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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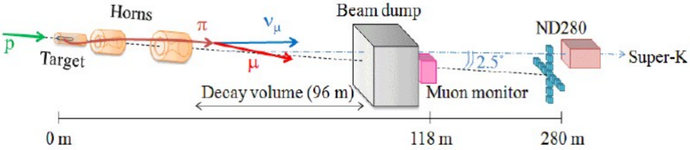
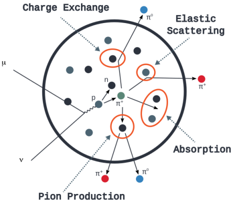
ν-A interaction models are essential for ν oscillation analyses

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**.

Current status of nuclear models in NEUT

Things to improve in the modelling of ν interactions:

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 needed 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 the inclusive CCQE CS.

Final state interactions: Relativistic Mean Field and Optical potentials

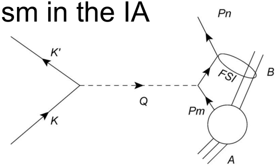
- **FSI** can be treated as a distortion of the outgoing nucleon wave functions by a nuclear potential $\Rightarrow$ **DWIA:** distorted wave impulse approximation.
- **RMF+FSI and ROP models** good agreement with $e-A$ and $\nu-A$ CS from low to high kinematics. **RMF potentials** fitted to saturation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

Final state interactions: 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.

- **Semi-inclusive CS:** final lepton + nucleon events.

Semi-inclusive neutrino-nucleus formalism in the IA



$$\left\langle \frac{d^6\sigma}{dk_l d\Omega_l dp_N d\Omega_N} \right\rangle = \int dk\, \phi(k) \times K \times L_{\mu\nu} H^{\mu\nu}$$

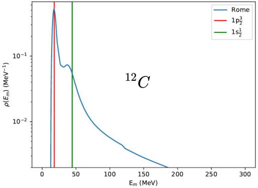
$$H^{\mu\nu}_{\kappa} = \rho_\kappa(E_m) \times \sum_{m_j,\, s_N} \left[J_{\kappa,\, m_j,\, s_N}(Q, P_N) \right]^\star J_{k,\, m_j,\, s_N}(Q,\, P_N) \Longrightarrow$$ No factorization!!

$$J^{\mu}_{\kappa,\, m_j,\, s_N} = \int d\mathbf{r}\, e^{i\mathbf{r}\cdot\mathbf{q}} \boxed{\overline{\Psi}_{s_N}(\mathbf{p}_N,\, \mathbf{r})} \boxed{\left(F_1 \gamma^\mu + \frac{iF_2}{2m_N} \sigma^{\mu\nu} Q_\nu + G_A \gamma^\mu \gamma^5 + \frac{G_P}{2m_N} Q^\mu \gamma^5 \right)} \boxed{\Psi^{m_j}_{\kappa}(\mathbf{r})} \Longrightarrow$$

- ● W.F. scattered nucleon
- ● CC2 operator
- ● W.F. bound nucleon

Description of the initial state:

- Pure shell model (first approximation): missing energy profile is given by a Dirac delta per shell
- Realistic model, i.e. Rome (Benhar spectral function) used in electron exclusive processes: short- and long-range correlations included



Different approaches for the propagation of the FS nucleon within the nucleus:

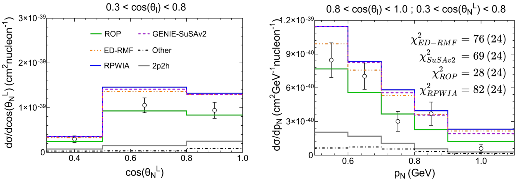
ED-RMF and ROP reproduces QE data, as SuSAv2 but improving low ω region.

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.

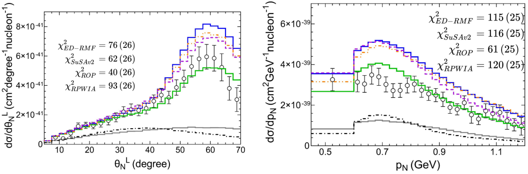
Cross sections vs proton kinematics: T2K and MINERvA



Phys. Rev. D 98, 032003(2018)

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

$p_N > 500\,MeV/c$

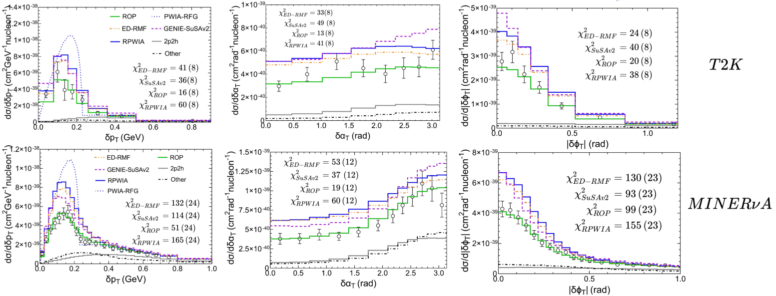


Phys. Rev. D 101, 092001(2020)

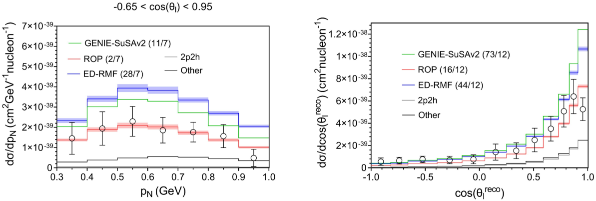
$MINER\nu A\ \nu_\mu - CC0\pi Np$

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



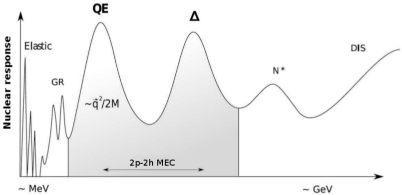
Cross sections vs MicroBooNE nu_mu -> 40Ar CC0piNp



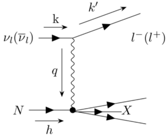
We can also add uncertainties in the nuclear potential parameters, SF profile, binding energies, occupancy, transparency, etc. Error bands included in MicroBooNE plots for reference.

See Phys. Rev. D 106, 113005 (2022) for details.

SuSAv2 model for inelastic neutrino-nucleus scattering



- 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)

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

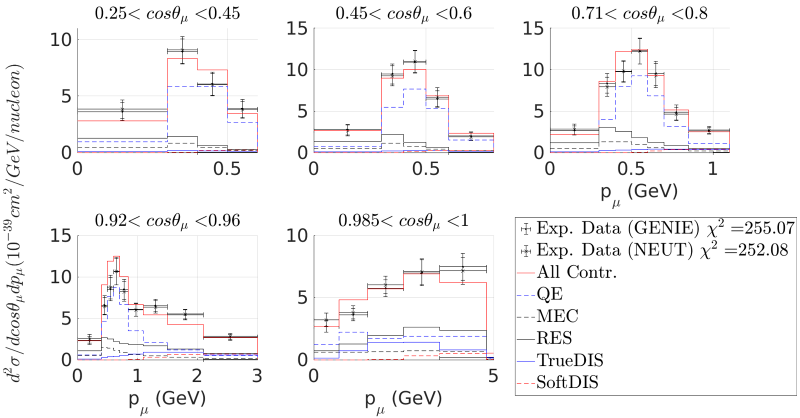
Dynamical Coupled Channels and Bodek-Ritchie/Bosted-Christy

SuSAv2 model for inelastic neutrino-nucleus scattering

Results: T2K

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

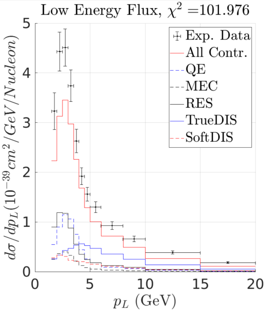
$\chi^2 = 218.3$
(GENIE)
$\chi^2 = 192.0$
(NEUT)



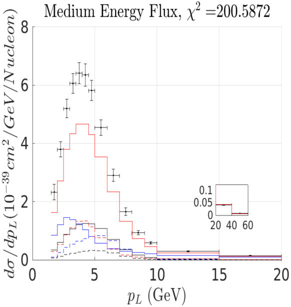
Overestimations at very forward angles in SuSAv2 are **solved using RMF/ROP**.

SuSAv2 model for inelastic neutrino-nucleus scattering

Results: MINERvA



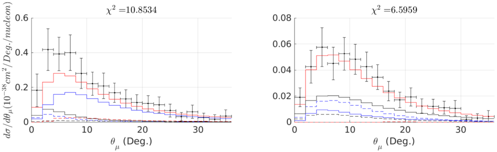
MINERvA CC $\nu_\mu, < E_{\nu_\mu} > \sim 3.5\ GeV$ (Low)



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)**

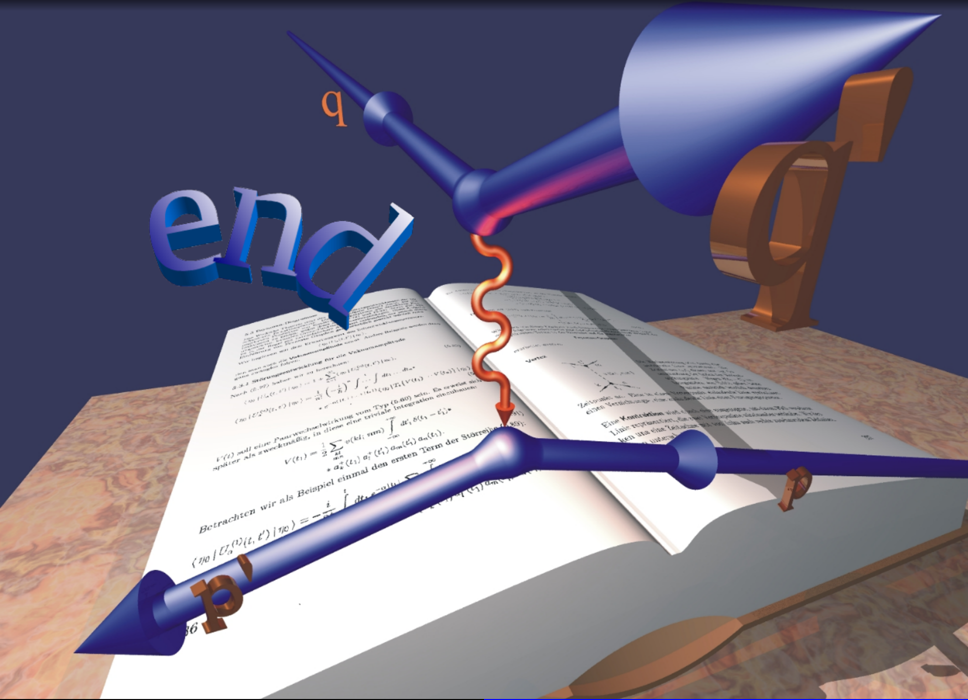
Results: ArgoNEUT



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

See Phys. Rev. D 105, 093009 (2022) for details.

Analysis with NOvA results are under way.


end
q
q'
p'
p