Neutrino induced weak pion production off the nucleon and coherent pion production in nuclei at low energies

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"Weak Pion Production off the Nucleon", Phys. Rev. D 76, 033005 (2007)
E.H., J. Nieves, M. Valverde
"Theoretical study of neutrino-induced coherent pion production off nuclei at T2K and MiniBooNE energies", Phys. Rev. D 79, 013002 (2009)
E. Amaro, E.H., J. Nieves, M. Valverde
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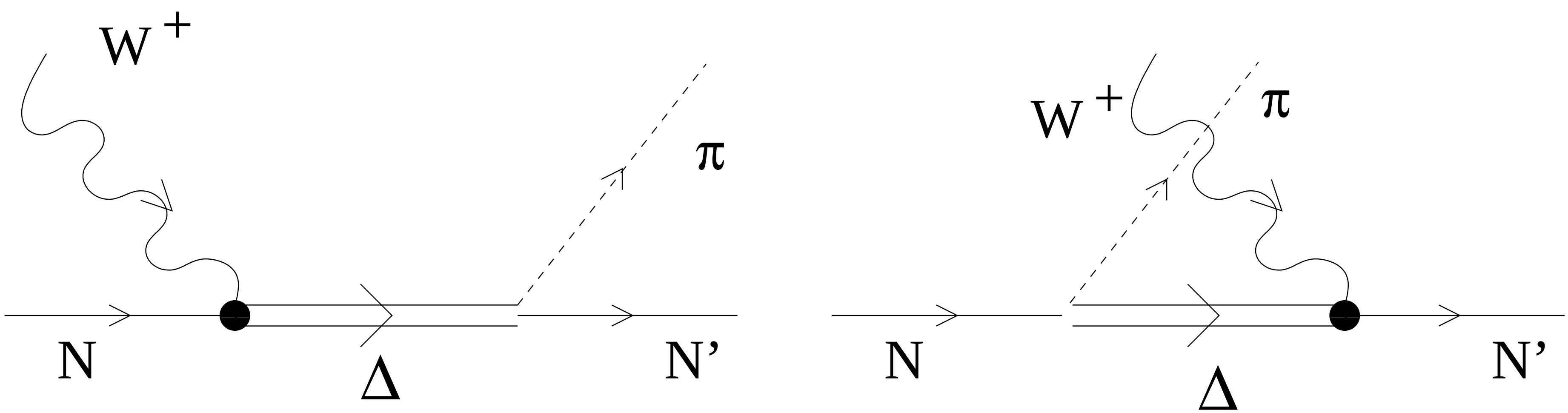
Delta Pole Term

The dominant contribution for weak pion production at intermediate energies is given by the Δ pole mechanism



Background Terms I

We shall also include background terms required by chiral symmetry. Starting with the effective lagrangian of the SU(2) non-linear σ model.

$$\mathcal{L}_{N\pi} = \bar{\Psi} \mathrm{i}\gamma^\mu \left[\partial_\mu + \mathcal{V}_\mu\right] \Psi - M\bar{\Psi}\Psi + g_A \bar{\Psi}\gamma^\mu\gamma_5 \mathcal{A}_\mu \Psi + \frac{1}{2}\mathrm{Tr}\left[\partial_\mu U^\dagger \partial^\mu U\right]$$

$$\Psi = \begin{pmatrix} p \\ n \end{pmatrix} \qquad \mathcal{V}_\mu = \frac{1}{2}\left(\xi\partial_\mu\xi^\dagger + \xi^\dagger\partial_\mu\xi\right) \qquad \mathcal{A}_\mu = \frac{\mathrm{i}}{2}\left(\xi\partial_\mu\xi^\dagger - \xi^\dagger\partial_\mu\xi\right)$$

$$\xi = e^{\mathrm{i}\,\vec{\tau}\cdot\vec{\phi}/(2f_\pi)} \qquad U = \frac{f_\pi}{\sqrt{2}}\xi^2 \qquad f_\pi \simeq 93\,\mathrm{Me}V$$

Explicit SU(2)$_A$ breaking terms are included in the model as

$$m_\pi^2 \frac{f_\pi}{\sqrt{2}} \frac{1}{2} \mathrm{Tr}(U + U^\dagger - \sqrt{2} f_\pi)$$

Background Terms II

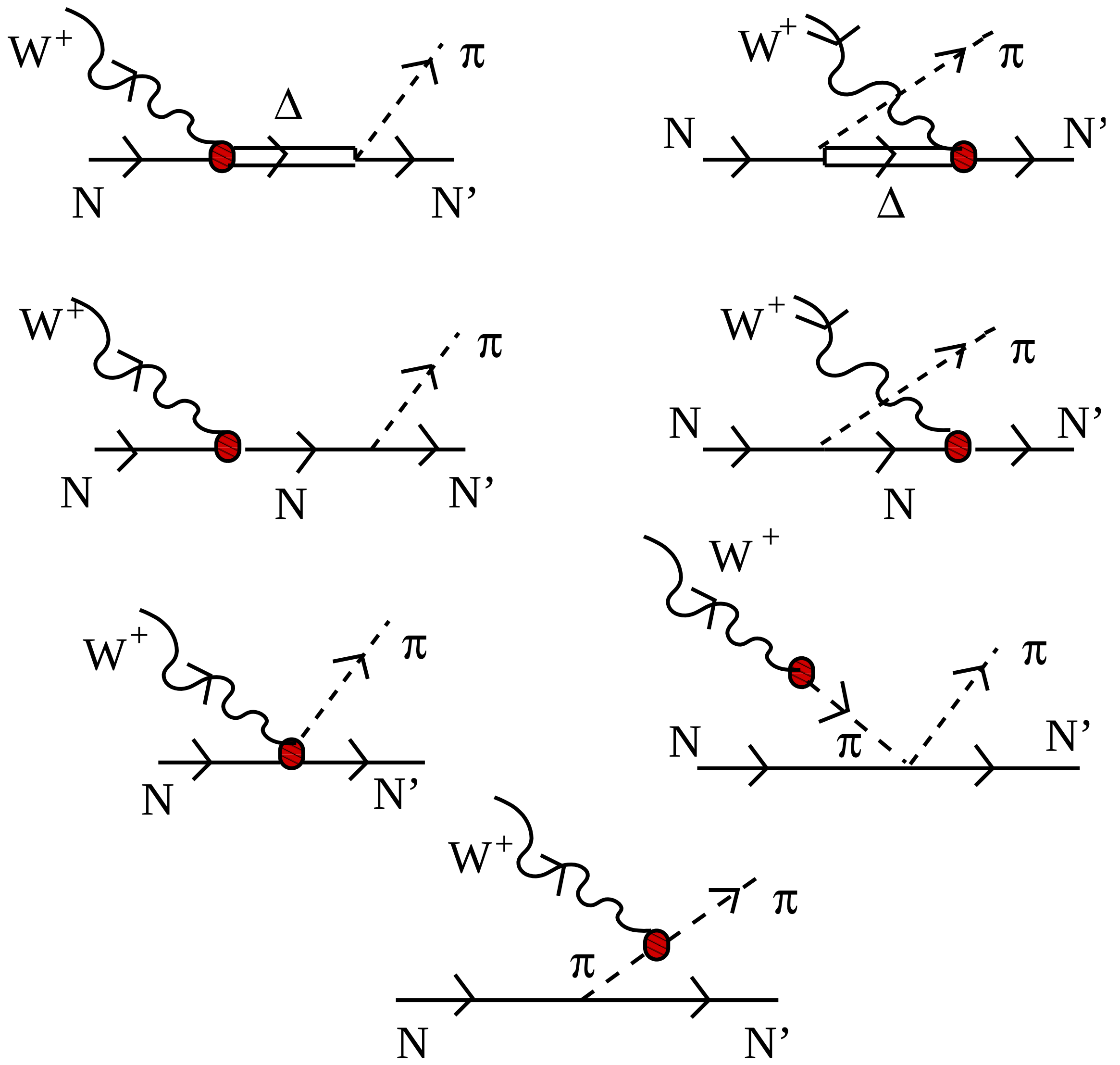
Neglecting $\mathcal{O}(1/f_\pi^4)$, the effective Lagrangian reads

$$\begin{aligned}
\mathcal{L} &= \bar{\Psi}[i\partial\!\!\!/ - M]\Psi + \frac{1}{2}\partial_\mu\vec{\phi}\partial^\mu\vec{\phi} - \frac{1}{2}m_\pi^2\vec{\phi}^{\,2} + \mathcal{L}_{\rm int}^\sigma \\
\mathcal{L}_{\rm int}^\sigma &= \frac{g_A}{f_\pi}\bar{\Psi}\gamma^\mu\gamma_5\frac{\vec{\tau}}{2}(\partial_\mu\vec{\phi})\Psi - \frac{1}{4f_\pi^2}\bar{\Psi}\gamma_\mu\vec{\tau}\left(\vec{\phi}\times\partial^\mu\vec{\phi}\right)\Psi - \frac{1}{6f_\pi^2}\left(\vec{\phi}^{\,2}\partial_\mu\vec{\phi}\partial^\mu\vec{\phi} - (\vec{\phi}\partial_\mu\vec{\phi})(\vec{\phi}\partial^\mu\vec{\phi})\right) \\
&+ \frac{m_\pi^2}{24f_\pi^2}(\vec{\phi}^{\,2})^2 - \frac{g_A}{6f_\pi^3}\bar{\Psi}\gamma^\mu\gamma_5\left[\vec{\phi}^{\,2}\frac{\vec{\tau}}{2}\partial_\mu\vec{\phi} - (\vec{\phi}\partial_\mu\vec{\phi})\frac{\vec{\tau}}{2}\vec{\phi}\right]\Psi + \mathcal{O}(\frac{1}{f_\pi^4})
\end{aligned}$$

The vector and axial currents that we derive from the lagrangian are

$$\begin{aligned}
\vec{V}^\mu &= \vec{\phi}\times\partial^\mu\vec{\phi} + \bar{\Psi}\gamma^\mu\frac{\vec{\tau}}{2}\Psi + \frac{g_A}{2f_\pi}\bar{\Psi}\gamma^\mu\gamma_5(\vec{\phi}\times\vec{\tau})\Psi \\
&- \frac{1}{4f_\pi^2}\bar{\Psi}\gamma^\mu\left[\vec{\tau}\vec{\phi}^{\,2} - \vec{\phi}(\vec{\tau}\cdot\vec{\phi})\right]\Psi - \frac{\vec{\phi}^{\,2}}{3f_\pi^2}(\vec{\phi}\times\partial^\mu\vec{\phi}) + \mathcal{O}(\frac{1}{f_\pi^3}) \\
\vec{A}^\mu &= f_\pi\partial^\mu\vec{\phi} + g_A\bar{\Psi}\gamma^\mu\gamma_5\frac{\vec{\tau}}{2}\Psi + \frac{1}{2f_\pi}\bar{\Psi}\gamma^\mu(\vec{\phi}\times\vec{\tau})\Psi + \frac{2}{3f_\pi}\left[\vec{\phi}(\vec{\phi}\cdot\partial^\mu\vec{\phi}) - \vec{\phi}^{\,2}\partial^\mu\vec{\phi}\right] \\
&- \frac{g_A}{4f_\pi^2}\bar{\Psi}\gamma^\mu\gamma_5\left[\vec{\tau}\vec{\phi}^{\,2} - \vec{\phi}(\vec{\tau}\cdot\vec{\phi})\right]\Psi + \mathcal{O}(\frac{1}{f_\pi^3})
\end{aligned}$$

CC Processes. Full Model I



CC Processes. Full Model II

Add form factors and fix the overall normalization

$$\langle p; \vec{p}\,' = \vec{p} + \vec{q}\, | j^\alpha_{cc+}(0) | n; \vec{p}\,\rangle = \cos\theta_C\; \bar{u}(\vec{p}\,')(V^\alpha_N(q) - A^\alpha_N(q))u(\vec{p}\,)$$

$$j^\mu_{\rm cc+} = -\sqrt{2} j^\mu_{\rm cc+1} = \cos\theta_C \bar{\Psi}_u \gamma^\mu (1-\gamma_5)\Psi_d$$

$$V^\alpha_N(q) = 2\times\left(F^V_1(q^2)\gamma^\alpha + {\rm i}\mu_V \frac{F^V_2(q^2)}{2M}\sigma^{\alpha\nu} q_\nu \right), \qquad A^\alpha_N(q) = G_A(q^2)\times\left(\gamma^\alpha\gamma_5 + \frac{\not q}{m^2_\pi - q^2} q^\alpha \gamma_5\right)$$

- $F^V_1(q^2) = \frac{1}{2}\left(F^p_1(q^2) - F^n_1(q^2)\right), \qquad \mu_V F^V_2(q^2) = \frac{1}{2}\left(\mu_p F^p_2(q^2) - \mu_n F^n_2(q^2)\right)$

$$F^N_1 = \frac{G^N_E + \tau G^N_M}{1+\tau}, \qquad \mu_N F^N_2 = \frac{G^N_M - G^N_E}{1+\tau}$$

$$G^p_E = \frac{G^p_M}{\mu_p} = \frac{G^n_M}{\mu_n} = -(1+\lambda_n\tau)\frac{G^n_E}{\mu_n\tau} = \left(\frac{1}{1-q^2/M^2_D}\right)^2$$

$$\tau = -q^2/4M^2,\ M_D = 0.843 GeV,\ \mu_p = 2.792847,\ \mu_n = -1.913043,\ \lambda_n = 5.6$$

(S. Galster *et al.*, Nucl. Phys. B32, 221 (1971))

CC Processes. Full Model III

- $G_A(q^2) = \frac{g_A}{(1-q^2/M_A^2)^2}, \quad g_A = 1.26, \quad M_A = 1.05 \text{ GeV}$

(T.E.O. Ericson and W. Weise *Pions and Nuclei*, Clarendon Press (Oxford) 1988)

To preserve CVC we have to include

$$F_{PF}(q^2) = F_{CT}^V(q^2) = 2F_1^V(q^2) = F_1^p(q^2) - F_1^n(q^2)$$

Besides in the PP term and the axial part of the CT we include

$$F_\rho(t) = \frac{1}{1 - t/m_\rho^2}, \quad m_\rho = 0.7758 \, \text{GeV}$$

CC Processes. Full Model IV

- $\mathcal{L}_{\pi N\Delta} = \frac{f^*}{m_\pi}\bar{\Psi}_\mu \vec{T}^\dagger(\partial^\mu \vec{\phi})\Psi + \text{h.c.}, \quad f^* = 2.14$
- $G^{\mu\nu}(p_\Delta) = \frac{P^{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta}$

$$P^{\mu\nu}(p_\Delta) = -(\not{p}_\Delta + M_\Delta)\left[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{2}{3}\frac{p_\Delta^\mu p_\Delta^\nu}{M_\Delta^2} + \frac{1}{3}\frac{p_\Delta^\mu\gamma^\nu - p_\Delta^\nu\gamma^\mu}{M_\Delta}\right]$$

$$\Gamma_\Delta(s) = \frac{1}{6\pi}\left(\frac{f^*}{m_\pi}\right)^2 \frac{M}{\sqrt{s}}\left[\frac{\lambda^{\frac{1}{2}}(s, m_\pi^2, M^2)}{2\sqrt{s}}\right]^3 \Theta(\sqrt{s} - M - m_\pi), \qquad s = p_\Delta^2$$

- $\langle \Delta^+; p_\Delta = p + q \,|j_{cc+}^\mu(0)|n; p\rangle = \cos\theta_C \bar{u}_\alpha(\vec{p}_\Delta)\Gamma^{\alpha\mu}(p,q)\, u(\vec{p})$

$$\begin{aligned}\Gamma^{\alpha\mu}(p,q) \quad &= \quad \left[\frac{C_3^V}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M^2}\left(g^{\alpha\mu}q\cdot p_\Delta - q^\alpha p_\Delta^\mu\right) + \frac{C_5^V}{M^2}(g^{\alpha\mu}q\cdot p - q^\alpha p^\mu)\right. \\ &\left. + C_6^V g^{\mu\alpha}\right]\gamma_5 \\ &+ \quad \left[\frac{C_3^A}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M^2}\left(g^{\alpha\mu}q\cdot p_\Delta - q^\alpha p_\Delta^\mu\right) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M^2}q^\mu q^\alpha\right]\end{aligned}$$

CC Processes. Full Model V

- Vector form factors: determined from the analysis of photo and electroproduction

  (O. Lalakulich *et al.*, Phys. Rev. D74, 014009 (2006))

$$C_3^V = \frac{2.13}{(1-q^2/M_V^2)^2} \cdot \frac{1}{1-\frac{q^2}{4M_V^2}}, \qquad C_4^V = \frac{-1.51}{(1-q^2/M_V^2)^2} \cdot \frac{1}{1-\frac{q^2}{4M_V^2}},$$

$$C_5^V = \frac{0.48}{(1-q^2/M_V^2)^2} \cdot \frac{1}{1-\frac{q^2}{0.776M_V^2}}, \qquad C_6^V = 0 \; (CVC), \qquad M_V = 0.84\,\mathrm{GeV}$$

- Axial form factors: use Adler model which assumes

$$C_4^A(q^2) = -\frac{C_5^A(q^2)}{4}, \qquad C_3^A(q^2) = 0$$

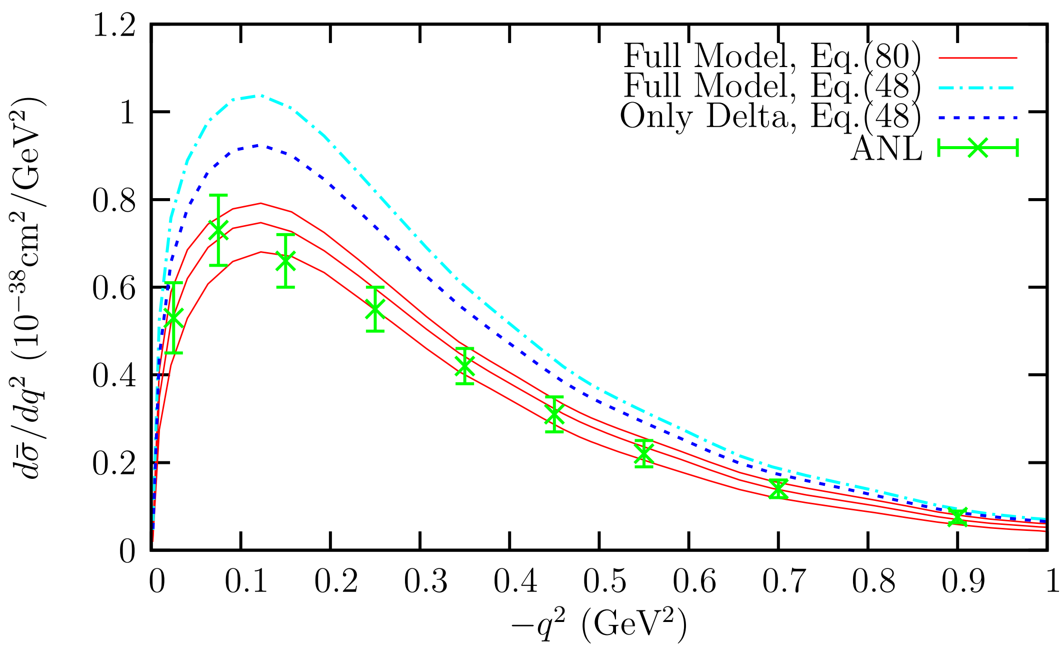
  and take (E.A. Paschos *et al.*, Phys. Rev. D69, 014013 (2004))

$$C_5^A(q^2) = \frac{1.2}{(1-q^2/M_{A\Delta}^2)^2} \cdot \frac{1}{1-\frac{q^2}{3M_{A\Delta}^2}}, \qquad C_6^A(q^2) = C_5^A(q^2)\frac{M^2}{m_\pi^2 - q^2}, \quad \text{with } M_{A\Delta} = 1.05\,\mathrm{GeV}$$

  where $C_5^A(0) = 1.2$ from the off-diagonal GT relation

CC Processes. Results I

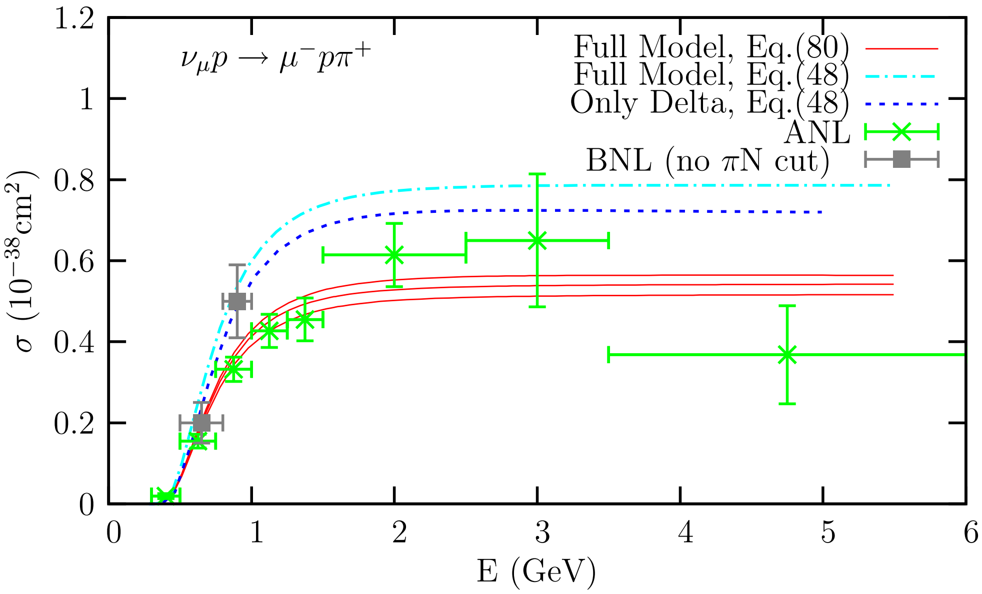
Flux averaged q^2-differential $\nu_\mu p \to \mu^- p \pi^+$ cross section $\int_{M+m_\pi}^{1.4\,\mathrm{GeV}} dW \frac{d\,\overline{\sigma}_{\nu_\mu \mu^-}}{dq^2 dW}$

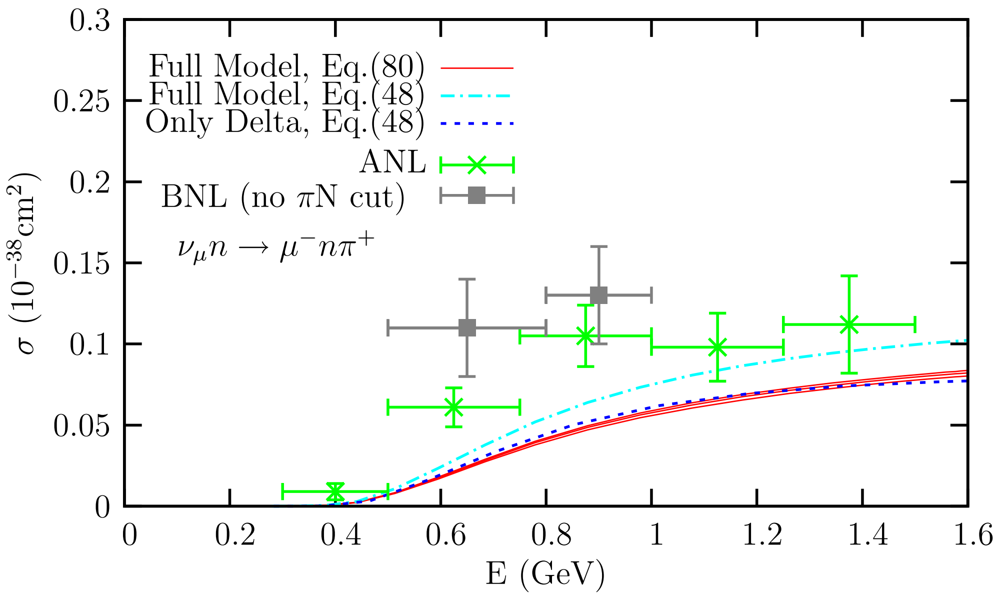


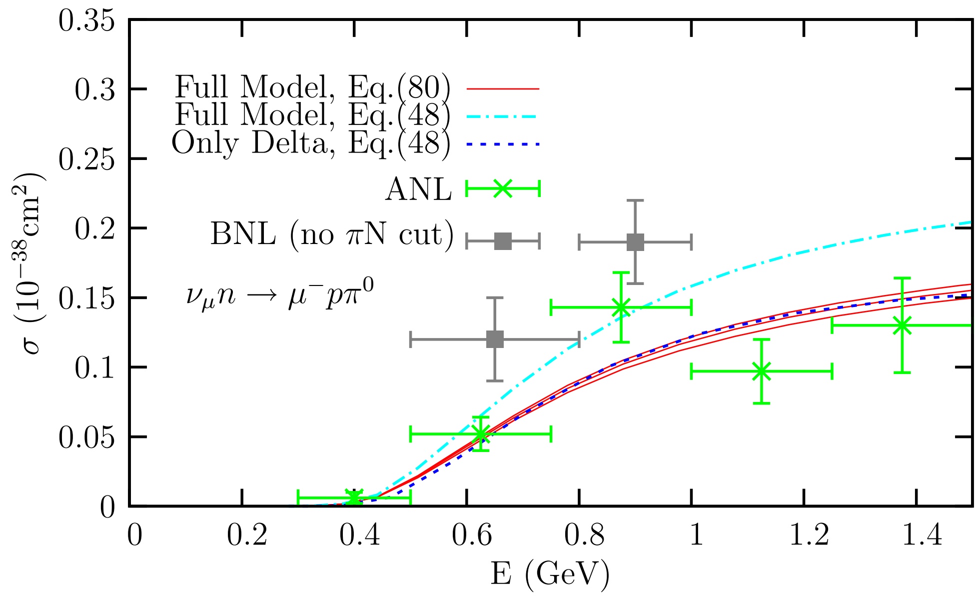
Results suggest a refit

$$C_5^A(0) = 0.867 \pm 0.075, \quad M_{A\Delta} = 0.985 \pm 0.082\,\mathrm{GeV}$$

CC Processes. Results II

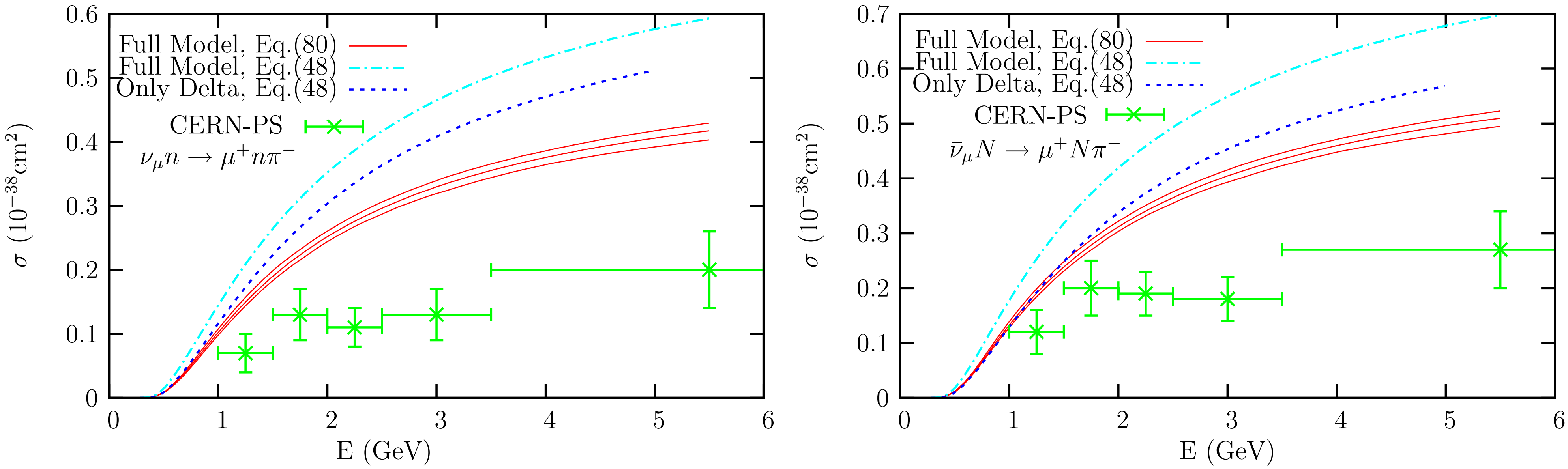






$W < 1.4$ GeV

CC Processes. Results IV



$W < 1.4$ GeV

Note $\langle n\pi^-|j^\mu_{\rm cc-}(0)|n\rangle = \langle p\pi^+|j^\mu_{\rm cc+}(0)|p\rangle$ and $L^{(\bar\nu)}_{\mu\sigma} = L^{(\nu)}_{\sigma\mu}$ so that $\sigma(\nu_\mu p \to \mu^- p\pi^+)$ and $\sigma(\bar\nu_\mu n \to \mu^+ p\pi^-)$ differ due to hadronic vector-axial interference.

Interference terms cancel in $\Sigma = \sigma(\nu_\mu p \to \mu^- p\pi^+) + \sigma(\bar\nu_\mu n \to \mu^+ p\pi^-)$

For instance at 3 GeV $\Sigma|_{theo.} \approx 1.11\ \Sigma|_{exp.}$

a difference not significative due to large error bars

According to S.K. Singh *et al.* (Phys. Rev. D75, 093003 (2007)) medium effects and pion absorption effects can perfectly explain the discrepancy between the theoretical results on the nucleon and experimental data actually measured in a freon-propane target.

NC Processes. Full Model I

$$j^\mu_{\rm nc} = \bar\Psi_q \gamma^\mu (1 - 2\sin^2\theta_W - \gamma_5)\tau_0^1 \Psi_q - 4\sin^2\theta_W\, s^\mu_{{\rm em},IS} - \bar\Psi_s\gamma^\mu(1-\gamma_5)\Psi_s, \qquad \Psi_q = \begin{pmatrix} \Psi_u \\ \Psi_d \end{pmatrix}$$

For the isoscalar part of the em current

$$\langle n\pi^+ \big| s^\mu_{{\rm em},IS} \big| p\rangle \quad = \quad \langle p\pi^- \big| s^\mu_{{\rm em},IS} \big| n\rangle = \sqrt{2}\langle p\pi^0 \big| s^\mu_{{\rm em},IS} \big| p\rangle = -\sqrt{2}\langle n\pi^0 \big| s^\mu_{{\rm em},IS} \big| n\rangle$$

Resonant Δ terms are not possible for an isoscalar operator

From the chiral Lagrangian we get ($\phi = (\phi_1 - i\phi_2)/\sqrt{2}$ creates a π^- or annihilates a π^+)

$$s^\mu_{\rm em} = \bar\Psi\gamma^\mu\left(\frac{\mathbf{1}+\tau_z}{2}\right)\Psi + \frac{{\rm i}g_A}{2f_\pi}\bar\Psi\gamma^\mu\gamma_5\left(\tau^1_{-1}\phi^\dagger + \tau^1_{+1}\phi\right)\Psi + {\rm i}\left(\phi^\dagger\partial^\mu\phi - \phi\partial^\mu\phi^\dagger\right) + \cdots$$

Only nucleon pole contributions are possible. Introducing form factors we have

$$\langle p| s^\mu_{{\rm em},IS}(0)|p\rangle = \bar u(\vec p\,')\left[F_1^{IS}(q^2)\gamma^\mu + {\rm i}\mu_{IS}\frac{F_2^{IS}(q^2)}{2M}\sigma^{\mu\nu}q_\nu\right]u(\vec p)$$

with

$$F_1^{IS}(q^2) = \frac{1}{2}\left(F_1^p(q^2) + F_1^n(q^2)\right), \qquad \mu_{IS}F_2^{IS}(q^2) = \frac{1}{2}\left(\mu_p F_2^p(q^2) + \mu_n F_2^n(q^2)\right)$$

NC Processes. Full Model II

Similarly, we a have nucleon pole contributions for the isoscalar piece $\bar{\Psi}_s\gamma^\mu(1-\gamma_5)\Psi_s$

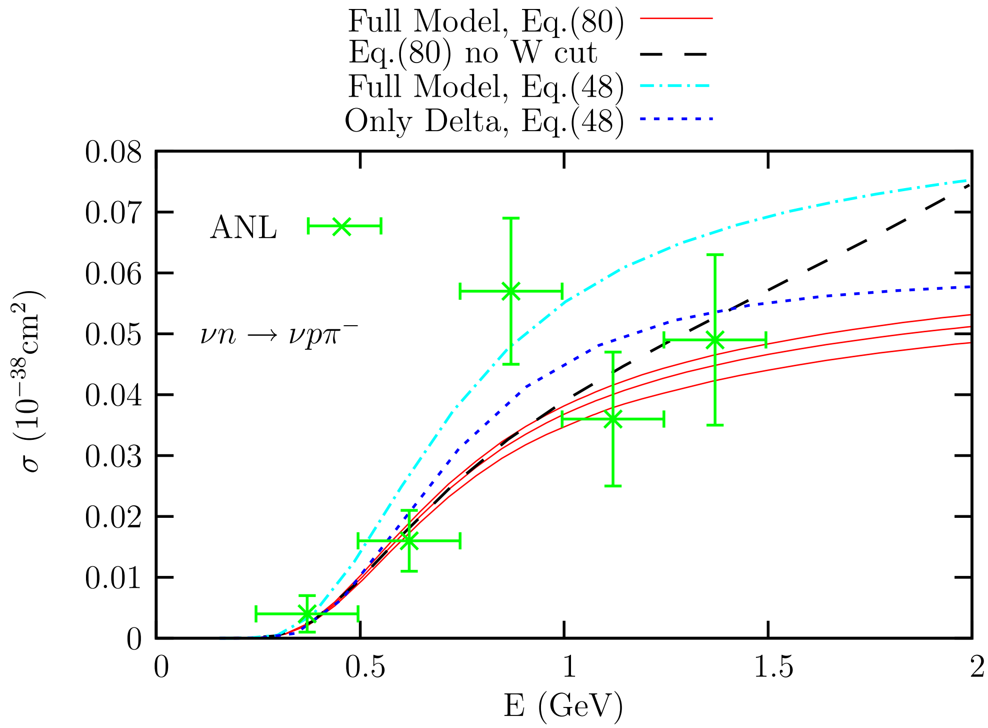
$$\langle p|(\bar{\Psi}_s\gamma^\mu(1-\gamma_5)\Psi_s)(0)|p\rangle = \bar{u}(\vec{p}\,') \left[F_1^s(q^2)\gamma^\mu + \mathrm{i}\mu_s \frac{F_2^s(q^2)}{2M}\sigma^{\mu\nu}q_\nu - G_A^s(q^2)\gamma^\mu\gamma_5 - G_P^s q^\mu\gamma_5\right] u(\vec{p})$$

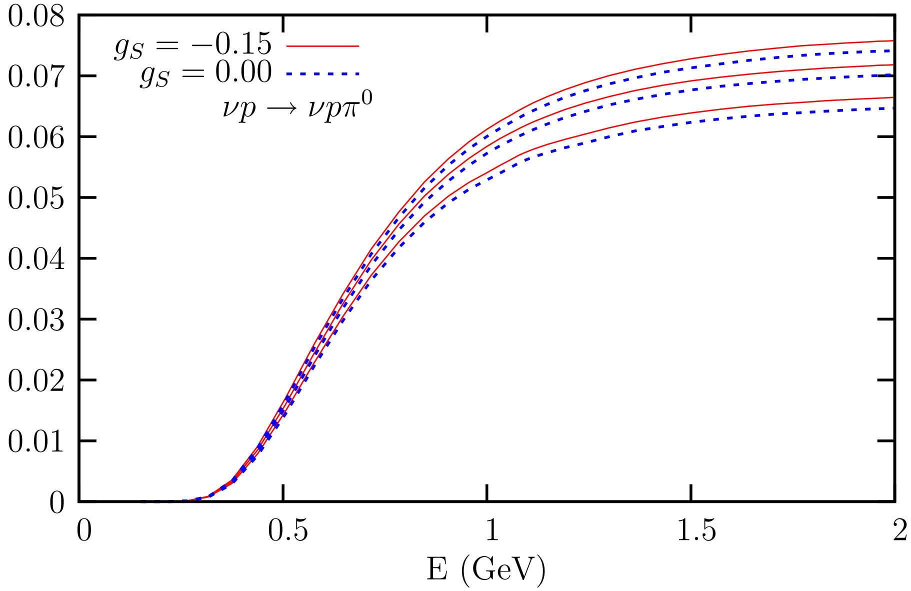
and we take from G.T. Garvey *et al.* (Phys. Rev. C48, 761 (1993))

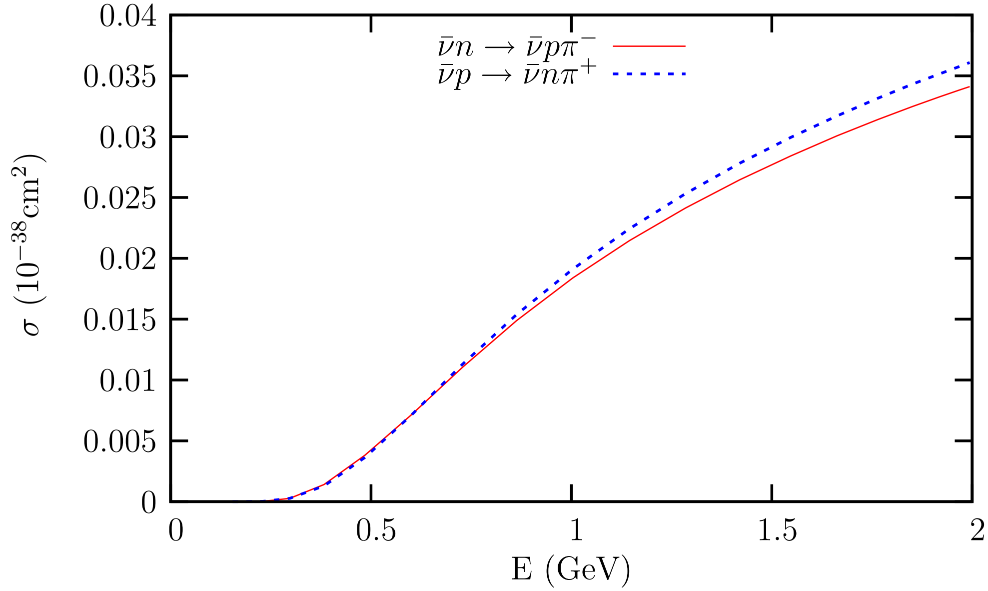
$$G_A^s(q^2) = \frac{g_S}{(1-q^2/(M_A^s)^2)^2}, \quad F_1^s(q^2) = \mu_s F_2^s(q^2) = 0, \quad g_S = -0.15, \; M_A^s = M_A$$

We neglect a possible contact term axial contribution

NC Processes. Results I







NC Processes. Results II

- $E_\nu = 0.6 - 1.2$ GeV

	ANL	Our results
$R_+ = \sigma(\nu p \to \nu n \pi^+)/\sigma(\nu p \to \mu^- p \pi^+)$	0.12 $\pm$ 0.04	0.12 – 0.10
$R_0 = \sigma(\nu p \to \nu p \pi^0)/\sigma(\nu p \to \mu^- p \pi^+)$	0.09 $\pm$ 0.05	0.18 – 0.14
$R_- = \sigma(\nu n \to \nu p \pi^-)/\sigma(\nu p \to \mu^- p \pi^+)$	0.11 $\pm$ 0.022	0.12 – 0.09

ANL data: M. Derrick *et al.*, Phys. Lett. B92,363 (1980);erratum B95, 461 (1981). M. Derrick *et al.*, Phys. Rev. D23, 569 (1981).

- $E_\nu = 2.2$ GeV, no cut in W, σ in $10^{-38}\mathrm{cm}^2$

	Hawker *et al.*	Our results
$\sigma(\nu p \to \nu p \pi^0)$	0.130 $\pm$ 0.020	0.105$\pm$0.006
$\sigma(\nu p \to \nu n \pi^+)$	0.080 $\pm$ 0.020	0.091$\pm$0.003
$\sigma(\nu n \to \nu n \pi^0)$	0.080 $\pm$ 0.020	0.104$\pm$0.006
$\sigma(\nu n \to \nu p \pi^-)$	0.110 $\pm$ 0.030	0.082$\pm$0.003

E.A. Hawker, talk at NUINT02. Reanalysis of the original Gargamelle data (W. Krenz *et al.*, Nuc. Phys. B135, 45 (1978))

Coherent Pion Production in Nuclei

- The hadronic amplitude at the nucleus level is written as a sum over the amplitudes for each nucleon. Neglecting non-localities and pion distortion one arrives at

$$\mathcal{A}^\mu_\pi(q,k_\pi) = \int d^3\vec{r}\, e^{\mathrm{i}(\vec{q}-\vec{k}_\pi)\cdot\vec{r}} \left\{ \rho_p(\vec{r}) \left[\mathcal{J}^\mu_{p\pi}(q,k_\pi) \right] + \rho_n(\vec{r}) \left[\mathcal{J}^\mu_{n\pi}(q,k_\pi) \right] \right\}$$

$$\mathcal{J}^\mu_{N\pi}(q,k_\pi) = \frac{1}{2}\sum_r \bar{u}_r(\vec{p}\,')\Gamma^\mu_{i;N\pi} u_r(\vec{p}) \frac{M}{\sqrt{p^0 p\,'^0}}, \quad i = \Delta P,\, C\Delta P,\, NP,\, CNP,\, CT,\, PP,\, PF$$

$$p^\mu = \left(\sqrt{M^2 + \frac{1}{4}\left(\vec{k}_\pi - \vec{q}\right)^2}, \frac{\vec{k}_\pi - \vec{q}}{2} \right),\; p' = p + q - k_\pi \;,\; q^0 = k^0_\pi \text{ (neglecting nucleus recoil)}$$

This prescription for the momenta allows to write

$$\mathcal{J}^\mu_{N\pi}(q,k_\pi) = \sum_i \mathcal{J}^\mu_{i;N\pi}(q,k_\pi), \quad i = \Delta P,\, C\Delta P,\, NP,\, CNP,\, CT,\, PP,\, PF$$

$$\mathcal{J}^\mu_{i;N\pi}(q,k_\pi) = \frac{1}{2}\mathrm{Tr}\left((\not{p} + M)\gamma^0 \Gamma^\mu_{i;N\pi} \right) \frac{M}{p^0},$$

- Antineutrino case

$$L^{(\bar\nu)}_{\mu\sigma} = L^{(\nu)}_{\sigma\mu} \;,\; \mathcal{J}^\mu_{p\pi^-[n\pi^-]}(\vec{r};q,k_\pi) = \mathcal{J}^\mu_{n\pi^+[p\pi^+]}(\vec{r};q,k_\pi)$$

Medium Modifications and Pion Distortion I

- Δ properties are strongly modified inside the nuclear medium. We consider selfenergy modifications due to quasielastic, two and three nucleon absorption and Pauli blocking.

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

(Oset, Salcedo, NPA 468,631 (1987); Nieves, Oset, García-Recio, NPA 554; 509 (1993); Nieves, Oset, García-Recio, NPA 554, 554 (1993))

Now $\mathcal{J}^\mu_{N\pi^+}(\vec{r}; q, k_\pi)$ becomes in effect $\vec{r}-$dependent so that factorization of the nuclear form factor is no longer possible.

- Pion distortion effects are also very important, specially for $|\vec{k}_\pi| < 0.5$ GeV

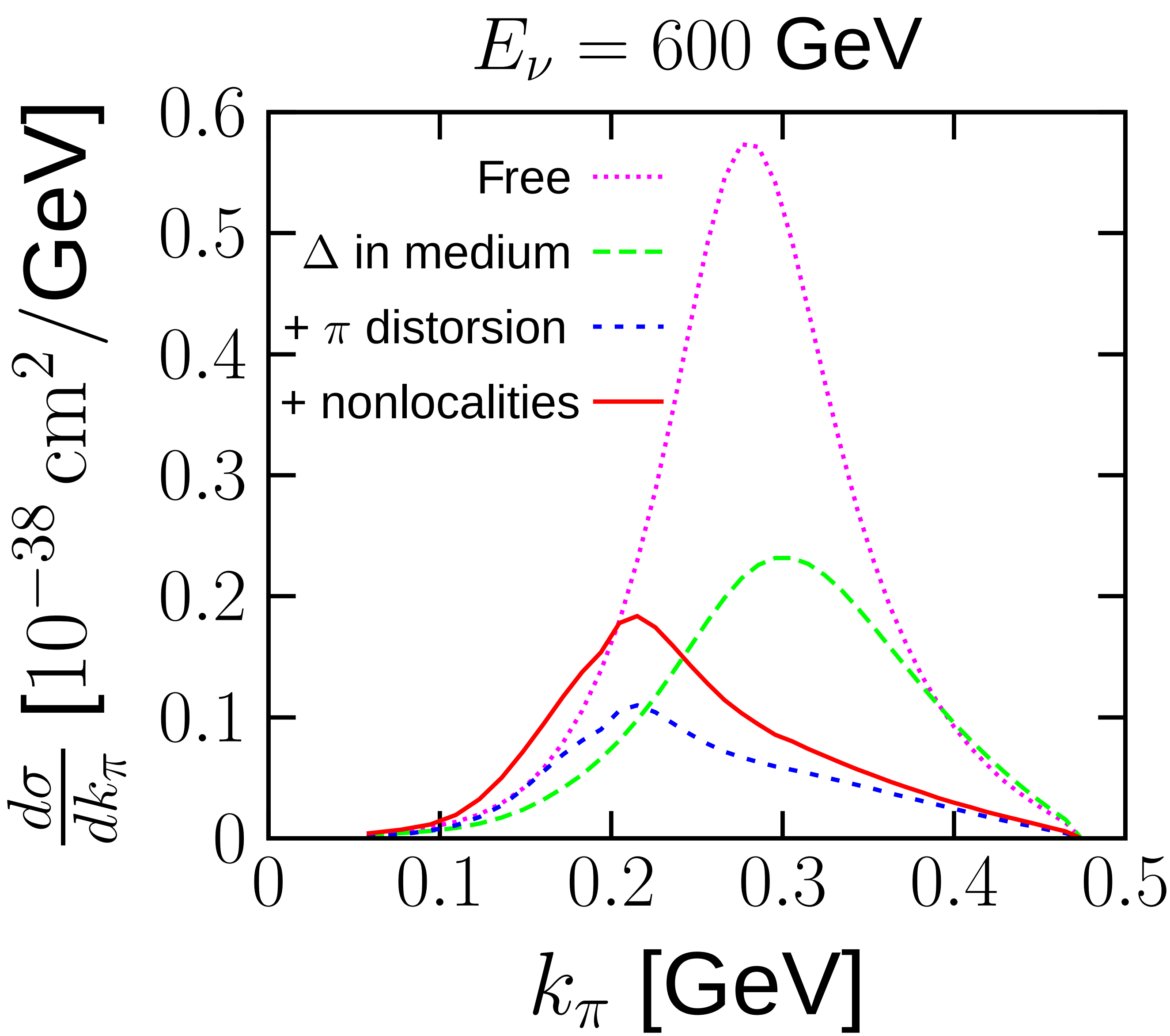
$$e^{-\mathrm{i}\vec{k}_\pi\cdot\vec{r}} \quad \rightarrow \quad \widetilde{\varphi}^*_\pi(\vec{r}; \vec{k}_\pi)$$

$$\left[-\vec{\bigtriangledown}^2 + m_\pi^2 + 2E_\pi V_{\mathrm{opt}}(\vec{r})\right]\widetilde{\varphi}^*_\pi(\vec{r}; \vec{k}_\pi) = E_\pi^2\widetilde{\varphi}^*_\pi(\vec{r}; \vec{k}_\pi)\,,$$

- Nonlocalities in pion momentum

$$\vec{k}_\pi e^{-\mathrm{i}\vec{k}_\pi\cdot\vec{r}} \quad \rightarrow \quad \mathrm{i}\vec{\nabla}\widetilde{\varphi}^*_\pi(\vec{r}; \vec{k}_\pi) \;\; (\text{only first order terms in } \mathrm{k}_\pi)$$

Medium Modifications and Pion Distortion II

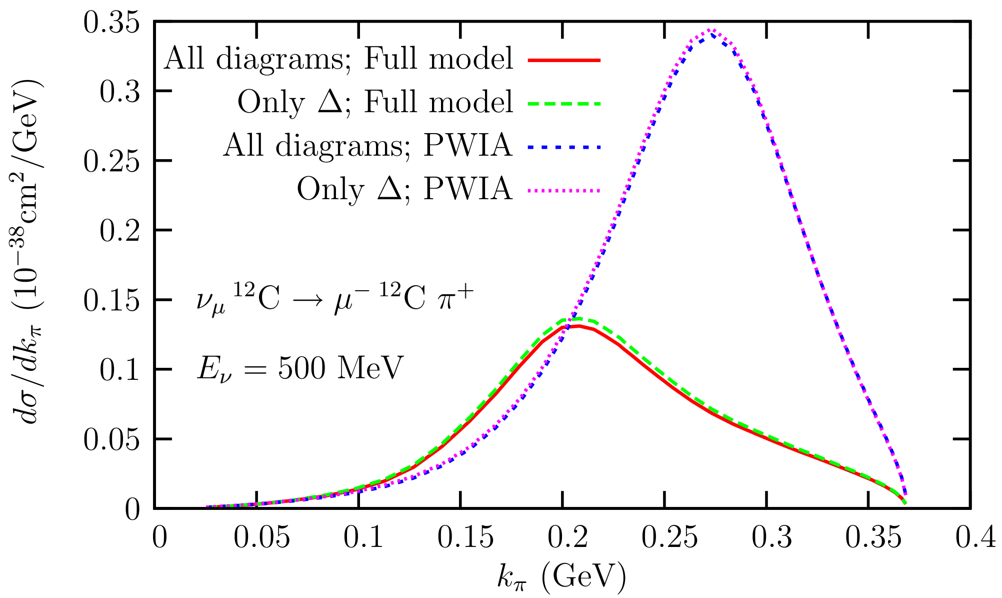


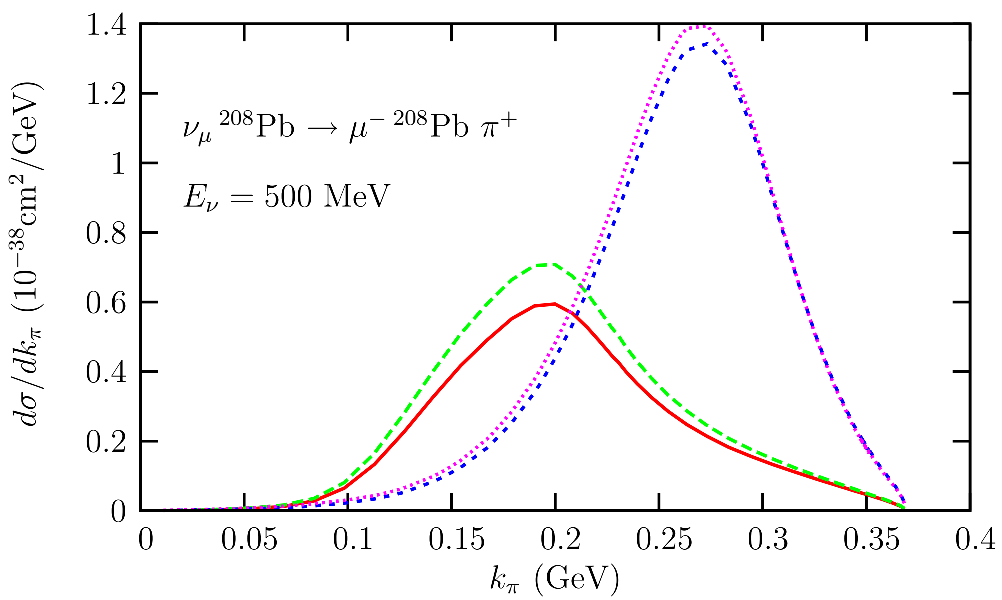
$\nu\ ^{16}O \rightarrow \mu^-\ ^{16}O\ \pi^+$

Irrelevance of Background Terms for Coherent Production I

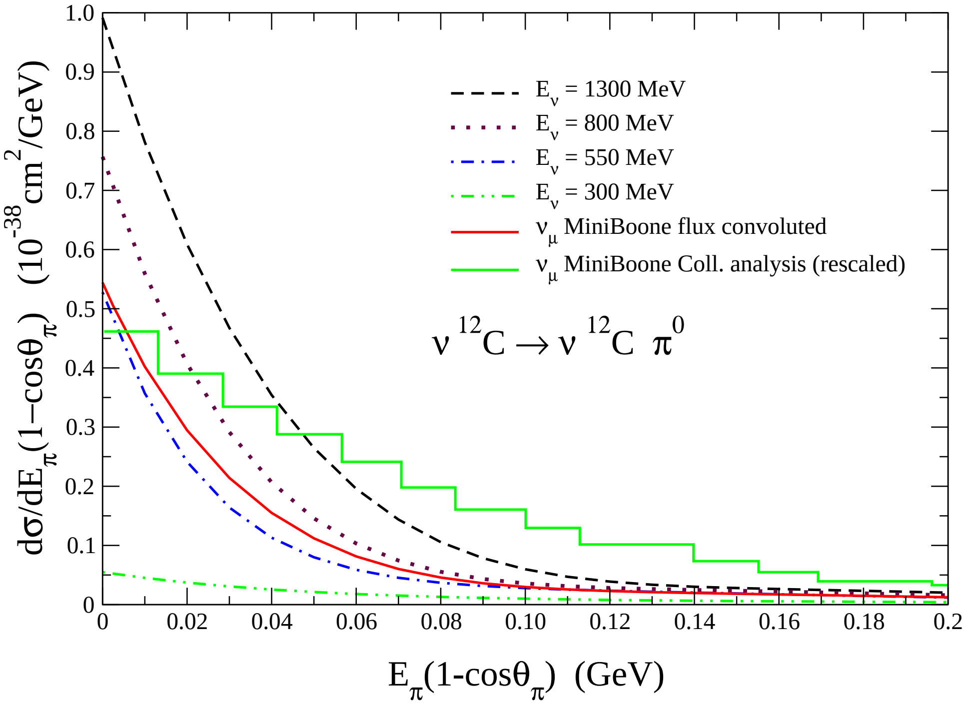
- CC case
  - $\mathcal{J}^{\mu}_{PF;N\pi^+}(q,k_\pi) = 0$ (Due to the trace)
  - $\mathcal{J}^{\mu}_{CT;p\pi^+}(q,k_\pi) = -\mathcal{J}^{\mu}_{CT;n\pi^+}(q,k_\pi) \Longrightarrow$ It cancels for symmetric nuclei
  - $\mathcal{J}^{\mu}_{PP;p\pi^+}(q,k_\pi) = -\mathcal{J}^{\mu}_{PP;n\pi^+}(q,k_\pi) \Longrightarrow$ It cancels for symmetric nuclei
  - $\mathcal{J}^{\mu}_{NP;p\pi^+}(q,k_\pi) = 0, \mathcal{J}^{\mu}_{CNP;n\pi^+}(q,k_\pi) = 0$
- NC case
  - $\mathcal{J}^{\mu}_{PF;N\pi^0}(q,k_\pi) = 0$
  - $\mathcal{J}^{\mu}_{CT;N\pi^0}(q,k_\pi) = 0$
  - $\mathcal{J}^{\mu}_{PP;N\pi^0}(q,k_\pi) = 0$
  - $\mathcal{J}^{\mu}_{NP;p\pi^0}(q,k_\pi) = -\mathcal{J}^{\mu}_{NP;n\pi^0}(q,k_\pi) \Longrightarrow$ It cancels for symmetric nuclei
  - $\mathcal{J}^{\mu}_{CNP;p\pi^0}(q,k_\pi) = -\mathcal{J}^{\mu}_{CNP;n\pi^0}(q,k_\pi) \Longrightarrow$ It cancels for symmetric nuclei

Irrelevance of Background Terms for Coherent Production II





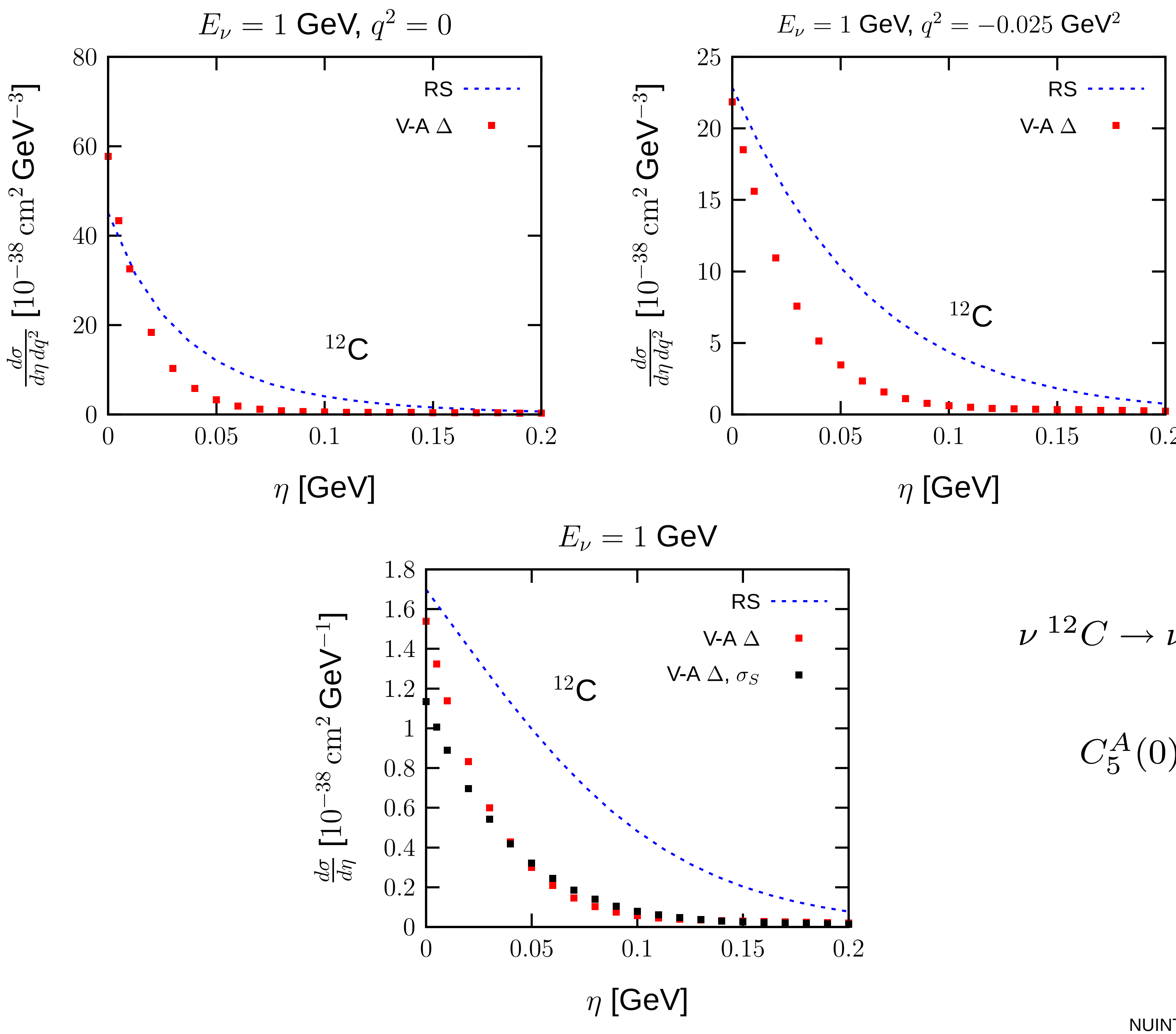
$\eta = E_\pi(1 - \cos\theta_\pi)$ distribution I



We have traced the differences to:

- $t = 0$ approximation in the Rein-Sehgal model used by the MiniBooNE Collaboration. This approximation is not good for low energies and light nuclei.
- Neglect of $\phi_{k_\pi q}$ dependence in PCAC-based models for $q^2 \neq 0$.

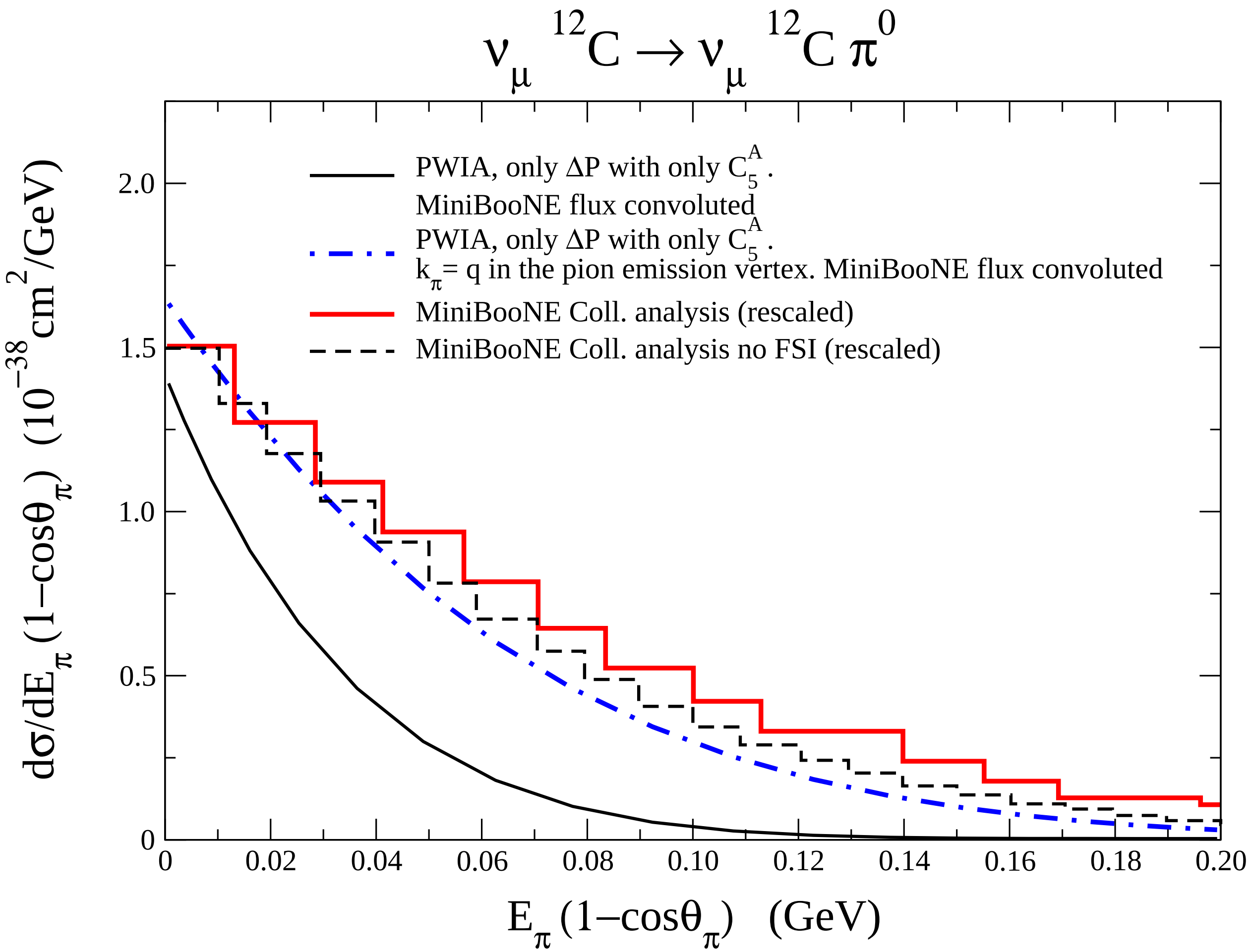
$\eta = E_\pi(1-\cos\theta_\pi)$ distribution II



$$\nu\, ^{12}C \rightarrow \nu\, ^{12}C\, \pi^0$$

$$C_5^A(0) = 1.2$$

$\eta = E_\pi(1 - \cos\theta_\pi)$ **distribution III**



$\vec{k}_\pi = \vec{q} \Longrightarrow t = 0$ (since $k_\pi^0 = q^0$) and no $\phi_{k_\pi q}-$dependence

- It is important to know what the actual value for $C_5^A(0)$ is
- I did not mention in this talk but, one has to clarify the role of nonlocalities in the nucleon momentum
- PCAC-based model predictions for angular distributions with respect to the incoming neutrino direction might not be reliable
- Maybe one should start to avoid the use of the Rein-Sehgal model for low energy neutrinos