MODELLING SEMI-INCLUSIVE NEUTRINO-NUCLEUS SCATTERING

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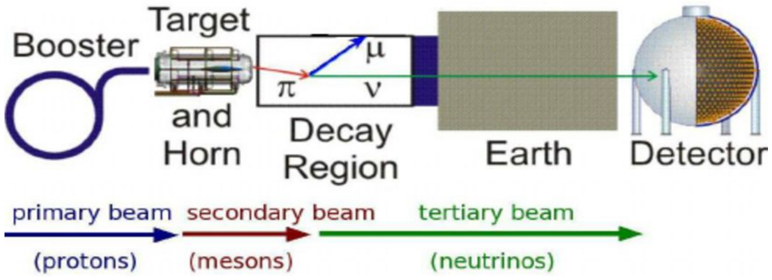
What do we need neutrino-nucleus scattering for?



Typical targets: C, O or Ar

To calculate the parameters in the neutrino mixing matrix U from the oscillation probability we need to know the energy of the neutrino

$$P_{\alpha\to\beta} \;=\; = \left| \sum_i U^{+}_{\alpha i} U_{\beta i} e^{i m_i^2 L / 2 E_\nu} \right|$$

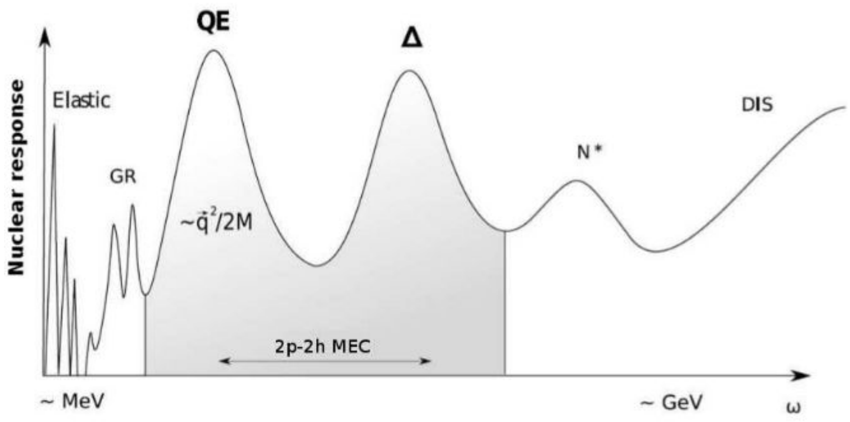
Large systematic uncertainty from modelling of neutrino-nucleus interactions -> room to improve oscillation measurements

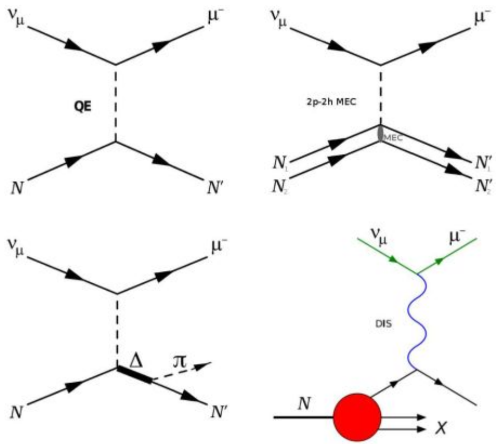
Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

Nature **580**, 339–344(2020)

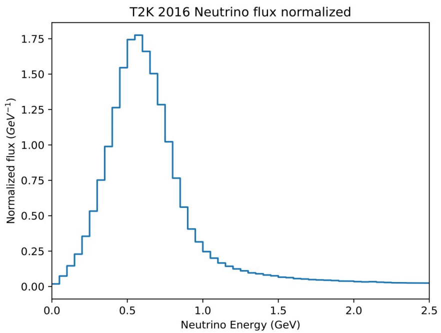
Charged-Current Neutrino-Nucleus Interaction

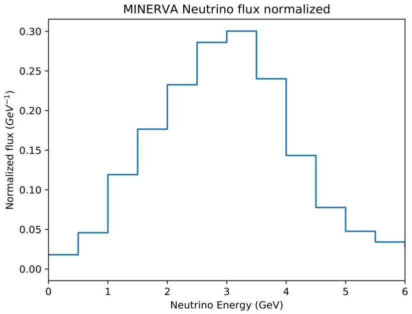
For neutrinos with energy from hundreds of MeVs to a few GeV, several nuclear processes can take place



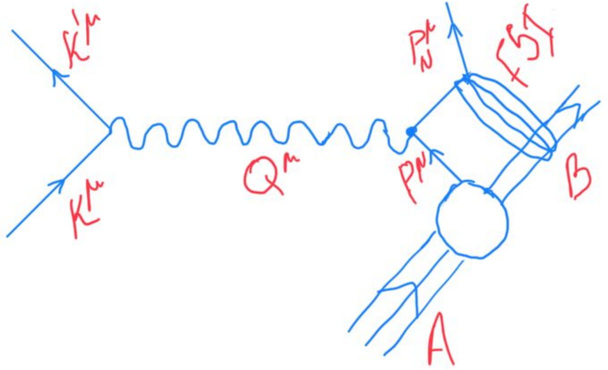


The energy distribution of the neutrinos in **the beam is very broad** compared with almost monochromatic beams used in electron scattering -> The experimental signal is a combination of all different processes happening inside the nucleus (QE+2p2h dominates T2K, DIS and RES are not negligible for MINERVA)





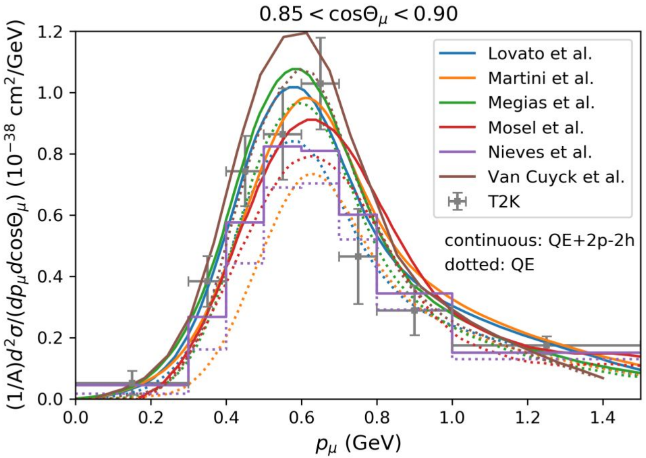
Inclusive vs Semi-Inclusive Scattering



- Inclusive process: only the final lepton k’ is detected
- Semi-inclusive process: one or more particles are detected in coincidence with the final lepton
- Exclusive process: the complete final system is known, including the residual nucleus (possible for electron but not for neutrino scattering)

So far, the majority of the experimental and theoretical work in neutrinos reactions have focused on inclusive reactions. A good agreement between theory and experiment for this kind of reactions can be achieved using very different approaches

Symmetry **2021**, 13, 1625



Semi-inclusive processes are more sensitive to nuclear-medium effects and improve the reconstruction of the neutrino energy

Semi-inclusive neutrino-nucleus formalism in the IA

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

- The leptonic tensor depends only on the initial and final leptons.
- The hadronic tensor holds all the information about nuclear dynamics

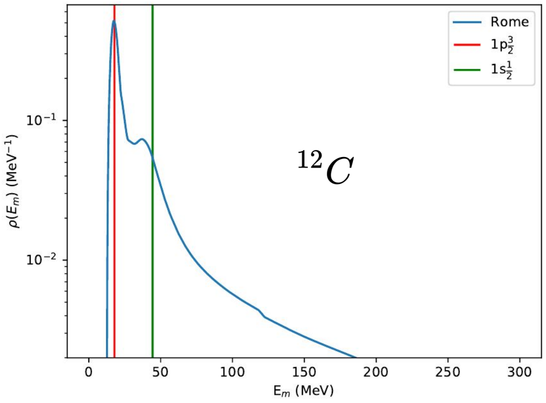
$$H^{\mu\nu}_{\kappa} = \rho_\kappa(E_m) \times \sum_{m_j,\, S_N} \left[J_{\kappa,\, m_j,\, S_N}(Q, P_N)\right]^{\star} J_{k,\, m_j,\, s_N}(Q,\, P_N)$$

$$J_{\kappa,\, m_j,\, S_N}(P_N,\, Q) = \int d\mathbf{p}\, \bar{\Psi}^{S_N}(\mathbf{p}_N,\, \mathbf{q} + \mathbf{p})\, \mathcal{Q}^{\mu}(Q)\, \Psi^{m_j}_{\kappa}(\mathbf{p}) \Longrightarrow$$

- W.F. scattered nucleon
- Boson-nucleon-nucleon operator
- W.F. bound nucleon

Description of the initial state:

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



Scattered Nucleon Description

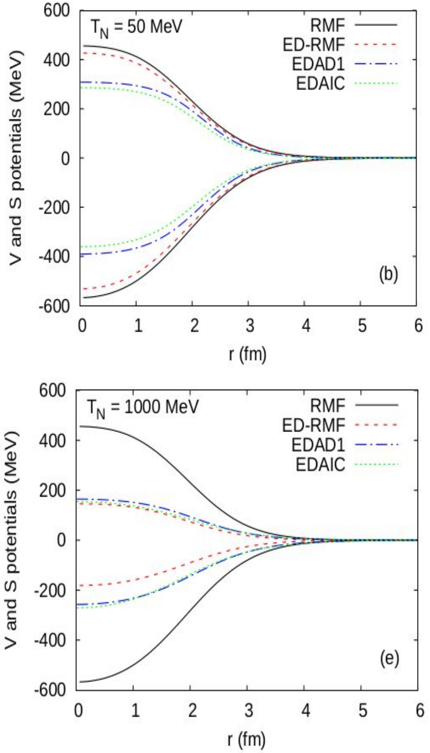
Regarding the scattered nucleon, we can consider several situations:

1. Relativistic Plane-Wave (RPW): the ejected nucleon is considered a plane-wave (i.e, there are not final state interactions)

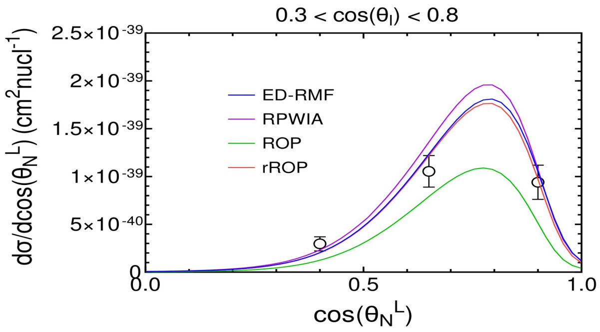
2. Energy-Dependent Relativistic Mean Field (ED-RMF): W.F. solution of the Dirac equation in the continuum using the same RMF potential that describes the initial state but weakened for high nucleon momentum

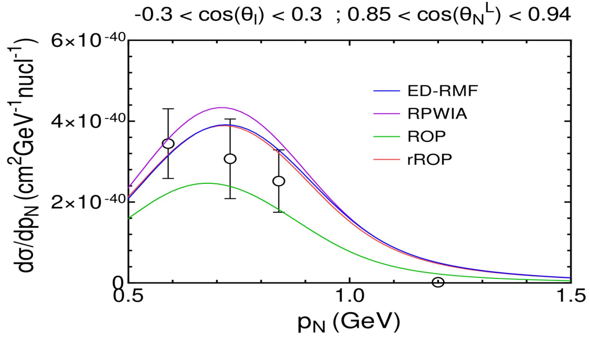
3. Relativistic Optical Potential (ROP): The scattered nucleon travels under the influence of a phenomenological complex relativistic optical potential adjusted to elastic proton scattering. Only the real part (rROP) must be used to analyze inclusive data

^{12}C



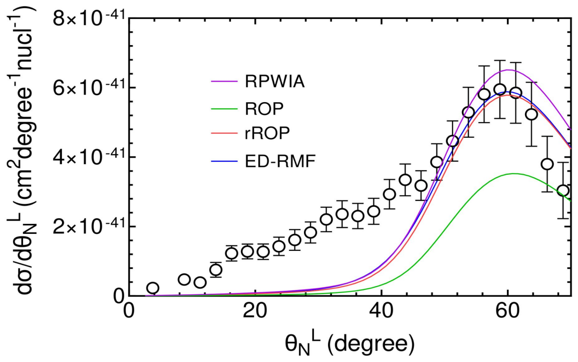
Cross sections vs proton kinematics: T2K and MINERvA

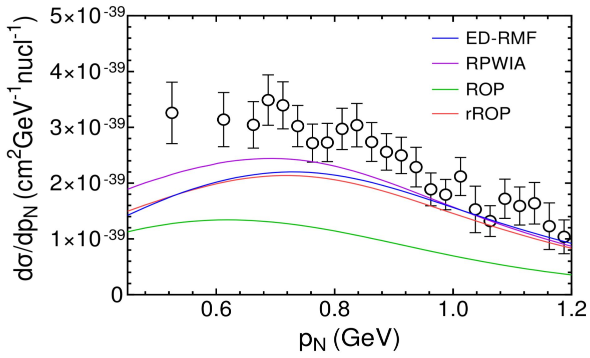




$K.\,Abe\,et\,al.,\,Phys.\,Rev.\,D\,98,032003(2018)$

$$T2K\ \nu_\mu - CC0\pi1p$$
$$p_N > 500\,MeV/c$$





$T.\,Cai\,et\,al.,\,Phys.\,Rev.\,D\,101,092001(2020)$

$$MINER\nu A\ \nu_\mu - CC0\pi1p$$

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	-

RPWIA overestimate the data. FSI reduce the cross section but 2p2p and/or RES are needed.

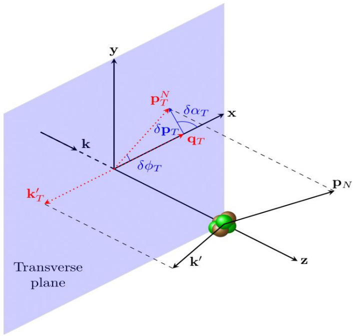
Cross sections vs TKI: T2K and MINERvA

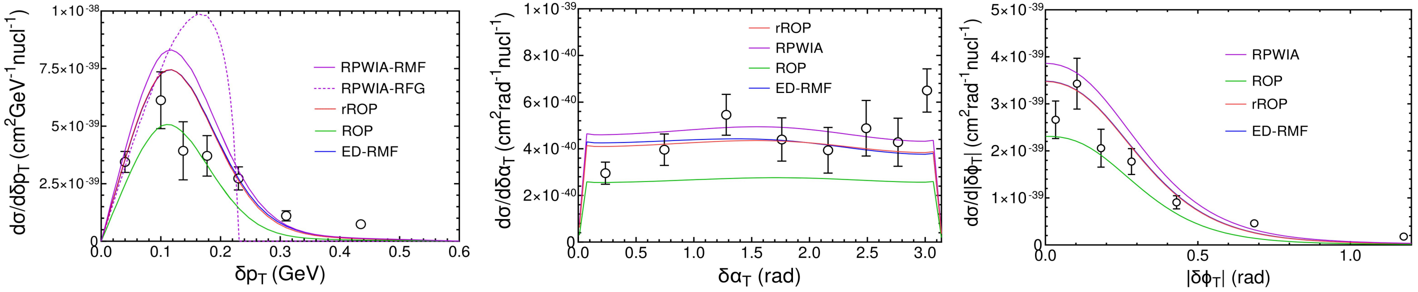
Free nucleon at rest

$$\delta p_T = \left|\mathbf{k}'_T + \mathbf{p}^{\mathbf{N}}_{\mathbf{T}}\right|$$ → Peaked distribution at zero

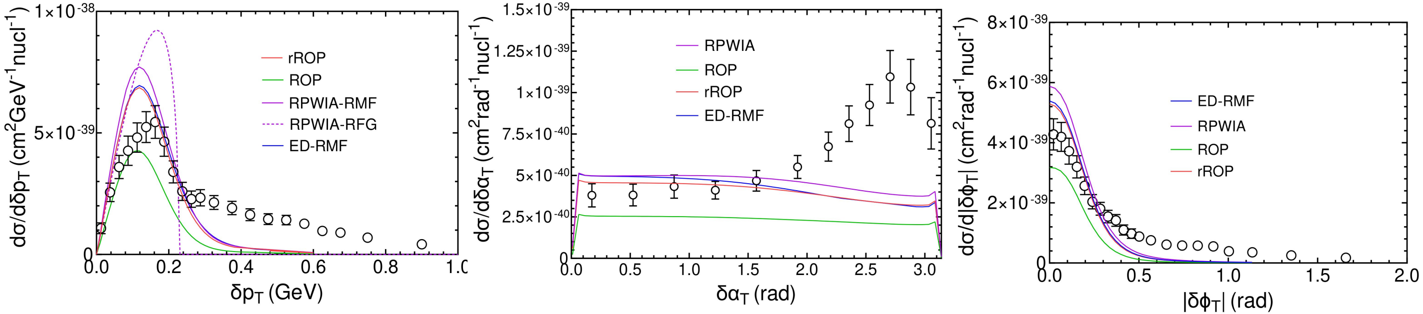
$$\delta\alpha_T = arc\cos\left(\frac{-\mathbf{k}'_{\mathbf{T}}\cdot\delta\mathbf{p}_{\mathbf{T}}}{k'_T\delta p_T}\right)$$ → Undefined, flat distribution

$$\delta\phi_T = arc\cos\left(\frac{-\mathbf{k}'_T\cdot\mathbf{p}^{\mathbf{N}}_{\mathbf{T}}}{k'_T p^N_T}\right)$$ → Peaked distribution at zero





T2K



MINERνA

Cross sections vs Inferred Variables: T2K

Inferred variables: difference between measured proton kinematics and proton kinematics calculated from muon variables supposing QE hypothesis holds (i.e. initial nucleon at rest)

$$\Delta p = |\mathbf{p}_N| - \left|\mathbf{p}_N^{inf}\right|$$

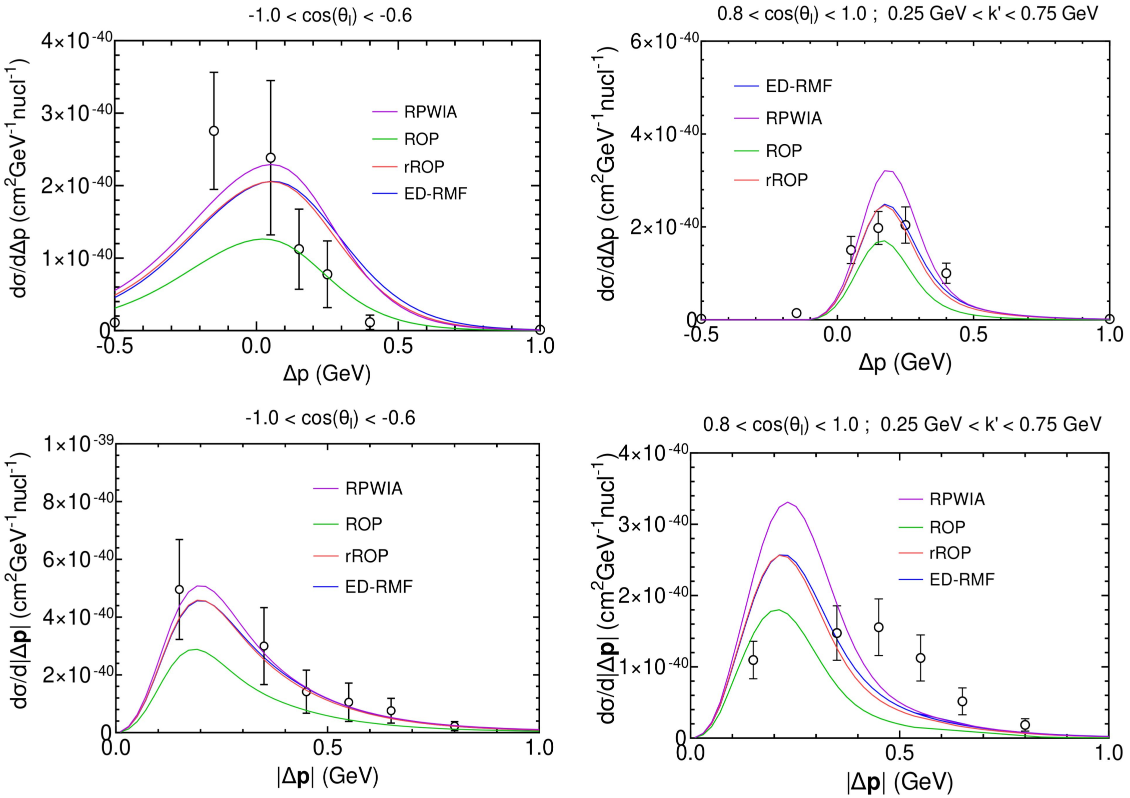
$$|\Delta \mathbf{p}| = \left|\mathbf{p}_N - \mathbf{p}_N^{inf}\right|$$

$$\mathbf{p}_N^{inf} = \left(-k'_x, \ -k'_y, \ -k'_z + E_\nu\right)$$

$$E_\nu = \frac{m_p^2 - m_\mu^2 + 2E'(m_n - E_b) - (m_n - E_b)^2}{2[m_n - E_b - E' + k' \cos(\theta_\mu)]}$$

⇩

Same formula used to reconstruct the neutrino energy in oscillations measurements at T2K



Summary

- Experimental and theoretical efforts to measure and describe semi-inclusive cross sections to help constrain nuclear models for oscillation experiments

- The RMF and ROP models have been successfully applied in the past to the study of inclusive and exclusive electron scattering. The same analysis is now being extended to neutrino scattering

- We have described several ways to include FSI in our theoretical model which improves in general the agreement with experimental data but we need to add effects beyond the impulse approximation to draw conclusions about which approach is better

THANKS FOR YOUR ATTENTION