Nuclear effects in neutrino-induced pion production

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Reference paper

PHYSICAL REVIEW C **109**, 024608 (2024)

Towards a more complete description of nucleon distortion in lepton-induced single-pion production at low-Q^2

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Theoretical predictions for lepton-induced single-pion production (SPP) on ^{12}C are revisited in order to assess the effect of different treatments of the current operator. On one hand we have the asymptotic approximation, which consists in replacing the particle four-vectors that enter in the operator by their asymptotic values, i.e., their values out of the nucleus. On the other hand we have the full calculation, which is a more accurate approach to the problem. We also compare with results in which the final nucleon is described by a relativistic plane wave, to rate the effect of the nucleon distortion. The study is performed for several lepton kinematics, reproducing the SPP contribution to the inclusive and semi-inclusive cross sections belonging to the low-Q^2 region (between 0.05 and 1 GeV^2), which is of special interest in charged-current (CC) neutrino-nucleus 1π production. The results of the SPP contribution to the inclusive electron cross section are compared with experimental data. We find nontrivial corrections comparable in size with the effect of the nucleon distortion, namely, corrections up to 6%, either increasing or diminishing the asymptotic prediction, and a shift of the distributions towards higher energy transfer. For the SPP contribution to the semi-inclusive cross section, we observe the correction to be prominent mainly at low values of the outgoing nucleon kinetic energy. Finally, for CC neutrino-induced $1\pi^+$ production, we find a reduction at low Q^2 with respect to both the plane-wave approach and the asymptotic case.

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MOTIVATION

Interaction mechanisms

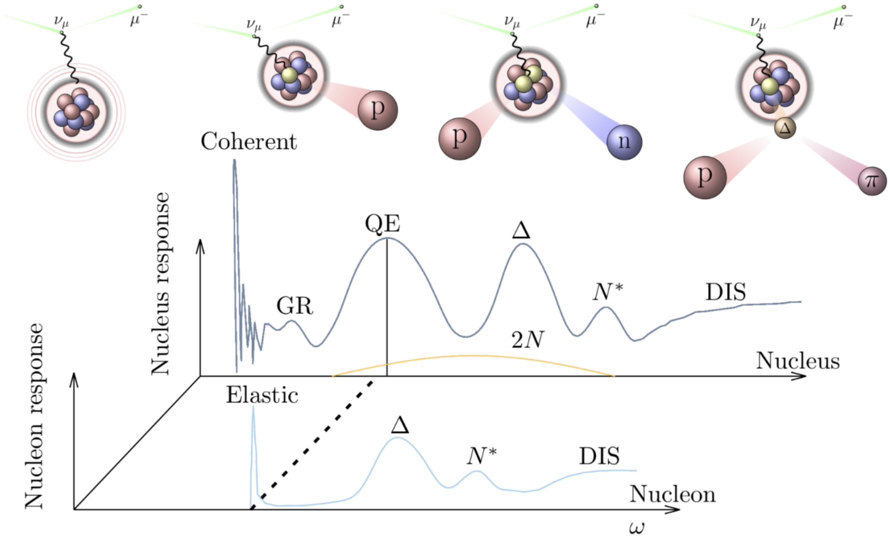
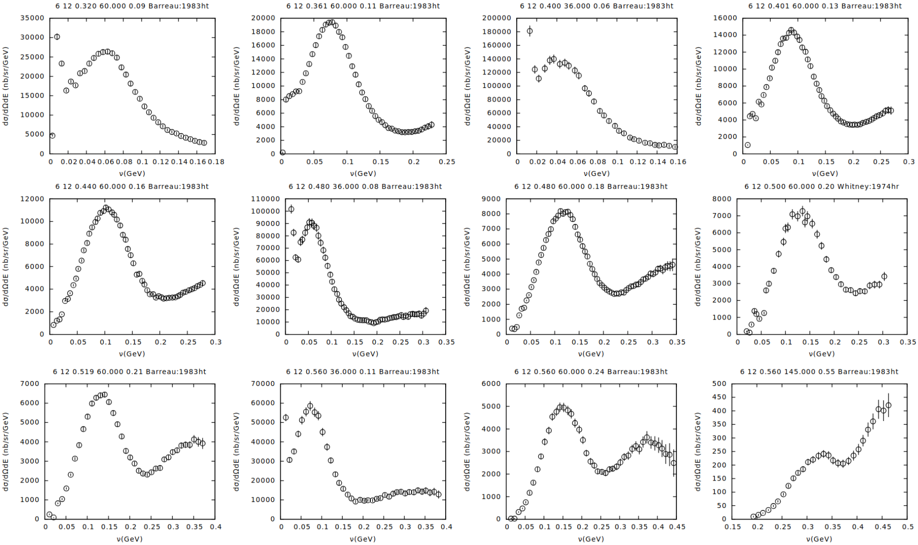


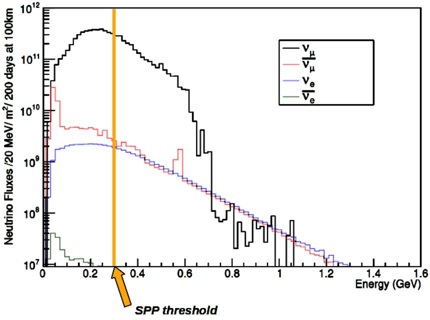
FIG. K. Niewczas

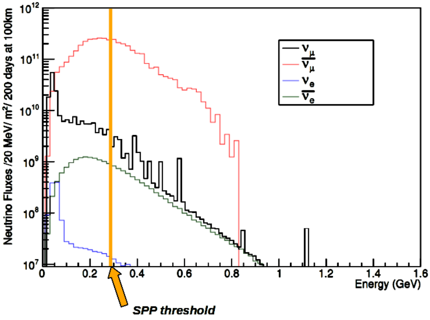
Interaction mechanisms

We see the QE and Δ peaks in $^{12}C(e, e')$ data... even for **ESSnuSB energies** !



SPP threshold @ ESSnuSB flux





From energy conservation

$$E_i - E_f = \omega = E_m + T_N + E_\pi \Rightarrow E_i = E_m + E_f + T_N + E_\pi$$

For $\nu_\mu/\bar{\nu}_\mu$ and ^{12}C (where all shells contribute)

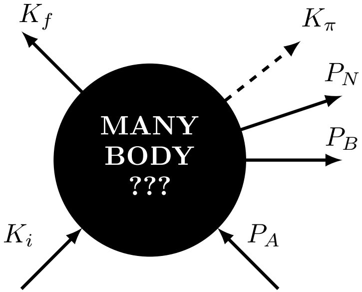
$$\min(E_i) = E_m + m_\mu + m_\pi \approx 290 \text{ MeV}$$

For the p-shell: $\min(E_i) \approx 260$ MeV

MODELING PION PRODUCTION ON NUCLEI

How do we model SPP on nuclei?

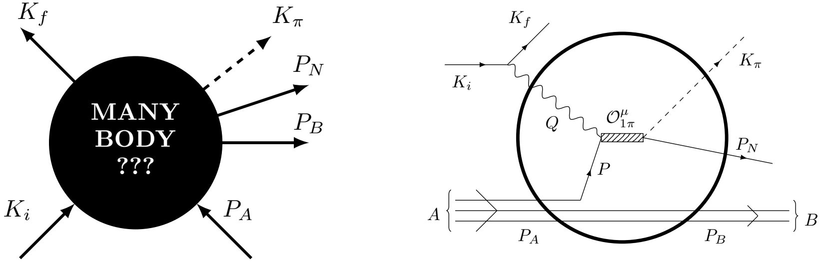
All the nuclear information is enclosed in the nuclear current J^μ



$$J^\mu = \langle N\pi, A-1|\mathcal{O}^\mu_{many-body}|A\rangle$$

How do we model SPP on nuclei?

All the nuclear information is enclosed in the nuclear current J^μ



The lepton only interacts with one nucleon inside the nucleus

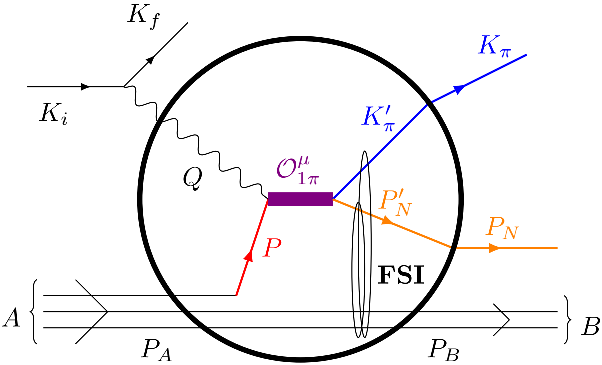
$$J^\mu = \langle N, A-1 | \mathcal{O}^\mu_{many-body} | A \rangle \xrightarrow{\textbf{IA}} J^\mu \propto \int \bar{\Psi}_F \, \phi^*_\pi \, \mathcal{O}^\mu_{one-body} \, \Psi_B$$

- $\mathcal{O}^\mu_{1\pi}$ from lepton-(free) nucleon interaction
- $\bar{\Psi}_F$, ϕ^*_π, and Ψ_B are single-particle wave functions
- Exchanged boson: $Q = (\omega, \mathbf{q})$

Impulse approximation and nuclear model

Most general: **both** pion and nucleon are **distorted waves**
They account for the **interaction with the residual nucleus**

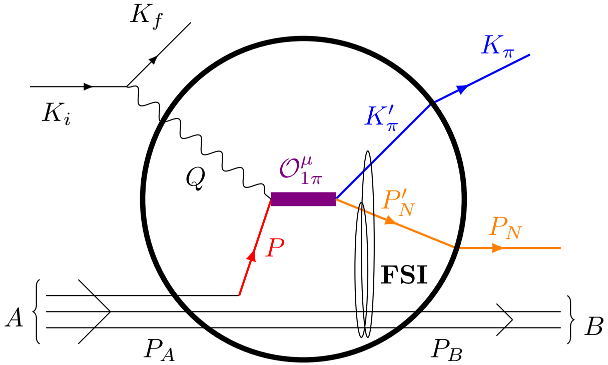
$$J^\mu \propto \int d\mathbf{p} \int d\mathbf{p}'_N \; \bar{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N)\, \phi^*_\pi(\mathbf{p} + \mathbf{q} - \mathbf{p}'_N, \mathbf{k}_\pi)\, \mathcal{O}^\mu_{1\pi}(Q, P'_N, P)\, \Psi_B(\mathbf{p})$$



Impulse approximation and nuclear model

Asymptotic (or local) approximation: $O^{\mu}_{1\pi}$ is evaluated **only once**

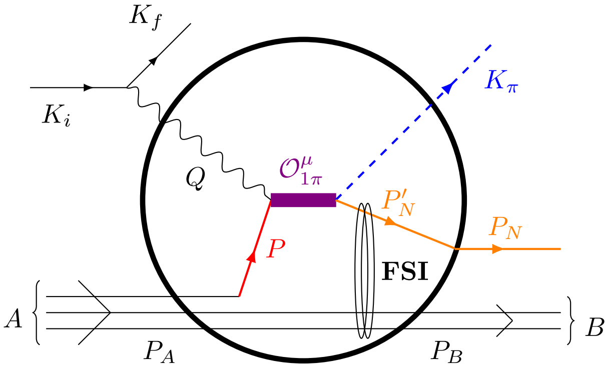
$$J^{\mu} \propto \int d\mathbf{p} \int d\mathbf{p}'_N \; \bar{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N)\, \phi^*_{\pi}(\mathbf{p}+\mathbf{q}-\mathbf{p}'_N, \mathbf{k}_{\pi})\, \boxed{\mathcal{O}^{\mu}_{1\pi}(Q, P_N, P)}\, \Psi_B(\mathbf{p})$$



Impulse approximation and nuclear model

The **pion** is a **plane wave**, the nucleon is still a distorted wave

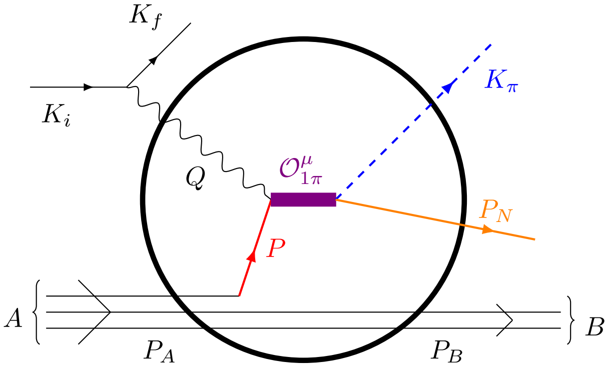
$$J^\mu \propto \frac{1}{\sqrt{2E_\pi}} \int d\mathbf{p}\ \bar{\Psi}_F(\mathbf{q}+\mathbf{p}-\mathbf{k}_\pi, \mathbf{p}_N)\ \mathcal{O}^\mu_{1\pi}(Q, P_N, P)\ \Psi_B(\mathbf{p})$$



Impulse approximation and nuclear model

Both **pion** and **nucleon** are **plane waves**

$$J^\mu \propto \sqrt{\frac{M_N}{2E_\pi E_N}}\,\bar{u}_F(\mathbf{p}_N, s_N)\;\mathcal{O}^\mu_{1\pi}(Q, P_N, P)\,\Psi_B(\mathbf{p}_N + \mathbf{k}_\pi - \mathbf{q})$$



To sum up...

$$\boxed{J^\mu \propto \int d\mathbf{p} \int d\mathbf{p}'_N \; \bar{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N)\, \phi^*_\pi(\mathbf{p}+\mathbf{q}-\mathbf{p}'_N, \mathbf{k}_\pi)\, \mathcal{O}^\mu_{1\pi}(Q, P'_N, P)\, \Psi_B(\mathbf{p})}$$

- Bound nucleon $\Psi_B(\mathbf{p})$ → Dirac + **RMF** potentials
- Final nucleon $\bar{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N)$ → Dirac **in the continuum** + **ED-RMF** potentials
- $\Psi_B(\mathbf{p})$ and $\bar{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N)$ are orthogonal → **Pauli Blocking** implemented !
- Pion $\phi^*_\pi(\mathbf{k}'_\pi, \mathbf{k}_\pi)$ → Klein-Gordon **in the continuum** + **suitable** optical potential [Work in progress]
- Operator $\mathcal{O}^\mu_{1\pi}(Q, P'_N, P)$

To sum up...

$$\boxed{J^\mu \propto \int d\mathbf{p} \int d\mathbf{p}'_N \; \bar{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N)\, \phi^*_\pi(\mathbf{p}+\mathbf{q}-\mathbf{p}'_N, \mathbf{k}_\pi)\, \mathcal{O}^\mu_{1\pi}(Q, P'_N, P)\, \Psi_B(\mathbf{p})}$$

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- Operator $\mathcal{O}^\mu_{1\pi}(Q, P'_N, P)$

Fully **relativistic** and **quantum mechanical** framework

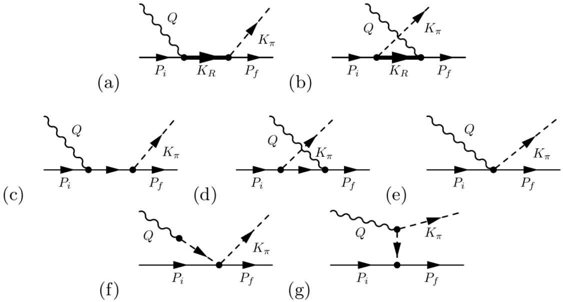
Realistic bound and final states

Can take into account **nuclear effects** consistently

PION PRODUCTION OFF THE NUCLEON

π production model: quick overview

Resonances + ChPT $N\pi$-Lagrangian

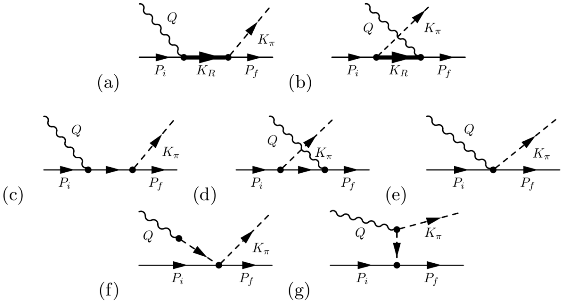


Resonances: $P_{33}(1232)$ (Δ-baryon), $D_{13}(1520)$, $S_{11}(1535)$, $P_{11}(1440)$
Works up to $\sqrt{s} = W < 1.4$ GeV $\rightarrow$ Extended via Regge Theory

PRD **76**, 033005 (2007)
PRD **95**, 113007 (2017)

π production model: quick overview

Resonances + ChPT $N\pi$-Lagrangian



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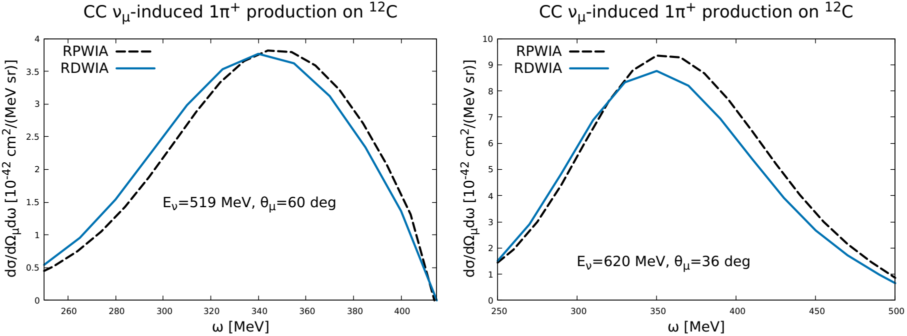
PRD **76**, 033005 (2007)
PRD **95**, 113007 (2017)

Matthias Hooft (UGent) is working on the **unitarization**... Stay tuned !

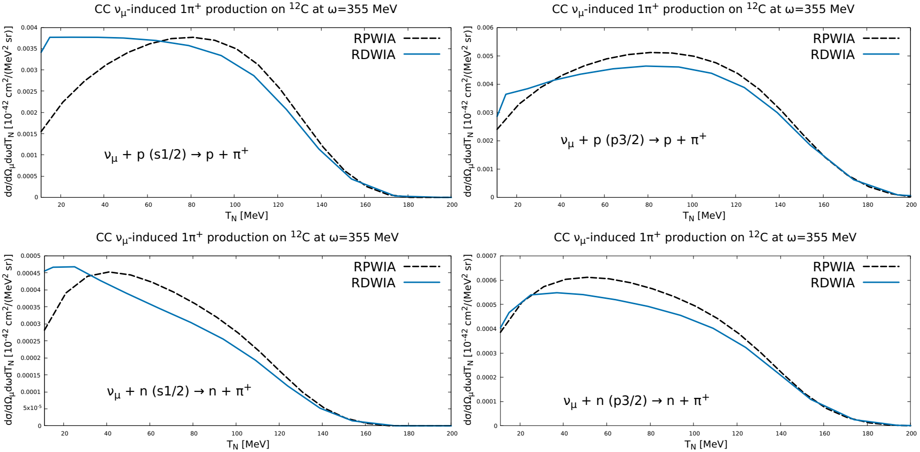
NUCLEAR EFFECTS IN THE FINAL STATE

Distortion of the final nucleon



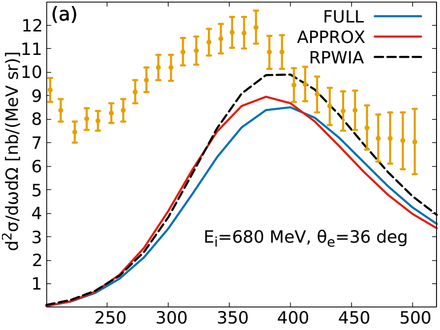
- The final nucleon interacts with the residual nucleus
- Pauli blocking naturally implemented
- Shift to lower energies
- Reduction of the strength
- Distortion of the final hadrons is important at low and intermediate energies

Distortion of the final nucleon



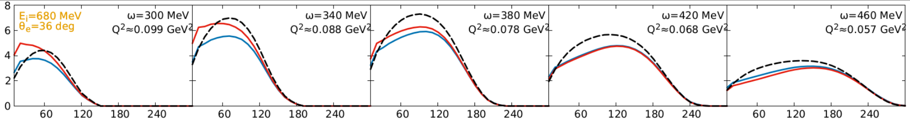
- Big effect at low-T_N
- Reduction at medium-T_N
- At high T_N (low-T_π) one expects **pion distortion** to play a role

Beyond the asymptotic approximation



ω [MeV]

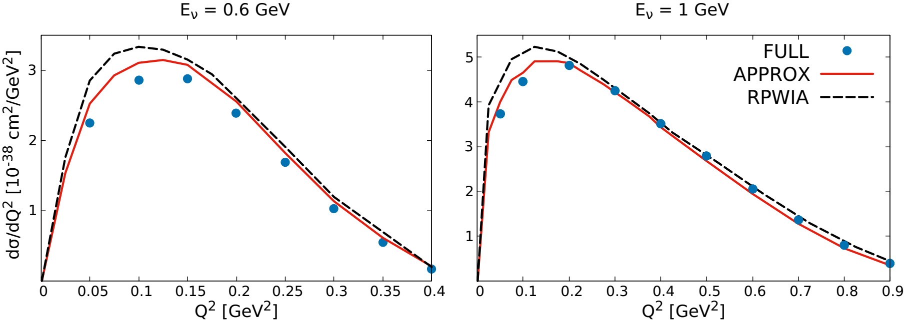
- Pion electroproduction on ^{12}C
- Nucleon distortion
- Pion is a plane wave
- No asymptotic approximation in $\mathcal{O}^{\mu}_{1\pi}$
- The effect of the nucleon distortion is even greater at energies below ~ 1 GeV



$\frac{d^3\sigma}{d\omega d\Omega dT_N}$ [10^{-2}nb/(MeV^{2}sr)] vs. T_N [MeV]

PRC **109**, 024608 (2024)

Beyond the asymptotic approximation: neutrinos



- π^+ neutrinoproduction on ^{12}C
- Nucleon distortion, pion is a plane wave
- No asymptotic approximation in $\mathcal{O}^{\mu}_{1\pi}$
- The effect of the nucleon distortion is even greater at energies below ~ 1 GeV

PRC **109**, 024608 (2024)

PIONS AT VERY LOW ENERGY

Very low energy... Hyperons !

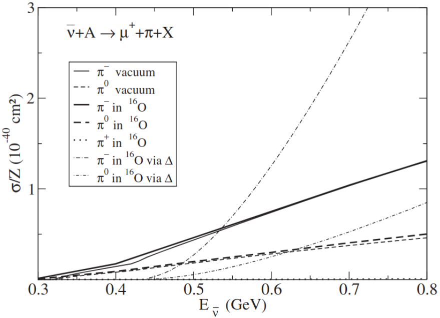


FIG. 10. Cross section for π production via an intermediate hyperon induced by a muonic antineutrino divided by the number of protons as a function of the antineutrino energy. Results compared with pions produced via Δ excitation.

PRD **74**, 053009 (2006)
PRD **110**, 030001 (2024)

- The pion is produced after hyperon (Y) excitation.
- In the low-energy region $\Delta S = 0$ and $\Delta S = 1$ processes are comparable
- Only antineutrino reactions in the $\Delta S = 1$ sector are allowed:

$$\bar{\nu}_l + p \rightarrow l^+ + \Lambda$$
$$\bar{\nu}_l + p \rightarrow l^+ + \Sigma^0$$
$$\bar{\nu}_l + n \rightarrow l^+ + \Sigma^-$$

- Λ and Σ^- decay into $N\pi$. Σ^0 decays into $\Lambda\gamma$.
- Probabilities of around 100%.

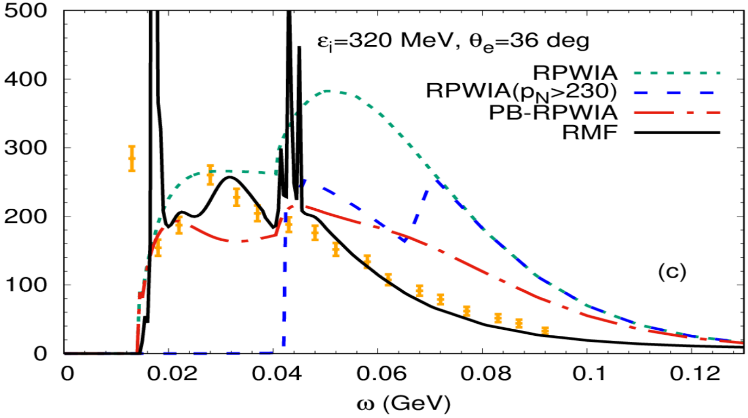
Final remarks

- Pion production may constitute an **important background** at ESSnuSB
- **Nuclear effects** are important when modeling neutrino-nucleus interactions
- **Final state interactions** via nucleon and pion distortions are paramount at low incoming energies (< 1 GeV)
- Only within a **relativistic quantum mechanical framework** a consistent address of these effects can be achieved
- **At very low energy**, pion production coming from **hyperons** (Y) may compete with pion production from the Δ

THANK YOU SO MUCH
FOR YOUR ATTENTION!

B A C K U P S L I D E S

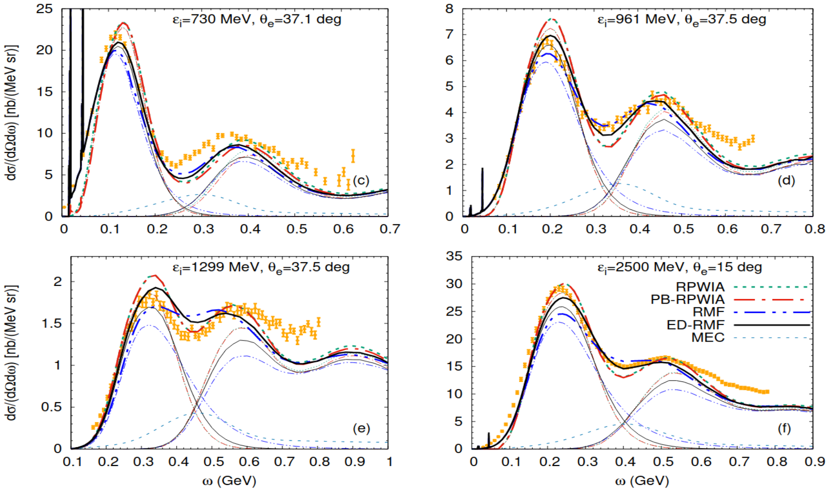
RDWIA at low-energies in the QE-regime



QE on $^{12}C(e,e')$

Phys. Rev. C **100** 045501 (2019)

QE+SPP results on $^{12}C(e, e')$



Phys. Rev. C **100** 045501 (2019)

$$\mathcal{L} = \bar{\Psi}\left(i\gamma_\mu\partial^\mu - M\right)\Psi + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - U(\sigma)$$
$$- \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\mathbf{R}_{\mu\nu}\mathbf{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\rho^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$- g_\sigma\bar{\Psi}\sigma\Psi - g_\omega\bar{\Psi}\gamma_\mu\omega^\mu\Psi - g_\rho\bar{\Psi}\gamma_\mu\boldsymbol{\tau}\rho^\mu\Psi - g_e\frac{1+\tau_3}{2}\bar{\Psi}\gamma_\mu A^\mu\Psi.$$

$$\Big[-i\boldsymbol{\alpha}\cdot\boldsymbol{\nabla} + V(r) + \beta(M + S(r))\Big]\Psi_i(\boldsymbol{r}) = E_i\Psi_i(\boldsymbol{r})$$

Regge Theory

- For increasing energies → higher order contributions
- RTh: Infinite summation over all partial waves in the $t-$channel amplitude (→ contour integral in complex angular momentum space)
- A Regge pole corresponds to a pole in that complex space
- Regge pole ≡ whole family of $t-$channel contributions
- Regge propagator (with Regge trajectory) replaces the previous one

$$P_\pi(t,s) = -\alpha'_\pi \varphi_\pi(t) \Gamma[-\alpha_\pi(t)] (\alpha'_\pi s)^{\alpha_\pi(t)}$$

$$\alpha_\pi(t) = \alpha'_\pi (t - m_\pi^2) \quad , \quad \Gamma[-\alpha_\pi(t)] = \frac{-\pi}{\sin[\pi \alpha_\pi(t)] \Gamma[-\alpha_\pi(t)+1]}$$

Nucl. Phys. A **627**, 645 (1997)

In medium modification of the Δ

- Delta propagator:

$$S_{\Delta,\alpha\beta} = \frac{-(\not{K}_\Delta + M_\Delta)}{K_R^2 - M_\Delta{}^2 + iM_\Delta \Gamma_{\text{width}}} \times f_{\alpha\beta}(M_\Delta, K_\Delta)$$

$$\Gamma^{\text{free}}_{\text{width}} \longrightarrow \Gamma^{\text{in-medium}}_{\text{width}} = \Gamma_{\text{Pauli}} - 2\,\mathcal{I}(\Sigma_\Delta)$$
$$M^{\text{free}}_\Delta \longrightarrow M^{\text{in-medium}}_\Delta = M^{\text{free}}_\Delta + \mathcal{R}(\Sigma_\Delta)$$

- Γ_{Pauli} is the free width corrected by Pauli blocking of the final nucleon
- Fixed $\rho/\rho_0 = 0.75$
- Free $\Delta\pi N$-decay constant may be modified: $f_{\Delta\pi N} \longrightarrow f^{\text{in-medium}}_{\Delta\pi N}$
- $\Delta\Gamma = \Gamma^{\text{in-medium}} - \Gamma^{\text{free}}$, $W = \sqrt{s}$
- Chen&Lee: $\Sigma_\Delta = -40 - i30$

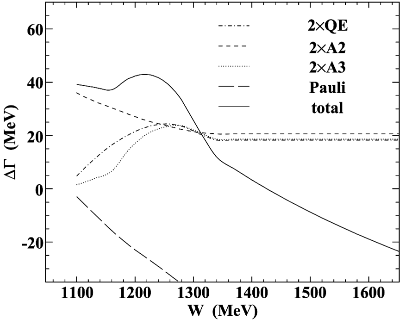


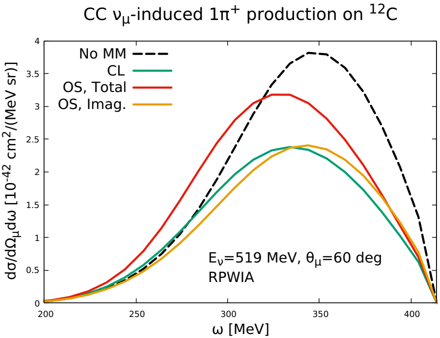
FIG. C. Praet, PhD Thesis, UGent (2009)

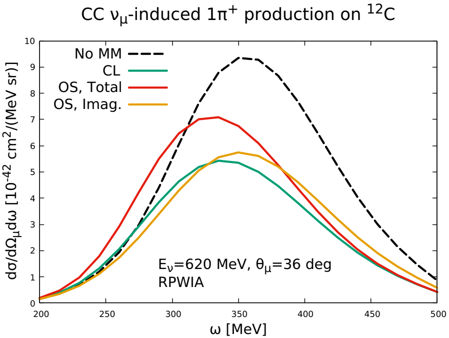
$$-\mathcal{I}(\Sigma_\Delta) = C_{QE}(\rho/\rho_0)^\alpha + C_{A2}(\rho/\rho_0)^\beta + C_{A3}(\rho/\rho_0)^\gamma \quad , \quad \mathcal{R}(\Sigma_\Delta) = 53\ (\rho/\rho_0)\ \text{MeV}$$

In medium modification of the Δ

- Delta propagator: $S_{\Delta,\alpha\beta} = \frac{-(\not{K}_\Delta + M_\Delta)}{K_R^2 - {M_\Delta}^2 + i M_\Delta \Gamma_{\text{width}}} \times f_{\alpha\beta}(M_\Delta, K_\Delta)$

$$\Gamma^{\text{free}}_{\text{width}} \to \Gamma^{\text{in-medium}}_{\text{width}} = \Gamma_{\text{Pauli}} - 2\,\mathcal{I}(\Sigma_\Delta) \quad , \quad M^{\text{free}}_\Delta \to M^{\text{in-medium}}_\Delta = M^{\text{free}}_\Delta + \mathcal{R}(\Sigma_\Delta)$$





- CL (Chen & Lee) → constant values for Σ_Δ
- OS (Oset & Salcedo) → constant value for $\mathcal{R}(\Sigma_\Delta)$. Parametrization for $\mathcal{I}(\Sigma_\Delta)$
- Reduction of the strength, shift to lower energies when $\mathcal{R}(\Sigma_\Delta)$ is included

NPA 468, 631 (1987)
NPA 554, 509 (1993)

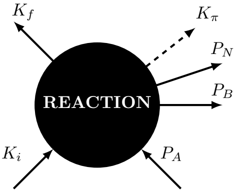
Independent variables and cross section

Lepton-induced SPP on nuclei: $l + A \longrightarrow l' + B + N + \pi$

Counting independent variables

4×6 particles	+24
four-mom. conservation	−4
5×on-shell ($E^2 = p^2 + m^2$)	−5
Target at rest	−3
Fixed projectile direction	−2
Fixed incoming energy	−1

$$\frac{d^9\sigma}{dE_f d\Omega_f \; dE_N d\Omega_N \; dE_\pi d\Omega_\pi} \propto L_{\mu\nu} H^{\mu\nu}$$



Four-momenta of every actor

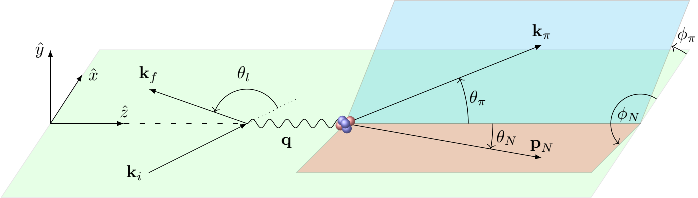
$l \to K_i$	$A \to P_A$	$l' \to K_f$	$B \to P_B$	$N \to P_N$	$\pi \to K_\pi$
$(E_i, \mathbf{k}_i)$	$(m_A, \mathbf{0})$	$(E_f, \mathbf{k}_f)$	$(E_B, \mathbf{p}_B)$	$(E_N, \mathbf{p}_N)$	$(E_\pi, \mathbf{k}_\pi)$

PoS(NuFACT2018)086

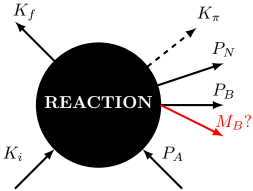
Kinematics of SPP on nuclei

Nothing depends on ϕ_l

Is the residual system **excited**?



$$\frac{d^9\sigma}{dE_f\, d\cos\theta_f\;\, dE_N d\Omega_N\;\, dE_\pi d\Omega_\pi\;\, dE_m} \propto \rho(E_m) L_{\mu\nu} H^{\mu\nu}$$

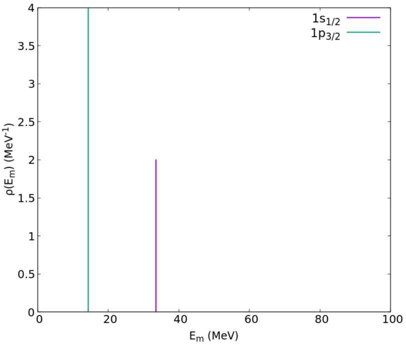


- Energy conservation: $\omega + m_A = E_B + E_N + E_\pi$
- Mom. conservation: $\mathbf{q} = \mathbf{p}_B + \mathbf{p}_N + \mathbf{k}_\pi$
- Mass of the residual system: $m_B = E_m + m_A - M$
- Nucleon binding energy: $E_\kappa = E_m$

Independent particle shell model

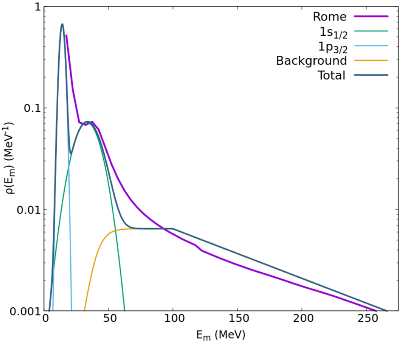
Let's take ^{12}C:

- In a pure shell model $\rho(E_m) = \delta(E_m - E_\kappa)$



$N_s = \mathbf{2}$ and $N_p = \mathbf{4}$

- More realistic approach: spectral function $S(E_m, p_m)$



$N_s = \mathbf{1.8}$ and $N_p = \mathbf{3.3}$
$N_{BG} = \mathbf{0.9}$ (SRC)

FIGS. Tania Franco-Munoz