Study of inelastic neutrino-nucleus scattering using the superscaling approach: Theory and Data comparison.

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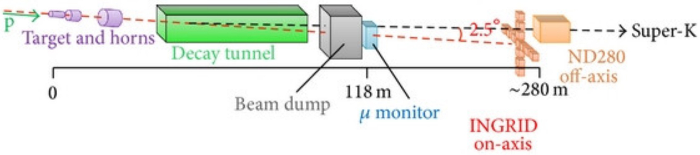
Neutrino oscillations.

- Neutrino oscillations could help us to understand the asymmetry between matter and antimatter.

$$P_{a\to b} = sin^2 2\theta sin^2\left(\frac{1.27\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}\right).$$

- Neutrinos produced as secondary decay products of hadrons generated in primary reactions of protons with nuclei producing a broad energy beam.



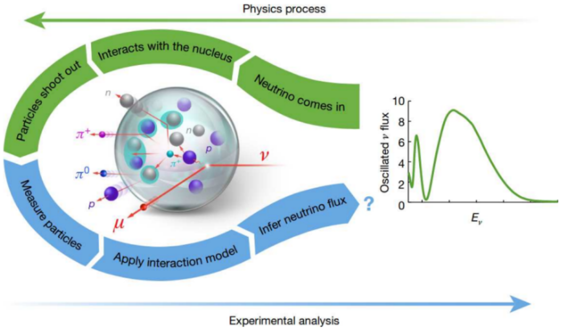
- Reconstructing the neutrino energy requires precise knowledge about neutrino-nucleus scattering.

Event generators and cross-section models.

Models can be improved via constraints from experimental data: electron data is used for validation and improvement of nuclear models in ν event and energy reconstruction methods; ν data for axial part and nuclear effects.

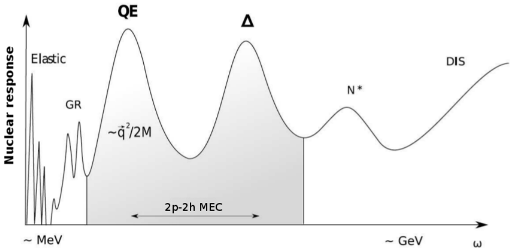
Limitations:

- Some models are specific for an interaction channel or limited phase-space.
- Some models only predict lepton kinematics. They need assumptions for hadron kinematics (factorization approaches).
- Model uncertainties missing.
- Simple models: FGs for 1p1h or 2p2h, Berger-Sehgal (RES) or PDFs in DIS.

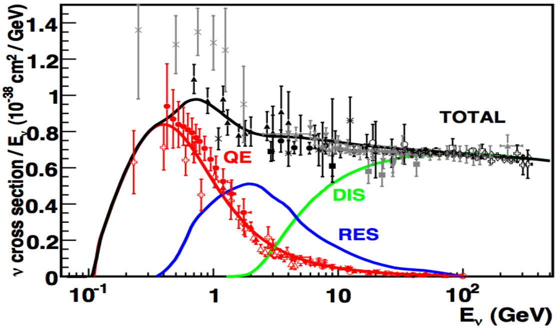


Well-tested theoretical models integrated in event generators can reduce the uncertainties associated to nuclear interactions.

Multiple overlapping channels participate in neutrino reactions and inelastic effects grow in importance at larger energies.



Original plot from G. D. Megias' PhD thesis (2017).

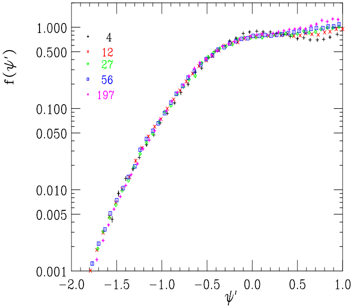


Original plot from J. M. Campbell *et al*.
arXiv:2203.11110 [hep-ph] (2024).

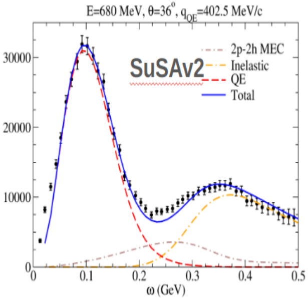
In the QE peak region, a nucleon is ejected from the nucleus in a reasonably "quasifree" manner. This forms the basis of the superscaling approach. The scaling function, $f(\psi)$, takes into account the nuclear effects.

$$\left(\frac{d^2\sigma}{d\Omega d\omega}\right) = \frac{1}{k_F} f(\psi) \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{s.n.}$$

The superscaling approach has been validated for the QE region and for the inelastic region (Δ, other resonance and deep inelastic scattering).

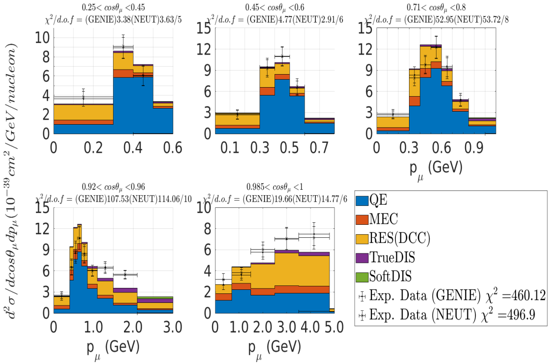


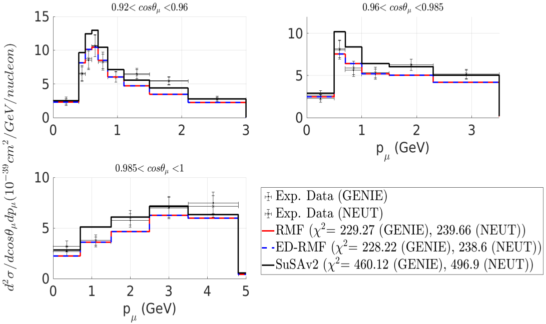
The scaling function does not depend explicitly on the transferred momentum or the nuclear species.
Original plot from T. W. Donnelly *et al.*, Phys. Rev. C 60,065502 (1999).



SuSAv2: Superscaling approach based on RMF theory. Validated against electron scattering data.

T2K [Phys. Rev. D 105, 093009 (2022)] & [Phys. Rev. D 108, 113008 (2023)].

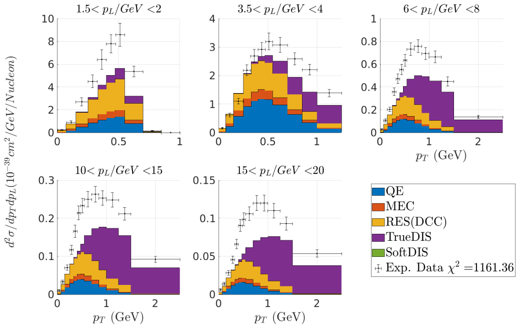




$\chi^2 = 192.0$ (GENIEv2.8); 218.7 (NEUTv5)

$\langle E_\nu \rangle = 0.8$ GeV ; CC $\nu_\mu - {}^{12}C$

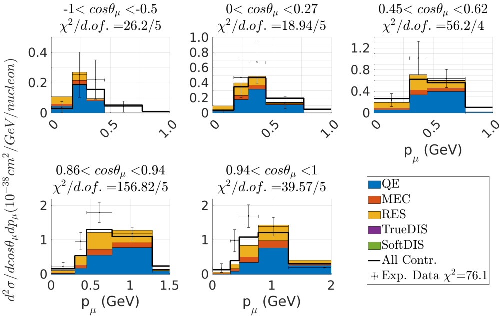
MINERνA [Phys. Rev. D 105, 093009 (2022)] & [Phys. Rev. D 108, 113008 (2023)].

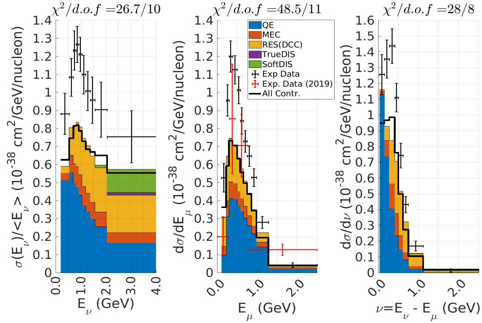


	χ^2
SuSAv2-DCC + DIS	1161.36
GENIE 2.8.4	422
GiBUU	767
MnvGENIEv.2	475

$\langle E_\nu \rangle = 4$ GeV ; CCν_μ–^{12}C
(MINERνA Low Energy Flux)

MicroBooNE [Phys. Rev. D 108, 113008 (2023)] & [Phys. Rev. D 111, 073002 (2025)].

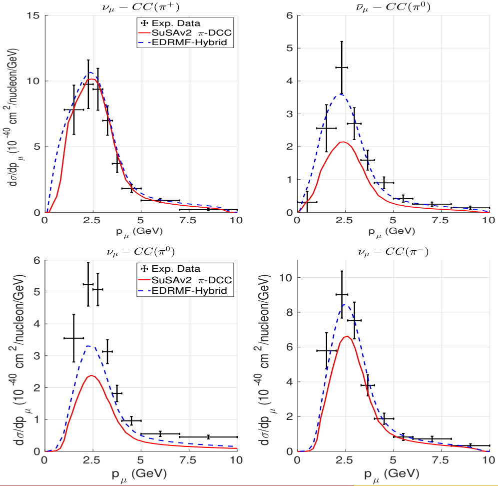


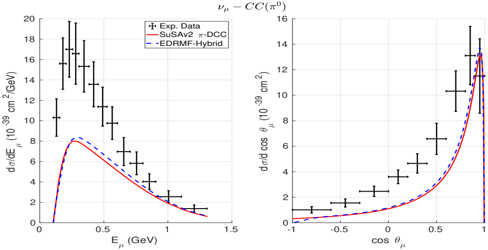


	χ^2
SuSAv2-DCC + DIS	76.1
GENIEv3	103.9

$$\langle E_\nu \rangle = 0.8 \text{ GeV}$$
$$CC\nu_\mu - {}^{40}Ar$$

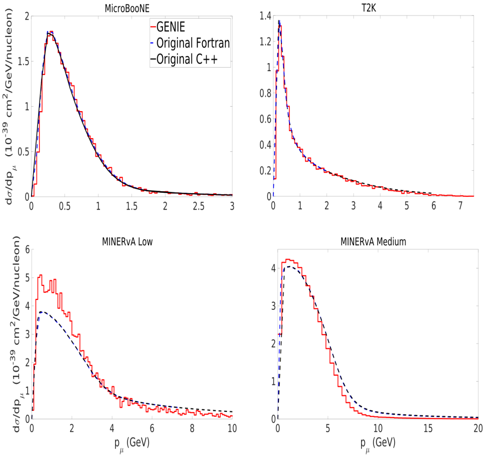
Neutrino-induced single-pion production [Universe 2026, 12(5), 121].





SuSAv2-DCC and EDRMF-Hybrid predictions for the MINERvA (left) and MiniBooNE (right) fluxes. Different treatments of single-nucleon interactions and nuclear effects lead to noticeable differences. Pion-production data remain only partially explained.

Implementation of SuSAv2-inelastic in GENIE.



Significant progress has been made in the implementation of the SuSAv2-inelastic model in GENIE. Nevertheless, the project is not yet complete, and further developments are ongoing in collaboration with Steven Gardiner at Fermilab.

Conclusion.

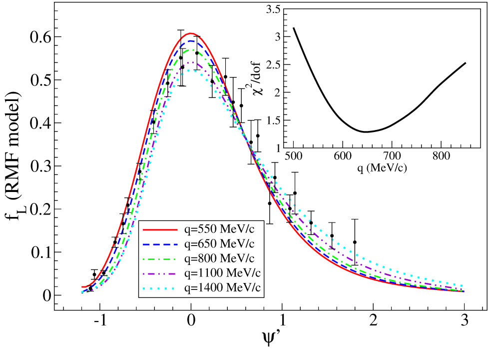
- Extension of the model to inelastic CC interactions: resonance + DIS.
- Validation against inclusive electron-scattering data shows overall good agreement across nuclei and kinematics.
- Good description of T2K data; discrepancies remain at low and high muon momenta.
- Systematic underprediction of MINERνA data, particularly regarding the resonance contribution.
- Good agreement with 2019 MicroBooNE CC-inclusive double-differential data; underprediction of 2022 inclusive measurements, indicating possible dataset tensions.
- CC1π predictions are rather model dependent and sensitive to nuclear effects; no model fully reproduces the data.
- SuSAv2-inelastic implementation in GENIE is well advanced. Collaborations with Fermilab and NEUT (Hayato-san, Abe-san) are in progress.

Thanks for your attention!

BTW, I finished my thesis, any postdocs? . . .

SuSAv2-QE scaling function.

- In the RMF model, the best fit to the data corresponds to $q = 650$ MeV which is taken as the nominal scaling function of the RMF.
- The RMF model fails as the transfer momentum increases. To solve this problem, we introduce the RPWIA predictions at higher q values. This is denoted as SuSAv2 (SuperScaling Approach Version 2).



Original plot from R. González-Jiménez *et al*. Phys. Rev. C 100(4):045501 (2019)

SuSAv2-QE scaling function.

The SuSAv2 scaling function is written as

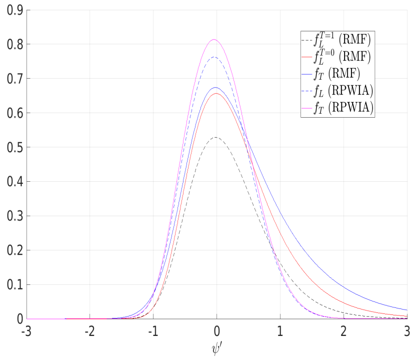
$$\mathcal{F}_L^{T=0,1} = cos^2\chi(q)\widetilde{f}_L^{T=0,1} + sin^2\chi(q)\widetilde{f}_L^{RPWIA},$$
$$\mathcal{F}_T = cos^2\chi(q)\widetilde{f}_T + sin^2\chi(q)\widetilde{f}_T^{RPWIA}.$$

The RMF/RPWIA transition is given by the blending function

$$\chi(q) = \frac{\pi}{2}\left(1 - \left[1 + e^{\left(\frac{q-q_0}{\omega_0}\right)}\right]^{-1}\right).$$

We can write the hadronic responses in terms of the single nucleon ones, e. g.,

$$R_L^{ee'}(q,\omega) = \frac{1}{k_F}\left[\mathcal{F}_L^{T=1}(\psi')G_L^{T=1}(q,\omega) + \mathcal{F}_L^{T=0}(\psi')G_L^{T=0}(q,\omega)\right].$$



SuSAv2-inelastic model.

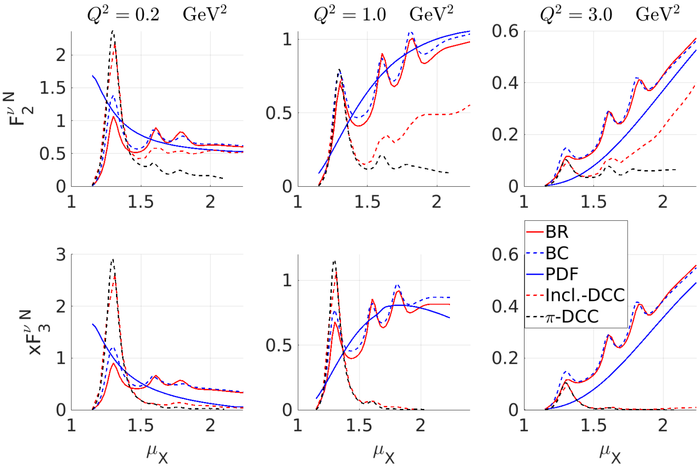
SuSAv2-inelastic model describes the full inelastic (Δ, **other res. and DIS**).

$$R^K_{inel}(\kappa,\tau) = \frac{N}{\kappa\eta_F^3}\xi_F \int_{\mu_X^{min}}^{\mu_X^{max}} d\mu_X \mu_X f^{model}(\psi_X) G^K(\kappa,\tau,\lambda)\,,$$

The hadronic response (R^K_{inel}) is given by an integration of the single-nucleon response (G^K) times the inelastic scaling function (f^{model}) over the invariant mass (μ_X). This single-nucleon response depends on the inelastic structure functions (F_{1-3}):

- Bodek-Ritchie (BR) [Phys. Rev. D 23, 1070 (1981)].
- Bosted-Christy (BC) [Phys. Rev. C 81, 055213 (2010)].
- Parton Distribution Functions (PDF) [J. Phys. G 48, 034001 (2021)].
- Dynamical Coupled-Channels (DCC) [Phys. Rev. D 92, 074024 (2015)].

Inelastic structure functions.



Comparison of inelastic structure functions obtained from different parametrizations. These functions characterize the single-nucleon hadronic responses and play a crucial role in describing the inelastic scattering process.

SuSAv2-DCC + DIS: QE + MEC + RES(DCC) + TrueDIS + SoftDIS

Abbreviation	Definition of the reaction channel	Model
QE	Quasielastic	SuSAv2-QE
MEC	2p2h MEC contributions	RFG-MEC
RES(DCC)	Resonant and non-resonant	SuSAv2-DCC
SoftDIS	Other inelastic effects	SuSAv2-inelastic
	$(m_N + m_\pi < W_X < 2.1$ GeV)	− SuSAv2-DCC
TrueDIS	Deep inelastic scattering ($W_X > 2.1$ GeV)	SuSAv2-inelastic

- DCC model is valid for $W_X \leq 2.1$ GeV and $Q^2 \leq 3.0$ GeV^2.

$$\left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{SoftDIS} = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{inelastic}^{W_X^{min}=m_N+m_\pi;W_X^{max}=2.1GeV} - \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{DCC}.$$

Integration Limits.

The kinematical limits of the invariant mass are

$$\mu_X^{min} = 1 + \frac{m_\pi}{m_N}; \mu_X^{max} = 1 + 2\lambda - \frac{E_{shift}}{m_N}.$$

Inelastic structure functions.

- In the context of QCD, F_2^ν and F_3^ν for neutrinos (likewise for antineutrinos) can be expressed as

$$F_2^\nu(x) = Q + \bar{Q}, \text{ e.g. } F_2^{\nu p}(x) = 2x[d(x) + s(x) + \bar{u}(x) + \bar{c}(x)],$$
$$xF_3^\nu(x) = Q - \bar{Q}, \text{ e.g. } xF_3^{\nu p}(x) = 2x[d(x) + s(x) - \bar{u}(x) - \bar{c}(x)],$$

  where $d(x)$, $s(x)$, $u(x)$ and $c(x)$ are the down, strange, up and charm distribution functions, respectively.
- The inelastic structure function F_1 can be written in terms of F_2 using the Callan-Gross relation:

$$F_2^\nu(x) = 2xF_1^\nu(x).$$

- A relation can be drawn between electromagnetic and weak inelastic structure functions:

$$F_2^e(x) = (5/18)F_2^\nu(x).$$

Inelastic structure functions.

Bodek-Ritchie

- Based on fits of electron scattering data (SLAC).
- The parametrization given for the F_2 structure function is

$$F_2^e(\omega, Q^2) = B(W_X, Q^2) g(\omega_\omega) \frac{\omega_\omega}{\omega},$$

where $B(W_X, Q^2)$ depends of the nucleon resonance parameters.

- It provides expressions for F_3^ν inelastic structure function.

$$xF_3^\nu(x, Q^2) = F_2^\nu(x, Q^2) - \frac{18}{5}(1 - \frac{1}{\omega_\omega})^7 B(W_X, Q^2) g(0) \frac{\omega_\omega}{\omega}.$$

Inelastic structure functions.

Bosted-Christy

- Based on fits of electron scattering data (Jeffeson Lab C).
- It is valid from $0< Q^2/\mathrm{GeV}^2 <8$ and $1.1< W_X/\mathrm{GeV}<3.1$.
- Kinematical limitation of $\omega < 10$ GeV.

Parton distribution functions

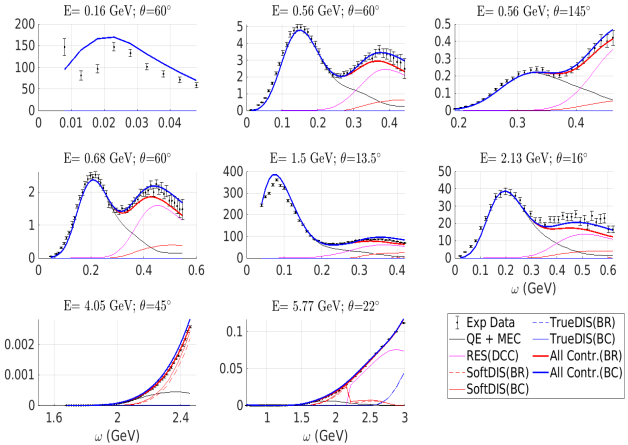
- Dynamical parton densities from QCD are used to built the structure functions.
- The model used is the Glück-Reya-Vogt 1998 (GRV98).
- Valid at $Q^2 > 0.8$ GeV^2 and verified in the region $10^{-8} < x <10^{-5}$.

Inelastic structure functions.

Dynamical Coupled-Channels (DCC)

- The DCC Osaka model was developed to study baryon resonance through electron- and neutrino-induced meson production reactions.
- The DCC model takes into account all reaction channels and the coupling between them. In the resonance region, we find $\pi N, \gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$.
- DCC is valid for $W_X \leq 2.1$ GeV and $Q^2 \leq 3.0$ GeV^2 and has been tested against ANL and BNL data.
- The resonance channels are strongly coupled. The double-pion production has been implemented. The interference between resonant and nonresonant processes is included.

Electron scattering [PhD Thesis].



The approach has been **benchmarked against inclusive electron scattering** data on various nuclei and at various kinematics showing an overall **good agreement**. This provides confidence that the model can reliably be applied to **neutrino–nucleus** scattering.