MODELLING SEMI-INCLUSIVE NEUTRINO-NUCLEUS SCATTERING

JUAN MANUEL FRANCO PATIÑO

PhD STUDENT

SUPERVISED BY J.A. CABALLERO AND M.B. BARBARO

UNIVERSITY OF SEVILLE, SPAIN

UNIVERSITY OF TURIN, ITALY

ISTITUTO NAZIONALE DI FISICA NUCLEARE (INFN), SEZIONE DI TORINO

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

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NEUTRINOS IN COSMOLOGY, ASTRO-, PARTICLE- AND NUCLEAR PHYSICS

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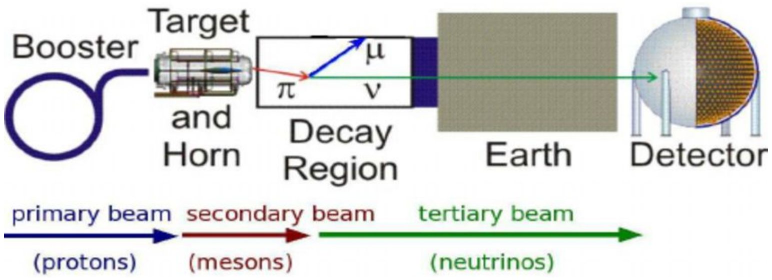
What do we need neutrino-nucleus scattering for?

$$P_{\nu_\alpha \to \nu_\beta} \approx \sin^2(2\theta)\sin^2\left(\frac{L\Delta m^2}{4E_\nu}\right)$$

To measure the oscillation parameters we need to know the energy of the neutrino



Typical targets: C, O or Ar

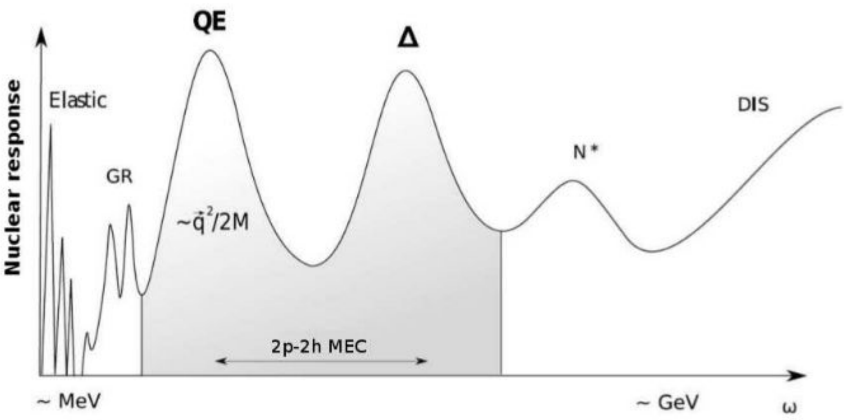
Large systematic uncertainty from modelling of neutrino-nucleus interactions -> room to improve oscillation measurements

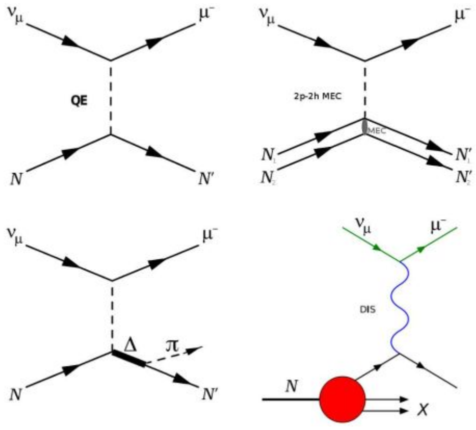
Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal 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)

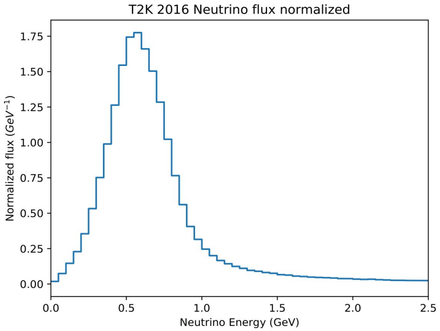
Charged-Current Neutrino-Nucleus Interaction

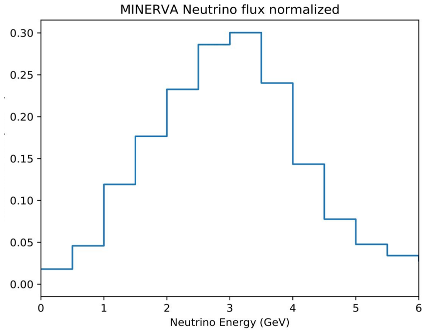
For neutrinos with energy from hundreds of MeV to a few GeV, several nuclear processes can take place





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 occurring inside the nucleus (QE+2p2h dominates T2K, DIS and RES are not negligible for MINERVA)





Charged-Current Neutrino-Nucleus Interaction

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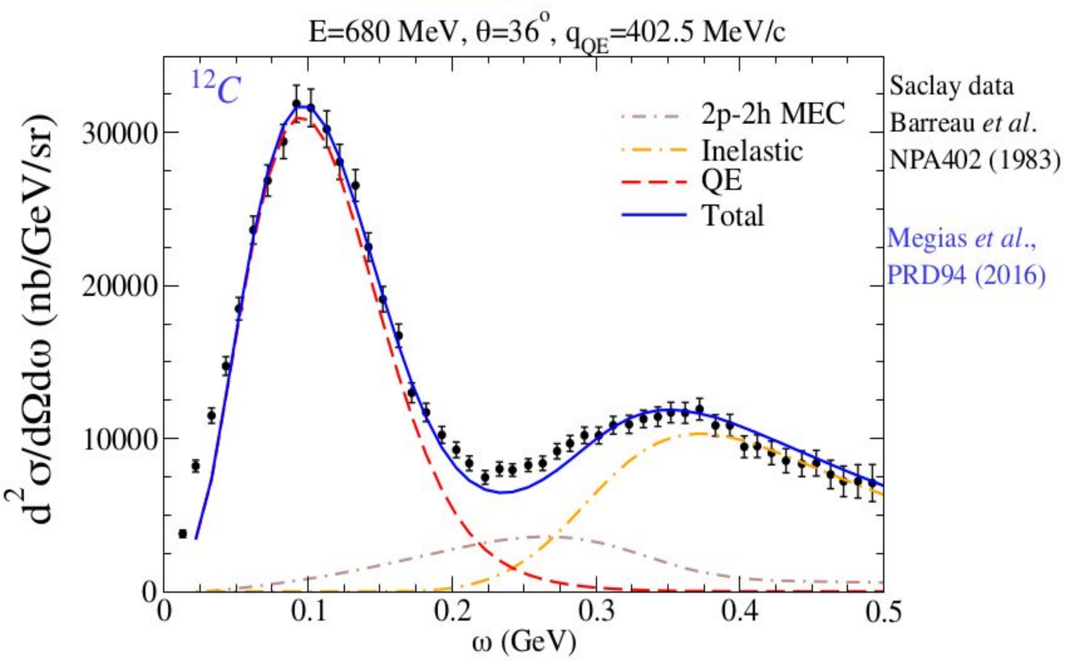
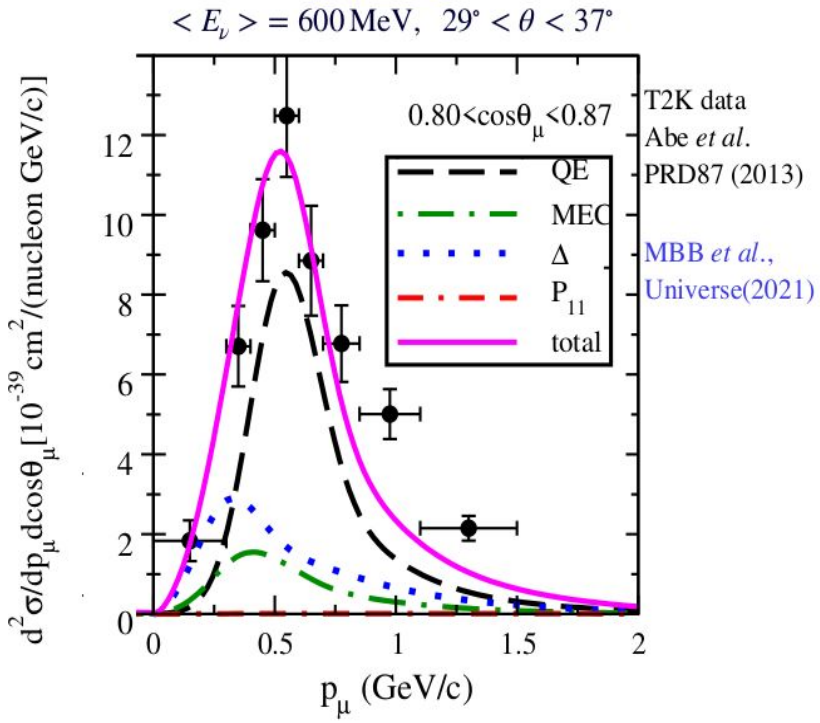
(e, e')

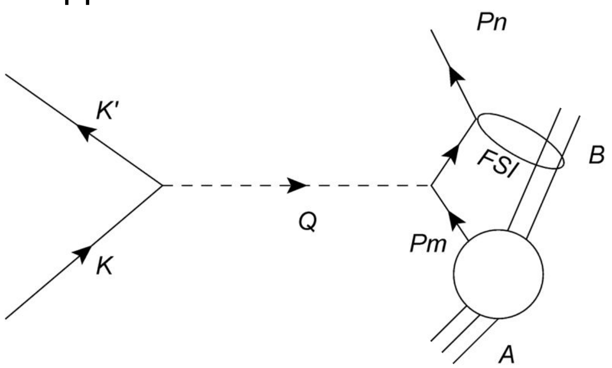


(ν_μ, μ)



Inclusive vs Semi-Inclusive Scattering

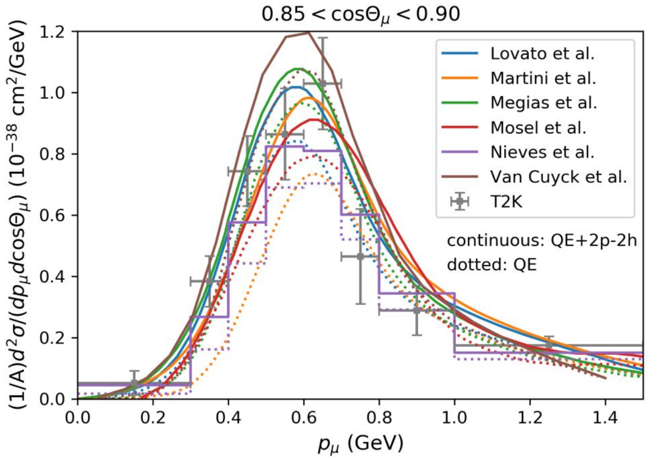
One proton knockout in the impulse approximation



- Inclusive process: only the final lepton k' is detected
- Semi-inclusive process: one or more particles are detected in coincidence with the final lepton (k' and pN)
- 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 neutrino 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

A. Branca et al., 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

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

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

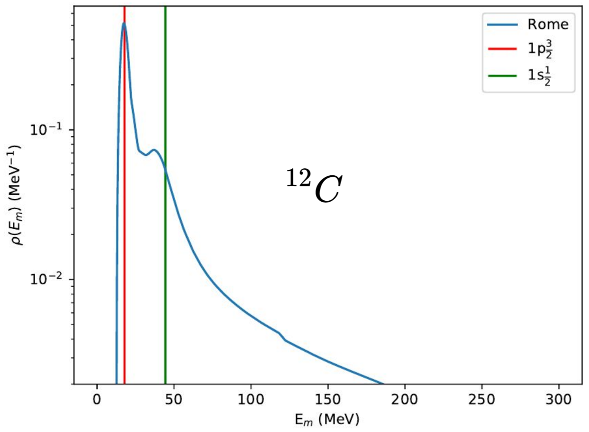
$$H^{\mu\nu}_{\kappa} = \rho_\kappa(E_m) \times \sum_{m_j,\, s_N} \left[J_{\kappa,\, m_j,\, s_N}(Q, P_N)\right]^\star J_{k,\, m_j,\, s_N}(Q,\, P_N)$$

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

- W.F. scattered nucleon (red)
- CC2 operator (blue)
- W.F. bound nucleon (green)

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 (Benhar spectral function) used in electron exclusive processes: short- and long-range correlations included



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 scattering data.

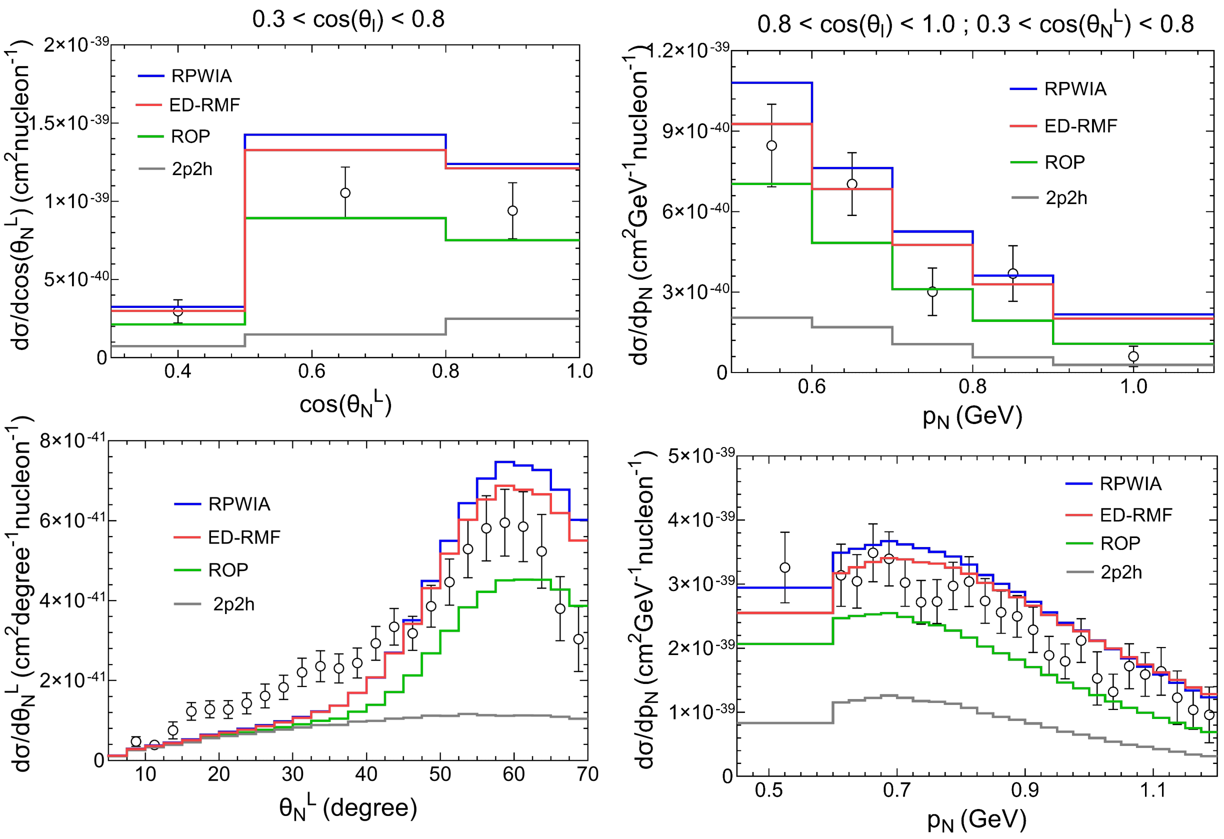
$$\Psi_{s_N}(\mathbf{r},\,\mathbf{p_N}) = 4\pi\sqrt{\frac{E_N+m_N}{2E_N}}\sum_{\kappa,\,m_l,\,m_j} e^{-i\delta^*_\kappa} i^l \langle l\, m_l\, 1/2\, s_N |\, j\, m_j\rangle Y^*_{l\,m_l}(\Omega_N)\psi^{m_j}_\kappa(\mathbf{r},\,E_N)$$

$$\psi^{m_j}_\kappa(\mathbf{r},\,E_N) = \begin{pmatrix} g_\kappa(r)\phi^{m_j}_\kappa(\Omega_r) \\ i f_\kappa(r)\phi^{m_j}_{-\kappa}(\Omega_r)\end{pmatrix}$$

$$\frac{dg_\kappa}{dr} = -\frac{\kappa}{r}g_\kappa + [E_N + S(r,\,E_N) - V(r,\,E_N)]f_\kappa$$

$$\frac{df_\kappa}{dr} = -\frac{\kappa}{r}f_\kappa + [E_N - S(r,\,E_N) - V(r,\,E_N)]g_\kappa$$

Cross sections vs proton kinematics



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 overestimates the data. FSI reduce the cross section and 2p2h is needed.

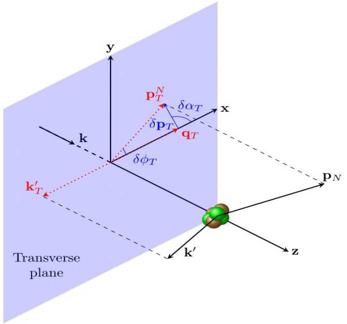
Cross sections vs transverse kinematic imbalances

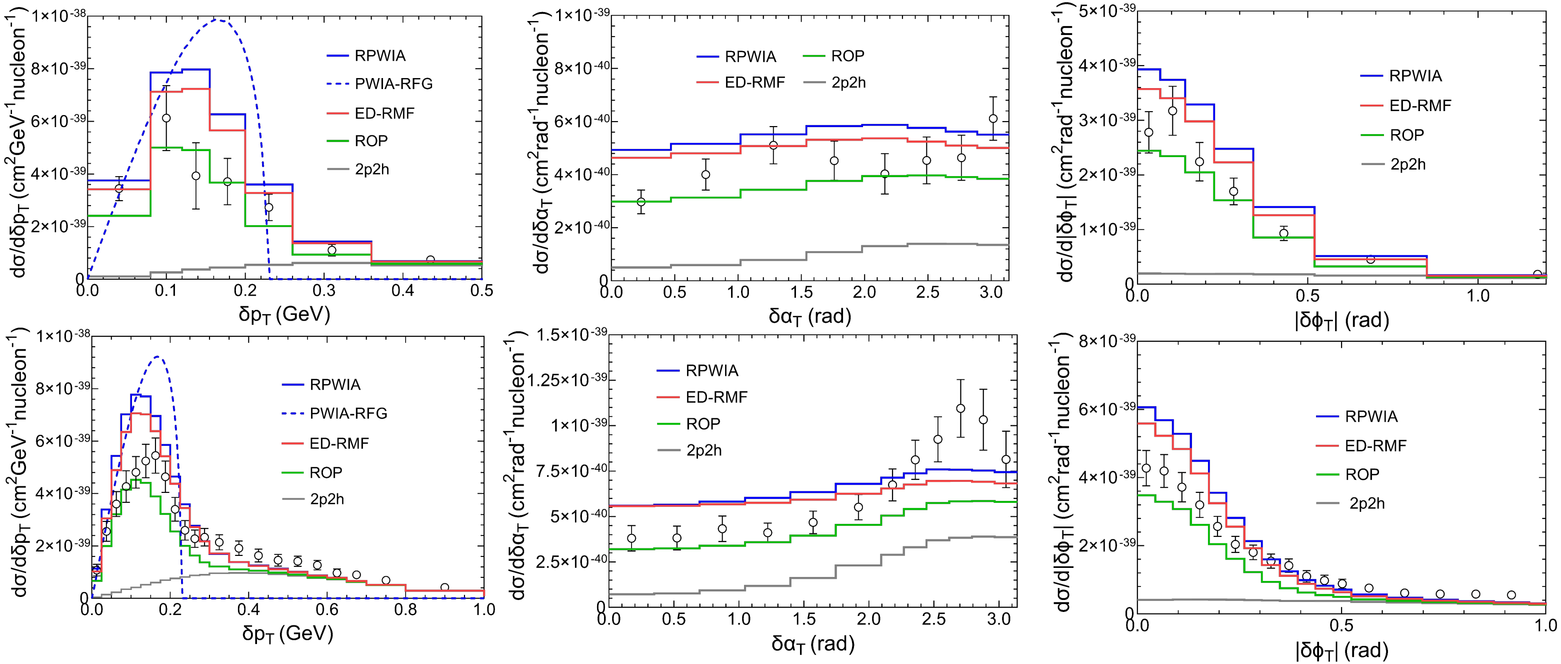
Free nucleon at rest

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

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

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





$T2K$

$MINER\nu A$

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. Variables that measure correlations between both particles in the final state like TKI allow us to discriminate between nuclear models and separate contributions from different channels.

J.M. Franco-Patino, J. Gonzalez-Rosa *et al.* Phys. Rev. C 102, 064626 (2020) ⟹ **General formalism**

J.M. Franco-Patino *et al.* Phys. Rev. D 104, 073008 (2021) ⟹ **Comparison with data in RPWIA**

J.M. Franco-Patino *et al.* arXiv:2207.02086 (submitted to PRD) ⟹ **Analysis of 12C data including FSI**

J.M. Franco-Patino *et al.* in preparation ⟹ **Analysis of 40Ar data including FSI**

THANKS FOR YOUR ATTENTION