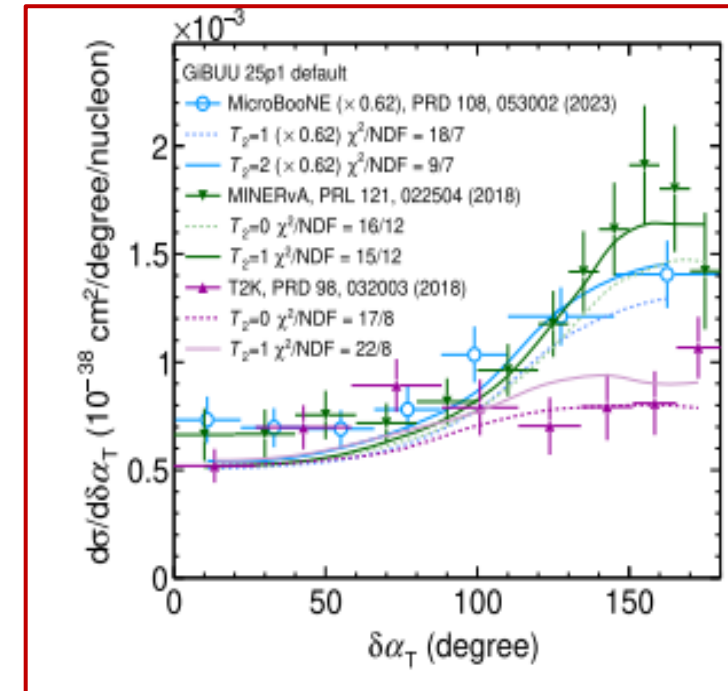


Figure 2: TKI Benchmarking ($\delta \alpha_t$). Cross-target validation of GiBUU predictions. The 0.62 scaling factor for MicroBooNE highlights the current irreducible flux and normalization uncertainties.

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ACHILLES: A Quantum Kinetic Framework for Event Generation

1. Theoretical Foundation: Beyond Semiclassical Approximations

- **Framework:** ACHILLES (A χ EFT Based Interaction and Lepton-nucleus Event Simulator) represents a transition toward a consistent **Quantum Kinetic Theory** approach.
- **Relativistic Consistency:** Unlike legacy generators that rely on non-relativistic or hybrid approximations, ACHILLES is designed to maintain Lorentz covariance at the interaction vertex and throughout the transport process.
- **Modular Architecture:** Systematic separation of the leptonic current, the nuclear spectral functions, and the hadronic final-state interactions (FSI) within a unified Many-Body framework.

2. Integration of First-Principles Inputs

- **Axial Sector:** Incorporation of **Lattice QCD** results for the nucleon axial form factor, reducing the dependence on empirical dipole parameterizations.
- **Nuclear Response:** Implementation of response functions derived from **Chiral Effective Field Theory (χ EFT)**, providing a systematic expansion of one- and two-body (2p2h) currents.
- **Consistency:** The transport phase is benchmarked against electron-scattering data to ensure that the vector sector of the nuclear medium response is constrained before extending to the neutrino axial sector.

3. Methodological Significance for DUNE/HK

- **Parameter-Free Modeling:** The objective is to provide a generator where the systematic uncertainties are derived from theoretical truncation errors (e.g., in χ EFT) rather than ad-hoc experimental tuning.
- **Energy Reconstruction:** By ensuring exact energy-momentum conservation in a relativistic framework, ACHILLES aims to minimize the "energy feed-down" biases inherent in semiclassical intranuclear cascade models

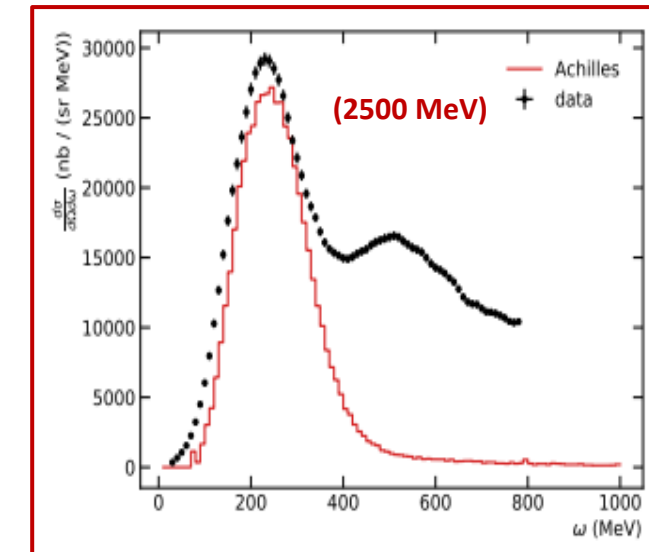
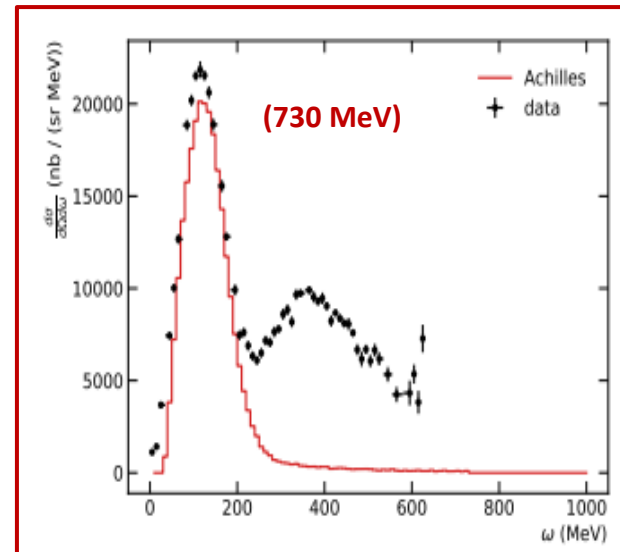


Figure : ACHILLES Validation against Electron-Carbon Data.

Comparison of the ACHILLES event generator to inclusive $e^{-12}\text{C}$ scattering data. The high level of agreement in the quasielastic peak demonstrates the robustness of the first-principles nuclear modeling.

Electron-Scattering Benchmarks: The e4nu Program

1. Methodology: Vector Current Validation

- **Principle:** Exploiting the conservation of the vector current (CVC) to test the vector sector of neutrino-nucleus interaction models using monochromatic electron beams.
- **The e4nu Initiative:** Utilizing the **CLAS/CLAS12** spectrometers at Jefferson Lab to measure exclusive final states (e, e'p), (e, e'n), (e, e'pπ) on neutrino-relevant targets (⁴He, ¹²C, ¹⁶O, ⁴⁰Ar).
- **Known Beam Energy:** Unlike neutrino beams, the incident electron energy is precisely determined, allowing for a direct quantification of energy reconstruction biases. [1]

3. Significance for Oscillation Physics

- **Systematic Constraint:** Failure to reconstruct a monochromatic electron beam energy within 1% implies an inherent bias in the neutrino oscillation analysis.
- **Impact:** e4nu provides the required hadronic-leptonic phase space mapping to validate the intranuclear cascade and 2p2h implementations before their application to the axial sector

2. Observed Model Deficiencies

- **Energy Reconstruction Bias:** Analysis of CLAS data at $E_{\text{beam}} = 1.1\text{-}4.4$ GeV reveals significant "low-energy tails" in the reconstructed spectrum. Even in the simplest (1p0π) (quasielastic-like) topology, existing generators (GENIE, GiBUU) fail to recover the peak energy for a substantial fraction of events.
- **Argon Modeling Gap:** Until recently, high-precision electron-argon scattering data were non-existent. New results from **JLab E12-14-012** are now being used to construct data-driven Spectral Functions specifically for DUNE.

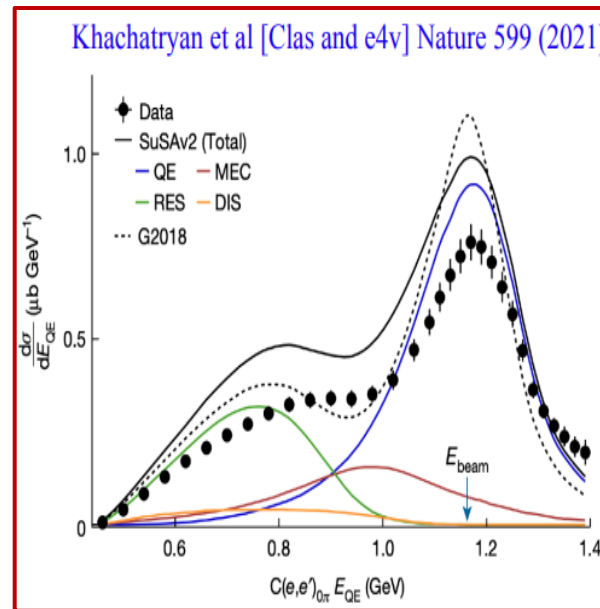


Figure 1: e4nu Energy Reconstruction Benchmarks. Reconstructed energy for a 1.16 GeV electron beam on Carbon. Discrepancies between Data (points) and G2018 (dashed line) reveal a failure to recover the peak energy, highlighting intrinsic reconstruction biases.

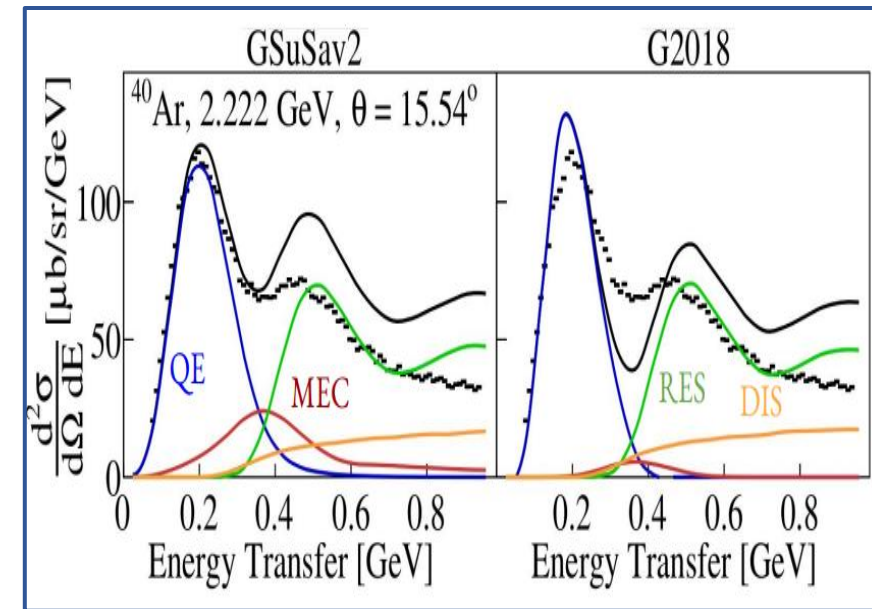


Figure 2: Closing the Argon Modeling Gap. Inclusive Ar(e,e') cross-sections at 2.22 GeV. The persistent discrepancies in the resonance (RES) and dip regions across GENIE versions (GSuSAv2 vs G2018) underscore the need for improved modeling specifically for DUNE.

Resolving the MiniBooNE Low-Energy Excess (LEE)

1. The MiniBooNE Anomaly (Historical Context)

- **Observation:** A significant excess of electron-like events (4.8σ) observed in the low-energy region (200–600 MeV) by the MiniBooNE experiment.
- **Initial Hypotheses:** Proposed interpretations included a 3+1 sterile neutrino model or exotic Beyond Standard Model (BSM) photon-producing processes.
- **Limitation:** MiniBooNE, a mineral oil Cherenkov detector, could not distinguish between electron tracks and photon-induced showers (e/γ) separation).

3. Implications for Future Searches

- **Standard Model Robustness:** The resolution of the LEE reinforces the 3-flavor paradigm while highlighting the risks of "spurious" discovery signals arising from underestimated nuclear systematics.
- **SBN Program:** These results define the baseline for the Short-Baseline Neutrino (SBN) program (SBND, MicroBooNE, ICARUS) to search for more subtle BSM signatures.

2. MicroBooNE Results & Signal Decomposition

- **LArTPC Advantage:** MicroBooNE utilized the Liquid Argon TPC technology to provide high-resolution imaging, enabling a definitive separation between electrons (dE/dx) and photons (gap identification).
- **Principal Findings (Status):**
 - **ν_e Interpretation:** No significant excess of electron neutrinos was observed, disfavoring the standard sterile neutrino explanation for the LEE.
 - **Photon Backgrounds:** The excess is consistent with a combination of standard neutral current (NC) $\Delta \rightarrow N\gamma$ processes and mismodeled nuclear backgrounds.
- **Nuclear Influence:** The "excess" is now largely reclassified as a challenge in modeling low-energy neutrino-nucleus interactions, specifically in the resonance and 2p2h overlap regions.

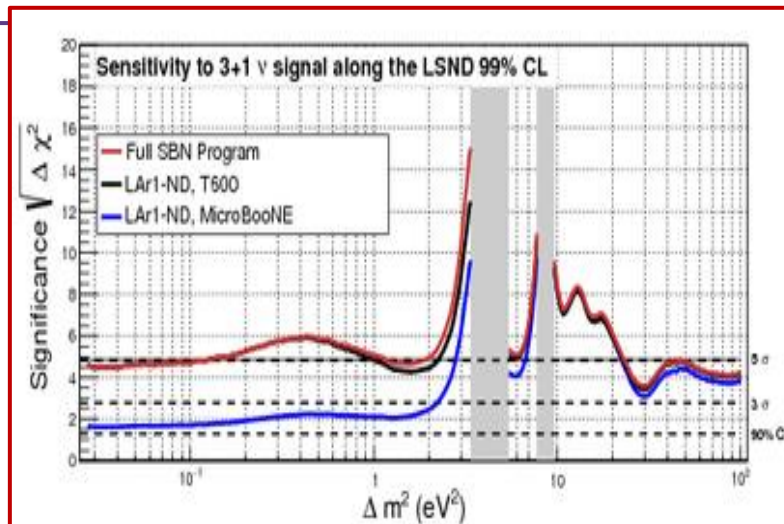


Figure 2 (SBN Sensitivity): "Sensitivity of the full SBN program (SBND, MicroBooNE, ICARUS). The 5 σ threshold is reached across the LSND-allowed region."

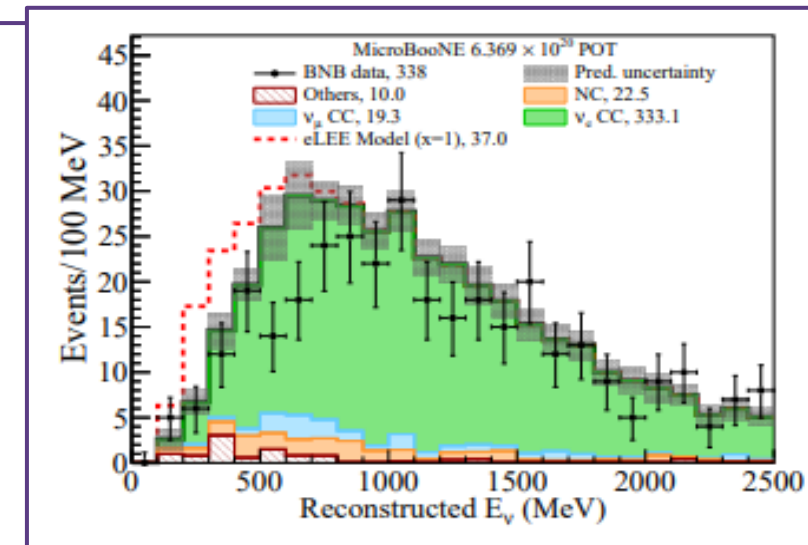


Figure 1 MicroBooNE Result
Reconstructed ν_e spectrum rejecting the eLEE hypothesis (dashed red line) in favor of the Standard Model.

Inclusive vs. Exclusive Measurements: Hadronic Multiplicity Tensions

1. Observational Hierarchy

- **Inclusive Cross-Sections:** Focus solely on the kinematics of the outgoing lepton (μ^\pm). These measurements are relatively robust as they integrate over all nuclear final states.
- **Exclusive/Semi-Inclusive Cross-Sections:** Focus on the full final-state topology, including the number and momentum of protons, pions, and neutrons.
- **The Discrepancy:** Models that successfully reproduce inclusive data (T2K/MINERvA) frequently fail to predict exclusive hadronic distributions, particularly **proton multiplicities** and correlated hadron-lepton kinematics.

2. Impact on Calorimetric Energy Reconstruction

- **Energy Fractioning:** Neutrino energy reconstruction in LArTPCs (DUNE) and Water Cherenkov detectors (HK) relies on the sum of the energies of all detected particles.
- **The Hadronic Gap:** Mismodeling the proton multiplicity leads to an incorrect energy assignment. If a model over-predicts the number of low-energy protons below the detection threshold, the "invisible" hadronic energy is underestimated.
- **Systematic Bias:** This inclusive-exclusive tension introduces non-linearities in the energy scale. A model "tuned" to fit inclusive data may still possess a 5–10% bias in its exclusive energy mapping, which is sufficient to shift the extracted value of δ_{CP}

3. Current Status

- **MicroBooNE & MINERvA Observations:** Recent datasets show a persistent under-prediction of multi-proton final states in standard generators.
- **Methodological Shift:** Transitioning toward **exclusive-based tuning** where generators are benchmarked against the full hadronic phase space to ensure energy conservation at the vertex.

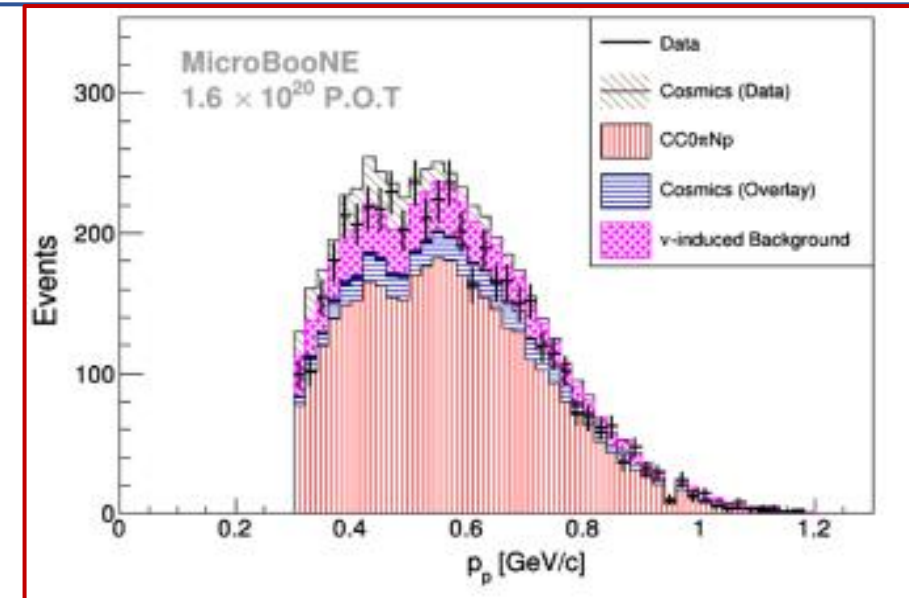


Figure: **Leading proton momentum (p_p) distribution in ν_μ -Ar interactions.** MicroBooNE data (points) vs. GENIE simulation (stacked colors). The discrepancies between data and model, particularly in the peak region, highlight the "hadronic gap" and the difficulty of accurately partitioning energy between the lepton and final-state nucleons.

Transverse Kinematic Imbalance (TKI): Diagnostic Observables

1. Formalism of Transverse Variables

- Definition:** In a neutrino-free-nucleon interaction, the outgoing lepton and proton are balanced in the transverse plane. TKI variables measure the deviation from this balance:
 - δp_t (**Transverse Momentum Imbalance**): The magnitude of the missing transverse momentum.
 - $\delta \phi_t$ (**Transverse Coplanarity Angle**): The angular deviation from back-to-back emission.
 - $\delta \alpha_t$ (**Transverse Acceleration Angle**): Probes the direction of the imbalance.
- Physical Sensitivity:** These variables are designed to be independent of the neutrino energy, making them pure probes of the nuclear environment.

2. Separation of Nuclear Effects

- The "Peak" Region ($\delta p_t \rightarrow 0$):** Dominated by Fermi motion in Quasielastic (QE) scattering. The width of the peak provides a direct measure of the nuclear Fermi momentum (k_F).
- The "Tail" Region (High δp_t):** Driven by non-QE dynamics:
 - 2p2h / MEC:** Interactions with correlated pairs increase the imbalance.
 - Final State Interactions (FSI):** Re-scattering of the proton within the nucleus "smears" the momentum and angle, populating the high- δp_t tail.

3. Benchmarking Generator Performance

- Model Discrimination:** TKI variables provide a high-resolution test for Intranuclear Cascade (INC) models.
- Current Observation:** Most generators (GENIE, NEUT) consistently under-predict the tail region, indicating an incomplete description of multinucleon correlations or FSI strength.

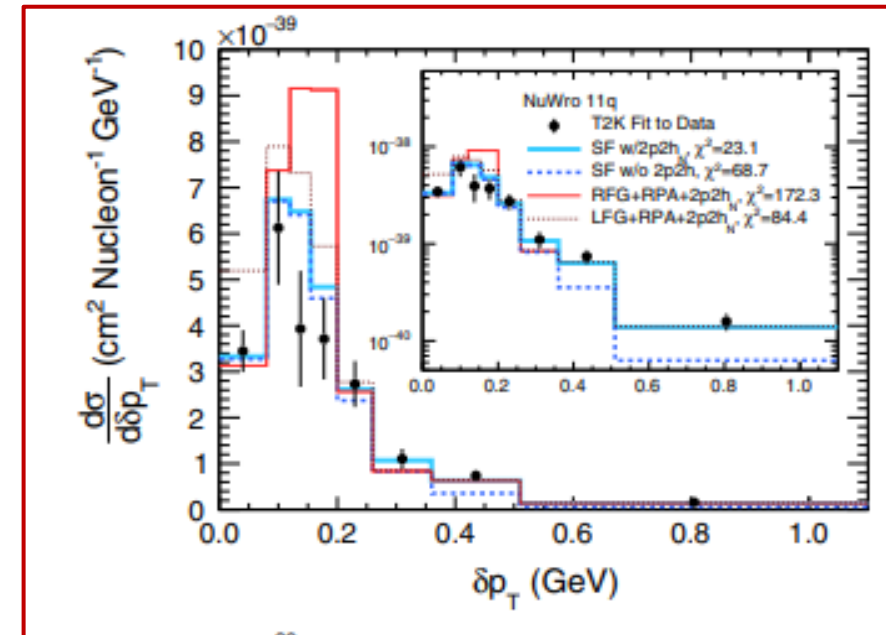


Figure: Differential cross-section as a function of δp_t .
 The distribution is compared against various initial-state models (RFG, LFG, SF). The low- δp_t peak corresponds to the Fermi motion of the initial nucleon, while the high- δp_t tail (beyond 0.2 GeV/c) provides a direct diagnostic for non-quasielastic processes like 2p2h and Final State Interactions (FSI).

Pion Production Tensions & Δ Resonance Modeling

1. Physical Channel: The Resonance Regime

- **Mechanism:** Neutrino-induced excitation of the nucleon into a resonance state, primarily the $\Delta(1232)$, followed by its decay into a nucleon and a pion ($N\pi$)
- **Significance:** At the energy scales of DUNE and Hyper-K, pion production represents approximately **30–40%** of the total event rate. It is the dominant process in the "transition" region between Quasielastic and DIS

2. Persistent Modeling Tensions

- **The MINERvA/T2K Discrepancy:** Datasets from different experiments show unresolved tensions in the absolute normalization and spectral shape of pion production.
- **Nuclear Medium Effects:** The Δ width and mass are modified within the nuclear environment (collisional broadening). Mismodeling these "in-medium" effects leads to a biased energy-to-momentum mapping.
- **Pion Absorption & Feed-down:** As discussed, the non-detection of pions due to absorption (FSI) causes CC1 π events to be misclassified as CC0 π . This **topology migration** is a primary source of systematic bias in ν_e appearance searches.

3. Impact on CP Violation Sensitivity

- **Background Contamination:** Neutral Current (NC) pion production $\nu + A \rightarrow \nu + A + \pi^0$ is the leading background for ν_e appearance, as the $\pi^0 \rightarrow \gamma\gamma$ decay can mimic an electron shower.
- **Systematic Limit:** Uncertainties in the π/p ratio and pion energy spectra directly propagate into the δ_{CP} sensitivity, setting a precision floor that currently exceeds 5%.

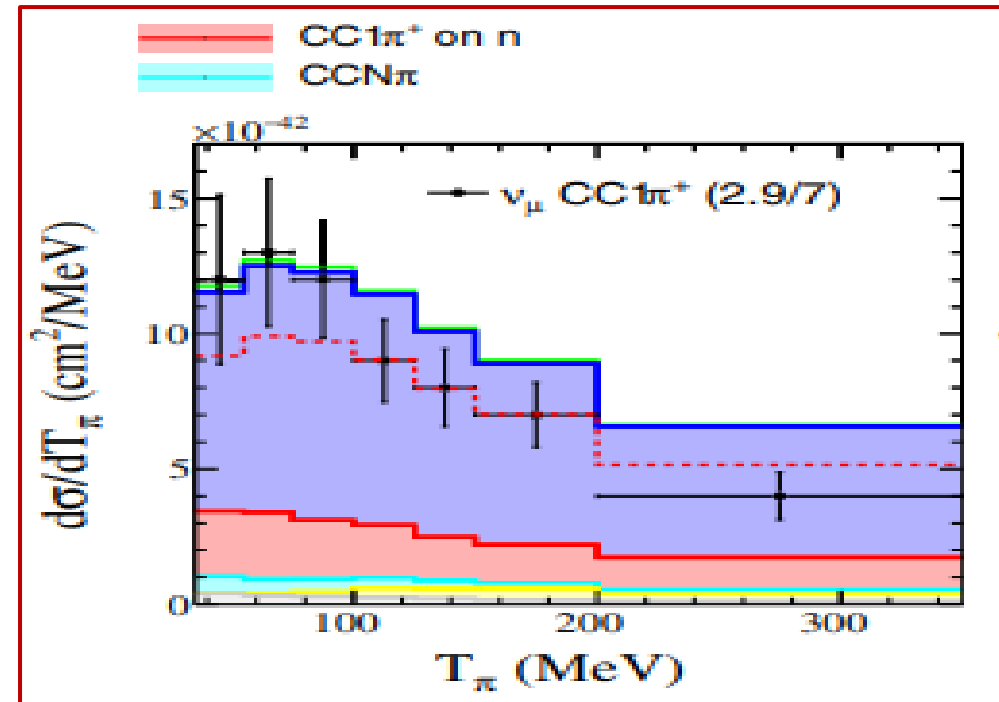


Figure: Differential cross-section $d\sigma/dT_\pi$ for CC1 π^+ production.

Comparison between MINERvA data (black points) and the GENIE model (stacked colors). The visible over-prediction by the model in the 100–200 MeV region highlights the difficulty in capturing the Δ -resonance width and pion absorption (FSI) within the nuclear medium.

Neutron Multiplicity & The "Missing Energy" Budget

1. The Invisible Hadronic Component

- **Energy Fraction:** Neutrons carry a significant portion of the total hadronic energy, particularly in antineutrino interactions ($\bar{\nu} + p \rightarrow \mu^+ + n$) where they can account for **15% to 30%** of the energy budget.
- **Detection Limitation:** In LArTPCs (DUNE), neutrons are primarily detected through secondary scatters, which are often spatially displaced from the primary vertex. In Water Cherenkov detectors (HK), they remain invisible unless captured by a nucleus (e.g., Gd or H).
- **The "Ghost" Component:** Because of low detection efficiency and the lack of charge, neutrons represent the most difficult component to calibrate in calorimetric energy reconstruction.

2. Model Dependency & Multiplicity

- **2p2h Influence:** The production of neutrons is highly sensitive to the underlying nuclear model. Discrepancies between frameworks (e.g., GENIE vs. GiBUU) show up to a **40% variation** in predicted neutron multiplicities for multinucleon interactions.
- **Binding Energy & Release:** Uncertainties in the average energy required to remove a neutron from the Argon or Oxygen nucleus directly shift the reconstructed neutrino energy peak.

3. Impact on CP Violation Sensitivity

- **$\nu/\bar{\nu}$ Asymmetry:** Since neutrons are more prevalent in antineutrino mode, mismodeling their energy contribution introduces a systematic difference between ν_e and $\bar{\nu}_e$ appearance rates.
- **Systematic Bias:** This "energy feed-down" creates a spurious asymmetry that can be misidentified as a leptonic CP-violation signal.

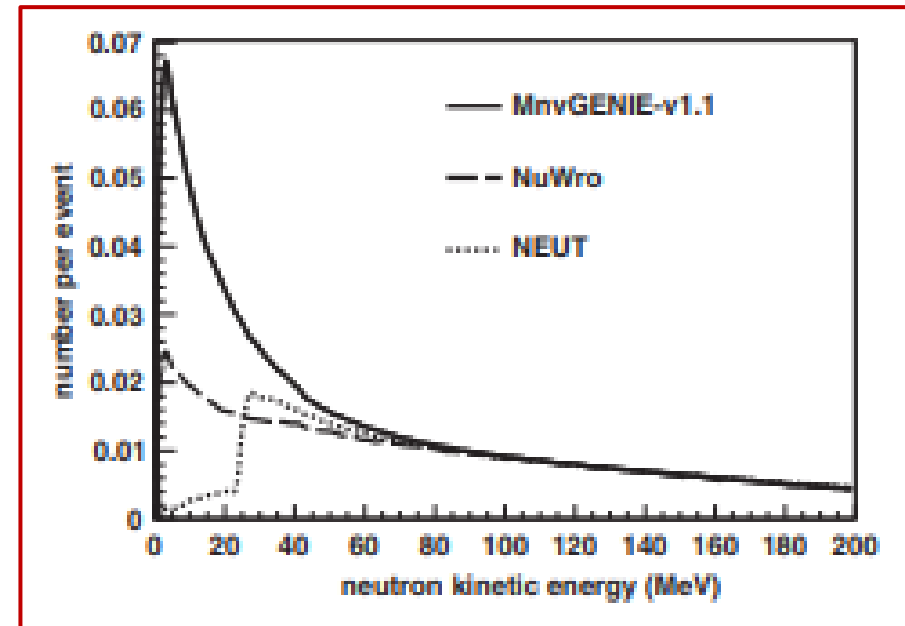


Figure : Predicted neutron kinetic energy spectra
Comparison between the GENIE, NuWro, and NEUT generators for 3 GeV antineutrinos. The massive spread in predictions for low-energy neutrons (< 50 MeV) illustrates the primary systematic challenge in calorimetric energy reconstruction.

QED Radiative Corrections (Percent-Level Regime)

1. Requirement for Sub-2% Precision

- **The Precision Floor:** As statistical errors drop to 1%, sub-percent QED effects (bremsstrahlung, virtual photon loops) become a dominant systematic limitation.
- **Kinematic Distortion:** Radiative effects modify the final-state lepton energy and angular distributions, directly shifting the reconstructed Q^2 and E_ν

2. Non-Universality & Flavor Bias

- **Flavor Dependence:** Corrections are **non-universal** between electron (ν_e) and muon (ν_μ) channels due to the large lepton mass difference (m_e vs. m_μ)
- **Residual Systematic:** Because these effects do not cancel in oscillation ratios $P(\nu_\mu \rightarrow \nu_e)$ they introduce a direct, flavor-dependent bias in the δ_{CP} phase extraction.

3. Implementation Status

- **Generator Integration:** Advanced radiative correction treatments are now standardized in **GENIE v3.4+** and next-generation frameworks like **ACHILLES** to meet the requirements of DUNE and Hyper-K.
- **Strategy:** Moving from simple "tree-level" physics to a full simulation chain that includes many-body electroweak effects.

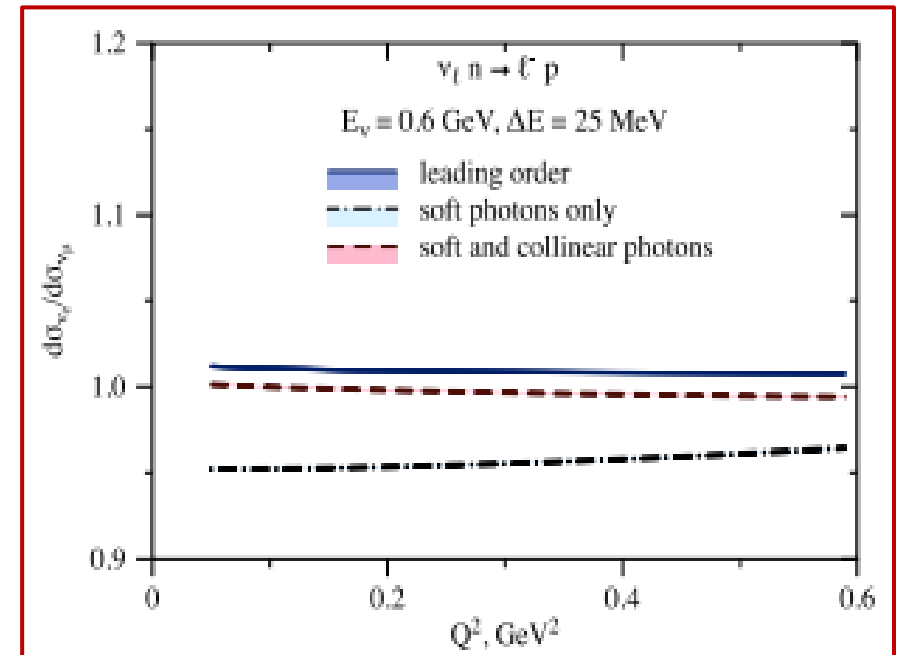
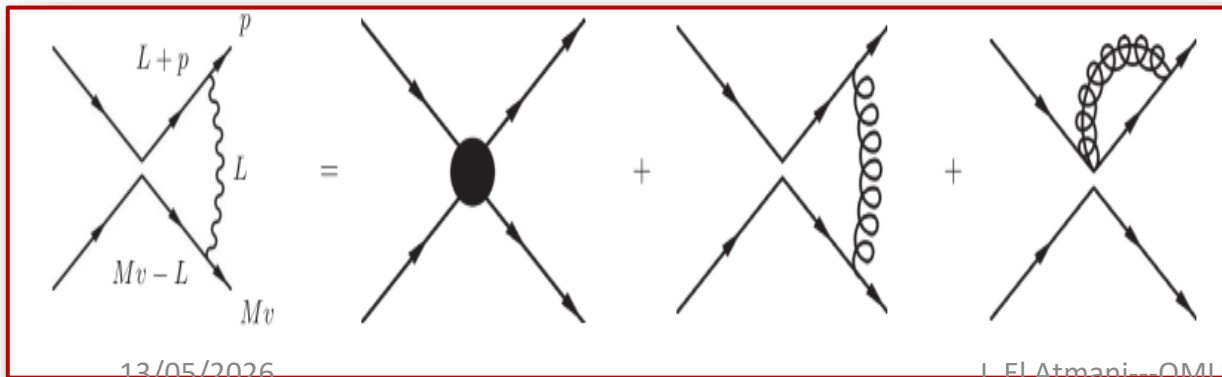


Figure : First-principles electroweak corrections. **Top:** Flavor non-universality in the ν_e/ν_μ cross-section ratio. **Bottom:** SCET factorization definition into hard, soft, and collinear regions

DUNE-PRISM: Flux Sampling & Model Independence

1. Methodology: Off-Axis Spectral Sampling

- **Mechanism:** Physical displacement of the DUNE Near Detector (ND-LAr and ND-GAr) up to 30 meters transversally to the beam axis.
- **Spectral Variation:** Sampling the neutrino flux at different angles provides access to varying energy spectra, shifting the peak toward lower energies as the off-axis angle increases.
- **The PRISM Objective:** Decoupling the neutrino flux from the interaction cross-section by characterizing the detector response across a wide range of incident energies.

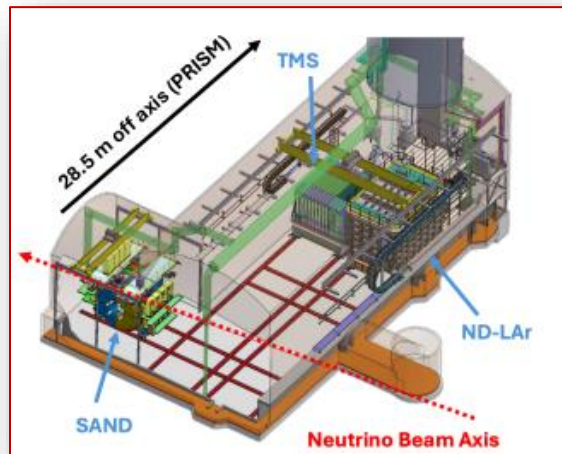


Figure 1: DUNE Near Detector Hall and PR(Detector ISM Movement. Schematic of the DUNE Near Detector complex (ND-LAr, TMS, and SAND).

3. Impact on Oscillation Systematics

Constraint: PRISM is the primary tool for mitigating the "convolution problem", targeting a reduction of energy-scale-induced biases in the δ_{CP} phase to below the statistical threshold.

2. Linear Combinations & "Gaussian" Fluxes

- **Data-Driven Flux Matching:** Taking linear combinations of different off-axis measurements to construct an effective "quasi-monoenergetic" neutrino response.
- **Model Independence:** This technique allows the prediction of the Far Detector signal using Near Detector data directly, minimizing the reliance on flawed theoretical cross-section models for the energy-mapping.
- **Direct Mapping:** Enables a robust determination of the relationship between true neutrino energy E_{true} and reconstructed energy E_{rec} .

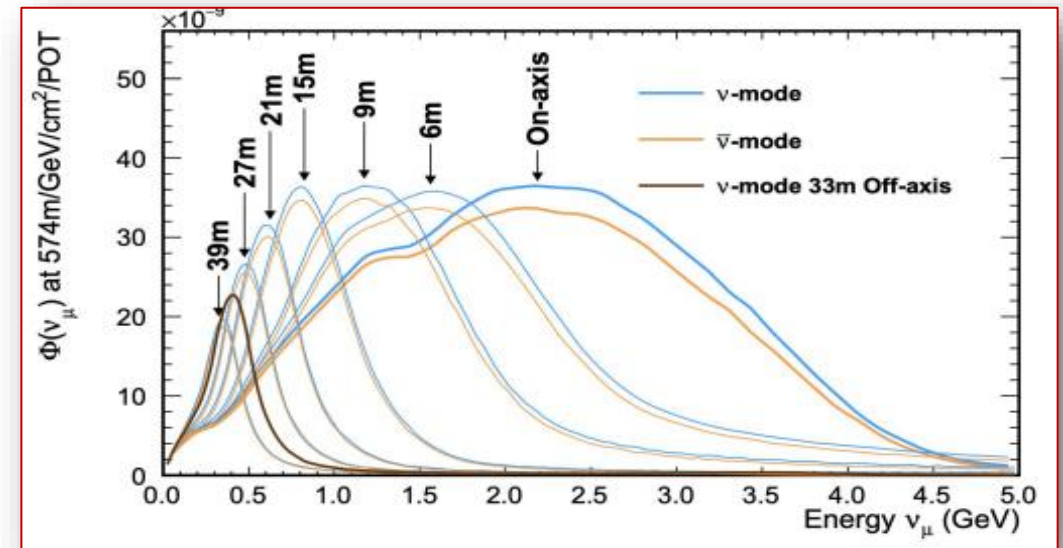


Figure 2: Off-Axis Neutrino Flux Evolution.

Muon neutrino flux spectra simulated at various off-axis positions. As the detector moves further from the beam axis (up to 39m), the energy spectrum narrows and the peak systematically shifts to lower energies.

Data-Driven Extrapolation: Near-to-Far Flux Constraints

1. The Near-to-Far (N/F) Ratio Methodology

- **Traditional Approach:** Relies on a double-ratio method where flux and cross-section uncertainties are assumed to cancel between the Near Detector (ND) and Far Detector (FD).
- **Limitation:** The cancellation is imperfect due to spectral differences (oscillations at FD), geometric acceptance, and potential target nucleus variance CH \rightarrow Ar

PRISM Enhancement: By utilizing multi-angle flux sampling, DUNE-PRISM allows for the reconstruction of an "oscillated-like" spectrum at the Near Detector, providing a direct measurement of the response for the energy bins relevant to the FD analysis

3. Impact on the Systematic Budget

- **Objective:** Targeting a reduction of the flux-induced systematic error on the oscillation parameters to a level below 2%.

Status : The integration of PRISM sampling with NA61/SHINE hadron production data establishes a data-driven constraint that significantly narrows the covariance between energy bins

2. Spectral Reweighting & Flux Matching

- **Mechanism:** Linear combinations of off-axis data are used to match the predicted FD oscillated flux. This minimizes the reliance on a priori cross-section simulations $MFD = \sum w_i \cdot MND_i$
- **Residual Systematics:** Despite spectral matching, residual uncertainties persist from:
 - **ν_e/ν_μ Cross-Section Ratios:** The ND primarily constrains the ν_μ flux, requiring theoretical input for the ν_e appearance cross-section.
 - **Geometric Acceptance:** Differences in the point-source (ND) vs. extended-source (FD) kinematics.

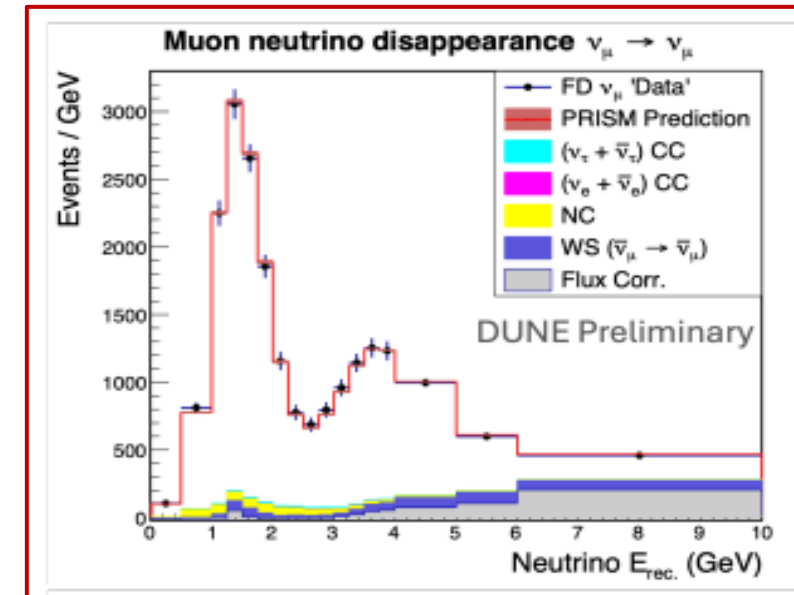
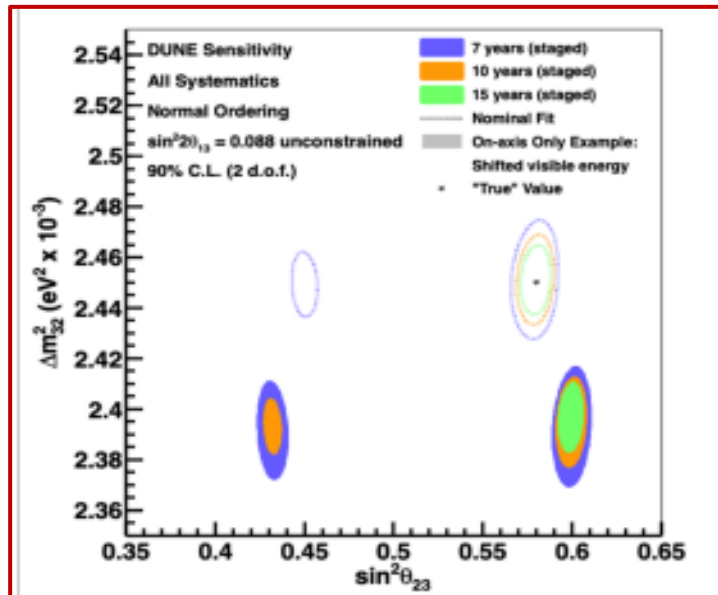


Figure: DUNE measurement of θ_{23} and Δm^2_{32} using the model dependent (left). Flux matching via DUNE-PRISM linear combination (right)

ND-GAr: Magnetized High-Pressure Gaseous Argon TPC

1. High-Resolution Vertex Reconstruction

- **Technology:** 1 ton fiducial mass of High-Pressure Gaseous Argon (HPgTPC) at 10 atm, integrated within a 0.5 T magnetic field and surrounded by a high-granularity electromagnetic calorimeter (ECAL).
- **Low-Threshold Advantage:** Unlike Liquid Argon (LAr), where the dense medium limits the track length of low-energy particles, the gaseous medium enables a **tracking threshold for protons down to < 5 MeV** (compared to ~30-50) MeV in LAr).
- **Hadronic Detail:** Direct sensitivity to low-energy hadronic stubs, which are critical for characterizing nuclear evaporation and (FSI).

2. Magnetic Spectrometry & Particle ID

- **Momentum Measurement:** The magnetic field allows for precise momentum determination via curvature, especially for particles that would be contained or stop in a LArTPC.
- **Sign Selection:** Enables the definitive separation of μ^+ vs. μ^- and π^+ vs. π^- a prerequisite for controlling the $\nu/\bar{\nu}$ flux asymmetry in CP violation analyses.

Electromagnetic Response: The ECAL allows for high-efficiency photon detection and π^0 reconstruction, reducing Neutral Current background uncertainties

3. Systematic Role in Phase II (Status)

Reference Dataset: Provides a "high-resolution" sample of neutrino-argon interactions with minimal secondary re-scattering, serving as a primary benchmark for validating the migration matrices $R(E_\nu, E_{rec})$ used across the DUNE complex

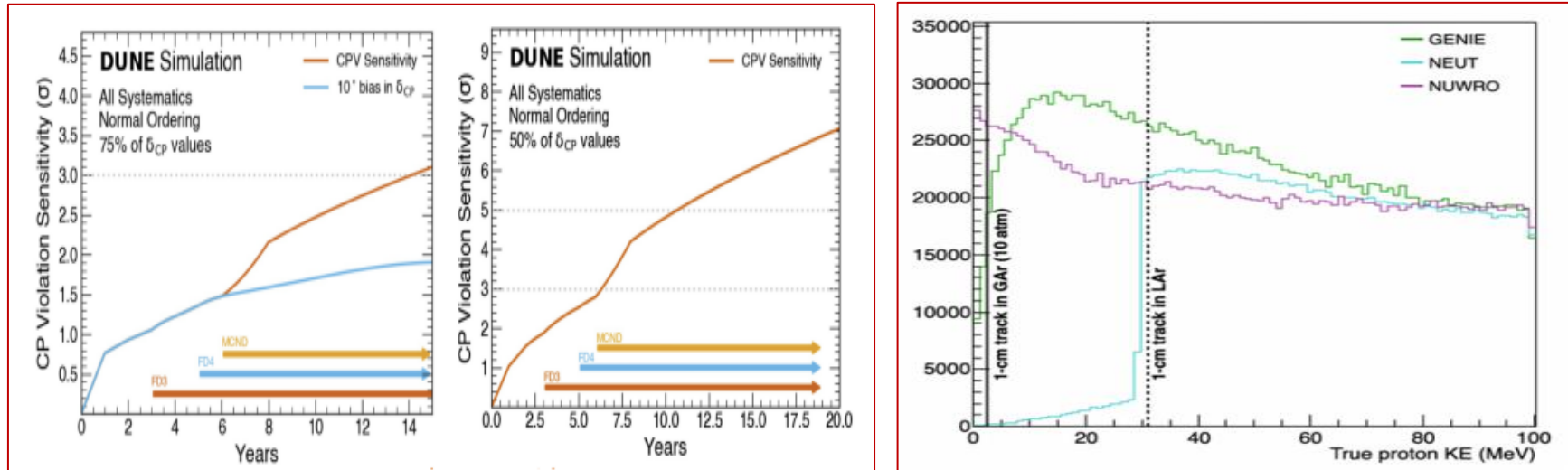


Figure : ND-GAr Physics Impact and Hadronic Thresholds. (Left) CP violation sensitivity over time, comparing Phase I vs. Phase II upgrades . (Right) Proton kinetic energy spectrum; vertical lines indicate 1-cm track thresholds, proving that the 10 atm gas TPC lowers the detection floor by a factor of 15 compared to liquid argon

SAND: Continuous On-Axis Monitoring & A-Dependence

1. Beam Stability & Normalization (System for On-Axis Neutrino Detection)

- **Mission** : Unlike mobile detectors (e.g., PRISM), SAND remains in a fixed position on the beam axis to ensure continuous (24/7) time monitoring of the neutrino energy spectrum.
- **Sensitivity** : It is capable of detecting beam anomalies (e.g., drift in the focusing horn current, misalignment of the target) within less than one week of data taking.
- **Components** : It reuses the 0.6 T solenoidal magnet and the electromagnetic calorimeter (ECAL) from the KLOE experiment, complemented by a new internal tracker (STT).

2. Multi-Target Strategy: Decoupling Nuclear Effects

- **Straw Tube Tracker (STT)** : A modular architecture alternating graphite (C) sheets and polymer (CH_2) targets.
- **Hydrogen measurement**: Using a statistical subtraction technique ($\text{CH}_2 - \text{C}$), SAND allows the isolation of neutrino interactions on pure hydrogen (free proton). This provides a measurement of the “naked” neutrino flux (free of nuclear effects) with sub-percent precision.
- **GRAIN (Granular Argon Target)** : A one-ton liquid argon volume placed upstream, enabling direct and immediate comparison with argon interactions measured by the other detectors in the complex.

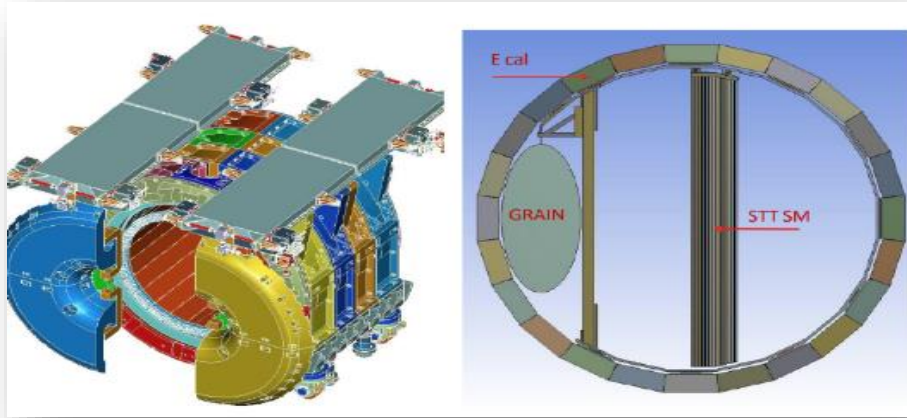


Figure 1: SAND Technical Layout and Sub-systems.

3. Impact on Systematics

Isospin Constraint: The study of the A-dependence (from H to Ar) allows validating nuclear transport models and verifying the consistency of oscillation parameters extracted on different targets.

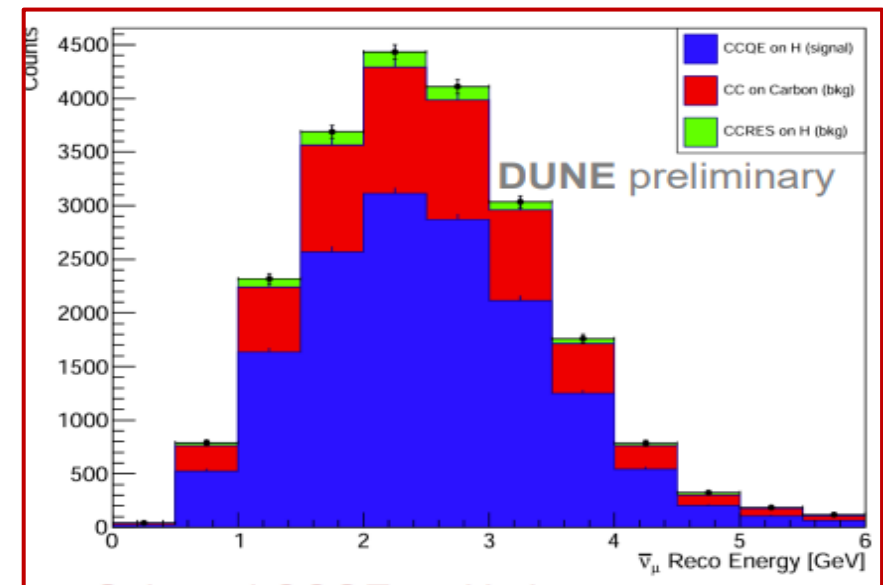


Figure 2: **Target Component Decomposition and Hydrogen Extraction.** Reconstructed neutrino energy spectrum within SAND. The statistical subtraction technique isolate the pure ν -Hydrogen CCQE interaction sample (blue) by subtracting the dominant, nuclear-smeared Carbon background (red).

Slide 29 — Hyper-Kamiokande: IWCD & Gadolinium-Loading Strategy

1. IWCD: Intermediate Water Cherenkov Detector

- **Mechanism:** A 1 kt-scale Water Cherenkov detector located approximately 1 km from the J-PARC production target.
- **Vertical PRISM Capability:** Utilizing a moving structure to scan off-axis angles from 1.5° to 4.0° , sampling varying neutrino energy spectra peaked between 0.4 GeV and 1.0 GeV.
- **Vertex Resolution:** Equipped with multi-PMT (mPMT) modules providing superior timing and spatial resolution for high-precision neutrino-nucleus interaction vertexing.
- **Goal:** Direct experimental constraint of the relationship between lepton kinematics and true neutrino energy E_ν specifically for water H_2O targets. [1]

3. Impact on Oscillation Precision

- **Systematic floor:** The combination of IWCD sampling and Gd-tagging targets a systematic floor of $<4\%$ (long-term objective $<2\%$ for the CP violation discovery analysis).
- **Supernova Relic Neutrino (SRN) Sensitivity:** Provides world-leading constraints on the diffuse supernova neutrino background by suppressing atmospheric neutrino backgrounds

2. Neutron Tagging via Gadolinium Gd Loading

- **Thermal Neutron Capture:** Dissolving Gadolinium sulfate $Gd_2(SO_4)_3 \cdot 8H_2O$ into the water to exploit the large neutron capture cross-section of Gd ($\sim 49,000$ barns)
- **Detection Efficiency:** Enhancing neutron identification via the 8 MeV gamma-ray cascade, increasing capture efficiency to $\sim 75\text{--}90\%$ compared to the $\sim 20\%$ efficiency on hydrogen.
- **Flavor Separation:** Critical for the statistical separation of neutrino ν and antineutrino $\bar{\nu}$ samples by tagging the final-state neutron in Inverse Beta Decay (IBD) interactions. [1]

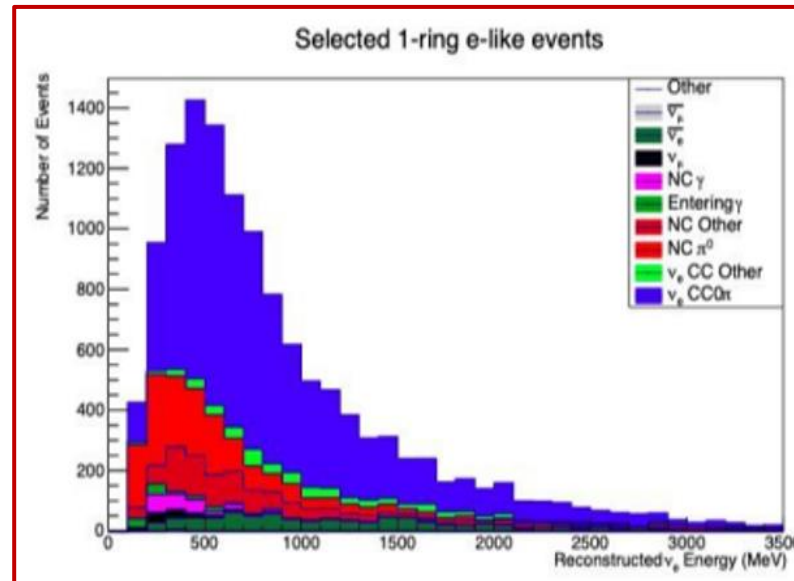


Figure 2: **Selected Electron Neutrino Spectrum.** Event distribution at IWCD. The presence of non-QE (green) and NC backgrounds (red) requires off-axis scanning to break model degeneracies.

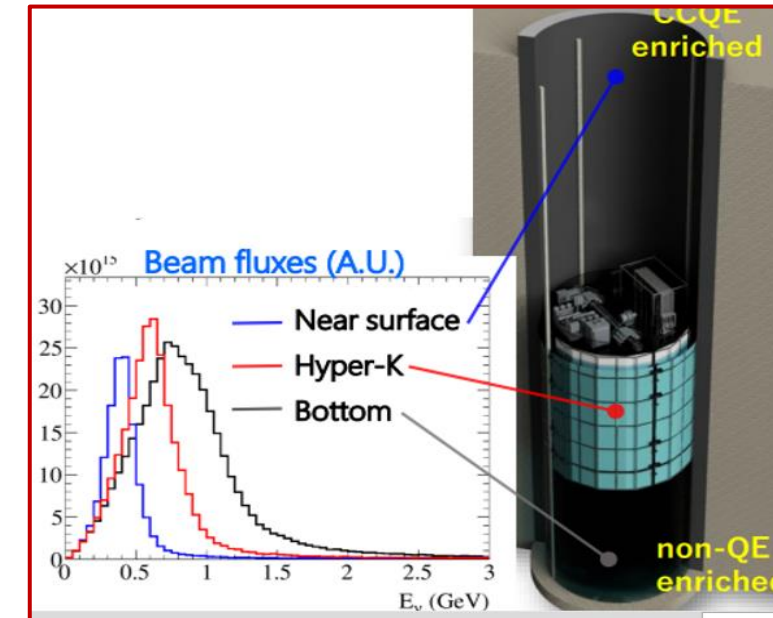


Figure 1: **IWCD Moving Framework.** Vertical displacement shifts the energy peak (left), enabling data-driven separation of CCQE and non-QE topologies

Graph Neural Networks (GNN) for 3D Event Reconstruction

1. Paradigm Shift: From Pixels to Graphs

- **Limitation of CNNs:** Traditional Convolutional Neural Networks (CNNs) treat LArTPC data as 2D or 3D images. This approach introduces artifacts through voxelization and fails to exploit the inherent sparsity of neutrino interaction data.
- **GNN Architecture:** Detector hits are represented as **nodes** in a graph, with **edges** encoding spatial and temporal correlations. This sparse representation preserves the full 3D resolution of the LArTPC without the computational overhead of dense volumetric grids.

2. Topological Reconstruction & Particle Flow

- **Semantic Labeling:** GNNs utilize message-passing layers to classify hits based on their local and global neighborhood (e.g., distinguishing track-like protons from shower-like electrons).
- **Edge Inference:** The network predicts the probability of edges between nodes, effectively performing **clustering and tracking** simultaneously. This is particularly robust for identifying "hadronic stubs"—short proton tracks near the vertex that are critical for energy scale calibration.

Vertex Resolution: Improved point-of-interaction (vertex) localization, even in high-multiplicity environments or SIS/DIS transition regimes

3. Impact on Systematic Bias Mitigation (Status)

- **Calorimetric Precision:** By accurately associating low-energy depositions with the primary vertex, GNN-based reconstruction reduces the "invisible energy" bias in the hadronic sector.
- **Model Robustness:** GNNs trained on diverse physics models (GENIE vs. GiBUU) exhibit higher generalization power, reducing the risk of reconstruction-induced biases in the δ_{CP} analysis.

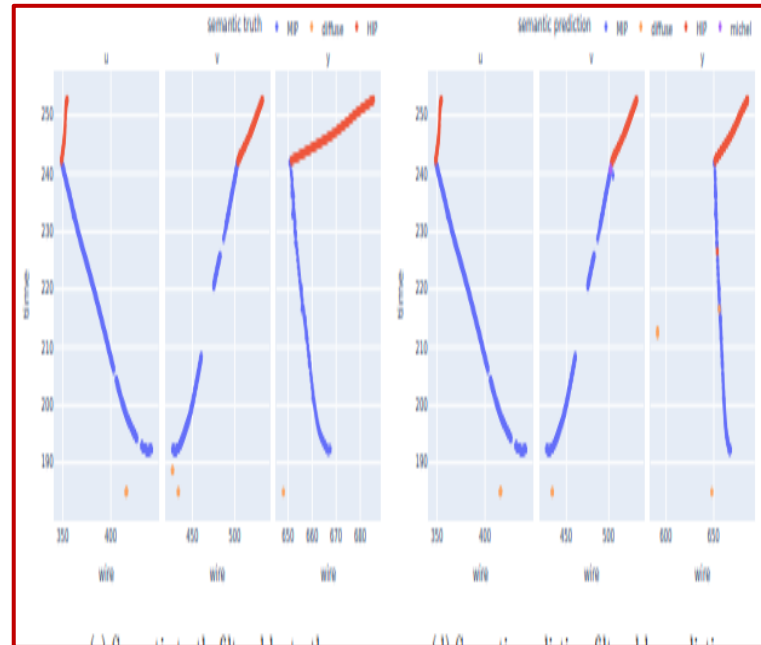


Figure 2: **Nu2Graph Semantic Labeling**. DUNE hit maps comparing truth (left) with GNN predictions (right). Multi-head attention allows automated hit filtering and simultaneous particle type classification.

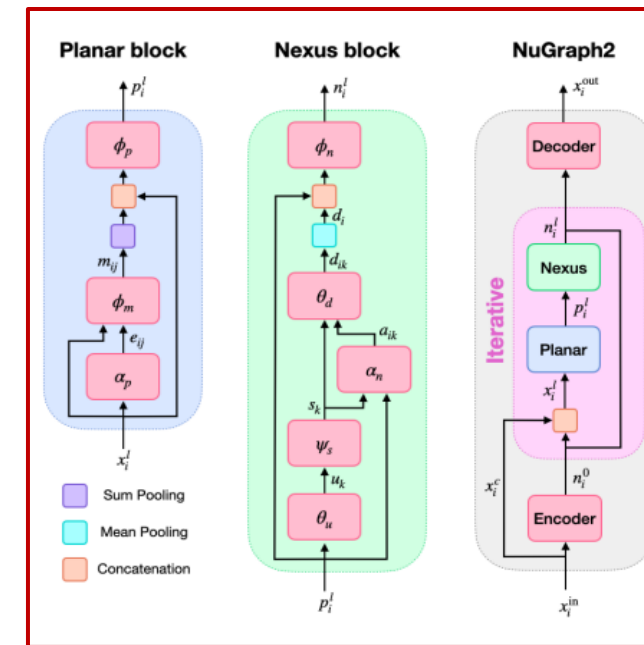


Figure 1: **NuGraph2 Message-Passing Engine**. Planar and nexus block layout. Planar layers process 2D hits independently, while the virtual 3D nexus block breaks spatial degeneracies without dense voxelization.

Complementary Frameworks: JUNO Vacuum Constraints

1. Solar Parameter Precision Operational Tracking:

- Initial measurements utilize the liquid scintillator detector matrix to record reactor $\bar{\nu}_e$ disappearance profiles. Statistical Constraints: The analysis provides independent evaluations of $\sin^2\theta_{12}$ and Δm^2_{21} narrowing the solar neutrino parametric discrepancies.

2. Resolution of Mass Ordering Degeneracies Parametric Decoupling:

- Evaluating the atmospheric mass-squared difference Δm^2_{21} via vacuum oscillations eliminates the Mass Ordering versus δ_{CP} correlation inherent to long-baseline experiments. Sensitivity Contribution: Providing a pure vacuum-dominated constraint allows long-baseline beam data to focus statistical sensitivity directly on leptonic CP violation

3. Electroweak Interaction Benchmarks Matter Dynamics:

- Direct comparison between JUNO vacuum parameters and DUNE matter-enhanced profiles serves as a standard model test for Non-Standard Interactions (NSI).

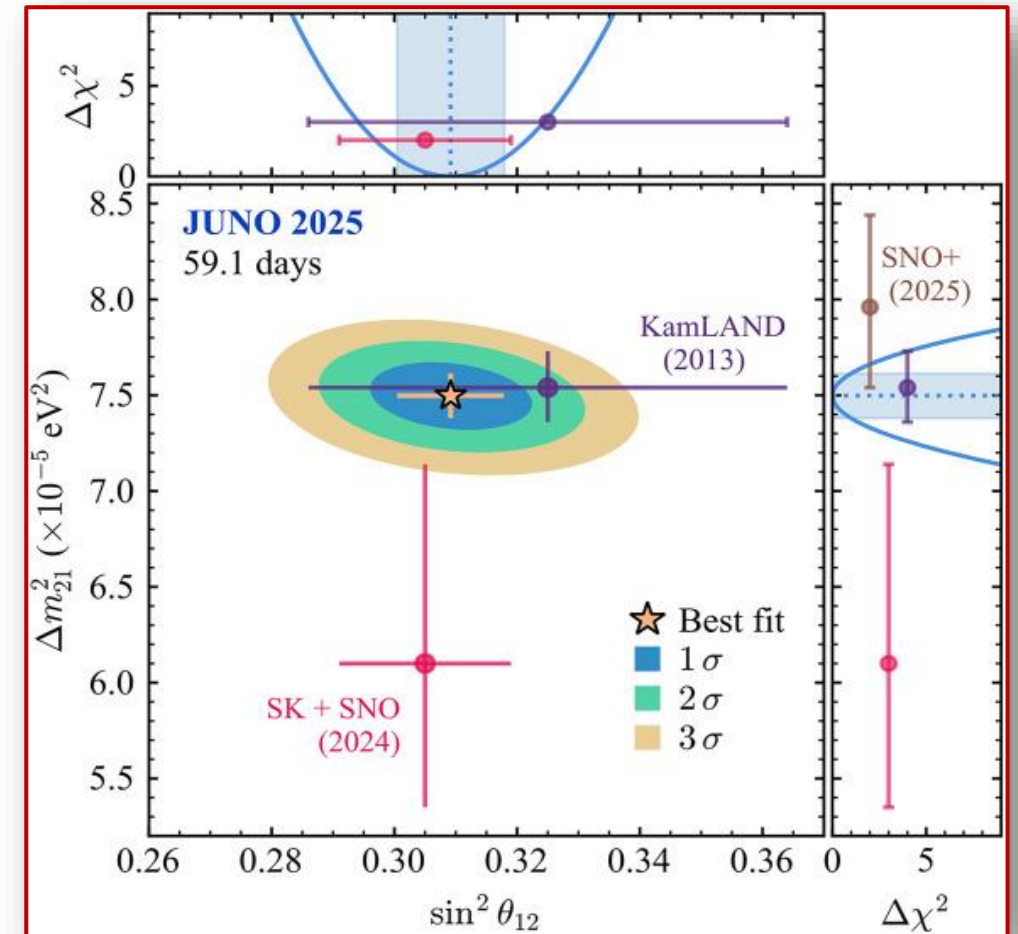


Figure : Initial JUNO constraints on solar oscillation parameters.
The multi-sigma confidence regions 1σ , 2σ , 3σ demonstrate the precision achieved by JUNO compared to KamLAND (2013), SNO+ (2025), and solar neutrino data (SK+SNO, 2024). This precise vacuum baseline resolves historical tensions and eliminates parametric degeneracies in global fits

Conclusion: Status and Perspectives of Long-Baseline Neutrino Analyses

1. Quantitative Requirements for the Determination of δ_{CP}

- **Systematic Uncertainties:** Restraining the total systematic uncertainty to $\leq 2 - 3\%$ across all oscillation channels is necessary to achieve a 5σ significance.
- **Statistical Constraints:** Additional exposure provides marginal sensitivity improvements if systematic errors exceed 5% , making the validation of neutrino-nucleus interaction models the primary prerequisite.

2. Secondary Physics Program

- **Searches Beyond the Standard Model:** Restraining systematic effects allows constraints on 3+1 sterile neutrino parameters and Non-Standard Interactions (NSI).
- **Astroparticle Physics and Baryon Number Violation:** Suppressing atmospheric backgrounds extends the sensitivity to the Diffuse Supernova Neutrino Background and the partial lifetime limit of the proton ($p \rightarrow K^+ \bar{\nu} > 1.3 \times 10^{34}$ years).

3. Methodological Synthesis & Technical Status

Table 1: Global systematic mitigation strategy.

The integration of high-resolution near detectors, data-driven flux sampling, and ab initio theory is required to achieve the targeted systematic constraints.

Uncertainty Source	Primary Mitigation Strategy	Experimental Tool / Framework
Flux Spectral Shape	Off-axis sampling / Hadron production data	DUNE-PRISM / NA61-SHINE
2p2h / MEC	Low-threshold vertex hadronic tracking	ND-GAr / TKI Observables
Missing Energy (π)	Neutron tagging & Machine Learning recovery	SK-Gd / Deep Learning
Model Independence	Flux matching & Mock data challenges	PRISM / Simulation Fits

- **Detector Installation:** The DUNE collaboration recently initiated the underground assembly of the far-detector structural design at the Sanford Underground Research Facility.
- **Global Experimental Framework:** The implementation of data-driven constraints from JUNO and the ongoing construction of Hyper-Kamiokande define the international experimental planning.

Neutrino–nucleus interactions as the limiting systematic for next-generation oscillation experiments

Why understanding the nucleus matters for measuring δ_{CP}

Thank you for your attention

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