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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Summary of FY2024 project

- **Ongoing project (2021 -)**
- **Budget approved: 80,000 yen. Purpose: travel and accommodation costs at ICRR.** It has not been requested in FY2024 $\Rightarrow$ Budget used to purchase equipment and supplies for the ICRR Neutrino Center.
- **Publications (acknowledging ICRR project in FY2024): 4** (1 of which under review).

  - *Analysis of NOvA and MicroBooNE charged-current inclusive neutrino measurements within the SuSAv2 framework.* J. Gonzalez-Rosa et al., arXiv:2412.18636 [hep-ph] (2025).

  - *Parametrized uncertainties in the SF model of neutrino charged-current quasielastic interactions for oscillation analyses.* J. Chakrani et al., Phys. Rev. D 109, 072006 (2024).

  - *Measurement of the $^{12}C(e,e')$ cross sections at $Q^2 = 0.8 GeV^2/c^2$.* M. Mihovilovic et al., Few-Body Systems 65, 78 (2024).

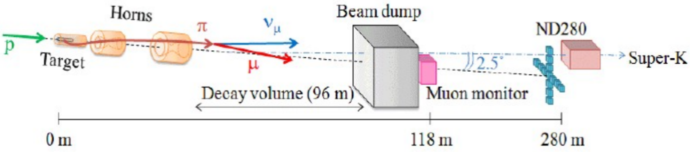
  - *Combined analysis of neutrino and antineutrino charged current inclusive interactions.* J. M. Franco-Patino et al., Symmetry 2024, 16(5), 592.

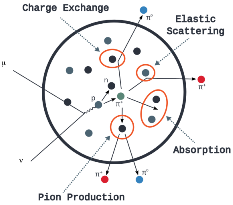
- **PhD thesis defended by members of this project in FY2024: 0 (1 expected in FY2025)** J. Gonzalez-Rosa, Univ. of Seville. Supervisors: J.A. Caballero and G.D. Megias

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 → 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.

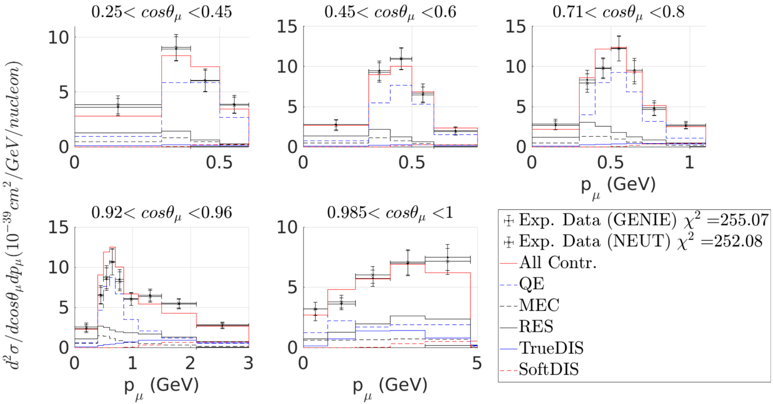
➠ Global experimental **systematics in T2K** are around a **4%** (**7%**) for ν_μ (ν_e) reactions and are dominated by flux and cross section uncertainties (**3%**) $\Rightarrow$ Need for development and **implementation** of sophisticated neutrino interaction models in **event generators**.

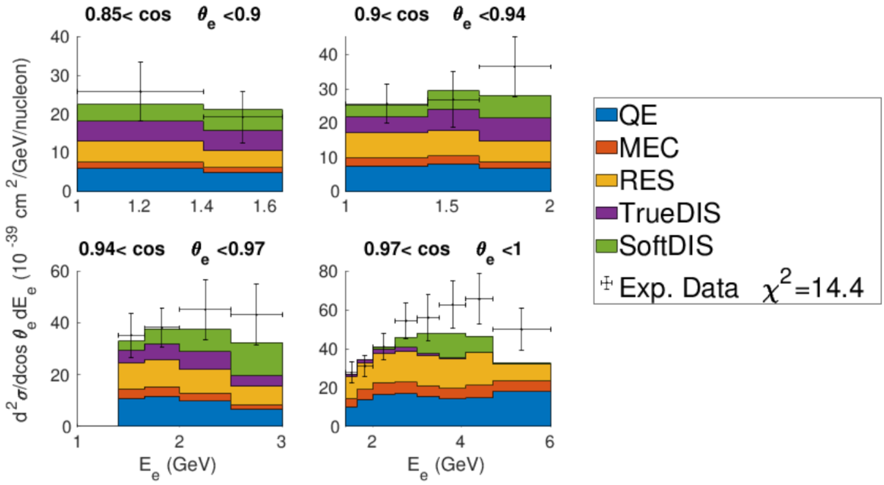
- **SuSAv2 model** based on scaling functions from RMF theory has been recently extended to the full inelastic regime (RES, SoftDIS, TrueDIS) where RMF models are not yet fully developed.
- **Unlike RMF**, SuSAv2 only predicts lepton kinematics but shows good agreement with *e* and ν data.
- Recent implementation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

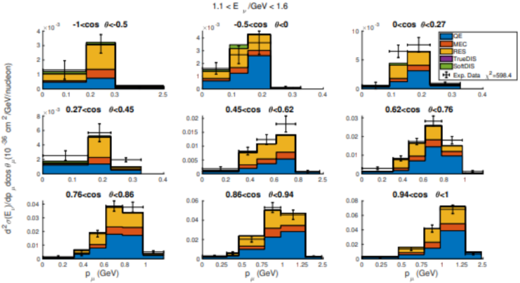
Results: T2K

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

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

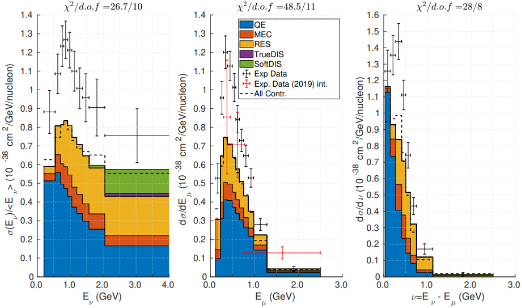



0.85< cos θe <0.9
0.9< cos θe <0.94
0.94< cos θe <0.97
0.97< cos θe <1
d2σ/dcos θe dEe (10-39 cm2/GeV/nucleon)
Ee (GeV)
Ee (GeV)
QE
MEC
RES
TrueDIS
SoftDIS
Exp. Data χ2=14.4



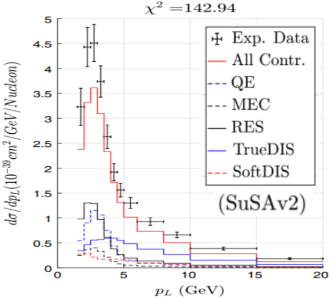
χ2/dnf(SuSAv2) = 598.4
Similar to the ones from the experimental paper: arXiv:2307.06413 [hep-ex] →

Model Name	χ^2/ndf
GENIE v2	752.2/138
MicroBooNE model	329.3/138
GENIE v3 untuned	324.6/138
GiBUU	275.2/138
NEUT	244.3/138
NuWro	214.1/138



--> Data from: PRL 128, 151801 (2022)

Different level of agreement from different exp. analyses even being the same experiment and flux.



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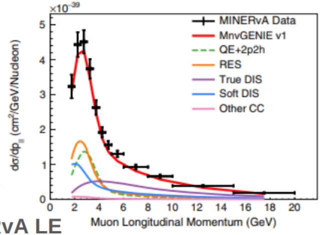
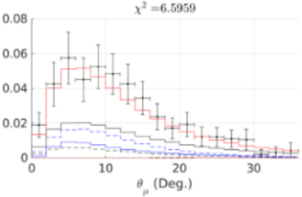
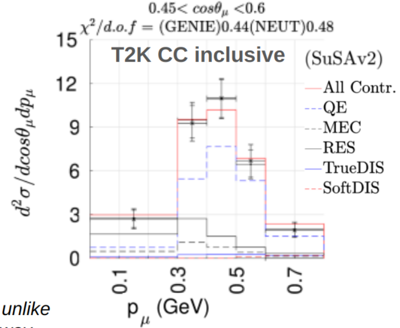


MINERvA LE CC inclusive

MINERvA data: PRD101, 112007 (2020)
T2K data: PRD98, 012004 (2018)
SuSAv2 results: PRD108, 113008 (2023)



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



SuSAv2-RES is similar to RES RMF and Ghent Hybrid Model, unlike Berger-Sehgal GENIE. Comparison with NEUT-DCC is on the way.

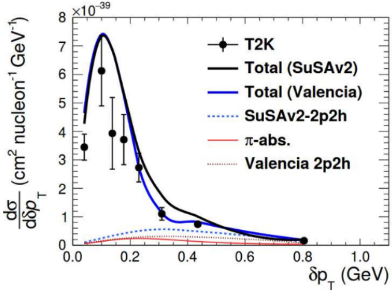
Semi-inclusive CC0πNp neutrino-nucleus data and FSI effects

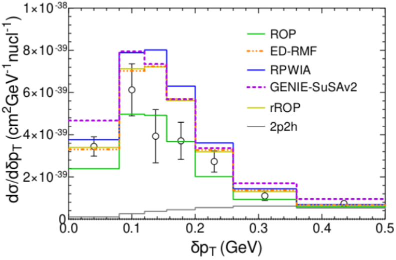
Modelling of ν interactions in generators:

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**: mainly RPA (nucleon-nucleon correlations) and FSI (Final State Interactions).

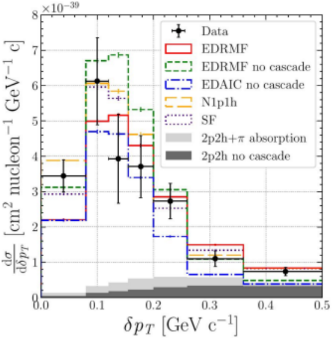
- **RPA and FSI effects** can introduce important differences in the experimental analyses.

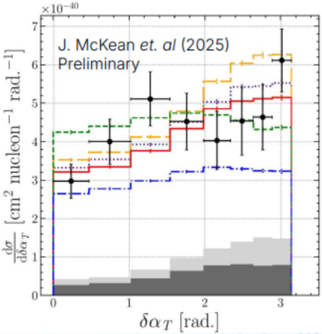
- These differences affect OA: E dependence of the CS, ν vs. $\bar{\nu}$, ν_e/ν_μ, C/O.
- Largest uncertainty in semi-inclusive neutrino CS (lepton+hadron kinematics).
- Different choice of **nuclear potentials** to analyze FSI effects.





T2K TKI





Model	δp_T	$\delta\phi_T$	$\delta\alpha_T$
EDMRF cas	42.1/8	27.1/8	17.6/8
EDMRF no cas	60.4/8	51.2/8	27.5/8
N1p1h cas	5.62/8	12.6/8	31.3/8
SF cas	11.3/8	8.49/8	19.4/8
EDAIC no cas	24.6/8	19.3/8	18.8/8

- **ED-RMF** is being implemented in **NEUT** for 12C, 16O and 40Ar via hadron *tensor tables* containing full lepton and nucleon kinematics.
- Different choice of nuclear potentials (real part) to analyze **elastic FSI**.
- *Inelastic FSI* can be generated by **NEUT cascade** or via **imaginary part** of nuclear potentials.

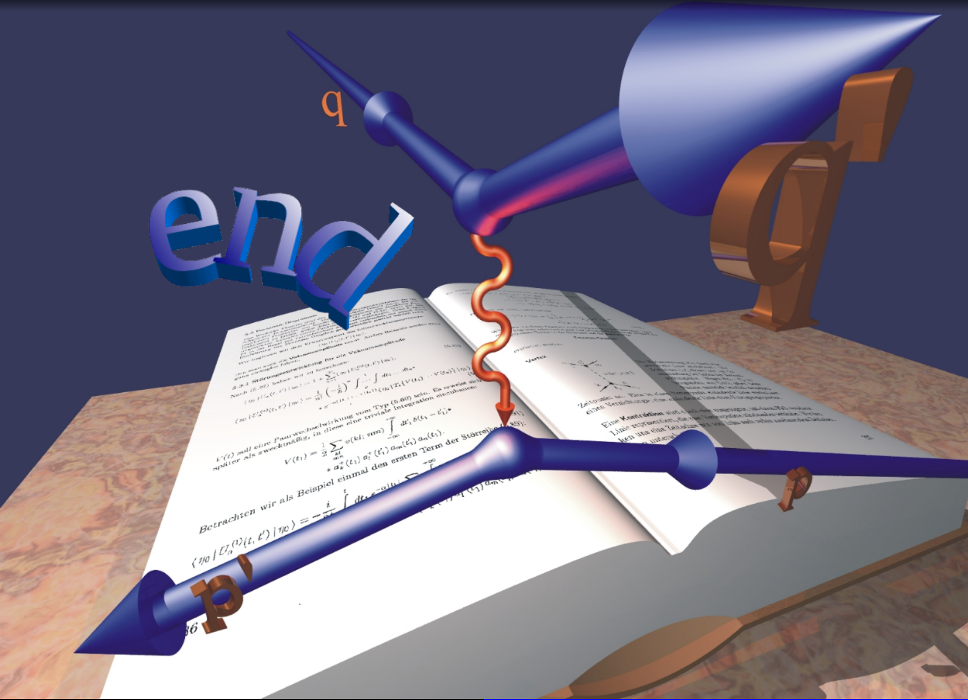
Summary and expected results

FY2024 results:

- Implementation of Osaka-DCC model in SuSAv2 to improve description or resonance regime and data analysis (T2K, NOvA, MicroBooNE, ArgoNEUT and MINERvA).
- Collaborations with electron experiments to analyze data within SuSAv2 framework.
- Analysis of $\nu - \bar{\nu}$ asymmetry at T2K kinematics.
- Studies of SF uncertainties for oscillation analyses.

FY2025 and beyond:

- ED-RMF implementation in NEUT.
- Comparison of RES models: SuSAv2-DCC, RMF-DCC vs. Berger-Sehgal NEUT-DCC.
- Implementation of SuSAv2-QE, 2p2h, RES and inelastic in NEUT. Reweighting of parameters. Analysis of model uncertainties.
- Testing validity of factorization approach in event generators via RMF and SuSAv2.


end
q
q'
p
p'

How are SuSAv2 and RMF models being implemented in generators?

1^{st} **step: Implemented the SuSAv2 1p1h and 2p2h models in GENIEv3** for both (e, e') and CC ν_μ scattering. **Next step: Implementation in NEUT.**

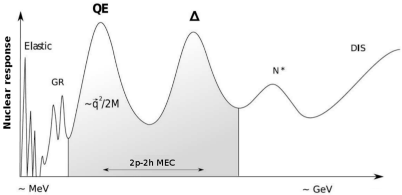
➲ **New 1p1h and 2p2h model calculated using pre-computed hadron tensors for (e, e') and CC ν reactions**. Global factor / lepton tensor are easily calculated - shared by other models. Use of a GENIE's bilinear interpolation function to evaluate specific q_0, q_3 values. Hadron tensors are initially provided for **a few targets** (C and O so far, may add others). Can easily scale to other nuclei.

2^{nd} **step:** Adding SuSAv2 formulas, parameters and parametrization of scaling functions into generators to speed up simulations and to allow reweighting (M_A^{QE}, p_F, E_b, etc.). Introducing RMF nucleon momentum distribution in generators to fully test factorization approach.

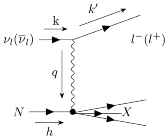
3^{rd} **step:** Implement full RMF semi-inclusive model in generators

- **SuSAv2-QE, RES and inelastic** are not computationally demanding codes and can be fully implemented for **reweighting** of parameters.
- **RMF** models are being implemented for the moment using precomputed tables. Complex codes.
- SuSAv2 models **only predict lepton kinematics** but can predict hadron kinematics via n(p) from RMF theory (n(p)) under factorization approach (work in progress). Currently: *SuSAv2(lepton)+LFG(hadron)*
- *Work in progress to implement SuSAv2-RES (DCC and MK) and SuSAv2-DIS in GENIE and NEUT*.

SuSAv2 model for inelastic neutrino-nucleus scattering Phys. Rev. D 105, 093009 (2022)



- 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

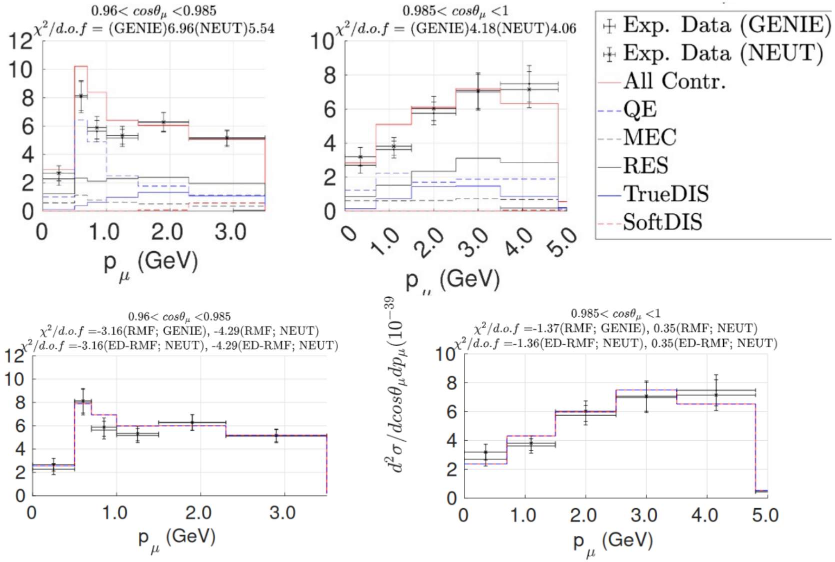
- SoftDIS (Deep inelastic scattering in the resonance region)

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

Dynamical Coupled Channels and Bodek-Ritchie/Bosted-Christy

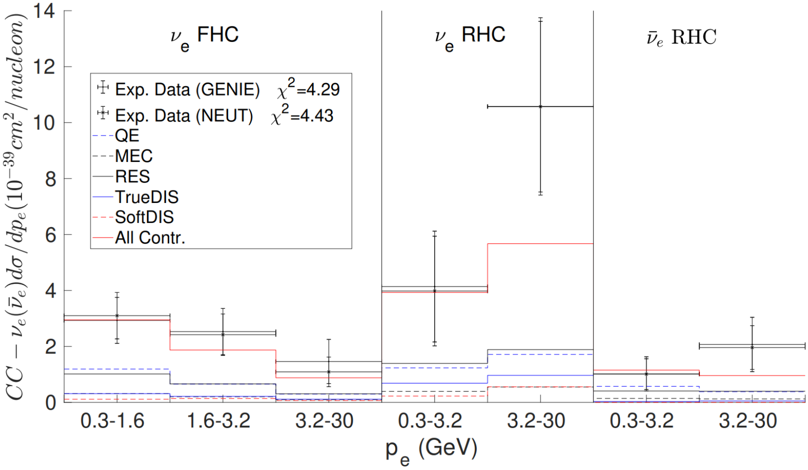
SuSAv2-DCC model vs. T2K CC inclusive data

Phys. Rev. D 108, 113008 (2023)

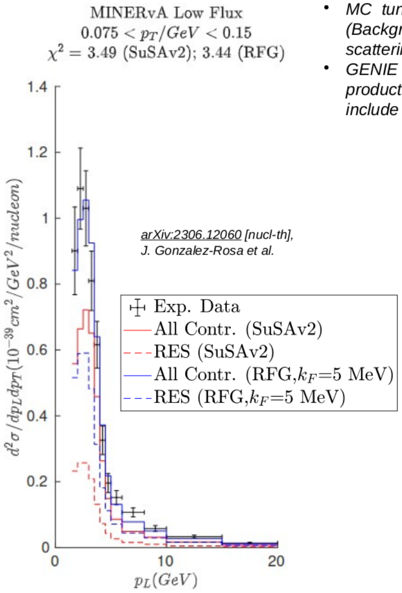


Overestimations at very forward angles in SuSAv2 are **solved using RMF models**.

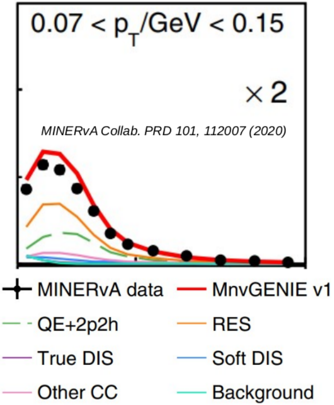
SuSAv2 model for inelastic electron neutrino-nucleus scattering



Overestimations at large p_e in RHC mode will be studied.



- *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.*



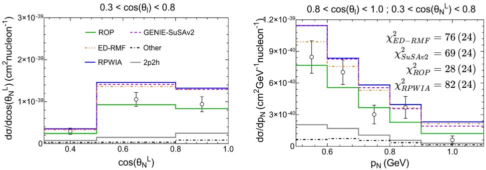
- **RMF and ROP models** can be implemented in **generators** to predict lepton and hadron kinematics in the FS. Partially implemented in GENIE. Work in progress for NEUT.
- **Uncertainties in nuclear potentials:** SF profiles, binding energies, occupancy, transparency, etc. can be added. See PRD106,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

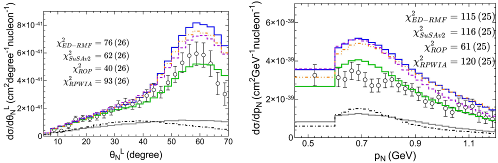
Cross sections vs proton kinematics: T2K and MINERvA



Phys. Rev. D 98, 032003(2018)

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

$p_N > 500\,MeV/c$

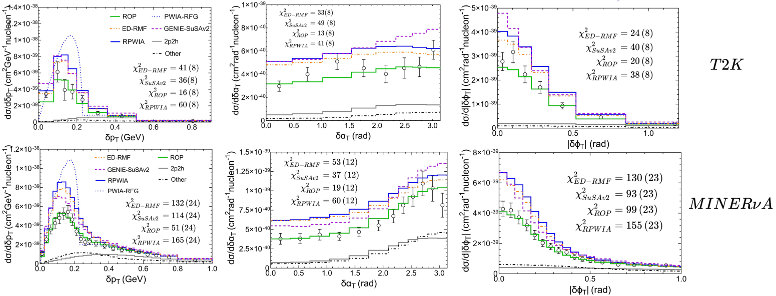


Phys. Rev. D 101, 092001(2020)

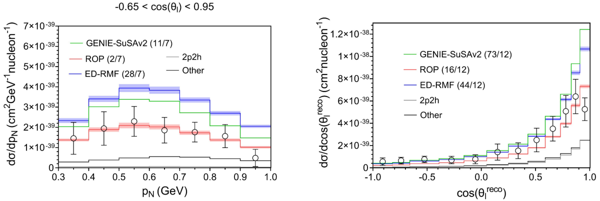
$MINER\nu A\ \nu_\mu - CC0\pi Np$

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	-

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.