Neutrino-nucleus scattering in the SuSAv2 model including Meson Exchange Currents

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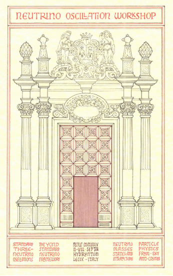
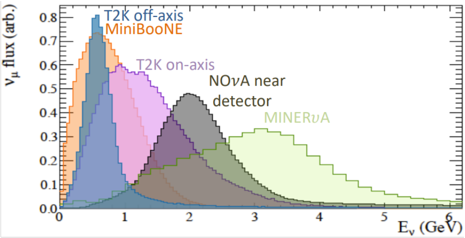


Neutrino physics

Neutrinos:

- Light fermions that interact through Weak interaction only $\Rightarrow$ Very low signals, heavy target needed: nuclei!
- Flavour Oscillation: mass eigenstate $\neq$ flavour eigenstate

Neutrino experiments want to study the properties of this particle, and extract information on the **Oscillation Matrix**, especially on the **CP violating phase**.



Incident neutrino fluxes distribution for several experiments

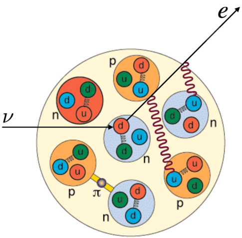
Experiments measure the number of events. In a neutrino oscillation experiment:

$$N_{\nu_\beta}(\overline{E_\nu}) \sim \int dE_\nu \Phi_{\nu_\alpha}(E_\nu) P_{\nu_\alpha \to \nu_\beta}(E_\nu) \sigma(E_\nu) \epsilon_{det} d(E_\nu, \overline{E_\nu})$$

Reconstructed energy $\overline{E_\nu} \Leftrightarrow E_\nu$ True neutrino energy

The nucleus is a very rich and complex target, composed by

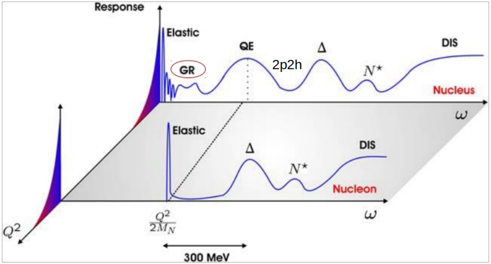
- Nucleons: not elementary particles
- Mesons: mediators of nuclear interaction



Lepton-Nucleus interaction: several processes

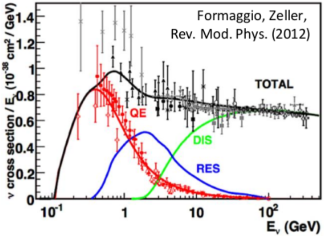
Nuclear Effects:
Free Nucleon → Nucleus

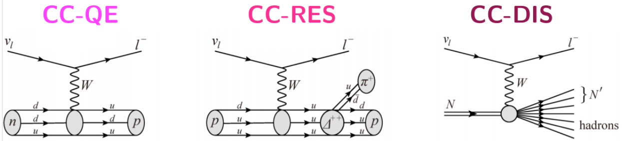
- Broadening of QE, Fermi motion → Initial hadronic state from nuclear model
- Pauli Blocking PB, Final State Interactions FSI
- Multinucleon excitations: **2p2h**



Channels Overlap

At a given E_ν, several channels are active





It is very difficult to reconstruct the interaction vertex:

- We don't know the initial hadronic state → **nuclear model**
- Incident flux wide in energy: we don't know the initial E_ν
- Outgoing hadron particles are affected by **final state interactions**

SuperScaling Approach SuSA

Suited for the QE channel, encompasses nuclear effects through the **scaling function** $f(\psi)$, extracted by **inclusive** (final lepton detected only) electron scattering data
$\Rightarrow$ **phenomelogical model**

- Inclusive electron-nucleus scattering cross section:

$$\frac{d^2\sigma}{dE_{k'}d\Omega_{k'}} = \sigma_{Mott}[V_L R_L + V_T R_T]$$

- **Nuclear responses R_i are combinations of the nuclear hadronic tensor components**
- V_i terms are connected to the leptonic tensor

- From $e - A$ scattering data:

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

$$\Downarrow$$

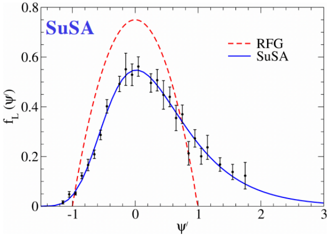
$$f(q,\omega;k_F) \Rightarrow f(\psi) \qquad \psi \equiv \psi(q,\omega;k_F)$$

- Pauli suppression: Rosenfelder method

$$f(\psi) = f(\psi(\omega,\mathbf{q})) - f(\psi(-\omega,\mathbf{q}))$$

- $E_{shift} = 20$ MeV

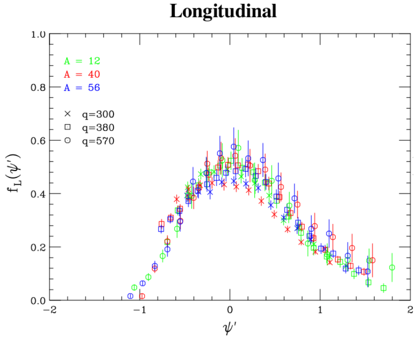
Day et al., Ann.Rev.Nucl.Part.Sci.40 (1990); Donnelly and Sick, PRL82; PRC60 (1999)

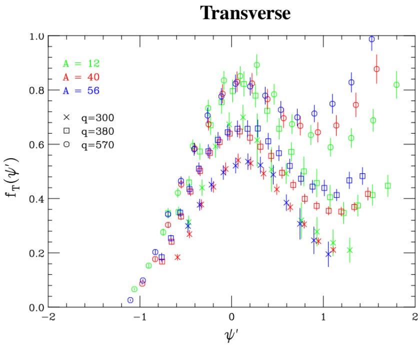


Exact and analytical results for RFG

$$f_L(\psi) = k_F \frac{R_L(q,\omega)}{G_L^{e,e'}(q,\omega)} \qquad f_T(\psi) = k_F \frac{R_T(q,\omega)}{G_T^{e,e'}(q,\omega)}$$

SuSA assumption: $f_L = f_T$, *Donnelly et al. PRC 60 (1999)*





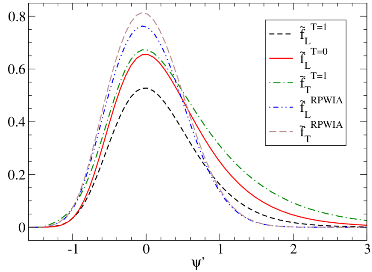
Scaling violation in f_T due to non-QE contributions and to **finite nucleus effects**

$\Rightarrow$ Microscopical nuclear description: **SuSAv2**

SuSAv2 and RMF

SuSAv2 is based on the Relativistic Mean Field RMF, but it follows the procedure of SuSA for the scaling behaviour

- Finite nucleus with scalar (attractive) and vector (repulsive) relativistic central potentials $\rightarrow \quad (i\partial\!\!\!/ - M - S(x) + V(x))\psi(x) = 0$
- Channel-dependent scaling functions $\rightarrow \quad f_T > f_L$ (relativistic effect, anti-particles) different isovector and isoscalar contributions $\rightarrow$ Important for neutrino scattering!



R. González-Jiménez et al, Phys. Rev. C88, 025502 (2013)

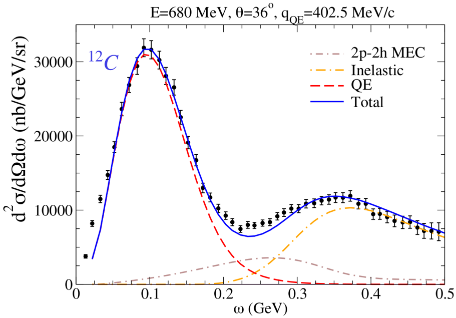
- Pauli blocking through use of orthogonal set of Hamiltonian eigenfunctions
- FSI too strong at high q values due to energy-independent potentials:
  - blended with Relativistic Plane Wave Impulse Approximation RPWIA $\leftarrow$ SuSAv2
  - Energy-Dependent potentials

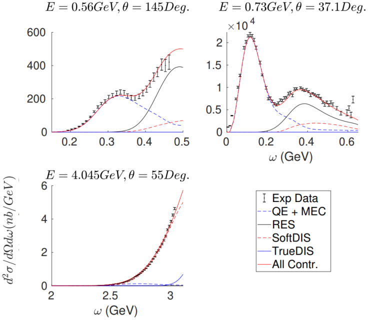
SuSAv2: some results

SuSAv2 describes inclusive QE, but it is possible to extend it to the full spectrum

- 2p2h through MEC formalism (see later)
- Resonances, defining a **generalized scaling variable** for each invariant mass
- Deep inelastic scattering, folding the elementary inelastic response with the SuSA scaling function *Barbaro et al., PRC69 (2004), Gonzalez-Rosa et al., PRD108 (2023)*

Model validation and fitting: **Electron Scattering**



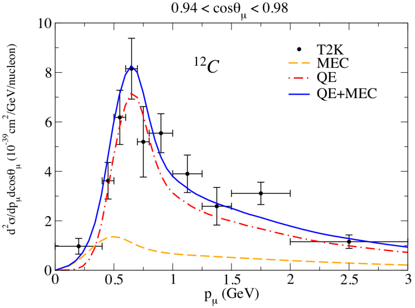


Megias et al., PRD94 (2016), Gonzalez-Rosa et al., PRD108 (2023) Data: *Barreau, NPA402 (1983)*

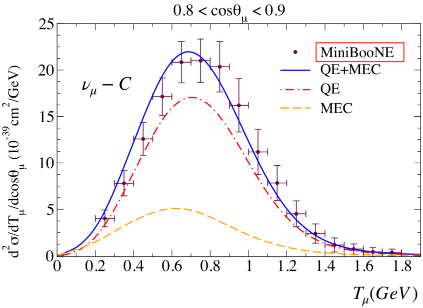
Scaling functions for the Electro-Weak interaction are the same extracted from electron-scattering:

- From **2 EM- to 5 EW-non vanishing inclusive responses**
- $f_T^{VV} = f_T^{AA} = f_{T'}^{VA} = \tilde{f}_T \qquad f_L^{VV} = \tilde{f}_L^{T=1}$
- Assumptions: $f_T^{T=0\,EM} = f_{CC,CL,LL}^{AA} = \tilde{f}_L^{T=1}$

$\nu_\mu - {}^{12}C$ inclusive scattering data CC0π

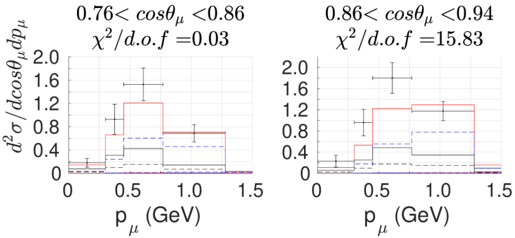


Megias et al., JPG46 (2019)

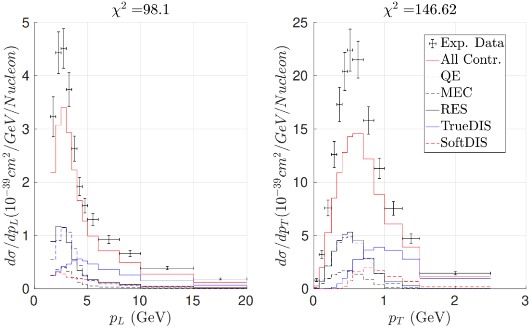


Megias et al., PRD94 (2016)

Neutrino-scattering inclusive data



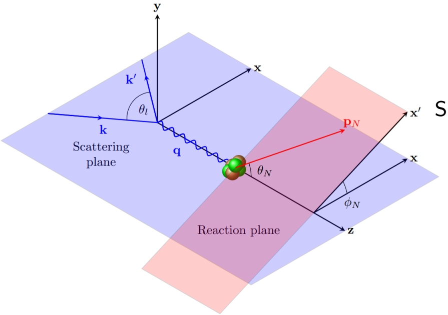
MicroBooNE (Ar)
Gonzalez-Rosa et al., PRD108 (2023)



MINERvA, *Gonzalez-Rosa et al., PRD108 (2023)*

Semi-inclusive process

Outgoing lepton and one ejected nucleon are detected in coincidence



SuSA and SuSAv2 are **intrinsecally inclusive**

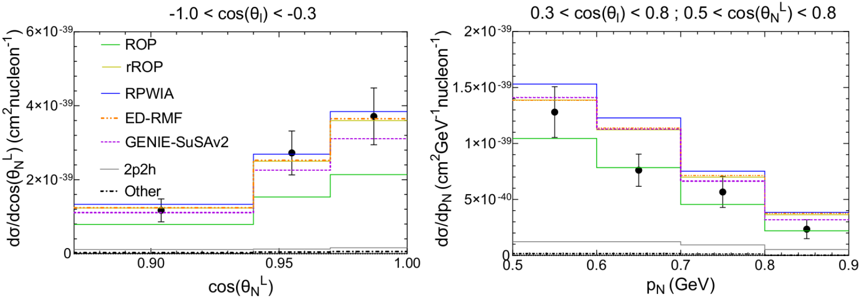
↓

do not predict hadronic observables

- RMF allows for hadronic observables predictions → ED-RMF *Franco-Patiño et al., PRD104 (2021)*
- GENIE SuSAv2 implementation *S. Dolan et al., PRD101 (2022)*

Semi-inclusive CC neutrino scattering

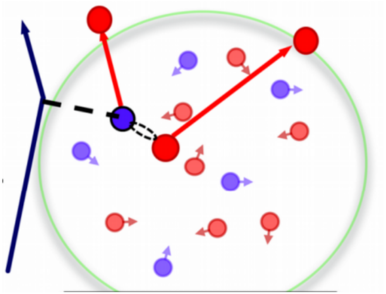
T2K data CC0π with at least one proton in the final state with momentum p_N above 0.5 GeV

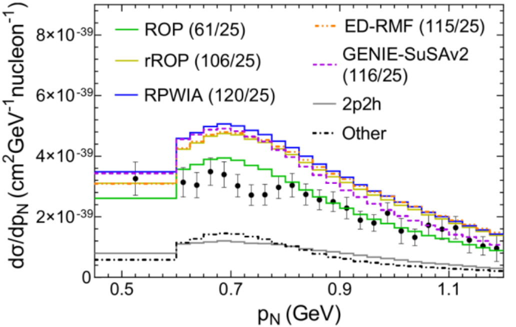


- Relativistic Optical Potentials can be added to improve reliability in FSI description
- Discrepancies between models and large uncertainties due to FSI, a defined trend does not emerge

QE... and Beyond: 2p2h

Increasing the transferred energy, two nucleons can be emitted: **2p2h**





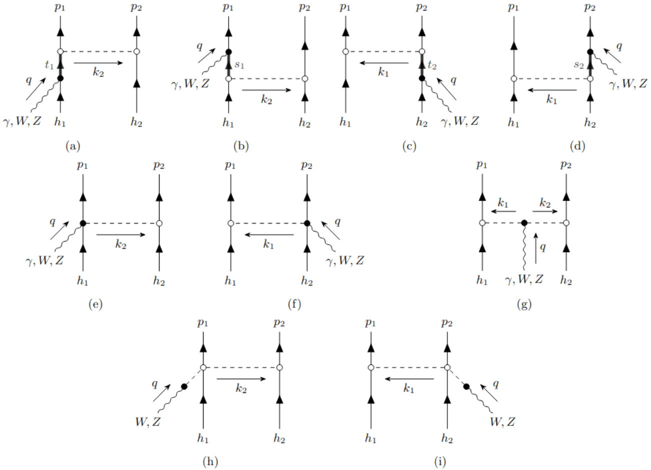
Semi-inclusive *2p2h* contribution is very important: **a reliable model is needed**

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	-

Current *CC 2p2h* predictions are **based on inclusive calculation**, thus their implementation for semi-inclusive processes is questionable and **strongly affect comparison of one-body semi-inclusive models to the experimental data**

Effective Field Theory EFT (pions and nucleons) + Δ description

De Pace et al., NPA 726 (2003), E. Hernandez et al., Phys. Rev. D 76, 033005 (2007)

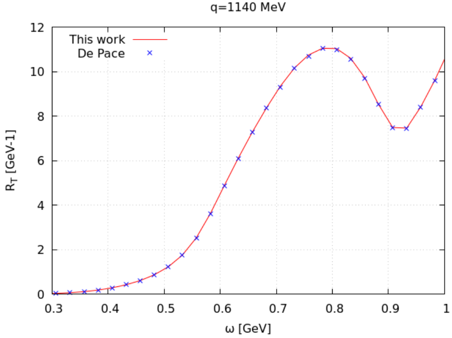


This work: RFG+MEC

Inclusive MEC results

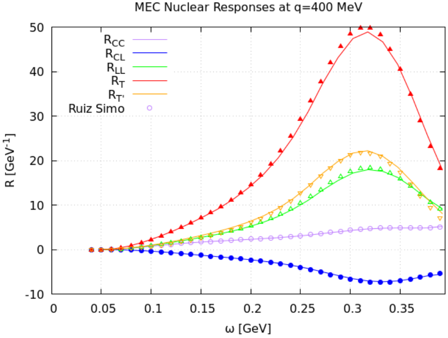
We tested our model with previous results:

$e - ^{56}Fe$



De Pace et al., NPA 741, 249 (2004)

$CC\, \nu_\mu - ^{12}C$

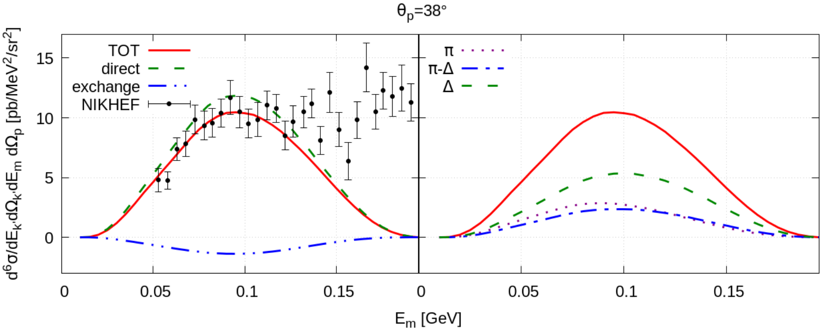


Ruiz Simo, Amaro et al., JPhG 44, 065105 (2017)

Semi-inclusive MEC results - electron scattering

- Our model is among the few that allow for a microscopic and fully relativistic computation of 2p2h semi-inclusive contributions

Electron scattering validation *Belocchi, Barbaro, De Pace, Martini, PRC109 (2024)*
Data: *Ryckebusch et al, PLB 333, 310 (1994)* Kinematics: $E_k = 470$ MeV, $\omega = 263$ MeV, $q = 303$ MeV

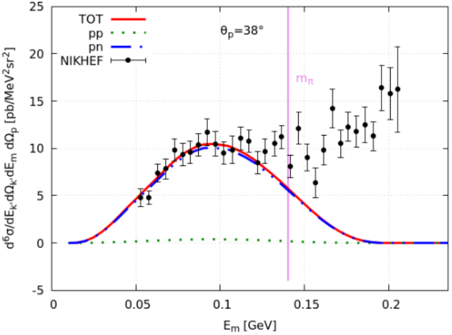


- Direct and exchange contribution included (exchange $\sim 12\%$ of direct, $\sim 13\%$ of total)
- Δ most important contribution ($\sim 50\%$), π and $\pi - \Delta$ similar
- **Very good agreement with data below $E_m \simeq 130$ MeV**
- For $E_m > 130$ MeV other processes start to contribute: π production via Δ excitation

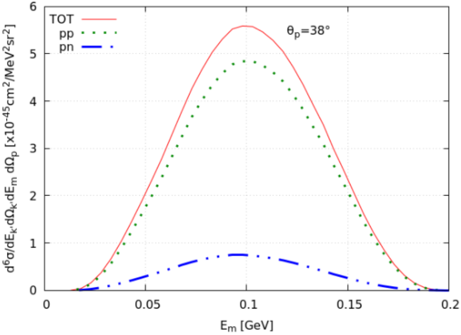
Isospin separation

Isospin separation of the **2-nucleons final state**
Kinematics: $E_k = 470$ MeV, $\omega = 263$ MeV, $q = 303$ MeV

Electron scattering



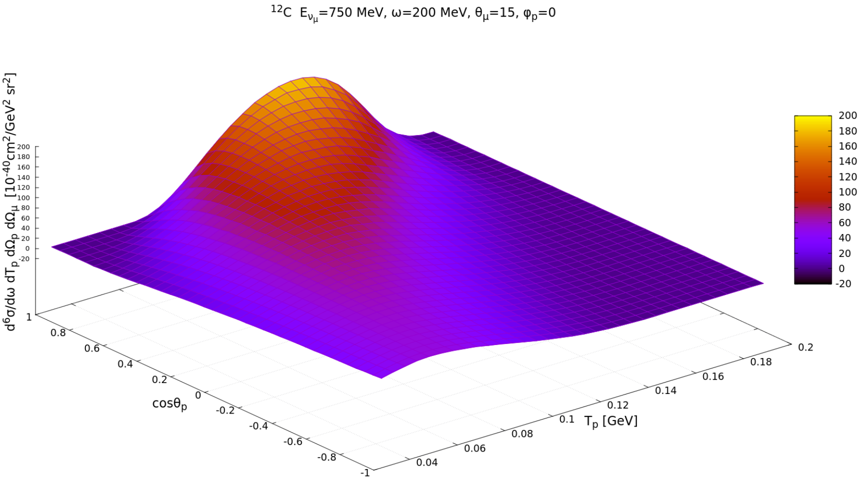
Neutrino *CC* scattering



- **Final** *pn* states for EM scattering and *pp* for CC EW dominate
- **Initial** *pn* states give the major contribution

EW semi-inclusive results

Fixing incident and four-momentum transfer we can span over the **detected particle phasespace**



Predictions for the same kinematical conditions as in *T. Van Cuyck et al., PRC 95 (2017)* and in *K. Niewczas, PhD thesis (2023)* → Similar results

Summary

- SuSAv2 is an excellent tool to reproduce inclusive data
- Semi-inclusive predictions are provided by ED-RMF (QE) and the present model ($2p2h$)
- Semi-inclusive EM $2p2h$ theoretical predictions are in a very good agreement with available data, providing a proof of the importance of this process and of the MEC model validity
- Semi-inclusive EW $2p2h$ theoretical predictions are among the few available on the market, not extracted in an effective way from inclusive computations

Work in Progress for $2p2h$ channel:

- Further investigation of the other TL and L nuclear responses
- Evaluate semi-inclusive cross-section vs the TKI variables, that mix leptonic and hadronic momentum variables
- Provide EW ν-flux folded predictions and compare with semi-inclusive data towards which the experimental community is moving to (T2K upgrade, Fermilab argon program)
- Implementation in Monte Carlo event generators

Thanks for the attention!

Backup

E_ν Reconstruction

We only know, in a reliable way, outgoing lepton kinematics. Modelling the nuclear initial state, it's possible to reconstruct the $\overline{E_\nu}$, using the inclusive CCQE formula:

$$\overline{E_\nu} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta)}$$

- There are biases due to Fermi motion inside the nucleus
- This formula doesn't work for other channels

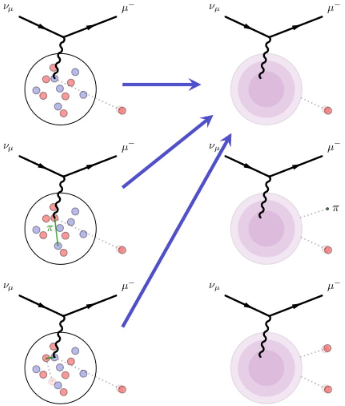
But what do we see? Event topology

$\Downarrow$

Classification based on detected final particles

$\nu_\mu + A \to \mu + X$ no π

CC0π event!



The general EM electron-nucleus cross-section formula is:

$$\frac{\mathrm{d}\sigma}{\mathrm{dE_{k'}}\,\mathrm{d}\Omega_{\mathrm{k'}}} = \underbrace{\frac{\alpha^2}{Q^2}\frac{|\mathbf{k}'|}{E_k}\nu_0}_{\sigma_{Mott}}(2\pi)^3\,\frac{L_{\mu\nu}}{\nu_0}\,W_A^{\mu\nu}$$

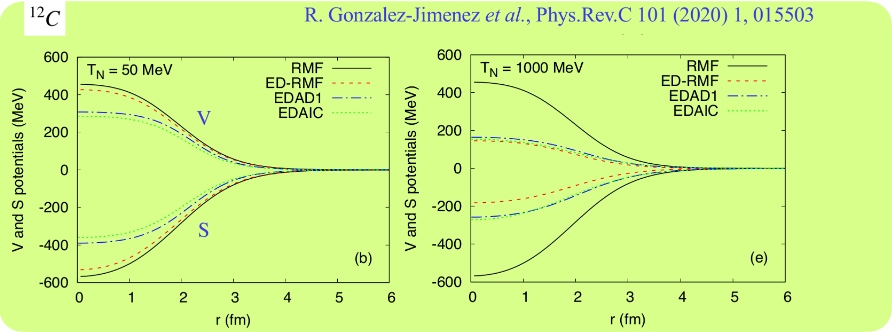
Nuclear Hadronic Tensor: described using a Nuclear Model

$$W_A^{\mu\nu} := \sum_X \langle A|\,(J_A^\mu)^\dagger\,|X\rangle\,\langle X|\,J_A^\nu\,|A\rangle\,\delta^4\,(M_A + q - P_X)$$

If the sum is performed over every possible final state X, W_A describes an inclusive process

RMF potentials

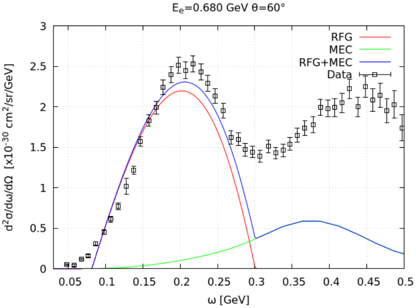
FSI can be described in several ways, introducing an outgoing nucleon energy dependency



- Optical Potentials: energy dependent A-(in)dependent **EDAD1 (EDAI)**
- RMF: energy independent potentials
- ED-RMF: energy dependent potentials

QE... and Beyond: MEC

Increasing the transferred energy, two nucleons can be emitted: **2p-2h**



Features:

- Leptonic probe interacts with a nucleon in a correlated pair of nucleons exchanging mediator (III order process, not FSI)
- Leptonic probe interacts directly with the exchanged virtual meson between two nucleons, exciting them both

$\Downarrow$

Meson Exchange Current: two-body current

Nuclear EW Lagrangian

Effective Field Theory to describe nucleons-mesons interaction:
E. Hernandez et al, Mod.Phys.Lett.A 23 (2008)

Non-Linear σ-model
Non-Linear: chirality is not like other simmetries, i.e. isospin
Lagrangian invariant under chiral transformation, constructed starting from pionic fields and isospin operators instead γ_5 and isospin operators

$$\mathcal{L} = \bar{\Psi}(i\partial\!\!\!/ - M)\Psi + \frac{1}{2}\partial_\mu\vec{\phi}\partial^\mu\vec{\phi} - \frac{1}{2}m_\pi^2\vec{\phi}^2 + \mathcal{L}_{\rm int}^\sigma$$

$$\mathcal{L}_{\rm int}^\sigma = \frac{g_A}{f_\pi}\bar{\Psi}\gamma^\mu\gamma_5\frac{\vec{\tau}}{2}(\partial_\mu\vec{\phi})\Psi - \frac{1}{4f_\pi^2}\bar{\Psi}\gamma^\mu\vec{\tau}(\vec{\phi}\times\partial^\mu\vec{\phi})\Psi - \frac{1}{6f_\pi^2}\left[\vec{\phi}^2\partial_\mu\vec{\phi}\partial^\mu\vec{\phi} - (\vec{\phi}\partial_\mu\vec{\phi})(\vec{\phi}\partial^\mu\vec{\phi})\right]$$
$$+\frac{m_\pi^2}{24f_\pi^2}(\vec{\phi}^2)^2 - \frac{g_A}{6f_\pi^3}\bar{\Psi}\gamma^\mu\gamma_5\left[\vec{\phi}^2\frac{\vec{\tau}}{2}\partial_\mu\vec{\phi} - (\vec{\phi}\partial_\mu\vec{\phi})\frac{\vec{\tau}}{2}\vec{\phi}\right]\Psi + \mathcal{O}(\frac{1}{f_\pi^4})$$

Effective Field Theory to describe nucleons-mesons interaction:
E. Hernandez et al, Mod.Phys.Lett.A 23 (2008)

Non-Linear σ-model

$$\mathcal{L} = \bar{\Psi}(i\partial\!\!\!/ - M)\Psi + \frac{1}{2}\partial_\mu\vec{\phi}\partial^\mu\vec{\phi} - \frac{1}{2}m_\pi^2\vec{\phi}^2 + \frac{g_A}{f_\pi}\bar{\Psi}\gamma^\mu\gamma_5\frac{\vec{\tau}}{2}(\partial_\mu\vec{\phi})\Psi + \mathcal{O}(1/f_\pi^2)$$

- Provides a description of a system composed by nucleons and pions
- Nucleon-pion vertex is dominated by pseudo-vector interaction
- πNN coupling is $\frac{g_{\pi NN}}{2m_N} = \frac{g_A}{2f_\pi}$ using the Goldberger-Treiman relation
- Ψ: nucleon, isospin doublet
- $\vec{\phi}$: pionic field, scalar isospin triplet, $\pi^\pm = \frac{1}{\sqrt{2}}(\phi_1 \pm i\phi_2)$
- $\vec{\tau}$: isospin Pauli matrices, $\tau^\pm = \tau_1 \pm i\tau_2$

Physical pions in the Lagrangian:

$$\vec{\tau}\vec{\phi} = \frac{1}{\sqrt{2}}(\tau^+\pi^- + \tau^-\pi^+) + \tau_3\pi^0$$

EW coupling

To 'switch on' the EW interaction in the previous Lagrangian, the standard $SU(2)_L \times U(1)_Y$ local symmetry procedure is performed, with associated gauge bosons $\vec{W}^\mu$ and B^μ, followed by the physical separation between weak and EM interactions

Covariant derivatives

$$\text{Fermions:} \quad D^\mu = \partial^\mu + ig\frac{\vec{\tau}}{2}\vec{W}^\mu + ig' Y B^\mu$$

$$\text{Pions:} \quad \mathcal{D}^\mu \phi_i = \partial^\mu \phi_i - g\epsilon_{ijk}\phi_j W_k^\mu$$

with

$$\frac{\vec{\tau}}{2}\vec{W}_\mu = \frac{1}{\sqrt{2}}(\tau^+ W_\mu^- + \tau^- W_\mu^+) + \frac{\tau_3}{2}W_{3\mu} \quad W_\mu^\pm = \frac{1}{\sqrt{2}}(W_{1\mu} \pm iW_{2\mu})$$

EM interaction

$$ig\frac{\vec{\tau}}{2}\vec{W}^\mu + ig' Y B^\mu \quad \rightarrow \quad ieA^\mu$$

$$g\epsilon_{ij3}W_3^\mu \quad \rightarrow \quad e\epsilon_{ij3}A^\mu$$

Δ-MEC Lagrangian

W^μ / A^μ $N\,\Delta$ transition

$$\mathcal{L} = g\bar{\Psi}_\mu \vec{T}^\dagger \vec{W}^\mu \Psi + h.c. \quad \rightarrow \quad \mathcal{L}_{EM} = e\bar{\Psi}_\mu T_3^\dagger A^\mu \Psi + h.c.$$

$N\,\Delta\,\pi$ transition

$$\mathcal{L} = \sqrt{\frac{3}{2}}\frac{f^*}{m_\pi}\bar{\Psi}_\mu \vec{T}^\dagger \partial^\mu \vec{\phi}\Psi + h.c.$$

- Ψ_μ : Rarita-Schwinger $\frac{3}{2}$-spinor, with four isospin indices (μ) and four Dirac indices -omitted-
- $T^\dagger$: $\frac{1}{2} \rightarrow \frac{3}{2}$ isospin transition 4x2 operator

$$T_1 = \frac{1}{\sqrt{6}}\begin{pmatrix} -\sqrt{3} & 0 & 1 & 0 \\ 0 & -1 & 0 & \sqrt{3} \end{pmatrix} \; T_2 = -\frac{i}{\sqrt{6}}\begin{pmatrix} \sqrt{3} & 0 & 1 & 0 \\ 0 & 1 & 0 & \sqrt{3} \end{pmatrix} \; T_3 = \sqrt{\frac{2}{3}}\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$T_i T_j^\dagger = \frac{2}{3}\delta_{ij} - \frac{i}{3}\epsilon_{ijk}\tau_k$$

Δ Propagator

In the MEC currents, Δ appears always as a virtual particle

Δ propagator

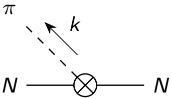
$$G_{\alpha\beta}(p) = \frac{\mathcal{P}_{\alpha\beta}(p)}{p^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta}$$

Where $\mathcal{P}_{\alpha\beta}$ is the projector over the physical states

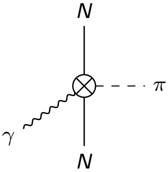
$$\sum_{spin} u_\alpha(p)\overline{u}_\beta(p) = \mathcal{P}_{\alpha\beta}(p) = -(\not{p} + M_\Delta)\left[g_{\alpha\beta} - \frac{1}{3}\gamma_\alpha\gamma_\beta - \frac{2}{3}\frac{p_\alpha p_\beta}{M_\Delta} + \frac{p_\alpha\gamma_\beta - p_\beta\gamma_\alpha}{3M_\Delta}\right]$$

In the following the imaginary contribution to the responses arising from the Δ propagator is not included

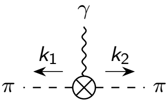
EM MEC vertices



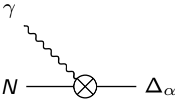
$-\frac{g_A}{2f_\pi}(k^2)\vec{\tau}k^\mu$



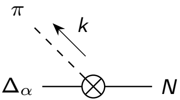
$$\frac{e}{\sqrt{2}}\frac{g_A}{2f_\pi}F_1^V(q^2)\gamma^\mu\gamma_5(\tau_-\pi^+ - \tau_+\pi^-)$$



$-ieF_1^V(q^2)(k_1^\mu - k_2^\mu)(\pi^+\pi^- - \pi^-\pi^+)$



$ieT_3^\dagger\Gamma^{\alpha\mu}$



$\sqrt{\frac{3}{2}}\frac{f^*}{m_\pi}\vec{T}k^\alpha$

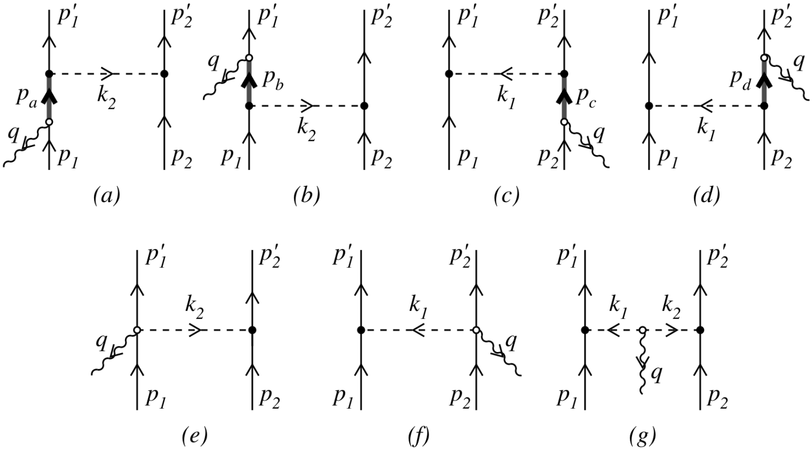
$\Gamma^{\alpha\mu}$ contains vector and axial form factors. EM case:

$$\Gamma_V^{\alpha\mu} = \Big[\overbrace{\frac{C_{3V}}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu)}^{\text{dominant FF}} + \frac{C_{4V}}{M^2}(g^{\alpha\mu}qp_\Delta - q^\alpha p_\Delta^\mu) + \frac{C_{5V}}{M^2}(g^{\alpha\mu}qp - q^\alpha p^\mu)\Big]\gamma_5$$

Meson Exchange Current

Describe the possibility that a probe excites two holes into two particles: *De Pace et al, Nucl.Phys.A 726 (2003)*

- Two-body ElectroMagnetic Meson Exchange Currents J^{μ}_{2p2h}



RFG 2p2h

Inclusive hadronic tensor, no hadronic particles detected:

$$W^{\mu\nu}_{2p2h} = (2\pi)^3 \frac{V}{4} \int_{|\mathbf{p}|\le p_F} \frac{m_N \mathrm{d}\mathbf{p_1}}{(2\pi)^3 E_{p1}} \frac{m_N \mathrm{d}\mathbf{p_2}}{(2\pi^3) E_{p2}} \frac{m_N \mathrm{d}\mathbf{p'_1}}{(2\pi)^3 E_{p1'}} \frac{m_N \mathrm{d}\mathbf{p'_2}}{(2\pi^3) E_{p2'}} \tilde{W}^{\mu\nu}_{2p2h} \delta^4 \{\theta_{PB}\}$$

Semi-inclusive hadronic tensor, one final proton detected (p'_1):

$$W^{\mu\nu}_{2p2h}(N'_1) = (2\pi)^3 \frac{V}{4} \int_{|\mathbf{p}|\le p_F} \frac{m_N \mathrm{d}\mathbf{p_1}}{(2\pi)^3 E_{p1}} \frac{m_N \mathrm{d}\mathbf{p_2}}{(2\pi^3) E_{p2}} \frac{m_N \mathrm{d}\mathbf{p'_2}}{(2\pi^3) E_{p2'}} \tilde{W}^{\mu\nu}_{2p2h} \delta^4 \{\theta_{PB}\}$$

$$\tilde{W}^{\mu\nu}_{2p2h} = \sum_{\substack{spin \\ isospin}} \langle 2p2h | J^{\mu}_{2p2h} | F \rangle \langle F | J^{\nu\dagger}_{2p2h} | 2p2h \rangle \qquad |2p2h\rangle = b^{\dagger}_{p'_2} b^{\dagger}_{p'_1} b_{p_1} b_{p_2} |F\rangle$$

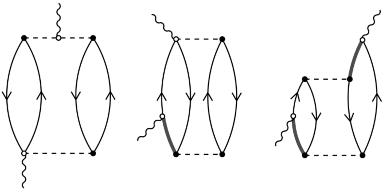
- J^{μ}_{2p2h} is a two-body operator, acting on the spin, isospin and momentum space
- Is possible to invert the two particles, obtaining another current that must be included

$$\downarrow$$

$$J^{\mu}_{2p2h} = J^{\mu}_{2p2h}(p_1, p_2, p'_1, p'_2) - J^{\mu}_{2p2h}(p_1, p_2, p'_2, p'_1)$$

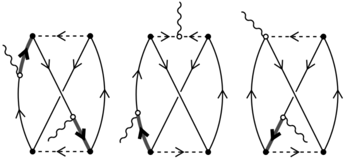
Combining two meson exchange currents → **Two possibilities!**

- Direct term: $J^\mu J^{\nu\dagger}(p_1, p_2, p_{1'}, p_{2'}) + J^\mu J^{\nu\dagger}(p_1, p_2, p_{2'}, p_{1'})$



3 examples of the 16 EM many body direct diagrams

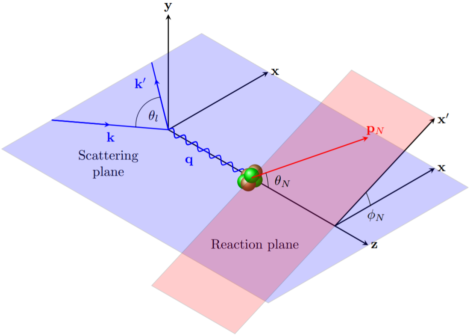
- Exchange term: $J^\mu(p_1, p_2, p_{1'}, p_{2'})J^{\nu\dagger}(p_1, p_2, p_{2'}, p_{1'}) + \mu \leftrightarrow \nu$



3 examples of the 12 EM many body exchange diagrams

Inclusive 2p2h process

Inclusive calculation, fixing ω, q



- Integration over two particles and two holes momenta
- Four-momentum conservation
- q-system: nucleus symmetry $\rightarrow$ azimuthal invariance

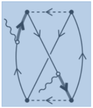
Non-vanishing responses

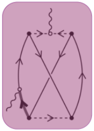
$$R_L = W^{00}_{2p2h} \qquad R_T = W^{11}_{2p2h} + W^{22}_{2p2h}$$

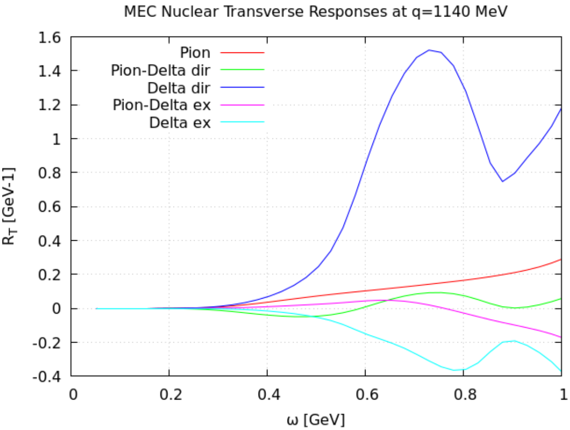
Electric charge conservation:
R_L includes contribution from W^{00}_{2p2h}, W^{03}_{2p2h}, W^{33}_{2p2h}

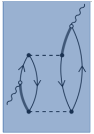
MEC Responses

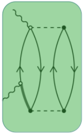
- RFG model in nuclear matter for Carbon target, $p_F = 228$ MeV
- Energy shift $E_s = 20$ MeV for each particle $\quad \rightarrow \quad E_s^{2p2h} = 2E_s$

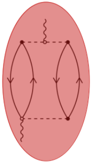






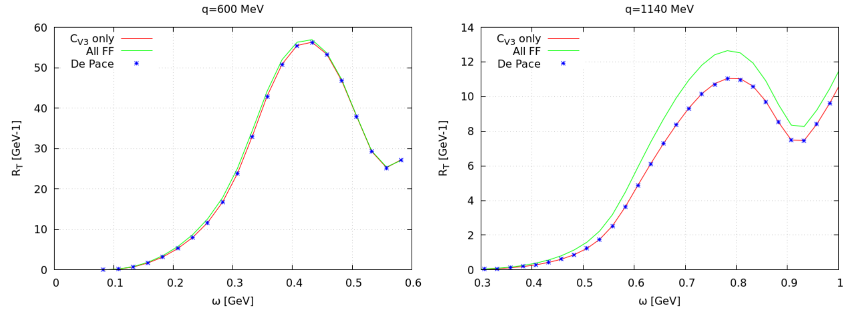






MEC Responses

We tested the results with previous work, for iron *De Pace et al, Nucl.Phys.A 726 (2003)*

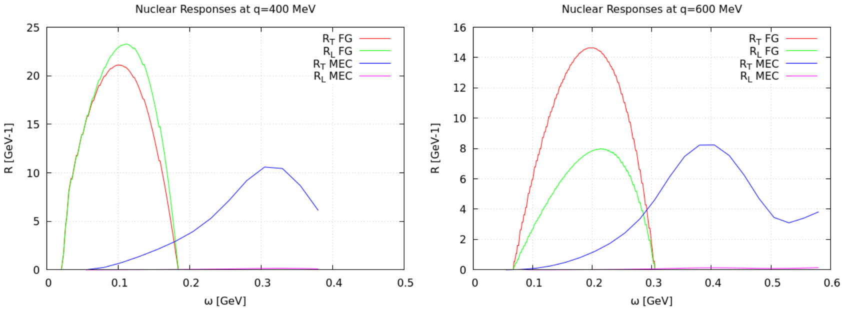


Delta Form Factors impact

- In *De Pace et al* only C_{3V} was included. Here all Δ form factors are included: responses increase, more relevant at high q-values

MEC Responses: Results

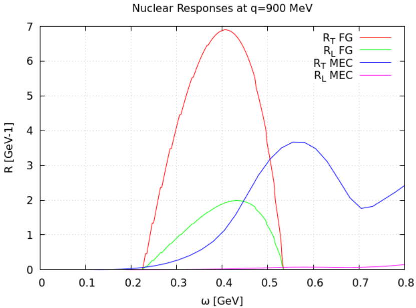
MEC Transverse and Longitudinal Nuclear Responses at several q-values:

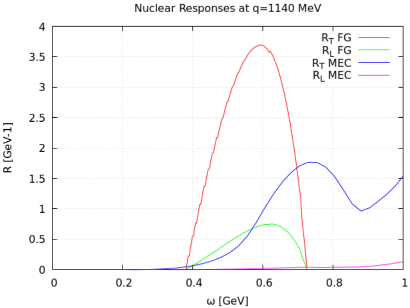


- EM MEC contribution is almost totally transverse with respect to q^μ
- MEC responses show a wide but defined peak, due to Δ role. Strenght is about a half of the transverse QE responses
- At low q-values QE peak is well separated from MEC contributions. As q increases the two peaks overlap
- MEC responses are truncated when the exchanged q^μ becomes time-like

MEC Responses: Results

Higher q-values:

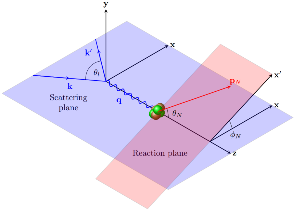




- Same considerations as before
- Ratio between RFG and MEC transverse responses is still the same

Semi-inclusive 2p2h process

Semi-inclusive calculation, fixing
ω, q, $\mathbf{p}'_1(p'_1, \theta_{p_1'}, \phi_{p_1'})$



- Integration over one particle and two holes momenta
- Four-momentum conservation
- q-system: nucleus symmetry
  $\rightarrow$ NO MORE azimuthal invariance

$\Rightarrow$ 5 dimension integration

Non-vanishing responses

$$R_L = W^{00}_{2p2h} \qquad R_T = W^{11}_{2p2h} + W^{22}_{2p2h}$$

$$R_{TT} = W^{22}_{2p2h} - W^{11}_{2p2h} \qquad R_{TL} = \frac{1}{2}(W^{10}_{2p2h} + W^{01}_{2p2h})$$

Electric charge conservation:
R_{TL} includes contributions from W^{10}_{2p2h}, W^{13}_{2p2h}

MEC Semi-Inclusive Responses

We tested our models with data showed in *J. Ryckebusch et al, Phys. Lett. B 333, 310 (1994), arXiv:nucl-th/9406015.*

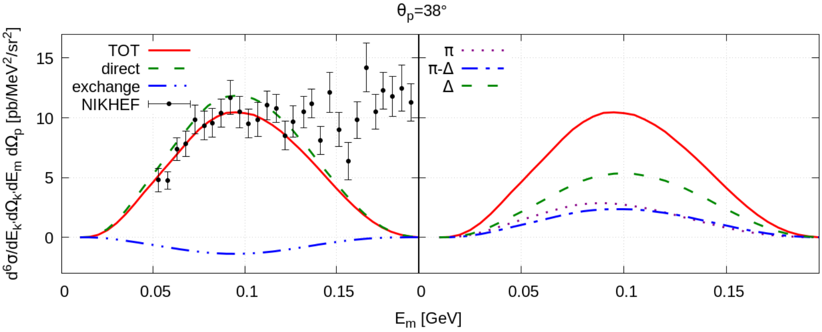
Experimental settings, q-system

- Fixed incident and final lepton energy E_k, $E_{k'}$, scattering angle and $\mathbf{p}'_1$
- Scattering plane $x - z \quad \rightarrow \quad$ no contribution from $W^{\mu 2}$, $\mu \neq 2$
- Proton detected in the scattering-plane $\quad \rightarrow \qquad \phi_{p_{1'}} = 0, \pi$
  Note that $\phi_{p_{1'}}$ value affects the sign of R_{TL} contribution
- 6^{th} differential cross-section

$$\frac{d\sigma}{d\omega d\Omega_{k'} dE_m d\Omega_{p_{1'}}}$$

$$E_m = \omega - T_{p_{1'}} \qquad T_{p_{1'}} = E_{p_{1'}} - m_N$$

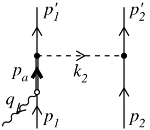
R_T and R_{TT} contributions included only
Kinematics: $E_k = 470$ MeV, $\omega = 263$ MeV, $q = 303$ MeV



- Defined peak
- Direct and exchange contribution included (exchange $\sim$ 12% of direct, $\sim$ 13% of total)
- Δ most important contribution ($\sim$ 50%), π and $\pi - \Delta$ similar
- **Very good agreement with data below $E_m \simeq 130$ MeV**
- For $E_m > 130$ MeV other process starts to contributes: π production via Δ excitation

Isospin channel separation

Example: Δ forward current



- Isospin operator: $$I_{\Delta F} = 2\tau_3^{(1)}\mathbb{1}^{(2)} - I_{V_3}$$

$$I_{V_3} = \frac{1}{2}(\tau_-^{(1)}\tau_+^{(2)} - \tau_+^{(1)}\tau_-^{(2)}) \qquad I_{V_3}^\dagger |pp\rangle = 0$$

- Δ current is the only term contributing to *pp* channel (pionic current has I_{V_3} only)

$$I_{\Delta F}^\dagger |pp\rangle = 2|pp\rangle \qquad I_{\Delta F}^\dagger |pn\rangle = 2|pn\rangle - 2|np\rangle$$

In the semi-inclusive channel, a proton is detected in the final state

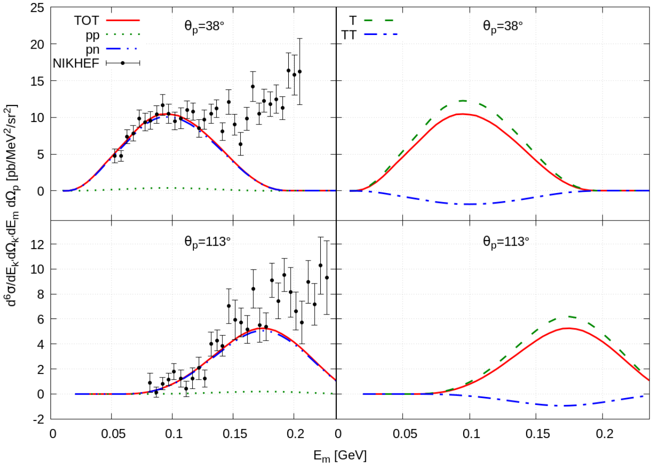
$\Downarrow$

$|pn\rangle$, $|np\rangle$ both contribute

$\Downarrow$

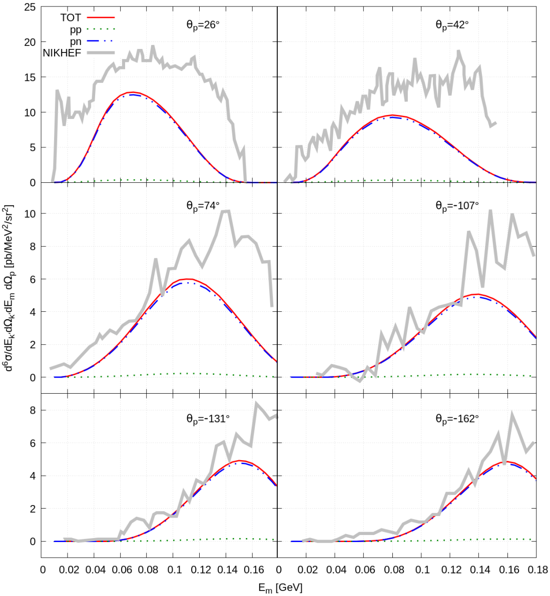
pn channel four times bigger than pp

Kinematics: $E_k = 470$ MeV, $\omega = 263$ MeV, $q = 303$ MeV

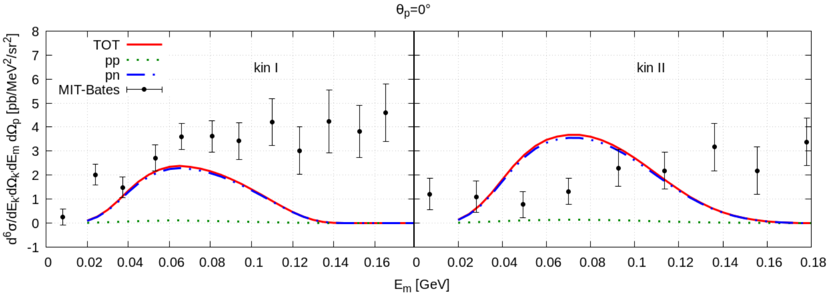


- *pn* dominates with to respect *pp* channel
- *T* contribution is the most important, *TT* reduces the strength for $\simeq 14\%$ (of T)

Kinematics: $E_k = 475$ MeV, $\omega = 212$ MeV, $q = 270$ MeV
data from *L. J. H. M. Kester et al., Phys. Lett. B 344, 79 (1995)*

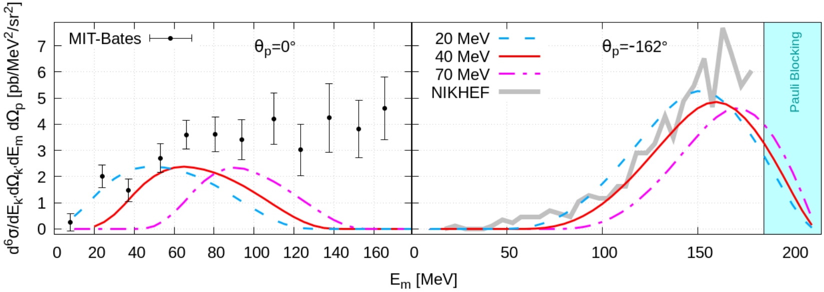


Higher Q^2 values, parallel kinematics ($\theta_p = 0$)
data from *H. Baghaei et al., Phys. Rev. C 39, 177 (1989).*



- kinI: $E_k = 460$ MeV, $\omega = 275$ MeV, $q = 401$ MeV
- kinII: $E_k = 647$ MeV, $\omega = 382$ MeV, $q = 473$ MeV
  Discrepancies:
- Higher Q^2 $\rightarrow$ RFG unable to describe very off-shell probe interaction
- Higher q values $\rightarrow$ $E_s^{2p2h} = 40$ MeV probably not enough, FSI effects reduced

E_s^{2p2h} dependence and Pauli Blocking effect



- Increasing E_s^{2p2h} , shift toward higher E_m
- Effect more relevant in parallel kinematics, response accumulated and localized at lower E_m
- Best agreement with data in the range $E_s^{2p2h} = 20 - 40$ MeV
- Pauli Blocking, included via step function, truncates the responses at $E_m = \omega - T_F$

EW Cross-Section

To extend the formalism to electronweak sector several changes must be made

Neutrino-nucleus CC cross-section formula

$$\frac{\mathrm{d}^2\sigma}{\mathrm{dE_{k'}}\,\mathrm{d}\Omega_{\mathrm{k'}}} = \underbrace{\frac{G_F^2 \cos\theta_C}{8\pi^2}\frac{|\mathbf{k}'|}{E_k}\nu_0}_{\sigma_0}(2\pi)^3\frac{L_{\mu\nu}}{\nu_0}W_A^{\mu\nu}$$

Inclusive non-vanishing responses

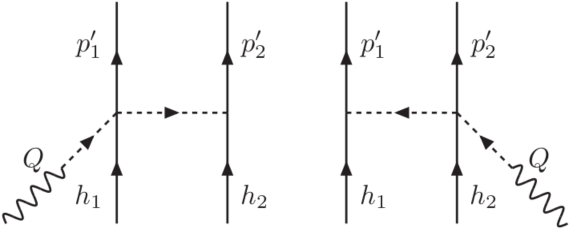
$$R_{CC} = W^{00}_{2p2h} \qquad R_{CL} = -\frac{1}{2}(W^{03}_{2p2h} + W^{30}_{2p2h}) \qquad R_{LL} = W^{33}_{2p2h}$$

$$R_T = W^{11}_{2p2h} + W^{22}_{2p2h} \qquad R_{T'} = -\frac{i}{2}(W^{12}_{2p2h} - W^{21}_{2p2h})$$

No electric charge conservation, so no grouped responses (due to axial contributions)

MEC are also modified, and new interactions are active

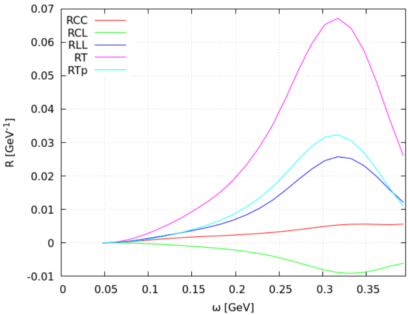
- Axial part and vector-axial interference
- New kind of interaction: pion-pole

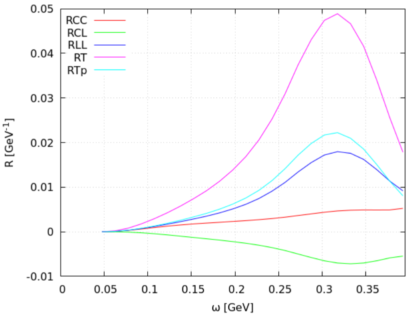


- Different isospin operators, especially important when separating different isospin channel in the final state

EW MEC Preliminary Results

EW MEC responses for $q = 400$ MeV, $p_F = 225$ MeV.





Left Panel: direct responses

Right Panel: direct + exchange responses