π production in neutrino-nucleus scattering

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Just one example:

Bringing the SciBar detector to the booster neutrino beam, SciBooNE Coll., FERMILAB-PROPOSAL-0954

In T2K ....measure θ_{23} accurately. The background to this channel is dominated by single pion charged current events... This figure makes it clear that the CCπ^+ cross-section at these energies needs to be known to 5% to keep any resulting error on the oscillation parameters within statistical uncertainties.

See also:*Precise Measurement of the Neutrino Mixing Parameter θ_{23} from Muon Neutrino Disappearance in an Off-axis Beam, T2K Coll., arXiv:1403.2552*

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... 5%?

Outline

- Pion production model at the nucleon level
  - Theoretical modelling
  - Experimental situation
- Pion production on nuclei
  - Incoherent pion production
    - Medium modifications of the elementary mechanisms
    - Pion final state interactions
  - Coherent pion production
- Room for improvement?
- Summary

π production on the nucleon

We need a good theoretical description of the process

$$\nu + N \to \pi + N'$$

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For the rest of energies theoretical calculations of any process involving hadrons are less predictive/reliable!

Low energy $\nu\pi$ production on nucleons

- Well described by χ*PT = QCD* at low energies

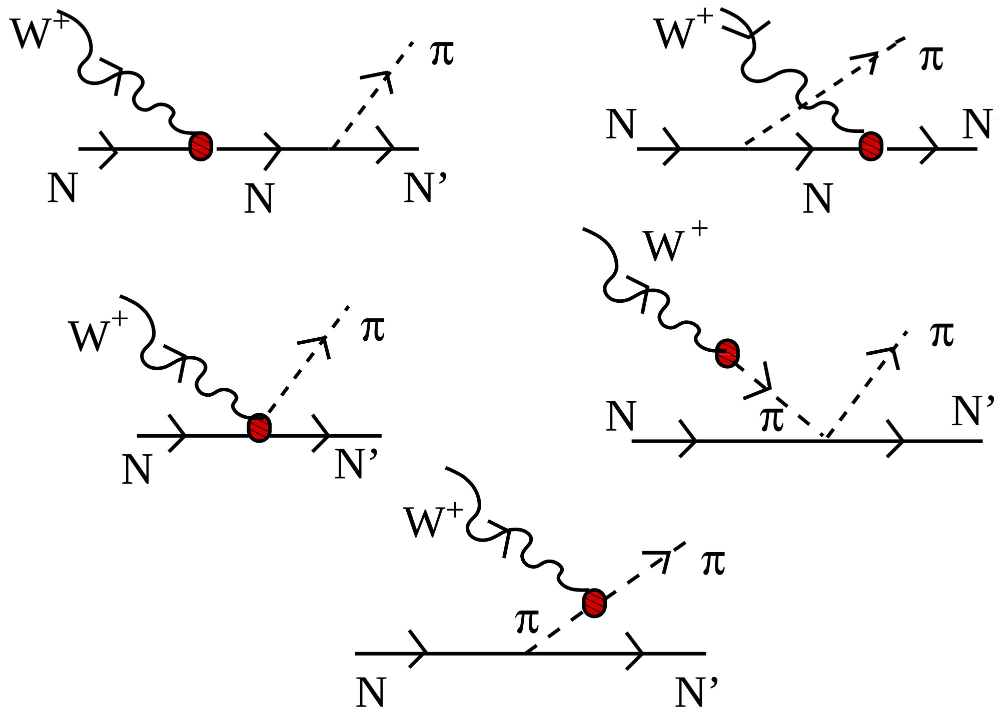
  At the lowest order the Lagrangian depends only on pion and nucleon masses and two well known constants:

  - $f_\pi = 92.4$ MeV, the pion decay constant (pion lifetime)
  - $g_A = 1.26$, the nucleon axial charge (β-decay or πN scattering)

- *"A Primer for Chiral Perturbation Theory", S. Scherer, M. Schindler, Lect.Notes Phys. 830 (2012)*
- *"Weak Pion Production off the Nucleon", E. Hernandez,J.N.,M.V., Phys.Rev. D76 (2007) 033005*

Low energy $\nu\pi$ production on nucleons

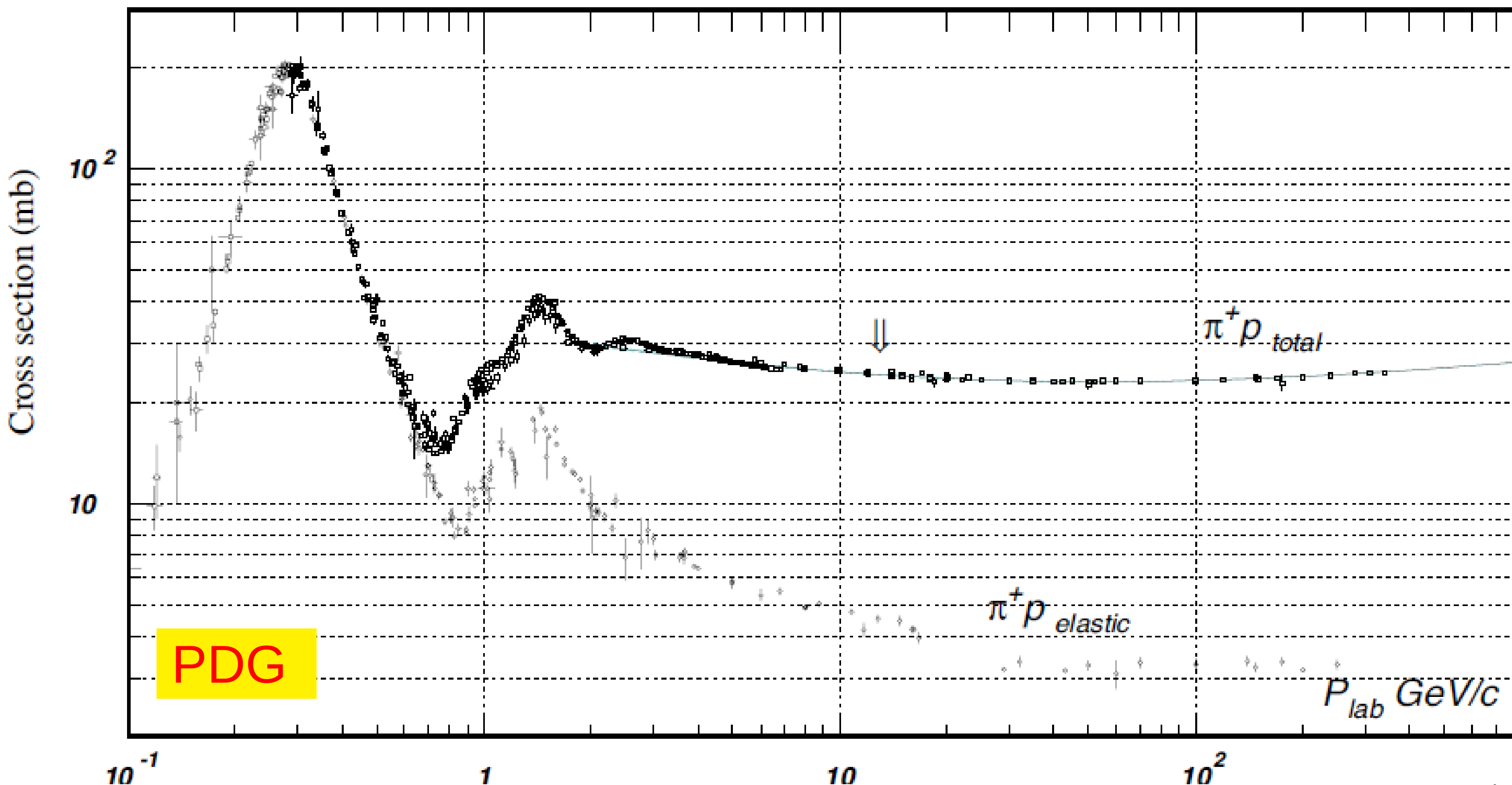
The lowest order chiral Lag. leads to the usually called *background* mechanisms



that describe the reaction only in the low energy limit! To reach higher energies one has several options, all of them mean additional and not so well known couplings!

Low energy $\nu\pi$ production on nucleons

- For pions of kinetic energy from 80 to 400 MeV the $\Delta(1232)$ plays a dominant role-1:



Low energy $\nu\pi$ production on nucleons

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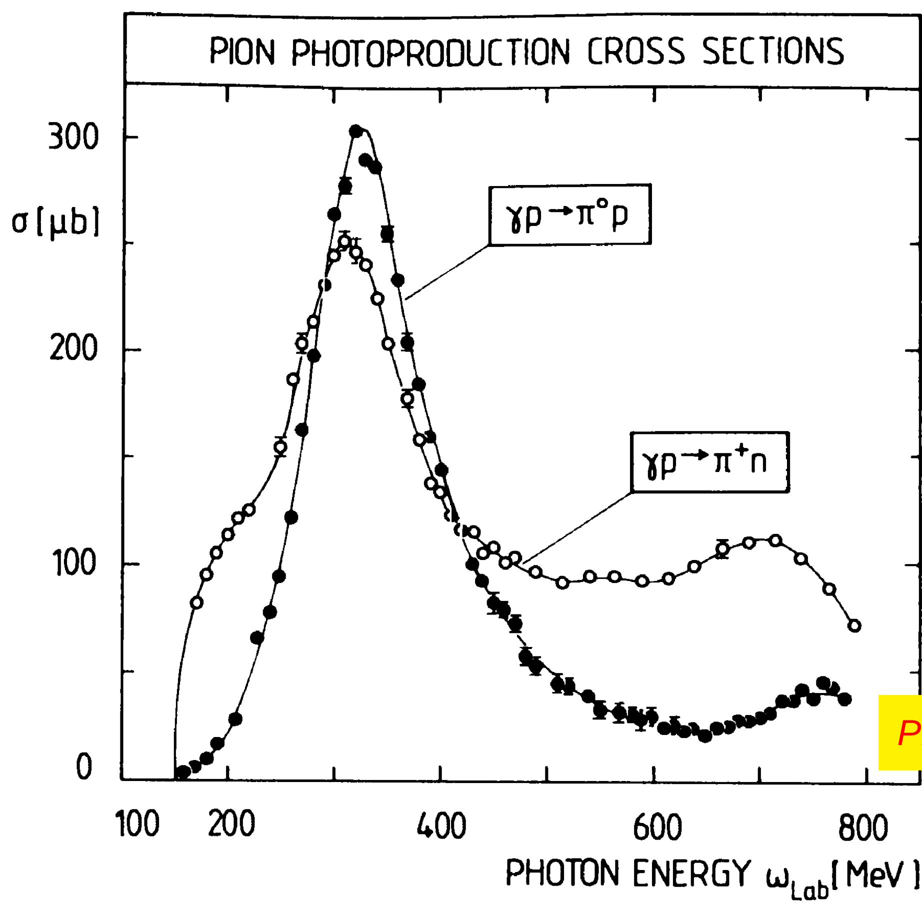
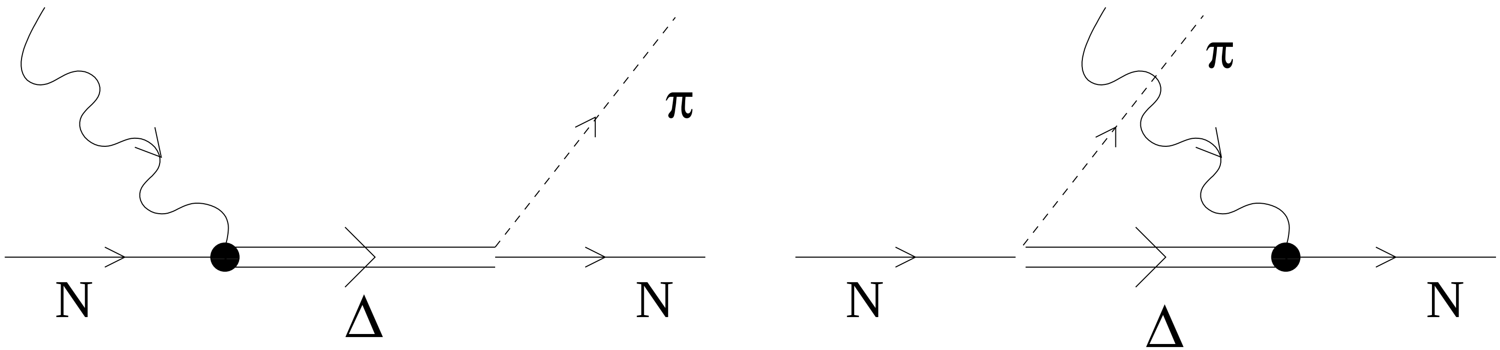
PION PHOTOPRODUCTION ON NUCLEONS



Pions and Nuclei, Ericson & Weise

Delta Pole Term for weak pion production off the nucleon

As for electro- and photo-production, at these intermediate energies the dominant contribution for weak pion production is also given by the $\Delta(1232)$ mechanisms



See,for instance

- *Photoproduction, electroproduction and weak single π production in the (3,3) resonance region Stephen L. Adler, Annals Phys. 50(1968)189*
- *Neutrino Reactions at Accelerator Energies C.H. Llewellyn Smith, Phys.Rept. 3 (1972) 261*
- *Charged current weak electroproduction of Delta resonance L. Alvarez-Ruso et al, PRC57 (1998) 2693; PRC59 (1999) 3386*

$N \to \Delta$ weak current I

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

For nucleon quasielastic scattering there are 4 Lorentz structures and the only couplings are g_A and the magnetic moment. However, for the Δ we have

$$\Gamma^{\alpha\mu}(p,q) =$$

$$\left[\frac{C_3^V}{M} \left(g^{\alpha\mu} \not{q} - q^\alpha \gamma^\mu \right) \right.$$

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just the vector part, plus..

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the axial part. How well known are all these couplings?

$N \to \Delta$ weak current II

- Vector form factors: well known, determined from the analysis of photo and electroproduction *[e.g. O. Lalakulich et al., Phys. Rev. D74, 014009 (2006)]*

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

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

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- Axial form factors are not so well known:
  - PCAC leads to $C_6^A(q^2) = C_5^A(q^2)\frac{M^2}{m_\pi^2 - q^2}$
  - off-diagonal GTR $\Rightarrow C_5^A(0) \approx 1.2$
  - $C_5^A(q^2)$?, $C_4^A(q^2)$?, $C_3^A(q^2)$?

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  - $C_5^A(q^2)$?, $C_4^A(q^2)$?, $C_3^A(q^2)$?

- Could χPT help?

$N \to \Delta$ weak current III

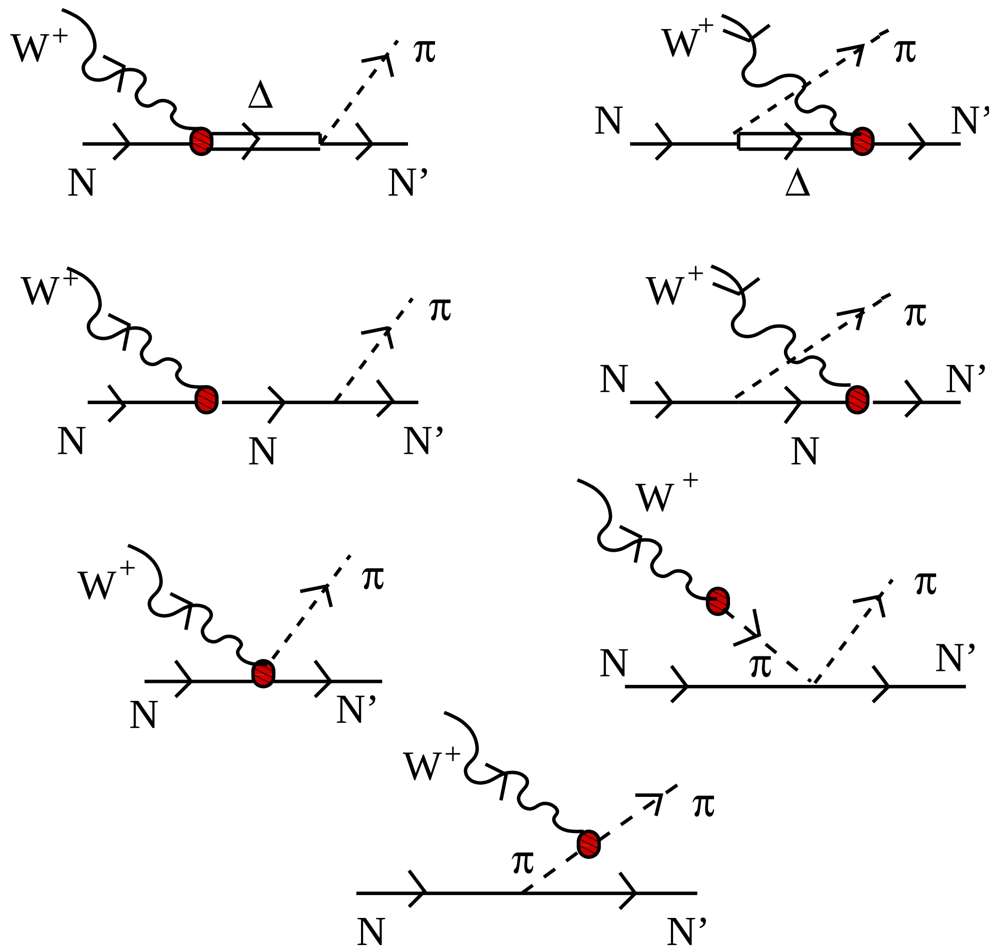
- χPT is not very predictive here: *$N \to \Delta$ axial transition form factors in relativistic baryon chiral perturbation theory, L.S. Geng, Jorge,Luis, Manolo, Phys.Rev. D78 (2008) 014011.*

Table 1: The axial $N \to \Delta$ transition form factors in chiral perturbation theory.

FF	$\delta^{(1)}$	$\delta^{(2)}$	$\delta^{(3)}$
$-\sqrt{\frac{3}{2}}\frac{C_3^A}{M_N}$	0	$-d_2$	$f_3\Delta + g_3(q^2)$
$-\sqrt{\frac{3}{2}}\frac{C_4^A}{M_N^2}$	0	$-d_1/M_\Delta$	$(f_4+f_6)\Delta/M_\Delta + g_4(q^2)$
$-\sqrt{\frac{3}{2}}C_5^A$	$-\frac{h_A}{2}$	$-(d_3+d_4)\Delta$	$(f_5+f_7)\Delta^2 + (f_1+f_2)q^2 + g_5(q^2)$
$-\sqrt{\frac{3}{2}}\frac{C_6^A}{M_N^2}$	$\frac{h_A/2}{q^2-m_\pi^2}$	$\frac{(d_3+d_4)\Delta}{q^2-m_\pi^2}$	$-f_1 + g_6(q^2) + \frac{-(f_5+f_7)\Delta^2 - f_2 q^2 - (g_5(q^2)+g_6(q^2)q^2)}{q^2-m_\pi^2}$

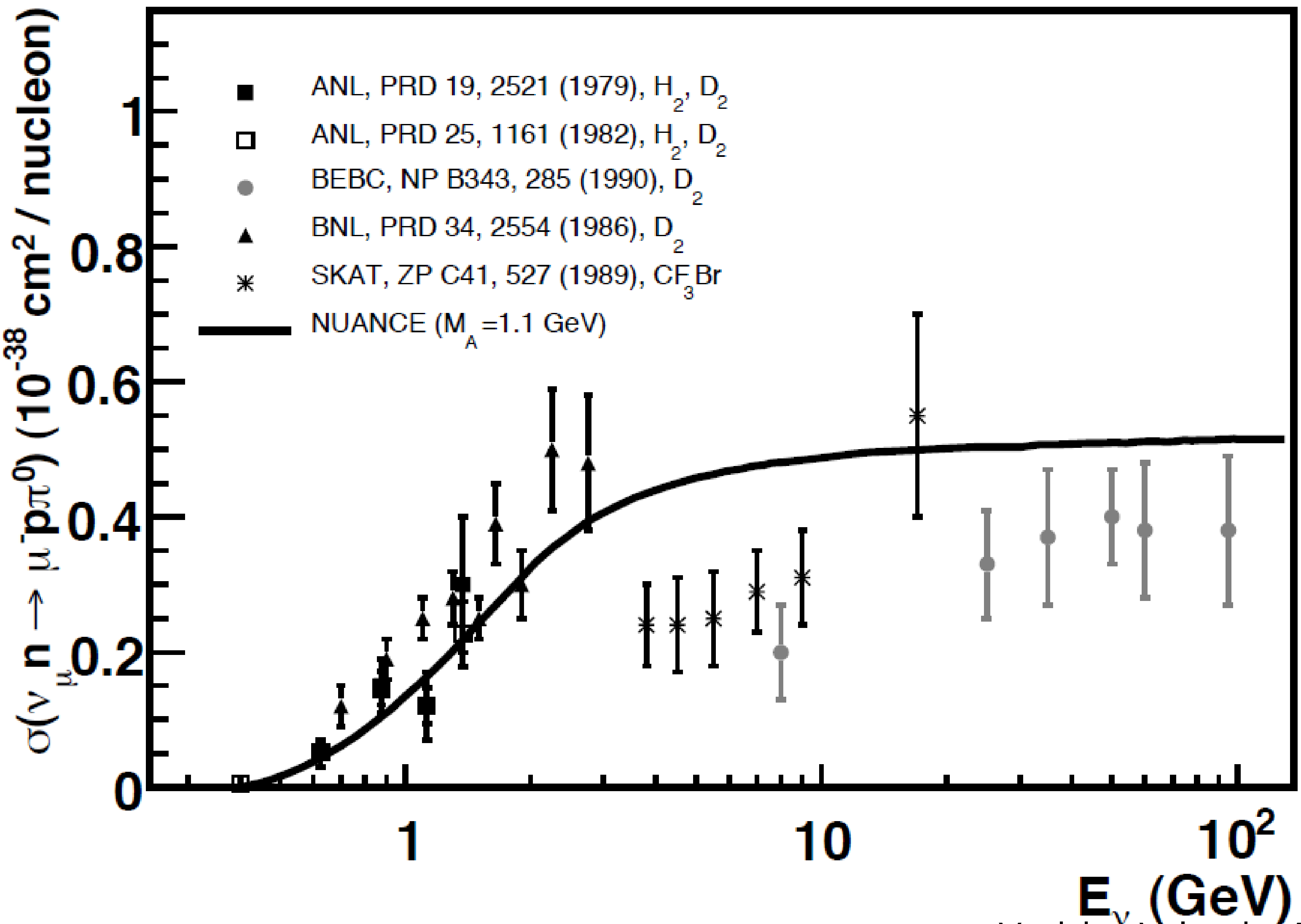
- Of these constants, h_A is known from π-nucleon scattering
- Some axial probe –such as neutrinos– should fix the rest! BUT
  - Scarce experimental information
  - C_5^A is largely dominant
  - $\rightsquigarrow$ a bit of hand-waving for $C_{3,4}^A \Rightarrow C_3^A = 0,\ C_4^A = -\frac{C_5^A}{4}$; *"Adler's model"*

Theor. model for low and intermediate energies



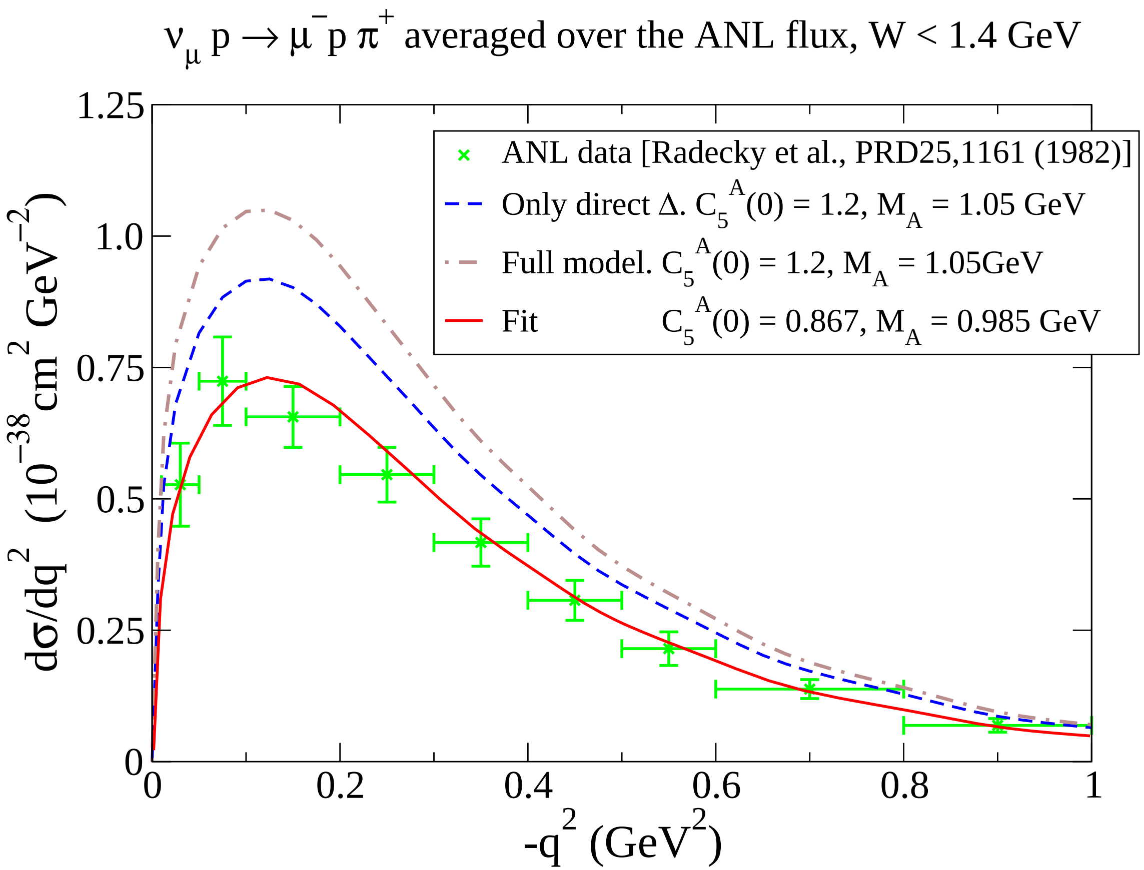
Experimental situation

- Review *From eV to EeV: Neutrino Cross Sections Across Energy Scales J.A. Formaggio, G.P. Zeller, Rev.Mod.Phys. 84 (2012) 1307*. As an example...



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

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



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

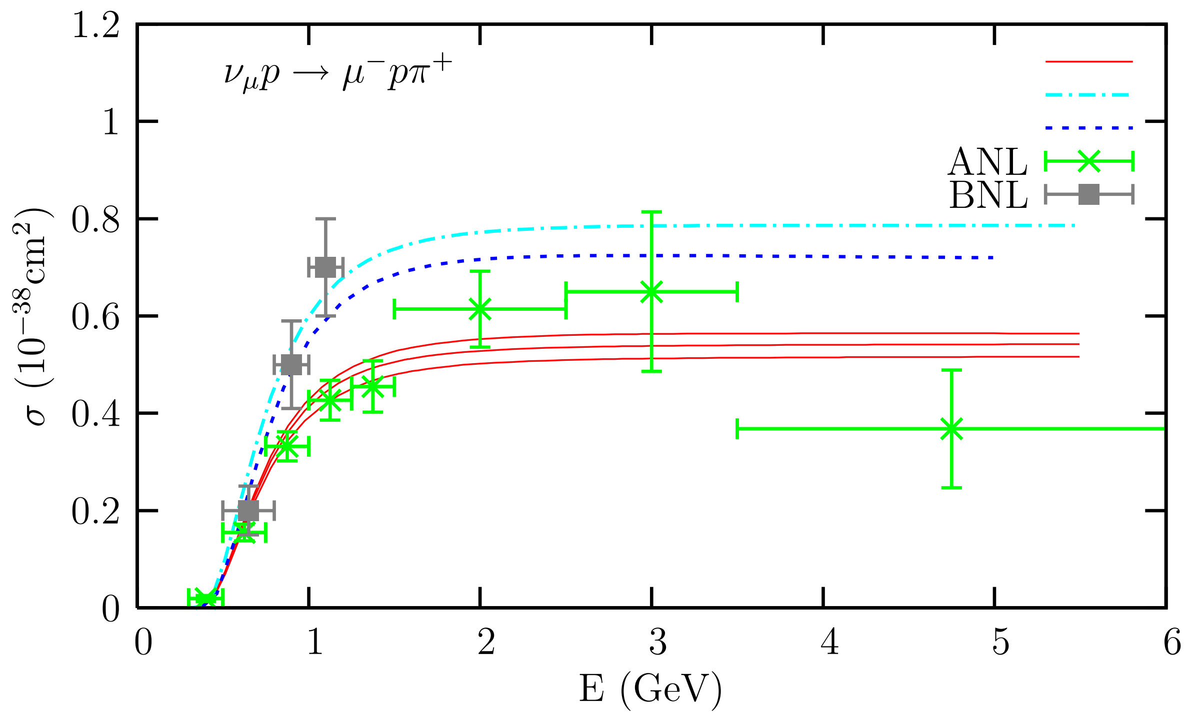
$$C_5^A(0) = 0.867 \pm 0.075$$

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

E. Hernandez et al,PRD 76, 033005(07)

- ANL data seems to prefer C_5^A values smaller than the off-diagonal GTR

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



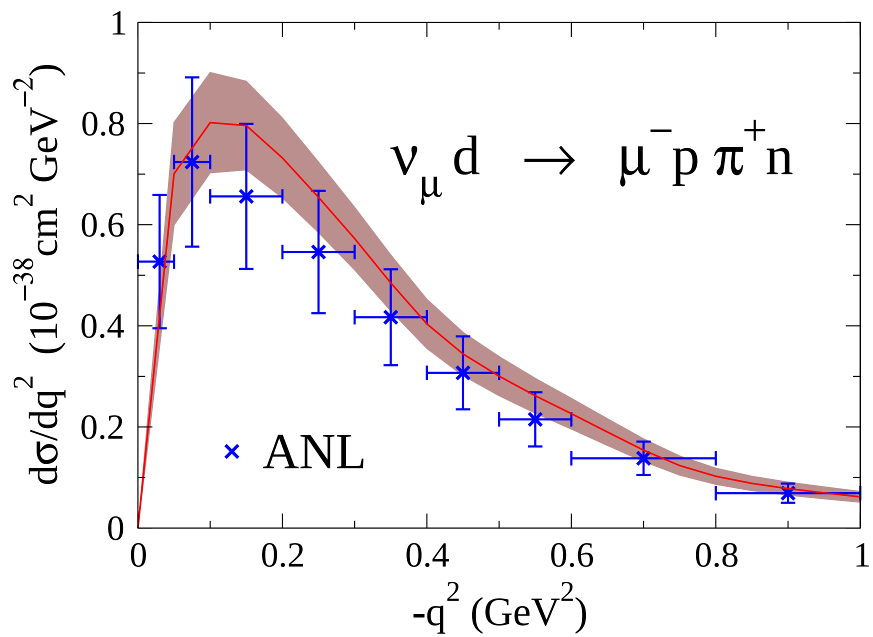
BNL data, T. Kitagaki et al., Phys. Rev. D34, 2554 (1986)

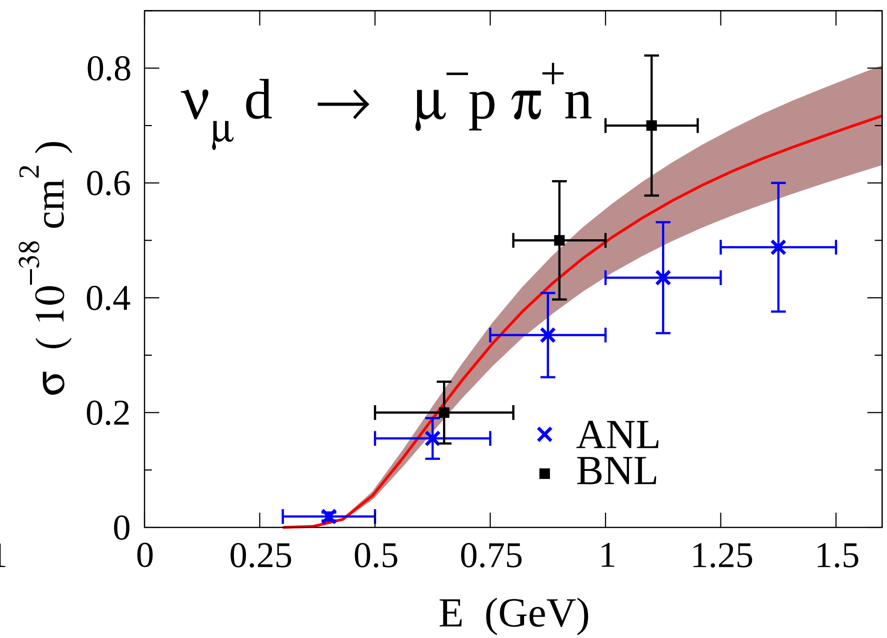
- BNL data is consistent with $C_5^A(0) = 1.2$
- Serious exp. discrepancy of almost a factor 2 in X sections!

Uncertainty will propagate to all (ν, π) predictions

$\nu_\mu p \to \mu^- p \pi^+$ reaction III-refinements

- Deuteron effects need to be considered *L. Alvarez-Ruso et al, PRC 59, 3386 (1999)*
- Uncertainties in the flux normalization, 10% for BNL and 20% for ANL require a careful statistical study
- Our best fit, using Adler's constraints, gives $C_5^A(0) = 1.00 \pm 0.11$, $M_{A\Delta} = 0.93 \pm 0.07\,\mathrm{GeV}$ **compatible with the GTR value at the 2σ level.**



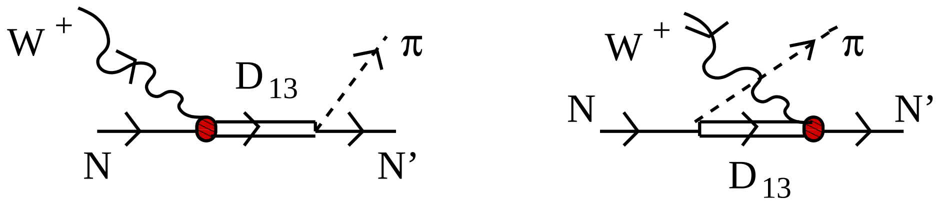


68% confidence bands from *E. Hernandez et al, PRD 81, 085046 (2010)* using a dipole form factor

See also *K.M. Graczyk et al.PRD 80, 093001 (2009)*, only Δ

Other resonances at still low energies...

The $D_{13}(1520)$ resonance (isospin 1/2, spin 3/2) appart from the Δ, gives the most important resonant contribution *T. Leitner et al., PRC 79, 034601 (2009)*



$\pi N N^*$ coupling from the $N^* \to N\pi$ width. GTR fixes $C_5^A(0) = -2.1$ for the $W^+ n \to N^{*+}$

Axial form factors from *O. Lalakulich et al, PRD74, 014009 (2006)*

$$C_3^A = C_4^A = 0, \;\; C_5^A = \frac{-2.1}{(1-q^2/M_A^2)^2}\frac{1}{1-q^2/(3M_A^2)}, \;\; C_6^A(q^2) = C_5^A(q^2)\frac{M^2}{m_\pi^2 - q^2}, \;\; M_A = 1\,\mathrm{Ge}$$

Vector form factors from *T. Leitner PhD thesis*

$\Rightarrow$ The $D_{13}(1520)$ does not affect the fit of the Δ form factors. Having $I = 1/2$, it does not contribute to the $\nu_\mu p \to \mu^- p \pi^+$ channel. Its global effect at intermediate energies is minor.

$\nu N \to l N \pi$ at low/int. energies

Sumarizing

- More or less well defined theoretical model with nucleons and Δ's
- Once constants are established, the same model can be used to predict the other charged and neutral current channels.*See the papers for results/predictions*
- Available data cannot fully constraint C_5^A and are inconsistent. *This uncertainty will propagate to all predictions*
- Lack of more differential cross sections implies $C_{3,4}^A$ are unknown *(Don't worry too much, their effect on X sections is minor)*

  To improve the quality of the theoretical descriptions new data on the axial $N\Delta$ transition

  in Hydrogen or Deuterium –either from ν or from e Parity Violating scattering– are required.

- Higher energies imply further resonances –baryons and mesons– and further uncertainties. *RS like stuff?, GiGo's theorem?, other?... 5%? Lasciate ogni speranza, voi ch'entrate.*

Hyperons? Watson's theorem? Lattice?

Remember that we are concerned about 5% effects!

- Who cares about hyperons at low energies? *below associated production threshold*

  $\bar{\nu}N \to l + Y$ followed by $Y \to N + \pi$: Two weak processes

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...Are they important? We'll come back to this.

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  ...Are they important? We'll come back to this.

- Watson's theorem is relevant for π photo-production. Could it play a role here? *Ask E. Hernandez!*

Hyperons? Watson's theorem? Lattice?

Remember that we are concerned about 5% effects!

- Who cares about hyperons at low energies? *below associated production threshold*

  $\bar{\nu} N \to l + Y$ followed by $Y \to N + \pi$: Two weak processes

  Nobody has paid much attention to them in the context of neutrino pion production because

  - ΔS don't appear with electrons and/or photons (mind's inertia)
  - Cabibbo suppressed –small Xsections–
  - Only for antineutrinos

  ...Are they important? We'll come back to this.

- Watson's theorem is relevant for π photo-production. Could it play a role here? *Ask E. Hernandez!*

- Lattice could provide the missing FF, but not as yet...

π production on nuclei

I must be cruel, only to be kind: Thus bad begins and worse remains behind.

Weak interaction is weak $\Rightarrow$ The inclusive cross section is very approximately the sum over the single nucleons cross sections.

However, for exclusive processes the situation is far more complex as you have seen for instance in QE scattering.

The main problem is that the Strong interaction is strong $\Rightarrow$ multi- step and many body mechanisms are pervasive.

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In our case we'll have

- Incoherent π production. The W or Z-boson collides with a single nucleon. Still the nucleon is bound, off-shell, moving,... and we must consider:
  - Fermi motion, Pauli blocking
  - Medium modifications of the elementary mechanisms due to the presence of other nucleons
  - π final state interactions: The pion has a short mean free path in the nuclei. Its charge can change, it can be absorbed, deflected, stopped,.... It could even produce more pions.

π production on nuclei

- Incoherent π production.
  - Fermi motion, Pauli blocking
  - Medium modifications of the elementary mechanisms
  - π final state interactions.

The W or Z-boson could also *see* the nucleus as a whole and scatter leaving it on the same state:

- Coherent π production

  Both processes are fully reliant on the π production on single nucleons.

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- Are there other mechanisms for π production? *–Many!* To name a few:
  - Two π production followed by absorption of one of the π's
  - π production by one of the scattered nucleons after a QE process
  - Meson exchange currents MEC: The neutrino could interact with some of the virtual mesons exchanged by the nucleons
  - Hyperons, Kaons, $2p2h$,...

Incoherent π production in nuclei.

We follow loosely E.Hernandez et al, PRD87 (2013) 11

Starting point is the differential cross section at the nucleon level. For instance for CC processes we have

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

with

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

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

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

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

Incoherent π production in nuclei.

We assume the nucleus can be described by its density. The cross section at the nucleus level for initial pion production (prior to any FSI) is then

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

To compare with experiment, we must still fold it with the neutrino flux $\Phi(|\vec{k}|)$

What else is left to do?

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

Incoherent π production in nuclei. Medium corrections

Δ mechanisms are dominant and the Δ properties are strongly modified in the nuclear medium. Its imaginary part is modified due to

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

This modifies the Δ propagator

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

and

$$\frac{\Gamma_\Delta}{2} \rightarrow \frac{\Gamma_\Delta^{\text{Pauli}}}{2} - \text{Im}\,\Sigma_\Delta$$

while keeping M_Δ in the particle propagator unchanged.

Incoherent π production in nuclei. Medium corrections

Following *E. Oset et al,NPA 468, 631 (1987)*

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

- The C_Q term accounts for changes in the π propagation.
- The C_{A2} term comes from Δ absorption by one nucleon $\Delta N \to NN$.
- The C_{A3} term accounts for the Δ absorption by two nucleons $\Delta NN \to NNN$.

Δ *becomes wider in nuclei* $\Rightarrow$ All these pieces quench the cross section!

Not only the Δ propagator is modified, but we have a new contribution to π production, related to the C_Q piece $\Rightarrow$ leads to small enhancement!

Altogether, one would predict a sizeable reduction of the *per nucleon* cross section

Incoherent π production in nuclei. Final state interaction

Once the pions are produced, they still have to get out of the nucleus $\Rightarrow$ Cascade...

Widely used, (e.g. *NEUT*) model from *L.L. Salcedo et al.,NPA484, 557 (1988)*

- π absorption.
- π quasielastic scattering on a nucleon.
  - Pions change energy and direction.
  - Pions could change charge.
  - etc...

Additional reduction of the *per nucleon* cross section

Coherent π production

$$\nu + A \rightarrow l + \pi + A$$

From *Neutrino Induced Coherent Pion Production off Nuclei and PCAC, E. Hernandez et al, PRD80(2009)013003*

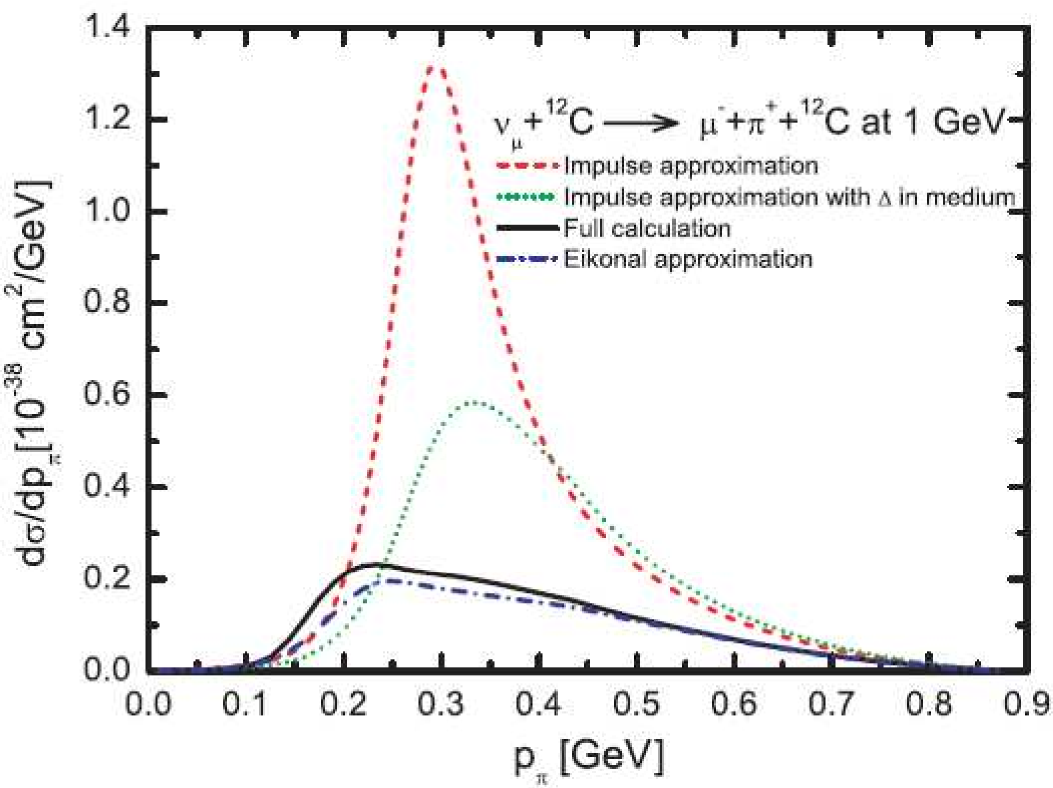
...theoretical modelling of neutrino-induced coherent pion production in nuclei in the low ($<$ 1 GeV) energy region is a quite complicated task. The reasons are twofold. First, our limited knowledge of the weak pion production on nucleons at these energies, that relies upon conflicting and low statistics bubble chamber experimental data. Second, the need of a quantum mechanical treatment of the multiple scattering involving the strong interaction of pions and nucleons that can hardly be accommodated in typical MonteCarlo approaches. Many different models have been proposed. Some of them are based on the assumption that coherent pion production is dominated by the divergence of the axial current and the use of the Partial Conservation of the Axial Current (PCAC) hypothesis. Other works develop a microscopical model for both pion production and distortion assuming that the pion nuclear interaction is dominated by the Δ(1232) resonance. Thus, they can only be applied at relatively low neutrino energies.

- RS models for coherent π's are great at high energies! Still with the common limitations from our knowledge of the π nucleus scattering
- RS doesn't work at low/intermediate energies. Why? –Read the paper..
- See status update in: *Progress and open questions in the physics of neutrino cross sections L. Alvarez-Ruso et al., arXiv:1403.2673*

Coherent π production

In microscopical models:

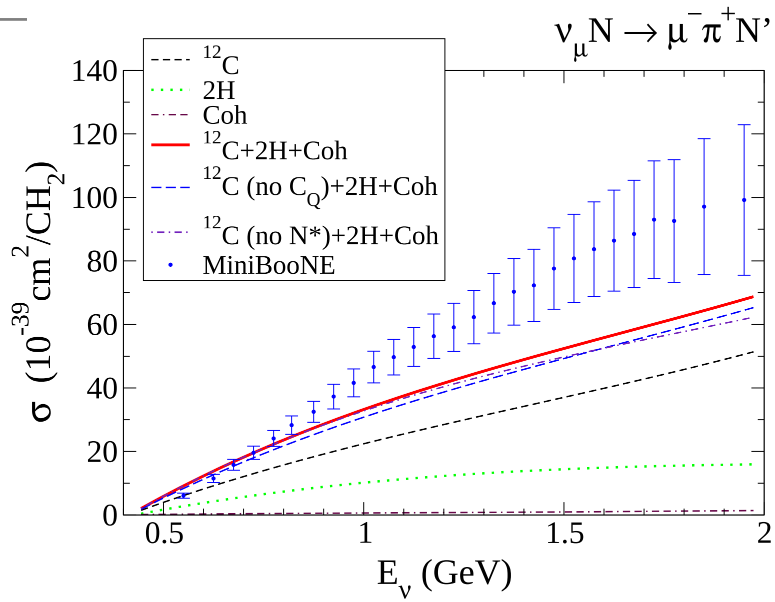
- Coherent sum of the scattering amplitudes over the nucleons. They could interfere constructively: *Not amenable to cascades!*
- Apart from the knowledge of the production on single nucleons one needs a good QM description of the π multiple scattering in the medium $\Rightarrow$ Optical potential to solve the Klein Gordon equation.
- Special sensitivity to C_5^A!

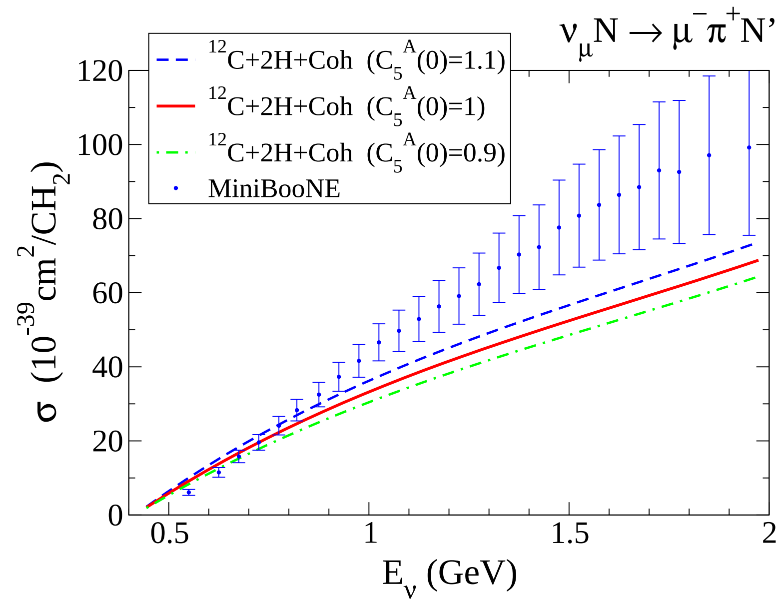


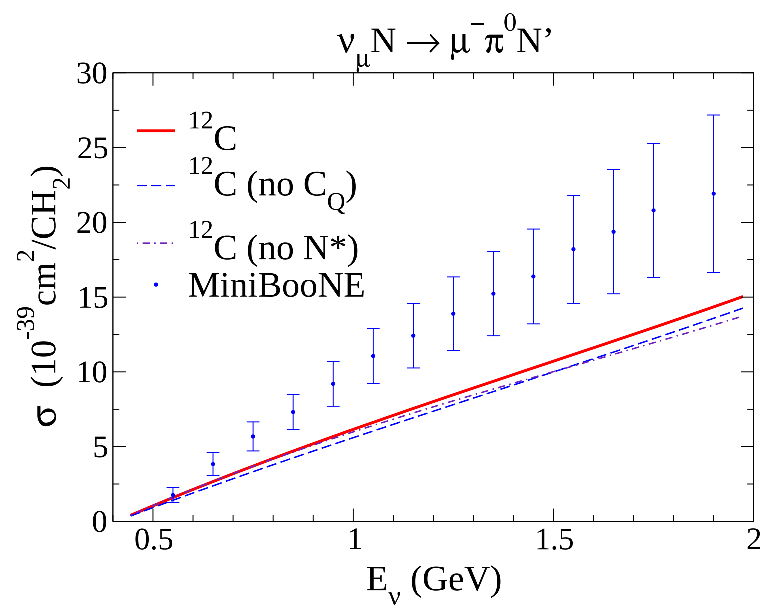
It's rather small!

L. Alvarez-Ruso et al, PRC80, 019906

π production in nuclei. CC Results

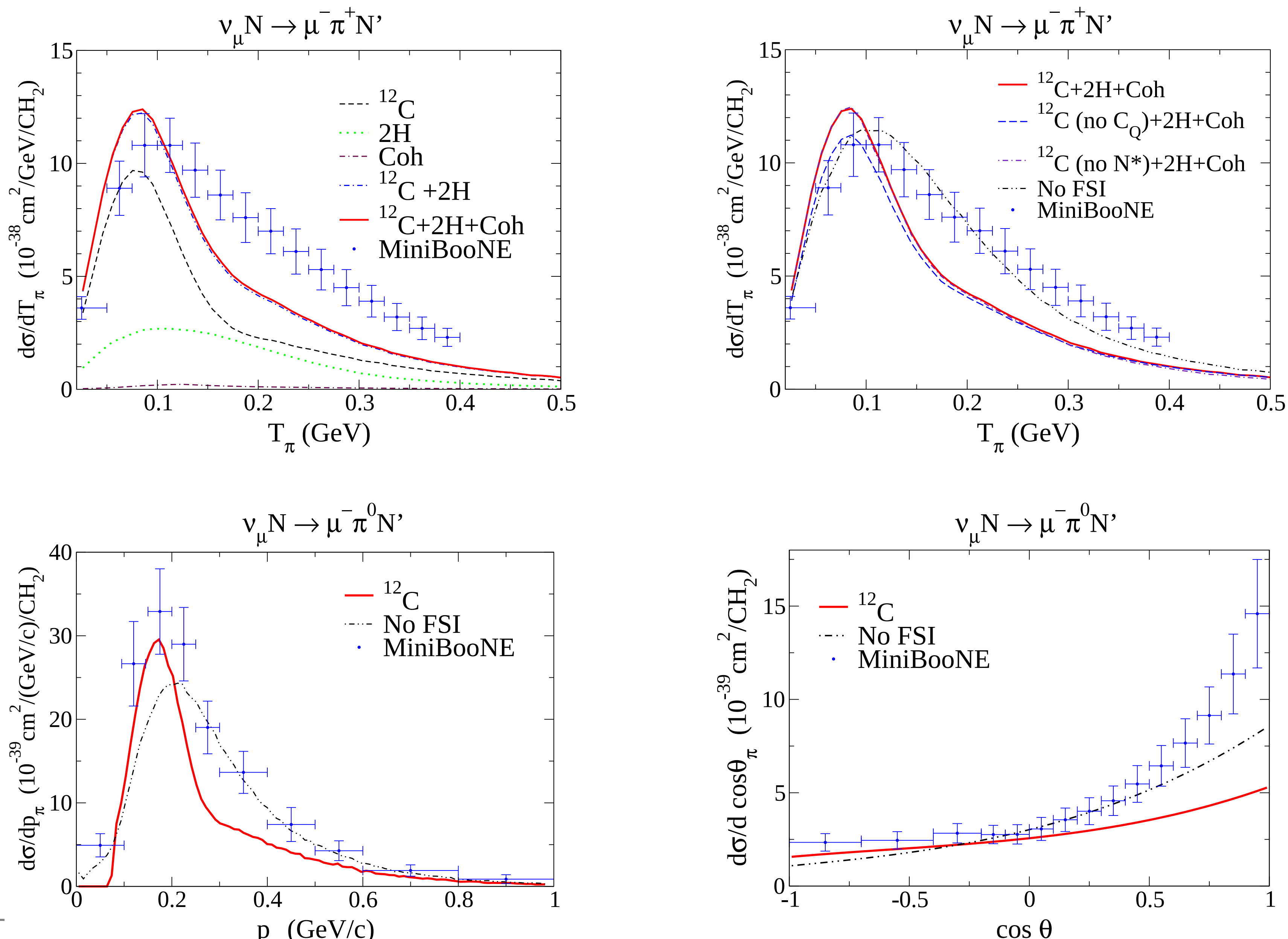




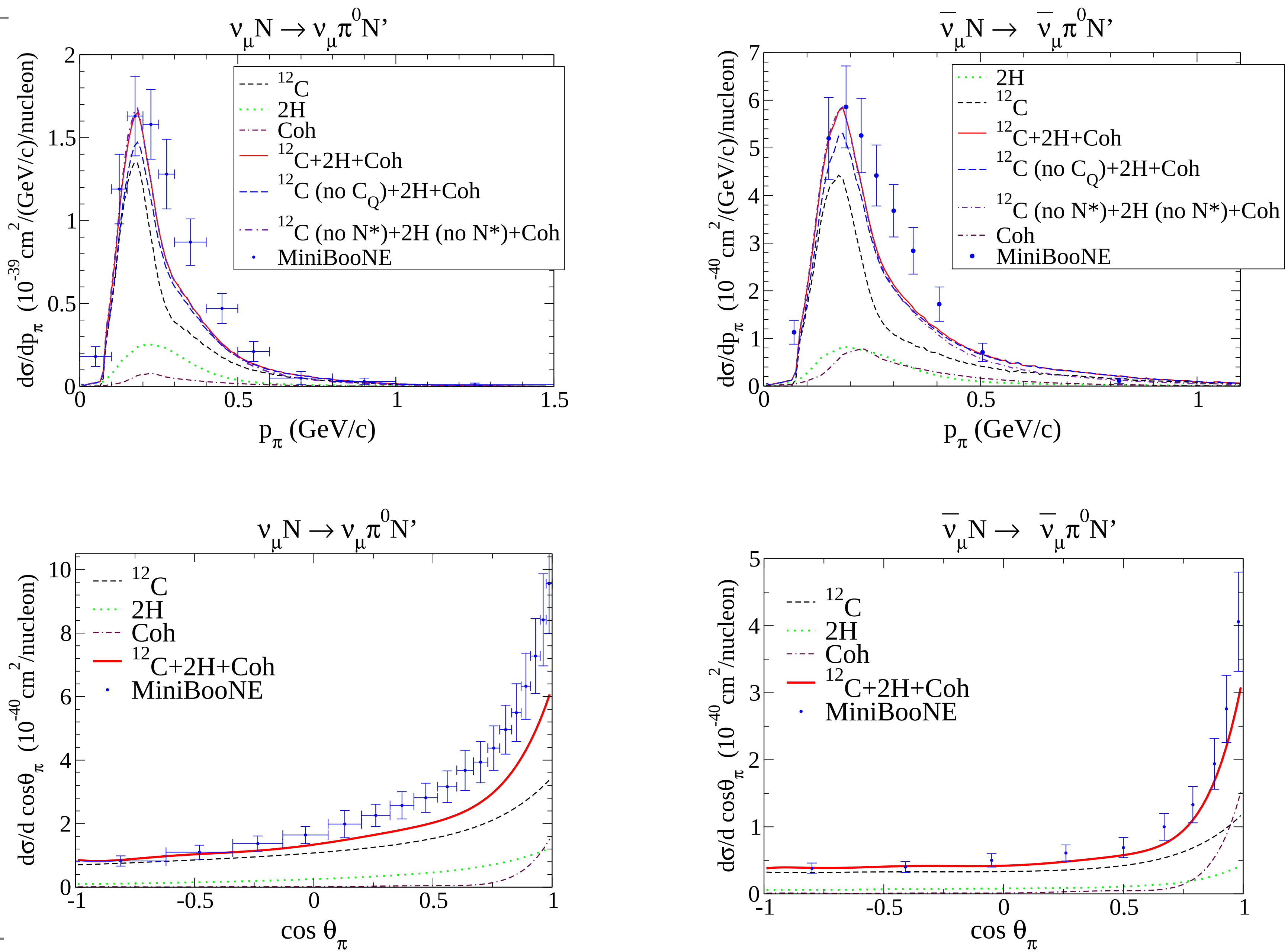


Data MiniBooNE Coll., PRD83, 052007 and 052009 (2011)

π production in nuclei. CC Results



π production in nuclei. NC Results



Data MiniBooNE Coll., PRD81, 013005 (2011)

π production in nuclei

- Results show a deficit of high energy forward pions when compared to experiment. This was to be expected. MB cross section per nucleon is larger or similar to the free Xsection and Nuclear effects (like strong π absorption) should reduce it!
- MiniBooNE data seems to prefer $C_5^A(0)$ values close to the PCAC prediction (≈ 1.2) and agrees better with BNL
- It's not just an scaling factor (high energy, forward,...) $\Rightarrow$ This suggests missing mechanisms like
  - Two π production followed by absorption of one of the π's
  - π production by one of the scattered nucleons after a QE process
  - Meson exchange currents MEC: The neutrino could interact with some of the virtual mesons exchanged by the nucleons
  - Hyperons, Kaons, $2p2h$,...

Room for Improvement?

- Is there any need for a better theoretical description?

  May be the quality of the best models is already good enough for the exp. analysis – Of course with some caveats:

  - always forgetting RS for coherent π's at low/intermediate energies,
  - At higher energies one could use RS model or other with resonances for incoherent π's, but please update FF, BR's, etc.

- If yes, then we need further good quality cross sections data, better in H o D

  These data (on nucleons) are needed to better determine the axial form factors. Lacking them severely limits the precision of any theoretical prediction for nuclei.

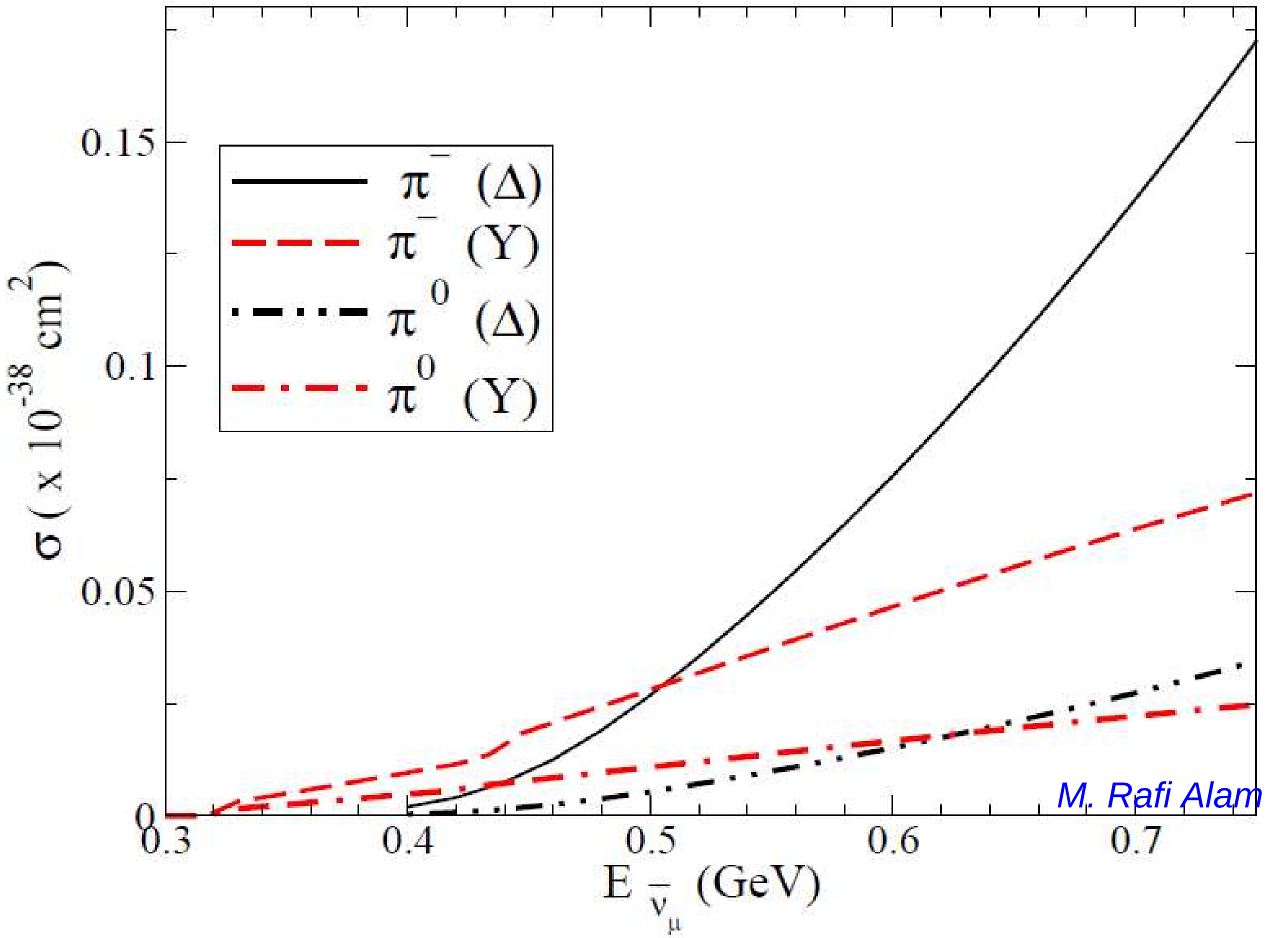
  Of course, there are several ways to improve the theoretical models but nobody will attempt to do it without the pressure of better data

Summary /Landscape

- There are reliable/precise Th. models for $\nu + nucleon \rightarrow l + \pi + nucleon$ at π energies below 0.5 GeV.
- They still need some further exp. info to get precise values for the Δ Form Factors. Lattice could provide them before!
- At the nucleus level, models are a bit more primitive/uncertain because
  - A large number of medium effects, all of them with their associated uncertainty
    - Bound nucleons: Off-shell, Long range correlations (RPA),...
    - π propagation inside the nucleus
      - absorption, CX, elastic+quasielastic scattering
      - Quantum effects: Should really cascades work at these low energies?
  - There are new nuclear mechanisms not yet or little explored and not so easy to implement in the Montecarlos – Lack of theoretical models and more...
    - multipion prod. followed by absorption (*Difficult!*)
    - Meson exchange currents &/or $2p2h$ (*Really difficult!*)
  - Some mechanisms (resonances, hyperons,...) could be strongly modified/enhanced/quenched by the medium

BU: Hyperons

^{12}C

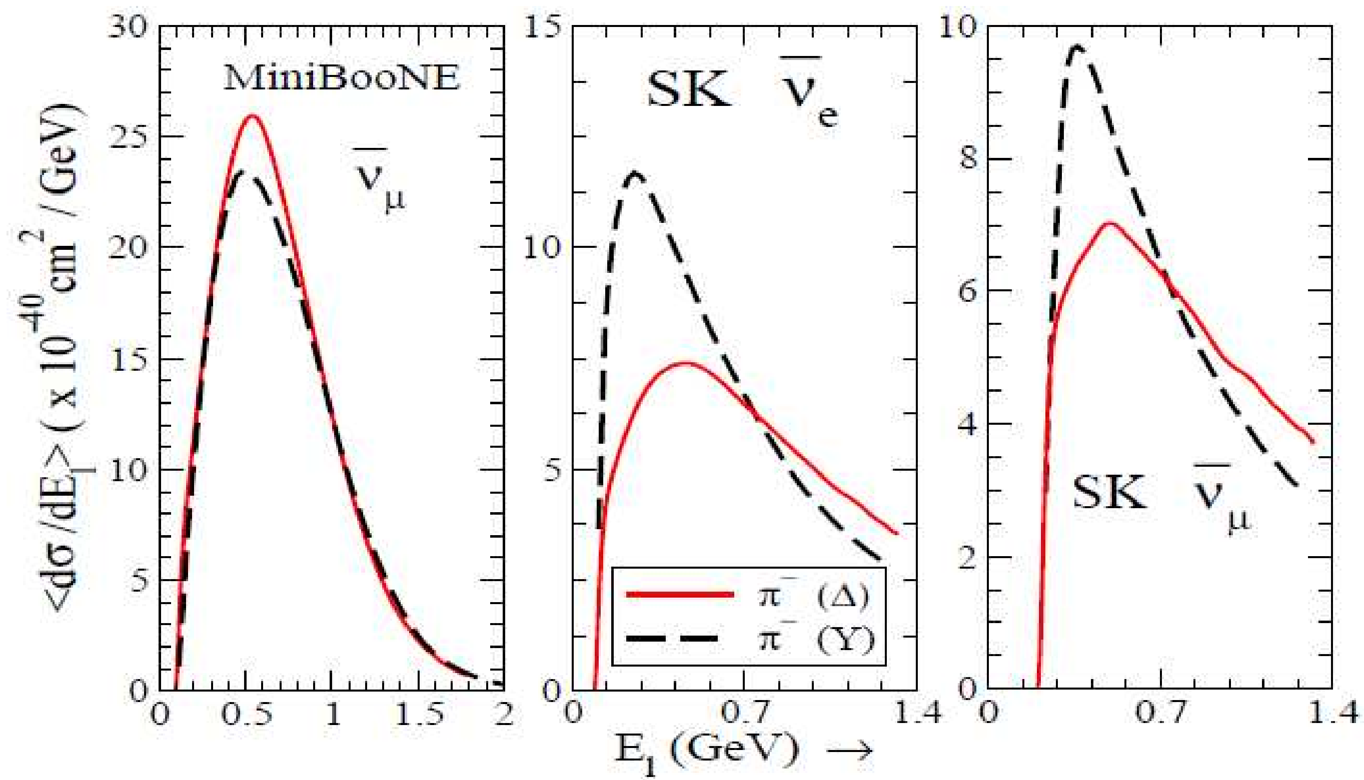


M. Rafi Alam et al, PRD88 (2013) 077301

$\bar{\nu}N \rightarrow l + Y$ followed by $Y \rightarrow N + \pi$: Two weak processes

- Cabibbo suppressed –small Xsections– but....

BU: Hyperons



^{16}O

Hyperon's scaled $\times 2.5$

- Why are they relatively more important in nuclei?

Their π's are not absorbed! The hyperons decay when already out of the nucleus!