Weak Coherent Meson Production

L. Alvarez-Ruso[1], L. Geng[2], J. Nieves[1], I. Ruiz Simo[3],
M. Valverde[4], M. Vicente Vacas[1]

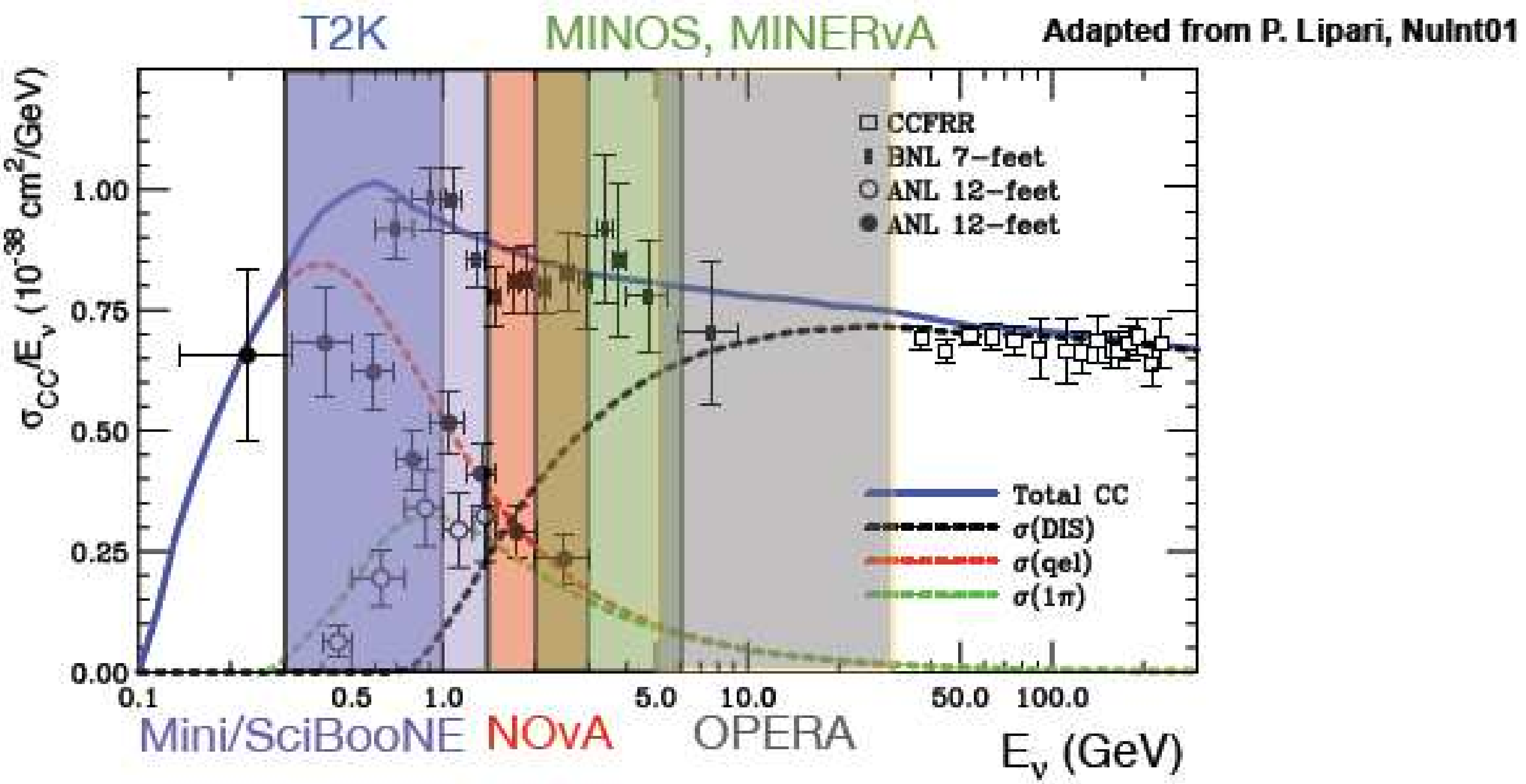
1. IFIC, Universidad de Valencia
2. BeiHang University
3. Universidad de Granada
4. RCNP, Osaka

General Introduction

- Neutrino interactions are important for:
  - Oscillation experiments
    - ν detection, E_ν reconstruction, ν flux calibration
    - Electron-like backgrounds:
      - NC π^0 production (incoherent, coherent)
      - Photon emission in NC
- Neutrino interactions are interesting for:
  - Hadronic physics
    - Nucleon and Nucleon-Resonance (N-Δ, N-N*) axial form factors
    - Strangeness content of the nucleon spin
  - Nuclear physics
    - Information about: nuclear correlations, MEC, spectral functions
    - nuclear effects: essential for the interpretation of the data

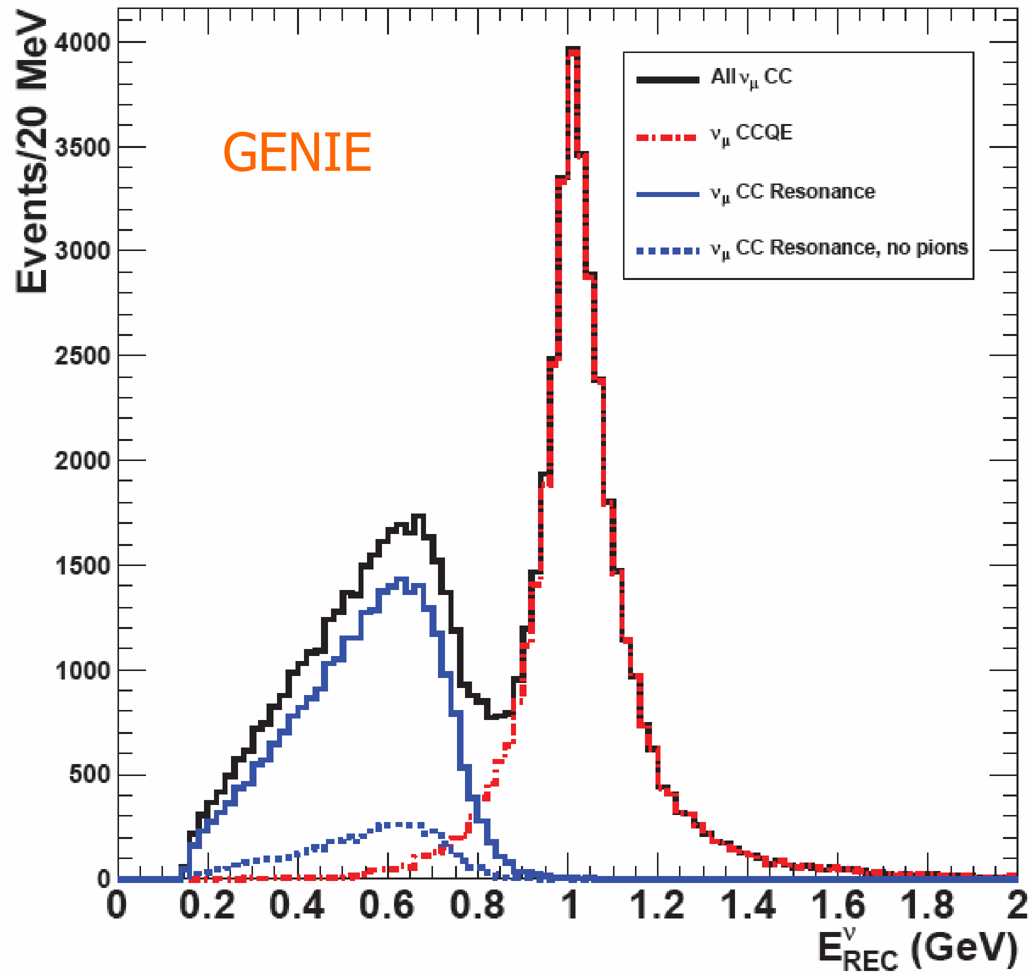
Motivation: 1π production

- CC: $\nu_l\, N \to l^-\, \pi\, N'$
- NC: $\nu_l\, N \to \nu_l\, \pi\, N'$



Motivation: 1π production

- CC: $\nu_l \, N \rightarrow l^- \, \pi \, N'$
  - source of CCQE-like events (in nuclei)
  - needs to be subtracted for a good E_ν reconstruction Leitner, Mosel, PRC81



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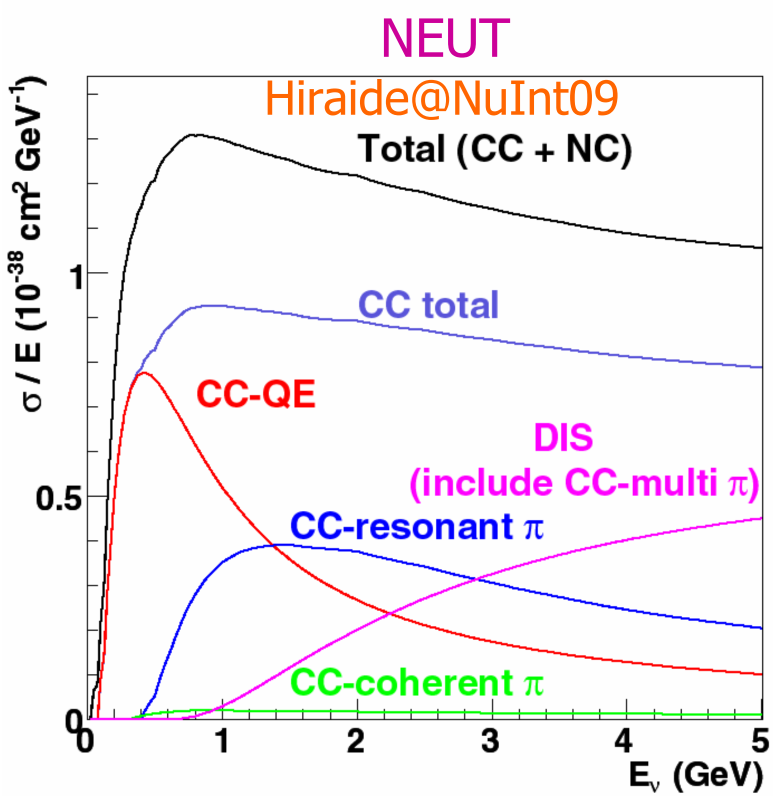
  - source of CCQE-like events (in nuclei)
  - needs to be subtracted for a good E_ν reconstruction

- NC: $\nu_l \, N \rightarrow \nu_l \, \pi \, N'$
  - π^o: e-like background to $\nu_\mu \rightarrow \nu_e$ searches

Coherent pion production

- CC $\nu_l \, A \to l^- \, \pi^+ \, A$
- NC $\nu \, A \to \nu \, \pi^0 \, A$
- Takes place at low q^2
- 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.



Coherent pion production

- CC $\nu_l \, A \rightarrow l^- \, \pi^+ \, A$
- NC $\nu \, A \rightarrow \nu \, \pi^0 \, A$
  - 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

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

$q=k-k'$ ← transferred by the ν

$t=(q-p_\pi)^2$ ← transferred to the nucleus

$y=q^0/E_\nu$

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

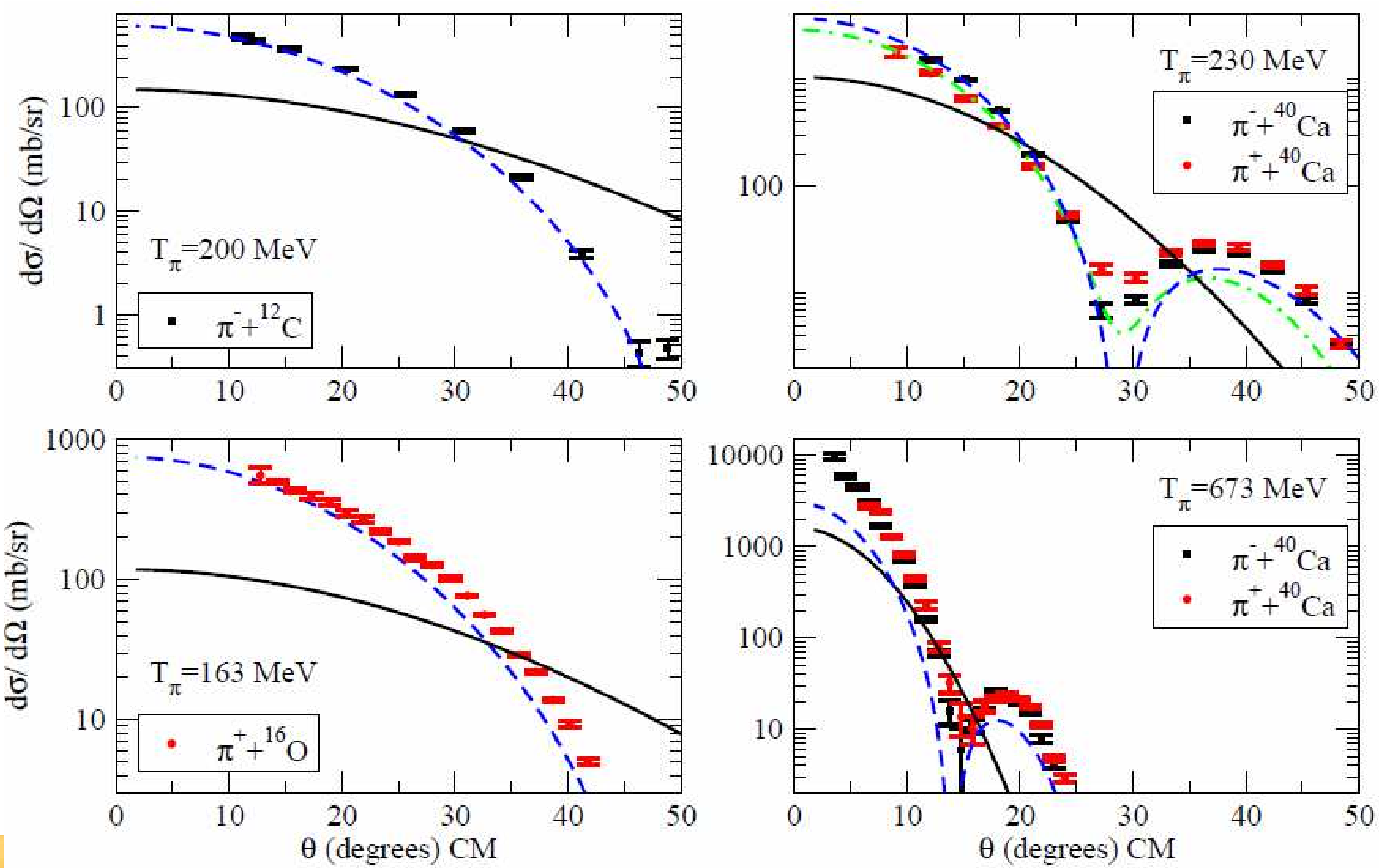
$$\times |F_{\mathcal{A}}(t)|^2 F_{\mathrm{abs}} \left(\frac{d\sigma}{dt}(\pi^0 N \to \pi^0 N)\right)_{t=0,\, E_\pi=q^0}$$

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

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

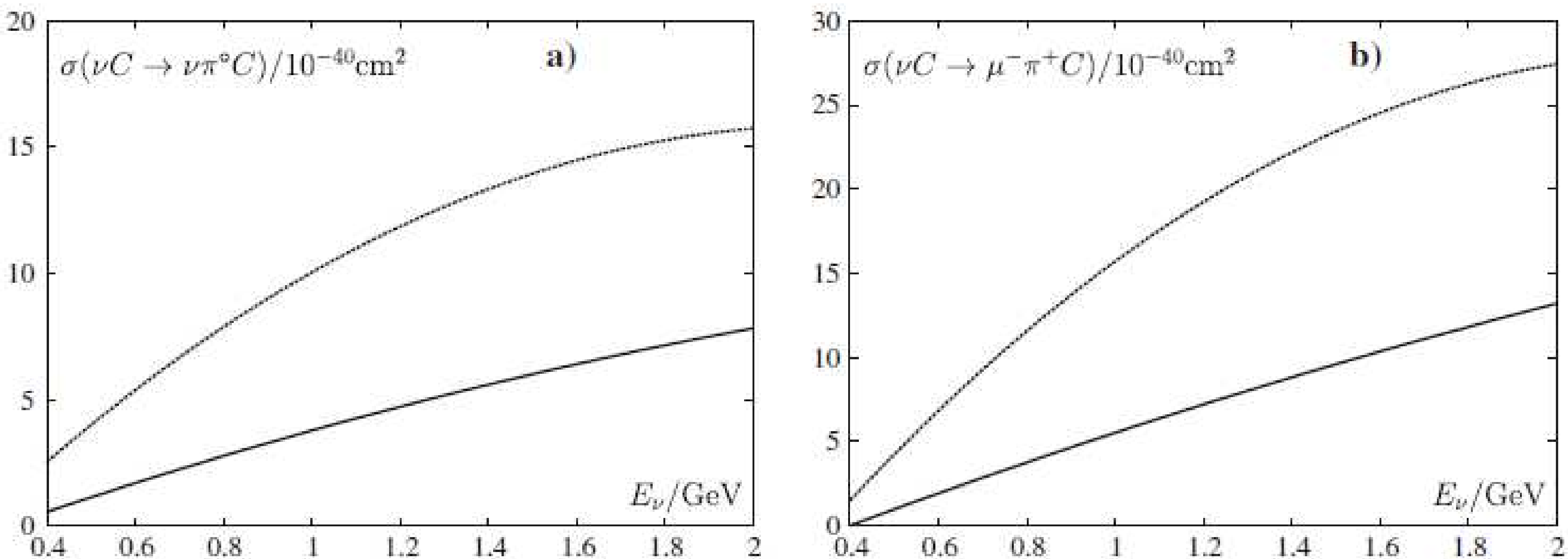
PCAC models

- 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

- 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:



R & S

B & S

Microscopic approach

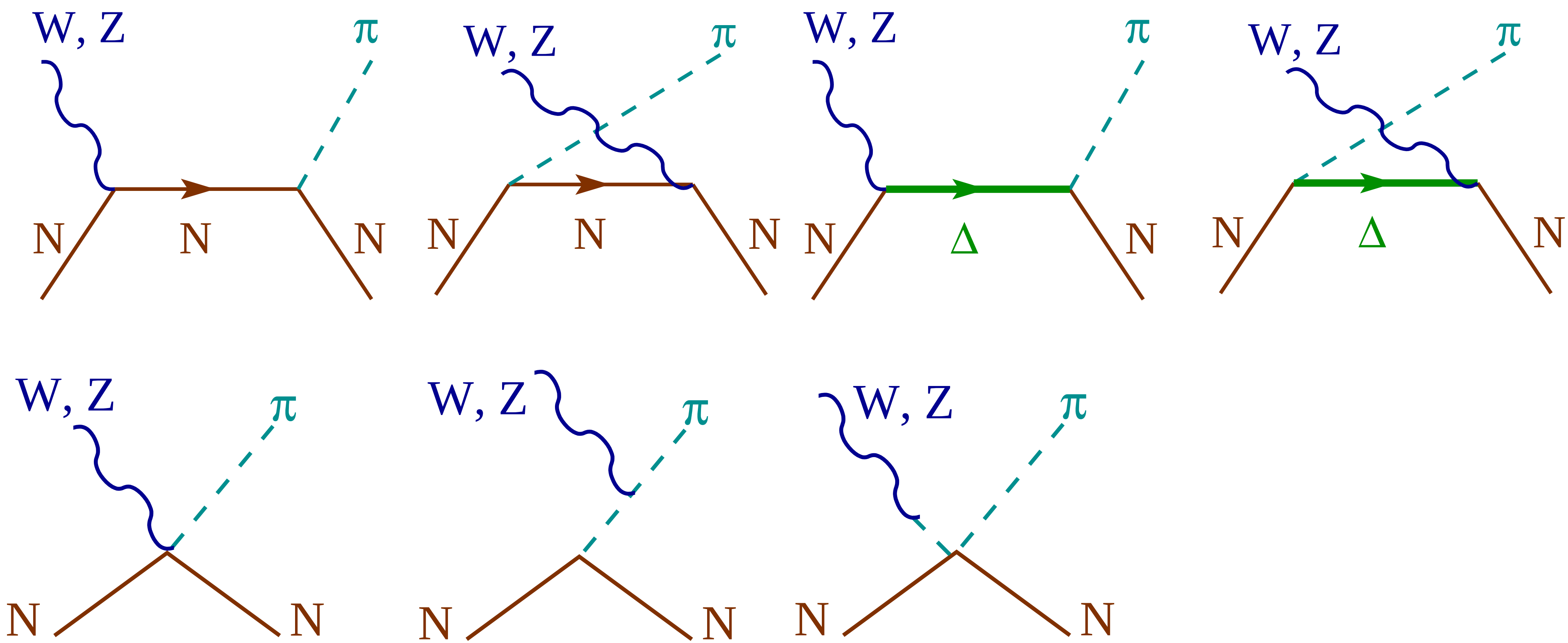
- Kelkar et al., PRC55 (1997); Singh et al., PRL 96 (2006); LAR et al., PRC 75, 76 (2007); Amaro et al., PRD 79 (2009), Hernandez et al., PRD 82 (2010); Leitner et al., PRC 79 (2009); Martini et al., PRC 80 (2009); Nakamura et al, PRC 81 (2010)

  - Model for the elementary $\nu \ N \to \ l \ N \ \pi$ 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

Microscopic approach

- Model for the elementary $\nu\ N \to\ l\ N\ \pi$ amplitude



Hernandez, PRD 76 (2006)

Microscopic approach

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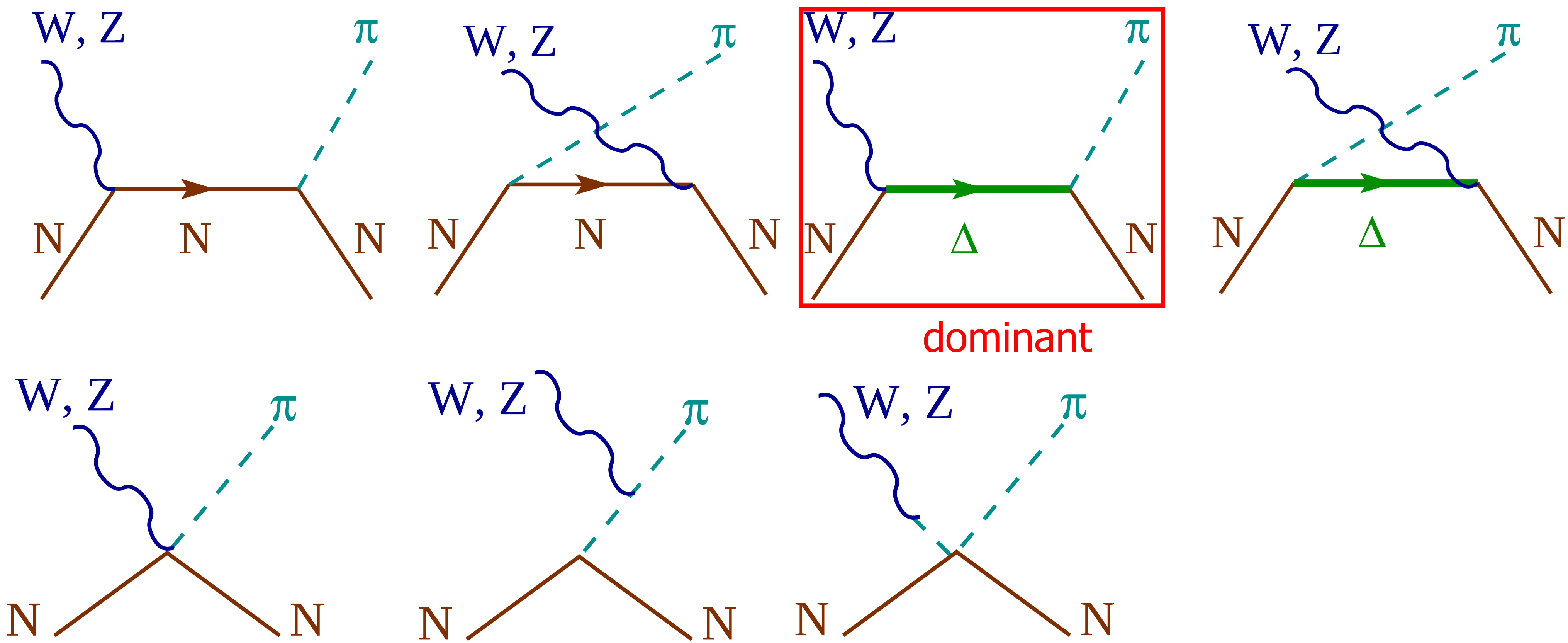

Hernandez, PRD 76 (2006)

Microscopic approach

- The amplitude for CC π^+ production:

$$\mathcal{M} = \frac{G}{\sqrt{2}} \cos\theta_c \, l_\mu J^\mu$$

- $J^\mu \leftarrow$ Nuclear current $\Leftrightarrow$ sum over all nucleons
- For the dominant direct Δ mechanism:

$$J^\mu = -\frac{\sqrt{3}}{2} i \int d\vec{r}\, e^{i\vec{q}\cdot\vec{r}} \left[\rho_p(r) + \frac{\rho_n(r)}{3}\right] \frac{f^*}{m_\pi} D_\Delta \, p_\pi^\alpha \, \mathrm{Tr}\left[\bar{u}\Lambda_{\alpha\beta}\mathcal{A}^{\beta\mu}u\right] \phi^*_{\mathrm{out}}$$

$D_\Delta \leftarrow$ propagator

$\Lambda_{\alpha\beta} \leftarrow$ spin 3/2 projection operator

$j^\mu = \bar{\psi}_\beta \mathcal{A}^{\beta\mu} u \leftarrow$ N-Δ weak current

$\phi^*_{\mathrm{out}} \leftarrow$ spin 3/2 projection operator

Microscopic approach

- N-Δ transition current

$$\mathcal{A}^{\beta\mu} = \left(\frac{C_3^V}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2}(g^{\beta\mu}q\cdot p - q^\beta p^\mu) + g^{\beta\mu}C_6^V \right)\gamma_5$$
$$+ \frac{C_3^A}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2}q^\beta q^\mu$$

- Helicity amplitudes can be extracted from data on π photo- and electro-production

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = -1/2 \right\rangle \zeta$$
$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 3/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$
$$S_{1/2} = -\sqrt{\frac{2\pi\alpha}{k_R}} \frac{|\mathbf{q}|}{\sqrt{Q^2}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^0 J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

- Helicity amplitudes $\Rightarrow$ Vector form factors

Microscopic approach

- N-Δ transition current

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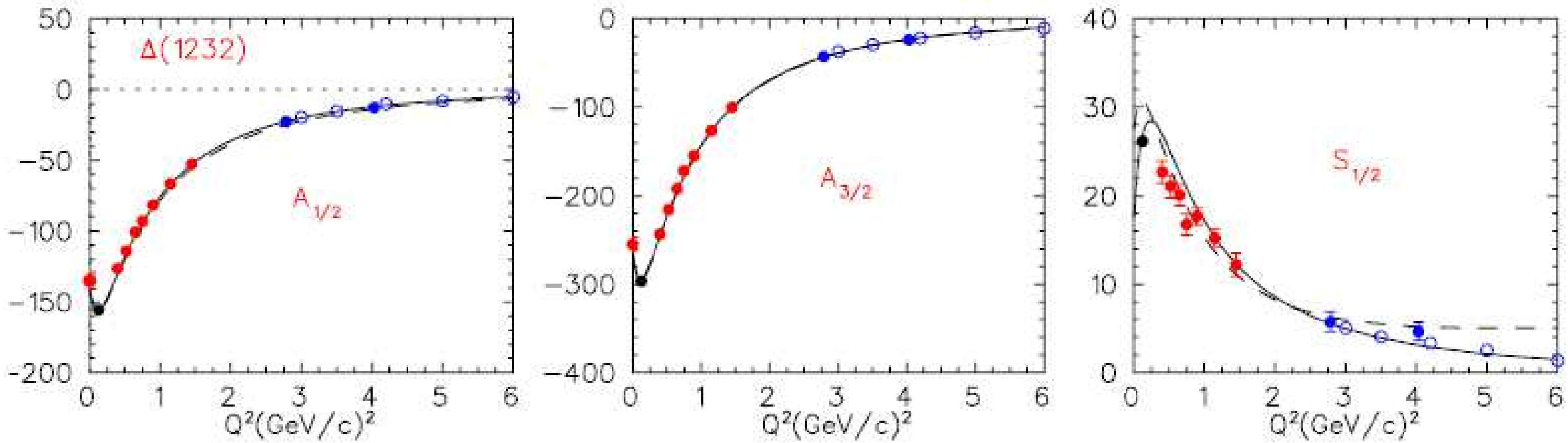
$$+ \frac{C_3^A}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2}q^\beta q^\mu$$

- Helicity amplitudes can be extracted from data on π photo- and electro-production (e.g. MAID)



- Helicity amplitudes $\Rightarrow$ Vector form factors

Microscopic approach

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- Axial form factors

$$C_6^A = C_5^A \frac{M^2}{m_\pi^2 + Q^2} \leftarrow \text{PCAC}$$

$$C_4^A = -\frac{1}{4} C_5^A \quad C_3^A = 0 \leftarrow \text{Adler model}$$

$$C_5^A = C_5^A(0)\left(1 + \frac{Q^2}{M_{A\Delta}^2}\right)^{-1}$$

Microscopic approach

- $\sigma \sim \left[C_5^A(0)\right]^2$

$$C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6}M} \approx 1.2 \leftarrow$$ off diagonal GT relation

- From ANL and BNL data on $\nu_\mu \, d \rightarrow \mu^- \, \pi^+ \, p \, n$
  - Hernandez et al., PRD 81 (2010)
  - Deuteron effects
  - Non-resonant background
  - $C^A_5(0) = 1.00 \pm 0.11$ GeV
  - 20 % reduction of the GT relation

Microscopic models

- Delta in the medium:

$$D_\Delta \Rightarrow \tilde{D}_\Delta(r) = \frac{1}{(W+M_\Delta)(W-M_\Delta-\mathrm{Re}\Sigma_\Delta(\rho)+i\tilde{\Gamma}_\Delta/2-i\mathrm{Im}\Sigma_\Delta(\rho))}$$

$\tilde{\Gamma}_\Delta \leftarrow$ Free width $\Delta \to N\,\pi$ modified by Pauli blocking

$$\mathrm{Re}\Sigma_\Delta(\rho) \approx 40\mathrm{MeV}\frac{\rho}{\rho_0}$$

$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$ many-body processes:

- $\Delta\, N \to N\, N$
- $\Delta\, N \to N\, N\, \pi$
- $\Delta\, N\, N \to N\, N\, N$

Microscopic approach

- Pion distortion: $\phi^*_{out}(\vec{p}_\pi, \vec{r}) \leftarrow$ solution of the Klein-Gordon equation

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

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

Nieves, Oset & Garcia Recio NPA 554 (93)

$$2\omega_\pi \hat{V}_{opt}(\vec{r}) = 4\pi \frac{M^2}{s} \left[\vec{\nabla} \cdot \frac{\mathcal{P}(r)}{1 + 4\pi g' \mathcal{P}(r)} \vec{\nabla} - \frac{1}{2} \frac{\omega}{M} \Delta \frac{\mathcal{P}(r)}{1 + 4\pi g' \mathcal{P}(r)} \right]$$

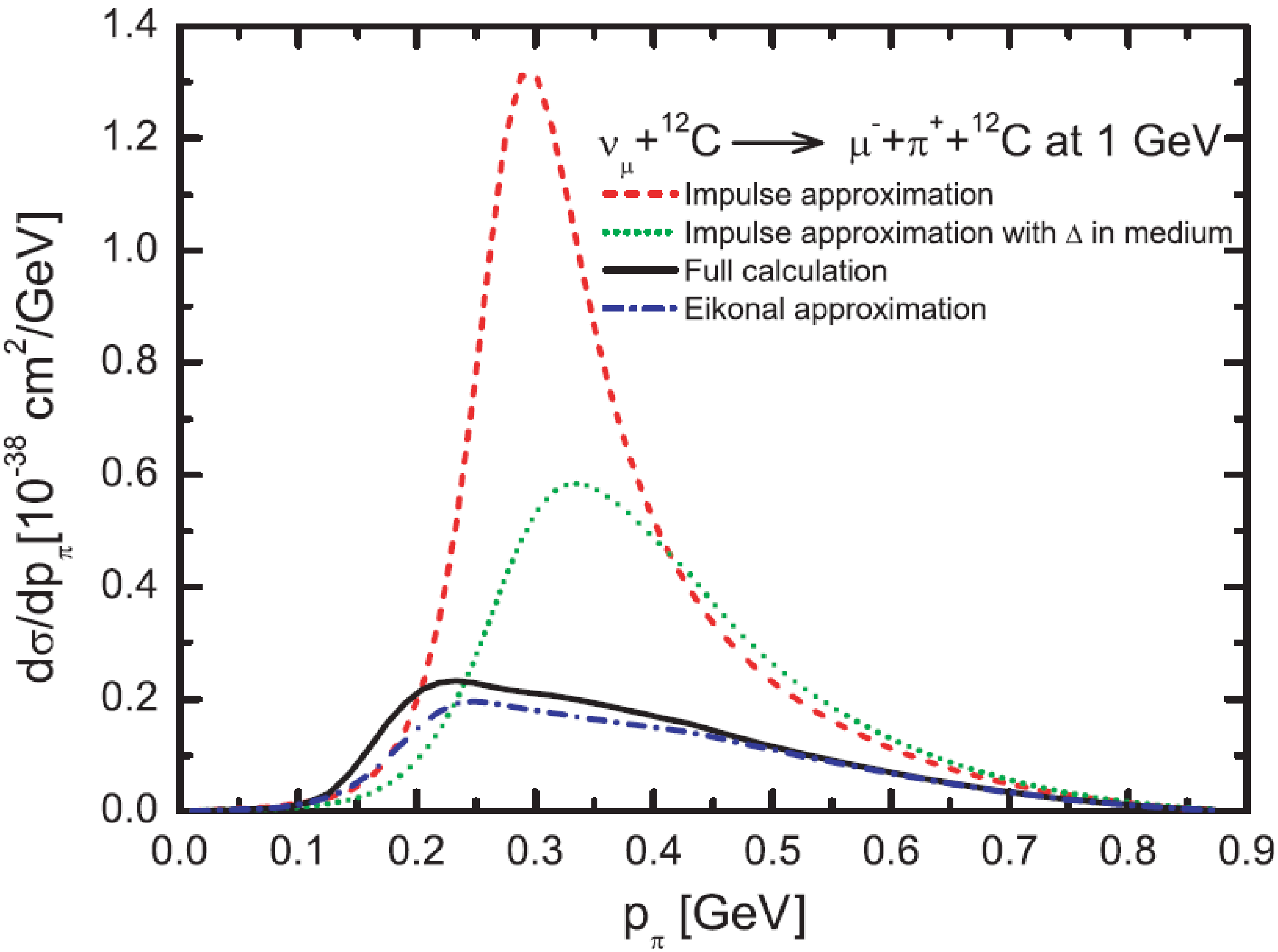
$$\mathcal{P} = -\frac{1}{6\pi} \left(\frac{f^*}{m_\pi} \right)^2 \left\{ \frac{\rho_p + \rho_n/3}{\sqrt{s} - M_\Delta - {\rm Re}\Sigma_\Delta + i\tilde{\Gamma}_\Delta/2 - i\,{\rm Im}\Sigma_\Delta} + \frac{\rho_n + \rho_p/3}{-\sqrt{s} - M_\Delta + 2M - {\rm Re}\Sigma_\Delta} \right\}$$

Direct Crossed

Δ–hole excitations

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

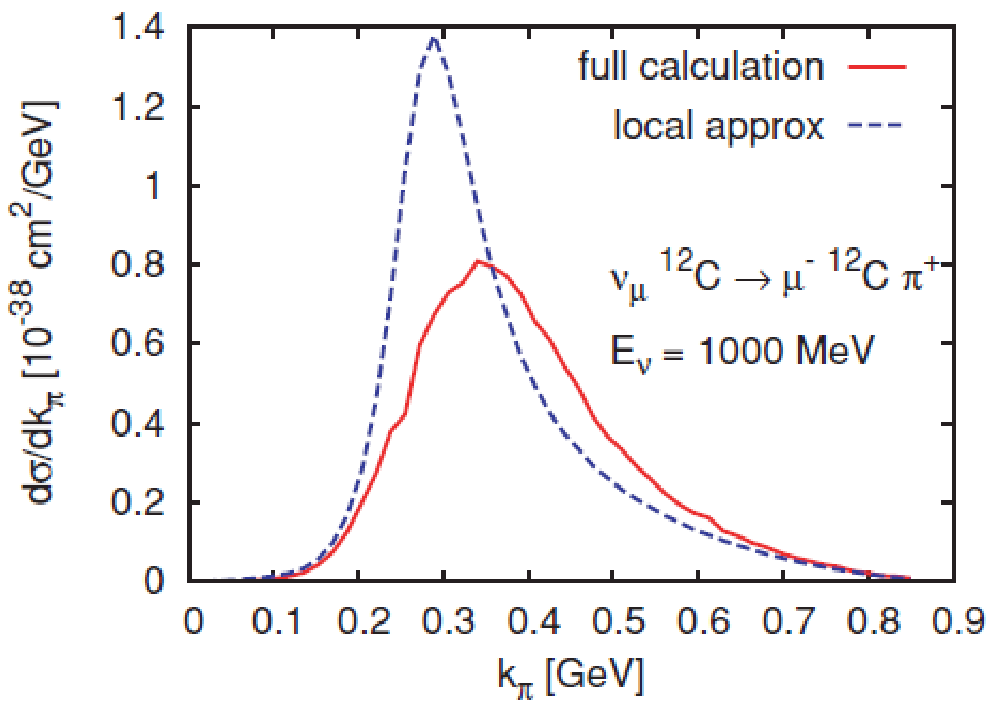
Microscopic approach



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

Microscopic models

- Non-local treatment of Δ propagation:
  - Leitner et al., PRC 79 (2009).
  - PWIA with bound state spinors in a mean field
  - $\sigma/\sigma_{local} \sim$ 0.5, 0.6 for E_ν =0.5, 1 GeV



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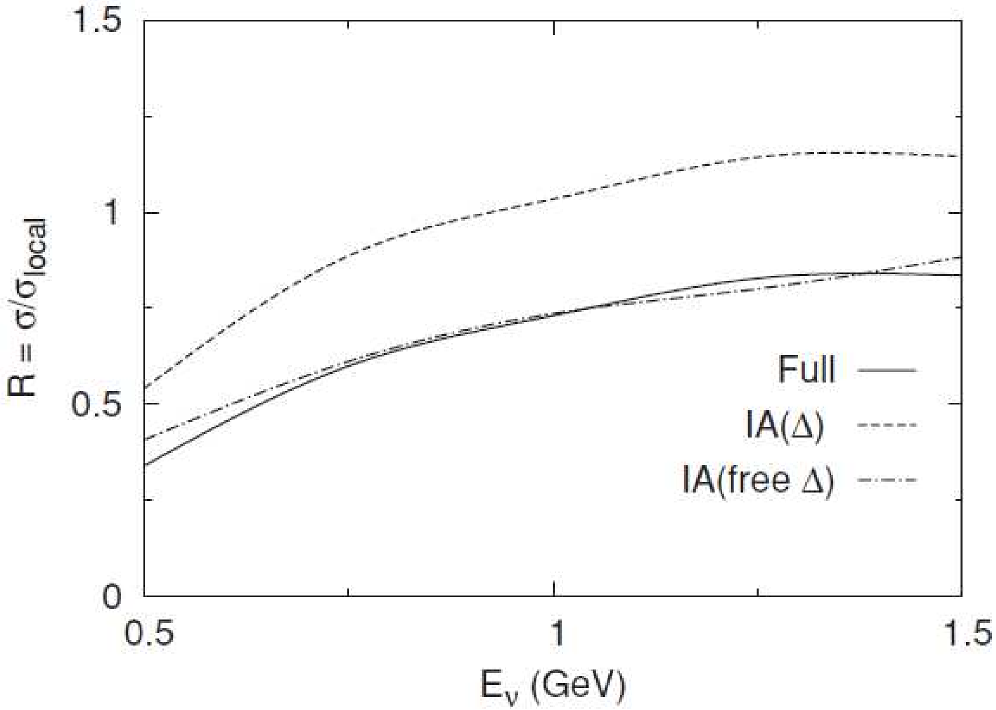
  - Nakamura et al, PRC 81 (2010)
  - Large effect persists with Δ modification and π distortion



Microscopic models

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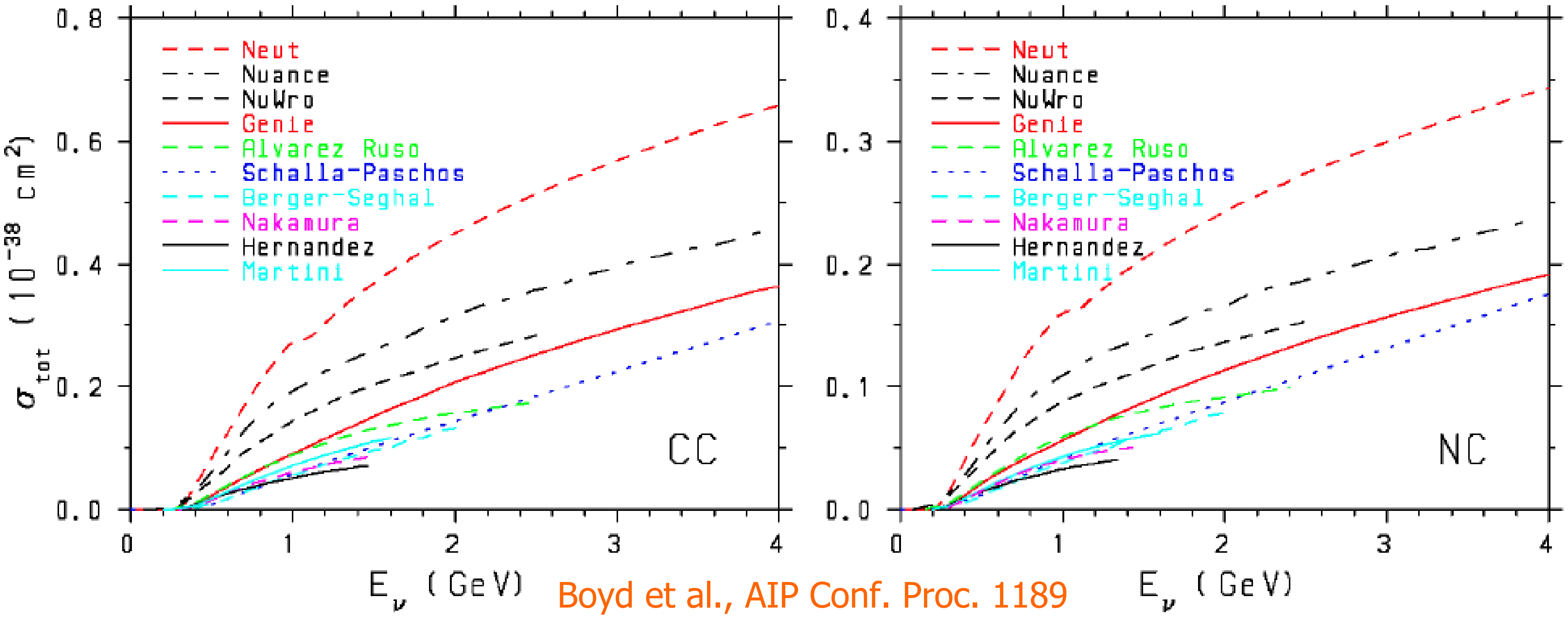
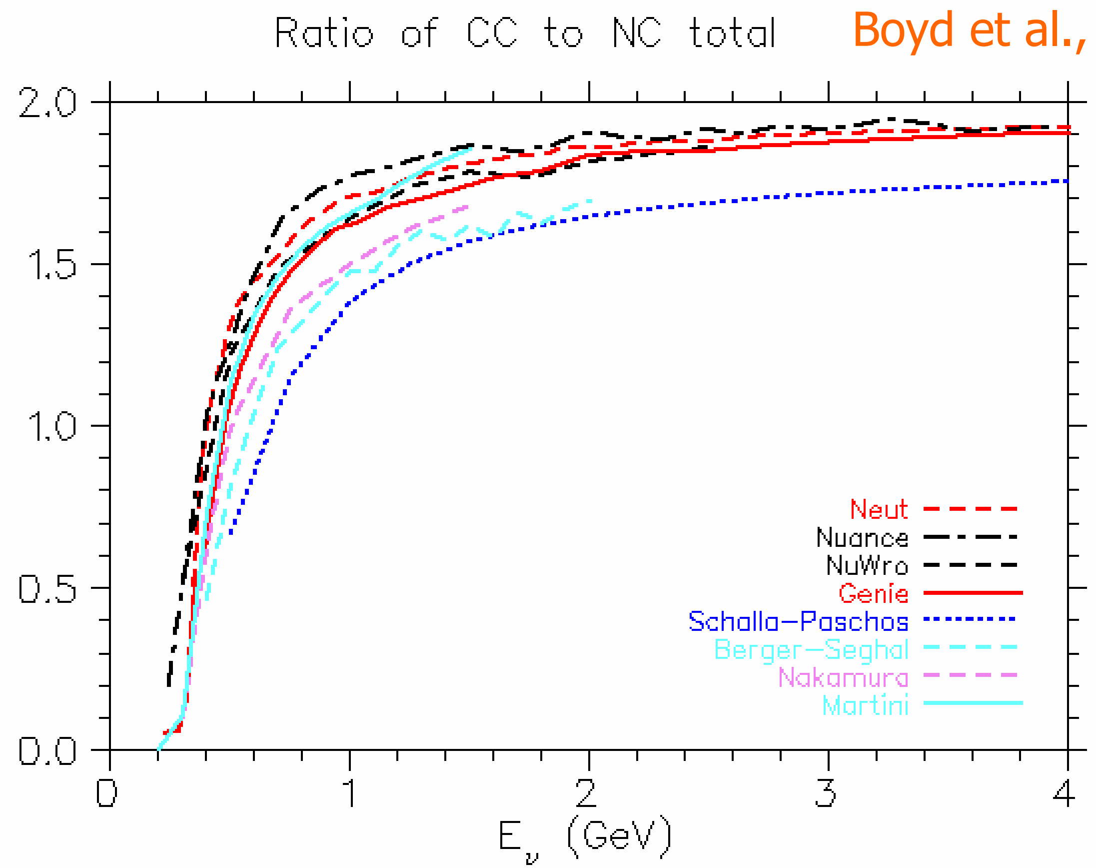
  - PWIA with bound state spinors in a mean field
  - $\sigma / \sigma_{local} \sim$ 0.5, 0.6 for E_ν =0.5, 1 GeV
  - Nakamura et al, PRC 81 (2010)
  - Large effect persists with Δ modification and π distortion
  - In local models: is this effect "operationally included" in the Δ mass shift?

CC/NC ratio



Boyd et al., AIP Conf. Proc. 1189

CC/NC ratio



Boyd et al., AIP Conf. Proc. 1189

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

Strangeness production

- ΔS = 0 e.g. $\nu_l\, p(n) \to l^-\, K^+\, \Sigma^+(\Lambda)$
- ΔS = 1 :
  - Cabibbo suppressed but with lower thresholds than ΔS = 0
  - Hyperon e.g. $\bar{\nu}_l\, p \to l^+\, \Sigma^0(\Lambda)$
  - Kaon: $$\begin{aligned} \nu_l\, p &\to l^-\, K^+\, p \\ \nu_l\, n &\to l^-\, K^0\, p \\ \nu_l\, n &\to l^-\, K^+\, n \end{aligned}$$

- Accessible by Minerνa but also MiniBooNE, T2K, …
- Background for proton decay p $\to \nu$ K^+
- There is a coherent channel $\nu_l\, A \to l^-\, K^+\, A$

Strangeness production

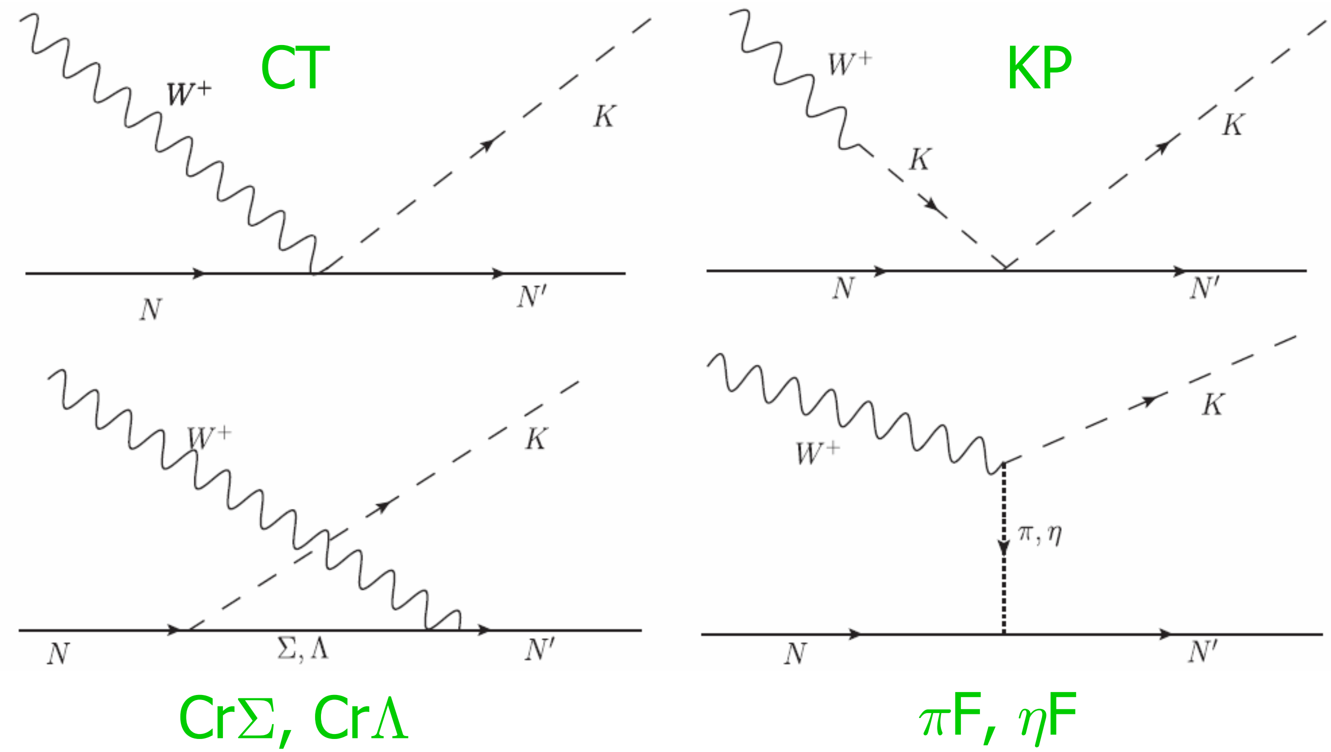
- ΔS = 0 e.g. $\nu_l \, p(n) \rightarrow l^- \, K^+ \, \Sigma^+ (\Lambda)$
- ΔS = -1 :
  - Cabibbo suppressed but with lower thresholds than ΔS = 0
  - antiKaon:

$$\bar{\nu}_l \, p \rightarrow l^+ \, K^- \, p$$
$$\bar{\nu}_l \, p \rightarrow l^+ \, \bar{K}^0 \, n$$
$$\bar{\nu}_l \, n \rightarrow l^+ \, K^- \, n$$

- Accessible by Minerνa but also MiniBooNE, T2K, …
- Potentially interesting for antiν beams
- There is a coherent channel $\bar{\nu}_l \, A \rightarrow l^+ \, K^- \, A$

K production model

- Microscopic K production on the nucleon Rafi Alam et al., PRD82
  - Includes all terms in SU(3) chiral Lagrangians at leading order



  - Parameters: f_π , μ_p and μ_n , D and F (from semileptonic decays)
  - A global dipole form factor : $F(q^2)=(1-q^2/M^2_F)^{-2}$, M_F = 1 GeV
  - Absence of S=1 baryon resonances $\Rightarrow$ Extended validity of model

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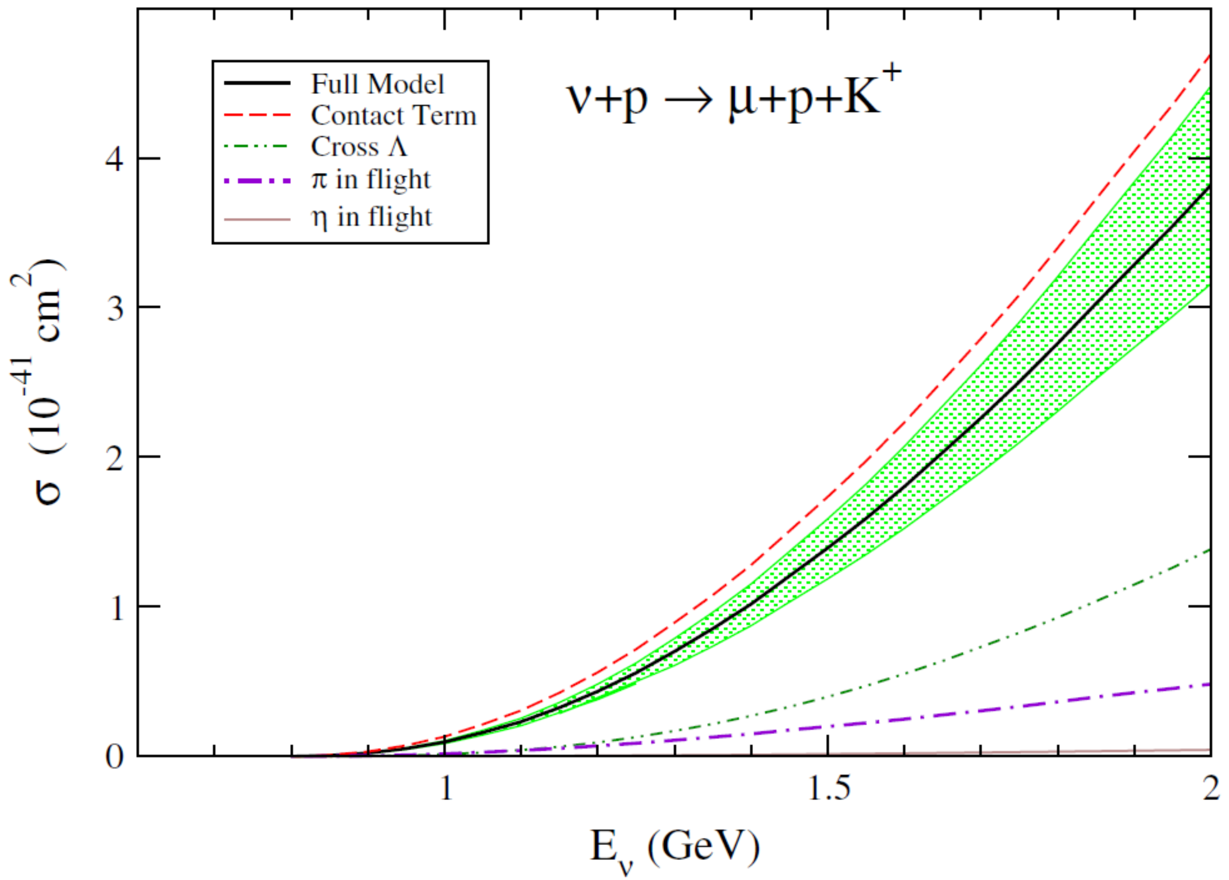
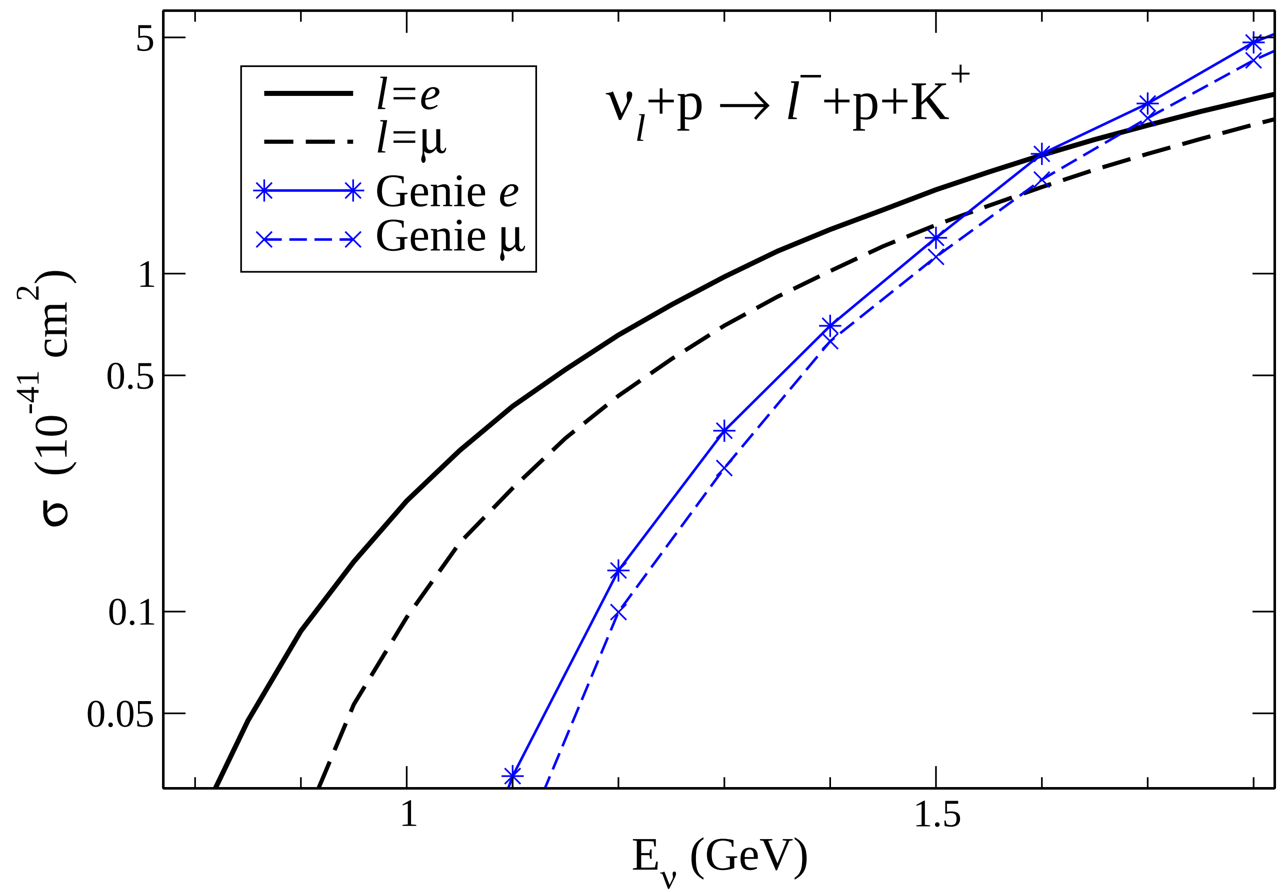


  - A global dipole form factor : $F(q^2)=(1-q^2/M^2_F)^{-2}$, M_F = 1 GeV (+- 10%)

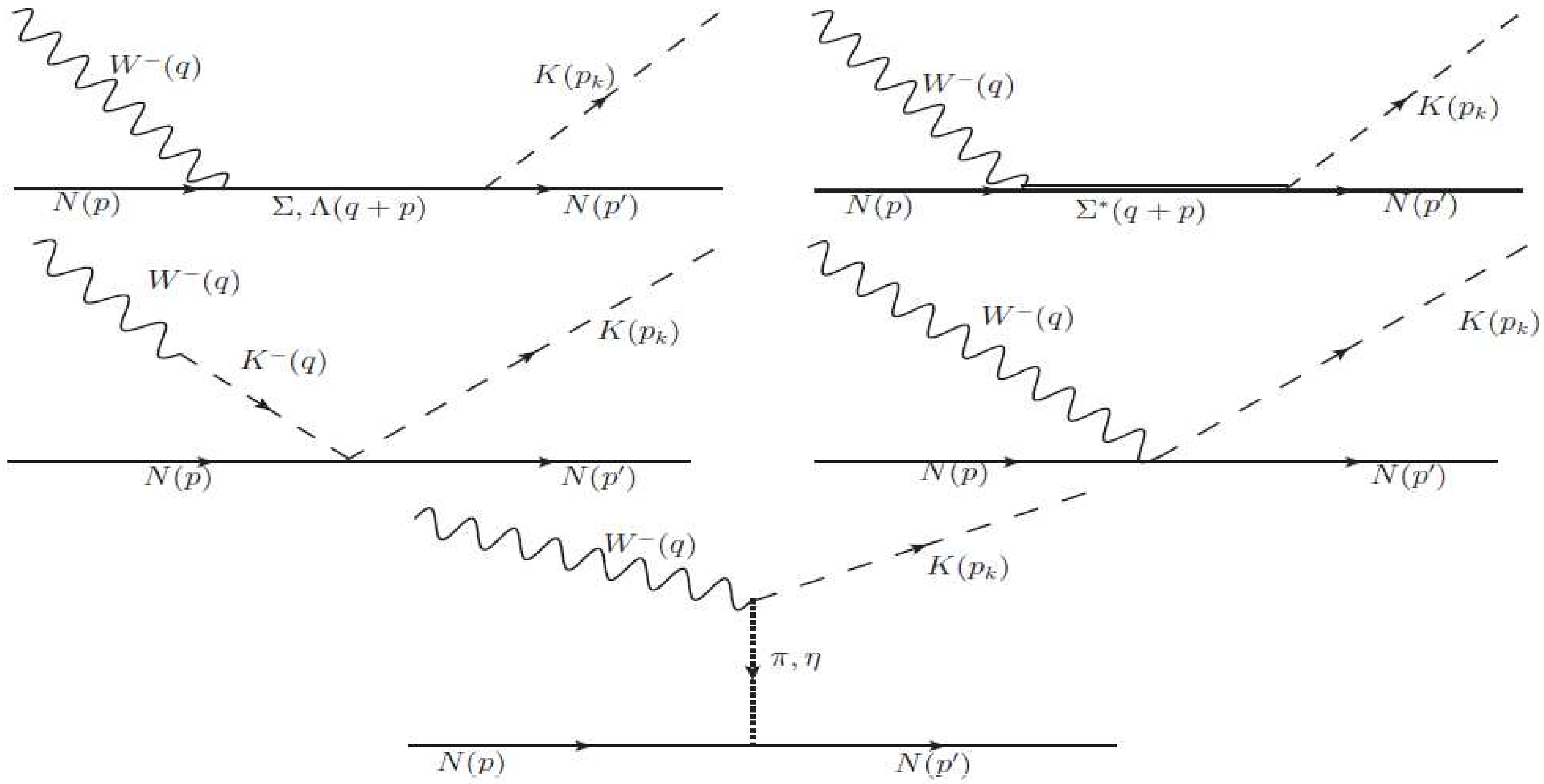
K production model

- Microscopic K production on the nucleon Rafi Alam et al., PRD82
  - vs $\Delta S = 0$ from GENIE



Kbar production model

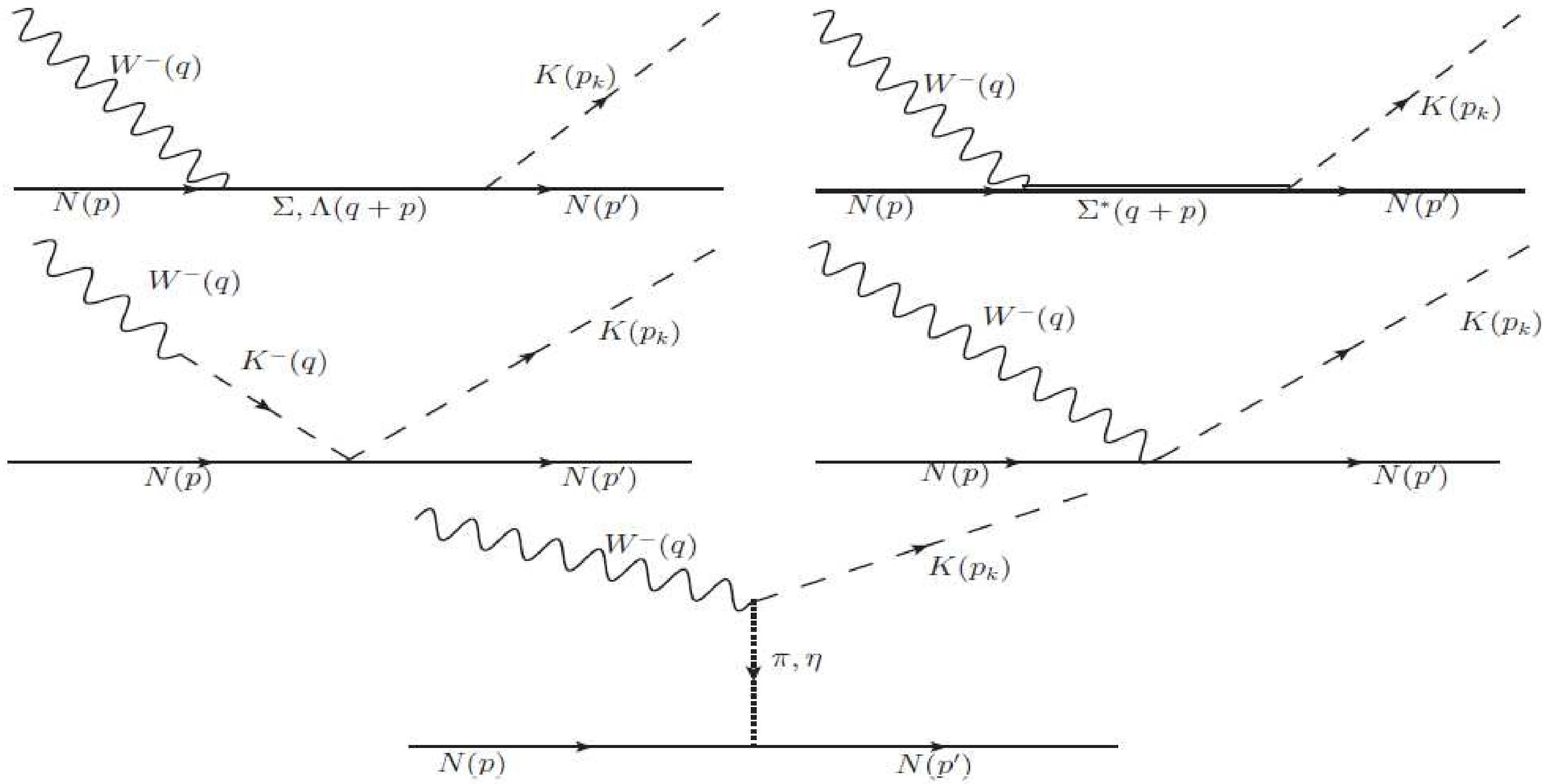
- Microscopic Kbar production on the nucleon Rafi Alam et al., PRD85



- Direct terms with strange baryons (Λ, Σ, Σ*(1385)) in the intermediate state

Kbar production model

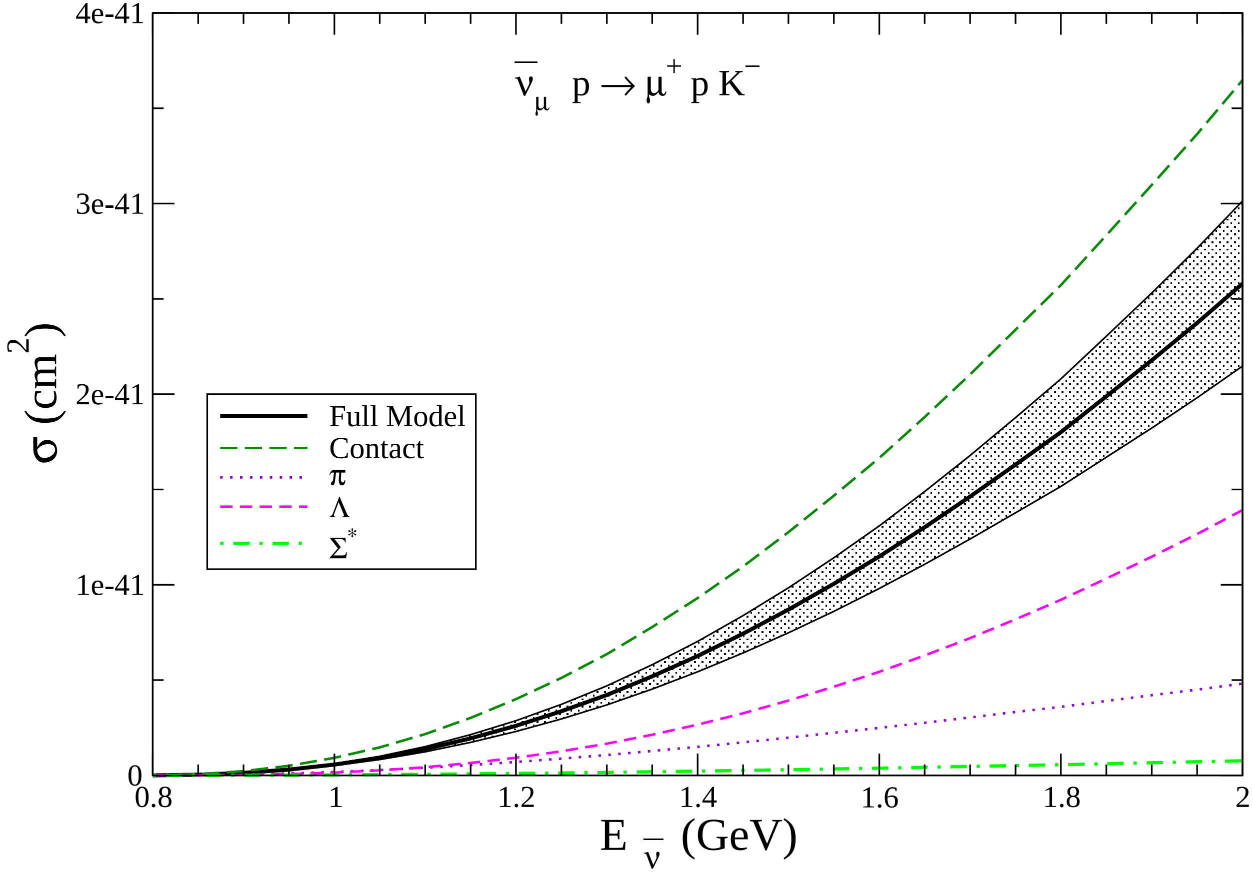
- Microscopic Kbar production on the nucleon Rafi Alam et al., PRD85



  - N- Σ*(1385) transition: C3V, C4V, C5V, C3A, C4A, C5A, C6A form factors related to those of N-Δ(1232) using SU(3) symmetry
  - In particular: C5A(0) $\leftarrow$ off-diagonal G-T

Kbar production model

- Microscopic Kbar production on the nucleon Rafi Alam et al., PRD85



- Small contribution from Σ*(1385): it is below Kbar production threshold

The coherent reaction

- Amplitude: $\mathcal{M} = \frac{G}{\sqrt{2}} \sin\theta_c \, l_\mu J^\mu$
- 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

- Kaon distortion:

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

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

The coherent reaction

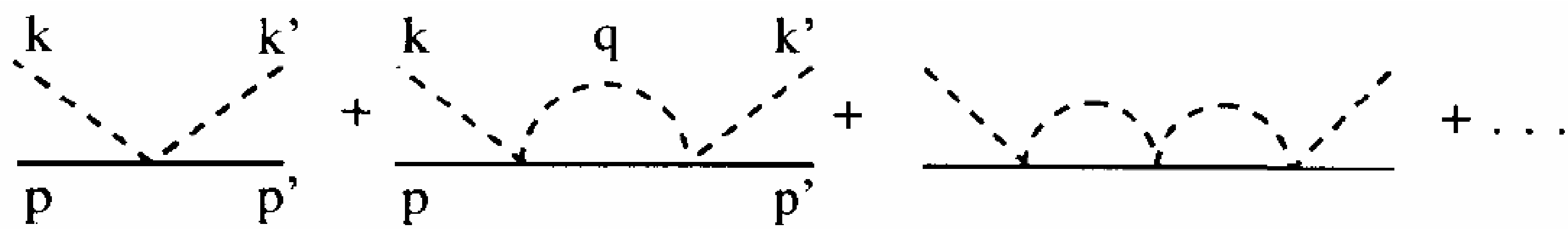
- K^+ optical potential

$$2\omega_K V_{\rm opt} = \Pi(r) = C m_K^2 \frac{\rho}{\rho_0} - i|\vec{p}_K| \sum_{N=p,n} \rho_N \, \sigma_{\rm tot}^{(K^+N)}$$

  - Well described in the $t\rho$ limit
  - Re(V_{opt}) :
    - Repulsive
    - Dominated by a Weinberg-Tomozawa term
      Waas et al., PLB 379(1996)
  - Im(V_{opt}) :
    - K N $\rightarrow$ K' N' (QE & CX)
    - K N $\rightarrow$ K' N' π
    - $\sigma_{tot} \leftarrow$ GiBUU parametrizations Buss et al., Phys. Rep. 512 (2012)

The coherent reaction

- K^- optical potential
  - K^-p interaction dominated by $\Lambda(1405)$ resonance
  - $\Lambda(1405)$ dynamically generated by s-wave meson-baryon rescattering in coupled channels

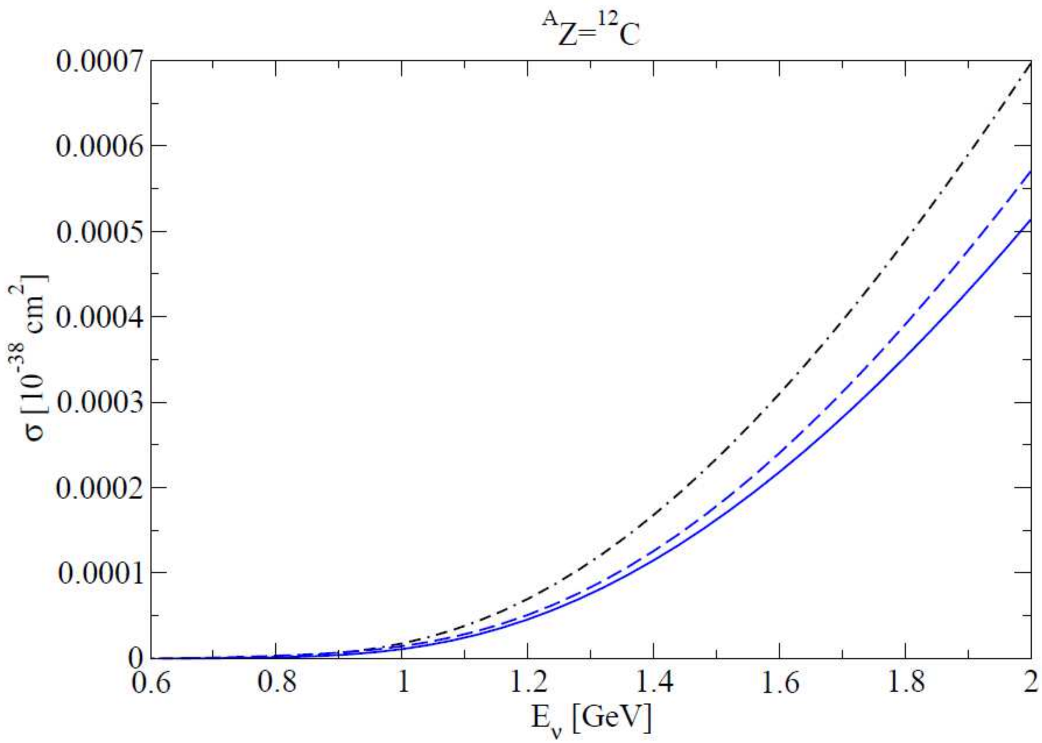


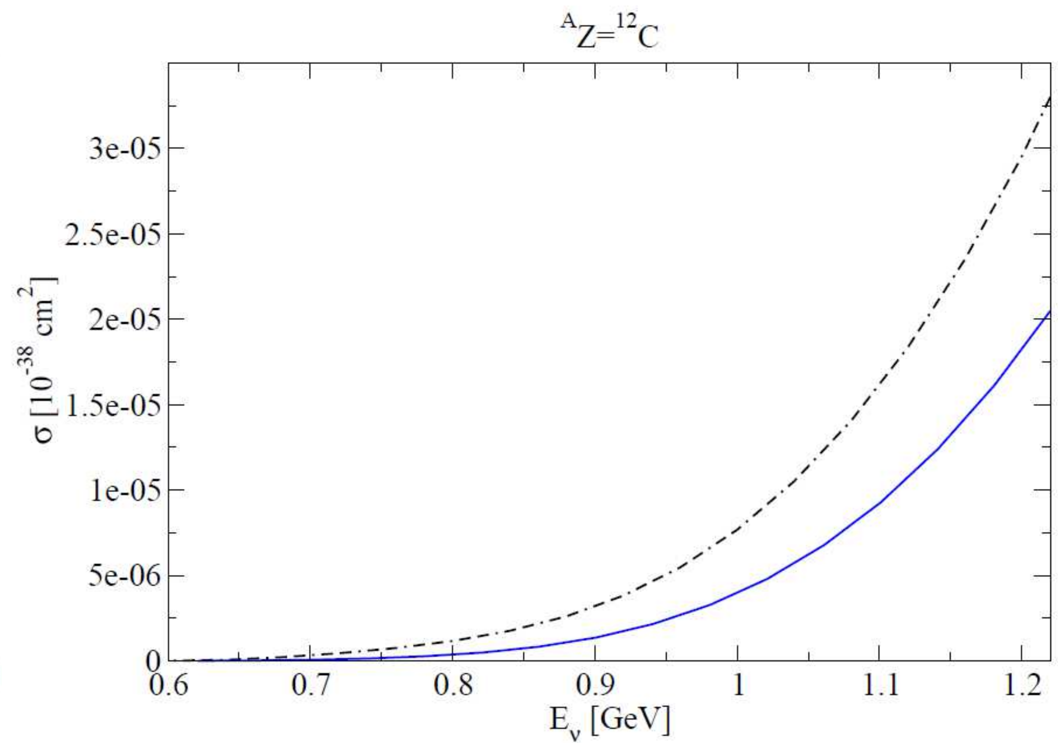
  - Dressing of meson propagators (1p1h, Δh)
  - Self consistent treatment of K^-
  - Ramos & Oset, NPA 671 (2000)

The coherent reaction

- Results:

$\nu_\mu \, A \to \mu^- \, K^+ \, A$ $\qquad\qquad$ $\bar{\nu}_\mu \, A \to \mu^+ \, K^- \, A$





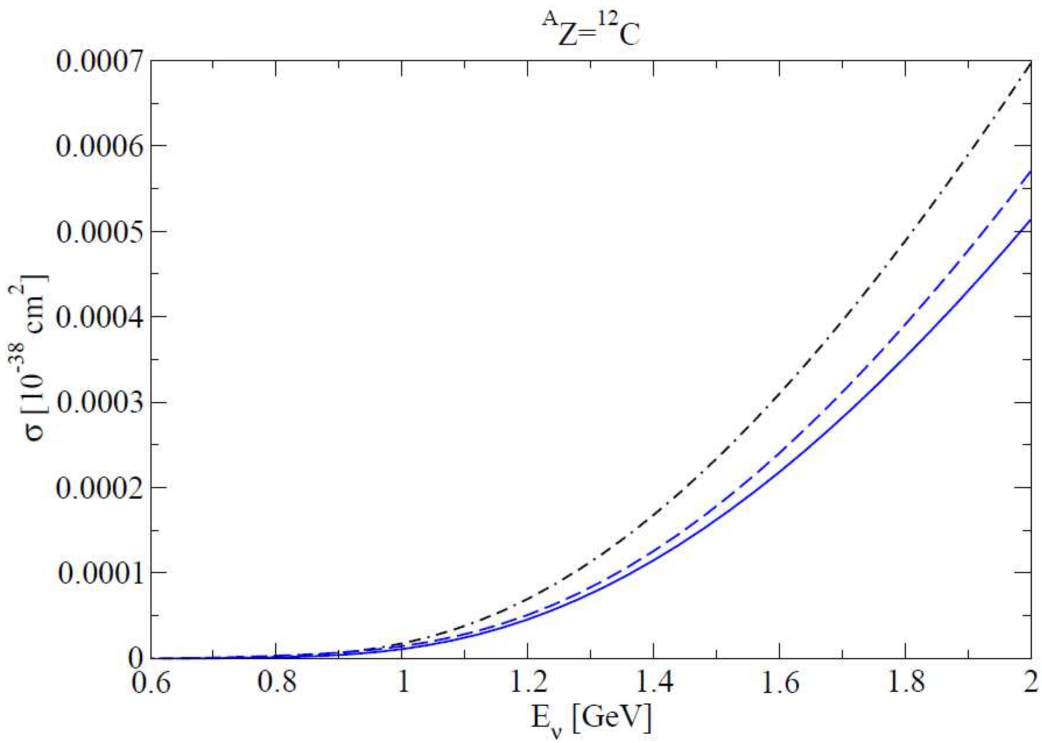
- Very small cross section...
- Compare to Cohπ^+ (on ^{12}C):

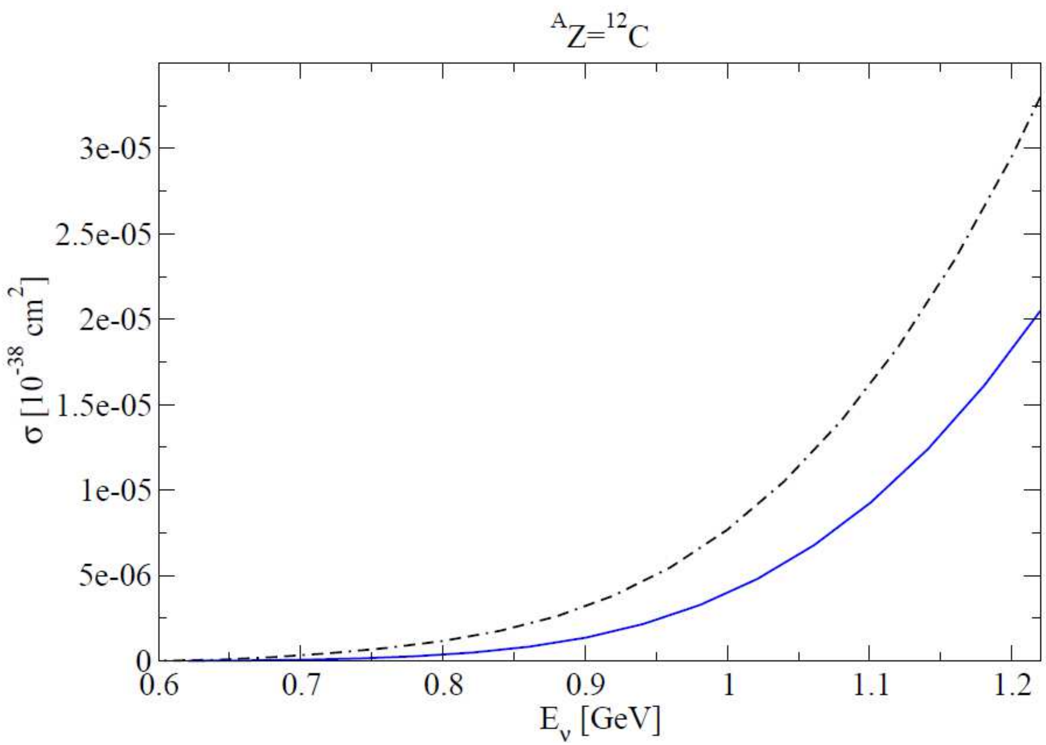
σ(Cohπ^+,1 GeV)~ 0.05-0.1 >> σ (CohK^+,1.35 GeV)~ 0.00014 x10^{-38} cm^2

The coherent reaction

- Results:

$\nu_\mu \, A \to \mu^- \, K^+ \, A$ $\bar{\nu}_\mu \, A \to \mu^+ \, K^- \, A$





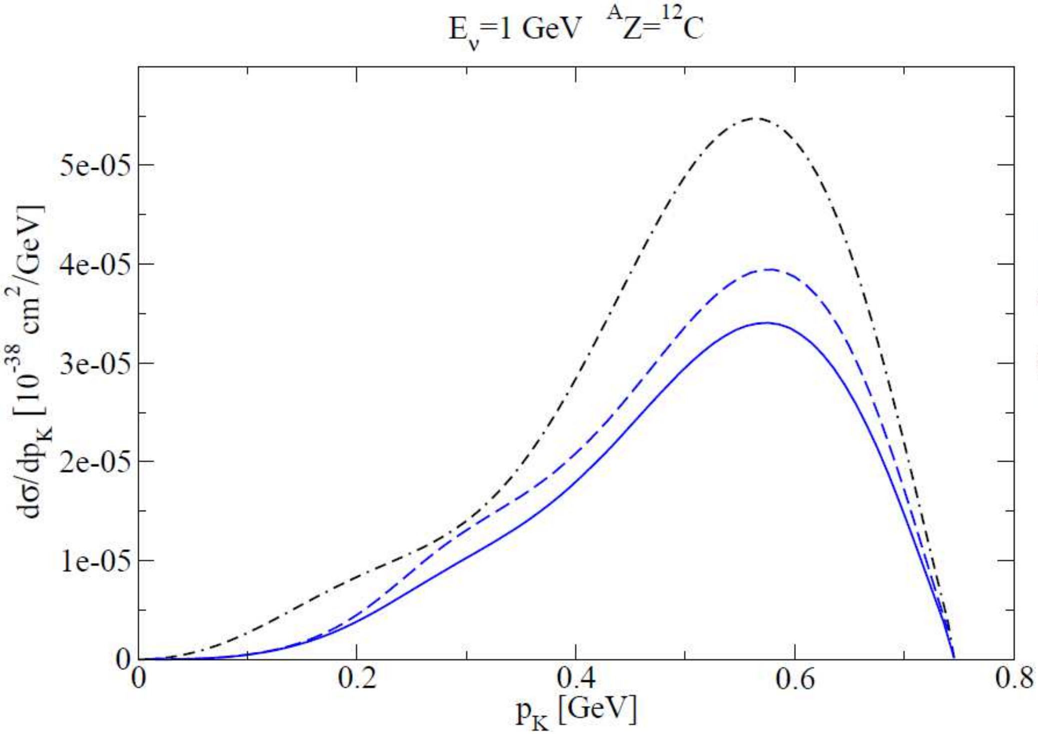
- Very small cross section... why?

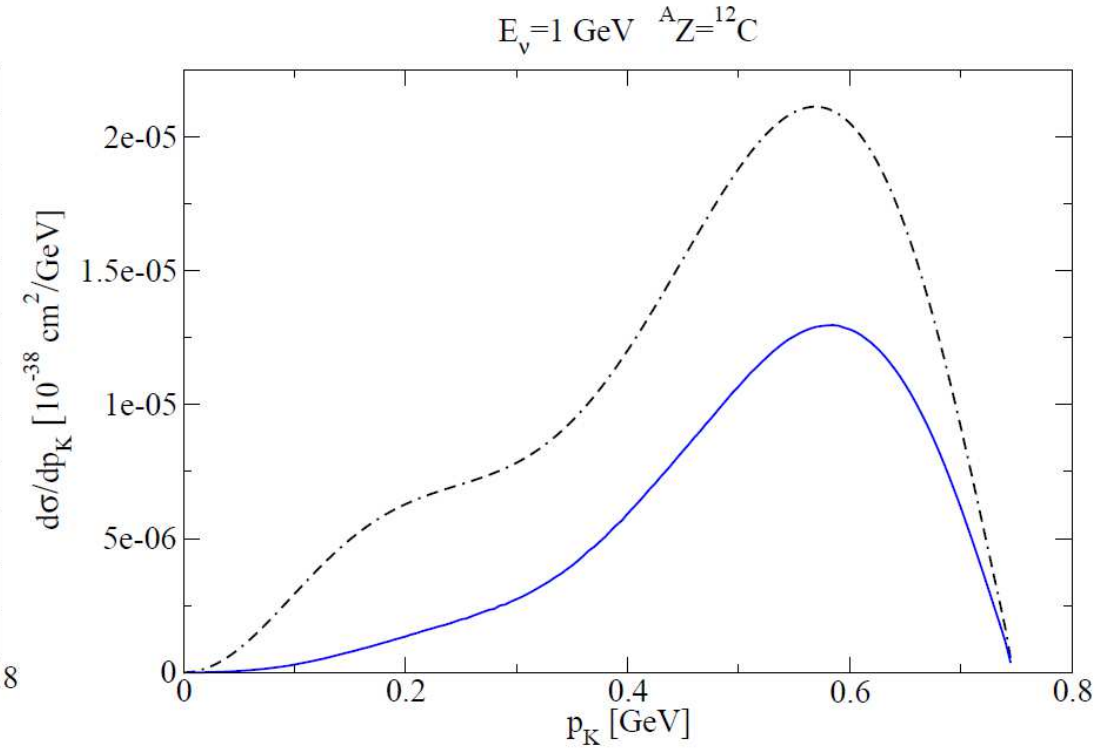
$$\frac{d\sigma}{d\Omega_\mu dE_\mu d\Omega_K} \sim F^2(|\vec{q} - \vec{p}_K|) \,, \; |\vec{q} - \vec{p}_K| > q_0 - |\vec{p}_K| = \sqrt{m_K^2 + \vec{p}_K^2} - |\vec{p}_K|$$

The coherent reaction

- Results:

$\nu_\mu \, A \to \mu^- \, K^+ \, A$ $\qquad$ $\bar{\nu}_\mu \, A \to \mu^+ \, K^- \, A$





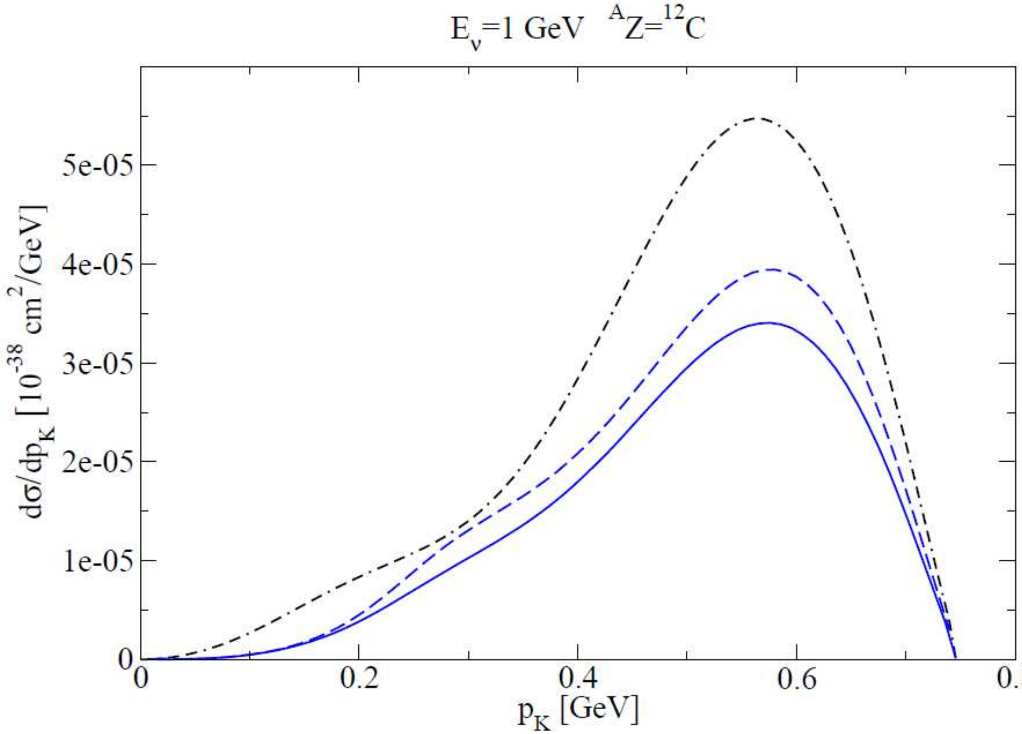
- Very small cross section… why? because K is heavy

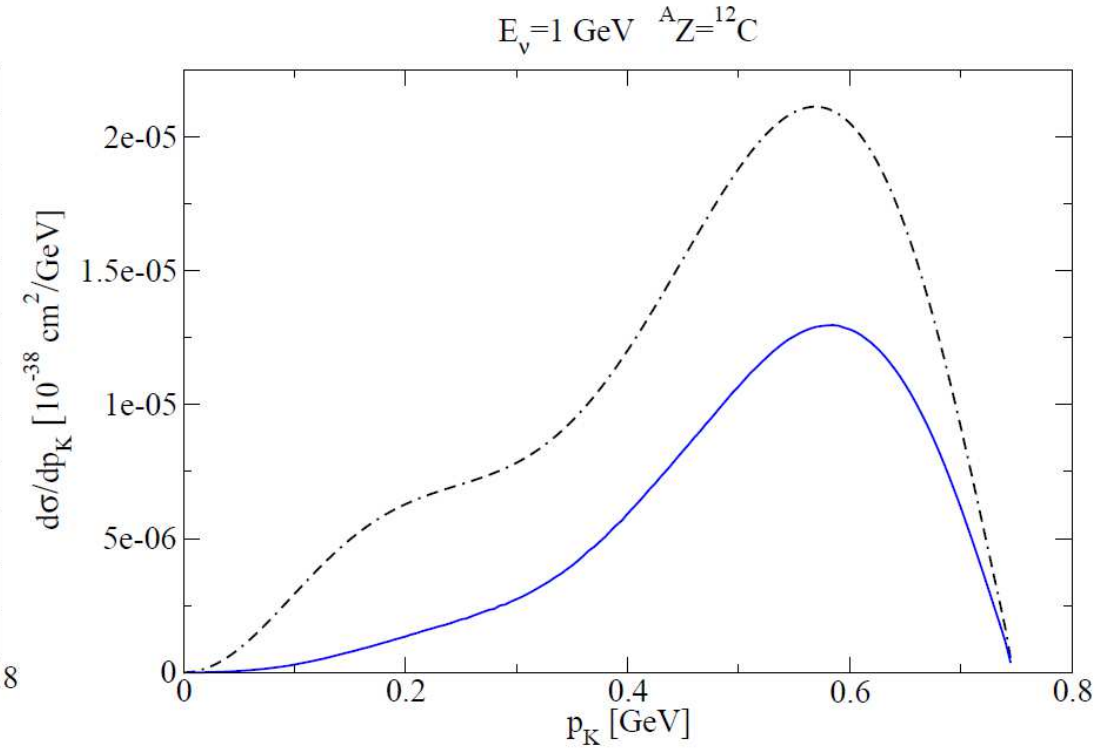
$$\frac{d\sigma}{d\Omega_\mu dE_\mu d\Omega_K} \sim F^2(|\vec{q} - \vec{p}_K|)\,,\;\; |\vec{q} - \vec{p}_K| > q_0 - |\vec{p}_K| = \sqrt{m_K^2 + \vec{p}_K^{\,2}} - |\vec{p}_K|$$

The coherent reaction

- Results:

$\nu_\mu \, A \to \mu^- \, K^+ \, A$ $\bar{\nu}_\mu \, A \to \mu^+ \, K^- \, A$



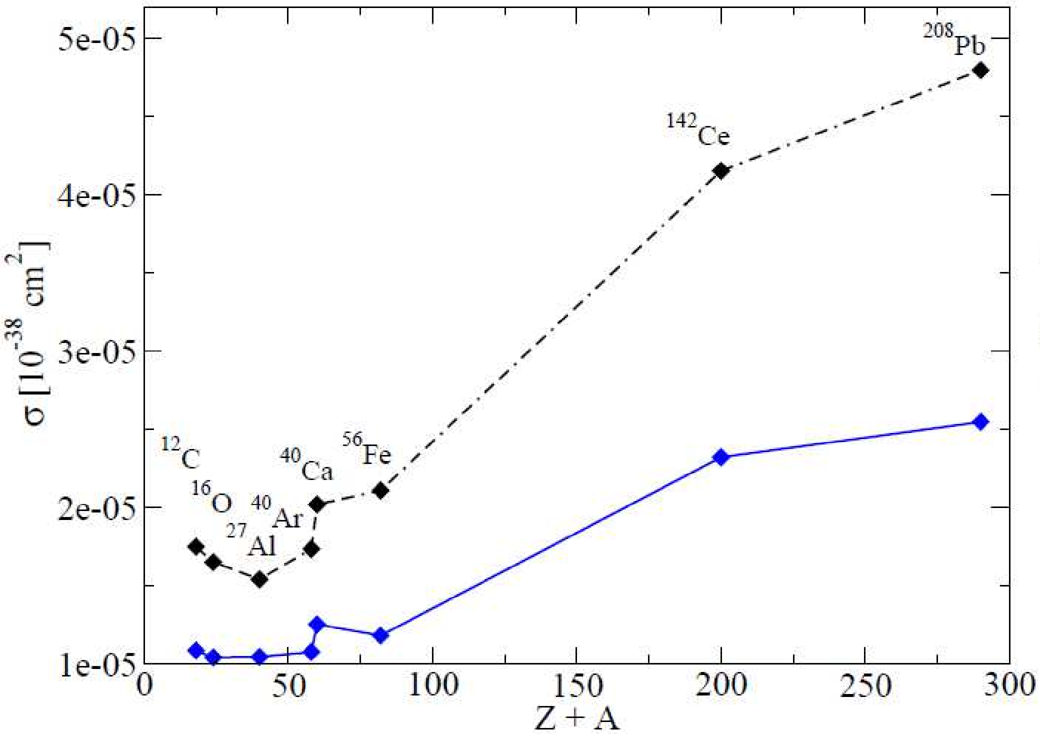


- Very small cross section… why? because K is heavy
  - $m_K \to m_K/2 \Leftrightarrow \sigma \to \sigma/2$
  - Sensitive to the nuclear density distribution

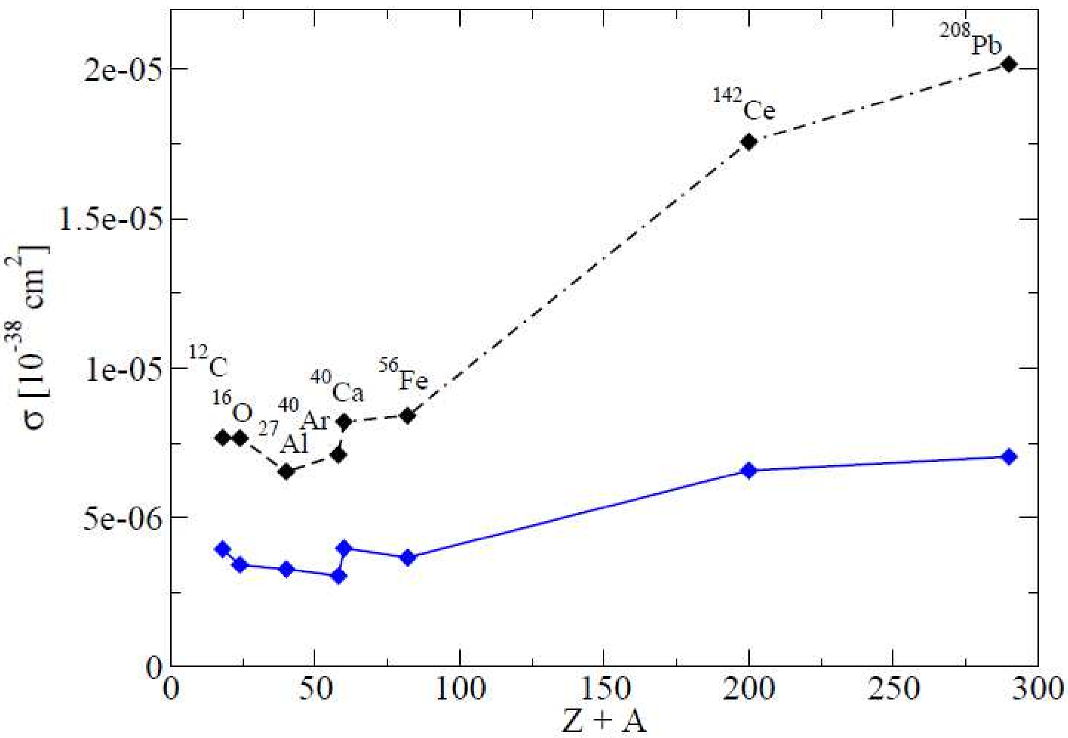
The coherent reaction

- Results:

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



$\bar{\nu}_\mu \, A \to \mu^+ \, K^- \, A$



- From the largest CT one naively expects: $\sigma \sim (Z+A)^2$
- Irregular trend: σ increase with A

  narrower nuclear form factors

  secondary diffractive maxima

Conclusions

- CC and NC Cohπ have been studied with PCAC and microscopic models
- PCAC (microscopic) models are better suited for high (low) energies
- Rein-Sehgal model overestimates Cohπ cross section
- Is Cohπ cross section too small to bother?
- $CC\pi^+/NC\pi^0 = 0.14^{+0.30}_{-0.28}$ from SciBooNE is hard to understand
- Cohπ has been studied with:
  - Microscopic production mechanism based on SU(3) chiral Lagrangians
  - (anti)kaon distortion from KG eq. with a realistic optical potential
- Small cross sections are obtained due to:
  - Small (Cabibbo suppressed) σ on nucleons
  - Large momentum transferred to the nucleus because of the large kaon mass
  - Destructive interference
  - Kaon distortion