Weak Pion Production off the Nucleon

E. Hernández, M. Valverde and JN

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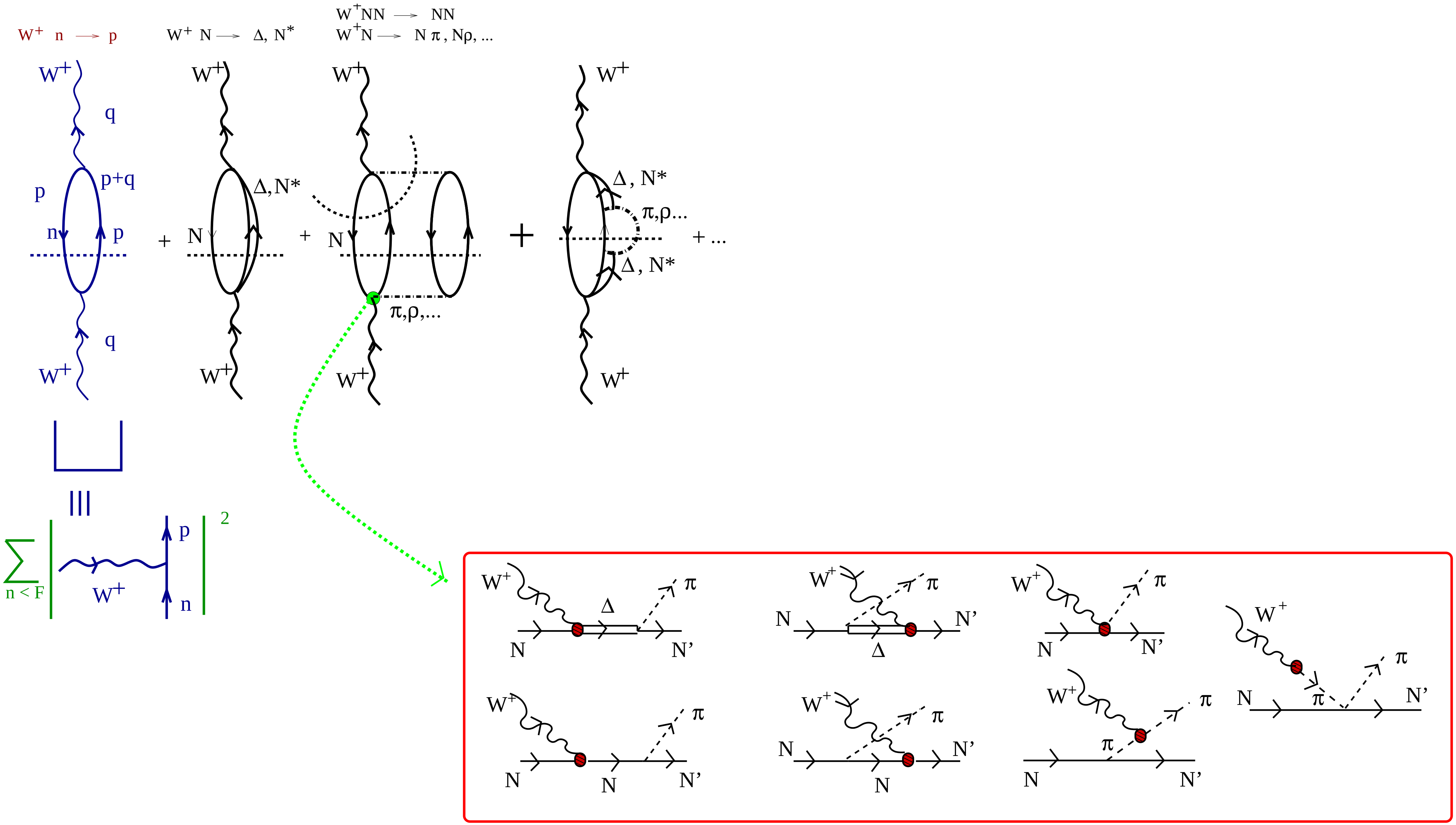
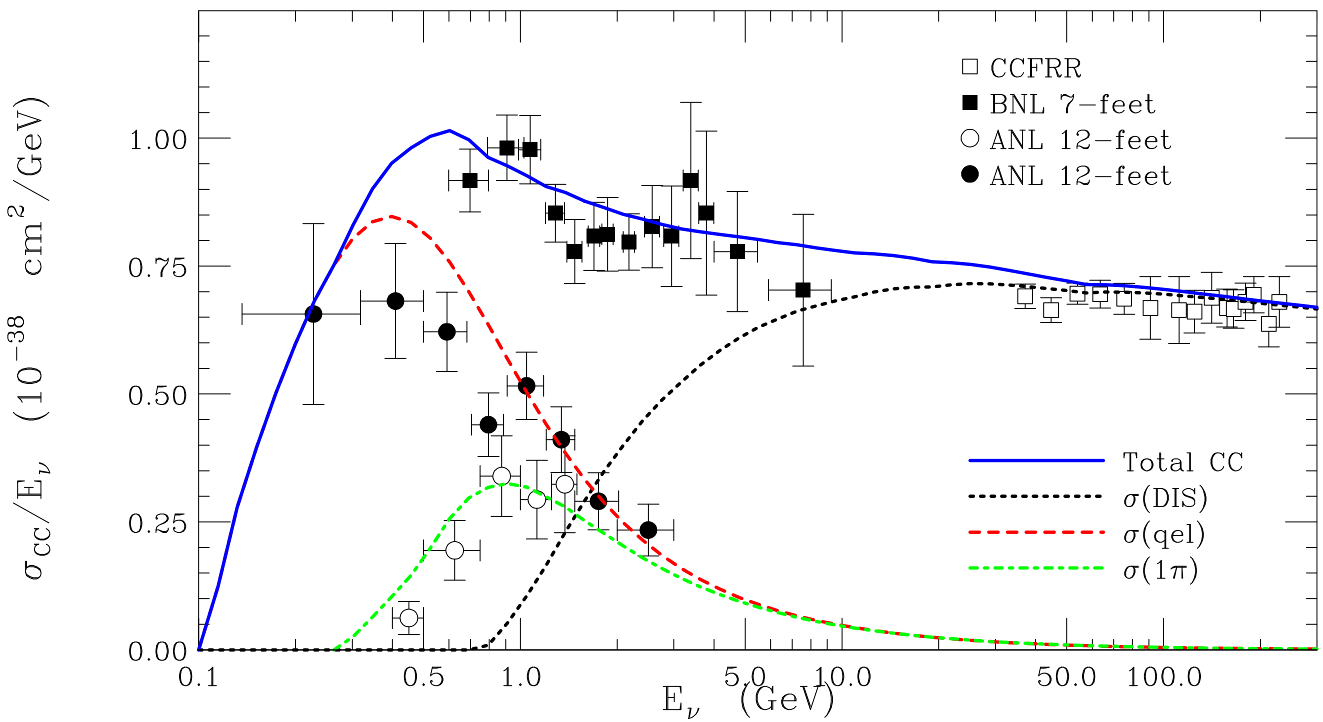
Motivation :

1. Explore some aspects of hadron dynamics/structure, no accessible with electrons/photons, by using a **weak probe**
2. First step to study **neutrino–nucleus inclusive scattering** above the QE peak


W+ n → p
W+ N → Δ, N*
W+NN → NN
W+N → N π, Nρ, ...
W+
q
p
p+q
n
p
Δ,N*
N
π,ρ,...
Δ, N*
π,ρ...
+ ...
n < F
2
W+
n



Theoretical knowledge of the one pion cross section is important to carry out a precise data analysis... Furthermore...

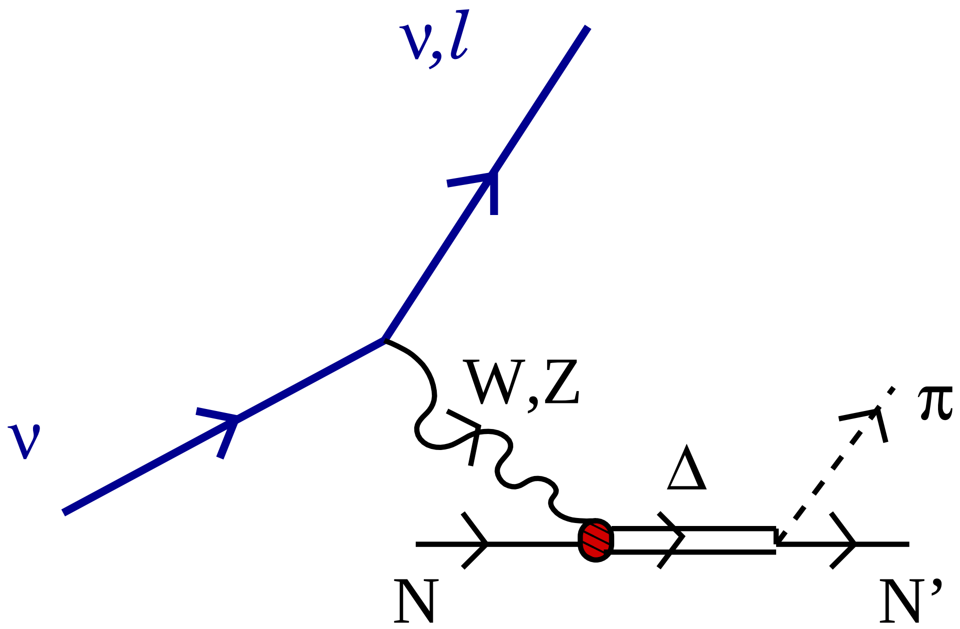
Pion production → identify *incorrectly* one-Čerenkov-ring events, which are assumed to be **CC QE** $\nu_\alpha A \to l_\alpha A'$.

- **Appearance probability** $P(\nu_\mu \to \nu_e)$**:** CC QE $\nu_e A \to eA'$ signal, which is used to identify ν_e, could be confused with that from 1π NC $\nu_\mu A \rightarrow \nu_\mu A \pi^0$ process

- **Survival probability $P(\nu_\mu \rightarrow \nu_\mu)$:** CC QE $\nu_\mu A \rightarrow \mu A'$ signal, which is used to identify ν_μ, could be confused with that from CC/NC 1π $\nu_{\tau,\mu} A \rightarrow (\nu_{\tau,\mu}$ ó $\tau, \mu) A' \pi$ signal, **if only one particle radiates Čerenkov light.**

  For instance, $(\nu_\mu, \mu\pi)$ **Incorrect E_ν re-construction** $\rightarrow L/E$ analysis ?

Theoretical Model $\nu_l N \to l N'\pi$, $\nu_l N \to \nu_l N'\pi$ **(C.H. Llewellyn Smith, 1972)**: weak excitation of the $\Delta(1232)$ resonance and its subsequent decay into $N\pi$,



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

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

$\mathbf{C^A_{3,4,5,6}}$ axial FF′s, $\mathbf{C^V_{3,4,5,6}}$ vector FF′s, furthermore

$$\mathcal{L}_{\pi N\Delta} = \frac{f^*}{m_\pi}\bar{\Psi}_\mu \vec{T}^\dagger(\partial^\mu\vec{\phi})\Psi + \text{h.c.}, \qquad f^* = 2.14$$

$$\mathbf{G}^{\mu\nu}(\mathbf{p}_\Delta) = \frac{\not{p}_\Delta + M_\Delta}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta}\left[-\mathbf{g}^{\mu\nu} + \frac{\mathbf{1}}{\mathbf{3}}\gamma^\mu\gamma^\nu + \frac{\mathbf{2}}{\mathbf{3}}\frac{\mathbf{p}^\mu_\Delta\mathbf{p}^\nu_\Delta}{\mathbf{M}^2_\Delta} - \frac{\mathbf{1}}{\mathbf{3}}\frac{\mathbf{p}^\mu_\Delta\gamma^\nu - \mathbf{p}^\nu_\Delta\gamma^\mu}{\mathbf{M}_\Delta}\right]$$

$eN \rightarrow e'\Delta \rightarrow e'N'\pi \Rightarrow C^V_{3,4,5,6}$ **FF's.** **CVC** $\Rightarrow C^V_6 = 0$ and $(M_V = 0.84\ \mathrm{GeV})$

$$\frac{\mathbf{C^V_3(q^2)}}{2.13} = \frac{\mathbf{C^V_4(q^2)}}{-1.51} = \frac{1-\frac{q^2}{0.776M_V^2}}{1-\frac{q^2}{4M_V^2}}\frac{\mathbf{C^V_5(q^2)}}{0.48} = \frac{1}{(1-q^2/M_V^2)^2}\times\frac{1}{1-\frac{q^2}{4M_V^2}}$$

$C^A_{3,4,5,6}$ **Axial FF's :** Δ^{++} $(\nu_\mu p \rightarrow \mu^- p\pi^+)$ **data taken in the ANL and BNL bubble chambers (filled in with deuterium)**

Dominant form factor: $\mathbf{C^A_5(q^2)}$. $\mathbf{C^A_3(q^2)}$ and $\mathbf{C^A_4(q^2)}$ contributions are small and we have taken (**Adler's model 1968**)

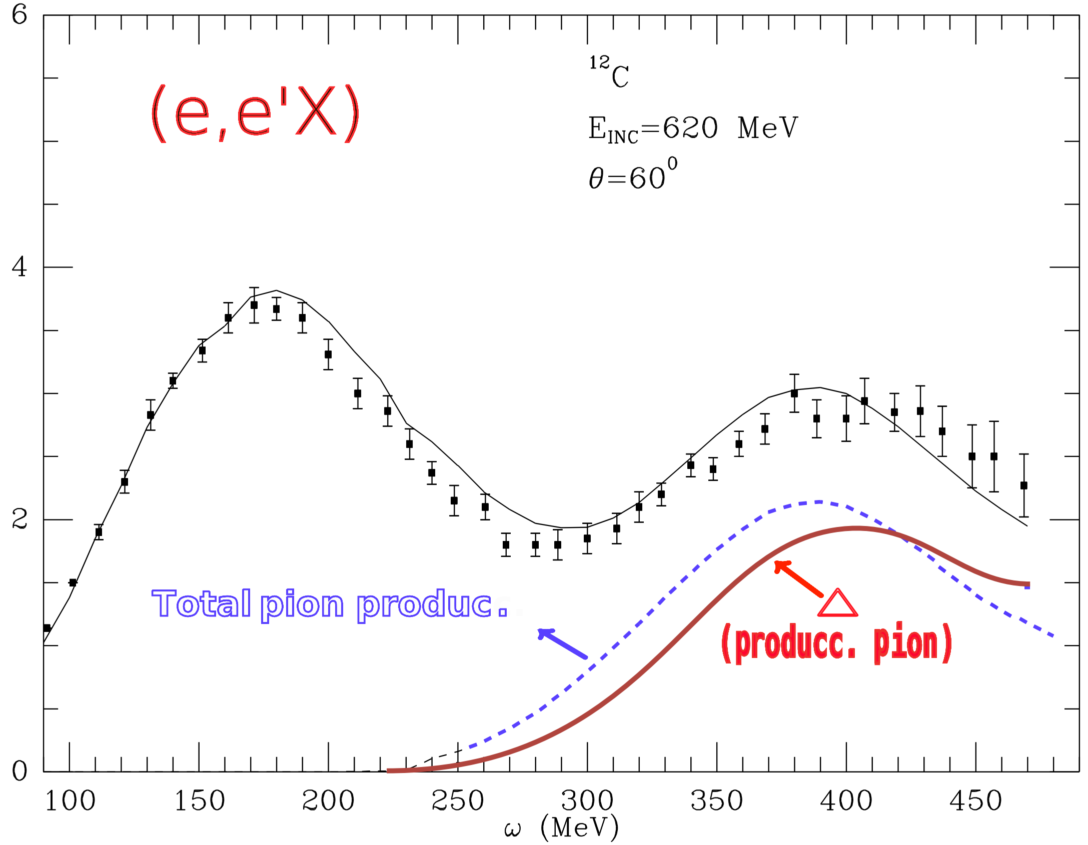
$$\mathbf{C^A_4(q^2)} = -\frac{\mathbf{C^A_5(q^2)}}{4},\ \mathbf{C^A_3(q^2)} = 0$$

Furthermore **PCAC** $(\partial_\mu A^\mu \propto m_\pi^2\ )$ **and Goldberger–Treiman** $C_5^A(0) \sim \sqrt{\frac{2}{3}}\frac{f_\pi}{m_\pi} f^* = 1.2$

$$\mathbf{C_5^A(q^2)} = \frac{\mathbf{1.2}}{(1-q^2/\mathbf{M^2_{A\Delta}})^2} \times \frac{1}{1-\frac{q^2}{3\mathbf{M^2_{A\Delta}}}}, \ \underbrace{\mathbf{C_6^A(q^2)} = \mathbf{C_5^A(q^2)}\frac{M^2}{m_\pi^2-q^2}}_{\text{PCAC}}$$

$M_{A\Delta}$ **fitted to the** q^2 **dependence of the** $\nu_\mu p \to \mu^- p \pi^+$ cross section (neutrino energy averaged) **with** $(M(\pi N) < 1.4$ GeV$)$ **measured at ANL and BNL.** It varies in the range 0.95 GeV (ANL) – 1.28 GeV (BNL). We set

$$\mathbf{M_{A\Delta} \sim 1.05\ GeV} \quad \text{(\textbf{axial nucleon mass})}$$

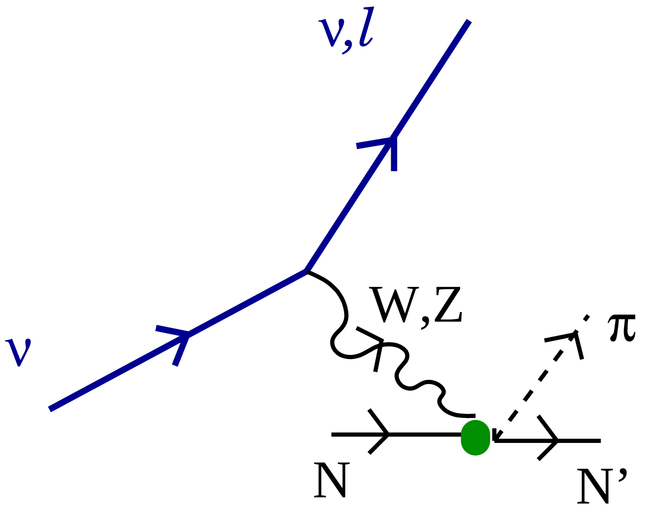


... but **only the Δ pole** contribution turns out to be **an <u>insufficient</u>** model, even at the Δ peak, and **specially close to pion threshold**. Close to pion threshold, the pion from the $(\nu_\mu, \mu\pi)$ **reaction will not radiate Čerenkov light** and thus it would be necessary an improved theoretical model to carry out a proper L/E **oscillation analysis.**

Such model for the $\nu_l N \to l N'\pi$, $\nu_l N \to \nu_l N'\pi$ reactions should include **<u>non resonant</u>** <u>terms</u> $\Rightarrow$ **Realization of the axial and vector currents, which couple to the W, Z^0 bosons, for a system of pions and nucleons.**

Non-linear $\sigma-$Model: EFT involving pions and nucleons which implements spontaneous chiral symmetry breaking.

If $\Psi_q = \begin{pmatrix} \Psi_u \\ \Psi_d \end{pmatrix}$, the CC and NC, which induce $W(Z^0)N \to N'\pi$



$$
\begin{aligned}
j^\mu_{\rm cc\pm} &= \cos\theta_C \bar\Psi_q \gamma^\mu (1-\gamma_5)\left(-\frac{\boxed{\tau^1_{\pm 1}}}{\sqrt{2}}\right)\Psi_q \\
j^\mu_{\rm nc} &= \bar\Psi_q \gamma^\mu (1 - 2\sin^2\theta_W - \gamma_5)\boxed{\tau^1_0}\Psi_q \\
&- \boxed{4\sin^2\theta_W \mathbf{s}^\mu_{\rm em,IS} - \bar{\boldsymbol{\Psi}}_{\mathbf{s}}\gamma^\mu(\mathbf{1}-\gamma_{\mathbf{5}})\boldsymbol{\Psi}_{\mathbf{s}}} \\
s^\mu_{\rm em} &= \underbrace{\frac{1}{6}\bar\Psi_q\gamma^\mu\Psi_q - \frac{1}{3}\bar\Psi_s\gamma^\mu\Psi_s}_{\mathbf{s}^\mu_{\rm em,IS}} + \frac{1}{\sqrt{2}}\bar\Psi_q\,\gamma^\mu\frac{\boxed{\tau^1_0}}{\sqrt{2}}\,\Psi_q
\end{aligned}
$$

$$\langle N'\pi | \mathbf{j}^\mu_{\rm cc+}(\mathbf{0}), \mathbf{j}^\mu_{\rm cc-}(\mathbf{0}), \mathbf{j}^\mu_{\rm nc}(\mathbf{0}) | N\rangle = ? \Leftarrow \text{QCD and its pattern of S}\chi\text{SB}$$

If $\Psi = \begin{pmatrix} p \\ n \end{pmatrix}$, $U = \frac{f_\pi}{\sqrt{2}} e^{\mathrm{i}\,\vec{\tau}\cdot\boxed{\vec{\phi}}/f_\pi} = \frac{f_\pi}{\sqrt{2}}\xi^2$, with $f_\pi \sim 93$ MeV,

$$\begin{aligned}\mathcal{L}_{N\pi} &= \bar{\Psi}\mathrm{i}\gamma^\mu\left[\partial_\mu + \mathcal{V}_\mu\right]\Psi - M\bar{\Psi}\Psi + g_A\bar{\Psi}\gamma^\mu\gamma_5\mathcal{A}_\mu\Psi \\ &+ \frac{1}{2}\mathrm{Tr}\left[\partial_\mu U^\dagger \partial^\mu U\right] \boxed{+m_\pi^2\frac{f_\pi}{2\sqrt{2}}\mathrm{Tr}(U + U^\dagger - \sqrt{2}f_\pi)}\end{aligned}$$

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

Isospin rotat. $\xi \to \mathbf{T_V}\,\xi\,\mathbf{T_V^\dagger}$, $\mathbf{\Psi} \to \mathbf{T_V}\,\mathbf{\Psi}$, $\quad T_V = e^{-\mathrm{i}\,\frac{\vec{\tau}\cdot\vec{\theta}_V}{2}}$

Axial rotat. $\xi \to \mathbf{T_A^\dagger}\,\xi\,\mathbf{T_\Lambda^\dagger} = \mathbf{T_\Lambda}\,\xi\,\mathbf{T_A^\dagger}$, $\mathbf{\Psi} \to \mathbf{T_\Lambda}\,\mathbf{\Psi}$, $\quad T_{\Lambda,A} = e^{-\mathrm{i}\,\frac{\vec{\tau}\cdot\vec{\theta}_{\Lambda,A}}{2}}$

Isospin rotat. $\Rightarrow \delta\mathcal{L}_{\mathbf{N}\pi} = \mathbf{0}$, **Axial rotat.** $\Rightarrow \delta\mathcal{L}_{\mathbf{N}\pi}\boxed{\propto m_\pi^2 \neq 0}$

Up to order $\mathcal{O}(1/f_\pi^4)$, $\mathcal{L}_{N\pi}$ reads,

$$\mathcal{L}_{\mathbf{N}\pi} = \bar\Psi[\mathrm{i}\partial\!\!\!/ - M]\Psi + \frac{1}{2}\partial_\mu\vec\phi\partial^\mu\vec\phi - \frac{1}{2}m_\pi^2\vec\phi^{\,2} \quad (\textbf{kinetic}) +$$

$$\frac{\mathbf{g_A}}{\mathbf{f}_\pi}\bar{\mathbf{\Psi}}\gamma^\mu\gamma_\mathbf{5}\frac{\vec\tau}{\mathbf{2}}(\partial_\mu\vec\phi)\mathbf{\Psi} - \frac{\mathbf{1}}{\mathbf{4f_\pi^2}}\bar{\mathbf{\Psi}}\gamma_\mu\vec\tau\left(\vec\phi\times\partial^\mu\vec\phi\right)\mathbf{\Psi} - \frac{\mathbf{g_A}}{\mathbf{6f_\pi^3}}\bar{\mathbf{\Psi}}\gamma^\mu\gamma_\mathbf{5}\left[\vec\phi^{\,\mathbf{2}}\frac{\vec\tau}{\mathbf{2}}\partial_\mu\vec\phi - (\vec\phi\partial_\mu\vec\phi)\frac{\vec\tau}{\mathbf{2}}\vec\phi\right]\mathbf{\Psi}$$

$$-\frac{\mathbf{1}}{\mathbf{6f_\pi^2}}\left(\vec\phi^{\,\mathbf{2}}\partial_\mu\vec\phi\partial^\mu\vec\phi - (\vec\phi\partial_\mu\vec\phi)(\vec\phi\partial^\mu\vec\phi)\right) + \frac{\mathbf{m_\pi^2}}{\mathbf{24f_\pi^2}}(\vec\phi^{\,\mathbf{2}})^\mathbf{2} + \mathcal{O}(1/f_\pi^4)$$

Contact interactions $N N\pi$, $\underbrace{NN\pi\pi}_{\mathrm{WT}}$, $NN\pi\pi\pi$ and $\pi\pi\pi\pi$.

Parameters: f_π and g_A . **Noether's currents**

$$j^\mu = \frac{\partial\mathcal{L}_{N\pi}}{\partial(\partial_\mu\varphi_a)}\delta\varphi_a, \quad a = 1, 2, \cdots$$

up to order $\mathcal{O}(1/f_\pi^3)$ ...

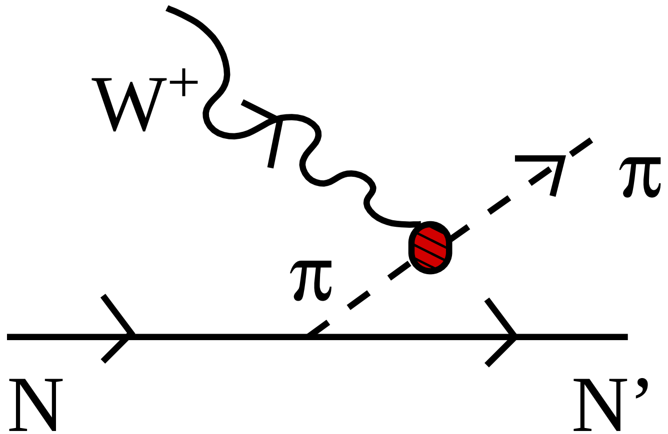
$$\vec{\mathbf{V}}^\mu = \vec\phi\times\partial^\mu\vec\phi + \frac{g_A}{2f_\pi}\bar\Psi\gamma^\mu\gamma_5(\vec\phi\times\vec\tau)\Psi + \bar\Psi\gamma^\mu\frac{\vec\tau}{2}\Psi - \frac{1}{4f_\pi^2}\bar\Psi\gamma^\mu\left[\vec\tau\vec\phi^{\,2} - \vec\phi(\vec\tau\cdot\vec\phi)\right]\Psi$$
$$- \frac{\vec\phi^{\,2}}{3f_\pi^2}(\vec\phi\times\partial^\mu\vec\phi) + \mathcal{O}(\frac{1}{f_\pi^3}), \quad \partial_\mu\vec{\mathbf{V}}^\mu = \mathbf{0}$$

$$\vec{\mathbf{A}}^\mu = f_\pi\partial^\mu\vec\phi + \frac{1}{2f_\pi}\bar\Psi\gamma^\mu(\vec\phi\times\vec\tau)\Psi + g_A\bar\Psi\gamma^\mu\gamma_5\frac{\vec\tau}{2}\Psi + \frac{2}{3f_\pi}\left[\vec\phi(\vec\phi\cdot\partial^\mu\vec\phi) - \vec\phi^{\,2}\partial^\mu\vec\phi\right]$$
$$- \frac{g_A}{4f_\pi^2}\bar\Psi\gamma^\mu\gamma_5\left[\vec\tau\vec\phi^{\,2} - \vec\phi(\vec\tau\cdot\vec\phi)\right]\Psi + \mathcal{O}(\frac{1}{f_\pi^3}), \quad \underbrace{\partial_\mu\vec{A}^\mu \propto m_\pi^2 \ldots}_{\text{PCAC}}$$

+ isospin relations ⇒ <u>evaluate</u> CC $\langle N'\pi|\, j^\mu_{cc+}(0), j^\mu_{cc-}(0)|N\rangle$

$$\langle p\pi^0|j^\mu_{cc+}(0)|n\rangle = -\frac{1}{\sqrt2}\left[\langle\mathbf{p}\pi^+|\mathbf{j}^\mu_{cc+}(\mathbf{0})|\mathbf{p}\rangle - \langle\mathbf{n}\pi^+|\mathbf{j}^\mu_{cc+}(\mathbf{0})|\mathbf{n}\rangle\right]$$
$$\langle p\pi^-|j^\mu_{cc-}(0)|p\rangle = \langle\mathbf{n}\pi^+|\mathbf{j}^\mu_{cc+}(\mathbf{0})|\mathbf{n}\rangle$$
$$\langle n\pi^-|j^\mu_{cc-}(0)|n\rangle = \langle\mathbf{p}\pi^+|\mathbf{j}^\mu_{cc+}(\mathbf{0})|\mathbf{p}\rangle$$
$$\langle n\pi^0|j^\mu_{cc-}(0)|p\rangle = -\langle p\pi^0|j^\mu_{cc+}(0)|n\rangle = \frac{1}{\sqrt2}\left[\langle\mathbf{p}\pi^+|\mathbf{j}^\mu_{cc+}(\mathbf{0})|\mathbf{p}\rangle - \langle\mathbf{n}\pi^+|\mathbf{j}^\mu_{cc+}(\mathbf{0})|\mathbf{n}\rangle\right]$$

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

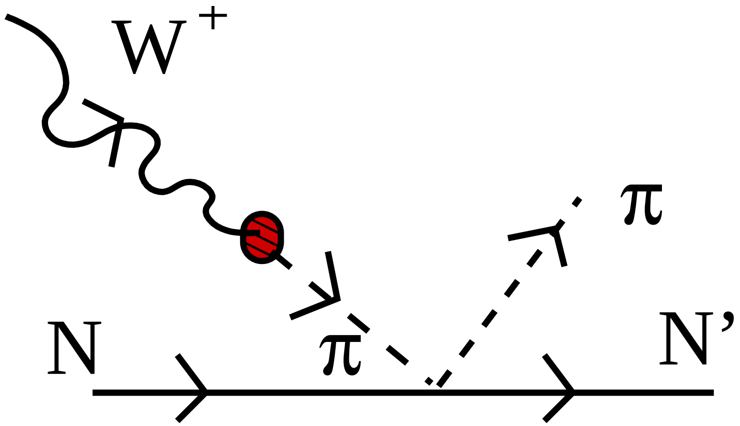


$$
j^\mu_{cc+}\Big|_{PF} = \mp\,\mathrm{i}\,\mathbf{F_{PF}(q^2)}\frac{\sqrt{2}Mg_A}{f_\pi}\cos\theta_C\frac{(2k_\pi-q)^\mu}{(k_\pi-q)^2-m_\pi^2}\bar u(\vec p\,')\gamma_5 u(\vec p)
$$

$$
(\,-\Rightarrow W^+p\to p\pi^+,\ +\Rightarrow W^+n\to n\pi^+\,)
$$

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

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

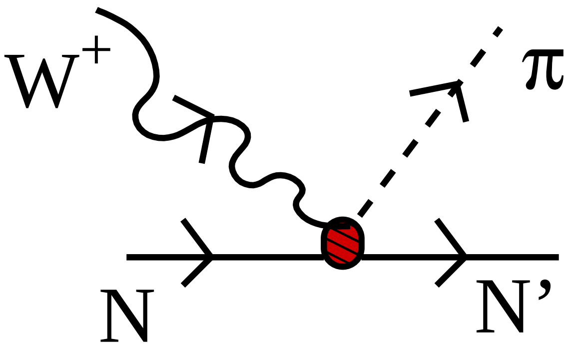


$$j^\mu_{cc+}\Big|_{PP} = \mp\,\mathrm{i}\,\mathbf{F}_\rho\left((\mathbf{q}-\mathbf{k}_\pi)^2\right)\frac{\cos\theta_C}{\sqrt{2}f_\pi}\frac{q^\mu}{q^2-m_\pi^2}\bar u(\vec{p}\,')\,\not{q}\,u(\vec{p})$$

$$(\ - \Rightarrow W^+p\to p\pi^+,\ + \Rightarrow W^+n\to n\pi^+\ )$$

$$\mathbf{F}_\rho(\mathbf{t}) = \frac{\mathbf{1}}{\mathbf{1}-\mathbf{t}/\mathbf{m}_\rho^2}$$

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

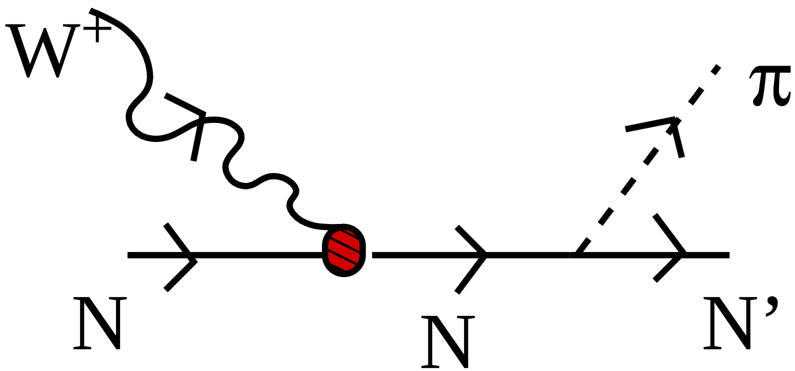


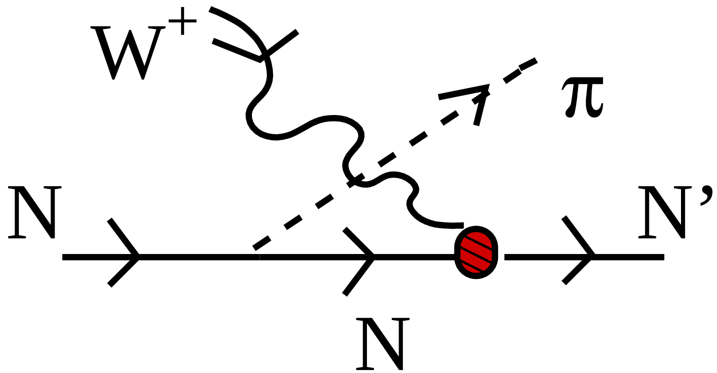
$$j^\mu_{cc+}\Big|_{CT} = \mp\, \mathrm{i}\,\frac{\cos\theta_C}{\sqrt{2}f_\pi}\bar{u}(\vec{p}\,')\gamma^\mu\left(g_A\mathbf{F^V_{CT}}(\mathbf{q^2})\gamma_5 - \mathbf{F}_\rho\left((\mathbf{q}-\mathbf{k}_\pi)^2\right)\right)u(\vec{p})$$

$$(\, - \Rightarrow W^+p \to p\pi^+,\ + \Rightarrow W^+n \to n\pi^+ \,)$$

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

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





... improve the WNN transition vertex

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

$$\mathbf{V}^\alpha_\mathbf{N}(\mathbf{q}) = 2\times\left(\mathbf{F}^\mathbf{V}_\mathbf{1}(\mathbf{q^2})\gamma^\alpha + \mathrm{i}\mu_\mathbf{V}\frac{\mathbf{F}^\mathbf{V}_\mathbf{2}(\mathbf{q^2})}{2M}\sigma^{\alpha\nu}q_\nu\right)$$

$$\mathbf{A}^\alpha_\mathbf{N}(\mathbf{q}) = \underbrace{\frac{g_A}{(1-q^2/M_A^2)^2}}_{\mathbf{G_A(q^2)}}\times\left(\gamma^\alpha\gamma_5+\underbrace{\frac{\not{q}}{m_\pi^2-q^2}}_{\text{PCAC}}q^\alpha\gamma_5\right), \quad \left\{\begin{array}{l} g_A = 1.26 \\ M_A = 1.05\ \text{GeV}\end{array}\right.$$

$$\mathbf{F}^\mathbf{V}_\mathbf{1}(\mathbf{q^2}) = \frac{1}{2}\left(\mathbf{F}^\mathbf{p}_\mathbf{1}(\mathbf{q^2}) - \mathbf{F}^\mathbf{n}_\mathbf{1}(\mathbf{q^2})\right), \qquad \mu_\mathbf{V}\mathbf{F}^\mathbf{V}_\mathbf{2}(\mathbf{q^2}) = \frac{1}{2}\left(\mu_\mathbf{p}\mathbf{F}^\mathbf{p}_\mathbf{2}(\mathbf{q^2}) - \mu_\mathbf{n}\mathbf{F}^\mathbf{n}_\mathbf{2}(\mathbf{q^2})\right),$$

furthermore **CVC** $\Rightarrow \boxed{F_{PF}(q^2) = F^V_{CT}(q^2) = 2F^V_1(q^2) = F^p_1 - F^n_1}$

$$
\begin{aligned}
\vec{\mathbf{V}}^{\mu} &= \vec{\phi} \times \partial^{\mu} \vec{\phi} + \frac{g_A}{2 f_\pi} \bar{\Psi} \gamma^{\mu} \gamma_5 (\vec{\phi} \times \vec{\tau}) \Psi + \bar{\Psi} \gamma^{\mu} \frac{\vec{\tau}}{2} \Psi - \frac{\mathbf{1}}{\mathbf{4 f_\pi^2}} \bar{\mathbf{\Psi}} \gamma^{\mu} \left[\vec{\tau} \vec{\phi}^{\mathbf{2}} - \vec{\phi} (\vec{\tau} \cdot \vec{\phi}) \right] \mathbf{\Psi} \\
&- \frac{\vec{\phi}^{\mathbf{2}}}{\mathbf{3 f_\pi^2}} (\vec{\phi} \times \partial^{\mu} \vec{\phi}) + \mathcal{O}(\frac{\mathbf{1}}{\mathbf{f_\pi^3}}) \\
\vec{\mathbf{A}}^{\mu} &= f_\pi \partial^{\mu} \vec{\phi} + \frac{1}{2 f_\pi} \bar{\Psi} \gamma^{\mu} (\vec{\phi} \times \vec{\tau}) \Psi + g_A \bar{\Psi} \gamma^{\mu} \gamma_5 \frac{\vec{\tau}}{2} \Psi + \frac{\mathbf{2}}{\mathbf{3 f_\pi}} \left[\vec{\phi} (\vec{\phi} \cdot \partial^{\mu} \vec{\phi}) - \vec{\phi}^{\mathbf{2}} \partial^{\mu} \vec{\phi} \right] \\
&- \frac{\mathbf{g_A}}{\mathbf{4 f_\pi^2}} \bar{\mathbf{\Psi}} \gamma^{\mu} \gamma_{\mathbf{5}} \left[\vec{\tau} \vec{\phi}^{\mathbf{2}} - \vec{\phi} (\vec{\tau} \cdot \vec{\phi}) \right] \mathbf{\Psi} + \mathcal{O}(\frac{\mathbf{1}}{\mathbf{f_\pi^3}})
\end{aligned}
$$

$\nu_l N \to l N' \pi\pi$, $\nu_l N \to \nu_l N' \pi\pi$ **close to threshold.** $N(1440)$

degrees of freedom?

Evaluation of NC $\langle N'\pi|\, j^\mu_{\rm nc}(0)|N\rangle$:

$$j^\mu_{\rm nc} = \bar\Psi_q \gamma^\mu (1-2\sin^2\theta_W - \gamma_5) \boxed{\tau^1_0} \Psi_q - \boxed{4\sin^2\theta_W \mathbf{s}^\mu_{\rm em,IS} - \bar{\boldsymbol\Psi}_{\mathbf s}\gamma^\mu(\mathbf{1}-\gamma_5)\boldsymbol\Psi_{\mathbf s}}$$

$$s^\mu_{\rm em} = \underbrace{\frac{1}{6}\bar\Psi_q\gamma^\mu\Psi_q - \frac{1}{3}\bar\Psi_s\gamma^\mu\Psi_s}_{\mathbf{s}^\mu_{\rm em,IS}} + \frac{1}{\sqrt2}\bar\Psi_q\,\gamma^\mu \frac{\boxed{\tau^1_0}}{\sqrt2}\,\Psi_q$$

- ME's j^μ_{cc+} $\Rightarrow$ ME's **isovector (τ^1_0) $j^\mu_{\rm nc}$ contribution**
- **Δ does not contribute to the isoscalar $j^\mu_{\rm nc}$ part**
- $\langle n\pi^+|s^\mu_{{\rm em},IS}|p\rangle = \langle p\pi^-|s^\mu_{{\rm em},IS}|n\rangle = \sqrt2 \langle \mathbf{p}\pi^{\mathbf 0}|\mathbf{s}^\mu_{\rm em,IS}|\mathbf{p}\rangle = -\sqrt2\langle n\pi^0|s^\mu_{{\rm em},IS}|n\rangle$

$$\langle p\pi^0|s^\mu_{{\rm em},IS}|p\rangle = -\frac{\langle n\pi^0|s^\mu_{\rm em}(0)|n\rangle - \langle p\pi^0|s^\mu_{\rm em}(0)|p\rangle}{2}$$

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

CT, PF do not contribute ⇒ PN and PNC ⇒ ME's of $s^\mu_{{\rm em},IS}$

- ME's $\mathbf{j}^\mu_{\rm nc,str} = \bar{\mathbf{\Psi}}_\mathbf{s}\gamma^\mu(\mathbf{1}-\gamma_\mathbf{5})\mathbf{\Psi}_\mathbf{s}$: *nucleon strange content*

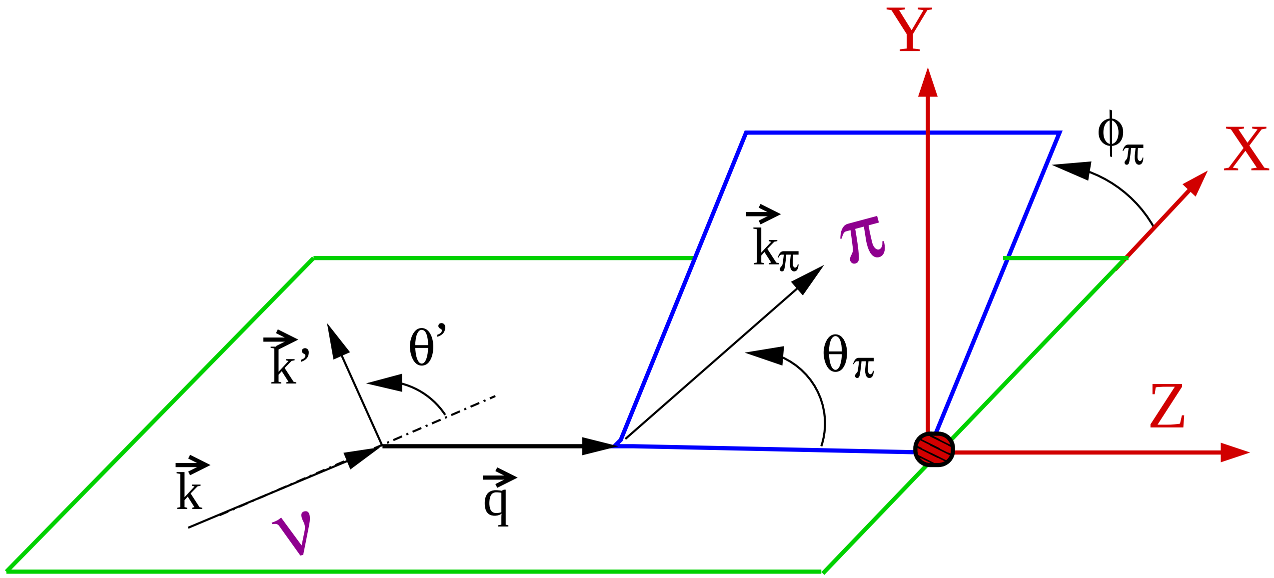
$$\langle p\pi^0|\mathbf{j}^\mu_{\rm nc,str}(\mathbf{0})|p\rangle = -{\rm i}\,\frac{g_A}{2f_\pi}\bar u(\vec p\,')\Bigg\{\not k_\pi\gamma_5\frac{\not p+\not q+M}{(p+q)^2-M^2+i\epsilon}\left[\mathbf{V}^\mu_{\mathbf{N,s}}(\mathbf{q})-\mathbf{A}^\mu_{\mathbf{N,s}}(\mathbf{q})\right]$$

$$+\left[\mathbf{V}^\mu_{\mathbf{N,s}}(\mathbf{q})-\mathbf{A}^\mu_{\mathbf{N,s}}(\mathbf{q})\right]\frac{\not p'-\not q+M}{(p'-q)^2-M^2+i\epsilon}\not k_\pi\gamma_5\Bigg\}u(\vec p) \quad \Leftarrow \mathbf{PN}+\mathbf{PNC}$$

$$\mathbf{V}^\mu_{\mathbf{N,s}}(\mathbf{q}) = \underbrace{F_1^s(q^2)}_{\approx 0}\gamma^\mu + {\rm i}\mu_s\frac{\overbrace{F_2^s(q^2)}^{\approx 0}}{2M}\sigma^{\mu\nu}q_\nu, \qquad \mathbf{A}^\mu_{\mathbf{N,s}}(\mathbf{q}) = \overbrace{G_A^s(q^2)}^{\boxed{g_S}\,(\mathbf{1-q^2/M_A^2})^{-2}}\gamma^\mu\gamma_5 + \underbrace{G_P^s}_{\rm don't\ contr.}q^\mu\gamma_5$$

Results :

$$\Rightarrow \mathrm{CC} : \nu_l(k) + N(p) \to l^-(k') + N(p') + \pi(k_\pi)$$



$$\frac{\mathbf{d}^{\mathbf{5}}\sigma_{\nu_\mathbf{l}\mathbf{l}}}{\mathbf{d}\Omega(\hat{\mathbf{k}}')\mathbf{d}\mathbf{E}'\mathbf{d}\Omega(\hat{\mathbf{k}}_\pi)} = \frac{|\vec{k}'|}{|\vec{k}\ |}\frac{G^2}{4\pi^2}\int_0^{+\infty}\frac{d|\vec{k}_\pi||\vec{k}_\pi|^2}{E_\pi}\boxed{L_{\mu\sigma}^{(\nu)}\left(W_{\mathrm{CC}\pi}^{\mu\sigma}\right)^{(\nu)}}$$

$$(W^{\mu\sigma}_{\mathrm{CC}\pi})^{(\nu)} = \frac{1}{4M}\overline{\sum_{\mathrm{spins}}}\int \frac{d^3p'}{(2\pi)^3}\frac{1}{2E'_N}\delta^4(p'+k_\pi-q-p)\langle \mathbf{N}'\pi|\mathbf{j}^\mu_{\mathrm{cc}+}(\mathbf{0})|\mathbf{N}\rangle\langle \mathbf{N}'\pi|\mathbf{j}^\sigma_{\mathrm{cc}+}(\mathbf{0})|\mathbf{N}\rangle^*$$

$$\mathbf{L}^{(\nu)}_{\mu\sigma} = (\mathbf{L}^{(\nu)}_{\mathbf{s}})_{\mu\sigma} + \mathrm{i}(\mathbf{L}^{(\nu)}_{\mathbf{a}})_{\mu\sigma} = k'_\mu k_\sigma + k'_\sigma k_\mu - g_{\mu\sigma} k\cdot k' + \mathrm{i}\epsilon_{\mu\sigma\alpha\beta}k'^\alpha k^\beta$$

$$\Rightarrow \mathrm{CC}: \bar\nu_l(k) + N(p) \rightarrow l^+(k') + N(p') + \pi(k_\pi)$$

$$\mathbf{L}^{(\bar\nu)}_{\mu\sigma} = \mathbf{L}^{(\nu)}_{\sigma\mu}, \quad \mathbf{j}^\sigma_{\mathrm{cc}+} \leftrightarrow \mathbf{j}^\sigma_{\mathrm{cc}-}$$

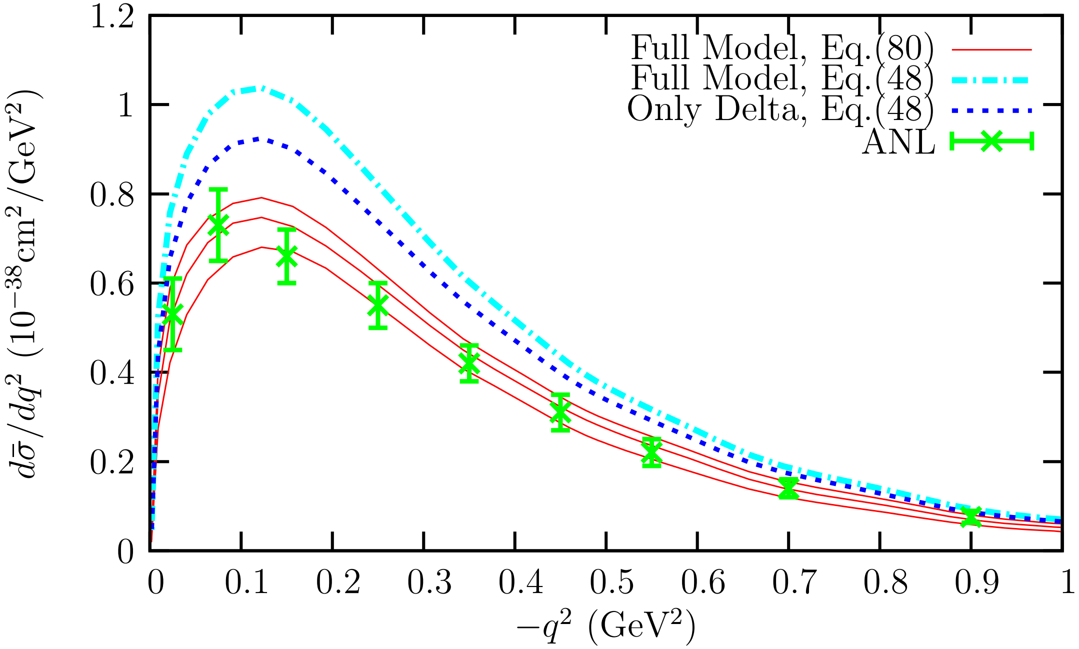
$$\Rightarrow \mathrm{NC}: \nu(k) + N(p) \rightarrow \nu(k') + N(p') + \pi(k_\pi)$$

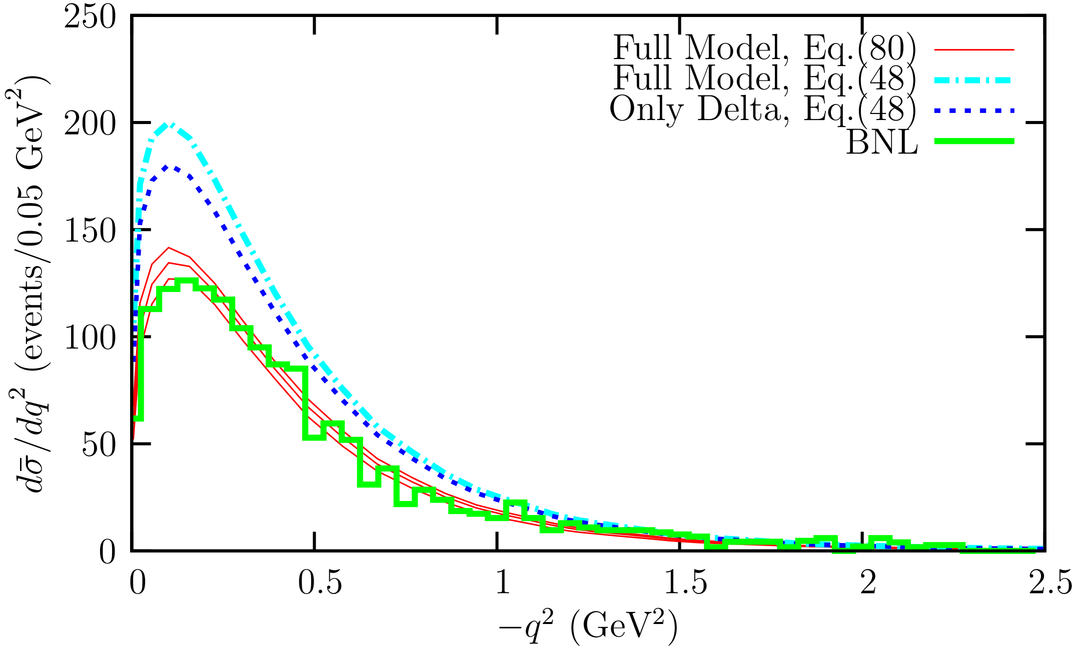
$$\mathbf{j}^\sigma_{\mathrm{cc}+} \leftrightarrow \frac{\mathbf{1}}{\mathbf{2}}\mathbf{j}^\sigma_{\mathrm{nc}}, \quad (\mathbf{W}^{\mu\sigma}_{\mathrm{NC}\pi})^{(\nu)} = (\mathbf{W}^{\mu\sigma}_{\mathrm{NC}\pi})^{(\bar\nu)}$$

Note $\underbrace{(E',\theta')}_{\text{outgoing lepton}} \leftrightarrow q^2, \underbrace{W^2 = (p+q)^2}_{\pi\text{N inv. mass}}$

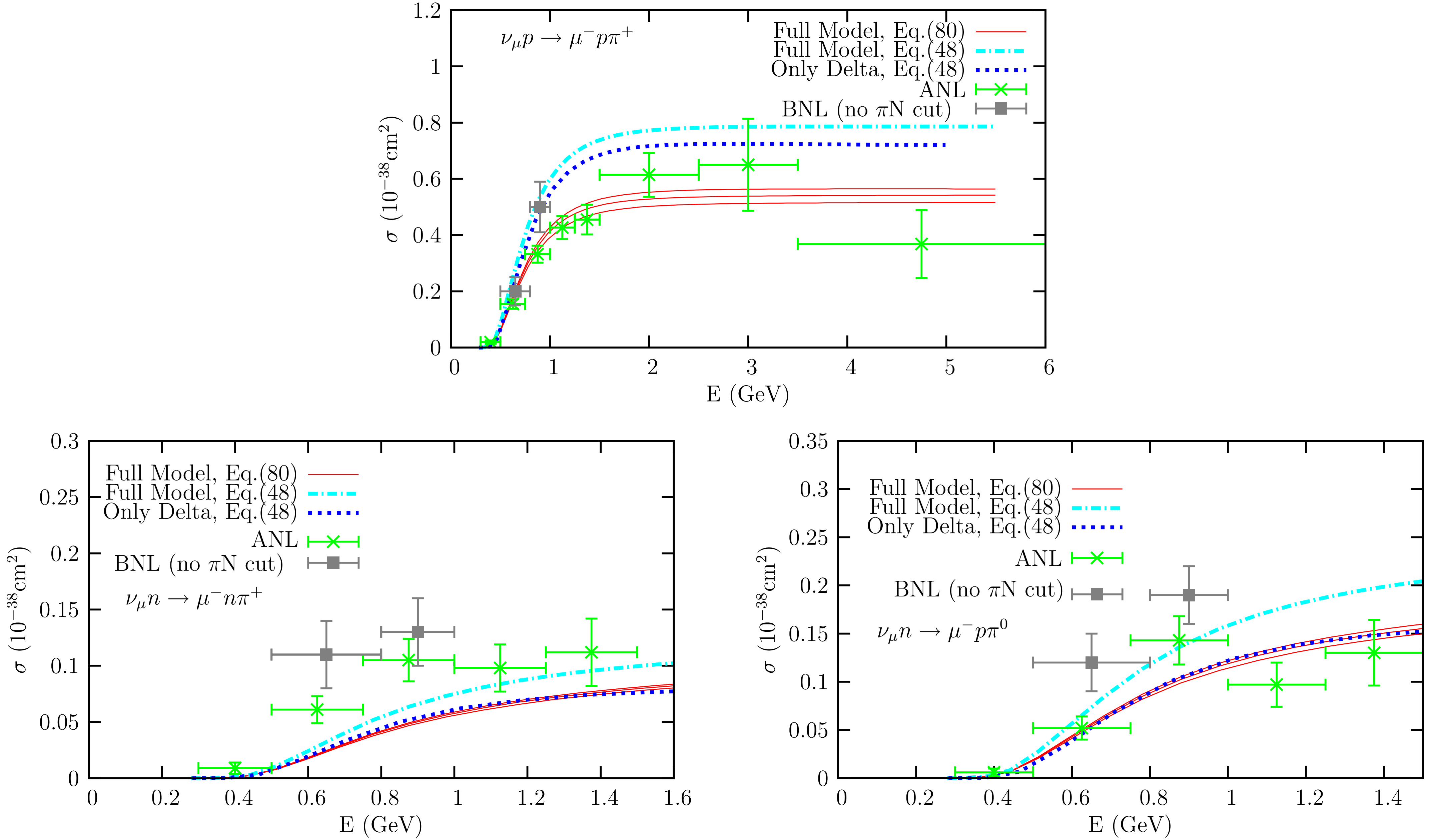
Differential cross section (flux averaged)

$$\int_{M+m_\pi}^{\boxed{1.4\,\mathrm{GeV}}} dW \frac{d\,\overline{\sigma}_{\nu_\mu \mu^-}}{dq^2 dW}, \quad \nu_\mu \mathbf{p} \to \mu^- \mathbf{p} \pi^+$$

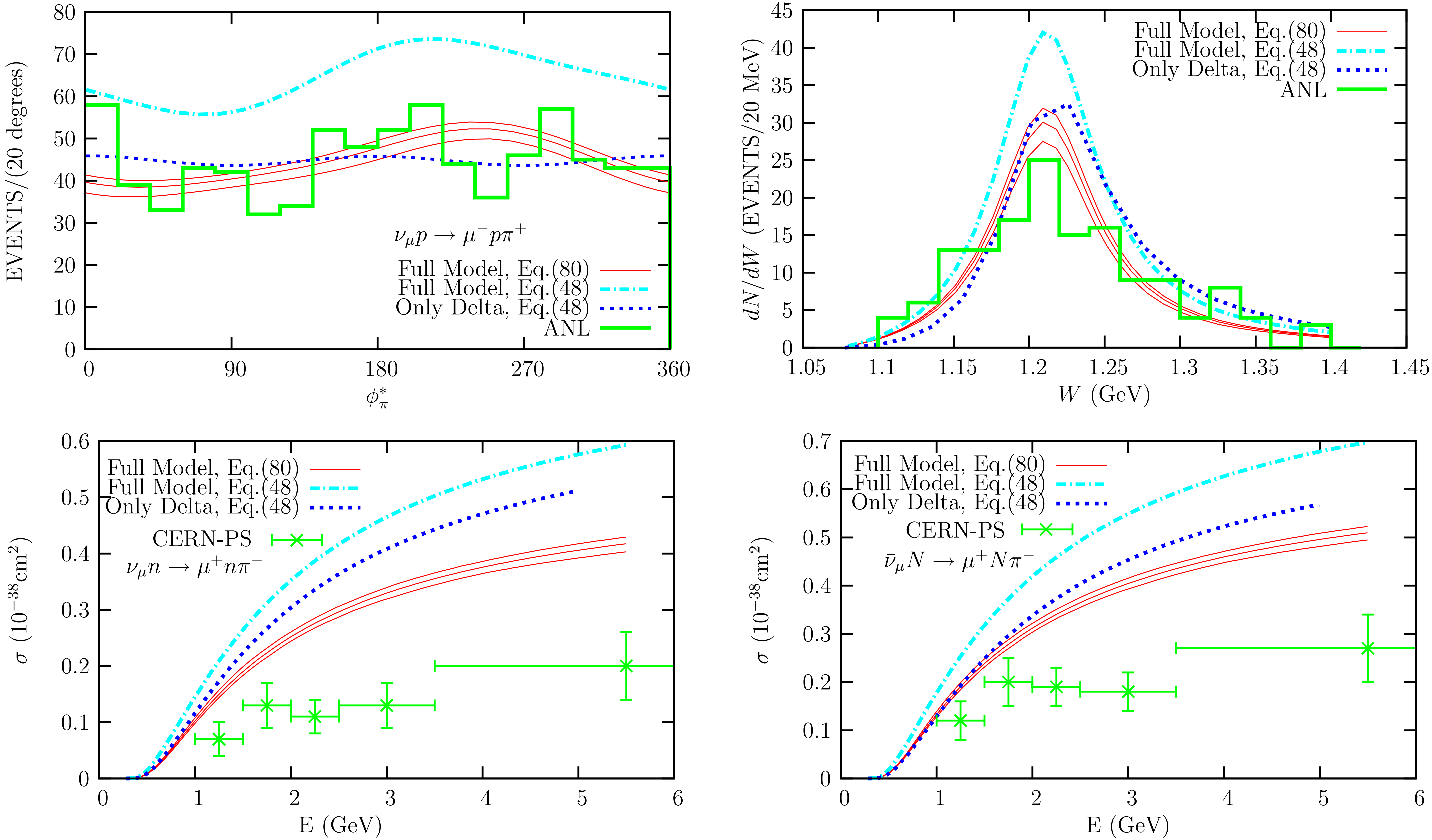


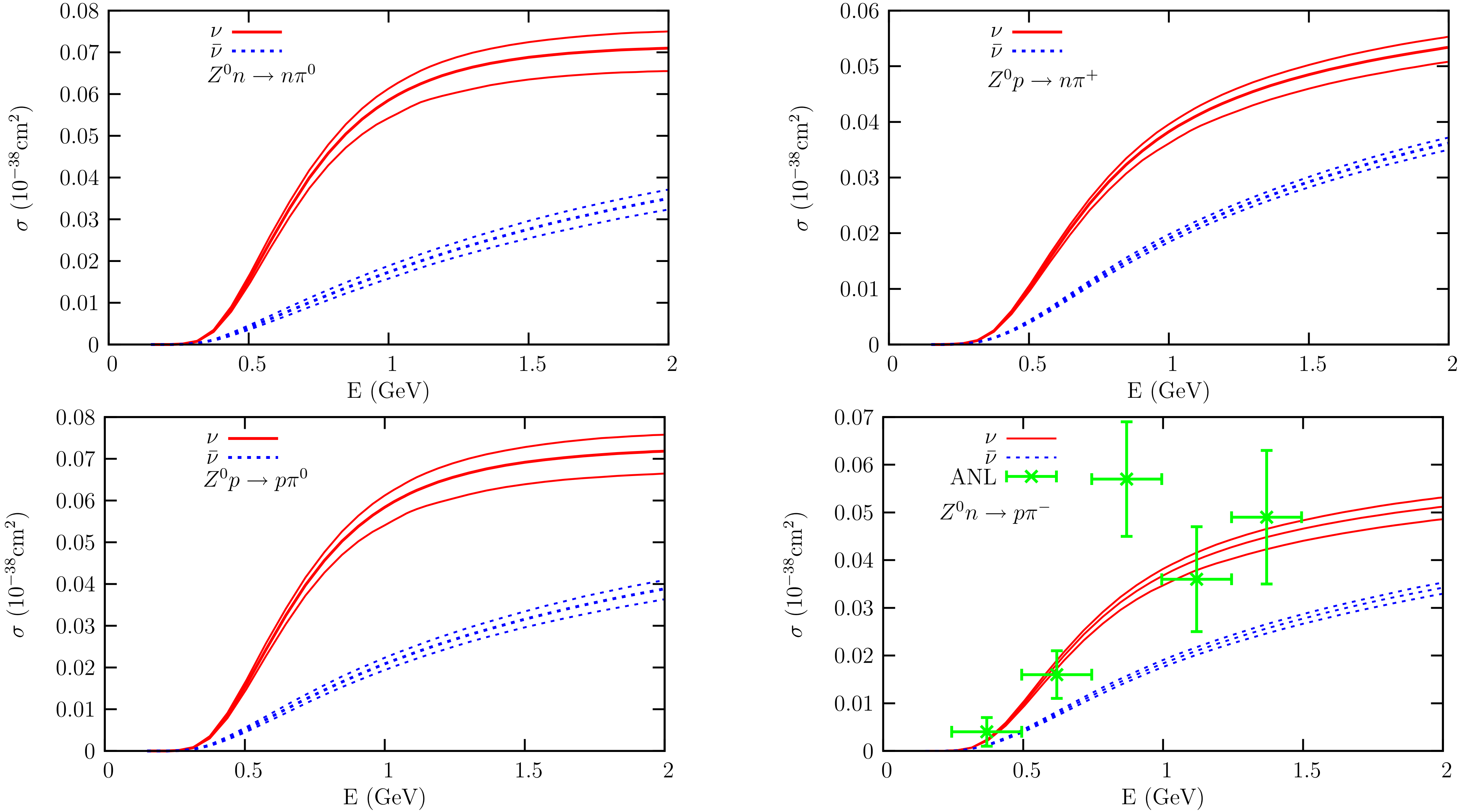


Fit to ANL : $C_5^A(0) = 0.869 \pm 0.075, \quad M_{A\Delta} = 0.981 \pm 0.081\,\mathrm{GeV}$



$\nu_\mu p \to \mu^- p \pi^+$
Full Model, Eq.(80)
Full Model, Eq.(48)
Only Delta, Eq.(48)
ANL
BNL (no πN cut)
σ (10^{-38}cm^2)
E (GeV)
$\nu_\mu n \to \mu^- n \pi^+$
$\nu_\mu n \to \mu^- p \pi^0$


EVENTS/(20 degrees)
ϕ^*_π
$\nu_\mu p \to \mu^- p \pi^+$
Full Model, Eq.(80)
Full Model, Eq.(48)
Only Delta, Eq.(48)
ANL
dN/dW (EVENTS/20 MeV)
W (GeV)
Full Model, Eq.(80)
Full Model, Eq.(48)
Only Delta, Eq.(48)
ANL
σ (10^{-38}cm^2)
E (GeV)
Full Model, Eq.(80)
Full Model, Eq.(48)
Only Delta, Eq.(48)
CERN-PS
$\bar{\nu}_\mu n \to \mu^+ n \pi^-$
σ (10^{-38}cm^2)
E (GeV)
Full Model, Eq.(80)
Full Model, Eq.(48)
Only Delta, Eq.(48)
CERN-PS
$\bar{\nu}_\mu N \to \mu^+ N \pi^-$



Below the τ prod. threshold, Distinguish ν_τ from $\bar{\nu}_\tau$?

$\sigma_{\rm NC}/\sigma_{\rm CC}$ ANL cross sections at $E = 0.6 - 1.2$ GeV

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

NC: Cross sections (10^{-38}cm^2) for $\langle E \rangle = 2.2$ GeV (no cut in W)

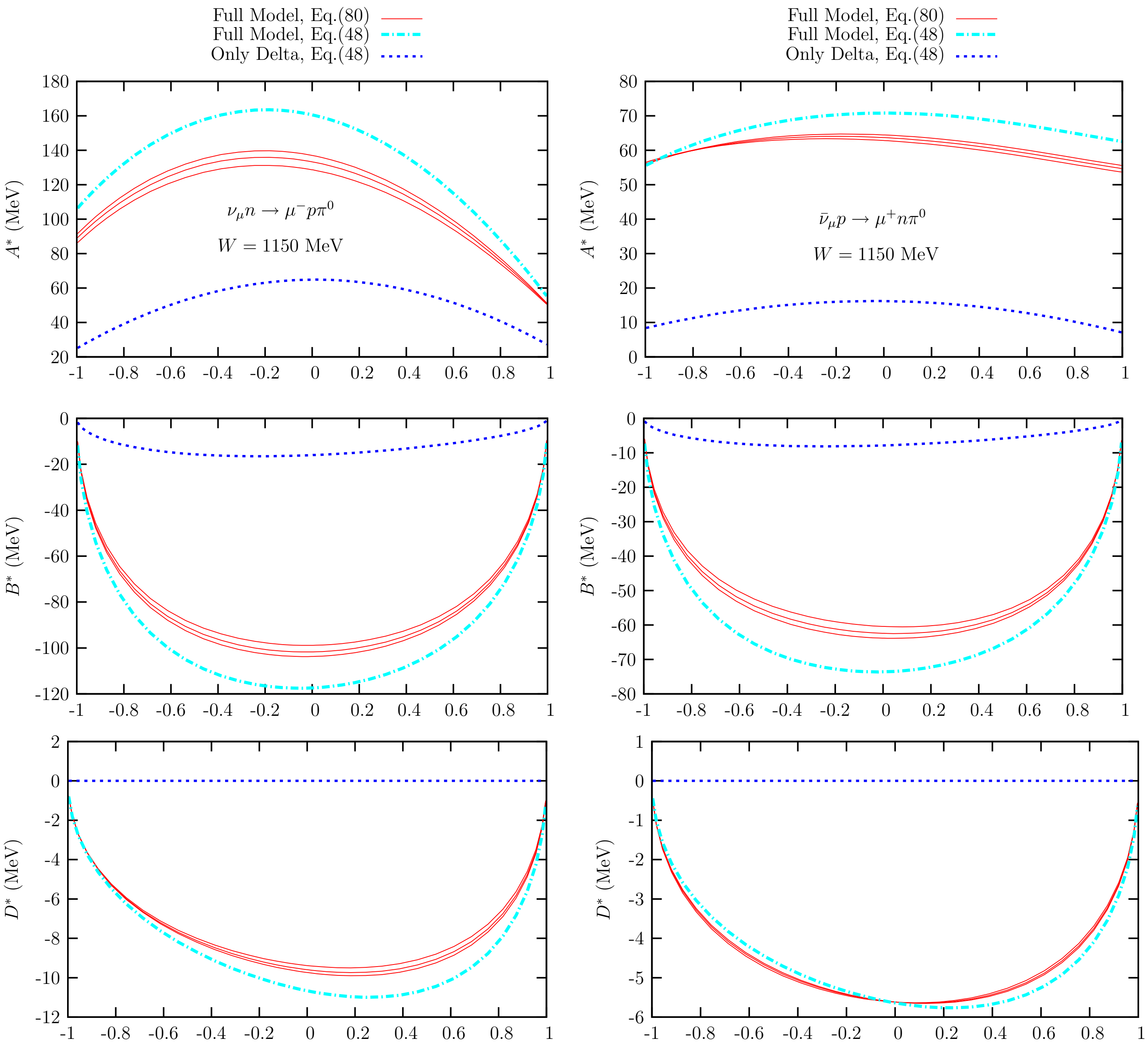
	CERN	Our results
$\sigma(\nu p \to \nu p \pi^0)$	0.130 ± 0.020	0.105 ± 0.006
$\sigma(\nu p \to \nu n \pi^+)$	0.080 ± 0.020	0.091 ± 0.003
$\sigma(\nu n \to \nu n \pi^0)$	0.080 ± 0.020	0.104 ± 0.006
$\sigma(\nu n \to \nu p \pi^-)$	0.110 ± 0.030	0.082 ± 0.003

Dependence on θ^*_π (<u>CM πN</u> pion polar angle). Lorentz invariance (f.i., CC) $\Rightarrow$

$$\frac{d^5\sigma_{\nu_l l}}{d\Omega(\hat{k}')dE'd\Omega^*(\hat{k}_\pi)} = \frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}\left\{\overbrace{A^* + B^*\cos\phi^*_\pi + C^*\cos 2\phi^*_\pi}^{\text{Similar to } eN\to e'N\pi}\right.$$

$$\left. + \underbrace{D^*\sin\phi^*_\pi + E^*\sin 2\phi^*_\pi}_{\text{parity violating}}\right\}$$

- <u>**Explicit**</u> ϕ_π dependence
- A^*, B^*, C^*, D^*, E^* functions of E, q^2, W, θ^*_π
- C^* and E^* are the same ν and $\bar{\nu}$, when $(W^{\mu\sigma})^{(\bar{\nu})} = (W^{\mu\sigma})^{(\nu)}$

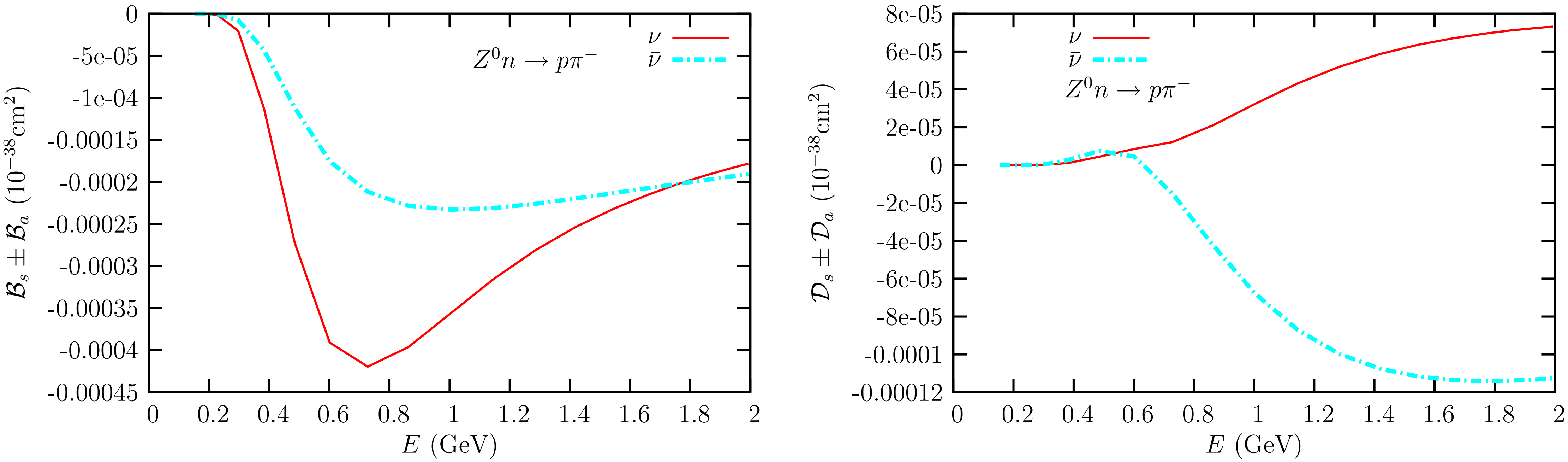


A^*, B^*, C^*, D^*, E^* **vs** $\cos\theta^*_\pi$, $E = 1.5$ GeV, $W = 1.15$ GeV and $q^2 = -0.5$ GeV^2. Reactions $\nu_\mu n \to \mu^- p \pi^0$ and $\bar\nu_\mu p \to \mu^+ n \pi^0$

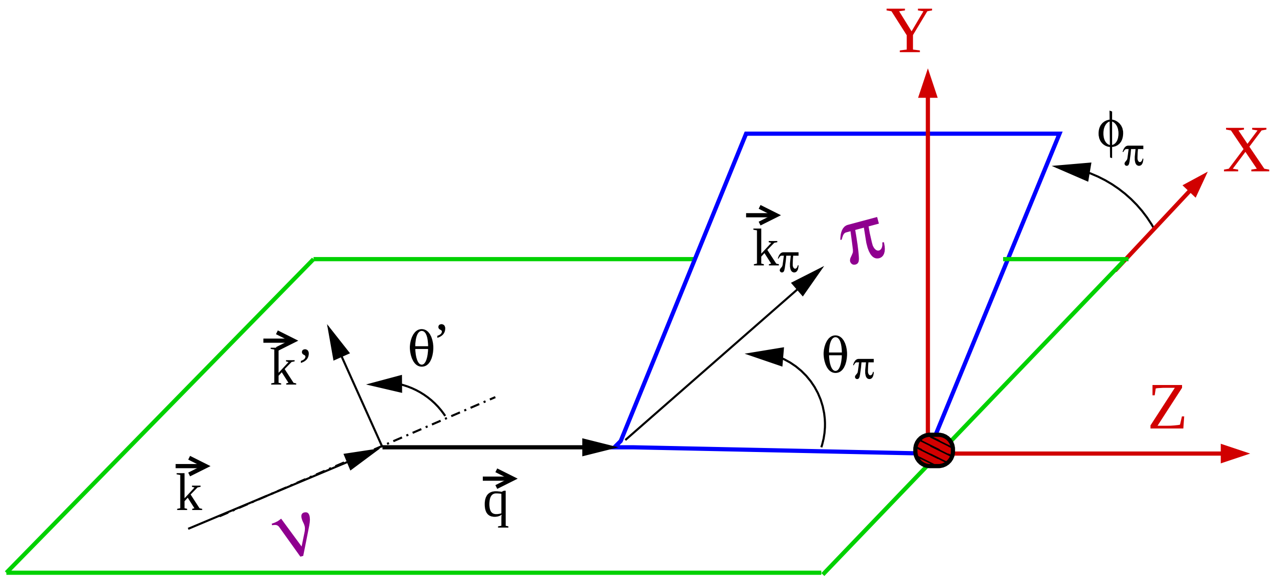
... new NC neutrino–antineutrino asymmetries

$$\frac{1}{2}\left(\frac{d\sigma(\phi_\pi)}{d\phi_\pi} - \frac{d\sigma(\phi_\pi+\pi)}{d\phi_\pi}\right)\Bigg|_\nu = (\mathcal{B}_s + \mathcal{B}_a)\cos\phi_\pi + (\mathcal{D}_s + \mathcal{D}_a)\sin\phi_\pi$$

$$\frac{1}{2}\left(\frac{d\sigma(\phi_\pi)}{d\phi_\pi} - \frac{d\sigma(\phi_\pi+\pi)}{d\phi_\pi}\right)\Bigg|_{\bar\nu} = (\mathcal{B}_s - \mathcal{B}_a)\cos\phi_\pi + (\mathcal{D}_s - \mathcal{D}_a)\sin\phi_\pi$$



Parity violation



$$\frac{d^5\sigma_{\nu_l l}}{d\Omega(\hat{k}')dE'd\Omega^*(\hat{k}_\pi)} = \frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}\left\{\overbrace{A^* + B^*\cos\phi^*_\pi + C^*\cos 2\phi^*_\pi}^{\text{Similar to } eN\to e'N\pi}\right.$$

$$\left. + \underbrace{D^*\sin\phi^*_\pi + E^*\sin 2\phi^*_\pi}_{\text{parity violating}}\right\}$$

$$L^{(\nu)}_{\mu\sigma} = (\mathbf{L}^{(\nu)}_{\mathbf{s}})_{\mu\sigma} + \mathrm{i}(\mathbf{L}^{(\nu)}_{\mathbf{a}})_{\mu\sigma} = k'_\mu k_\sigma + k'_\sigma k_\mu - g_{\mu\sigma} k\cdot k' + \mathrm{i}\epsilon_{\mu\sigma\alpha\beta} k'^\alpha k^\beta$$

By construction (similar for both CC and NC),

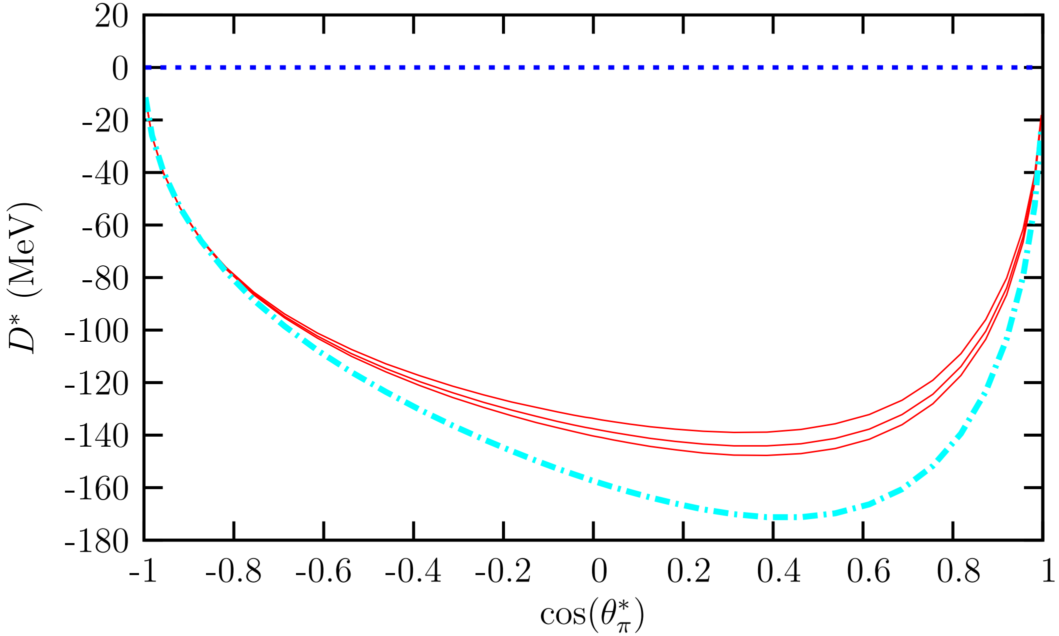
$$W^{\mu\sigma} = \mathbf{W}^{\mu\sigma}_{\mathbf{s}} + \mathrm{i}\mathbf{W}^{\mu\sigma}_{\mathbf{a}}, \quad W^{\mu\nu}_{s,a} = \left(W^{\mu\nu}_{s,a}\right)^{\mathrm{PC}} + \left(\mathbf{W}^{\mu\nu}_{\mathbf{s,a}}\right)^{\mathrm{PV}}$$

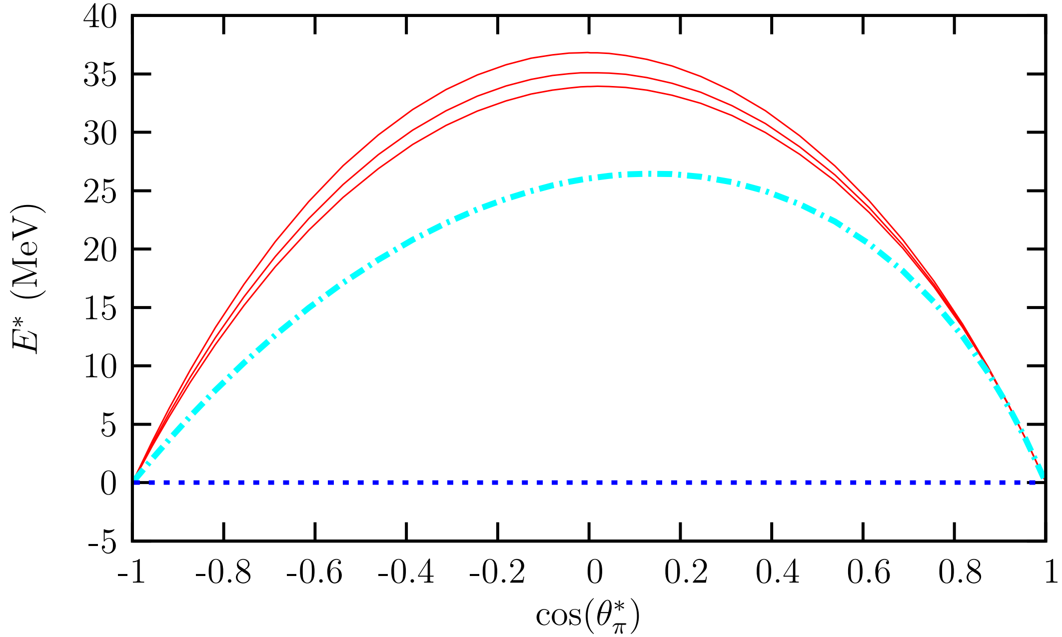
$$\begin{aligned}
(W^{\mu\nu}_s)^{\mathrm{PC}} &= W_1 g^{\mu\nu} + W_2 p^\mu p^\nu + W_3 q^\mu q^\nu + W_4 k^\mu_\pi k^\nu_\pi + \cdots \\
(W^{\mu\nu}_a)^{\mathrm{PC}} &= W_{14}\epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta + W_{15}\epsilon^{\mu\nu\alpha\beta} p_\alpha k_{\pi\beta} + W_{16}\epsilon^{\mu\nu\alpha\beta} q_\alpha k_{\pi\beta} + \cdots \\
(\mathbf{W}^{\mu\nu}_{\mathbf{s}})^{\mathrm{PV}} &= \mathbf{W_8}\left(\mathbf{q}^\mu \epsilon^\nu_{.\alpha\beta\gamma}\mathbf{k}^\alpha_\pi \mathbf{p}^\beta \mathbf{q}^\gamma + \mathbf{q}^\nu \epsilon^\mu_{.\alpha\beta\gamma}\mathbf{k}^\alpha_\pi \mathbf{p}^\beta \mathbf{q}^\gamma\right) + \cdots \\
(\mathbf{W}^{\mu\nu}_{\mathbf{a}})^{\mathrm{PV}} &= \mathbf{W_{11}}(\mathbf{q}^\mu \mathbf{p}^\nu - \mathbf{q}^\nu \mathbf{p}^\mu) + \mathbf{W_{12}}(\mathbf{q}^\mu \mathbf{k}^\nu_\pi - \mathbf{q}^\nu \mathbf{k}^\mu_\pi) + \cdots
\end{aligned}$$

Under Parity

$$L^{(\nu)}_{\mu\nu} \to (L^{\nu\mu})^{(\nu)}, \quad (W_{\mu\nu})^{\mathrm{PC}} \to (W^{\nu\mu})^{\mathrm{PC}}, \quad (\mathbf{W}_{\mu\nu})^{\mathrm{PV}} \to -(\mathbf{W}^{\nu\mu})^{\mathrm{PV}}$$

- $d^5\sigma/d\Omega(\hat{k}')dE'd\Omega(\hat{k}_\pi)$ **is not inv. under parity,** since the pseudovector $\vec{k} \times \vec{k}'$ is used to define the Y axis.
- $d^3\sigma/d\Omega(\hat{k}')dE'$ **scalar,** except for the factor $|\vec{k}'|/|\vec{k}\,| \Rightarrow$ parity violation **disappears** when performing the $\int d\Omega^*(\hat{k}_\pi)$



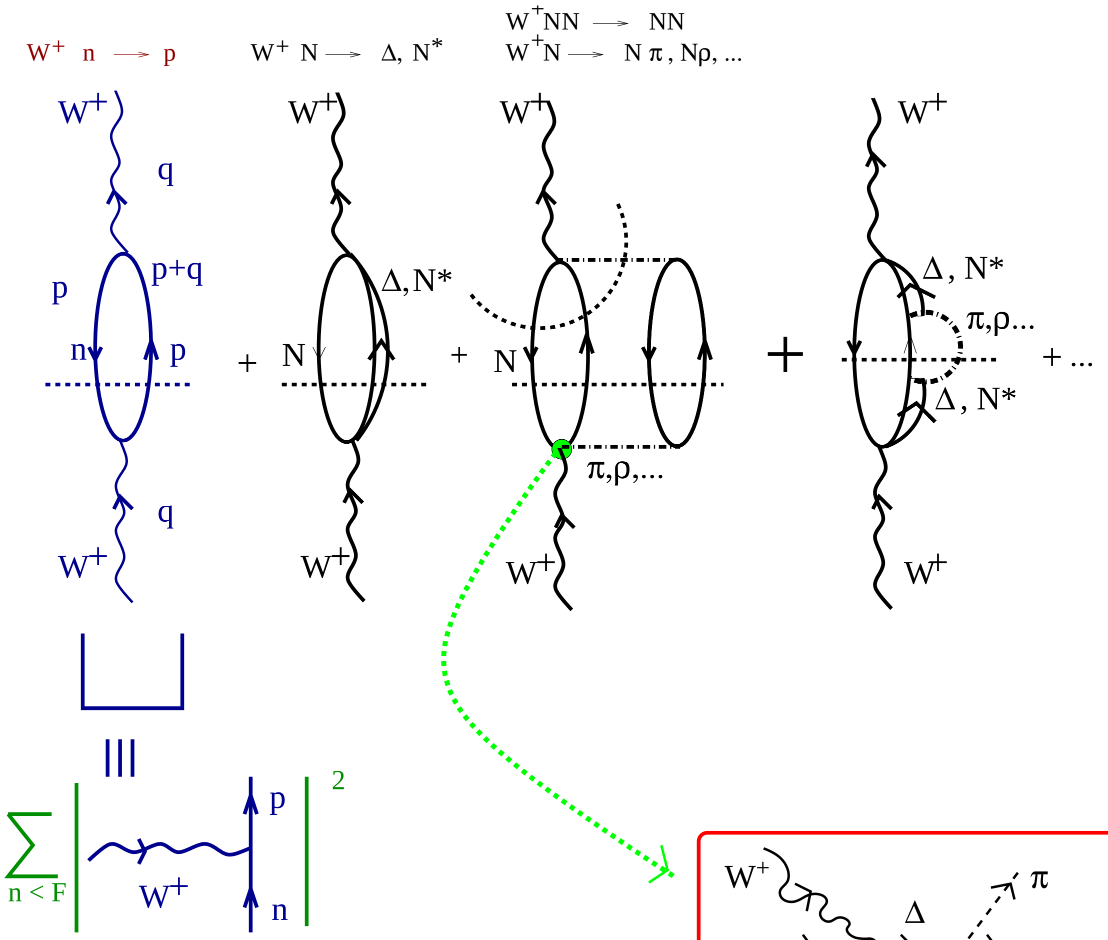


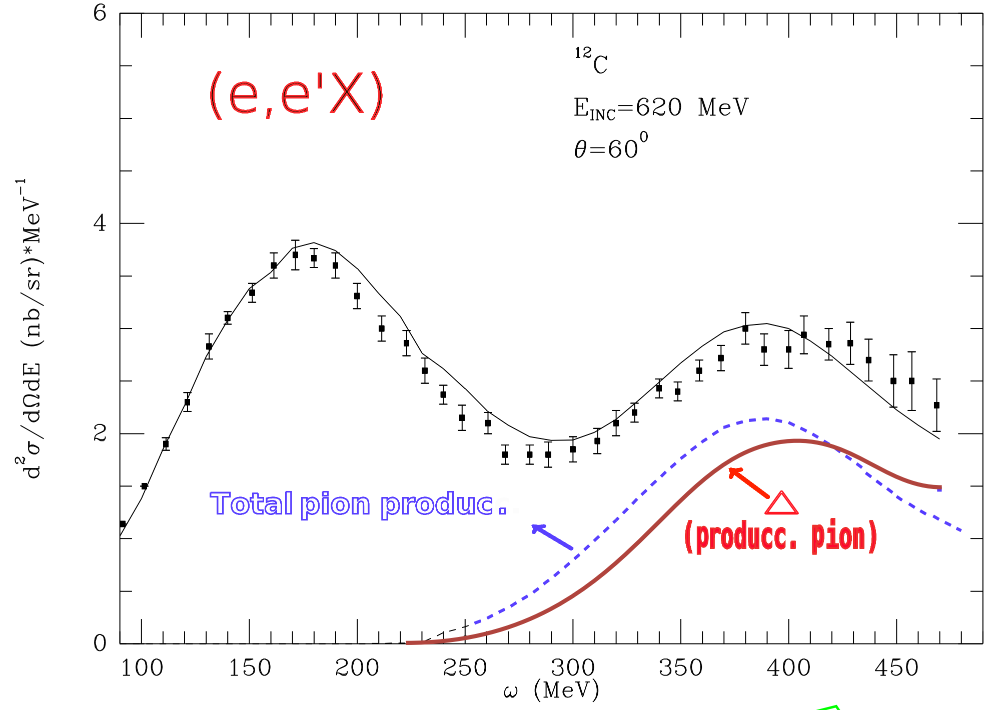
$\nu_\mu n \to \mu^- p \pi^0$ $(E = 1.5\ \text{GeV},\ W = M_\Delta,\ q^2 = -0.5\ \text{GeV}^2)$

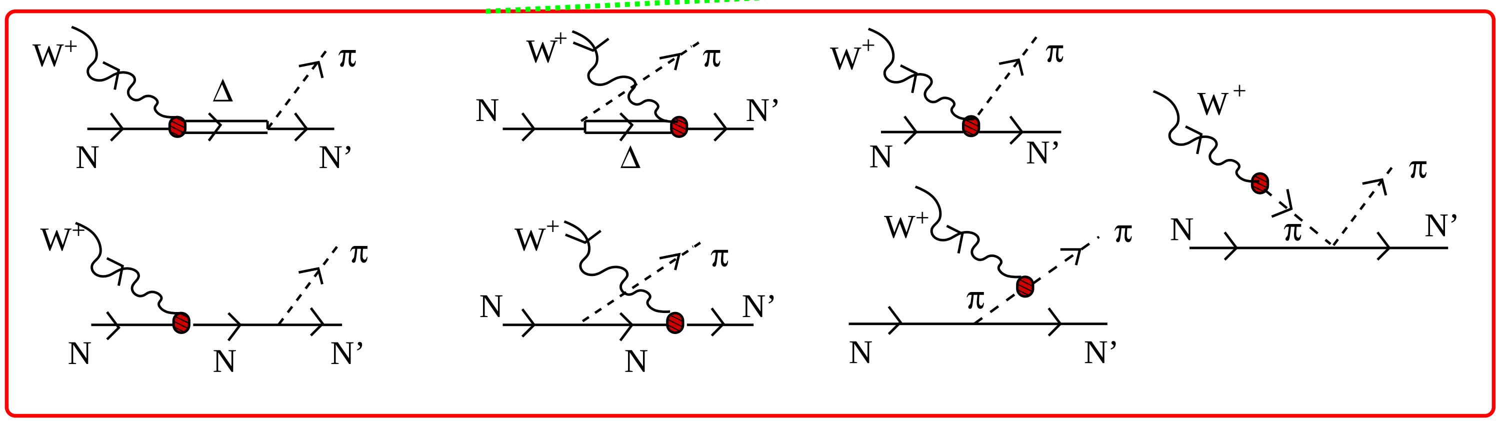
- **Non-resonant terms are needed to produce non-vanishing parity violating structure functions**

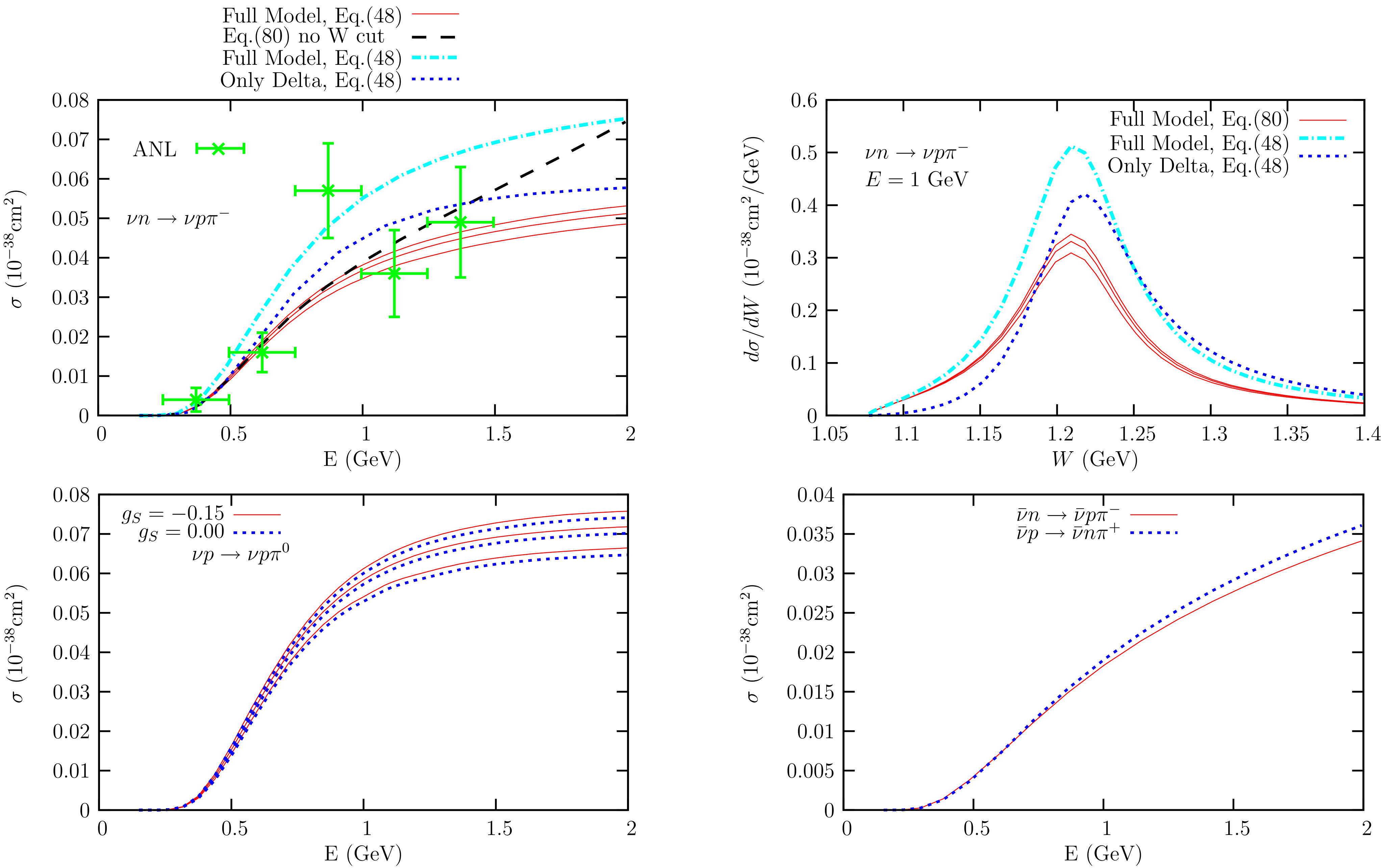
Conclusions: **We have derived a model** for CC and NC weak pion production off the nucleon

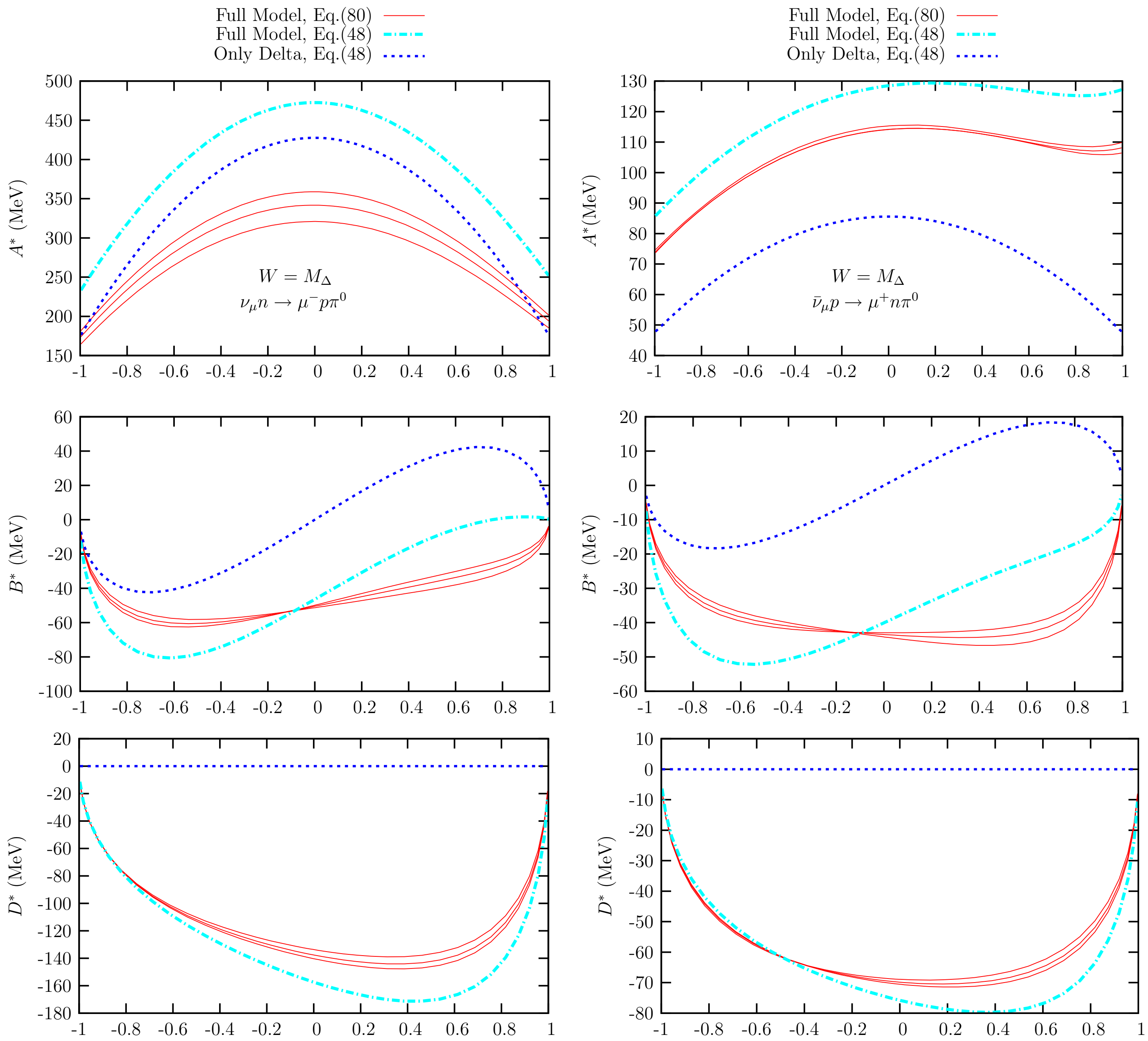
1. **In addition to the** Δ resonance, we include **non-resonant contributions $\Leftarrow$ QCD SχSB.**
2. **Non resonant contributions** are important $\Rightarrow$ **re-adjust of** $C_5^A(q^2)$.
3. $\nu - \bar{\nu}$ **Asymmetries**, **distinguish** ν_τ **from** $\bar{\nu}_\tau$ **?**
4. **Parity violation effects due to the interferences between the non resonant and** Δ **contributions.**
5. **Starting point** to study **inclusive and exclusive neutrino-nucleus scattering above the QE region.**

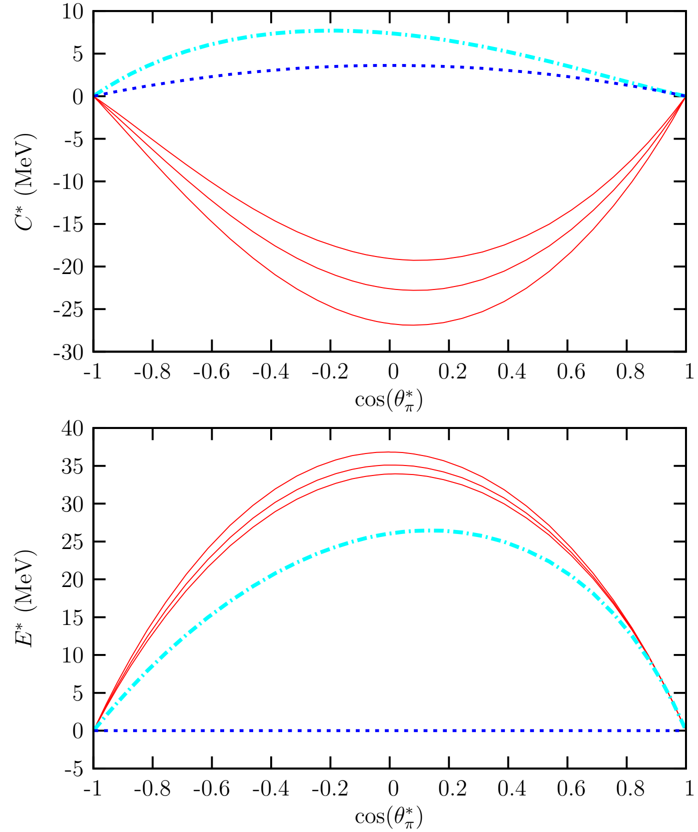

W+ n ⟶ p
W+ N ⟶ Δ, N*
W+NN ⟶ NN
W+N ⟶ N π, Nρ, ...
W+
q
p
p+q
n
p
Δ,N*
N
π,ρ,...
Δ, N*
+ ...
n < F
2


(e,e'X)
12C
EINC=620 MeV
θ=60°
d²σ/dΩdE (nb/sr)*MeV⁻¹
ω (MeV)
Total pion produc.
(producc. pion)
Δ


W+
N
N'
Δ
π


Full Model, Eq.(48)
Eq.(80) no W cut
Full Model, Eq.(48)
Only Delta, Eq.(48)
ANL
$\nu n \to \nu p \pi^-$
σ (10^{-38}cm^2)
E (GeV)
Full Model, Eq.(80)
Full Model, Eq.(48)
Only Delta, Eq.(48)
$\nu n \to \nu p \pi^-$
$E = 1$ GeV
$d\sigma/dW$ (10^{-38}cm^2/GeV)
W (GeV)
$g_S = -0.15$
$g_S = 0.00$
$\nu p \to \nu p \pi^0$
σ (10^{-38}cm^2)
E (GeV)
$\bar\nu n \to \bar\nu p \pi^-$
$\bar\nu p \to \bar\nu n \pi^+$
σ (10^{-38}cm^2)
E (GeV)





A^*, B^*, C^*, D^*, E^* vs $\cos\theta^*_\pi$,

$E = 1.5$ GeV, $W = M_\Delta$ and $q^2 = -0.5$ GeV^2. Reactions $\nu_\mu n \to \mu^- p \pi^0$ and $\bar\nu_\mu p \to \mu^+ n \pi^0$