Inclusive Nucleon Emission Induced by Quasi-Elastic Neutrino-Nucleus Interactions

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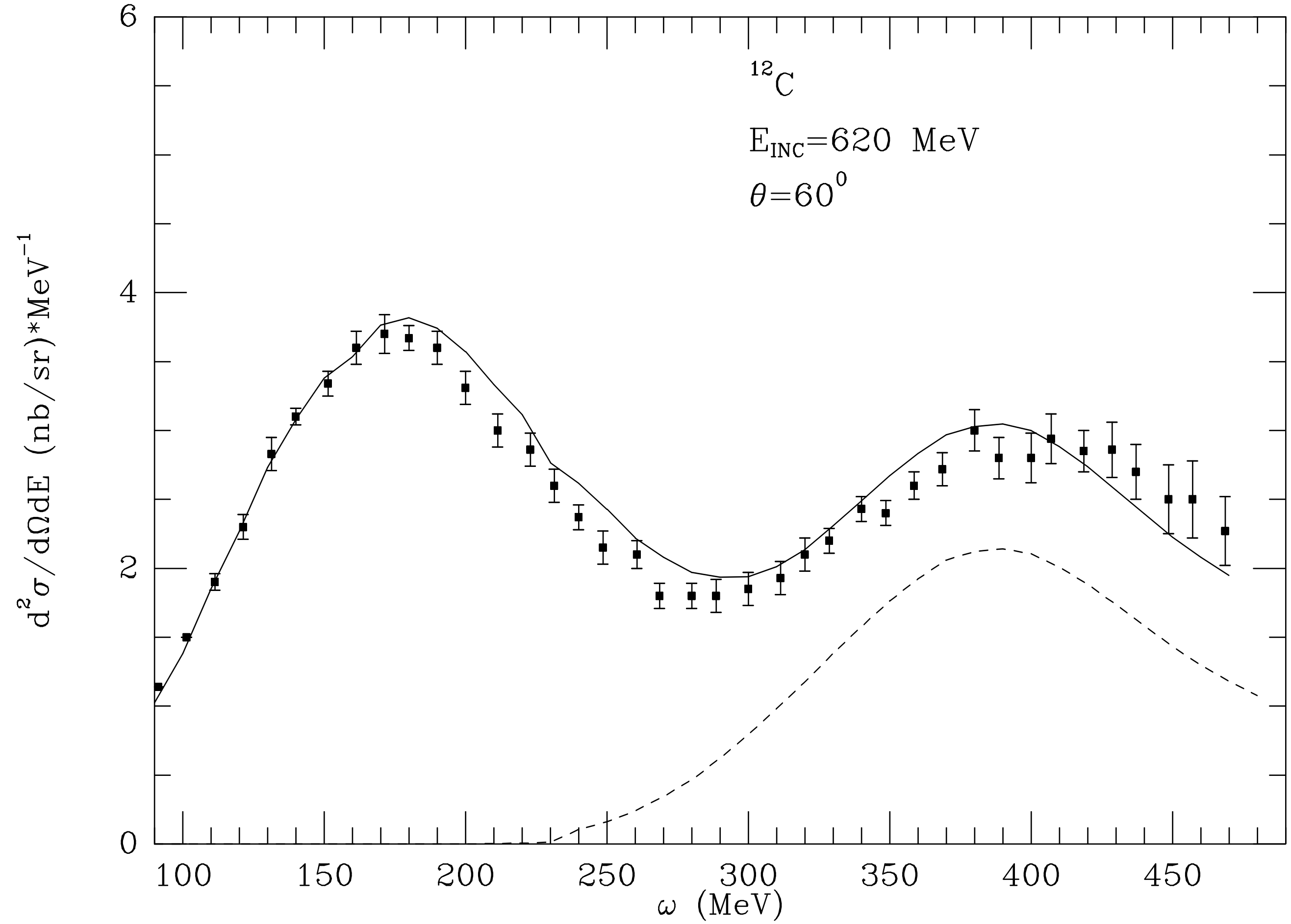
$e + {}^{12}\mathrm{C} \rightarrow e' + X$



A.Gil, J.Nieves and E.Oset, Nucl.Phys. **A627**:543,(1997)

Low Energy Neutrino Inclusive Cross Sections

- $\nu_\mu\,^{12}\text{C} \to \mu^- X \qquad (\overline{\sigma}[10^{-40}\text{cm}^2])$

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

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

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

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.

J.Nieves, J.E.Amaro and M.Valverde, Phys.Rev. **C70**:055503,(2004)

1 – Many Body Framework

- We work on an Infinite Nuclear Medium
- Results for Finite Nuclei using Local Density Approximation (LDA)

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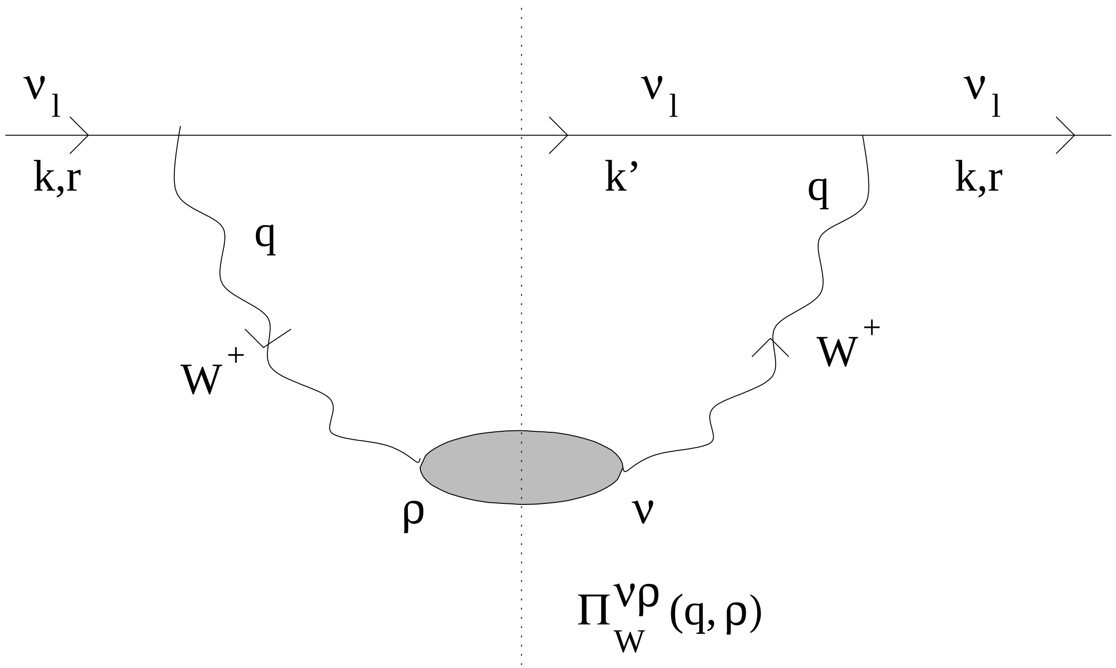
...but include dynamical effects:

- Long (RPA) and Short Range Correlations (SRC)
- $\Delta(1232)-$ Degrees of Freedom

1.1 – Model For The Reaction

Neutrino-selfenergy inside a nuclear medium of density ρ:



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

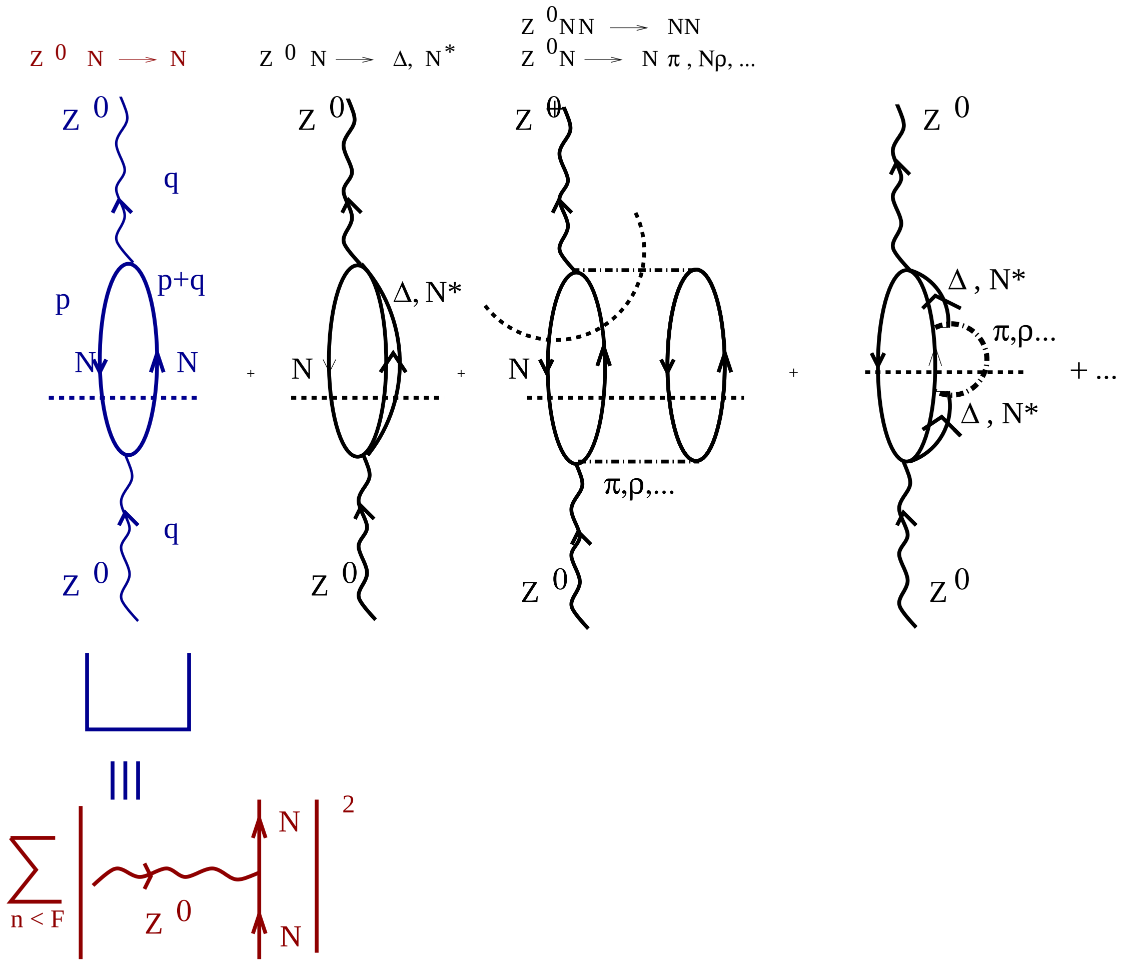
Self-energy of the Gauge Boson

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

We perform a Many Body expansion , where the relevant gauge boson absorption modes are systematically incorporated:

- Absorption by $\boxed{\textbf{one Nucleon}}$, pair of Nucleons, 3N
- Real and virtual (MEC) meson (π, ρ, $\cdots$) production
- Excitation of Δ or higher resonance degrees of freedom

Absorption Diagrams



$\nu_l A_Z \rightarrow l^- X$ cross section

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

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

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

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

The Hadronic Tensor

We find

$$W^{\mu\nu}_{s,a}(q) = -\frac{1}{2M^2}\int_0^\infty dr r^2 dp^3 F(q,p) A^{\mu\nu}_{s,a}(p,q)$$

Can be written in terms of the relativistic Lindhard function

$$\text{Im}\bar{U}^N_R(q) = 2\int \frac{d^3p}{(2\pi)^3}\frac{M}{E(\vec{p})}\frac{M}{E(\vec{p}+\vec{q})}\Theta(k^N_F(r) - |\vec{p}\,|)\Theta(q^0)$$
$$\Theta(|\vec{p}+\vec{q}\,| - k^N_F(r))(-\pi)\delta(q^0 + E(\vec{p}) - E(\vec{p}+\vec{q}\,))$$

- Relativistic *ph* propagator
- Includes Pauli Blocking effects

NC Quasielastic contribution

Z^0 absorption by one nucleon

$V - A$ current:

$$\langle p; \vec{p}\,' \, | j^\alpha(0) | n; \vec{p}\, \rangle = \bar{u}(p') \left[V^\alpha - A^\alpha \right] u(p)$$

$$V_N^\alpha = 2 \times \left(F_1^Z(q^2)\gamma^\alpha + \mathrm{i}\mu_Z \frac{F_2^Z(q^2)}{2M}\sigma^{\alpha\nu}q_\nu \right)_N$$

$$A_N^\alpha = \left(G_A^Z(q^2)\gamma^\alpha\gamma_5 + G_P^Z(q^2)q^\alpha\gamma_5 \right)_N$$

Form Factors

- Vector form factors

$$F_1^Z(q^2) = \pm F_1^V - 2\sin^2\theta_W F_1^N - \frac{1}{2}F_1^s$$
$$\mu_Z F_2^Z(q^2) = \pm \mu_V F_2^V - 2\sin^2\theta_W F_2^N - \frac{1}{2}\mu_s F_2^s$$

- Axial form factors

$$G_A^Z(q^2) = \pm G_A - G_A^s$$
$$G_P^Z(q^2) = \pm G_P - G_P^s$$

Parametrization

- Galster parametrization for E.-M. form factors
- Axial form factors

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

$$g_A = 1.257,\ M_A = 1049\,\text{MeV}$$

- Strange form factors

$$G_A^s(q^2) = \frac{g_A^s}{(1 - q^2/(M_A^s)^2)^2}$$

$$g_A^s = -0.15,\ M_A^s = 1049\,\text{MeV}$$

$$F_1^s = F_2^s = 0$$

1.2 – Further Nuclear Effects

- Correct Energy Balance
- Long Range Correlation (RPA)

Correct Energy Balance

Experimental Q value

$$\delta(q^0 + E(\vec{p}) - E(\vec{p} + \vec{q}\,)) \longrightarrow \delta(q^0 - \boxed{Q} + E(\vec{p}) - E(\vec{p} + \vec{q}\,))$$

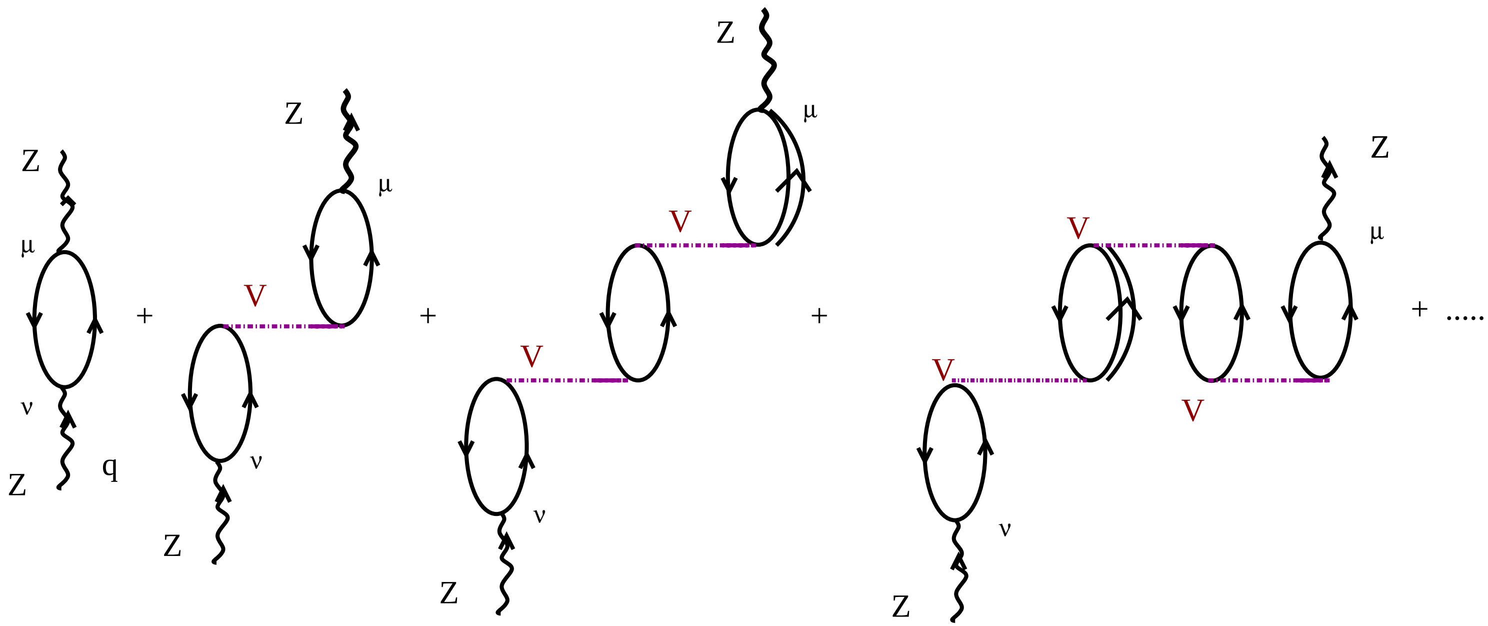
Q is the nucleon separation energy S_N

$$S_p = M(A - 1_{Z-1}) + M(p^+) - M(A_Z)$$

$$S_n = M(A - 1_Z) + M(n^0) - M(A_Z)$$

RPA Response

ph excitation $\longrightarrow$ series of ph and Δh excitations.



The ph interaction

We use a contact Landau-Migdal interaction

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

- Short Range Correlations (SRC)

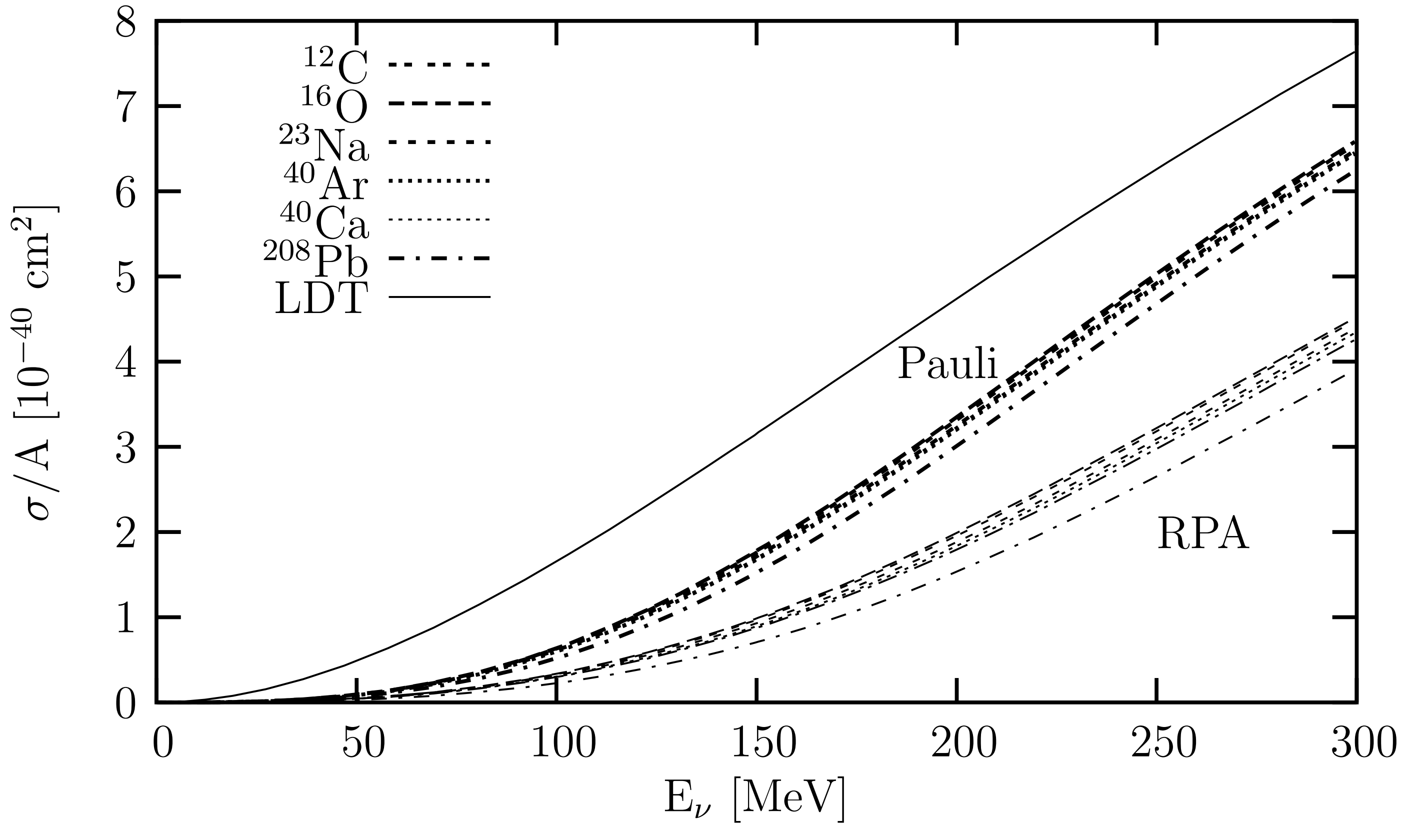
$$V(\vec{q}) \rightarrow \int \frac{d^3k}{(2\pi)^3} V(\vec{k})\Omega(\vec{q} - \vec{k})$$

- Δh excitations
- Crossed diagrams

E.Oset, H.Toki and W.Weise Phys.Rep. **83**:281,(1982)

Nuclear effects on NC inclusive cross section

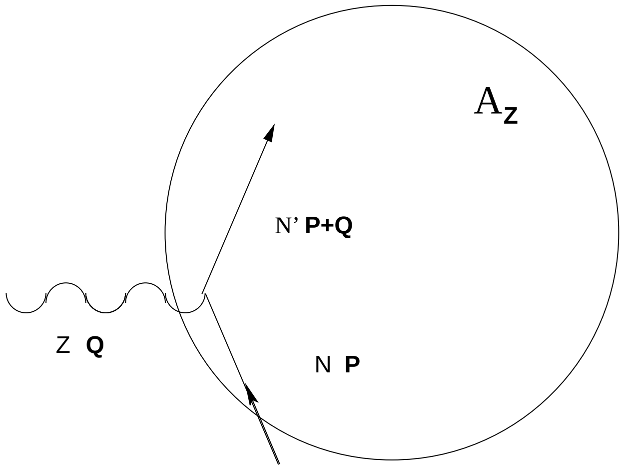
$\nu_l A_Z \rightarrow \nu_l X$



2 – Nucleon rescattering

Probability of a q^μ boson being absorbed at $\vec{r}$

$$d^5\sigma/d\Omega' dE' d^3r$$



... by a p^μ nucleon the nucleus (random Fermi momentum).

We simulate its trajectory through finite d length steps

$$d << \lambda$$

$\sigma^{N_1 N_2} \propto 1/\lambda$ induces new outgoing nucleons

Quasielastic NN collision

The probability of a N_1N_2 collision is considered at every step

A random Fermi sea nucleon is selected (secondary)

Kinematics are selected according with:

$$\hat{\sigma}^{N_1N_2} = \int d\Omega_{CM} \frac{d\sigma^{N_1N_2}}{d\Omega_{CM}} C_T(q,\rho)\Theta\left(\kappa - \frac{|\vec{P}\cdot\vec{p}_{CM}|}{|\vec{P}||\vec{p}_{CM}|}\right)$$

Medium polarization and Pauli blocking effects

Nucleon Propagation

Semiclassical aprrox. used to simulate finite length trajectories

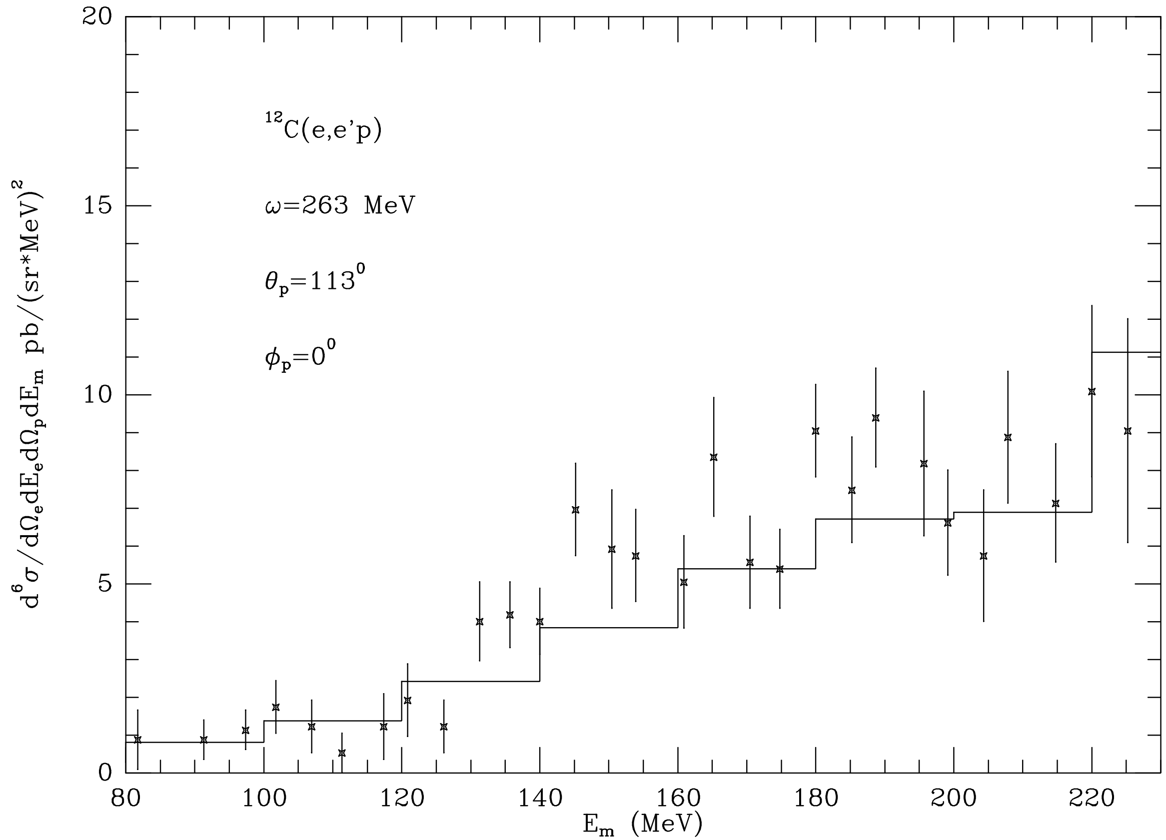
$$V(r) = V_\infty - \mathcal{E}(r) = -\frac{k_F^2(r)}{2M}$$

We keep track of all nucleons

3 – Results (Still Preliminar)

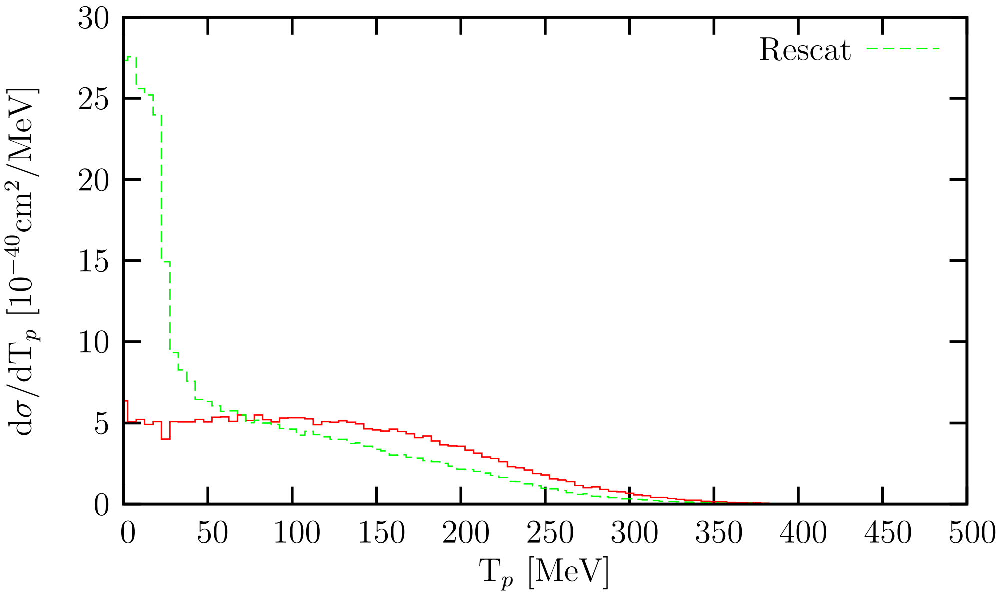
Predictions for QE neutrino and antineutrino integrated, **single and double differential cross sections** for different nuclei.

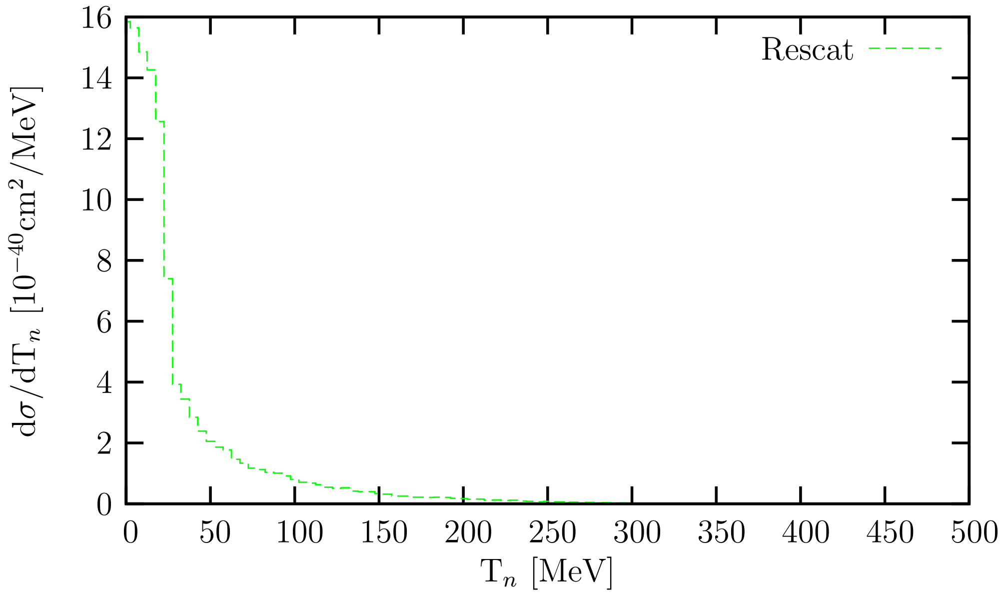
$(e, e'N)$



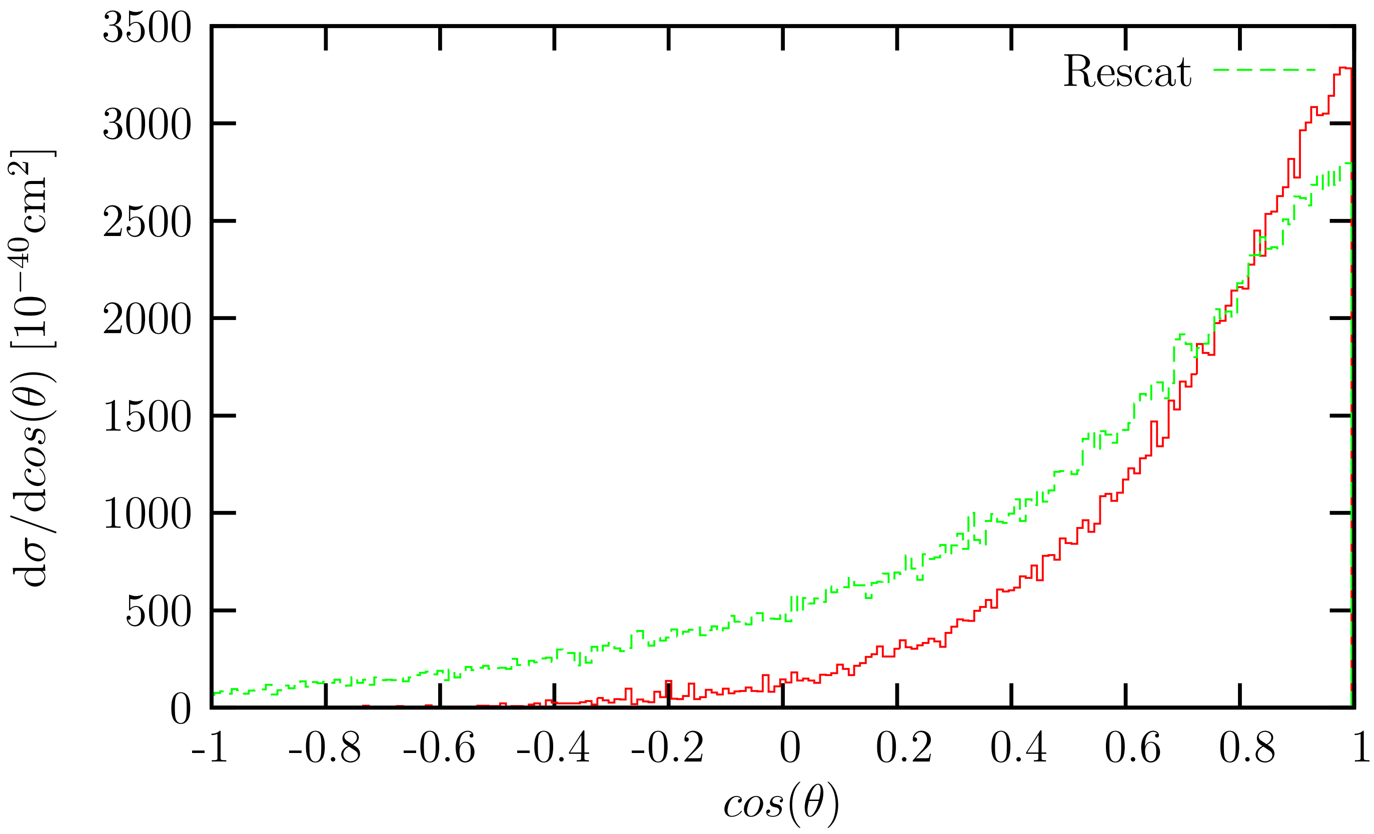
A.Gil, J.Nieves and E.Oset, Nucl.Phys. **A627**:599,(1997)

CC, E_ν=500 MeV $\quad {}^{40}Ar(\nu, N)$

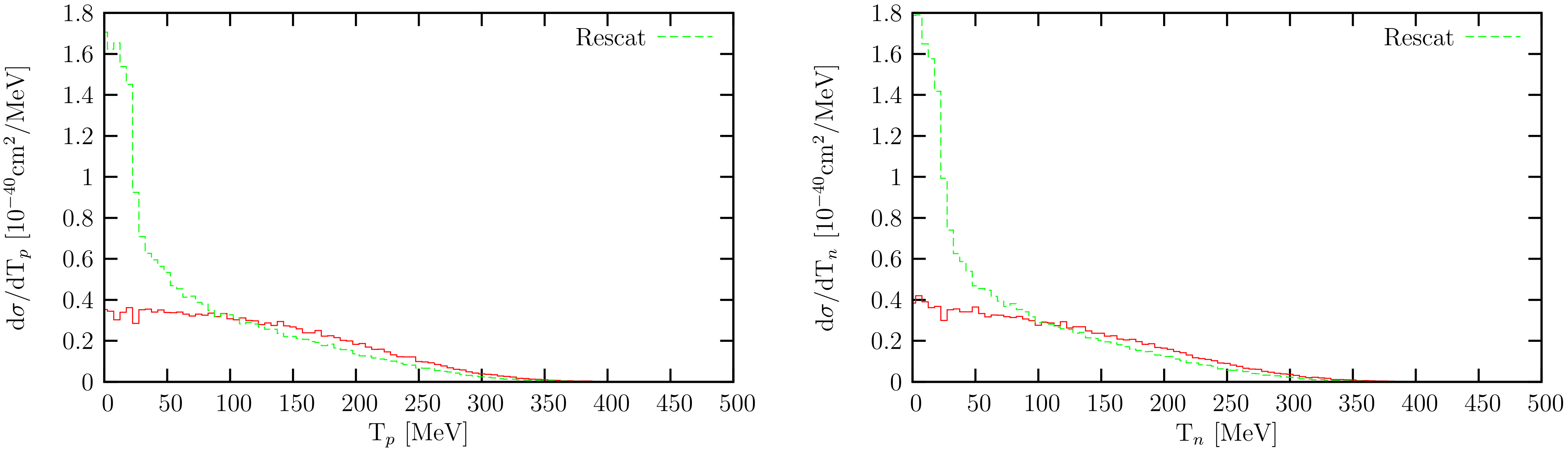




CC, E_ν=500 MeV $^{40}Ar(\bar{\nu}, p^+)$



NC E$_\nu$=500 MeV $^{16}O(\nu, N)$



4 – Outlook

- Contributions from resonances and MEC
- Systematic error dependence

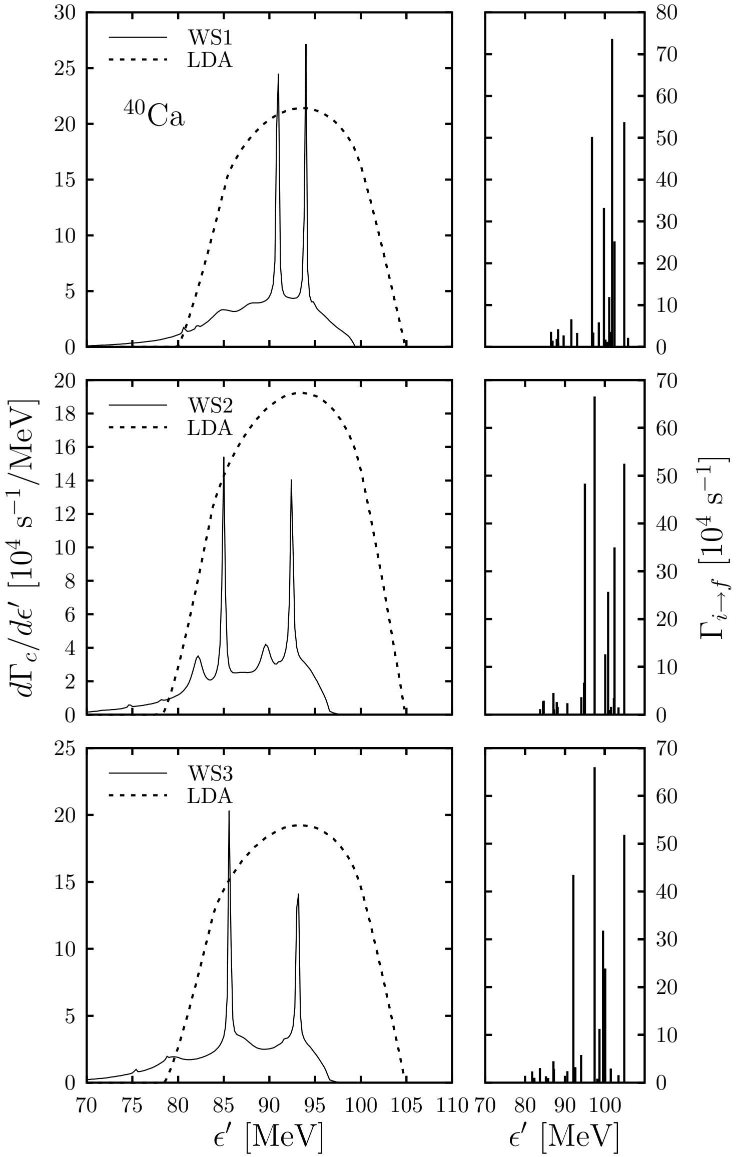
5 – Summary

- Many body approach to inclusive reactions in nuclei. It systematically accounts for RPA, SRC, $\Delta(1232)$.
- Extension takes into account nucleon observables.
- Sizeable nucleon rescattering effects.

SM vs FG

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.

J.E. Amaro, C.Maieron, J.Nieves and M.Valverde, EPJA, in press


WS1
LDA
^{40}Ca
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