The relevance of neutrino-nucleus interaction models in T2K and SuperKamiokande: Implementation of the SuSAv2-MEC model in generators and analysis of low-energy nuclear effects

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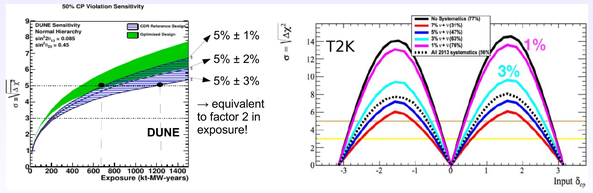
1. Precise knowledge of ν oscillation properties require accurate $\nu - A$ interaction models

➥ **Exp. systematics in T2K** are around a **4**% (**7**%) for ν_μ (ν_e) reactions and are dominated by flux and ν-A cross section uncertainties (**3**%). *PRD91, 072010(2015).*

➥ Oscillation measurements in future experiments (HyperK, DUNE) aim to $\sim 1-3\%$ systematic uncertainty and determine mass hierarchy and δ_{CP} violation phase. *Nature 580, 339-344(2020).*

➥ A reduction of 2% would improve CPV sensitivity from 5σ to 6σ while reducing by two experimental exposure ➠ Need for development and **implementation** of sophisticated $\nu - A$ models in **MC generators**.



arXiv:1512.06148 [physics.ins-det] ; *arXiv:1607.08004 [hep-ex]*

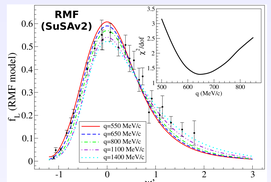
The implementation of more accurate models can help to understand $\nu/\bar{\nu}$ asymmetry, to improve hadron detection efficiency, the characterization of FS particles or the extrapolation from the usual ^{12}C target analysis to other nuclei (^{16}O [T2K ND280 upgrade], ^{40}Ar, etc.)

2. Relativistic Mean Field Theory and SuperScaling Approach: RMF, ED-RMF and SuSAv2 models

✪ **Relativistic Mean Field (RMF)**: Fully relativ. shell model with accurate description of nuclear dynamics and FSI. Energy-independent (EI) nuclear potentials fitted to nuclear matter properties ⇒ good description of (e,e') and ν-A data at low and intermediate kinematics, fulfiling the (e,e') data scaling behavior, while other models fails. EI RMF potentials are too strong to describe FSI at high kinematics where **RPWIA** ("RMF w/o FSI, final-state plane waves") does a better job.

✪ **SuSAv2** (SuperScaling Approach v2, *PRC90, 035501 (2014) ; PRD94, 013012 (2016)*) builds a trade-off between RMF and RPWIA models (through a combination of RMF and RPWIA scaling functions), but low-energy nuclear effects are not properly included at very low kinematics ($< 50-100$ MeV).

✪ **ED-RMF**: introduces Energy-Dependent potentials (weighted by SuSAv2 results at intermediate-high kinematics ($T_N > 100MeV$)) to the RMF to keep the strength for slow nucleons while making RMF potentials softer for high nucleon momenta, thus solving SuSAv2 drawbacks at very low energies and RMF ones at high kinematics.



Comparison of experimental (e,e') scaling data on 12C with the theoretical RMF scaling functions at different kinematics. The scaling function contains the information about the nuclear dynamics of the process.

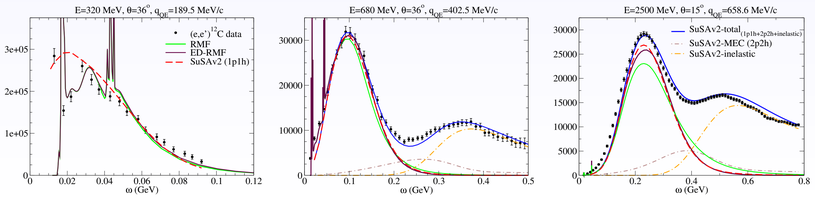
$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(^{\text{nuclear}}_{\text{effects}})}{\sigma_{\text{single nucleon}}(^{\text{no nuclear}}_{\text{effects}})}$$

$$f(\psi') = k_F \frac{\left(\frac{d^2\sigma}{d\Omega_{\epsilon'} d\omega}\right)_{exp}}{\sigma_{Mott}(v_L G_L^{ee'} + v_T G_T^{ee'})}$$

RMF-based models could help to reduce low-energy and nuclear-medium systematics as well as to reveal C/O differences related to the corresponding binding energy (E_b) and shell effects, FSI, Coulomb distortions, etc.

See *arXiv:1912.10612 [nucl-th]* for details about SuSAv2 (1p1h≡QE), SuSAv2-MEC (1p1h and 2p2h), SuSAv2-inelastic, RMF and ED-RMF (1p1h, CC1π) models.

$d^2\sigma/d\Omega/d\omega$ vs. ω for $(e,e')^{12}$C — PRC 100, 045501 (2019) — PRD 94, 013012(2016)

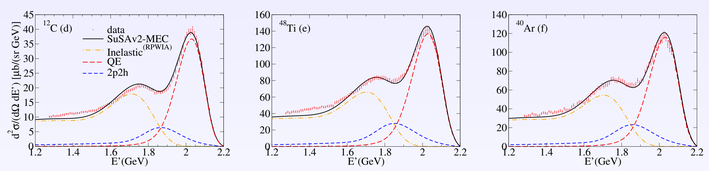


SuSAv2-MEC model contains the RMF-based SuSAv2 model for 1p1h and a RFG-based model for 2p2h.

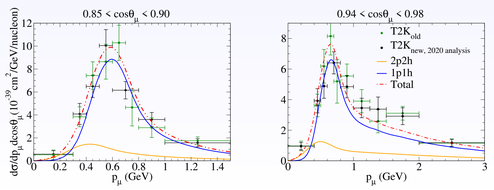
3. Validation of the SuSAv2-MEC model against (e,e') and CC $\nu - A$ scattering data

➢ The widely-proven validity of the SuSAv2-MEC (and ED-RMF) model to analyze (e,e') and $\nu - A$ data for several nuclei of interest for current and future ν oscillation analyses makes it a promising candidate to be implemented in event generators (NEUT, GENIE, NuWro).

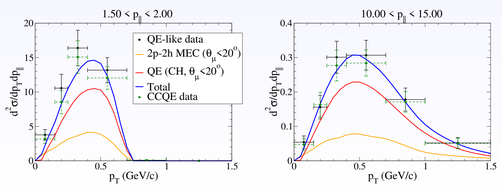
Analysis of JLab (e,e') data — PRC99, 042501(R), 2019



T2K CC0π ν_μ–C_8H_8 data — PRD 94, 093004(2016)



MINERvA $\bar{\nu}_\mu$–CH data — PRD 99, 113002(2019)



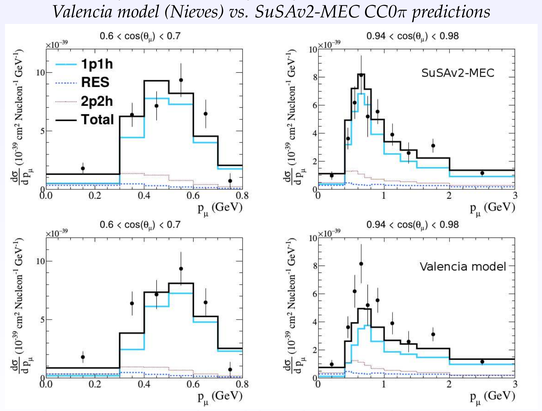
4. SuSAv2-MEC Implementation in MC event generators *PRD 101, 033003(2020)*

➲ **The SuSAv2-MEC (1p1h and 2p2h) model has been implemented in GENIEv3** for both (e,e') and CC ν_μ scattering, using pre-computed hadron tensors (q_0, q_3). No kinematical restrictions. Use 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.

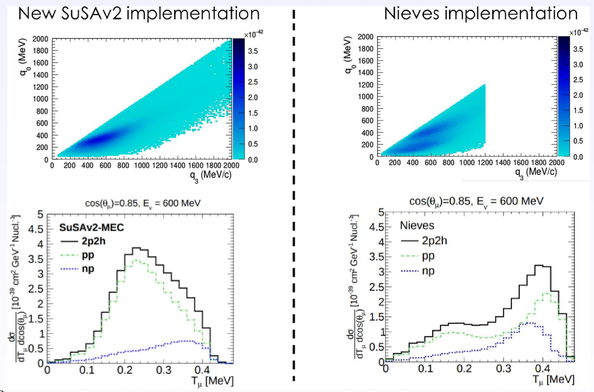
➲ **Next steps and Work in progress**: **Implementation of SuSAv2-MEC and ED-RMF (1p1h, 1π) in NEUT** through pre-computed tables, and also implementing the full code to allow reweighting and calculate systematic uncertainties in oscillation analyses.

➲ Imaginary part of nuclear potentials needed for **semi-inclusive reactions** (*joint detection of lepton and hadrons in the FS*) to produce FS absorption, i.e., flux lost into the unobserved channels, can be switched on/off and used to test and compare with intranuclear **cascade effects** in generators.

Comparison between 1p1h+2p2h models in GENIE: Valencia model (Nieves) vs. SuSAv2-MEC CC0π predictions



Comparison of 2p2h contributions in GENIE: SuSAv2-MEC vs. Valencia model (Nieves)

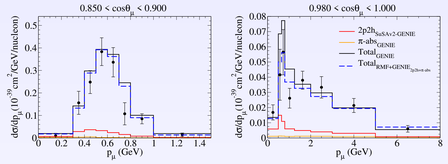


➲ Valencia (Nieves) 2p2h model produce more forward-angle (low Q^2) events than SuSAv2-MEC, in contrast to higher kinematics (see also q_3-restrictions). On the contrary, SuSAv2-MEC 1p1h predictions (RMF-based) are slightly higher at low kinematics than Valencia ones (LFG).

➲ Differences in np/pp separation of the FS 2p2h nucleon pairs are mostly related to the treatment of direct/exchange interference terms (absent in Nieves model) → strongly affects np/pp ratio by a factor ~ 2 (PRC 94, 054610(2016)) ⇒ Implications in nucleon multiplicity and hadron E_{reco}

5. Low-energy nuclear effects and C/O differences *(Preliminary)*

Low-energy nuclear effects for T2K CC0π $0p > 500$ MeV/c data *(PRD 101, 033003(2020))* are more significant at very forward angles (low Q^2 region) where differences between models emerge. ED-RMF (RMF) is more accurate than SuSAv2 at these kinematics, also providing full description of hadron kinematics.



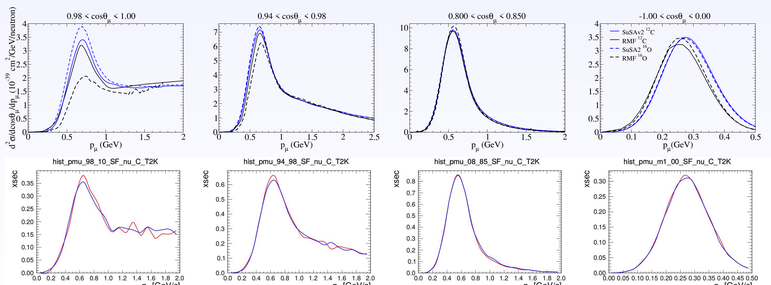
ED-RMF (and RMF) improves data agreement with regard to SuSAv2 at very forward angles and low kinematics for T2K C and O analysis *(arXiv:2004.05434 [hep-ex])* while keeping (only ED-RMF) similar good agreement for increasing kinematics.

➠ Accurate description of low-energy nuclear effects is essential for the **C to O extrapolation** in T2K and HK. C and O model predictions are rather similar but the recent T2K measurements on C and O ((*arXiv:2004.05434 [hep-ex]*)) have revealed some C/O tensions probably due to nuclear-medium uncertainties.

➠ **RFM predictions for C and O** at T2K kinematics and very forward angles (low Q^2) show relevant contrast due to different C and O nuclear effects (shell binding energies, E_b, nuclear potentials). These features are mostly absent or have no effects in other models (SuSAv2, NEUT SF, etc.)

✔ See Stephen Dolan's talk for more details about *Neutrino Interaction Measurements at T2K.*

$d^2\sigma/dp_\mu/d\cos\theta_\mu$ vs. p_μ for C and O: SuSAv2 and RMF (top) vs NEUT SF (bottom)



SF curves: Red (^{12}C), Blue (^{16}O) ; SF (^{12}C) $\sim$ RMF (^{12}C) SF (^{16}O) > RMF (^{16}O) at low-kinematics

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