Do we theoretically understand/control CC and NC coherent pion production at low and intermediate neutrino energies?

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It depends on what we mean by control/understand. We have a deep understanding of the process and sophisticated calculations are available, though there still exist some uncertainties...

NC Rein–Sehgal model [NPB 223 (1983) 29]

- **PCAC**

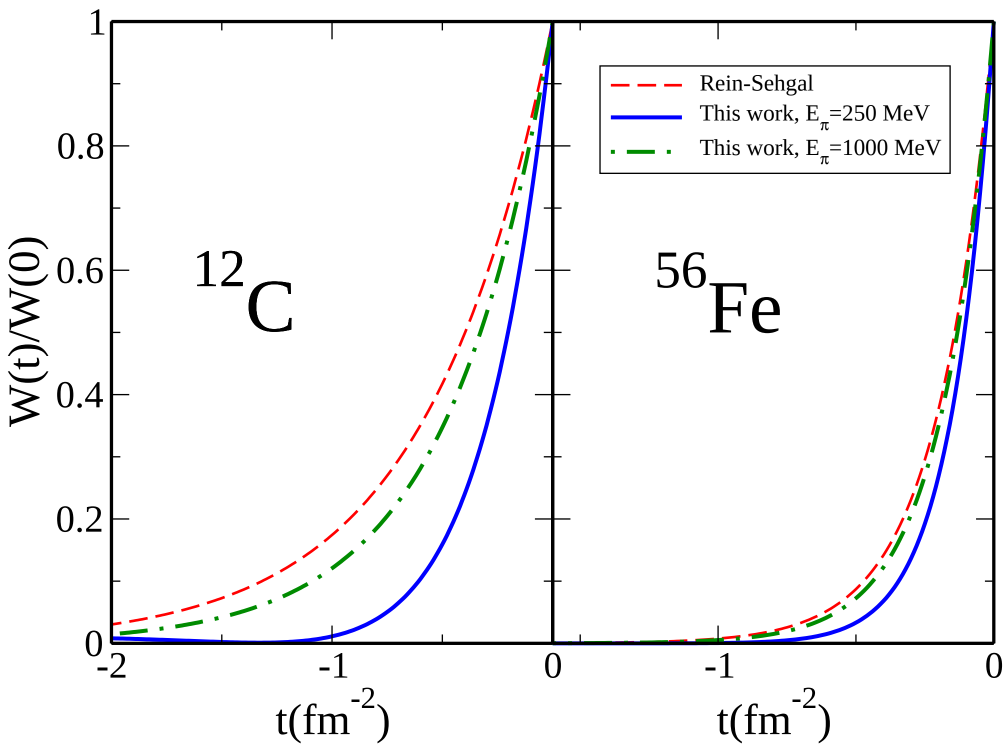
$$\left\langle \mathcal{N}_{gs}\pi^0(k_\pi)|q_\mu A^\mu_{NC}|\mathcal{N}_{gs}\right\rangle_{\mathbf{q^2=0}} = 2f_\pi \left\langle \mathcal{N}_{gs}\pi^0(k_\pi)| - \mathrm{i}T|\pi^0(q)\mathcal{N}_{gs}\right\rangle_{\mathbf{q^2=0}}$$

elastic $\pi^0\mathcal{N}_{gs}$ Xsect and pion distortion effects...?

- $t=(q-p_\pi)^2=0;\ q^2=(k_\nu-k'_\nu)^2=0$ **approximations**

$$\frac{d\sigma}{dq^2\,dq^0\,dt} \propto \frac{1}{(1-\frac{q^2}{1\ \mathrm{GeV}^2})^2}\left(|\mathbf{F}_{\mathcal{A}}(\mathbf{t})|^{\mathbf{2}}\mathbf{F}_{\mathrm{abs}}\frac{d\sigma(\pi^0N\to\pi^0N)}{dt}\Big|_{\mathbf{E}_\pi=\mathbf{q^0},\ \boxed{\mathrm{t}=0}}\right)$$

$$F_{\mathcal{A}}(t) = \int d^3\vec{r}\ e^{\mathrm{i}\left(\vec{q}-\vec{k}_\pi\right)\cdot\vec{r}}\left\{\rho_p(\vec{r})+\rho_n(\vec{r})\right\}$$



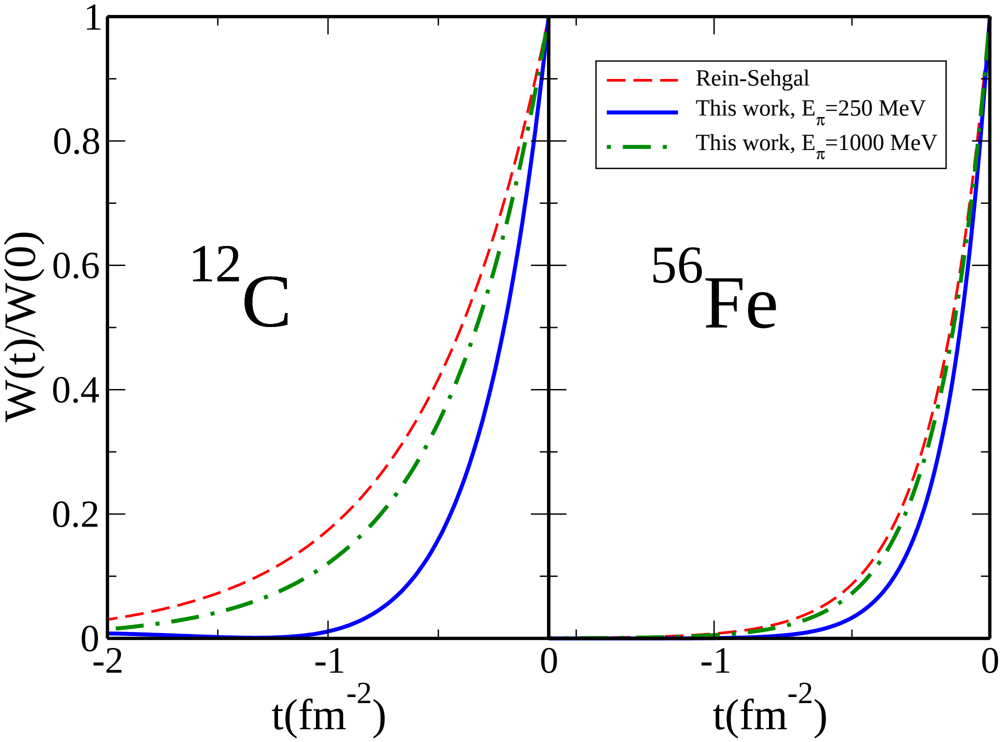
(Hernández, Nieves and Vicente–Vacas, arXiv:0903.5285)

$$W(t) = |F_{\mathcal{A}}(t)|^2 \frac{d\sigma_{nsf}(\pi^0 N \to \pi^0 N)}{dt} \,,$$

Large (and negative) q^2 values are suppressed by the elastic pion–nucleus differential cross section that strongly favours $t = 0$.

(Hernández, Nieves and Vicente–Vacas, arXiv:0903.5285)

$$W^{\rm RS}(t) = |F_{\mathcal{A}}(t)|^2 \frac{d\sigma_{nsf}(\pi^0 N \to \pi^0 N)}{dt}\Big|_{\mathbf{t=0}}$$

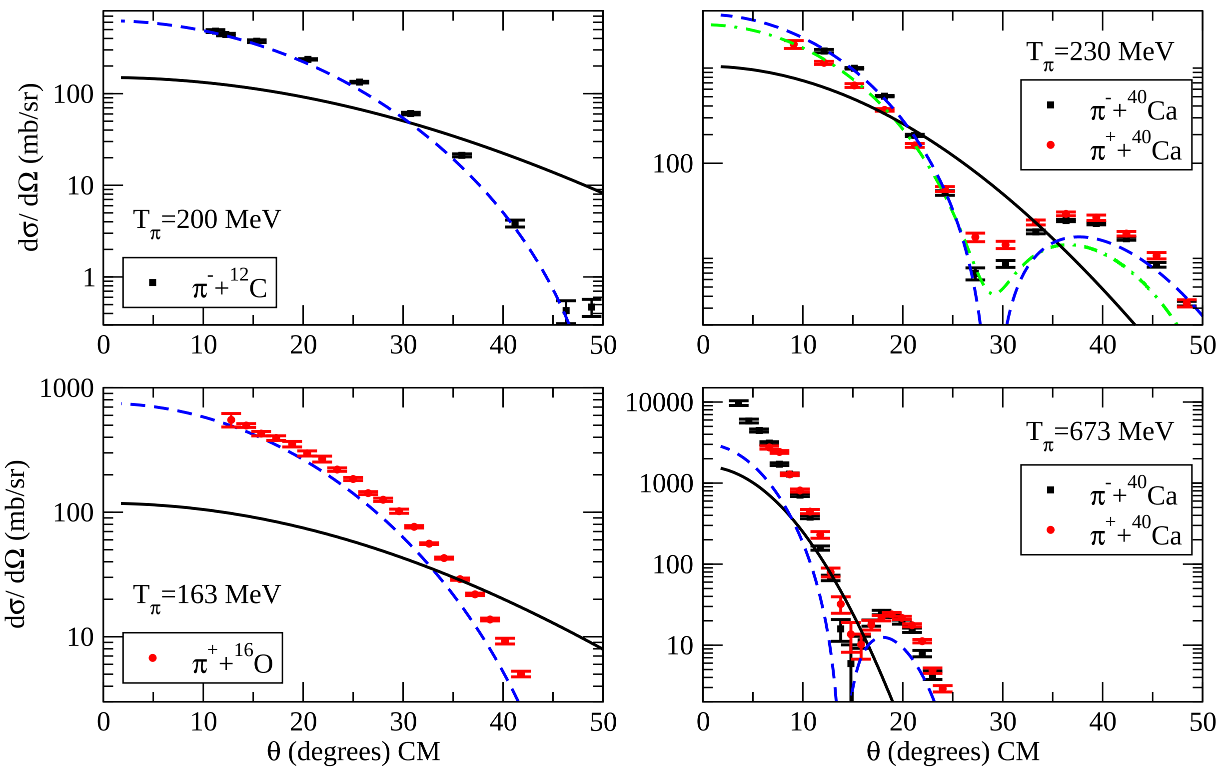


Original RS work: medium size nucleus, aluminum, and neutrino energies above 2 GeV ⇒ OK

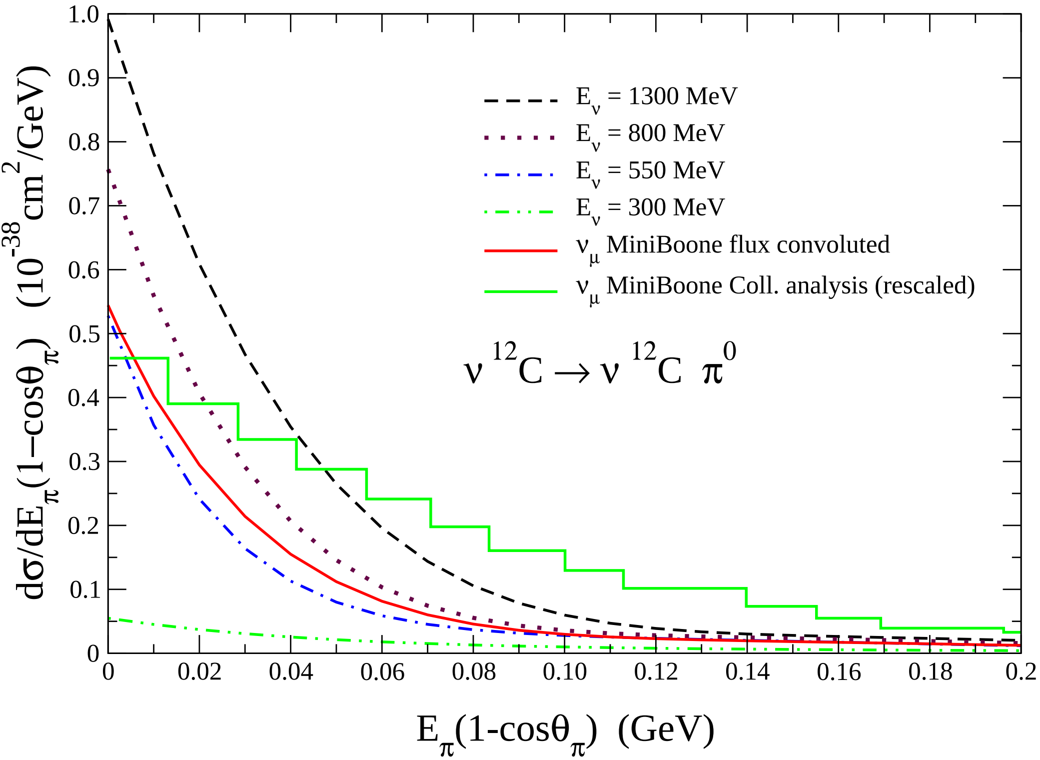
However, for neutrino energies below 1 GeV and lighter nuclei, like carbon or oxygen, the nuclear form factor is not enough forward peaked to render the finite t−dependence of the pion–nucleon cross section negligible, and even in the forward direction the t value is not close enough to zero.

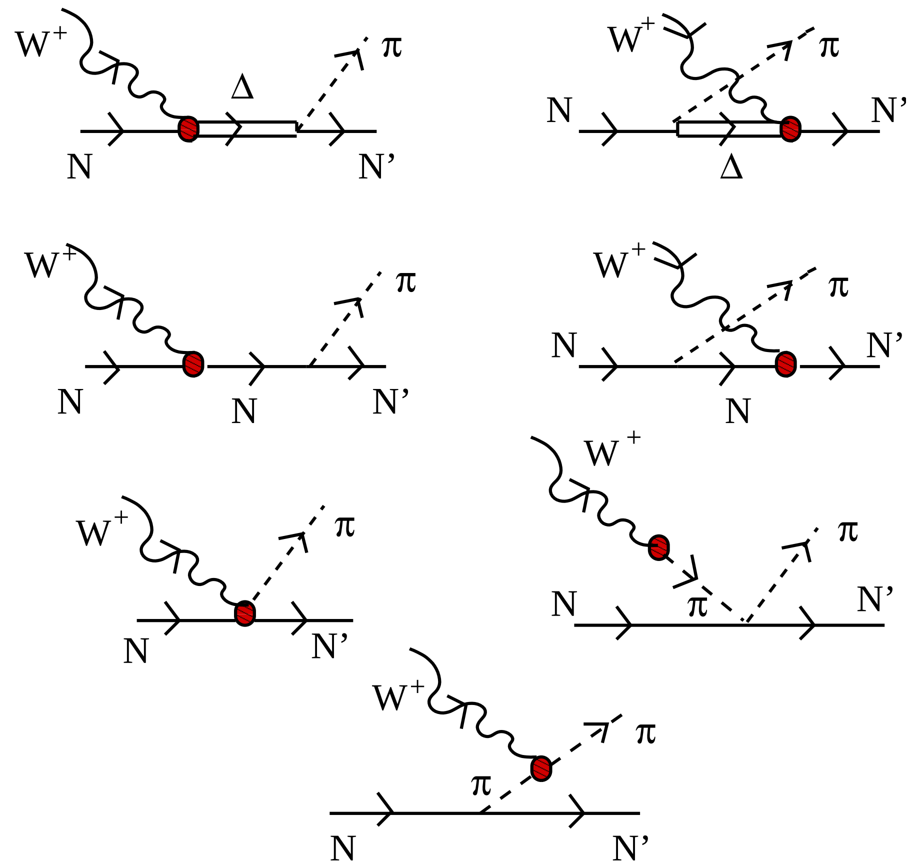
$q^2 \neq 0$ contributions beyond PCAC and further $t \neq 0$ dependences neglected within the RS model turn out to be now relevant.

Thus at low neutrino energies, for instance those relevant in MiniBooNE, RS model would predict **elastic $\pi\mathcal{N}_{gs}$ Xsects** strongly disfavored by data ...

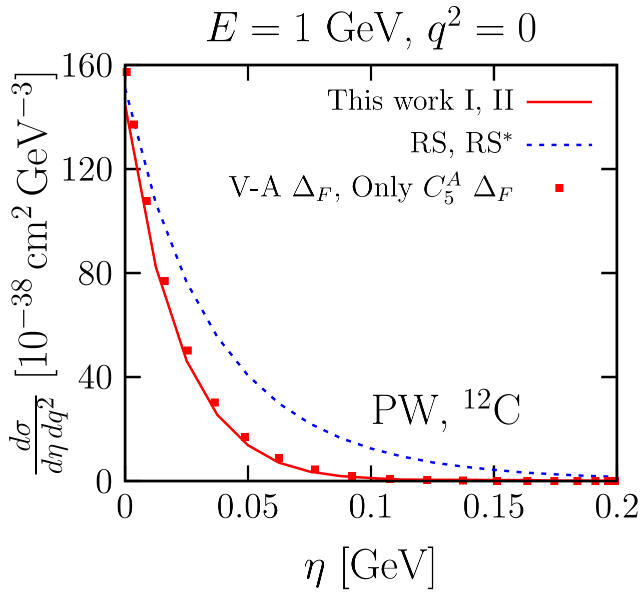


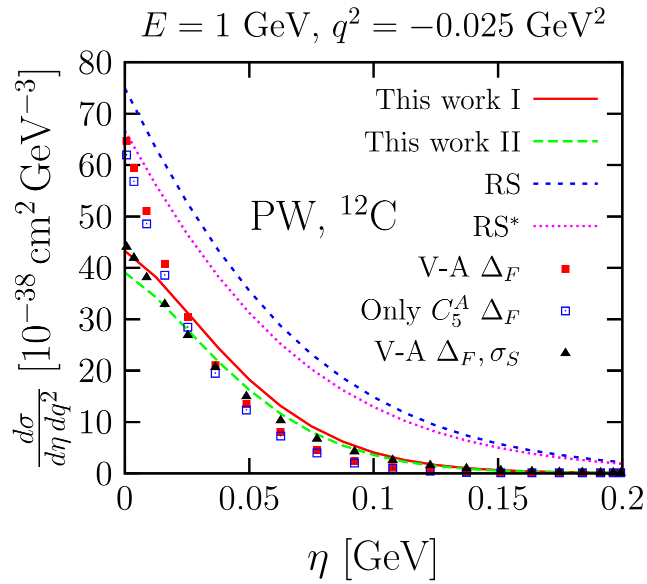
(Amaro, Hernández, Nieves and Valverde, PRD 79: 013002)

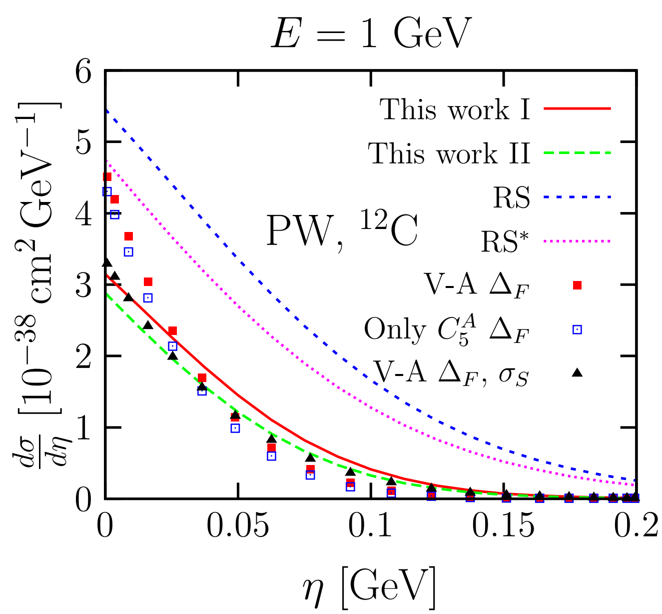




CC vs NC ?


$E = 1$ GeV, $q^2 = 0$
This work I, II
RS, RS*
V-A Δ_F, Only C_5^A Δ_F
PW, ^{12}C
$\frac{d\sigma}{d\eta\, dq^2}$ [10^{-38} cm^2 GeV^{-3}]
η [GeV]
0
40
80
120
160
0
0.05
0.1
0.15
0.2

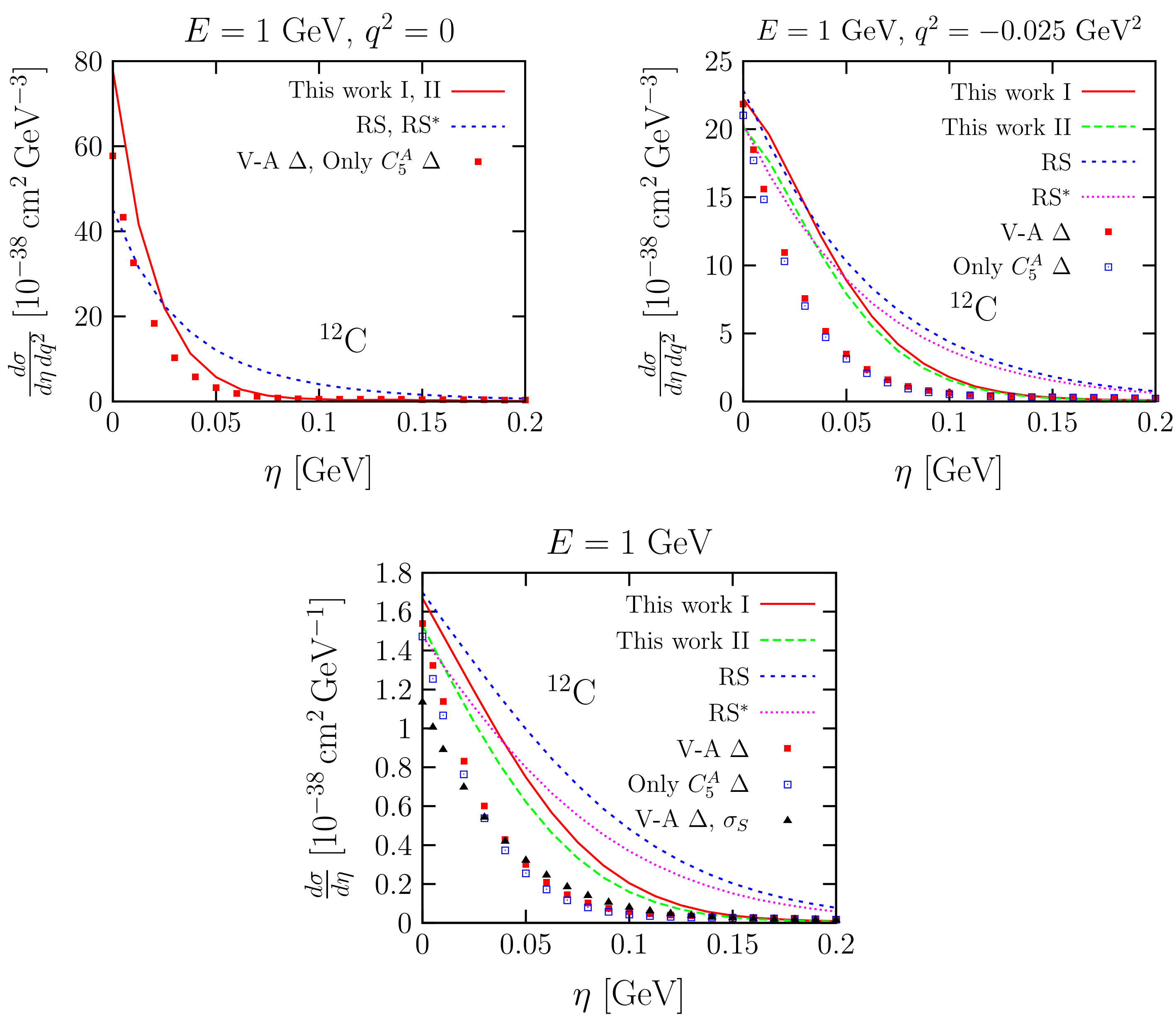

$E = 1$ GeV, $q^2 = -0.025$ GeV^2
This work I
This work II
RS
RS*
V-A Δ_F
Only C_5^A Δ_F
V-A Δ_F, σ_S
PW, ^{12}C
$\frac{d\sigma}{d\eta\, dq^2}$ [10^{-38} cm^2 GeV^{-3}]
η [GeV]
0
10
20
30
40
50
60
70
80
0
0.05
0.1
0.15
0.2


$E = 1$ GeV
This work I
This work II
RS
RS*
V-A Δ_F
Only C_5^A Δ_F
V-A Δ_F, σ_S
PW, ^{12}C
$\frac{d\sigma}{d\eta}$ [10^{-38} cm^2 GeV^{-1}]
η [GeV]
0
1
2
3
4
5
6
0
0.05
0.1
0.15
0.2

Remarks:

- **No distortion for outgoing pion**
- **RS*: RS model including some kinematical corrections that vanish at $q^2 = 0$ and recently proposed by Berger and Sehgal (PRD 79: 053003)**
- $L_{\mu\nu} H^{\mu\nu} \neq q_\mu q_\nu A^\mu A^\nu$ **except for** $q^2 = 0$
  - **PCAC based models only work when the $q^2 = 0$ contribution is totally dominant.**
  - **When $q^2 \neq 0$ contributions cannot be neglected, PCAC models cannot provide the incoming neutrino–outgoing pion angular distribution.**

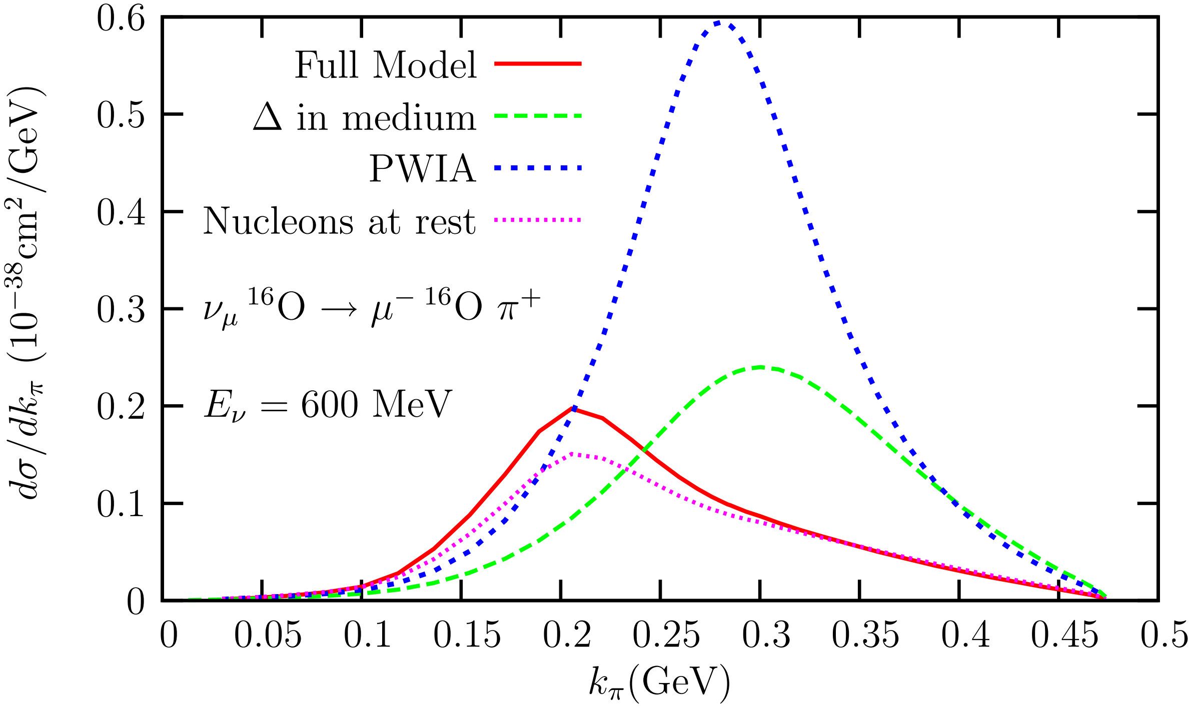
Once the pion distortion is taken into account...



$E = 1$ GeV, $q^2 = 0$
This work I, II
RS, RS*
V-A Δ, Only C_5^A Δ
^{12}C
$\frac{d\sigma}{d\eta\, dq^2}$ [10^{-38} cm^2 GeV^{-3}]
η [GeV]
$E = 1$ GeV, $q^2 = -0.025$ GeV^2
This work I
This work II
RS
RS*
V-A Δ
Only C_5^A Δ
^{12}C
$\frac{d\sigma}{d\eta\, dq^2}$ [10^{-38} cm^2 GeV^{-3}]
η [GeV]
$E = 1$ GeV
This work I
This work II
RS
RS*
V-A Δ
Only C_5^A Δ
V-A Δ, σ_S
^{12}C
$\frac{d\sigma}{d\eta}$ [10^{-38} cm^2 GeV^{-1}]
η [GeV]

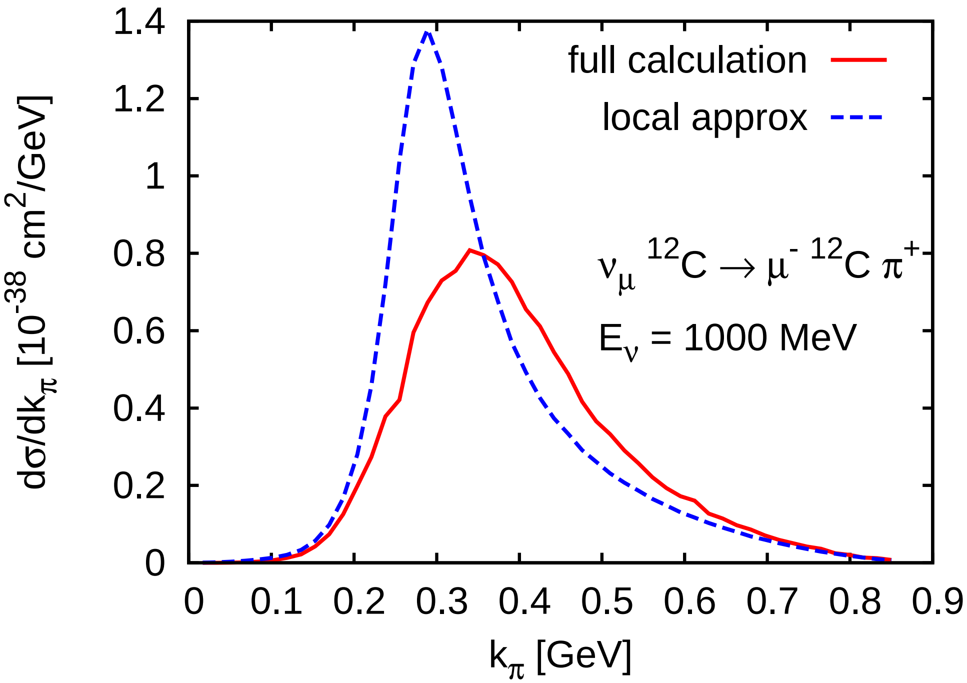
Microscopical models

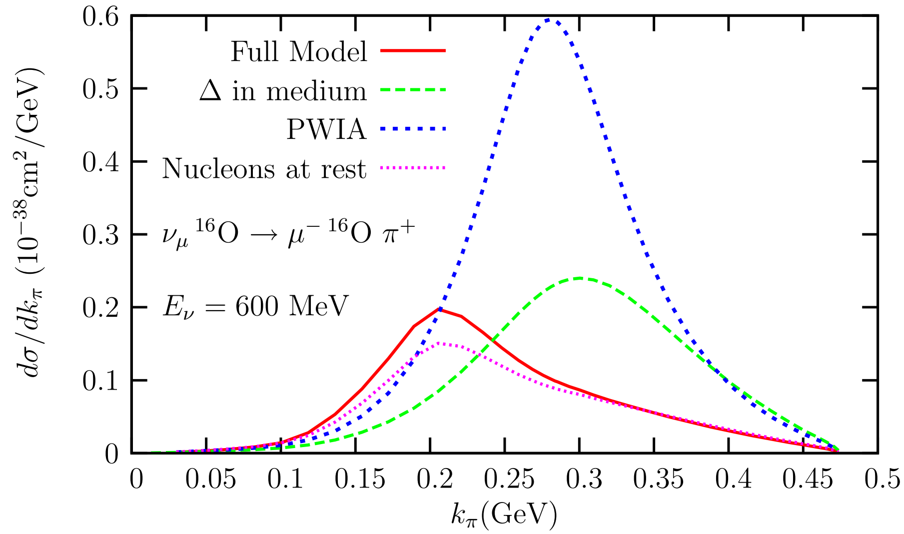
- Singh, Athar and Ahmad, PRL 96: 241801
- Alvarez-Ruso, Geng and Vicente-Vacas, PRC76:068501
- Amaro, Hernández, Nieves and Valverde, PRD 79: 013002



- Δ excitation dominant mechanism for $E_\nu \leq 1$ GeV
- Many nuclear effects,
  - Δ−selfenergy in the medium
  - outgoing pion distortion
  - non-localities: momentum of the pion inside of the nucleus, momentum of the nucleons...
  - $C_5^A(q^2) = ?$ **(axial ΔN transition vertex)**

(Leitner, Mosel and Winkelmann, arXiv:0901.2837)





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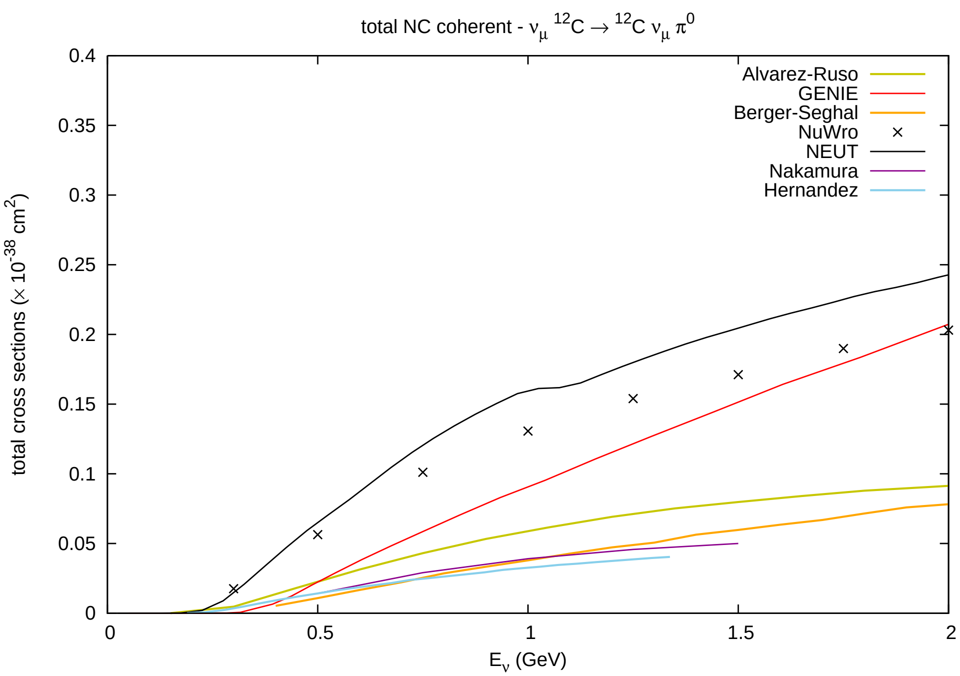
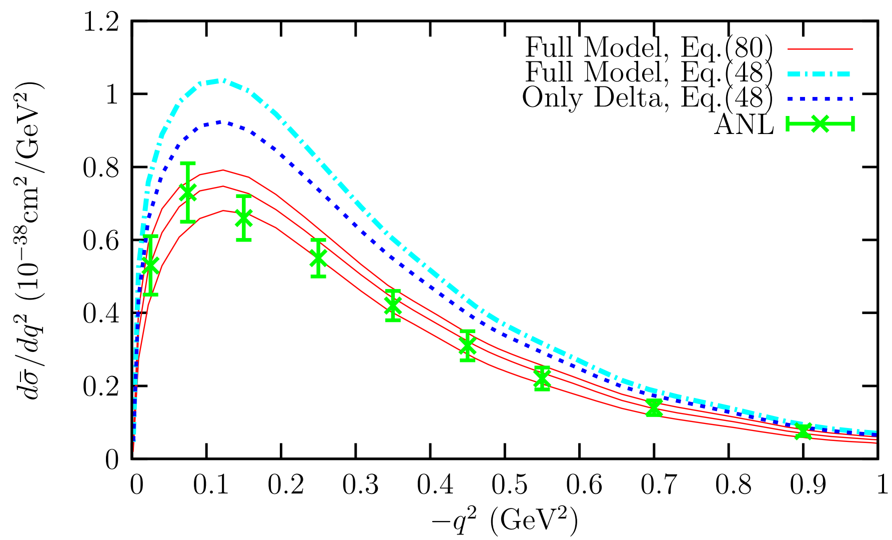


- $C_5^A(q^2)$ **is crucial!! Uncertainties in Xsects of about a factor of 2.**



- **Beyond, let us say** $E_\nu > 1.3$ **GeV for NC (phase space peaks around** $W_{\pi N}$ **∼1.5 GeV), other resonances and mechanisms might play a significant role.**
- **Above** $E_\nu > 2$ **GeV: PCAC based models should work.**