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EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

The Valencia model for neutrino-nucleus interactions

Luis Alvarez Ruso

IFIC INSTITUT DE FÍSICA CORPUSCULAR

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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT ID VALÈNCIA

Valencia

From Wikipedia, the free encyclopedia

This article is about the city in Spain. For other uses, see Valencia (disambiguation).

Valencia (/vəˈlɛnsiə/; Spanish: [baˈlenθja]), officially **València** (Valencian: [vaˈlensia]),[4] on the east coast of Spain, is the capital of the autonomous community of Valencia and the third-largest city in Spain after Madrid and Barcelona, with around 800,000 inhabitants in the administrative centre. Its urban area extends beyond the

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Introduction

- Valencia: IFIC (UV, CSIC)
  - Oset, Vicente Vacas, Nieves...
  - Interactions of particles with nucleons and nuclei
    - E.g. with electroweak probes:
      - $\gamma^{(*)}$, $W^{\pm}$, Z N $\rightarrow$ N', N' π, N' π π, ...
    - Incoherent (semi-)inclusive scattering in nuclei
    - Coherent particle production
  - Few-GeV/intermediate energy region: hadronic degrees of freedom

Introduction

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    - Coherent particle production
  - Few-GeV/intermediate energy region: hadronic degrees of freedom

  - First application to neutrino interactions:

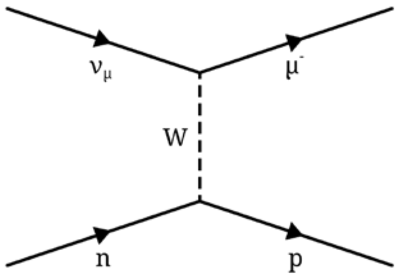
Quasielastic neutrino (anti-neutrino) reactions in nuclei and the axial vector form-factor of the nucleon

S. K. Singh, E. Oset, NPA542 (1992)

Elementary processes

- QE scattering

$$
\begin{aligned}
\text{CCQE}: \nu(k) + n(p) &\rightarrow l^-(k') + p(p') \\
\bar{\nu}(k) + p(p) &\rightarrow l^+(k') + n(p') \\
\text{NCE}: \nu(k) + N(p) &\rightarrow \nu(k') + N(p') \\
\bar{\nu}(k) + N(p) &\rightarrow \bar{\nu}(k') + N(p')
\end{aligned}
$$



$$\mathcal{M} = \frac{G_F \cos\theta_C}{\sqrt{2}} l^\alpha J_\alpha$$

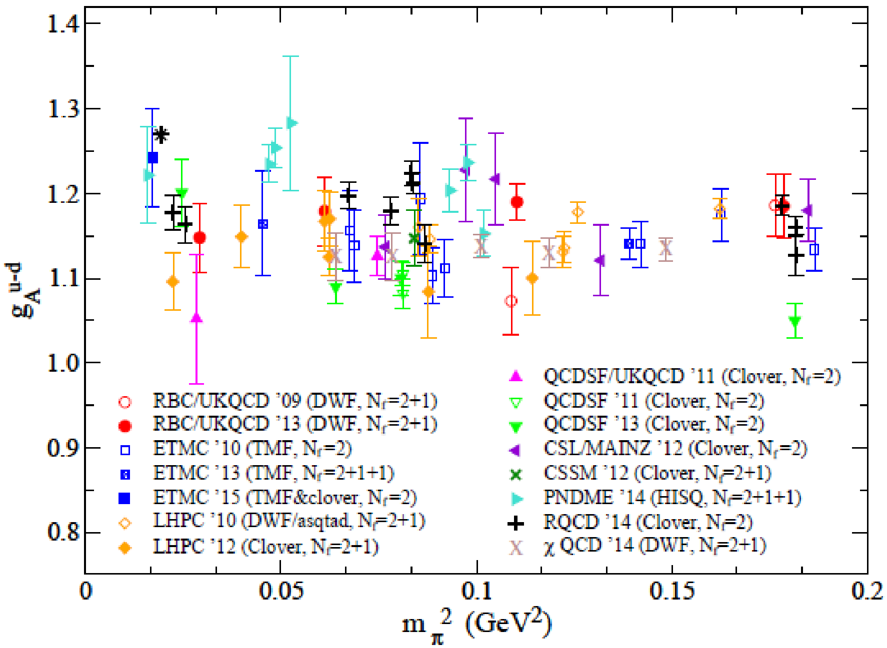
$$J_\alpha = \bar{u}(p') \left[\gamma_\alpha F_1^V + \frac{i}{2M} \sigma_{\alpha\beta} q^\beta F_2^V + \gamma_\mu \gamma_5 F_A + \frac{q_\mu}{M} \gamma_5 F_P \right] u(p)$$

- Vector form factors: $F_{12}^V = F_{12}^p - F_{12}^n$ $\leftarrow$ isospin symmetry
- Axial form factors:

$$F_A(Q^2) = g_A F(Q^2)\,,\ F_P(Q^2) = \frac{2M^2}{Q^2 + m_\pi^2} F_A(Q^2)\,,\ Q^2 = -q^2 > 0$$

F_A & LQCD

- g_A : lower than exp. values have been recurrently obtained



Constantinou, PoS CD15 (2015) 009

- Recent progress:
  - improved algorithms for a careful treatement of excited states
  - low pion masses
  - A per-cent-level determination of the nucleon axial coupling from QCD

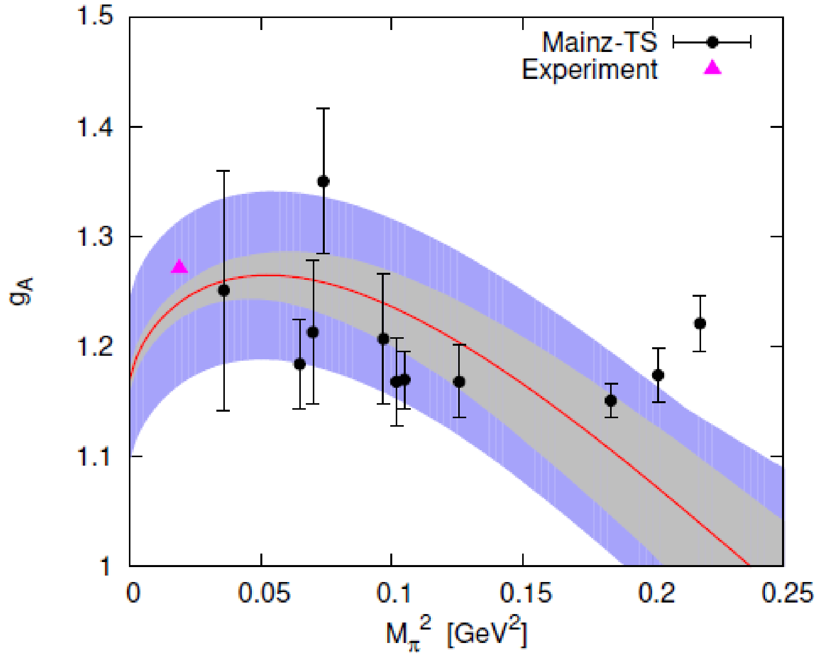
    Chang et al., Nature 558 (2018)

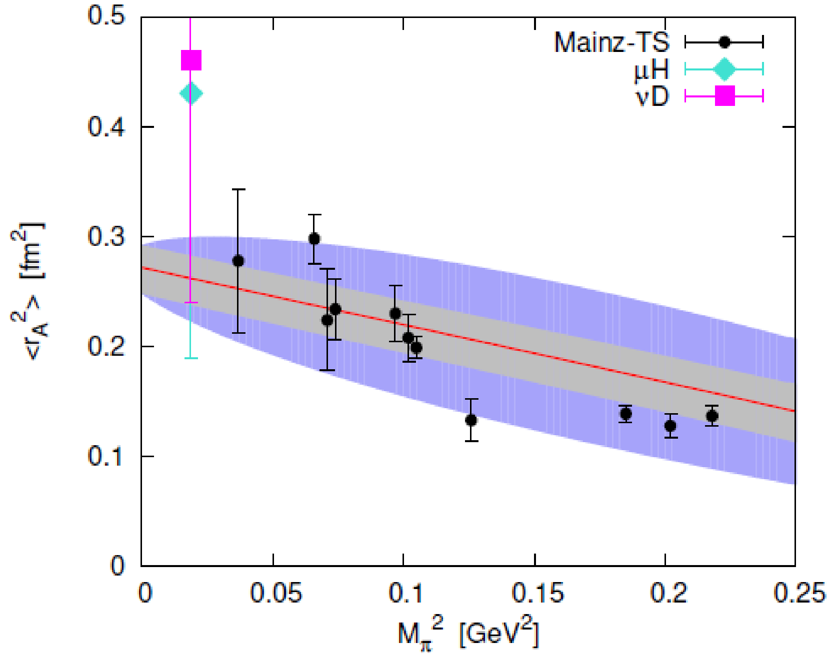
F_A & LQCD

- Recent progress:

  Alexandrou et al., PRD 96 (2017)
  Capitani et al., arXiv:1705.06186
  Gupta et al., PRD 96 (2017)

- Baryon ChPT analysis: Yao, LAR, Vicente Vacas, PRD 96 (2017)
  - $O(p^3)$, $Q^2 < 0.36$ GeV^2, 130 MeV $< M_\pi <$ 473 MeV, explicit $\Delta(1232)$





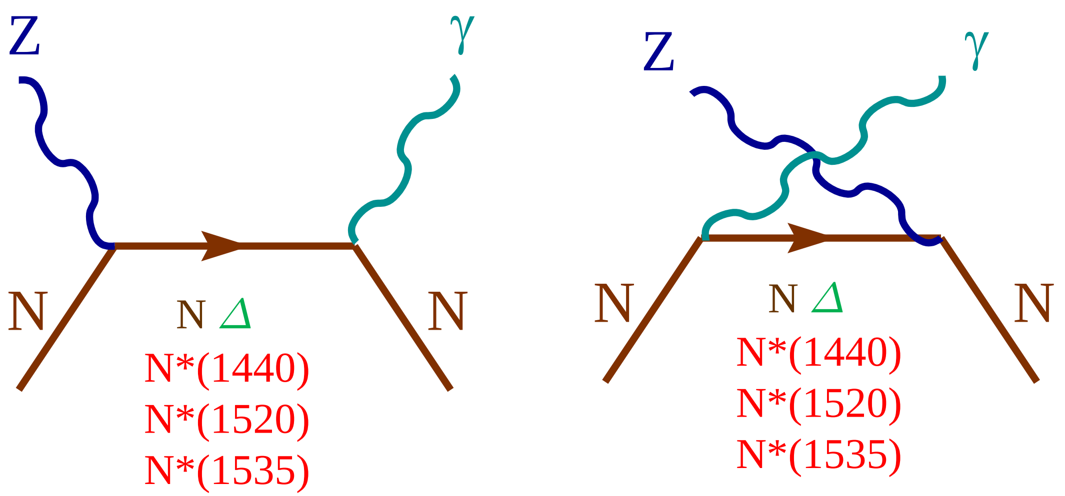
  - $g_A = 1.237(74)$, $\langle r_A^2 \rangle = 0.263(38)$ fm^2

Elementary processes

- Meson production: $\nu_l \, N \to l \, N' \, \pi$ $\leftarrow$ Eli's talk on Monday

  $\nu_l \, N \to l \, N' \, \eta$ Alam, LAR, Vicente Vacas, in preparation

- NC photon emission: $\nu_l \, N \to \nu_l \, N' \, \gamma$ Wang, LAR, Nieves, PRC89 (2014)



- Weak vector and EM N, N-Δ and N-N^* form factors extracted from electron scattering experiments

Elementary processes

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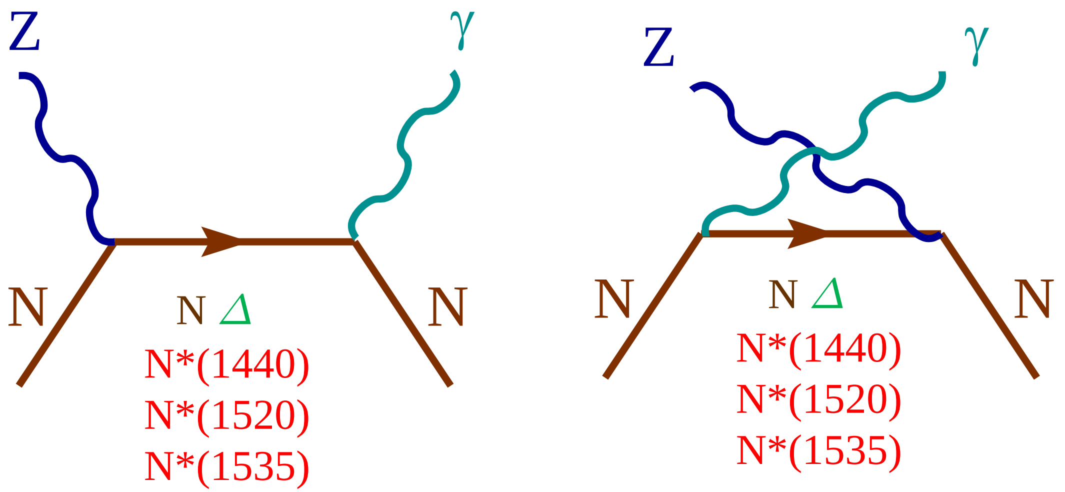
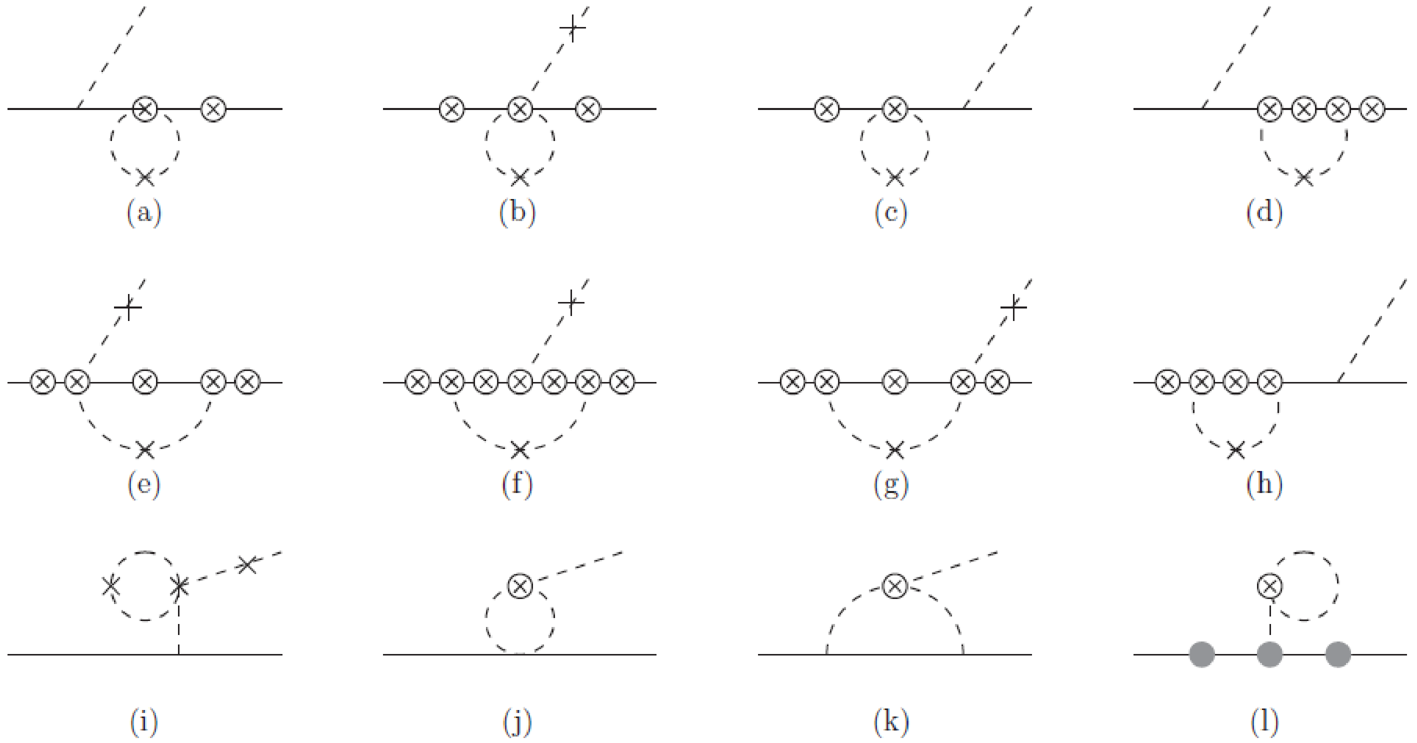


- Weak axial N, N-Δ and N-N* form factors:
  - (off-)diagonal Goldberger-Treiman relations for leading couplings
    - q^2 dependence: dipole
      - N-Δ : consistent with $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$ ANL,BNL data
      - N-N*: estimated (M_A = 1 GeV)

Weak pion production in BChPT

- Yao, LAR, Hiller, Vicente Vacas, PRD 98 (2018);
  Yao, LAR, Vicente Vacas, arXiv:1901.00773, PLB (2019)
- First comprehensive study in ChPT
- $O(p^3)$ in EOMS regularization scheme
- Explicit $\Delta(1232)$, in the δ-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$



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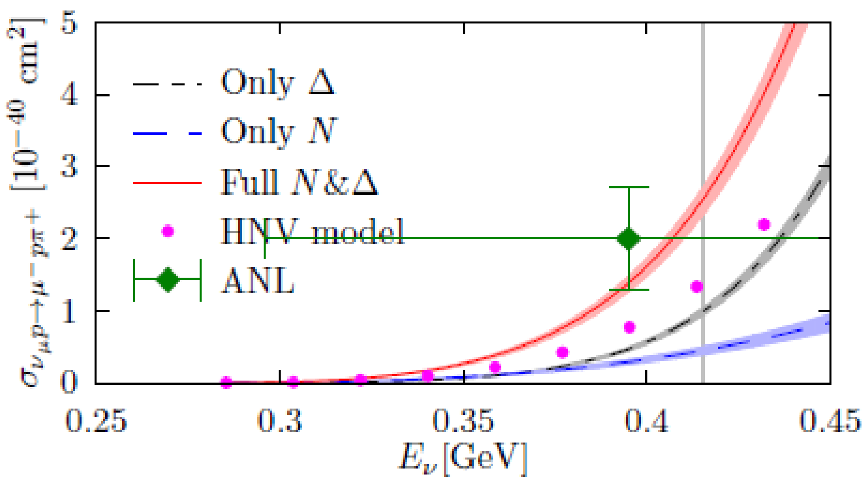
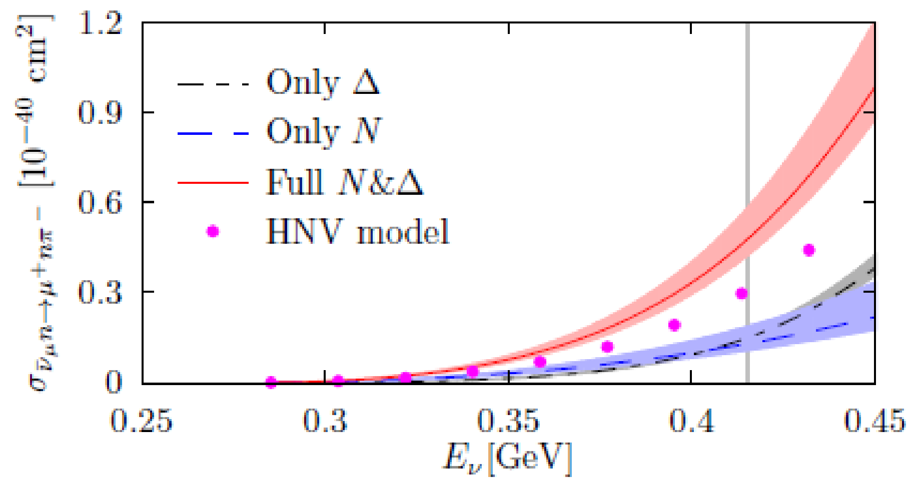
- Valid only close to threshold
- Benchmark for phenomenological models





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- Explicit $\Delta(1232)$, in the δ-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$

- LECs :
  - 22 in total (CC case)
  - 7 unknown (but not very relevant)
    - 4 of them can be extracted from pion electroproduction
  - information about remaining 3 LEC could be obtained from new close-to-threshold measurements of ν-induced π production on protons

Elementary processes

- Strangeness production
- ΔS = 1
- Kaon: $$\begin{aligned} \nu_l\, p &\to l^-\, K^+\, p \\ \nu_l\, n &\to l^-\, K^0\, p \\ \nu_l\, n &\to l^-\, K^+\, n \end{aligned}$$

Alam, Ruiz Simo, Athar, Vicente Vacas, PRD82 (2010)

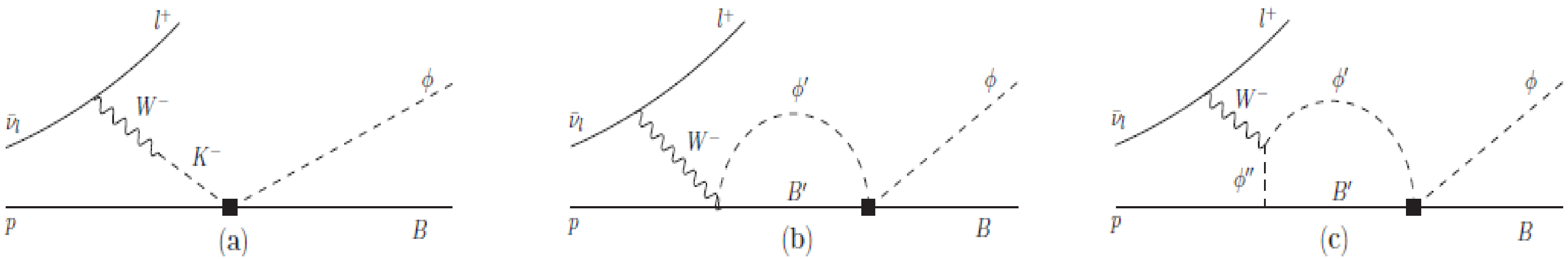
  - Background for proton decay p $\to \nu$ K^+

Elementary processes

- Strangeness production
- ΔS = -1 :
  - Hyperon $$\bar{\nu}_l \, p \rightarrow l^+ \, \Sigma^0 (\Lambda)$$ $$\bar{\nu}_l \, n \rightarrow l^+ \, \Sigma^-$$ $\leftarrow$ Asia's talk on Tue
    - Additional source of pions: Y $\rightarrow$ N π
  - antiKaon: $$\bar{\nu}_l \, p \rightarrow l^+ \, K^- \, p$$ $$\bar{\nu}_l \, p \rightarrow l^+ \, \bar{K}^0 \, n$$ $$\bar{\nu}_l \, n \rightarrow l^+ \, K^- \, n$$ Alam, Ruiz Simo, Athar, Vicente Vacas, PRD85 (2012)
  - $\Sigma \, \pi$: $$\bar{\nu}_l \, p \rightarrow l^+ \, \Sigma^0 \, \pi^0$$ $$\bar{\nu}_l \, p \rightarrow l^+ \, \Sigma^+ \, \pi^-$$ $$\bar{\nu}_l \, p \rightarrow l^+ \, \Sigma^- \, \pi^+$$

Elementary processes

- Strangeness production
- $\bar{\nu}_l \, p \rightarrow l^+ \, \Sigma \, \pi$
- Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)



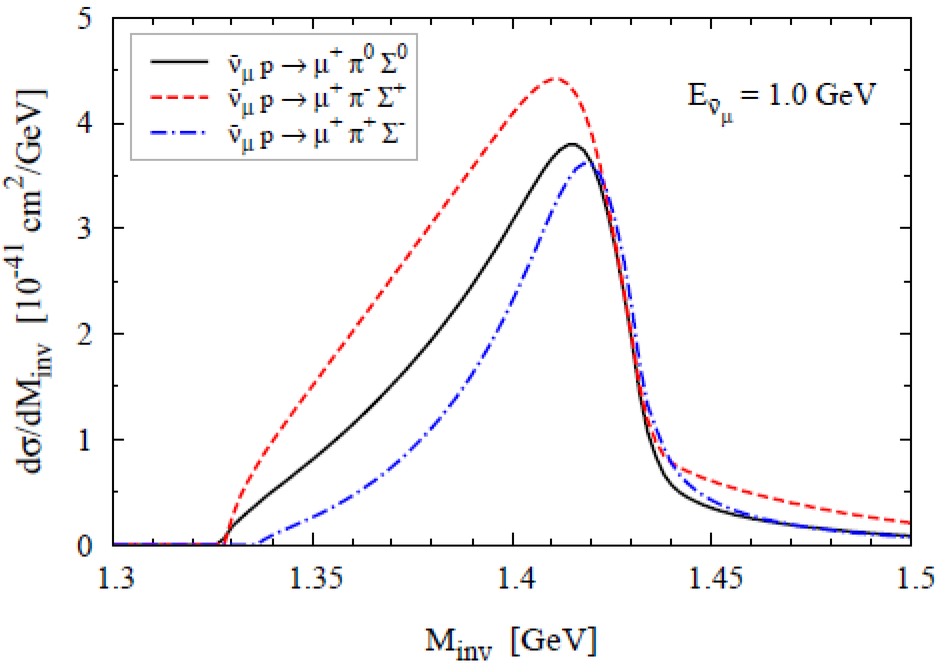
- T: Solution of the Bethe-Salpeter eq. in coupled channels

$$T = V + VGT = [1 - VG]^{-1} V$$

- V: from leading order chiral Lagrangian

Elementary processes

- Strangeness production
- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$
- Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)
- Λ(1405) dynamically generated
- Two poles:
  - M≈ 1385 MeV, $\Gamma \approx$ 150 MeV
  - M≈ 1420 MeV, $\Gamma \approx$ 40 MeV



Incoherent scattering on nuclei

- Many-body framework in infinite nuclear matter
- $\Rightarrow$ finite nuclei: local density approximation $\rho_{n,p}(r)$
  - cannot describe $\omega \sim$ 10s MeV, shell effects, giant resonances (only accounts for their average strenght)
  - simplicity
  - relativistic (in principle)
  - applicable for any nucleus with $A \gtrsim {}^{12}C$ with theoretically or experimentally known $\rho_{n,p}(r)$
  - applicable for incoherent (inclusive in the excited states of the residual target) processes

ν–A scattering

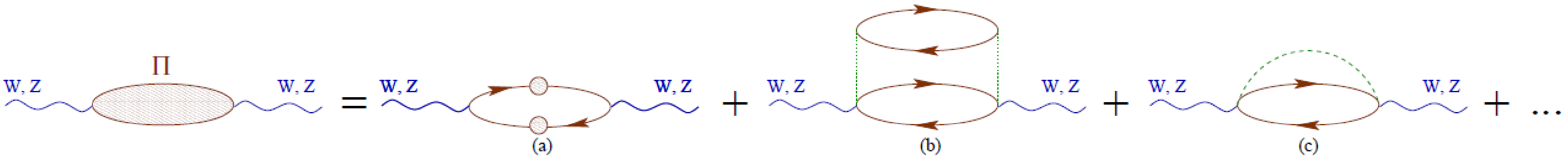
- Inclusive cross section per unit volume (well defined for an extended system)

$$\frac{d}{d^3r}\left(\frac{d\sigma}{dk_0' d\Omega(\vec{k}')}\right) = \frac{G_F^2}{(2\pi)^2}\frac{|\vec{k}'|}{k_0} L_{\mu\nu} W^{\mu\nu}$$

$$W^{\alpha\beta} = W_s^{\alpha\beta} + i W_a^{\alpha\beta}$$

$$W_{(s,a)}^{\alpha\beta} = -\frac{1}{\pi}\,\mathrm{Im}\,\Pi_{(s,a)}^{\alpha\beta}$$

- Polarization propagator:



Polarization propagator

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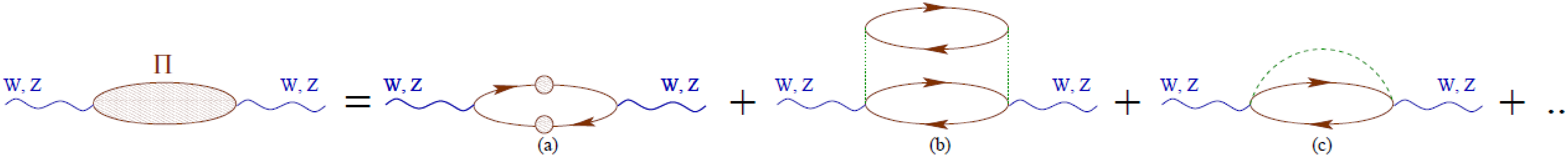
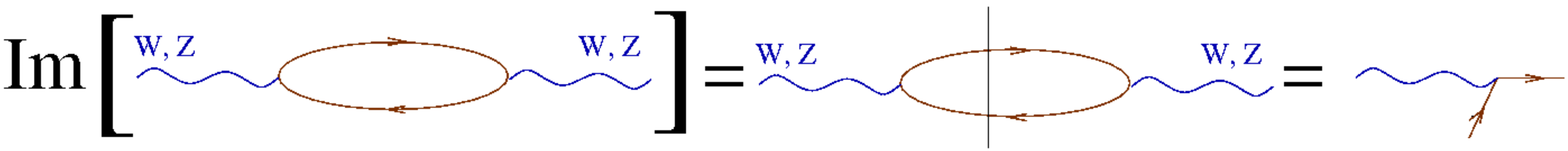


- Cutkosky rules:

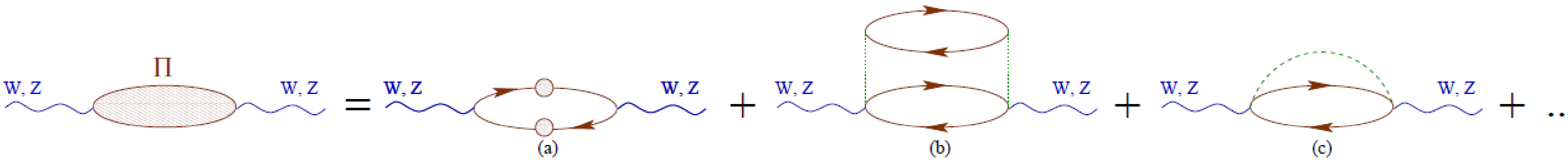


- Free nucleon propagator:

$$
\begin{aligned}
D(p) &= (\not{p} + M) G_0(p) \\
G_0(p) &= \frac{1}{p^2 - M^2 + i\epsilon} + 2\pi i \delta(p^2 - M^2)\theta(p^0) n(\vec{p}) \\
&= \frac{n(\vec{p})\theta(p^0)}{p^2 - M^2 - i\epsilon} + \frac{1 - n(\vec{p})\theta(p^0)}{p^2 - M^2 + i\epsilon} \\
&= \frac{1}{p^0 + E_p - i\epsilon}\left[\frac{n(\vec{p})}{p^0 - E_p - i\epsilon} + \frac{1 - n(\vec{p})}{p^0 - E_p + i\epsilon}\right]
\end{aligned}
$$

Polarization propagator

$$W^{\alpha\beta}_{(s,a)} = -\frac{1}{\pi}\,\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)}$$



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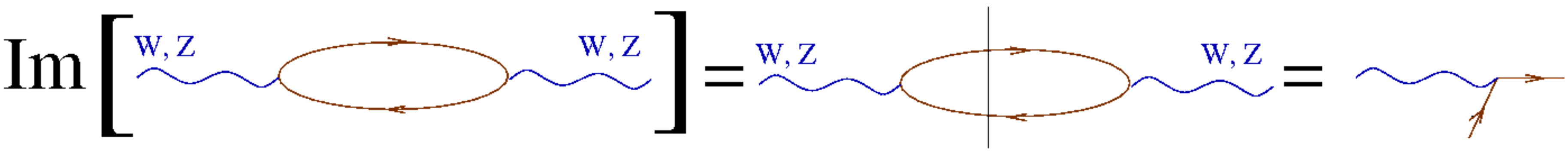
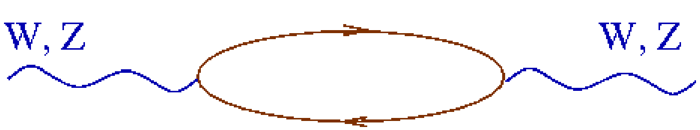


- Free nucleon propagator:

$$D(p) = (\not{p} + M) G_0(p)$$

$$G_0(p) = \frac{1}{p^2 - M^2 + i\epsilon} + 2\pi i \delta(p^2 - M^2)\theta(p^0) n(\vec{p})$$

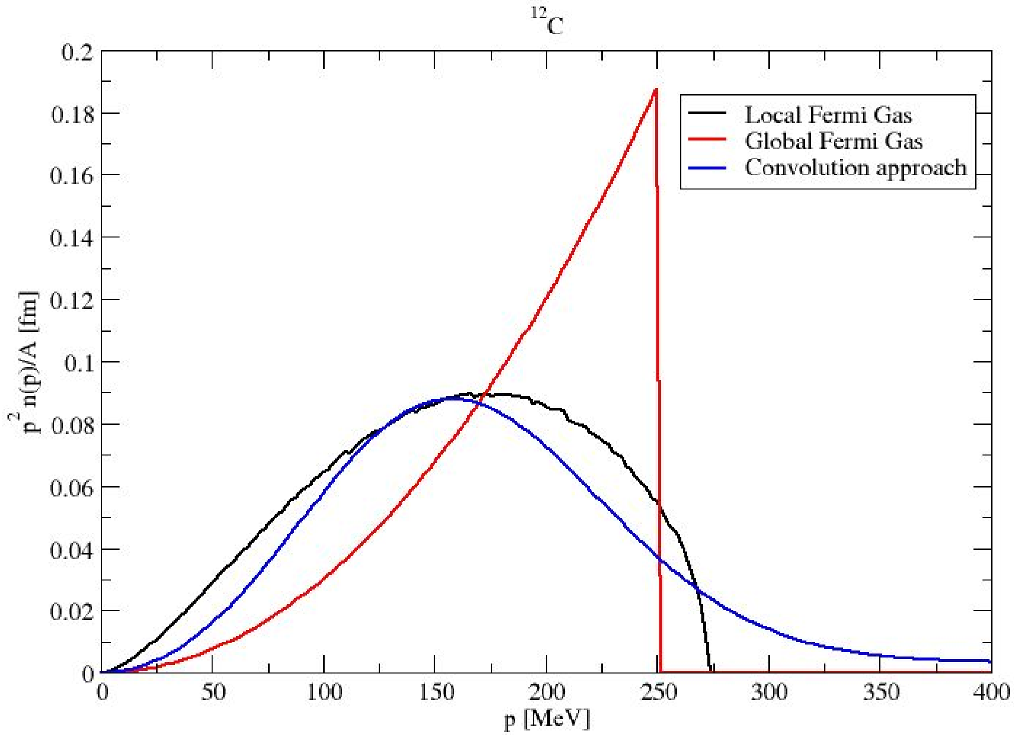
$$n(p,r) = \theta(p_F(r) - p) \qquad p_F(r) = \left[\frac{3}{2}\pi^2 \rho_{p,n}(r)\right]^{1/3}$$



$\Leftrightarrow$ Relativistic Local Fermi Gas

Local Fermi Gas

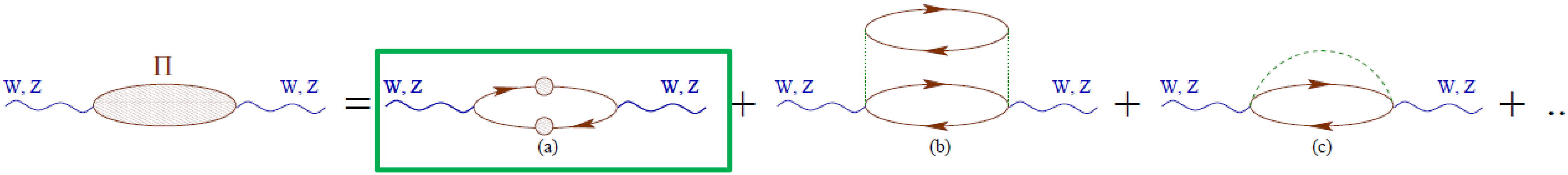
- Contains, through $\rho(r)$, empirical information about the ground state absent in the Relativistic Global Fermi Gas



Convolution model:
Ciofi degli Atti, Simula, PRC 53 (1996)

Polarization propagator

$$W^{\alpha\beta}_{(s,a)} = -\frac{1}{\pi}\,\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)}$$



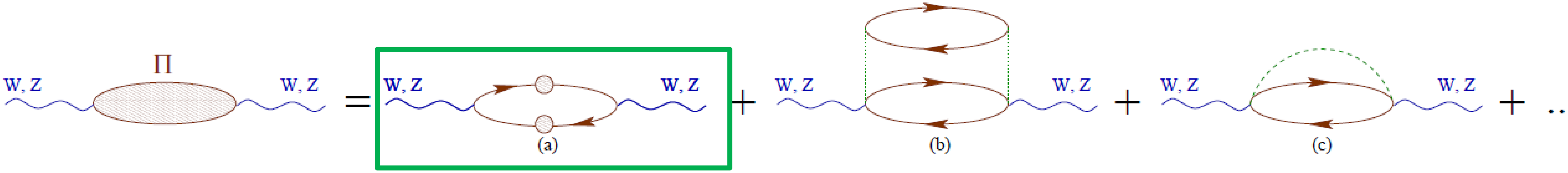
- Full nucleon propagator:

$$\begin{aligned} D(p) &= (\not{p} + M)G(p) \\ G(p) &= \frac{1}{p^0 + E_p - i\epsilon}\left[\int_{-\infty}^{\mu} \frac{\mathcal{A}_h(\omega,\vec{p})}{p^0 - \omega - i\epsilon} d\omega + \int_{\mu}^{\infty} \frac{\mathcal{A}_p(\omega,\vec{p})}{p^0 - \omega + i\epsilon} d\omega\right] \end{aligned}$$

$$\mu^2 = \vec{p}_F^{\,2} + M^2 + \mathrm{Re}\Sigma(\mu, p_F)$$

Polarization propagator

$$W^{\alpha\beta}_{(s,a)} = -\frac{1}{\pi}\,\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)}$$



$$\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)} = -2\pi^2 \int \frac{d^4p}{(2\pi)^4} H^{\beta\alpha}_{(s,a)} \mathcal{A}_p(p+q)\,\mathcal{A}_h(p)$$

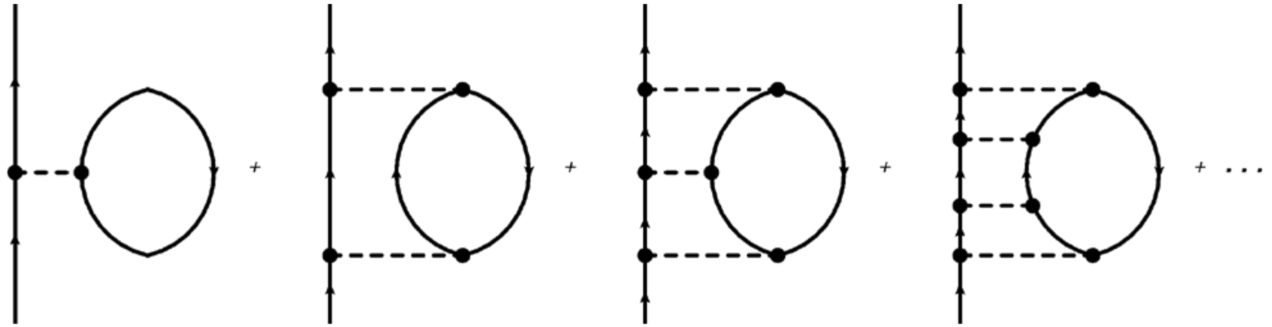
$$\mathcal{A}_{p,h}(p) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2}$$

$$\Gamma^\mu = \gamma^\mu F_1 + \frac{i}{2M}\sigma^{\mu\nu}q_\nu F_2 - \gamma^\mu\gamma_5 F_A - \frac{q^\mu}{M}\gamma_5 F_P$$

$$H^{\alpha\beta} = \mathrm{Tr}\left[(\not p + M)\,\gamma^0\,(\Gamma^\alpha)^\dagger\,\gamma^0\,(\not p' + M)\,\Gamma^\beta\right].$$

Nucleon selfenergy

- Fernández de Córdoba, Oset, PRC46 (1992)
- Semiphenomenological approach
  - Non-relativistic
  - Effective NN potential derived from experimental NN cross section
  - Medium-polarization corrections

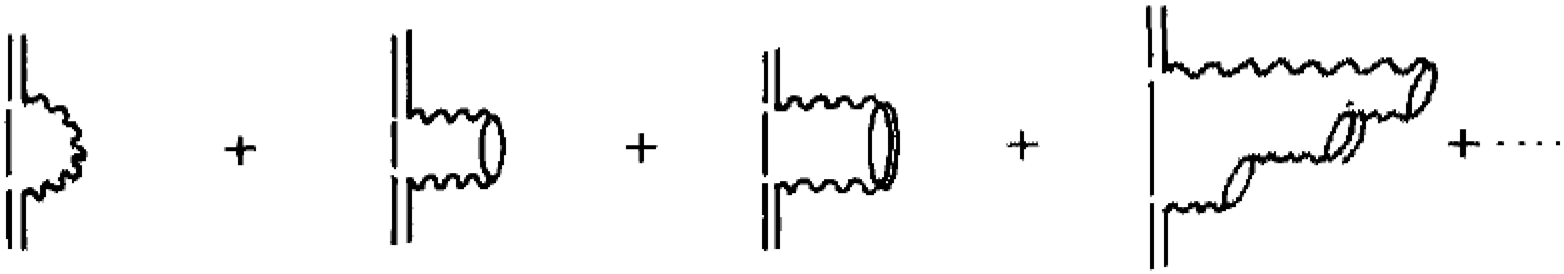


Sobczyk, Rocco, Lovato, Nieves, PRC97 (2018)

  - ReΣ obtained from ImΣ using dispersion relations
    - + Hartree term
    - + pheno Cρ with C fixed from binding energy

Δ selfenergy

- Oset, Salcedo, NPA468 (1987)
- Many body calculation of Δ selfenergy in the medium

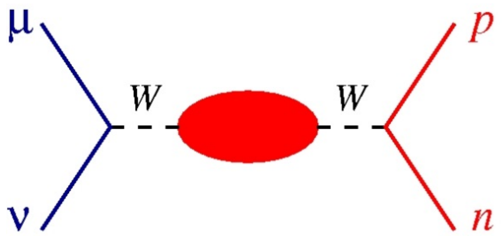


- Free width $\Delta \to N\,\pi$ modified by Pauli blocking
- $\mathrm{Im}\Sigma_\Delta(\rho)$: in-medium broadening:
  - $\Delta N \to N N$
  - $\Delta N \to N N \pi$
  - $\Delta N N \to N N N$
- $\mathrm{Re}\Sigma_\Delta(\rho) \approx$ - 50 MeV ρ/ρ_0

$$\frac{1}{p^2 - m_\Delta^2 + i m_\Delta \Gamma_\Delta(p^2)}$$

$$M_\Delta \to M_\Delta + \mathrm{Re}\Sigma_\Delta(\rho)$$
$$\Gamma_\Delta \to \tilde{\Gamma}_\Delta(\rho) - 2\mathrm{Im}\Sigma_\Delta(\rho)$$

RPA



- RPA equation (schematically):

$$\Pi_{\mathrm{RPA}} = \Pi_0 + \Pi_0 V \Pi_{\mathrm{RPA}}$$

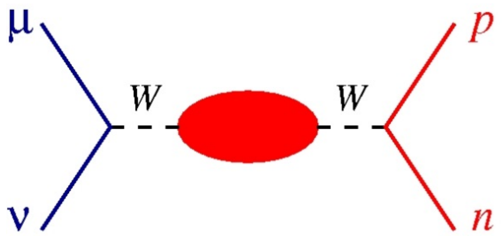
V=V(ρ) $\leftarrow$ effective, density dependent, NN interaction

$$V_{NN} = \vec{\tau}_1 \vec{\tau}_2 \sigma_1^i \sigma_2^j [\hat{q}_i \hat{q}_j V_L(q) + (\delta_{ij} - \hat{q}_i \hat{q}_j) V_T(q)] + g \vec{\sigma}_1 \vec{\sigma}_2 + f' \vec{\tau}_1 \vec{\tau}_2 + f I_1 I_2$$

$$V_L = \frac{f_{NN\pi}^2}{m_\pi^2} \left\{ \left(\frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - q^2} \right)^2 \frac{\vec{q}^{\,2}}{q^2 - m_\pi^2} + g' \right\}$$

$$V_T = \frac{f_{NN\pi}^2}{m_\pi^2} \left\{ C_\rho \left(\frac{\Lambda_\rho^2 - m_\rho^2}{\Lambda_\rho^2 - q^2} \right)^2 \frac{\vec{q}^{\,2}}{q^2 - m_\rho^2} + g' \right\}$$

Poor man's RPA



- RPA equation (schematically):

$$\Pi_{\mathrm{RPA}} = \Pi_0 + \Pi_0 V \Pi_{\mathrm{RPA}}$$

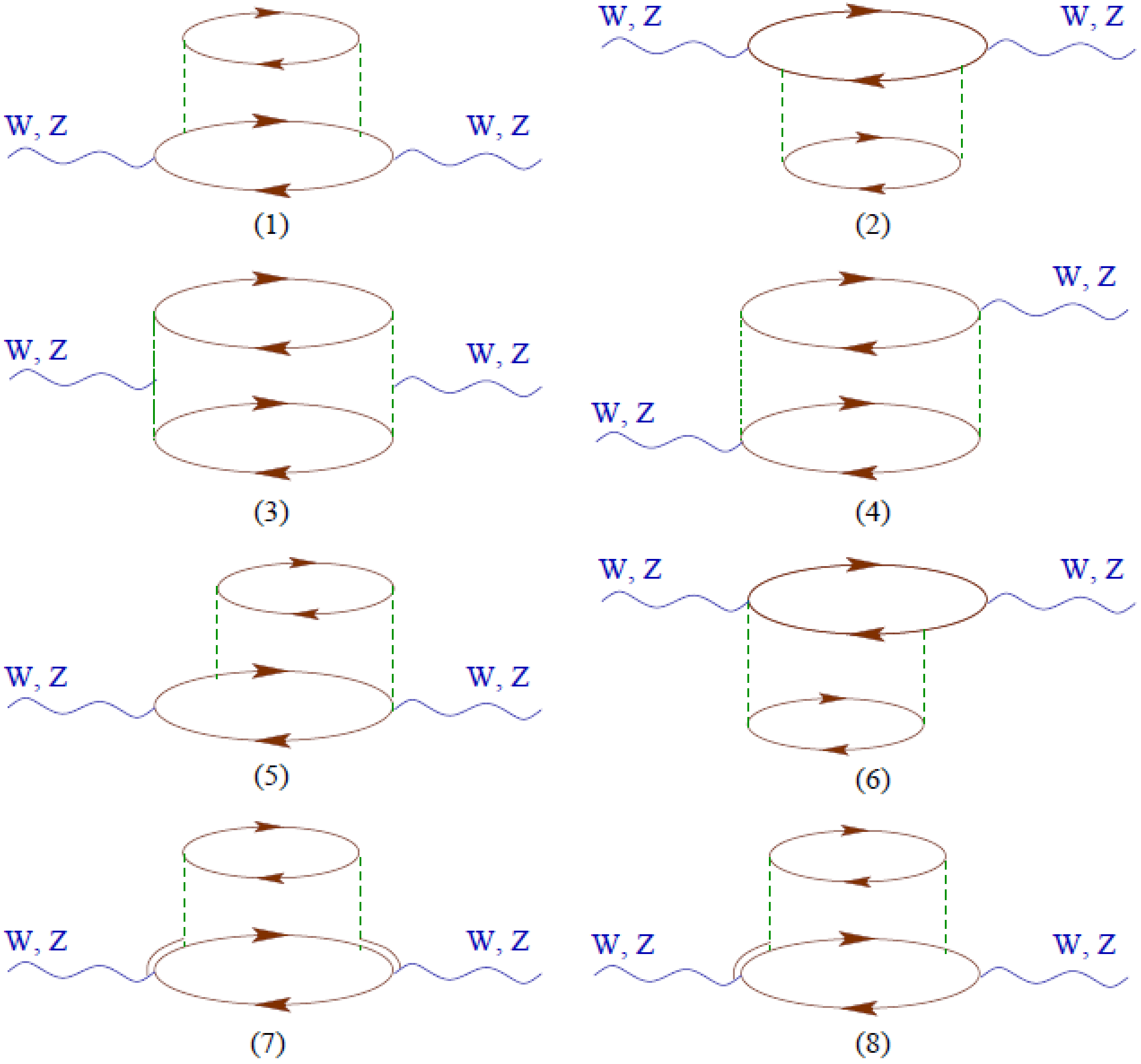
V=V(ρ) $\leftarrow$ effective, density dependent, NN interaction

  - Non-relativistic analytic solution: new ρ–dependent terms of the hadron tensor.
  - Incorporates explicitly π and ρ exchange and Δ-hole states
  - Describes correctly μ capture on ^{12}C and LSND CCQE

Nieves, Amaro, Valverde, PRC 70 (2004) 055503

Nieves, Sobczyk, Annals Phys. 383 (2017)

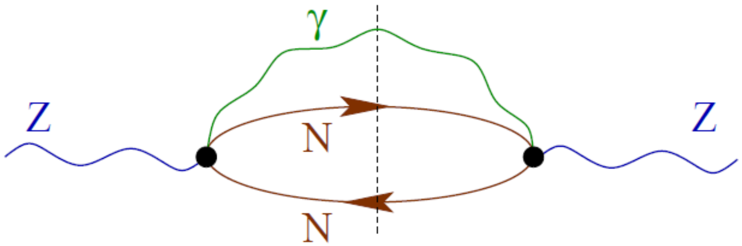
2p2h examples



Photon emission in NC interactions

- $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, X$

- 1p1h1γ excitations:



- In-medium Δ(1232)

Wang, LAR, Nieves, PRC89 (2014)

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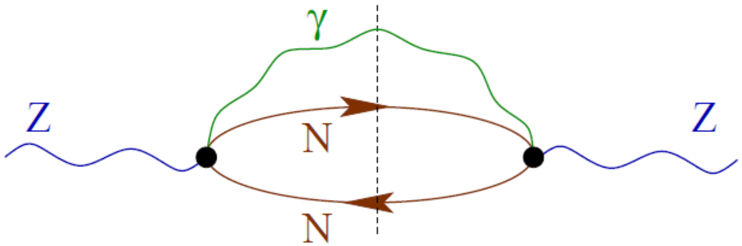
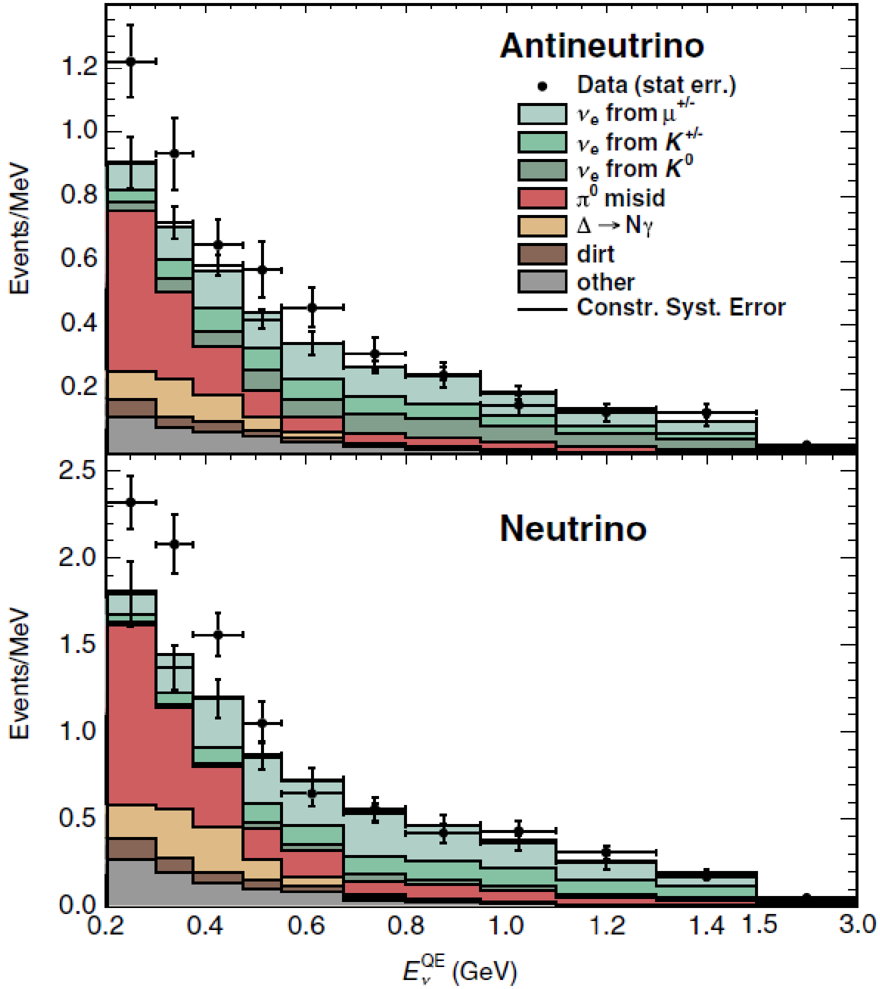


- In-medium $\Delta(1232)$

Wang, LAR, Nieves, PRC89 (2014)



Aguilar-Arevalo et al., PRL110 (2013) 161801

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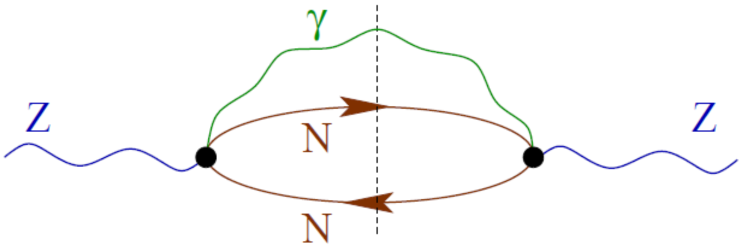
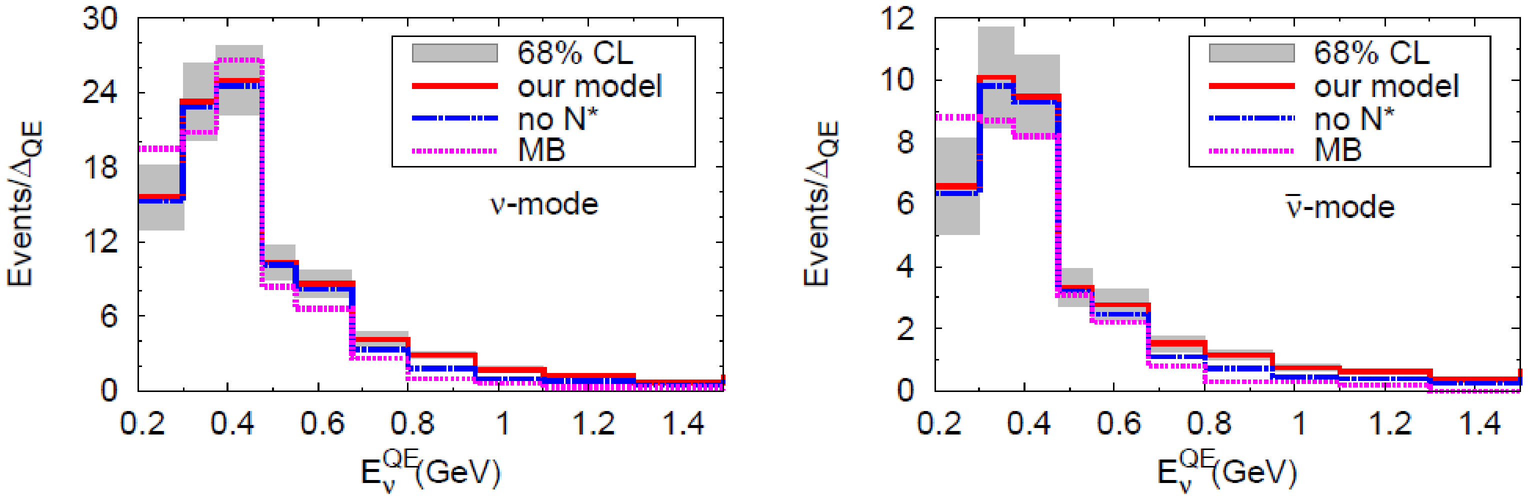


- In-medium Δ(1232)

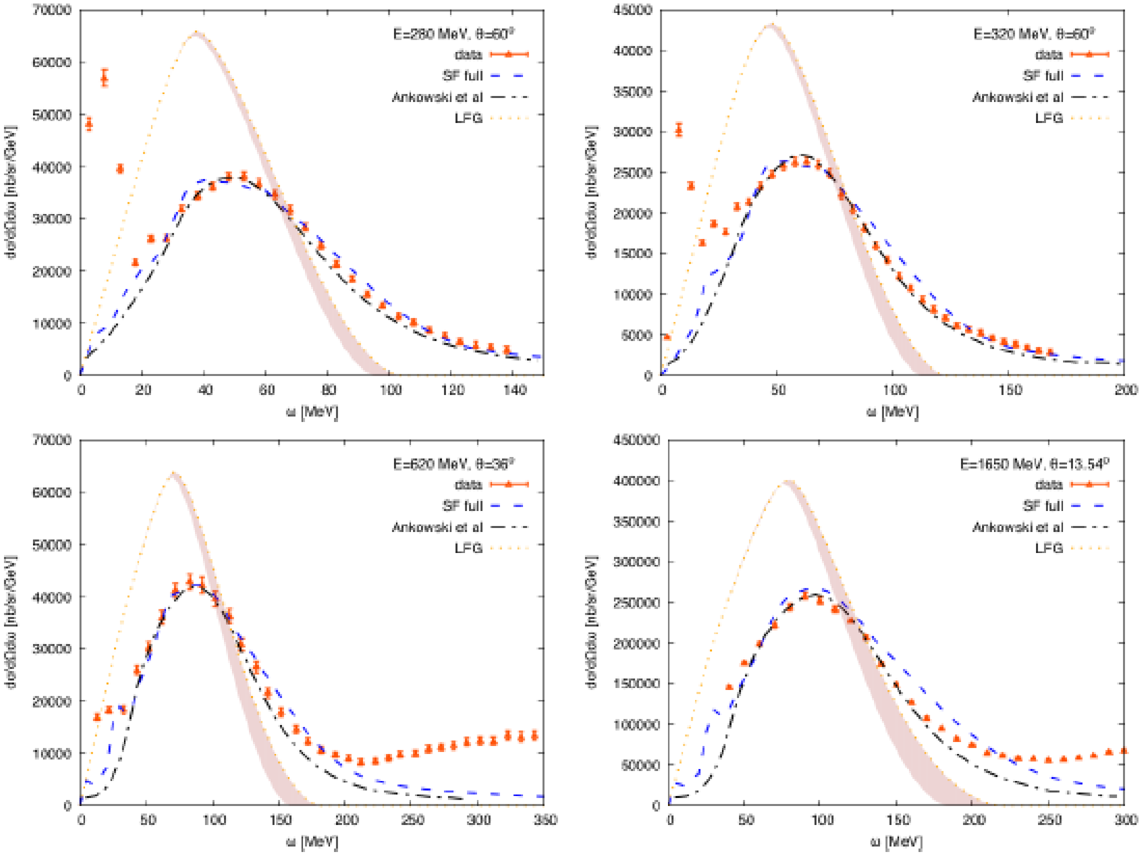
E. Wang, LAR, J. Nieves, PLB 740 (2015)



- NCγ : insufficient to explain the excess of e-like events at MiniBooNE
- NCγ : under analysis @ MicroBooNE

Electron scattering

- Inclusive $^{12}C(e,e')X$ in the QE region

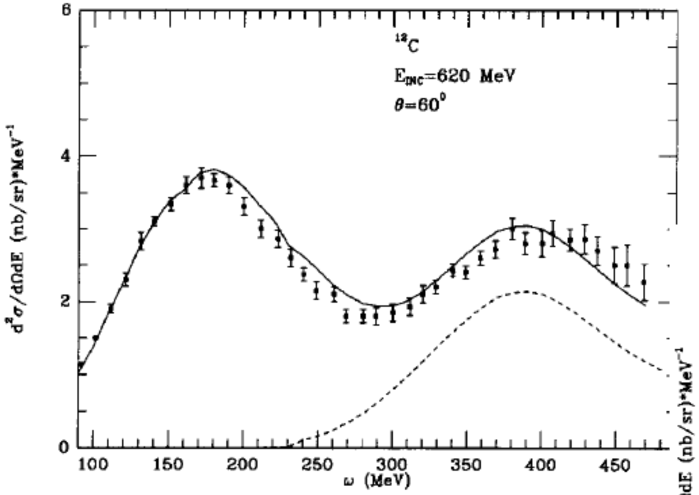


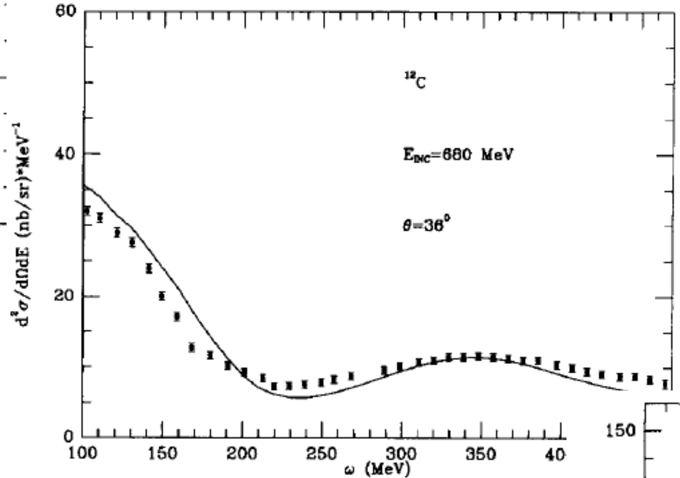
Nieves, Sobczyk, Annals Phys. 383 (2017)

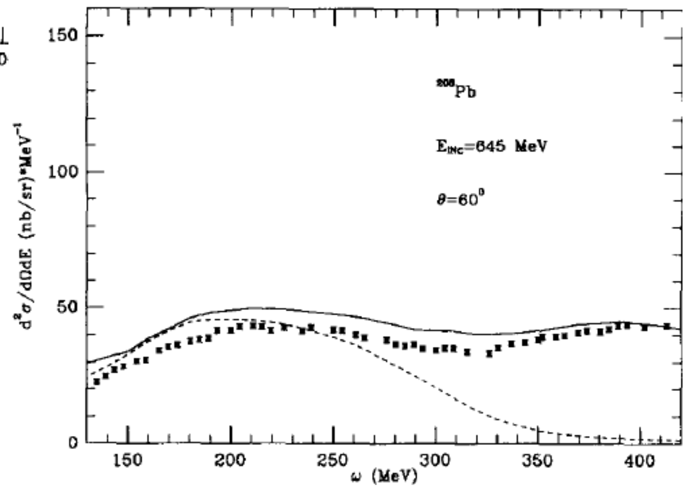
- "RPA effects in integrated decay rates or cross sections become significantly smaller when SF corrections are also taken into account (...)"

Electron inclusive scattering

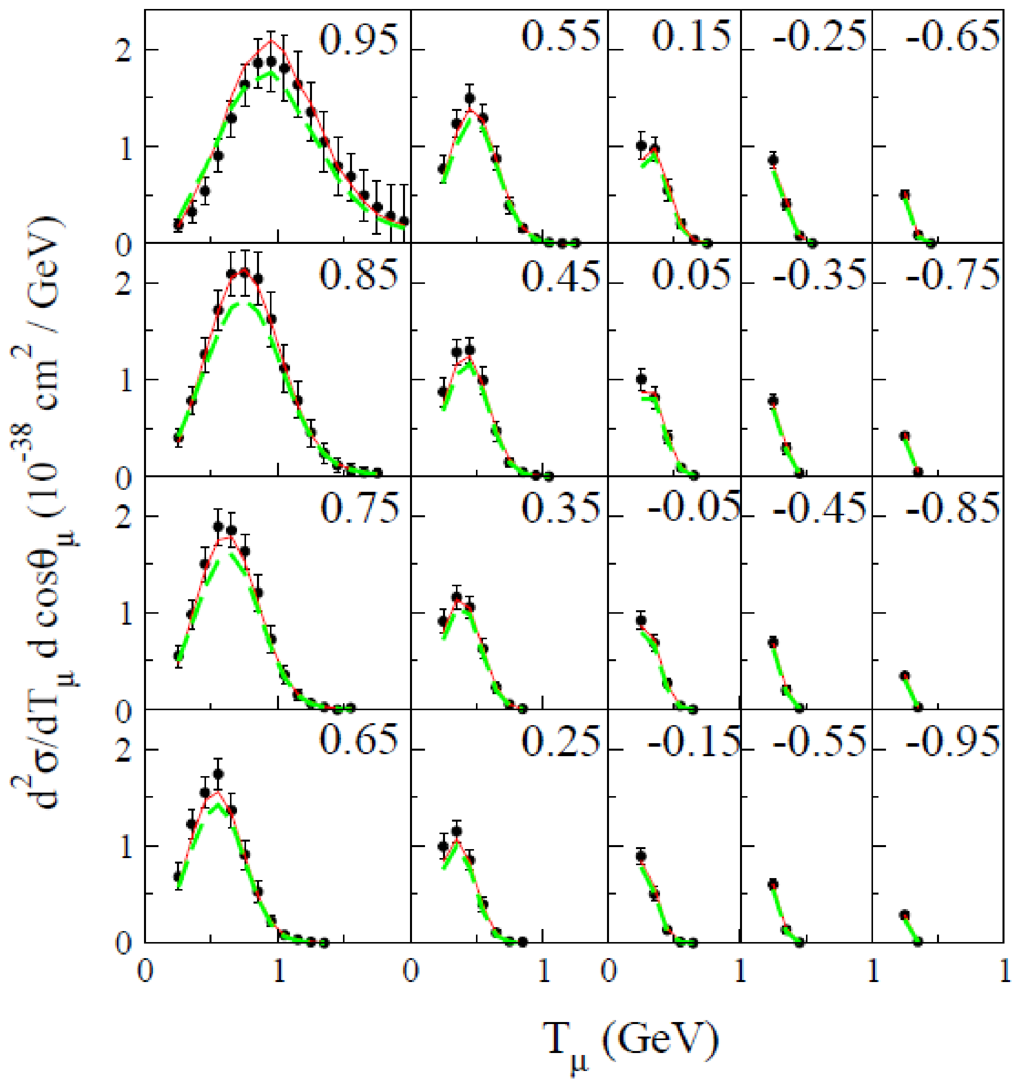
- Gil, Nieves, Oset, NPA627 (1999)







CCQE-like scattering



Nieves, Ruiz Simo, Vicente Vacas, PLB 707 (2012)

Weak coherent reactions

- Coherent = final nucleus remains in the ground state

  - Charged Current coherent particle production

$$\nu_l \, A \to l^- \, m^+ \, A$$
$$\bar{\nu}_l \, A \to l^+ \, m^- \, A$$

$$m^{\pm} = \pi^{\pm}, K^{\pm}, \ldots$$

  - Neutral Current coherent particle production

$$\nu \, A \to \nu \, m^0 \, A$$
$$\bar{\nu} \, A \to \bar{\nu} \, m^0 \, A$$

$$m^0 = \gamma, \pi^0, \ldots$$

Weak coherent reactions

- Amplitude: $\mathcal{M} \sim \frac{G}{\sqrt{2}} l_\mu J^\mu$
- Nuclear current:

$$J^\mu = \sum_i \sum_{r=p,n} \int d\vec{r}\, e^{i\vec{q}\cdot\vec{r}} \rho_r(r) \frac{1}{2} \mathrm{Tr}\left[\bar{u}\, \Gamma^\mu_{i(r)}\, u\right] \phi^*_{\mathrm{out}}$$

i=all mechanisms

- Prescription for nucleon momenta:

$$p = \left(\sqrt{M^2 + \frac{1}{4}(\vec{q}_\gamma - \vec{q})^2}, \frac{\vec{q}_\gamma - \vec{q}}{2}\right) \qquad p' = q - q_\gamma + p = \left(\sqrt{M^2 + \frac{1}{4}(\vec{q}_\gamma - \vec{q})^2}, -\frac{\vec{q}_\gamma - \vec{q}}{2}\right)$$

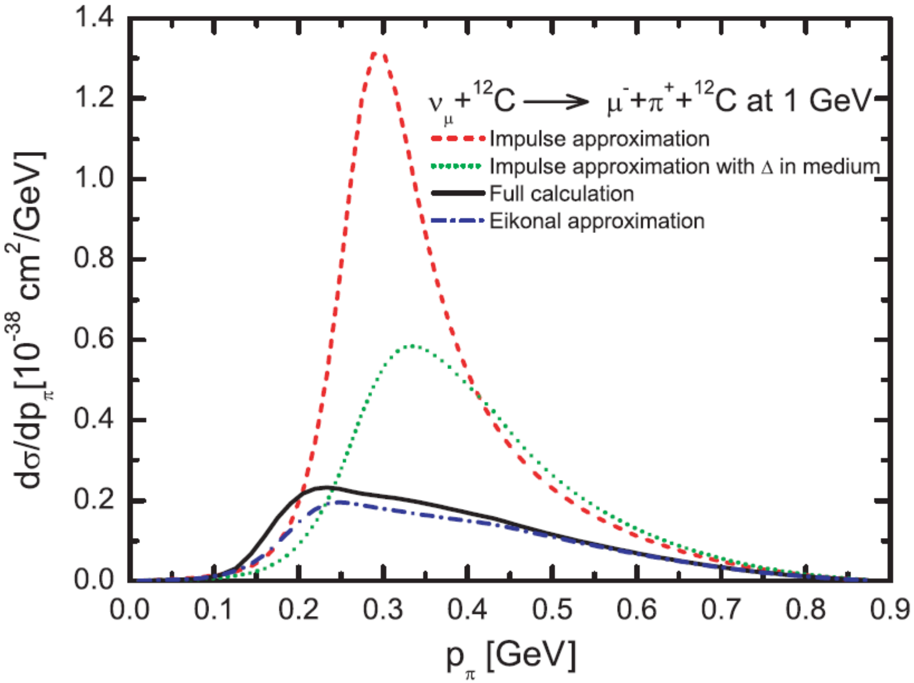
  - Momentum equally shared by initial and final nucleons

- Meson distortion:

$$\left(-\vec{\nabla}^2 - \vec{p}_K^{\,2} + 2\omega_K V_{\mathrm{opt}}\right)\phi^*_{\mathrm{out}} = 0$$ $\leftarrow$ Klein-Gordon equation

$$\vec{p}_K \phi^*_{\mathrm{out}}(\vec{p}_K, \vec{r}) \rightarrow i\vec{\nabla}\phi^*_{\mathrm{out}}(\vec{p}_K, \vec{r})$$

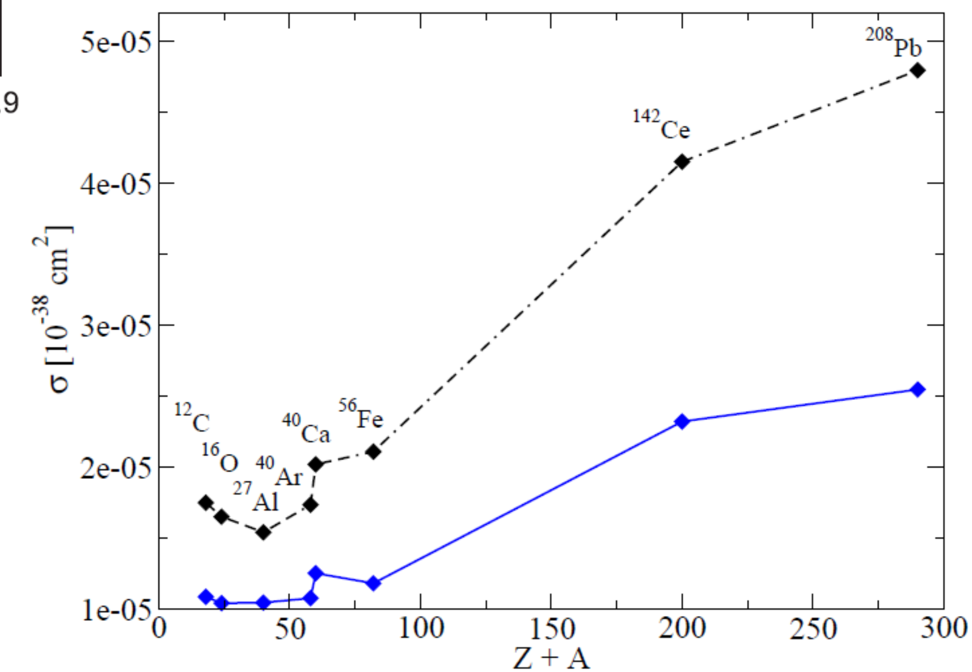
Weak coherent reactions



LAR et al., PRC 75 (2007)

LAR et al., PRC 87 (2013);

$$\nu_\mu\, A \to \mu^-\, K^+\, A$$



Conclusion

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