FINAL STATE INTERACTIONS IN SEMI-INCLUSIVE NEUTRINO-NUCLEUS SCATTERING: APPLICATION TO T2K AND MINERνA EXPERIMENTS

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Semi-inclusive neutrino-nucleus reactions

AIM: Realistic description of semi-inclusive neutrino-nucleus scattering for neutrino oscillation experiments

WHY?: In neutrino oscillation experiments the information about the oscillation signal comes from detection of the final-state muons only ⟹ little dependence with the nuclear model used

Semi-inclusive scattering is more sensitive to nuclear-medium effects

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

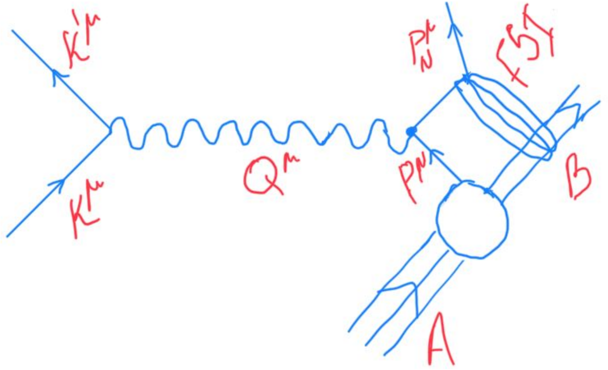
Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal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

HOW?: Using the Relativistic Distorted-Wave Impulse Approximation (RDWIA)

⟹ Unfactorized relativistic and fully quantum approach extensively applied in the past to exclusive and inclusive electron scattering

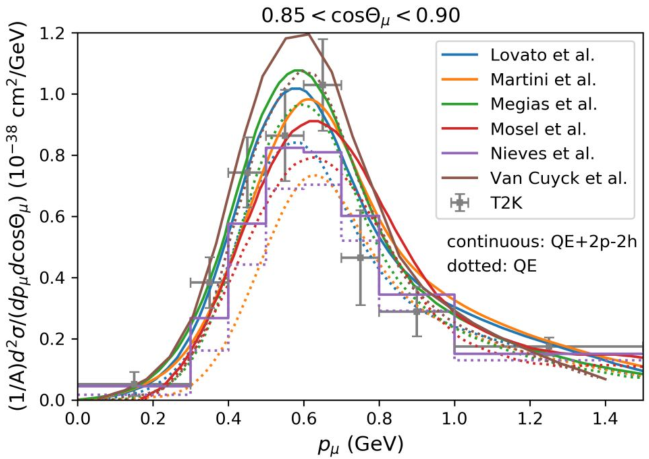
Inclusive vs semi-inclusive scattering



- 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)

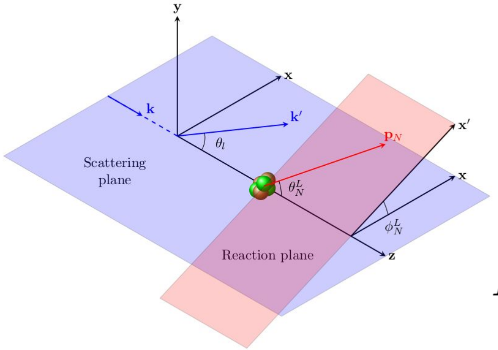
So far, the majority of the experimental and theoretical works in neutrino reactions have focused on inclusive reactions. A good agreement between theory and experiment for this kind of reactions can be achieved using very different approaches

Martini 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



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

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

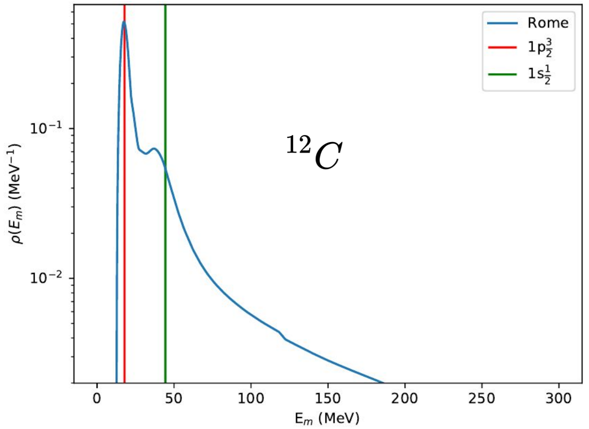
Factorization NOT assumed!!

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

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

Description of the initial state:

- Pure shell model (first approximation): energy density is given by a Dirac delta per shell
- Realistic model (i.e. Rome 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 reproduce elastic proton scattering data. Keeping only the real part of the OP (rROP) is an effective way to take into account all the channels (elastic and inelastic)

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

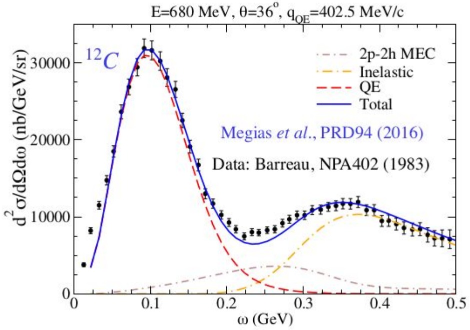
$$\psi^{m_j}_\kappa(\mathbf{r}) = \begin{pmatrix} g_\kappa(r)\phi^{m_j}_\kappa(\Omega_r) \\ i f_\kappa(r)\phi^{m_j}_{-\kappa}(\Omega_r) \end{pmatrix}$$

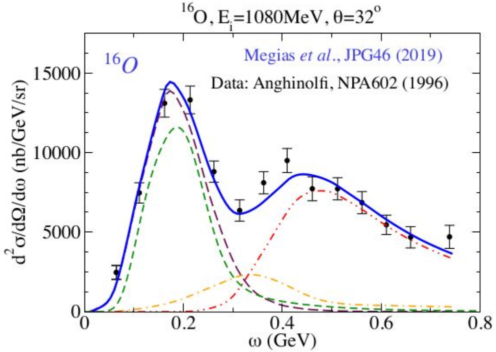
$$\frac{dg_\kappa}{dr} = -\frac{\kappa}{r}g_\kappa + [E_N + S(r,\, E_N) - V(r,\, E_N)]f_\kappa$$

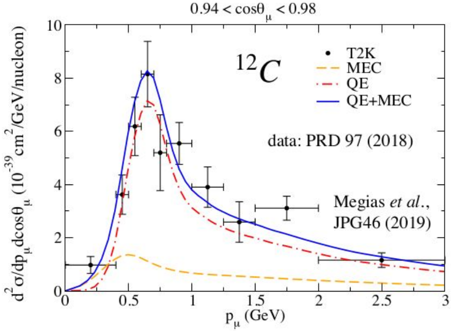
$$\frac{df_\kappa}{dr} = -\frac{\kappa}{r}f_\kappa + [E_N - S(r,\, E_N) - V(r,\, E_N)]g_\kappa$$

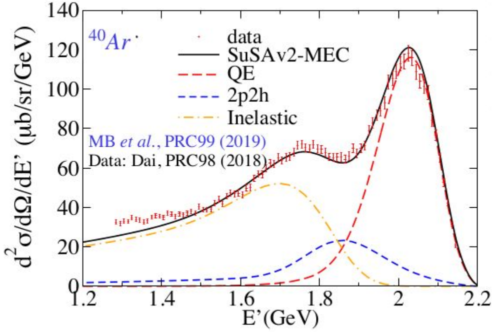
SuSAv2-MEC implementation in GENIE

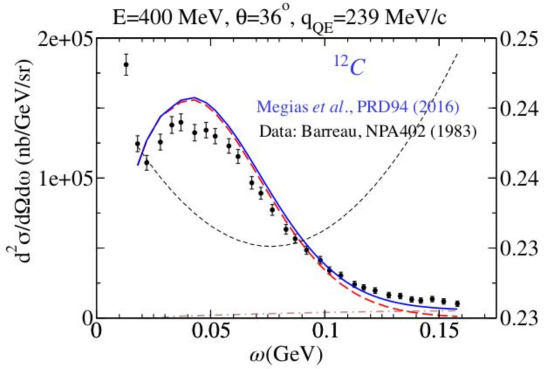
The SuSAv2 model (see G.D. Megias Thesis, PRC 90 035501 (2014) and PRD 94 013012(2016) for details) is an inclusive model based on the SuperScaling approach and RMF results widely used to describe electron and neutrino inclusive data at high momentum transfer (q > 300 MeV/c)

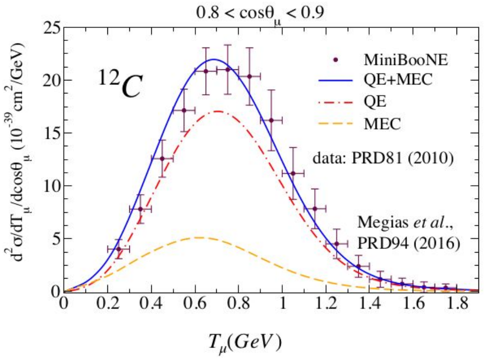






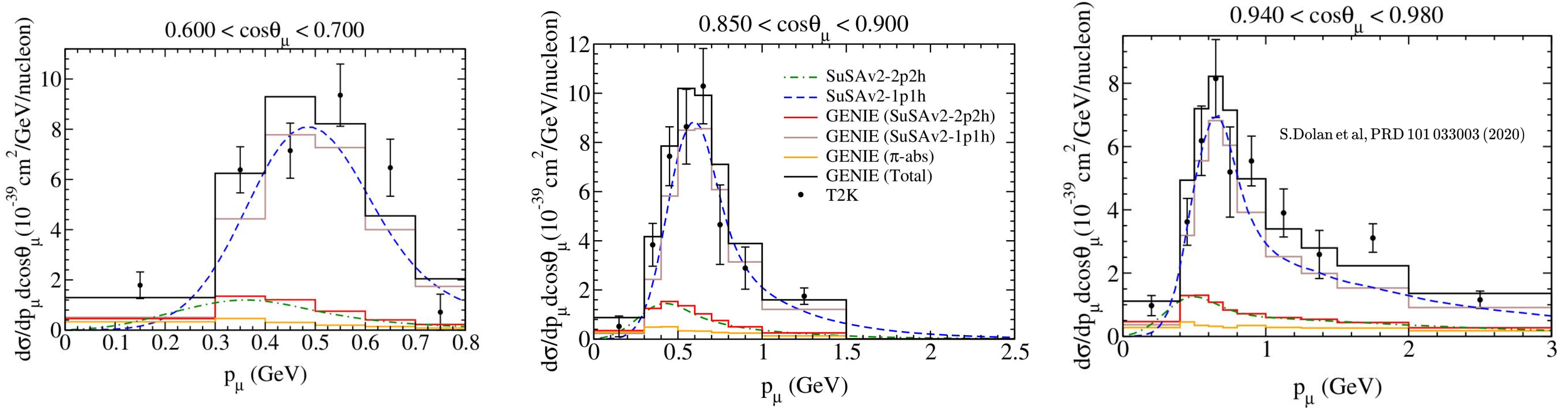






SuSAv2-MEC implementation in GENIE

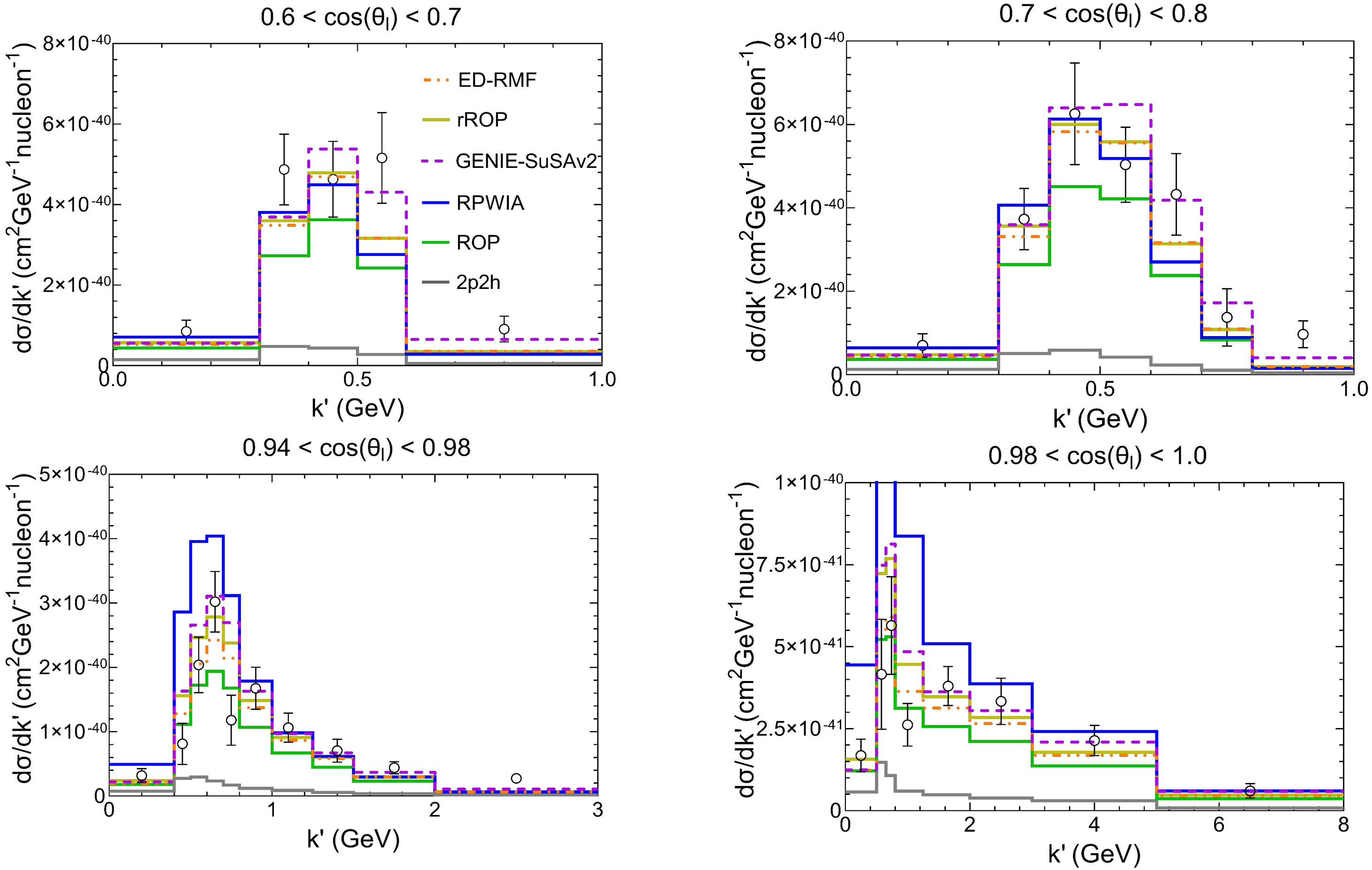
SuSAv2 1p1h and 2p2h models were implemented in GENIE neutrino generator for (e,e') and CC ν_μ



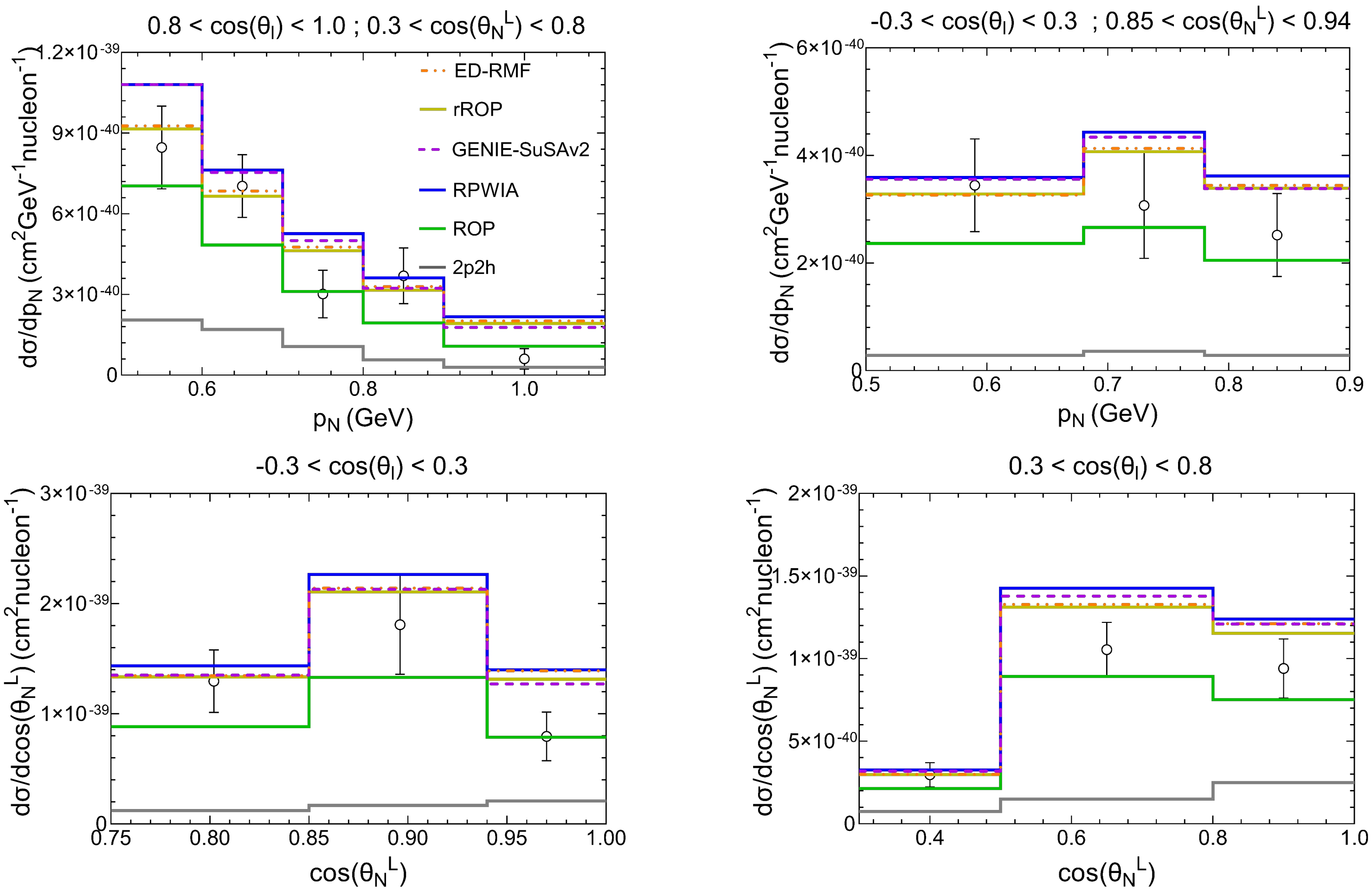
The implementation was tested against the original calculation and the agreement was found to be very good

However, the model remains <u>inclusive</u> because the hadronic tensor only depends on two variables (q, ω). Assuming a factorization of the leptons and hadrons kinematics (different from the typical factorization involving the spectral function!!), an inclusive model implemented in a neutrino generator can generate <u>semi-inclusive results</u> by independently sampling from a Fermi gas the momentum of the initial nucleon

Cross Sections vs Muon Kinematics: T2K pN < 500 MeV



Cross Sections vs Proton Kinematics: T2K pN > 500 MeV

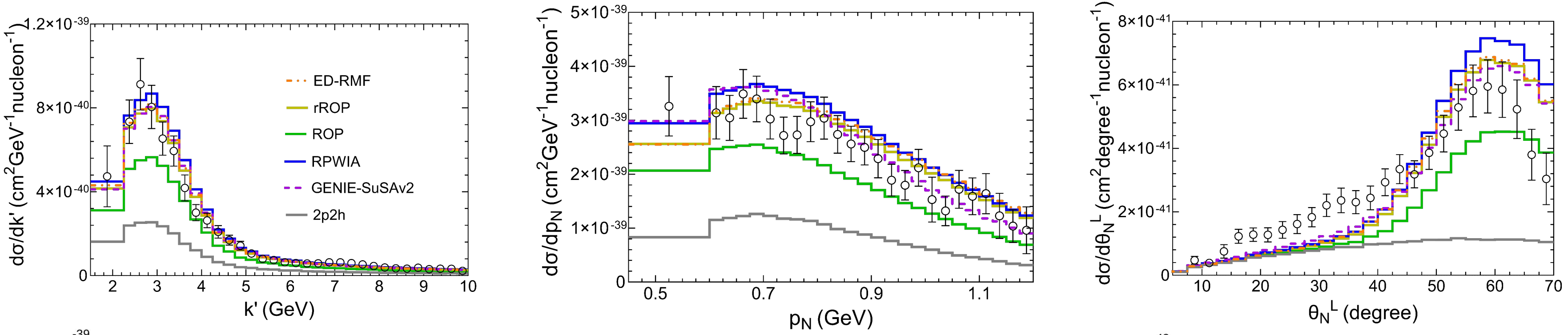


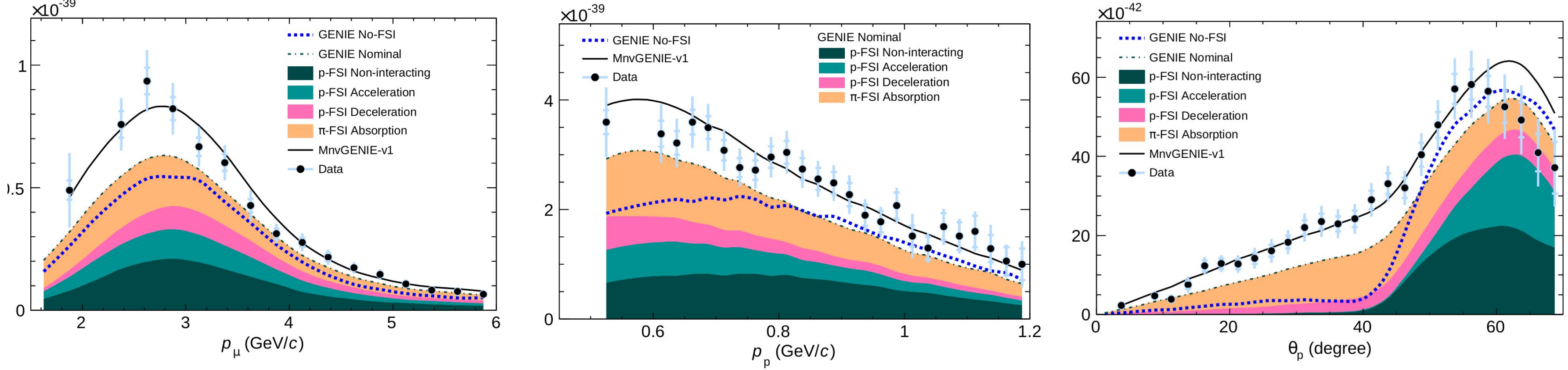
Cross sections vs Muon and Proton Kinematics: MINERvA

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

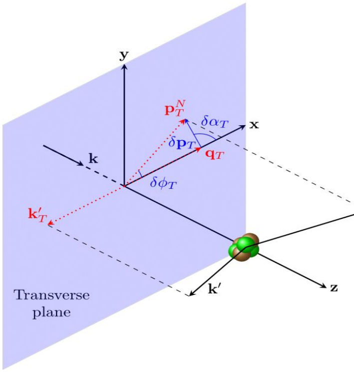
$MINER\nu A\ \ \nu_\mu - CC0\pi Np$

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 TKI

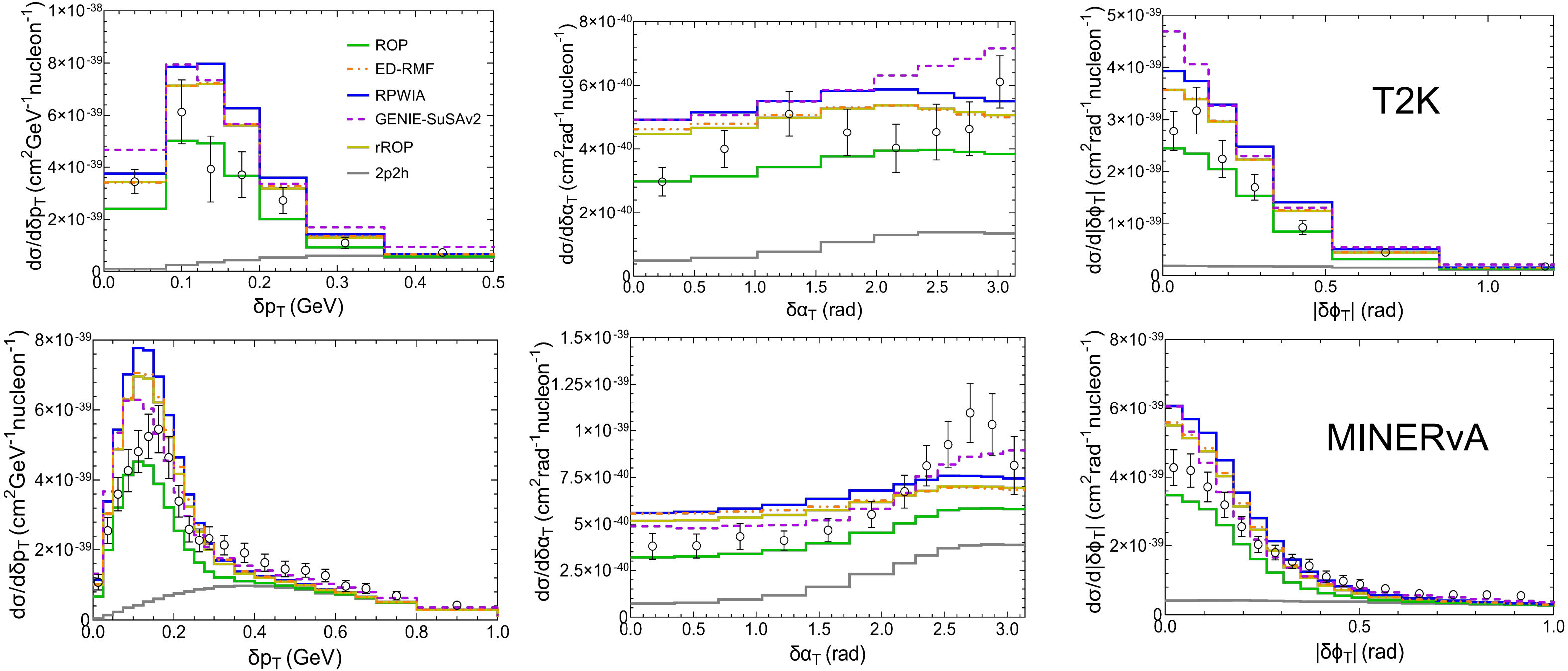


Free nucleon at rest

$$\delta p_T = \left|\mathbf{k'}_T + \mathbf{p_T^N}\right|$$ → Peaked distribution at zero

$$\delta\alpha_T = arc\cos\left(\frac{-\mathbf{k'_T}\cdot\delta\mathbf{p_T}}{k'_T\delta p_T}\right)$$ → Undefined, flat distribution

$$\delta\phi_T = arc\cos\left(\frac{-\mathbf{k}'_T\cdot\mathbf{p_T^N}}{k'_T p_T^N}\right)$$ → Peaked distribution at zero

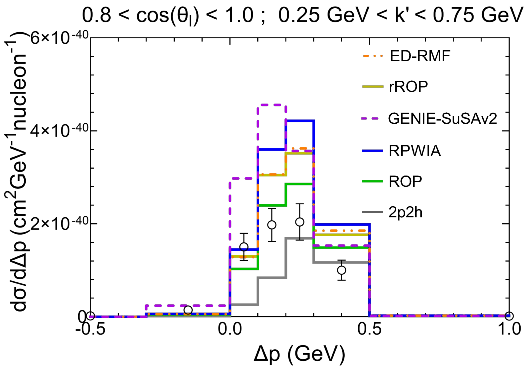


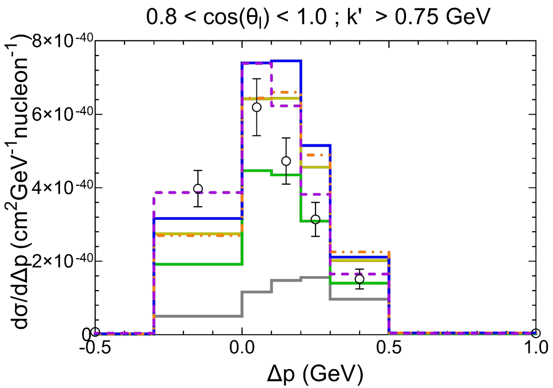
Cross sections vs Inferred Variables: T2K

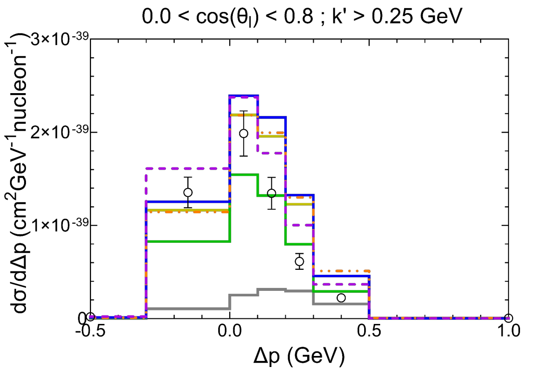
$$\Delta p = |\mathbf{p}_N| - \left|\mathbf{p}_N^{inf}\right|$$
$$|\Delta \mathbf{p}| = \left|\mathbf{p}_N - \mathbf{p}_N^{inf}\right|$$
$$\Delta\theta = \theta_N^L - \theta_N^{L,\,inf}$$

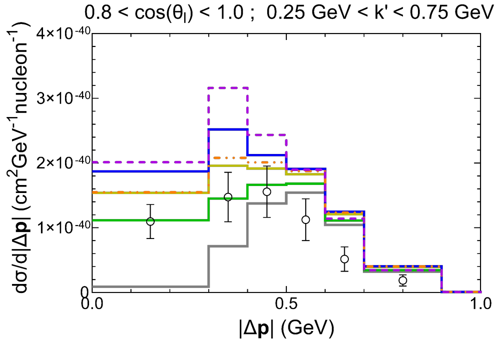
$$\mathbf{p}_N^{inf} = \left(-k'_x,\ -k'_y,\ -k'_z + E_\nu\right)$$
$$E_\nu = \frac{m_p^2 - m_\mu^2 + 2E'(m_n - E_b) - (m_n - E_b)^2}{2[m_n - E_b - E' + k' \cos(\theta_\mu)]}$$

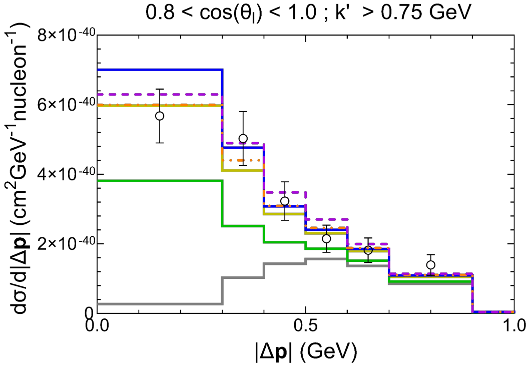
$\Rightarrow$ Same formula used to reconstruct the neutrino energy in oscillations measurements at T2K

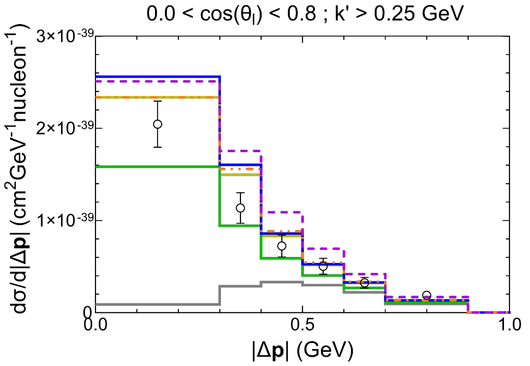












Summary

- 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

- Although it is difficult to draw precise conclusions about the individual effects of the approximations used to obtain semi-inclusive results with the SuSAv2 model, the microscopic calculation based on RMF theory improves the agreement with exp. measurements at low momentum and energy transfer kinematics where factorization and SuSAv2 model fail

- All the results shown here and many more are available and discussed in arxiv: 2207.02086 (2022)

- **Work in progress**: Comparison of the models with CC0πNp and CC0π1p measurements from MicroBooNE collaboration on 40Ar

THANKS FOR YOUR ATTENTION

BACKUP SLIDES

Final nucleon kinematics generation in GENIE-SuSAv2

Extracted from Alexis Nikolakopoulos talk in NuSTEC Cross Theory and Generators Working Group called "Final-State Interactions in inclusive and exclusive one-nucleon knockout"

1. Draw initial nucleon momentum $\mathbf{p_m}$ from a Fermi gas distribution
2. Compute $E_m^2 = p_m^2 + M_N^2$
3. $E_N = E_m + \omega - E_b(q)$
4. $p_N^2 = E_N^2 - M_N^2\,;\ |\mathbf{p_m} + \mathbf{q}| \neq p_N = \sqrt{E_N^2 - M_N^2}\,;\ \mathbf{p_N} = \dfrac{p_N}{|\mathbf{p_m} + \mathbf{q}|}(\mathbf{p_m} + \mathbf{q})$
5. Give the residual momentum to the remnant

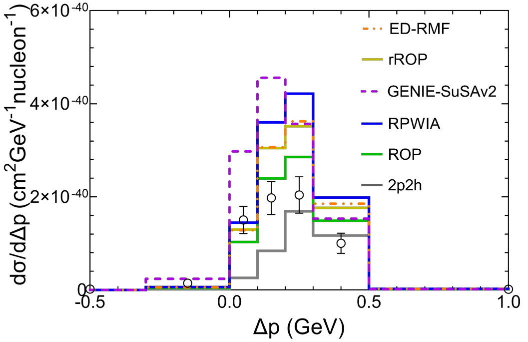
Cross sections vs Inferred Variables: T2K

$$\Delta p = |\mathbf{p}_N| - \left|\mathbf{p}_N^{inf}\right|$$
$$|\Delta \mathbf{p}| = \left|\mathbf{p}_N - \mathbf{p}_N^{inf}\right|$$
$$\Delta\theta = \theta_N^L - \theta_N^{L,\,inf}$$

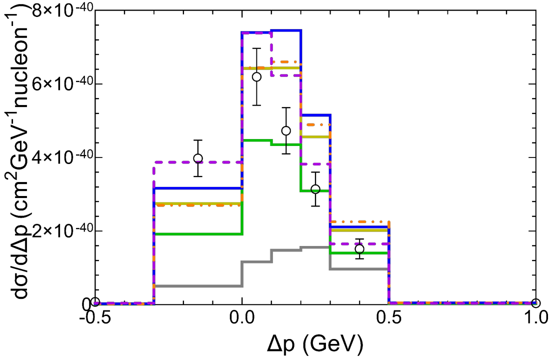
$$\mathbf{p}_N^{inf} = (-k'_x,\ -k'_y,\ -k'_z + E_\nu)$$
$$E_\nu = \frac{m_p^2 - m_\mu^2 + 2E'(m_n - E_b) - (m_n - E_b)^2}{2[m_n - E_b - E' + k'\cos(\theta_\mu)]}$$

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

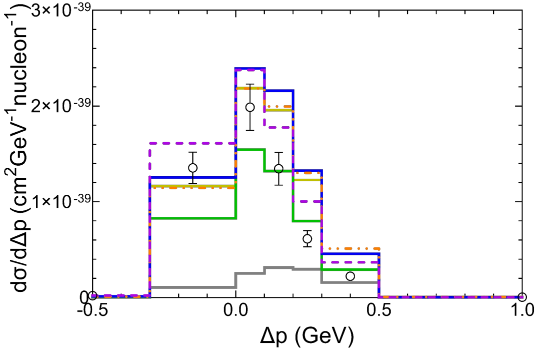
0.8 < cos(θ$_l$) < 1.0 ; 0.25 GeV < k' < 0.75 GeV



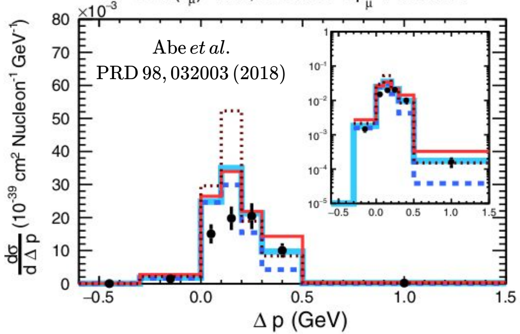
0.8 < cos(θ$_l$) < 1.0 ; k' > 0.75 GeV



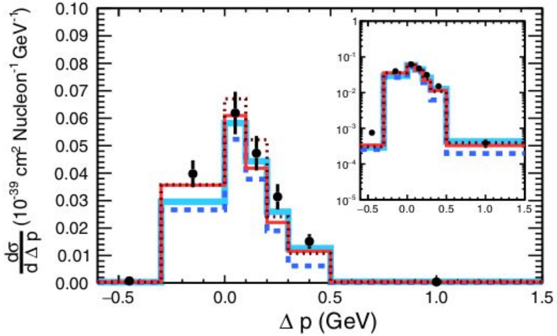
0.0 < cos(θ$_l$) < 0.8 ; k' > 0.25 GeV



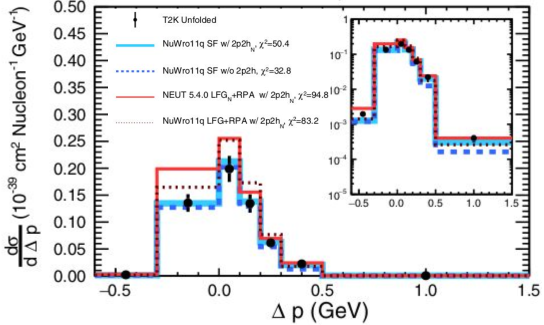
0.8 < cos(θ$_\mu$) < 1.0, 250 MeV < p$_\mu$ < 750 MeV



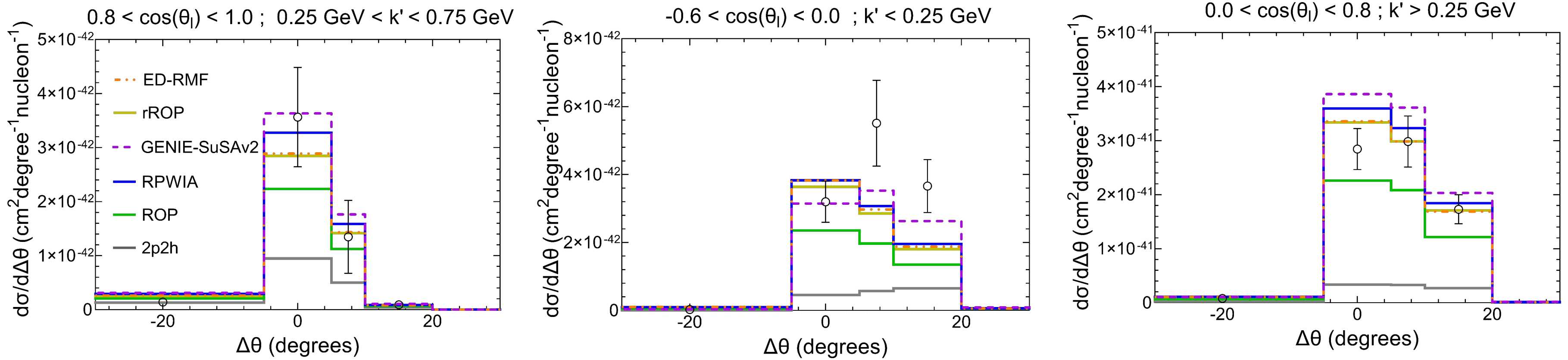
0.8 < cos(θ$_\mu$) < 1.0, p$_\mu$ > 750 MeV

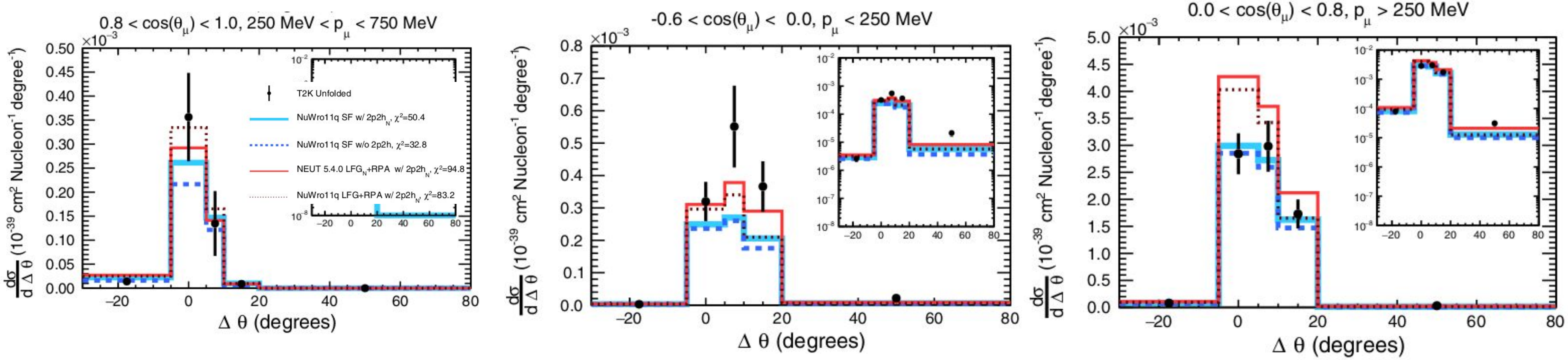


0.0 < cos(θ$_\mu$) < 0.8, p$_\mu$ > 250 MeV

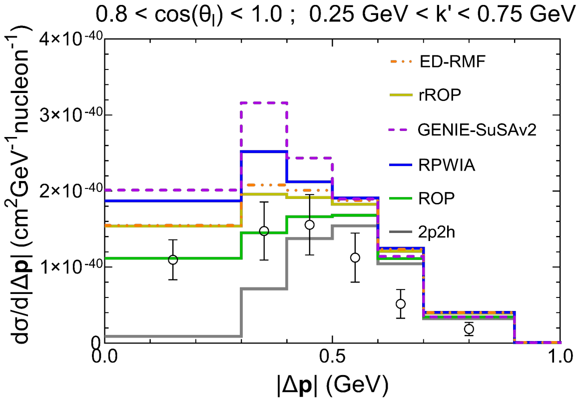


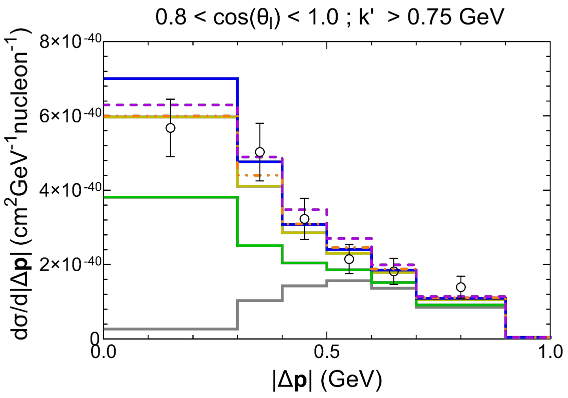
Cross sections vs Inferred Variables: T2K

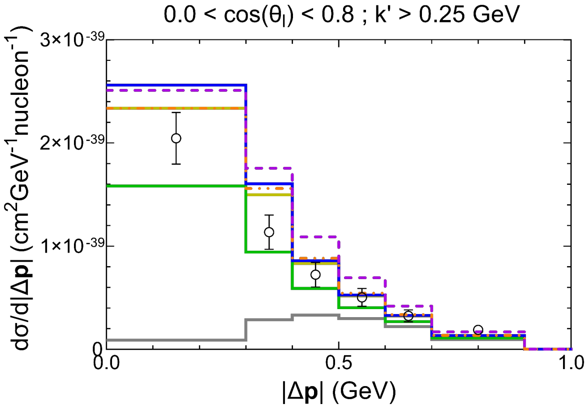


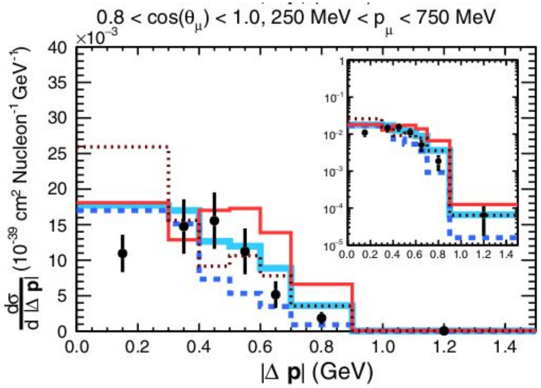


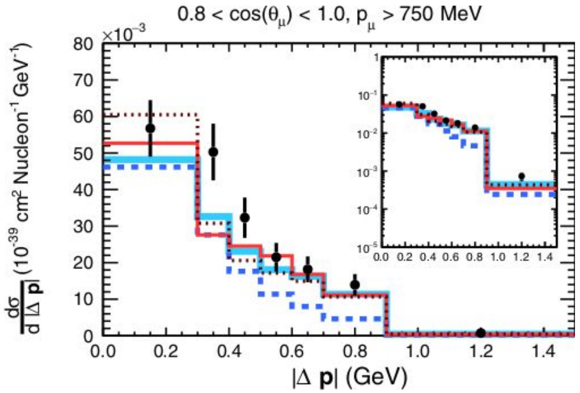
Cross sections vs Inferred Variables: T2K

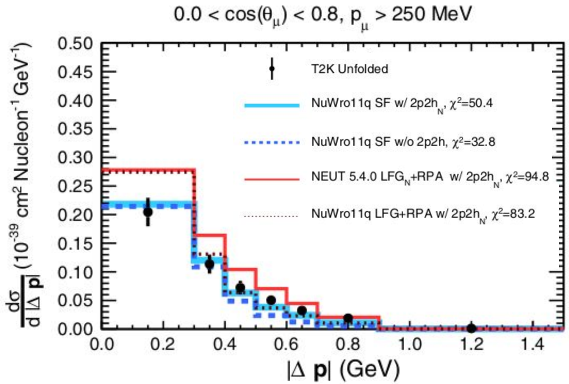












Cross sections vs TKI: cont.