NuSTEC Neutrino Generator School

Lecture T9

Weak coherent meson production

Luis Alvarez Ruso

Outline

- Weak coherent reactions
- Coherent pion production
  - PCAC models
  - Microscopic models

Weak coherent reactions

- Coherent = final nucleus remains in the ground state
  - Neutral Current elastic scattering

$$\nu\, A \rightarrow \nu\, A$$

$$\bar{\nu}\, A \rightarrow \bar{\nu}\, A$$

  - Charged Current coherent particle production

$$\nu_l\, A \rightarrow l^-\, m^+\, A$$

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

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

  - Neutral Current coherent particle production

$$\nu\, A \rightarrow \nu\, m^0\, A$$

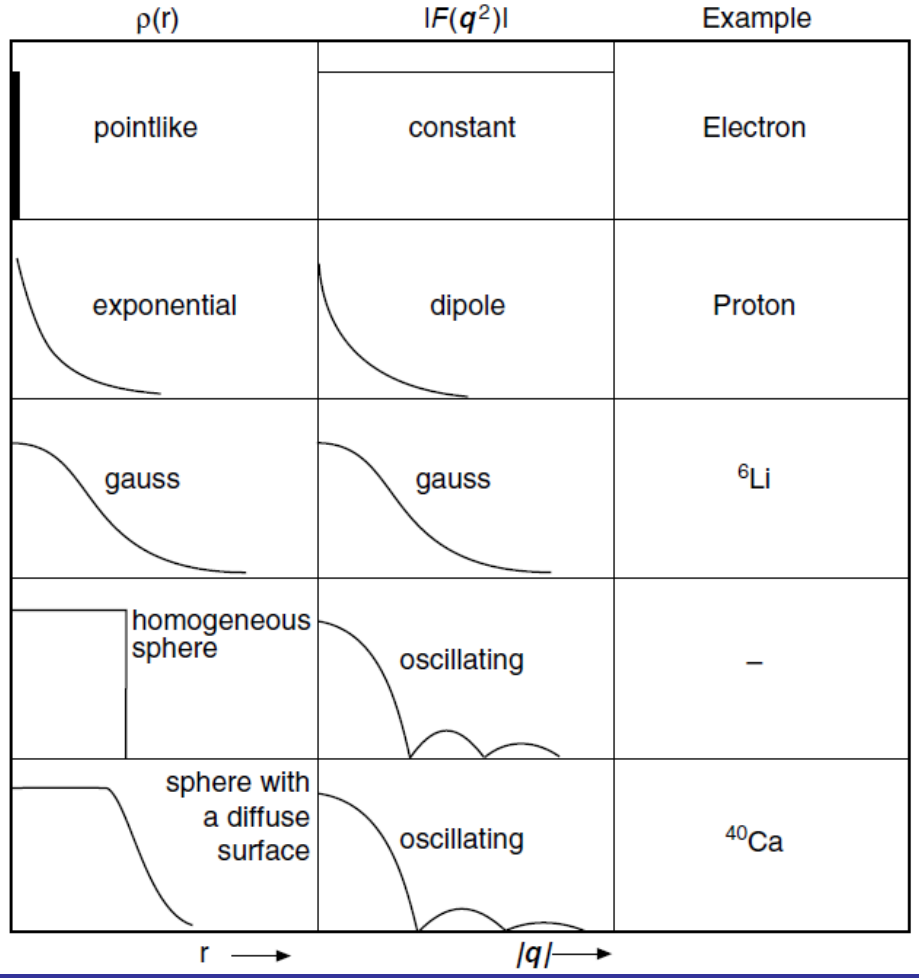
$$\bar{\nu}\, A \rightarrow \bar{\nu}\, m^0\, A$$

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

Weak coherent reactions

- $d\sigma \sim F^2(t)$ ← nuclear form factor: $F_{\mathcal{A}}(t) = \int d^3\vec{r}\; e^{i(\vec{q}-\vec{p}_\pi)\cdot\vec{r}}\,\{\rho_p(\vec{r}) + \rho_n(\vec{r})\}$

$$t = (p' - p)^2 = 2M_A^2 - 2M_A\sqrt{M_A^2 + \vec{p}'^2} \approx -2M_A T_A$$



Weak coherent reactions

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$$t = (p' - p)^2 = 2M_A^2 - 2M_A\sqrt{M_A^2 + \vec{p}'^2} \approx -2M_A T_A = q^2$$

$$\frac{d\sigma}{dT_A} = \frac{G_F^2}{4\pi}\left[F_n(Q^2) - (1 - 4\sin^2\theta_W)F_p^2(Q^2)\right]^2 M_A\left(1 - \frac{M_A T_A}{2E_\nu^2}\right)$$

  - Experimental problem: small recoil energies
  - Similar detection techniques than in **dark matter** exps.

Weak coherent reactions

- CC/NC coherent particle production

$$q_0 + M_A = p_m^0 + \sqrt{M_A^2 + \vec{p}'^2}$$

$$q_0 = p_m^0 + T_A \approx p_m^0$$

$$t = (q - q_m)^2 \approx -(\vec{q} - \vec{p}_m)^2$$

$$|\vec{p}_m| = \sqrt{q_0^2 - m^2}$$

- Favored kinematics:
  - Parallel $\vec{q}, \vec{p}_m$
  - Forward: $q_0 \approx |\vec{q}| \Rightarrow q^2 \approx 0$
  - Small m

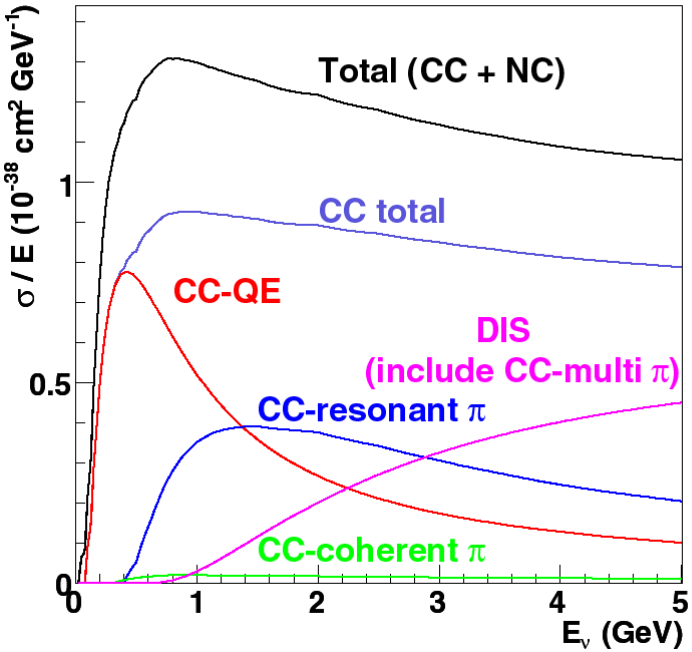
Coherent pion production

- m = π

$$\nu A \rightarrow \nu \pi^0 A$$
$$\bar{\nu} A \rightarrow \bar{\nu} \pi^0 A$$

$\Leftrightarrow$ background for ν_e appearance

- Very small cross section but relatively larger than in coherent π production with photons or electrons
- At $q^2 \sim 0$ the axial current is not suppressed while the vector is



NEUT
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Coherent pion production

- Models:
  - PCAC
  - Microscopic

PCAC models

- Rein-Sehgal NPB 223 (83) 29
  - In the $q^2=0$ limit, PCAC is used to relate ν induced coherent pion production to πA elastic scattering

$$\left.\frac{d\sigma}{dq^2 dy dt}\right|_{q^2=0} = \frac{G_F^2 f_\pi^2}{2\pi^2}\frac{(1-y)}{y}\frac{d\sigma}{dt}(\pi^0 A \to \pi^0 A)\Big|_{q^2=0,\, E_\pi = q^0}$$

$y = q^0/E_\nu$

  - Continuation to $q^2 \neq 0$: $\times \left(1 - q^2/1\mathrm{GeV}^2\right)^{-2}$
  - πA in terms of πN scattering:

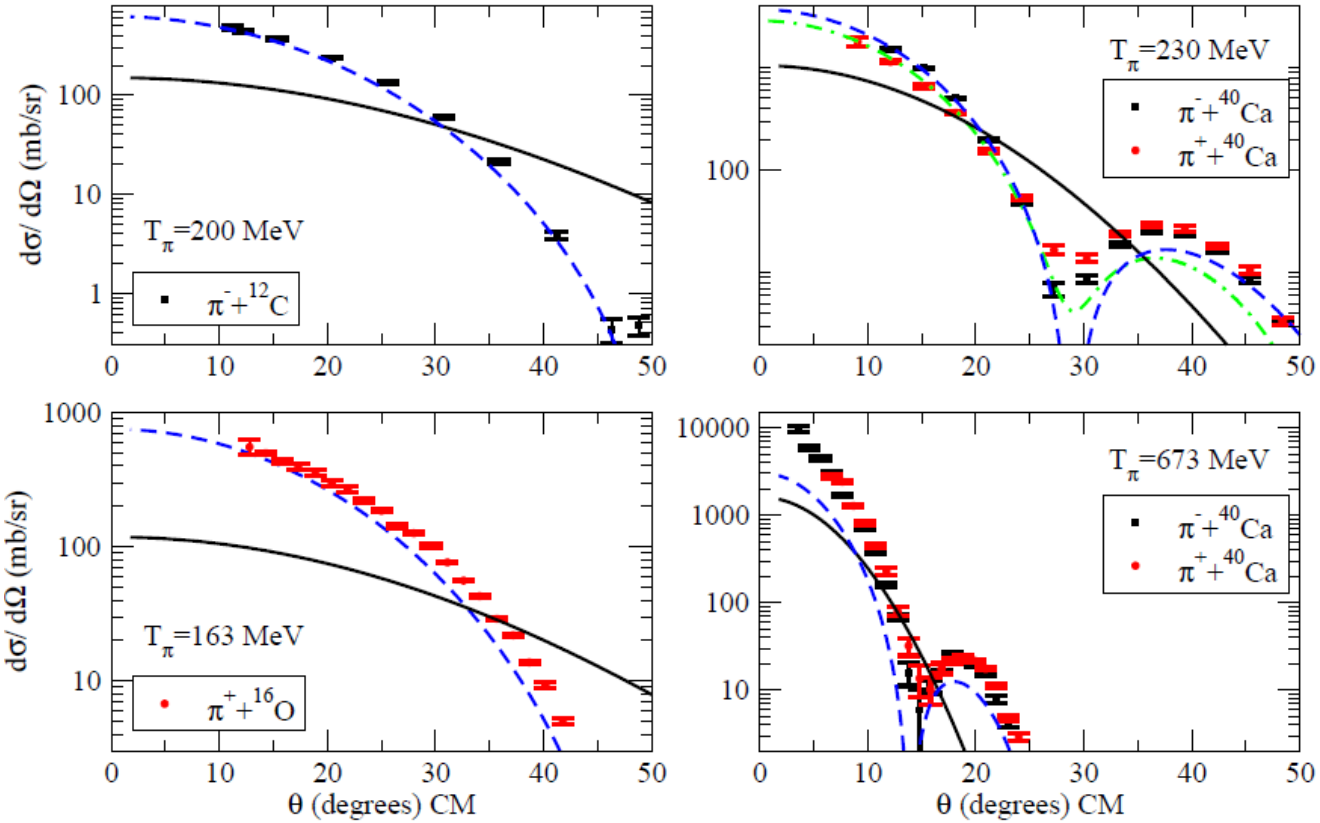
$$\times |F_{\mathcal{A}}(t)|^2 \, F_{\mathrm{abs}} \left(\frac{d\sigma}{dt}(\pi^0 N \to \pi^0 N)\right)_{t=0,\, E_\pi = q^0}$$

$$F_{\mathcal{A}}(t) = \int d^3\vec{r}\, e^{i(\vec{q}-\vec{p}_\pi)\cdot\vec{r}} \{\rho_p(\vec{r}) + \rho_n(\vec{r})\}$$ ← nuclear form factor

F_{abs} ← removes from the flux outgoing π that undergo inelastic collisions

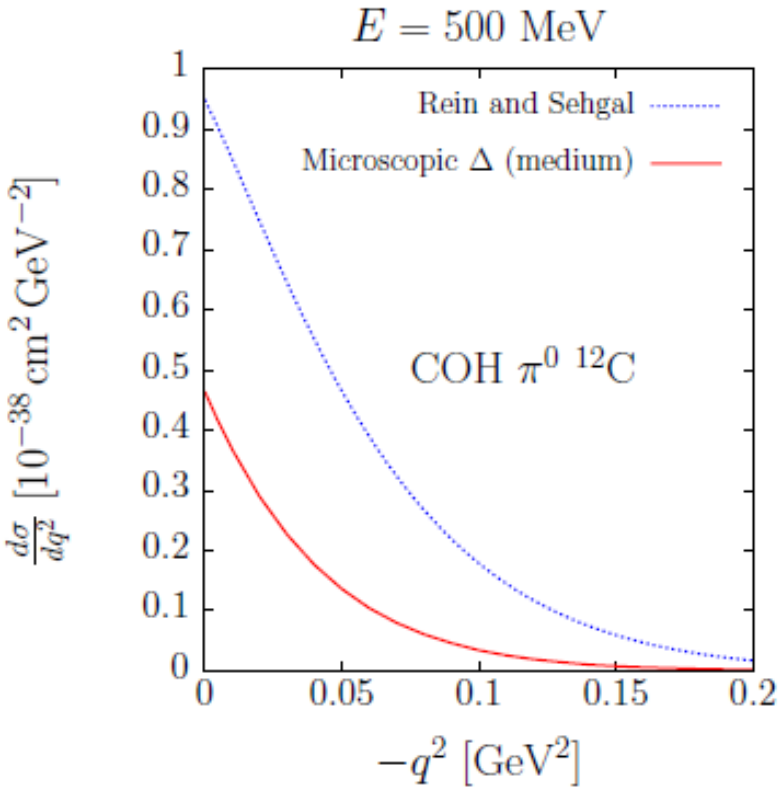
PCAC models

- Rein-Sehgal NPB 223 (83) 29
  - Problems: Hernandez et al., PRD 80 (2009) 013003
    - $q^2=0$ approximation neglects important angular dependence at low energies and for light nuclei
    - The πA elastic description is not realistic



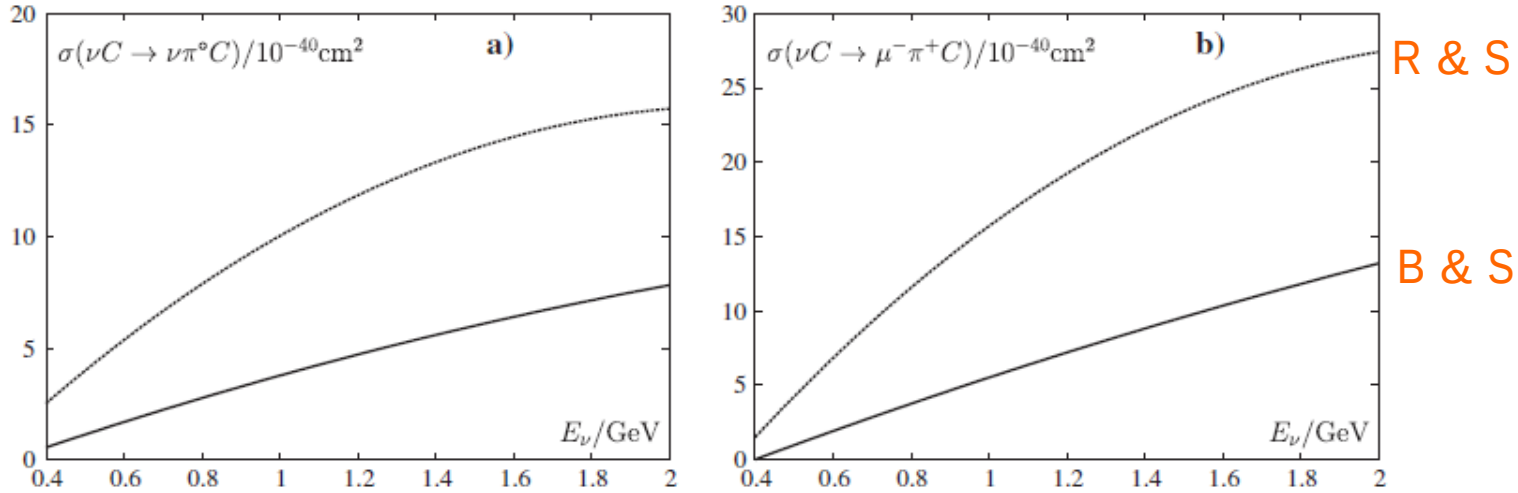
PCAC models

- Rein-Sehgal NPB 223 (83) 29
  - Problems: Hernandez et al., PRD 80 (2009) 013003
    - Predicts larger cross sections and wider q^2 distributions than microscopic models



PCAC models

- Kartavtsev et al., PRD 74 (2006), Berger & Sehgal, PRD 79 (2009), Paschos & Schalla, PRD 80 (2009)
  - Some $q^2 \neq 0$ kinematical corrections introduced
  - Use experimental πA cross section
    - Problem:
      - PCAC relates Cohπ with off-shell πA: $q^2 \leq 0 \neq m^2_\pi$
      - Incoming π do not penetrate inside A (absorption & rescattering) but ν do
      - Spurious π distortion is introduced
  - Smaller σ than R&S:



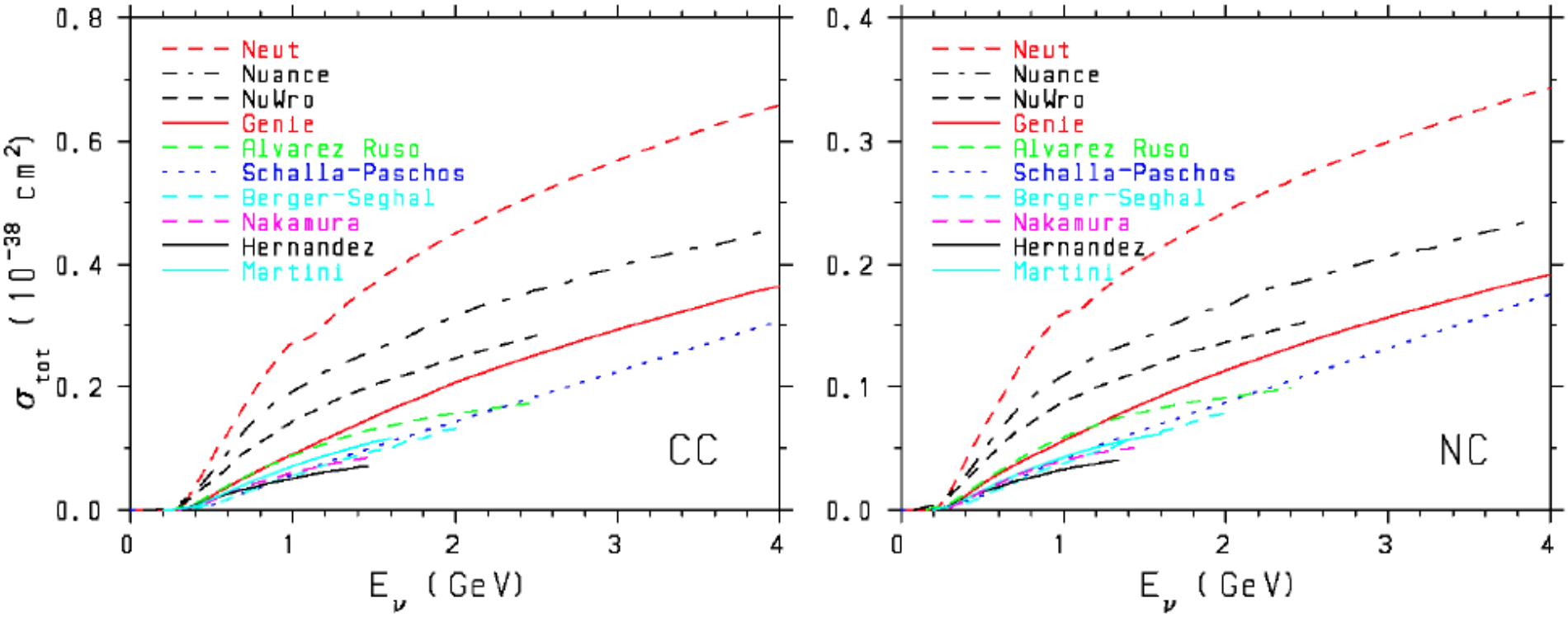
PCAC models

- Kartavtsev et al., PRD 74 (2006), Berger & Sehgal, PRD 79 (2009), Paschos & Schalla, PRD 80 (2009)
  - Problems of PCAC models: less relevant at high energies and for heavy nuclei
    - NOMAD: $\sigma = 72.6 \pm 8.1(\text{stat}) \pm 6.9(\text{syst}) \times 10^{-40}$ cm^2
    - Energy range: $2.5 \leq E_\nu \leq 300$ GeV
    - Consistent with R&S: $\sigma \approx 78 \times 10^{-40}$ cm^2

      Kullenberg et al., PLB 682 (2009) 177

PCAC models

- Which R&S ?
  - Different implementations in Monte Carlo generators



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PCAC models

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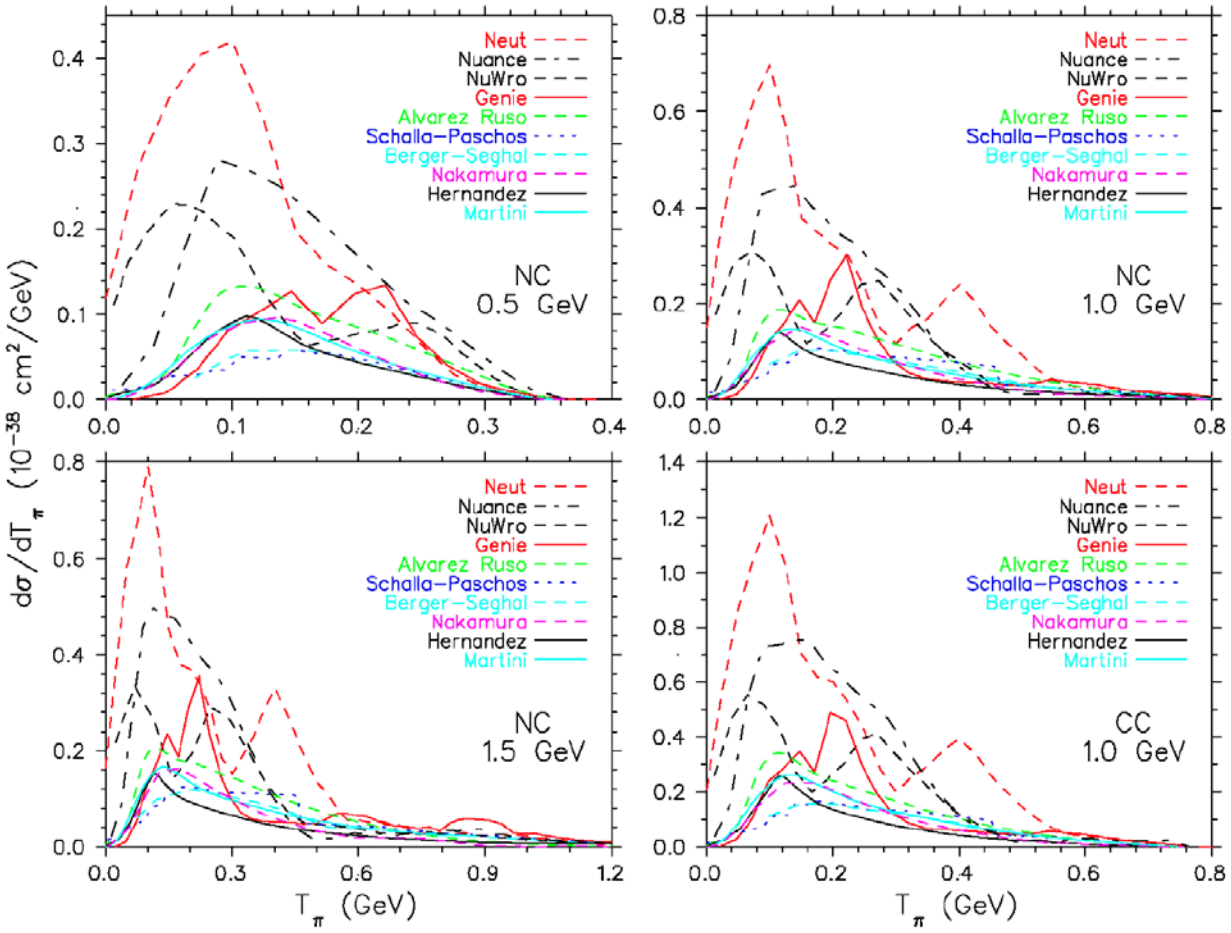

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PCAC models

- Which R&S ?
  - Different implementations in Monte Carlo generators
    - Different πN cross sections
    - Different F_{abs}
    - π FSI? π distortion: a π that rescatters should be removed (coherence broken)
    - Instead, πA data could be directly used

Microscopic models

- Kelkar et al., PRC55 (1997); Singh et al., PRL 96 (2006); LAR et al., PRC 75, 76 (2007); Amaro et al., PRD 79 (2009), Hernandez et al., PRD 82 (2010);
  Leitner et al., PRC 79 (2009); Martini et al., PRC 80 (2009); Nakamura et al, PRC 81 (2010); Zhang et al. PRC 86 (2012)
  - Model for the elementary $\nu\ N \rightarrow\ l\ N\ \pi$ amplitude
  - Coherent sum over all nucleons
  - Medium effects
  - Distortion of the outgoing pion
  - Nonlocalities

  - 👍 Same hadronic/nuclear input as for the incoherent(resonant) channel
  - 👍 Can be applied/validated in other reactions (γ, e, π, ...)
  - 👎 Limited to low energies

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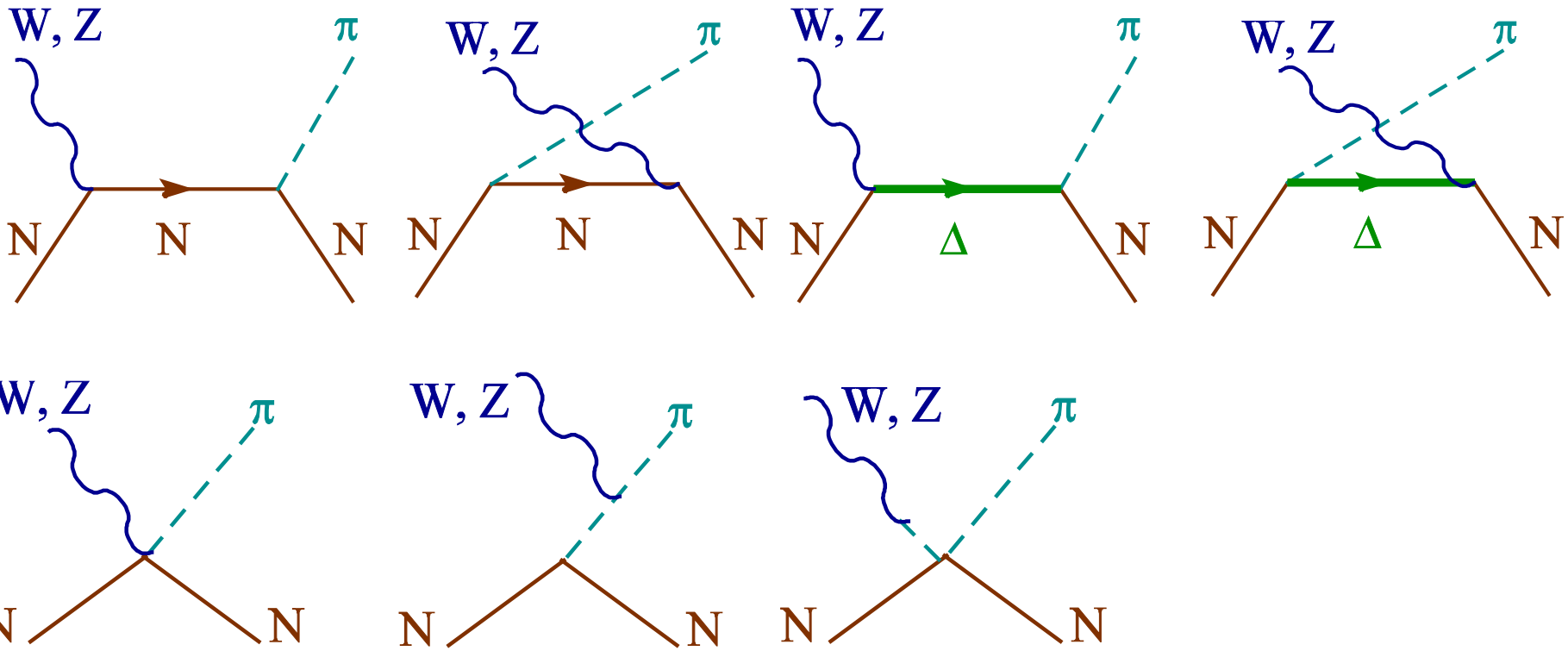

Hernandez, PRD 76 (2006)

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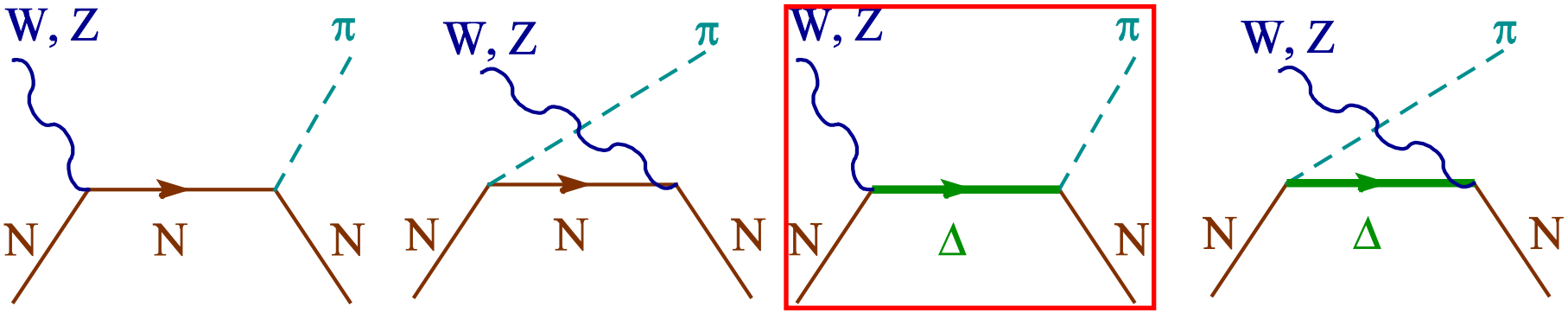
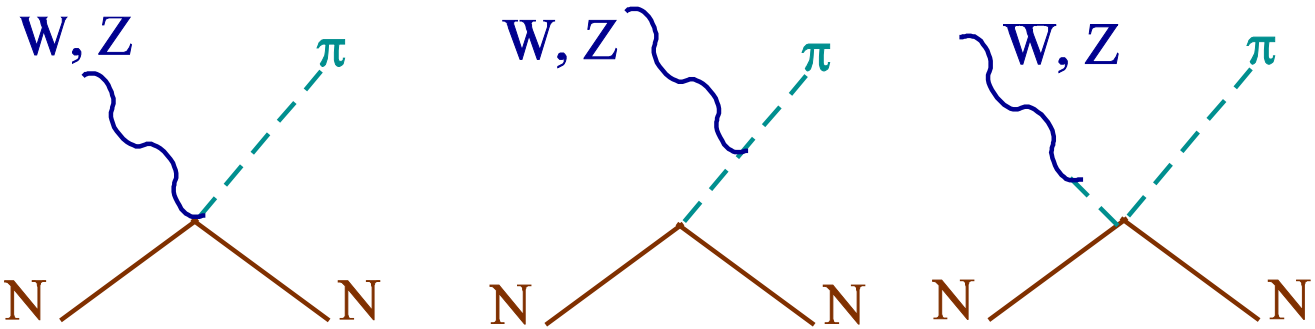


dominant



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  - Medium effects
    - Δ properties change in the nuclear medium

$$M_\Delta \to M_\Delta + \mathrm{Re}\Sigma_\Delta$$
$$\Gamma_\Delta/2 \to \Gamma_\Delta^{\mathrm{Pauli}}/2 - \mathrm{Im}\Sigma_\Delta$$

    - Δ-h RPA resummation
    - Distortion of the outgoing pion $e^{-i\vec{p}_\pi\cdot\vec{r}} \to \phi^*_{out}(\vec{p}_\pi,\vec{r})$

$$\left(-\vec{\nabla}^2 - \vec{p}_\pi^{\,2} + 2\omega_\pi \hat{V}_{\mathrm{opt}}\right)\phi^*_{out} = 0$$

$\hat{V}_{\mathrm{opt}}(r) \leftarrow$ Nonlocal optical potential in the Δ-hole model

    - Nonlocalities in the π momentum $\vec{p}_\pi e^{-i\vec{p}_\pi\cdot\vec{r}} \to i\vec{\nabla}\phi^*_{out}(\vec{p}_\pi,\vec{r})$

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  - Mediu
    - Δ
    - Δ
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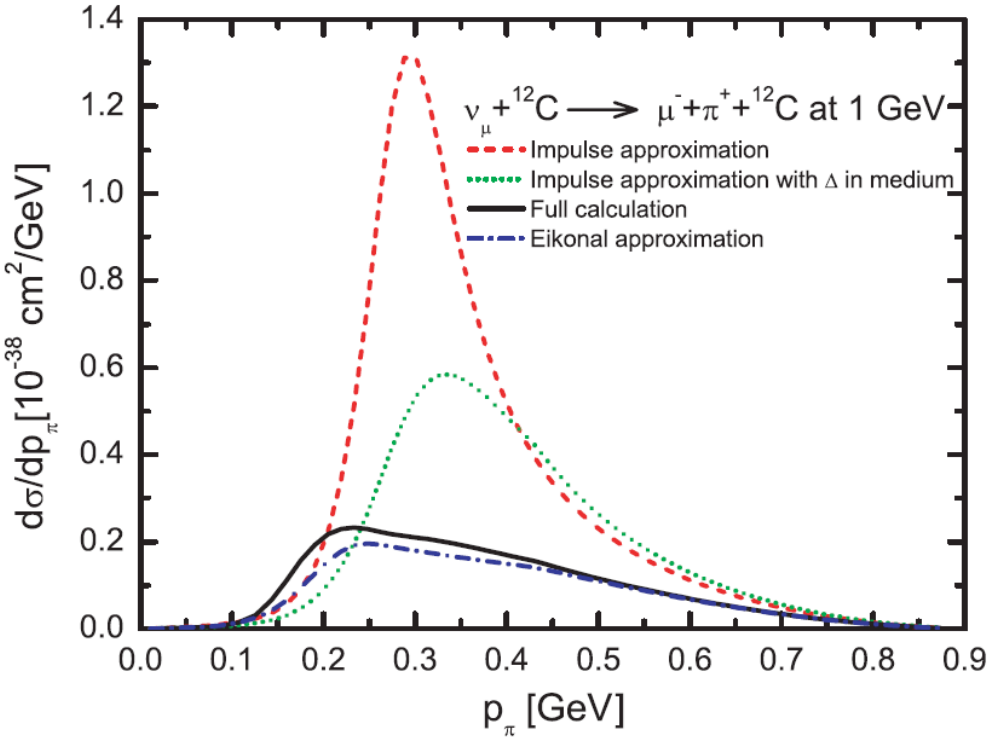

$$\phi^*_{out}(\vec{p}_\pi, \vec{r})$$

- Medium effects reduce considerably de cross section
- Pion distortion shifts down the peak

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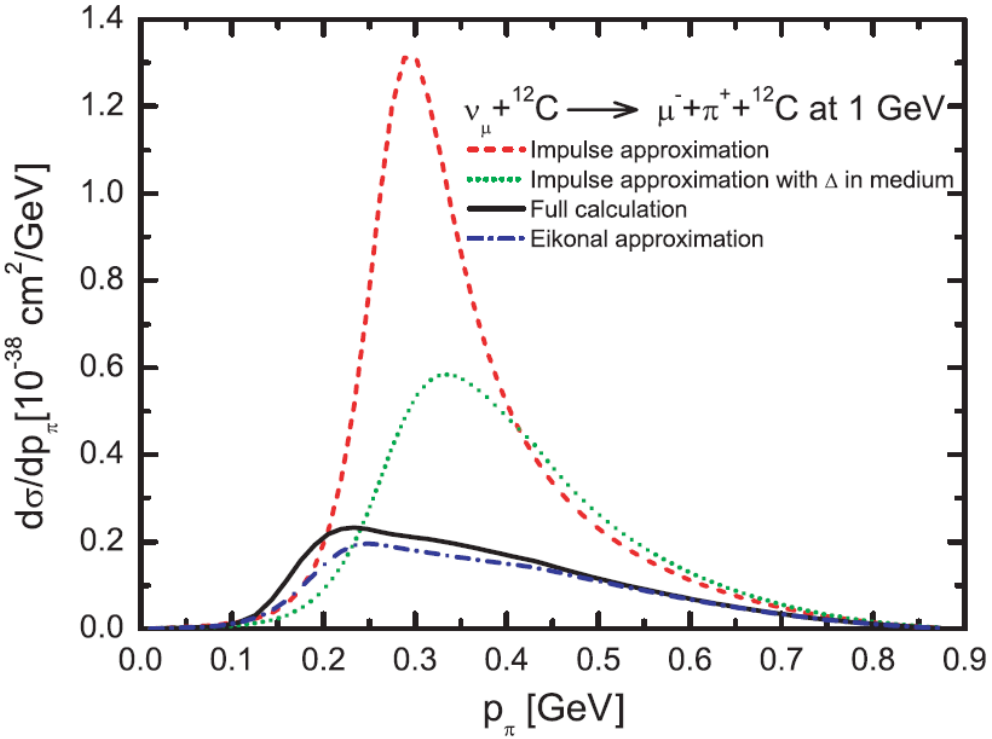

$\phi^*_{out}(\vec{p}_\pi, \vec{r})$

Eikonal: not accurate at low π momentum... but good enough, and simpler!

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$$M_\Delta \to M_\Delta + \mathrm{Re}\Sigma_\Delta$$
$$\Gamma_\Delta/2 \to \Gamma_\Delta^{\mathrm{Pauli}}/2 - \mathrm{Im}\Sigma_\Delta$$

    - p-h, Δ-h RPA
    - Local
    - No distortion of the outgoing pion
    - Good description of πA elastic with the same input

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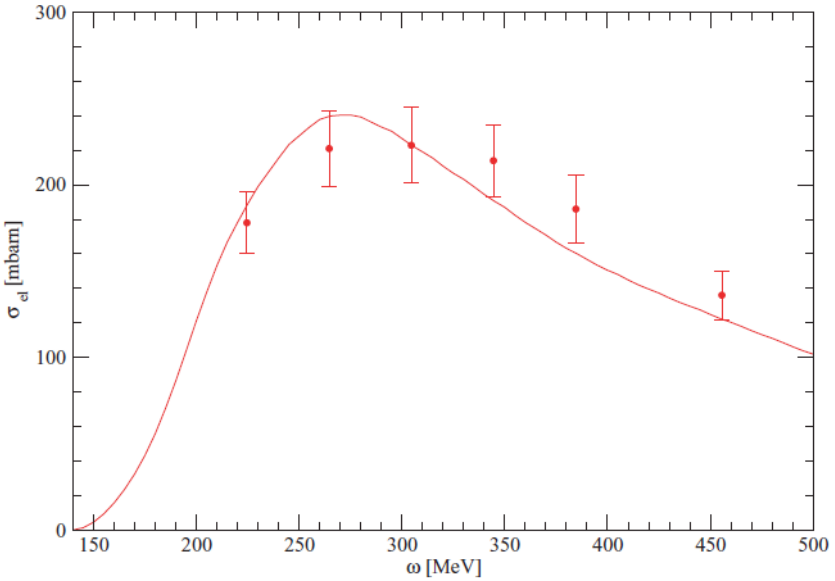

ar medium

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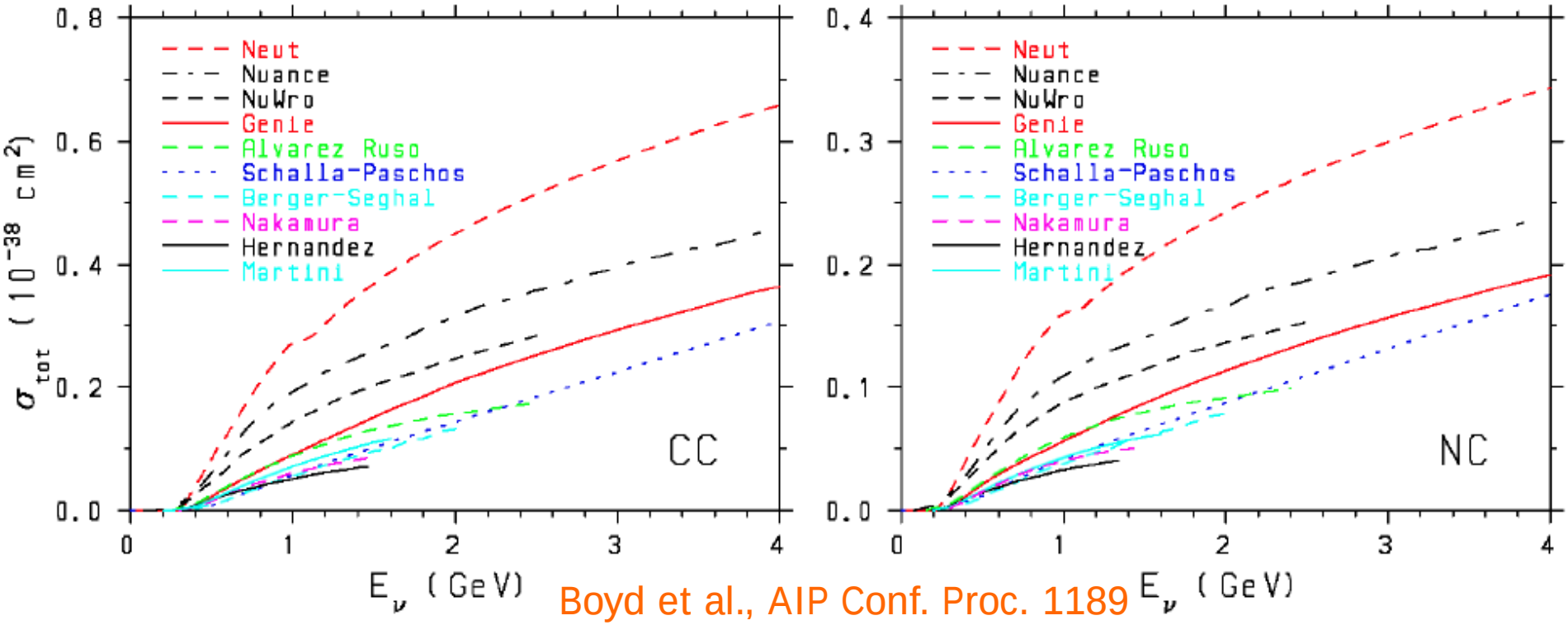
  - Dynamical model in coupled channels for $\nu\ N \rightarrow l\ N\ \pi$ (Sato & Lee)
  - Bare ΔN renormalized by meson clouds (30 %)
  - In-medium modification of Δ properties
  - π distortion based on the Δ-h model
  - Non-local treatment of Δ propagation
  - Good description of πA elastic and $\gamma\ A \rightarrow A\ \pi$
  - Significant contribution of unitarized non-resonant amplitudes at $E_\nu \leq 0.5$ GeV

All together now



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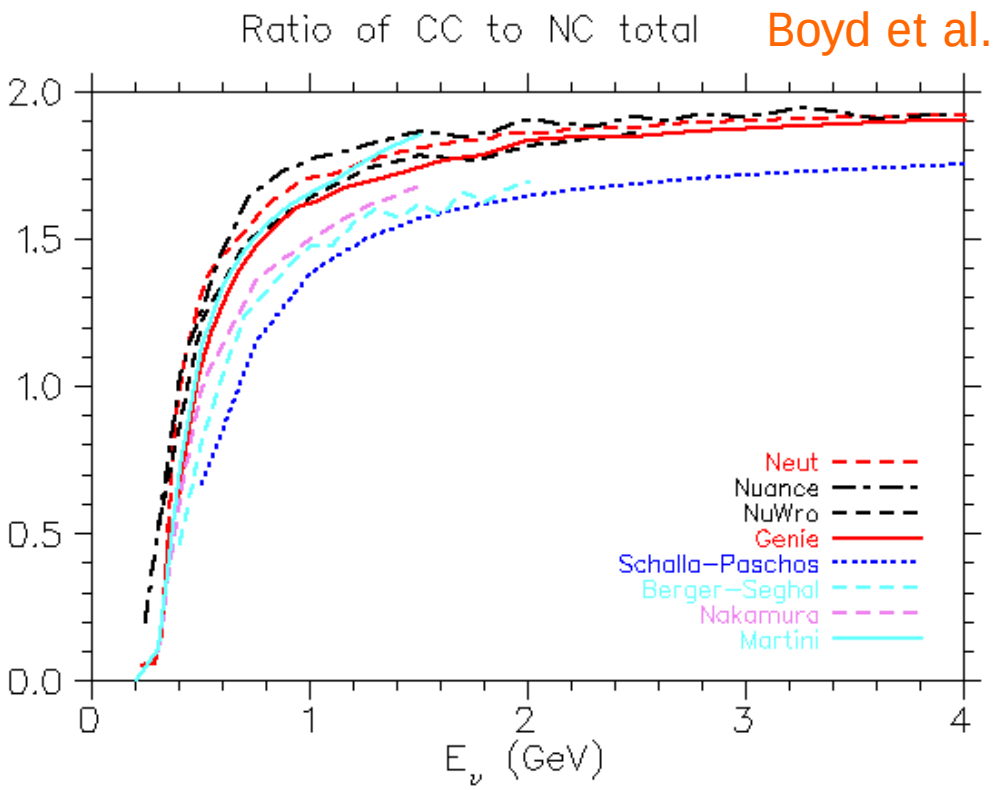
CC/NC ratio



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- SciBooNE: PRD 81 (2010)
- NC π^o σ compatible with R&S
- $CC\pi^+/NC\pi^o = 0.14^{+0.30}_{-0.28}$
- Theoretical models predict $CC\pi^+/NC\pi^o \sim$ 1-2 !

Bibliography

- J. A. Formaggio, G. P. Zeller, From eV to EeV: Neutrino cross sections across energy scales, Rev. Mod. Phys. 84 (2012)1307
- LAR, Review of weak coherent pion production, AIP Conf Proc. 1382 (2011) 161
- LAR, Y. Hayato, J. Nieves, Progress and open questions in the physics of neutrino cross sections, arXiv:1403.2673, New J. Phys.
- Hernandez et al., PRD 80 (2009) 013003

NuSTEC Training in Neutrino Nucleus Scattering Physics

- Where: Fermilab When: October 17-27, 2014
- Topics:

1. Electroweak interactions on the nucleon (3 hours)
2. Strong and electroweak interactions in nuclei (4 hours)
3. The nuclear physics of electron and neutrino scattering in nuclei in the quasi-elastic regime and beyond

3.1 Approximate methods for nuclei (I) (3 hours)

3.2 Approximate methods for nuclei (II) (3 hours)

3.3 Ab initio methods for nuclei (3 hours)

4. Pion production (3 hours)
5. Description of exclusive channels and final state interactions (3 hours)
6. Inclusive electron and neutrino scattering in the deep inelastic regime (3 hours)
7. Impact of uncertainties in neutrino cross sections (3 hours)
8. Selected experimental illustrations (4 hours)