QE scattering, 2p2h and $\nu-$energy reconstruction

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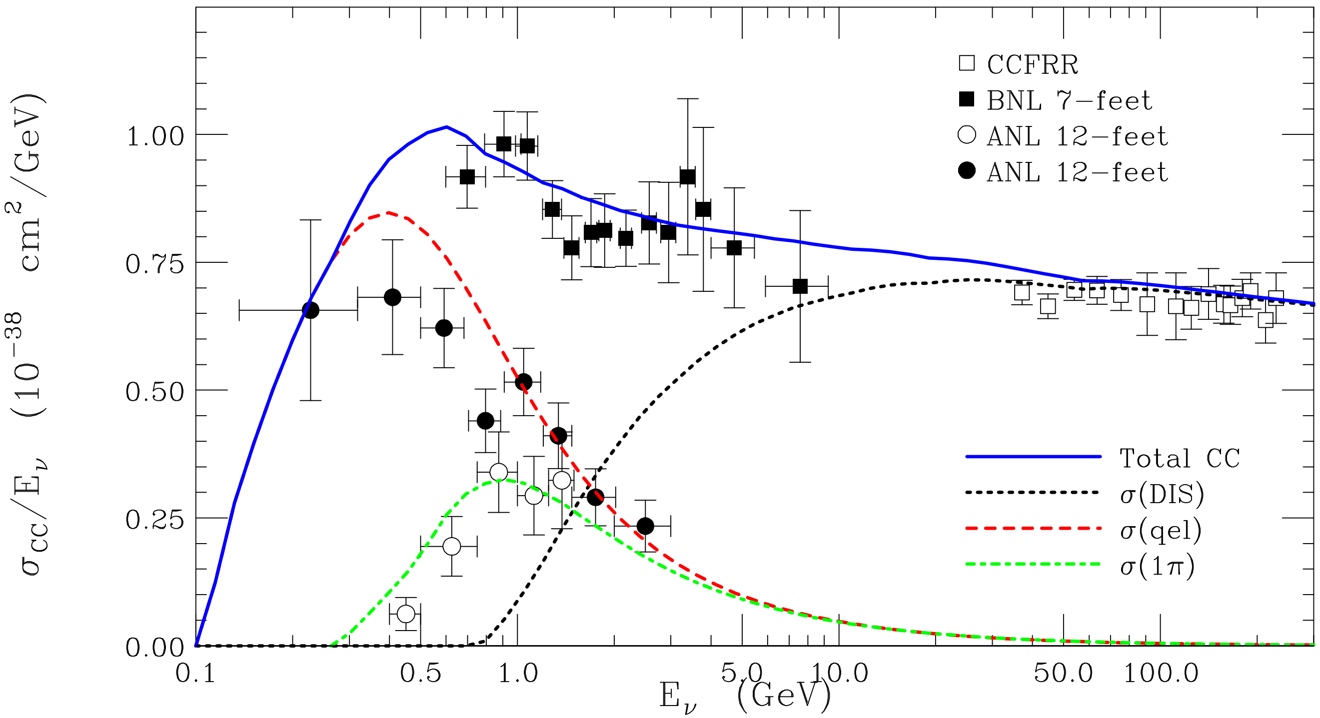
- arXiv:1307.8105 (ν and $\bar{\nu}$ CCQE-like up to 10 GeV)
- arXiv:1302.0703 PLB 721 (2013) 90 ($\bar{\nu}$ CCQE-like)
- arXiv:1204.5404 PRD 85 (2012) 113008 (E_ν reconstruct.)
- arXiv:1106.5374 PLB 707 (2012) 72 (ν CCQE-like)
- arXiv:1102.2777 PRC 83 (2011) 045501
  (CC QE, 2p2h and inclusive π production)

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

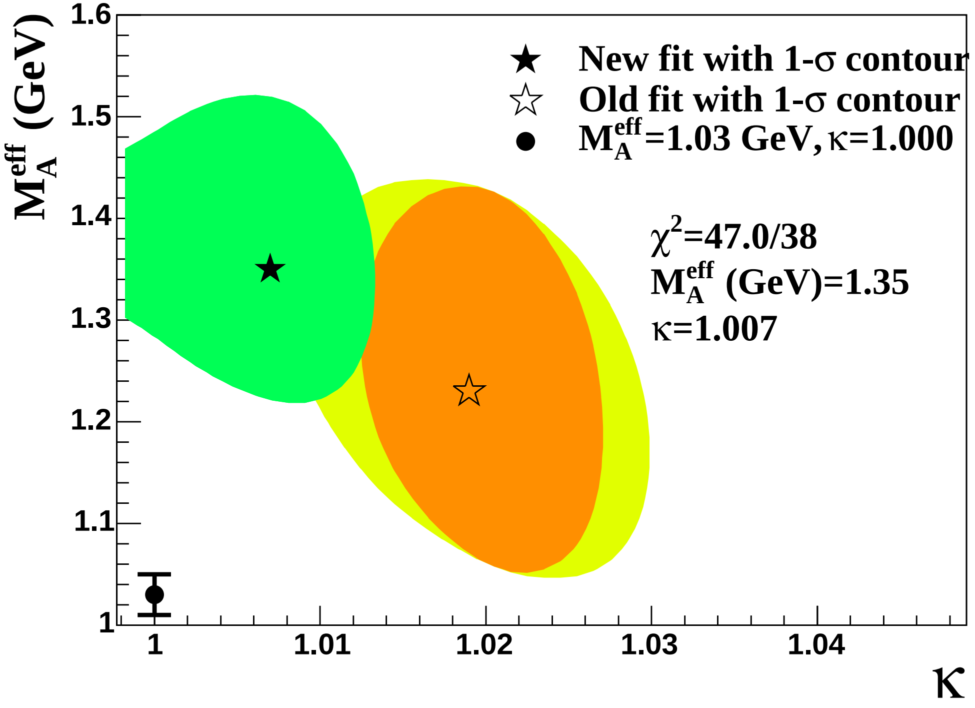
Motivation: **Details on the axial structure of hadrons in the free space and inside of nuclei, and**



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)

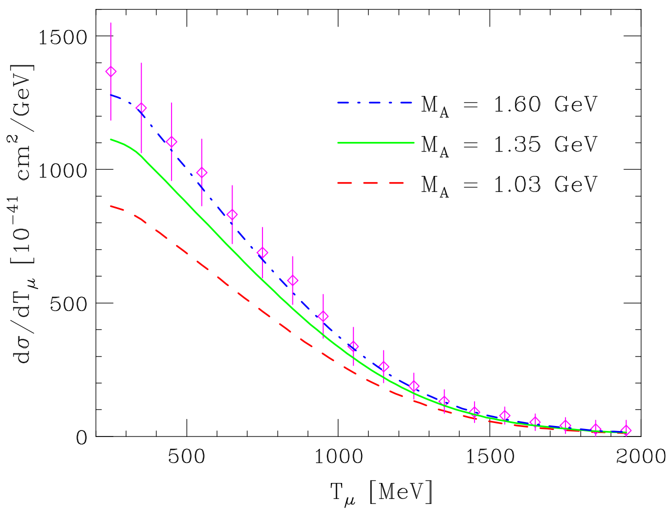


$M_A^{\rm eff} = 1.35$ **GeV**

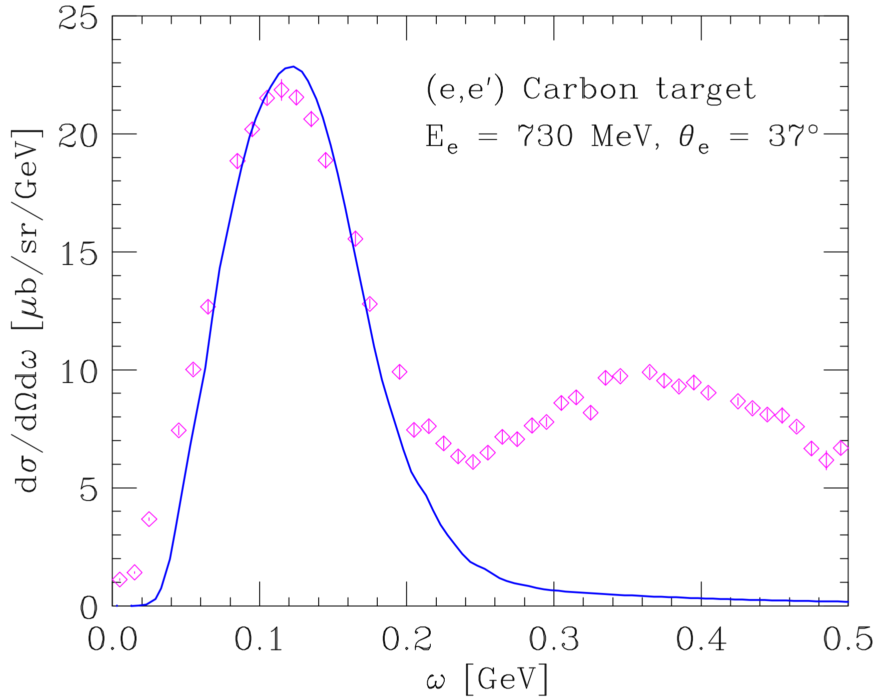
vs

1.03 GeV (world avg)

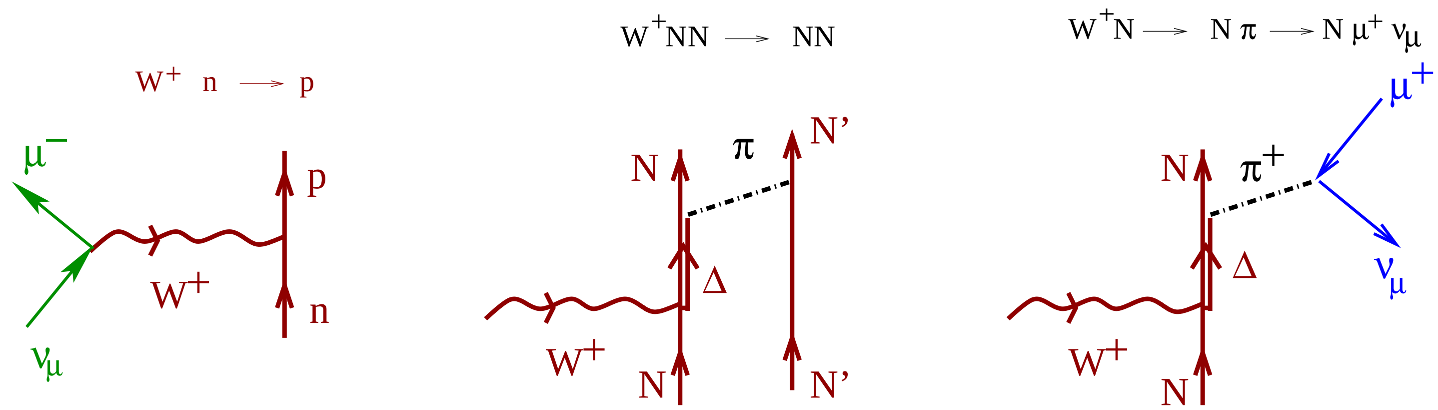
confirmed by many other groups, for instance by Benhar et al. (PRL 105, 132301)



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

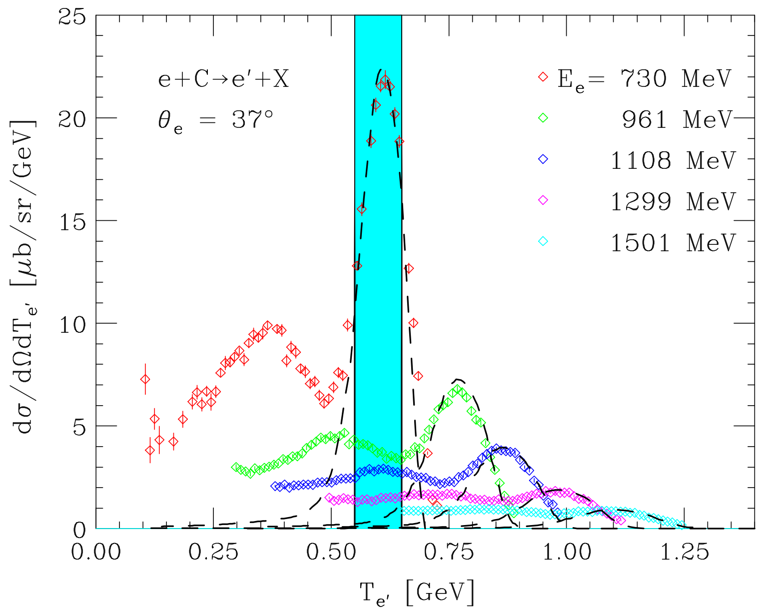


...but key observation (Martini et al., PRC 81, 045502): in most **theoretical** works QE is used for processes where the gauge boson $W^\pm$ **or** Z^0 **is absorbed by just one nucleon**, which together with a lepton is emitted, **however in the recent MiniBooNE measurements, QE is related to processes 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,

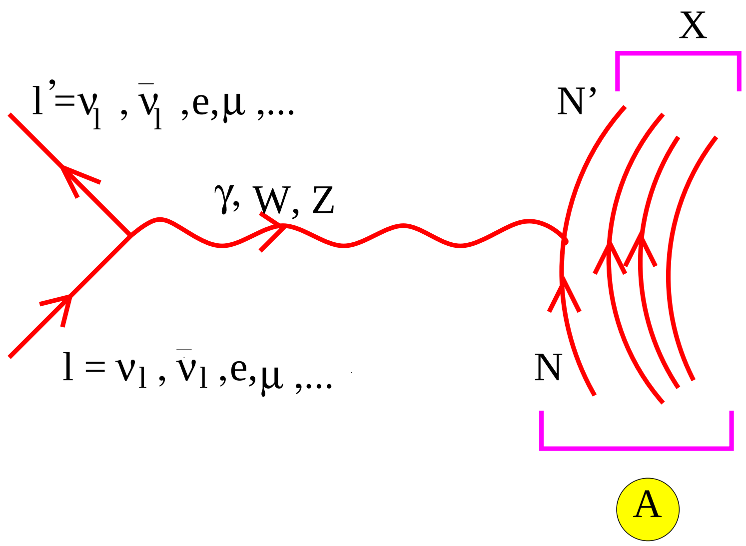


The energy bin corresponding to **the top of the QE peak at $E_e =$ 730 MeV receives significant contributions from** cross sections corresponding to different beam energies and **different mechanisms!**

- **MiniBooNE experimental results cannot be directly compared to most theoretical previous calculations!**
- **We present a microscopic calculation of the ν and $\bar{\nu}$ <u>CCQE-like</u> 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**

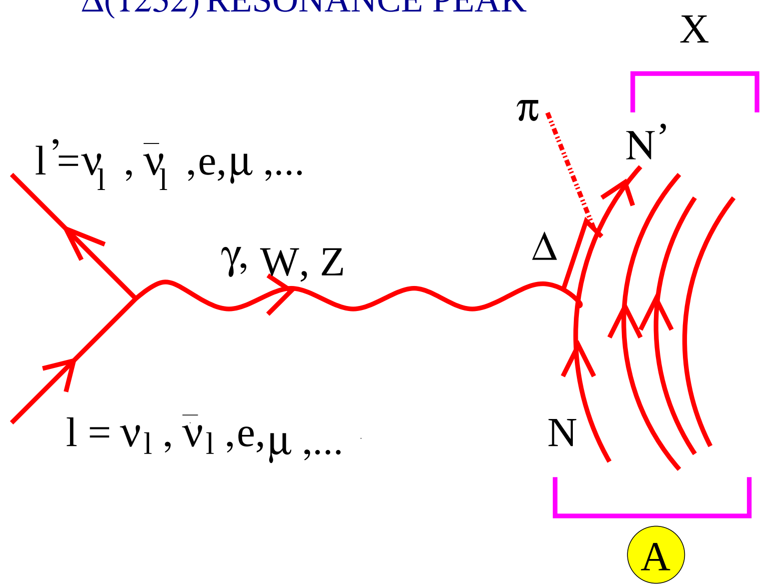
Nuclear renormalization effects on electroweak inclusive reactions in nuclei at intermediate energies

QUASIELASTIC PEAK



VIRTUAL γ / W / Z BY ONE NUCLEON

Δ(1232) RESONANCE PEAK



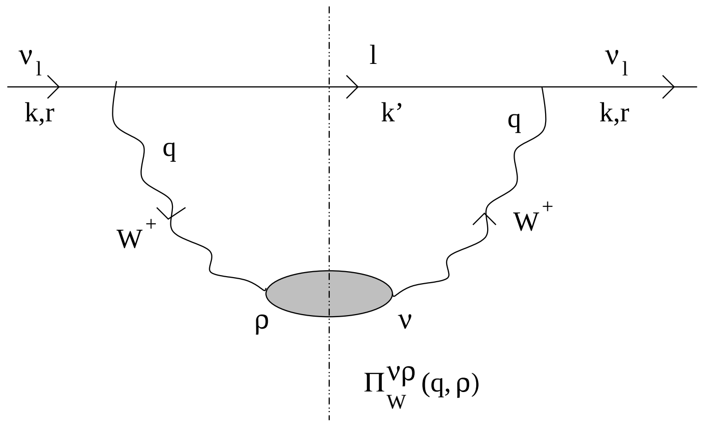
EXCITATION OF Δ (1232) DEGREES OF FREEDOM

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 $\nu_l + A_Z \longrightarrow l + X$



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

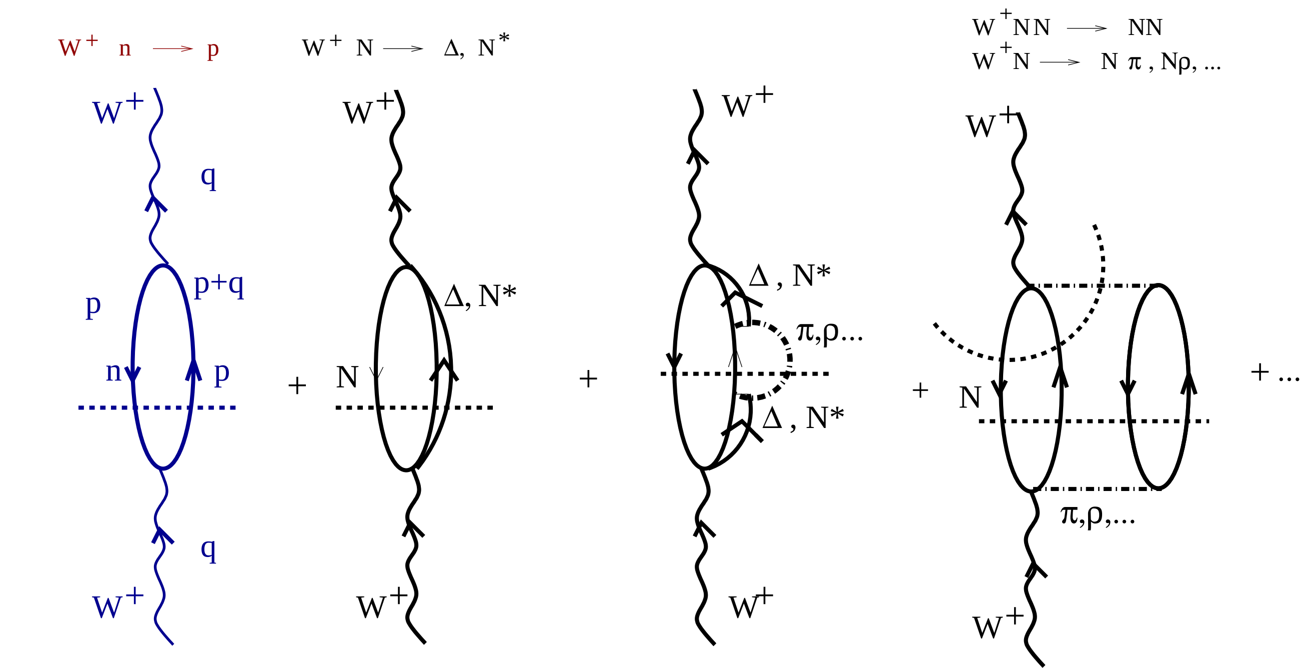
$$L_{\mu\sigma} = k'_\mu k_\sigma + k'_\sigma k_\mu - g_{\mu\sigma}k\cdot k' + \mathrm{i}\epsilon_{\mu\sigma\alpha\beta}k'^\alpha k^\beta$$

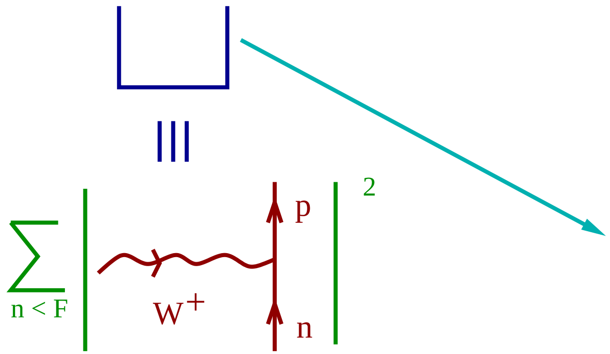
$$W^{\mu\sigma} = W_s^{\mu\sigma} + \mathrm{i}W_a^{\mu\sigma}$$

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

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

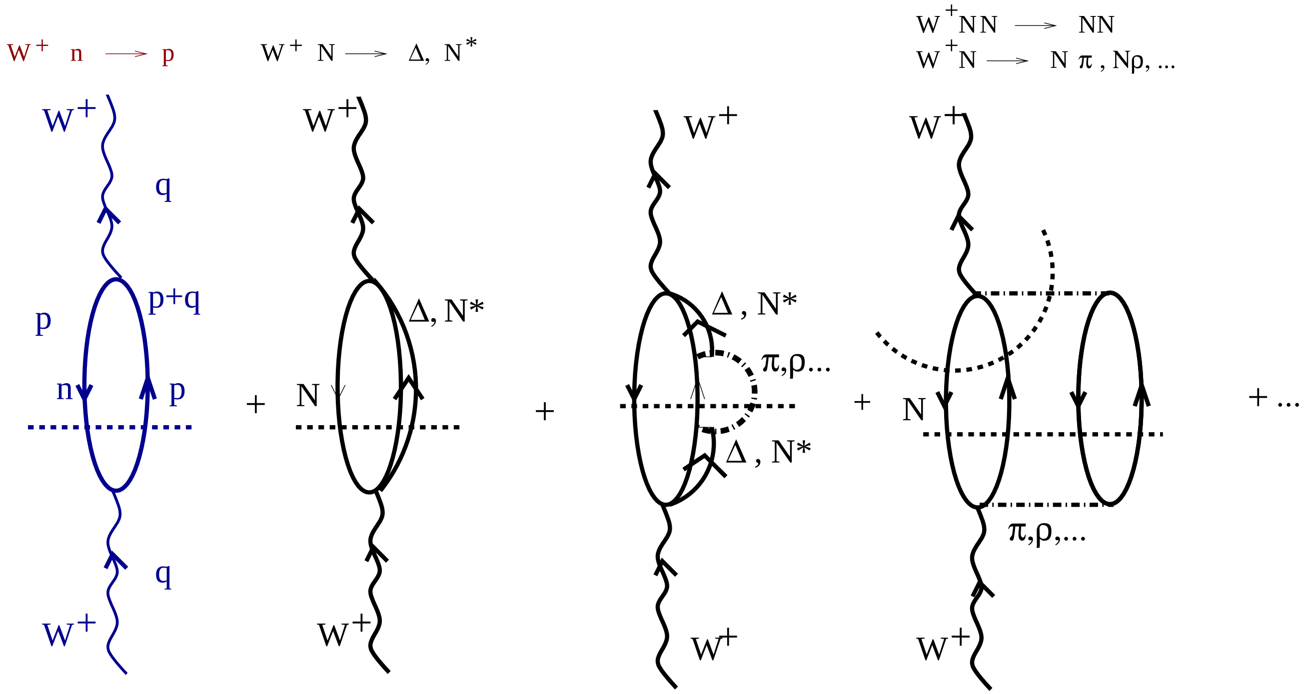
Basic object $\boxed{\Pi^{\nu\rho}_{W,Z^0,\gamma}(q,\rho)}$ $\equiv$ Selfenergy of the Gauge Boson $(W^\pm, Z^0, \gamma)$ inside of the nuclear medium. Perform a Many Body expansion, where the relevant gauge boson absorption modes should be systematically incorporated: absorption by one N, or NN or even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

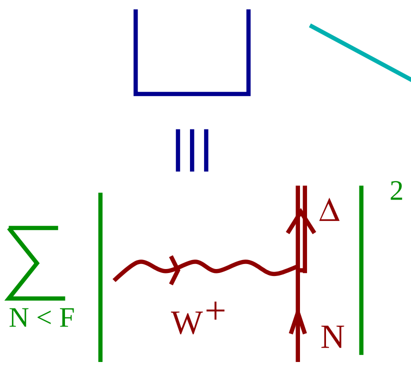




QE

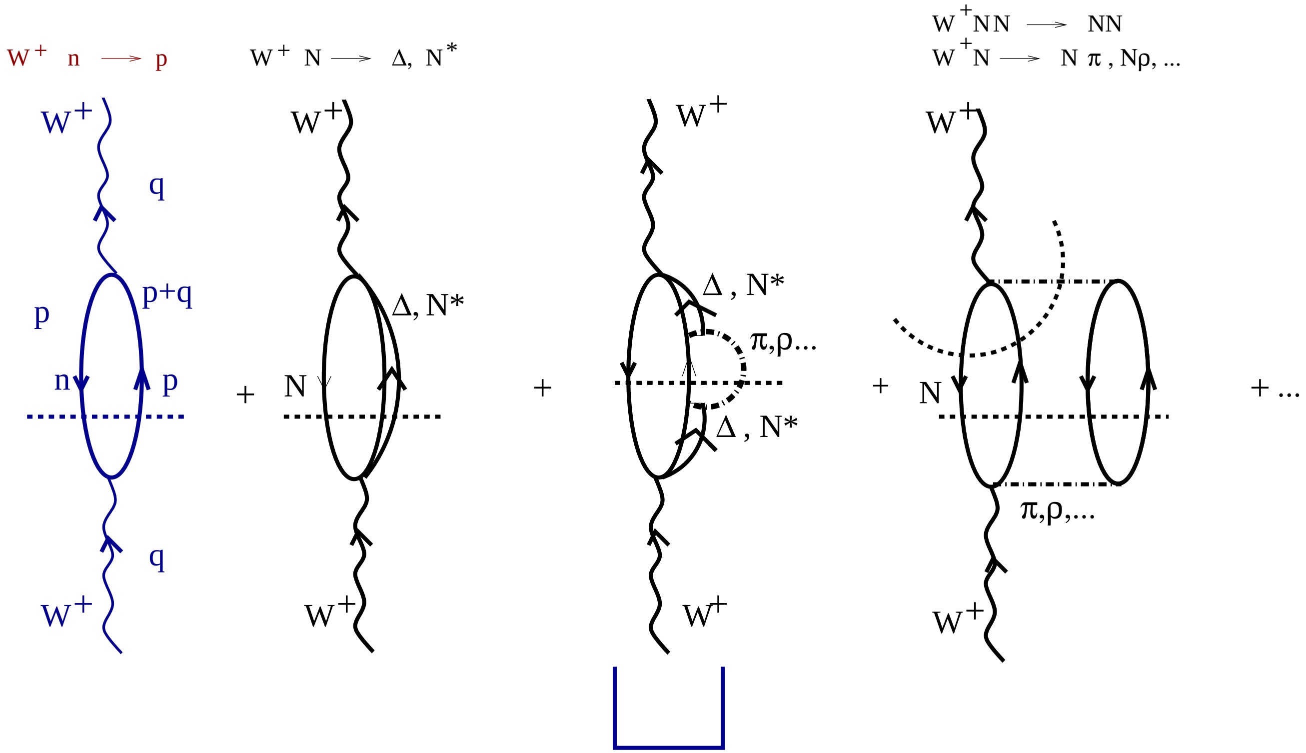
PRC 70 (2004) 055503 (CC)
PRC 73 (2006) 025504 (NC)





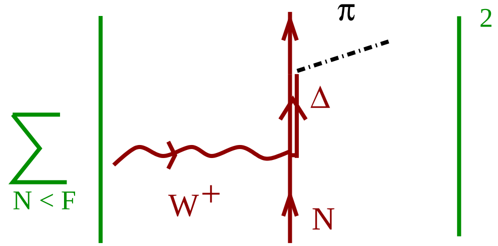
Δh prod.

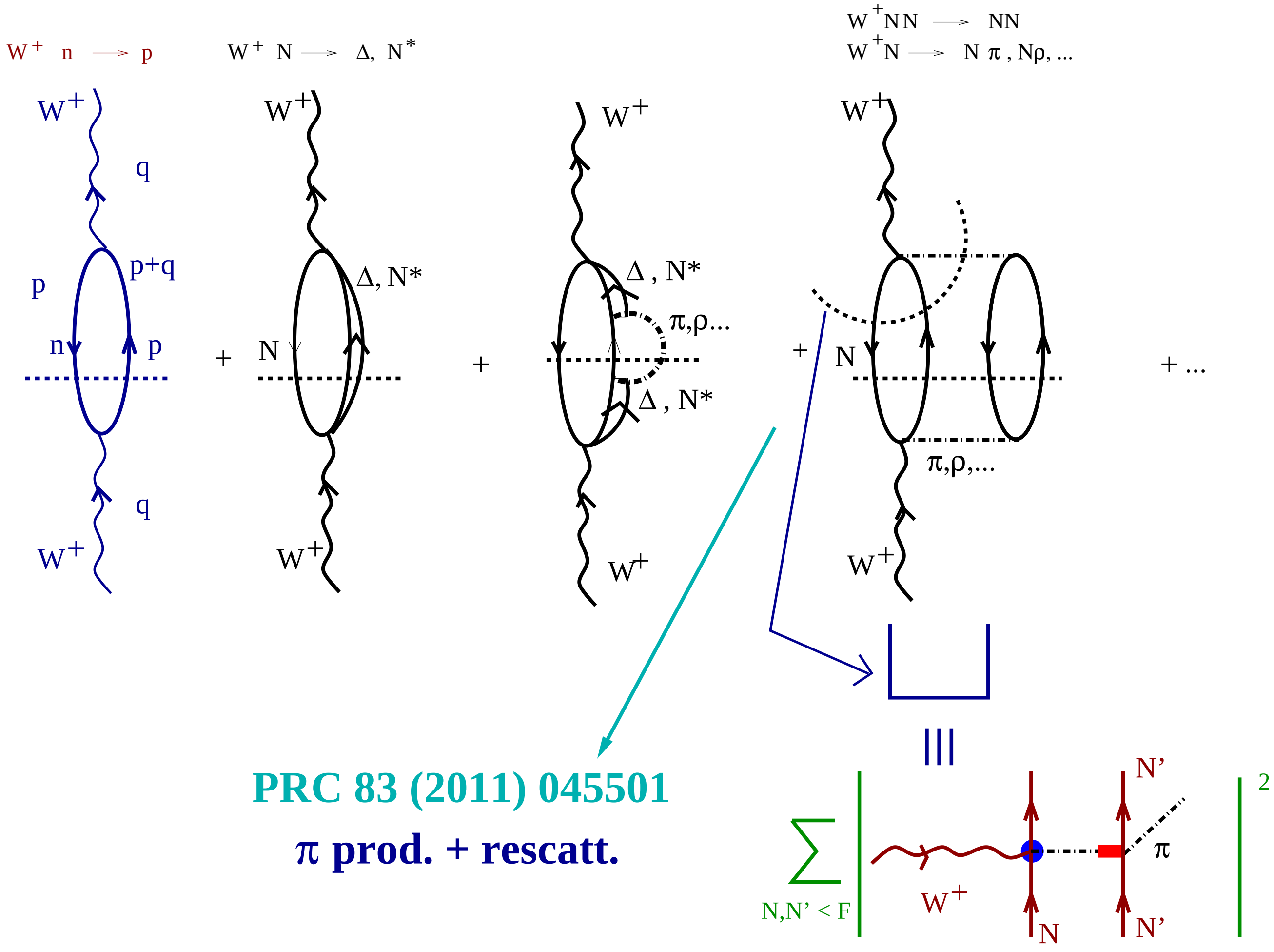
PRC 83 (2011) 045501



PRC 83 (2011) 045501

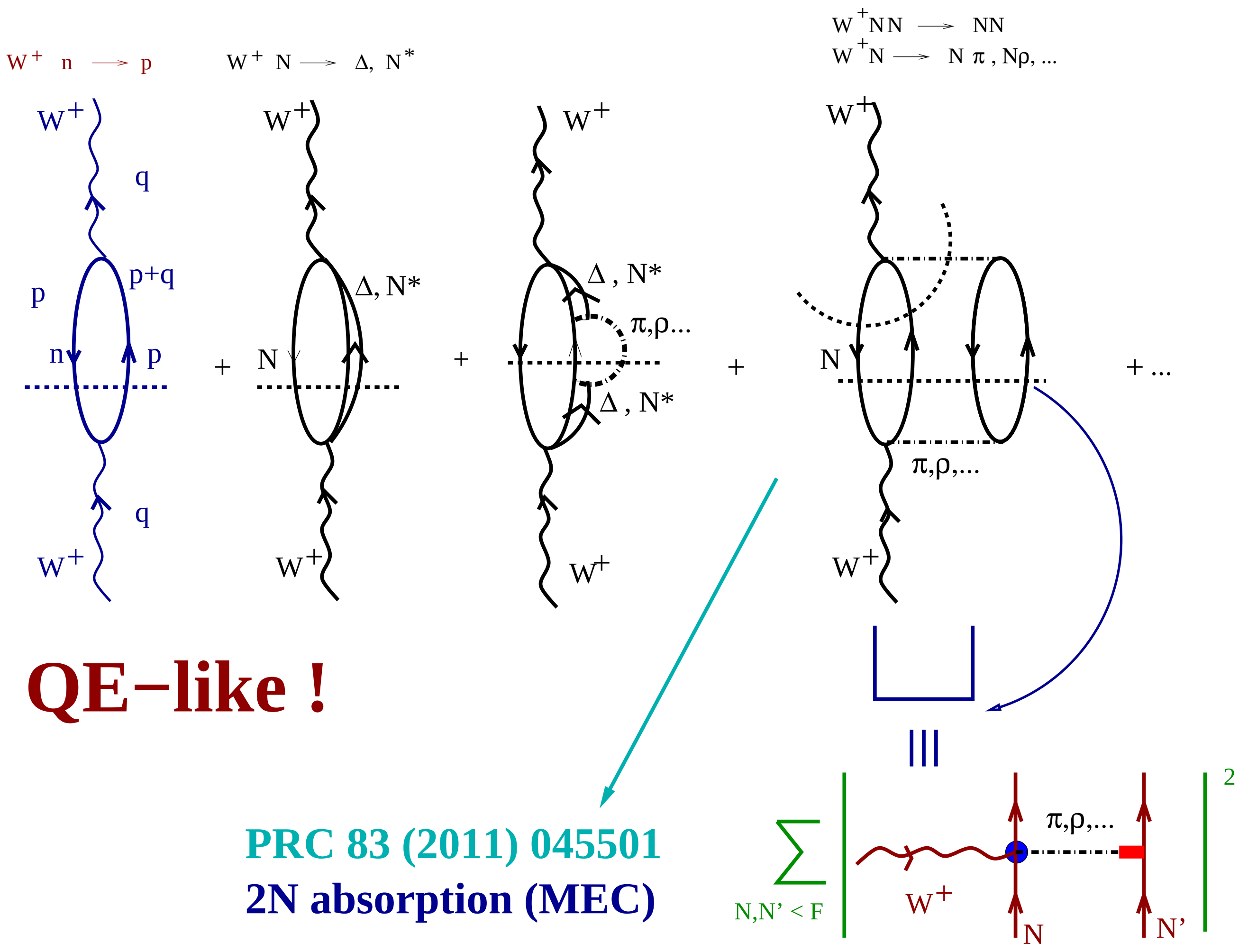
π prod.





PRC 83 (2011) 045501

π prod. + rescatt.


W+ n → p
W+ N → Δ, N*
W+NN → NN
W+N → N π , Nρ, ...
W+
q
p
p+q
n
p
Δ, N*
N
+
Δ , N*
π,ρ...
Δ , N*
N
π,ρ,...
+ ...
QE−like !
PRC 83 (2011) 045501
2N absorption (MEC)
N,N' < F
π,ρ,...
N
N'
2

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.

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

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

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

with vector form factors related to the electromagnetic ones and

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

One finds (quasielastic peak)

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

Relativistic Local Fermi Gas that includes Pauli Blocking !

in addition we include some nuclear corrections...

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

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

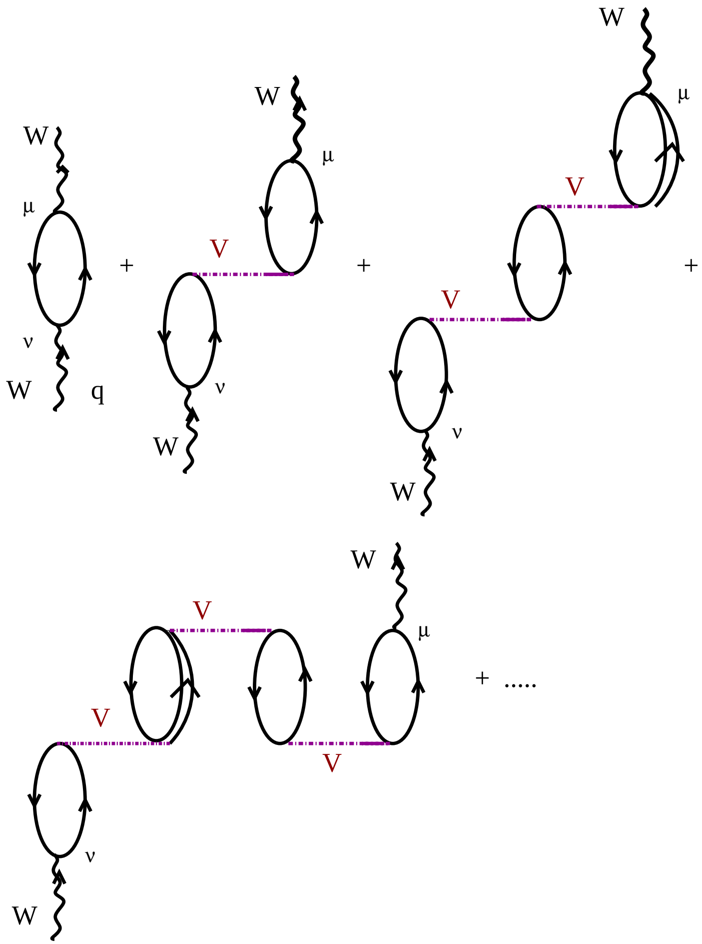
$\int d^3r \to$ N (number of neutrons) and $\sigma_{\nu_l A \to l X} = \mathrm{N} \sigma_{\nu_l n \to l^- p}$

- 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

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

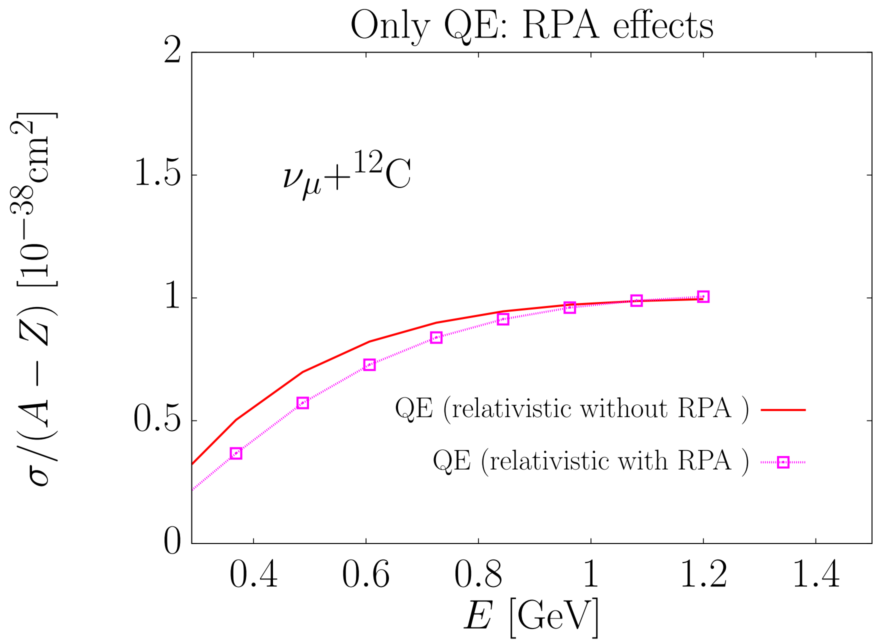
Isoscalar terms $\boxed{}$ do not contribute to CC

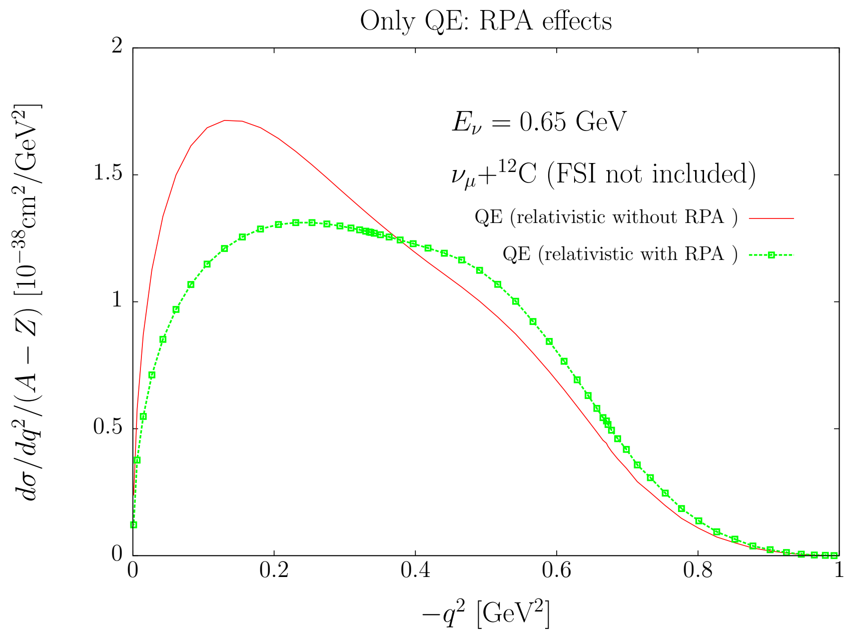
2. $S=T=1$ channel of the ph–ph interaction → s longitudinal (π) and transverse (ρ) + **SRC**

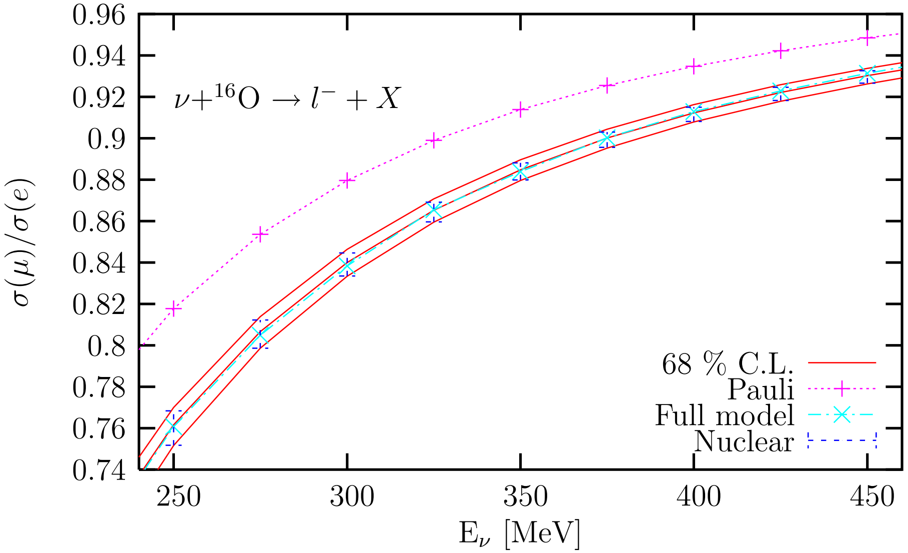
$$g_0'\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \to [V_l(q)\hat{q}_i\hat{q}_j + V_t(q)(\delta_{ij}-\hat{q}_i\hat{q}_j)]\,\sigma_1^i\sigma_2^j\vec{\tau}_1\vec{\tau}_2$$

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

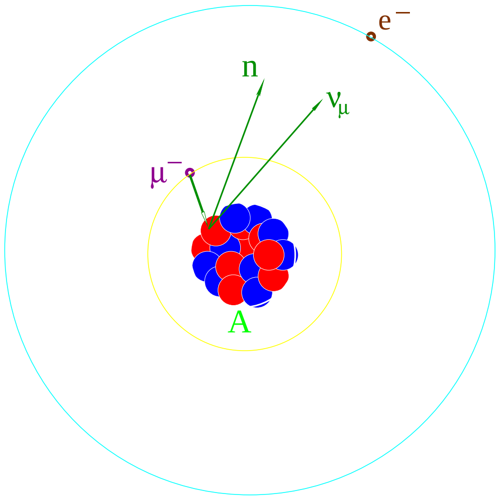
3. Contribution of Δh excitations important







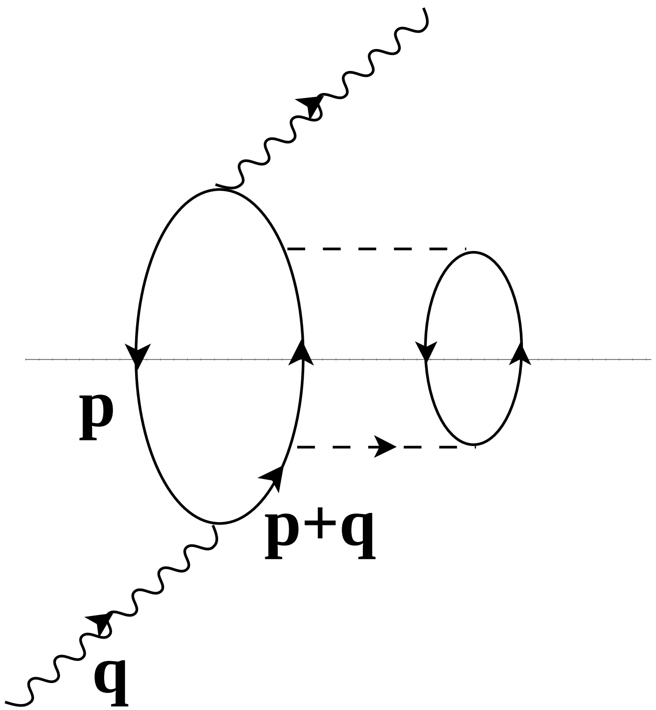
RPA corrections strongly decrease as the neutrino energy increases. However, their effects might account for a low Q^2 deficit of CCQE events and affect the σ_μ/σ_e ratio (~ 5 %)



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	$609{\pm}4$	-0.11
^{112}Cd	1825	1078	$1061{\pm}9$	-0.02
^{208}Pb	1939	1310	$1311{\pm}8$	0.00

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 $\Rightarrow$ Interacting Fermi sea (SF)**
  - **particle $\Rightarrow$ Interaction of the ejected nucleon with the final nuclear state (FSI)**

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

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

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

with $\omega \geq \mu$ or $\omega \leq \mu$ for S_p and S_h, respectively.

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

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

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

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

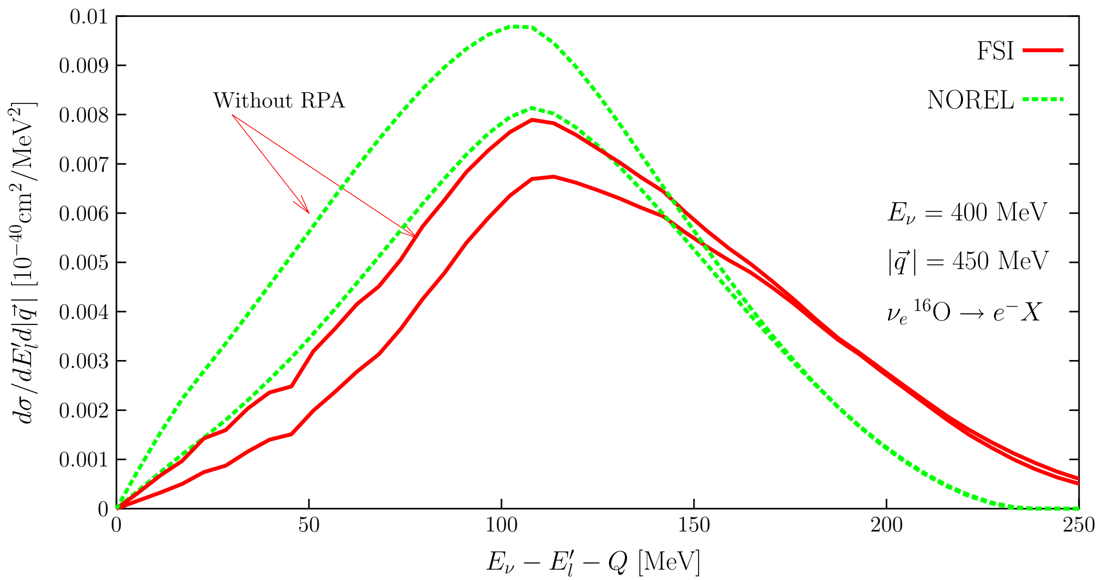
and only Pauli blocking is incorporated!!

To take into account SF+FSI we should **replace** $\mathrm{Im}\bar{U}_R^N(q)$ **by a new response function**:

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

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

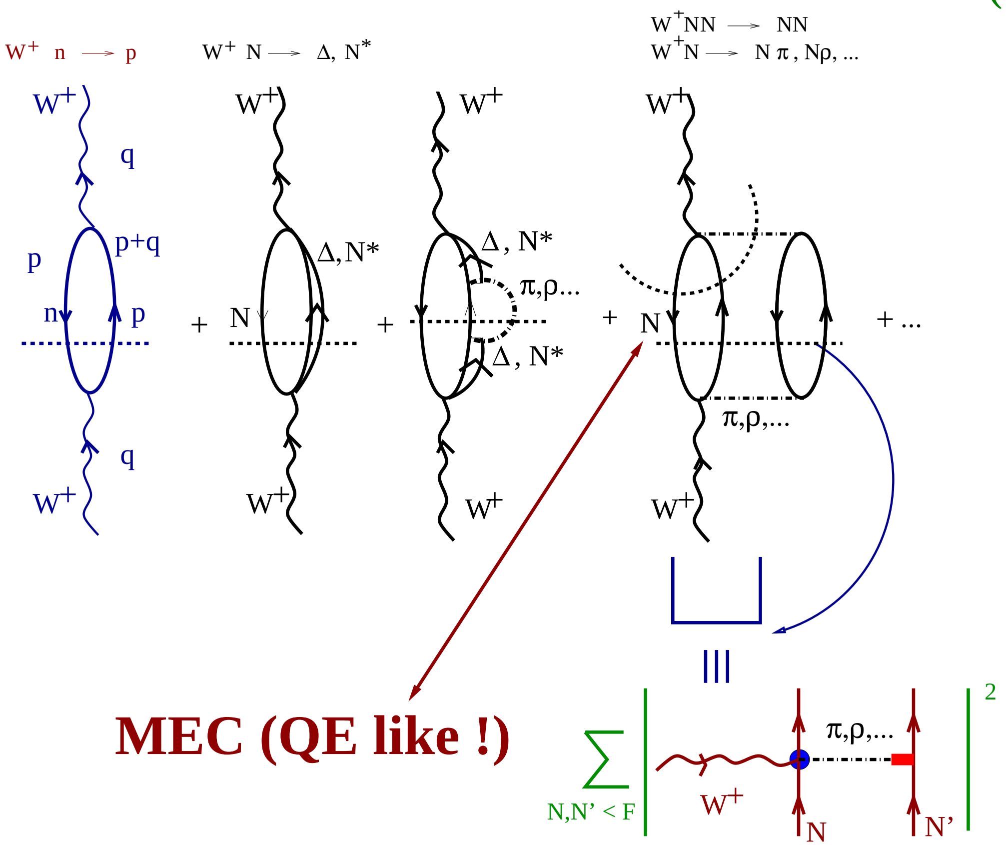
This nuclear effect is additional to those due to RPA (long range) correlations !!

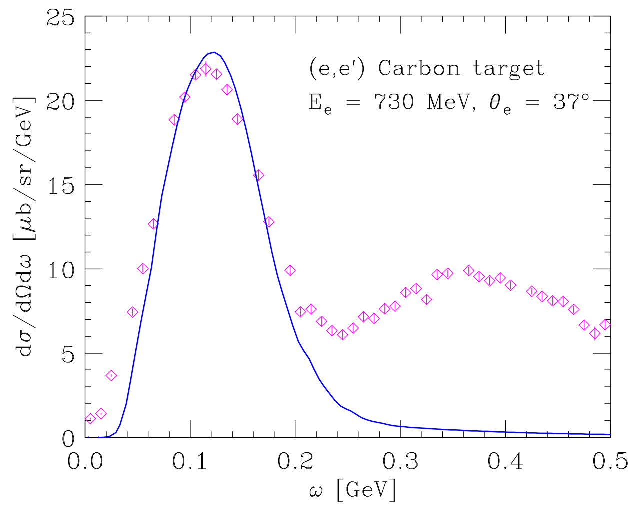


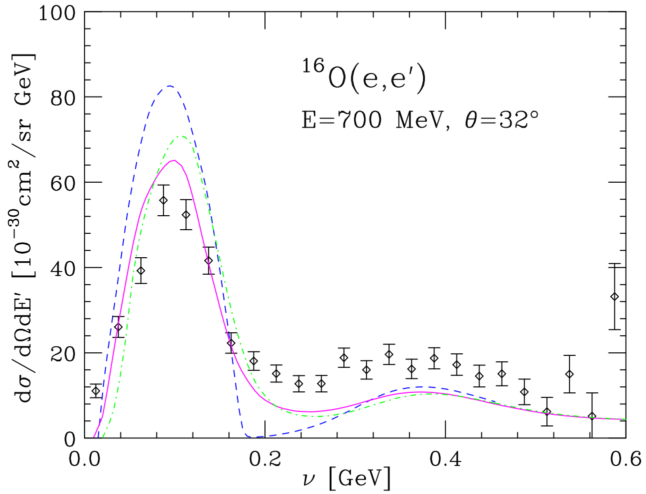
- **Sizeable reduction of the strength at the QE peak, which is slightly shifted. Neutrino energy re-construction uses $q^0 = -q^2/2M$, problems??**
- **Enhancement of the high energy transfer tail, which partially compensates the above reduction and thus the effect on the total (integrated) cross section is smaller.**

Above QE Region: π Production

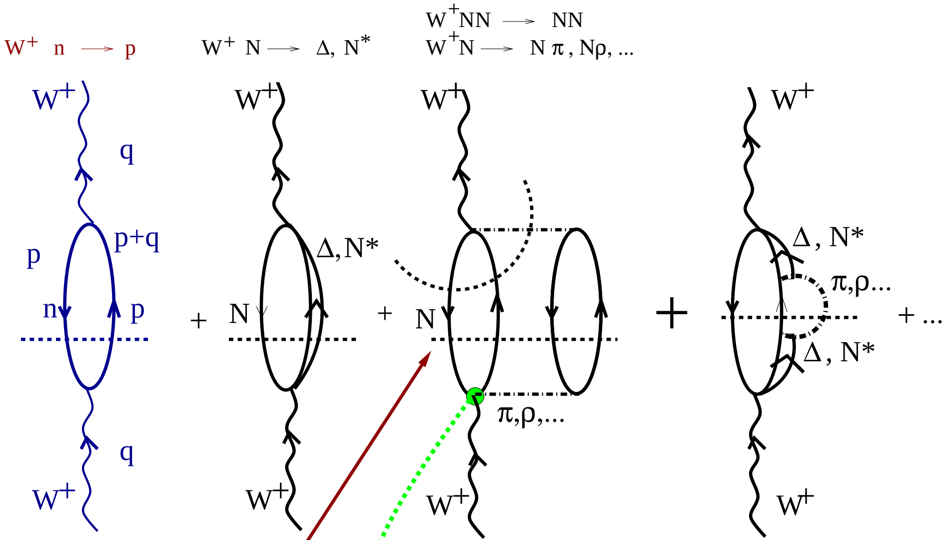
(e,e') PRL 105, 132301 & PRD 72 053005

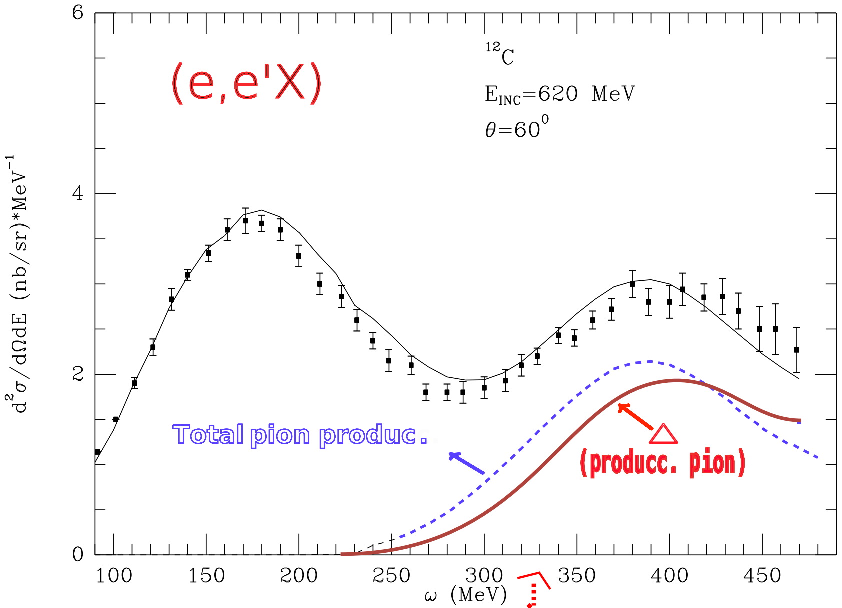






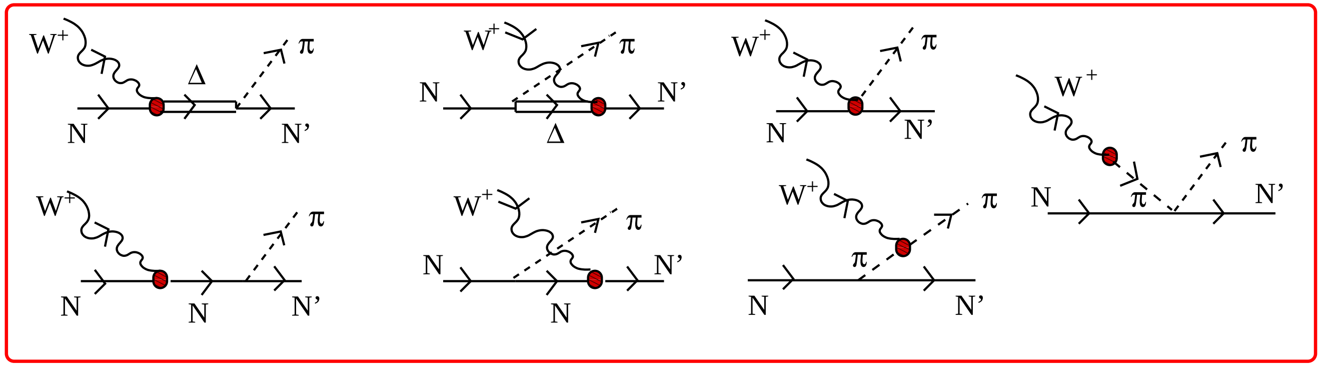
Above QE Region: π Production





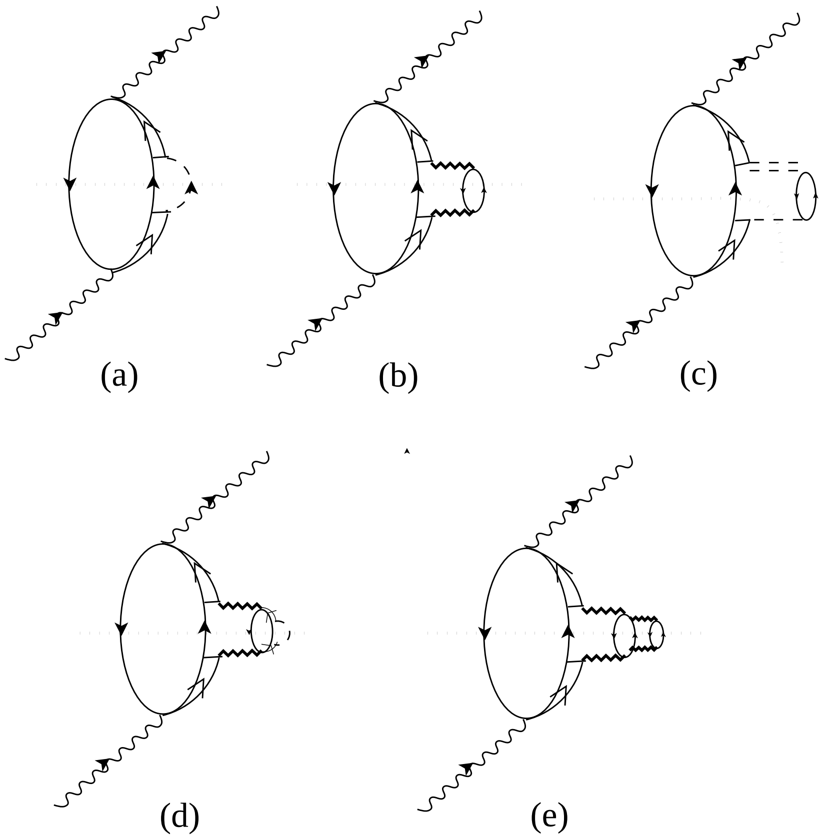
MEC ⟶ QE like !

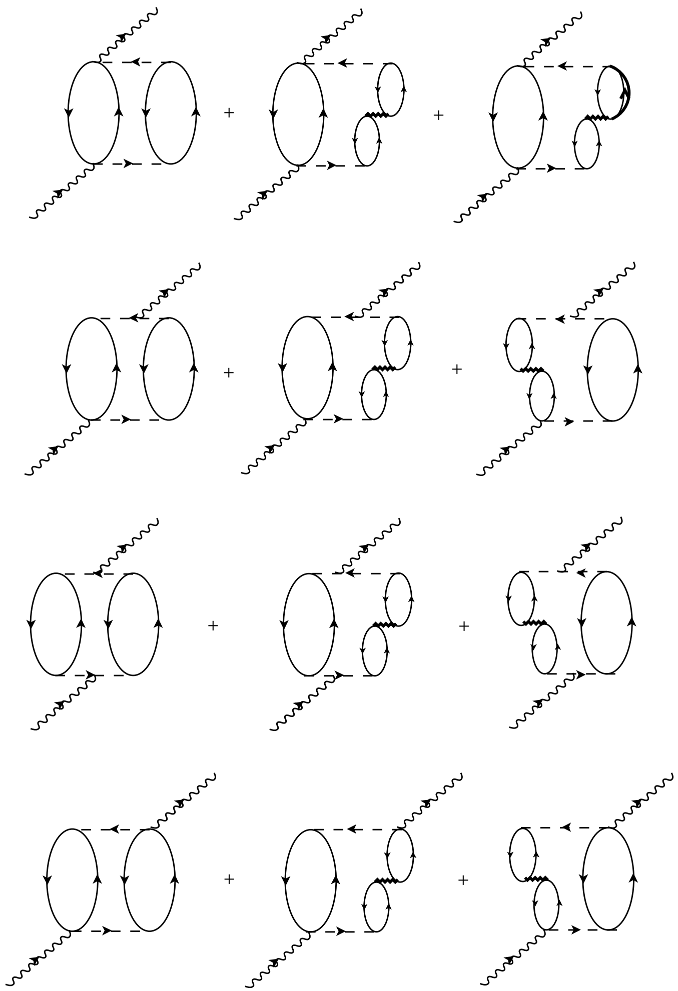
PRD D76 (2007) 033005
PRD D81 (2010) 085046 →

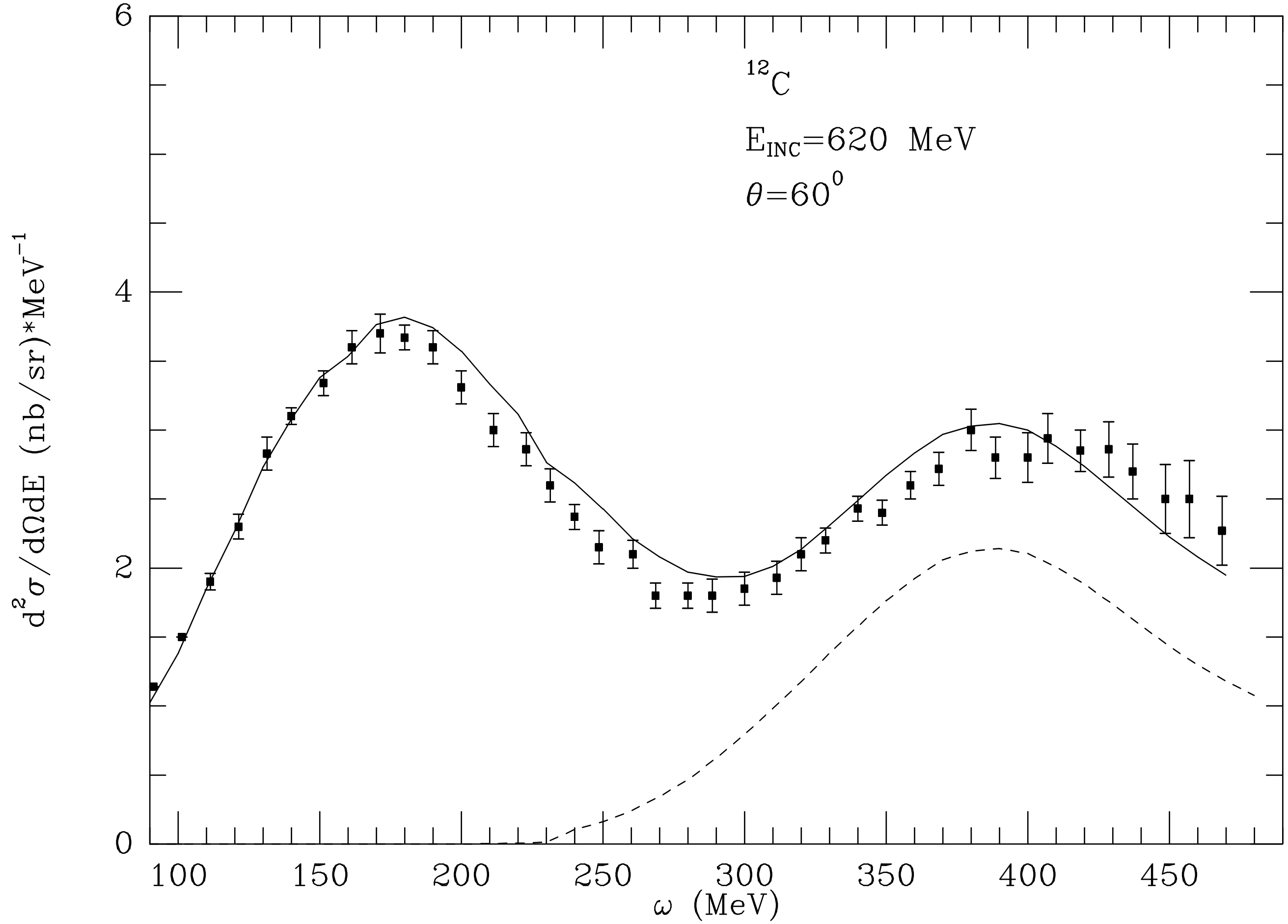


(e, e') Results

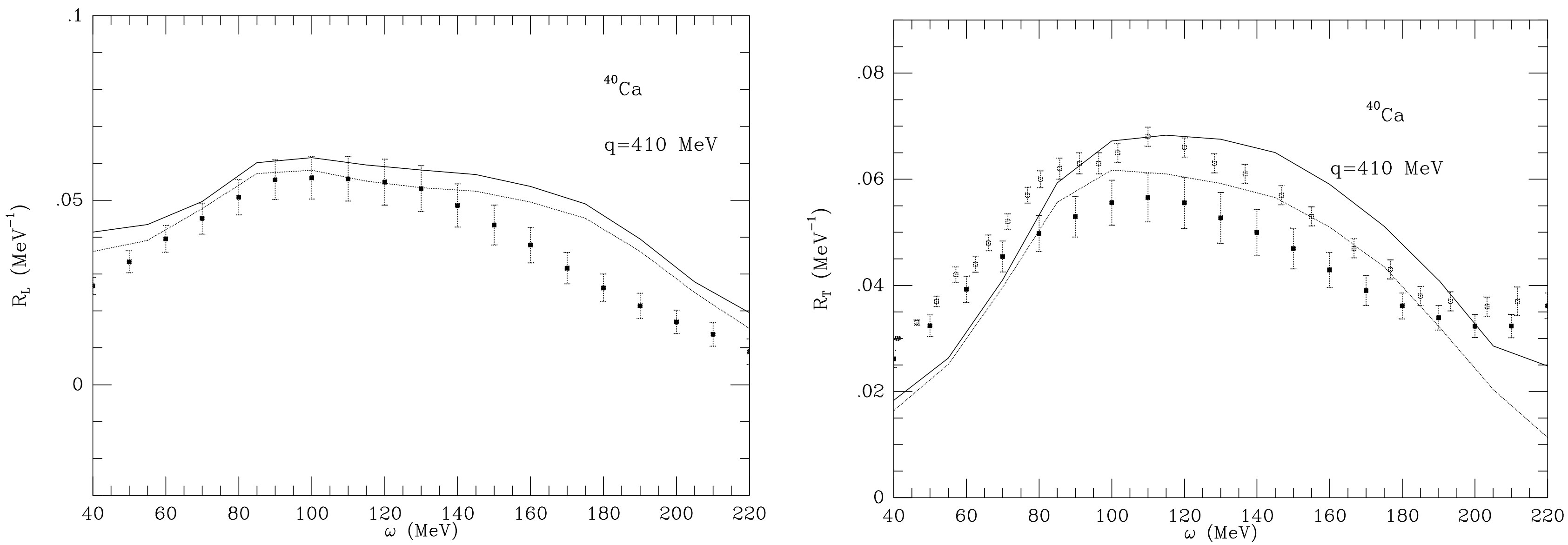
Same formalism applied to the study of inclusive processes (e, e'), $(e, e'N)$, $(e, e'NN)$, $(e, e'\pi)$, ... in nuclei at intermediate energies **[Gil+Nieves+Oset, NPA 627 (1997) 543-619]** leads to excellent results both in the quasielastic and Δ excitation regions. To describe the Δ peak and the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


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



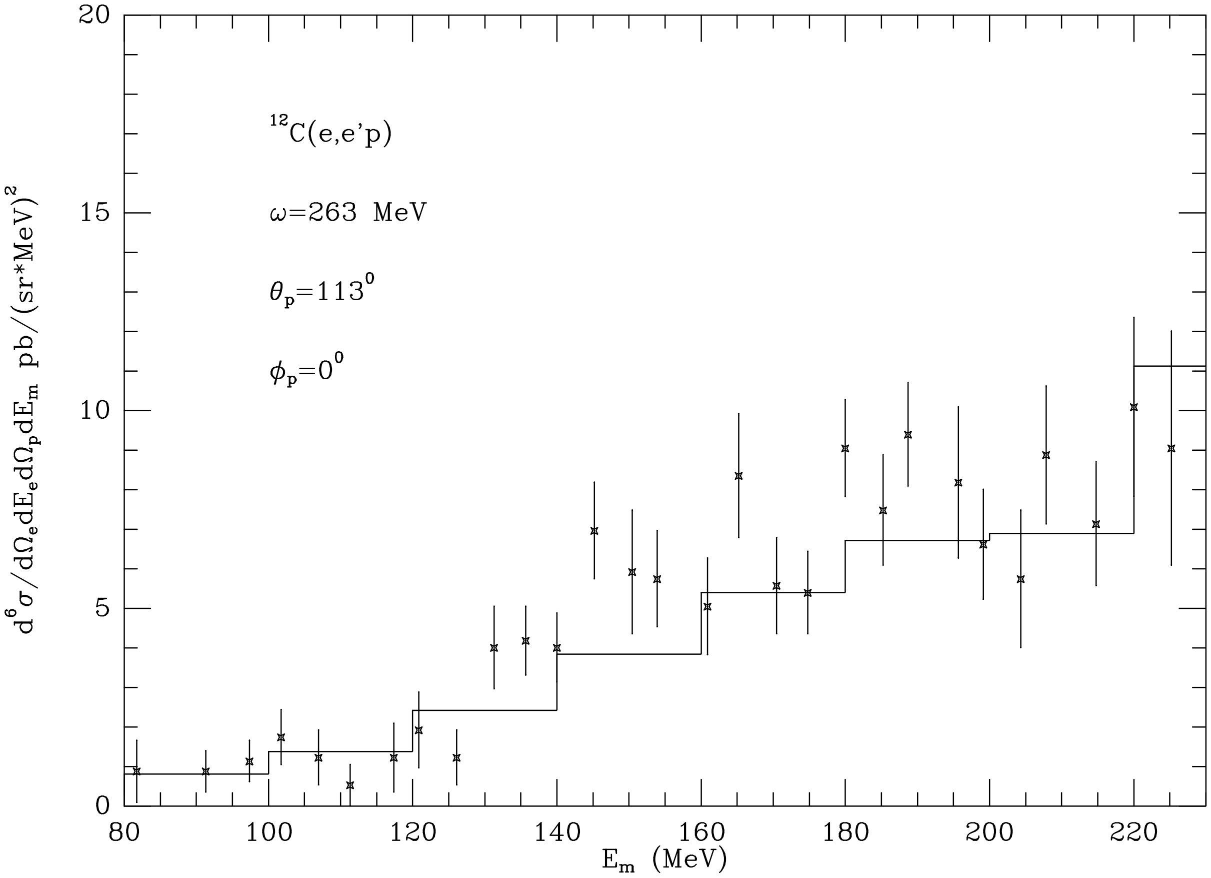


$$e + {}^{12}\mathrm{C} \to e' + X$$



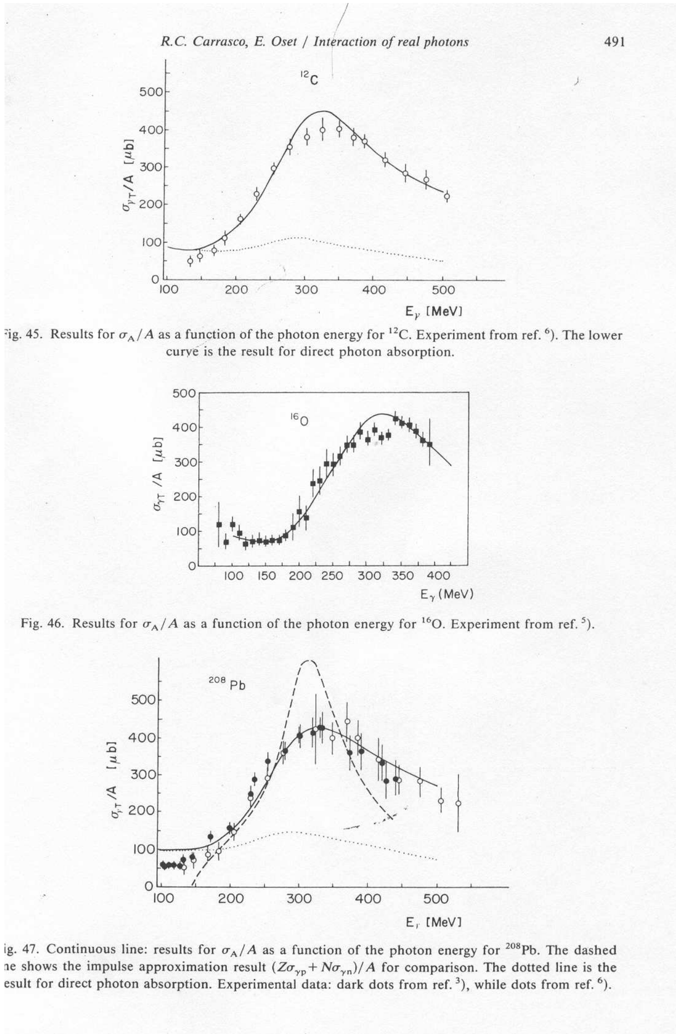
R_L and R_T QE response functions for $e + {}^{40}\mathrm{Ca} \to e' + X$

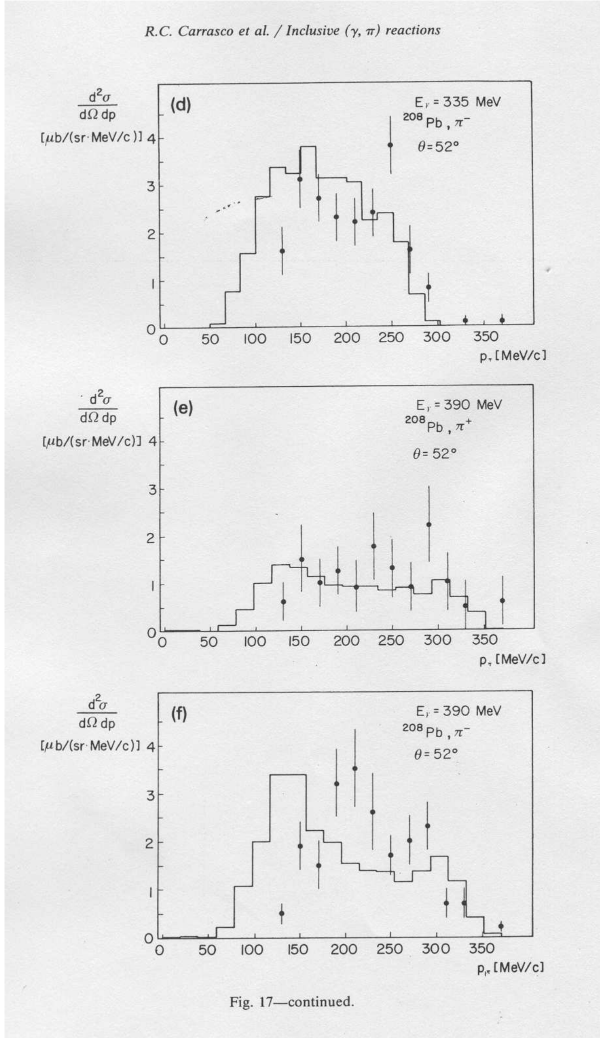
and by means of a Monte Carlo simulation we obtain cross sections for the processes $(e, e'N)$, $(e, e'NN)$, $(e, e'\pi)$, ...



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

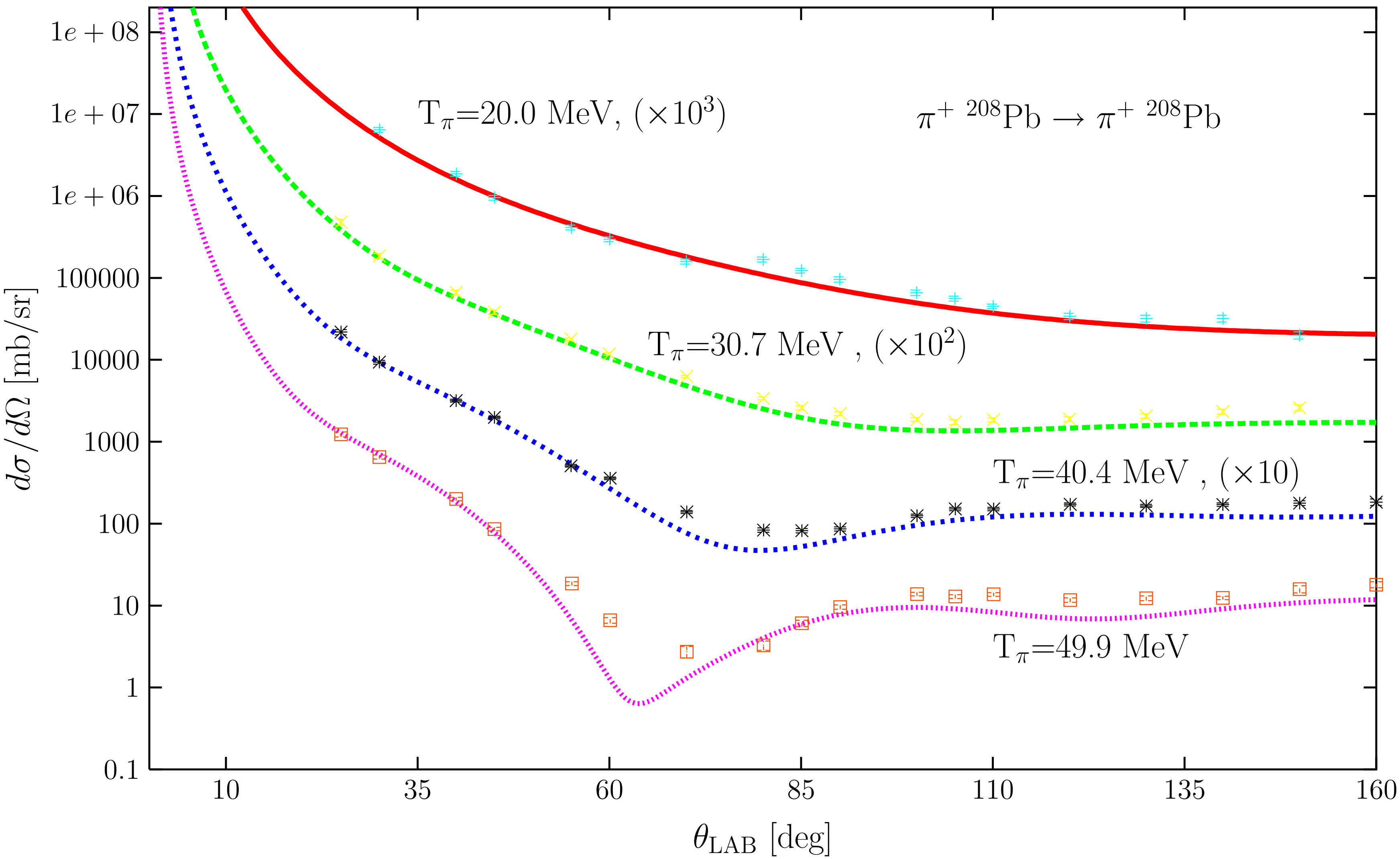
García-Recio+Oset+Salcedo+Strottman, NPA 526, 685

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

Nieves+Oset, PRC 47 (1993) 1478

Amaro+Nieves, PRL 89 (2002) 032501

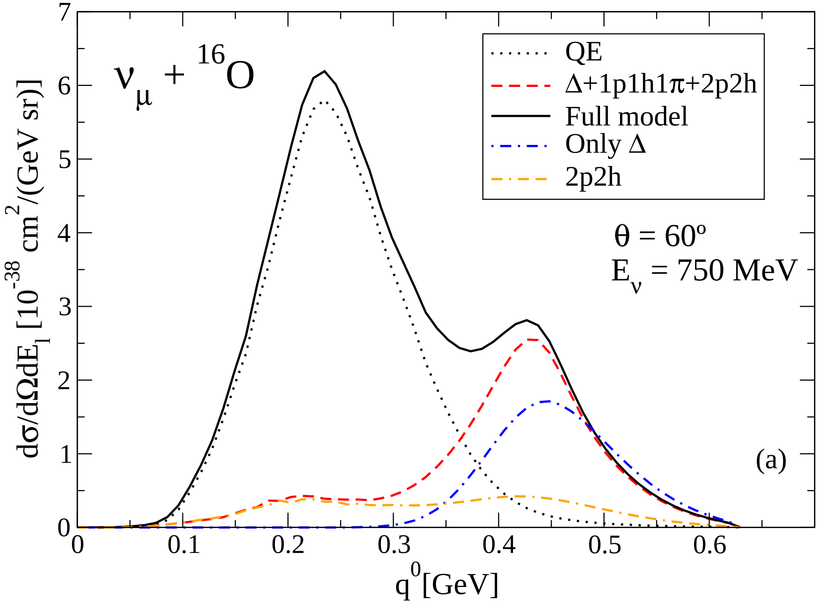
Albertus+Amaro+Nieves, PRC 67 (2003) 034604

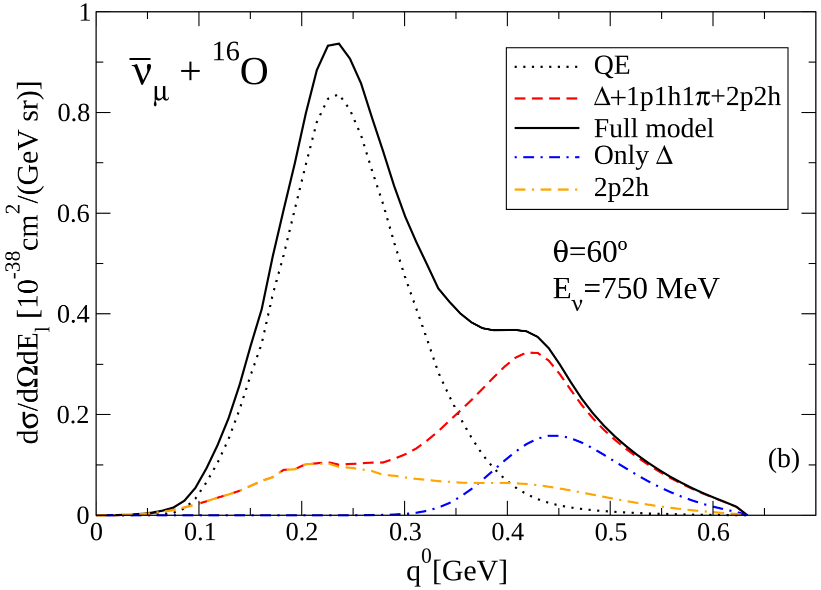


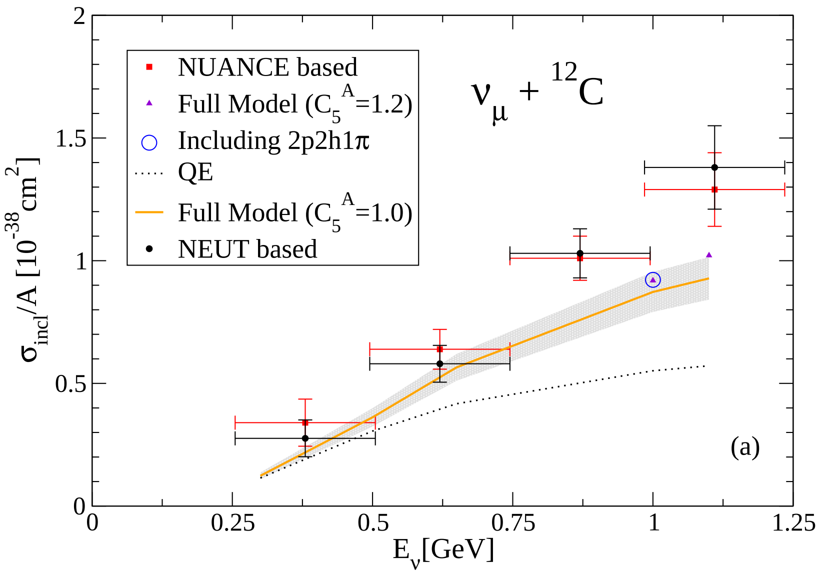
T_π=20.0 MeV, ($\times 10^3$)
$\pi^+ \, ^{208}$Pb $\rightarrow \pi^+ \, ^{208}$Pb
T_π=30.7 MeV , ($\times 10^2$)
T_π=40.4 MeV , ($\times 10$)
T_π=49.9 MeV
$d\sigma/d\Omega$ [mb/sr]
$\theta_{\rm LAB}$ [deg]
1e + 08
1e + 07
1e + 06
100000
10000
1000
100
10
1
0.1
10
35
60
85
110
135
160

(ν_μ, μ^-) Results

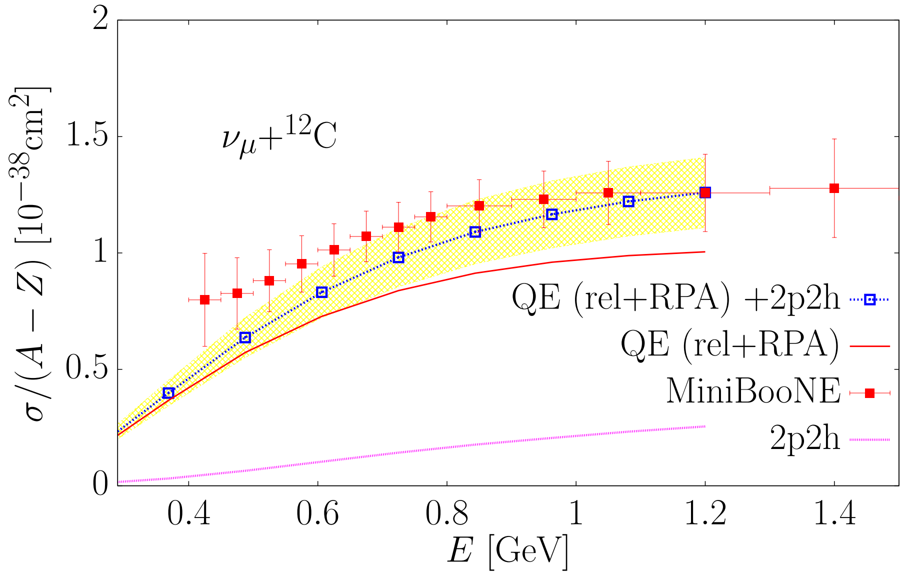
PRC 83 (2011) 045501 [M_A= 1.049 GeV]







NUANCE based
Full Model (C5A=1.2)
Including 2p2h1π
QE
Full Model (C5A=1.0)
NEUT based
νμ + 12C
(a)
σincl/A [10-38 cm2]
Eν[GeV]



νμ+12C
QE (rel+RPA) +2p2h
QE (rel+RPA)
MiniBooNE
2p2h
σ/(A − Z) [10−38cm2]
E [GeV]

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

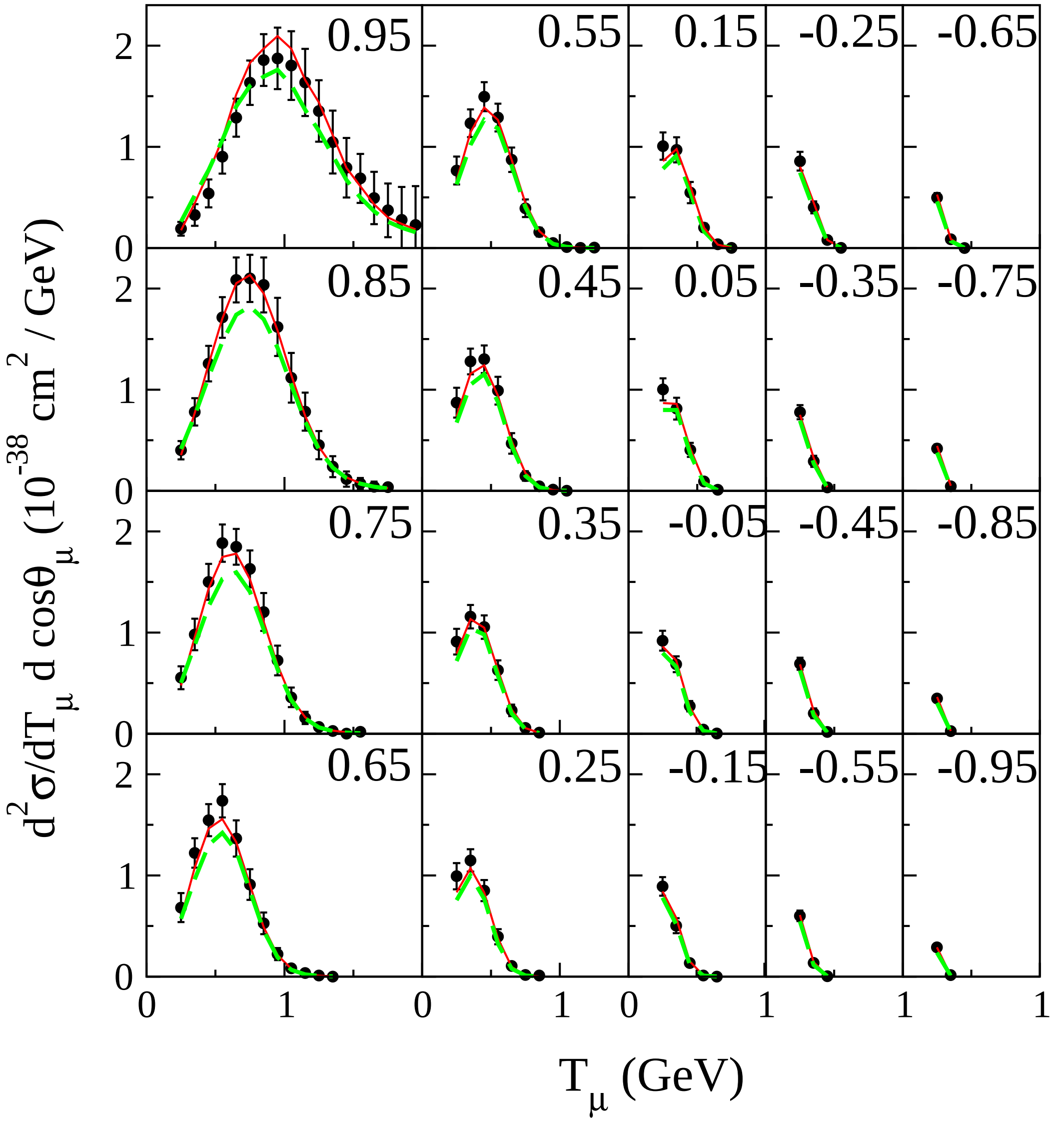
We define a **merit function** and consider our **QE+2p2h results**

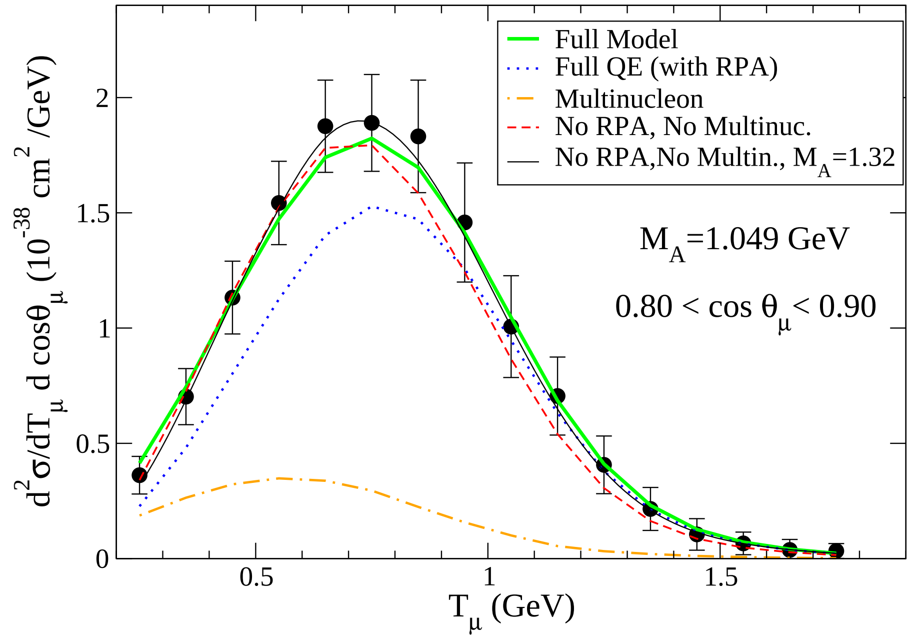
$$\chi^2 = \sum_{i=1}^{137} \left[\frac{\lambda \left(\frac{d^2\sigma^{exp}}{dT_\mu d\cos\theta}\right)_i - \left(\frac{d^2\sigma^{th}}{dT_\mu d\cos\theta}\right)_i}{\lambda\Delta\left(\frac{d^2\sigma}{dT_\mu d\cos\theta}\right)_i} \right]^2 + \left(\frac{\lambda - \mathbf{1}}{\mathbf{\Delta}\lambda}\right)^{\mathbf{2}},$$

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 $\lambda = 0.89 \pm 0.01$.

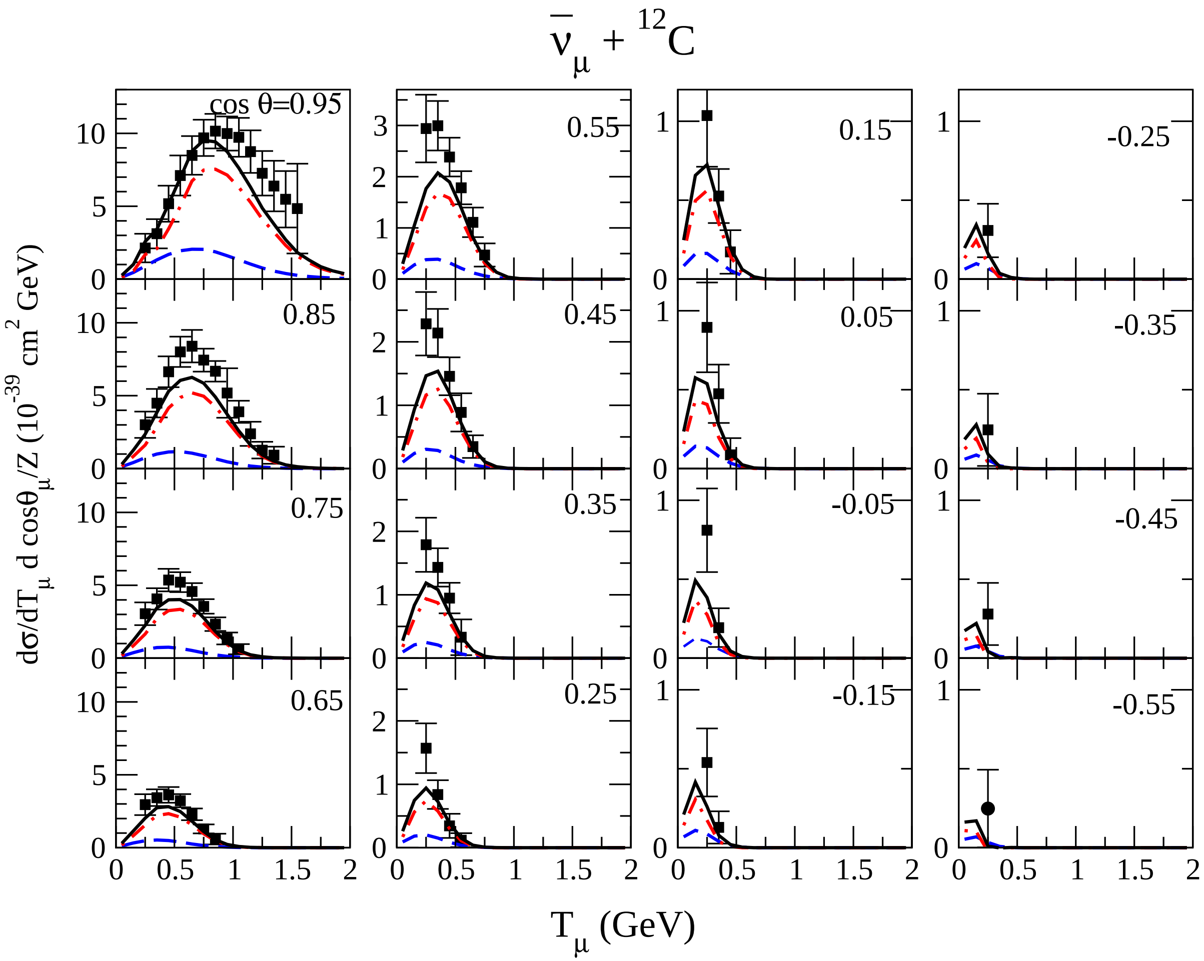
The microscopical model, with no free parameters, agrees remarkably well with data! The shape is very good and χ^2 strongly depends on λ, which is strongly correlated with M_A.

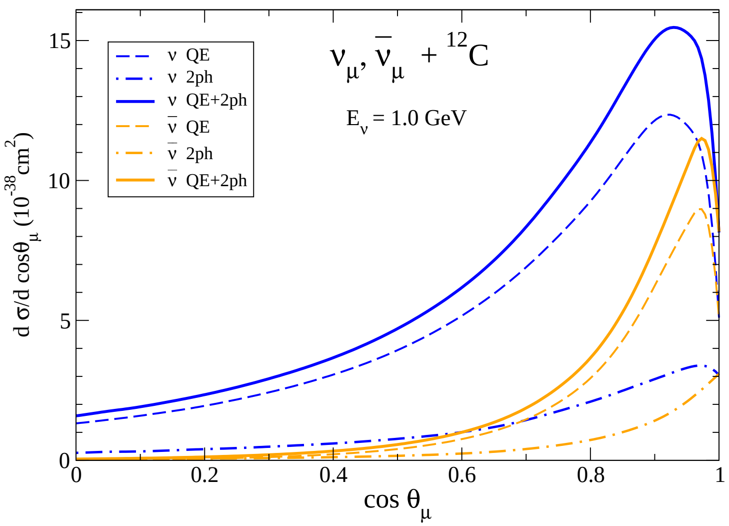




Model	Scale	M_A (GeV)	$\frac{\chi^2}{\#bins}$
LFG	0.96±0.03	1.32±0.03	35/137
Full	**0.92±0.03**	**1.08±0.03**	**50/137**
Full $\vert q\vert > 0.4^\dagger$ GeV	0.83±0.04	1.01±0.03	30/123

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


$\bar{\nu}_\mu$ + ^{12}C
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/dT$_\mu$ d cosθ$_\mu$/Z (10^{-39} cm^2 GeV)
T$_\mu$ (GeV)

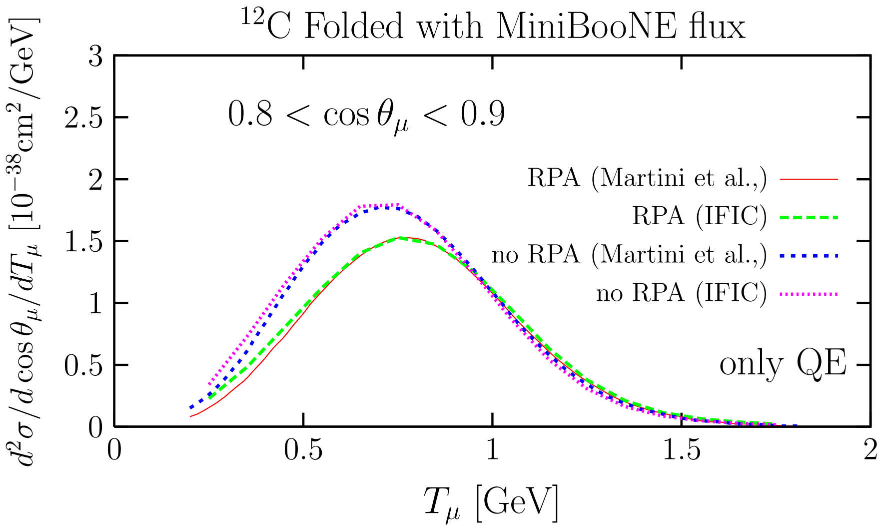

ν QE
ν 2ph
ν QE+2ph
$\bar{\nu}$ QE
$\bar{\nu}$ 2ph
$\bar{\nu}$ QE+2ph
ν$_\mu$, $\bar{\nu}_\mu$ + ^{12}C
E$_\nu$ = 1.0 GeV
d σ/d cosθ$_\mu$ (10^{-38}cm^2)
cos θ$_\mu$

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

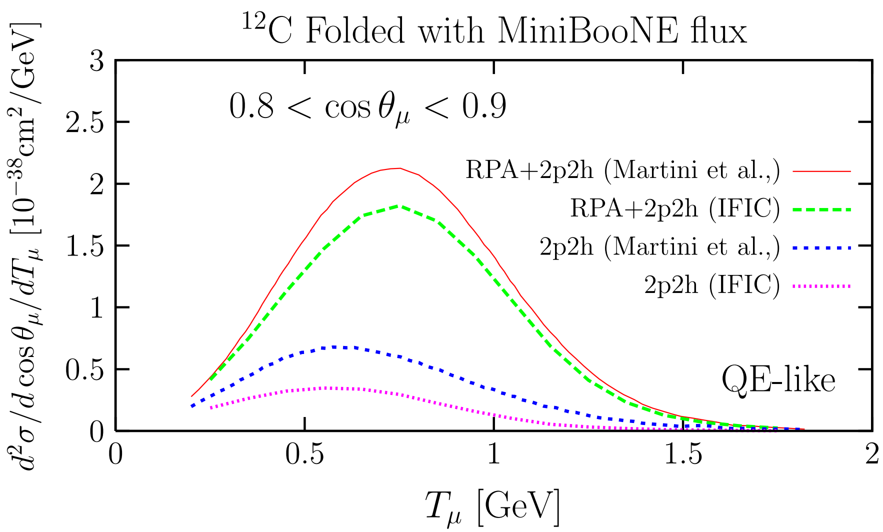
1. **Similar for the 2p2h contributions driven by Δh excitation** (both groups use the same model for the $\Delta-$selfenergy in the medium).

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

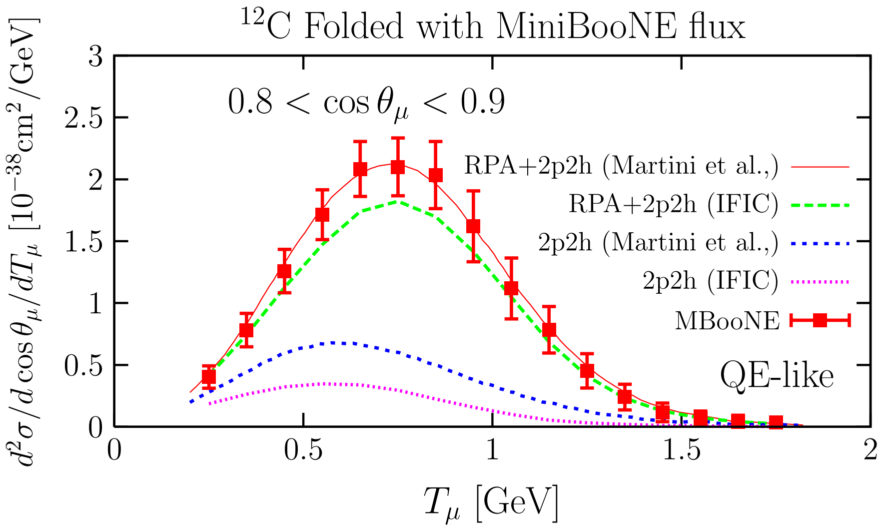
3. **Martini et al. give approximate estimates for the rest of 2p2h contributions** [relate them to the absorptive part of the $p-$wave pion-nucleus optical potential at threshold or to a microscopic calculation by Alberico et al. (Annals Phys. 154, 356) specifically aimed at the evaluation of the 2p-2h contribution to the isospin spin-transverse response, measured in inclusive (e, e') scattering].



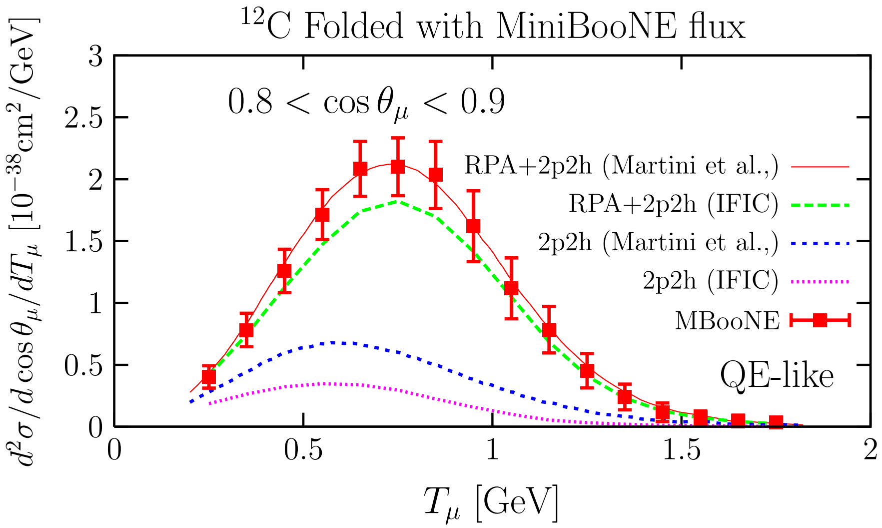
We compare rather well with Martini et al., PRC 84, 055502 for bare QE and QE+RPA



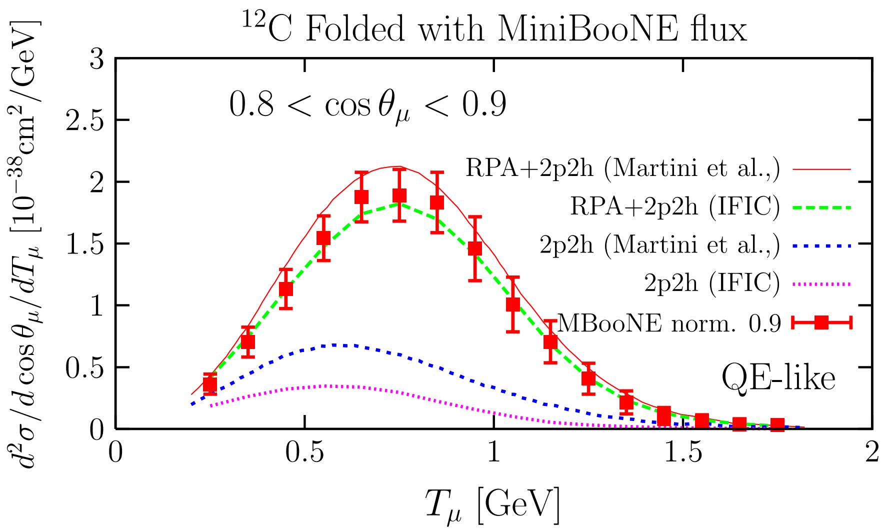
...however our 2p2h contribution is about a factor of 2 smaller!



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

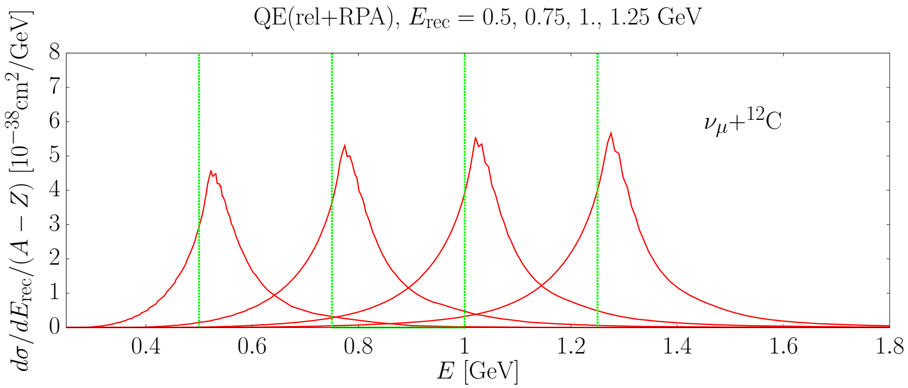
$$P(E_{\rm rec}|E) \quad \underline{\text{is determined by}} \quad \frac{d\sigma}{dE_{\rm rec}}(E; E_{\rm rec})$$

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

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

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

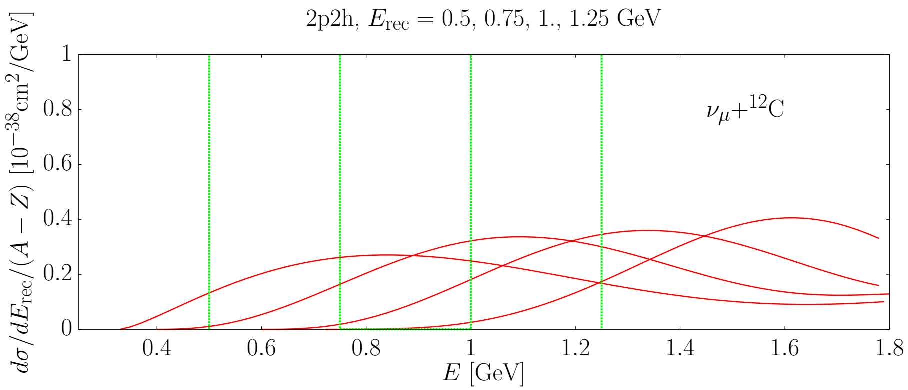
$$\frac{d\sigma}{dE_{rec}}(E; E_{rec}) = \int_{m_\mu}^{E} dE_\mu \left| \frac{\partial(\cos\theta_\mu)}{\partial E_{rec}} \right| \underbrace{\frac{d^2\sigma}{d(\cos\theta_\mu) dE_\mu}(E; E_{rec})}_{\text{theory!}}$$



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

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

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



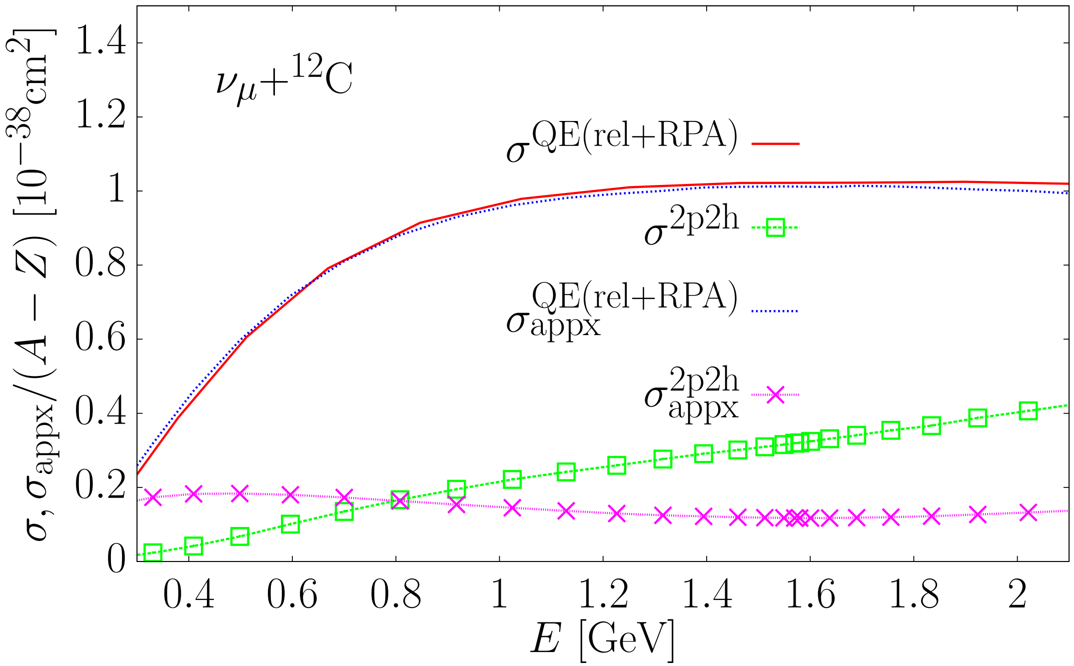
For each $E_{\rm rec}$, there exists a distribution of true neutrino energies that could give rise to events whose muon kinematics would lead to the given value of $E_{\rm rec}$.

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

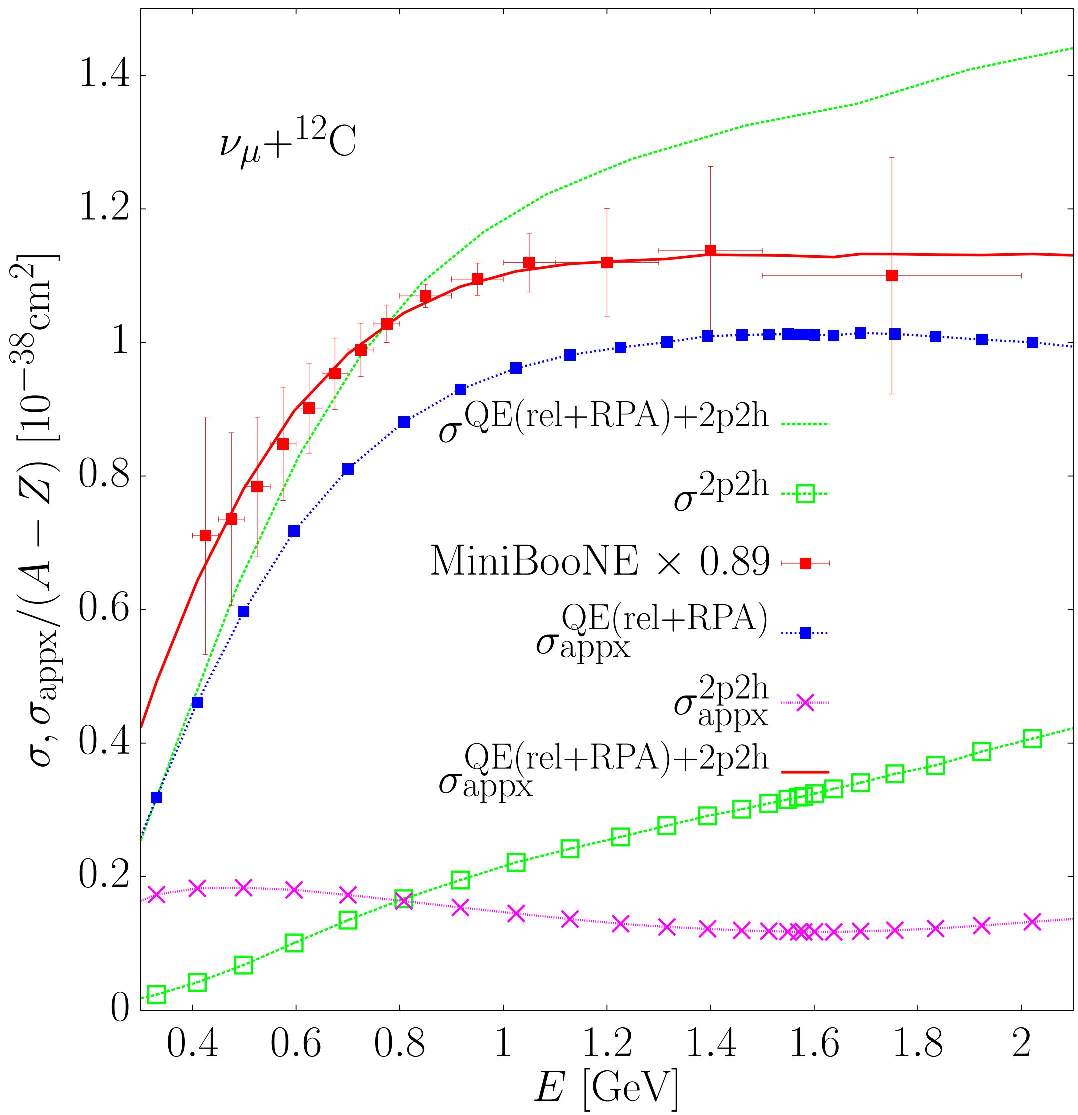
$$\sigma = \underbrace{\sigma^{\rm QE({\bf RPA})}}_{M_A=1.05\ {\rm GeV}} + \sigma^{\rm 2p2h}$$

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

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



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



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

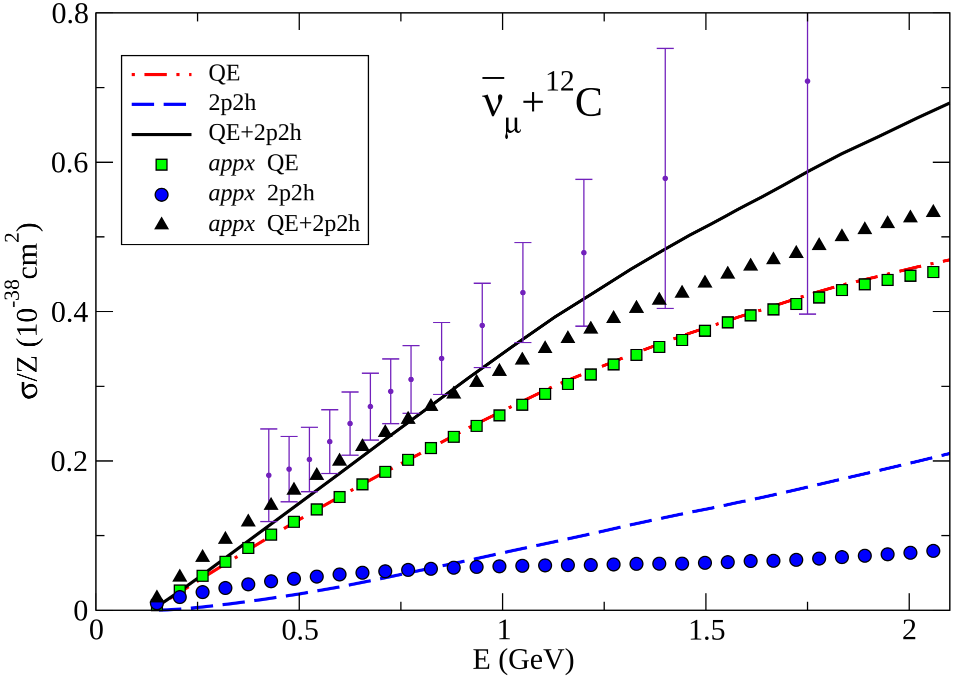
$$\int\left(\frac{d\sigma}{dE_{rec}}(E';E_{rec})\Big|^{M_A=1.049\ \text{GeV}}_{\text{QE+RPA},} + \frac{d\sigma^{2p2h}}{dE_{rec}}(E';E_{rec})\right)\Phi(E')dE'$$

... and

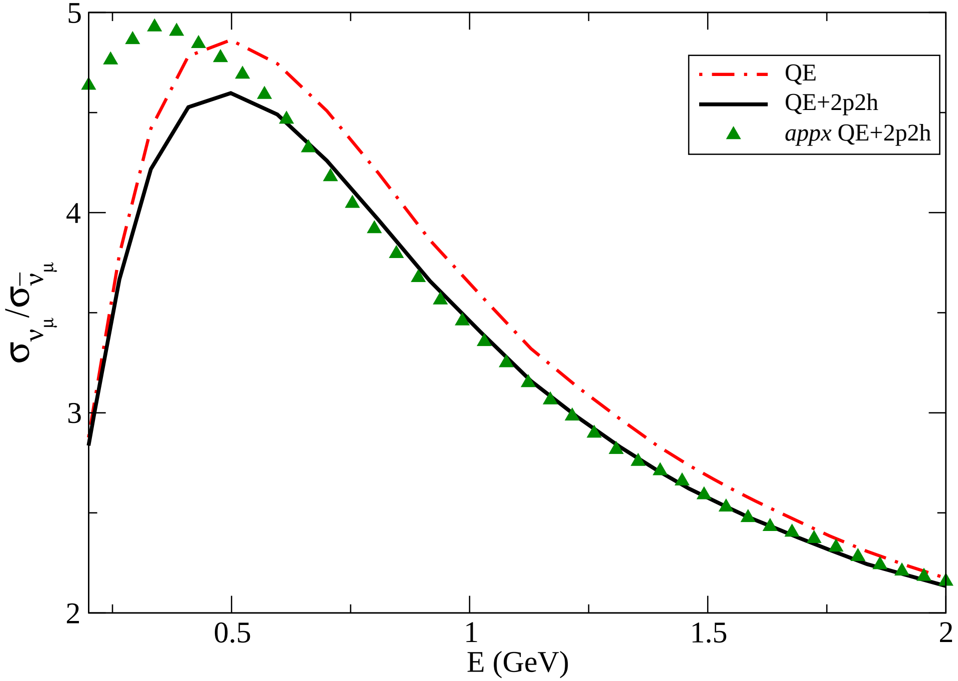
$$\underbrace{\left[\frac{d\sigma/dE_{rec}(E;E_{rec})}{\int dE''\Phi(E'')d\sigma/dE_{rec}(E'';E_{rec})}\right]}$$

ONLY QE $,M_A=1.32$ GeV **and noRPA**

For $\bar{\nu}$

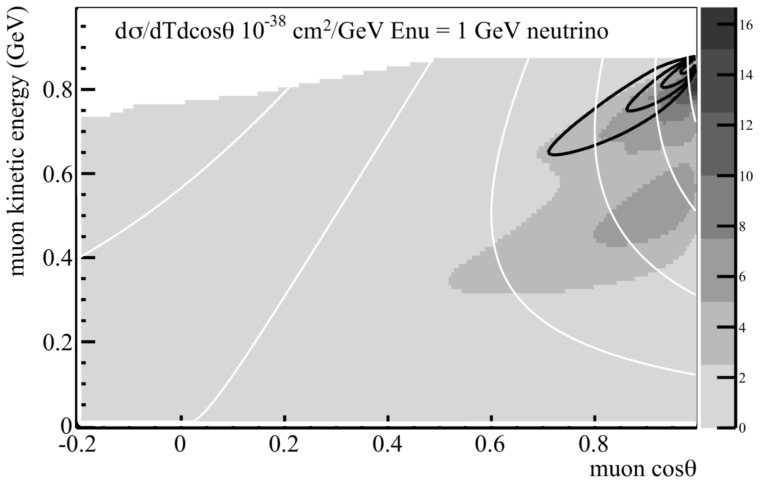


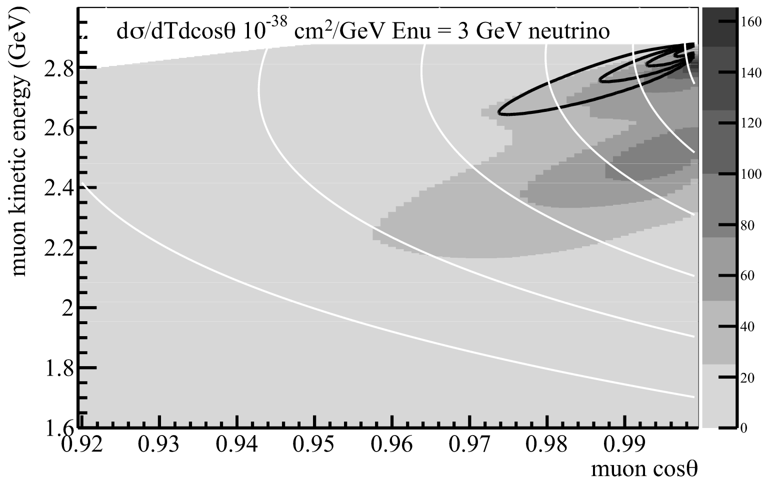
0.8
0.6
0.4
0.2
0
σ/Z (10^-38 cm^2)
0
0.5
1
1.5
2
E (GeV)
QE
2p2h
QE+2p2h
appx QE
appx 2p2h
appx QE+2p2h
ν̄μ + 12C

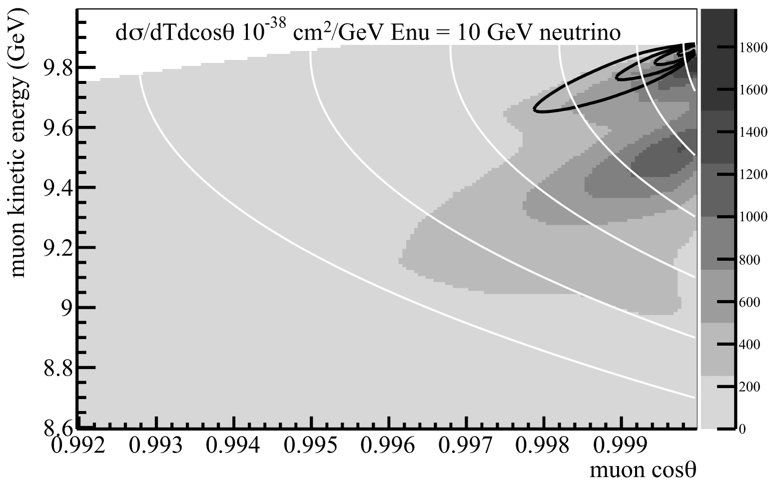


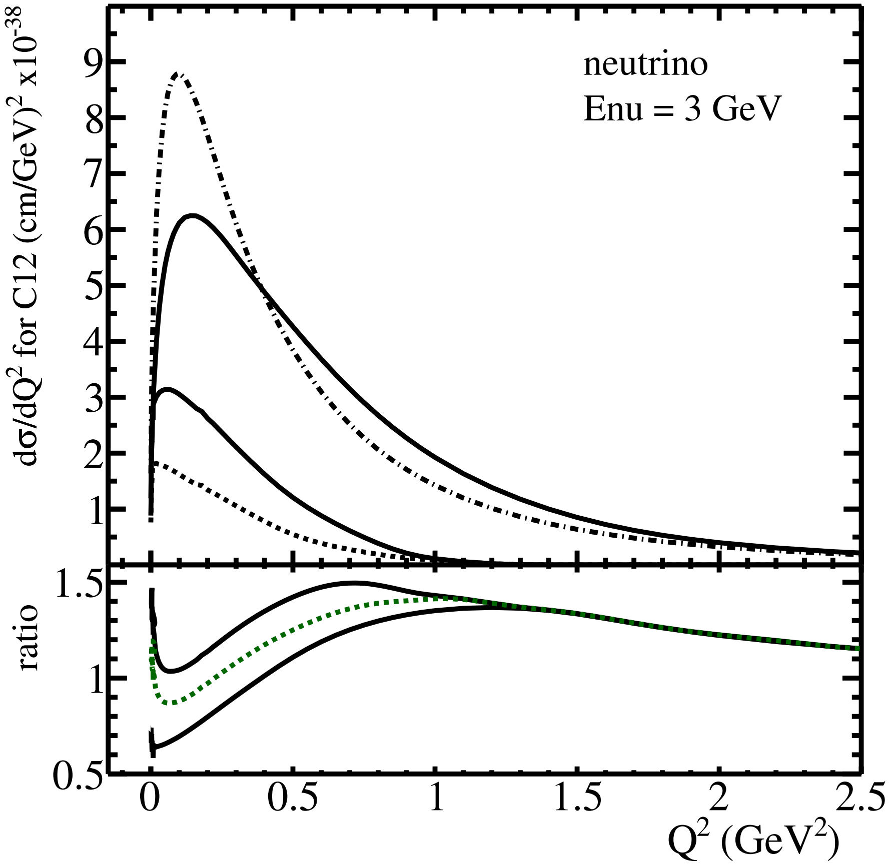
5
4
3
2
σνμ/σν̄μ
0.5
1
1.5
2
E (GeV)
QE
QE+2p2h
appx QE+2p2h

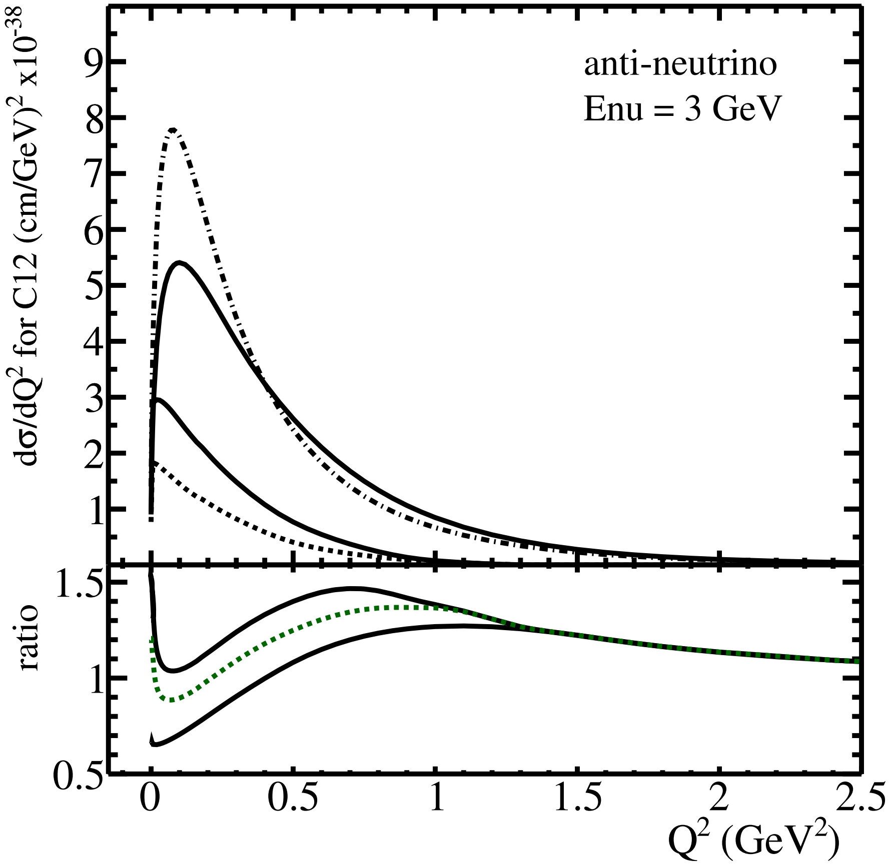
At higher ν energies



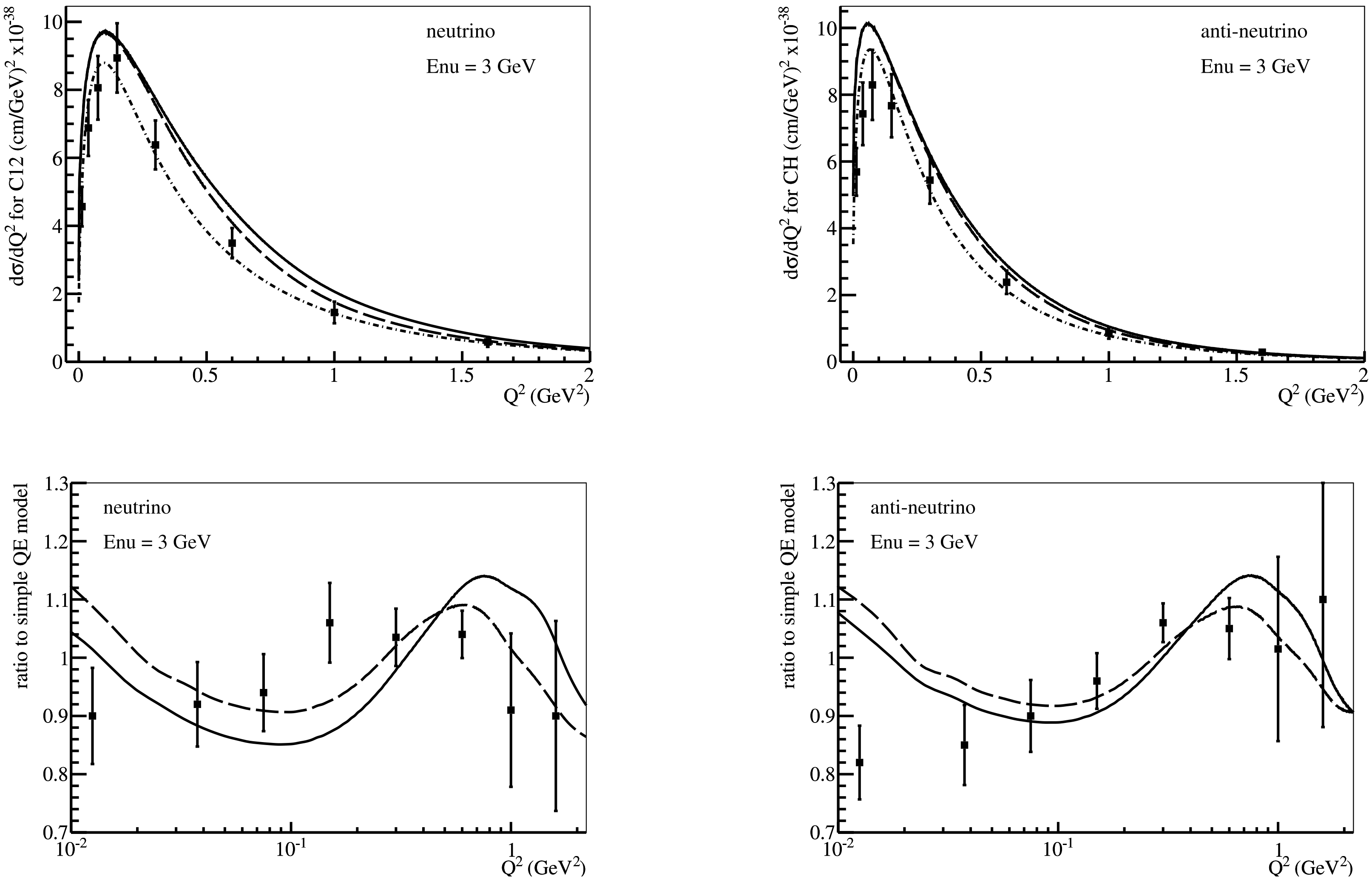





neutrino
Enu = 3 GeV
dσ/dQ² for C12 (cm/GeV)² x10⁻³⁸
ratio
Q² (GeV²)
9
8
7
6
5
4
3
2
1
1.5
1
0.5
0
0.5
1
1.5
2
2.5


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


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

Conclusions

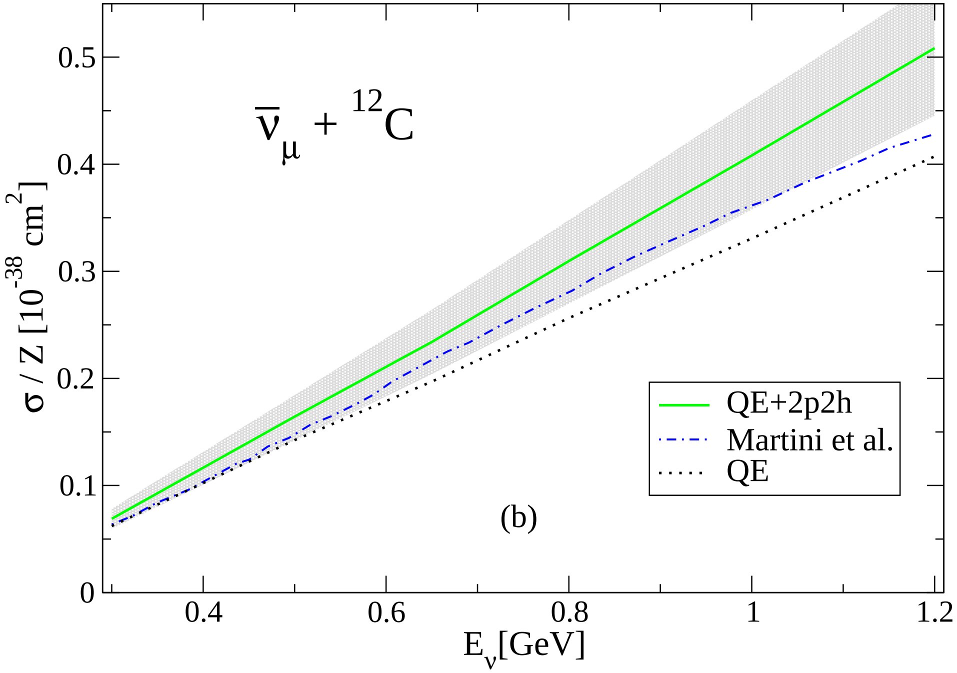
- **We have analyzed the MiniBooNE CCQE $\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$ data using a theoretical model that has proved to be quite successful in the analysis of nuclear reactions with electron, photon and pion probes and contains no additional free parameters.**
- **RPA and multinucleon knockout 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 ($\sim 10\%$)**

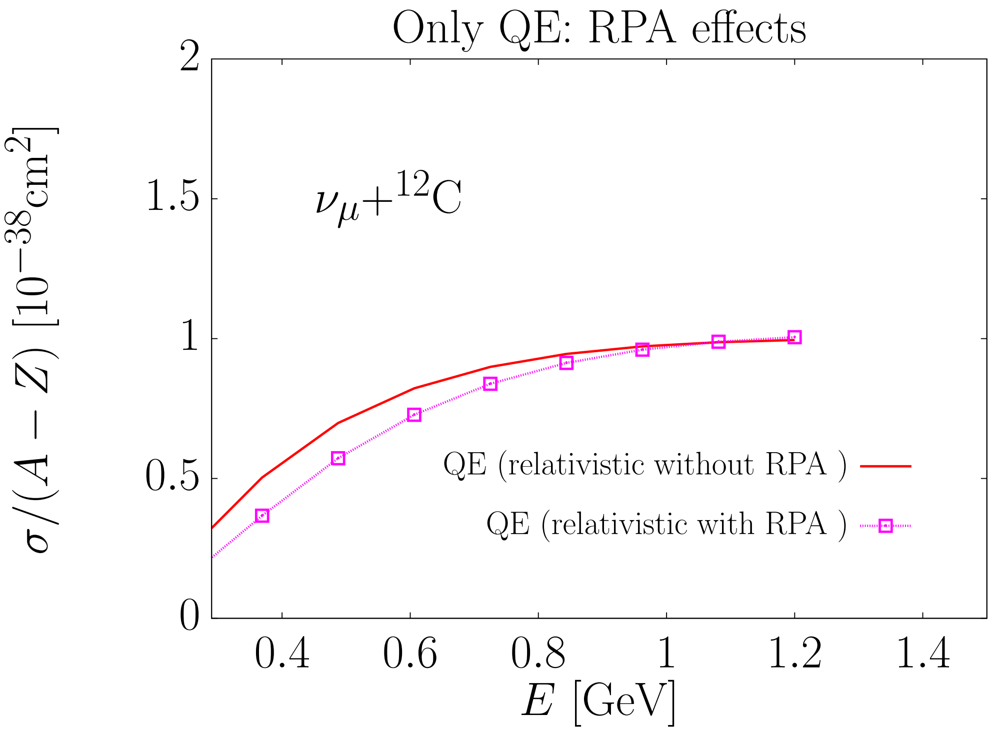
- **Because of the the multinucleon mechanism effects, the algorithm used to reconstruct the neutrino energy is not adequate when dealing with quasielastic-like events.**

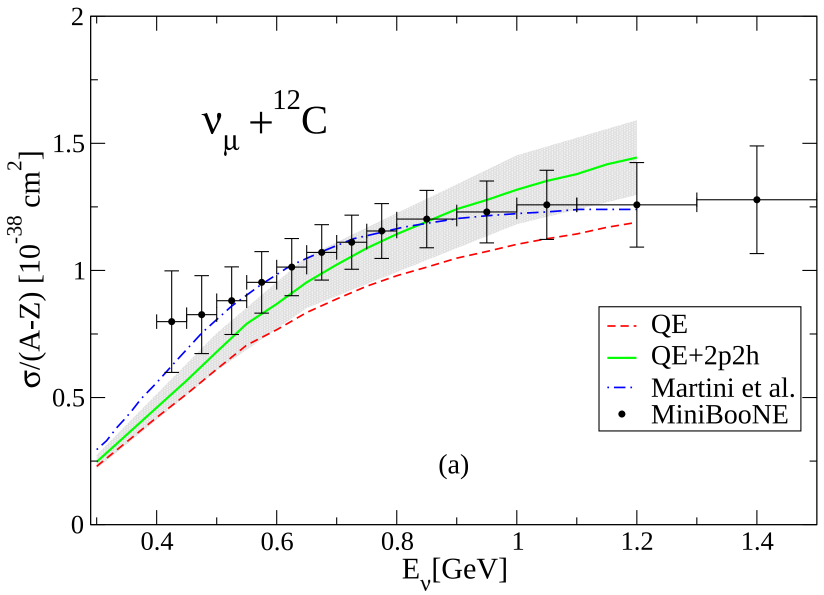
- **The inclusion of nucleon-nucleon correlation effects in the RPA series yields a much larger shape distortion toward relatively more high-q^2 interactions, with the 2p2h component filling in the suppression at very low q^2.**

- **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

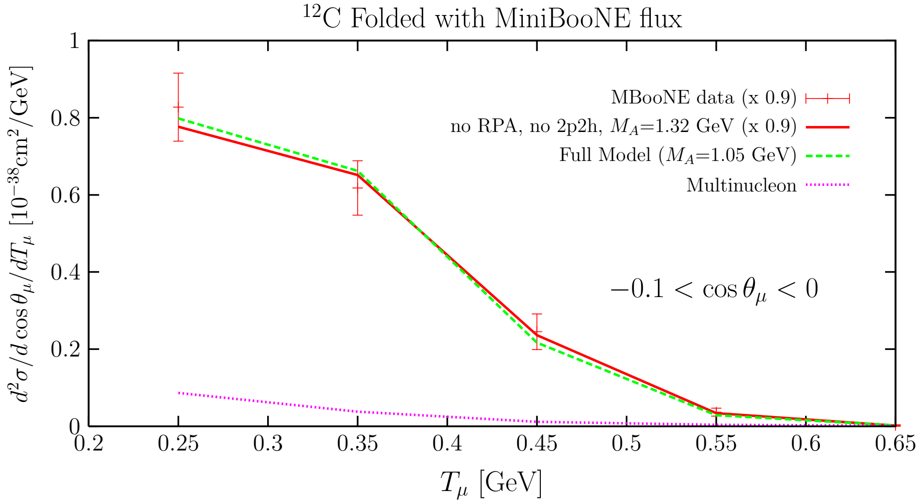


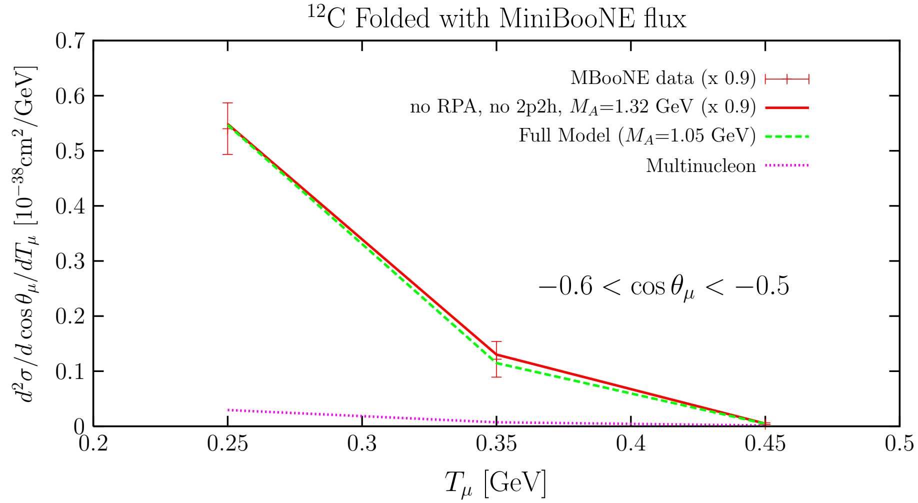




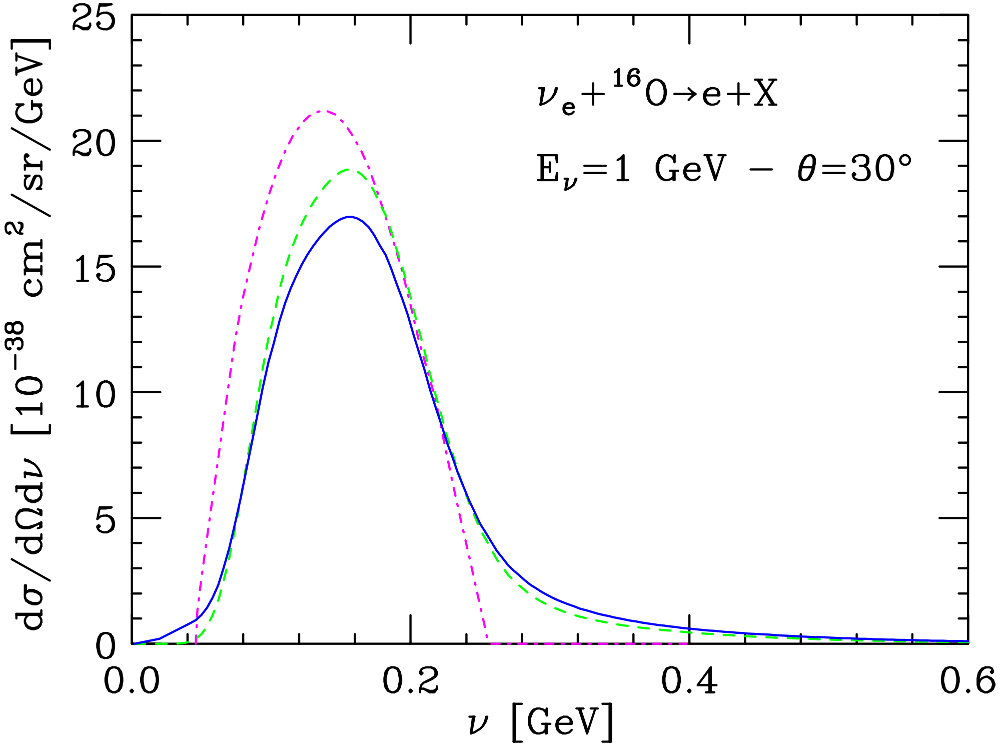
$\nu_\mu + {}^{12}C$
σ/(A-Z) [10^-38 cm^2]
E_ν[GeV]
QE
QE+2p2h
Martini et al.
MiniBooNE
(a)

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

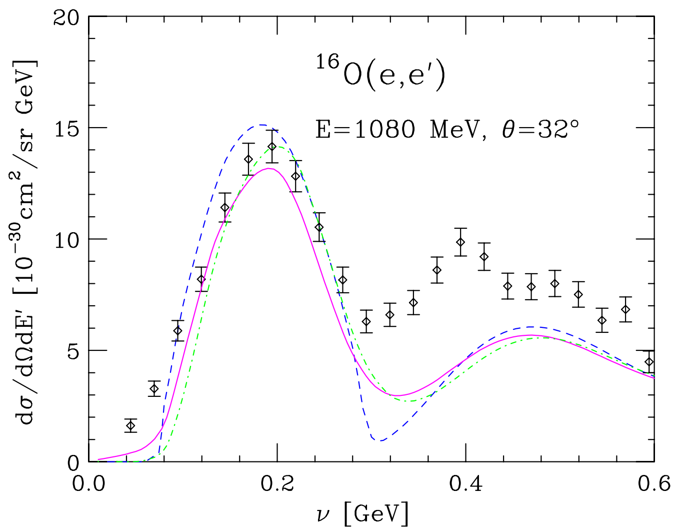




$$
\begin{aligned}
A_s^{\mu\nu}(p,q) &= 16(F_1^V)^2 \left\{ (p+q)^\mu p^\nu + (p+q)^\nu p^\mu + \frac{q^2}{2} g^{\mu\nu} \right\} \\
&+ 2q^2(\mu_V F_2^V)^2 \left\{ 4g^{\mu\nu} - 4\frac{p^\mu p^\nu}{M^2} - 2\frac{p^\mu q^\nu + q^\mu p^\nu}{M^2} \right. \\
&- \left. q^\mu q^\nu (\frac{4}{q^2} + \frac{1}{M^2})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



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



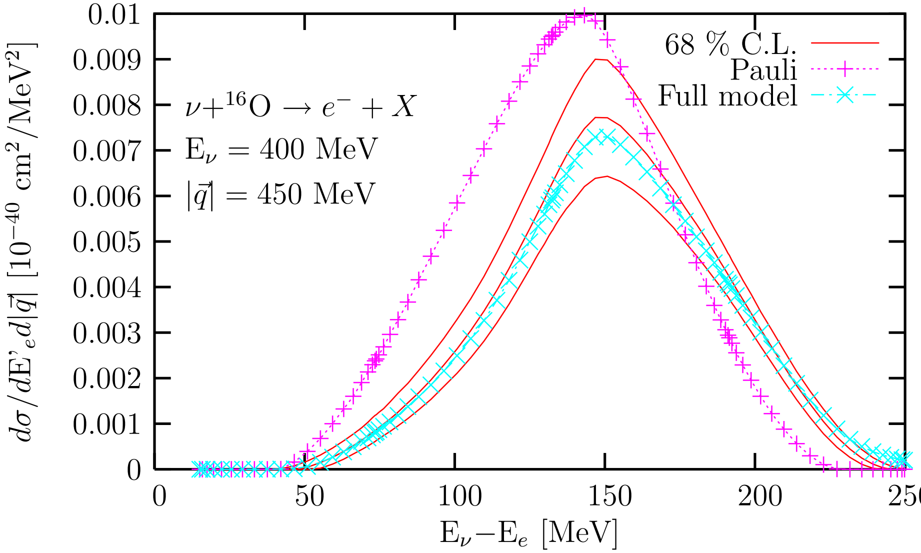
- RPA corrections are not included, but probably small for $|\vec{q}| \geq 500$ MeV
- Pion production and 2N channels should be included in the "dip" and Δ regions.

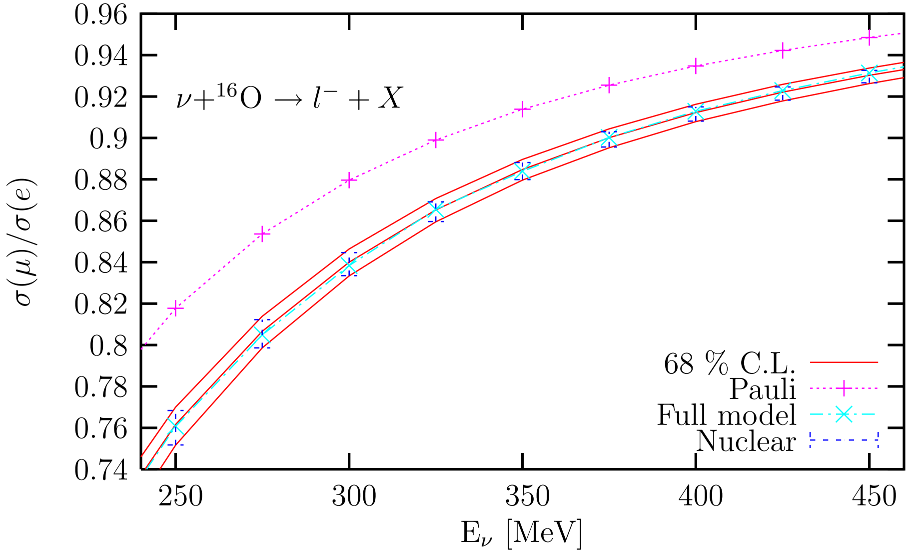
Theoretical Uncertainties: PLB 638,325

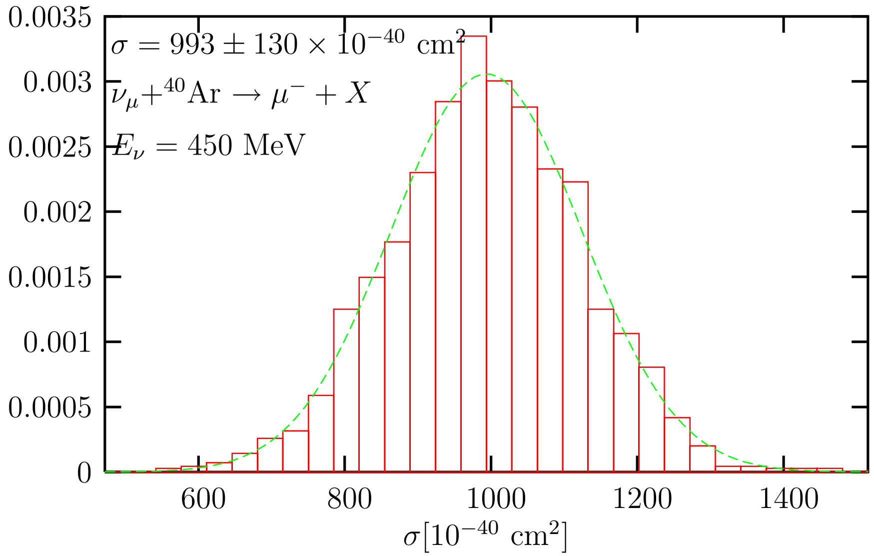
Predictions for CC and NC QE neutrino induced reactions in nuclei at intermediate energies of interest for future neutrino experiments. Uncertanties: $\sigma_{e,\mu} \sim 10 - 15\%$, $\sigma(\mu)/\sigma(e) \sim 5\%$

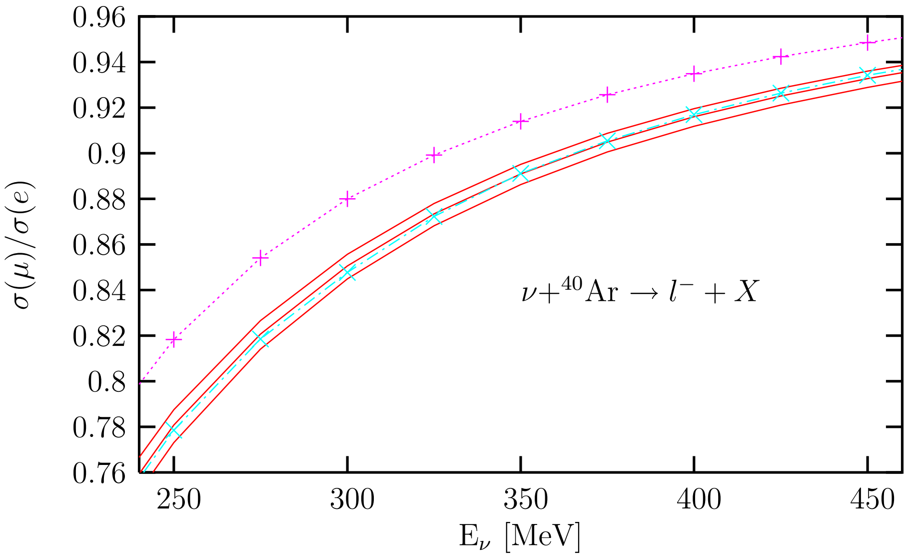
Form Factors					**Nucleon Interaction**				
M_D	$=$	0.843	$\pm$	0.042 GeV	$f_0^{\prime(in)}$	$=$	0.33	$\pm$	0.03
λ_n	$=$	5.6	$\pm$	0.6	$f_0^{\prime(ex)}$	$=$	0.45	$\pm$	0.05
M_A	$=$	1.05	$\pm$	0.14 GeV	f	$=$	1.00	$\pm$	0.10
g_A	$=$	1.26	$\pm$	0.01	f^*	$=$	2.13	$\pm$	0.21
					Λ_π	$=$	1200	$\pm$	120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

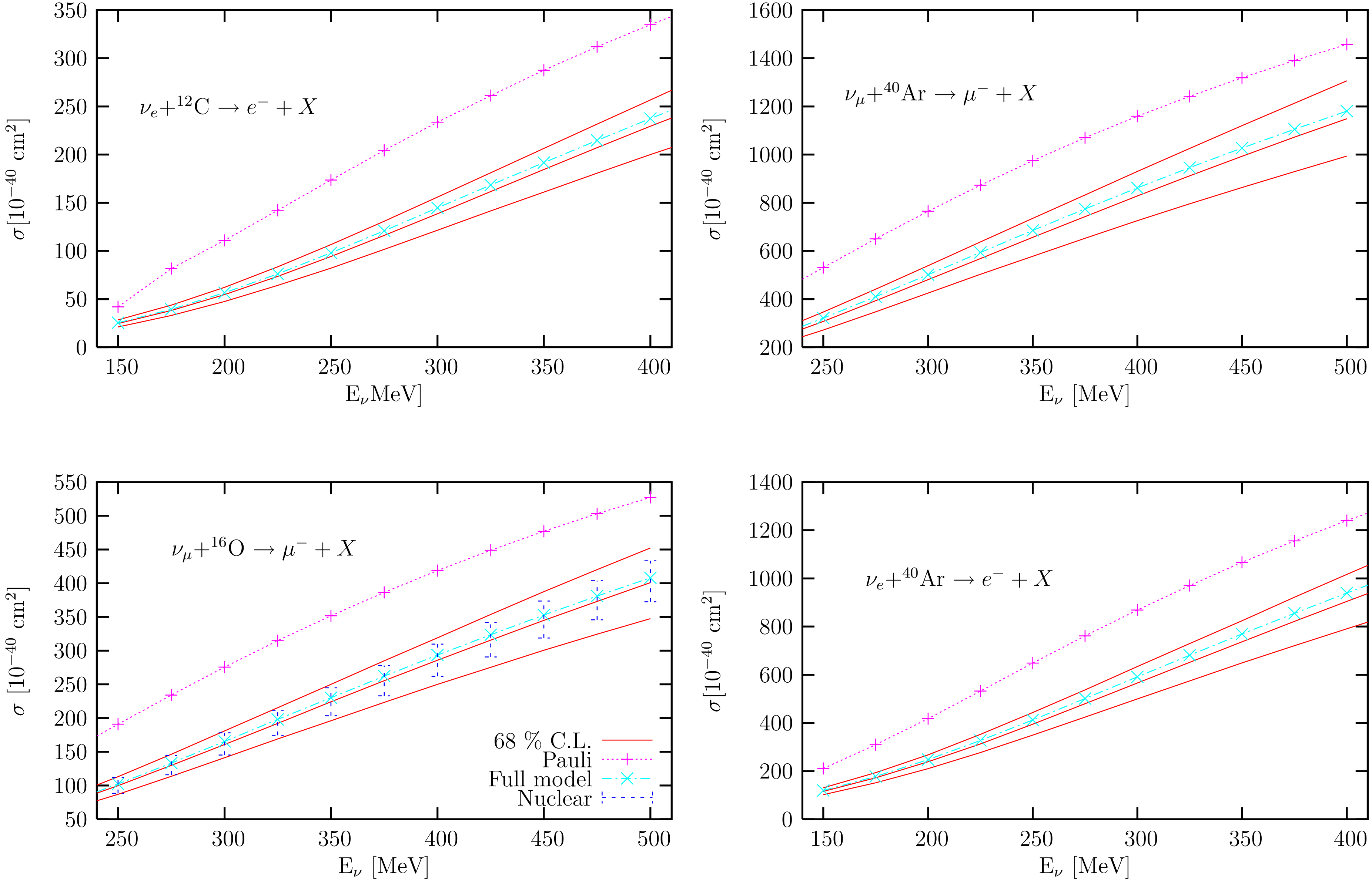
$+10\%$ in Σ (nucleon self-energy)


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]

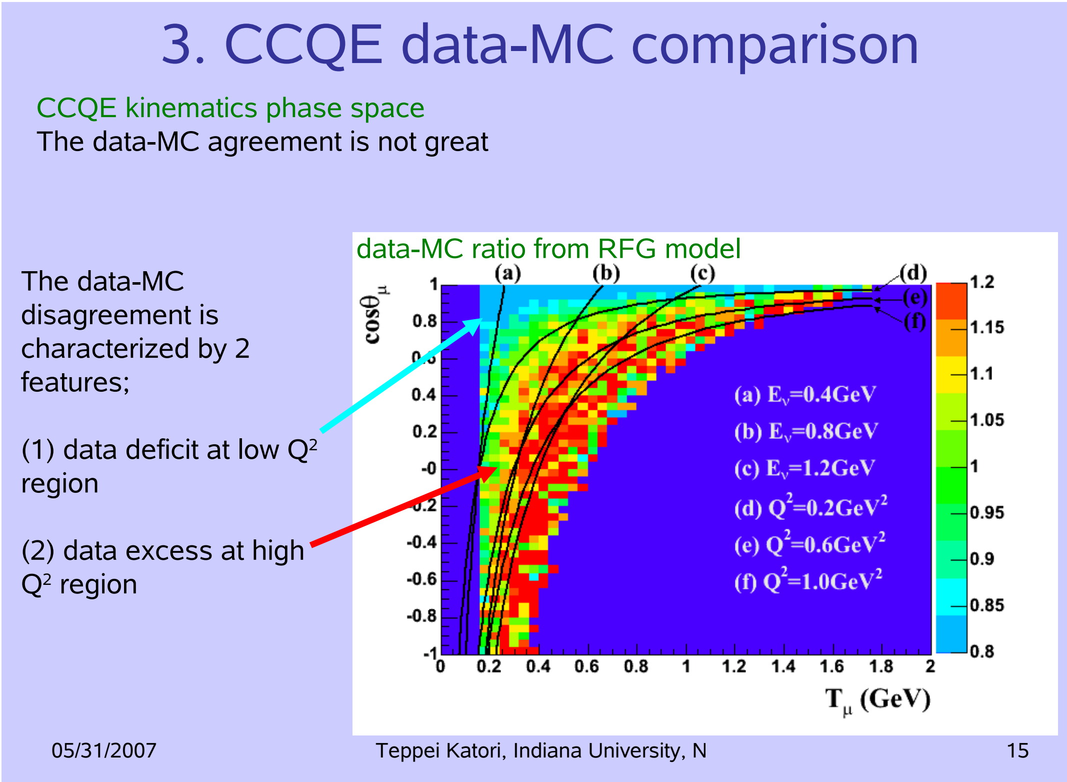

$\sigma = 993 \pm 130 \times 10^{-40}$ cm^2
$\nu_\mu + {}^{40}Ar \to \mu^- + X$
$E_\nu = 450$ MeV
$\sigma[10^{-40}$ cm$^2]$

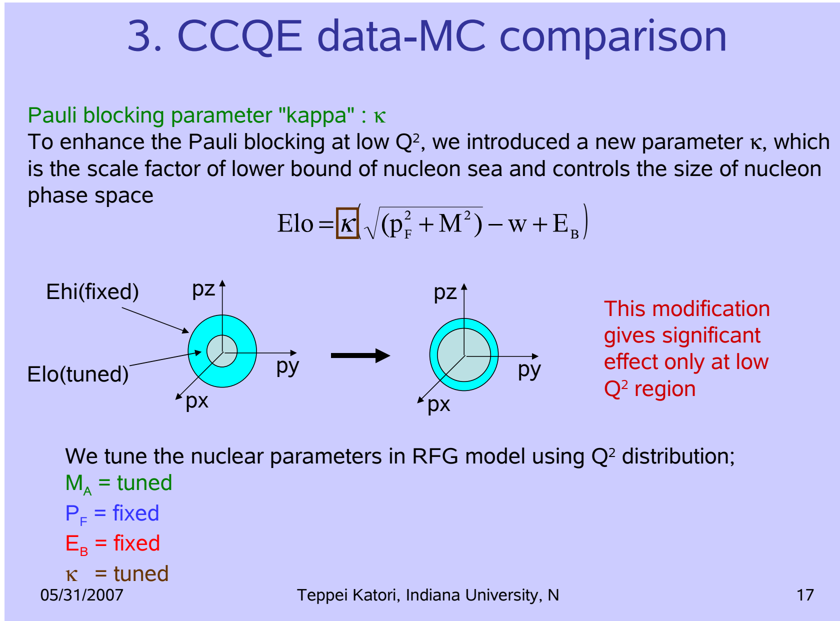

$\nu + {}^{40}Ar \to l^- + X$
$\sigma(\mu)/\sigma(e)$
E_ν [MeV]



$\nu_e + {}^{12}C \rightarrow e^- + X$
$\sigma[10^{-40}\ cm^2]$
E$_\nu$MeV]
$\nu_\mu + {}^{40}Ar \rightarrow \mu^- + X$
E$_\nu$ [MeV]
$\nu_\mu + {}^{16}O \rightarrow \mu^- + X$
$\sigma\ [10^{-40}\ cm^2]$
68 % C.L.
Pauli
Full model
Nuclear
$\nu_e + {}^{40}Ar \rightarrow e^- + X$

RPA effects might explain the data deficit at low Q^2 in the MiniBooNE CCQE events reported in PRL 100, 032301.



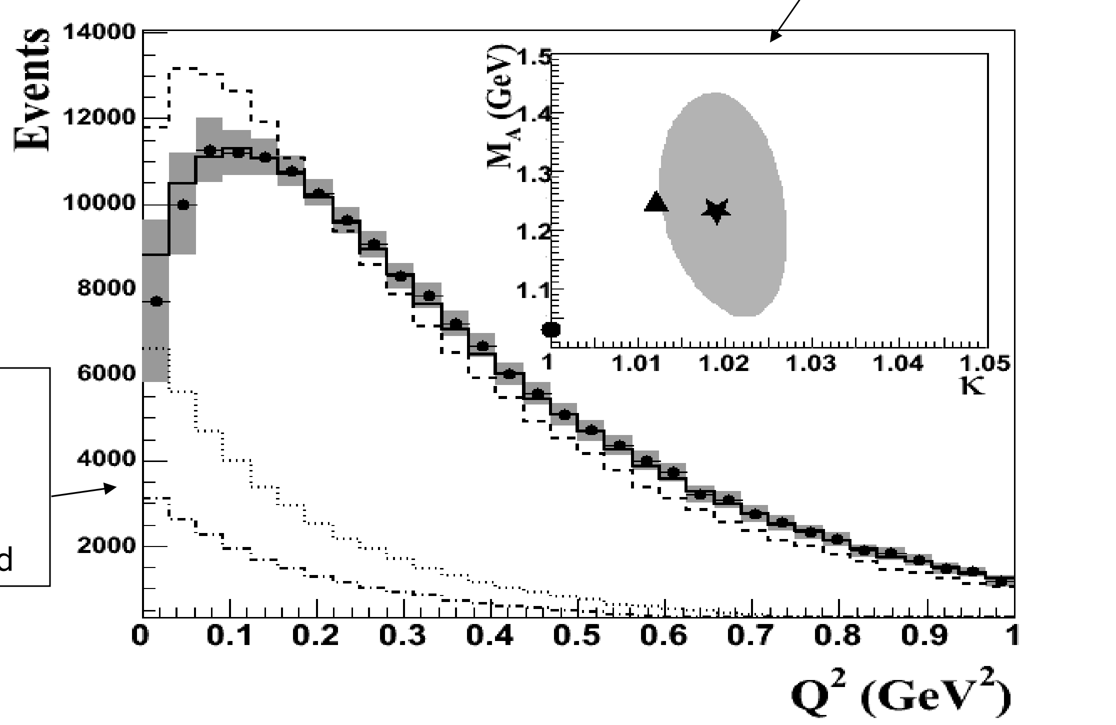


M_A - κ fit result

M_A = 1.23 ± 0.20(stat+sys)

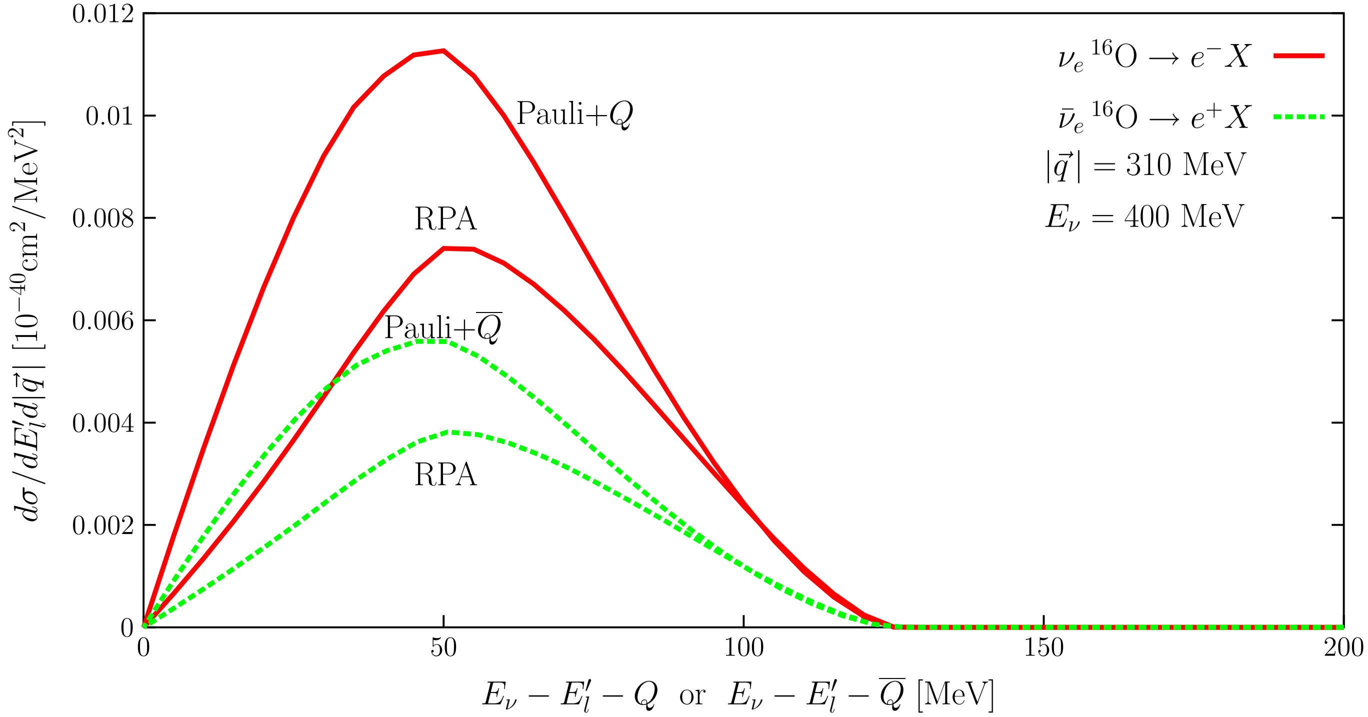
κ = 1.019 ± 0.011(stat+sys)

circle: before fit
star: after fit with 1-sigma contour
triangle: bkgd shape uncertainty



dots : data with error bar
dashed line : before fit
solid line : after fit
dotted line : background
dash-dotted :non-CCQElike bkgd

05/31/2007 Teppei Katori, Indiana University, N 21

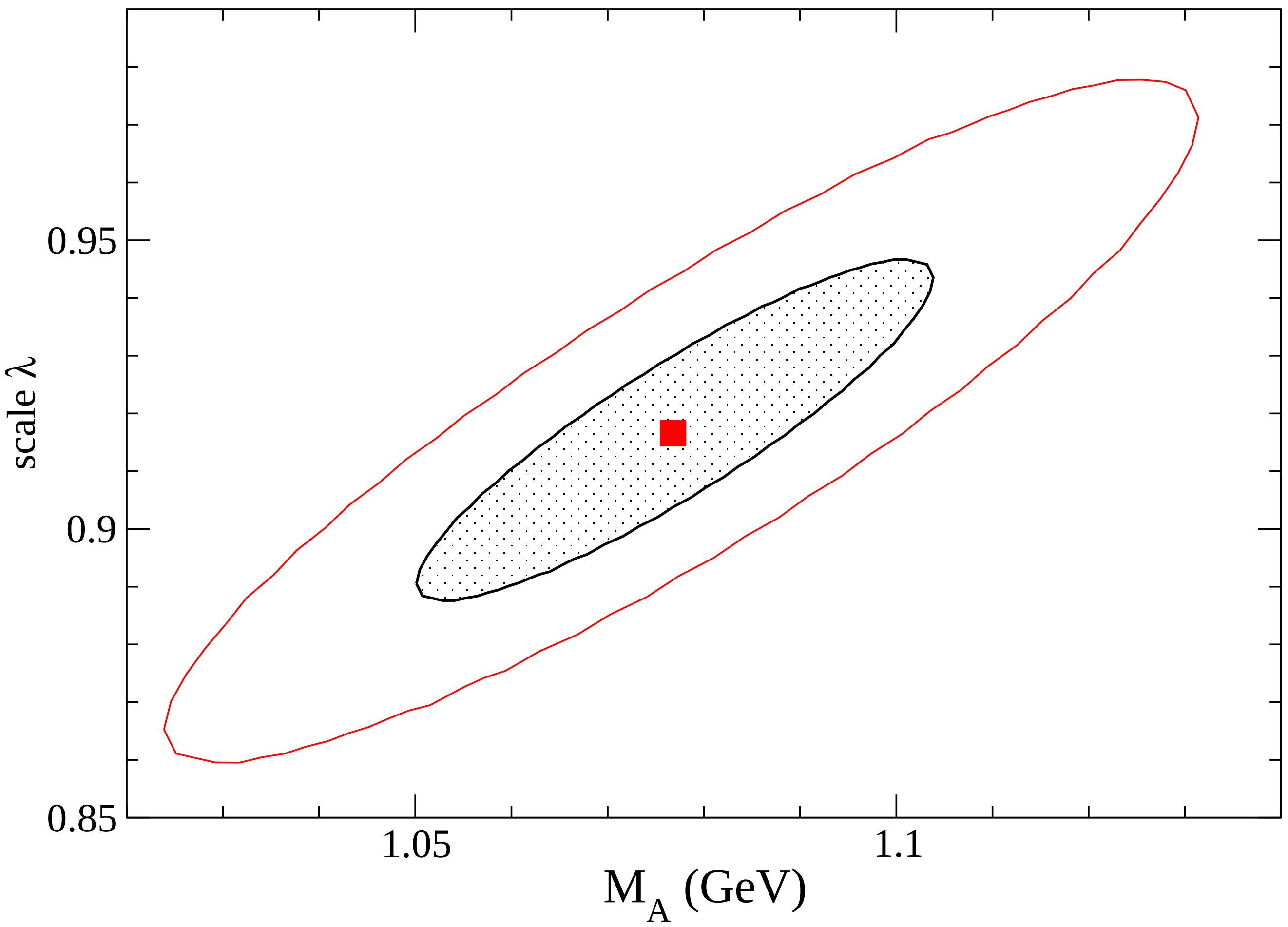


Examples of the RPA effect

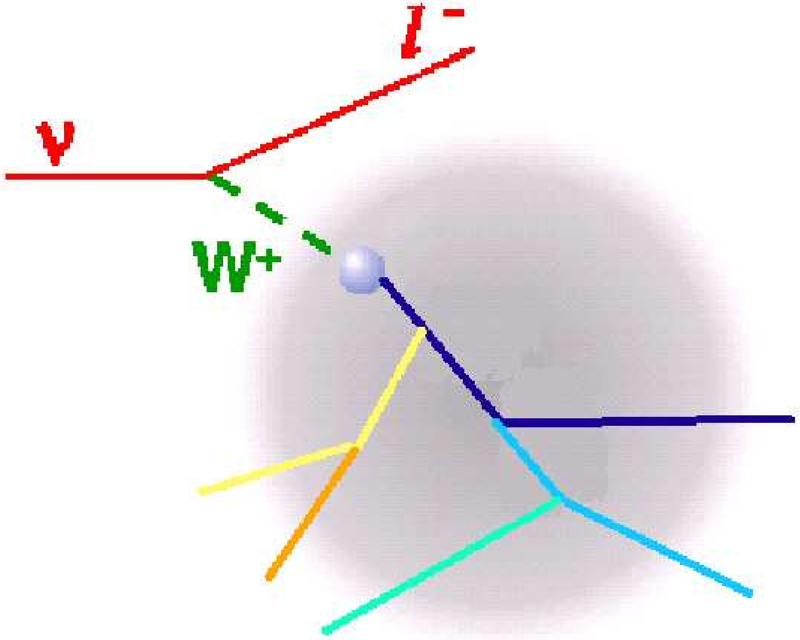
$$G_A^2 \delta^{ij} \quad \to \quad G_A^2 \left(\frac{\hat{q}^i \hat{q}^j}{|1 - U(q)V_l(q)|^2} + \frac{\delta^{ij} - \hat{q}^i \hat{q}^j}{|1 - U(q)V_t(q)|^2} \right)$$

$$(F_1^V)^2 \quad \to \quad \frac{(F_1^V)^2}{|1 - c_0 f_0'(\rho) U_N(q)|^2}, \quad \text{etc...}$$

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

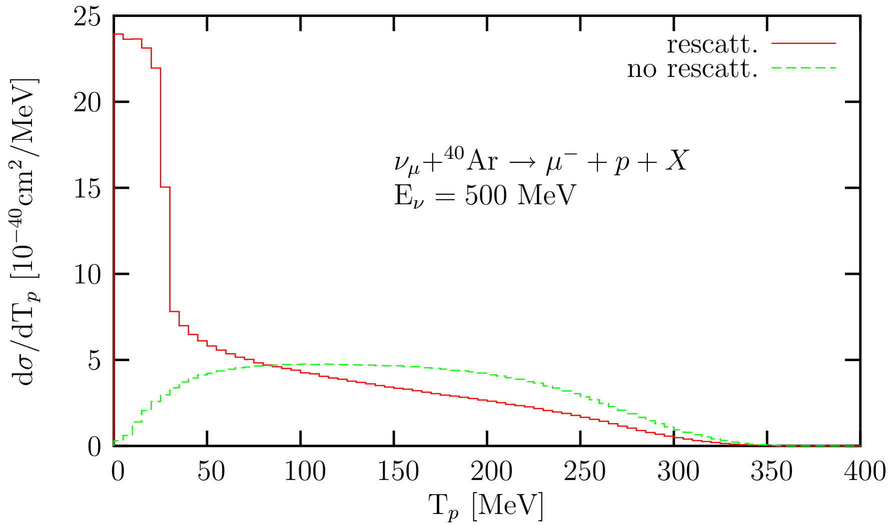

0.95
0.9
0.85
1.05
1.1
scale λ
M_A (GeV)

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**

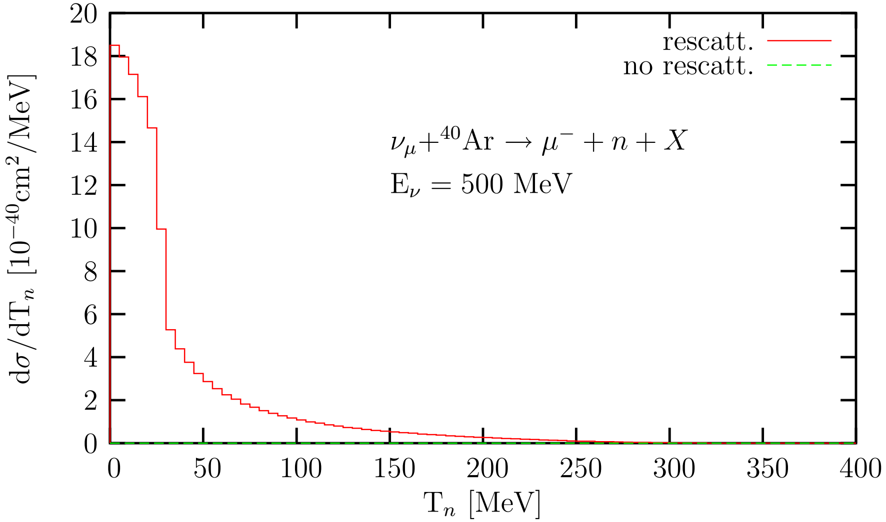
Why a MC Simulation?



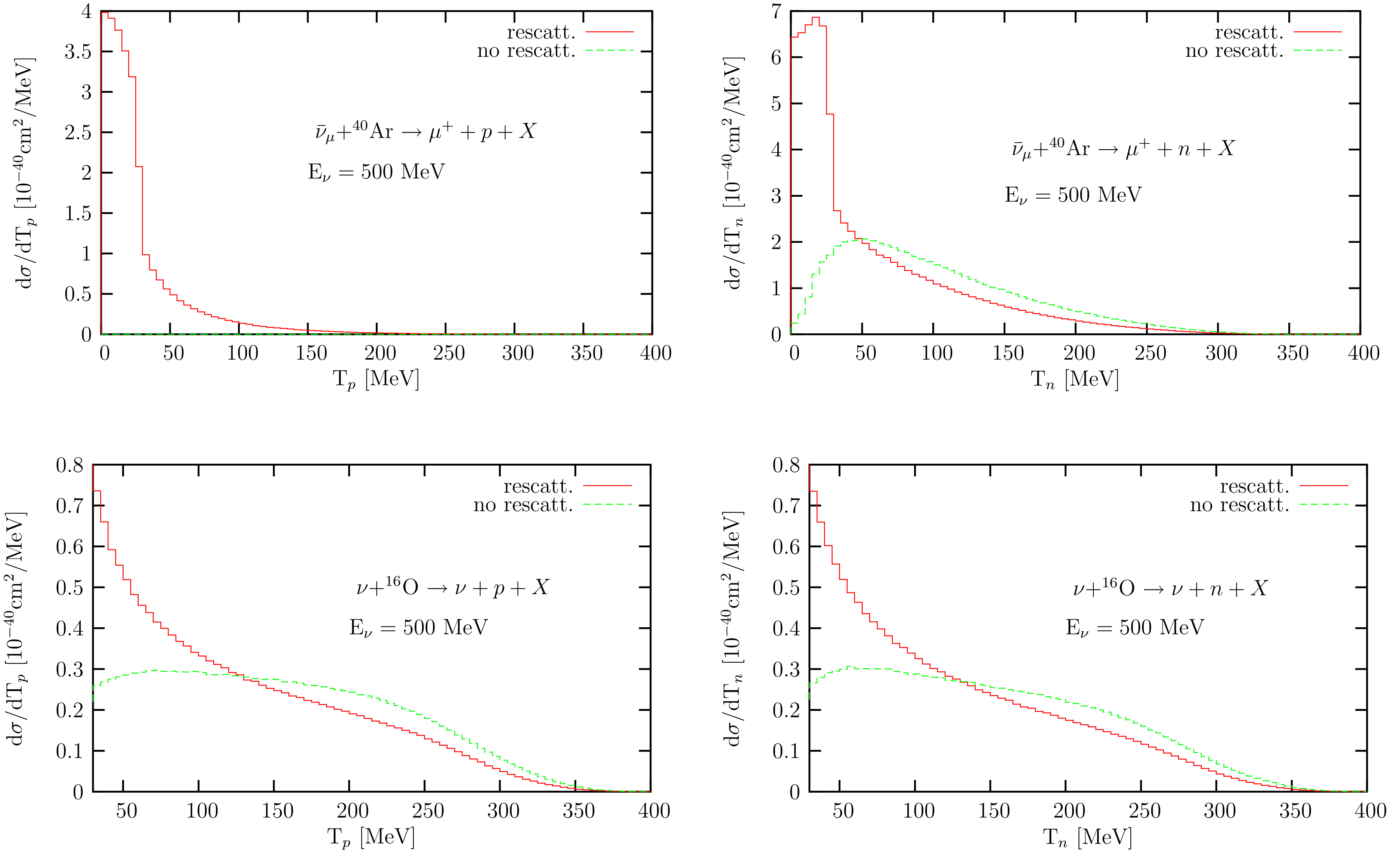
The **distortion** of the nucleon wave function by a **complex optical potential** **removes** all events where the nucleons collide with other nucleons:

- 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]
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]
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]
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]