

Modern Physics Letters A  
 © World Scientific Publishing Company

## NEUTRINO INDUCED WEAK PION PRODUCTION OFF THE NUCLEON

E. HERNÁNDEZ

*Departamento de Física Fundamental e IUFFyM, Universidad de Salamanca  
 37008 Salamanca, Spain  
 gajatee@usal.es*

J. NIEVES and M. VALVERDE

*Departamento de Física Atómica, Molecular y Nuclear, Universidad de Granada  
 18071 Granada, Spain*

Received (Day Month Year)

Revised (Day Month Year)

We study neutrino induced one-pion production off the nucleon in and around the Delta resonance region. Apart from the Delta-pole mechanism we include background terms required by chiral symmetry. These background terms give sizeable contributions in all channels. To better reproduce the ANL  $q^2$ -differential cross section data, we make a new fit of the  $C_5^A(q^2)$  axial nucleon to Delta form factor. The new result  $C_5^A(0) = 0.867 \pm 0.075$  is some 30% smaller than the commonly accepted value. This correction is compatible with most quark model estimates and a recent lattice calculation<sup>1</sup>.

*Keywords:* Chiral symmetry, pion production; neutrino reactions.

PACS Nos.: 25.30.Pt, 13.15.+g, 12.15.-y, 12.39.Fe.

### 1. Introduction and brief description of the model

Pion production reactions induced by neutrinos are very interesting as a means to study hadronic structure. Besides, they have become very relevant in the analysis of neutrino oscillation experiments where pion production contributes to the background. Most previous studies<sup>2,3,4,5,6</sup> of pion production processes at intermediate energies considered only the Delta pole ( $\Delta P$ ) mechanism (See Fig.1). Here, we shall also include background terms required by chiral symmetry. Some background terms have been included before in the works of Ref.<sup>7</sup> although they are not fully consistent with chiral counting rules.

For charged current (CC) processes our model includes all contributions depicted in Fig. 1. We have the  $\Delta P$  terms and background terms which include nucleon-pole terms ( $NP$ ), contact term ( $CT$ ), pion-pole term ( $PP$ ), and pion in flight term ( $PF$ ). For that purpose we use a SU(2) nonlinear  $\sigma$ -model with nucleon and pion degrees of freedom. On top of the vertices and currents provided by this model we include phenomenological form factors for the weak  $NN$  vertex that we take from the work of Ref.<sup>8</sup>. A different form factor is included in the purely axial  $PP$  term to account for the  $\rho$ -meson dominance of the  $\pi\pi NN$  vertex. Vector current

2 *E. Hernández, J. Nieves, M. Valverde*

conservation (CVC) and partial conservation of the axial current (PCAC) require the introduction of corresponding form factors in the  $PF$  term, and the vector and axial parts of the  $CT$  term. The weak nucleon-Delta vertex is parametrized in

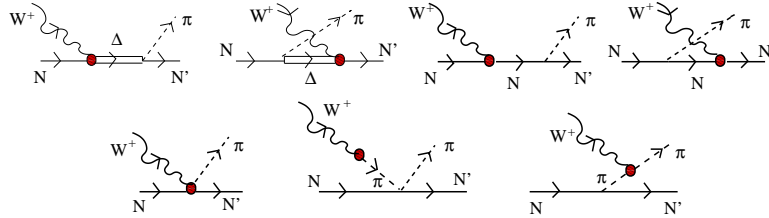


Fig. 1. Model for the  $W^+N \rightarrow N'\pi$  reaction. We have direct and crossed  $\Delta(1232)$  and nucleon pole terms, contact and pion pole contribution, and finally the pion-in-flight term.

terms of four vector and four axial form factors<sup>3</sup>. We use the set of vector form factors of Ref.<sup>6</sup> determined from the analysis of photo and electroproduction data. Initially we shall take the set of axial form factors in Ref.<sup>5</sup>. In this latter work Adler's model<sup>2</sup> is used to fix  $C_3^A = 0$  and  $C_4^A = -C_5^A/4$ , while  $C_6^A$  is obtained from  $C_5^A$  by PCAC. For  $C_5^A$  they use the parameterization

$$C_5^A(q^2) = \frac{C_5^A(0)}{\left(1 - \frac{q^2}{M_{A\Delta}^2}\right)\left(1 - \frac{q^2}{3M_{A\Delta}^2}\right)} ; \quad \text{with } C_5^A(0) = 1.2, \quad M_{A\Delta} = 1.05 \text{ GeV} \quad (1)$$

$C_5^A(0) = 1.2$  corresponds to the value obtained from the  $g_{\pi N\Delta}$  coupling constant using the off-diagonal Goldberger-Treiman relation. We shall call this Set I.

Due to the lack of space we can not give a full account of our model and all the results we have obtained. Interested readers can find all the relevant information in Ref.<sup>9</sup>.

## 2. Results and discussion

In the top left panel of Fig.2 we show the flux-averaged  $q^2$ -differential  $\nu_\mu p \rightarrow \mu^- p \pi^+$  cross section  $\int_{M+m_\pi}^{1.4\text{GeV}} dW \frac{d\bar{\sigma}_{\nu_\mu p}}{dq^2 dW}$ , where  $W$  is the invariant mass of the final hadronic state. The inclusion of the background terms spoils the agreement with ANL data if Set I is used. The least well known ingredients of the model are the axial nucleon-Delta form factors, of which  $C_5^A$  gives the largest contribution. This strongly suggests a new fit of  $C_5^A$  to the ANL experimental data. Keeping the parameterization in Eq.(1) we obtain the new values

$$C_5^A(0) = 0.867 \pm 0.075, \quad M_{A\Delta} = 0.985 \pm 0.082 \text{ GeV} \quad (2)$$

that we shall call Set II. The new  $C_5^A(0)$  value is some 30% smaller than the commonly assumed one, but it is not in contradiction with a recent lattice determination<sup>1</sup>. In the panel we also show a 68% confidence level band deduced from the statistical errors quoted above. In the rest of the panels we show the results for different CC and neutral current (NC) driven processes. In all of them the

background terms give sizeable contributions. The use of Set II of axial nucleon-Delta form factor increase the overall agreement with data. For the neutrino induced

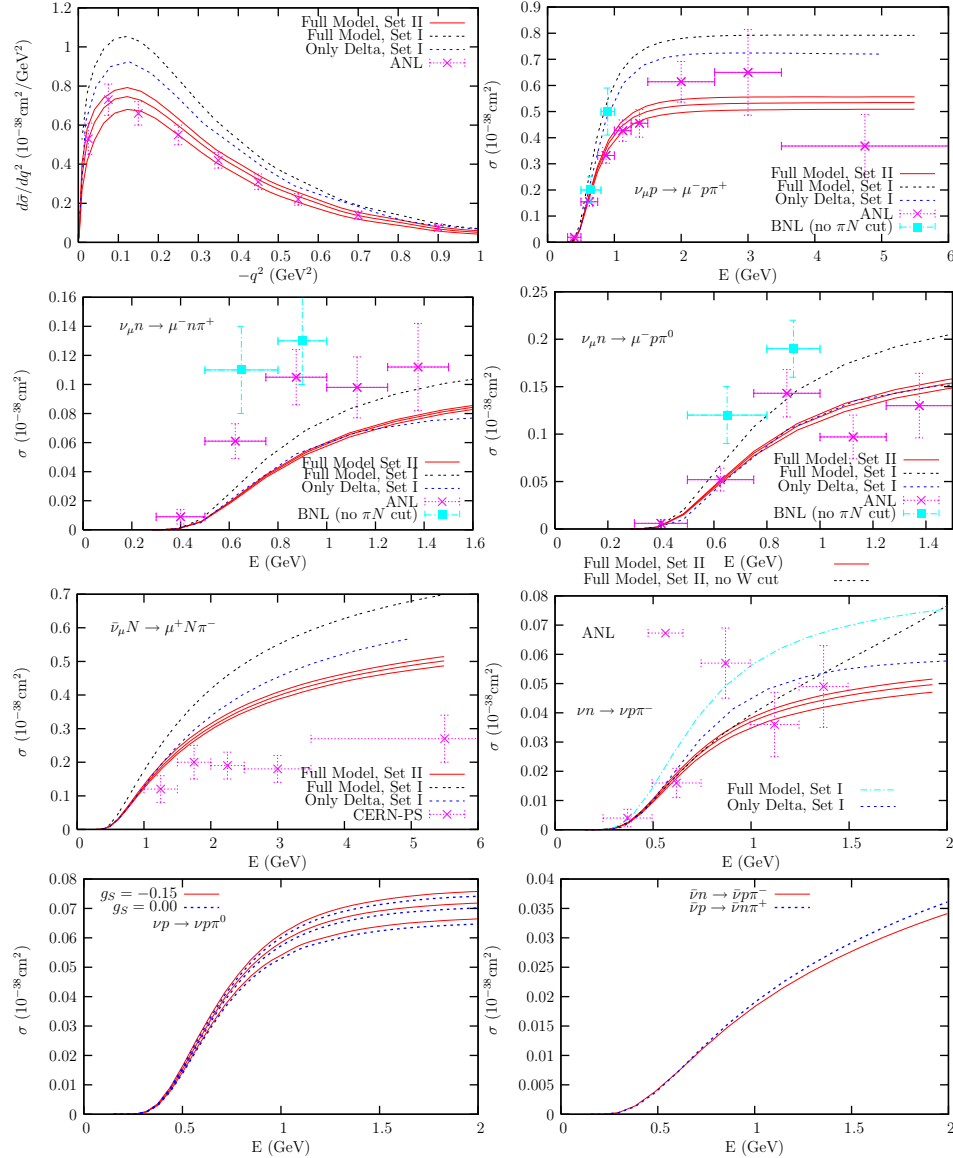


Fig. 2. Top left panel: Flux-averaged  $q^2$ -differential cross section  $\int_{M+m_{\pi}}^{1.4\text{GeV}} dW \frac{d\bar{\sigma}_{\nu_{\mu}\mu^{-}}}{dq^2 dW}$  for  $\nu_{\mu}p \rightarrow \mu^{-}p\pi^{+}$ .  $W$  stands for the final pion-nucleon invariant mass. Other panels: different charged current and neutral current reactions results. We compare our results with ANL and BNL data. With the exception of the  $\nu n \rightarrow \nu p\pi^{-}$  reaction, ANL data has a cut at  $W = 1.4\text{GeV}$  which we have also implemented in our calculation.

4 *E. Hernández, J. Nieves, M. Valverde*

CC processes we also show BNL data<sup>11</sup> which seem to favor a larger  $C_5^A(0)$  value. For antineutrino induced CC processes we see our full model calculation with Set II gives the best results but it is still larger than the experimental data obtained at CERN<sup>12</sup>. A recent calculation<sup>13</sup> claims that medium and pion absorption effects can perfectly explain this discrepancy between theoretical results on the nucleon and antineutrino experimental data actually measured in a freon-propane target.

The last three panels of Fig 2 show results for NC processes. The isovector contributions to these can be obtained directly from the CC ones using isospin symmetry. Besides, there are two different isoscalar contributions, one given in terms of the isoscalar part of the electromagnetic current and another one related to the  $s\bar{s}$  content of the nucleon. Both are of the  $NP$  type and their expressions and the form factors used in this case are given in Ref.<sup>9</sup>. Our full model using Set II reproduces fairly well the experimental results for  $\nu n \rightarrow \nu p \pi^-$ . The bottom left panel shows our results results are not sensitive to the  $s\bar{s}$  content of the nucleon. Last panel serves two purposes. First, it exemplifies the fact that antineutrino induced NC processes are suppressed with respect to neutrino induced ones, and second, it shows there is little isovector-isoscalar interference. In fact the isovector contribution is dominant.

### Acknowledgments

This research was supported by DGI and FEDER funds, under contracts FIS2005-00810, FIS2006-03438 and FPA2007-65748, by J. de Andalucía and J. de Castilla y León under contracts FQM0225 and SA016A07, and it is part of the EU integrated infrastructure initiative Hadron Physics Project under contract number RII3-CT-2004-506078.

### References

1. C. Alexandrou *et al.*, *Phys. Rev. Lett.* **98**, 122001 (2007); C. Alexandrou *et al.*, *Phys. Rev. D* **76**, 094511 (2007)
2. S.L. Adler, *Ann. Phys.* **50**, 189 (1968).
3. C.H. Llewellyn Smith, *Phys. Rep.* **3**, 261 (1972).
4. P. A. Schreiner *et al.*, *Phys. Rev. Lett.* **30**,339 (1973); L. Alvarez-Ruso *et al.*, *Phys. Rev. C* **57**, 2693 (1998); L. Alvarez-Ruso *et al.*, *Phys. Rev. C* **59**, 3386 (1999); O. Lalakulich *et al.*, *Phys. Rev. D* **71**, 074003 (2005); T. Leitner *et al.*, *Phys. Rev. C* **73**, 065502 (2006).
5. E.A. Paschos *et al.*, *Phys. Rev. D* **69**, 014013 (2004).
6. O. Lalakulich *et al.*, *Phys. Rev. D* **74**, 014009 (2006).
7. G.L. Fogli *et al.*, *Nucl. Phys. B* **160**, 116 (1979); G.L. Fogli *et al.*, *Nucl. Phys. B* **165**, 162 (1980); T. Sato *et al.*, *Phys. Rev. C* **67**, 065201 (2003).
8. S. Galster *et al.*, *Nucl. Phys. B* **32**, 221 (1971).
9. E. Hernández *et al.*, *Phys. Rev. D* **76**, 033005 (2007).
10. S.J. Barish *et al.*, *Phys. Rev. D* **19**, 2521 (1979); G.M. Radecky *et al.*, *Phys. Rev. D* **25**, 1161 (1982).
11. T. Kitagaki *et al.*, *Phys. Rev. D* **34**, 2554 (1986); T. Kitagaki *et al.*, *Phys. Rev. D* **42**, 1331 (1990).
12. T. Bolognese *et al.*, *Phys. Lett. B* **81**, 393 (1979).

13. M. Sajjad Athar *et al.*, *Phys. Rev. D* **75**, 093003 (2007).