Neutrino-induced one-pion production revisited: The $\nu_\mu n \to \mu^- n \pi^+$ channel

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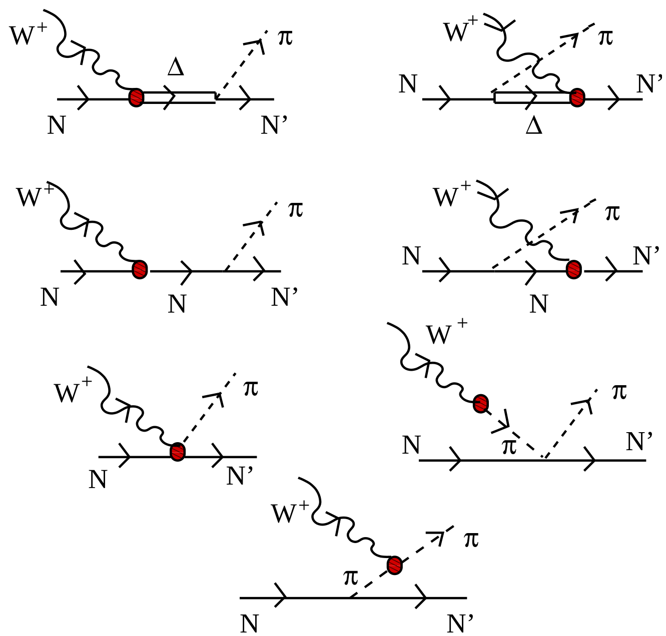
E. H., J. Nieves, Phys. Rev. D 95, 053007 (2017)

Outline of the talk

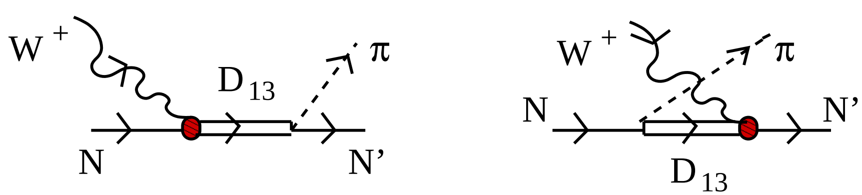
- A brief reminder of our model for pion production at the nucleon level
- The problem in the $\nu_\mu n \to \mu^- n \pi^+$ channel and its possible origin
- Modified model
- Results and conclusions

One pion production model I



E.H., J. Nieves and M. Valverde, Phys. Rev. D76, 033005 (2007)

Later we included the $D_{13}(1520)$ resonance [E.H., J. Nieves and M.J. Vicente-Vacas, Phys. Rev. D 87, 113009 (2013)]



One pion production model II

Partial unitarization. Implementation of Watson theorem

[L. Alvarez-Ruso, E.H., J. Nieves and M.J. Vicente Vacas, Phys. Rev. D 93, 014016 (2016)]

Watson theorem is a consequence of unitarity and time reversal invariance and it states that the phase of the weak (or electromagnetic) pion production amplitude should be equal to the phase of the strong $\pi N \to \pi N$ amplitude

Following M. G. Olsson [Nuc. Phys. B78, 55 (1974)], we modified

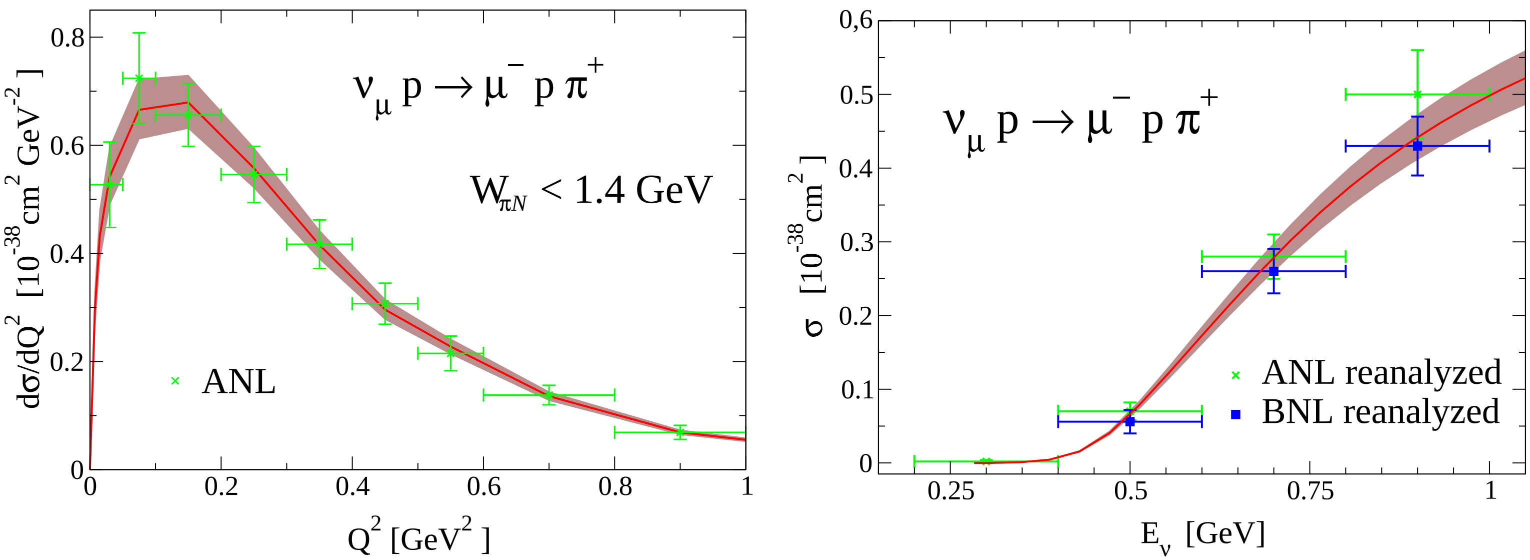
$$T_B + T_\Delta \to T_B + e^{i\psi(q^2, W^2_{\pi N})}\, T_\Delta$$

so that the dominant multipoles for the $J = 3/2$, $I = 3/2$ and $L = 1$ channel had the right $\delta_{P_{33}}$ phase. Two independent ψ phases were considered for the vector and axial parts of the transition amplitude.

A result of this procedure is that the value of the axial nucleon-to-delta form factor $C_5^A(0) = 1.14 \pm 0.07$ that we obtained from the fit to data was in better agreement with the off-diagonal Goldberger-Treiman prediction of $C_5^A(0) = \sqrt{\frac{2}{3}}\frac{f_\pi}{m_\pi}\, f^* \approx 1.15 - 1.20$.

Fitted data

The results were evaluated taking into account deuteron effects as disccussed in E. H., J. Nieves, M. Valverde and M.J. Vicente-Vacas, Phys. Rev. D81, 085046 (2010)

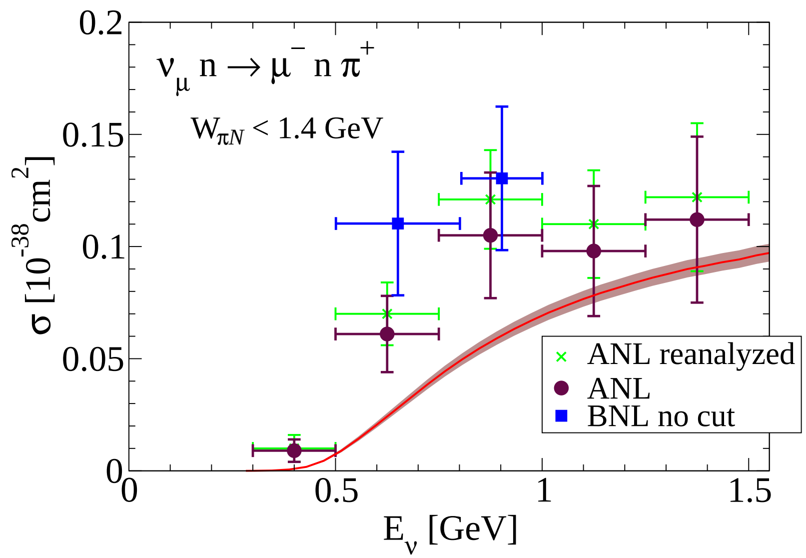


ANL data taken from G. Radecky et *al.*, Phys. Rev. D 25, 1161 (1982).
ANL and BNL reanalyzed data taken from C. Wilkinson, P. Rodrigues, S. Cartwright, L. Thompson and K. McFarland, Phys. Rev. D 90, 112017 (2014).

$C_5^A(q^2) = C_5^A(0)/(1 - q^2/M_{A\Delta}^2)^2,$ $\qquad C_6^A(q^2) = C_5^A(q^2)\frac{M^2}{m_\pi^2 - q^2}$

Adler's constraints: $C_3^A(q^2) = 0, C_4^A(q^2) = -C_5^A(q^2)/4$

The $\nu_\mu n \to \mu^- n \pi^+$ channel

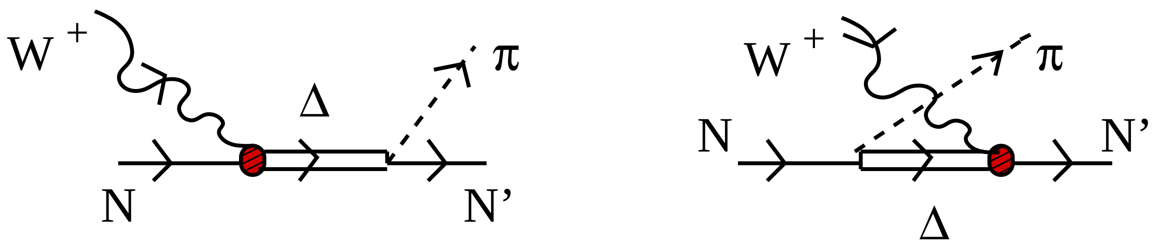


BNL data taken from T. Kitagaki *et al.*, Phys. Rev. D 34, 2554 (1986).
ANL reanalyzed data taken from P. Rodrigues, C. Wilkinson and K. McFarland, Eur. Phys. J. C 76, 474 (2016).

This underprediction of experimental data is a common problem to other models.

The $\nu_\mu n \to \mu^- n \pi^+$ channel and the spin 1/2 components in the Δ propagator

As shown in E.H., J. Nieves and M. Valverde, Phys. Rev. D76, 033005 (2007) the $\nu_\mu n \to \mu^- n \pi^+$ channel gets a large contribution from the crossed Delta term



being very sensitive to the spin 1/2 components in the Δ propagator.

In the zero width limit, the Δ propagator is given by

$$G_{\mu\nu}(p_\Delta) = \frac{P_{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2 + i\epsilon}$$

with

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

Spin 1/2 components in the Δ propagator I

$$P_{\mu\nu}(p) = P^{\frac{3}{2}}_{\mu\nu}(p) + \underbrace{(p^2 - M_\Delta^2)\left[\frac{2}{3M_\Delta^2}(\not p + M_\Delta)\frac{p_\mu p_\nu}{p^2} - \frac{1}{3M_\Delta}\left(\frac{p^\rho p_\nu \gamma_{\mu\rho}}{p^2} + \frac{p^\rho p_\mu \gamma_{\rho\nu}}{p^2}\right)\right]}_{\mathrm{spin}-1/2},$$

with

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

$P^{\frac{3}{2}}_{\mu\nu}(p)$ satisfies the relations

$$0 = [\not p, P^{\frac{3}{2}}_{\mu\nu}(p)] = p^\mu P^{\frac{3}{2}}_{\mu\nu}(p) = P^{\frac{3}{2}}_{\mu\nu}(p)p^\nu = \gamma^\mu P^{\frac{3}{2}}_{\mu\nu}(p) = P^{\frac{3}{2}}_{\mu\nu}(p)\gamma^\nu,$$
$$P^{\frac{3}{2}}_{\mu\nu}(p)[P^{\frac{3}{2}}(p)]^{\nu\rho} = -(\not p + M_\Delta)[P^{\frac{3}{2}}(p)]^\rho_\mu$$

being the true spin-3/2 projection operator

Spin 1/2 components in the Δ propagator II

$$\underbrace{(p^2 - M_\Delta^2)\left[\frac{2}{3M_\Delta^2}(\not p + M_\Delta)\frac{p_\mu p_\nu}{p^2} - \frac{1}{3M_\Delta}\left(\frac{p^\rho p_\nu \gamma_{\mu\rho}}{p^2} + \frac{p^\rho p_\mu \gamma_{\rho\nu}}{p^2}\right)\right]}_{\mathrm{spin}-1/2}$$

Due to the $(p^2 - M_\Delta^2)$ factor that cancels the corresponding factor in the propagator denominator, the spin-1/2 component do not propagate giving rise to contact interactions.

Besides, its contribution is small for the direct-Δ term while it is large for the crossed-Δ term.

For some authors [See for instance V. Pascalutsa, Phys. Lett. B 503, 85 (2001)] the use of this spin-1/2 part should be avoided.

One way of achieving this goal is by the use of “consistent couplings”

Consisent Δ couplings

Consistent couplings are the ones that respect the gauge symmetry

$$\Psi_\mu \rightarrow \Psi_\mu + \partial_\mu \epsilon$$

present in the free-massless Rarita-Schwinger lagrangian. This symmetry requires that in any linear interaction term the Δ field couples only to conserved currents

$$\mathcal{L}_{\rm int} = g\bar{\Psi}_\beta J^\beta + H.c., \qquad\qquad \partial_\beta J^\beta = 0.$$

Couplings not respecting that symmetry are called inconsistent.

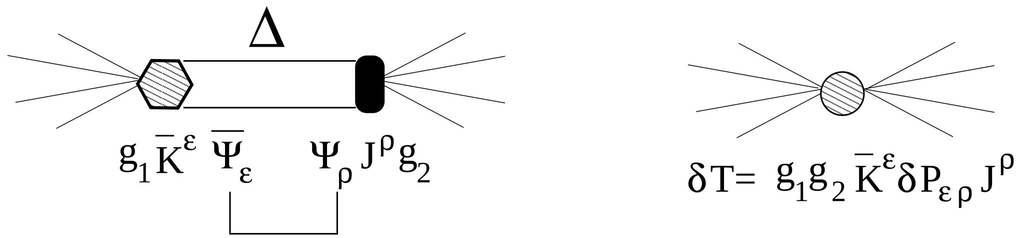
As shown in V. Pascalutsa, Phys. Lett. B 503, 85 (2001), inconsistent couplings can be transformed into consistent ones by a redefinition of the Δ field resulting in a new consistent interaction lagrangian

$$\mathcal{L}'_{\rm int} = g\,\bar{\Psi}_\beta \mathcal{J}^\beta + H.c.,$$

plus an additional contact interaction lagrangian. Both theories give the same predictions for physical observables.

Consistent versus inconsistent Δ couplings

Let us have a look at a process mediated by an intermediate Δ



$$T = g_1 g_2 \bar{K}^\epsilon \frac{P_{\epsilon\rho}}{p_\Delta^2 - M_\Delta^2} J^\rho,$$

$$T_{consistent} = g_1 g_2\, \bar{\mathcal{K}}^\epsilon \frac{P_{\epsilon\rho}}{p_\Delta^2 - M_\Delta^2} \mathcal{J}^\rho = g_1 g_2 \bar{K}^\epsilon \frac{p_\Delta^2}{M_\Delta^2} \frac{P_{\epsilon\rho}^{\frac{3}{2}}}{p_\Delta^2 - M_\Delta^2} J^\rho.$$

Then, one has $T = T_{consistent} + \delta T$ with $\delta T = g_1 g_2 \bar{K}^\epsilon \frac{P_{\epsilon\rho} - \frac{P_\Delta^2}{M_\Delta^2} P_{\epsilon\rho}^{\frac{3}{2}}}{p_\Delta^2 - M_\Delta^2} J^\rho$. Since,

$$\begin{aligned} P_{\epsilon\rho} - \frac{P_\Delta^2}{M_\Delta^2} P_{\epsilon\rho}^{\frac{3}{2}} &= (p_\Delta^2 - M_\Delta^2)\, \delta P_{\epsilon\rho}, \\ \delta P_{\epsilon\rho} &= \frac{1}{M_\Delta^2} (\not{p}_\Delta + M_\Delta) \left(g_{\epsilon\rho} - \frac{1}{3} \gamma_\epsilon \gamma_\rho \right) + \frac{1}{3M_\Delta^2} \left(p_{\Delta\,\epsilon} \gamma_\rho - p_{\Delta\,\rho} \gamma_\epsilon \right) \end{aligned}$$

the δT contributions amount to a contact (nonpropagating) interaction.

Modification of our model

The moral behind the above discussion is that, as far as all relevant contact interactions are taken into account, descriptions using consistent or inconsistent couplings are equivalent.

Is is only the coupling constants of the contact terms that differ. Those constants have to be fitted to experimental data.

Aiming at improving the description of the $\nu_\mu n \to \mu^- n \pi^+$ channel we supplement the model with additional contact terms by modifying

$$\frac{P_{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2 + i\epsilon} \quad \to \quad \frac{P_{\mu\nu}(p_\Delta) + c\left(P_{\mu\nu}(p_\Delta) - \frac{p_\Delta^2}{M_\Delta^2} P^{\frac{3}{2}}_{\mu\nu}(p_\Delta)\right)}{p_\Delta^2 - M_\Delta^2 + i\epsilon} = \frac{P_{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2 + i\epsilon} + c\,\delta P_{\mu\nu}(p_\Delta)$$

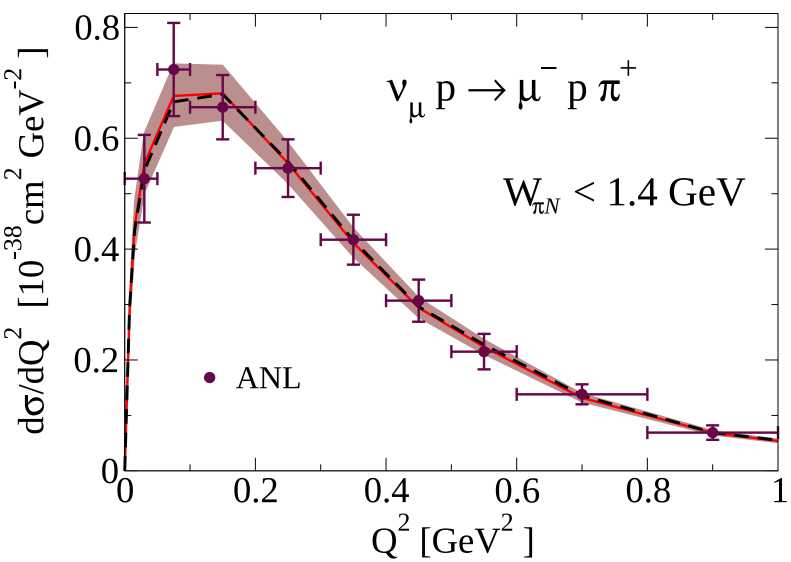
$$\to \quad \frac{P_{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta} + c\,\delta P_{\mu\nu}(p_\Delta)$$

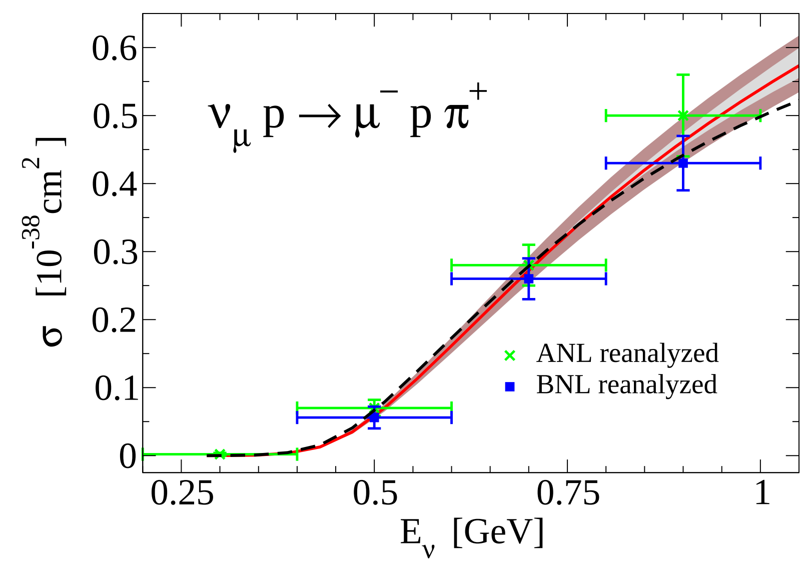
$$= \quad \frac{p_\Delta^2}{M_\Delta^2}\frac{P^{\frac{3}{2}}_{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta} + \frac{(1+c)(p_\Delta^2 - M_\Delta^2) + icM_\Delta\Gamma_\Delta}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta}\,\delta P_{\mu\nu}(p_\Delta)$$

Due to the presence of Γ_Δ, a value of $c = -1$ does not corresponds exactly to the use of a consistent $\pi N \Delta$ coupling.

Fitted data and results for the parameters in the modified model

Cross sections evaluated in deuterium



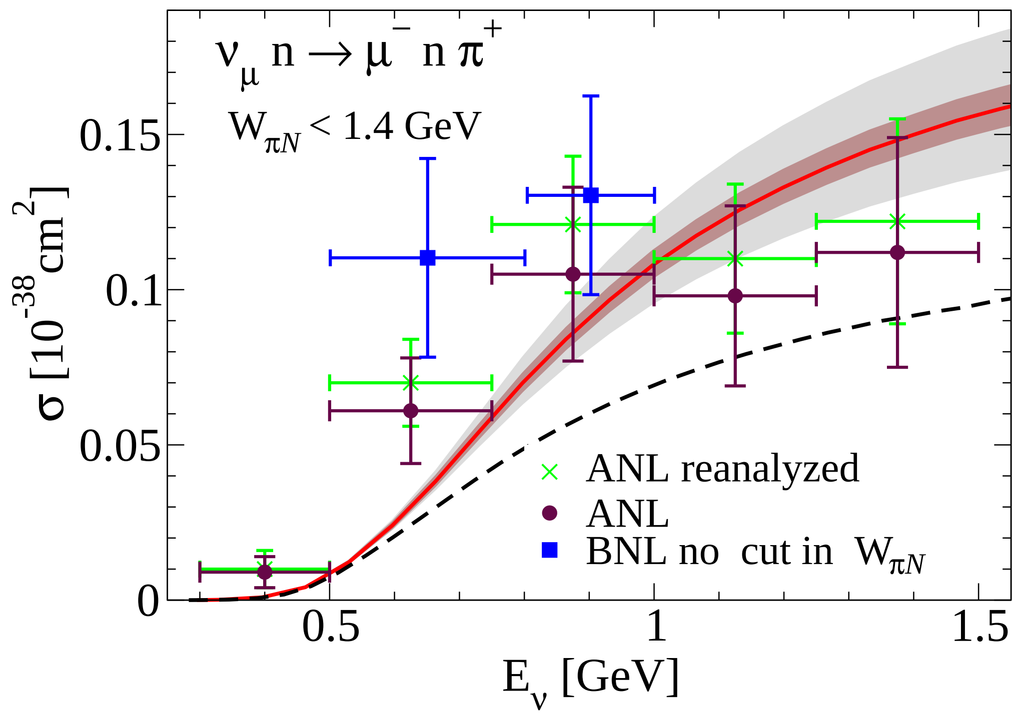


$$C_5^A(q^2) = \underbrace{C_5^A(0)/(1-q^2/M_{A\Delta}^2)^2}_{C_5^A(0)=1.18\pm0.07,\ M_{A\Delta}=950\pm60\,\mathrm{MeV}}$$

$$c = -1.11 \pm 0.21,\ \beta = 1.23 \pm 0.08$$

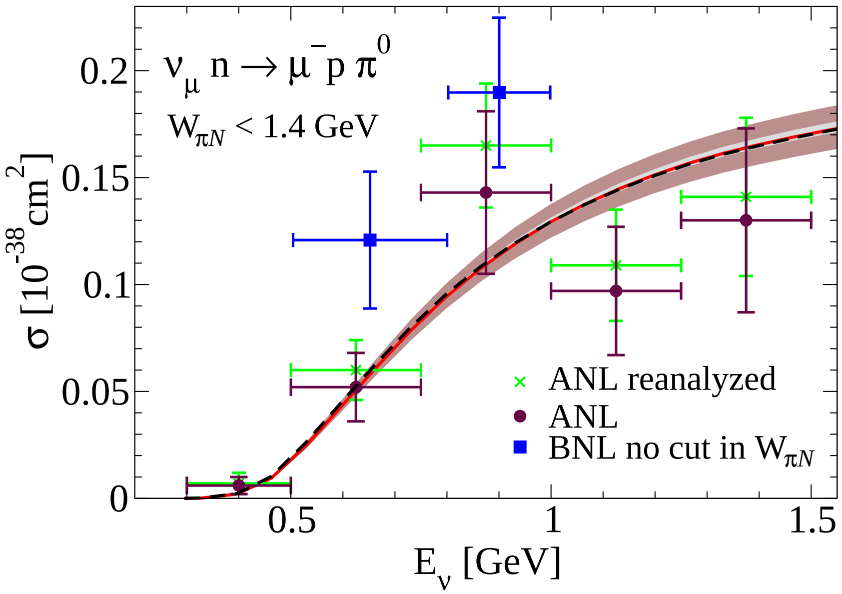
Fitted data and results for the parameters in the modified model II

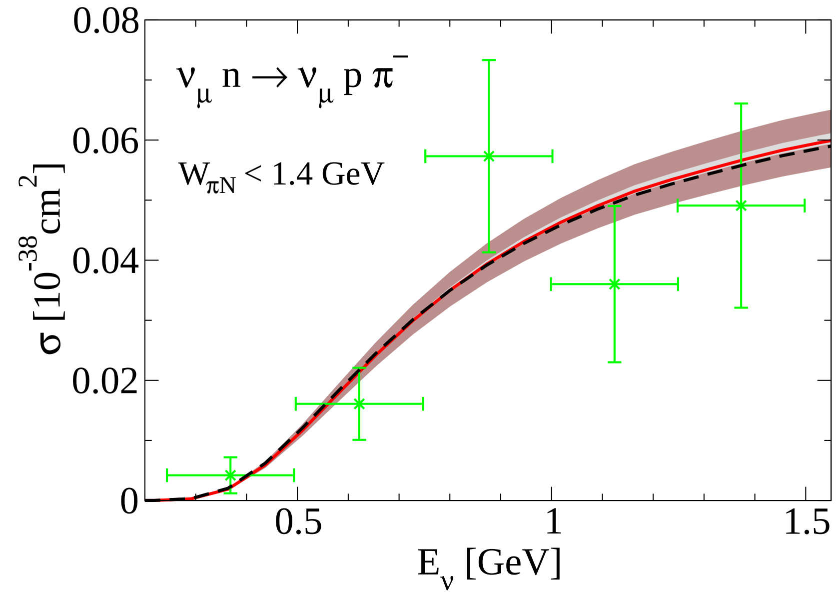
Cross sections evaluated in deuterium



For the total cross sections we had only used reanalyzed data.

Modified model: Results in other channels

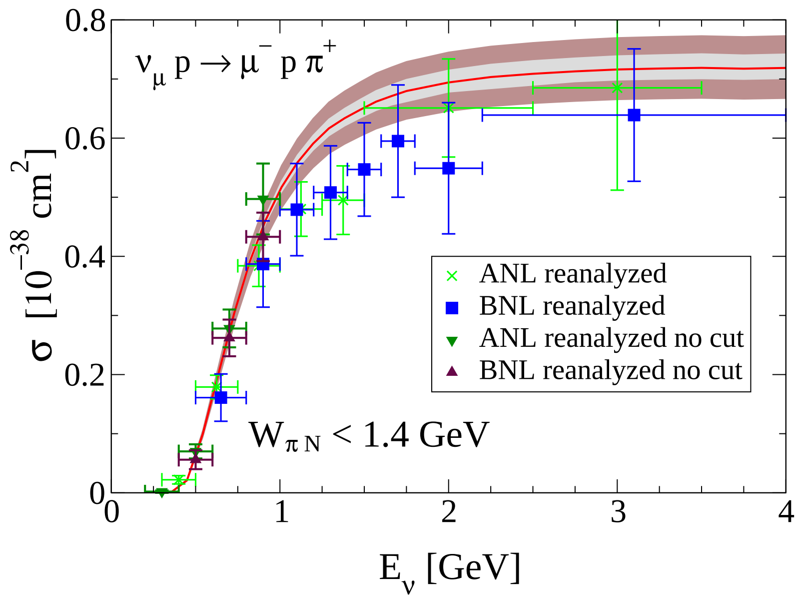




Experimental data in the right panel taken from M. Derrick *et al.*, Phys. Lett. 92B, 363 (1980); 95B, 461(E) (1980).

Another good feature of the present model is that the ψ_V and ψ_A Olsson phases are smaller than in the previous fit. This means the present model without the phases is closer to satisfying watson theorem than the previous one.

The $\nu_\mu p \to \mu^- p \pi^+$ at higher energies for $W_{\pi N} < 1.4$ GeV

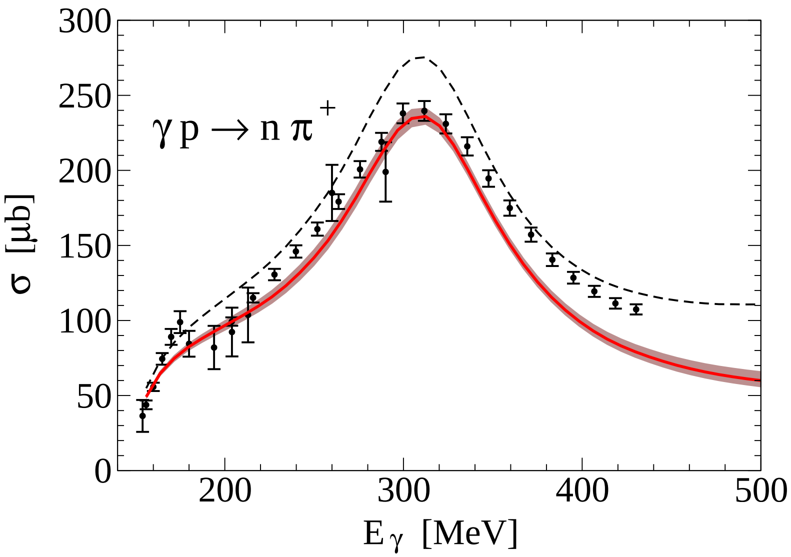


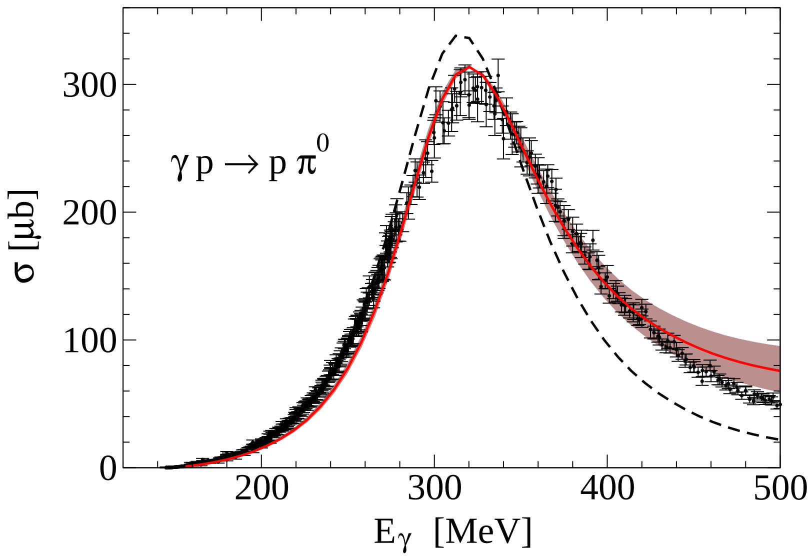
The discrepancies at higher neutrino energies in this and the other channels can be corrected by the use of form factors (see R. González-Jiménez *et al.*, arXiv:1612.05511).

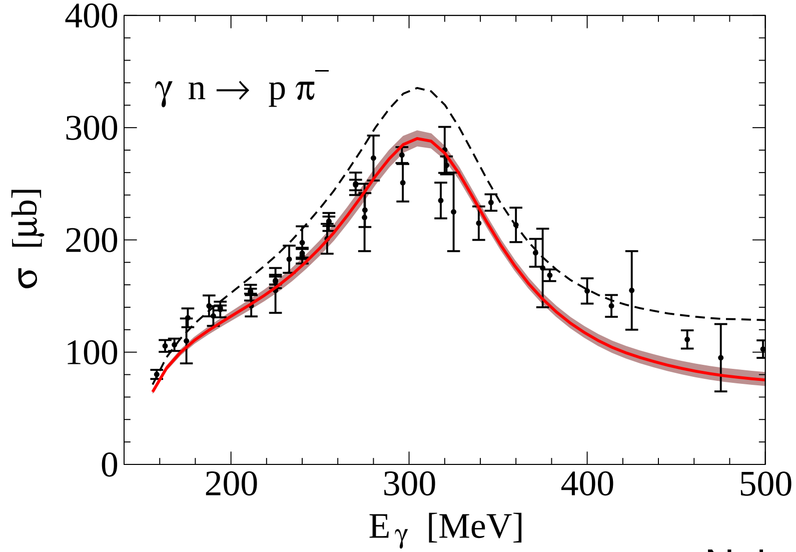
Besides, the terms that come with the C_3^A and C_4^A nucleon-to-Delta axial form factors become more relevant at higher energies, since larger q^2 values are allowed. Deviations from Adler's constraints ($C_3^A(q^2) = 0, C_4^A(q^2) = -C_5^A(q^2)/4$), that we implement so far, might play a role in describing the data at higher energies.

Effect of the new terms in pion photoproduction

The model for pion photoproduction is constructed from the vector part of our weak pion production model, including the implementation of Watson theorem







Conclusions

- We had modified our model by the addition of extra contact interaction terms.
- The new terms cancel to a large extent the effect of the nonpropagating spin-1/2 part of the usual Delta propagator.
- As a result we now get a better description of the $\nu_\mu n \to \mu^- n \pi^+$ reaction without worsening the agreement in other production channels.
- We think these new contact interactions are part of the solution to that problem.
- The changes also improve our description of pion photoproduction

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