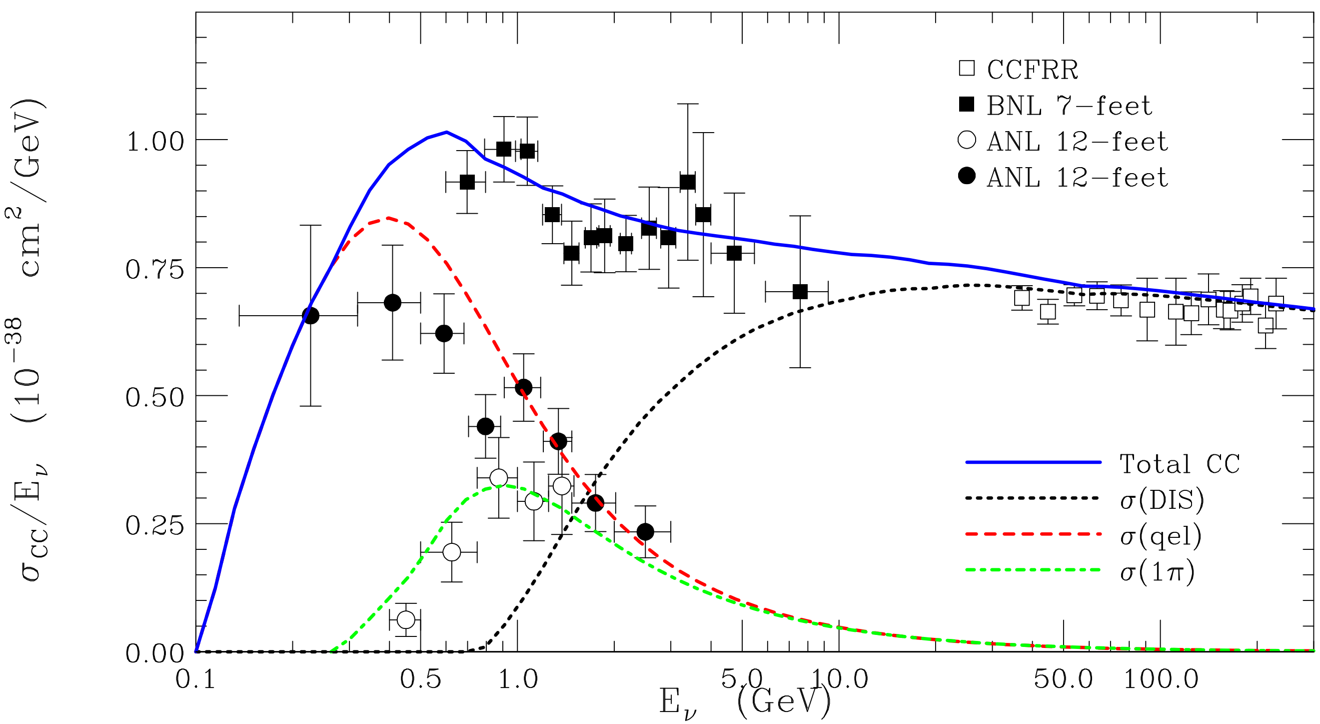
QE and QE-like scattering

- arXiv:1403.2673: (Progress and open questions in the physics of neutrino cross sections)
- arXiv:1307.8105: PRD 88 (2013) 113007 ($\nu, \bar{\nu}$ CCQE-like up to 10 GeV)
- arXiv:1302.0703: PLB 721 (2013) 90 ($\bar{\nu}$ CCQE-like)
- arXiv:1204.5404: PRD 85 (2012) 113008 (E_ν reconstruct.)
- arXiv:1106.5374: PLB 707 (2012) 72 (ν CCQE-like)
- arXiv:1102.2777: PRC 83 (2011) 045501 (CCQE, 2p2h, ...)

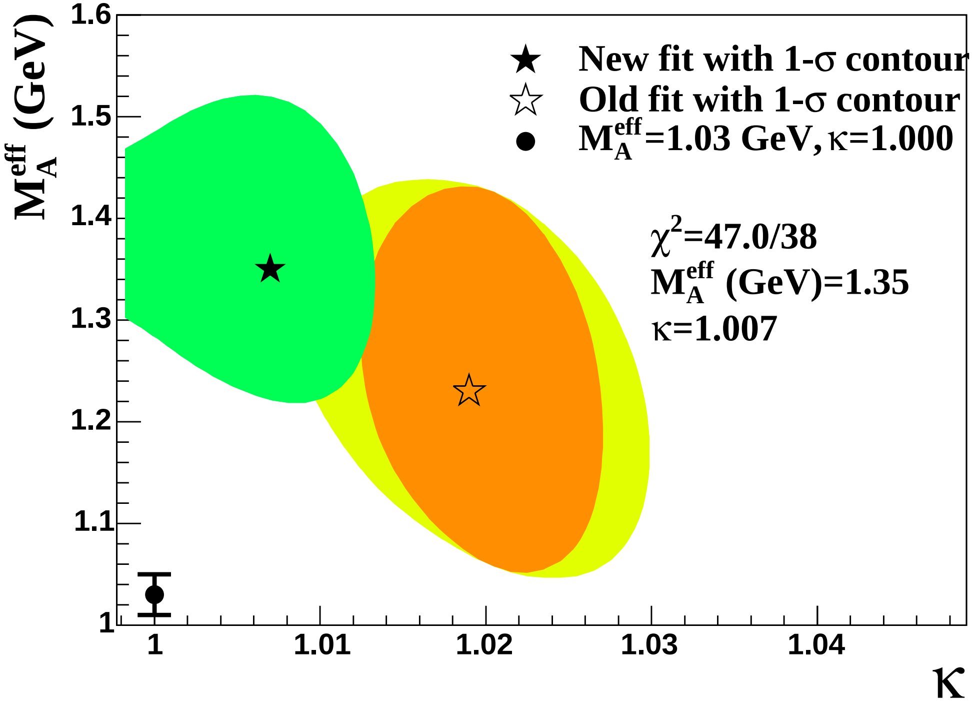
- nucl-th/0408005: PRC 70 (2004) 055503 (CCQE)
- hep-ph/0604042: PLB 638 (2006) 325 (Errors in CCQE)
- hep-ph/0511204 : PRC 73 (2006) 025504 (NCQE & MC)

Motivation: Details on the axial structure of hadrons in the free space and inside of nuclei, and



Theoretical knowledge of QE and 1π cross sections is important to carry out a precise neutrino oscillation data analysis...

Motivation: MiniBooNE CCQE (PRD 81, 092005)

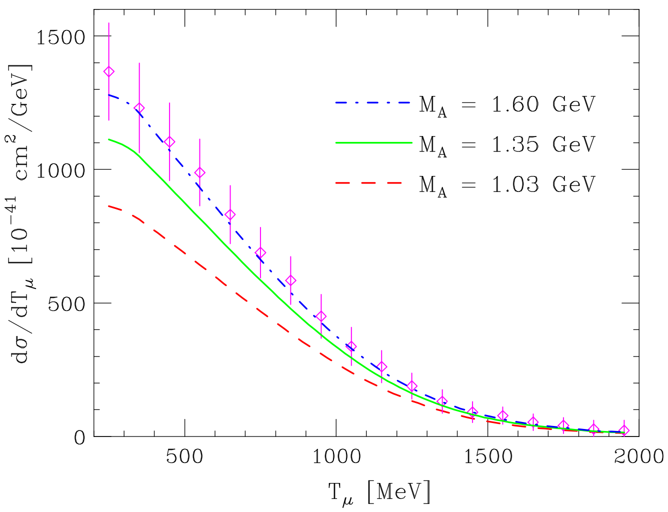


$M_A^{\rm eff} = 1.35$ **GeV**

vs

1.03 GeV (world avg)

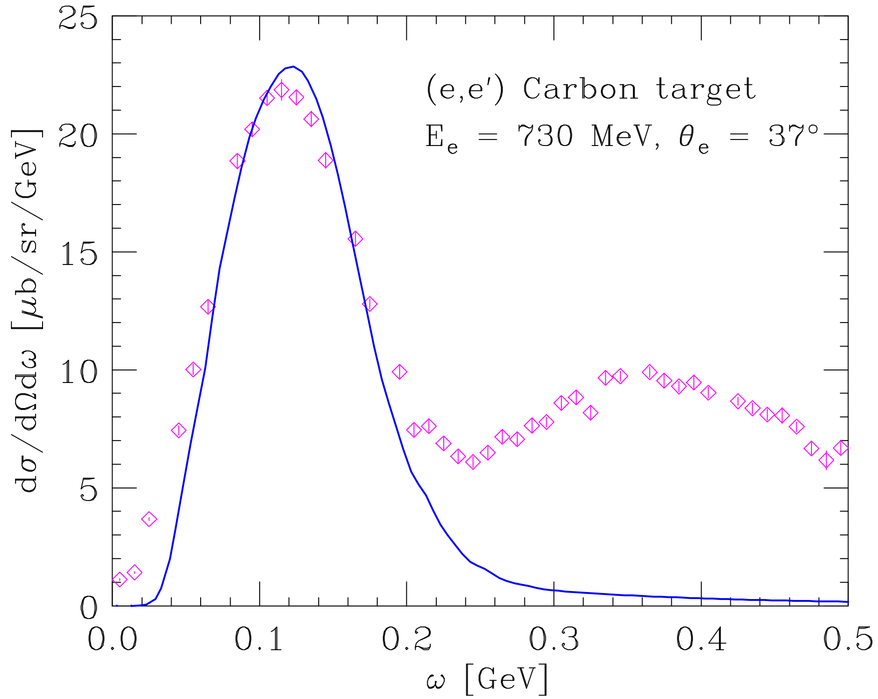
confirmed by many other groups, for instance by Benhar et al. (PRL 105, 132301)



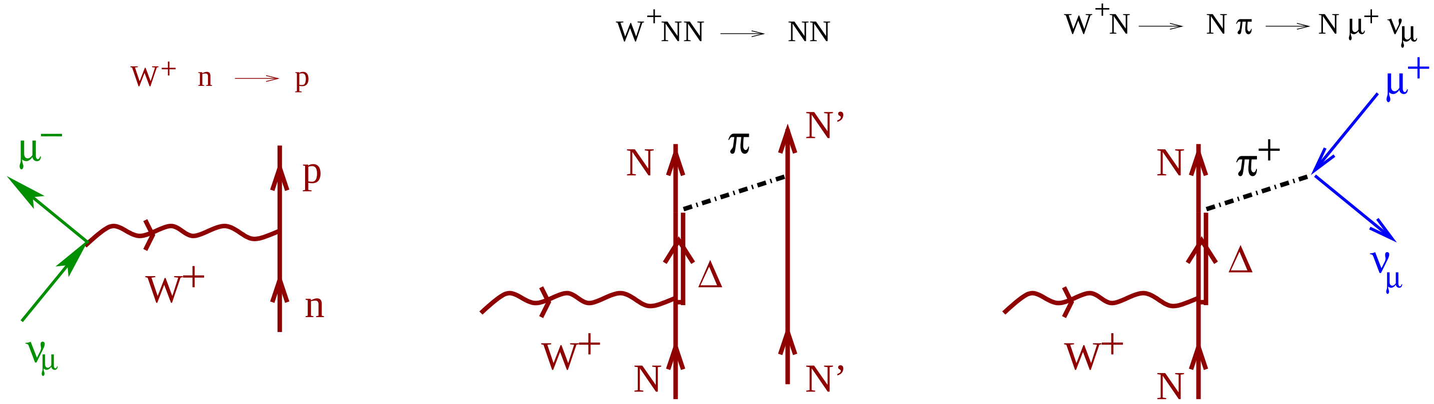
- ChPT $\mathcal{O}(p^3)$ + single pion electroproduction data: $M_A = 1.014 \pm 0.016$ GeV (V. Bernard, N. Kaiser, and U. G. Meissner, Phys.Rev.Lett. 69, 1877 (1992))

- CCQE measurements on deuterium and, to lesser extent, hydrogen targets is $M_A = 1.016 \pm 0.026$ GeV (A. Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, Eur.Phys.J. C53, 349 (2008))

The problem turned out to **even more worrying** since the height, position, and width of the **QE peak in the case of electron scattering are well reproduced in most of used models,** for instance see results of Benhar et al. at similar energies and in carbon

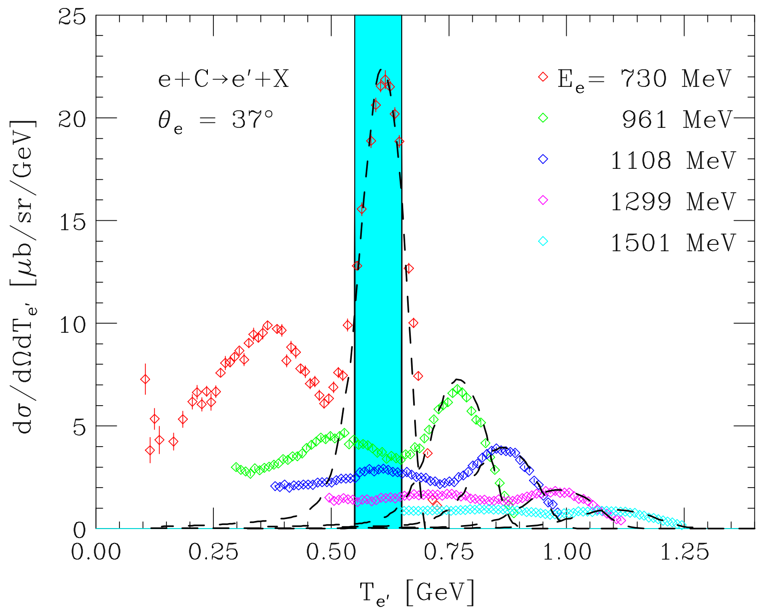


...but key observation (Martini et al., PRC 81, 045502): in most **theoretical** works QE is used for processes where the gauge boson $W^{\pm}$ **or** Z^0 **is absorbed by just one nucleon**, which together with a lepton is emitted, **however in the recent MiniBooNE measurements, QE is related to processes in which only a muon is detected** (ejected nucleons are not detected !) $\equiv$ **CCQE-like**



It **includes multinucleon processes and others like** π **production followed by absorption** (MBooNE analysis Monte Carlo corrects for those events). **It discards pions coming off the nucleus, since they will give rise to additional leptons after their decay.**

O. Benhar@NuFacT11: [arXiv : 1110.1835] measured electron-carbon scattering cross sections for a fixed outgoing electron angle $\theta = 37^o$ and different beam energies $\in [730, 1501]$ GeV, plotted as a function of E_e,



The energy bin corresponding to **the top of the QE peak at $E_e =$ 730 MeV receives significant contributions from** cross sections corresponding to different beam energies and **different mechanisms!**

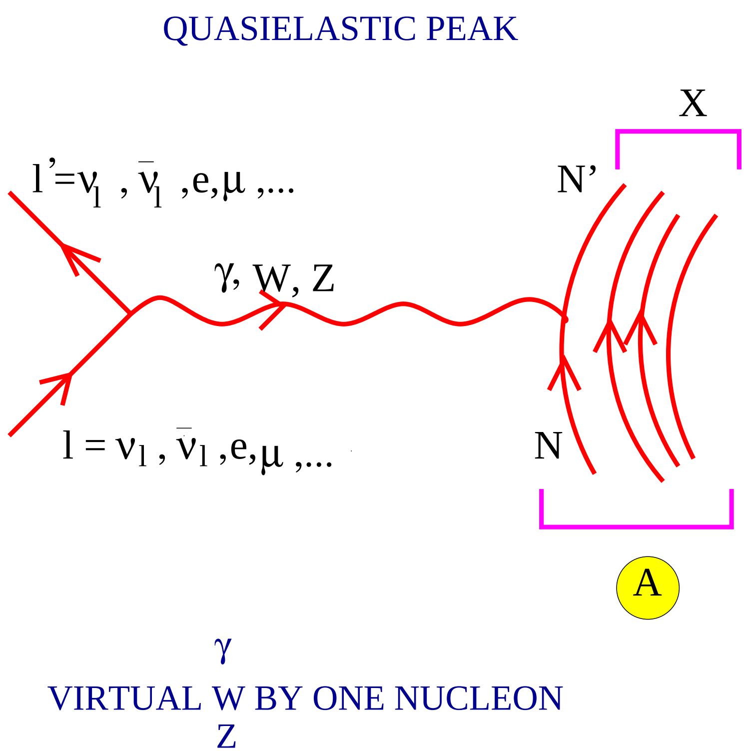
- **MiniBooNE experimental results cannot be directly compared to most theoretical previous calculations!**

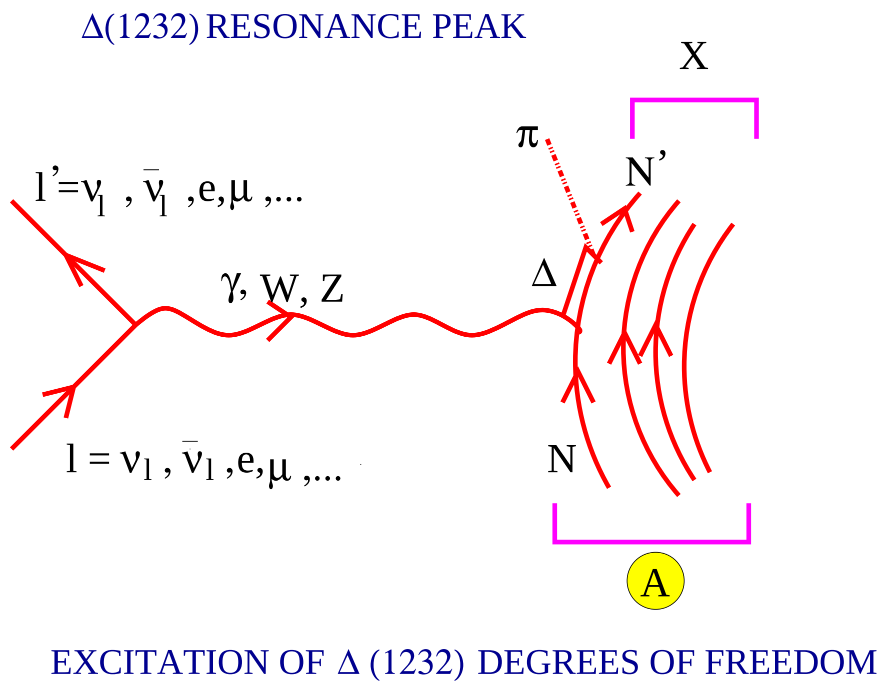
- **We present a microscopic calculation of the ν and $\bar{\nu}$ CCQE-like double differential cross sections $\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$ measured by MiniBooNE and we will use the ν data to extract M_A**

- **Neutrino Energy Reconstruction and the Shape of the CCQE-like Total Cross Section**

- **Neutrino-nucleus quasi-elastic and 2p2h interactions up to 10 GeV**

Nuclear renormalization effects on electroweak inclusive reactions in nuclei at intermediate energies



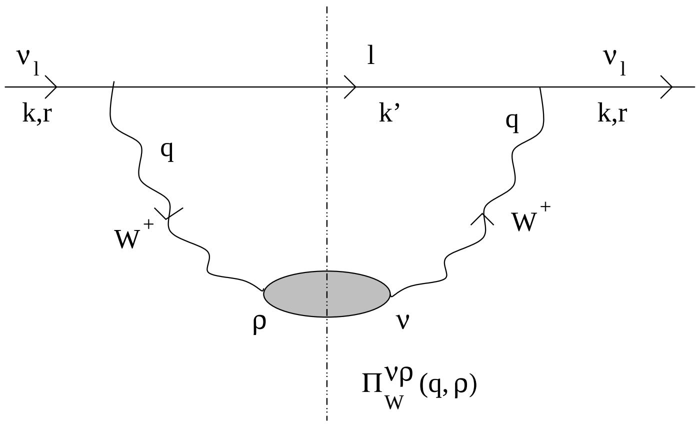


To describe the propagation of particles inside of the nuclear medium $\Rightarrow$ microscopic framework:

- Pauli Blocking
- RPA and Short Range Correlations (SRC)
- $\Delta(1232)$–Degrees of Freedom
- Spectral Function (SF) + Final State Interaction (FSI)
- Meson Exchange Currents (MEC)

compute the imaginary part of the lepton-selfenergy inside of the **nucleus**:

For instance, let's look at $\nu_l + A_Z \longrightarrow l + X$



$$\frac{d^2\sigma}{d\Omega(\hat{k}')dE'} = \frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$

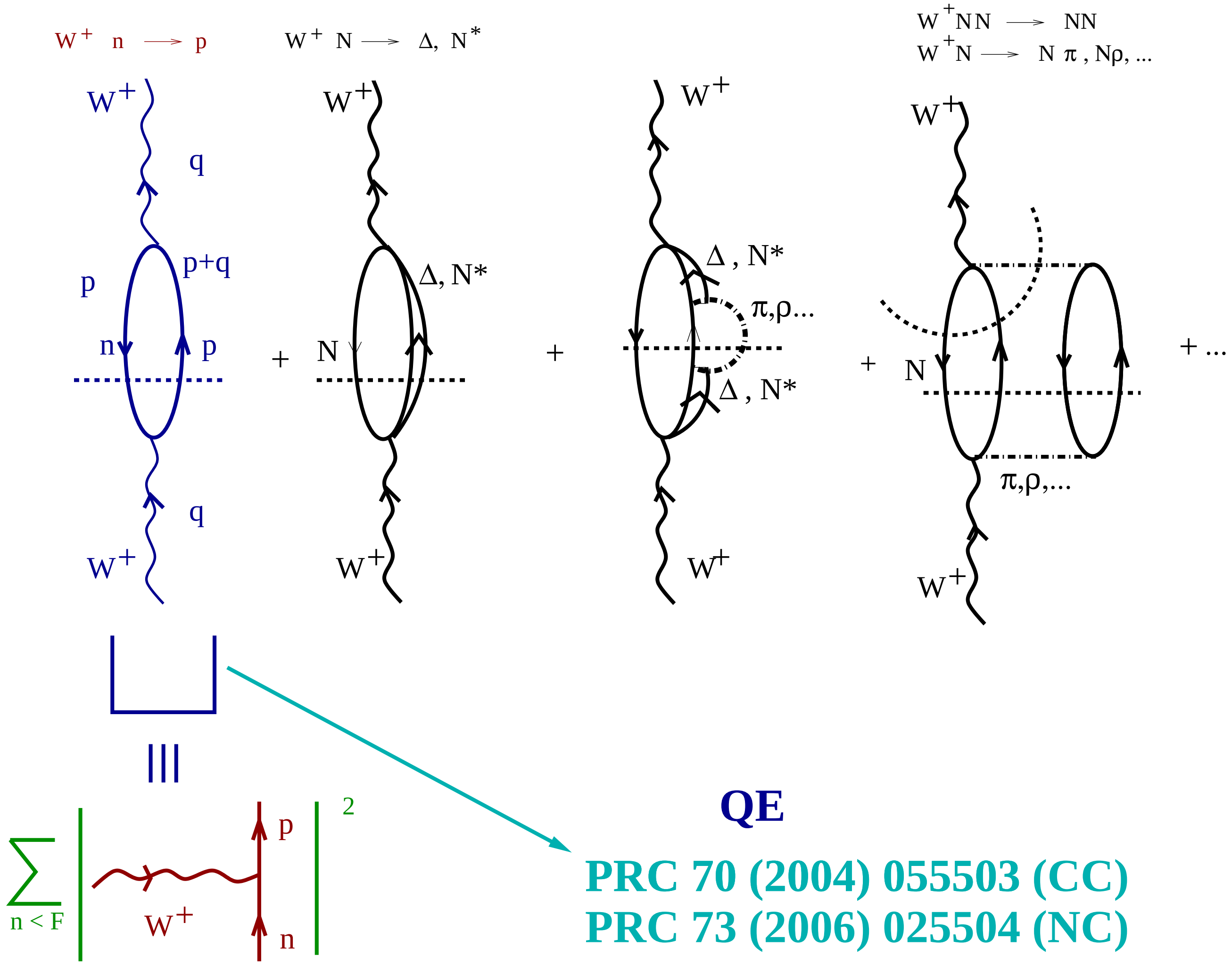
$$L_{\mu\sigma} = k'_\mu k_\sigma + k'_\sigma k_\mu - g_{\mu\sigma}k\cdot k' + \mathrm{i}\epsilon_{\mu\sigma\alpha\beta}k'^\alpha k^\beta$$

$$W^{\mu\sigma} = W_s^{\mu\sigma} + \mathrm{i}W_a^{\mu\sigma}$$

$$W_s^{\mu\sigma} \propto \int \frac{d^3r}{2\pi}\,\mathrm{Im}\,\left\{\Pi_W^{\mu\sigma}(q,\rho) + \Pi_W^{\sigma\mu}(q,\rho)\right\}\Theta(q^0)$$

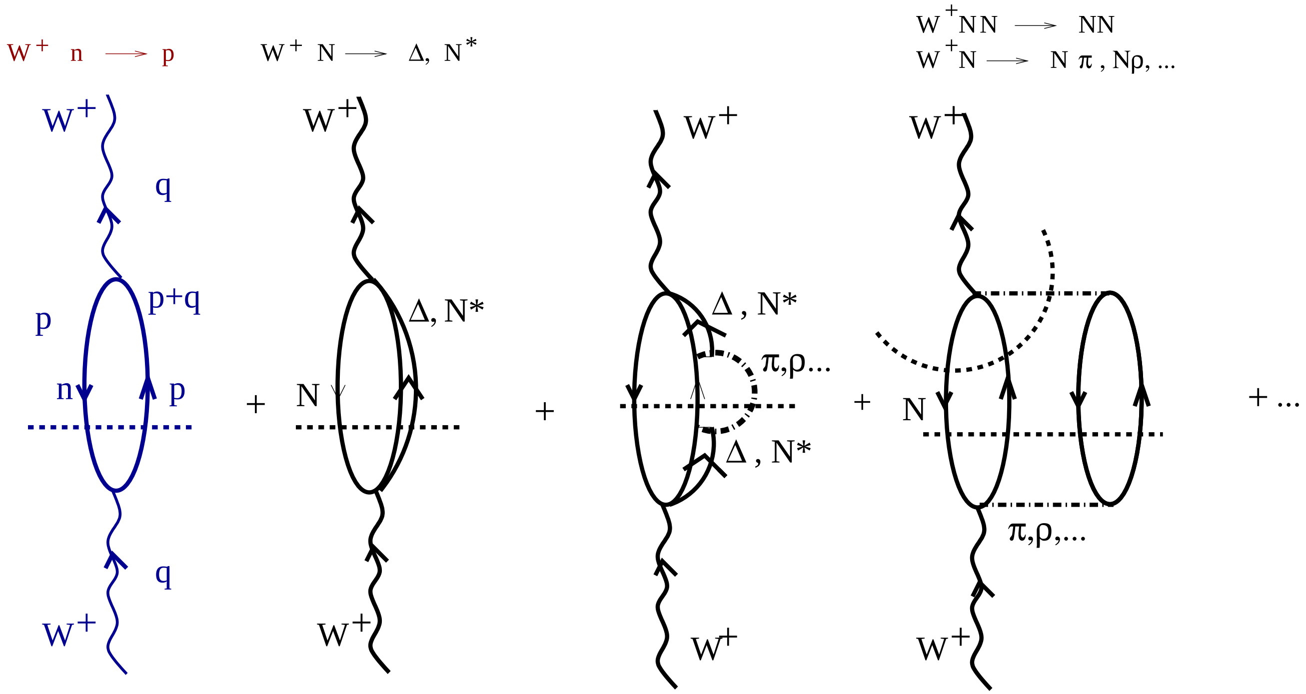
$$W_a^{\mu\sigma} \propto \int \frac{d^3r}{2\pi}\,\mathrm{Re}\,\left\{\Pi_W^{\mu\sigma}(q,\rho) - \Pi_W^{\sigma\mu}(q,\rho)\right\}\Theta(q^0)$$

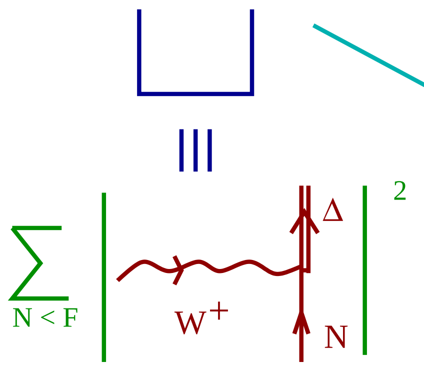
Basic object $\boxed{\Pi^{\nu\rho}_{W,Z^0,\gamma}(q,\rho)}$ $\equiv$ Selfenergy of the Gauge Boson $(W^\pm, Z^0, \gamma)$ inside of the nuclear medium. Perform a Many Body expansion, where the relevant gauge boson absorption modes should be systematically incorporated: absorption by one N, or NN or even 3N, real and virtual (MEC) meson $(\pi,\ \rho,\ \cdots)$ production, Δ excitation, etc...



QE

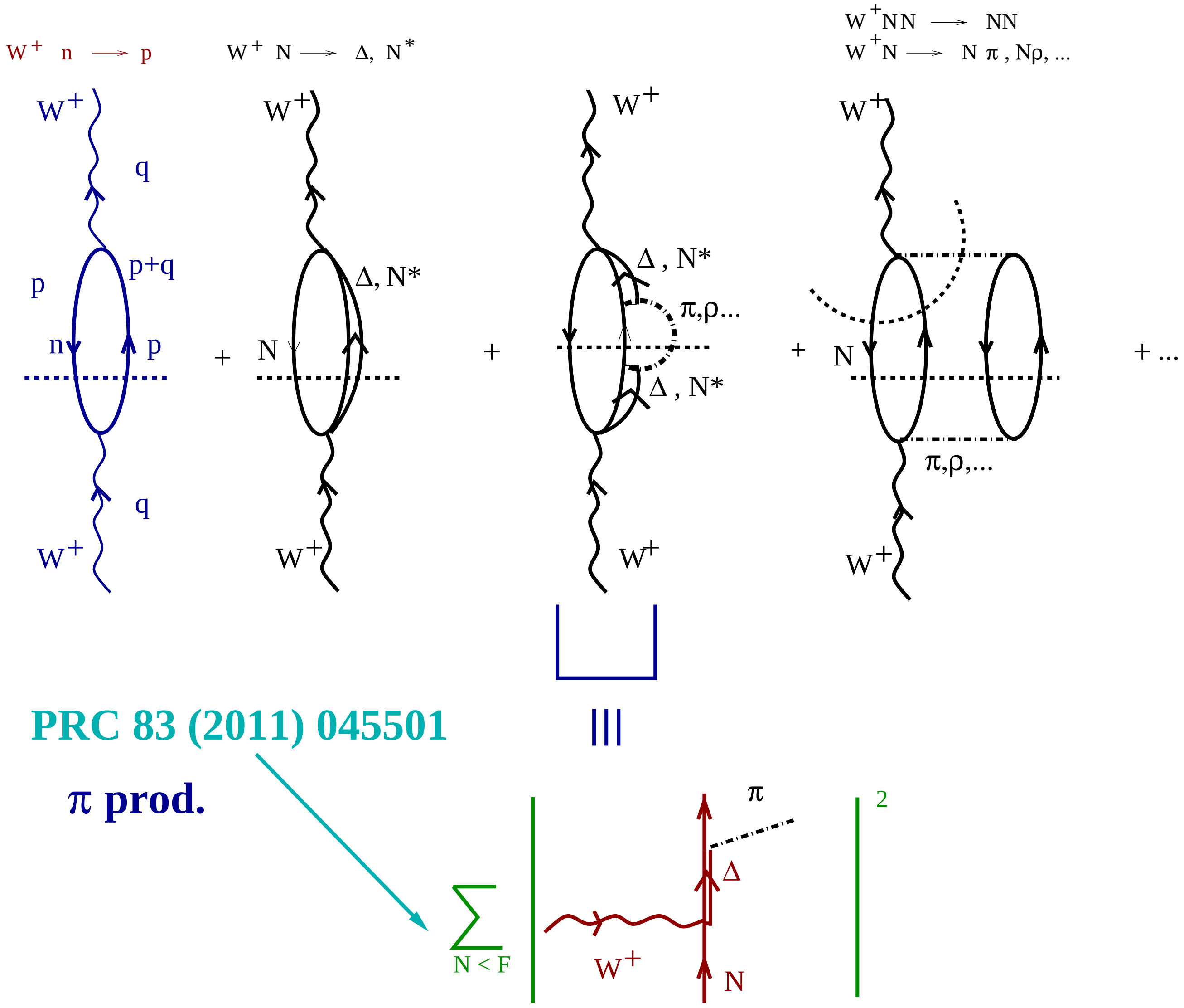
PRC 70 (2004) 055503 (CC)
PRC 73 (2006) 025504 (NC)

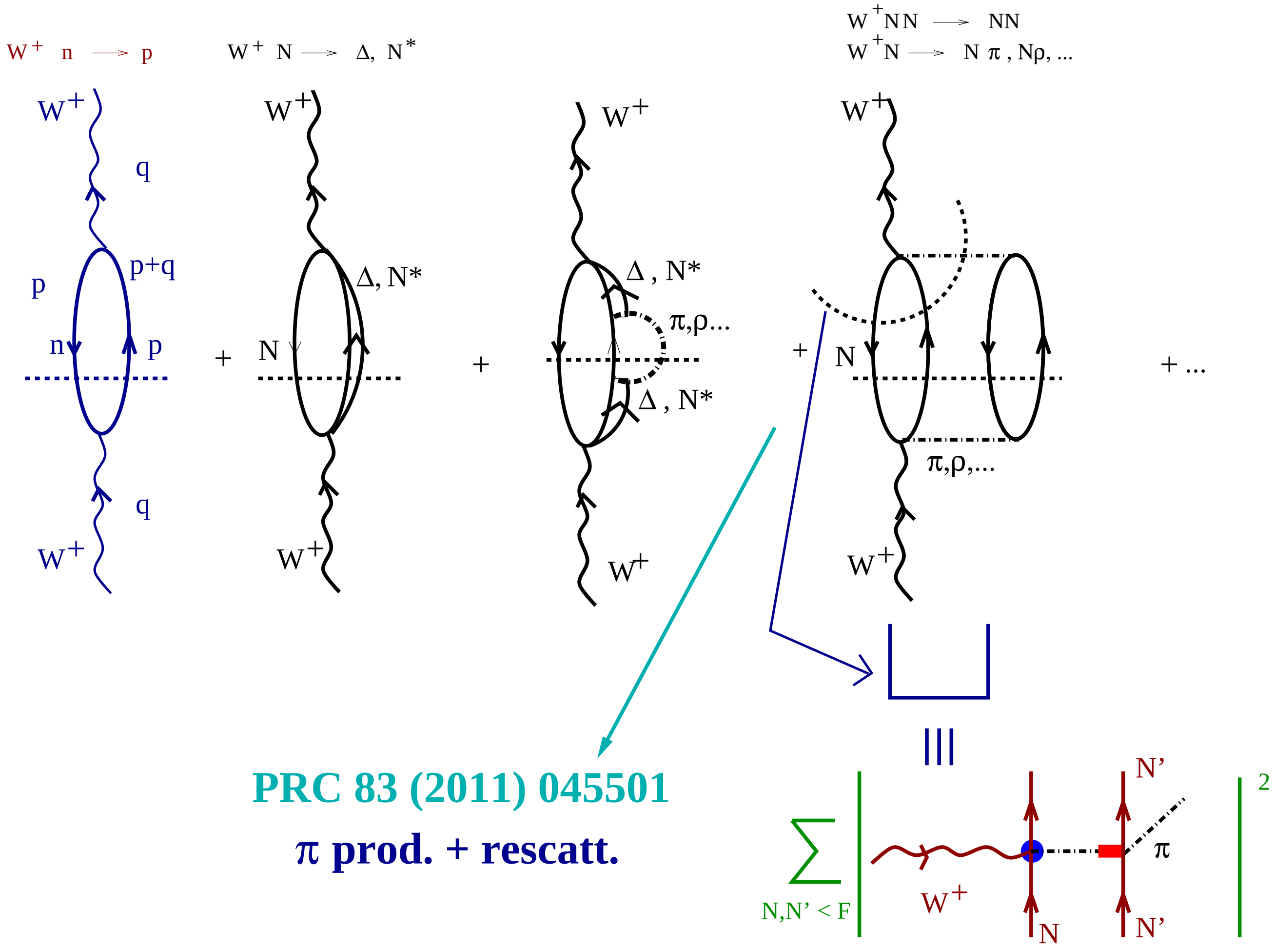




Δh prod.

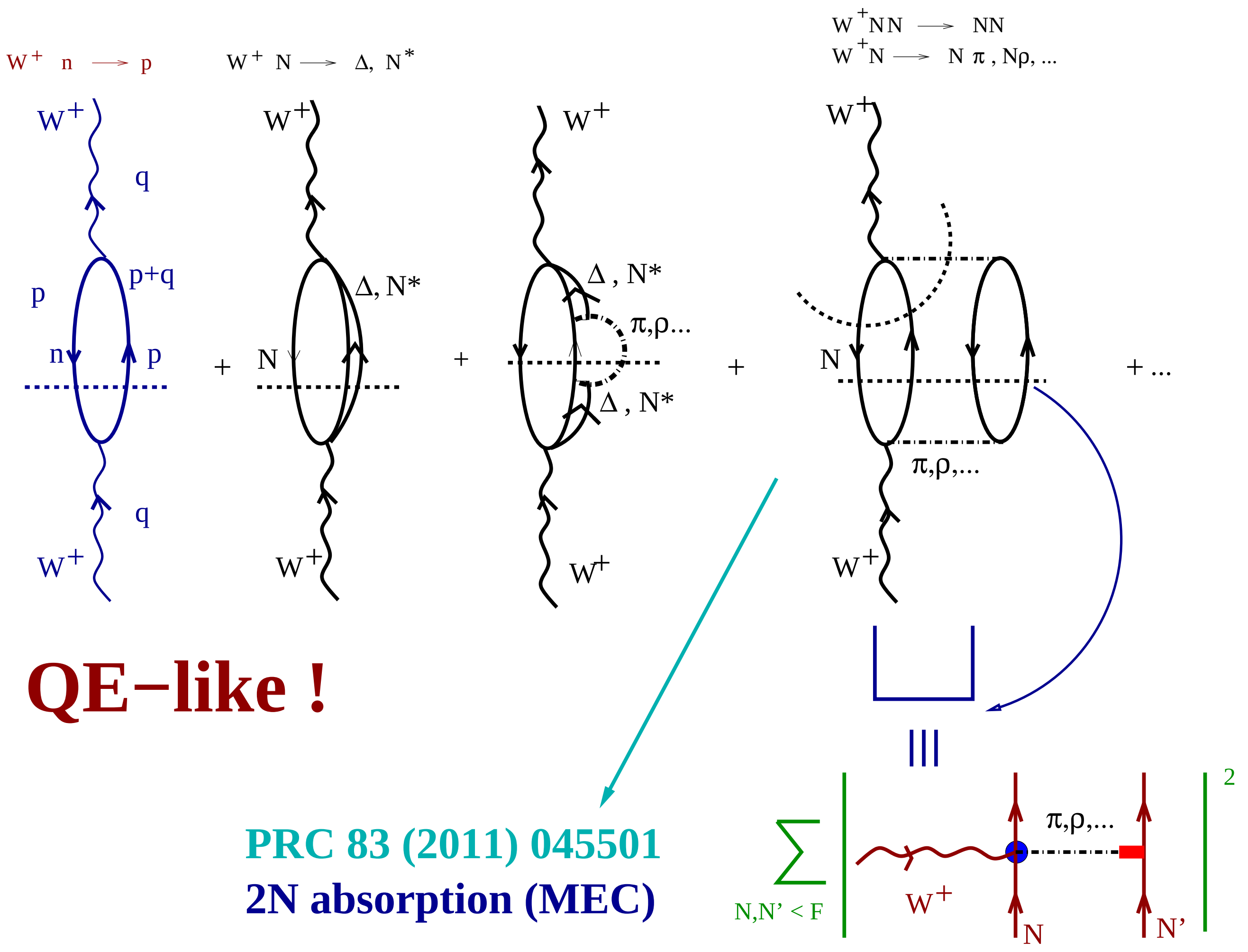
PRC 83 (2011) 045501


W+ n → p
W+ N → Δ, N*
W+NN → NN
W+N → N π , Nρ, ...
W+
q
p+q
p
n
p
Δ, N*
N
Δ , N*
π,ρ...
Δ , N*
N
π,ρ,...
+ ...
PRC 83 (2011) 045501
π prod.
π
Δ
N < F
W+
N
2



PRC 83 (2011) 045501

π prod. + rescatt.



QE−like !

PRC 83 (2011) 045501

2N absorption (MEC)

Inclusive QE processes [f.i. (ν_l, l)]

($W^\pm$, Z^0 absorption by one nucleon)

First ingredient: M.E. of the CC/NC current between nucleons.

$$< p; \vec{p}\,' = \vec{p} + \vec{q}\,|j^\alpha_{\rm cc}(0)|n; \vec{p}\;> \quad = \quad \bar{u}(\vec{p}\,')\,[V^\alpha - A^\alpha]\,u(p)$$

$$V^\alpha = 2\cos\theta_c \times \left(F_1^V(q^2)\gamma^\alpha + {\rm i}\mu_V \frac{F_2^V(q^2)}{2M}\sigma^{\alpha\nu}q_\nu \right)$$

$$A^\alpha = \cos\theta_c G_A(q^2) \times \left(\gamma^\alpha\gamma_5 + \frac{2M}{m_\pi^2 - q^2} q^\alpha\gamma_5 \right) \quad \textbf{(PCAC)}$$

with vector form factors related to the electromagnetic ones and

$$G_A(q^2) = \frac{g_A}{(1 - q^2/\boxed{M_A^2}\,)^2}, \quad g_A = 1.257$$

One finds (quasielastic peak)

$$W^{\mu\nu}_{s,a}(q) = -\frac{1}{2M^2}\int_0^\infty \mathbf{drr^2}\Bigg\{2\int \frac{d^3p}{(2\pi)^3}\frac{M}{E(\vec p)}\frac{M}{E(\vec p+\vec q)}\Theta(q^0)$$
$$\times\ \boldsymbol{\Theta}(\mathbf{k_F^n}(\mathbf{r}) - |\vec{\mathbf{p}}\,|)\boldsymbol{\Theta}(|\vec{\mathbf{p}}+\vec{\mathbf{q}}\,| - \mathbf{k_F^p}(\mathbf{r}))$$
$$\times\ (-\pi)\delta(q^0 + E(\vec p) - E(\vec p+\vec q\,))A^{\mu\nu}_{s,a}(p,q)\Bigg\}$$

Relativistic Local Fermi Gas that includes Pauli Blocking !

$$A^{\mu\nu}_s(p,q) = 16(F_1^V)^2\left\{(p+q)^\mu p^\nu + (p+q)^\nu p^\mu + \frac{q^2}{2}g^{\mu\nu}\right\}$$
$$+\ 2q^2(\mu_V F_2^V)^2\left\{4g^{\mu\nu} - 4\frac{p^\mu p^\nu}{M^2} - 2\frac{p^\mu q^\nu + q^\mu p^\nu}{M^2}\right.$$

$$
\begin{aligned}
&- \quad q^\mu q^\nu \left(\frac{4}{q^2} + \frac{1}{M^2}\right)\Bigg\} - 16 F_1^V \mu_V F_2^V \left(q^\mu q^\nu - q^2 g^{\mu\nu}\right) \\
&+ \quad 4 G_A^2 \Bigg\{ 2p^\mu p^\nu + q^\mu p^\nu + p^\mu q^\nu + g^{\mu\nu}\left(\frac{q^2}{2} - 2M^2\right) \\
&- \quad \frac{2M^2(2m_\pi^2 - q^2)}{(m_\pi^2 - q^2)^2} q^\mu q^\nu \Bigg\} \\
A_a^{\mu\nu}(p,q) \quad &= \quad 16 G_A \left(\mu_V F_2^V + F_1^V\right) \epsilon^{\mu\nu\alpha\beta} q_\alpha p_\beta
\end{aligned}
$$

- Nucleus dependence: $k_F^{p,n}(r) = [3\pi^2 \rho_{p,n}(r)]^{\frac{1}{3}}$, with $\rho_{p,n}(r)$ proton and neutron center densities.
- The leading contribution ($1ph$) in the density expansion, is fully relativistic.
- Analytical $\int d^3p$ integration in terms of the imaginary part of the relativistic ph Lindhard function:

$$\mathrm{Im}\bar{U}_R^N(q) = 2\int \frac{d^3p}{(2\pi)^3} \frac{M}{E(\vec{p})} \frac{M}{E(\vec{p}+\vec{q})} \Theta(k_F^n(r) - |\vec{p}\,|)$$
$$\Theta(q^0)\Theta(|\vec{p}+\vec{q}\,| - k_F^p(r))(-\pi)\delta(q^0 + E(\vec{p}) - E(\vec{p}+\vec{q}\,))$$

in addition we include some nuclear corrections...

- **Low Density Theorem.** For low densities

$$\mathrm{Im}\bar{U}_R^N(q) \approx -\pi\rho_n(r)\frac{M}{E(\vec{q})}\delta(q^0+M-E(\vec{q}))+\cdots$$

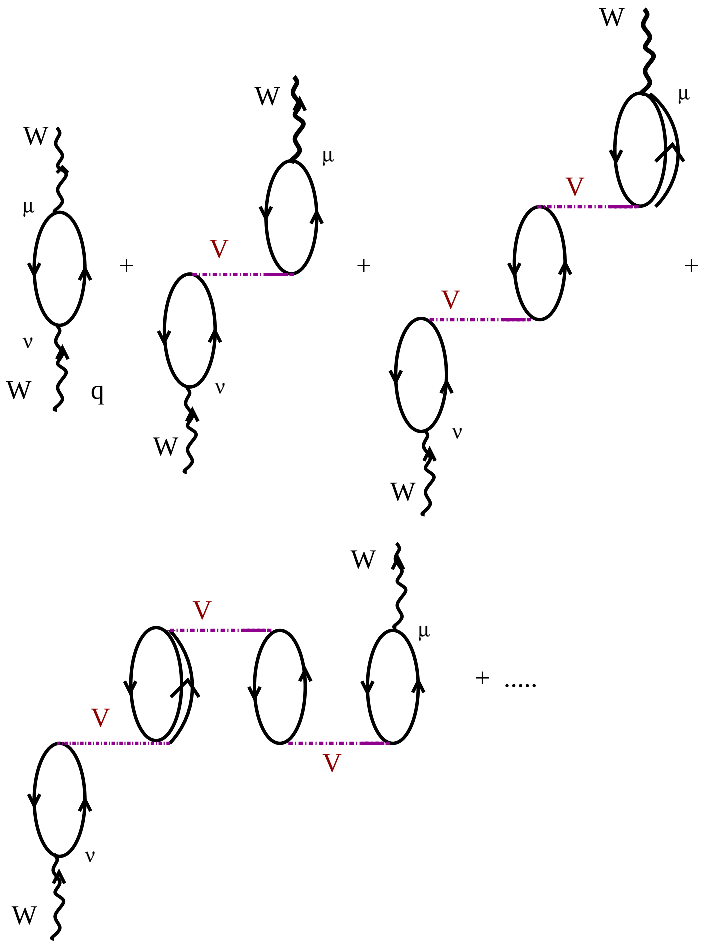
$\int d^3r \to \mathrm{N}$ (number of neutrons) and $\sigma_{\nu_l A\to l X} = \mathrm{N}\sigma_{\nu_l n\to l^- p}$

- Low energies:

1. Correct Energy Balance, incorporating the experimental Q value, $\to \delta(q^0 - \boxed{\mathrm{Q}} + E(\vec{p}) - E(\vec{p}+\vec{q}\,))$ with $Q = M(A_{Z+1}) - M(A_Z)$.
2. Coulomb distortion of outgoing lepton

$$(k'^2 - m_l^2 + \mathrm{i}\epsilon)^{-1} \to (k'^2 - m_l^2 - \boxed{\Sigma_{\mathrm{Coul}}} + \mathrm{i}\epsilon)^{-1}$$

- Polarization (RPA) effects. Substitute the ph excitation by an RPA response: series of ph and Δh excitations.



1. Effective Landau-Migdal interaction

$$V(\vec{r}_1,\vec{r}_2) = c_0\delta(\vec{r}_1-\vec{r}_2)\left\{\boxed{f_0(\rho)} + f_0'(\rho)\vec{\tau}_1\vec{\tau}_2 + \boxed{g_0(\rho)\vec{\sigma}_1\vec{\sigma}_2} + g_0'(\rho)\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2\right\}$$

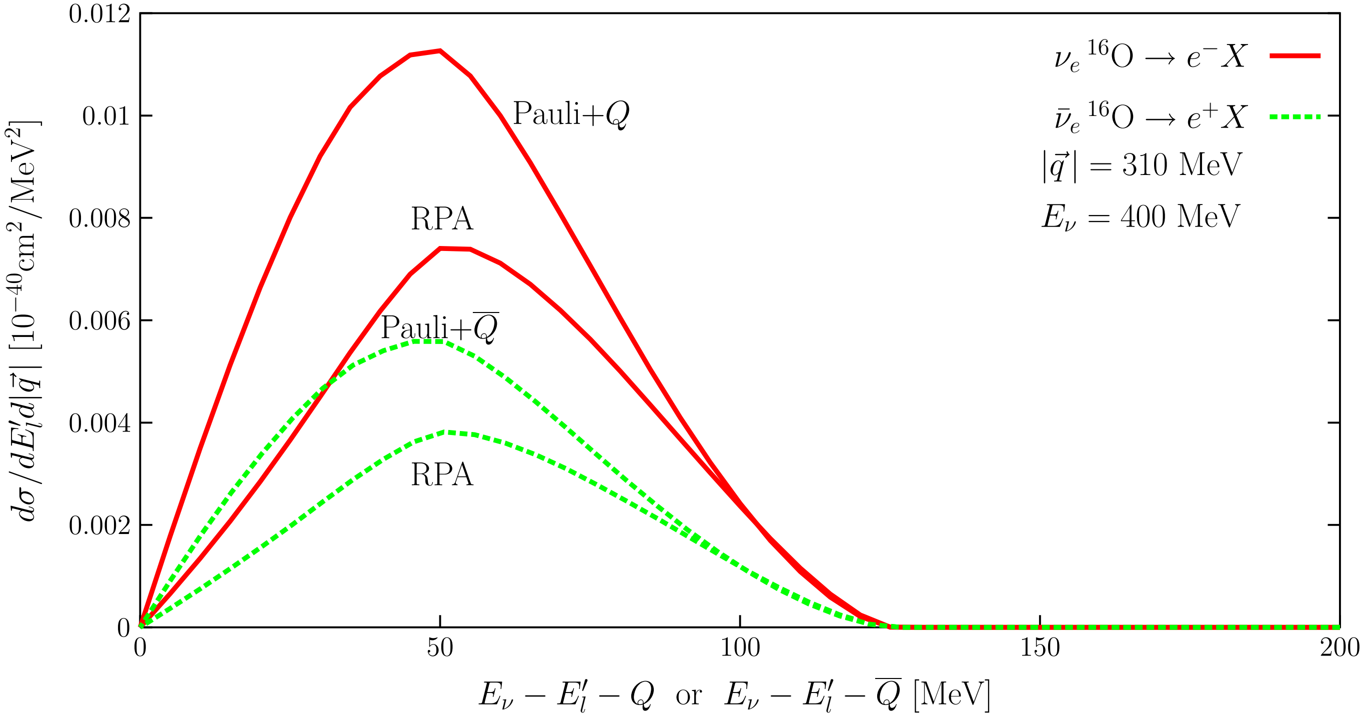
Isoscalar terms $\boxed{}$ do not contribute to CC

2. $S=T=1$ channel of the ph–ph interaction $\to$ s longitudinal (π) and transverse (ρ) + **SRC**

$$g_0'\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \to \left[V_l(q)\hat{q}_i\hat{q}_j + V_t(q)(\delta_{ij}-\hat{q}_i\hat{q}_j)\right]\sigma_1^i\sigma_2^j\vec{\tau}_1\vec{\tau}_2$$

$$V_{l,t}(q) = \frac{f_{\pi NN,\rho NN}}{m^2_{\pi,\rho}}\left(F_{\pi,\rho}(q^2)\frac{\vec{q}^{\,2}}{q^2-m^2_{\pi,\rho}} + g'_{l,t}(q)\right)$$

3. Contribution of Δh excitations important

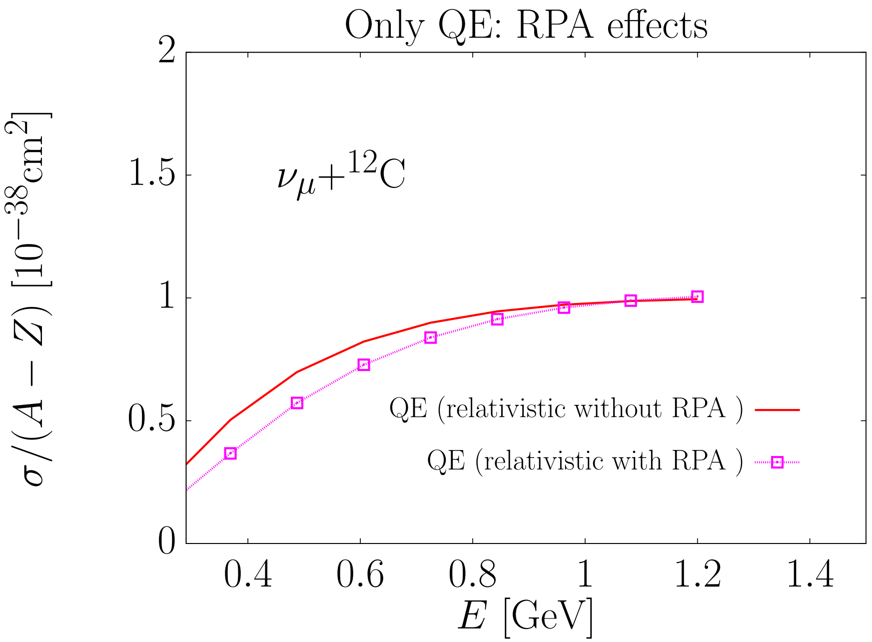


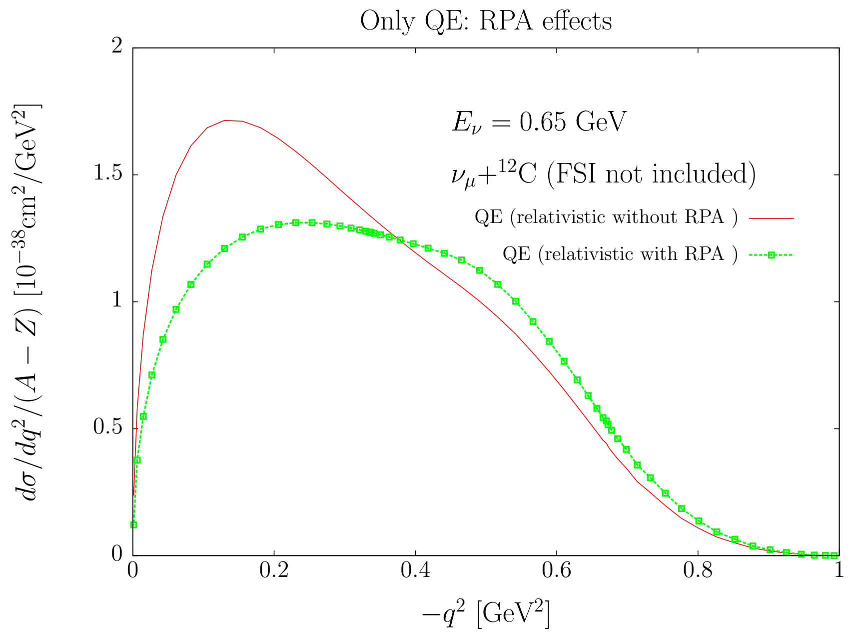
Examples of the RPA effect

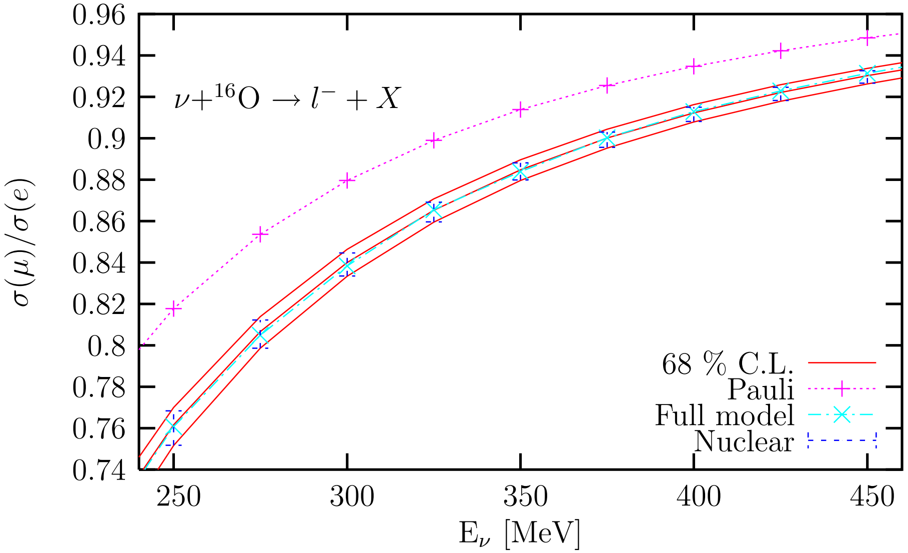
$$G_A^2 \delta^{ij} \quad \to \quad G_A^2 \left(\frac{\hat{q}^i \hat{q}^j}{|1 - U(q) V_l(q)|^2} + \frac{\delta^{ij} - \hat{q}^i \hat{q}^j}{|1 - U(q) V_t(q)|^2} \right)$$

$$(F_1^V)^2 \quad \to \quad \frac{(F_1^V)^2}{|1 - c_0 f'_0(\rho) U_N(q)|^2}, \quad \text{etc...}$$

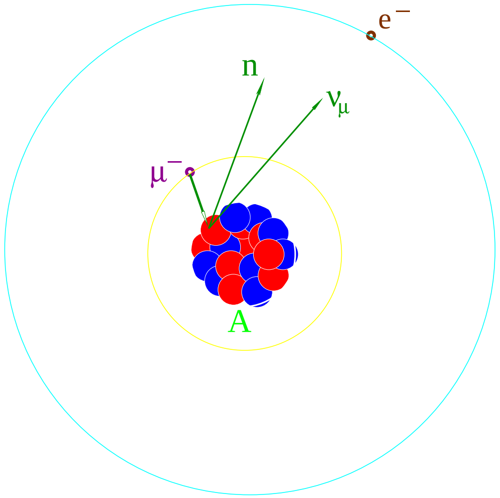
The Lindhard function $U(q) = U_N + U_\Delta \quad [ph + \Delta h]$





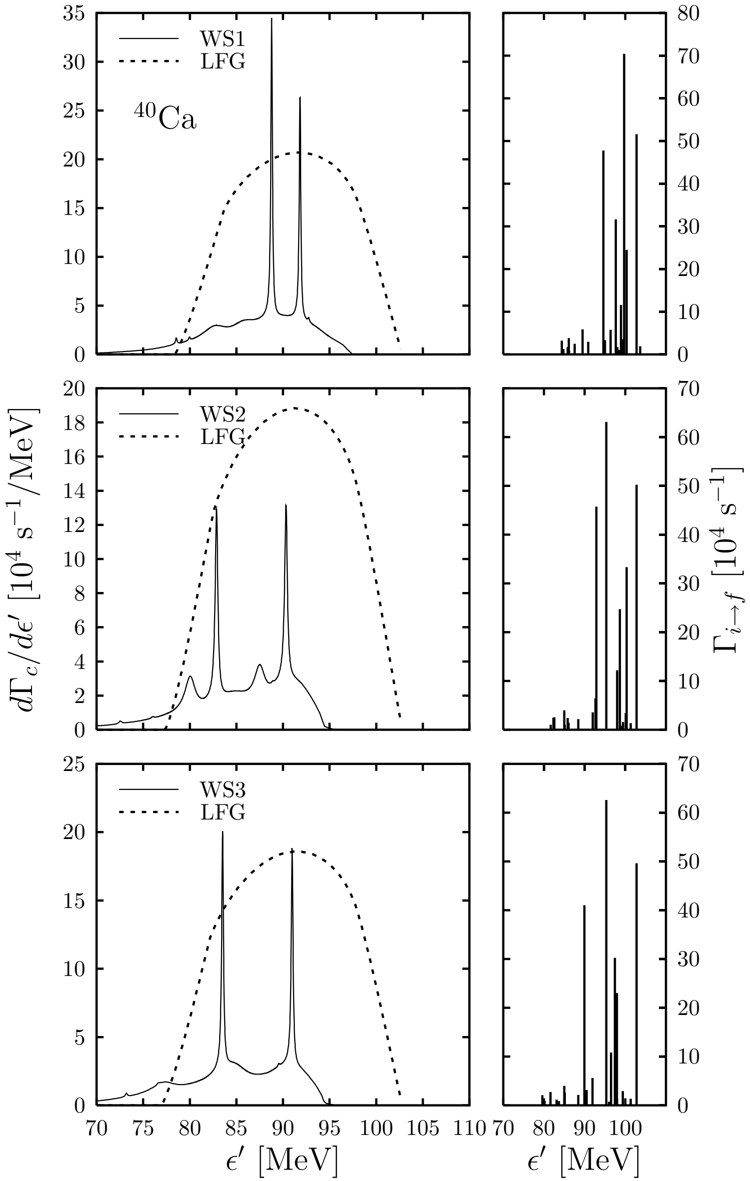


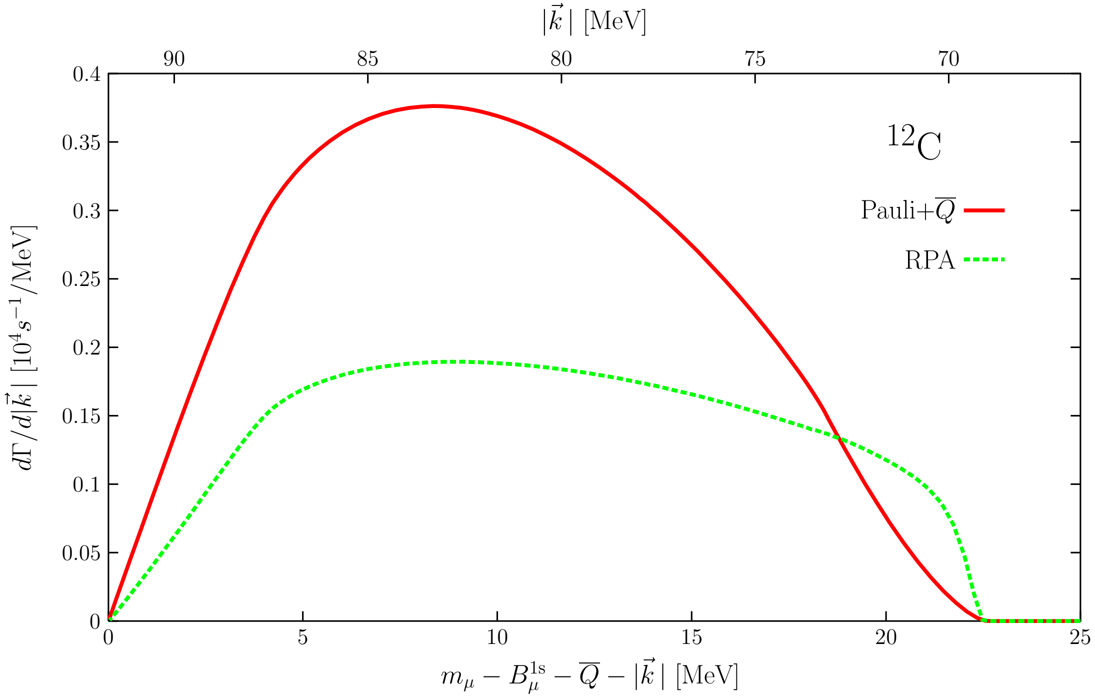
RPA corrections strongly decrease as the neutrino energy increases. However, their effects might account for a low Q^2 deficit of CCQE events and affect the σ_μ/σ_e ratio (~ 5 %)



Inclusive Muon Capture: $\Gamma\left[(A_Z - \mu^-)^{1s}_{\rm bound}\right]$

	Pauli $[10^4\ s^{-1}]$	RPA $[10^4\ s^{-1}]$	Exp $[10^4\ s^{-1}]$	$\left(\Gamma^{\rm Exp} - \Gamma^{\rm Th}\right)/\Gamma^{\rm Exp}$
^{12}C	5.42	3.21	3.78 ± 0.03	0.15
^{16}O	17.56	10.41	10.24 ± 0.06	−0.02
^{18}O	11.94	7.77	8.80 ± 0.15	0.12
^{23}Na	58.38	35.03	37.73 ± 0.14	0.07
^{40}Ca	465.5	257.9	252.5 ± 0.6	−0.02
^{44}Ca	318	189	179 ± 4	−0.06
^{75}As	1148	679	609 ± 4	−0.11
^{112}Cd	1825	1078	1061 ± 9	−0.02
^{208}Pb	1939	1310	1311 ± 8	0.00



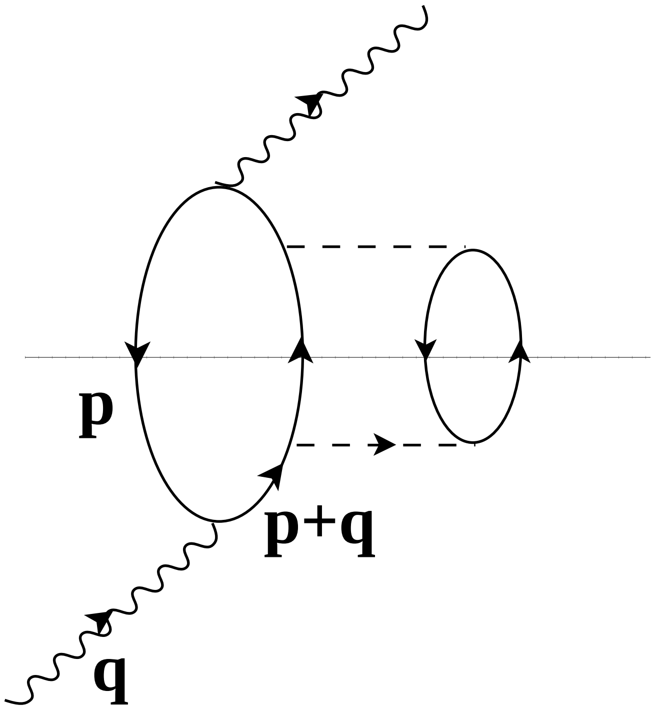


	discrete	total	LFG	%
WS1	29.10	37.12	36.73	−1.1
WS2	27.79	33.79	34.90	3.3
WS3	26.28	32.73	35.03	7.0

Nuclear Effects? SM vs FG

(Amaro, Nieves, Maieron and Valverde EPJA 24, 343)

- **Spectral Function (SF) + Final State Interaction (FSI):** dressing up the nucleon propagator of the hole (SF) and particle (FSI) states in the *ph* excitation



- **Change of nucleon dispersion relation:**
  * **hole ⇒ Interacting Fermi sea (SF)**
  * **particle ⇒ Interaction of the ejected nucleon with the final nuclear state (FSI)**

$$G(p) \to \int_{-\infty}^{\mu} d\omega \frac{S_h(\omega, \vec{p}\,)}{p^0 - \omega - i\epsilon} + \int_{\mu}^{+\infty} d\omega \frac{S_p(\omega, \vec{p}\,)}{p^0 - \omega + i\epsilon}$$

The hole and particle spectral functions are related to nucleon self-energy $\boxed{\Sigma}$ **in the medium,**

$$S_{p,h}(\omega,\vec{p}\,) \;=\; \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(\omega,\vec{p}\,)}{\left[\omega^2-\vec{p}^{\,2}-M^2-\mathrm{Re}\Sigma(\omega,\vec{p}\,)\right]^2+\left[\mathrm{Im}\Sigma(\omega,\vec{p}\,)\right]^2}$$

with $\omega \geq \mu$ or $\omega \leq \mu$ for S_p and S_h, respectively (μ is the chemical potential).

$$W^{\mu\nu}_{s,a}(q) \;\propto\; -\int_0^\infty \mathbf{dr}\,\mathbf{r^2}\left\{\int\frac{d^4p}{(2\pi)^4}A^{\mu\nu}_{s,a}(p,q)S_p(p+q)S_h(p)\right\}$$

The simplest description $\Rightarrow$ relativistic Fermi Gas

$$\text{chemical potential}: \mu \sim \frac{k_F^2}{2M}+\frac{\mathrm{Re}\Sigma(\mu,k_F)}{2E(k_F)}$$

with $E(\vec{p}\,)=\sqrt{M^2+\vec{p}^{\,2}}-E_B$, $\cdots$ **(P. Fernández de Córdoba and E. Oset, PRC46 (1992) 1697))**

$$S_{p,h}(\omega,\vec{p}\,) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(\omega,\vec{p}\,)}{\left[\omega^2-\vec{p}^{\,2}-M^2-\mathrm{Re}\Sigma(\omega,\vec{p}\,)\right]^2+\left[\mathrm{Im}\Sigma(\omega,\vec{p}\,)\right]^2}$$

with $\omega \geq \mu$ or $\omega \leq \mu$ for S_p and S_h, respectively (μ is the chemical potential).

$$W^{\mu\nu}_{s,a}(q) \propto -\int_0^\infty dr r^2 \left\{ \int \frac{d^4p}{(2\pi)^4} A^{\mu\nu}_{s,a}(p,q) S_p(p+q) S_h(p) \right\}$$

For non interacting fermions $\boxed{\Sigma = 0}$,

$$S_p(\omega,\vec{p}\,) = \frac{\theta(|\vec{p}\,|-k_F)}{2E(\vec{p}\,)}\delta(\omega-E(\vec{p}\,))$$

$$S_h(\omega,\vec{p}\,) = \frac{\theta(k_F-|\vec{p}\,|)}{2E(\vec{p}\,)}\delta(\omega-E(\vec{p}\,))$$

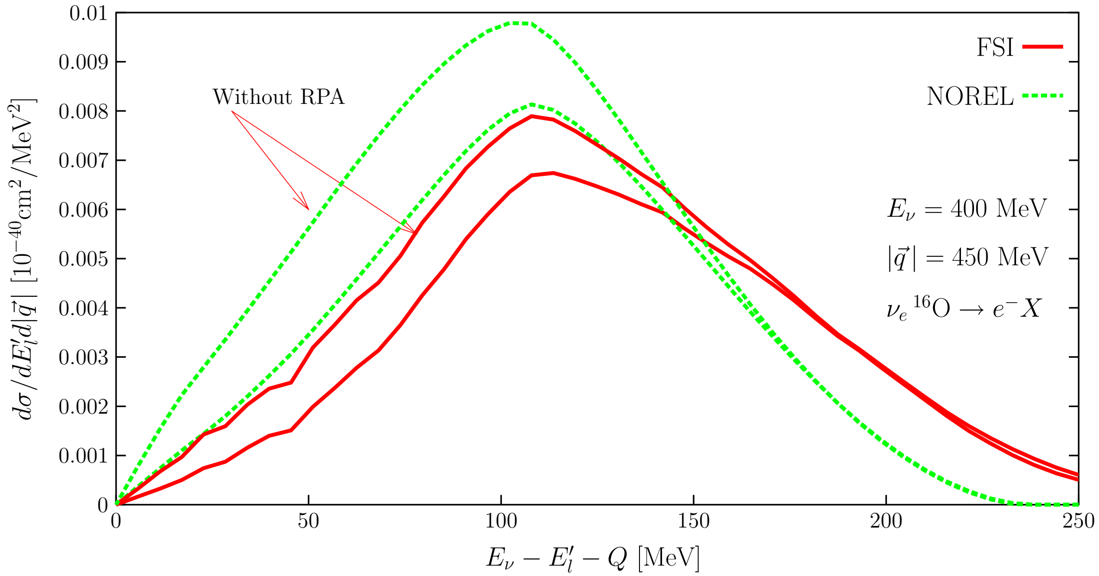
and only Pauli blocking is incorporated!!

To take into account SF+FSI $\rightarrow$ replace $\mathrm{Im}\bar{U}_R^N(q)$ by the response function:

$$-\frac{1}{2\pi}\int_0^{+\infty} dpp^2 \int_{-1}^{+1} dx \int_{\mu-q^0}^{\mu} d\omega \mathbf{S_h}(\omega, \vec{\mathbf{p}}) \mathbf{S_p}(\mathbf{q^0} + \omega, \mathbf{t})$$

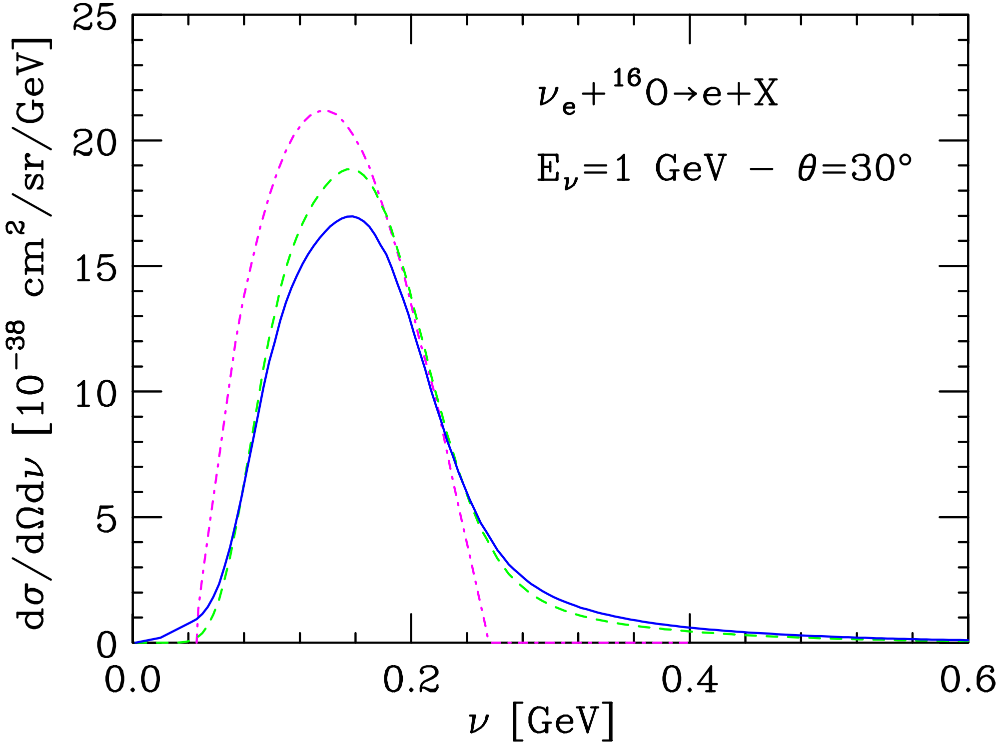
with $t^2 = \vec{p}^{\,2} + \vec{q}^{\,2} + 2|\vec{p}||\vec{q}|x$.

This nuclear effect is additional to those due to RPA (long range) correlations !!

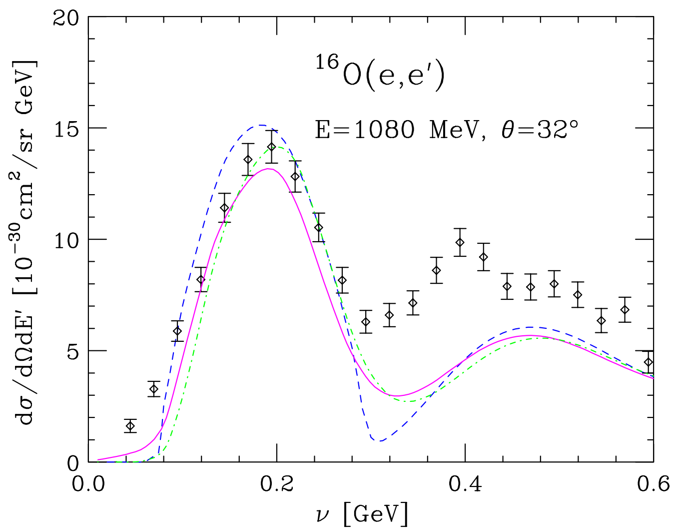


– **Sizeable reduction of the strength at the QE peak, which is slightly shifted. Neutrino energy re-construction uses $q^0 = -q^2/2M$, problems??**

– **Enhancement of the high energy transfer tail, which partially compensates the above reduction and thus the effect on the total (in-tegrated) cross section is smaller.**

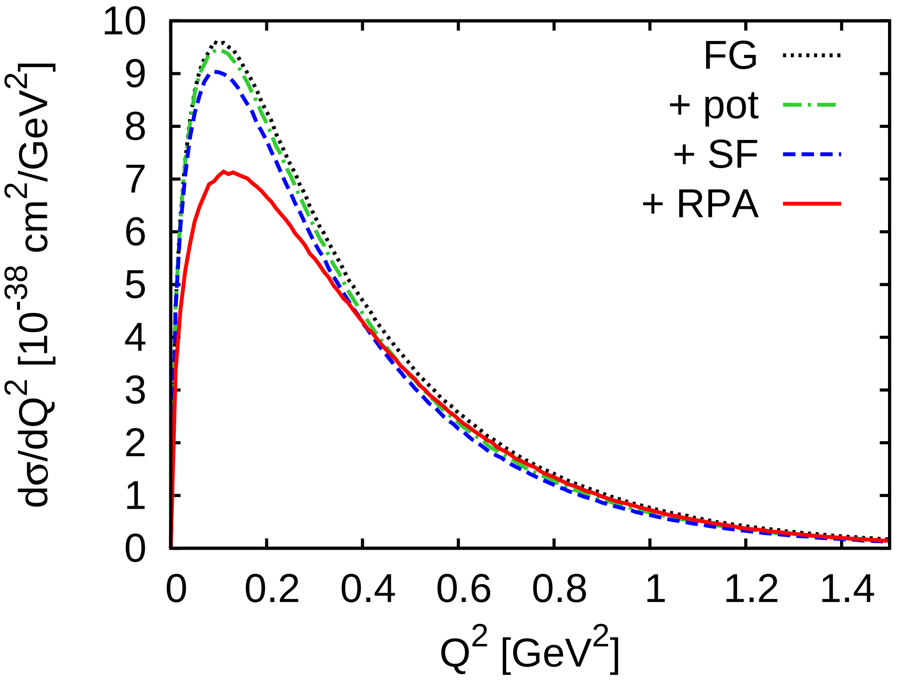


Qualitatively agreement with Benhar, Farina, Nakamura, Sakuda and Seki [PRD 72 (2005) 053005]



– RPA corrections are not included, but probably small for $|\vec{q}| \geq 500$ MeV

– Pion production and 2N channels should be included in the "dip" and Δ regions.



RPA vs SF effects: Differential cross sections for the CCQE reaction on ^{12}C averaged over the MiniBooNE flux.

RPA $\gg$ SF

The simplest description $\Rightarrow$ relativistic Fermi Gas with **non interacting fermions** $\boxed{\Sigma = 0}$,

$$\begin{aligned} S_p(\omega,\vec{p}\,) &= \frac{\theta(|\vec{p}\,|-k_F)}{2E(\vec{p}\,)}\delta(\omega - E(\vec{p}\,)) \\ S_h(\omega,\vec{p}\,) &= \frac{\theta(k_F-|\vec{p}\,|)}{2E(\vec{p}\,)}\delta(\omega - E(\vec{p}\,)) \end{aligned}$$

and only Pauli blocking is incorporated!!

Local vs Global Fermi Gas ?

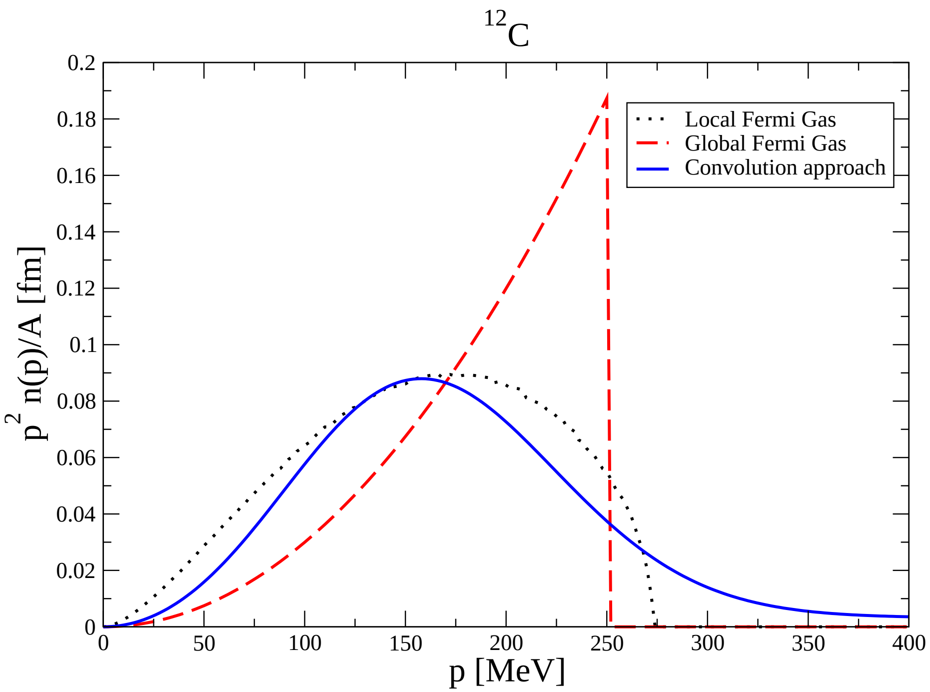
$k_F^{p,n}(r) = \left[3\pi^2\rho^{p,n}(r)\right]^{1/3}$ **vs** $k_F^{p,n}$**= cte ?**

Local vs Global Fermi Gas ?

$$k_F(r) = \left[3\pi^2\rho(r)/2\right]^{1/3} \textbf{ vs } k_F \textbf{= cte ?}$$

$$S_h(\omega,\vec{p}) = \delta(\omega - E(\vec{p}))\theta(k_F - |\vec{p}\,|)/2\omega$$

$$\begin{aligned} n^{\rm RgFG}(|\vec{p}\,|) &= \frac{4V}{(2\pi)^3}\int d\omega 2\omega S_h(\omega,\vec{p}) \\ &= \frac{3A}{4\pi k_F^3}\theta(k_F - |\vec{p}\,|) \\ n^{\rm LDA}(|\vec{p}\,|) &= 4\int\frac{d^3r}{(2\pi)^3}\int d\omega 2\omega S_h(\omega,\vec{p}) \\ &= 4\int\frac{d^3r}{(2\pi)^3}\theta(\mathbf{k_F(r)} - |\vec{p}\,|) \end{aligned}$$

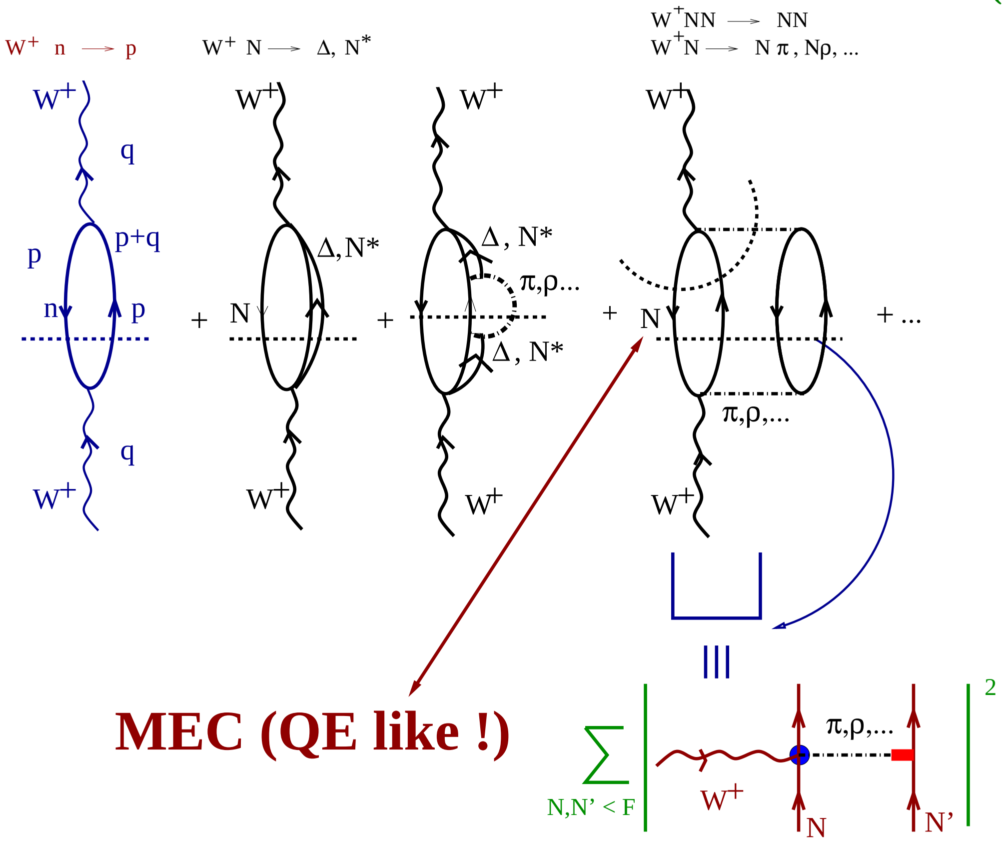


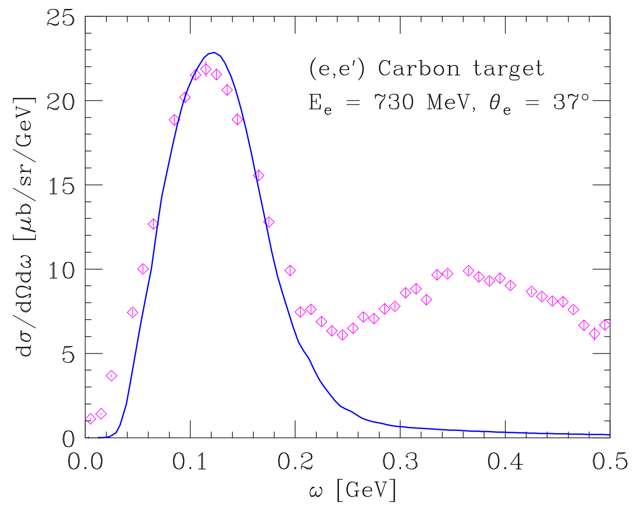
$$\left(\int d^3p\, n(|\vec{p}\,|) = A\right)$$

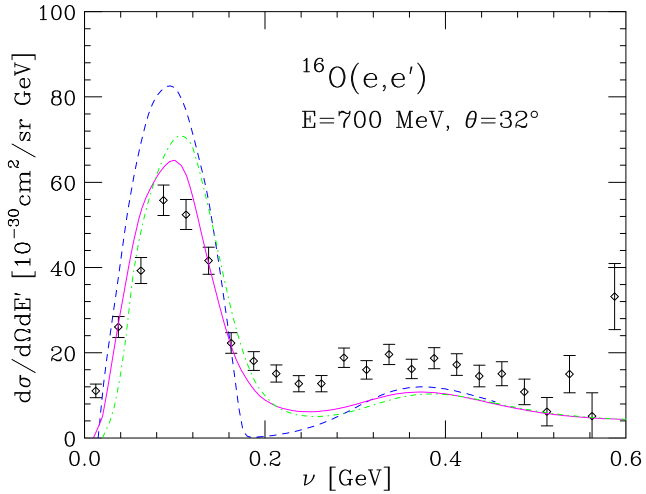
Convolution approach: C. Ciofi degli Atti, S. Liuti, and S. Simula, PRC 53, 1689 (1996), provide realistic distribution due to short-range correlations !

Above QE Region: π Production

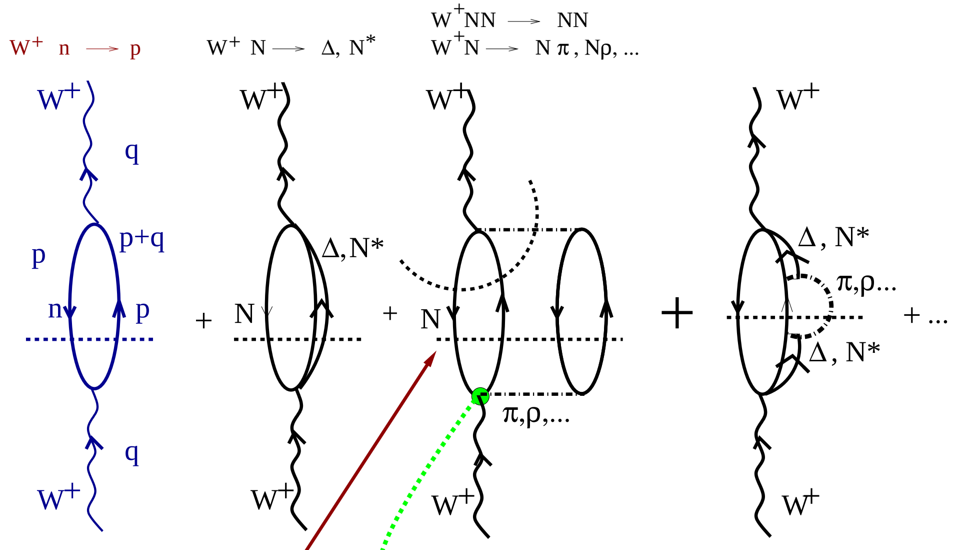
(e,e') PRL 105, 132301 & PRD 72 053005

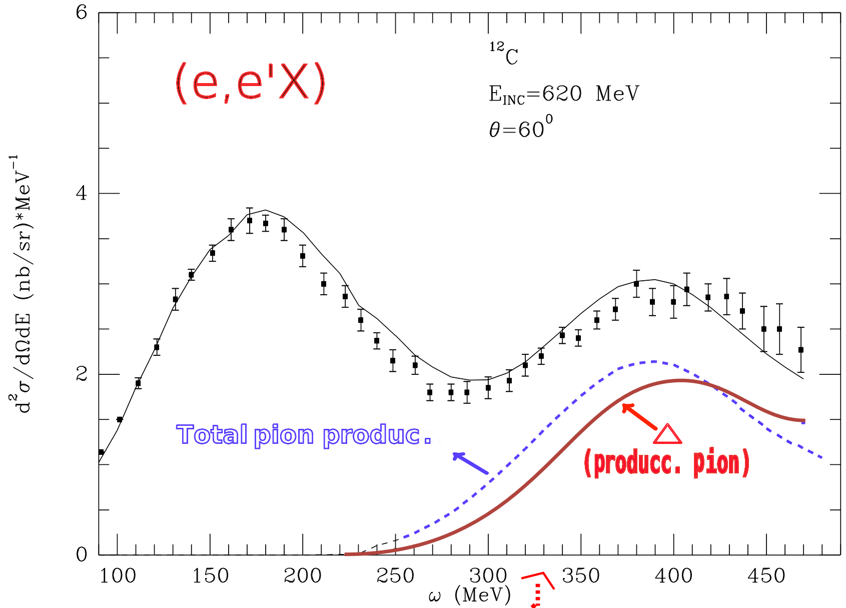






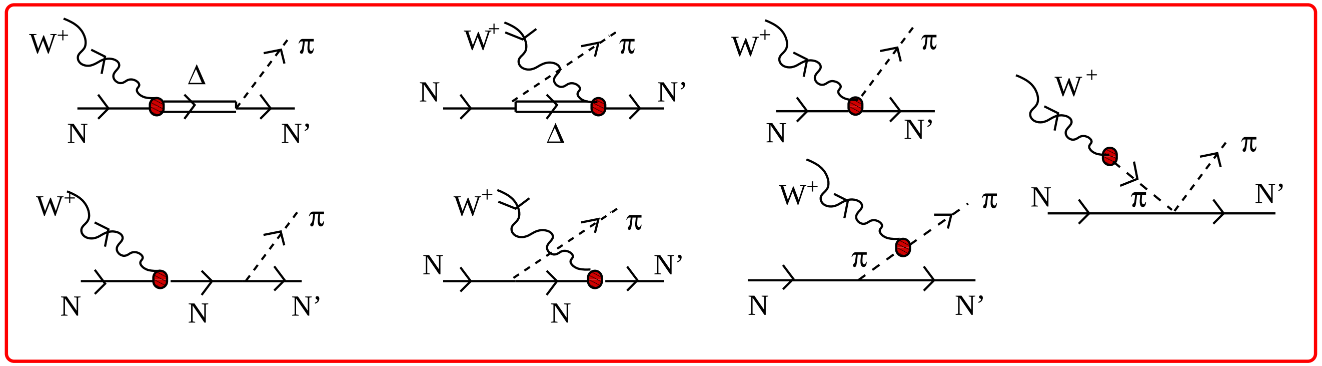
Above QE Region: π Production

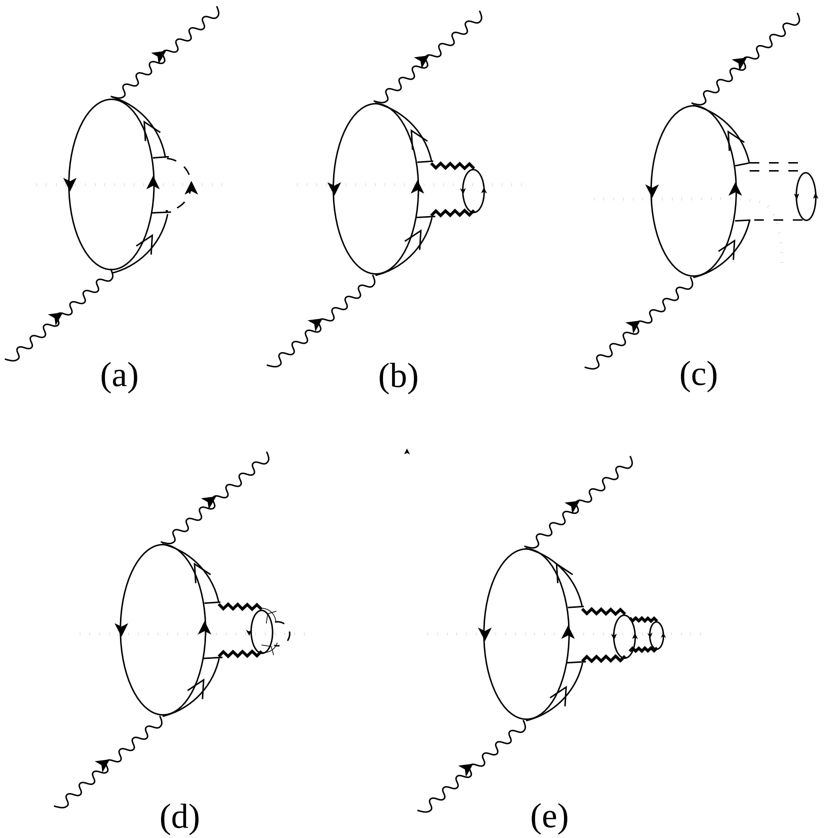


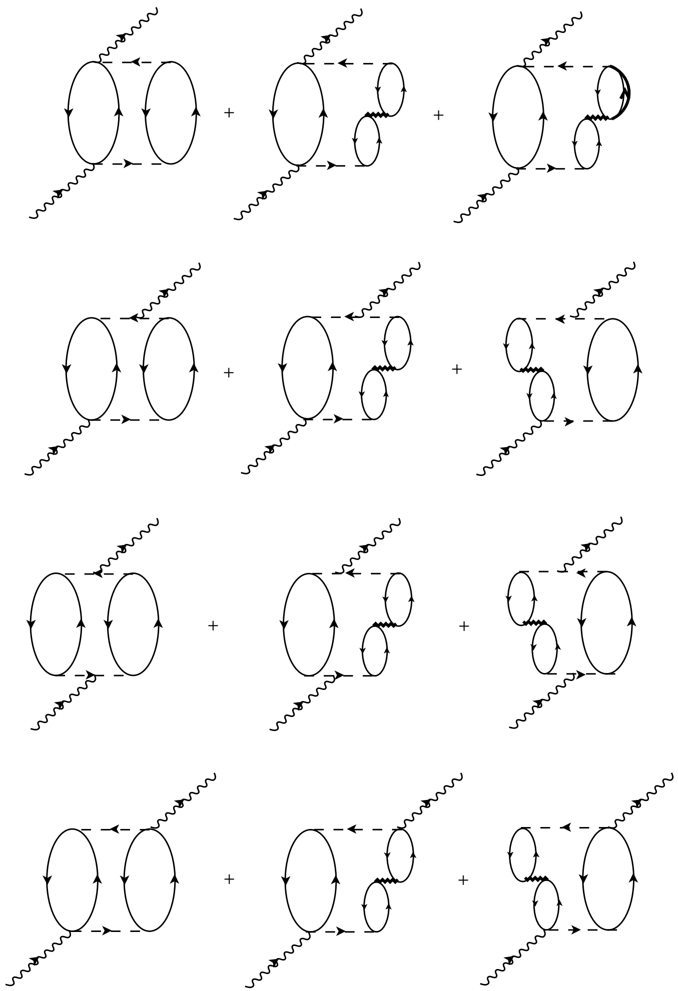


MEC ⟶ QE like !

PRD D76 (2007) 033005
PRD D81 (2010) 085046

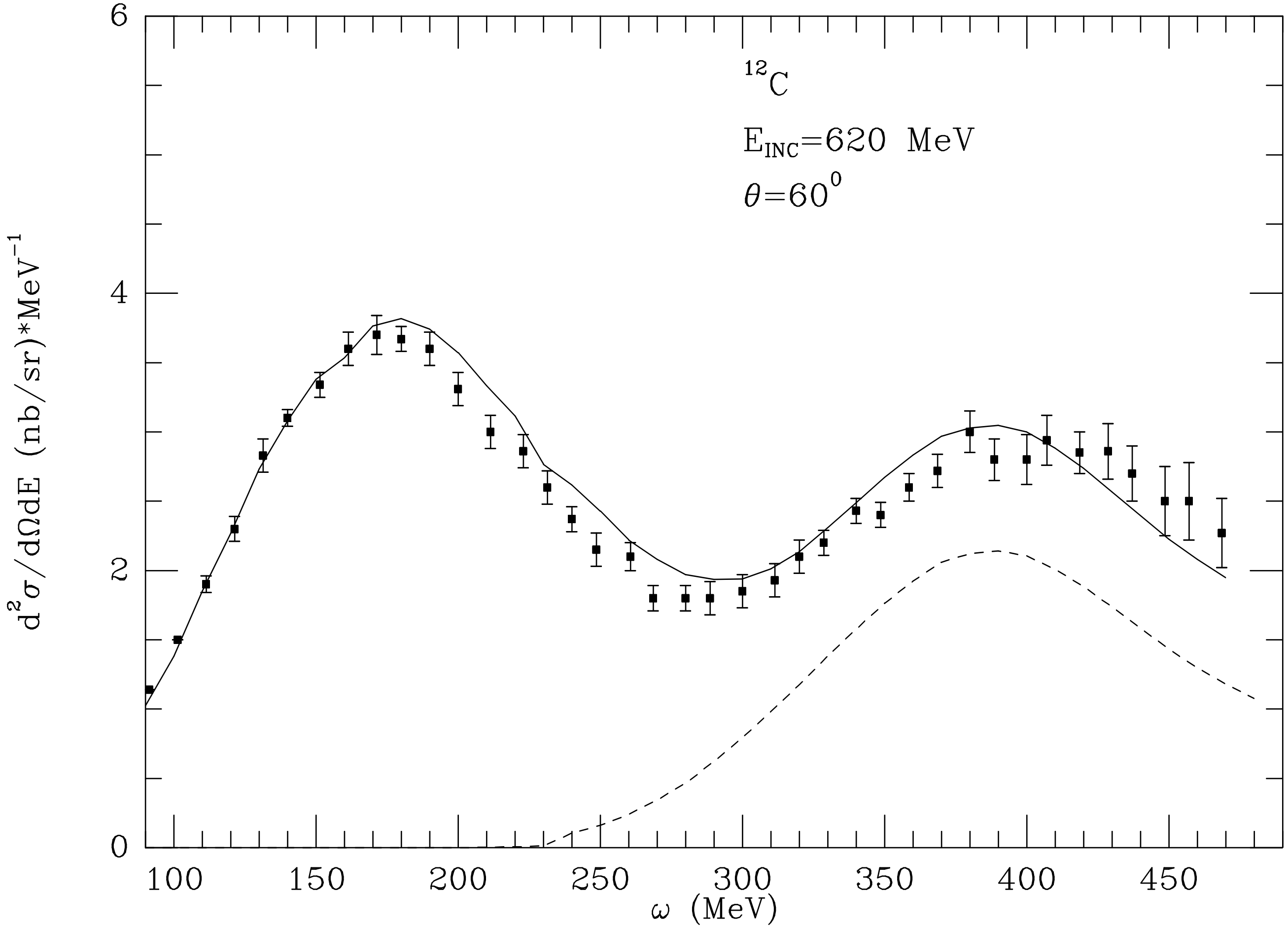



(a)
(b)
(c)
(d)
(e)

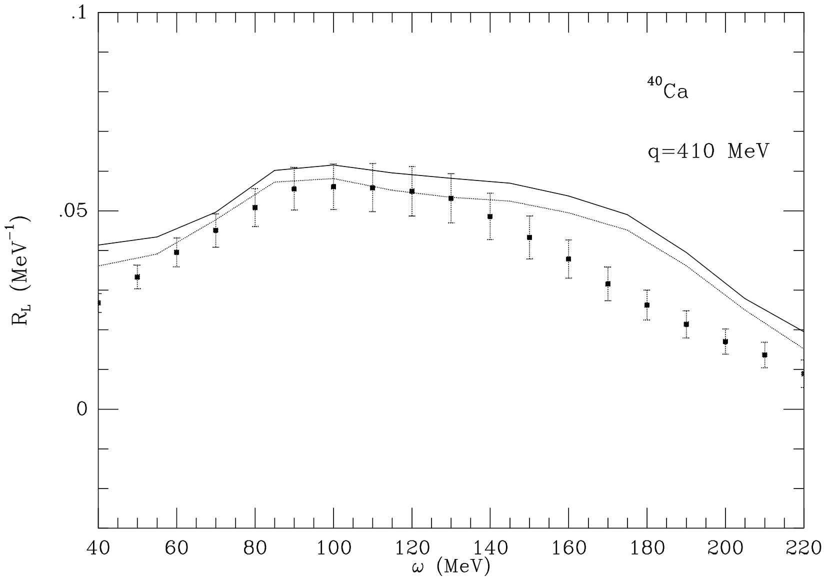


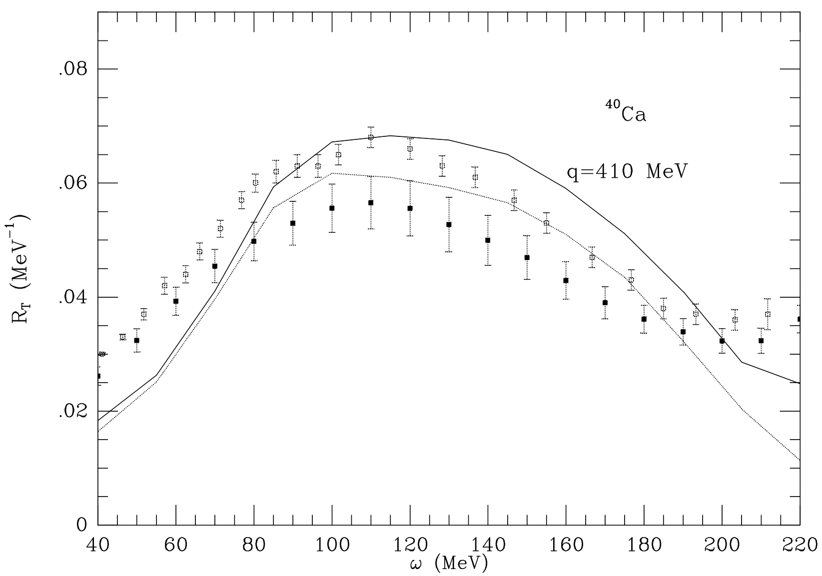
(e, e') Results

Same formalism applied to the study of inclusive processes (e, e'), $(e, e'N)$, $(e, e'NN)$, $(e, e'\pi)$, ... in nuclei at intermediate energies **[Gil+Nieves+Oset, NPA 627 (1997) 543-619]** leads to excellent results both in the quasielastic and Δ excitation regions. To describe the Δ peak and the "dip" regions, we include Δh and MEC contributions + ...



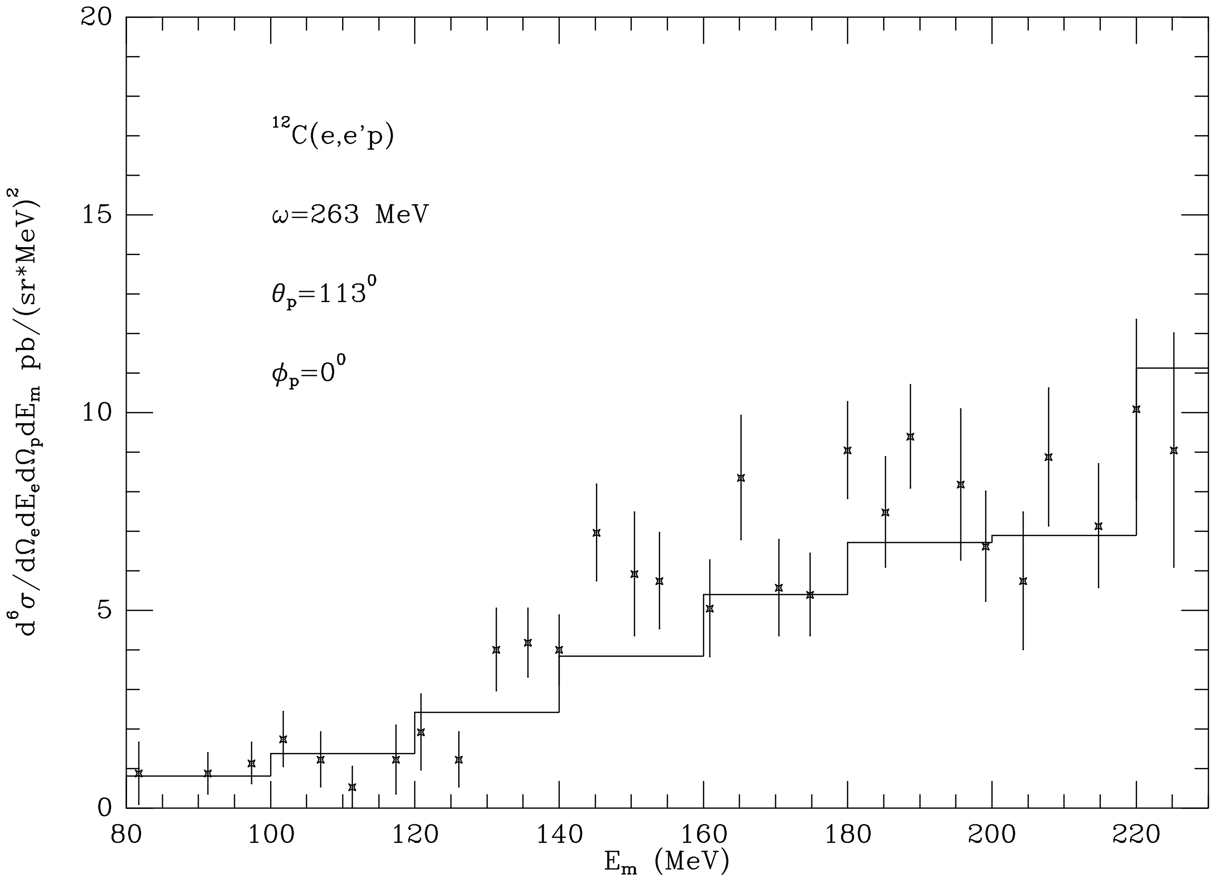
$$e + {}^{12}\mathrm{C} \rightarrow e' + X$$





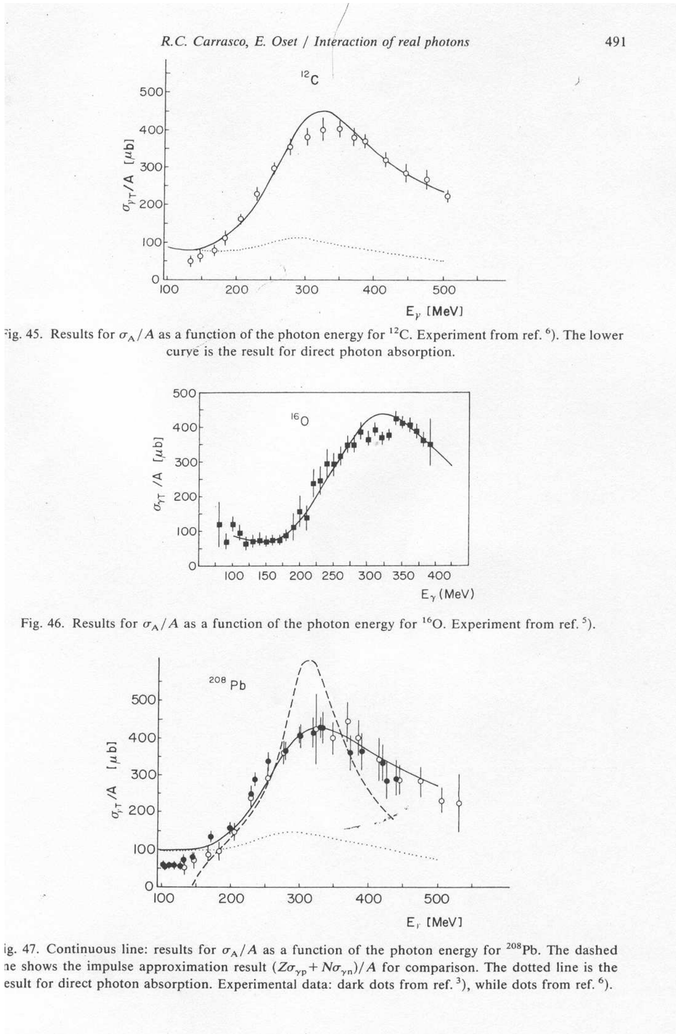
R_L and R_T QE response functions for $e + {}^{40}\mathrm{Ca} \to e' + X$

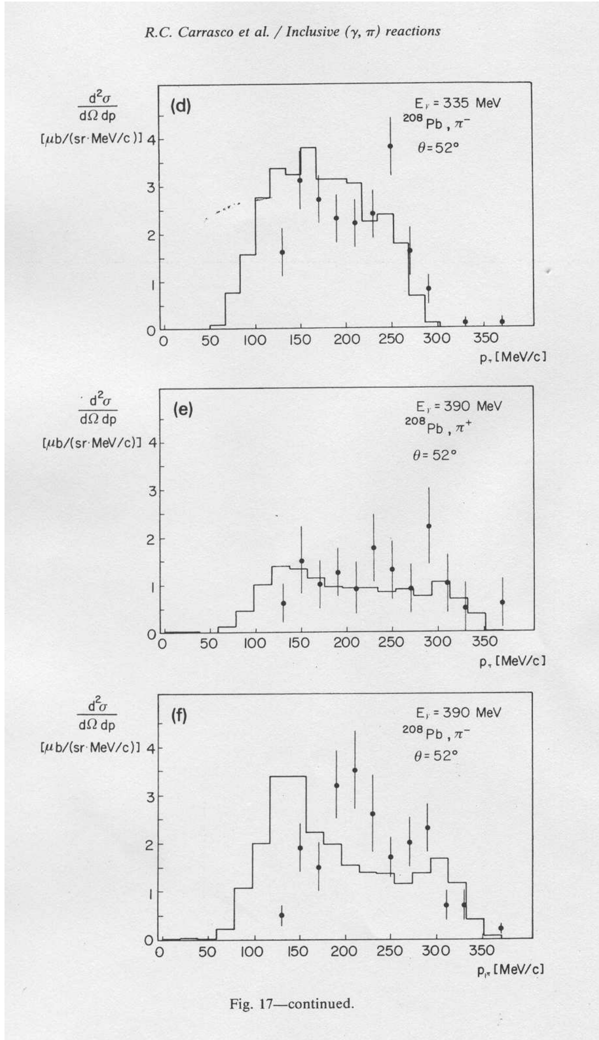
and by means of a Monte Carlo simulation we obtain cross sections for the processes $(e, e'N)$, $(e, e'NN)$, $(e, e'\pi)$, ...



Real Photon Results

Same formalism applied to the study of the interaction of Real Photons with Nuclei at Intermediate Energies: Total Photo-absorption cross section $\gamma A_Z \to X$ [Carrasco + Oset, NPA 536 (1992) 445] and Inclusive (γ,π), (γ,N), (γ,NN) and $(\gamma,N\pi)$ reactions [Carrasco + Oset + Salcedo NPA 541 (1992) 585 and Carrasco+Vicente-Vacas+ Oset NPA 570 (1994) 701]





$$\gamma + A \to X \qquad\qquad \gamma + {}^{208}\mathrm{Pb} \to X + \pi^{\pm}$$

Pion Physics

Same Many Body framework applied to the study of different nuclear processes involving pions at intermediate energies. For instance, pionic atoms, elastic and inelastic pion-nucleus scattering, Λ hypernuclei, etc.. Oset+Toki+Weise, Phys. Rep. 83 (1982) 281

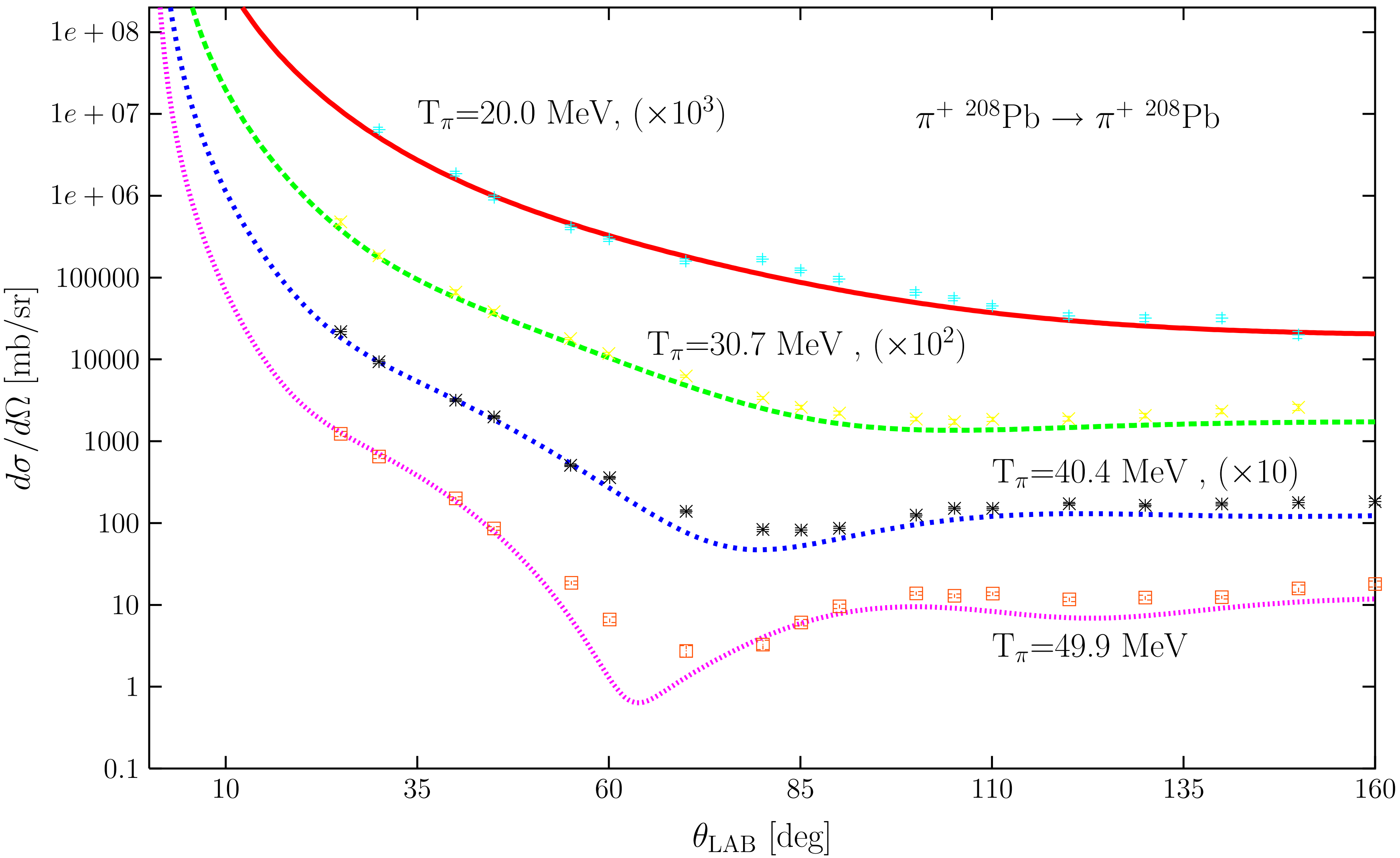
García-Recio+Oset+Salcedo+Strottman, NPA 526, 685

Nieves+Oset+García-Recio, NPA 554 (1993), 509-579

Nieves+Oset, PRC 47 (1993) 1478

Amaro+Nieves, PRL 89 (2002) 032501

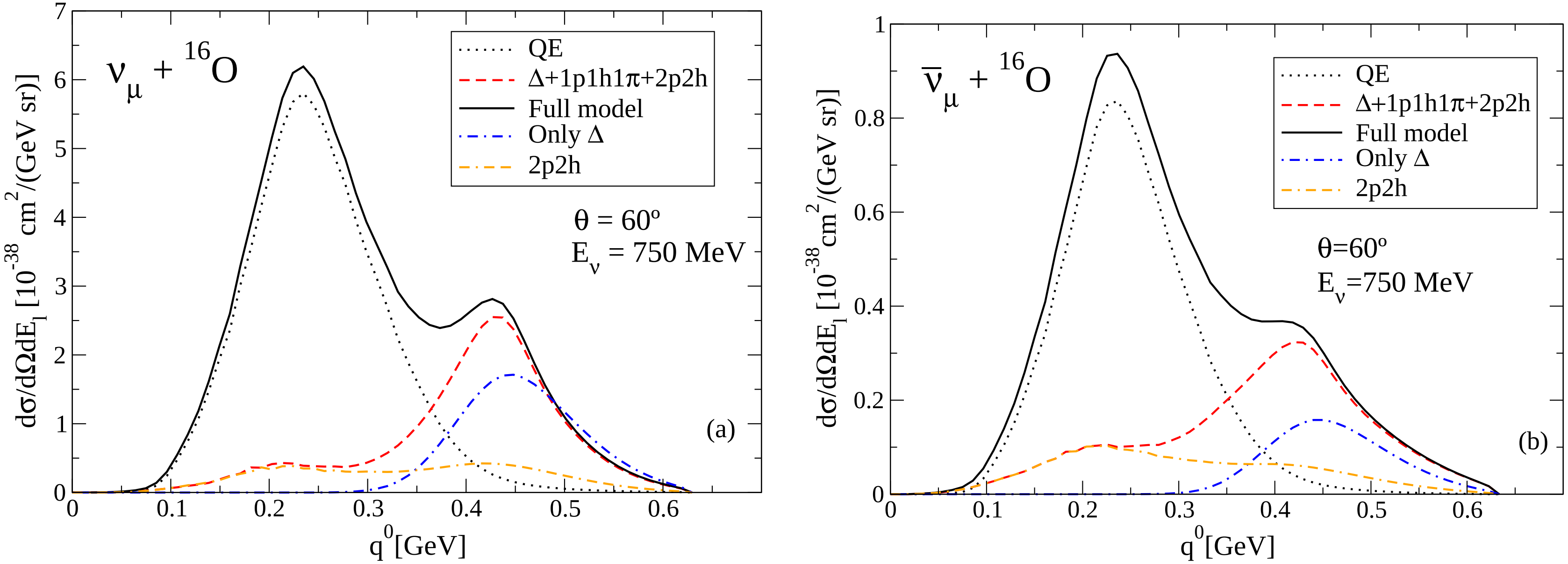
Albertus+Amaro+Nieves, PRC 67 (2003) 034604

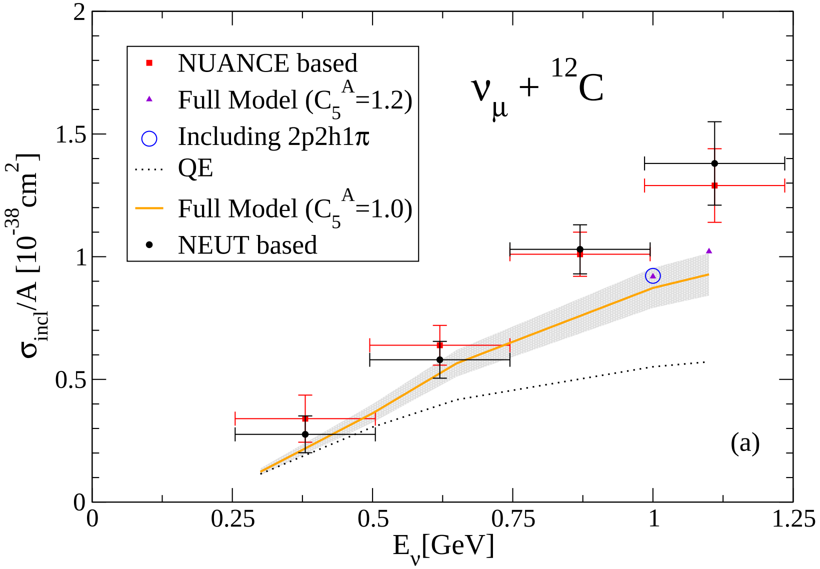


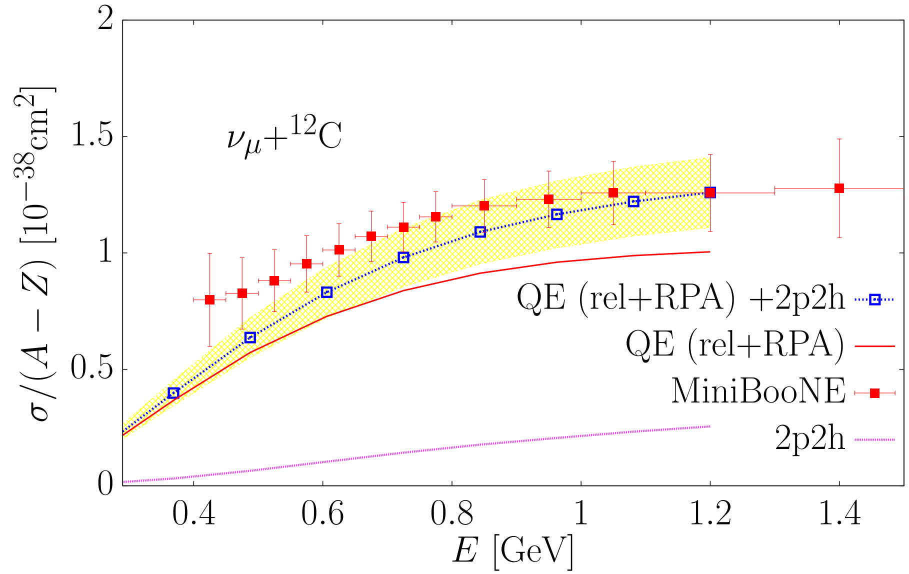
1e + 08
1e + 07
1e + 06
100000
10000
1000
100
10
1
0.1
dσ/dΩ [mb/sr]
10
35
60
85
110
135
160
θLAB [deg]
Tπ=20.0 MeV, (×10³)
π⁺ ²⁰⁸Pb → π⁺ ²⁰⁸Pb
Tπ=30.7 MeV , (×10²)
Tπ=40.4 MeV , (×10)
Tπ=49.9 MeV

(ν_μ, μ^-) Results

PRC 83 (2011) 045501 [M_A= 1.049 GeV]




NUANCE based
Full Model (C_5^A=1.2)
Including 2p2h1π
QE
Full Model (C_5^A=1.0)
NEUT based
$\nu_\mu + {}^{12}C$
(a)
σ_{incl}/A [10^{-38} cm^2]
E_ν[GeV]

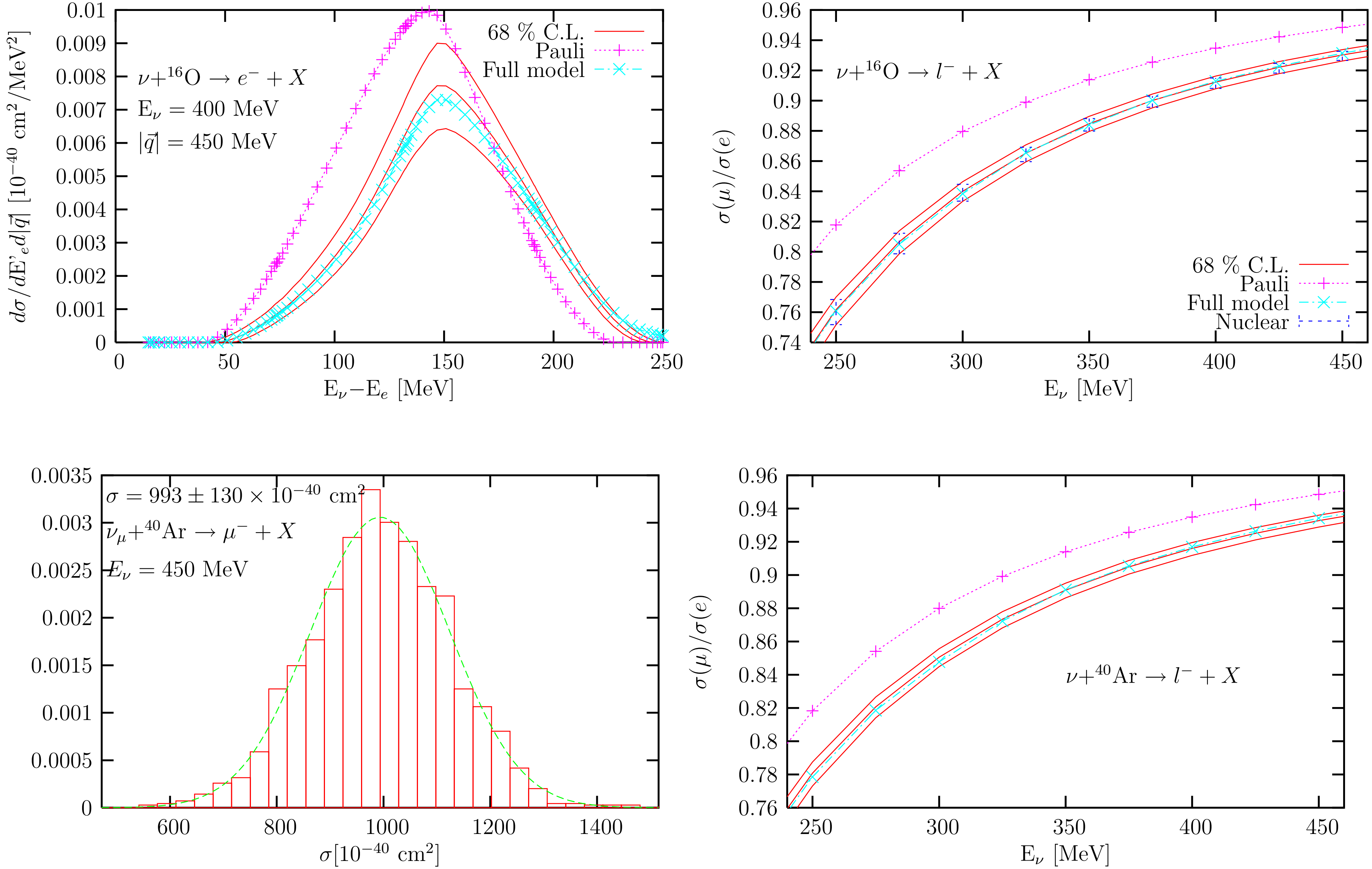

$\nu_\mu + {}^{12}C$
QE (rel+RPA) +2p2h
QE (rel+RPA)
MiniBooNE
2p2h
$\sigma/(A-Z)$ [10^{-38}cm^2]
E [GeV]

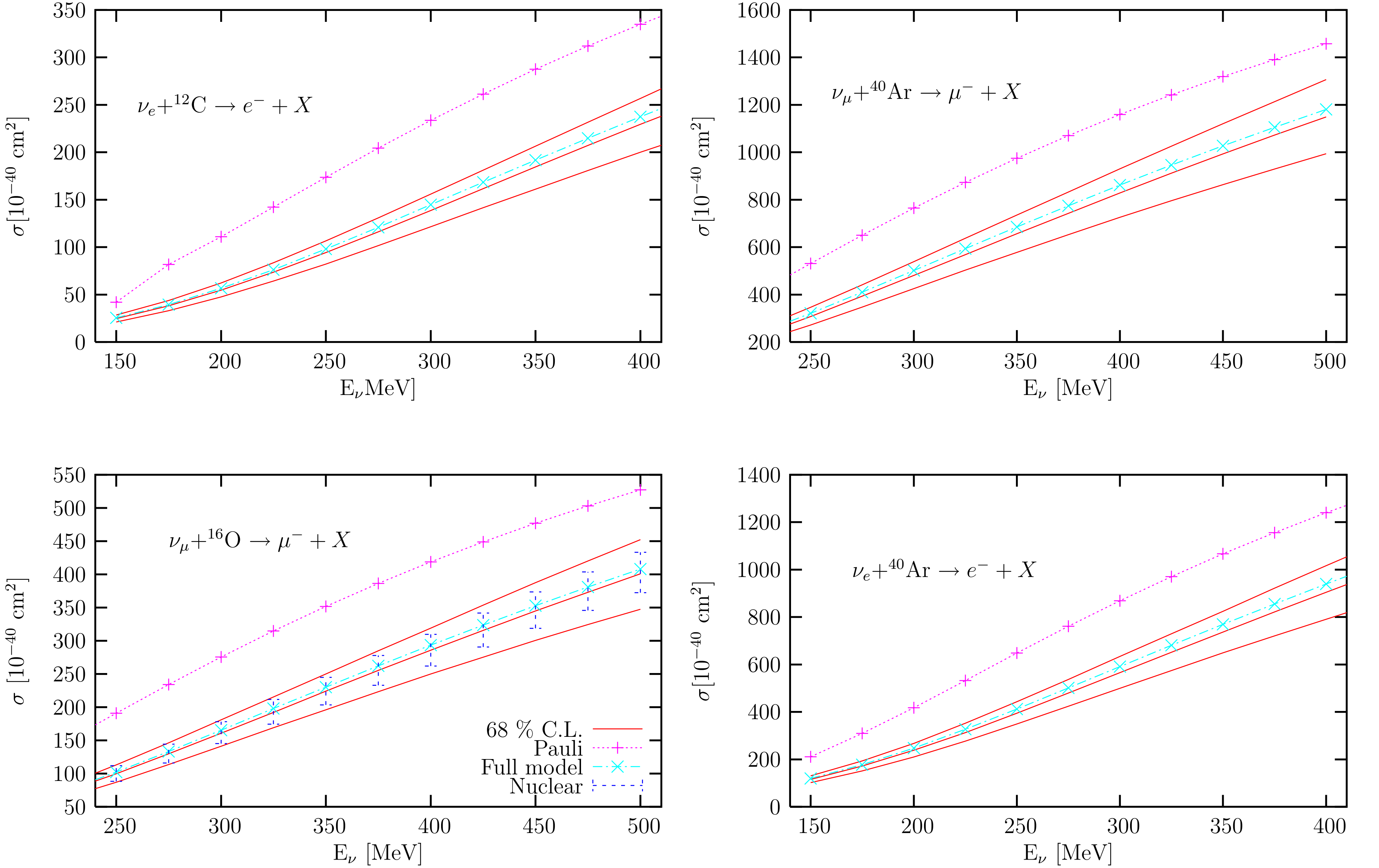
Theoretical Uncertainties: PLB 638,325

Predictions for CC and NC QE neutrino induced reactions in nuclei at intermediate energies of interest for future neutrino experiments. Uncertanties: $\sigma_{e,\mu} \sim 10 - 15\%$, $\sigma(\mu)/\sigma(e) \sim 5\%$

Form Factors					Nucleon Interaction				
M_D	$=$	0.843	$\pm$	0.042 GeV	$f_0^{\prime(in)}$	$=$	0.33	$\pm$	0.03
λ_n	$=$	5.6	$\pm$	0.6	$f_0^{(\prime ex)}$	$=$	0.45	$\pm$	0.05
M_A	$=$	1.05	$\pm$	0.14 GeV	f	$=$	1.00	$\pm$	0.10
g_A	$=$	1.26	$\pm$	0.01	f^*	$=$	2.13	$\pm$	0.21
					Λ_π	$=$	1200	$\pm$	120 MeV
					C_ρ	$=$	2.0	$\pm$	0.2
					Λ_ρ	$=$	2500	$\pm$	250 MeV
					g'	$=$	0.63	$\pm$	0.06

$+10\%$ in Σ (nucleon self-energy)


68 % C.L.
Pauli
Full model
$\nu + {}^{16}O \to e^- + X$
$E_\nu = 400$ MeV
$|\vec{q}| = 450$ MeV
$d\sigma/dE'_e d|\vec{q}|$ [10^{-40} cm^2/MeV^2]
$E_\nu - E_e$ [MeV]
$\nu + {}^{16}O \to l^- + X$
68 % C.L.
Pauli
Full model
Nuclear
$\sigma(\mu)/\sigma(e)$
E_ν [MeV]
$\sigma = 993 \pm 130 \times 10^{-40}$ cm^2
$\nu_\mu + {}^{40}Ar \to \mu^- + X$
$E_\nu = 450$ MeV
$\sigma[10^{-40}$ cm$^2]$
$\nu + {}^{40}Ar \to l^- + X$
$\sigma(\mu)/\sigma(e)$
E_ν [MeV]



350
300
250
200
150
100
50
0
150 200 250 300 350 400
$\sigma[10^{-40}\ \mathrm{cm}^2]$
E_νMeV]
ν_e+^{12}C $\rightarrow e^- + X$
1600
1400
1200
1000
800
600
400
200
250 300 350 400 450 500
$\sigma[10^{-40}\ \mathrm{cm}^2]$
E_ν [MeV]
ν_μ+^{40}Ar $\rightarrow \mu^- + X$
550
500
450
400
350
300
250
200
150
100
50
250 300 350 400 450 500
$\sigma\ [10^{-40}\ \mathrm{cm}^2]$
E_ν [MeV]
ν_μ+^{16}O $\rightarrow \mu^- + X$
68 % C.L.
Pauli
Full model
Nuclear
1400
1200
1000
800
600
400
200
0
150 200 250 300 350 400
$\sigma[10^{-40}\ \mathrm{cm}^2]$
E_ν [MeV]
ν_e+^{40}Ar $\rightarrow e^- + X$

MiniBooNE CCQE-like double differential cross section $\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$

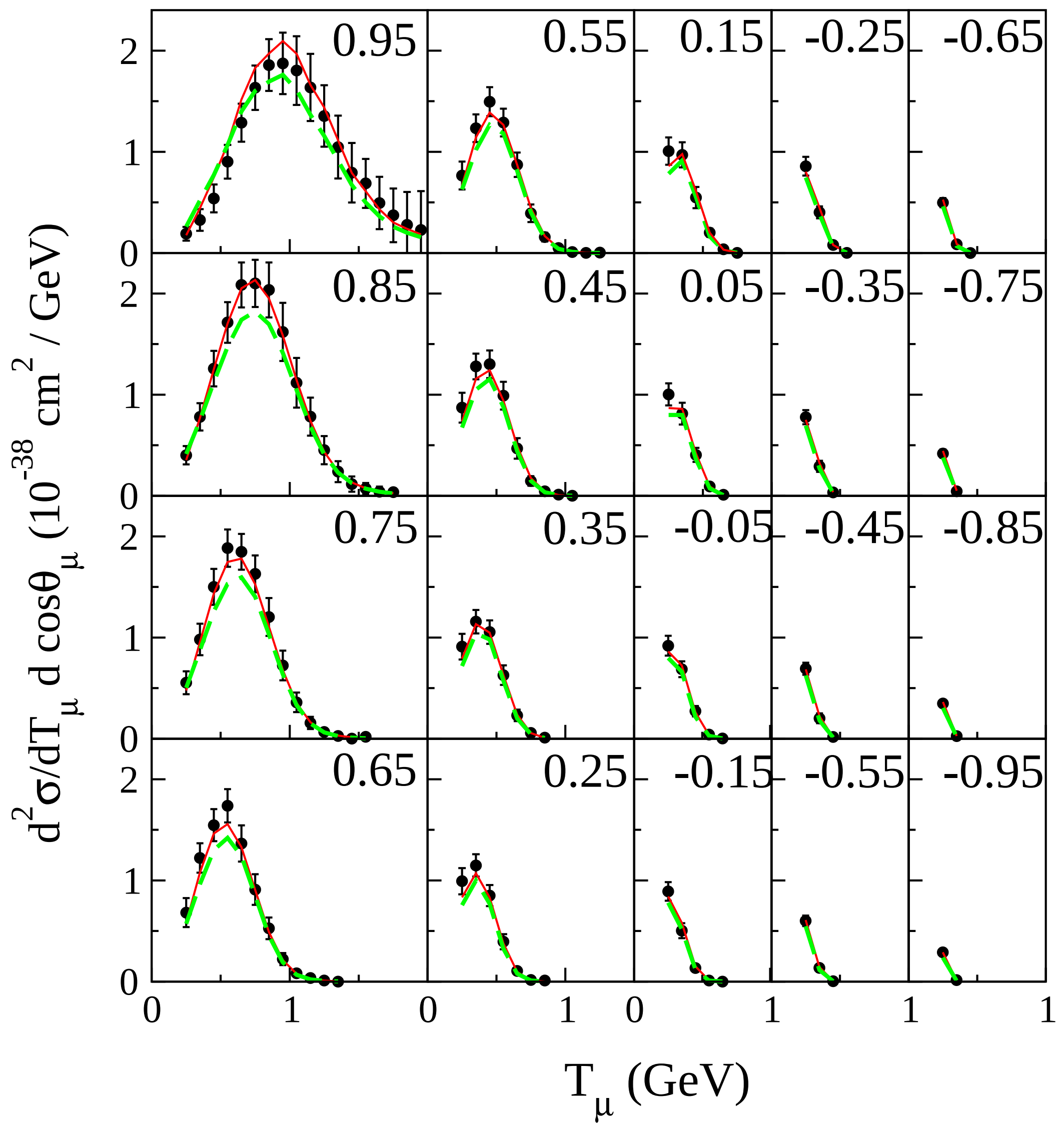
We define a **merit function** and consider our **QE+2p2h results**

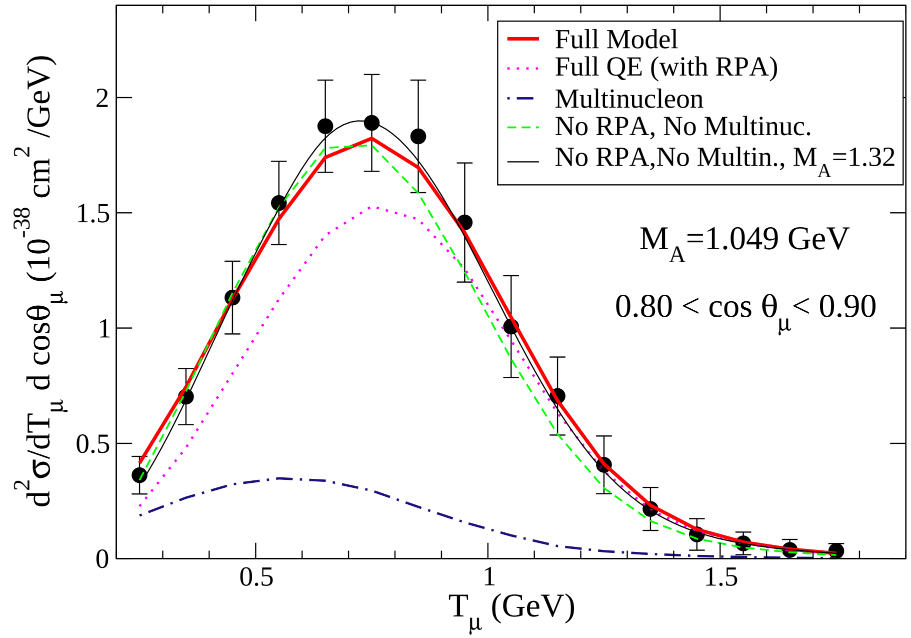
$$\chi^2 = \sum_{i=1}^{137} \left[\frac{\lambda \left(\frac{d^2\sigma^{exp}}{dT_\mu d\cos\theta} \right)_i - \left(\frac{d^2\sigma^{th}}{dT_\mu d\cos\theta} \right)_i}{\lambda\Delta \left(\frac{d^2\sigma}{dT_\mu d\cos\theta} \right)_i} \right]^2 + \left(\frac{\lambda - \mathbf{1}}{\mathbf{\Delta}\lambda} \right)^{\mathbf{2}},$$

that takes into account the **global normalization uncertainty ($\Delta\lambda = 0.107$)** claimed by the MiniBooNE collaboration.

We fit λ to data with a fixed value of M_A (=1.049 GeV).
We obtain $\chi^2/\#$ bins =52/137 with $\lambda = 0.89 \pm 0.01$.

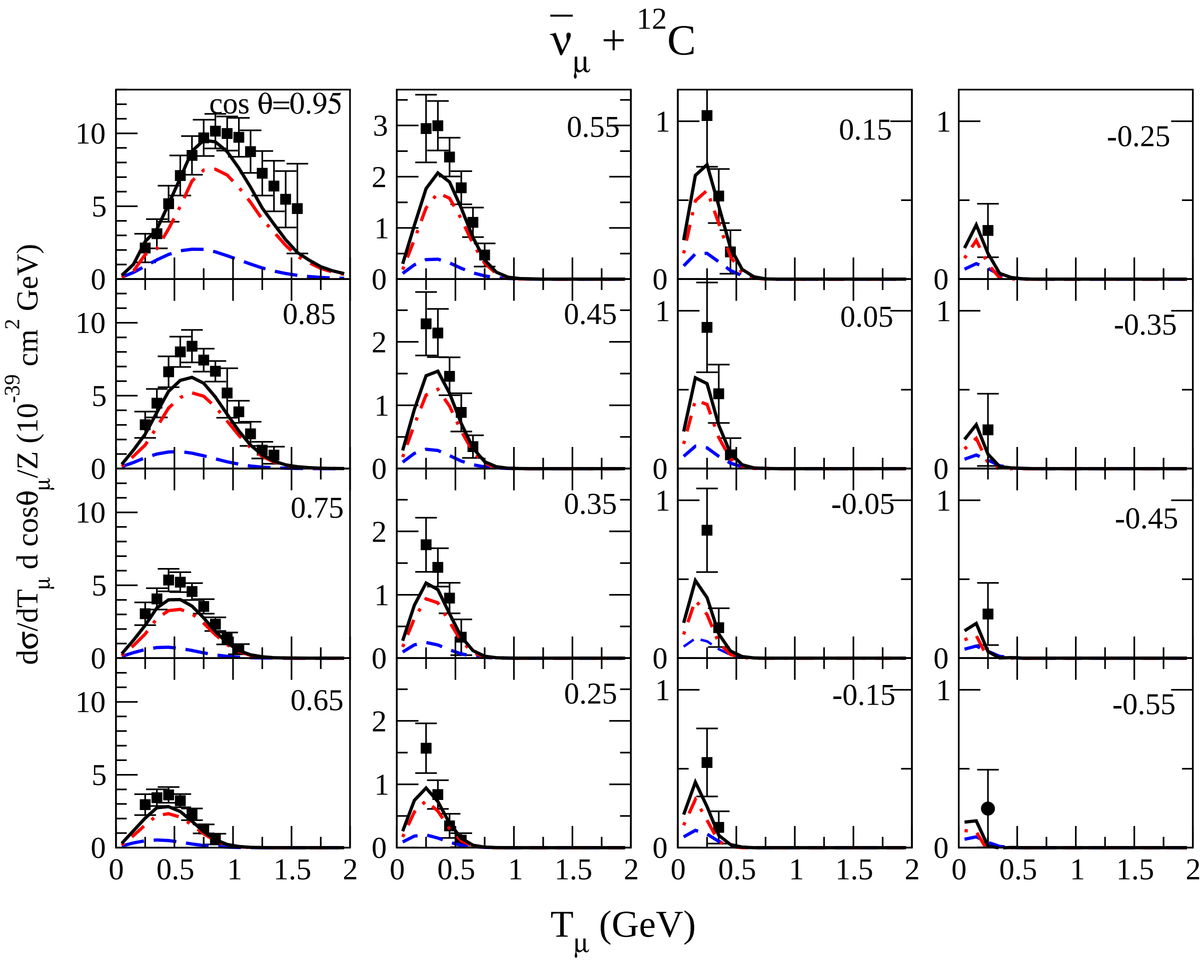
The microscopical model, with no free parameters, agrees remarkably well with data! The shape is very good and χ^2 strongly depends on λ, which is strongly correlated with M_A.



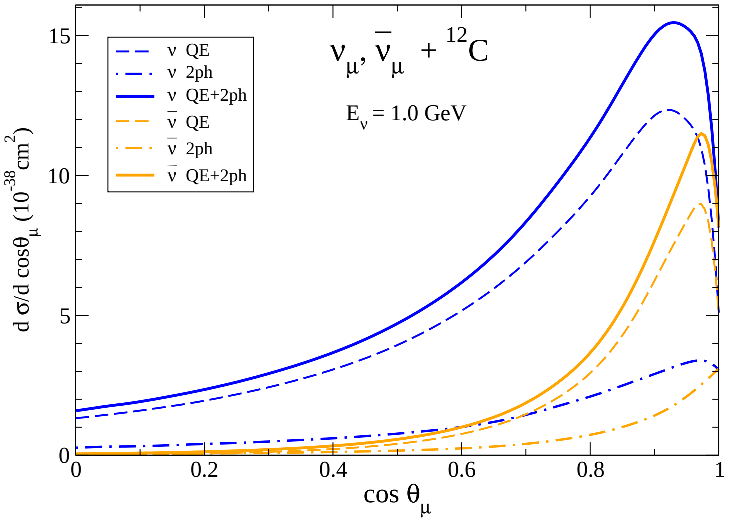


Model	Scale	M_A (GeV)	$\frac{\chi^2}{\#\text{bins}}$
LFG	0.96±0.03	1.32±0.03	35/137
Full	**0.92±0.03**	**1.08±0.03**	**50/137**
Full $\lvert q\rvert > 0.4^\dagger$ GeV	0.83±0.04	1.01±0.03	30/123

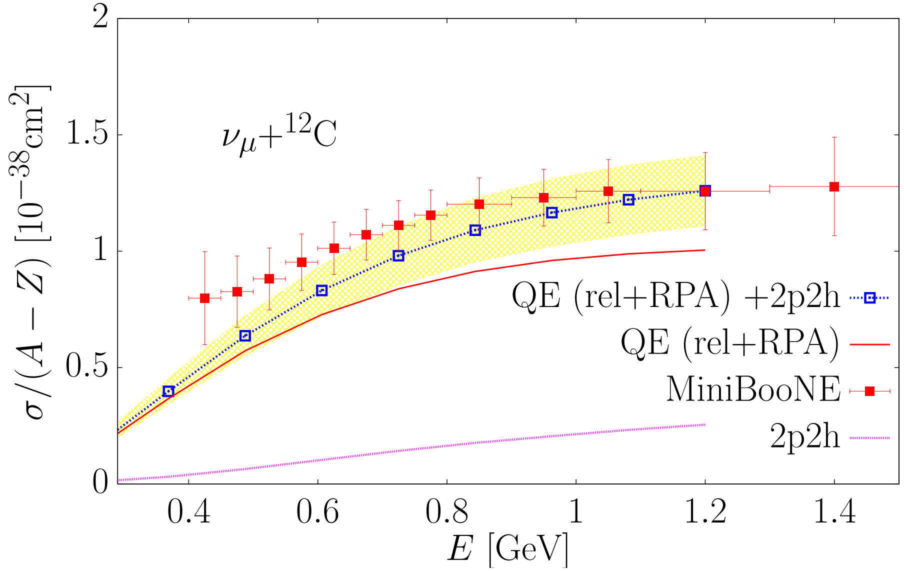
† : As suggested by Sobczyk et al. PRC 82, 045502



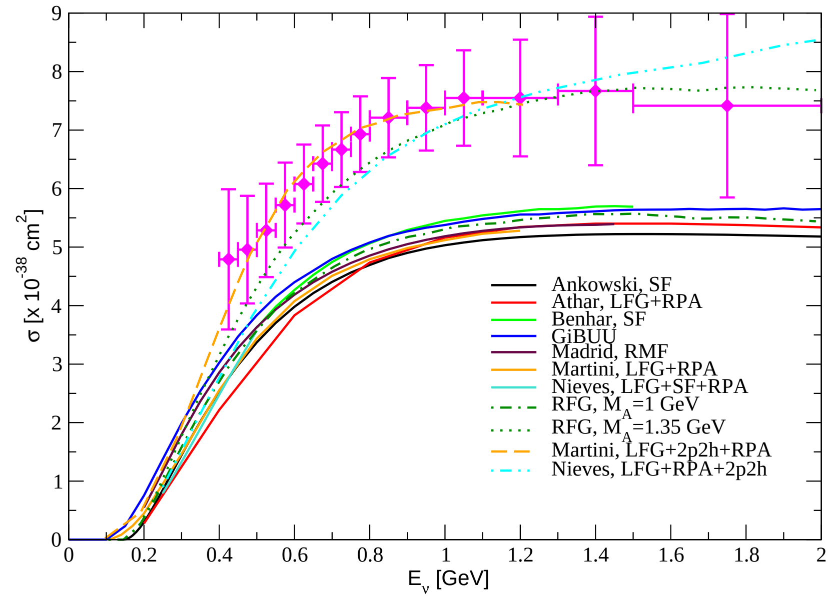
ν̄μ + 12C
cos θ=0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.05
-0.05
-0.15
-0.25
-0.35
-0.45
-0.55
dσ/dTμ d cosθμ/Z (10^-39 cm^2 GeV)
Tμ (GeV)



νμ, ν̄μ + 12C
Eν = 1.0 GeV
ν QE
ν 2ph
ν QE+2ph
ν̄ QE
ν̄ 2ph
ν̄ QE+2ph
d σ/d cosθμ (10^-38 cm^2)
cos θμ


$\nu_\mu + {}^{12}C$
$\sigma/(A-Z)$ [10^{-38}cm^2]
E [GeV]
QE (rel+RPA) +2p2h
QE (rel+RPA)
MiniBooNE
2p2h

CCQE on ^{12}C

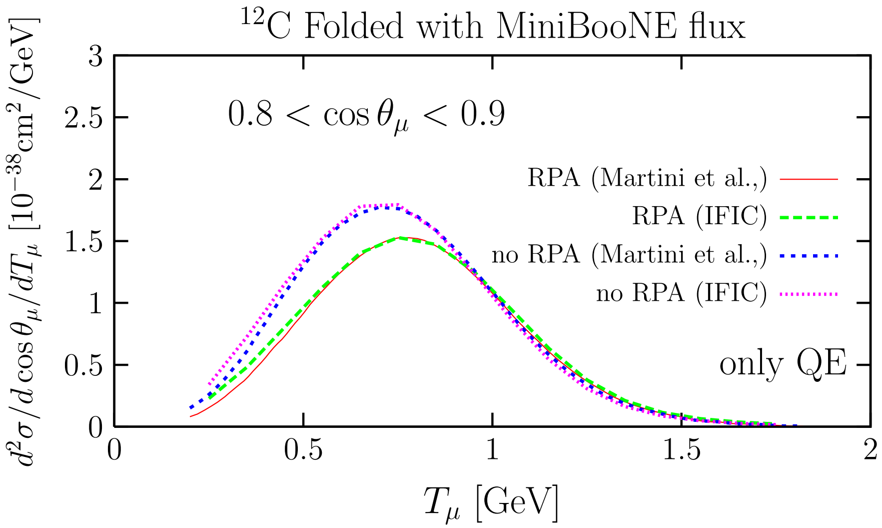

σ [x 10^{-38} cm^2]
E$_\nu$ [GeV]
Ankowski, SF
Athar, LFG+RPA
Benhar, SF
GiBUU
Madrid, RMF
Martini, LFG+RPA
Nieves, LFG+SF+RPA
RFG, M$_A$=1 GeV
RFG, M$_A$=1.35 GeV
Martini, LFG+2p2h+RPA
Nieves, LFG+RPA+2p2h

Differences with the work of Martini et al. (PRC80,065501)

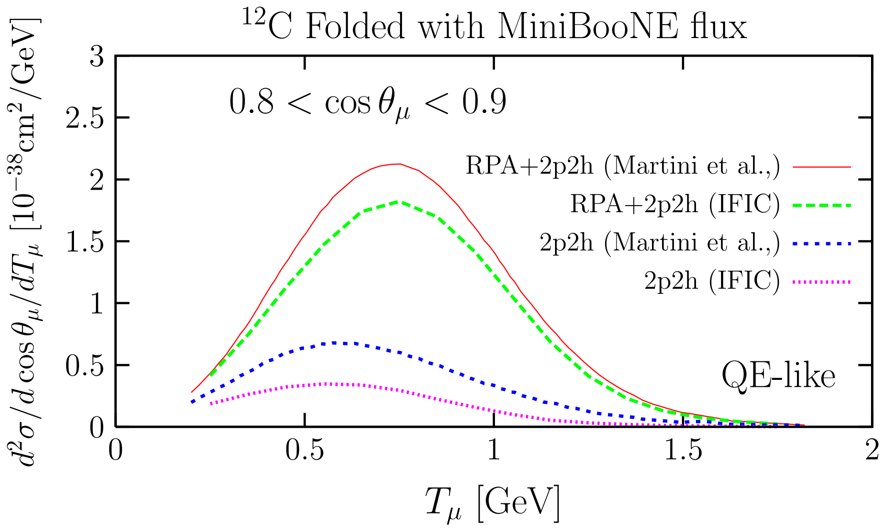
1. **Similar for the 2p2h contributions driven by Δh excitation** (both groups use the same model for the $\Delta-$selfenergy in the medium).

2. **Martini et al. do not consider 2p2h contributions driven by contact, pion pole and pion in flight terms.**

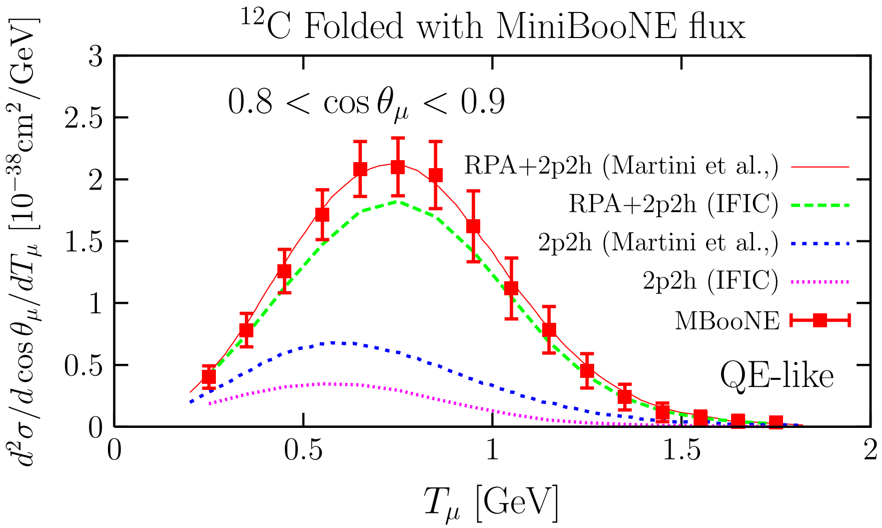
3. **Martini et al. give approximate estimates (no microscopical calculation) for the rest of 2p2h contributions** [relate them to the absorptive part of the $p-$wave pion-nucleus optical potential at threshold or to a microscopic calculation by Alberico et al. (Annals Phys. 154, 356) specifically aimed at the evaluation of the 2p-2h contribution to the isospin spin-transverse response, measured in inclusive (e, e') scattering].



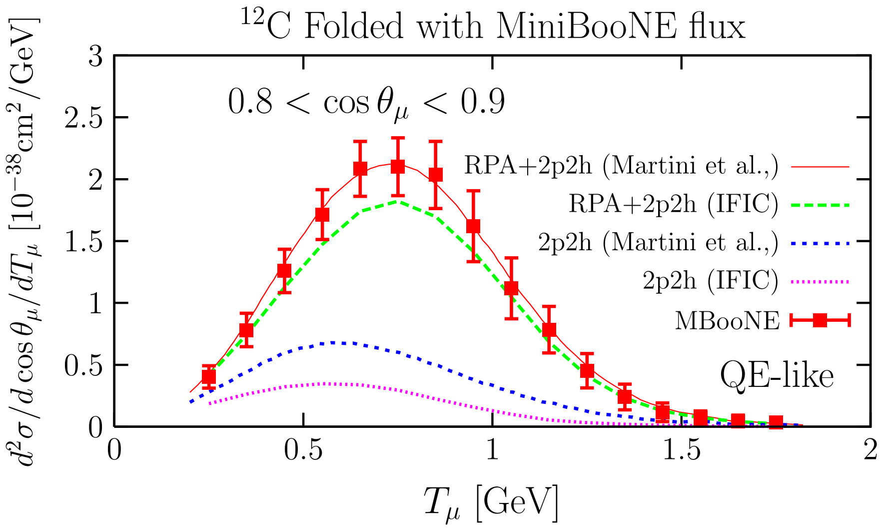
We compare rather well with Martini et al., PRC 84, 055502 for bare QE and QE+RPA



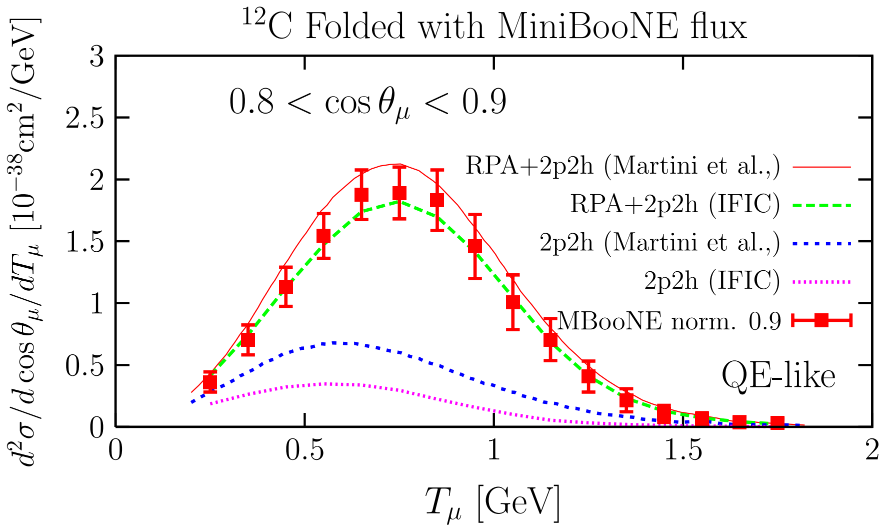
...however our 2p2h contribution is about a factor of 2 smaller!



Martini et al., predictions look consistent with MiniBooNE data ...



Martini et al., predictions look consistent with MiniBooNE data ..., but their estimate rely on some computation of the 2p2h mechanisms for (e, e') (Alberico et al.,) $\Rightarrow$ no info on axial part of the interaction!



...however our predictions for the 2p2h contribution would favor a global normalization scale of about 0.9. This would be consistent with the MiniBooNE estimate of a total normalization error of 10.7%.

Neutrino beams ARE NOT monochromatic. For QE-like events, only the charged lepton is observed and the only measurable quantities are then its direction (scattering angle θ_μ with respect to the neutrino beam direction) and its energy E_μ. **The energy of the neutrino that has originated the event is unknown.** Assuming QE dynamics is defined a **"reconstructed" energy**

$$E_{\rm rec} = \frac{ME_\mu - m_\mu^2/2}{M - E_\mu + |\vec{p}_\mu|\cos\theta_\mu}$$

(genuine quasielastic event on a nucleon at rest, ie. $E_{\rm rec}$ is determined by the QE-peak condition $q^0 = -q^2/2M$). Note that **each event contributing to the flux averaged double differential cross section $d\sigma/dE_\mu d\cos\theta_\mu$ defines unambiguously a value of $E_{\rm rec}$. The actual ("true") energy, E, of the neutrino that has produced the event will not be exactly $E_{\rm rec}$.**

Flux-folded $d\sigma/dT_\mu d\cos\theta_\mu \overbrace{\rightarrow}^{?}$ CCQE-like unfolded $\sigma(E)$

Unfolding procedure needs theoretical input!

$$P_{\rm true}(E) = \int dE_{\rm rec} \underbrace{P_{\rm rec}(E_{\rm rec})}_{\rm EXP} \underbrace{P(E|E_{\rm rec})}_{theory!}$$

$P_{\rm rec}(E_{\rm rec})$ is the *pd* of measuring an event with reconstructed energy $E_{\rm rec}$. $P(E|E_{\rm rec})$ is, given an event of reconstructed energy $E_{\rm rec}$, the conditional *pd* of being produced by a neutrino of energy E.

...using Bayes's theorem $P(E|E_{\rm rec})$ could be related to

$$P(E_{\rm rec}|E) \quad \underline{\text{is determined by}} \quad \frac{d\sigma}{dE_{\rm rec}}(E; E_{\rm rec})$$

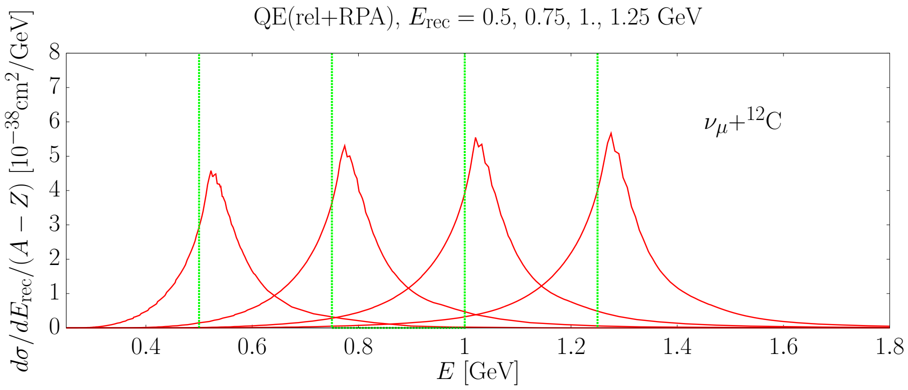
$$\mathbf{P}(\mathbf{E}|\mathbf{E}_{\rm rec}) = \frac{\mathbf{P}(\mathbf{E}_{\rm rec}|\mathbf{E}) P_{\rm true}(E)}{P_{\rm rec}(E_{\rm rec})}$$

$P(E_{\rm rec}|E)$ is the conditional *pd* of measuring an event with reconstructed energy $E_{\rm rec}$ and induced by the interaction with the nuclear target of a neutrino of energy E.

$$P(E_{\rm rec}|E) = \frac{1}{\sigma(E)} \frac{d\sigma}{dE_{\rm rec}}(E; E_{\rm rec}), \qquad P_{\rm true}(E) \propto \Phi(E)\sigma(E)$$

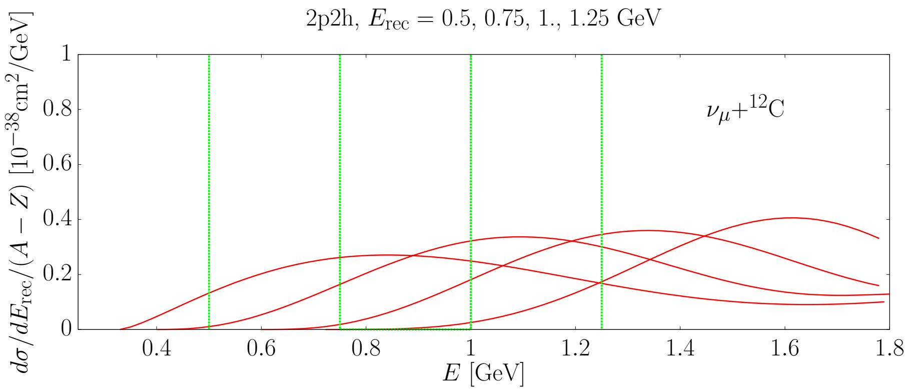
$$\frac{d\sigma}{dE_{\rm rec}}(E; E_{\rm rec}) = \int_{m_\mu}^{E} dE_\mu \left| \frac{\partial(\cos\theta_\mu)}{\partial E_{\rm rec}} \right| \underbrace{\frac{d^2\sigma}{d(\cos\theta_\mu) dE_\mu}(E; E_{\rm rec})}_{\text{theory!}}$$

Neutrino Energy Reconstruction and the Shape of the CCQE-like Total Cross Section



(qualitatively in agreement with Martini et al., PRD85 093012)

$$\frac{d\sigma}{dE_{\rm rec}}(E;E^0_{\rm rec}) = \int_{m_\mu}^{E} dE_\mu \frac{d^2\sigma}{dE_{\rm rec}dE_\mu}(E;E^0_{\rm rec}) = \int_{m_\mu}^{E} dE_\mu \left|\frac{\partial(\cos\theta_\mu)}{\partial E_{\rm rec}}\right| \frac{d^2\sigma}{d(\cos\theta_\mu)dE_\mu}(E;E^0_{\rm rec})$$



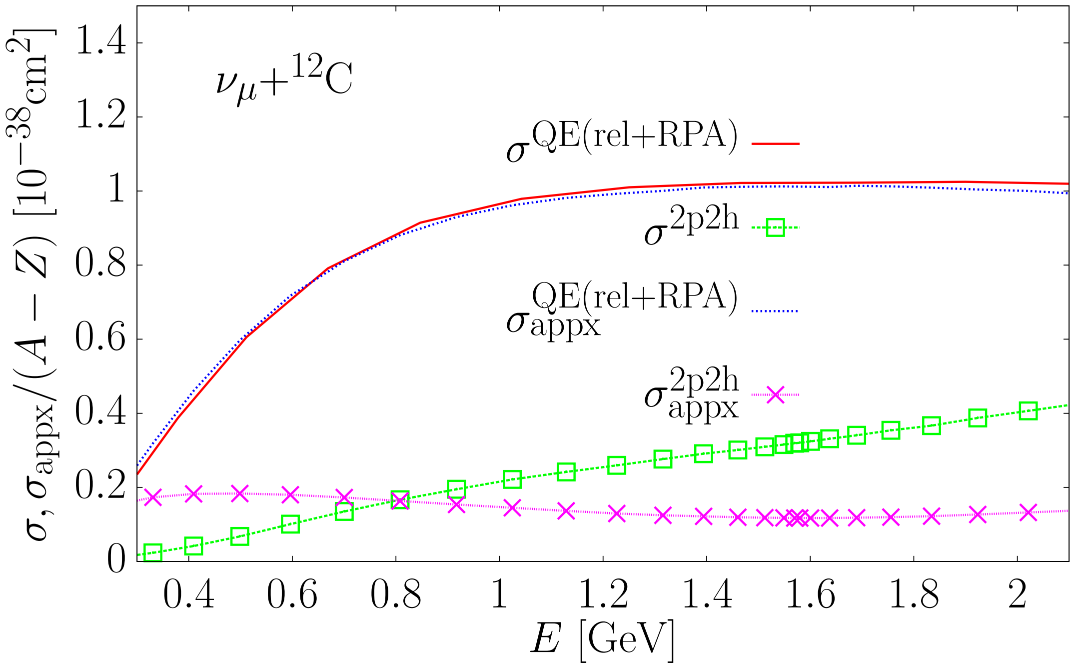
For each $E_{\rm rec}$, there exists a distribution of true neutrino energies that could give rise to events whose muon kinematics would lead to the given value of $E_{\rm rec}$.

$$\sigma(E) = \int dE_{\rm rec} \underbrace{\left[\langle\sigma\rangle P_{\rm rec}(E_{\rm rec})\right]}_{\textbf{EXP}} \times \overbrace{\underbrace{\left[\frac{d\sigma/dE_{\rm rec}(E;E_{\rm rec})}{\int dE''\Phi(E'')d\sigma/dE_{\rm rec}(E'';E_{\rm rec})}\right]}_{MODEL}}^{P(E|E_{\rm rec})}$$

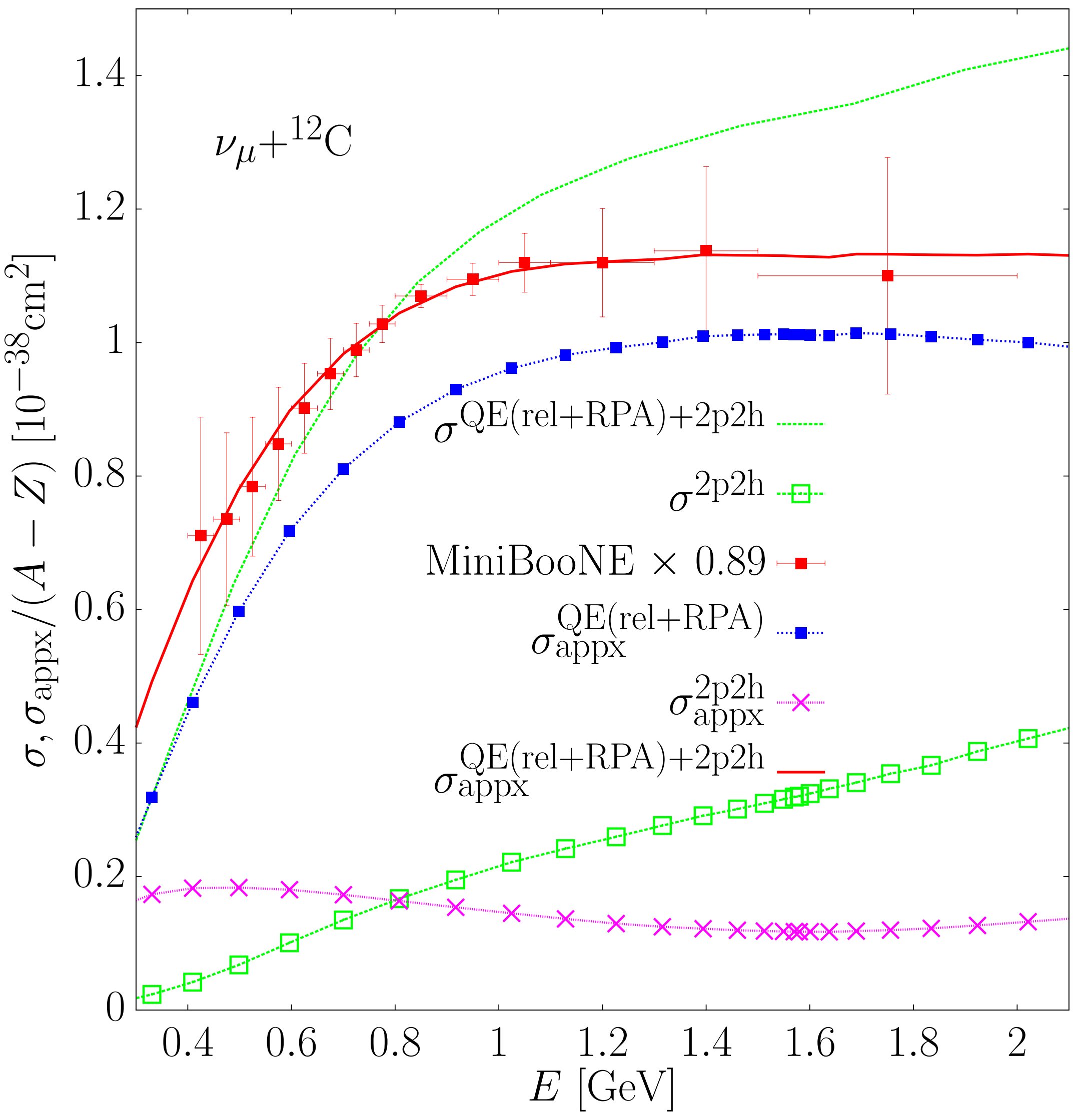
$$\sigma = \underbrace{\sigma^{\rm QE(\textbf{RPA})}}_{M_A=1.05\ \rm GeV} + \sigma^{\rm 2p2h}$$

$$\sigma(E) = \int dE_{\rm rec} \underbrace{\left[\langle\sigma\rangle P_{\rm rec}(E_{\rm rec})\right]}_{\rm EXP} \times \underbrace{\left[\frac{d\sigma/dE_{\rm rec}(E;E_{\rm rec})}{\int dE''\Phi(E'')d\sigma/dE_{\rm rec}(E'';E_{\rm rec})}\right]}_{MODEL:\ \textbf{ONLY QE},\ \mathbf{M_A=1.32}\ \text{GeV}\ \textbf{and noRPA}}$$

$$\sigma = \underbrace{\sigma^{\rm QE(\mathbf{noRPA})}}_{M_A=1.32\ \text{GeV}} + \underbrace{\sigma^{\rm 2p2h}}_{\text{neglected!}}$$



$$\left[\langle\sigma\rangle P_{\rm rec}(E_{\rm rec})\right]_{\rm Exp} \sim \int \left(\frac{d\sigma}{dE_{\rm rec}}(E';E_{\rm rec})\Big|^{M_A=1.049\ \text{GeV}}_{\text{QE+RPA},} + \frac{d\sigma^{\rm 2p2h}}{dE_{\rm rec}}(E';E_{\rm rec}) \right) \Phi(E')dE'$$



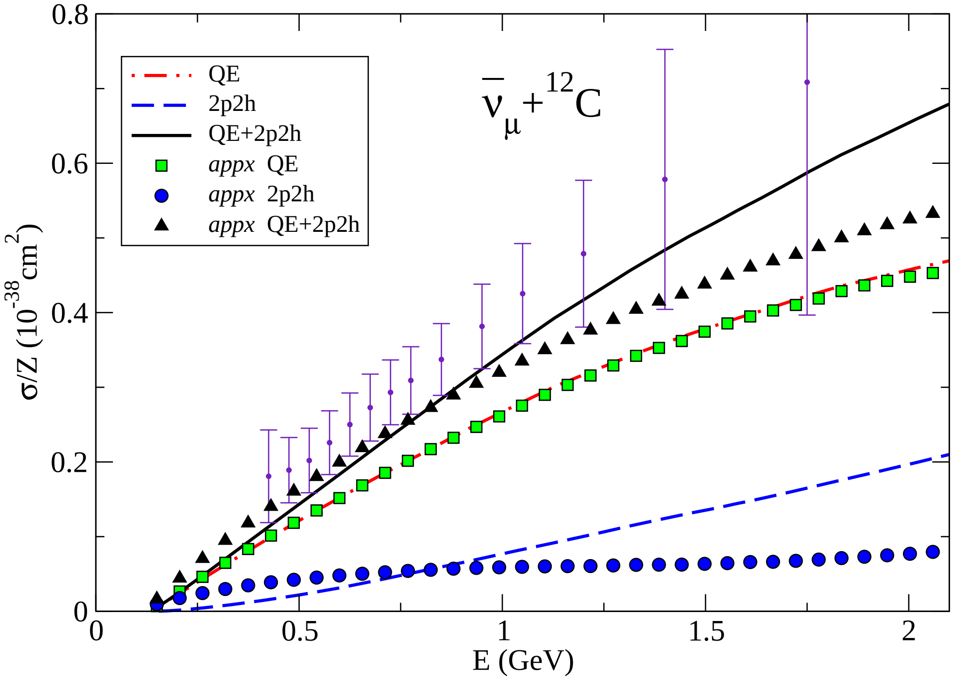
$$\Big[\langle\sigma\rangle P_{\rm rec}(E_{\rm rec})\Big]_{\rm Exp} \sim$$

$$\int \left(\frac{d\sigma}{dE_{\rm rec}}(E';E_{\rm rec})\Big|^{M_A=1.049\ {\rm GeV}}_{\rm QE+RPA,} + \frac{d\sigma^{\rm 2p2h}}{dE_{\rm rec}}(E';E_{\rm rec}) \right) \Phi(E')dE'$$

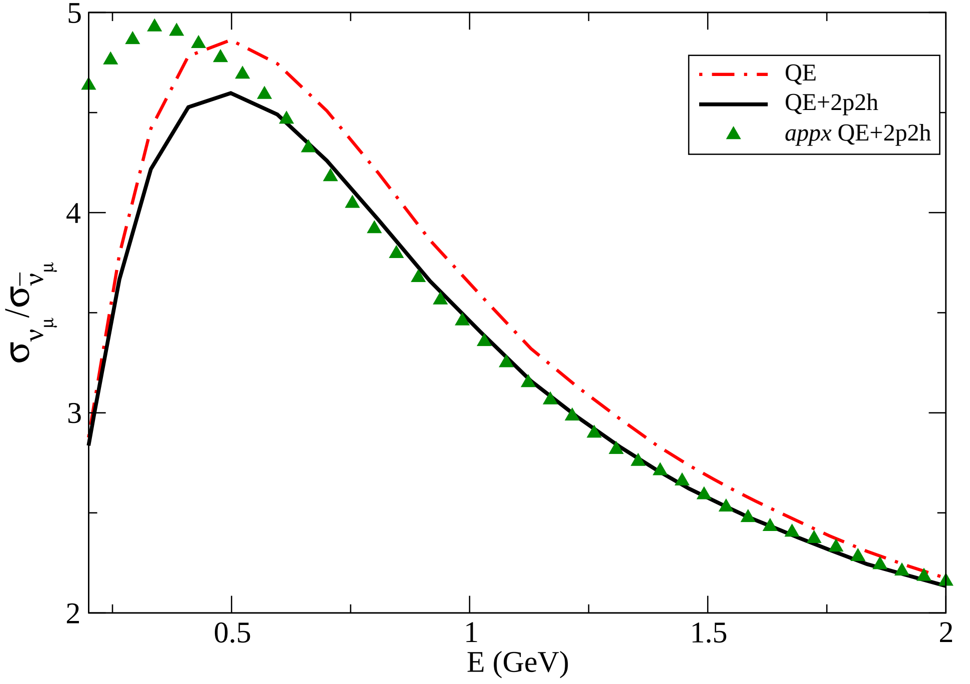
... and

$$\underbrace{\left[\frac{d\sigma/dE_{\rm rec}(E;E_{\rm rec})}{\int dE''\Phi(E'')d\sigma/dE_{\rm rec}(E'';E_{\rm rec})}\right]}_{\text{ONLY QE },M_A=1.32\text{ GeV and noRPA}}$$

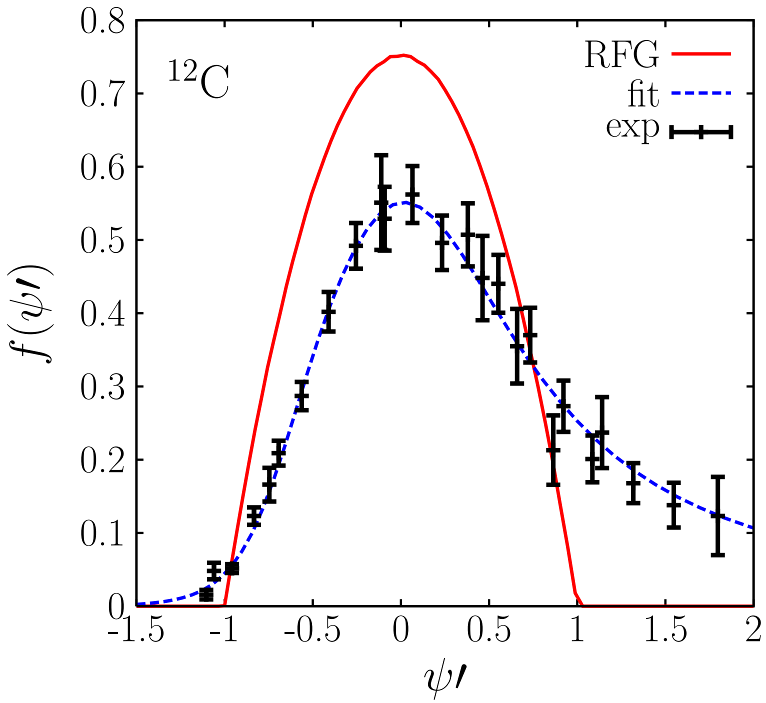
For $\bar{\nu}$



QE
2p2h
QE+2p2h
appx QE
appx 2p2h
appx QE+2p2h
ν̄μ + 12C
σ/Z (10^-38 cm^2)
E (GeV)
0
0.2
0.4
0.6
0.8
0
0.5
1
1.5
2



QE
QE+2p2h
appx QE+2p2h
σνμ/σν̄μ
E (GeV)
2
3
4
5
0.5
1
1.5
2



Superscaling approach: Inclusive electron scattering data exhibit interesting systematics that can be used to predict (anti)neutrino-nucleus cross sections (T. Donnelly and I. Sick, PRL 82, 3212 (1999)),

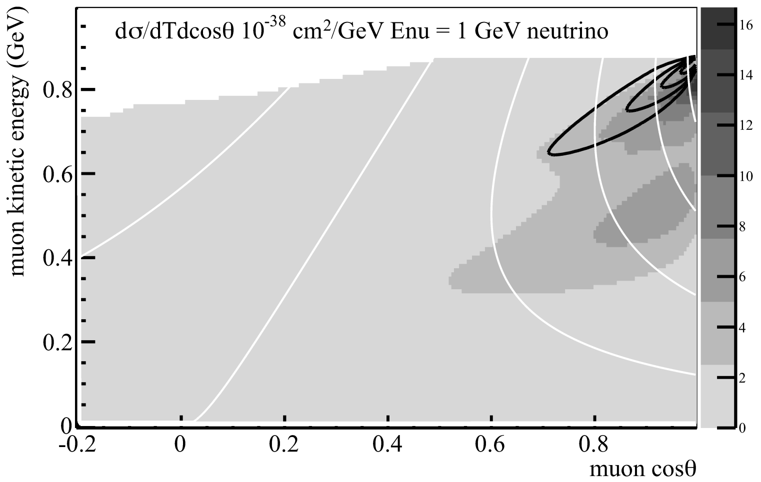
$$f = k_F \frac{\frac{d\sigma}{d\Omega' dE'}}{Z\sigma_{ep} + N\sigma_{en}}$$

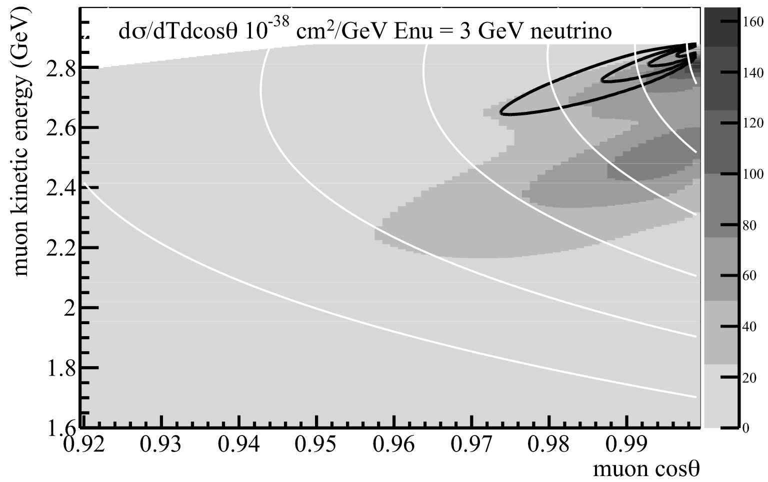
- **$f = f(\psi')$, with $\psi' = \psi'(q^0, |\vec{q}\,|)$**
- **f is largely independent of the specific nucleus**

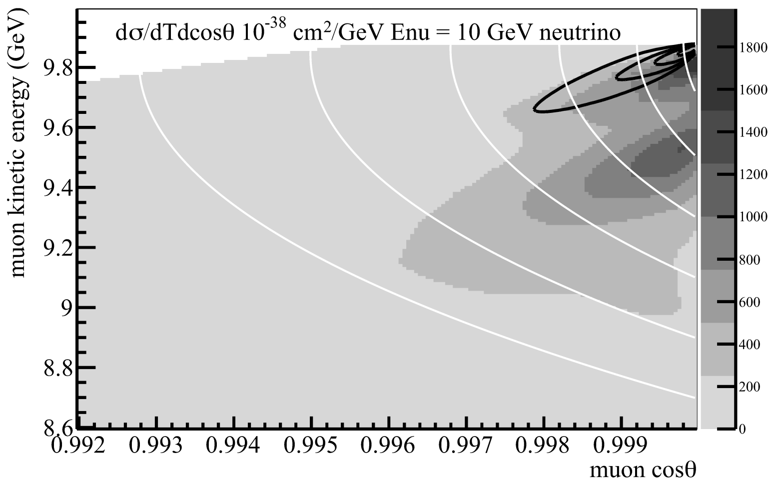
Scaling violations reside mainly in R_T: excitation of resonances, meson production, 2p2h mechanisms and even the tail of DIS. An experimental scaling function $f(\psi')$ could be reliably extracted by fitting the data for R_L.

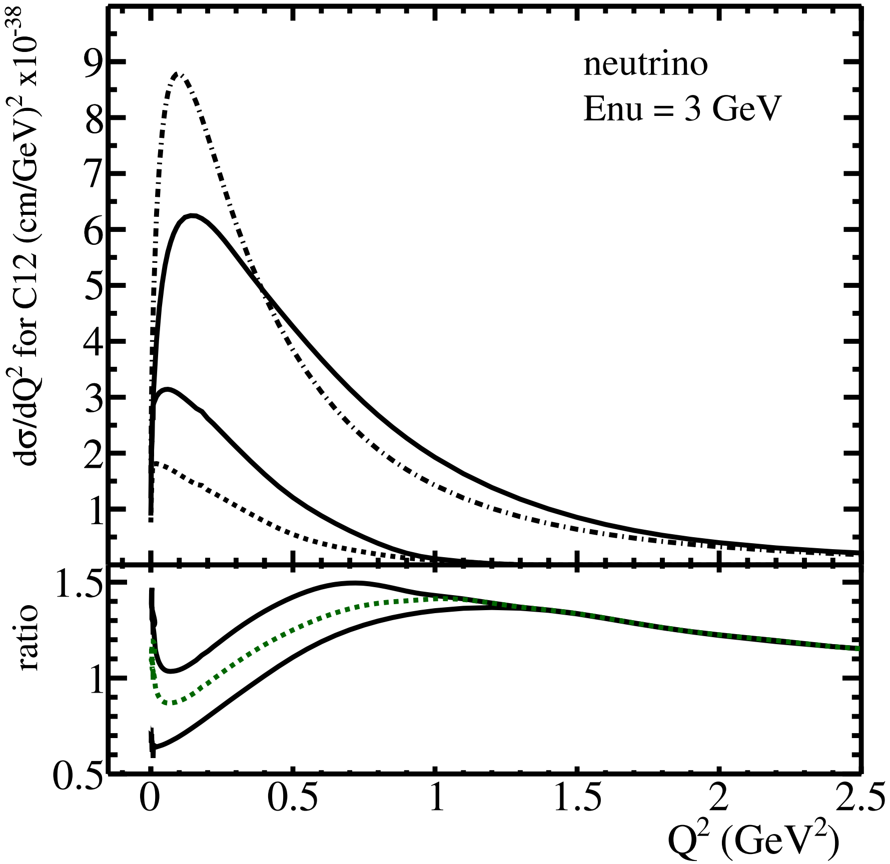
ν QE cross sections can be calculated with the simple RgFG model followed by the replacement $f_{RgFG} \to f_{\exp}$.

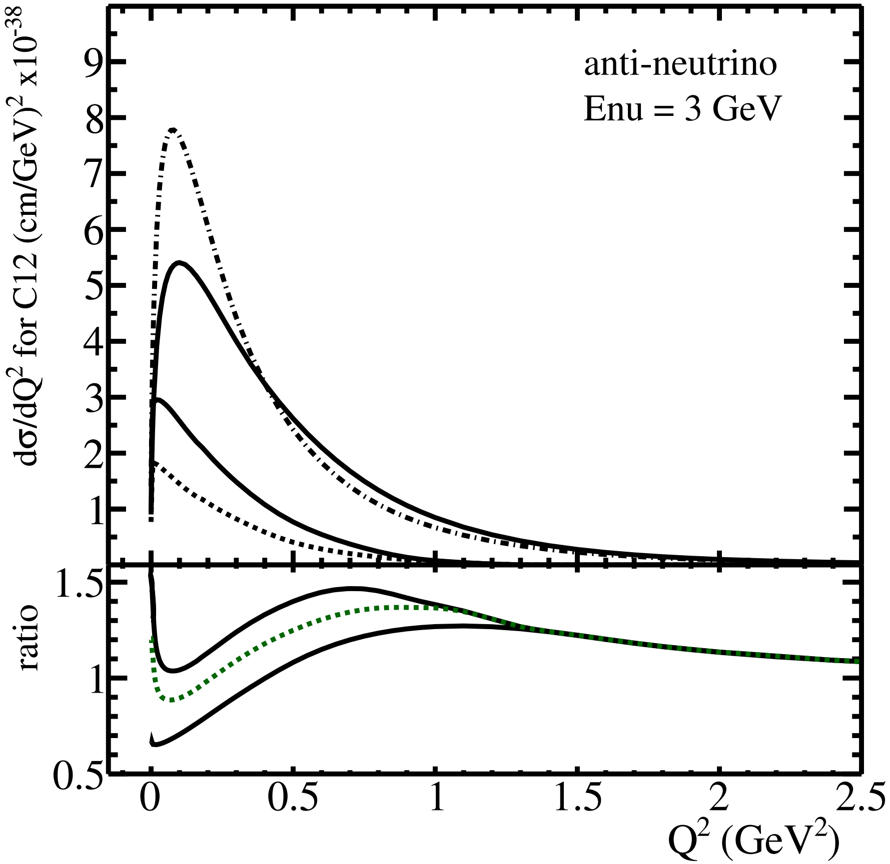
At higher ν energies



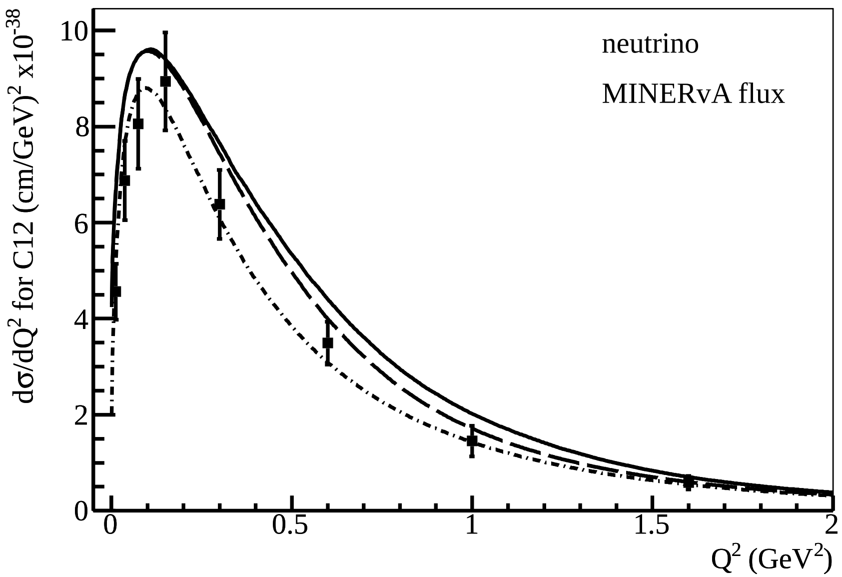


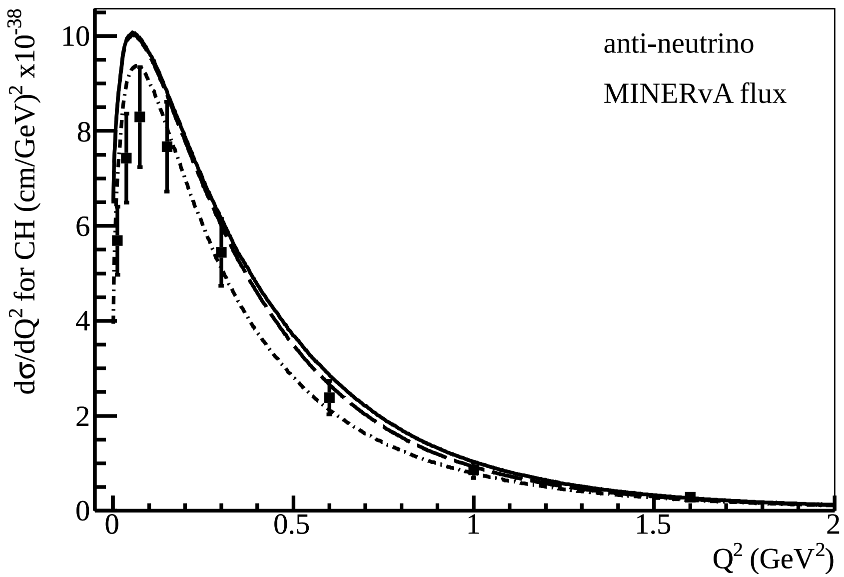



neutrino
Enu = 3 GeV
dσ/dQ² for C12 (cm/GeV)² x10⁻³⁸
ratio
Q² (GeV²)
9
8
7
6
5
4
3
2
1
1.5
1
0.5
0
0.5
1
1.5
2
2.5


anti-neutrino
Enu = 3 GeV
dσ/dQ² for C12 (cm/GeV)² x10⁻³⁸
ratio
Q² (GeV²)
9
8
7
6
5
4
3
2
1
1.5
1
0.5
0
0.5
1
1.5
2
2.5

MINERνA


neutrino
MINERvA flux
dσ/dQ² for C12 (cm/GeV)² x10⁻³⁸
Q² (GeV²)
0
2
4
6
8
10
0
0.5
1
1.5
2


anti-neutrino
MINERvA flux
dσ/dQ² for CH (cm/GeV)² x10⁻³⁸
Q² (GeV²)
0
2
4
6
8
10
0
0.5
1
1.5
2

Conclusions

- **We have analyzed the MiniBooNE CCQE $\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$ data using a theoretical model that has proved to be quite successful in the analysis of nuclear reactions with electron, photon and pion probes and contains no additional free parameters.**

- **RPA and multinucleon knockout have been found to be essential for the description of the data.**

- **MiniBooNE ν and $\bar{\nu}$ CCQE-like data are fully compatible with former determinations of M_A in contrast with several previous analyses. We find, $\boxed{M_A = 1.08 \pm 0.03}$.**

- **The ν_μ flux could have been underestimated ($\sim 10\%$)**

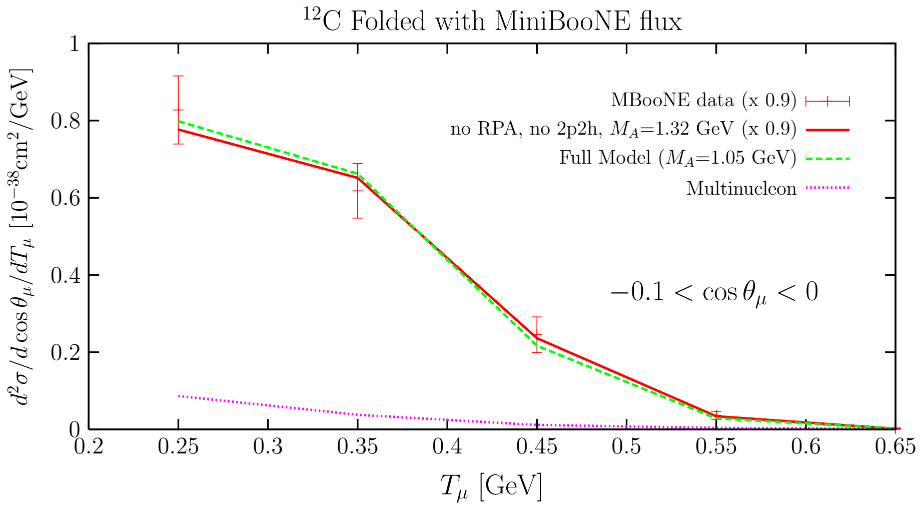
- **Because of the the multinucleon mechanism effects, the algorithm used to reconstruct the neutrino energy is not adequate when dealing with quasielastic-like events.**

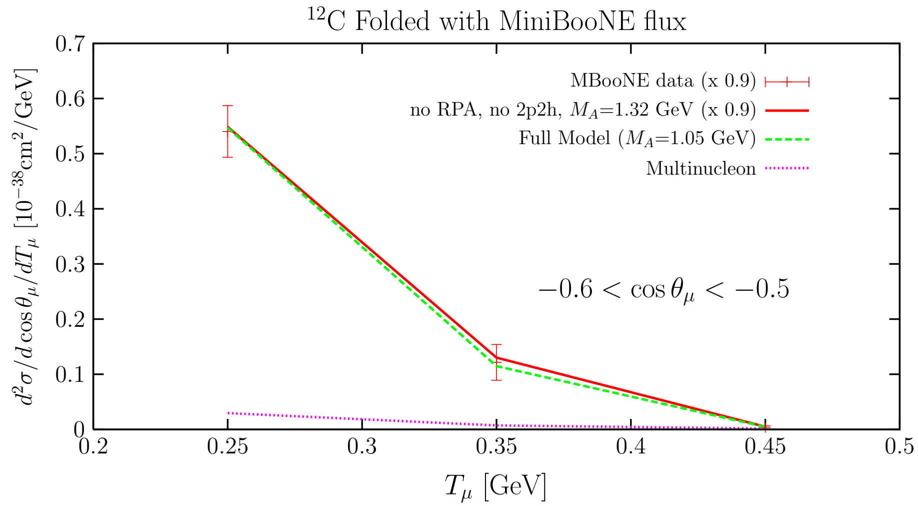
- **The inclusion of nucleon-nucleon correlation effects in the RPA series yields a much larger shape distortion toward relatively more high-q^2 interactions, with the 2p2h component filling in the suppression at very low q^2.**

- **When confronted with the MINERνA data and its small uncertainties, the model has the qualitative features and magnitude to give reasonable agreement.**

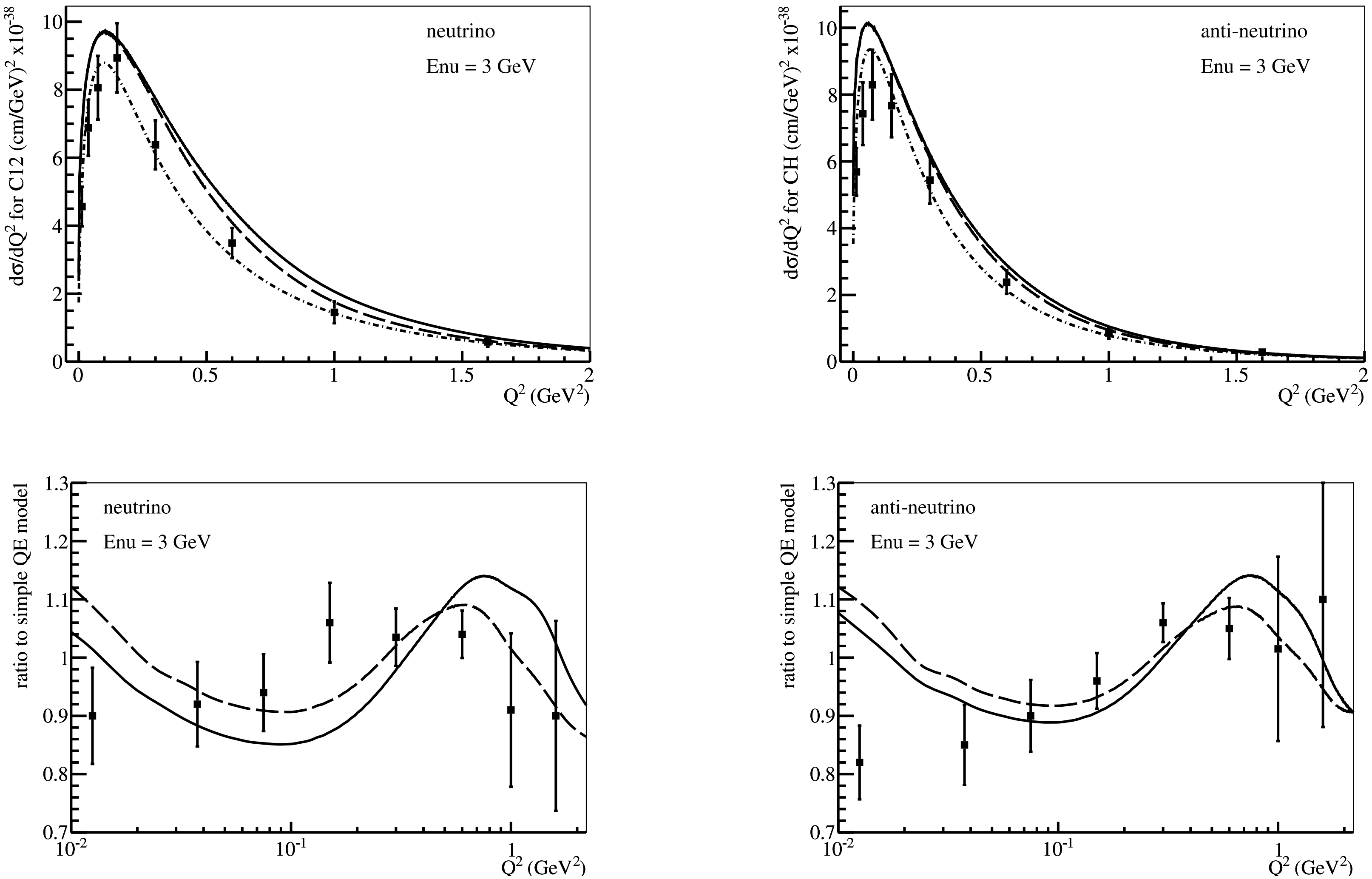
Back up material

Dependence of the 2p2h contribution on $\cos\theta_\mu$





MINERνA


neutrino
Enu = 3 GeV
dσ/dQ² for C12 (cm/GeV)² x10⁻³⁸
Q² (GeV²)
anti-neutrino
Enu = 3 GeV
dσ/dQ² for CH (cm/GeV)² x10⁻³⁸
Q² (GeV²)
neutrino
Enu = 3 GeV
ratio to simple QE model
Q² (GeV²)
anti-neutrino
Enu = 3 GeV
ratio to simple QE model
Q² (GeV²)

CC ν Physics: PRC 70-055503, PLB 638,325

Low Energies

1. $\nu_\mu\,{}^{12}\mathrm{C} \rightarrow \mu^- X \qquad (\overline{\sigma}[10^{-40}\mathrm{cm}^2])$

THEORY						EXP (LSND)		
LDT	Pauli	RPA	[A]	[B]	[C]	1995	1997	2002
66.1	20.7	11.9	13.2	15.2	19.2	8.3 ± 1.7	11.2 ± 1.8	10.6 ± 1.8

A Shell Model: A.C. Hayes and I.S. Towner, Phys. Rev. C61 (2000) 044603.

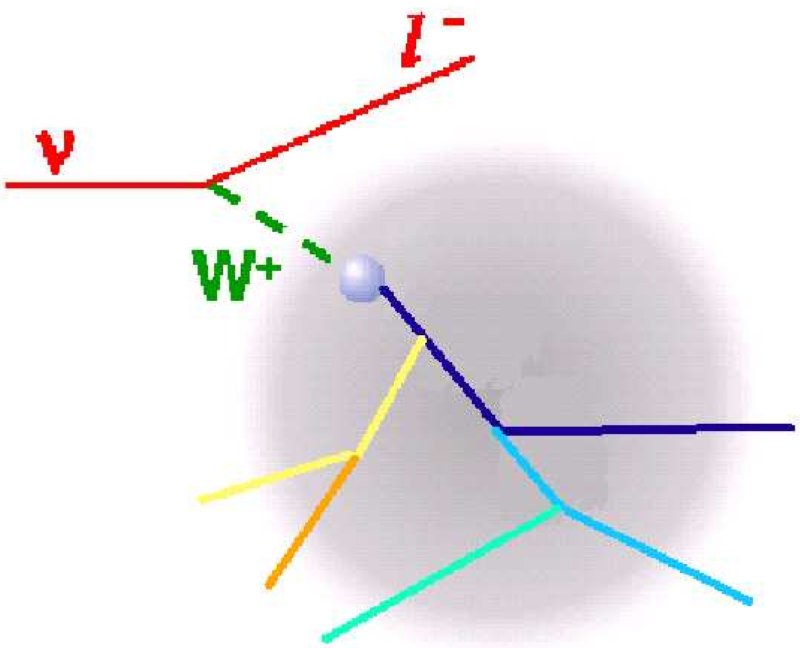
B Shell Model: C. Volpe, et al., Phys. Rev. C62 (2000) 015501.

C CRPA: E. Kolbe, et al., J. Phys. G29 (2003) 2569.

2. $\nu_e\,{}^{12}\mathrm{C} \rightarrow e^- X \qquad (\overline{\sigma}[10^{-41}\mathrm{cm}^2])$

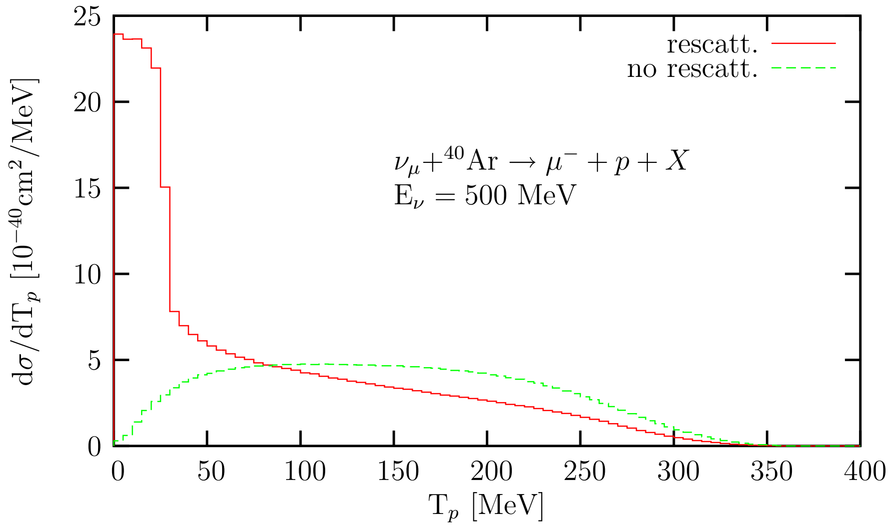
THEORY						EXP		
LDT	Pauli	RPA	[A]	[B]	[C]	KARMEN	LSND	LAMPF
59.7	1.9	1.4	1.2	1.6	1.5	1.50 ± 0.14	1.50 ± 0.14	1.41 ± 0.23

CC and NC Nucleon Emission: PRC 73-025504



- ⋆ Gauge boson ($W^{\pm}$ or Z^0), with four momentum q^μ, absorbed by one nucleon in a point of the nucleus $\vec{r} \to d^2\sigma/d\Omega' dE' d^3r$.
- ⋆ Kinematics of the outgoing nucleon: We generate a random $\vec{p}$ from the local Fermi sea and impose momentum conservation and take into account Pauli blocking.
- ⋆ We move the primary nucleon through the nucleus, considering NN collisions, according to the NN elastic cross section, incorporating some medium modifications (Fermi motion, Pauli blocking and polarization). We also move the **produced (secondary) nucleons** through the nucleus. **When one nucleon (primary or secondary) leaves the nucleus, it is counted as a contribution to σ**

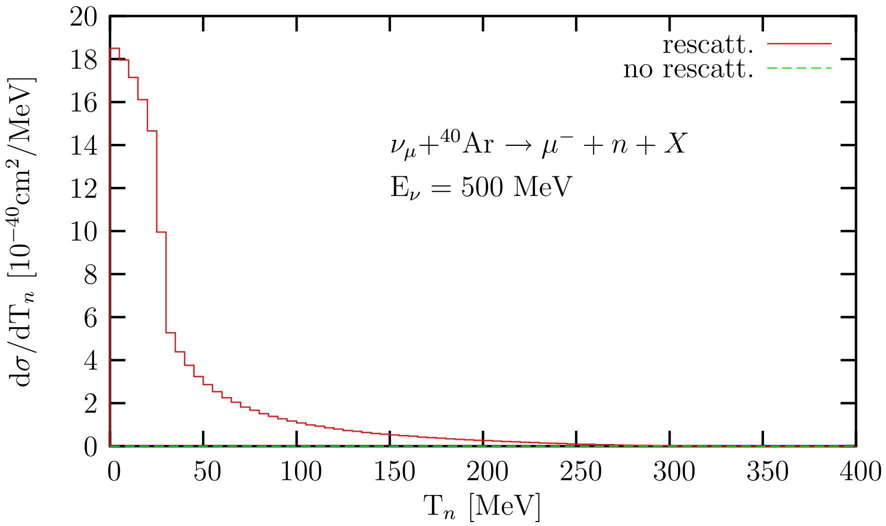
Why a MC Simulation?



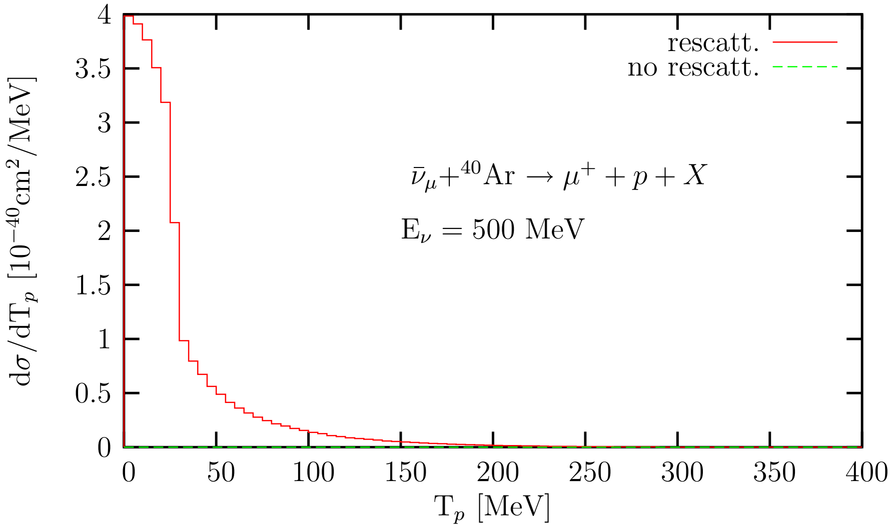
The **distortion** of the nucleon wave function by a **complex optical potential** **removes** all events where the nucleons collide with other nucleons:

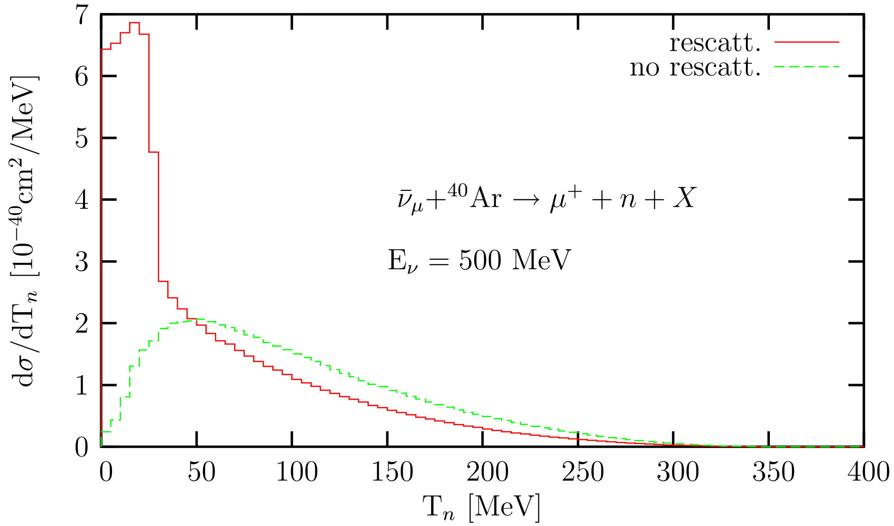
- This is correct when the final nucleus is left in the ground or in a particular excited state, but
- **not when the final nuclear state is unobserved**

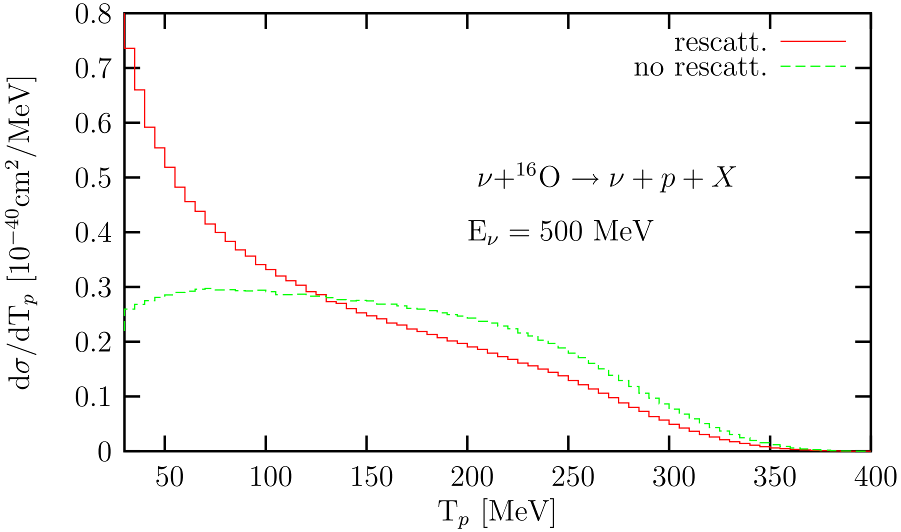
DWIA $\rightarrow$ the nucleons that interact are **lost** when in the physical process **they simply come off the nucleus** with a different energy, angle, and may be charge, and they should definitely be **taken into account**.

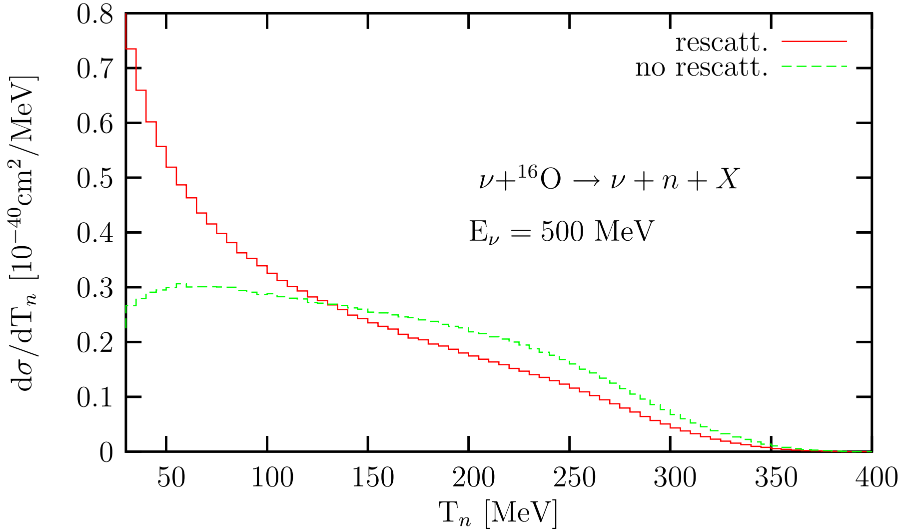


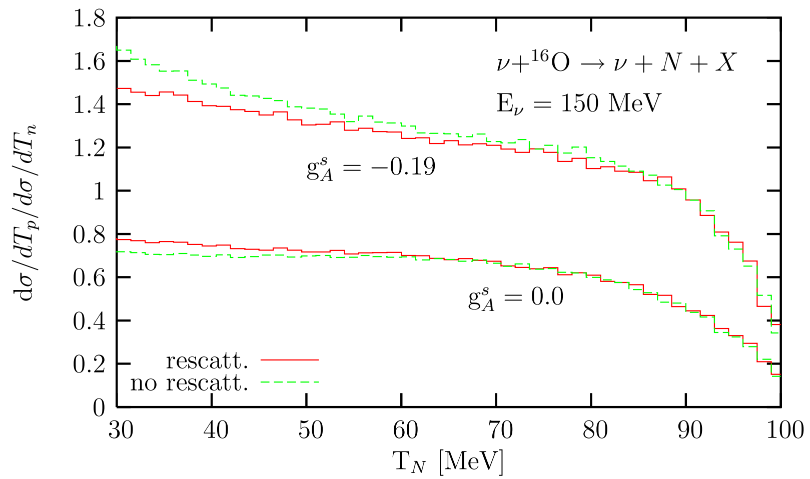
- Within the IA **neutrinos** only interact via CC with **neutrons** and would emit **protons** **($\nu_l n \rightarrow l^- p$)**, and therefore DWIA will predict **zero** cross sections for the neutron emission reaction: $(\nu_l, l^- n)$
- However, the primary **protons** interact strongly with the medium and collide with other nucleons which are also ejected. As a consequence there is a reduction of the flux of high energy **protons** but a large number of secondary nucleons, many of them **neutrons**, of lower energies appear.
- Similar for $(\bar{\nu}_l, l^+ p)$


rescatt.
no rescatt.
$\bar{\nu}_\mu + ^{40}\mathrm{Ar} \to \mu^+ + p + X$
$E_\nu = 500$ MeV
$d\sigma/dT_p$ [$10^{-40}\mathrm{cm}^2$/MeV]
T_p [MeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
0
50
100
150
200
250
300
350
400

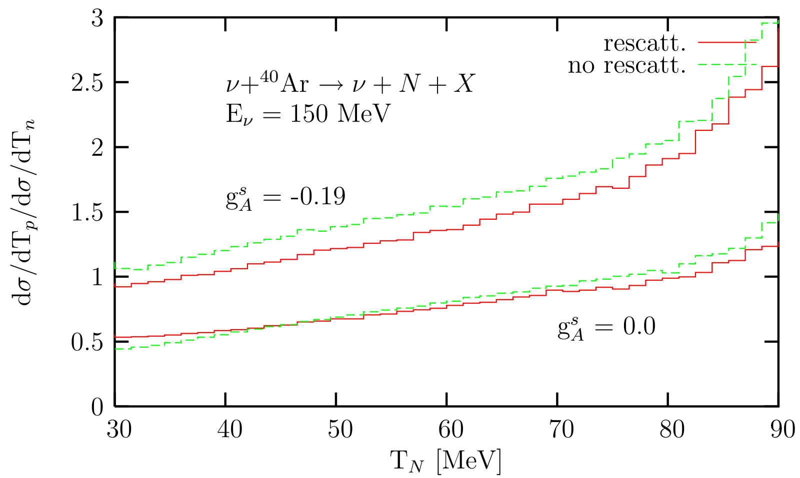

rescatt.
no rescatt.
$\bar{\nu}_\mu + ^{40}\mathrm{Ar} \to \mu^+ + n + X$
$E_\nu = 500$ MeV
$d\sigma/dT_n$ [$10^{-40}\mathrm{cm}^2$/MeV]
T_n [MeV]
0
1
2
3
4
5
6
7
0
50
100
150
200
250
300
350
400


rescatt.
no rescatt.
$\nu + ^{16}\mathrm{O} \to \nu + p + X$
$E_\nu = 500$ MeV
$d\sigma/dT_p$ [$10^{-40}\mathrm{cm}^2$/MeV]
T_p [MeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
50
100
150
200
250
300
350
400

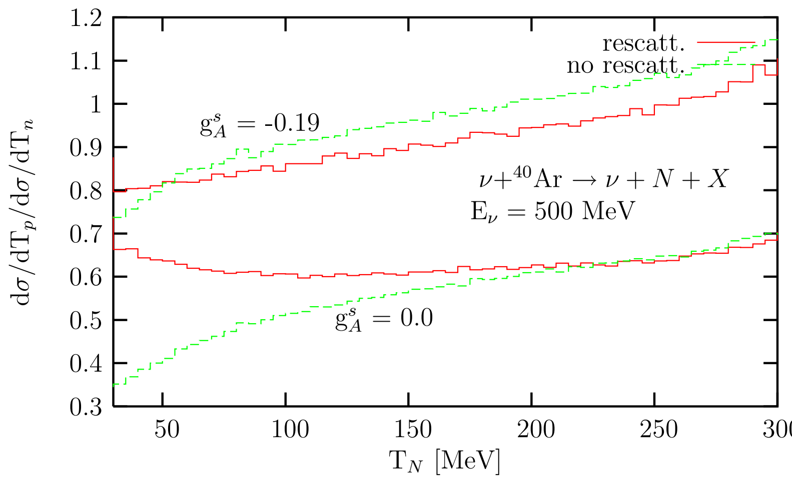

rescatt.
no rescatt.
$\nu + ^{16}\mathrm{O} \to \nu + n + X$
$E_\nu = 500$ MeV
$d\sigma/dT_n$ [$10^{-40}\mathrm{cm}^2$/MeV]
T_n [MeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
50
100
150
200
250
300
350
400



1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
30
40
50
60
70
80
90
100
dσ/dT_p/dσ/dT_n
T_N [MeV]
ν+16O → ν + N + X
E_ν = 150 MeV
g^s_A = −0.19
g^s_A = 0.0
rescatt.
no rescatt.



3
2.5
2
1.5
1
0.5
0
30
40
50
60
70
80
90
dσ/dT_p/dσ/dT_n
T_N [MeV]
rescatt.
no rescatt.
ν+40Ar → ν + N + X
E_ν = 150 MeV
g^s_A = -0.19
g^s_A = 0.0



1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
50
100
150
200
250
300
dσ/dT_p/dσ/dT_n
T_N [MeV]
rescatt.
no rescatt.
g^s_A = -0.19
ν+40Ar → ν + N + X
E_ν = 500 MeV
g^s_A = 0.0