

Coherent neutrino scattering

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E. Hernandez, J.E. Amaro, J. Nieves and M. V., Phys.Rev.**D79**:013002,2009

E. Hernandez, J. Nieves and M. V. Phys.Rev.**D76**:033005,2007

Coherent reaction

$$\boxed{\nu_l + A_Z|_{gs} \rightarrow l^- + A_Z|_{gs} + \pi^+}$$

Initial and final nuclear states are the same

- Dominated by Δ mechanism
Background process largely suppressed in isoscalar nuclei
- Important background in neutrino oscillation experiments

The reaction is dominated by nuclear form factor thus
it is very forward peaked

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Outline

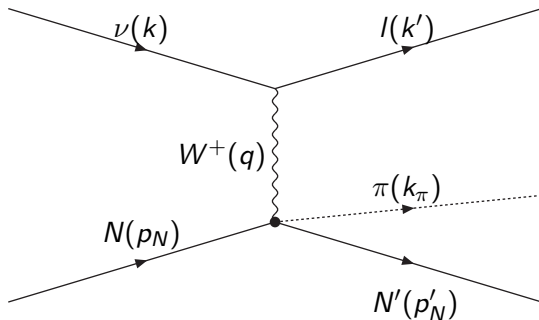
- 1 Free nucleon reaction
- 2 Nuclear medium effects
- 3 Results and comparisons with other models

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Free nucleon reaction

$$\nu + N \rightarrow l^- + N' + \pi$$



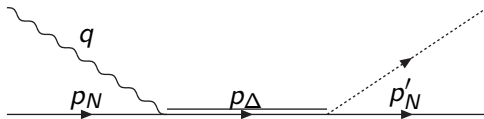
Charge channels

- $\nu + p \rightarrow l^- + p + \pi^+$
- $\nu + n \rightarrow l^- + n + \pi^+$
- $(\nu + n \rightarrow l^- + p + \pi^0)$

Direct Δ term

The dominant mechanism is

$$\nu + N \rightarrow l^- + \Delta(1232) \rightarrow l^- + N' + \pi$$



- Resonance dominated studies are most common:
 - Lalakulich and Paschos [PRD**71**:074003,2005]
 - Graczyk and Sobczyk [PRD**77**:053001,2008]
- Non-resonant terms have also been studied
 - Sato, Uno and Lee [PRC**67**:065201,2006]

Δ -N vertex

$$\begin{aligned}
 \langle \Delta^+; \mathbf{p}_\Delta | V^\mu - A^\mu | N; \mathbf{p}_N \rangle &= \bar{u}_\alpha(\mathbf{p}_\Delta) \Gamma^{\alpha\mu} u(\mathbf{p}) \cos \theta_C \\
 \Gamma^{\alpha\mu} &= \left[\frac{C_3^V}{M} (g^{\alpha\mu} \not{q} - q^\alpha \gamma^\mu) + \frac{C_4^V}{M^2} (g^{\alpha\mu} q \cdot p_\Delta - q^\alpha p_\Delta^\mu) \right. \\
 &\quad \left. + \frac{C_5^V}{M^2} (g^{\alpha\mu} q \cdot p - q^\alpha p^\mu) + \frac{C_6^V}{M^2} q^\alpha q^\mu \right] \gamma_5 \\
 &\quad + \frac{C_3^A}{M} (g^{\alpha\mu} \not{q} - g^\alpha \gamma^\mu) + \frac{C_4^A}{M^2} (g^{\alpha\mu} q \cdot p_\Delta - q^\alpha p_\Delta^\mu) \\
 &\quad + \boxed{C_5^A g^{\alpha\mu}} + \frac{C_6^A}{M^2} q^\alpha q^\mu
 \end{aligned}$$

Δ -N vertex: form factor parametrization

Vector part

Fit to exp electron scattering data (Lalakulich and Paschos)

$$C_3^V(q^2) = \frac{C_3^V(0)}{(1 - q^2/M_V^2)^2} \frac{1}{1 - q^2/4M_V^2}$$
$$C_5^V = 0, \quad C_4^V = -C_3^V \frac{m_N}{W}, \quad C_3^V(0) = 1.95$$

Only assume CVC

Δ -N vertex: form factor parametrization

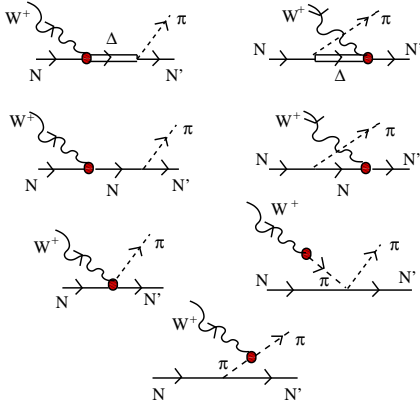
Axial part

Non-diagonal Goldberger-Treiman relation

$$C_5^A(q^2) = \frac{C_5^A(0)}{(1 - q^2/M_A^2)^2} \frac{1}{1 - q^2/3M_A^2}$$
$$C_4^A = -\frac{C_5^A}{4}, \quad C_6^A = C_5^A \frac{m_N^2}{m_\pi^2 - q^2}, \quad C_3^A = 0$$
$$C_5^A(0) = \sqrt{\frac{2}{3}} \frac{f_\pi}{m_\pi} f^* = 1.2, \quad M_A = 1.05 \text{ GeV}$$

Mainly theoretical assumptions

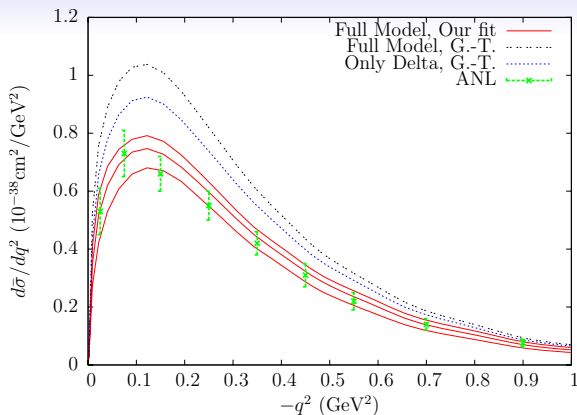
Δ and Background terms



- $\Delta(1232)$ resonance pole terms
- Nucleon pole terms
- Other background terms

Non resonant terms computed using chiral SU(2) sigma model with no free parameters

ANL results for $d\sigma/dq^2$



Refit of $C_5^A(0)$

$$C_5^A(0) = 1.2 \rightarrow \boxed{C_5^A(0) = 0.870 \pm 0.075}, \quad M_A = 0.982 \pm 0.082 \text{ GeV}$$

How good is Goldberger-Treiman?

	$C_5^A(0)$			
G.-T.	1.2			
Our fit	0.870 ± 0.075			
Quark models	0.97	0.83	0.93	0.87
Exp. fit	1.15 ± 0.23	1.39 ± 0.14	1.1 ± 0.2	1.22 ± 0.06
Current algebra	0.98			

Taken from Barquilla-Cano, Buchmann and E. Hernández [PRC**75**,2007]

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Nuclear Model: Fermi Gas

We describe the nucleus as a Fermi Gas in
Local Density Approximation

$$\mathcal{A}_{\pi^+}^{\mu}(q, k_{\pi}) = \int d^3\vec{r} \, e^{i(\vec{q} - \vec{k}_{\pi}) \cdot \vec{r}} \rho_N(\vec{r}) \mathcal{J}_{N\pi^+}^{\mu}(\vec{r}; q, k_{\pi})$$

Nuclear effects: Δ is in the medium

Modify $M_\Delta \rightarrow M_\Delta + \text{Re}\Sigma_\Delta(\rho(r))$ and

$$\Gamma_\Delta/2 \rightarrow \Gamma_\Delta^{\text{Pauli}}/2 - \text{Im}\Sigma_\Delta(\rho(r))$$

- Potential with attractive real part
- Decay width Γ_Δ modified by:
 - Pauli blocking
 - New decay channels are open

[E. Oset and L. L. Salcedo, NPA **468**:631,1987]

Outgoing pion FSI

For the pion wave function we solve the Klein-Gordon equation

$$\left[-\vec{\nabla}^2 + m_\pi^2 + 2E_\pi V_{\text{opt}}(\vec{r}) \right] \tilde{\varphi}_{\pi^+}^*(\vec{r}; \vec{k}_\pi) = E_\pi^2 \tilde{\varphi}_{\pi^+}^*(\vec{r}; \vec{k}_\pi)$$

Optical imaginary potential

OK because we are dealing with an **exclusive** reaction

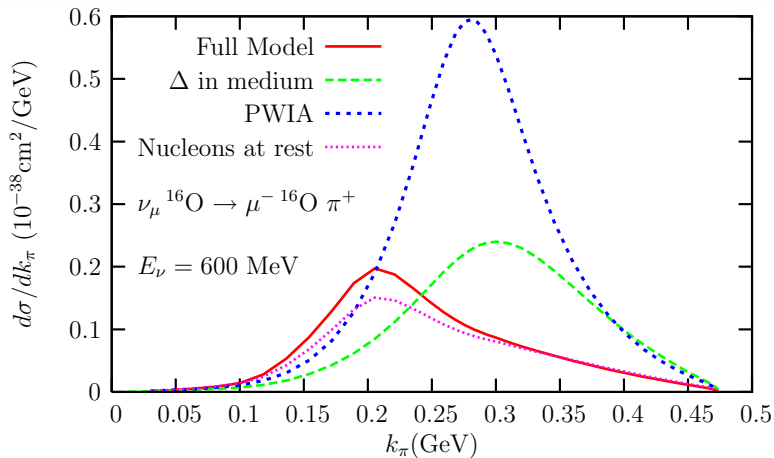
Model by [Nieves, Oset and Garcia-Recio, NPA554,554:1993]

- Δ -dominance at high energies
- Improved model at low energies:
s and p wave πN in first and second order
- Coulomb effects (Found to be negligible)

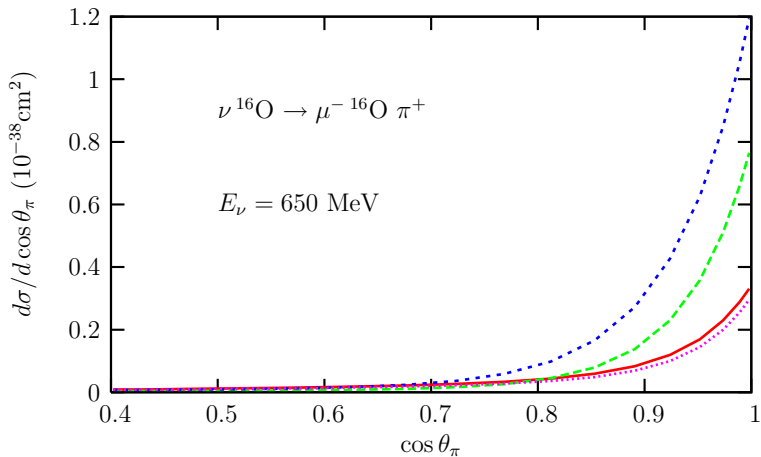
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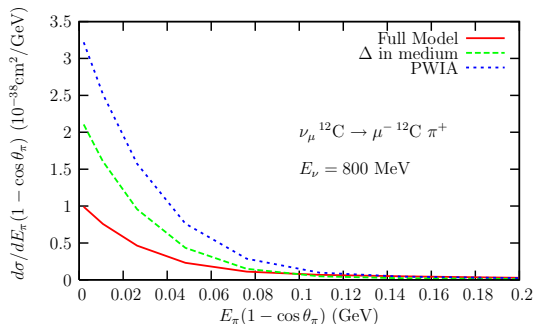
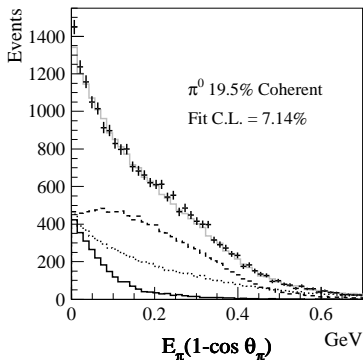
Pion momentum distribution



Pion angular distribution



Pion observables for MiniBoone



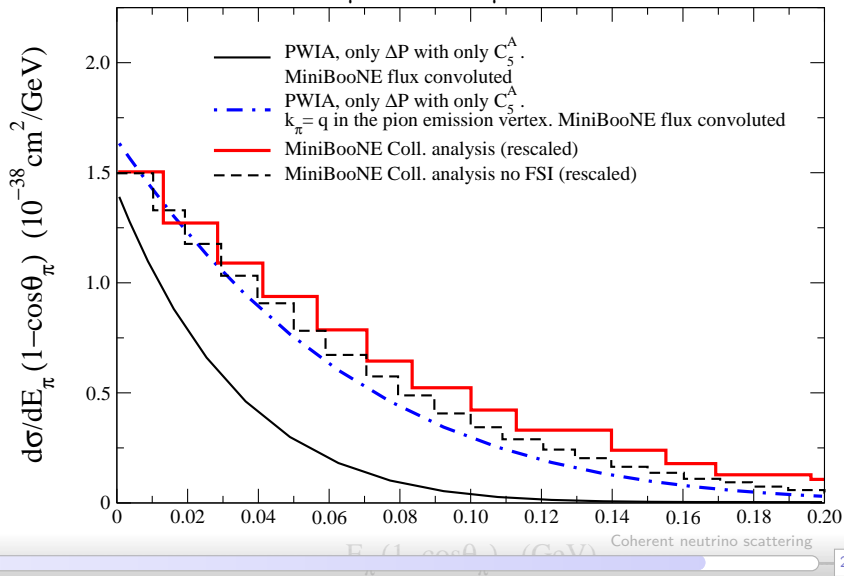
Rein-Sehgal model

Extension of Adler's PCAC theorem

$$\left(\frac{d\sigma_{\nu\nu}}{dx dy d|t|} \right)_{q^2=0} = \frac{G^2 M E_\nu}{\pi^2} f_\pi^2 (1-y) |F_{\mathcal{A}}(t)|^2 F_{\text{abs}} \frac{d\sigma(\pi^0 N \rightarrow \pi^0 N)}{d|t|} \Big|_{q^0=E_\pi, t=0}$$

It assumes completely forward kinematics so
there is no t -dependence on the single nucleon matrix element
This is good approximation for neutrinos over 2 GeV, but...

$$\nu_{\mu} \, {}^{12}\text{C} \rightarrow \nu_{\mu} \, {}^{12}\text{C} \, \pi^0$$



Final State Interactions

- In Rein-Sehgal model the pion distortion is taken into account by a Glauber-type absorption factor, but it does not take into account pion absorption or QE scattering
- MiniBoone (NUANCE) uses cascade model but ... this is a one step processes (the nuclear final state is known) so multiple scattering events should be removed
- We can take into account those QE events in our model by removing that interaction from our optical potential

Integrated cross section results

Reaction	Experiment	$\bar{\sigma}$ [10^{-40}cm^2]	σ_{exp} [10^{-40}cm^2]
CC $\nu_{\mu} + {}^{12}\text{C}$	K2K	4.68	< 7.7
CC $\nu_{\mu} + {}^{12}\text{C}$	MiniBooNE	2.99	
CC $\nu_{\mu} + {}^{12}\text{C}$	T2K	2.57	
CC $\nu_{\mu} + {}^{16}\text{O}$	T2K	3.03	
NC $\nu_{\mu} + {}^{12}\text{C}$	MiniBooNE	1.97	$7.7 \pm 1.6 \pm 3.6$
NC* $\nu_{\mu} + {}^{12}\text{C}$	MiniBooNE	2.38*	
NC $\nu_{\mu} + {}^{12}\text{C}$	T2K	1.82	
NC $\nu_{\mu} + {}^{16}\text{O}$	T2K	2.7	
CC $\bar{\nu}_{\mu} + {}^{12}\text{C}$	T2K	2.12	
NC $\bar{\nu}_{\mu} + {}^{12}\text{C}$	T2K	1.50	

Conclusions

- Coherent is suitable reaction to study $C_5^A(0)$
- Nuclear effects, including pion absorption are crucial
- Rein-Sehgal is not reliable below 2 GeV

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However, still some work to do

- At high energies other resonances become important
- Exp analysis relies on theoretical analysis which is not so well under control
- Possible nuclear structure effects?