Incoherent one-pion production in neutrino-nucleus scattering

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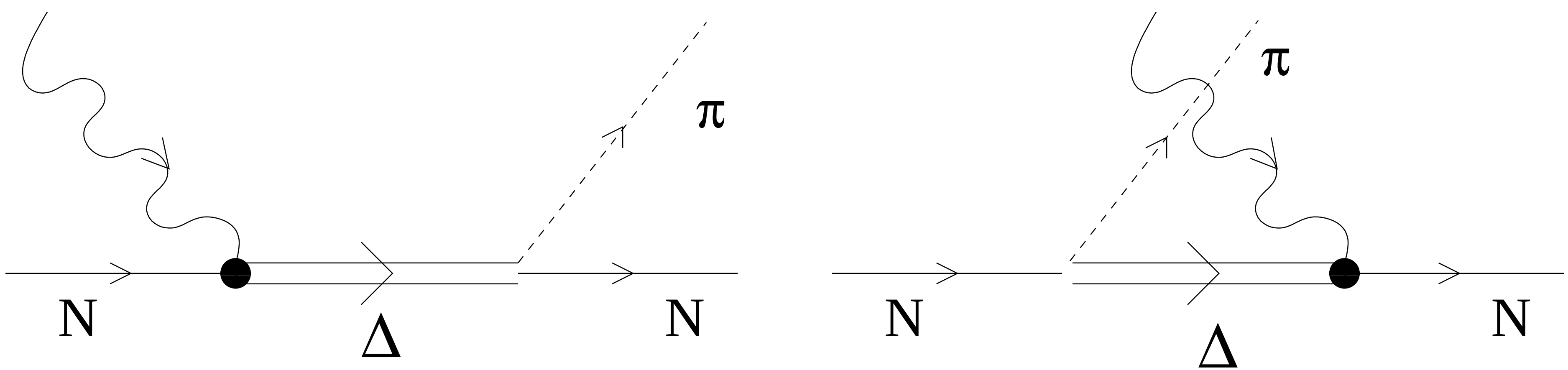
Outline of the talk

- Pion production model at the nucleon level
- Incoherent pion production
  - Pion production inside the nucleus
  - Medium modifications
  - Pion FSI
  - Results

Delta Pole Term for weak pion production off the nucleon

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



$N \to \Delta$ weak current I

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

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

$N \to \Delta$ weak current II

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

and PCAC $\quad C_6^A(q^2) = C_5^A(q^2)\frac{M^2}{m_\pi^2 - q^2}$

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

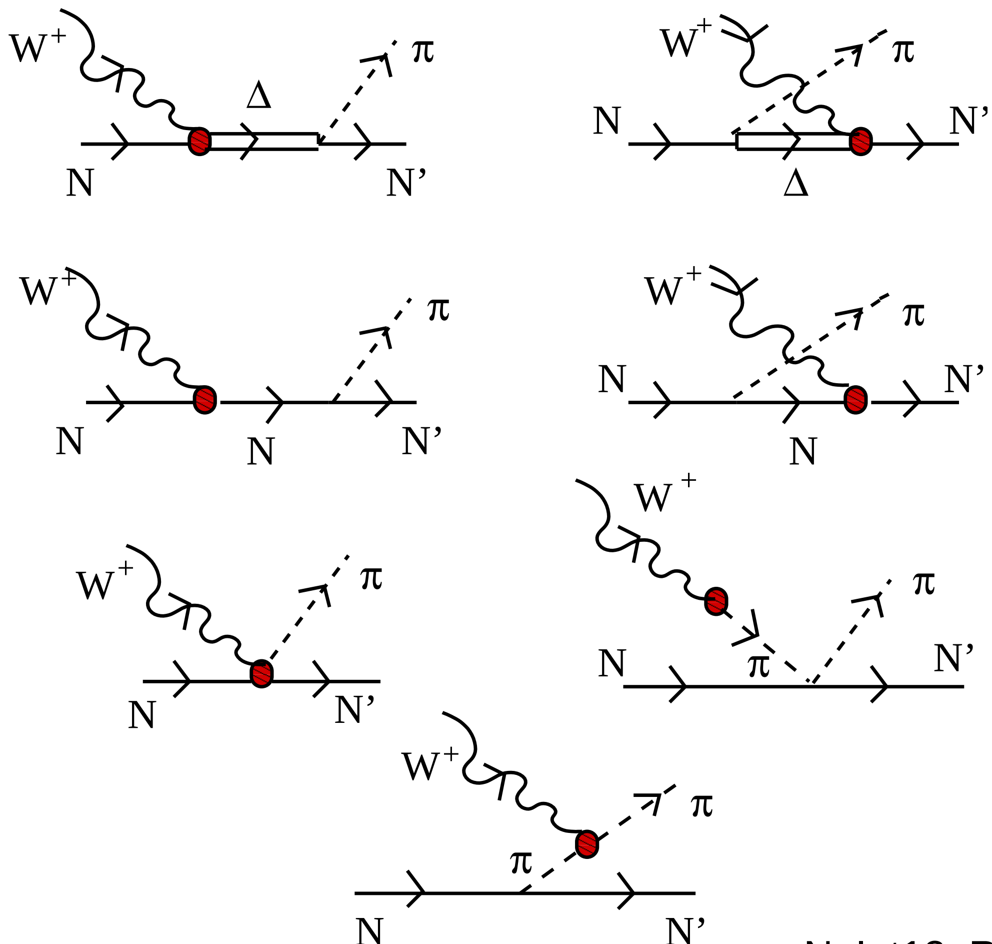
$$C_5^A(q^2) = \frac{C_5^A(0)}{(1-q^2/M_{A\Delta}^2)^2} \cdot \frac{1}{1-\frac{q^2}{3M_{A\Delta}^2}}$$

with $C_5^A(0) = 1.2$ (as given by the off-diagonal GTR) and $M_{A\Delta} = 1.05\,$GeV.

Background Terms

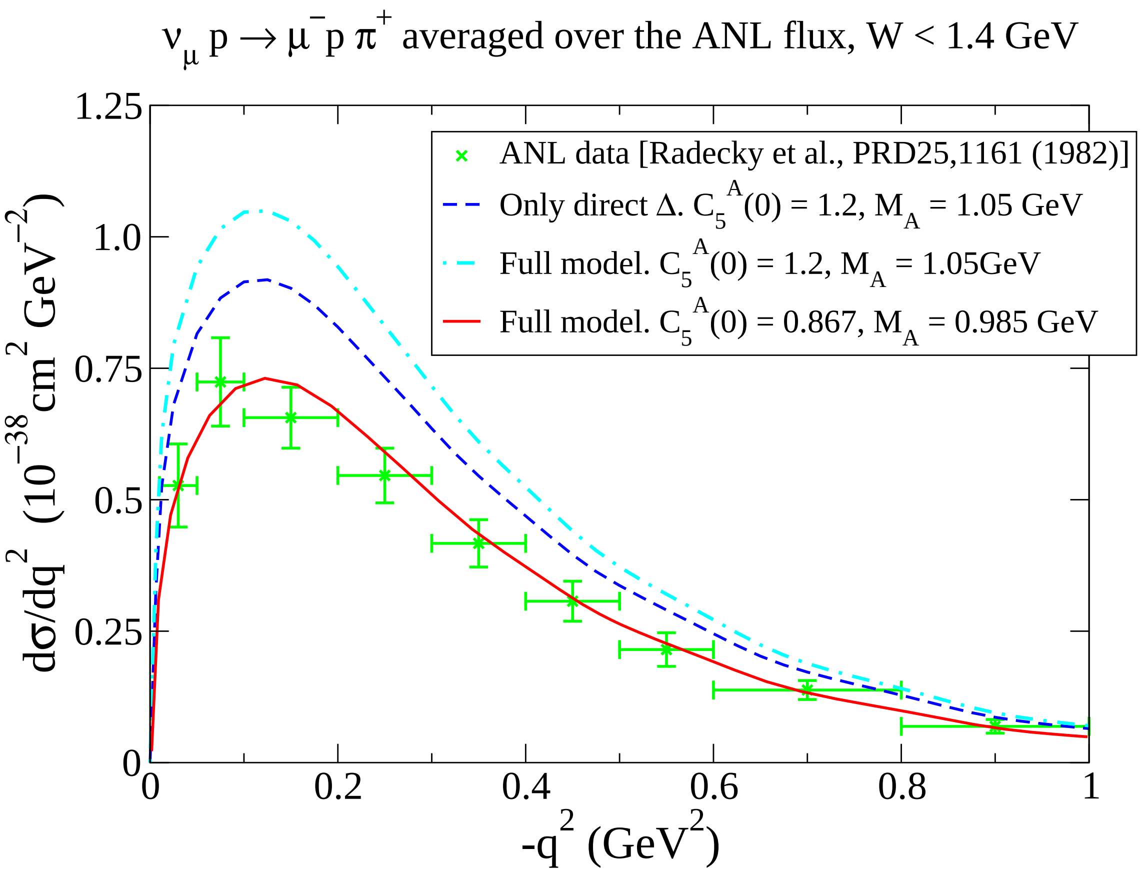
Our model in Phys. Rev. D 76, 033005 (2007) includes background terms required by chiral symmetry. To that purpose we use a SU(2) non-linear σ model Lagrangian.

- No freedom in coupling constants
- We supplement it with well known form factors



$\nu_\mu p \to \mu^- p \pi^+$ **reaction I**

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



$$C_5^A(q^2) = \frac{C_5^A(0)}{(1-q^2/M_{A\Delta}^2)^2} \cdot \frac{1}{1-\frac{q^2}{3M_{A\Delta}^2}}$$

Results suggested a refit of C_5^A

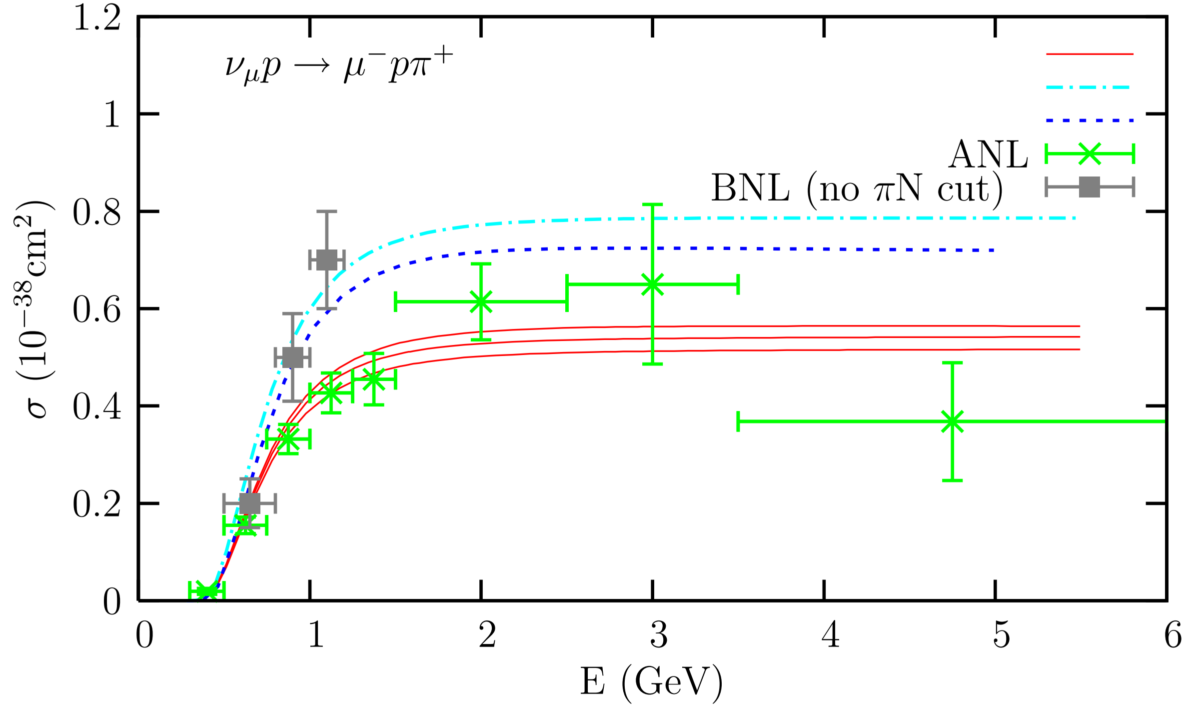
$C_5^A(0) = 0.867 \pm 0.075$

$M_{A\Delta} = 0.985 \pm 0.082\,\mathrm{GeV}$

[Phys. Rev. D 76, 033005 (2007)]

ANL data seems to prefer $C_5^A(0)$ values smaller than the one provided by the off-diagonal GTR

$\nu_\mu p \to \mu^- p \pi^+$ reaction II



BNL data [T. Kitagaki et al., Phys. Rev. D34, 2554 (1986)]

Note BNL data prefers $C_5^A(0) = 1.2$

How to reconcile ANL & BNL data and still have $C_5^A(0) \approx 1.2$

K.M. Graczyk et al. [Phys. Rev. D 80, 093001 (2009)]

- ANL and BNL data were measured in deuterium
  - Deuteron effects were estimated by L. Alvarez-Ruso et al [Phys. Rev. C 59, 3386 (1999)] to reduce the cross section by 5-10% .
- Large uncertainties in the neutrino flux normalization, 10% for BNL data and 20% for ANL data.

They made a combined fit to both ANL&BNL data, assuming that only the Δ mechanism contributed, including deuteron effects, and treating flux uncertainties as systematic errors. They found

$$C_5^A(0) = 1.19 \pm 0.08, \qquad M_{A\Delta} = 0.94 \pm 0.03\,\mathrm{GeV}$$

for a pure dipole parameterization for $C_5^A(q^2)$.
A very good agreement with the off-diagonal GTR is found!

No background terms included

Background terms included

In our work in Phys. Rev. D 81, 085046 (2010) we included background terms in a combined fit to ANL & BNL data that took into account deuteron effects and flux normalization uncertainties.

We used a simpler dipole parameterization for $C_5^A(q^2)$

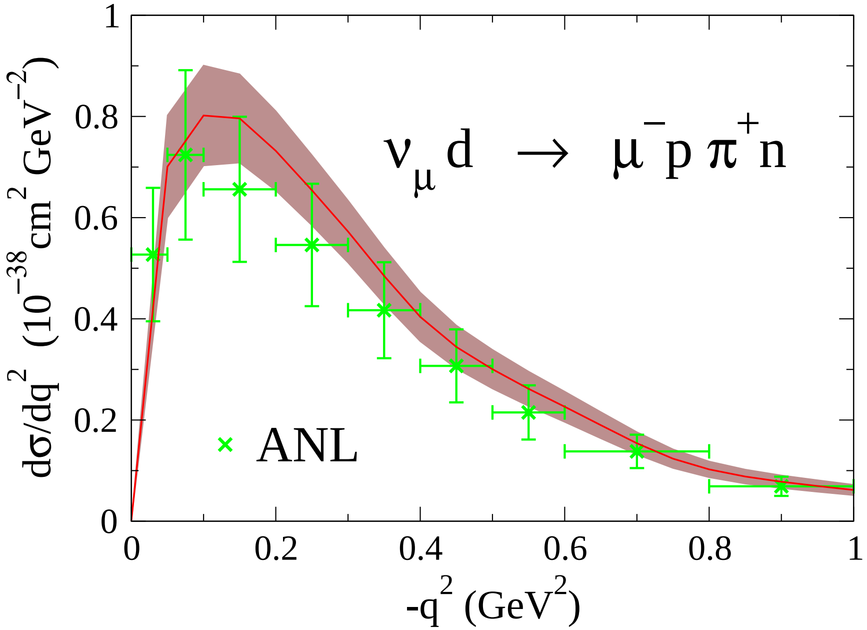
$$C_5^A(q^2) = \frac{C_5^A(0)}{(1 - q^2/M_{A\Delta}^2)^2}$$

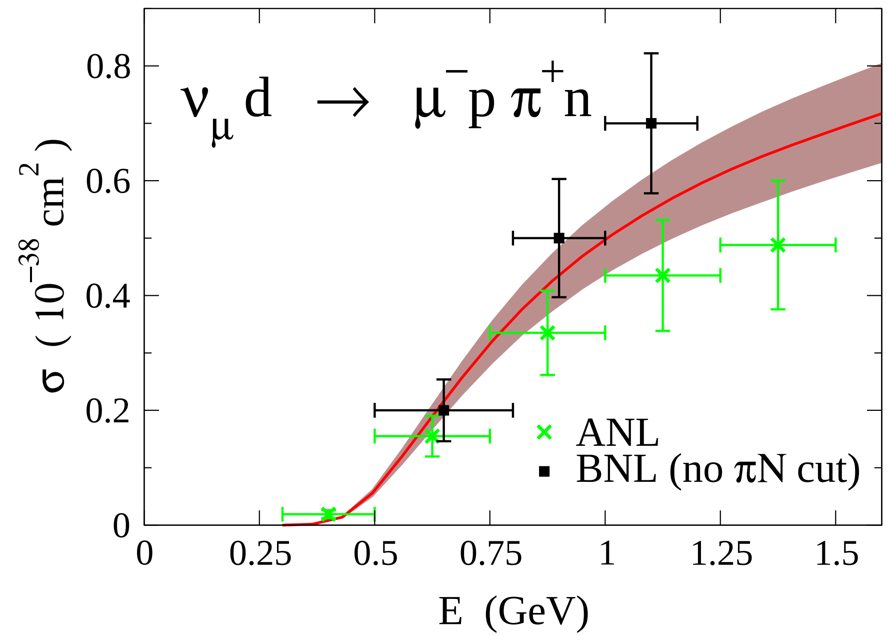
Using Adler's constraints we got

$$C_5^A(0) = 1.00 \pm 0.11, \qquad M_{A\Delta} = 0.93 \pm 0.07\,\mathrm{GeV}$$

$C_5^A(0)$ **compatible with its GTR value at the** 2σ **level.**

Comparison with ANL & BNL data



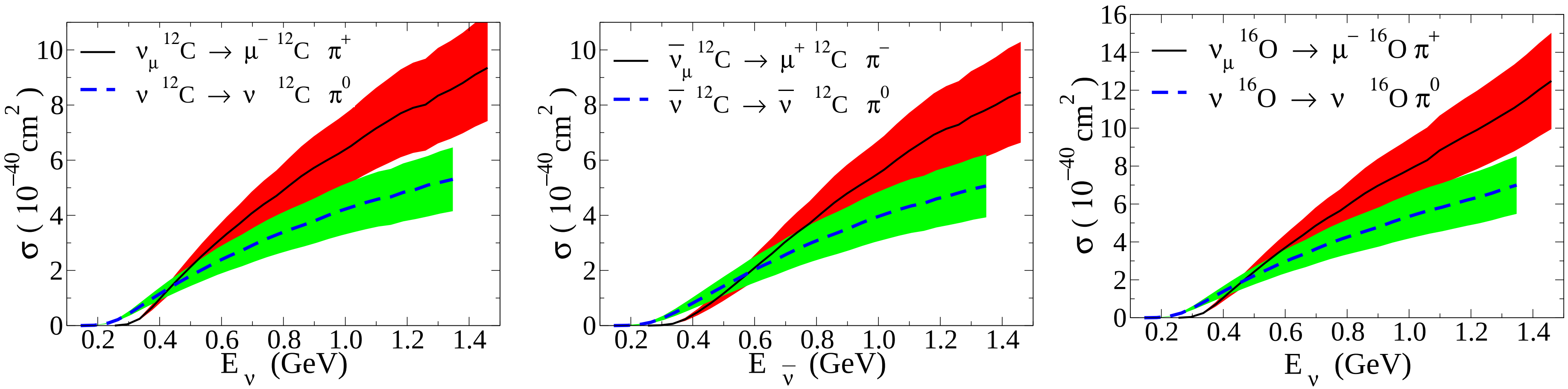


68% confidence level bands are shown.

The total experimental errors shown contain flux uncertainties that are considered as systematic errors and have been added in quadratures to the statistical ones.

Implications for coherent pion production I

Coherent pion production is a low q^2 process which is dominated by the Δ mechanism and thus very sensitive to $C_5^A(0)$



Central values for cross sections increased by 23-30% compared to our former results [Essentially by a factor $(\,C_5^A(0)\big|_{new}\,/\,C_5^A(0)\big|_{former})^2 = (1/0.867)^2 = 1.33$]

J.E. Amaro et al, Phys. Rev. D 79, 013002 (2009)

E. Hernández et al., Phys. Rev. D 82, 077303 (2010)

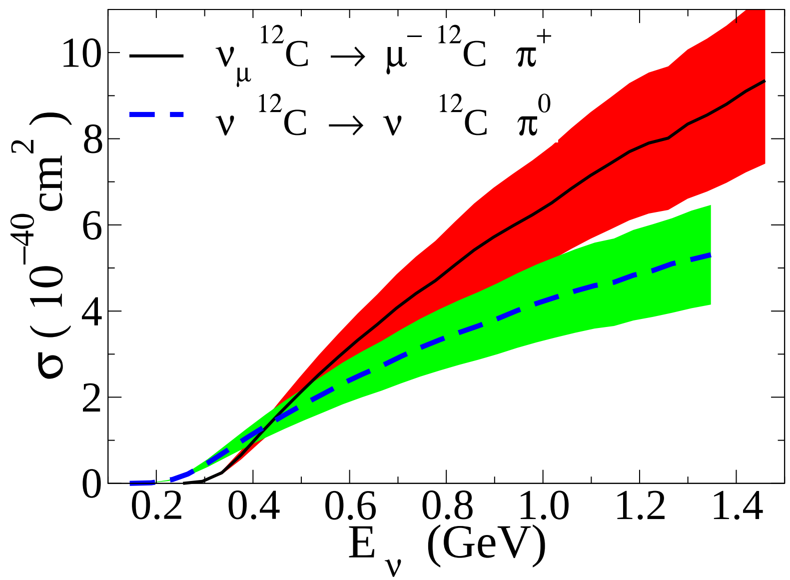
Implications for coherent pion production II

Reaction	Flux	$\bar{\sigma}$ $[10^{-40}\text{cm}^2]$	σ_{exp} $[10^{-40}\text{cm}^2]$	E_{max} [GeV]	$\int dE\phi(E)\sigma(E)$ $[10^{-40}\text{cm}^2]$	$\int dE\phi(E)$
CC ν_μ^{12}C	K2K	6.1 ± 1.3	< 7.7 [1]	1.80	5.0 ± 1.0	0.82
CC ν_μ^{12}C	MiniBooNE	3.8 ± 0.8		1.45	3.5 ± 0.7	0.93
NC ν_μ^{12}C	MiniBooNE	2.6 ± 0.5	$7.7 \pm 1.6 \pm 3.6$ [2]	1.34	2.2 ± 0.5	0.89
CC ν_μ^{12}C	T2K	3.2 ± 0.6		1.45	2.9 ± 0.6	0.91
NC ν_μ^{12}C	T2K	2.3 ± 0.5		1.34	2.1 ± 0.5	0.90
CC ν_μ^{16}O	T2K	3.8 ± 0.8		1.45	3.4 ± 0.7	0.91
NC ν_μ^{16}O	T2K	2.9 ± 0.6		1.35	2.6 ± 0.6	0.90
CC $\bar{\nu}_\mu^{12}$C	T2K	2.6 ± 0.6		1.45	1.8 ± 0.4	0.67
NC $\bar{\nu}_\mu^{12}$C	T2K	2.0 ± 0.4		1.34	1.3 ± 0.3	0.64

For CC K2K the experimental threshold $|\vec{k}_\mu| > 450$ MeV is considered

[1] M. Hasegawa *et al.* [K2K Collaboration], Phys. Rev. Lett. **95**, 252301 (2005)
[2] J.L. Raaf, FERMILAB-THESIS-2007-20 (2005) (NOT an official number by the MiniBooNE Collaboration)

Coherent NC/CC ratio and the SciBooNE $\frac{\sigma(\mathrm{CCcoh}\pi^+)}{\sigma(\mathrm{NCcoh}\pi^0)}$ ratio



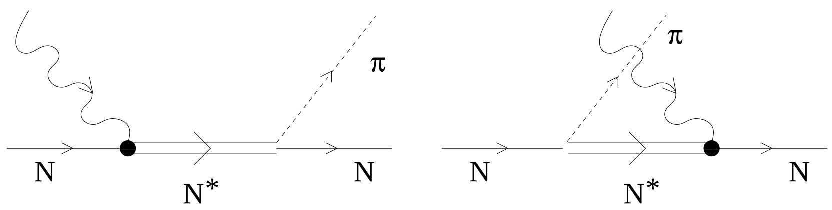
We get
$$\left.\frac{\sigma(\mathrm{CCcoh}\pi^+)}{\sigma(\mathrm{NCcoh}\pi^0)}\right|_{0.8\mathrm{GeV}} = 1.45 \pm 0.03$$

to be compared with the value reported by the SciBooNE Collaboration [Y. Kurimoto et al., Phys. Rev. D 81,111102 (2010)]
$$\left.\frac{\sigma(\mathrm{CCcoh}\pi^+)}{\sigma(\mathrm{NCcoh}\pi^0)}\right|_{\mathrm{SciBooNE}} = 0.14^{+0.30}_{-0.28}$$

For isoscalar nuclei, neglecting vector current contributions and lepton mass effects, isospin symmetry predicts $\frac{\sigma(\mathrm{CCcoh}\pi^+)}{\sigma(\mathrm{NCcoh}\pi^0)} = 2$

Other resonances

In order to go to higher neutrino energies, we include in our model the $D_{13}(1520)$ resonance (isospin 1/2, spin 3/2) that, apart from the Δ, gives the most important contribution [T. Leitner et al., Phys. Rev. C 79, 034601 (2009)]



We adjust the $\pi N N^*$ coupling to the $N^* \to N\pi$ width and get $g_D = 20$ GeV^{-1}. GTR then fixes the value $C_5^A(0) = -2.1$ for the $W^+ n \to N^{*+}$ transition.

For the axial form factors we take [O. Lalakulich *et al.*, Phys. Rev. D74, 014009 (2006)]

$$C_3^A = C_4^A = 0, \;\; C_5^A = \frac{-2.1}{(1-q^2/M_A^2)^2}, \;\; C_6^A(q^2) = C_5^A(q^2)\frac{M^2}{m_\pi^2 - q^2}, \;\; M_A = 1\,\mathrm{GeV}$$

while for vectors we fit to form factor results in T. Leitner's thesis to get

$$C_3^V = \frac{-2.98}{[1-q^2/(1.4M_V^2)]^2}, \;\; C_4^V = \frac{4.21/D_V}{1-q^2/(3.7M_V^2)}, \;\; C_5^V = \frac{-3.13/D_V}{1-q^2/(0.42M_V^2)}, \;\; C_6^V = 0$$

with $M_V = 0.84$ GeV and $D_V = (1-q^2/M_V^2)^2$

The inclusion of the $D_{13}(1520)$ does not affect the initial fit of the Δ form factors

- Having $I = 1/2$, it does not contribute to the $\nu_\mu p \to \mu^- p \pi^+$ channel

Incoherent one-pion production in nuclei.

Our starting point is the differential cross section at the nucleon level. For instance for CC processes and massless neutrinos we have

$$\frac{d\sigma(\nu N \to l^- N'\pi)}{d\cos\theta_\pi dE_\pi} = 2\pi \frac{G_F^2}{4\pi^2} \frac{|\vec{k}_\pi|}{|\vec{k}|} \frac{1}{4E_N} \frac{1}{(2\pi)^3} \int d\Omega' dE' |\vec{k}'| \frac{1}{2E_{N'}} \delta(E_N + q^0 - E_\pi - E_{N'}) \, \mathcal{L}_{\mu\sigma} \mathcal{W}^{\mu\sigma}$$

with

$$q = k - k', \; E_{N'} = \sqrt{M^2 + (\vec{p}_N + \vec{q} - \vec{k}_\pi)^2}$$

$$\mathcal{L}_{\mu\sigma} = k_\mu k'_\sigma + k_\sigma k'_\mu - k\cdot k' g_{\mu\sigma} + i\epsilon_{\mu\sigma\alpha\beta} k'^\alpha k^\beta$$

$$\mathcal{W}^{\mu\sigma}(p_N, q, k_\pi) = \overline{\sum_{\rm spins}} \left\langle N'\pi | j^\mu_{CC}(0) | N \right\rangle \left\langle N'\pi | j^\sigma_{CC}(0) | N \right\rangle^*$$

For incoherent production on a nucleus we have to sum over all nucleons in the nucleus.

Incoherent one-pion production in nuclei.

We assume the nucleus can be described by its density and we shall use the local density approximation

The cross section at the nucleus level for initial pion production (prior to any FSI) is then

$$\frac{d\sigma}{d\cos\theta_\pi\, dE_\pi} = \int d^3r \sum_{N=n,p} 2 \int \frac{d^3p_N}{(2\pi)^3}\, \theta(E_F^N(r) - E_N)\, \theta(E_N + q^0 - E_\pi - E_F^{N'}(r))\, \frac{d\sigma(\nu N \to l^- N'\pi)}{d\cos\theta_\pi\, dE_\pi}$$

To compare with experiment, we have to convolute it with the neutrino flux $\Phi(|\vec{k}|)$

$$\frac{d\sigma}{d\cos\theta_\pi\, dE_\pi} = \int d|\vec{k}|\, \Phi(|\vec{k}|)\, 4\pi \int dr r^2 \sum_{N=n,p} 2 \int \frac{d^3p_N}{(2\pi)^3}\, \theta(E_F^N(r) - E_N)\, \theta(E_N + q^0 - E_\pi - E_F^{N'}(r)) \times \frac{d\sigma(\nu N \to l^- N'\pi)}{d\cos\theta_\pi\, dE_\pi}$$

From there we obtain

$$\frac{d\sigma}{d|\vec{k}|\, dr\, d\cos\theta_\pi\, dE_\pi} = \Phi(|\vec{k}|)\, 4\pi r^2 \sum_{N=n,p} 2 \int \frac{d^3p_N}{(2\pi)^3}\, \theta(E_F^N(r) - E_N)\, \theta(E_N + q^0 - E_\pi - E_F^{N'}(r))\, \frac{d\sigma(\nu N \to l^- N'\pi)}{d\cos\theta_\pi\, dE_\pi}$$

What else is left to do?

- Medium effects in the production process.
- Final state interaction of the outgoing pion.

Incoherent one-pion production in nuclei.

Prior to that, there is an approximation in the evaluation of $\frac{d\sigma}{d|\vec{k}|\,dr\,d\cos\theta_\pi\,dE_\pi}$.

Doing the d^3p_N integral first we have (We define $Q = q - k_\pi$ and refer the nucleon polar angles to the $\vec{Q}$ axis)

$$\int_{-1}^{1} d\cos\theta_N \int_0^{2\pi} d\varphi_N \int_M^\infty |\vec{p}_N| E_N dE_N\ \theta(E_F^N - E_N)\,\theta(E_N + Q^0 - E_F^{N'})$$
$$\times \frac{1}{E_N E_{N'}}\ \delta(E_N + Q^0 - E_{N'})\,\mathcal{W}^{\mu\sigma}(p_N, q, k_\pi)$$
$$= \frac{\theta(-Q^2)\theta(Q^0)\theta(E_F^N - \mathcal{E})}{|\vec{Q}|} \int_0^{2\pi} d\varphi_N \int_{\mathcal{E}}^{E_F^N} dE_N\,\mathcal{W}^{\mu\sigma}(p_N, q, k_\pi)\big|_{\cos\theta_N^0}$$

where

$$\cos\theta_N^0 = \frac{Q^2 + 2E_N Q^0}{2|\vec{p}_N||\vec{Q}|},\ E' = \frac{-Q^0 + |\vec{Q}|\sqrt{1 - 4M^2/Q^2}}{2},\ \mathcal{E} = \max\{M, E_F^{N'} - Q^0, E'\}$$

Taking an average $\tilde{\varphi}_N$, $\tilde{E}_N$ and the corresponding value for $\cos\theta_N^0$ in $\mathcal{W}^{\mu\sigma}(p_N, q, k_\pi)$ we have

$$\approx 2\pi\frac{(E_F^N - \mathcal{E})\mathcal{W}^{\mu\sigma}(\tilde{p}_N, q, k_\pi)}{|\vec{Q}|}\theta(-Q^2)\theta(Q_0)\,\theta(E_F^N - \mathcal{E})$$

Incoherent one-pion production in nuclei. Medium corrections

Δ properties are strongly modified in the nuclear medium.

Its imaginary part is modified due

- Pauli blocking of the final nucleon affects the free width.
- In medium modification of the pionic decay width others than Pauli blocking
- Absorption processes $\Delta N \to NN$ and $\Delta NN \to NNN$.

We thus modify the Δ propagator of the direct Δ contribution approximating

$$\frac{1}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta} \approx \frac{1}{\sqrt{p_\Delta^2} + M_\Delta} \frac{1}{\sqrt{p_\Delta^2} - M_\Delta + i\Gamma_\Delta/2}$$

and substituting

$$\frac{\Gamma_\Delta}{2} \to \frac{\Gamma_\Delta^{\text{Pauli}}}{2} - \operatorname{Im}\Sigma_\Delta$$

while keeping M_Δ in the particle propagator unchanged.

Incoherent one-pion production in nuclei. Medium corrections

The evaluation of $\mathrm{Im}\,\Sigma_\Delta$ was done by E. Oset and L.L. Salcedo [Nucl. Phys. A 468, 631 (1987)].

The imaginary part can be parameterized as

$$-\mathrm{Im}\,\Sigma_\Delta = C_Q \left(\frac{\rho}{\rho_0}\right)^\alpha + C_{A2} \left(\frac{\rho}{\rho_0}\right)^\beta + C_{A3} \left(\frac{\rho}{\rho_0}\right)^\gamma$$

- The C_Q term corrects the pion production in the medium.
- The C_{A2} term gives rise to W absorption by two nucleons $W^* NN \rightarrow NN$.
- The C_{A3} term gives rise to W absorption by three nucleons $W^* NNN \rightarrow NNN$.

Not only the Δ propagator is modified, but we have a new contribution to pion production, corresponding to the C_Q piece, that have to be added incoherently.

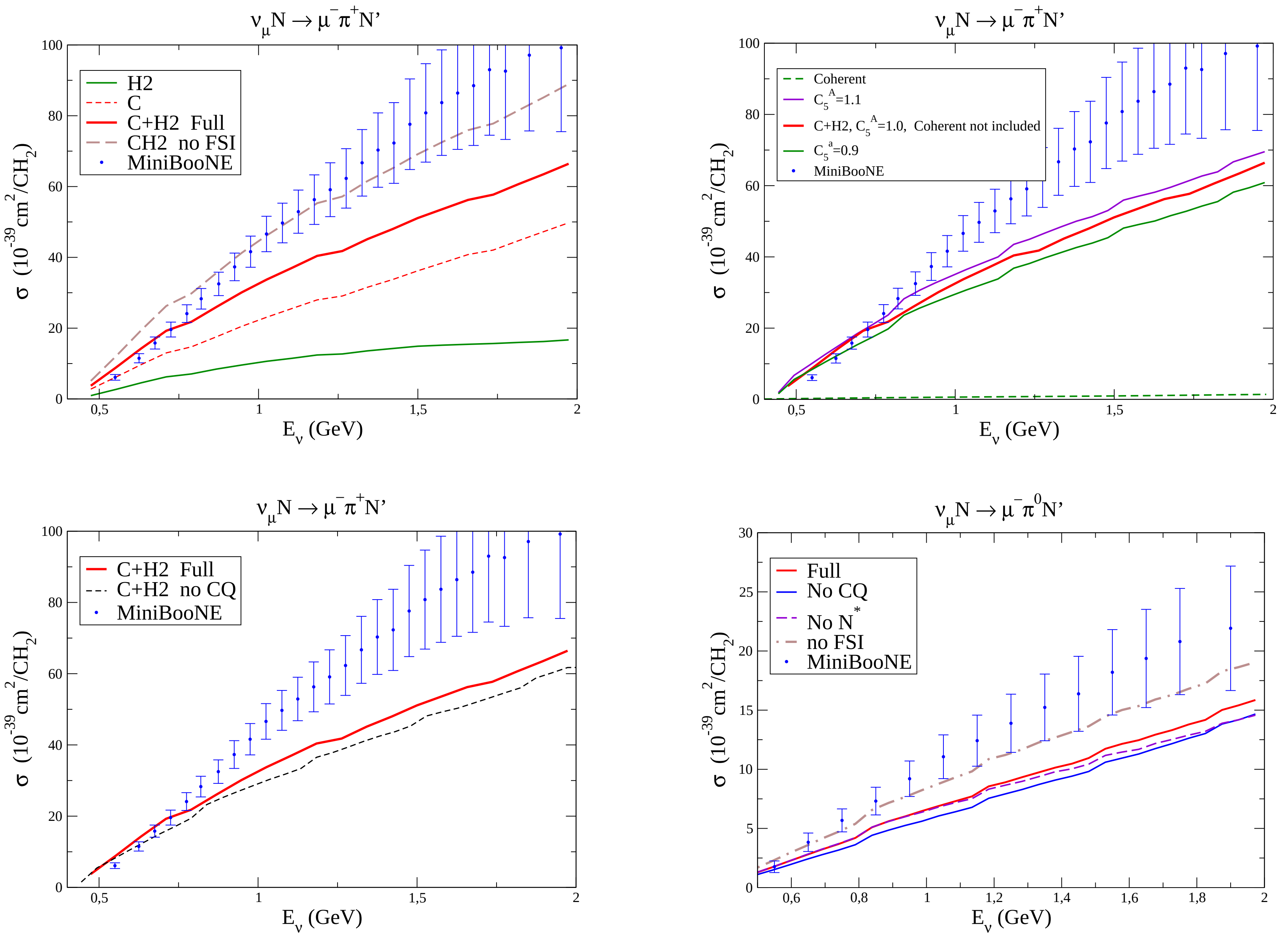
Incoherent one-pion production in nuclei. Final state interaction

Once the pions are produced, we follow their path on its way out of the nucleus.

We use, with slight modifications, the model of L.L. Salcedo et al. [Nuc. Phys. A484, 557 (1988)]

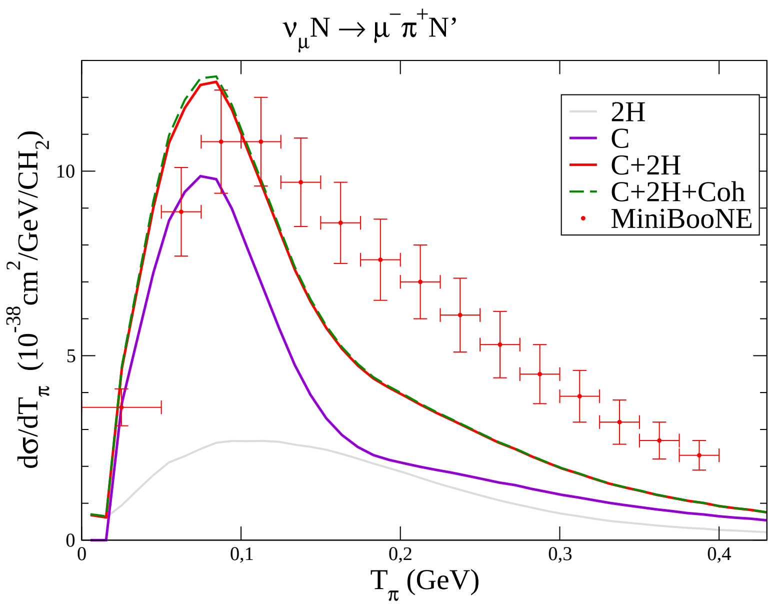
- P-wave and S-wave pion absorption.
- P-wave (mediated by Δ production) quasielastic scattering on a nucleon.
  - Pions change energy and direction.
  - Pions could change charge.
- Pion propagate on straight lines in between collisions.

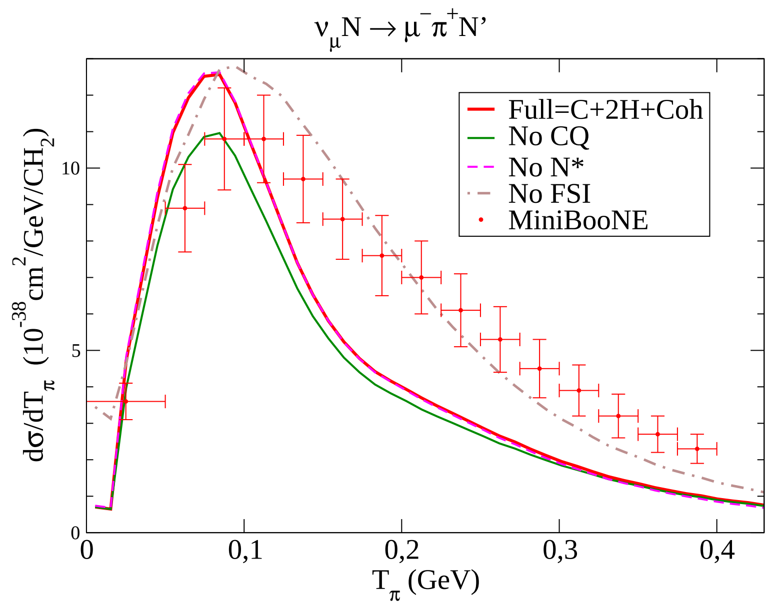
Incoherent pion production in nuclei. CC Results

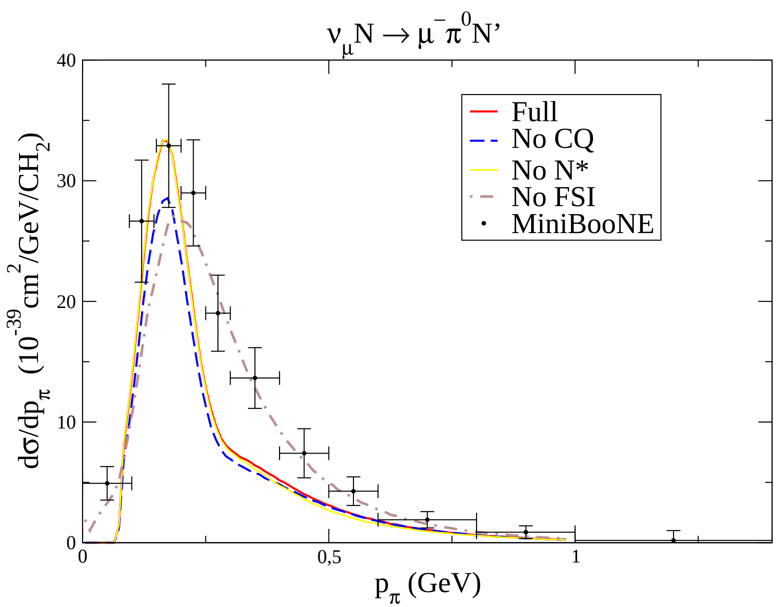


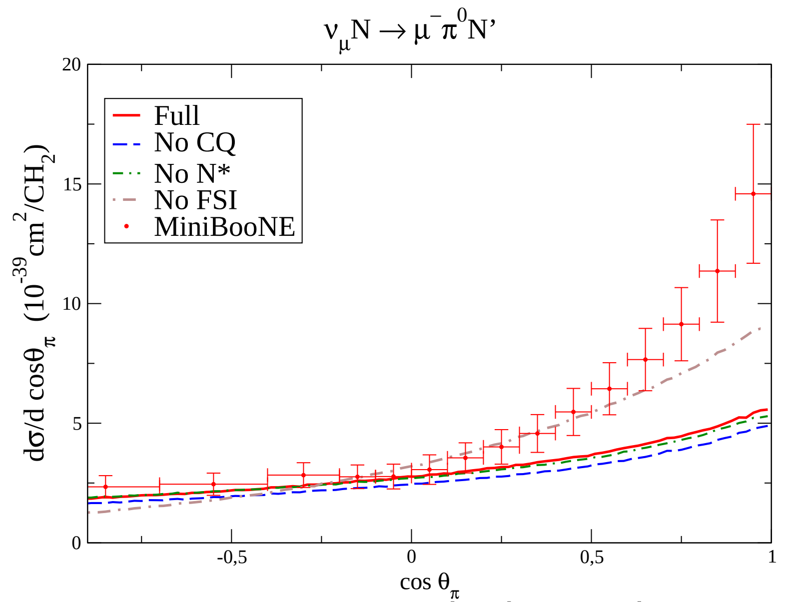
Data MiniBooNE Coll., Phys. Rev. D 83, 052007 and 052009 (2011)

Incoherent one-pion production in nuclei. CC Results

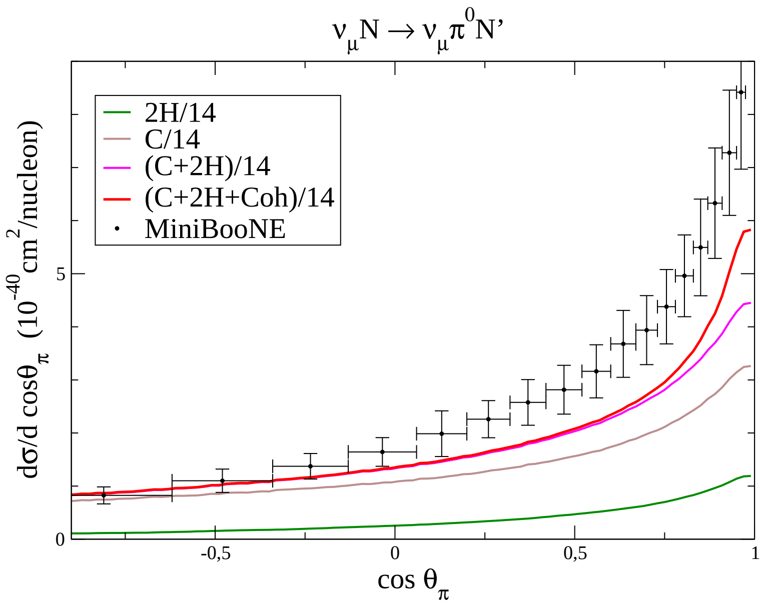


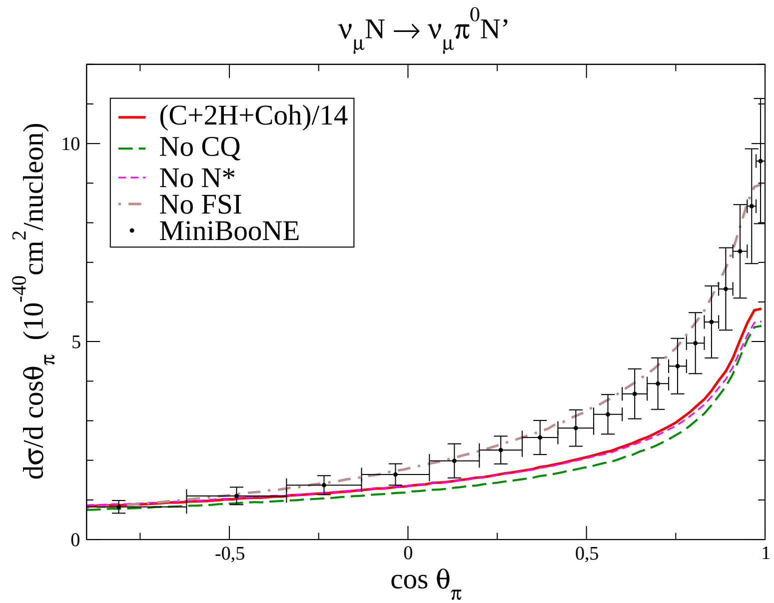


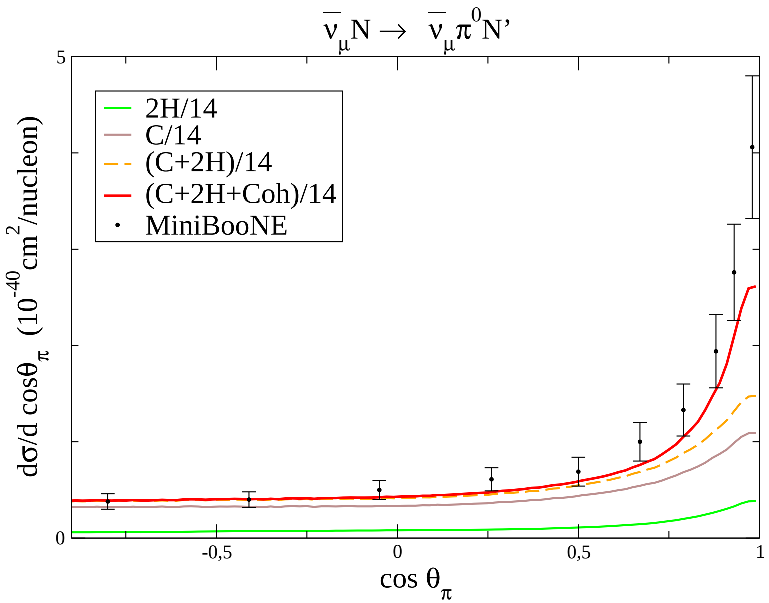


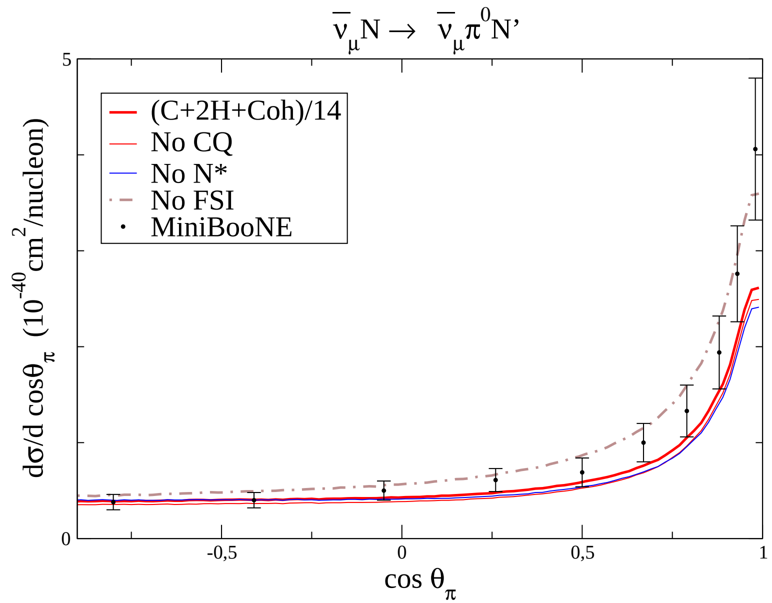


Incoherent one-pion production in nuclei. NC Results



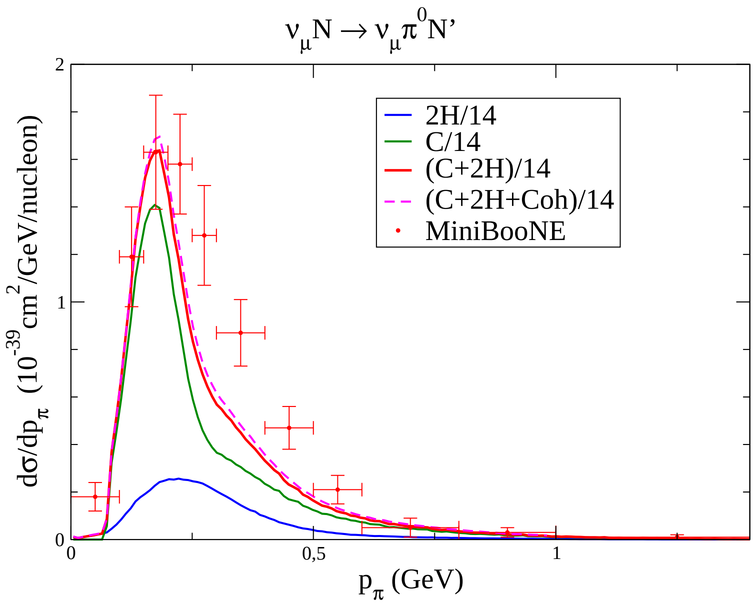


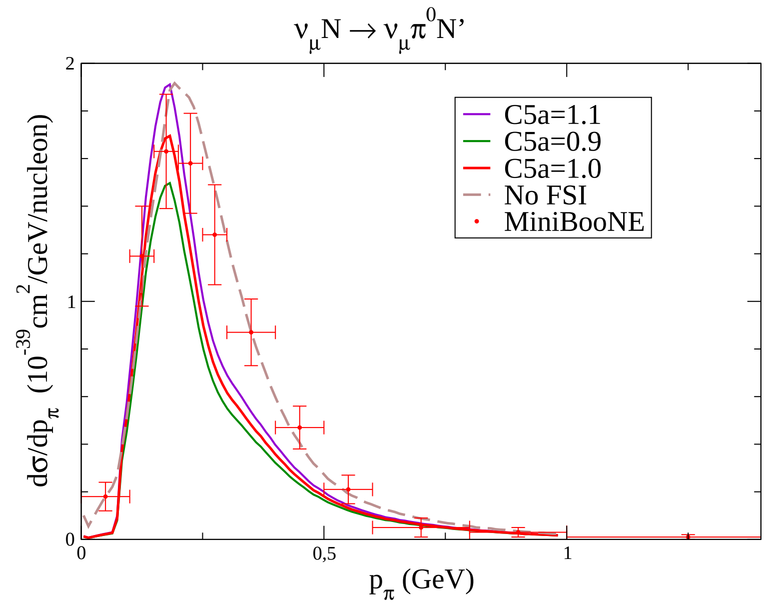


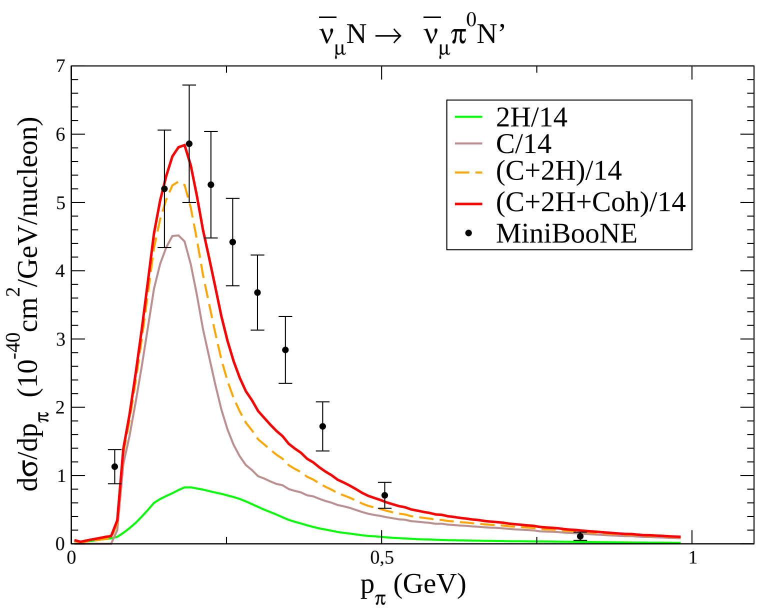


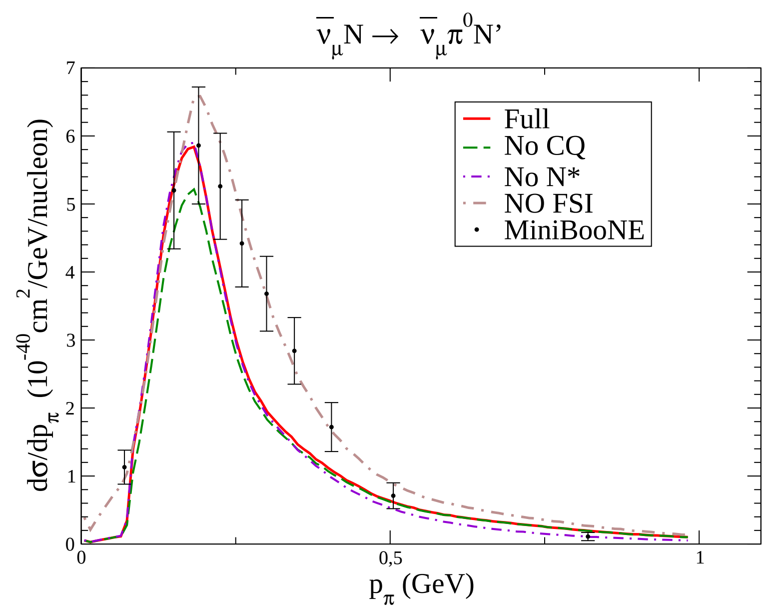
Data MiniBooNE Coll., Phys. Rev. D 81, 013005 (2011)

Incoherent one-pion production in nuclei. NC Results









Summary

- I have shown the ingredients of the Monte Carlo program we have developed to describe incoherent pion production in nuclei
  - Microscopic model for pion production on the free nucleon modified by
    - The presence of the nuclear medium
      - Δ propagator is modified inside the medium
      - New net contribution to pion decay due to the in medium modification of the pionic width of the Δ
    - The inclusion of a new resonance contribution with small effects on the cross sections
  - Simulation of the pion's path on its way out of the nucleus
    - Absorption
    - Quasielastic scattering
- Our results without FSI reproduce the experimental data