Constraining systematics at T2K and SuperKamiokande oscillation analyses using ν-nucleus interaction models

ICRR Inter-University Research Project Ref. J1
(Research Center for Cosmic Neutrinos)

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ICRR Inter-University Research Program Meeting, 21 February 2024

Summary of FY2023 project

- **Ongoing project (2021 -)**
- **Budget approved: 90,000 yen. Purpose: travel and accommodation costs at ICRR.** They have not been requested in FY2023 $\Rightarrow$ Budget used to purchase equipment and supplies for the ICRR Neutrino Center.
- **Publications (acknowledging ICRR project in FY2023): 5** (1 of which under review).

  - *New model comparison for semi-inclusive charged-current electron and muon neutrino scattering by Ar40 in the energy range of the MicroBooNE experiment.* J. M. Franco-Patino et al., Phys. Rev. D 109, 013004 (2024).

  - *Superscaling in the resonance region for neutrino-nucleus scattering: The SuSAv2 dynamical coupled-channels model.* J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023).

  - *Measurements of neutrino oscillation parameters from the T2K experiment using 3.6 x 10^{21} protons on target.* K. Abe et al. [T2K Collaboration], Eur. Phys. J. C 83, 782 (2023).

  - *Parametrized uncertainties in the SF model of neutrino charged-current quasielastic interactions for oscillation analyses.* J. Chakrani et al., arXiv:2308.01838 [hep-ex] (2023).

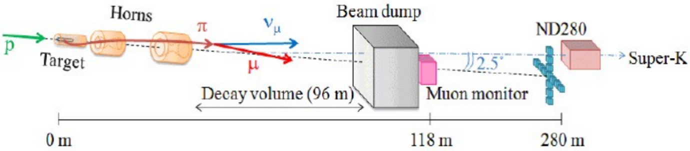
  - *Weak Neutrino (Antineutrino) Charged-Current Responses and Scaling for Nuclear Matter in the Relativistic Mean Field.* S. Cruz-Barrios et al., Universe 2023, 9, 240 (2023).

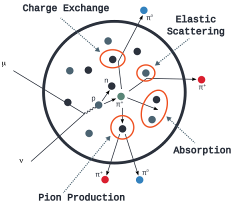
- **PhD thesis defended by members of this project in FY2023: 1**
  J.M. Franco-Patino, Univ. of Seville. Supervisors: J.A. Caballero and M.B. Barbaro

ν-A interaction models are essential for ν oscillation analyses

Long-baseline accelerator neutrino oscillation experiments

Neutrinos produced as secondary decay products of hadrons (π, K) generated in primary reactions of p with nuclei $\Rightarrow$ broad energy beam.





Experimental difficulties:

➠ The neutrino flux: broad energy distribution around a maximum $\rightarrow$ True energy for a detected event is unknown.

➠ To reduce flux uncertainties, two identical detectors are employed. *Near Detector* placed near the neutrino production region and *Far Detector* where a maximum/minimum oscillation is expected. MC simulations are employed to reconstruct E_ν for each detected event.

➠ The reliability of ν-oscillation experiments depends on a precise determination of the ν-nucleus cross section measurements and on the ν flux at ND.

➠ Global experimental **systematics in T2K** are around a **4%** (**7%**) for ν_μ (ν_e) reactions and are dominated by flux and cross section uncertainties (**3%**) $\Rightarrow$ Need for development and **implementation** of sophisticated neutrino interaction models in **event generators**.

Semi-inclusive Relativistic Mean Field models

Modelling of ν interactions in generators:

NEUT models (SF, LFG) used in T2K start from **PWIA**: the interacting nucleon does not feel any nuclear potential after the interaction. Not realistic at low and intermediate energy transfer. Corrections are being considered to account for effects **beyond PWIA**:

- 2p2h nucleon ejection.
- Improving descriptions of the initial state, removal energy and PB description.
- RPA (nucleon-nucleon correlations) and FSI (Final State Interactions).

· **RPA and FSI effects** can introduce important differences in the experimental analyses.

- These differences affect OA: E dependence of the CS, ν vs. $\bar{\nu}$, ν_e/ν_μ, C/O.

- Largest uncertainty in semi-inclusive neutrino CS (lepton+hadron kinematics).

Description of final state interactions: Relativistic Mean Field and Optical potentials

- **FSI** can be treated as a distortion of the outgoing nucleon wave functions by a nuclear potential $\Rightarrow$ **DWIA:** distorted wave impulse approximation.
- **RMF+FSI and ROP models** yield good agreement with $e-A$ and $\nu-A$ inclusive CS from low to high kinematics. **RMF potentials** fitted to saturation properties of nuclear matter, radii and nuclear masses. **Optical potentials (OP)** phenom. fits adjusted to $e-A$ data.

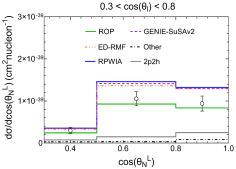
- **RMF and ROP models** can be implemented in **generators** to predict lepton and hadron kinematics in the FS. Partially implemented in GENIE. Work in progress for NEUT.
- **Uncertainties in nuclear potentials:** SF profiles, binding energies, occupancy, transparency, etc. can be added. See PRD106, 113005 (2022) and PRD109, 013004 (2024) for details.

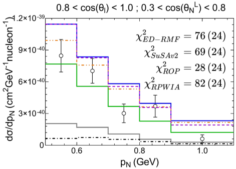
Scattered Nucleon Description

Regarding the scattered nucleon, we can consider several situations:

- Relativistic Plane-Wave Impulse Approximation (RPWIA): the ejected nucleon is considered a plane-wave (i.e, there are not final state interactions)
- Energy-Dependent Relativistic Mean Field (ED-RMF): W.F. solution of the Dirac equation in the continuum using the same RMF potential that describes the initial state times a phenomenological function that weakens the potentials at high energies.
- Relativistic Optical Potential (ROP): The scattered nucleon travels under the influence of a phenomenological relativistic optical potential fitted to elastic proton-nucleus scattering data.

Cross sections vs proton kinematics: T2K and MINERvA

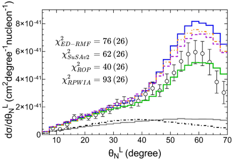


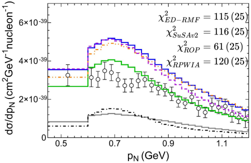


Phys. Rev. D 98, 032003(2018)

$T2K\ \nu_\mu - CC0\pi Np$

$p_N > 500\,MeV/c$





Phys. Rev. D 101, 092001(2020)

$MINER\nu A\ \nu_\mu - CC0\pi Np$

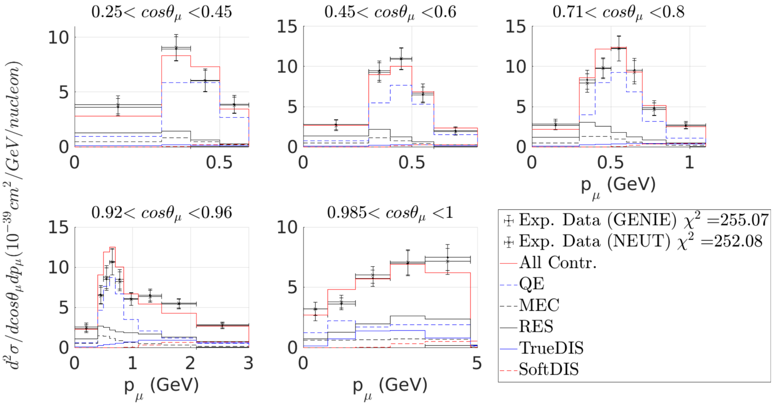
k'	$\cos\theta_l$	p_N	$\cos\theta_N^L$	ϕ_N^L
1.5-10 GeV	> 0.939	0.45-1.2 GeV	> 0.342	-

- **SuSAv2 model** based on scaling functions from RMF theory has been recently extended to the full inelastic regime (RES, SoftDIS, TrueDIS) where RMF models are not yet fully developed.
- **Unlike RMF**, SuSAv2 only predicts lepton kinematics but shows good agreement with e and ν data.
- Recent implementation of **Osaka-DCC** RES model (**SuSAv2-DCC**). Comparisons with **NEUT-DCC** are under way.

Results: T2K

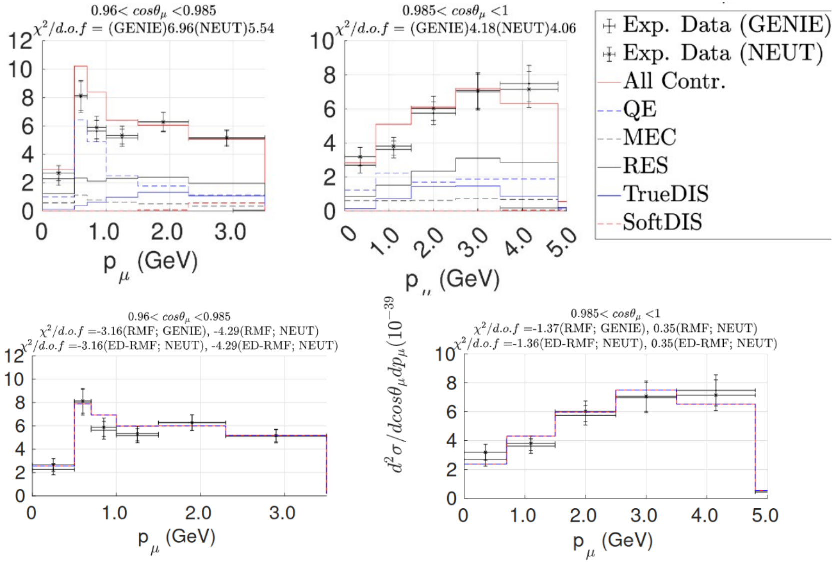
T2K CC ν_μ, $< E_{\nu_\mu} > \sim 0.6\ GeV$

$\chi^2 = 218.3$ (GENIE)
$\chi^2 = 192.0$ (NEUT)



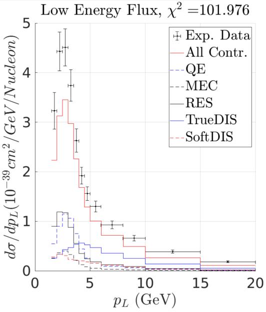
SuSAv2-DCC model vs. T2K CC inclusive data

Phys. Rev. D 108, 113008 (2023)

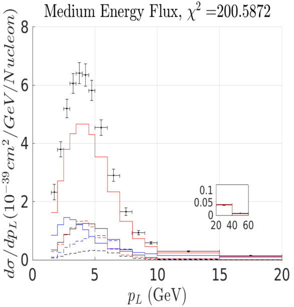


Overestimations at very forward angles in SuSAv2 are **solved using RMF models**.

Results: MINERvA



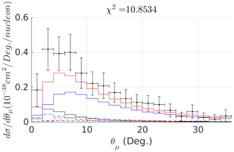
MINERvA CC $\nu_\mu, < E_{\nu_\mu} > \sim 3.5$ GeV (Low)

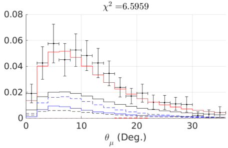


MINERvA CC $\nu_\mu, < E_{\nu_\mu} > \sim 6.0$ GeV (Medium)

More strength seems to be needed in **RES** channel to compare with **MINERvA** and **MnvGENIE**, unlike **ArgoNEUT (similar E_ν)** and **T2K (lower E_ν)**

Results: ArgoNEUT

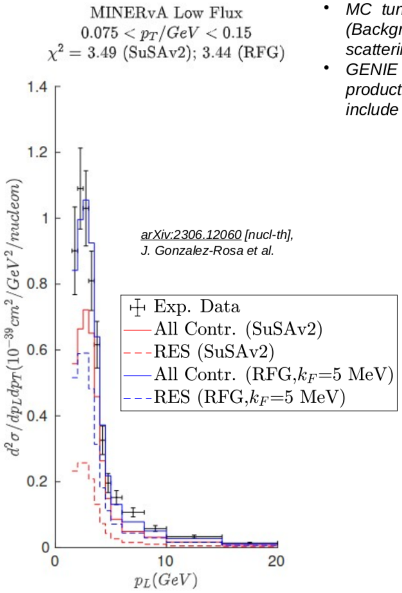




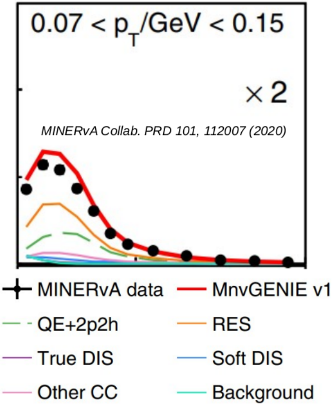
ArgoNEUT CC $\nu_\mu, < E_{\nu_\mu} > \sim 9.6$ GeV; CC$\bar{\nu}_\mu, < E_{\nu_\mu} > \sim 3.6$ GeV

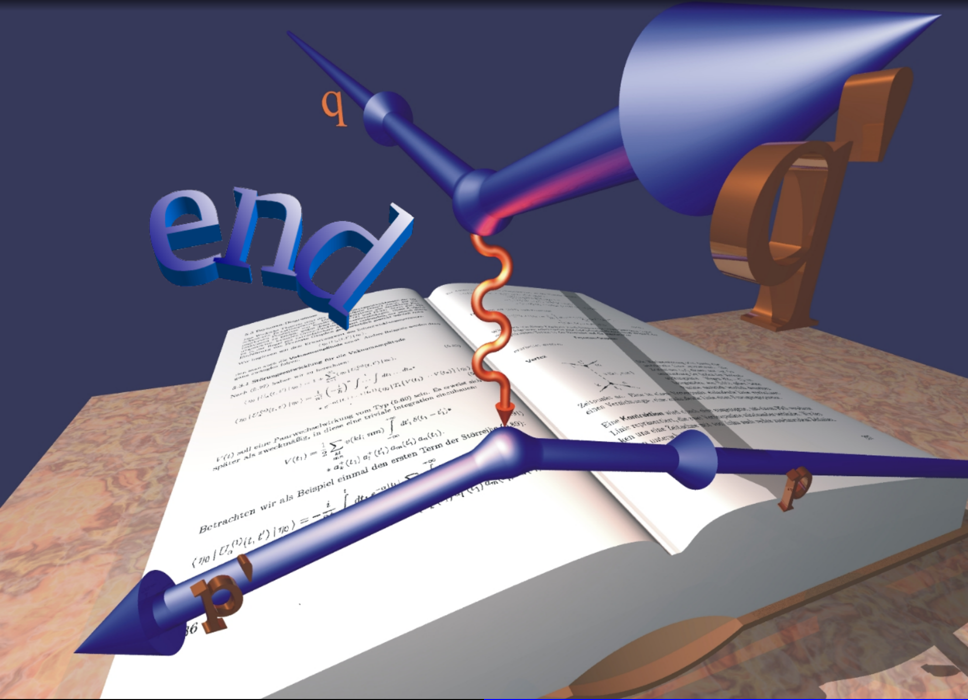
See PRD 105, 093009 (2022) and PRD 108, 113008 (2023) for details.

Analysis with NOvA results are under way.



- *MC tuning, reweighting or model approaches in the RES and SoftDIS (Background) channels for neutrinos should be validated against electron scattering data.*
- *GENIE Mnv RES approach is based on a single-nucleon Rein-Sehgal pion production model with lepton mass corrections and other modifications to include nuclear effects. But, it looks similar to a low-pF RFG model.*

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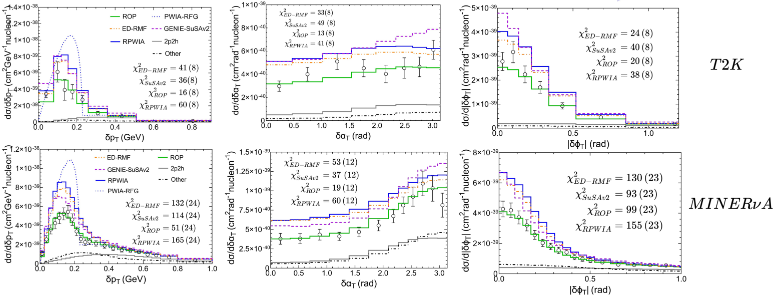
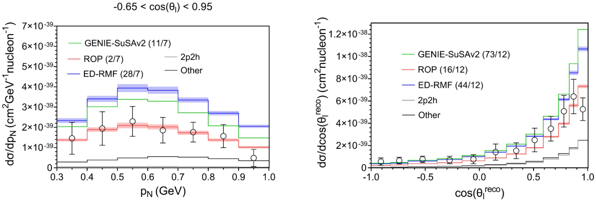
Cross sections vs transverse kinematic imbalances

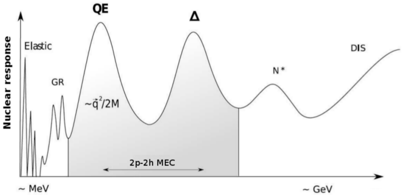


Cross sections vs MicroBooNE nu_mu -> 40Ar CC0piNp

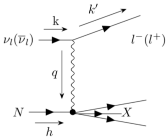


We can also add uncertainties in the nuclear potential parameters, SF profile, binding energies, occupancy, transparency, etc. Error bands included in MicroBooNE plots for reference.

See Phys. Rev. D 106, 113005 (2022) and Phys. Rev. D 109, 013004 (2024) for details.



- Quasielastic region.
- 2p-2h excitations.
- **Δ** resonance, other resonances and DIS.



SuSAv2-inelastic model describes the full inelastic spectrum (Δ, other res. And DIS)[G. D. Megias, PhD Thesis (2017), M. B. Barbaro et al., Phys. Rev. C 69, 035502 (2004), J. Gonzalez-Rosa et al., Phys. Rev. D 105, 093009 (2022)]. Good agreement with (e,e') data.

$$R^K_{inel}(\kappa,\tau) = \frac{N}{\eta_F^2 \kappa}\xi_F \int_{\mu_X^{min}}^{\mu_X^{max}} d\mu_X f^{model}(\psi'_X) U^k$$

- **SuSAv2 model for QE** uses RMF scaling function to model nuclear dependence. Similar approach is done for **inelastic regime**.
- **Inelastic hadron tensor** includes: **RES** (DCC model) + **DIS** (Bodek-Ritchey/Bosted-Christy/PDFs) + **soft DIS** (merge).
- **SuSAv2 inelastic** can be implemented in NEUT or GENIE to predict lepton kinematics and shortly for nucleon kinematics (work in progress with S. Dolan and L. Munteanu).
- Comparisons with **NEUT DCC (RFG)** in collaboration with Hayato-san *et al.* are under way.
- This approach can **incorporate** other inelastic models.

- TrueDIS (Deep inelastic scattering)

$W_x^{min} = 2.1\ GeV;\ \ W_x^{max} = m_N + \omega - E_s$

Bodek-Ritchie/ Bosted-Christy/ Parton Distribution Function

- RES (Resonances)

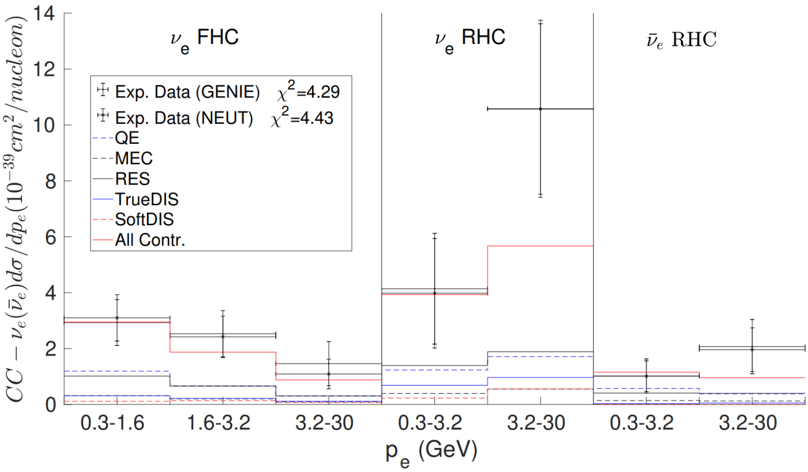
$W_x^{min} = m_N + m_\pi;\ \ W_x^{max} = 2.1\ GeV$

Dynamical Coupled Channels

- SoftDIS (Deep inelastic scattering in the resonance region)

$W_x^{min} = m_N + m_\pi;\ \ W_x^{max} = 2.1\ GeV$

Dynamical Coupled Channels and Bodek-Ritchie/Bosted-Christy



Overestimations at large p_e in RHC mode will be studied.