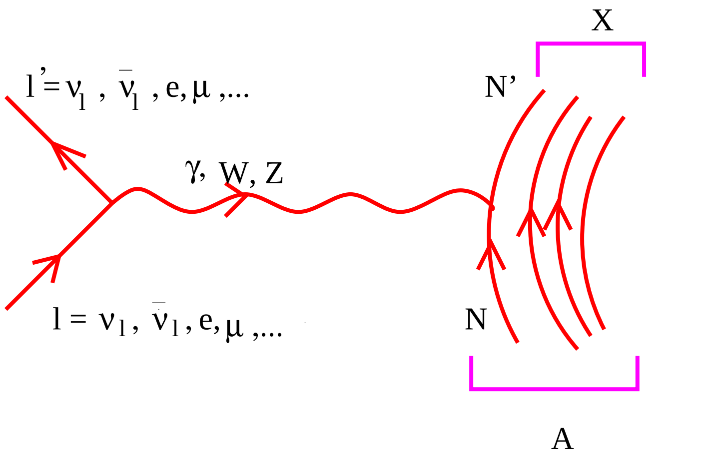
Electroweak Nuclear Reactions at Intermediate Energies.

Juan Nieves, U. Granada

- CC neutrino induced nuclear reactions **(J.E. Amaro, M. Valverde and J.N.)**
- Electronuclear reactions **(A.Gil, E.Oset, M.J. Vicente-Vacas and J.N.)**
- Photonuclear reactions **(R.C. Carrasco, E.Oset, L.Salcedo and M.J. Vicente-Vacas)**

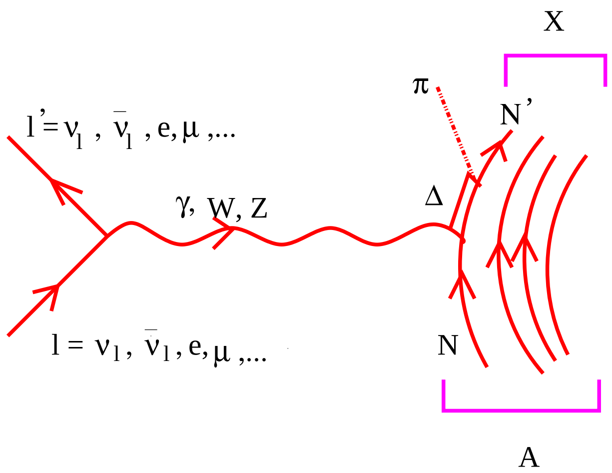
Nuclear renormalization effects on electroweak inclusive reactions in nuclei at intermediate energies

QUASIELASTIC PEAK

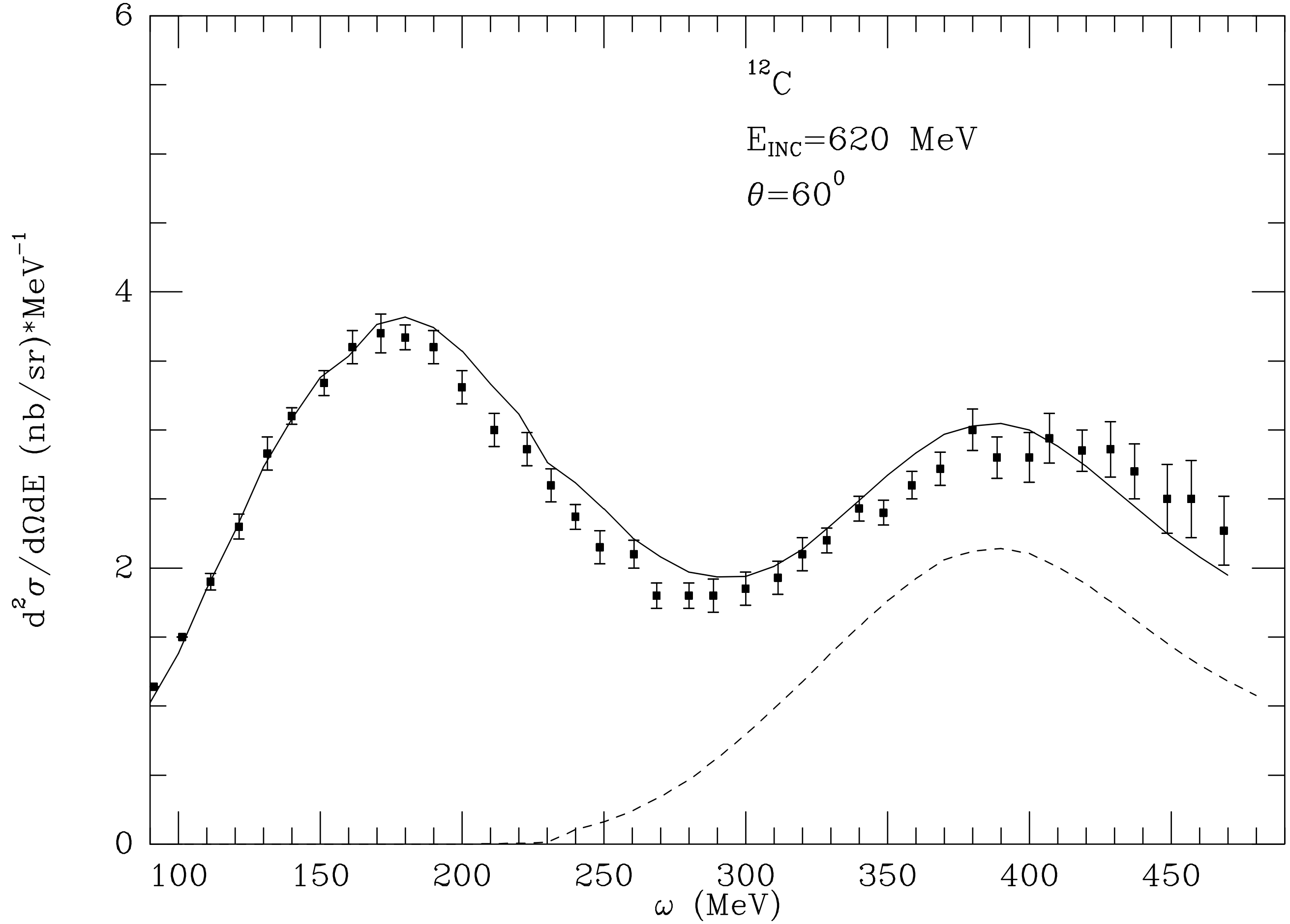


VIRTUAL γ W Z ABSORPTION BY ONE NUCLEON

Δ(1232) RESONANCE PEAK



EXCITATION OF Δ (1232) DEGREES OF FREEDOM



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

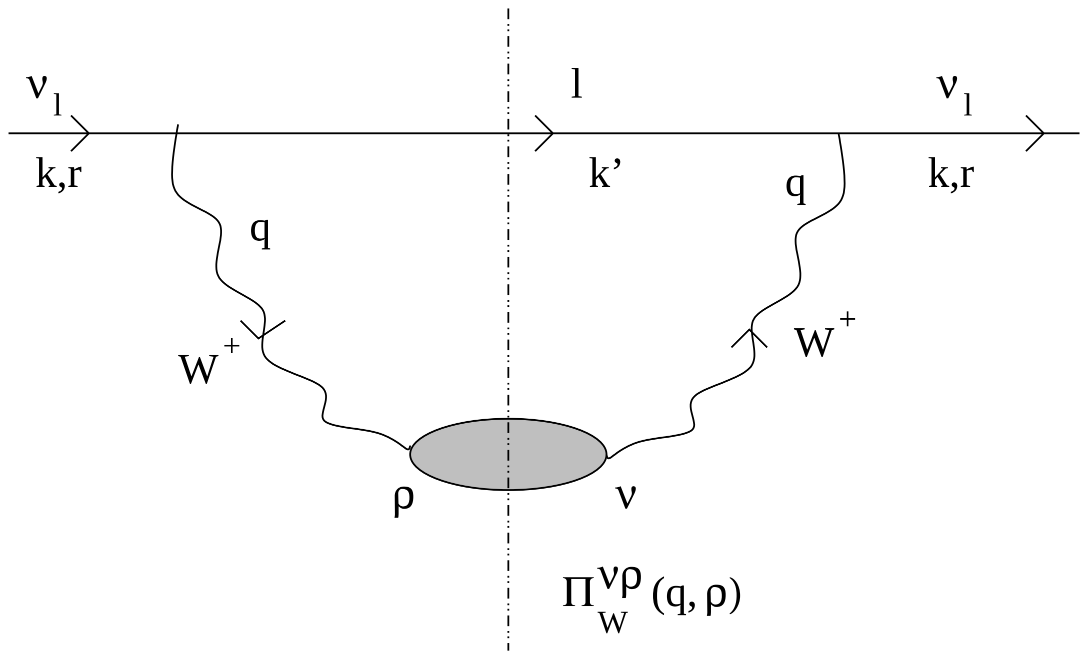
To describe the propagation of particles inside of the nuclear medium, we use a microscopic Many Body framework:

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

Simplification: We work on an Infinite Nuclear Medium and obtain results for Finite Nuclei using the Local Density Approximation (LDA). LDA: Excellent approximation to deal with volume processes (no screening or absorption effects)[Carrasco+Oset NPA 536 (1992) 445.]

We compute the imaginary part of the lepton-selfenergy inside of a nuclear medium of constant density ρ:

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



$$
\begin{aligned}
-\mathrm{i}\Sigma_r(k) &= \int \frac{d^4q}{(2\pi)^4}\bar{u}_r(k)\left\{\frac{-\mathrm{i}g}{2\sqrt{2}}\gamma^\mu(1-\gamma_5)\ \mathrm{i}\frac{-g_{\mu\nu}+\frac{q_\mu q_\nu}{M_W^2}}{q^2-M_W^2+\mathrm{i}\epsilon}\right. \\
&\times \left[-\mathrm{i}\Pi_W^{\nu\rho}(q,\rho)\right]\ \mathrm{i}\frac{-g_{\rho\sigma}+\frac{q_\rho q_\sigma}{M_W^2}}{q^2-M_W^2+\mathrm{i}\epsilon}\ \mathrm{i}\frac{\not{k}'+m_l}{k'^2-m_l^2+\mathrm{i}\epsilon} \\
&\times \left.\frac{-\mathrm{i}g}{2\sqrt{2}}\gamma^\sigma(1-\gamma_5)\right\}u_r(k)
\end{aligned}
$$

The $\nu_l A_Z \to lX$ cross section is related to the imaginary part of the above self-energy by (LDA):

$$
\sigma(k) = -\propto \frac{1}{k}\int d^3r\ \mathrm{Im}\Sigma(k,\rho(r))
$$

We get ImΣ by following the prescription of the Cutkosky's rules, and thus the differential cross section (LAB) reads:

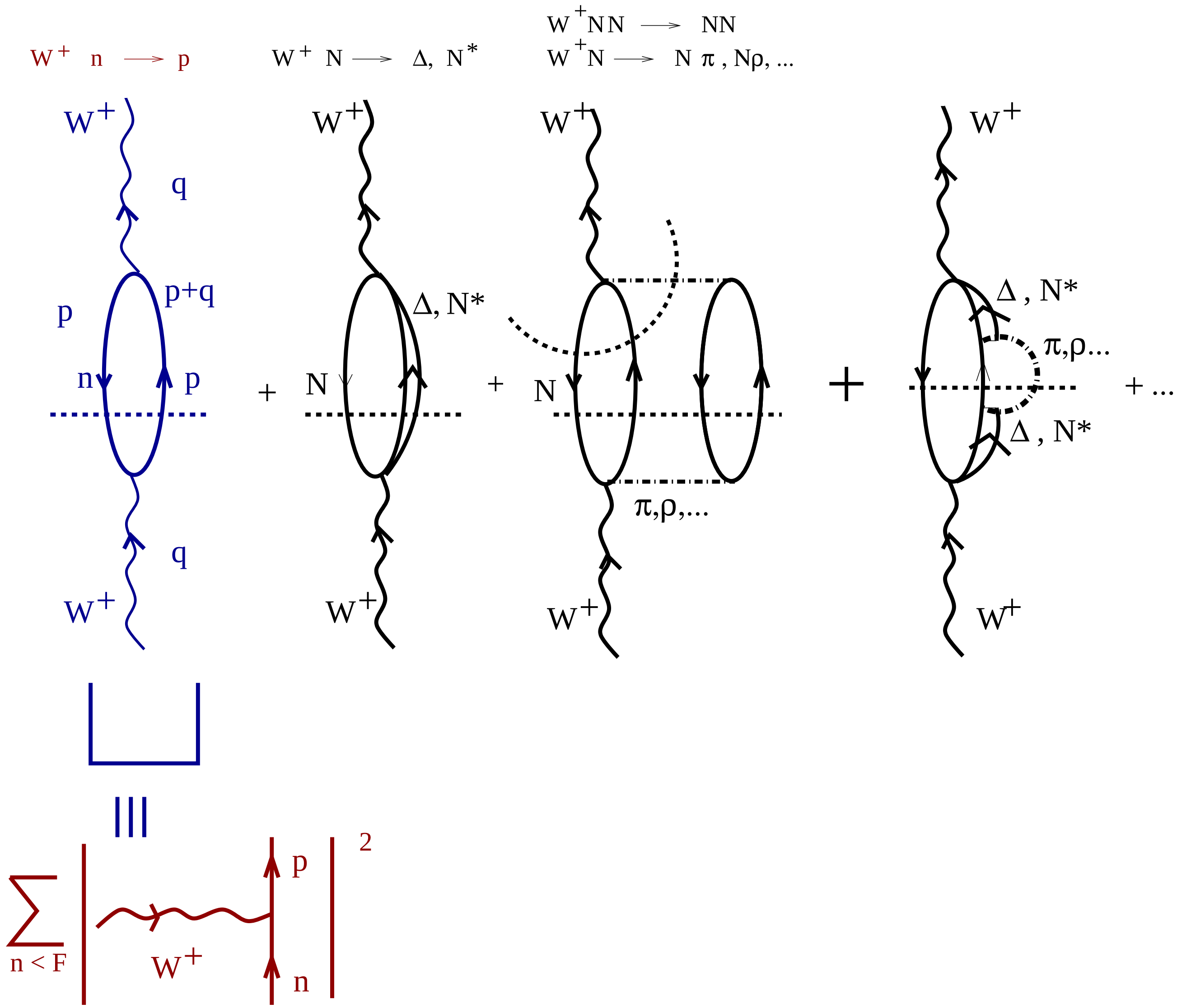
$$\frac{d^2\sigma}{d\Omega(\hat{k}')dE'} = \frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$

with the Leptonic (L) and Hadronic (W) tensors given by:

$$\begin{aligned}
L_{\mu\sigma} &= k'_\mu k_\sigma + k'_\sigma k_\mu - g_{\mu\sigma}k\cdot k' + \mathrm{i}\epsilon_{\mu\sigma\alpha\beta}k'^\alpha k^\beta \\
W^{\mu\sigma} &= W_s^{\mu\sigma} + \mathrm{i}W_a^{\mu\sigma} \\
W_s^{\mu\sigma} &= -\left(\frac{2\sqrt{2}}{g}\right)^2\int\frac{d^3r}{2\pi}\ \mathrm{Im}\ \left\{\Pi_W^{\mu\sigma}(q,\rho)+\Pi_W^{\sigma\mu}(q,\rho)\right\}\Theta(q^0) \\
W_a^{\mu\sigma} &= -\left(\frac{2\sqrt{2}}{g}\right)^2\int\frac{d^3r}{2\pi}\ \mathrm{Re}\ \left\{\Pi_W^{\mu\sigma}(q,\rho)-\Pi_W^{\sigma\mu}(q,\rho)\right\}\Theta(q^0)
\end{aligned}$$

Basic object $\boxed{\Pi^{\nu\rho}_{W,Z^0,\gamma}(q,\rho)}$

Selfenergy of the Gauge Boson $(W^\pm, Z^0, \gamma)$ inside of the nuclear medium. We perform a Many Body expansion , where the relevant gauge boson absorption modes are systematically incorporated: absorption by one Nucleon, or a pair of Nucleons or even 3N mechanisms, real and virtual (MEC) meson (π, ρ, $\cdots$) production, excitation of Δ of higher resonance degrees of freedom, etc... Besides, nuclear effects such as RPA or SRC are also taken into account within the formalism.


W+ n → p
W+ N → Δ, N*
W+NN → NN
W+N → N π , Nρ, ...
W+
q
p+q
p
n
p
+
N
Δ, N*
+
N
π,ρ,...
+
Δ , N*
π,ρ...
Δ , N*
+ ...
W+
n < F
p
n
2

For instance, let's keep focusing on the inclusive (ν_l, l) reaction and compute the relevant contributions to the quasielastic process **(W^+ absorption by one nucleon)**. We use

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

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

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

with vector form factors related to the electromagnetic ones

$$
\begin{aligned}
2F_1^V(q^2) &= F_1^p(q^2) - F_1^n(q^2) \\
2\mu_V F_2^V(q^2) &= \mu_p F_2^p(q^2) - \mu_n F_2^n(q^2)
\end{aligned}
$$

and

$$
G_A(q^2) = \frac{g_A}{(1 - q^2/M_A^2)^2}, \quad g_A = 1.257, \quad M_A = 1.049 \text{ GeV}
$$

We find (quasielastic peak)

$$
\begin{aligned}
W_{s,a}^{\mu\nu}(q) &= -\frac{1}{2M^2}\int_0^\infty dr r^2 \Bigg\{ 2\int \frac{d^3p}{(2\pi)^3}\frac{M}{E(\vec{p})}\frac{M}{E(\vec{p}+\vec{q})}\Theta(q^0) \\
&\times \Theta(k_F^n(r) - |\vec{p}\,|)\Theta(|\vec{p}+\vec{q}\,| - k_F^p(r)) \\
&\times (-\pi)\delta(q^0 + E(\vec{p}) - E(\vec{p}+\vec{q}\,))A_{s,a}^{\mu\nu}(p,q)\Bigg\}
\end{aligned}
$$

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

- 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:

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

$$\Theta(q^0)\Theta(|\vec{p}+\vec{q}\,| - k_F^p(r))(-\pi)\delta(q^0 + E(\vec{p}) - E(\vec{p}+\vec{q}\,))$$

- Low Density Theorem. For low densities

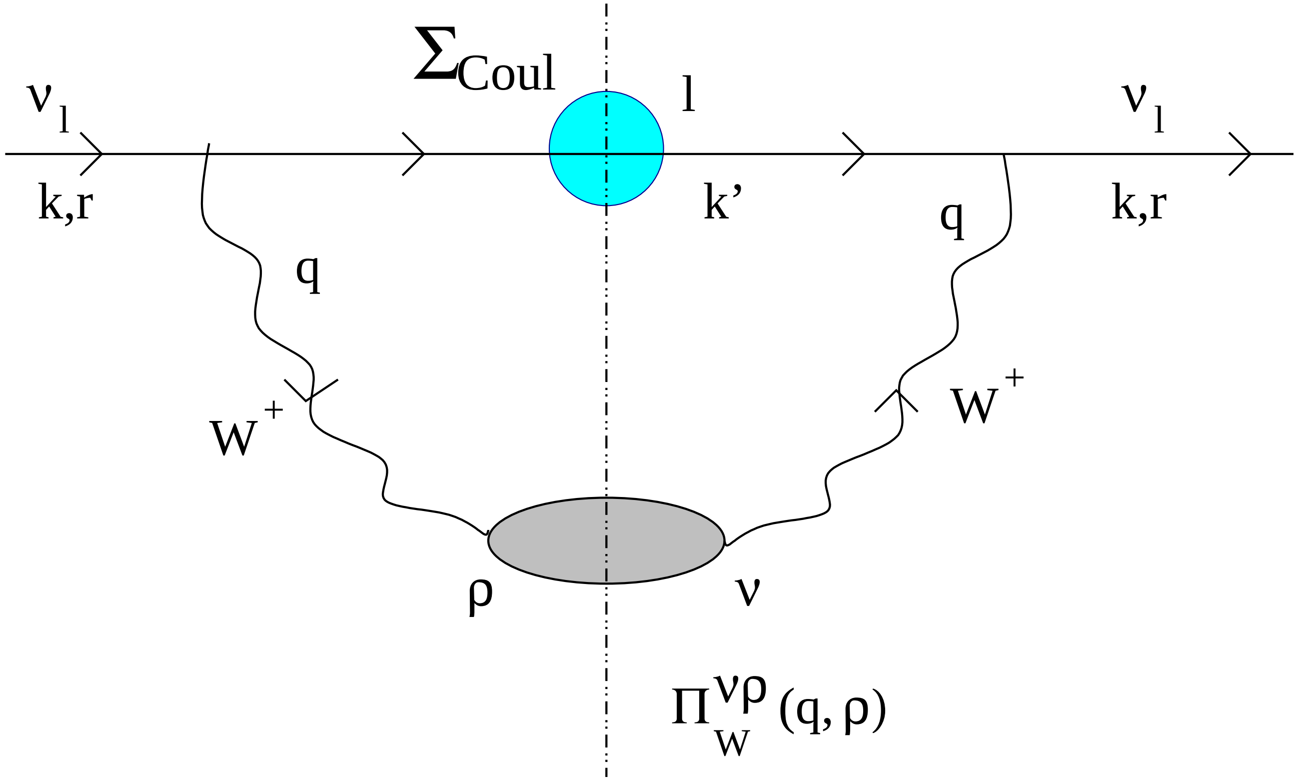
$$\mathrm{Im}\bar{U}_R^N(q) \approx -\pi\rho_n(r)\frac{M}{E(\vec{q})}\delta(q^0 + M - E(\vec{q})) + \cdots$$

$\int d^3r \longrightarrow$ 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, $\longrightarrow \delta(q^0 - \boxed{\mathrm{Q}} + E(\vec{p}) - E(\vec{p} + \vec{q}\,))$ with $Q = M(A_{Z+1}) - M(A_Z)$.
2. Coulomb distortion of outgoing lepton

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

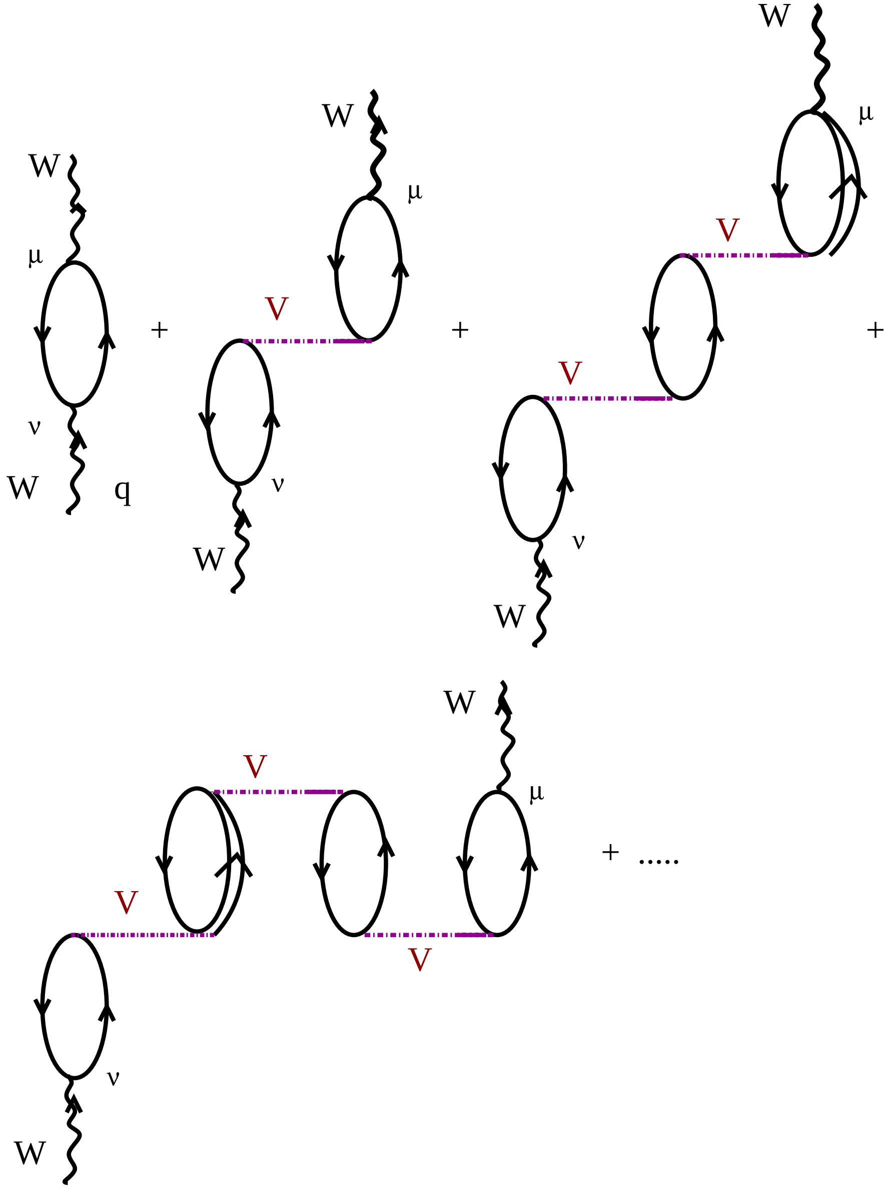

Σ Coul
ν l
l
ν l
k,r
k'
q
k,r
q
W +
W +
ρ
ν
Π W νρ (q, ρ)

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

1. We use an effective Landau-Migdal interaction

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

Isoscalar terms $\boxed{}$ do not contribute to Charged Current processes


W
μ
ν
W
q
+
V
W
μ
ν
W
+
W
μ
V
V
ν
W
+
W
μ
V
V
V
ν
W
+ .....

2. $S = T = 1$ channel of the *ph–ph* interaction $\rightarrow$ split into longitudinal (π−exchange) and transverse (ρ−exchange) parts

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

+ SRC: $V(\vec{q}) \rightarrow \int \frac{d^3k}{(2\pi)^3} V(\vec{k}) \Omega(\vec{q} - \vec{k})$ where $\Omega(\vec{p})$ is the Fourier transform of a nuclear correlation function.

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

3. We include the contribution of Δh excitations
4. In the RPA resummation we neglect $\mathcal{O}(\rho^2 \vec{t}^{\,2}/M^2)$,

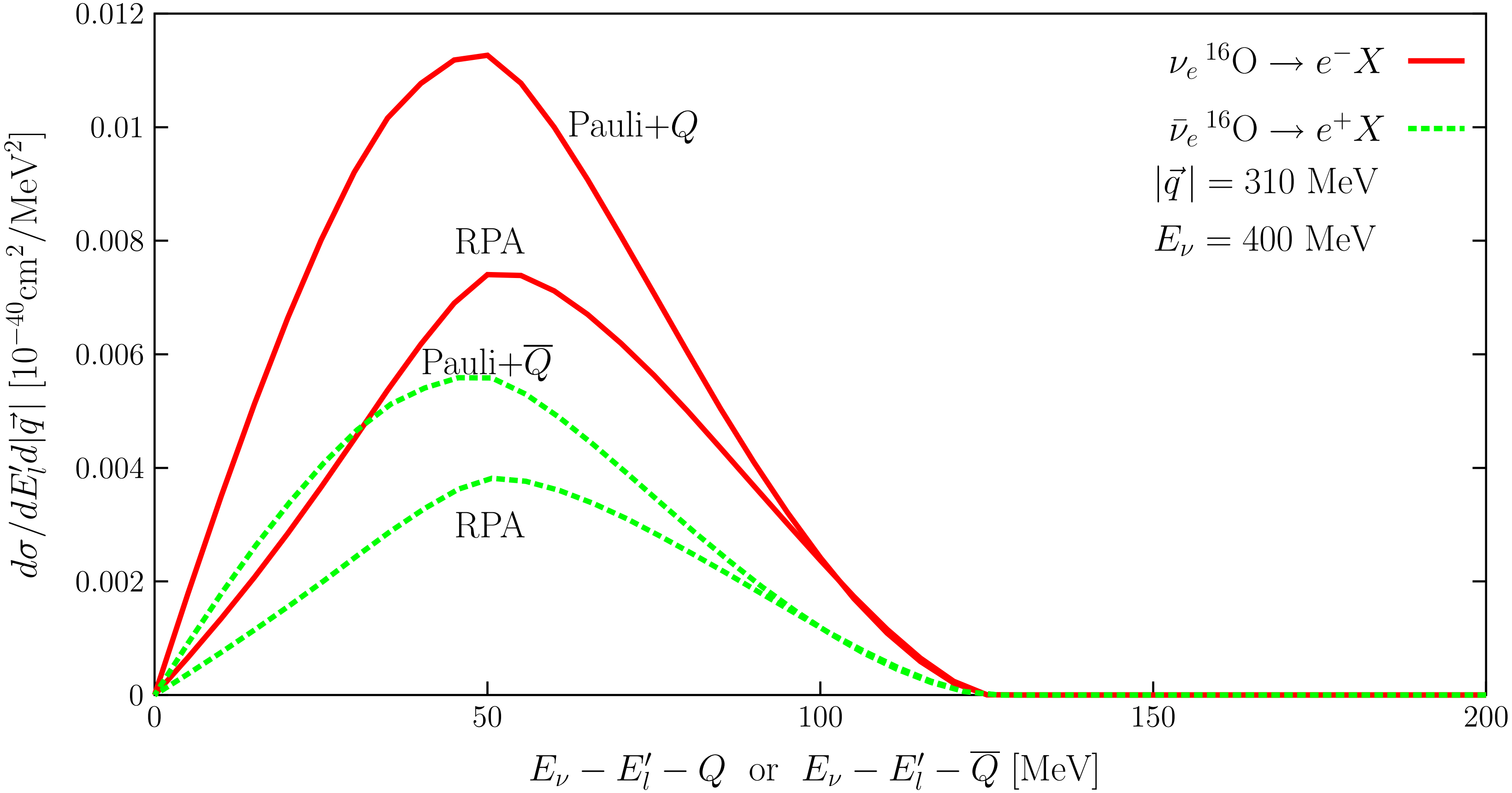
$\vec{t} = \vec{p}, \vec{q}$. At this point, the treatment is not fully relativistic.

Some examples of the RPA effect

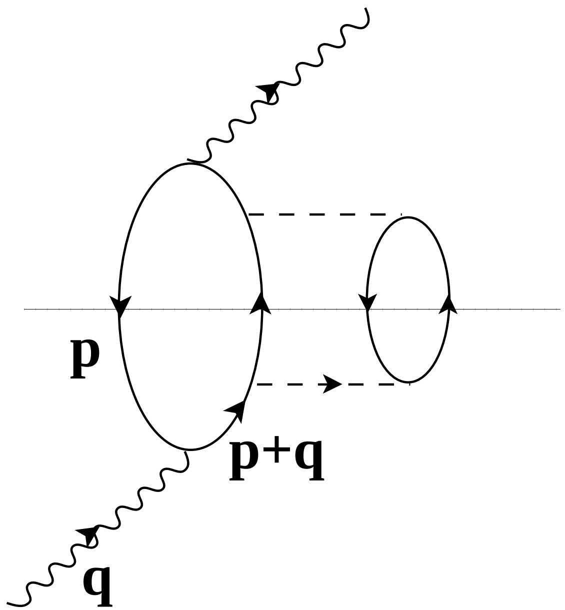
$$G_A^2 \delta^{ij} \rightarrow G_A^2 \left(\frac{\hat{q}^i \hat{q}^j}{|1 - U(q) V_l(q)|^2} + \frac{\delta^{ij} - \hat{q}^i \hat{q}^j}{|1 - U(q) V_t(q)|^2} \right)$$

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

The Lindhard function $U(q)$ contains both ph (U_N) and Δh (U_Δ) excitation contributions.


$\nu_e\,^{16}O \to e^- X$
$\bar\nu_e\,^{16}O \to e^+ X$
$|\vec q\,| = 310$ MeV
$E_\nu = 400$ MeV
Pauli+Q
RPA
Pauli+$\overline{Q}$
RPA
$d\sigma/dE'_l d|\vec q\,|$ $[10^{-40}\text{cm}^2/\text{MeV}^2]$
$E_\nu - E'_l - Q$ or $E_\nu - E'_l - \overline{Q}$ [MeV]
0.012
0.01
0.008
0.006
0.004
0.002
0
50
100
150
200

- Final State Interaction: FSI is taken into account by dressing up the nucleon propagator of the particle state in the *ph* excitation



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

the hole and particle spectral functions are related to nucleon self-energy Σ in the medium

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

with $\omega \geq \mu$ or $\omega \leq \mu$ for S_p and S_h, respectively. The chemical potential μ is determined by

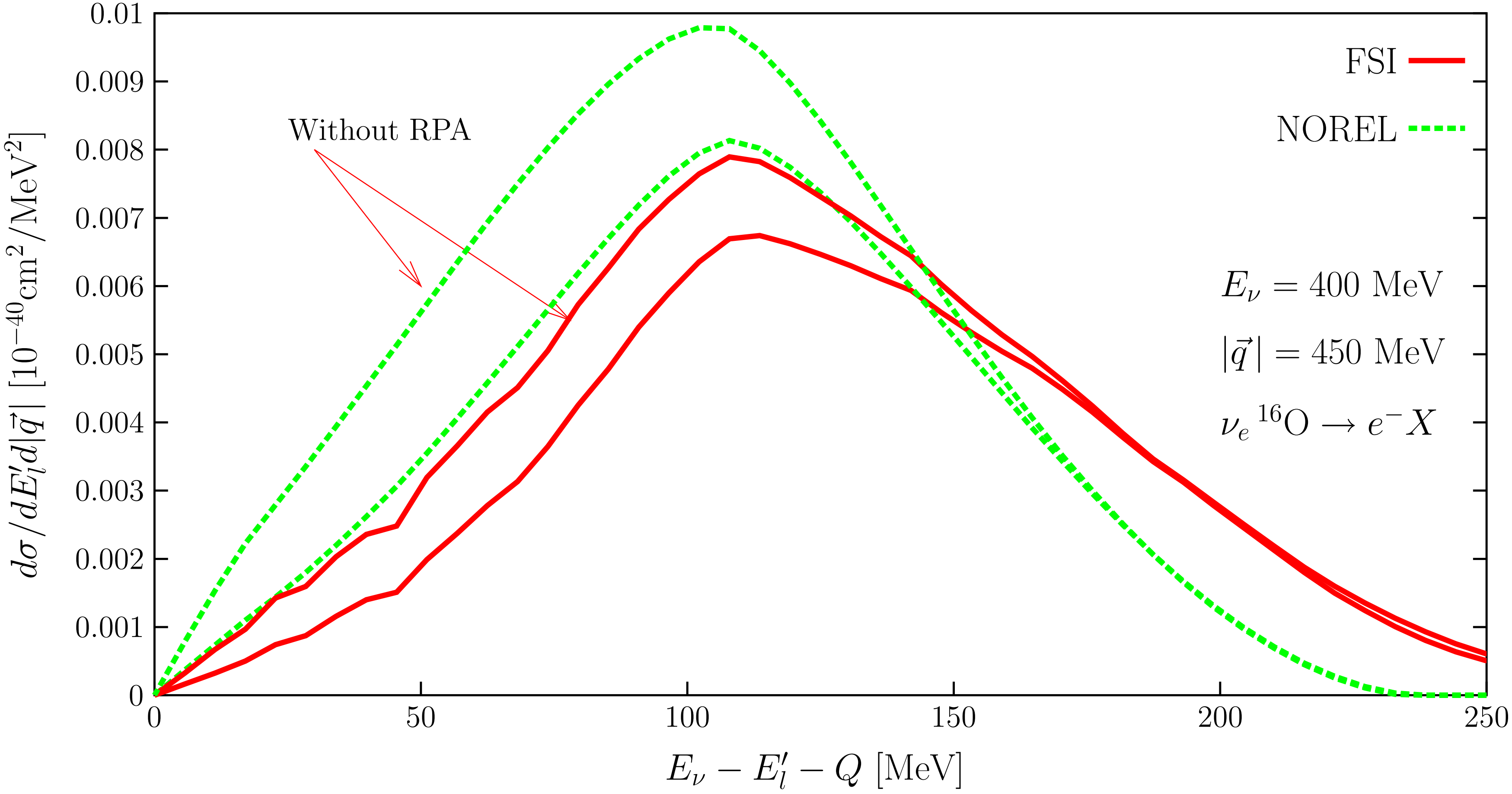
$$\mu = \frac{k_F^2}{2M} + \mathrm{Re}\Sigma(\mu, k_F)$$

Thus to take into account FSI we should replace $\mathrm{Im}\bar{U}_R^N(q)$ by

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

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

We use the non-relativistic model of Fernández de Córdoba+Oset [PRC 46 (1992) 1697] for the nucleon selfenergy Σ.



0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
50
100
150
200
250
$d\sigma/dE'_l d|\vec{q}|$ $[10^{-40}\mathrm{cm}^2/\mathrm{MeV}^2]$
$E_\nu - E'_l - Q$ [MeV]
Without RPA
FSI
NOREL
$E_\nu = 400$ MeV
$|\vec{q}| = 450$ MeV
$\nu_e\,{}^{16}\mathrm{O} \to e^- X$

Neutrino Physics: PRC 70-055503

- 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

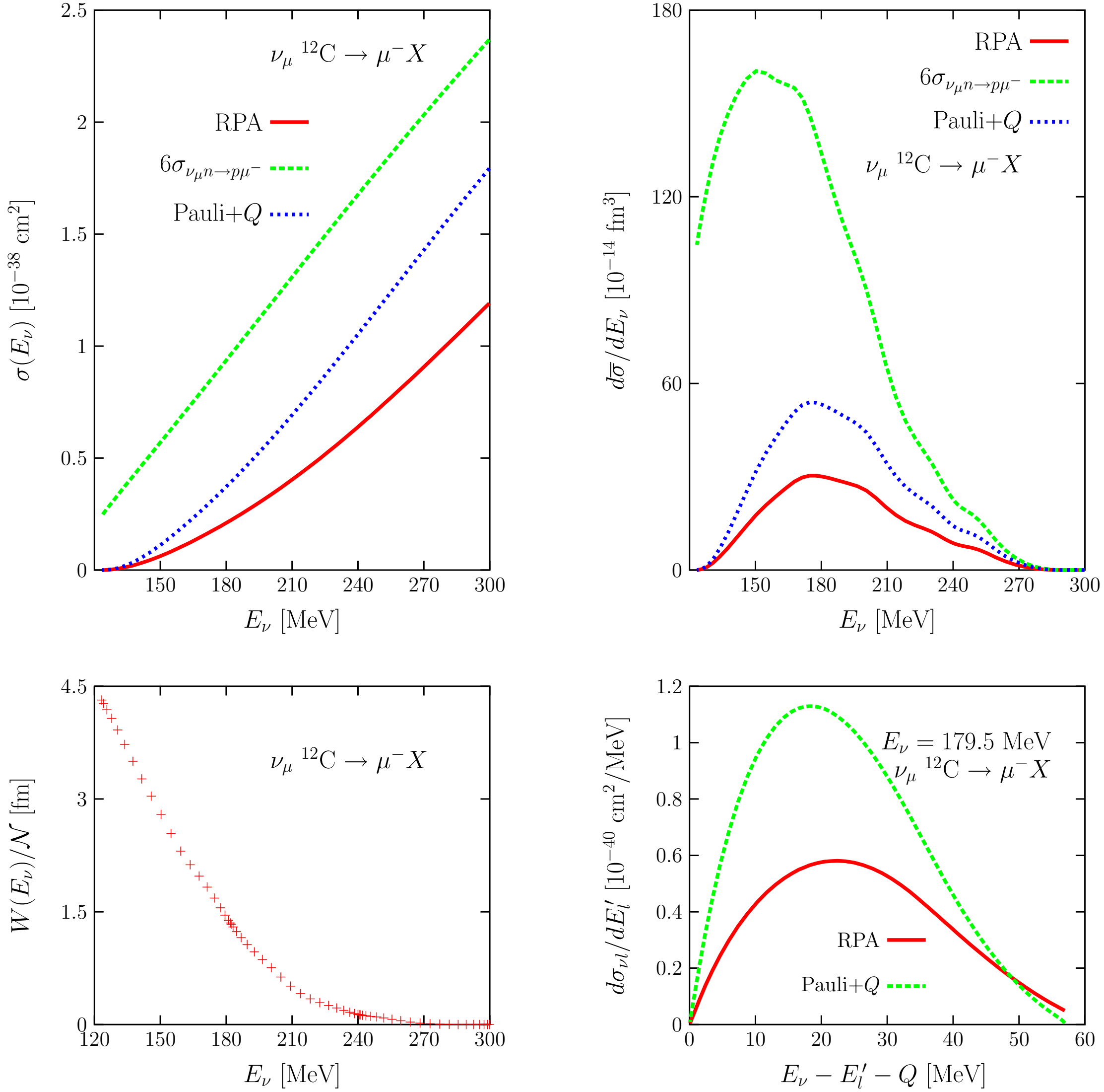
A Shell Model: A.C. Hayes and I.S. Towner, Phys. Rev. C61 (2000) 044603.

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

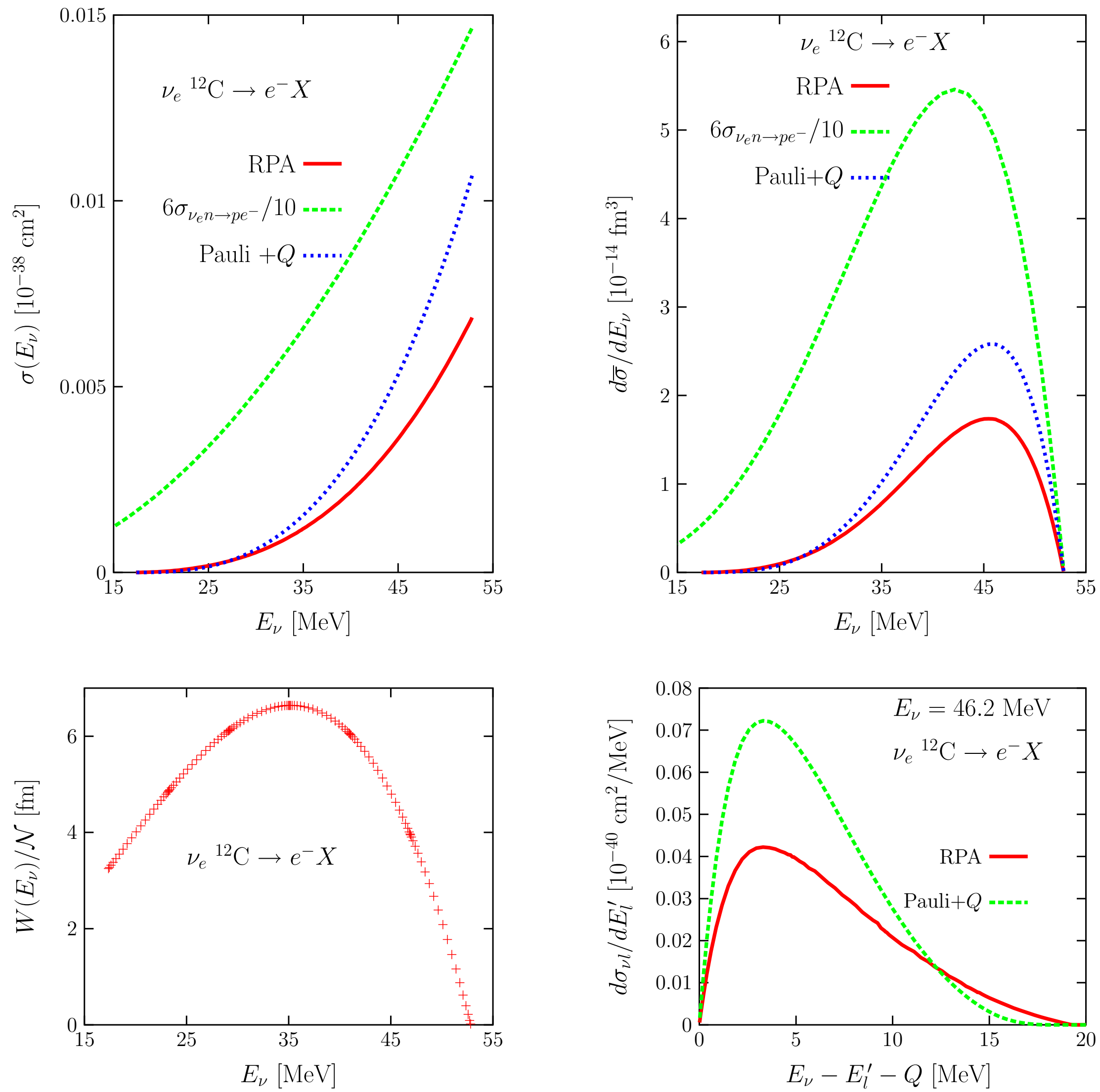
C CRPA: E. Kolbe, et al., J. Phys. G29 (2003) 2569.

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



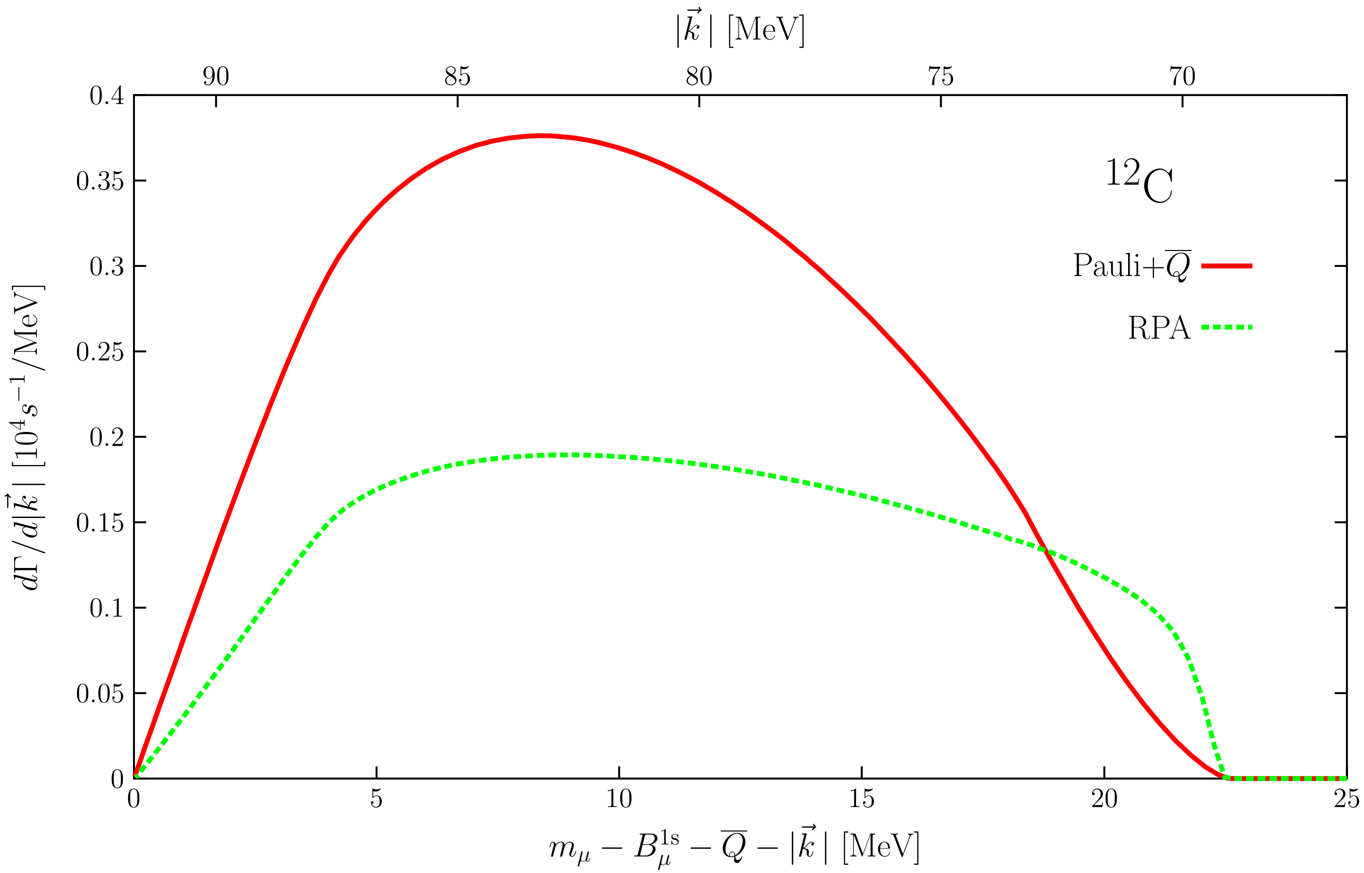
$\nu_\mu\ ^{12}\mathrm{C} \to \mu^- X$
RPA
$6\sigma_{\nu_\mu n \to p\mu^-}$
Pauli+Q
$\sigma(E_\nu)$ [10^{-38} cm^2]
E_ν [MeV]
$d\overline{\sigma}/dE_\nu$ [10^{-14} fm^3]
$W(E_\nu)/\mathcal{N}$ [fm]
$E_\nu = 179.5$ MeV
$d\sigma_{\nu l}/dE'_l$ [10^{-40} cm^2/MeV]
$E_\nu - E'_l - Q$ [MeV]


0.015
0.01
0.005
0
15
25
35
45
55
$\sigma(E_\nu)$ $[10^{-38}$ cm$^2]$
E_ν [MeV]
$\nu_e\ ^{12}\mathrm{C} \to e^- X$
RPA
$6\sigma_{\nu_e n \to p e^-}/10$
Pauli $+Q$
$d\overline{\sigma}/dE_\nu$ $[10^{-14}$ fm$^3]$
6
5
4
3
2
1
0
E_ν [MeV]
$\nu_e\ ^{12}\mathrm{C} \to e^- X$
RPA
$6\sigma_{\nu_e n \to p e^-}/10$
Pauli$+Q$
$W(E_\nu)/\mathcal{N}$ [fm]
E_ν [MeV]
$\nu_e\ ^{12}\mathrm{C} \to e^- X$
$d\sigma_{\nu l}/dE'_l$ $[10^{-40}$ cm^2/MeV]
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
5
10
15
20
$E_\nu - E'_l - Q$ [MeV]
$E_\nu = 46.2$ MeV
$\nu_e\ ^{12}\mathrm{C} \to e^- X$
RPA
Pauli$+Q$

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

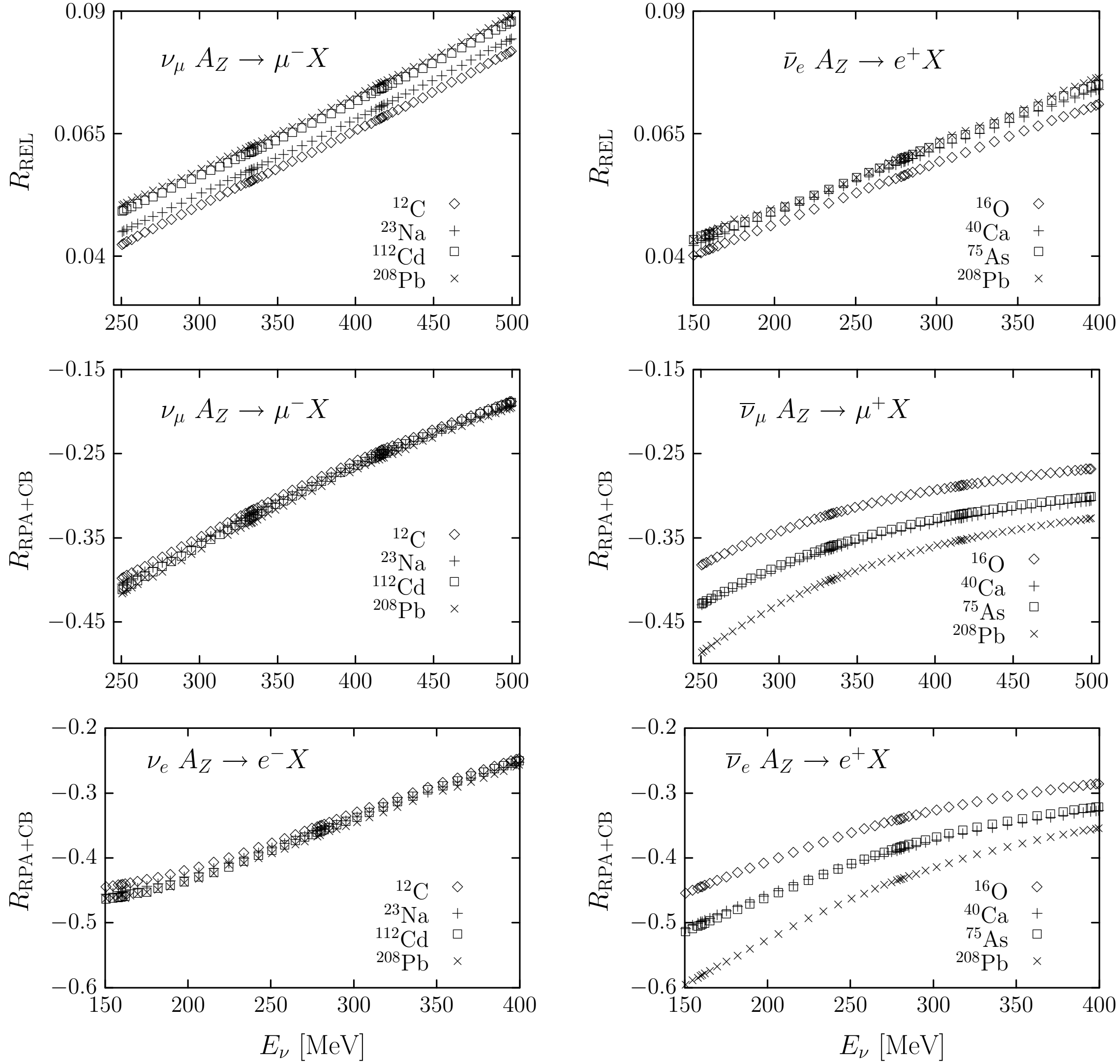
	Pauli $[10^4\ s^{-1}]$	RPA $[10^4\ s^{-1}]$	Exp $[10^4\ s^{-1}]$	$\left(\Gamma^{\rm Exp}-\Gamma^{\rm Th}\right)/\Gamma^{\rm Exp}$
^{12}C	5.42	3.21	3.78 ± 0.03	0.15
^{16}O	17.56	10.41	10.24 ± 0.06	−0.02
^{18}O	11.94	7.77	8.80 ± 0.15	0.12
^{23}Na	58.38	35.03	37.73 ± 0.14	0.07
^{40}Ca	465.5	257.9	252.5 ± 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

The present model provides one of the best combined description of the inclusive muon capture in ^{12}C and the LSND measurement of the $^{12}{\rm C}(\nu_\mu,\mu^-)X$ reaction near threshold.

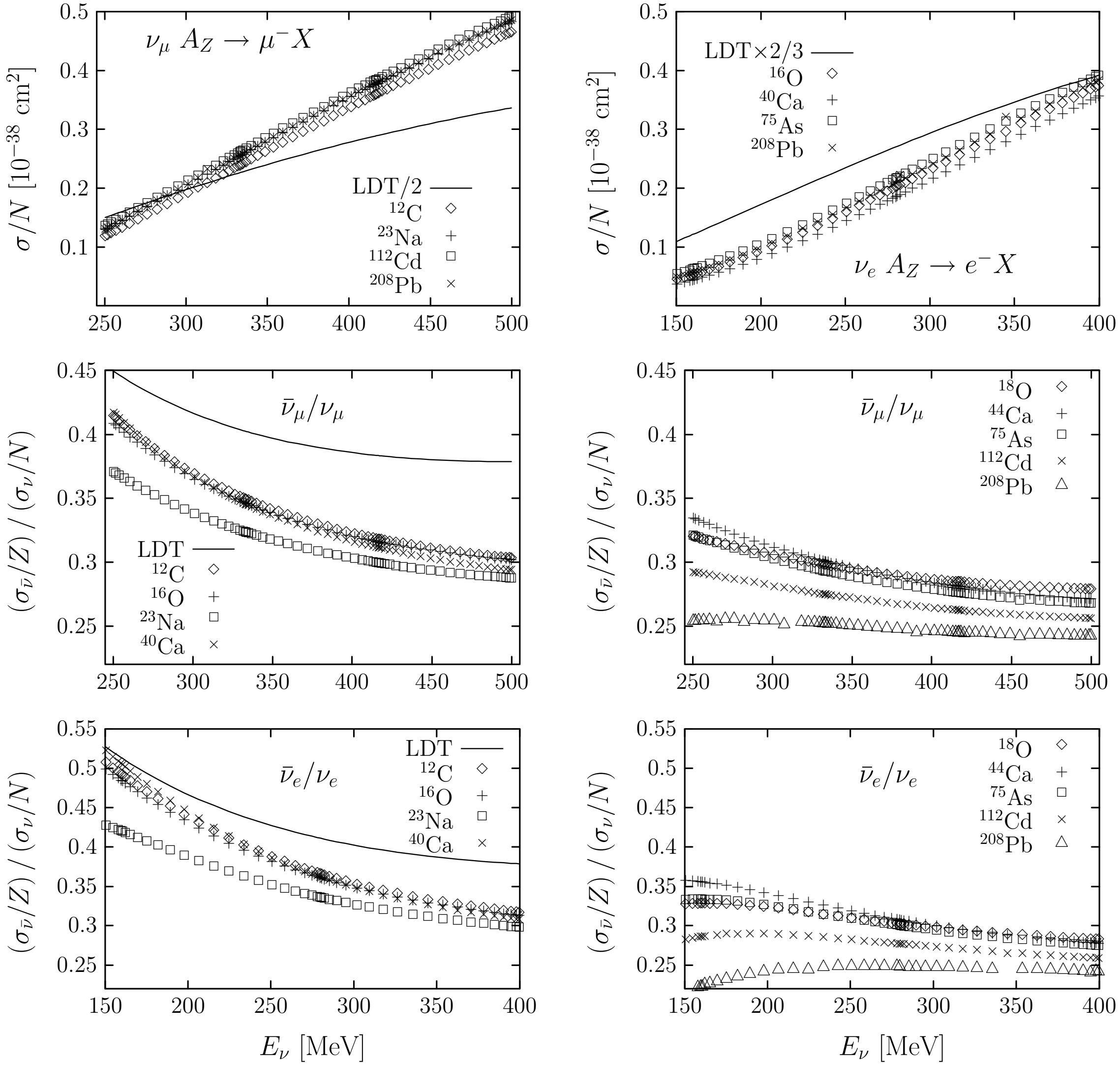


|k| [MeV]
90
85
80
75
70
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
dΓ/d|k| [10^4 s^-1/MeV]
12C
Pauli+Q
RPA
0
5
10
15
20
25
m_μ − B_μ^1s − Q − |k| [MeV]

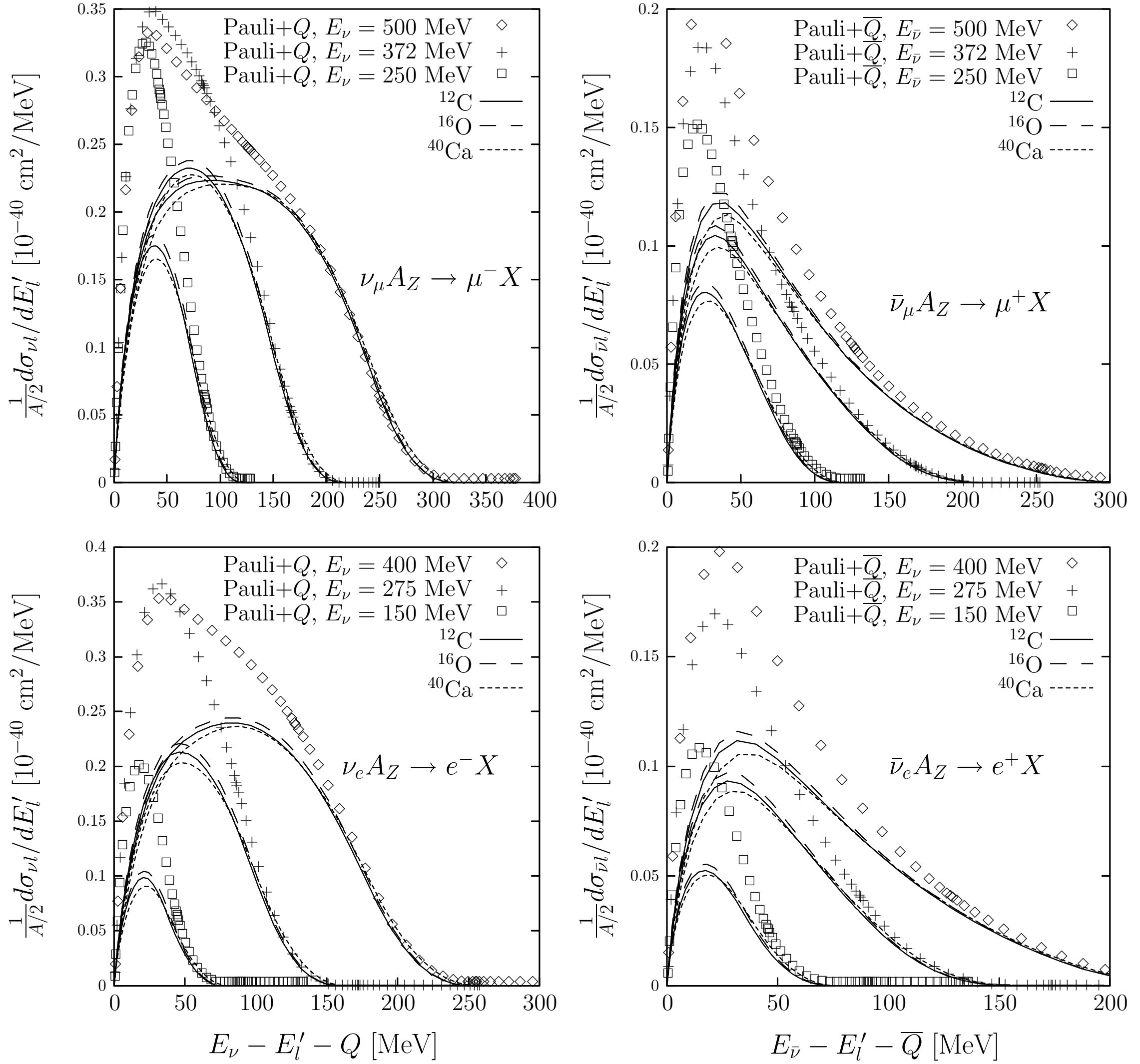
- Intermediate Energies ($E_\nu = 100 - 500$ MeV): Predictions for QE electron and muon neutrino and antineutrino integrated, single and double differential cross sections for different nuclei, which can be used to guide future experiments and eventually could be compared to forthcoming data.



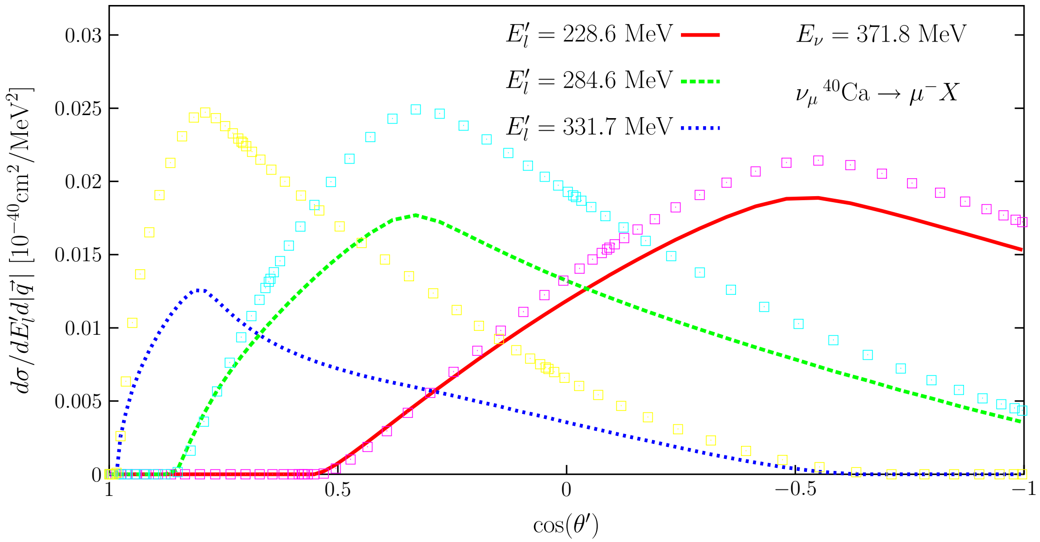
$\nu_\mu A_Z \to \mu^- X$
$\bar{\nu}_e A_Z \to e^+ X$
$\nu_\mu A_Z \to \mu^- X$
$\overline{\nu}_\mu A_Z \to \mu^+ X$
$\nu_e A_Z \to e^- X$
$\overline{\nu}_e A_Z \to e^+ X$
$R_{\rm REL}$
$R_{\rm RPA+CB}$
^{12}C
^{23}Na
^{112}Cd
^{208}Pb
^{16}O
^{40}Ca
^{75}As
E_ν [MeV]

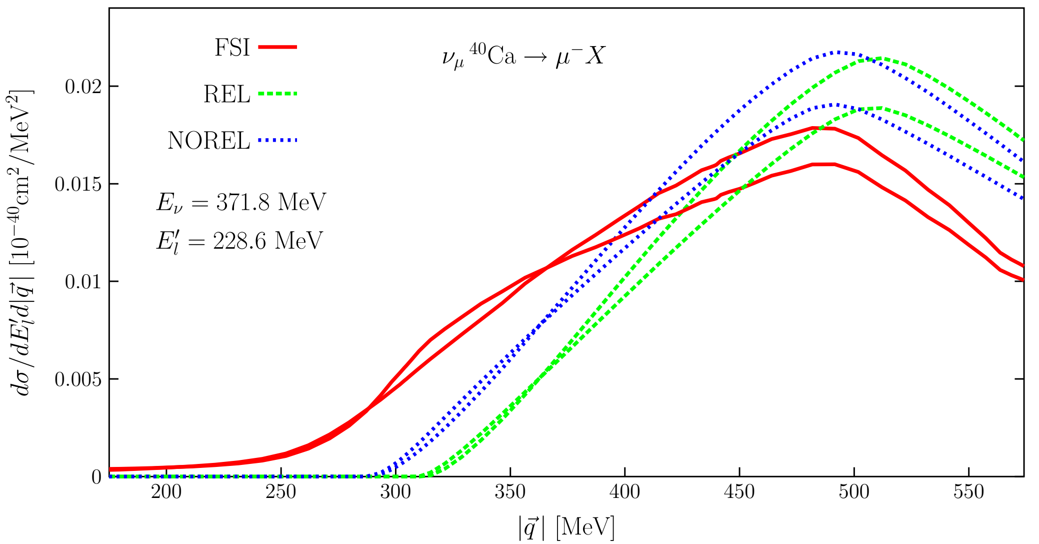


ν_μ A_Z → μ⁻X
LDT/2
¹²C
²³Na
¹¹²Cd
²⁰⁸Pb
σ/N [10⁻³⁸ cm²]
LDT×2/3
¹⁶O
⁴⁰Ca
⁷⁵As
²⁰⁸Pb
ν_e A_Z → e⁻X
ν̄_μ/ν_μ
LDT
¹²C
¹⁶O
²³Na
⁴⁰Ca
(σ_ν̄/Z) / (σ_ν/N)
¹⁸O
⁴⁴Ca
⁷⁵As
¹¹²Cd
²⁰⁸Pb
ν̄_e/ν_e
E_ν [MeV]



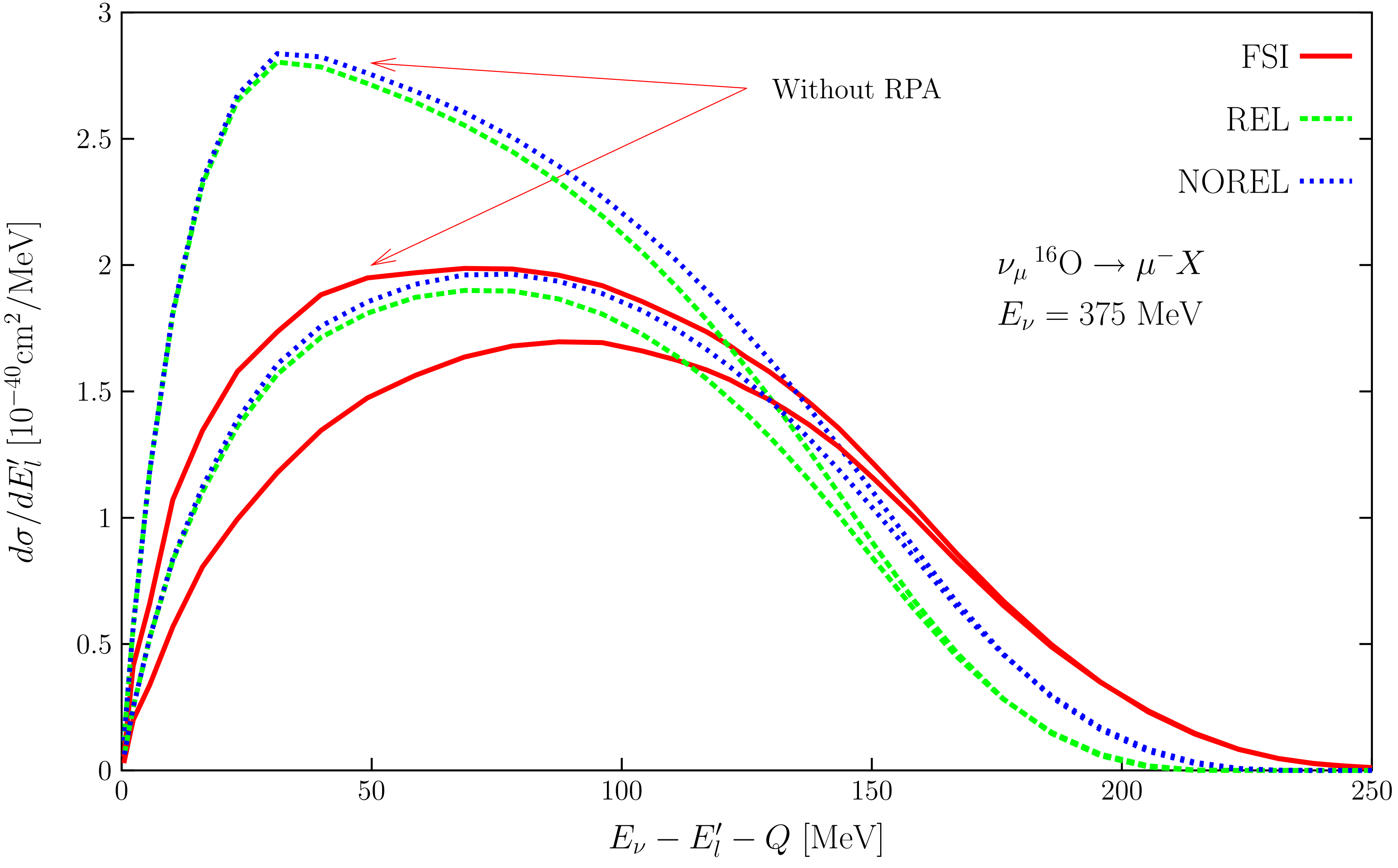
Pauli+Q, Eν = 500 MeV
Pauli+Q, Eν = 372 MeV
Pauli+Q, Eν = 250 MeV
12C
16O
40Ca
νμ AZ → μ− X
Pauli+Q̄, Eν̄ = 500 MeV
Pauli+Q̄, Eν̄ = 372 MeV
Pauli+Q̄, Eν̄ = 250 MeV
ν̄μ AZ → μ+ X
Pauli+Q, Eν = 400 MeV
Pauli+Q, Eν = 275 MeV
Pauli+Q, Eν = 150 MeV
νe AZ → e− X
Pauli+Q̄, Eν = 400 MeV
Pauli+Q̄, Eν = 275 MeV
Pauli+Q̄, Eν = 150 MeV
ν̄e AZ → e+ X
1/(A/2) dσνl/dE′l [10−40 cm2/MeV]
1/(A/2) dσν̄l/dE′l [10−40 cm2/MeV]
Eν − E′l − Q [MeV]
Eν̄ − E′l − Q̄ [MeV]


$E'_l = 228.6$ MeV
$E'_l = 284.6$ MeV
$E'_l = 331.7$ MeV
$E_\nu = 371.8$ MeV
$\nu_\mu\,^{40}\mathrm{Ca} \to \mu^- X$
$d\sigma/dE'_l d|\vec{q}|$ [10^{-40}cm^2/MeV^2]
$\cos(\theta')$
0.03
0.025
0.02
0.015
0.01
0.005
0
1
0.5
0
−0.5
−1


FSI
REL
NOREL
$\nu_\mu\,^{40}\mathrm{Ca} \to \mu^- X$
$E_\nu = 371.8$ MeV
$E'_l = 228.6$ MeV
$d\sigma/dE'_l d|\vec{q}|$ [10^{-40}cm^2/MeV^2]
$|\vec{q}|$ [MeV]
0.02
0.015
0.01
0.005
0
200
250
300
350
400
450
500
550

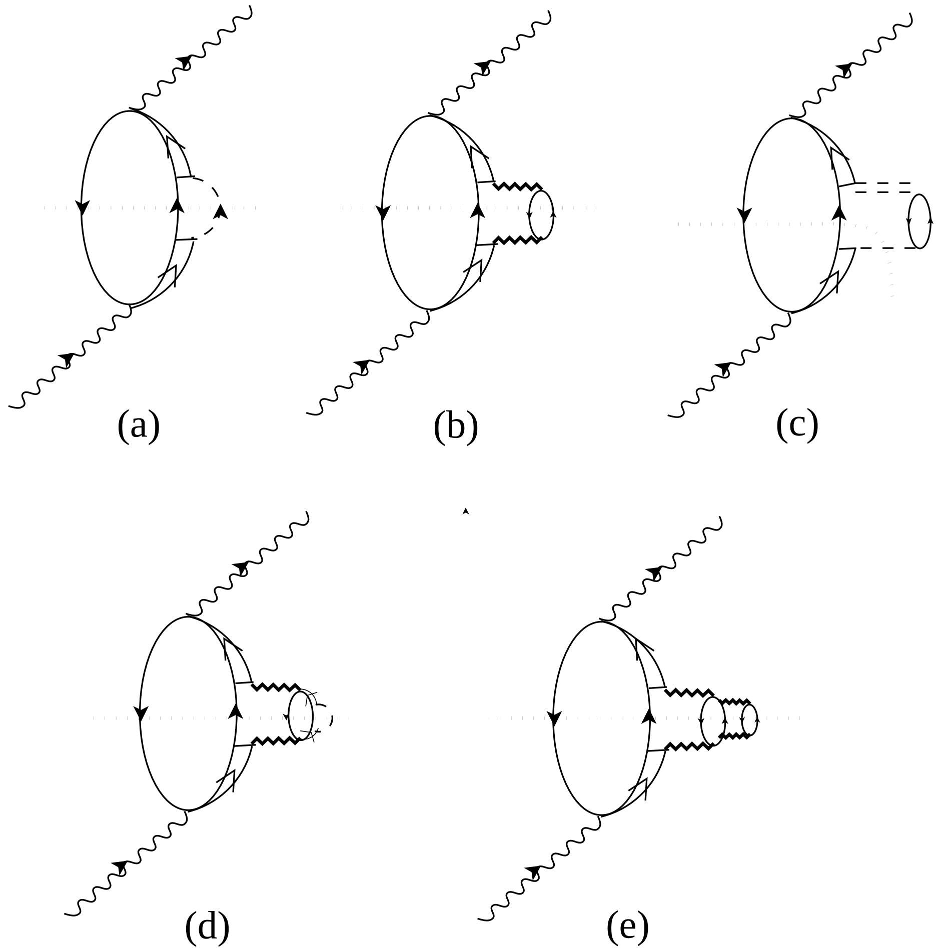
E_ν [MeV]		$\sigma\left({}^{16}\mathrm{O}(\nu_\mu,\mu^- X)\right)$ $[10^{-40}\ \mathrm{cm}^2]$			$\sigma\left({}^{16}\mathrm{O}(\bar\nu_\mu,\mu^+ X)\right)$ $[10^{-40}\ \mathrm{cm}^2]$		
		REL	NOREL	FSI	REL	NOREL	FSI
500	Pauli	460.0	497.0	431.6	155.8	168.4	149.9
	RPA	375.5	413.0	389.8	113.4	126.8	129.7
375	Pauli	334.6	354.8	292.2	115.1	122.6	105.0
	RPA	243.1	263.9	243.9	79.8	87.9	87.5
250	Pauli	155.7	162.2	122.5	63.4	66.4	52.8
	RPA	94.9	101.9	93.6	38.8	42.1	40.3

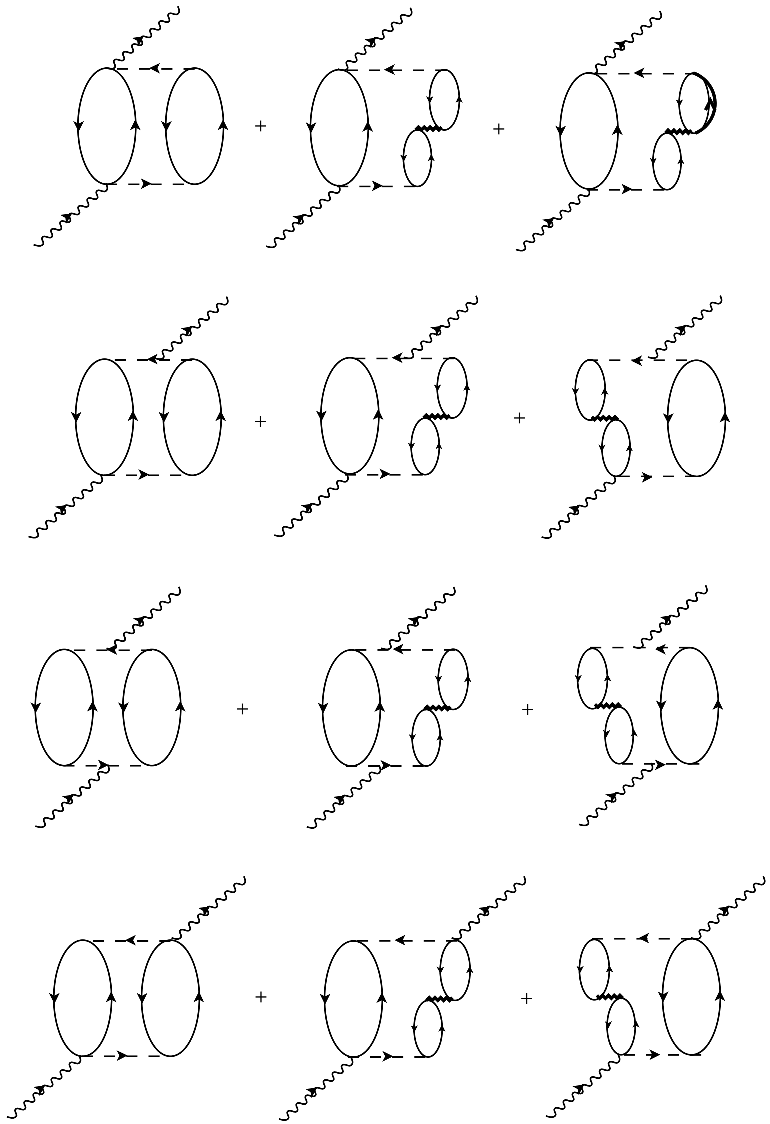
E_ν [MeV]		$\sigma\left({}^{16}\mathrm{O}(\nu_e,e^- X)\right)$ $[10^{-40}\ \mathrm{cm}^2]$			$\sigma\left({}^{16}\mathrm{O}(\bar\nu_e,e^+ X)\right)$ $[10^{-40}\ \mathrm{cm}^2]$		
		REL	NOREL	FSI	REL	NOREL	FSI
400	Pauli	389.4	416.6	352.5	130.0	139.1	121.0
	RPA	294.7	322.6	303.6	91.9	101.9	104.8
310	Pauli	281.4	297.4	240.6	98.1	104.0	87.2
	RPA	192.2	209.0	195.2	65.9	72.4	73.0
220	Pauli	149.5	156.2	121.2	60.7	63.6	51.0
	RPA	90.1	97.3	92.8	36.8	40.0	40.2

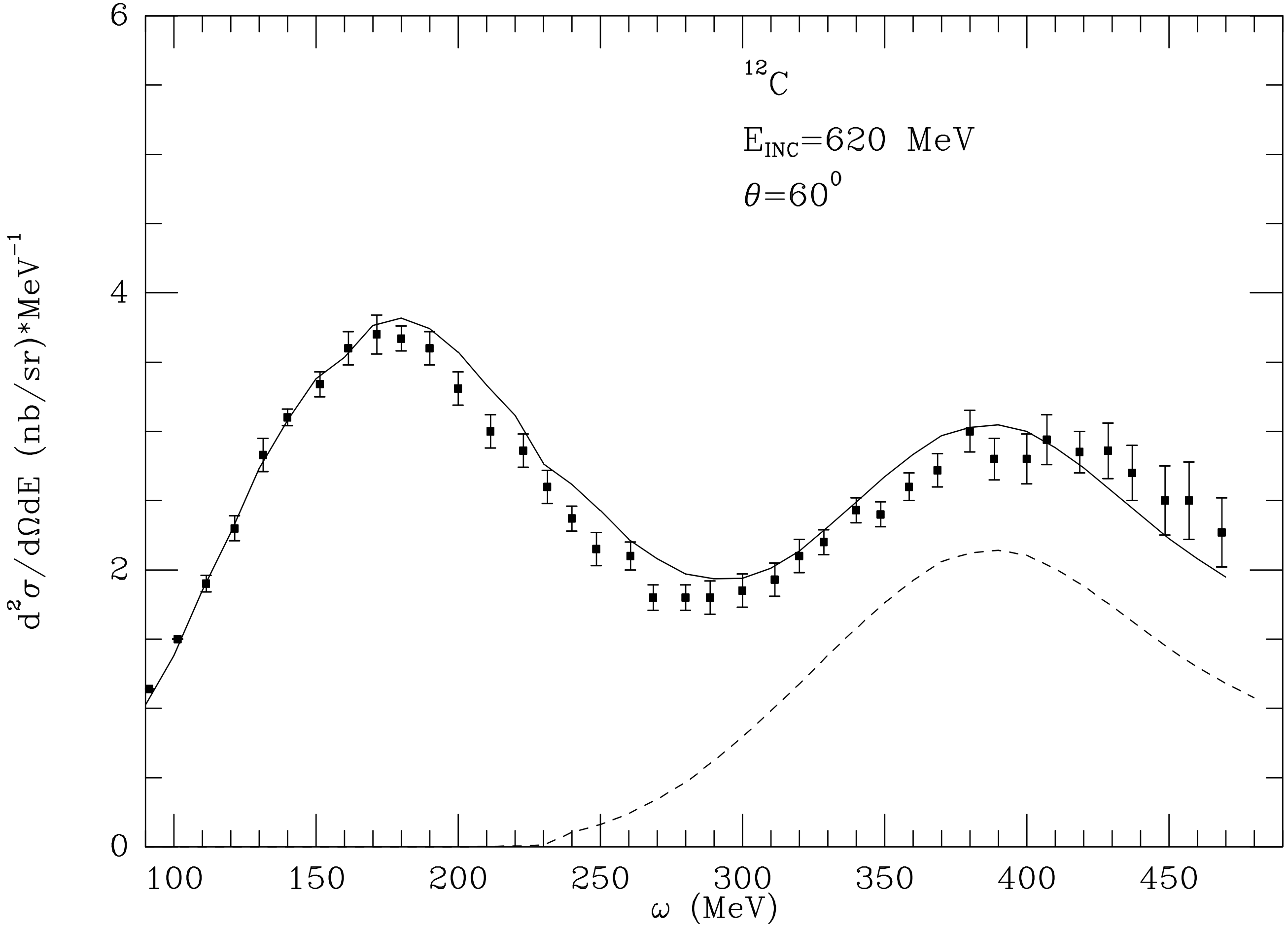

FSI
REL
NOREL
Without RPA
$\nu_\mu\,{}^{16}\mathrm{O} \to \mu^- X$
$E_\nu = 375$ MeV
$d\sigma/dE'_l\;[10^{-40}\mathrm{cm}^2/\mathrm{MeV}]$
$E_\nu - E'_l - Q$ [MeV]
0
0.5
1
1.5
2
2.5
3
0
50
100
150
200
250

(e, e') Results

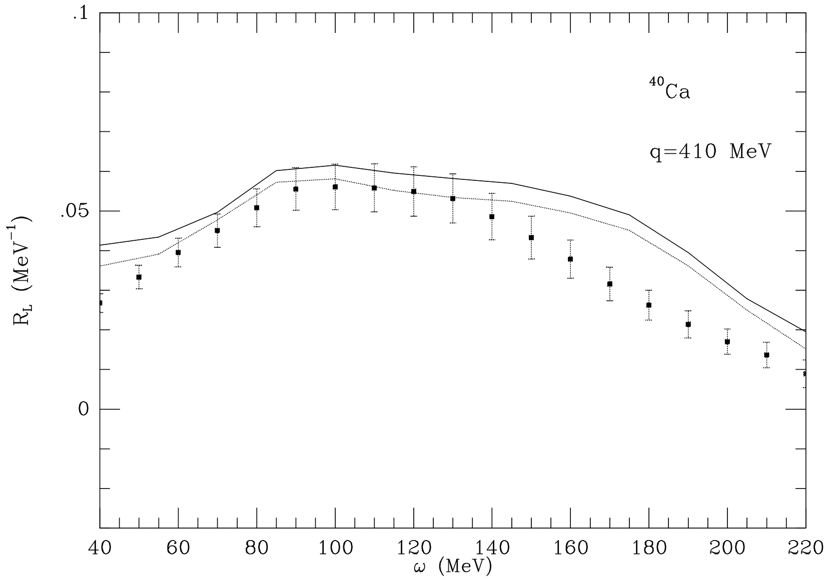
Same formalism applied to the study of inclusive processes (e, e'), $(e, e'N)$, $(e, e'NN)$, $(e, e'\pi)$, ... in nuclei at intermediate energies **[Gil+Nieves+Oset, NPA 627 (1997) 543-619]** leads to excellent results both in the quasielastic and Δ excitation regions. To describe the Δ peak and the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

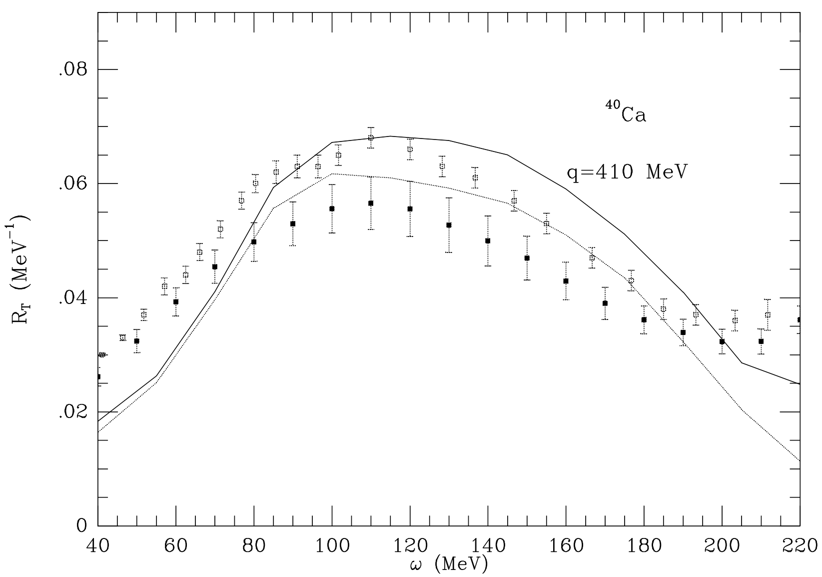

(a)
(b)
(c)
(d)
(e)





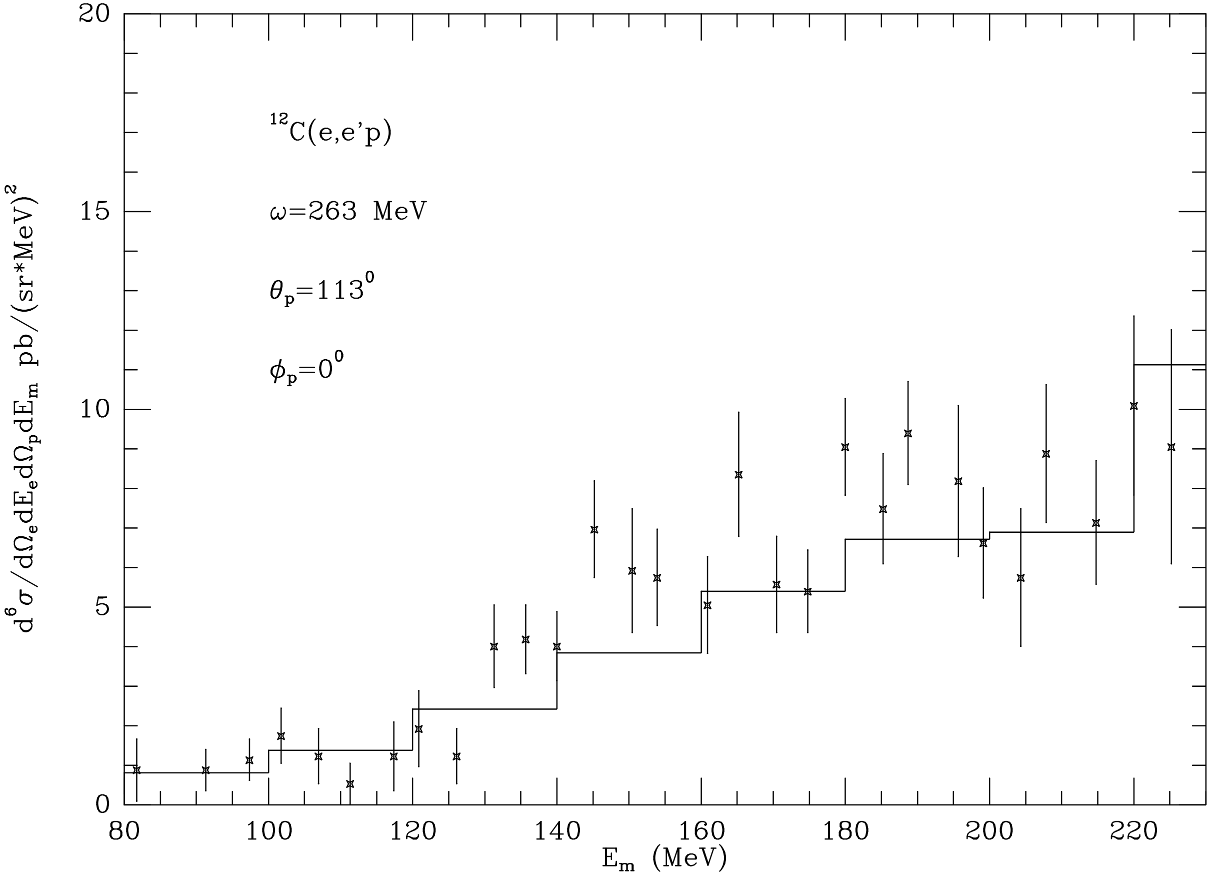
$$e + {}^{12}\mathrm{C} \rightarrow e' + X$$





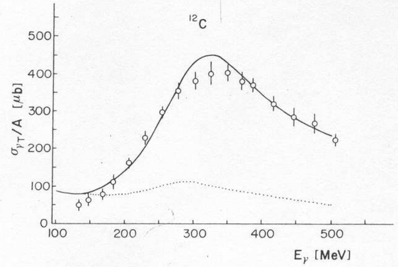
R_L and R_T QE response functions for $e + {}^{40}\text{Ca} \to e' + X$

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]



ig. 45. Results for σ_A/A as a function of the photon energy for ^{12}C. Experiment from ref. [6]). The lower curve is the result for direct photon absorption.

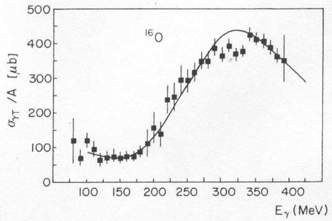
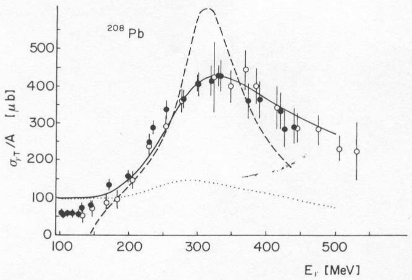


Fig. 46. Results for σ_A/A as a function of the photon energy for ^{16}O. Experiment from ref. [5]).



ig. 47. Continuous line: results for σ_A/A as a function of the photon energy for ^{208}Pb. The dashed ie shows the impulse approximation result $(Z\sigma_{\gamma p}+N\sigma_{\gamma n})/A$ for comparison. The dotted line is the esult for direct photon absorption. Experimental data: dark dots from ref. [3]), while dots from ref. [6]).

$$\gamma + A \to X$$

R.C. Carrasco et al. / Inclusive (γ, π) reactions

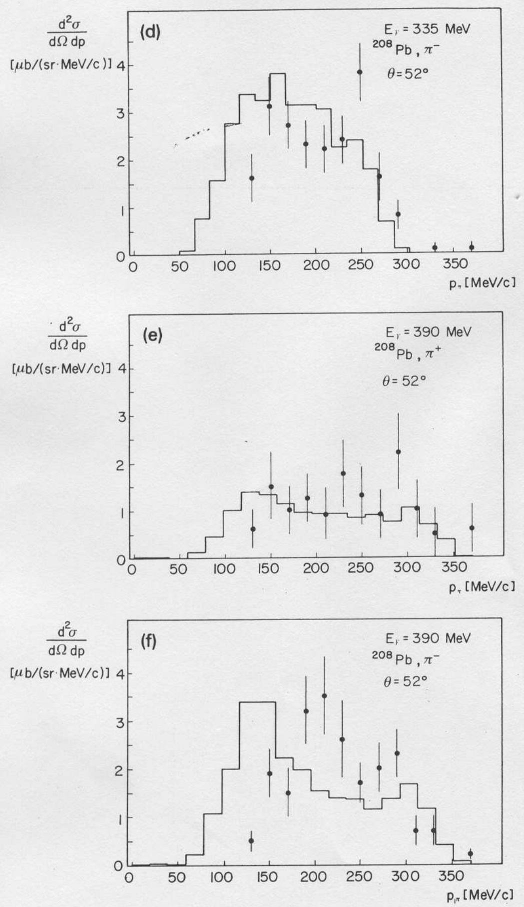


Fig. 17—continued.

$$\gamma + {}^{208}\mathrm{Pb} \rightarrow X + \pi^{\pm}$$

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

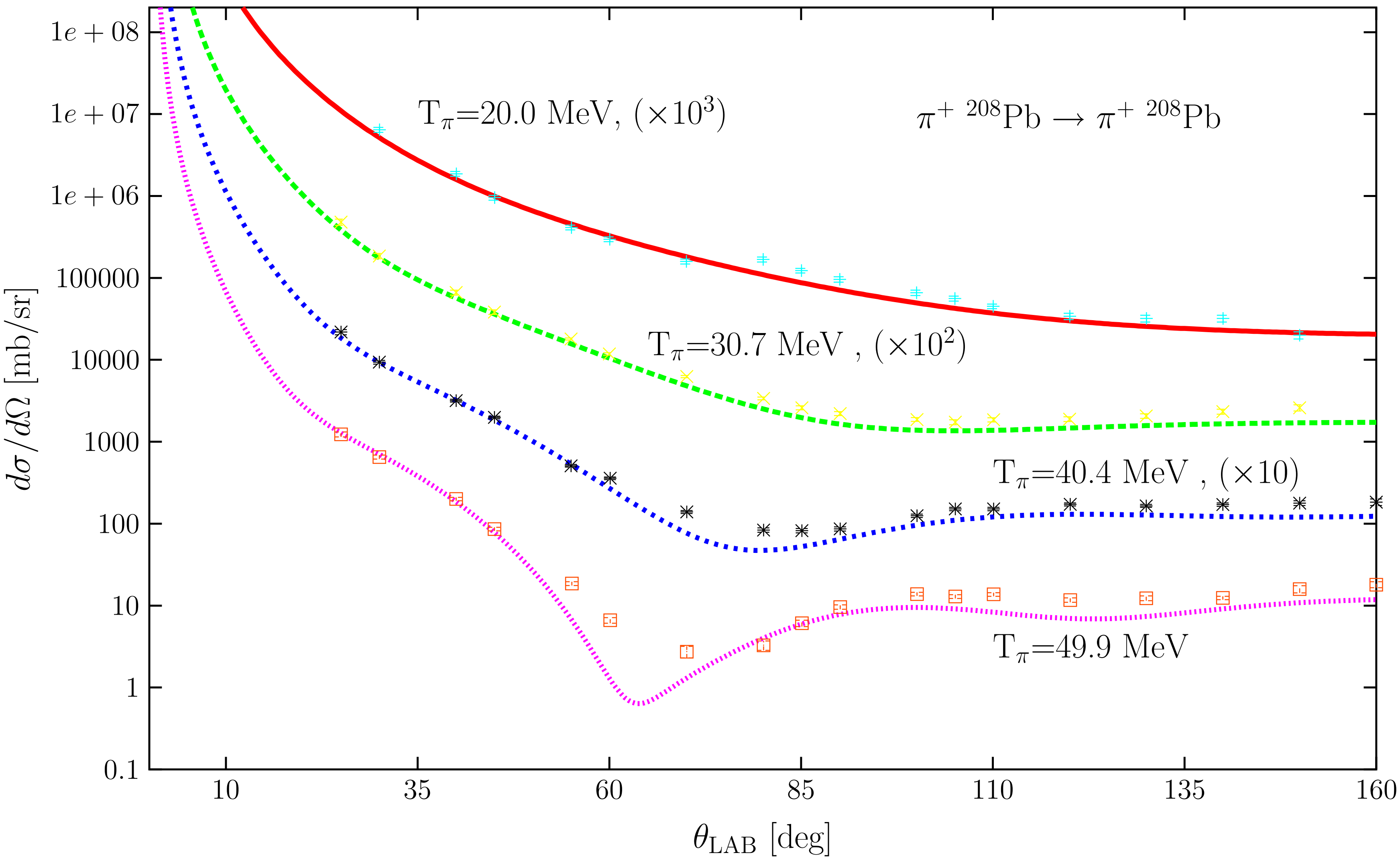
García-Recio+Oset+Salcedo+Strottman, NPA 526, 685

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]
1e + 08
1e + 07
1e + 06
100000
10000
1000
100
10
1
0.1
10
35
60
85
110
135
160
$\theta_{\rm LAB}$ [deg]

Conclusion

- Many body approach to inclusive electroweak reactions in nuclei, at intermediate energies (nuclear excitation energies below 500 MeV). It systematically takes into account for RPA, SRC, $\Delta(1232)$, FSI and MEC effects. The meson-nucleon and nucleon-nucleon dynamics of the approach have been successfully tested in former pionic reactions.

  Successful to describe

  1. Real and virtual photo-absorption and π, N, NN, $N\pi$ electro and photoproduction processes in nuclei.
  2. Charged current inclusive neutrino (ν_μ or ν_e)- ^{12}C

cross sections at low energies and Inclusive Muon Capture in Nuclei, where **nuclear effects reduce the cross sections by factors as large as 30. RPA leads to reductions of about a factor 2.**

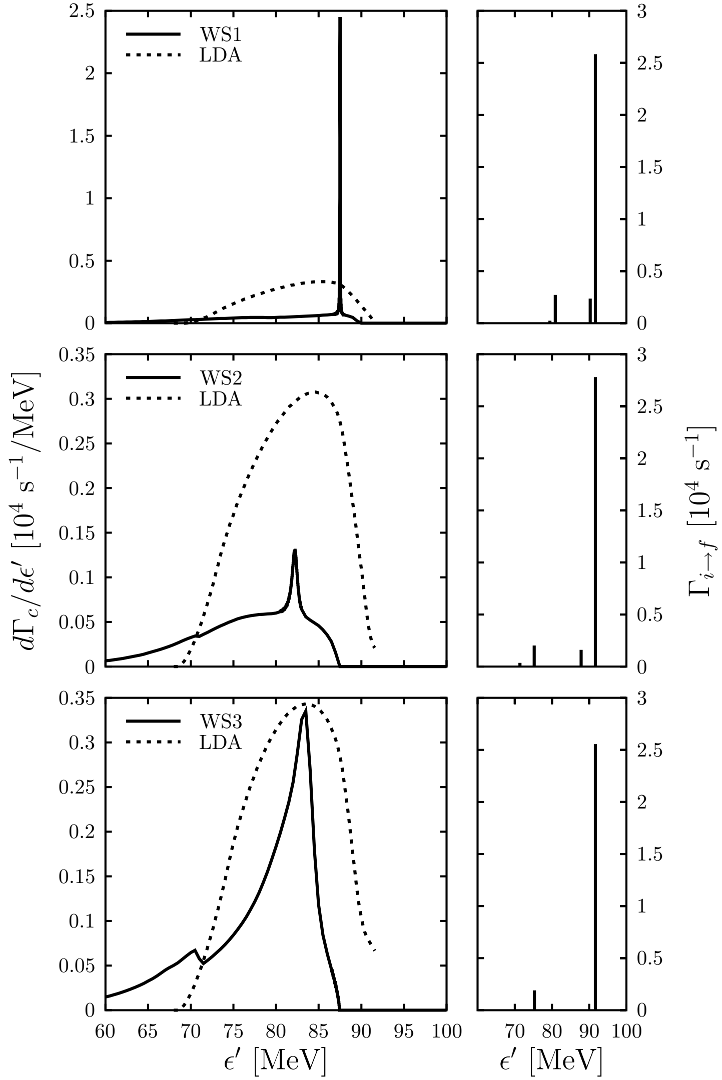
- Predictions for QE neutrino induced reactions in nuclei at intermediate energies of interest for future neutrino experiments.

Outlook

- **Charged Currents: Contributions from resonance degrees of freedom and MEC.**
- **Neutral Currents** (Valverde+Vicente-Vacas)

SM vs FG: nucl-th/0408008

Finite nuclei effects are expected to be sizeable for differential magnitudes (outgoing lepton energy distributions). In addition to the excitation of discrete states and narrow resonances, a finite nuclei treatment also provides a certain quenching of the LFG energy distribution in the neighborhood of the peak and a spreading of the strength to the sides of it. However, the integrated strength over energies, including the discrete state and resonance contributions, remains practically unchanged.


WS1
LDA
WS2
LDA
WS3
LDA
$d\Gamma_c/d\epsilon'$ [10^4 s^{-1}/MeV]
$\Gamma_{i\to f}$ [10^4 s^{-1}]
ϵ' [MeV]
ϵ' [MeV]

Inclusive Muon Capture in ^{12}C $(\Gamma[10^5 s^{-1}])$

	discrete	total	LFG	%
WS1	0.3115	0.4406	0.4542	3.1
WS2	0.3179	0.4289	0.4408	2.8
WS3	0.2746	0.5510	0.4874	−11.5