RECENT PROGRESS IN MODELING NEUTRINO-NUCLEUS INTERACTIONS FOR OSCILLATION EXPERIMENTS

UNIVERSITÀ DI TORINO

Maria Barbaro
University of Turin and INFN

INFN TORINO

MAYORANA WORKSHOP

Multi-Aspect Young ORiented Advanced Neutrino Academy

June 16–18 2025, Modica, Sicily

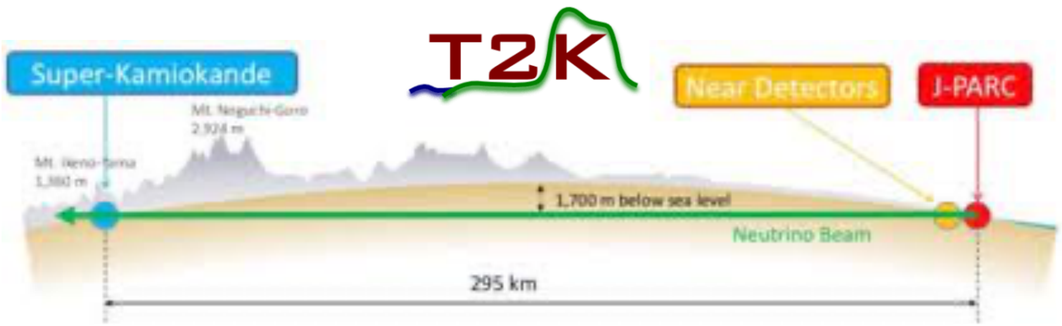
Collaborators

Turin: **V. Belocchi,** A. De Pace
Seville: J.A. Caballero, **J.M. Franco-Patiño**, **R. Gonzalez-Jimenez, J. Gonzalez-Rosa, G.D. Megias**
Granada: J.E. Amaro, **P. Casale,** I. Ruiz Simo
Paris: M. Martini
Madrid: J.M. Udias
Sofia: A. Antonov, M. Ivanov
MIT: T.W. Donnelly
Pavia: C. Giusti

Motivation

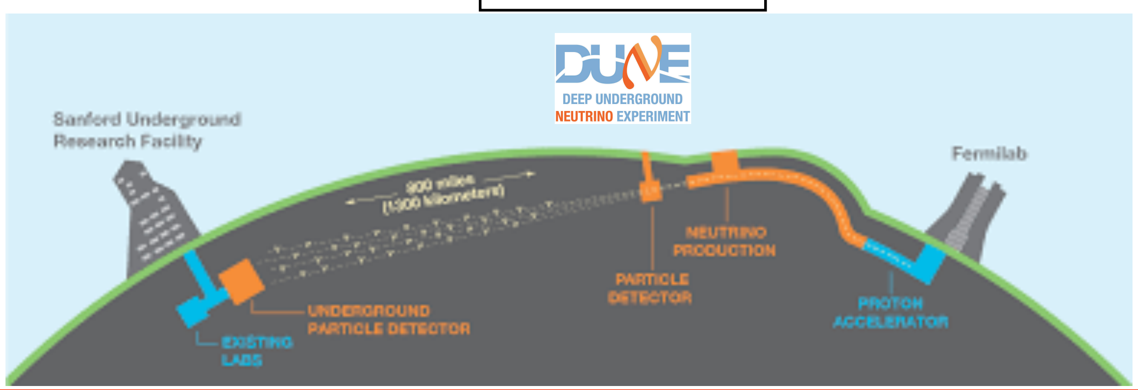
Long baseline oscillations experiments

J-PARC



Running	**T2K**
Future	**HyperK**

Fermi Lab



Running	**NOvA**
Future	**DUNE**
Past	**MiniBooNE**

Experiments collecting cross section data

µBooNE — **MicroBooNE** largest LArTPC detector

MINERvA dedicated to $\sigma_{\nu A}$ on different nuclei

Systematic uncertainties

Source (T2K)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	3.8%
Total Syst.	**5.2%**

NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics

Source (NOvA)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	7.7%
Total Syst.	**9.2%**

Phys. Rev. D **98**, 032012

- Neutrinos with ~ GeV energy travel between two detectors situated at ~100s Km distance. The appearance or disappearance of neutrinos of given flavour provides information on oscillation parameters.
- Why nuclear physics? Cross sections are extremely small ~10^{-38} cm^2: intense beams and large detectors made of medium/heavy nuclei are needed.

Experimental analyses need nuclear physics input
Detectors: Carbon, Oxygen, Argon

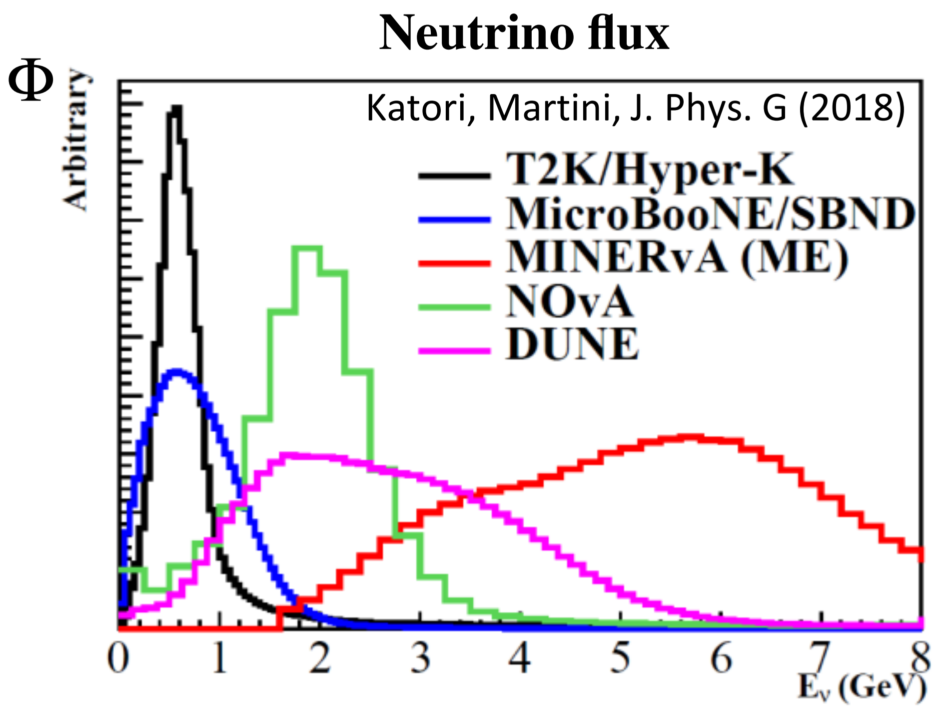
Neutrino interaction uncertainties dominate the systematic error
They must be reduced for DUNE and HYPERK to succeed

Flux-integration and energy reconstruction

The true neutrino energy E_ν is not precisely known:

ν beams are not mono-energetic: broad flux distribution

E_ν must be reconstructed from the detected final state: **nuclear model dependence**



What experiments want to extract

Oscillation probability from flavour α to β

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\alpha | \nu_\beta(t) \rangle \right|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{i m_i^2 L / 2 E_\nu} \right|^2$$

U matrix encodes oscillation parameters

What they do measure

Number of events: convolution over the true neutrino energy spectrum

$$N_{\nu_\beta}(\overline{E}_\nu) \sim \int \Phi_{\nu_\alpha}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu, L, \{\theta\}) \times \sigma_{\nu_\beta}(E_\nu) \times \epsilon_{\text{det.}} \times d(E_\nu, \overline{E}_\nu) \, dE_\nu$$

- $N_{\nu_\beta}(\overline{E}_\nu)$: reconstructed ν energy
- $\Phi_{\nu_\alpha}(E_\nu)$: ν flux
- $P_{\nu_\alpha \to \nu_\beta}$: oscillation probability
- $\sigma_{\nu_\beta}(E_\nu)$: $\nu - A$ cross section
- $\epsilon_{\text{det.}}$: detector efficiency
- $d(E_\nu, \overline{E}_\nu)$: migration matrix
- dE_ν: true ν energy

$E_\nu \longrightarrow \overline{E}_\nu$ **Monte Carlo event generators**

Monte Carlo generators

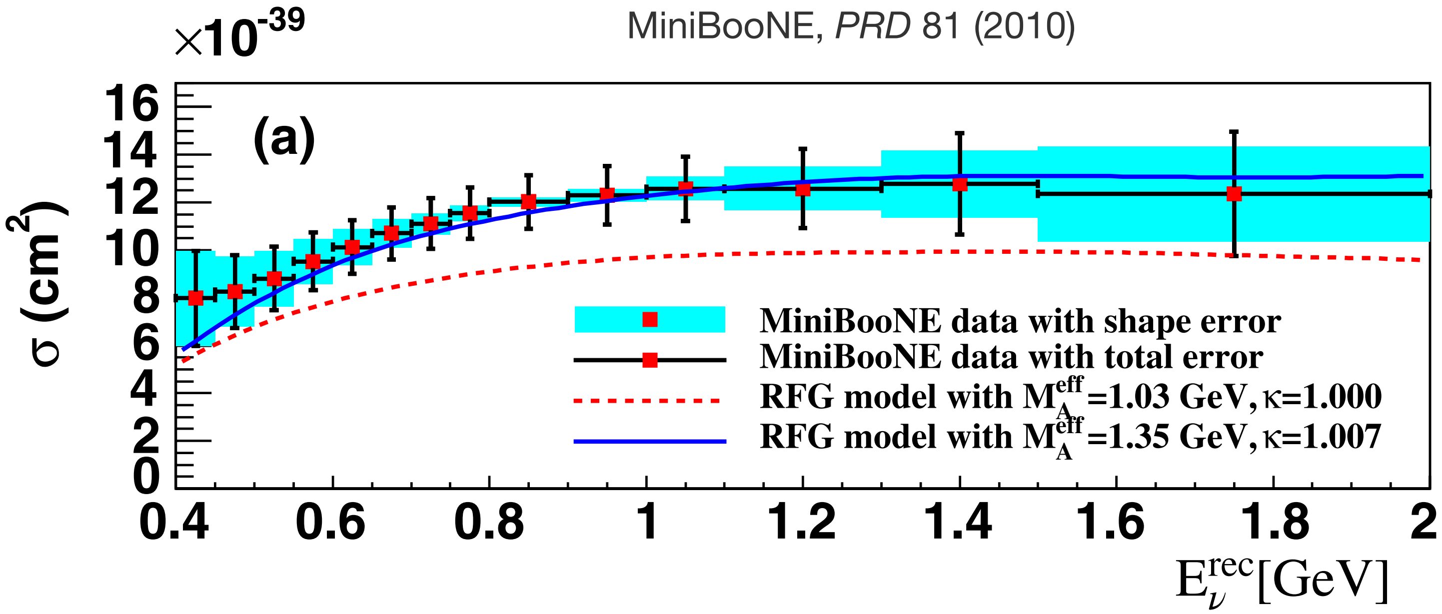
In order to reconstruct the neutrino energy and extrapolate it to the true one, **nuclear models** are implemented in **MC event generators** which simulate neutrino interactions with nucleons and nuclei

- **GENIE** widely used by FermiLab experiments MicroBooNE, NOvA, MINERvA
- **NEUT** used in T2K
- **NUWRO** used for comparisons of experimental data with calculations
- **GIBUU** transport-based theoretical framework

The ideal generator should contain consistent models, valid across the full energy spectrum.
In reality tunings to specific data are performed, sometimes hiding the correct physics.
It is crucial that reliable and tested nuclear models are implemented in generators.

A prominent example: the "M_A puzzle"

MiniBooNE, *PRD* 81 (2010)

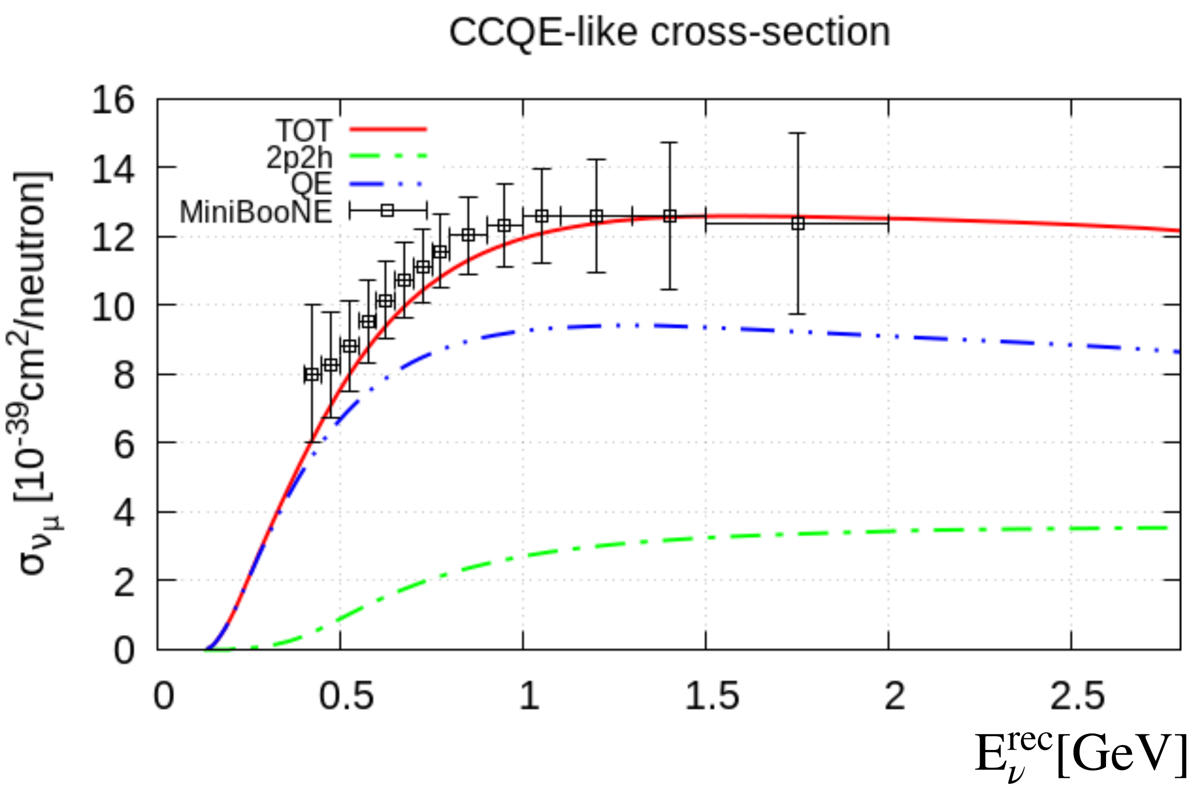


The 2010 MiniBooNE "CCQE-like" muonic neutrino data on C12 analyzed using the pure **RFG model** suggested an **axial mass** larger than the standard value of 1

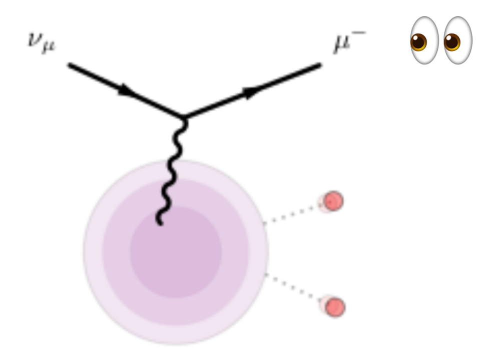
Dipole axial mass

$$G_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2}$$

M_A=1.35 GeV ?



Including 2p2h excitations



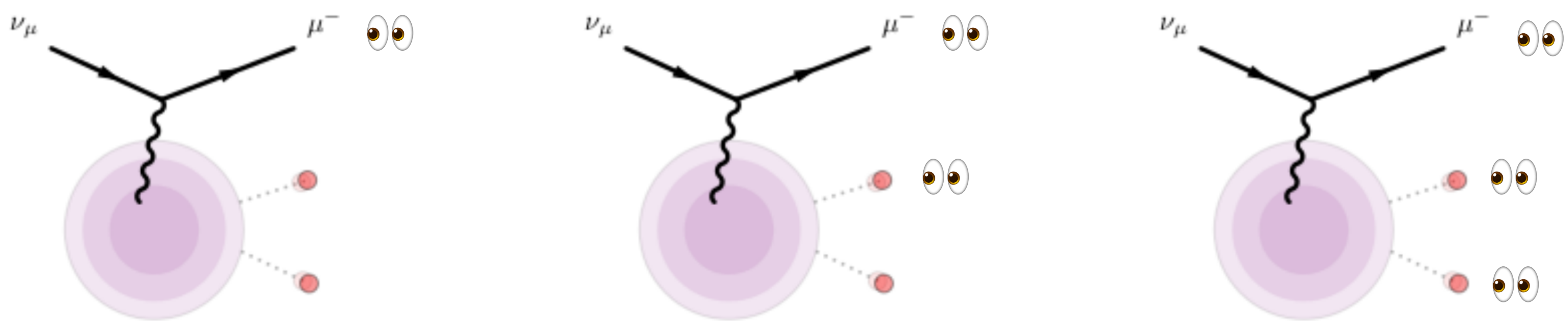
The data are reproduced without need of increasing the axial mass

Inclusive and exclusive measurements

Lepton-nucleus cross-section measurements are usually classified depending on the final particles detected

- **inclusive**: only the final charged lepton is detected
- **semi-inclusive**: some final hadron is detected in coincidence with the lepton
- **exclusive**: all the final particles are detected

<u>Example</u>: neutrino-nucleus two-nucleon knockout



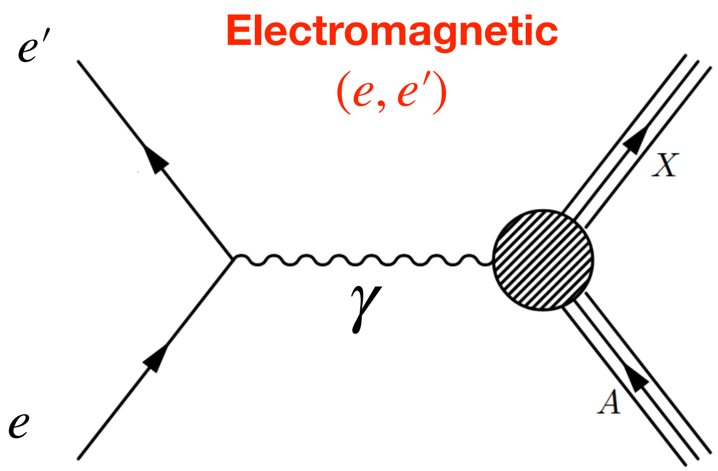
Exclusive processes are more sensitive to nuclear model details than inclusive ones

They can better discriminate between different nuclear models

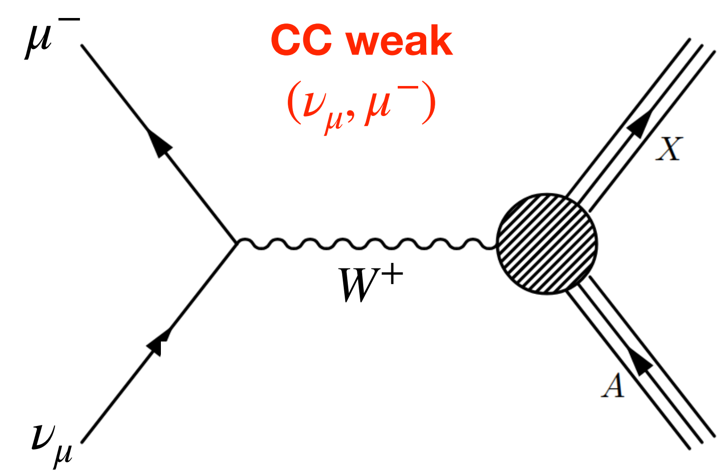
Experimental measurements are more demanding

Electron and neutrino inclusive scattering

$e + A \rightarrow e' + X$



$\nu_\mu + A \rightarrow \mu^- + X$



$$\frac{d\sigma}{dk_e d\Omega_e}$$

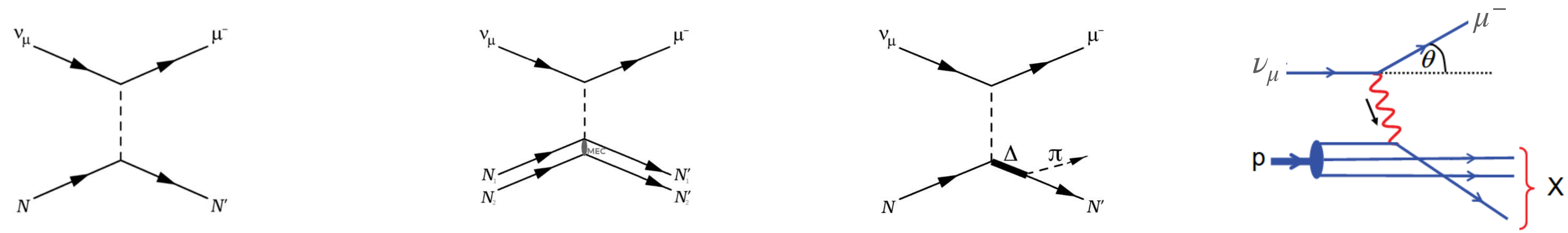
Inclusive cross section at fixed electron beam energy

$$\left\langle \frac{d\sigma}{dk_\mu d\Omega_\mu} \right\rangle = \int dE_\nu \, \Phi(E_\nu) \left[\frac{d\sigma}{dk_\mu d\Omega_\mu} \right]_{E_\nu}$$

Flux-averaged inclusive cross section

- Nuclear effects in e-A and ν-A are the same, in both initial and final state.
- Different **experimental conditions:** monochromatic electron beams versus broadly distributed ν beams
- Different **couplings and currents:** axial vector EM current versus V-A weak current
- **Many high quality inclusive electron scattering data** exist (Saclay, Bates, Mainz, Nikhef, JLab)
- Electron scattering data are necessary **test** for any model for neutrino-nucleus cross sections
- They can also be used as **input** to predict neutrino cross sections, at least for the vector responses

Energy spectrum

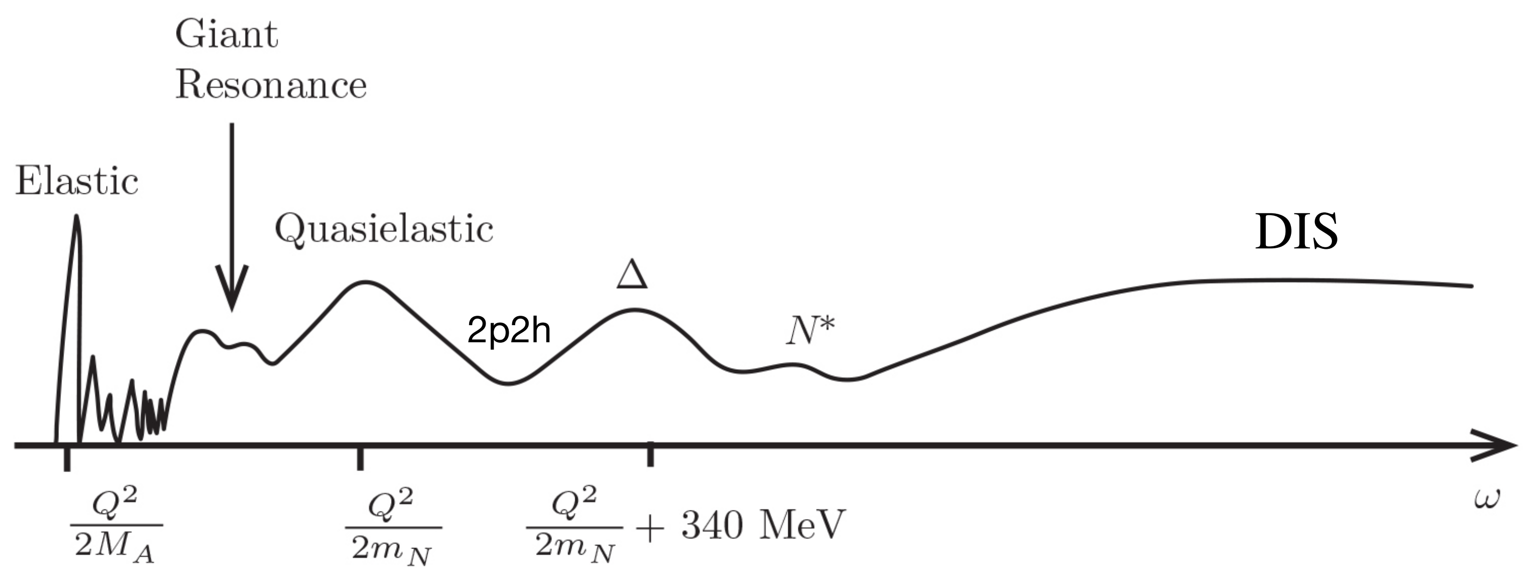


QE
elastic interaction with a bound nucleon

2p2h
interaction with a pair of correlated nucleons
Meson Exchange Currents

RES
resonance production

DIS
deep inelastic scattering interaction with quarks

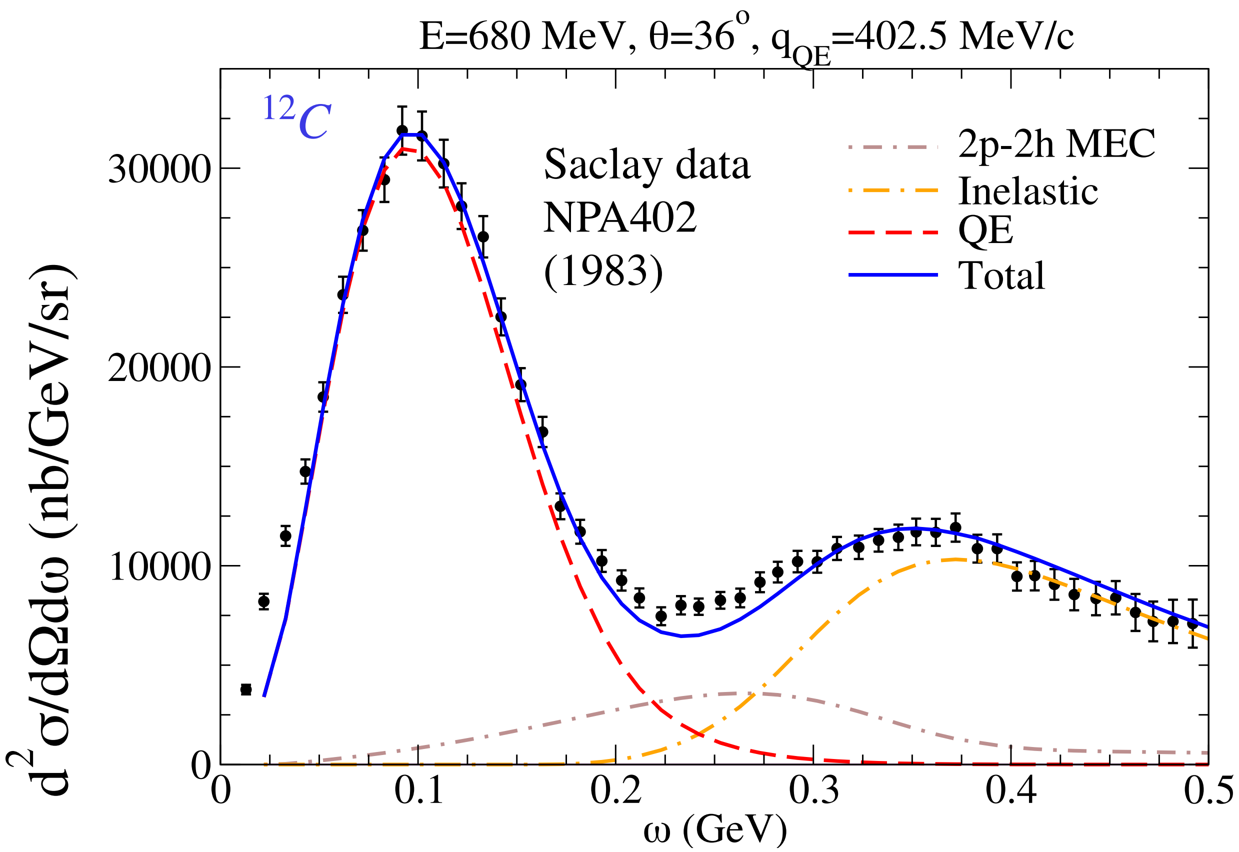


In electron scattering the experimental conditions can be chosen to isolate a specific channel
In neutrino scattering, due to the flux integration, different processes contribute to the same experimental signal
→ need to model several channels at the same time

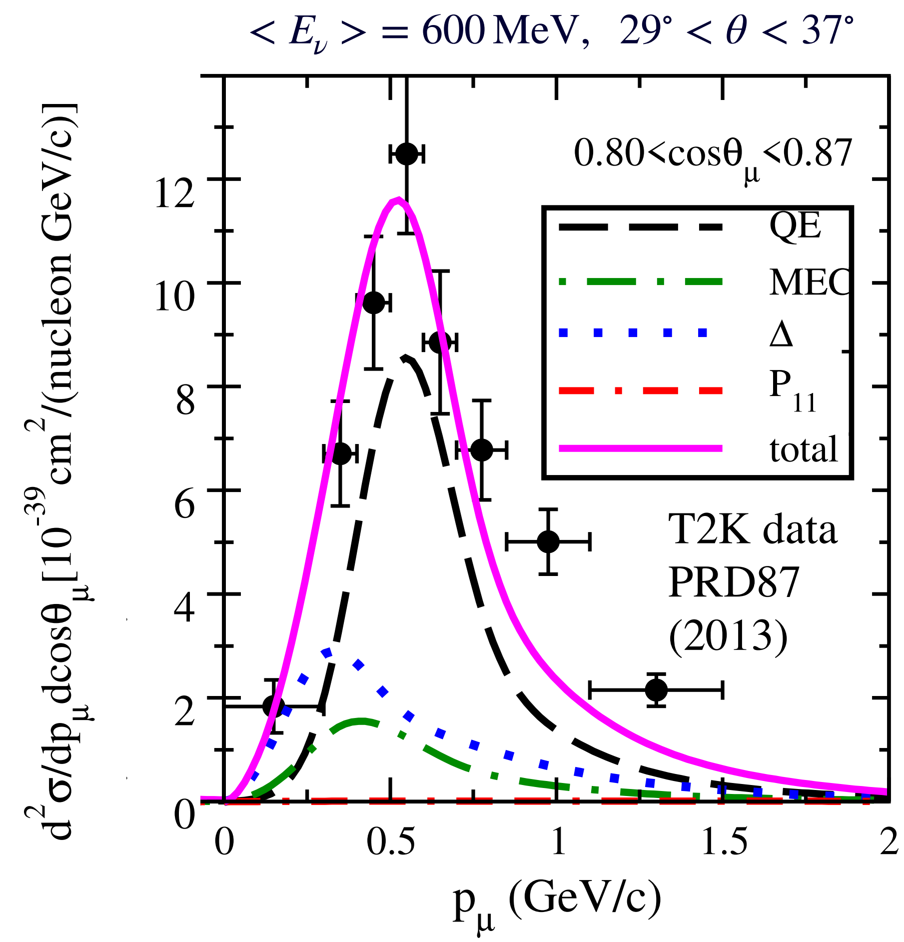
Channel overlap

As a consequence of the flux integration, in neutrino experiments different processes occurring in the nucleus cannot be disentangled in the experimental inclusive signal.

(e, e') Similar kinematics (ν_μ, μ)



Megias *et al.*, PRD94 (2016)



MBB *et al.*, Universe (2021)

The **quasi-elastic** and **Δ resonance** peaks can be separately identified in the *(e,e')* spectrum, the **2p2h** response filling the dip in ω between the two. In neutrino data the three contributions overlap due to the flux integration.

"Tuning" one of the three contributions to adjust theory to ν-A data may destroy the agreement with e-A data.

Theoretical framework

Inclusive lepton-nucleus cross section

$$\frac{d\sigma}{dk_l d\Omega_l} = \sigma_0\, \eta_{\mu\nu} W^{\mu\nu}$$

σ_0 contains couplings and kinematic factors

Leptonic tensor $\eta_{\mu\nu} = \overline{\sum} j_\mu^\dagger j_\nu$: very well known, depends on the analyzed interaction (EM or weak)

Nuclear hadronic tensor $W^{\mu\nu} = \sum_X < A|J^{\mu\dagger}|X > < X|J^\nu|A > \ \delta(M_A + q - P_X)$

$|A >$ nuclear ground state, described using a nuclear model

$|X >$ hadronic final states: residual nucleus + hadrons $|(A-1)^*, N > , |(A-2)^*, NN > , |(A-1)^*, N\pi > \cdots$

J^μ nuclear current, depends on the process and interaction: $J^\mu = J^\mu(1b) + J^\mu(2b)$

Rosenbluth decomposition

V_K leptonic kinematic factors

$R_K(q,\omega)$ response functions embodying nuclear dynamics components of the hadronic tensor

$$\left[\frac{d\sigma}{dk_e d\Omega_e}\right]^{(e,e')} = \sigma_{Mott}\left(V_L R_L^{\rm em} + V_T R_T^{\rm em}\right)$$

2 electromagnetic responses

$$\left[\frac{d\sigma}{dk_\mu d\Omega_\mu}\right]^{(\nu_\mu,\mu)}_\pm = \sigma_0\left(V_{CC}R_{CC} + 2V_{CL}R_{CL} + V_{LL}R_{LL} + V_T R_T \pm V_{T'}R_{T'}\right)$$

5 weak responses

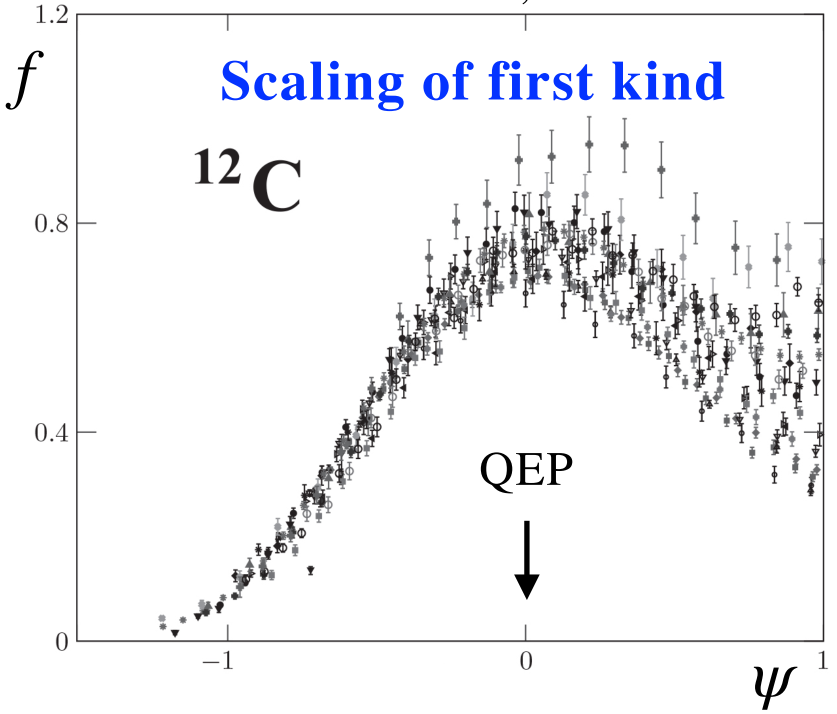
Super Scaling Approach (SuSA): use (e,e') data as input

1. Start from the reduced *(e,e')* cross section defined as

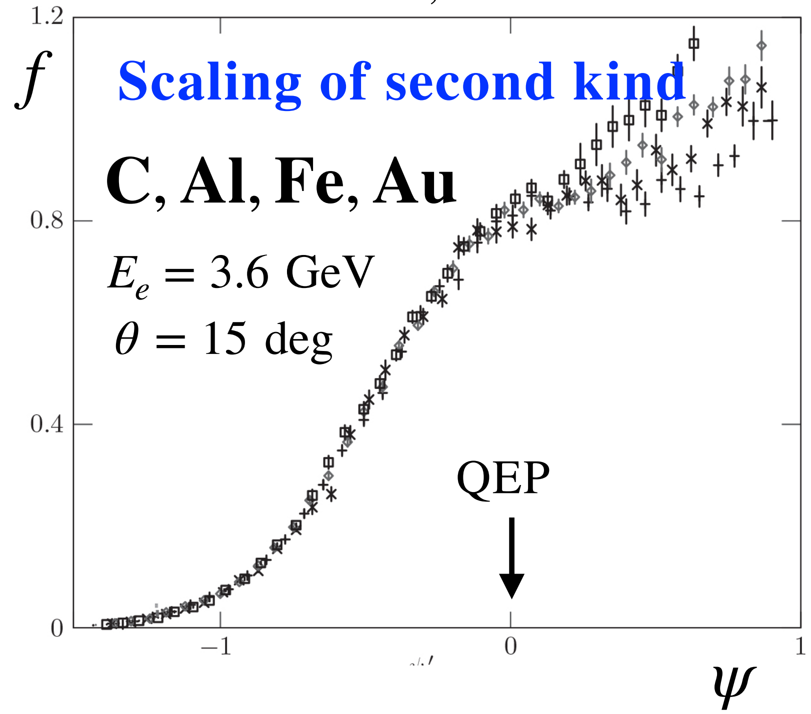
$$f(q,\omega;k_F) = k_F \times \frac{\left[d^2\sigma/d\omega d\Omega\right]^{(e,e')}_{exp}}{\overline{\sigma}_{eN}} \longrightarrow f(\psi)$$

In certain conditions (scaling region) f depends on one, instead of three, **scaling variable** $\psi \equiv \psi(q,\omega;k_F)$

Different kinematics, same nucleus



Different nuclei, same kinematics



SuperScaling

Day et al., ARNPS 40 (1990);
Donnelly and Sick, PRL82 (1999)

$$f(q,\omega;k_F) \rightarrow f(\psi)$$

Very well realized by data in the region below the QEP and for $q \gtrsim 400$ MeV

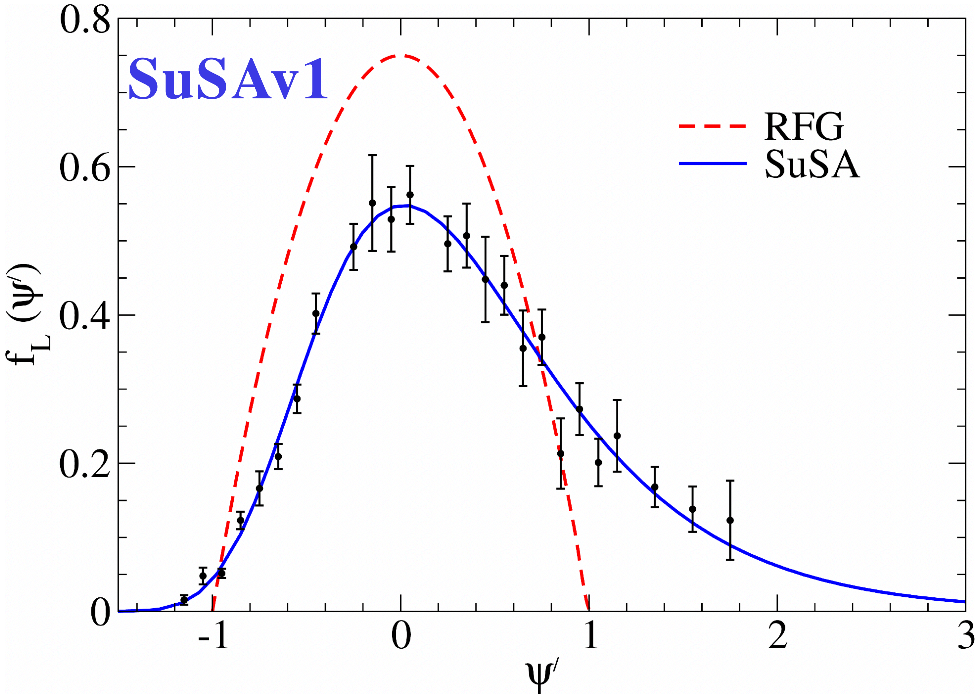
- The scaling function ***f*** **encodes the nuclear dynamics, in both the initial and final state**, for different kinematics and nuclei. Superscaling sets stringent constraints to nuclear models.
- The analysis of separated L and T data has shown that **scaling violations** mainly occur in the **transverse** channel and arise from non-QE processes: Δ production and 2p2h excitations

2. Use f to **predict the neutrino scattering cross section** (ν, l) as

$$\left[d^2\sigma/d\omega d\Omega\right]^{(\nu,l)} = \frac{1}{k_F}\overline{\sigma}_{\nu N}\ f(\psi)$$

I. Quasi-elastic scattering: SuSA model (v1 and v2)

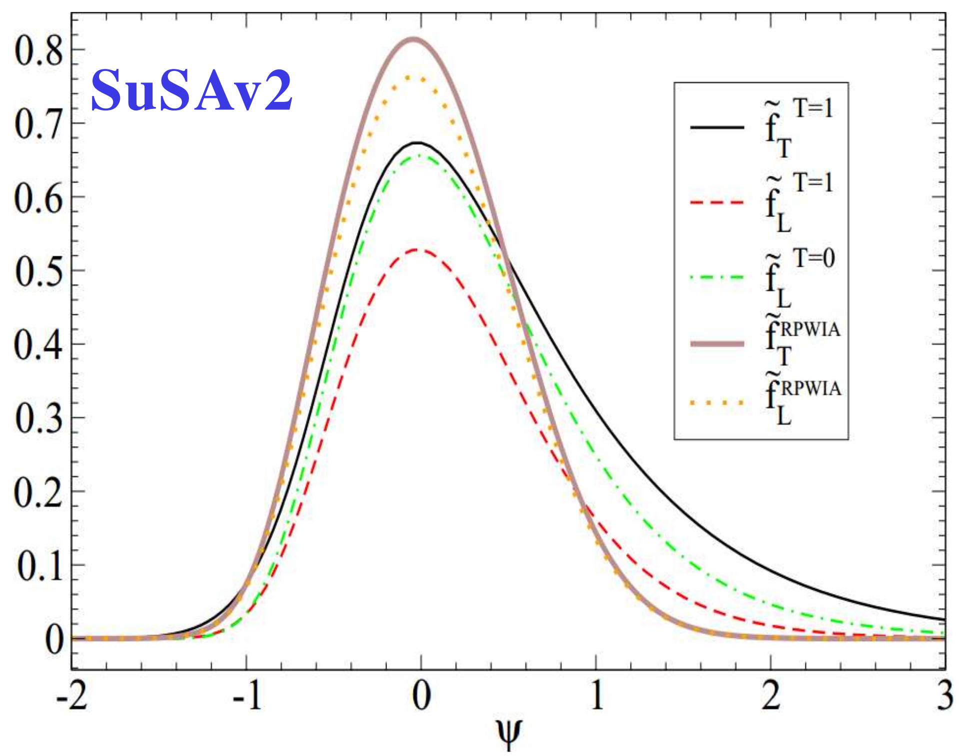
The scaling function f can be extracted from longitudinal data or calculated within a model.



SuSAv1 model (phenomenological)

- one scaling function extracted from longitudinal *(e,e')* world data [J. Jourdan, Nucl. Phys. A 603 (1996)]
- great improvement on the Relativistic Fermi Gas result
- it is assumed that $f_L = f_T$ (assumption, true in RFG)

Amaro *et al.*, PRC71 (2005)



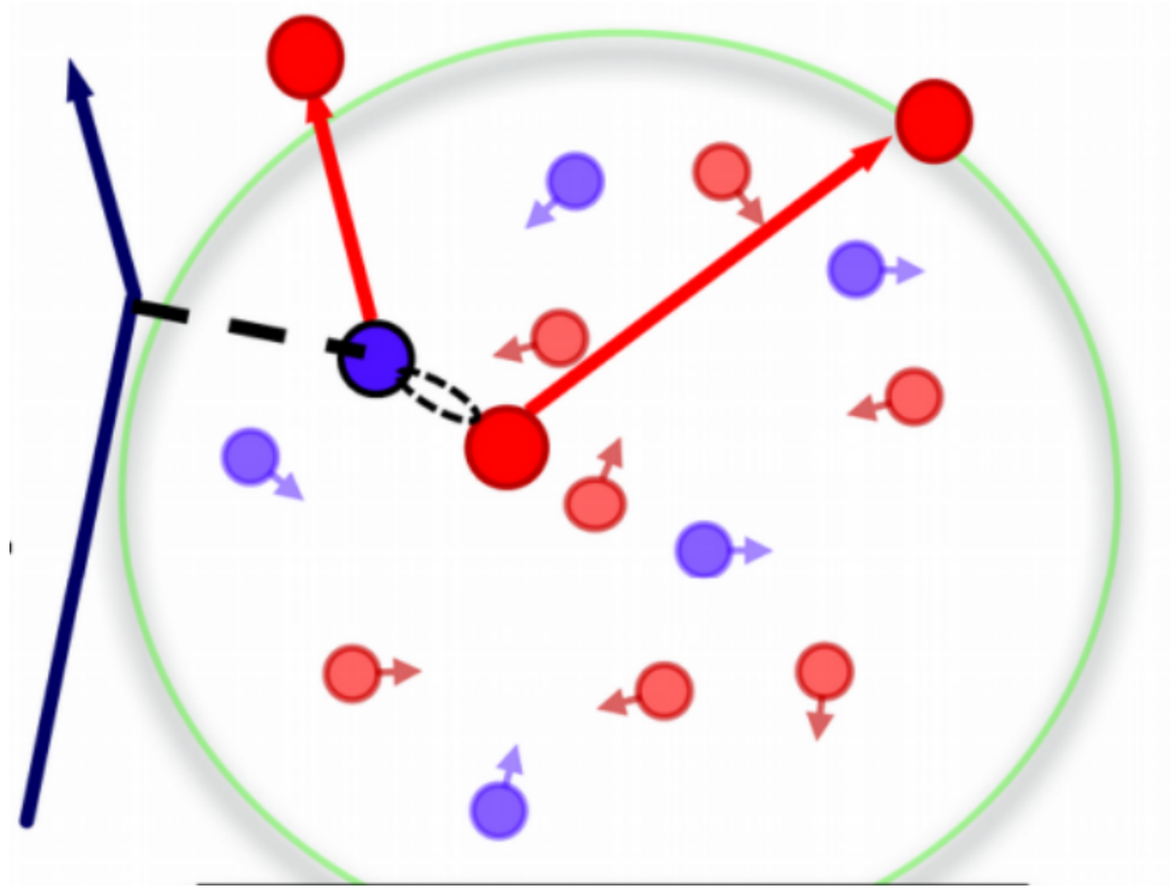
SuSAv2 model (microscopic)

- a set of scaling functions in L,T and isospin channels, based on Relativistic Mean Field calculation
- $f_T > f_L$ in agreement with L/T separated *(e,e')* data
- parameters fitted once and for all to carbon data

Gonzalez-Jimenez *et al.*, PRC90 (2014)

The superscaling approach describes simultaneously electron and neutrino scattering

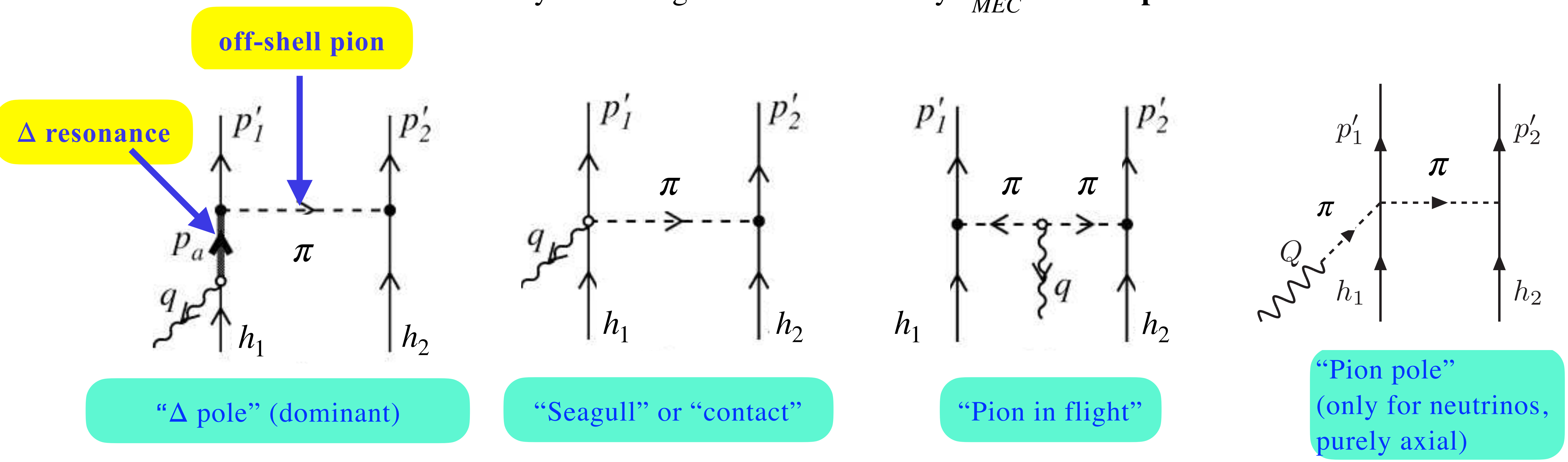
II. Beyond QE scattering: Two-Body Currents



Meson Exchange Currents

MEC is derived from a chiral Lagrangian (nucleon and pions) plus Δ interaction terms.

Feynman diagrams for the 2-body J^{μ}_{MEC} in **free space**



The corresponding inclusive nuclear tensor $W^{\mu\nu}_{2p2h}$ is evaluated in the RFG model, where the ground state is the Fermi sphere $|F>$ and the final states are $|2p2h> = a^{\dagger}_{p_1} a^{\dagger}_{p_2} a_{h_1} a_{h_2} |F>$.

Inclusive RFG 2p2h hadronic tensor

$$
\begin{aligned}
W^{\mu\nu}_{\text{2p-2h}} = & \frac{V}{(2\pi)^9} \int d^3 p'_1 d^3 p'_2 d^3 h_1 d^3 h_2 \frac{m_N^4}{E_1 E_2 E'_1 E'_2} \\
& \times r^{\mu\nu}(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{h}_1, \mathbf{h}_2) \delta(E'_1 + E'_2 - E_1 - E_2 - \omega) \\
& \times \Theta(p'_1, p'_2, h_1, h_2) \delta(\mathbf{p}'_1 + \mathbf{p}'_2 - \mathbf{h}_1 - \mathbf{h}_2 - \mathbf{q}),
\end{aligned}
$$

—> 7-dimensional integral

- **fully relativistic** calculation
- all many-body diagrams involving 2 pions included
- each many-body diagram is a 7D integral+flux integration
- **np, nn and pp can be separated**

Many-body 2p2h diagrams

Direct diagrams

Exchange diagrams

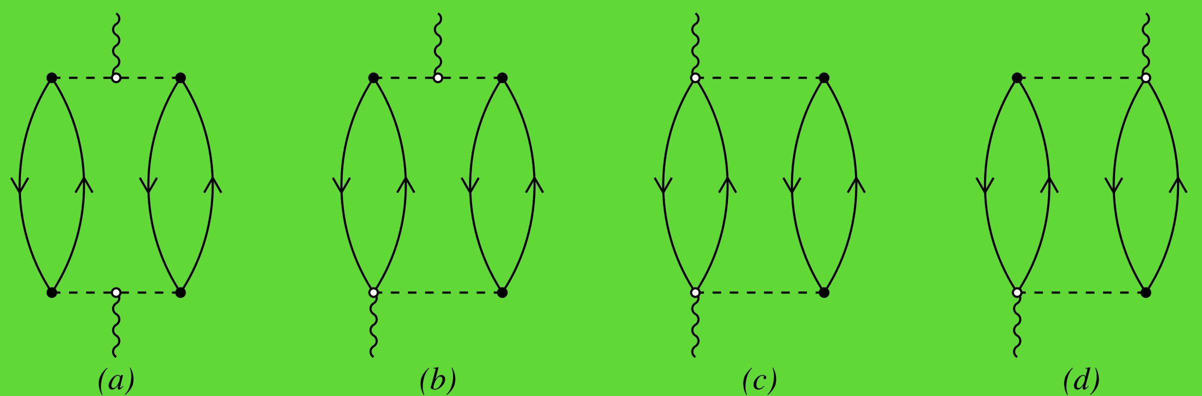


FIG. 2: The direct pionic contributions to the MEC 2p-2h response function.

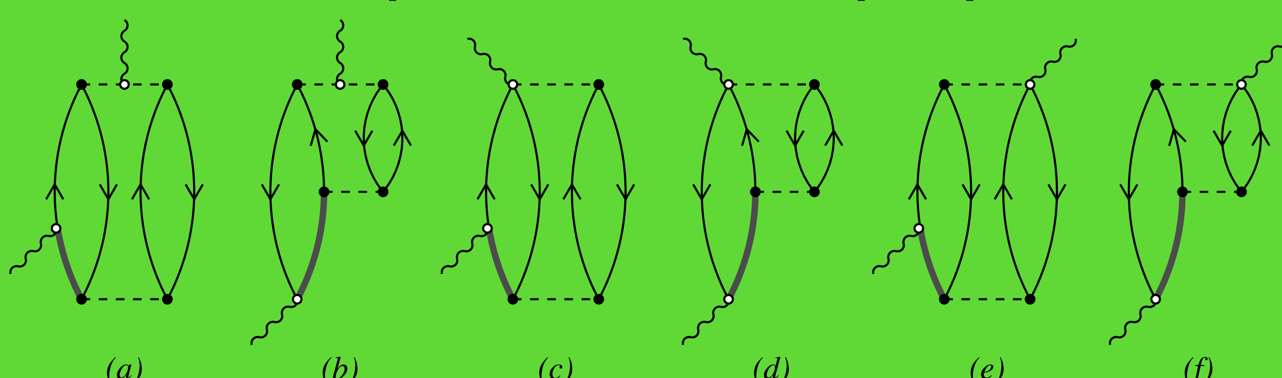


FIG. 3: The direct pionic/Δ interference contributions to the MEC 2p-2h response function.

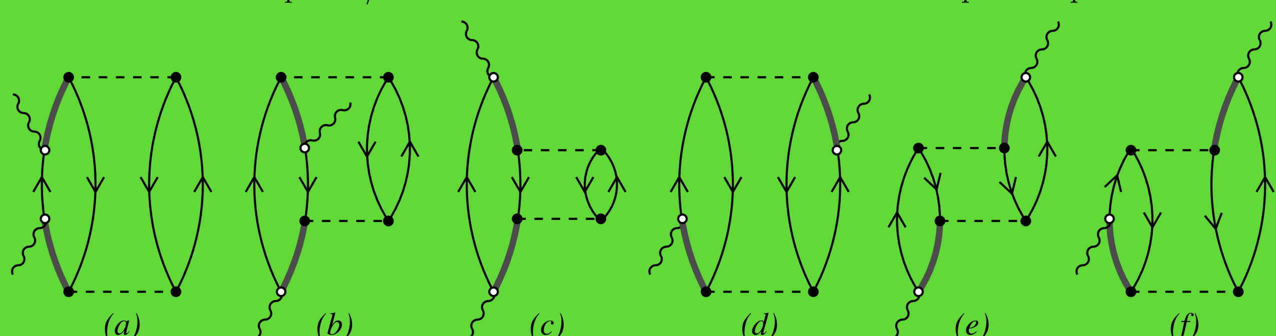


FIG. 4: The direct Δ contributions to the MEC 2p-2h response function.

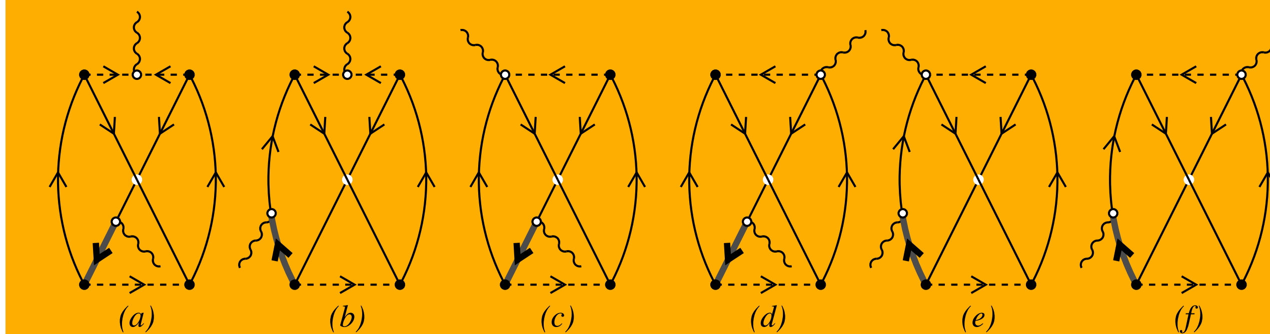


FIG. 5: The exchange pionic/Δ interference contributions to the MEC 2p-2h response function.

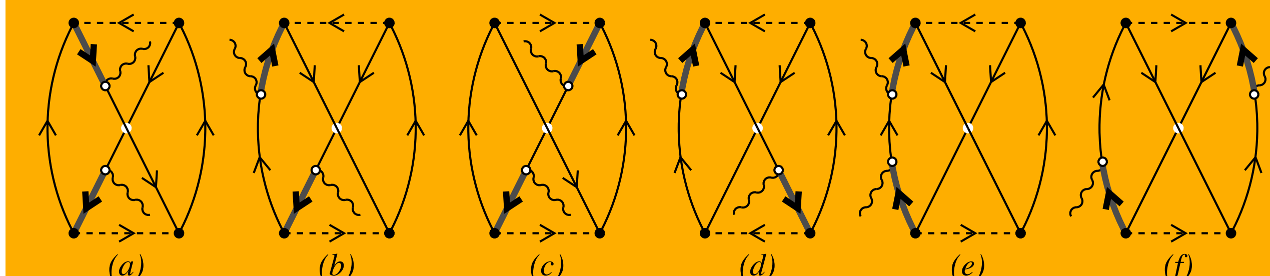
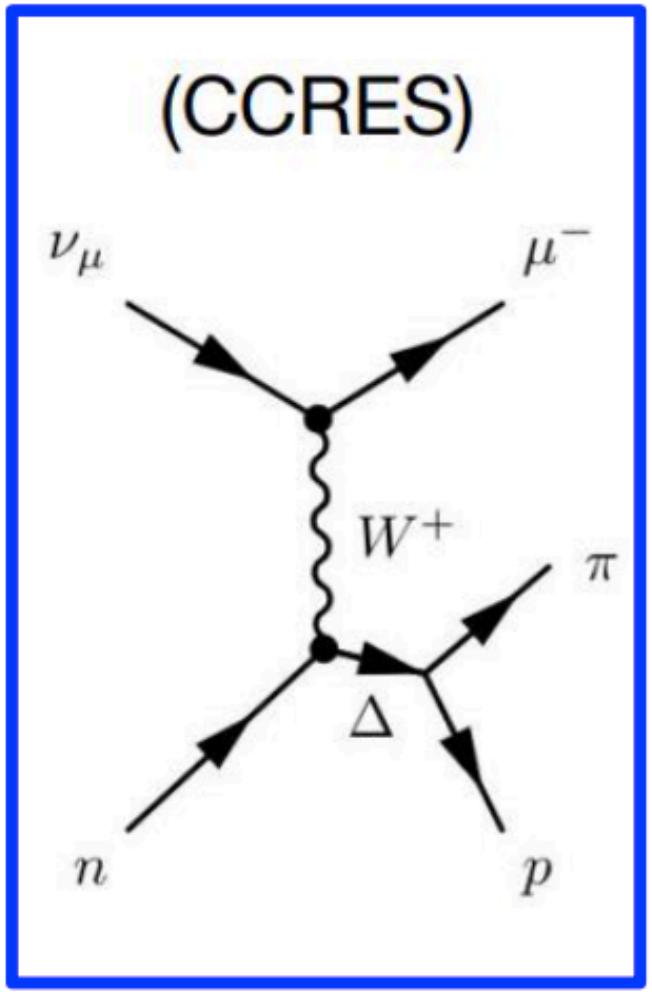
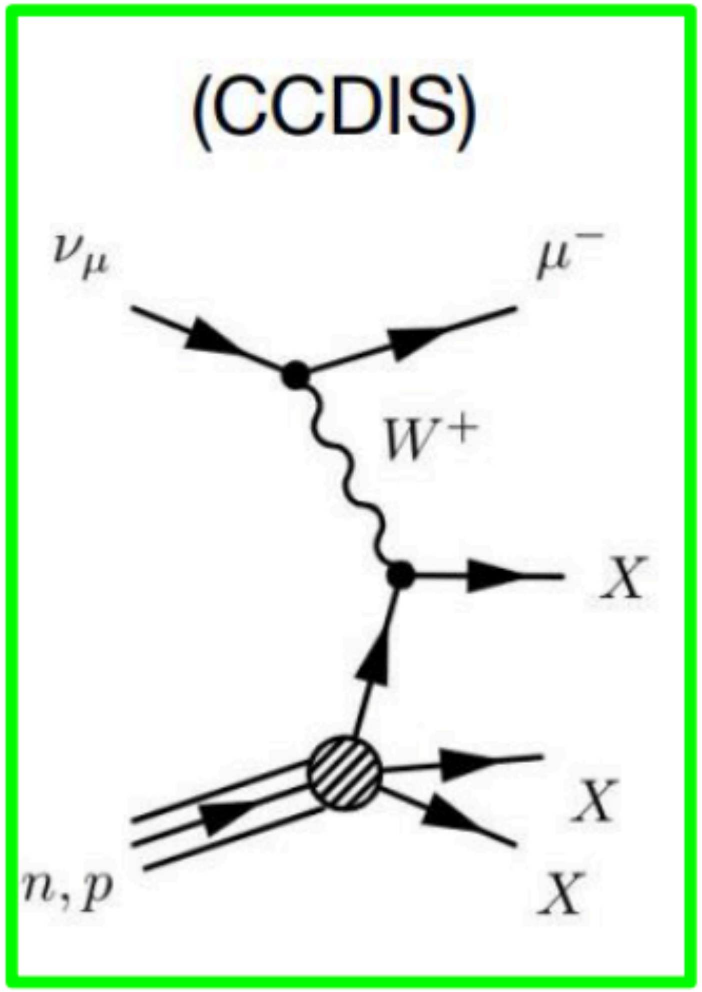


FIG. 6: The exchange Δ contributions to the MEC 2p-2h response function.

De Pace et al., Nucl.Phys. A726 (2003) EM
Ruiz Simo et al., J.Phys. G44 (2017) WEAK

III. High energy spectrum: Resonance production and deep inelastic scattering





Extension of SuSA to the inelastic channel

MBB et al., PRC69 (2004) (electrons), Gonzalez-Rosa et al., PRD105 (2022) & PRD11 (2025) (neutrinos)

- introduce a **generalized scaling variable** ψ_X for each invariant mass W_X
- fold the **elementary inelastic structure functions** with the SuSA scaling variable

Quasielastic

$$R^K_{QE}(q,\omega) \propto f(\psi)\, U^K(q,\omega)$$

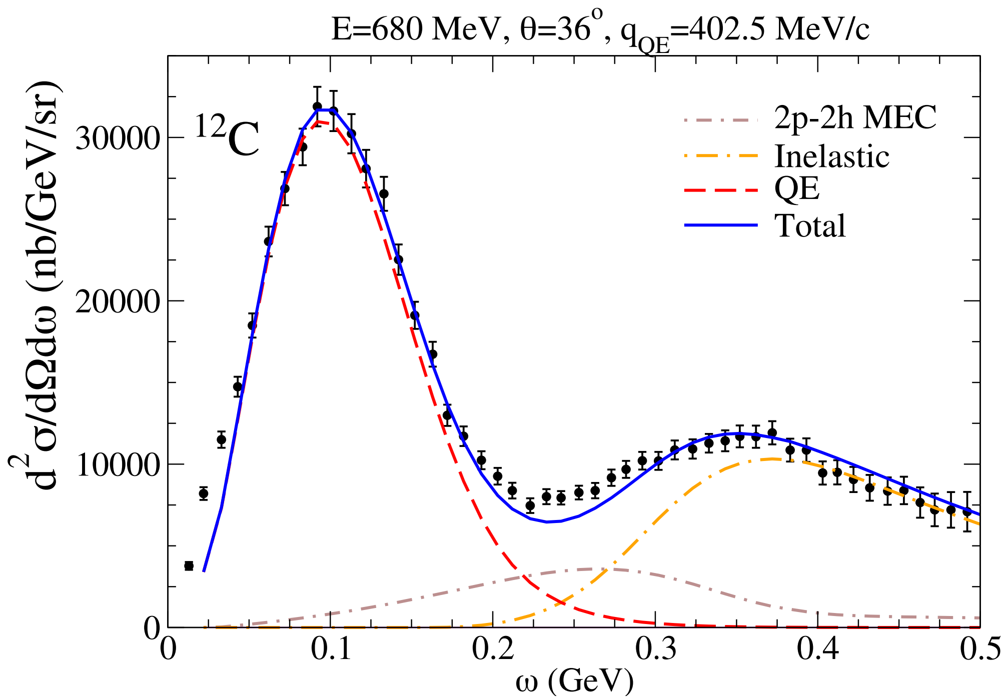
Inelastic

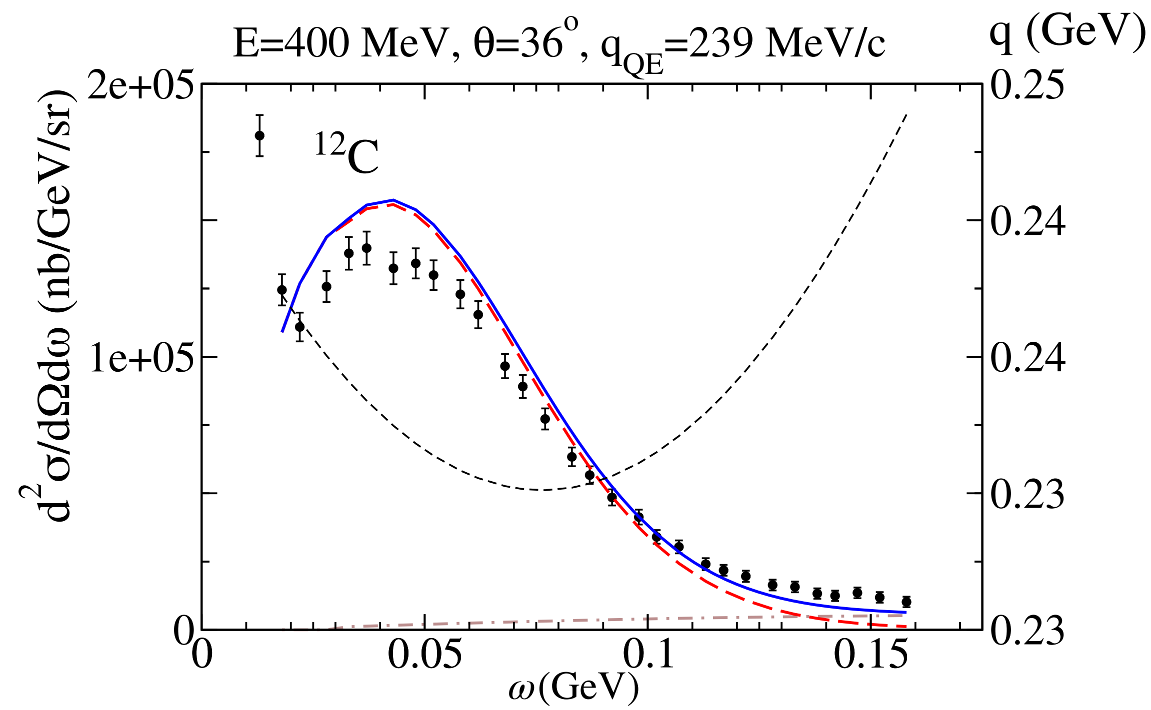
$$R^K_{inel}(q,\omega) \propto \int_{W_{min}}^{W_{max}} dW_X f(\psi_X)\, U^K_{inel}(q,\omega)$$

U^K_{inel} single-nucleon inelastic structure functions taken from available parameterizations:

- **Electron scattering:** w_1, w_2 from Bodek and Ritchie PRD 24 (1981), Bosted and Christy PRC76 (2008), PRC81 (2010)
- **Neutrino scattering:** w_1, w_2, w_3 weak structure functions (less well known)
  - **RES**: Dynamical Coupled Channel model [S. Nakamura et al., PRD 92 (2015)]
  - **DIS**: Bodek and Ritchie parametrization plus quark-parton model assumptions

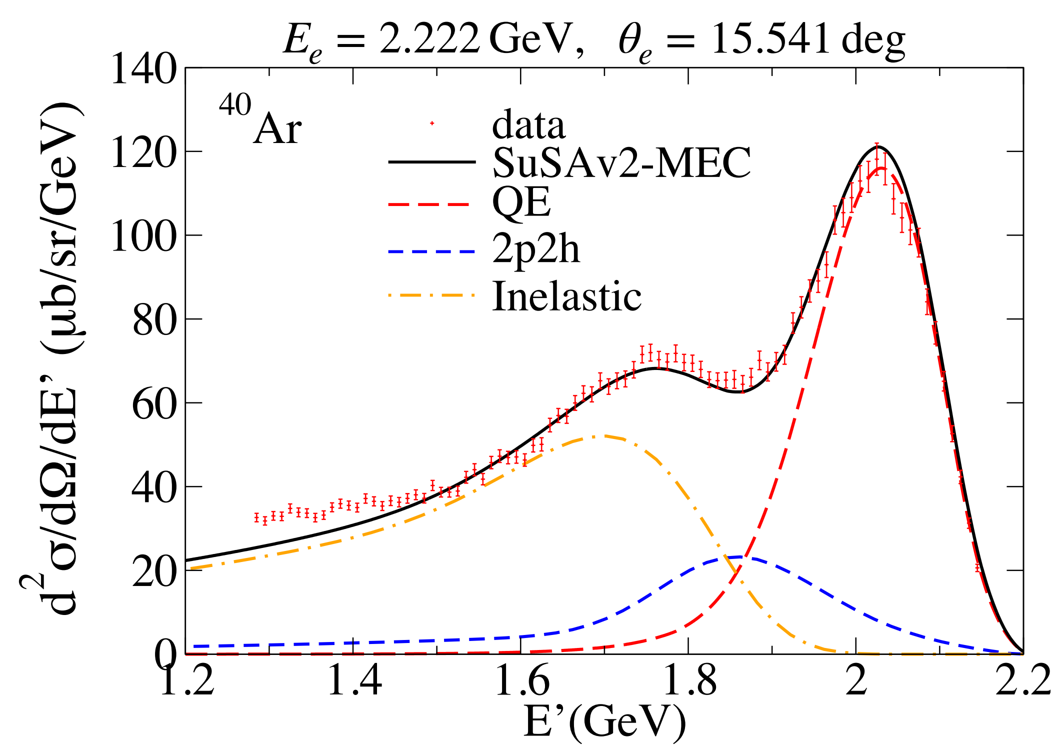
Validation: SuSAv2+2p2h comparison with (e,e') data





Megias *et al.*, PRD94 (2016)

Data: Barreau, NPA402 (1983)

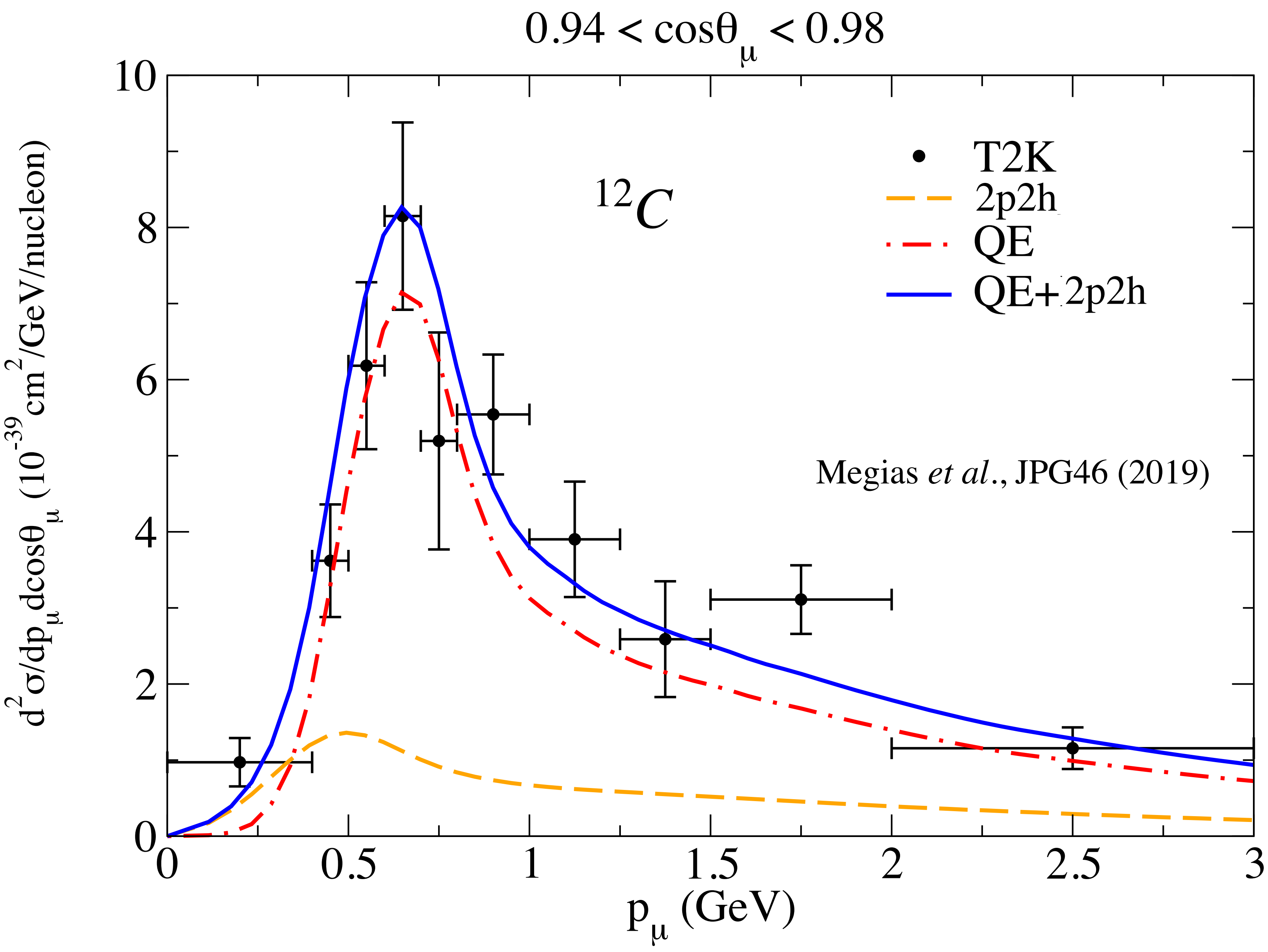


MB *et al.*, PRC99 (2019)

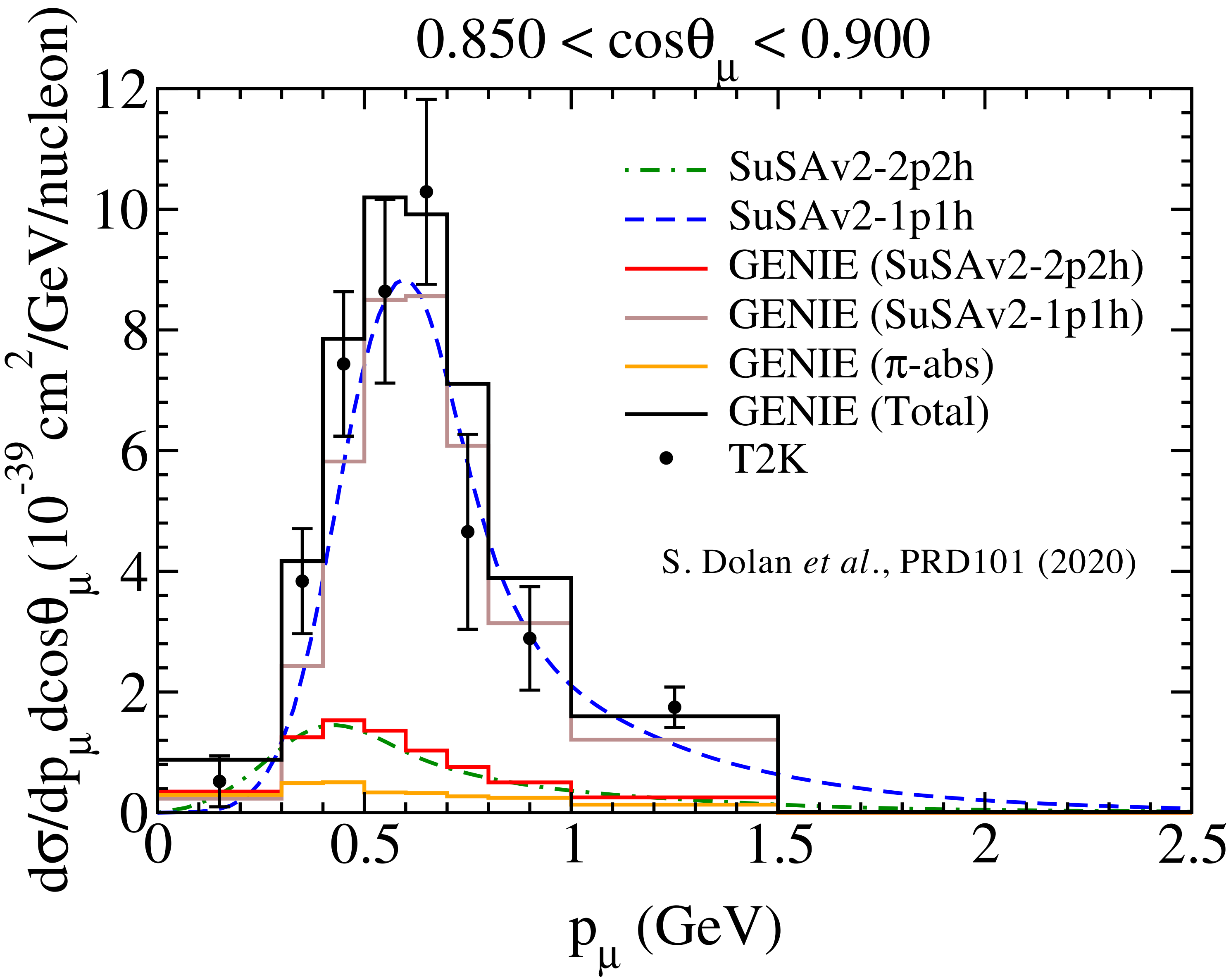
Data: Dai, PRC98 (2018)

Good agreement with data for different nuclei in a wide kinematical region, with the exception of the very low *q* regime, where the superscaling approach and IA fail and collective effects dominate.

SuSAv2+2p2h comparison with (ν_μ, μ) CC0π data



Implementation of SuSAv2+2p2h in GENIE



The SuSAv2 model is now implemented in GENIE, in both the QE and 2p2h channels

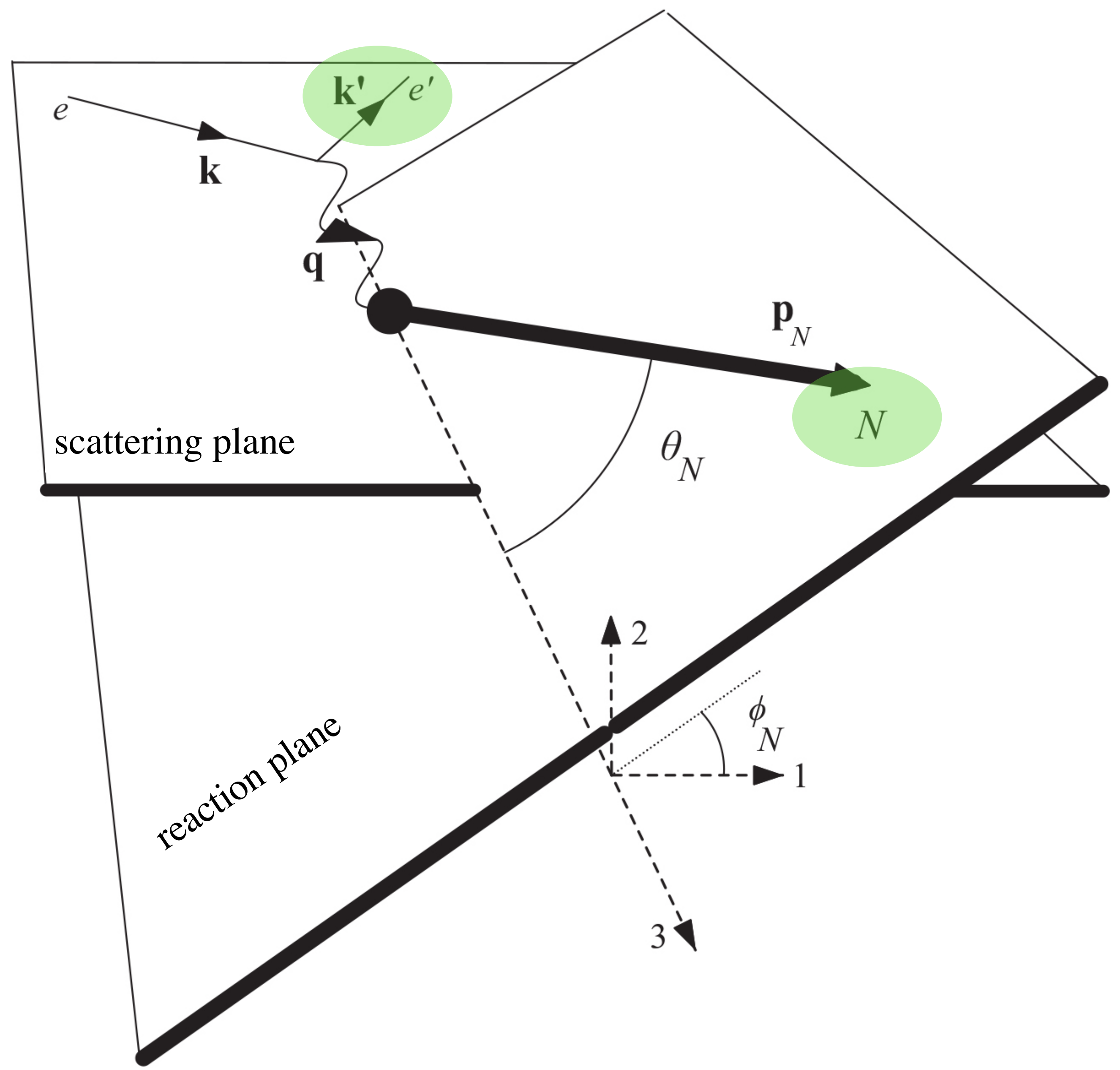
Check: for the *inclusive* cross section versus the muon variables, the results of the implementation (histograms) are in good agreement with the original calculation (curves)

Important warning: **the SuSA model is intrinsically inclusive, hadronic variables do not appear in the calculation —> GENIE-SuSAv2 cannot be used to predict final proton(s) distributions**

The model implemented in GENIE must be improved starting from the semi-inclusive calculation. Very few microscopic models for the semi-inclusive neutrino-nucleus cross section exist at present

Semi-inclusive scattering

Recently semi-inclusive data have been published by T2K, MINERvA, MicroBooNE
The outgoing lepton and one ejected nucleon are detected in coincidence



Semi-inclusive scattering

Quasi-elastic channel

University of Seville & University of Turin

PhD Thesis

SEMI-INCLUSIVE NEUTRINO-NUCLEUS REACTIONS AT INTERMEDIATE ENERGIES

by

JUAN MANUEL FRANCO PATIÑO

B.S., University of Seville, 2017
M.S., University of Seville, 2018

Supervised by: Juan Antonio Caballero and Maria Benedetta Barbaro

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

2023

Two-particle-two-hole channel

Università degli Studi di Torino
Dipartimento di Fisica

Scuola di Dottorato

Dottorato in Fisica, XXXVII ciclo

Meson-exchange currents in lepton-nucleus scattering

Thesis presented by: Valerio Belocchi

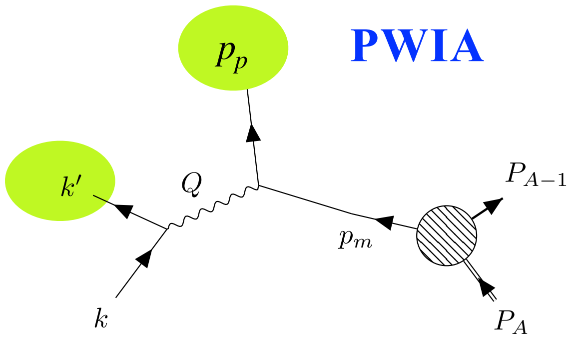
Supervisors: Prof.ssa Maria Benedetta Barbaro, Prof. Marco Martini

PhD Program Coordinator: Prof. Paolo Olivero

Academic years: 2021-2024

I. QE scattering

$$\left\langle \frac{d^6\sigma}{dk' d\Omega' dp_p d\Omega_p} \right\rangle = \int_0^\infty dk \frac{\Phi_\nu(k)}{k} K_0 S(p_m, E_m) \mathscr{F}^2 \theta(E_m - E_s)$$



$\mathbf{p}_m = \mathbf{q} - \mathbf{p_N} = \mathbf{p_{A-1}}$ missing momentum

$E_m = \omega - T_N - T_{A-1}$ missing energy

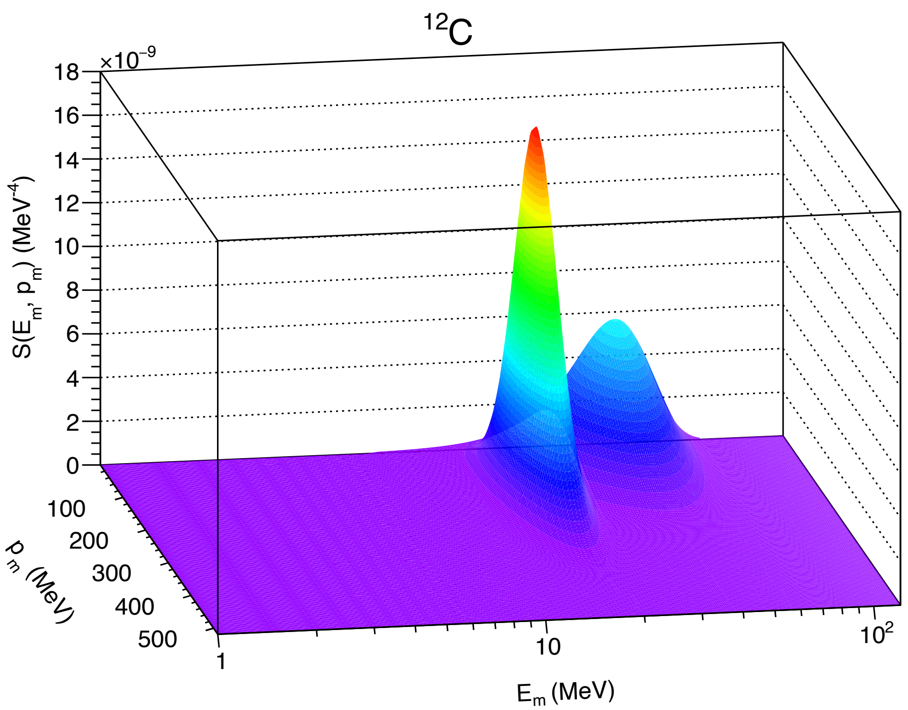
Initial state:
Spectral function

$$S(p_m, E_m) = S_{\rm SP}(p_m, E_m) + S_{\rm corr}(p_m, E_m)$$

Joint probability of finding a nucleon of momentum p_m in the nuclear ground state A and reaching final states in the daughter nucleus A-1 characterised by missing energy E_m

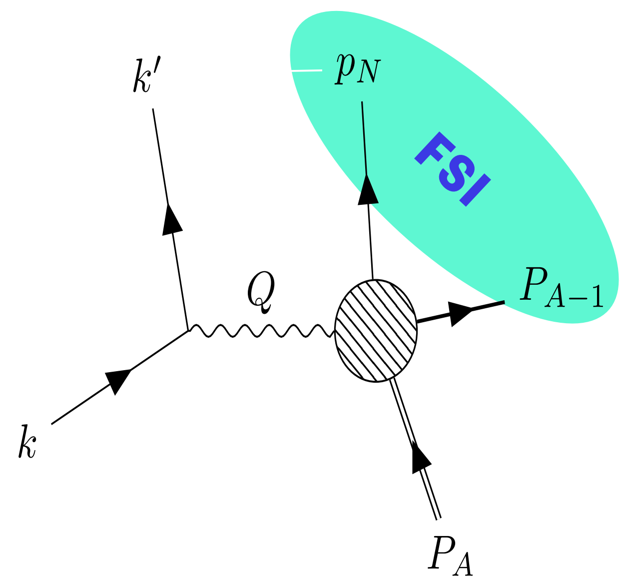
$S_{\rm SP}(p, E)$ shell contribution evaluated in the RMF model, including spectroscopic factors extracted from (e,e'p) data, accounts for ~80% of the strength

$S_{\rm corr}(p, E)$ high missing energy and momentum tail due to NN correlation extrapolated from nuclear matter using LDA [Benhar et al., NPA 579 (1994)]

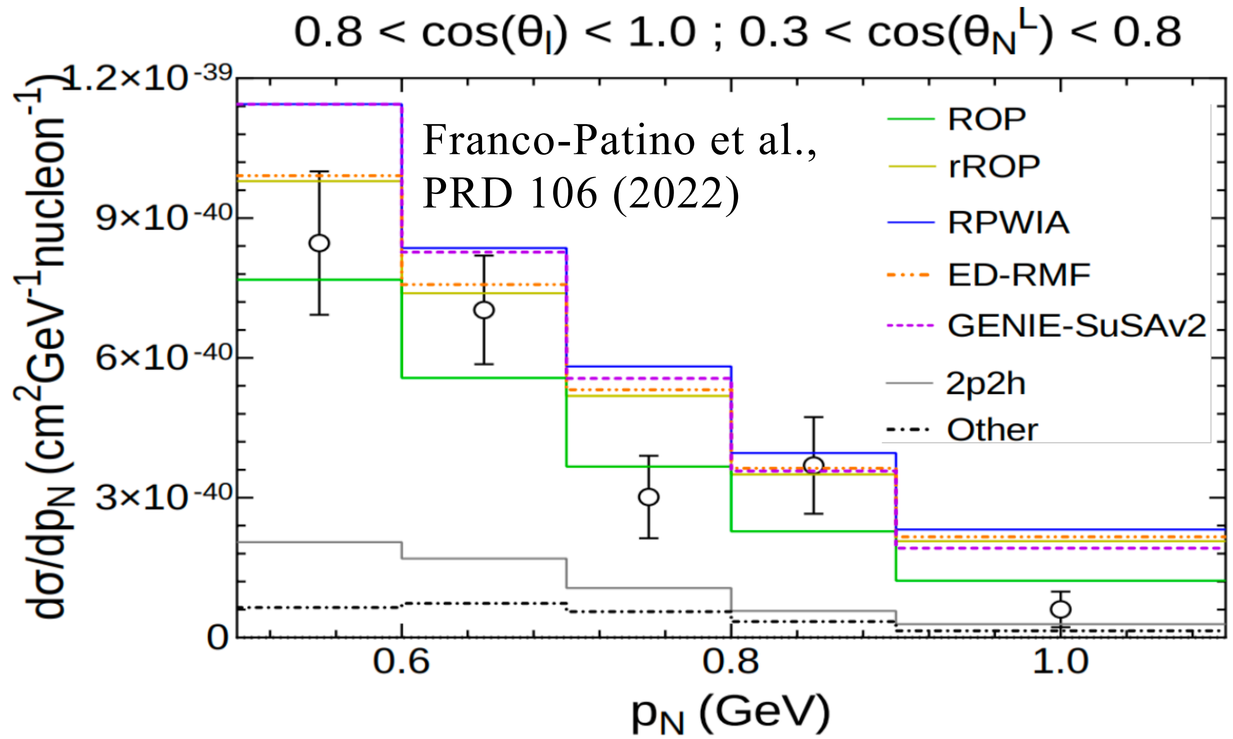


Final-state interactions

Distorted wave impulse approximation

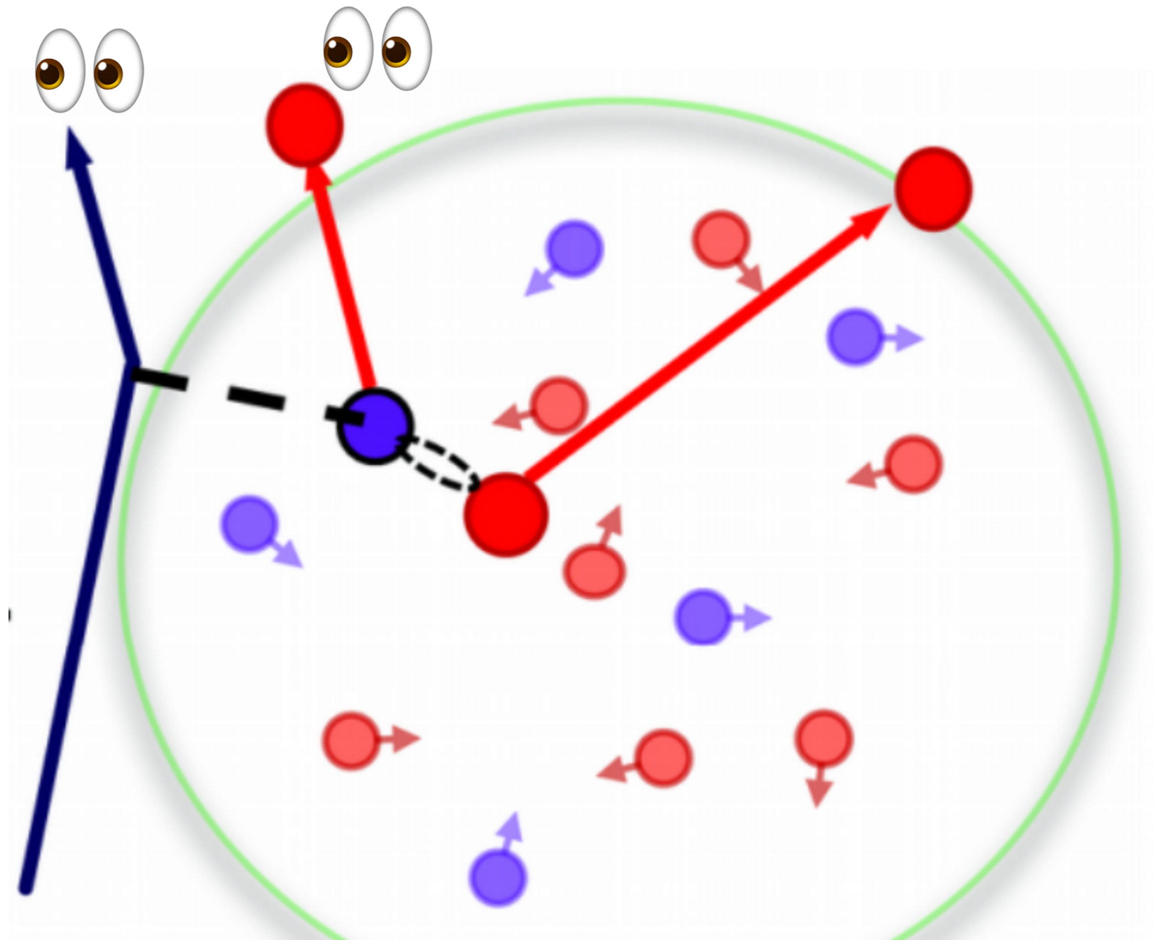


T2K $1\mu CC0\pi Np$ signal: at least one proton in the final state with momentum above 0.5 GeV



- **Srong dependence on the treatment of FSI**
- All curves include 2p2h from GENIE simulation, based on *inclusive* predictions (unreliable)
- Relativistic Optical Potential (ROP) model seems to agree better with the data BUT the model/data comparison is much affected by the 2p2h contribution
- No clear conclusions on the best treatment of FSI
- **Microscopic calculations for the 2p2h semi-inclusive process are needed**

II. Two-body currents in semi-inclusive scattering



2p2h semi-inclusive cross section

$$\frac{d^6\sigma}{d\omega d\Omega_\mu dT_p d\Omega_p} \sim \eta_{\mu\nu} W^{\mu\nu}_{2p2h(N)} = \sigma_0\, p\, E_p\, \mathscr{F}^2$$

Hadronic tensor: same model used in the inclusive case, RFG based

$$W^{\mu\nu}_{2p2h(N)} = \frac{V}{(2\pi)^6} \int d^3p_2 d^3h_1 d^3h_2 \frac{m_N^3}{E_1 E_2 E_2'} r^{\mu\nu}(p_1, p_2, h_1, h_2)\, \Theta(p_1, p_2, h_1, h_2)$$
$$\times\, \delta(E_1' + E_2' - E_1 - E_2 - \omega)\, \delta(\mathbf{p_1} + \mathbf{p_2} - \mathbf{h_1} - \mathbf{h_2} - \mathbf{q})$$

- Integration over one particle and two holes momenta
- Four-momentum conservation
- No more azimuthal invariance
- 5-dimensional integral

Response functions

$$\mathscr{F}^2 = V_L R_L + V_T R_T - V_{LT} R_{LT} + V_{TT} R_{TT}$$

- 4 EM responses

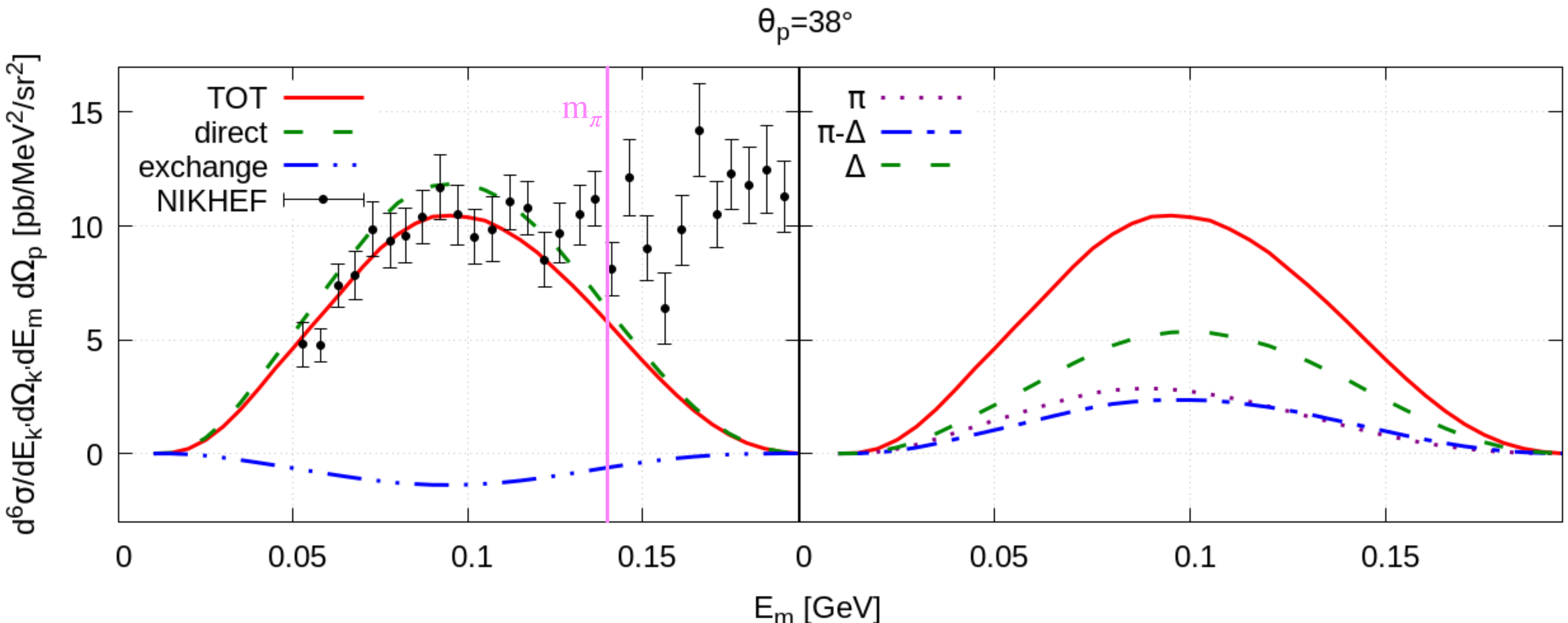
$$\mathscr{F}^2 = V_{CC} R_{CC} - 2 V_{CL} R_{CL} + V_{LL} R_{LL} + V_T R_T + 2 V_{T'} R_{T'}$$
$$- V_{CT} R_{CT} + V_{LT} R_{LT} + V_{TT} R_{TT} - V_{C\bar{T}'} R_{C\bar{T}'} + V_{L\bar{T}'} R_{L\bar{T}'}$$

- 10 weak responses

Comparison with semi-inclusive EM data

$E_e = 470\,\text{MeV},\ \omega = 263\,\text{MeV}\,,\ q = 303\,\text{MeV}$

kinematics selected to hit the dip region between QE and Δ



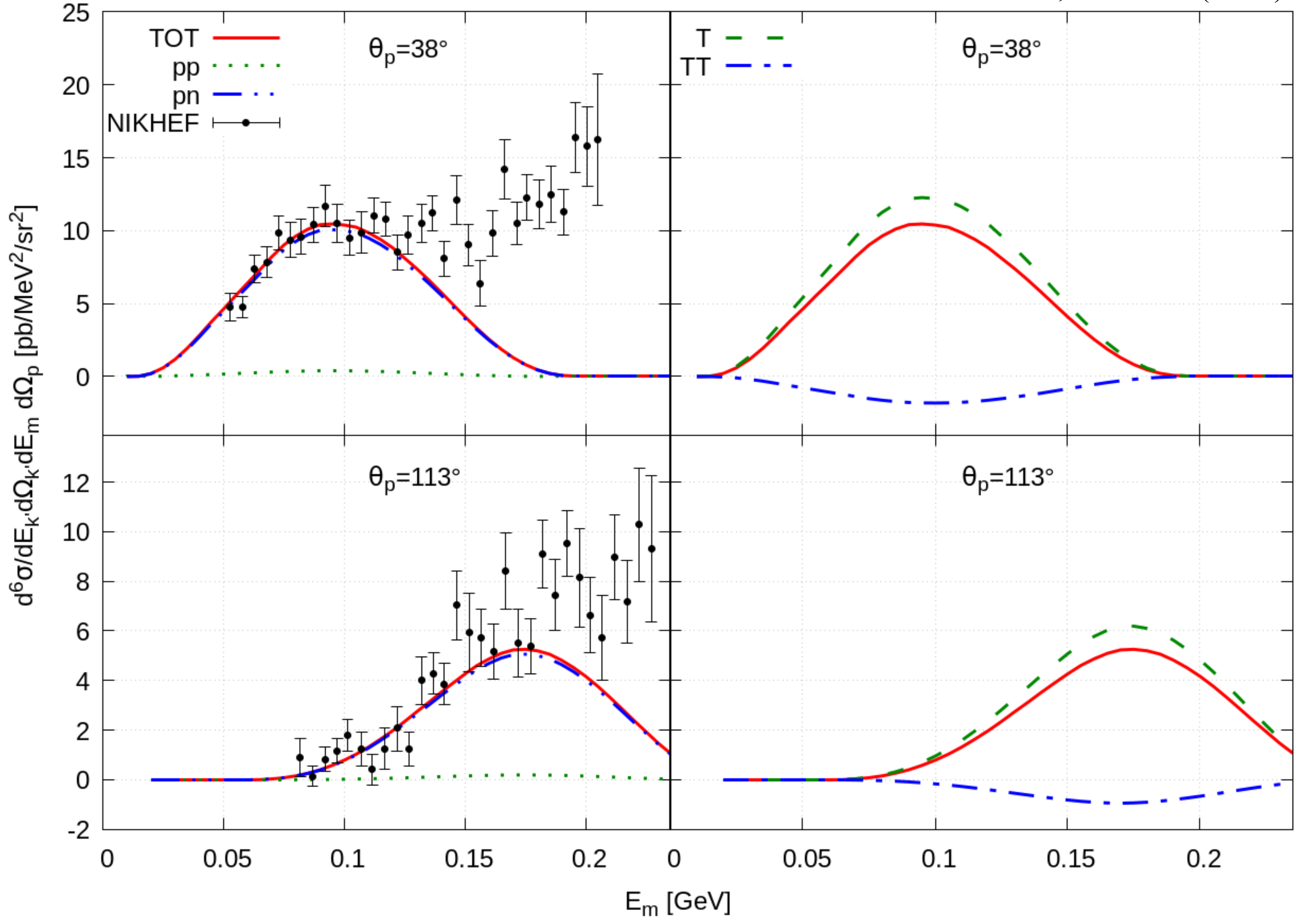
V. Belocchi et al., PRC 109 (2024)

- Pronounced peak corresponding to 2p2h excitation
- Direct and exchange contributions included
- Δ dominates (~ 50%) over pure π and $\pi - \Delta$ interference
- **Very good agreement with data below** $E_m \simeq 130\,\text{MeV}$
- For $E_m > 130\,\text{MeV}$ pion production starts to contribute

Isospin separation in 2p2h

Kinematics: $E_e = 470\,\mathrm{MeV}$, $\omega = 263\,\mathrm{MeV}$, $q = 303\,\mathrm{MeV}$ $\rightarrow$ dip region

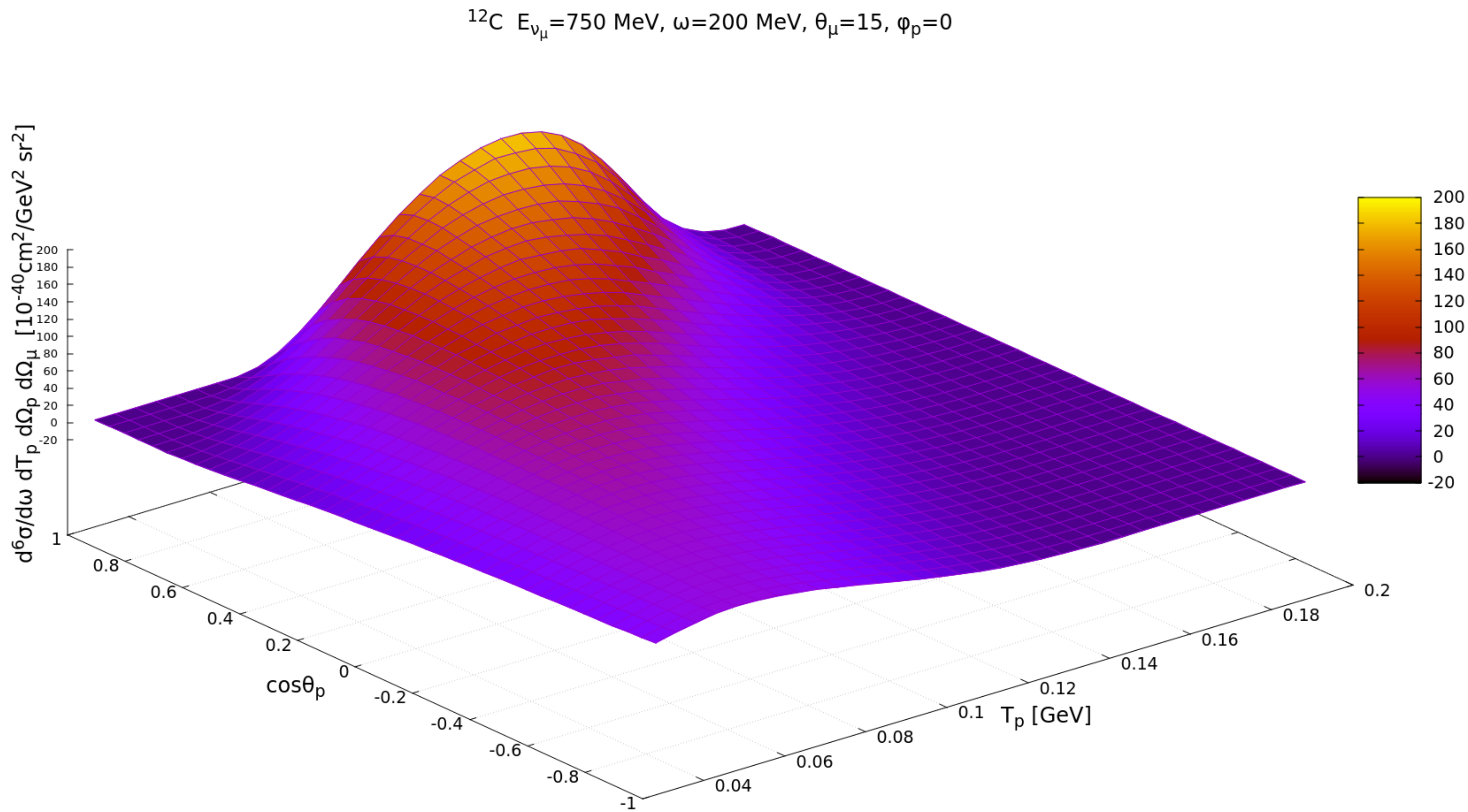
V. Belocchi et al., PRC 109 (2024)



- pn channel dominates over pp
- T contribution is the most important, TT reduces by ~ 15%

$\nu_\mu - C$ semi-inclusive 2p2h cross section

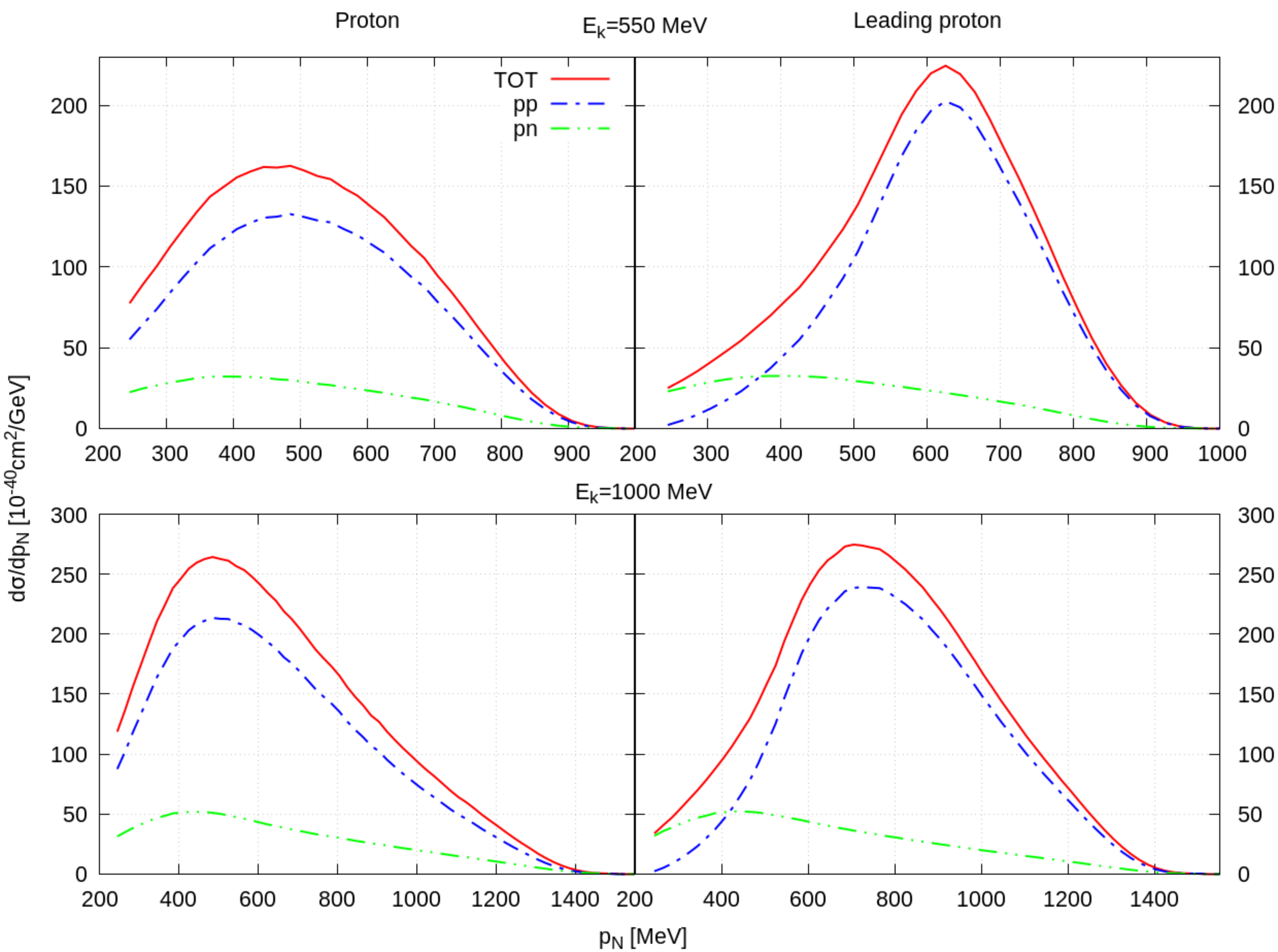
Incident energy and four-momentum transfer fixed ⇒ span over the detected particle phasespace



Valerio Belocchi: https://tesidottorato.depositolegale.it/handle/20.500.14242/199440

p_N distribution from 2p2h at fixed neutrino energy

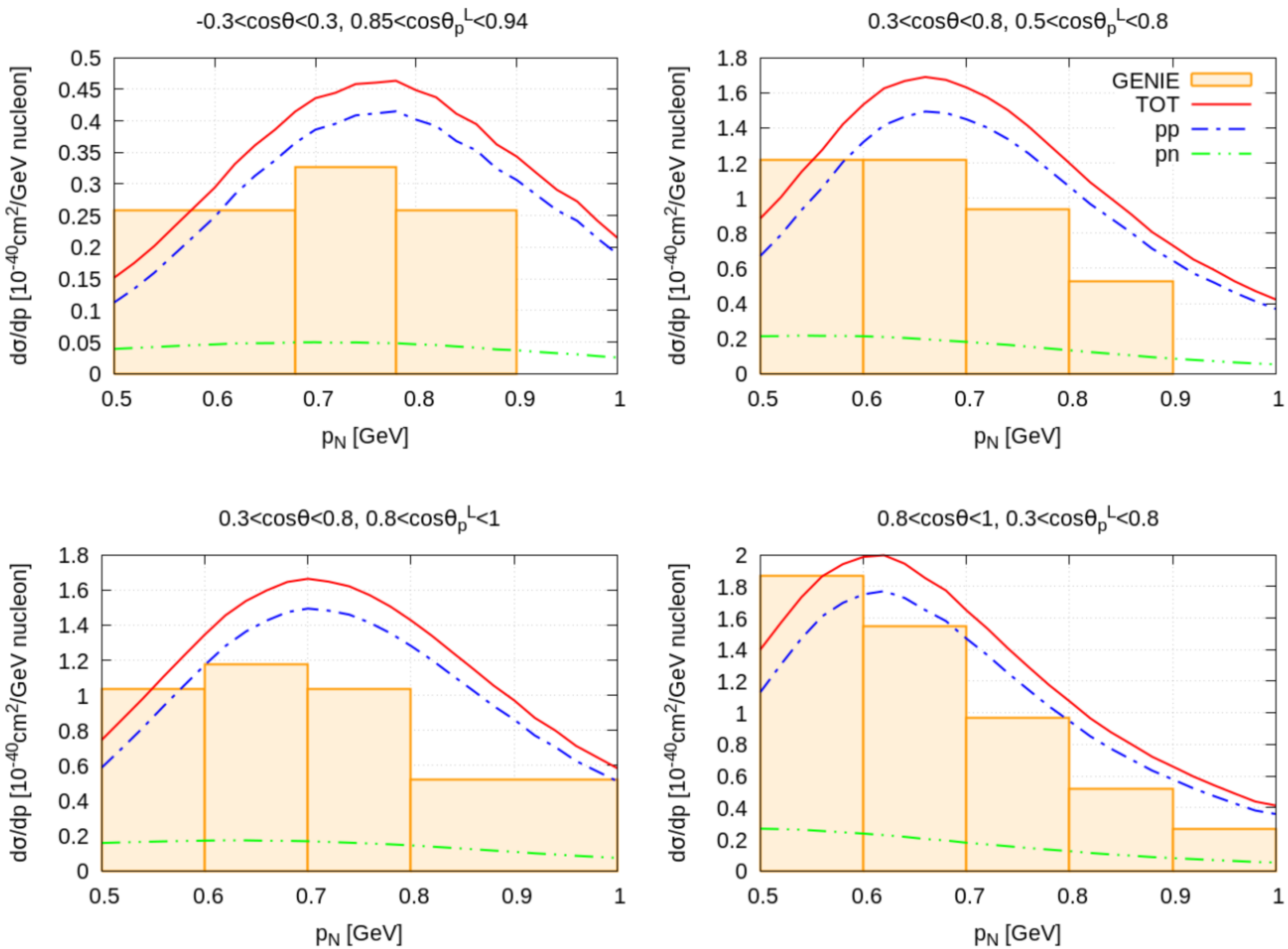
Leading proton: the proton carrying the highest momentum in a multinucleon knockout event



- pp emission channel dominates over pn

p_N distribution from 2p2h at experimental conditions

2p2h contribution to the CC0πNp cross section averaged over the incident T2K flux. Experimental cuts applied



V. Belocchi et al, in preparation

- GENIE 2p2h from Dolan et al., PRD 101.3 (2020), based on inclusive model results, FSI included (cascade model)
- Present computation: consistently higher cross section, peaked at higher pN, but FSI not included

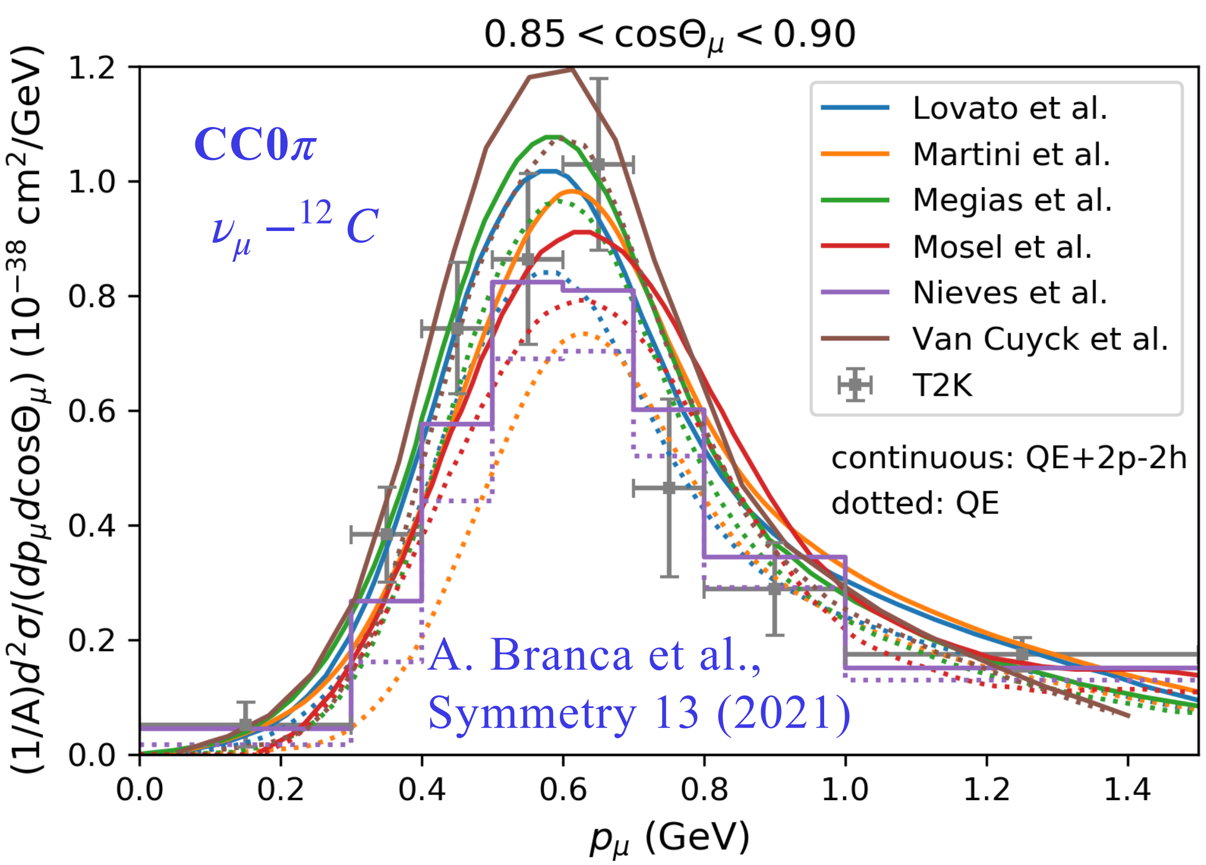
Summary

- **Nuclear physics** input is crucial for present and future long baseline oscillation experiments. The present situation does not match the desired precision.
- **SuSAv2** model with the addition of **2p2h** successfully **tested against inclusive (e,e') data**, yields CC0π neutrino cross sections compatible with errorbars.
- Several new data (T2K, MINERvA, MicroBooNE) on **semi-inclusive** measurements: both leptons and hadrons detected in the final state. More sensitive to nuclear effects, theoretical studies still quite rare.
- We have studied the **QE semi-inclusive** process in the framework of the **RMF model**. Results are **extremely sensitive to the treatment of FSI**. The comparison with data requires the inclusion of 2p2h contribution, until now not available.
- A **new calculation of the 2p2h contribution to the CC semi-inclusive** cross section has been recently completed. Test against the (few) available electron scattering data is satisfactory, but FSI must be included. Comparison with neutrino data is underway.
- **Future work:** inclusion of FSI, 2p2h beyond RFG, contribution of heavier mesons MEC, sensitivity to form factors….

THANKS FOR YOUR ATTENTION

Backup slides

Model comparison in the QE channel

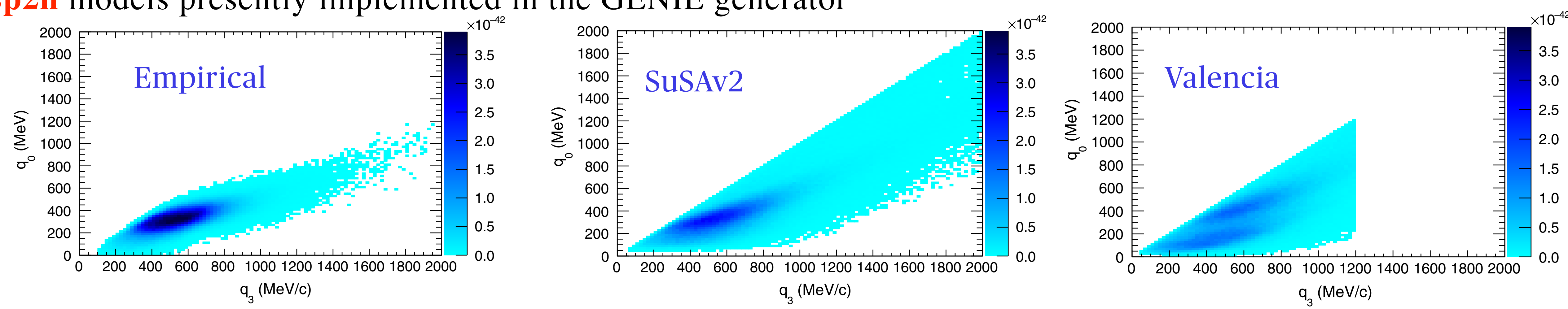


- GFMC ab initio
- RPA/Paris-Lyon
- SuSAv2
- GIBUU
- RPA/Valencia
- HF-CRPA Ghent

- Quite large spread between theory predictions for the "no pions" process
- Present experimental precision not sufficient to discriminate between models
- All results agree on the important role of two-body currents (2p2h excitations)
- However, large differences between 2p2h calculations

2p2h models presently implemented in the GENIE generator

S. Dolan et al., PRD101 (2020)



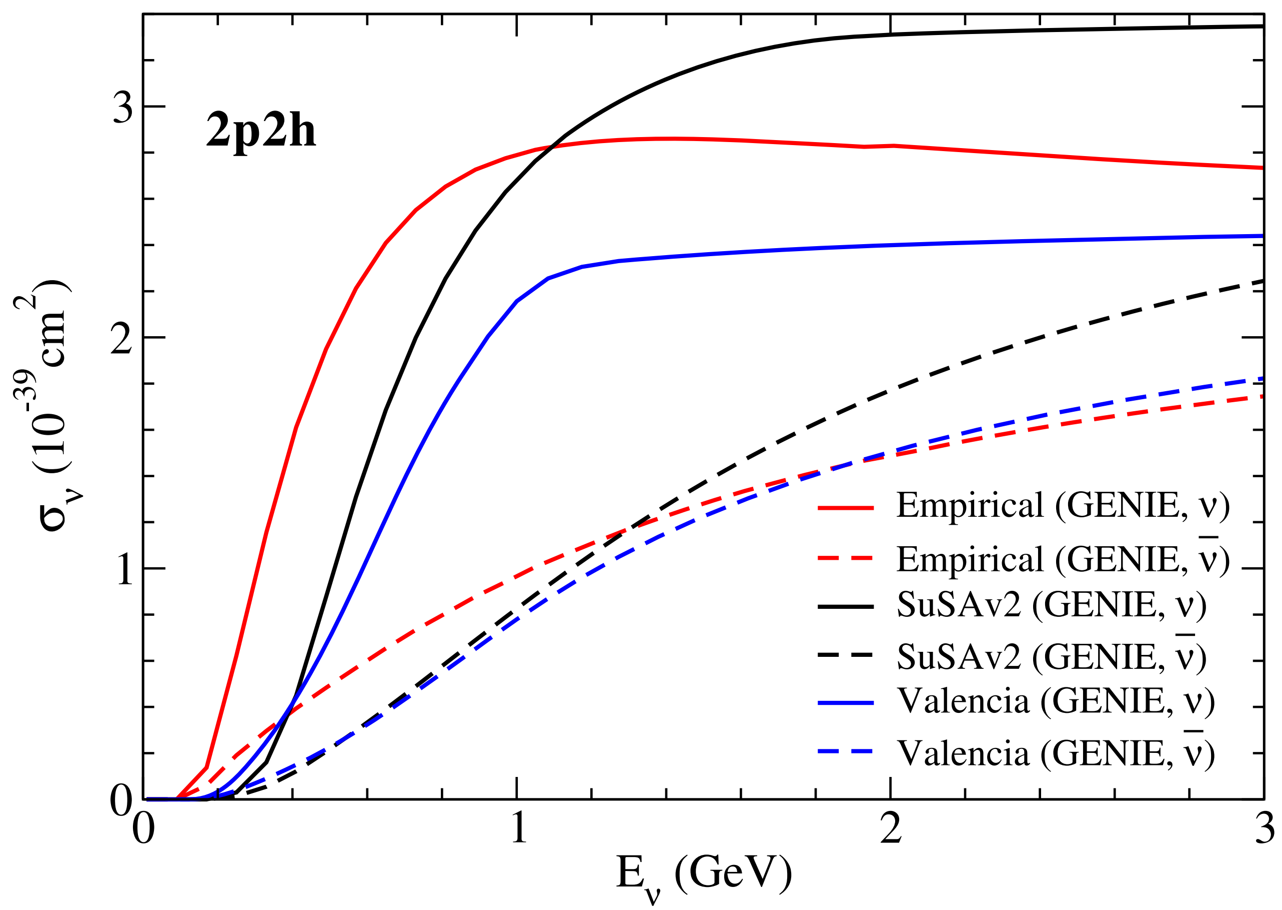
How to resolve discrepancies?

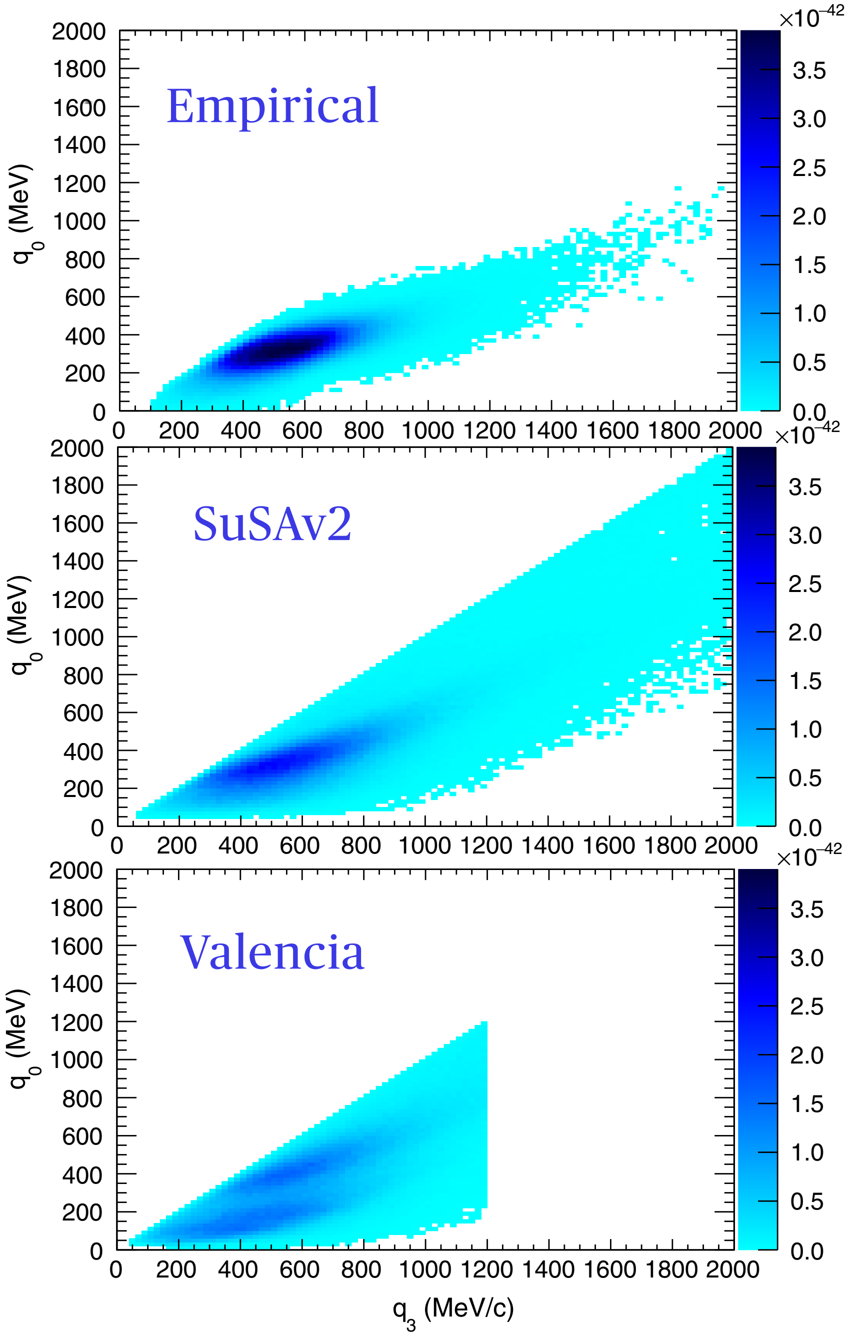
- validation versus other data: **electron scattering** ideal tool to discriminate between models
- comparison with **more exclusive neutrino data**, involving the final hadrons variables, now available from T2K, MINERvA, MicroBooNE

2p2h calculations

Large discrepancies between 2p2h models implemented in the GENIE generator

S. Dolan et al., PRD101 (2020)





Further constrains can be obtained from:

1. validation versus other data: electron scattering
2. comparison with more exclusive data, involving the final proton variables, now available from T2K, MINERvA, MicroBooNE

Scaling variable

The scaling variable ψ is defined in the framework of QE scattering the relativistic Fermi gas model

$$\psi(q,\omega) \equiv \pm\sqrt{\frac{T_0}{T_F}}$$

$$T_0 = \frac{q}{2}\sqrt{1+1/\tau} - \frac{\omega}{2} - m_N$$

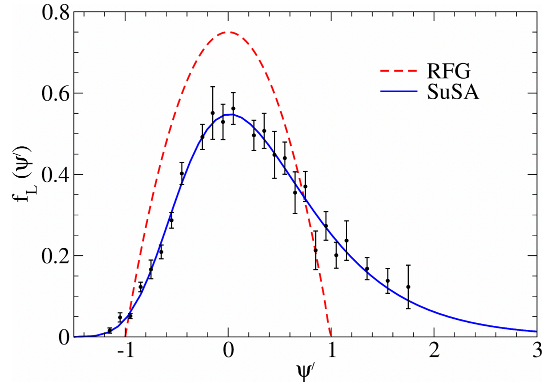
T_0 is the minimum kinetic energy of the hit nucleon at given momentum and energy transfer

$$\psi(q,\omega) \simeq \frac{m_N}{qk_F}\left(\omega - \frac{|Q^2|}{2m_N}\right)$$

$\psi = 0$ at the QEP

In the relativistic Fermi gas model

$$f^{RFG}(\psi) = \frac{3}{4}\left(1-\psi^2\right)\theta\left(1-\psi^2\right)$$



ψ is analogous to the Bjorken variable x in DIS

Extension to the inelastic regime

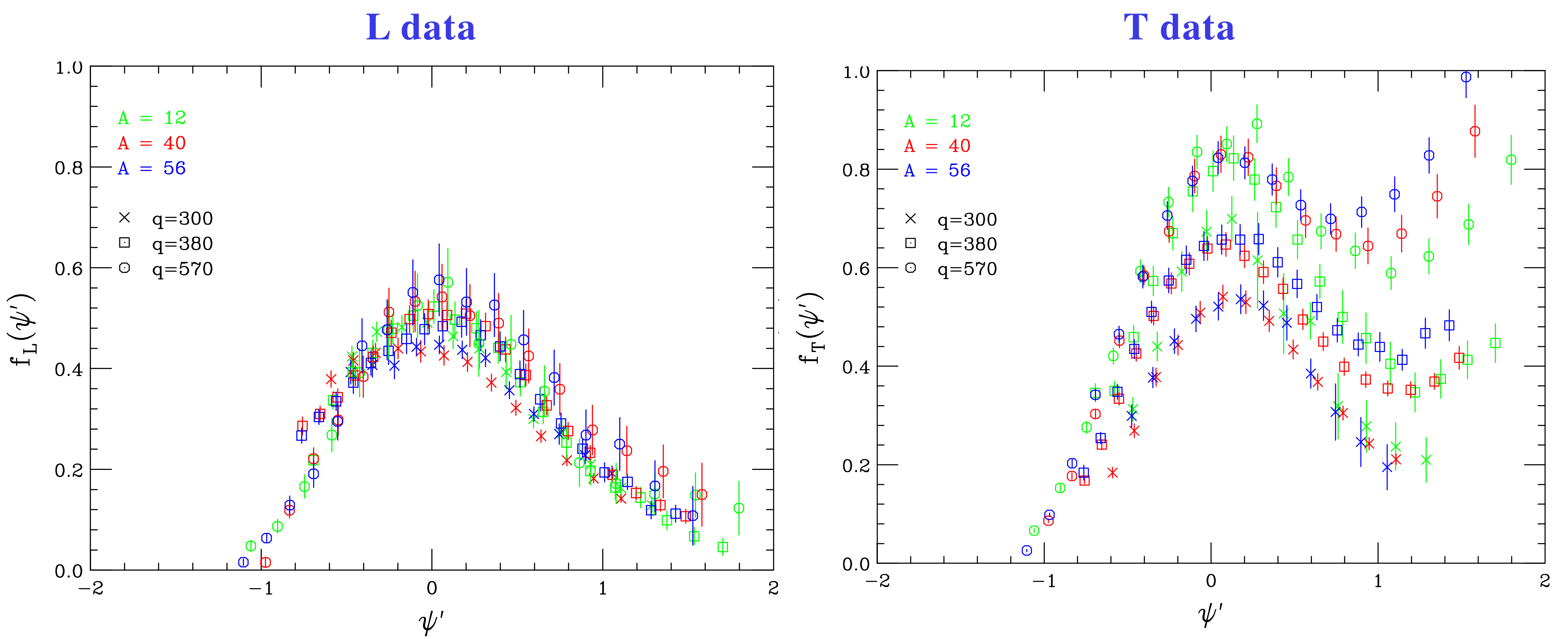
$$\psi(q,\omega) \equiv \pm\sqrt{\frac{T_0^*}{T_F}}$$

$$T_0^* = \frac{q}{2}\sqrt{1+1/\tau} - \frac{\omega}{2} - W$$

W is the invariant mass of the final hadronic state

Super Scaling in the Longitudinal and Transverse channels

Donnelly and Sick, PRL82; PRC60 (1999)



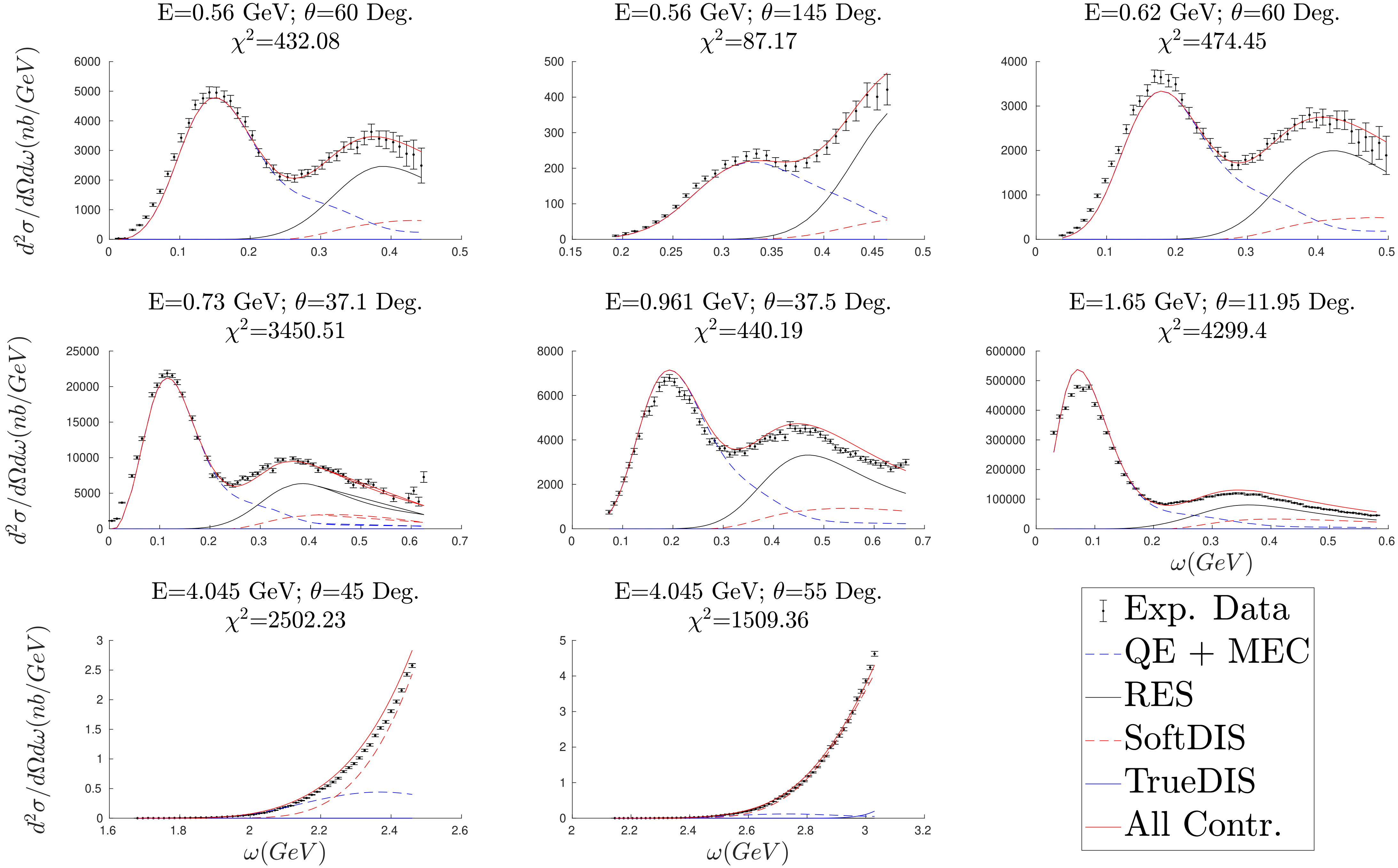
The analysis of the separate longitudinal and transverse responses shows that

- the **longitudinal response scales**

- **scaling violations** are mainly **transverse** (2p2h, Δ resonance and other inelastic processes)

Validation: electron scattering

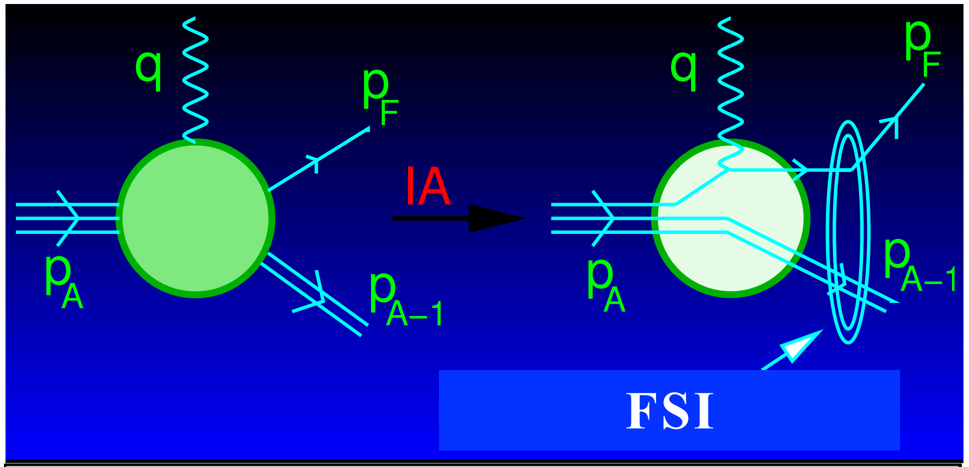
$e -^{12} C$



J. Gonzalez-Rosa et al., PRD 108 (2023)

Relativistic Mean Field

The RMF model is based on the **impulse approximation (IA)**:
scattering off a nucleus = incoherent sum of single nucleon scattering processes.

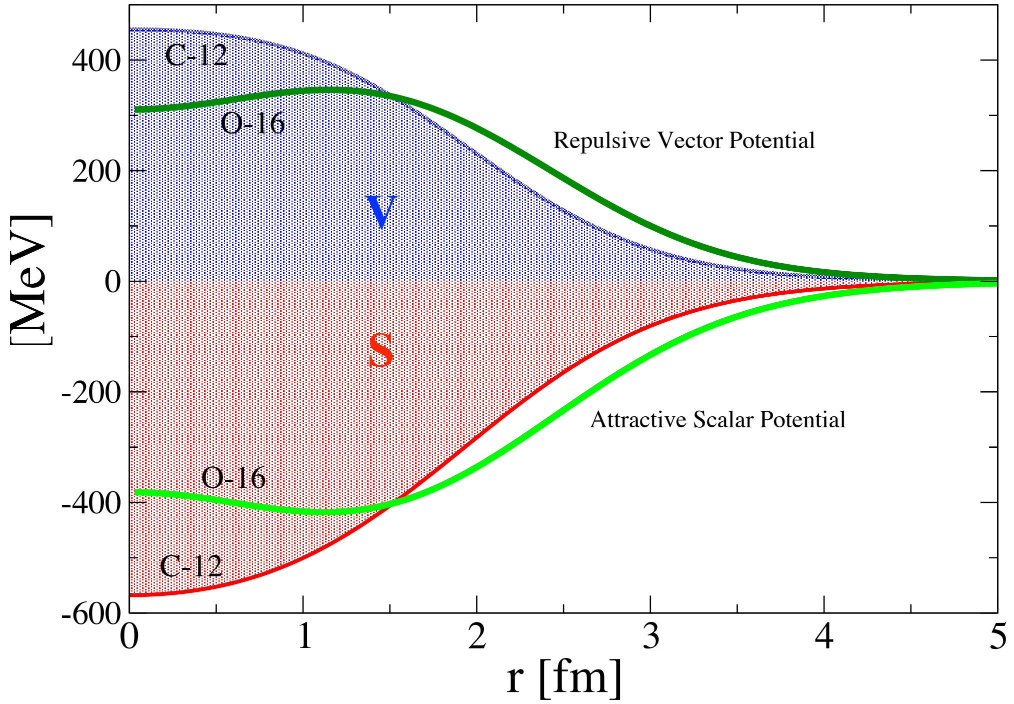


Nuclear Current $\Longrightarrow$ One-body operator

$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\, \overline{\Psi}_F(\vec{p}+\vec{q})\hat{J}_N^\mu \Psi_B(\vec{p})$$

The nucleon wave functions are **finite nucleus** solutions of the Dirac equation with **relativistic scalar and vector potentials** obtained from a Walecka-type Lagrangian fitted to properties of nuclear radii and masses:

$$(i\gamma^\mu \partial_\mu - M - S + V)\psi(\vec{r},t) = 0$$



Bound wave function

$$\Psi_B = \begin{pmatrix} \phi^{up} \\ \phi^{down} \end{pmatrix} = \begin{pmatrix} \phi^{up} \\ \frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{E+M+S-V}\phi^{up} \end{pmatrix} = \alpha u + \beta v$$

Scattered wave function

The ejected nucleon wave function is distorted by FSI with the residual nucleus.
It is a scattering solution of the Dirac equation with the same potentials used to describe the bound state.
Orthogonality is preserved: the initial and final nucleons are eigenstates of the same Hamiltonian.

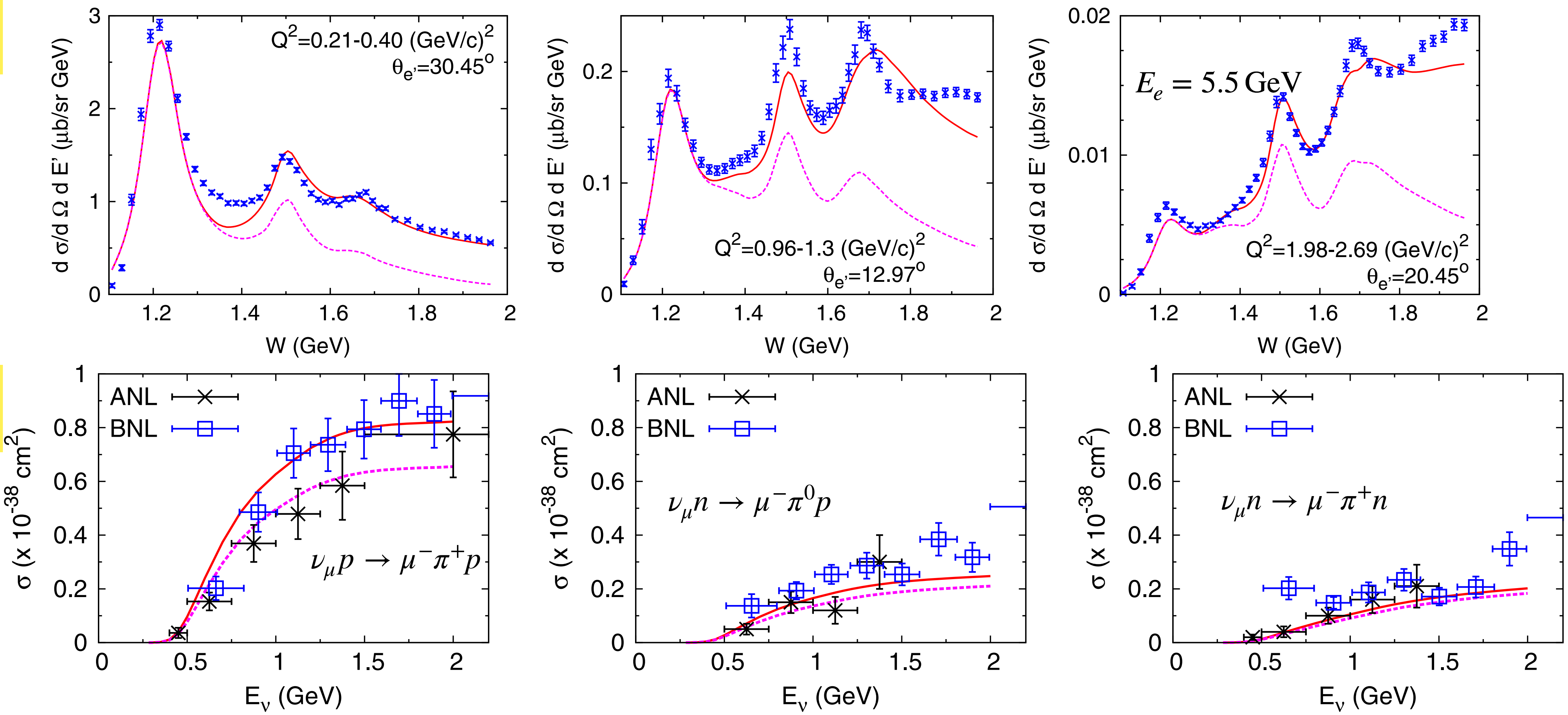
Resonance region: DCC model

To describe the inelastic $\nu - N$ scattering in the RES region we use the **Dynamical Coupled Channel** model [S. Nakamura et al., PRD 92 (2015)]

- Widely tested for electron and neutrino scattering off a single nucleon
- Describes the resonant and non-resonant regimes, including the interaction between the different resonance channels (πN, ππN, ηN, KΛ, KΣ), the interference between resonant and non-resonant amplitudes and the neutrino induced two-pion production.
- Validity range $m_N + m_\pi < W < 2.1$ GeV

$e - p$

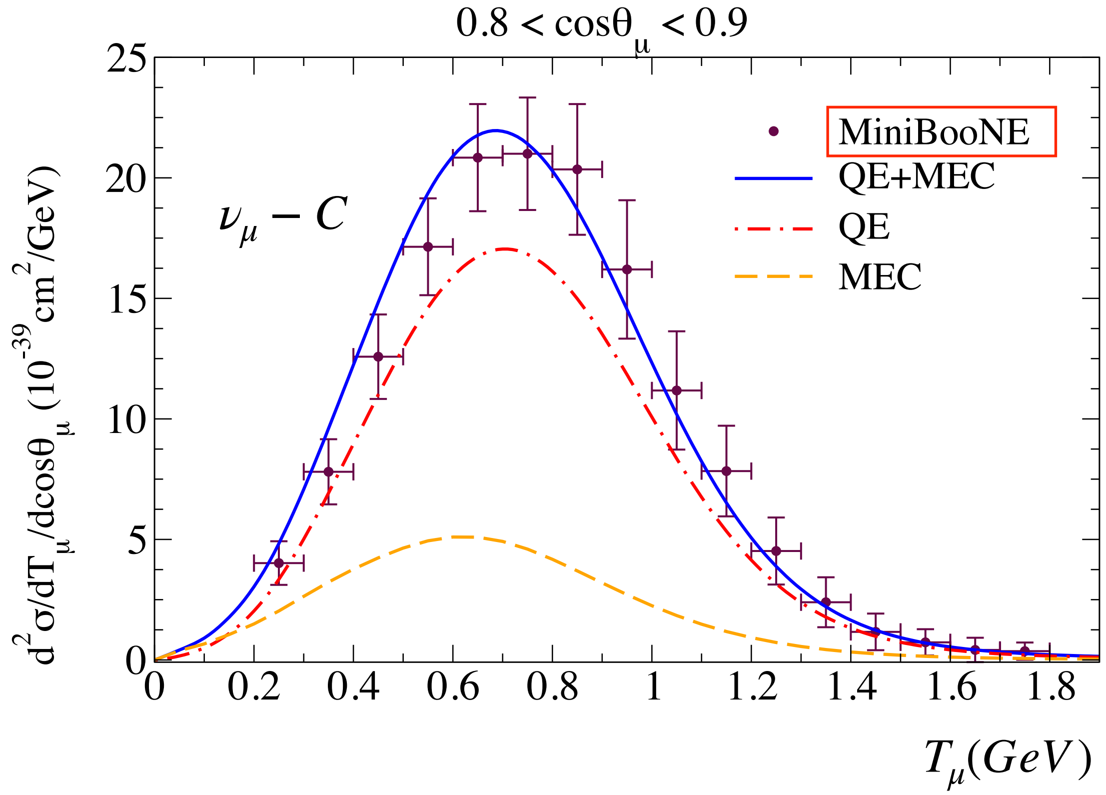
$\nu - N$



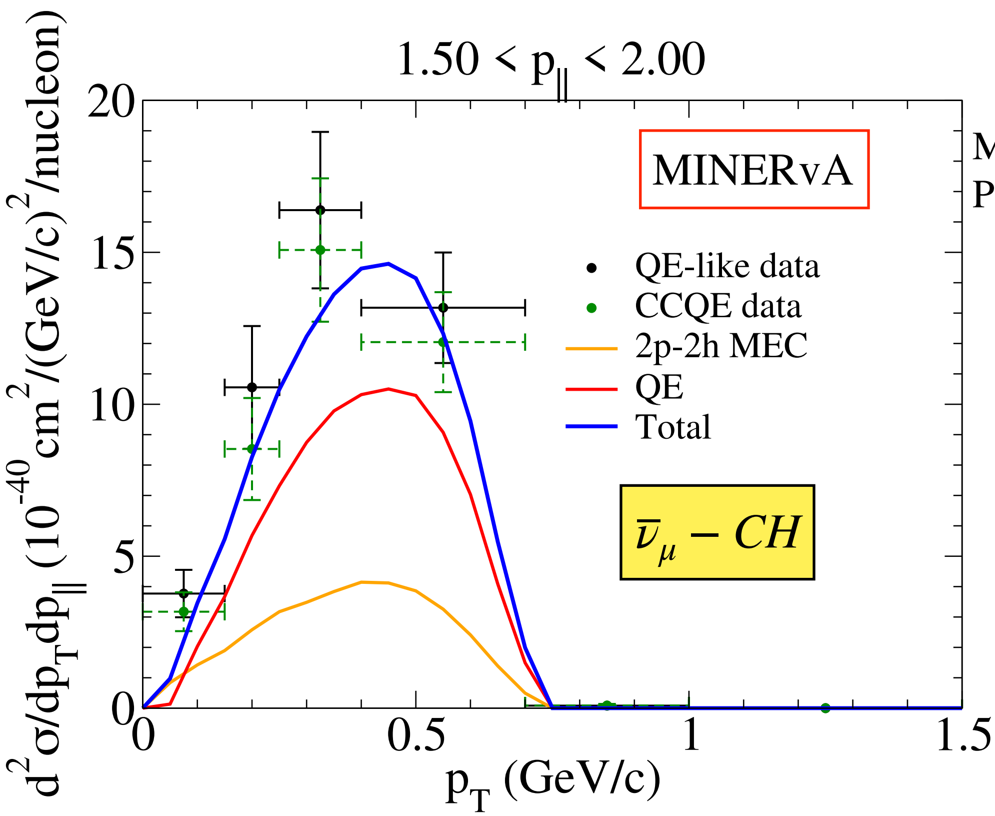
CC0π

Some more examples: neutrino and antineutrino cross sections, different experiments, kinematics and nuclei

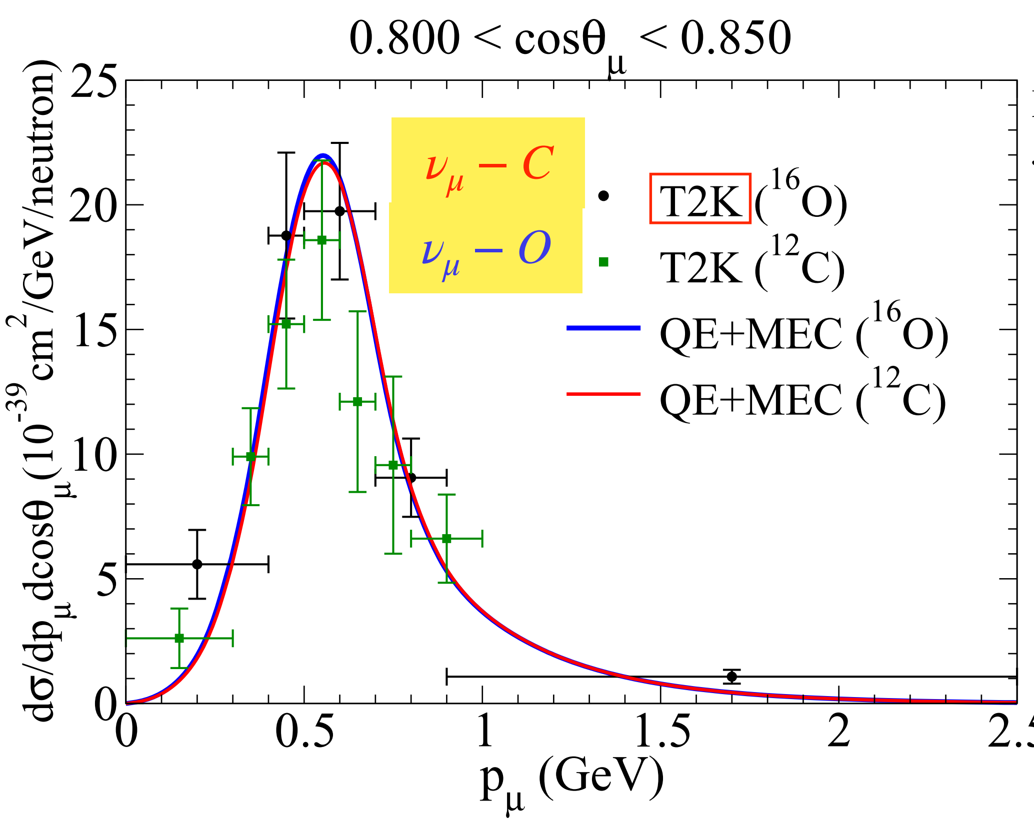
In general good agreement with data (but large error bars)



Megias *et al.*, PRD94 (2016)



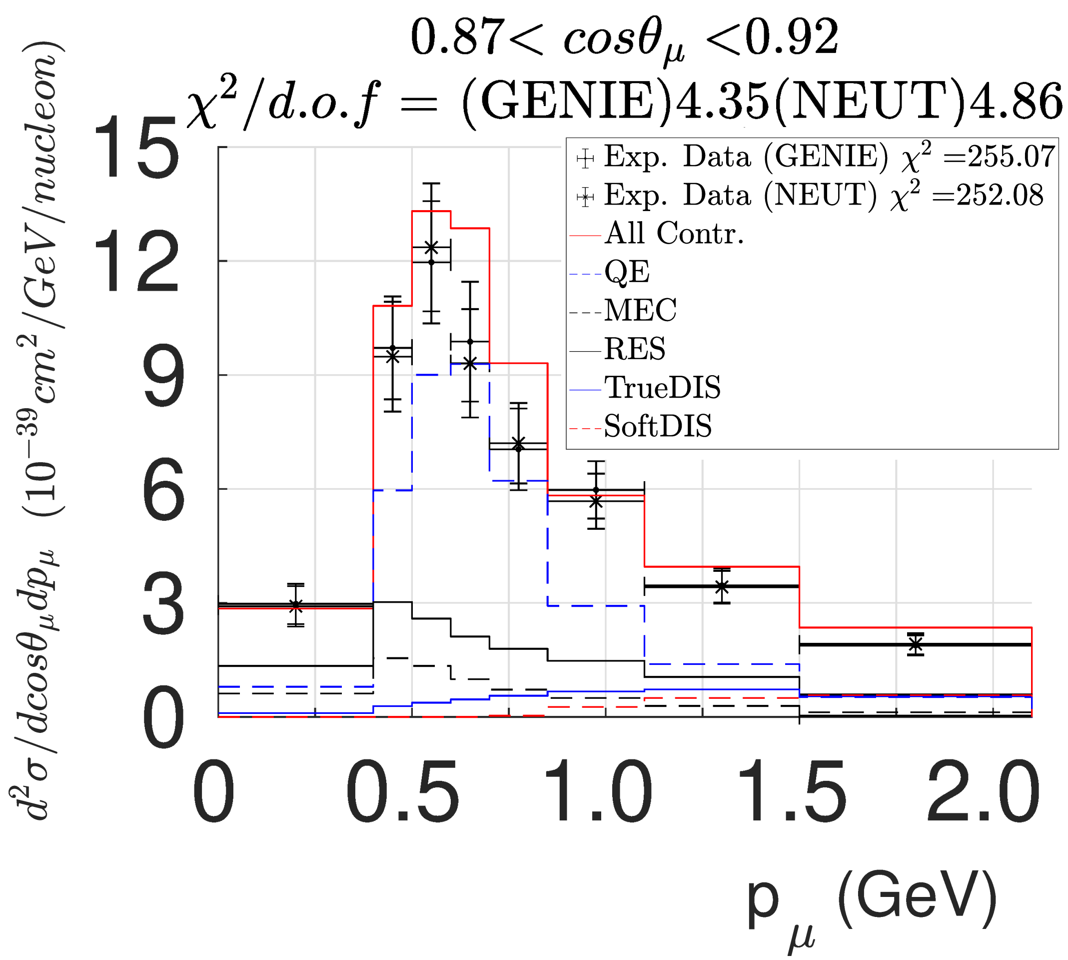
Megias *et al.*, PRD 99 (2019)



Megias *et al.*, JPG46 (2019)

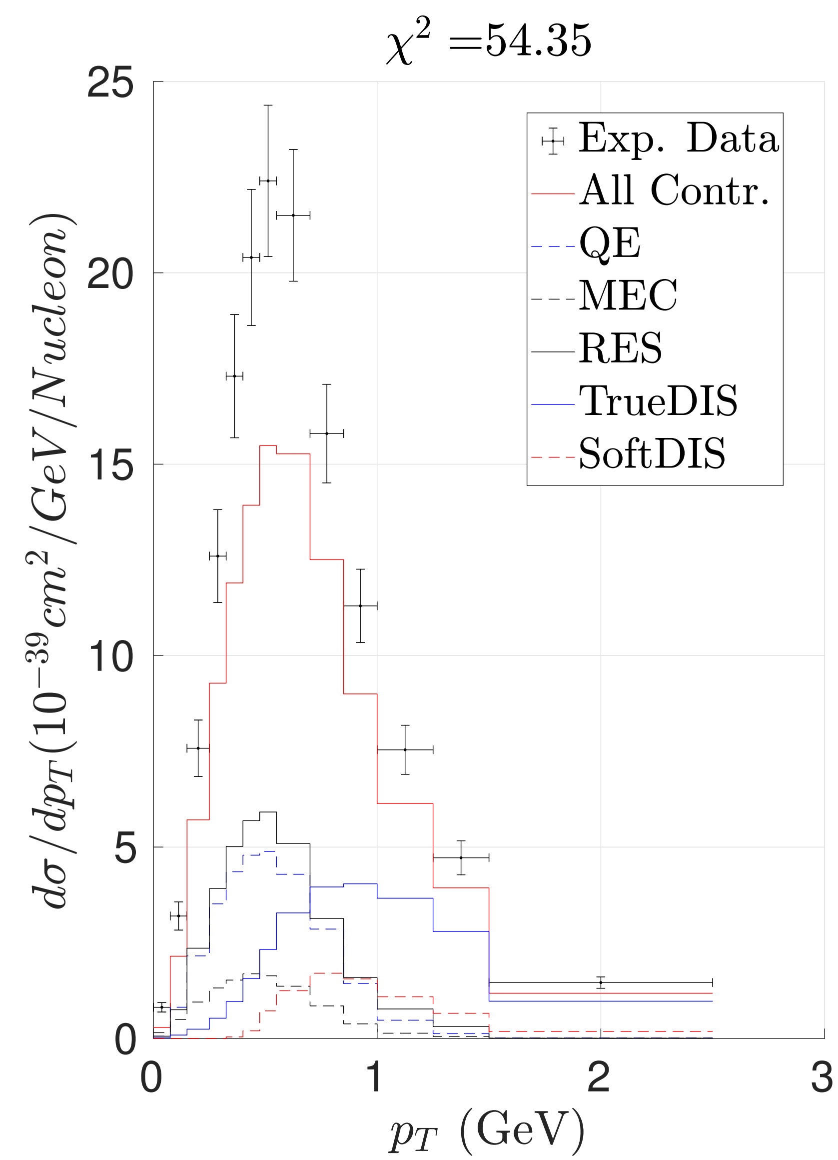
Inclusive neutrino scattering in the SuSAv2-DCC model

T2K E ~ 0.6 GeV



- Fair agreement with data
- QE dominates
- RES essential to reproduce the data
- DIS small contribution

MINERvA (ME) E ~ 6 GeV



- Data are underestimated
- All channels are comparable in size
- The discrepancy is likely due to poor description of the “SoftDIS” region

J. Gonzalez-Rosa et al., PRD 108 (2023)

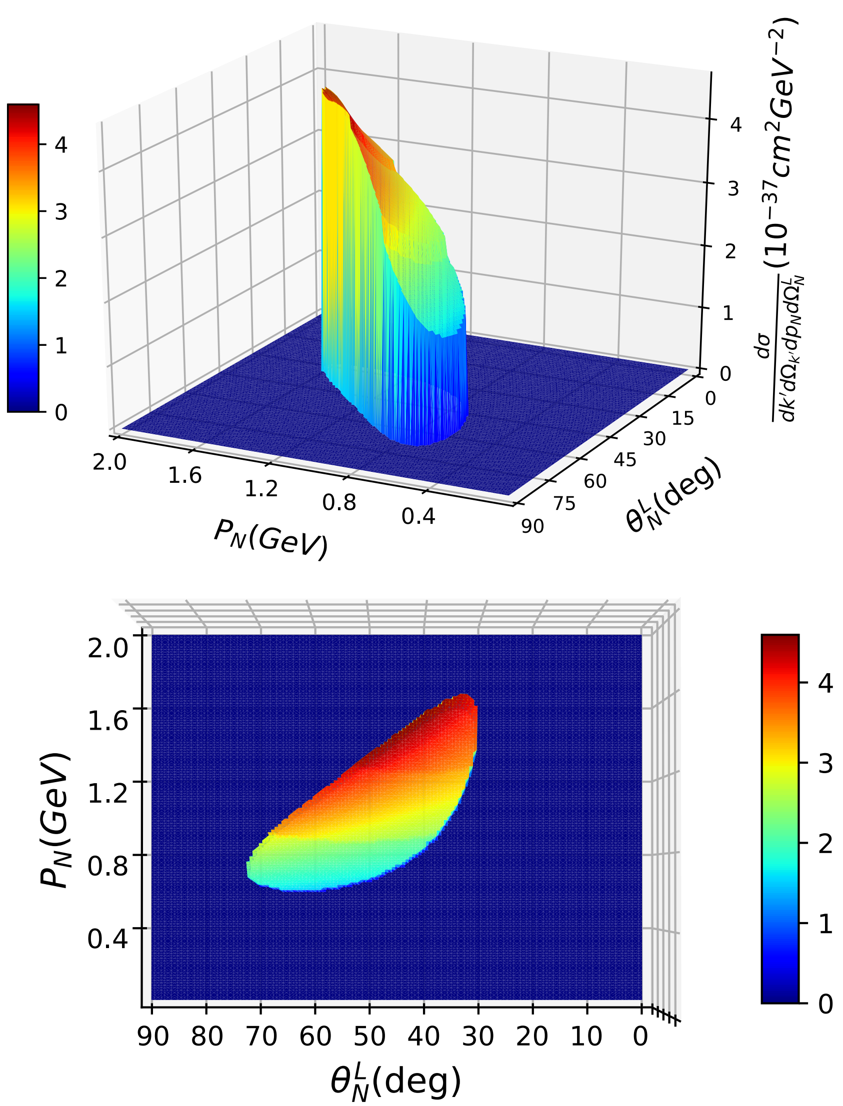
$^{40}Ar(\nu_\mu, \mu^- p)^{39}Cl$ DUNE flux $d^6\sigma$ six-differential $k' = 1.5\,\mathrm{GeV}, \theta_\mu = 30^0, \phi_N^L = \pi$

Relativistic Plane Wave Impulse Approximation (no FSI included)

Striking differences in the cross section due to initial state physics described by different spectral functions. The precise knowledge of the SF is crucial for a reliable modelling of semi-inclusive reactions.

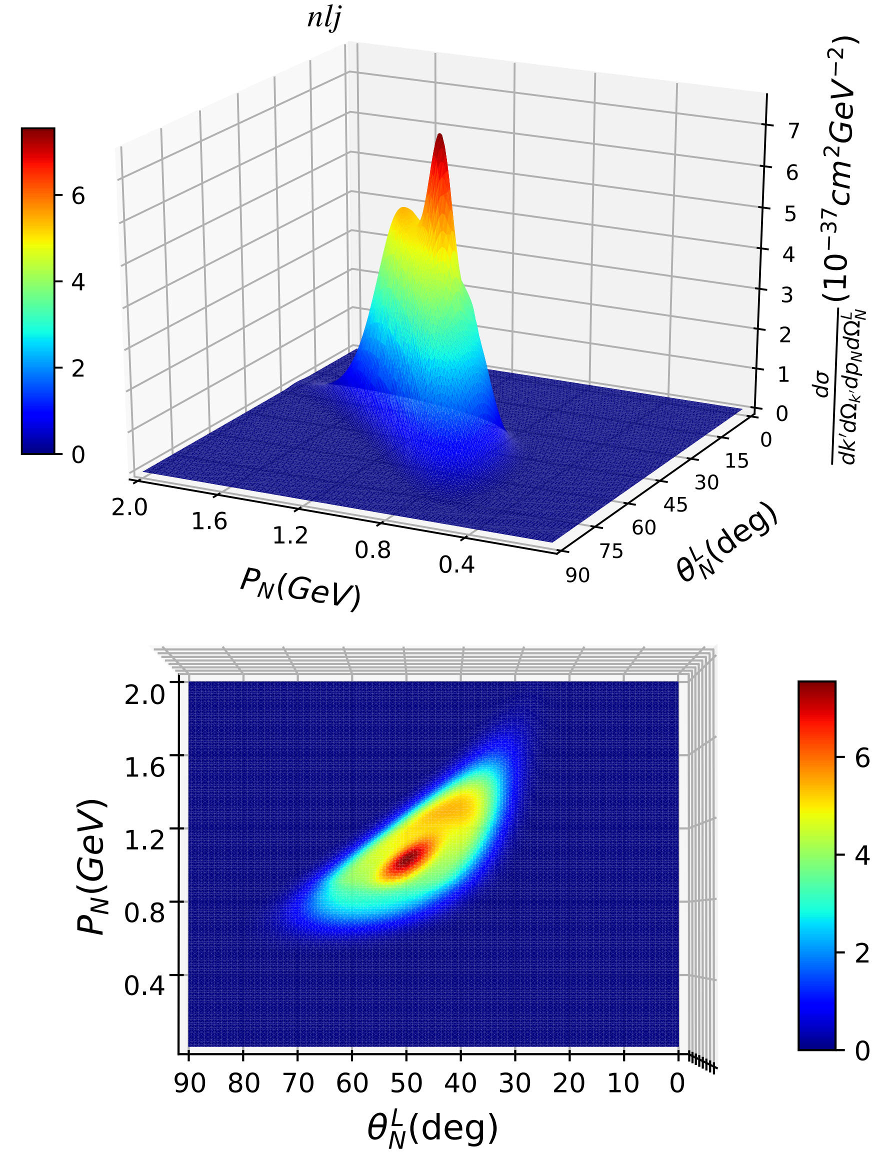
Relativistic Fermi Gas

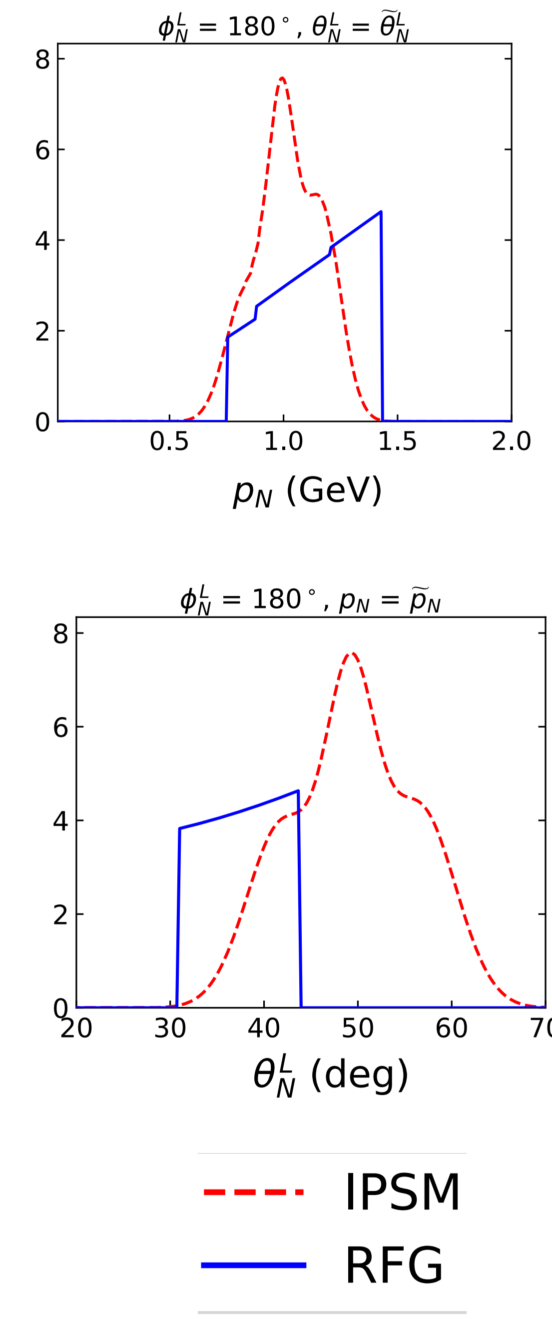
$$S_{\mathrm{RFG}}(p_m, E_m) = \theta(p_F - p_m)\,\delta\left(E_m - \sqrt{p_m^2 + m_N^2}\right)$$



Independent Particle Shell Model

$$S_{\mathrm{IPSM}}(p, E) = \sum_{nlj} (2j+1)\; n_{nlj}(p)\; \delta(E - E_{nlj})$$

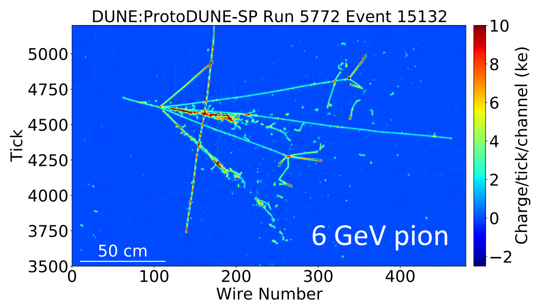




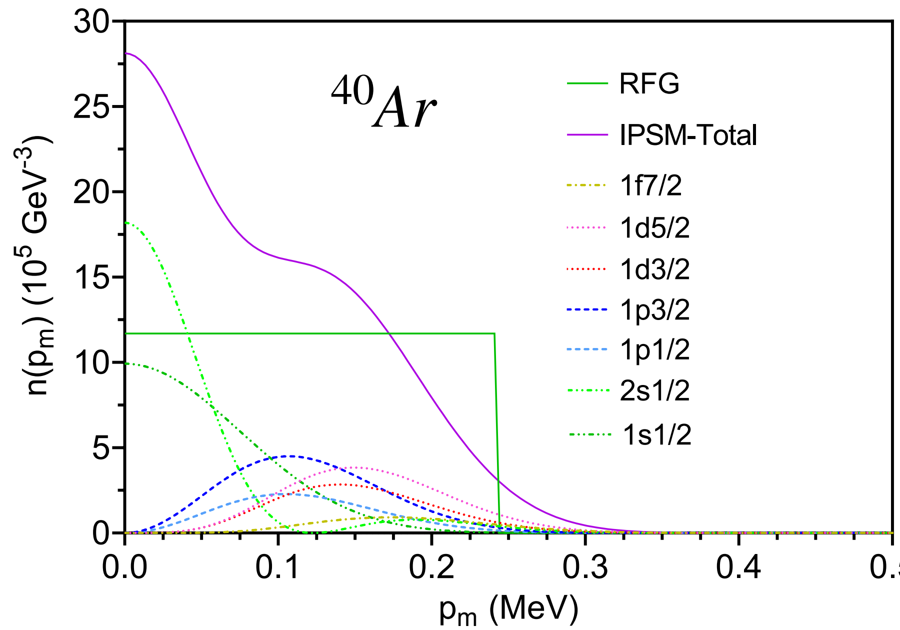
J.M. Franco-Patiño *et al.*, PRC 102, 064626 (2020)

Argon spectral function

^{40}Ar is the target in experiments using Liquid Argon Time Projection Chambers technique

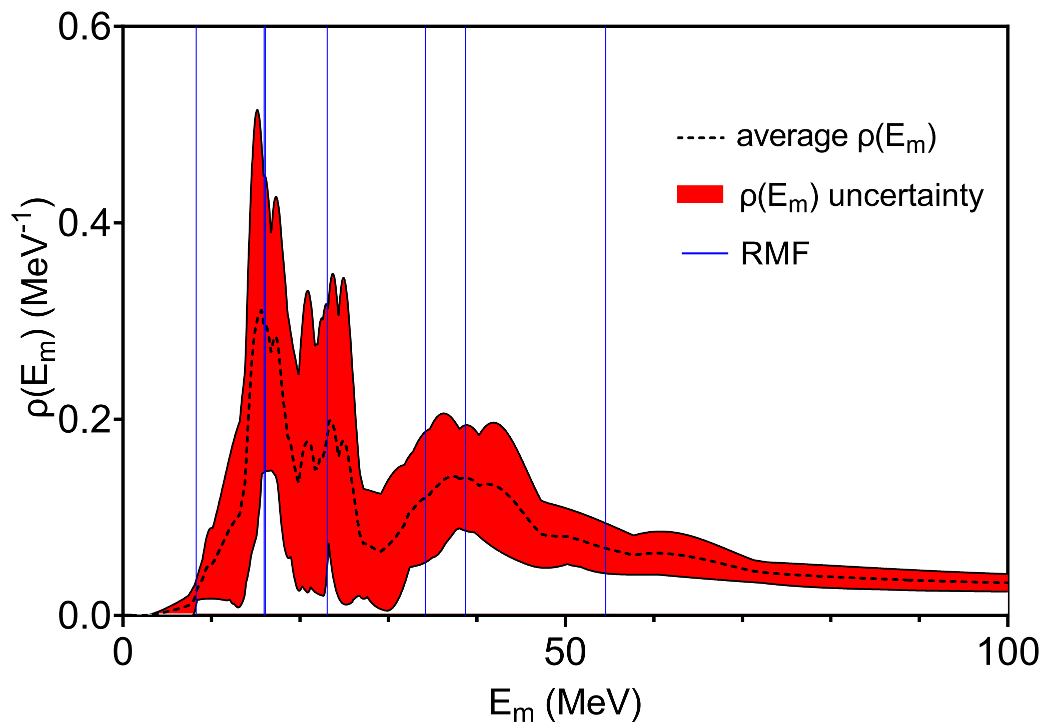


α	E_κ (MeV)	σ_κ (MeV)	S_κ
$1s_{1/2}$	55 ± 6	30 ± 15	0.9 ± 0.15
$1p_{3/2}$	39 ± 4	12 ± 6	0.9 ± 0.15
$1p_{1/2}$	34 ± 3	12 ± 6	0.9 ± 0.15
$1d_{5/2}$	23 ± 2	5 ± 3	0.75 ± 0.15
$2s_{1/2}$	16.1 ± 1.6	5 ± 3	0.75 ± 0.15
$1d_{3/2}$	16.0 ± 1.6	5 ± 3	0.75 ± 0.15
$1f_{7/2}$	9.869 ± 0.005	5 ± 3	0.75 ± 0.15



$$n(p_m) = \int_0^\infty dE_m \, S(p_m, E_m)$$

Missing energy distribution for the 22 neutrons of ^{40}Ar

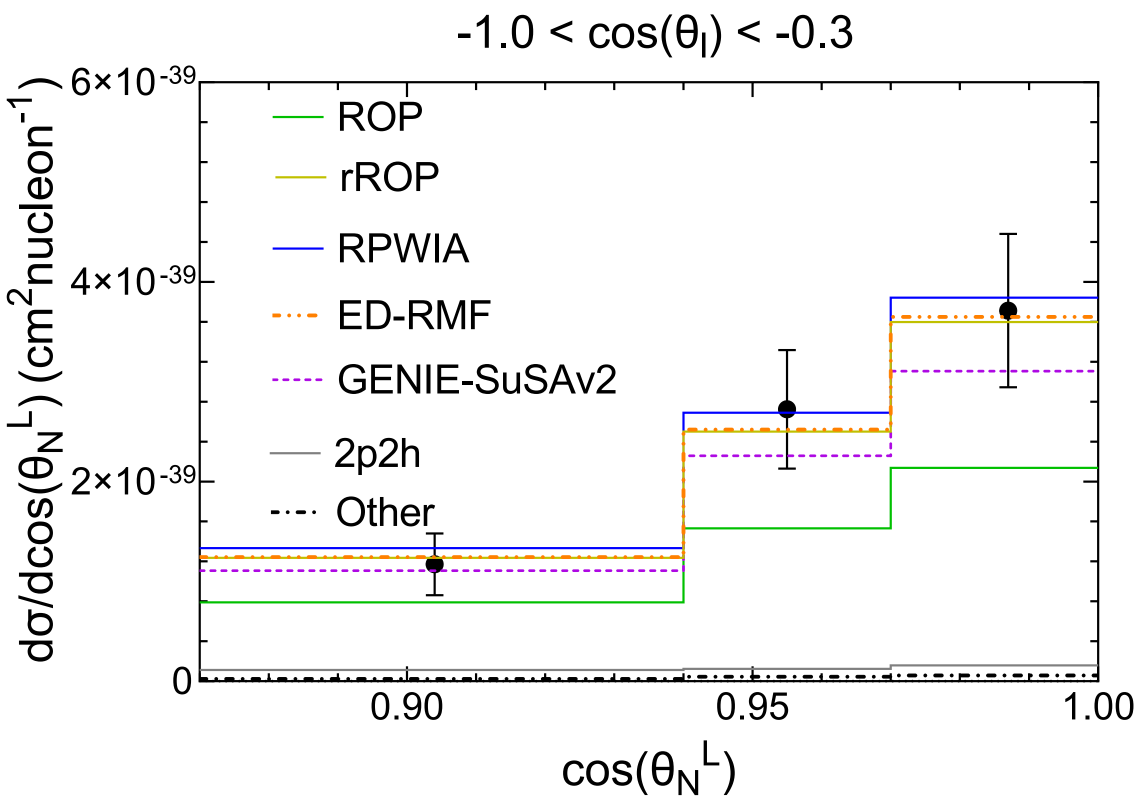


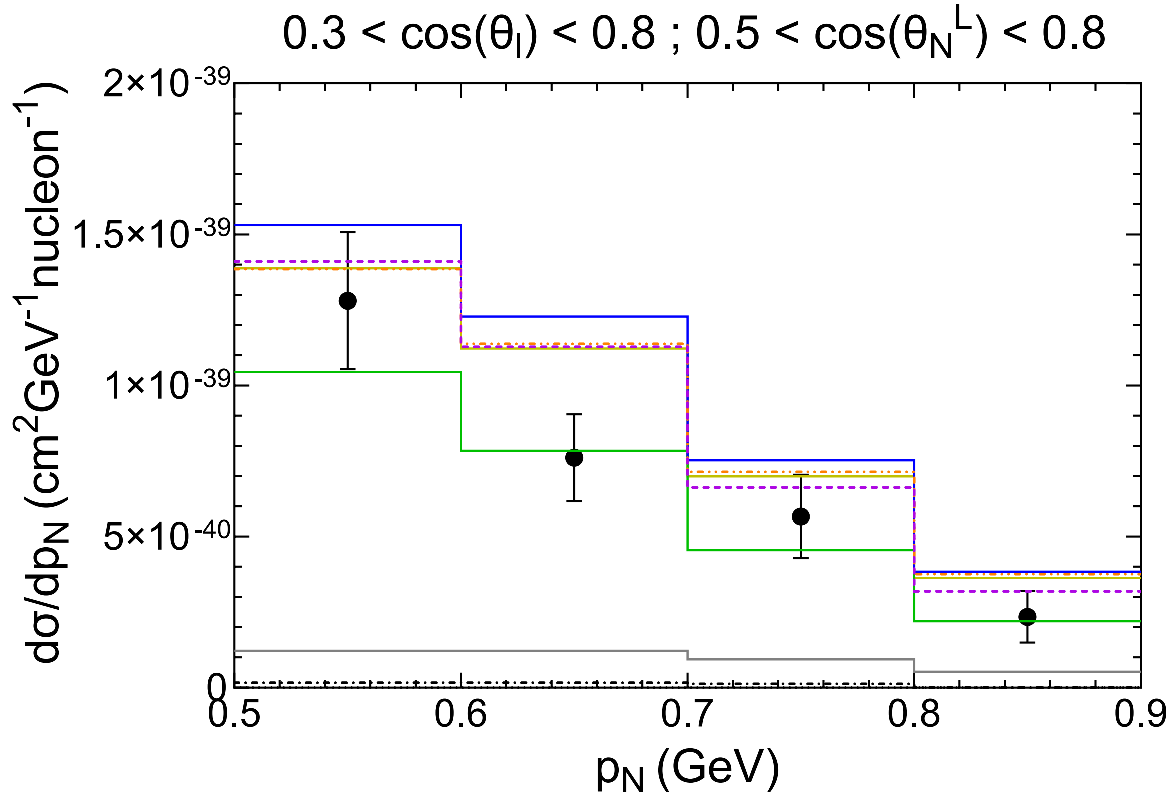
- positions E_k from **RMF calculation**
- widths σ_k from **JLab (e,e'p) experiment** on Ar [Jiang et al., PRD 105, 2022]
- spectroscopic factors S_k from phenomenology

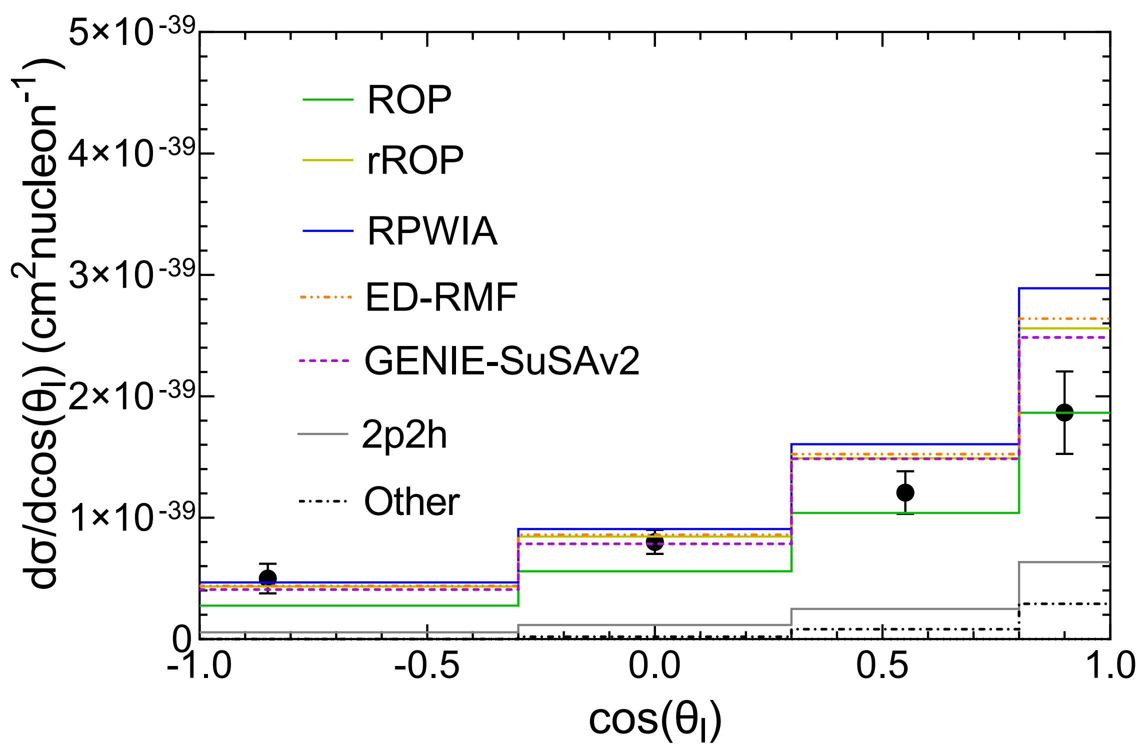
Conservative error bands are assigned to the SF parametrization, related to the extraction from (e,e'p) data

Comparison with T2K semi-inclusive data

$1\mu CC0\pi Np$ with at least one proton in the final state with momentum above 0.5 GeV







J.M. Franco-Patino, PRD 106 (2022)

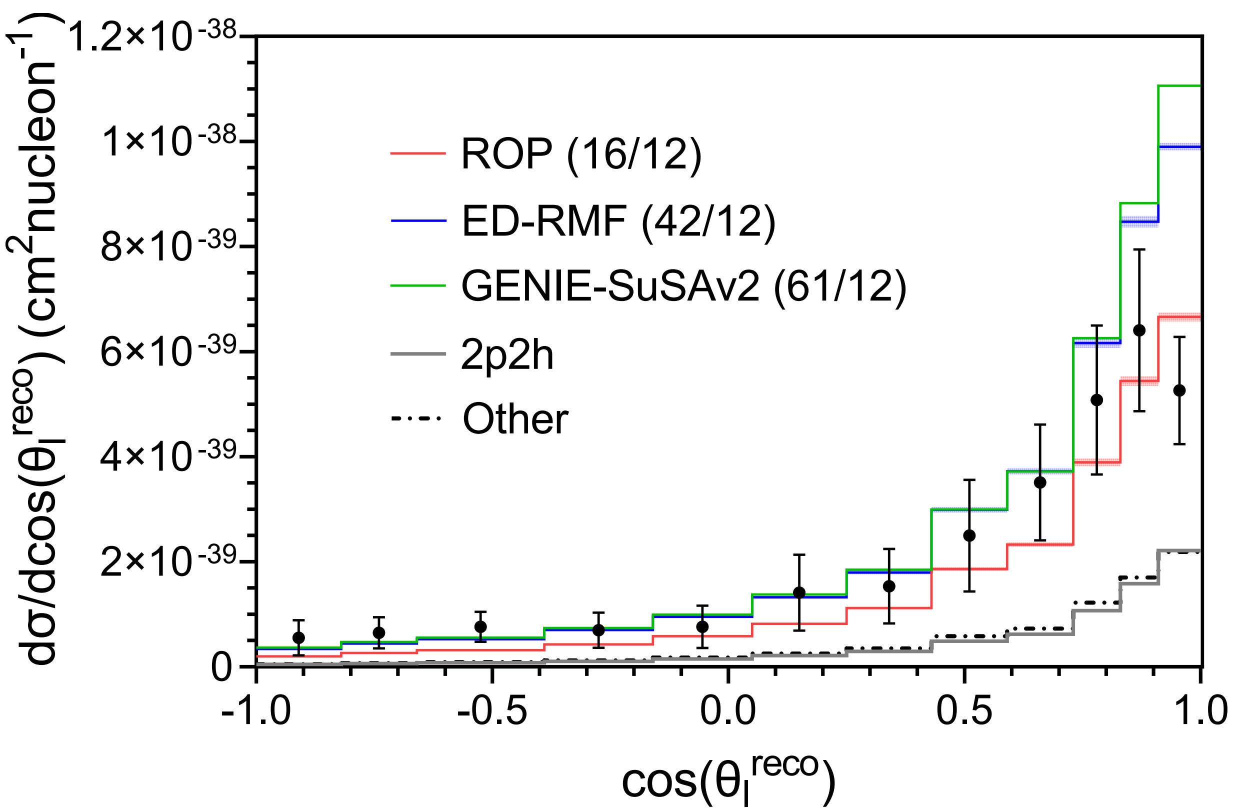
No clear trend emerges from the model/data comparison at different lepton and proton kinematics

All curves include 2p2h and “Other” (pion emission followed by re-absorption) from GENIE simulation.

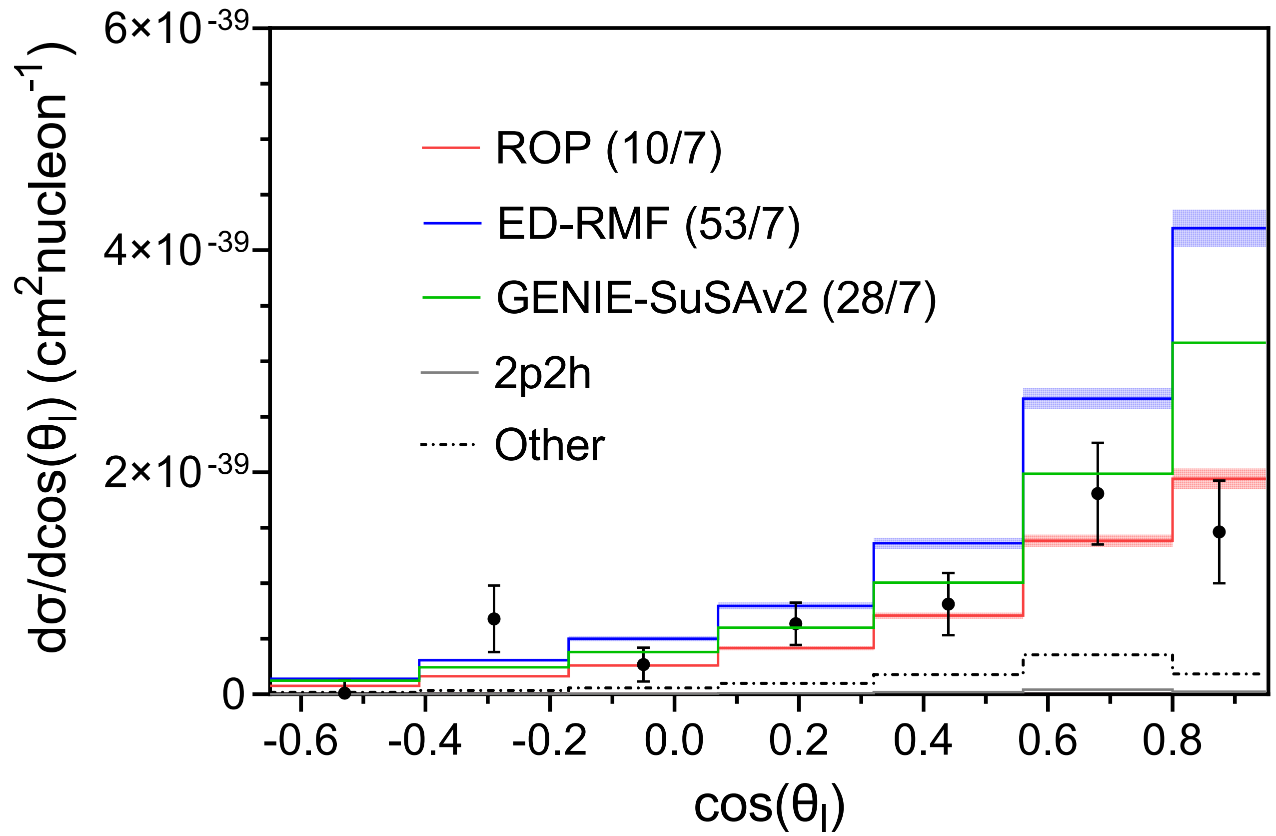
Microscopic calculations for these processes are needed!

MicroBooNE

1μCC0πNp "at least one proton"



1μCC0π1p "one and only one proton"



J.M. Franco-Patino, PRD 109 (2024)

No clear trend emerges from the model/data comparison at different lepton and proton kinematics

- ROP model is the closest to data
- 2p2h give sizeable contribution and are evaluated using GENIE simulation, based on inclusive SuSAv2-MEC model
- Microscopic calculations for exclusive 2p2h are much needed!

- ROP model is the closest to data
- 2p2h are negligible in the "only one proton" data

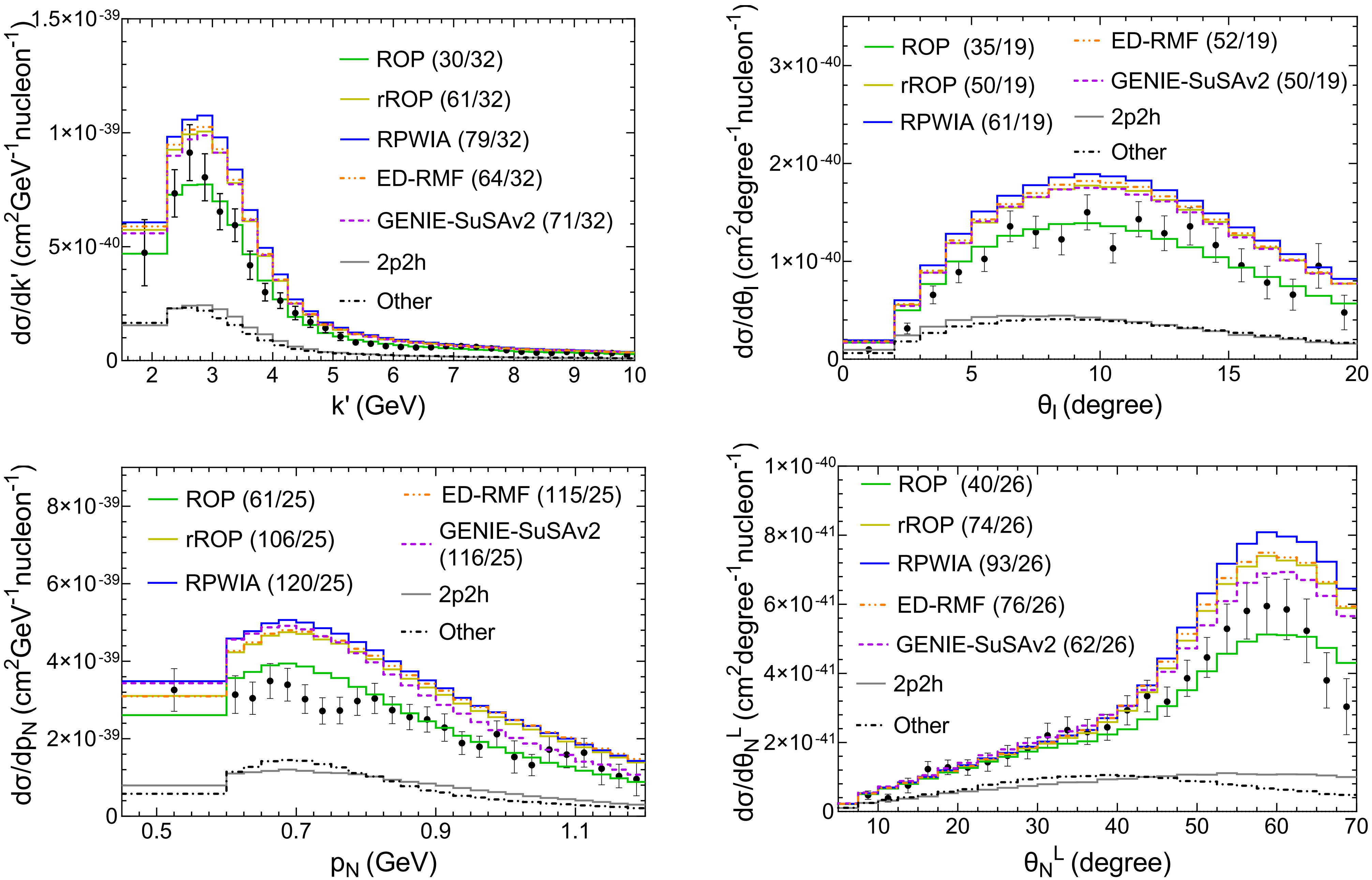
MINERvA

$1\mu CC0\pi Np$ with at least one proton in the final state

Natural lepton and proton variables

kinematic restrictions

MINERνA	k' (GeV)	$\cos\theta_l$	p_N (GeV)	$\cos\theta_N^L$	ϕ_N^L (°)
	1.5-10	> 0.939	0.45-1.2	> 0.342	-



- ROP is favoured by data
- 2p2h provide ~30% of the strength at MINERvA kinematics (E ~ 3 GeV)

Transverse Kinematic Imbalance (TKI)

Data are often represented in terms of new variables devised to enhance sensitivity to nuclear effects

Lu et al., PRC94, 015503 (2016)

$$\delta p_T = |\delta \mathbf{p_T}| = |\mathbf{k'_T} + \mathbf{p_{N,T}}| \ ,$$

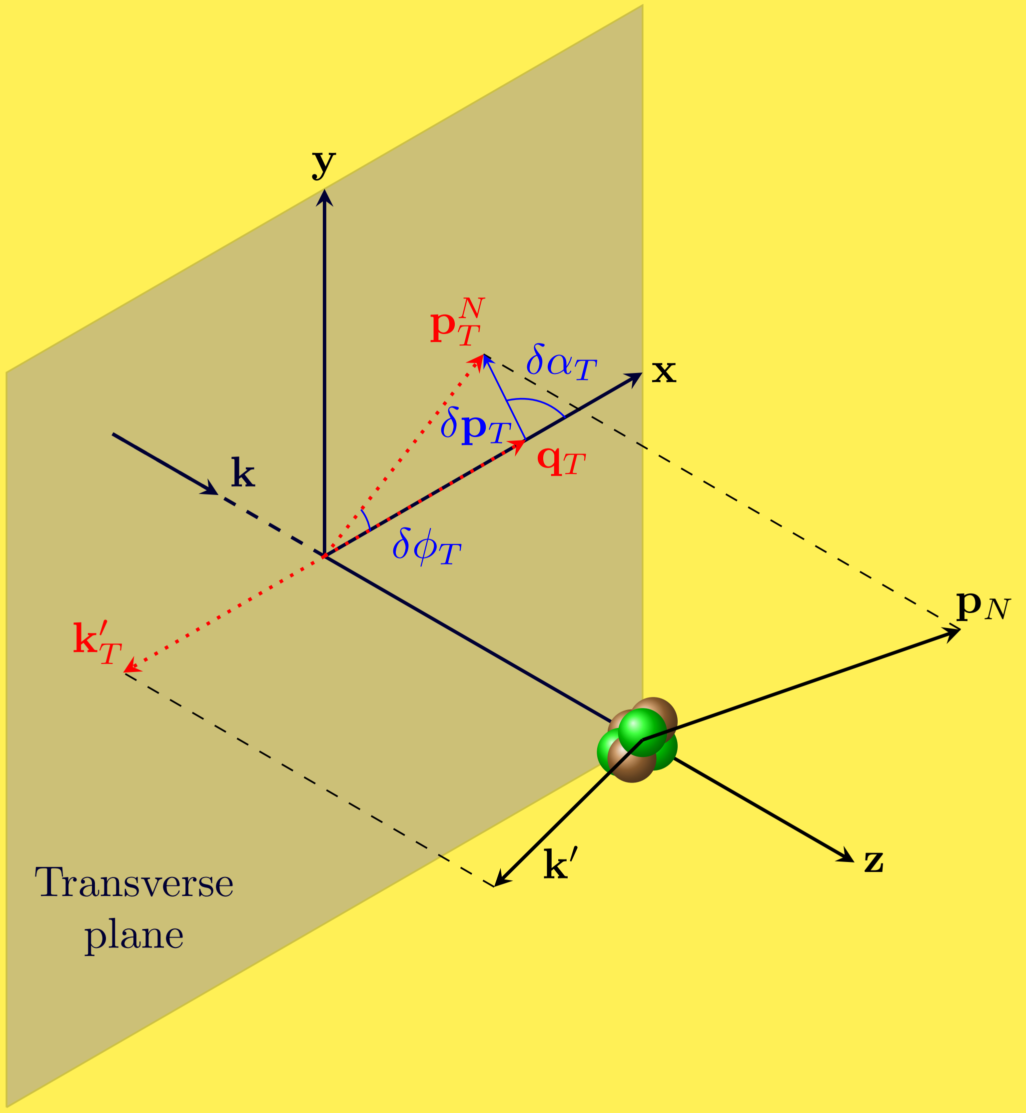
$$\delta\alpha_T = \arccos\left(-\frac{\mathbf{k'_T}\cdot\delta\mathbf{p_T}}{|\mathbf{k'_T}|\ |\delta\mathbf{p_T}|}\right) \ ,$$

$$\delta\phi_T = \arccos\left(-\frac{\mathbf{k'_T}\cdot\mathbf{p_{N,T}}}{|\mathbf{k'_T}|\ |\mathbf{p_{N,T}}|}\right) \ ,$$

On a free nucleon at rest $\mathbf{k'_T} = -\,\mathbf{p_{N,T}}$

$\delta p_T = \delta\phi_T = 0$ —> peaked distribution

$\delta\alpha_T$ undefined —> flat distribution



Deviations from these behaviours "measure" nuclear effects with minimum dependence upon the neutrino energy:

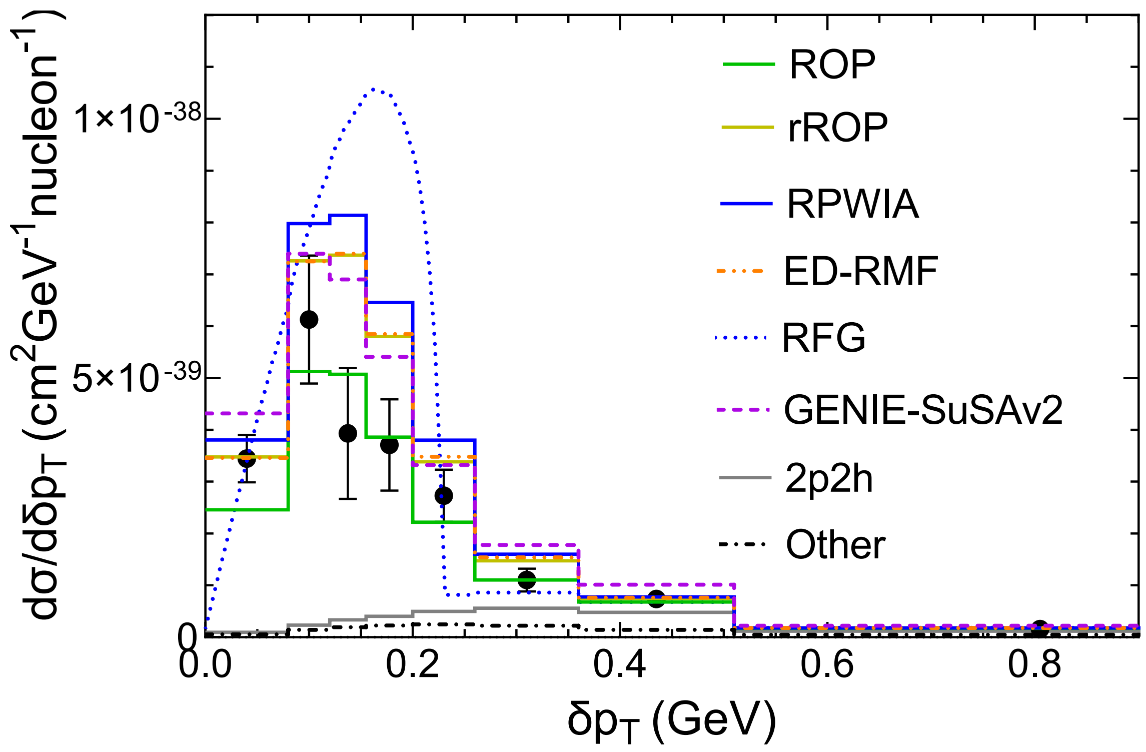
δp_T distribution is related to the nucleon momentum distribution

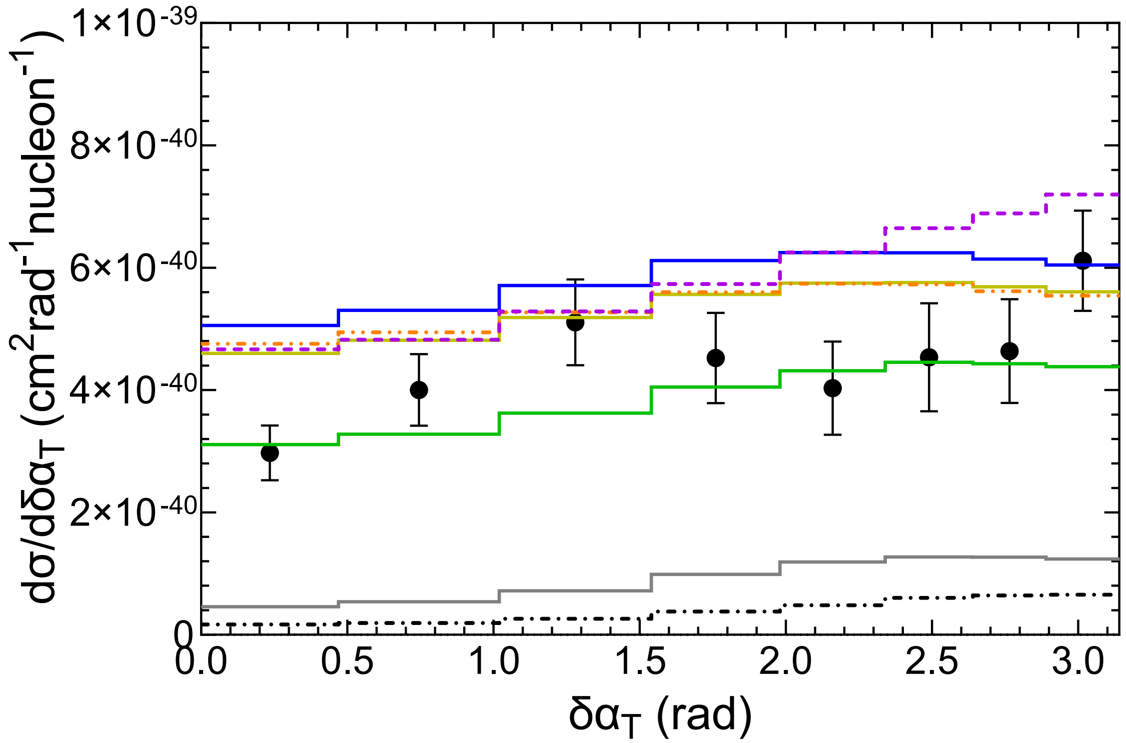
$\delta\alpha_T$ sensitive to non-QE effects (2p2h) and FSI

T2K

TKI distributions

$1\mu CC0\pi Np$ $p_N > 500$ MeV





- In the absence of FSI, the δp_T distribution is related to the nucleon momentum distribution: the RFG is clearly ruled out
- The role of FSI is sizeable, especially in the ROP approach
- 2p2h mainly affect the high momentum tail

- ROP describes better the data versus $\delta\alpha_T$
- The departure from flat distribution is determined by the 2p2h contribution
- No model is able to reproduce the oscillatory behaviour of data

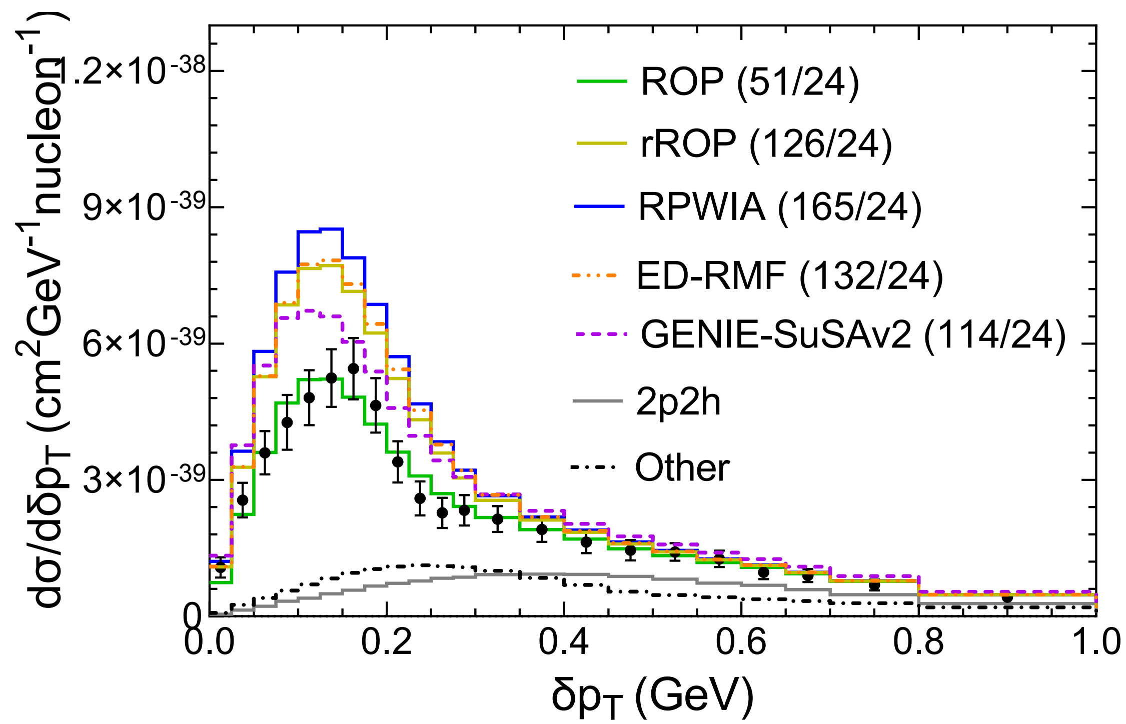
MINERvA

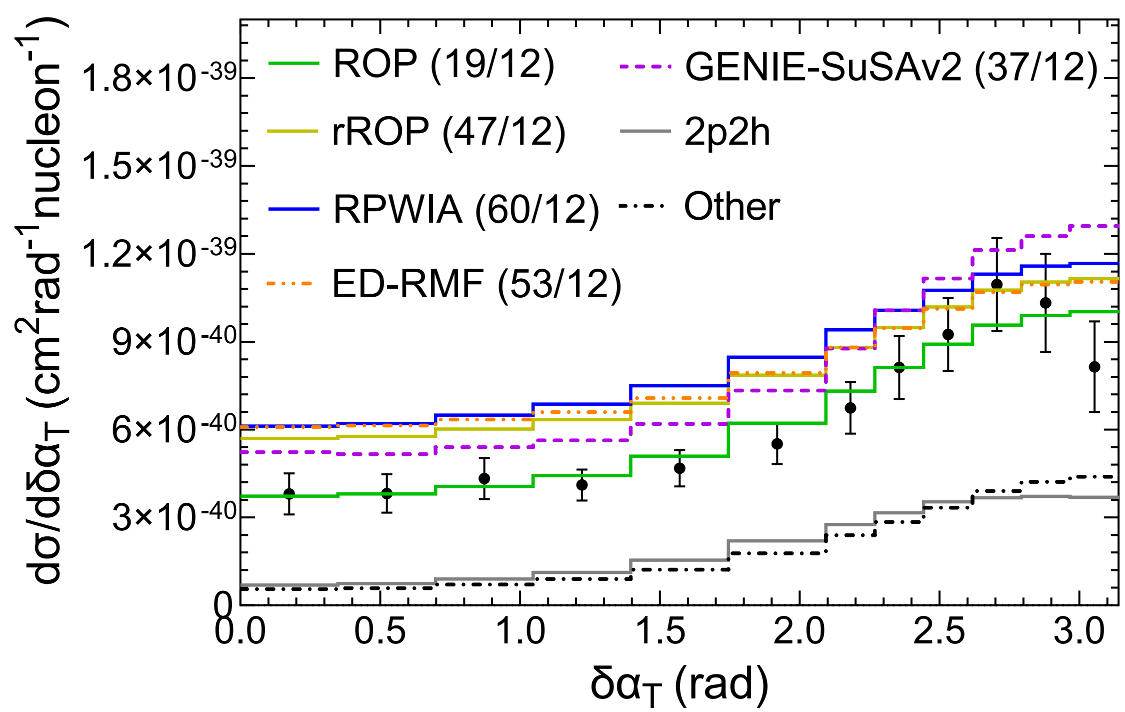
1μCC0πNp with at least one proton in the final state

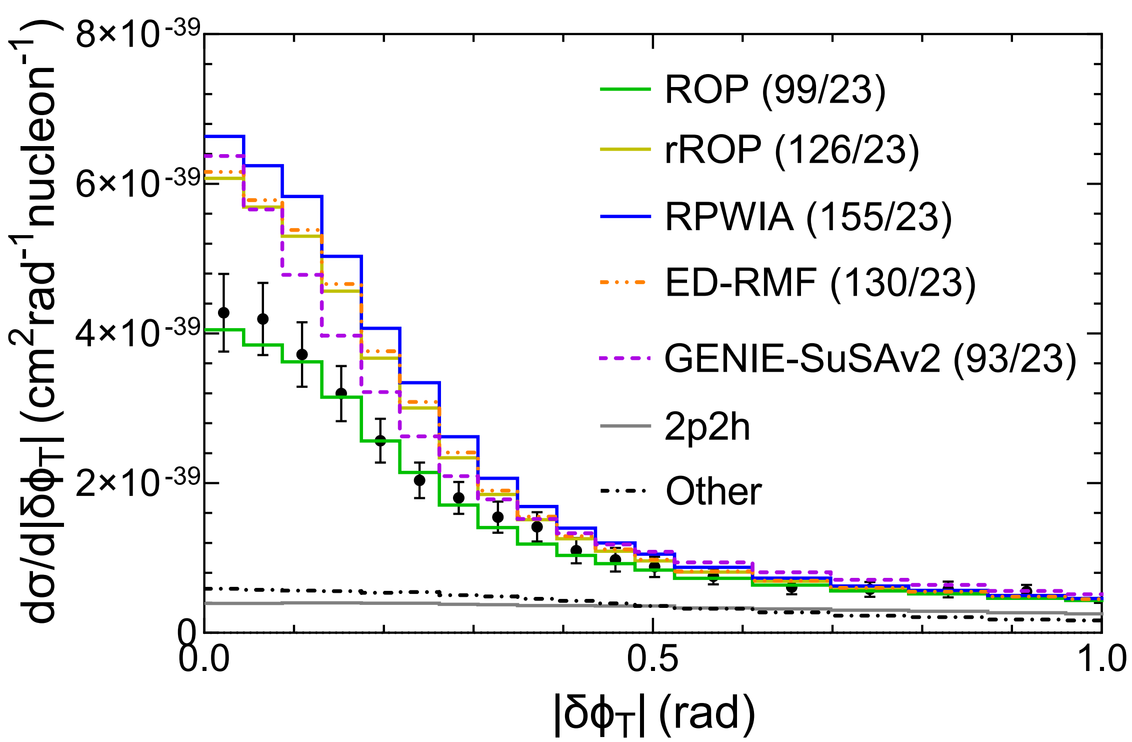
TKI variables

kinematic restrictions

MINERνA	k' (GeV)	$\cos\theta_l$	p_N (GeV)	$\cos\theta_N^L$	ϕ_N^L (°)
	1.5-10	> 0.939	0.45-1.2	> 0.342	-

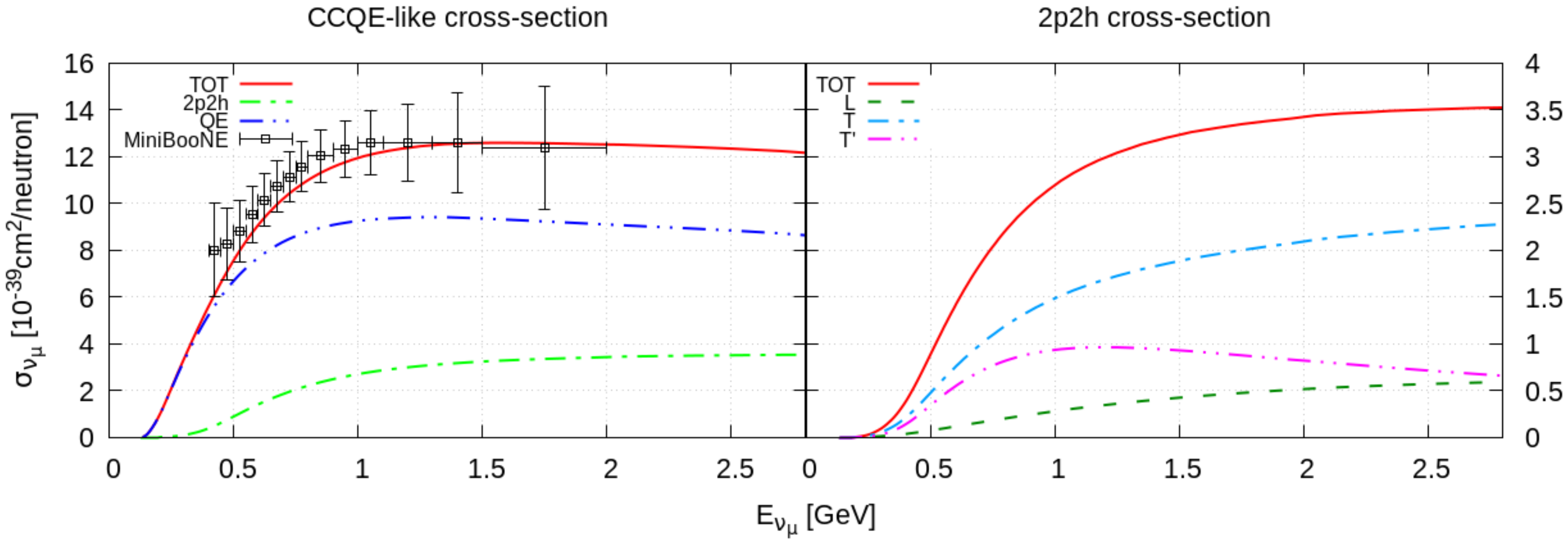




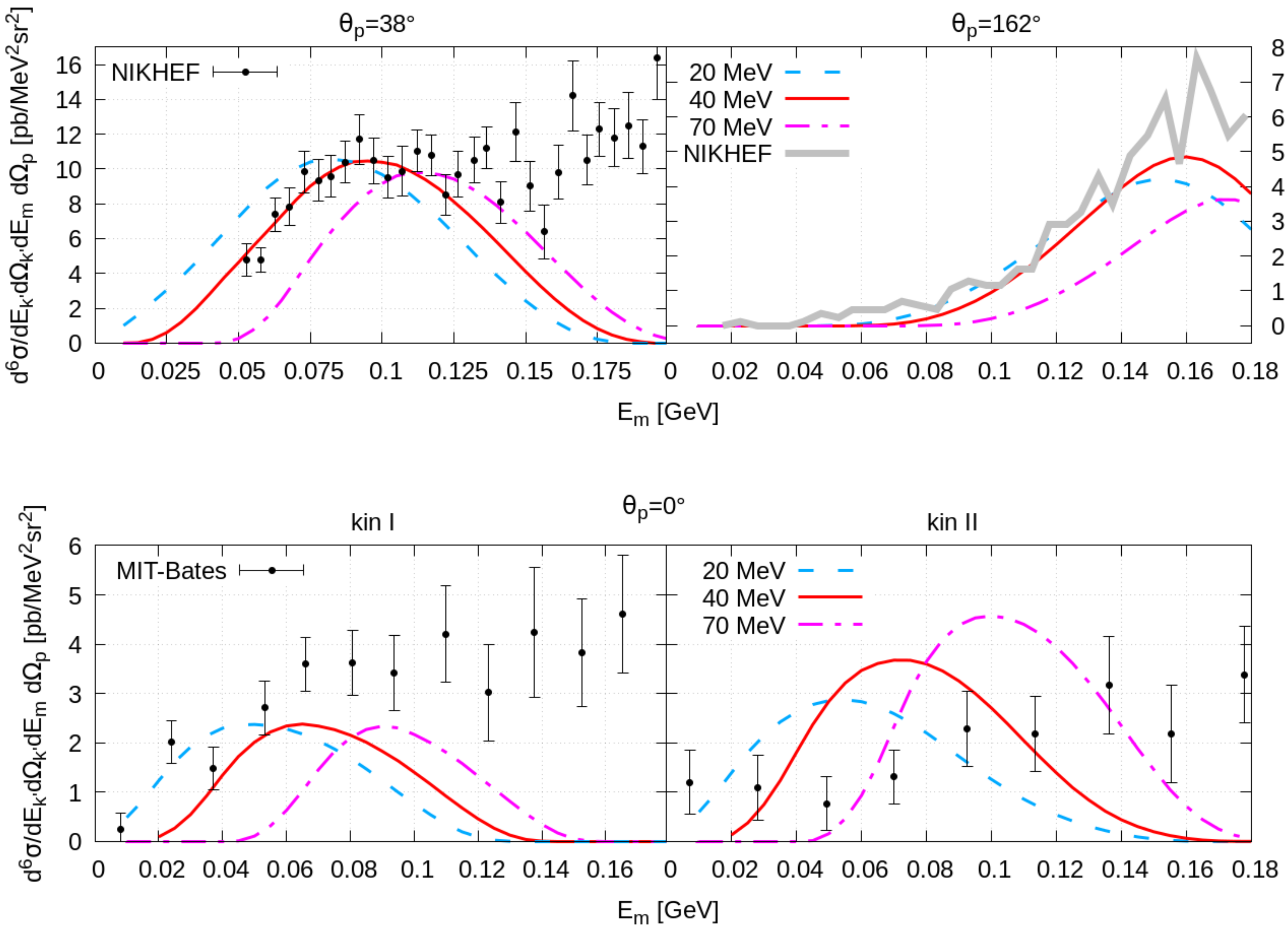


- ROP is favoured by data
- 2p2h provide ~30% of the strength at MINERvA kinematics (E ~ 3 GeV)

MEC in total neutrino cross section: L,T, T' channel separation



Dependence on the energy shift

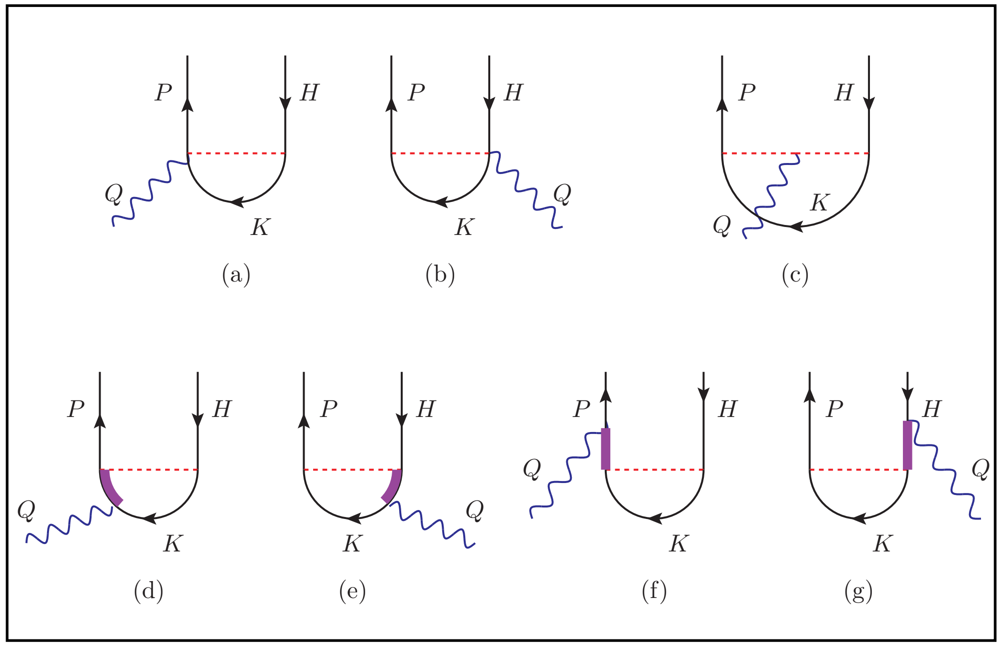


MEC in the 1p1h channel

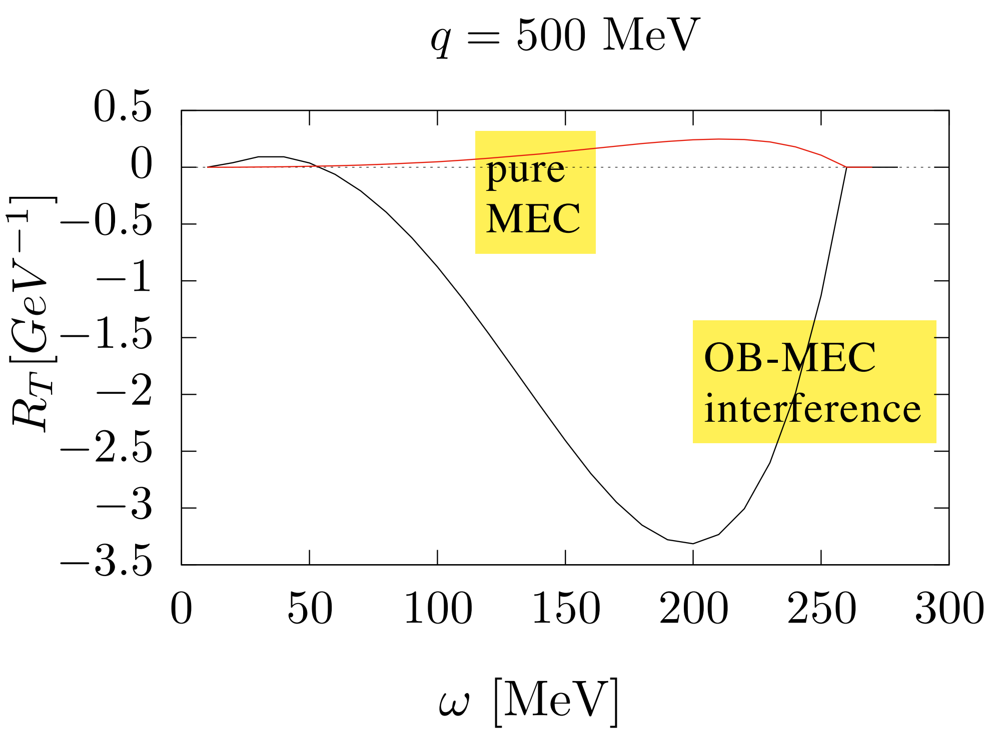
Two-body currents can also excite 1p1h states

$$W^{\mu\nu}_{1p1h} \sim \sum_{ph} < ph|\hat{J}^\mu|A >^* < ph|\hat{J}^\nu|A >$$

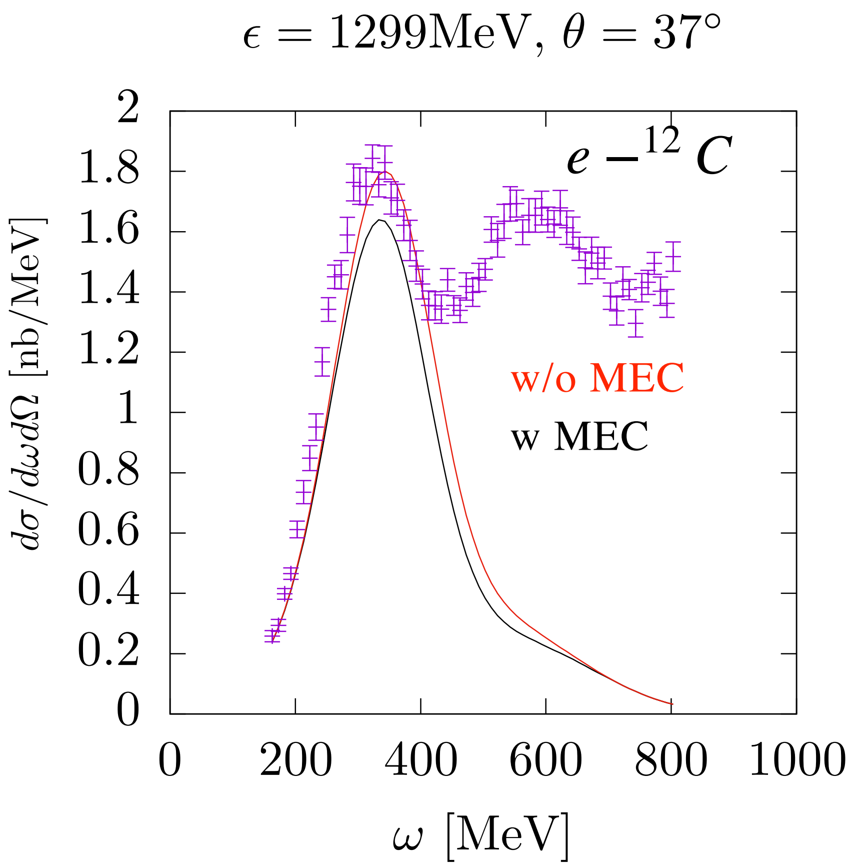
$$\hat{J}^\mu = \hat{J}^\mu_{1b} + \hat{J}^\mu_{2b} \rightarrow W^{\mu\nu}_{1p1h} = W^{\mu\nu}_{OB} + W^{\mu\nu}_{MEC} + W^{\mu\nu}_{OB-MEC}$$



The negative interference dominates



1p1h MEC can be incorporated in the SuSA formalism



P. Casale, J.E. Amaro, MBB, Symmetry 15 (2023)