2p2h effects on the weak pion production cross section

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1 Motivation

Neutrino oscillation experiments search a distortion in the neutrino flux at a detector positioned far away (L) from the source.

- By comparing near and far neutrino energy spectra, one gains information about the oscillation probability

$$P(\nu_i \to \nu_j) = sin^2 2\theta_{ij} sin^2 \frac{\Delta m^2_{i,j} L}{2E_\nu},$$

and then about the θ_{ij} mixing angles and $\Delta m^2_{i,j}$ mass squared differences.

- New high quality data are becoming from MiniBoone, MINOS, NOMAD, Minerνa and SciBoone full dedicated to measure cross sections.

- **Problems :**
CCQE $\nu_l n \to l^- p$ on the A target is used as signal event or/and to reconstruct the neutrino energy, not directly measurable but reconstructed from two-body kinematics (exact only for free nucleons), and competition of another processes could lead misidentification of the arriving neutrinos.
$\nu_\mu \to \nu_x$ uses $\nu_\mu n \to \mu^- p$ CCQE to detect neutrinos and reconstruct its energy. E_ν determination could be wrong for a fraction of CC$1\pi^+$ background events (20%) $\nu_\mu p \to \mu^- p \pi^+$, that can mimic a CCQE one if the pion is absorbed and/or not detected.
In $\nu_\mu \to \nu_e$, one detects ν_e in an (almost) ν_μ beam. Signal event $\nu_e n \to e^- p$ is dominated by a NC$1\pi^0$ $\nu_\mu N \to \nu_\mu N \pi^0$ background, and the detector can not distinguish between e^- and π^0 if one of both photons from the $\pi^0 \to \gamma\gamma$ decay escapes.

- Nuclear effects: Smearing of the reconstructed energy by the momentum distribution of the target bound nucleons (GSC+Bounding). FSI of the emerging nucleon generate energy lost,change of direction,charge transfer or multiple nucleon knock out(np-nh). All these affecting QE events determination.

- MEC processes lead to additional contributions to one-body current generated.

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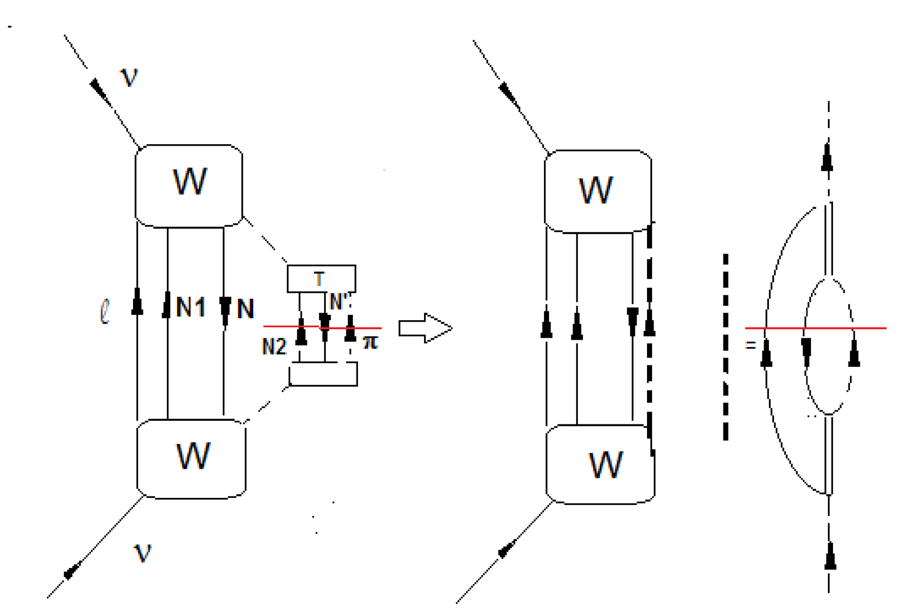

FIGURE 3: Simplification to calculate πN rescattering.

4 Bounding, Smearing, FSI

Here we resume the main ingredients of the model:

- Binding within the RHA of QHD I (σ, ω mesons), for N and Δ (universal coupling)
- GSC (2p2h+4p4h) in the ground state

$$n_A(\mathbf{k}) = \langle\tilde{0}|a^\dagger_{\mathbf{k}m} a_{\mathbf{k}m}|\tilde{0}\rangle, \quad \int d^3k \;\; n_A(\mathbf{k}) = \frac{A}{4}$$

$$|\widetilde{0}\rangle = \mathcal{N}\left[|0\rangle + \frac{1}{(2!)^2}\sum_{p's,h's} c_{p_1p_2h_1h_2}|p_1p_2h_1h_2\rangle + \frac{1}{(4!)^2}\sum_{p's,h's} c_{p_1p_2p_3p_4h_1h_2h_3h_4}|p_1p_2p_3p_4h_1h_2h_3h_4\rangle\right],$$

where the coefficients are calculated through perturbation theory in nuclear matter.

- FSI on nucleons is taken (Toy model !) through the used effective fields within the RHA also for final N, While for pions we use the Eikonal approach in its simplest version, that is $\phi_\pi \to \phi^*_\pi$, where

$$\phi^*_\pi(\mathbf{r}) \sim e^{-i\mathbf{p}_\pi\cdot\mathbf{r}} e^{-i/v_\pi \int_{z_\pi}^{\infty} V_{opt}(\mathbf{b},\mathbf{z}')\mathbf{dz}'}, \mathbf{r} = (\mathbf{b}, \mathbf{z}'), \quad (1)$$

assuming a mean distance of trip for π in nucleus, constant nucleon density and the Δ-h model for the π-optical potential

2 1p1h+1π process

A precise knowledge of cross sections is a prerequisite in order to make simulations in event generators to substract fake 1π events in QE countings. Assuming only $1p1h+1\pi$ final states

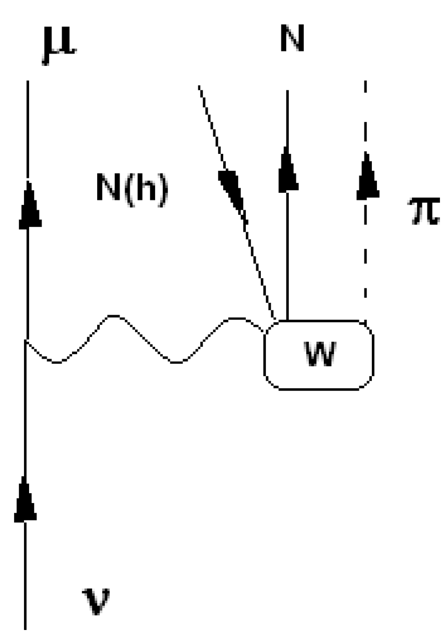

FIGURE 1: Amplitude for $\nu N \to l N' \pi$ considering only $1p1h + 1\pi$ states, shown for $l = \mu$.

and including bounding, smearing and FSI effects we have concluded (NUFACT2012)

- Claculations are $\sim$ 50% below MiniBooNE for CC 1π (comparable to GiBUU Jul 2011) and $\sim$ 30% for NC π^0 production.
- From $\nu n \to \mu^- N\pi$, with $N = n, p$ and $\pi = \pi^+, \pi^0$, πN invariance mass distribution from ANL - BNL shows that contribution of higher resonances could be important $\to$ and need to be added consistently to the elemental amplitude.
- FSI were included in a primitive way (Eikonal approx.) that should be improved, but
- Note that at for example $E_\nu = 1.5 GeV$ for MiniBooNE and ANL or BNL (without cuts) data :
$\sigma^{exp}_{ACC1\pi^+}/A\sigma^{exp}_{NCC1\pi^+} \sim 95\%$
$\sigma^{exp}_{ACC1\pi^0}/A\sigma^{exp}_{NCC1\pi^0} \sim 83\%$
$\sigma^{exp}_{ANC1\pi^0}/A\sigma^{exp}_{NNC1\pi^0} \sim 92\%$,
what seems indicate that nuclear effects should be of much minor importance, if the IA is assumed or that another mechanisms should be considered as 2p2h, MEC

5 Results

Here we show results for π^+ and π^0 production in the CC mode, showing the gradual effect of the bounding, smearing, FSI and 2p2h addition

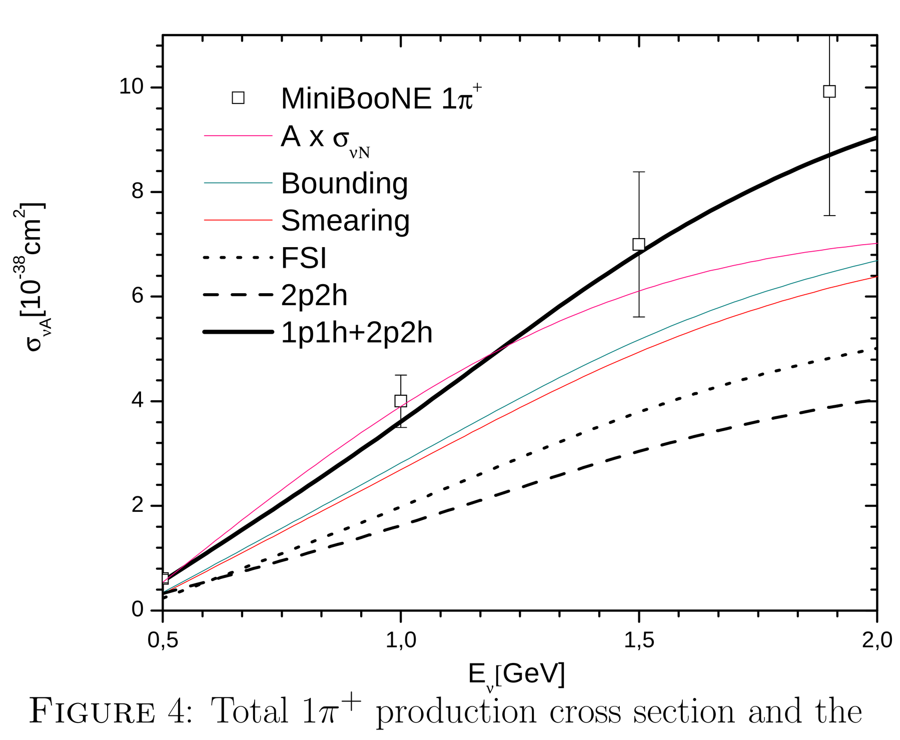

FIGURE 4: Total $1\pi^+$ production cross section and the size of the different effects.

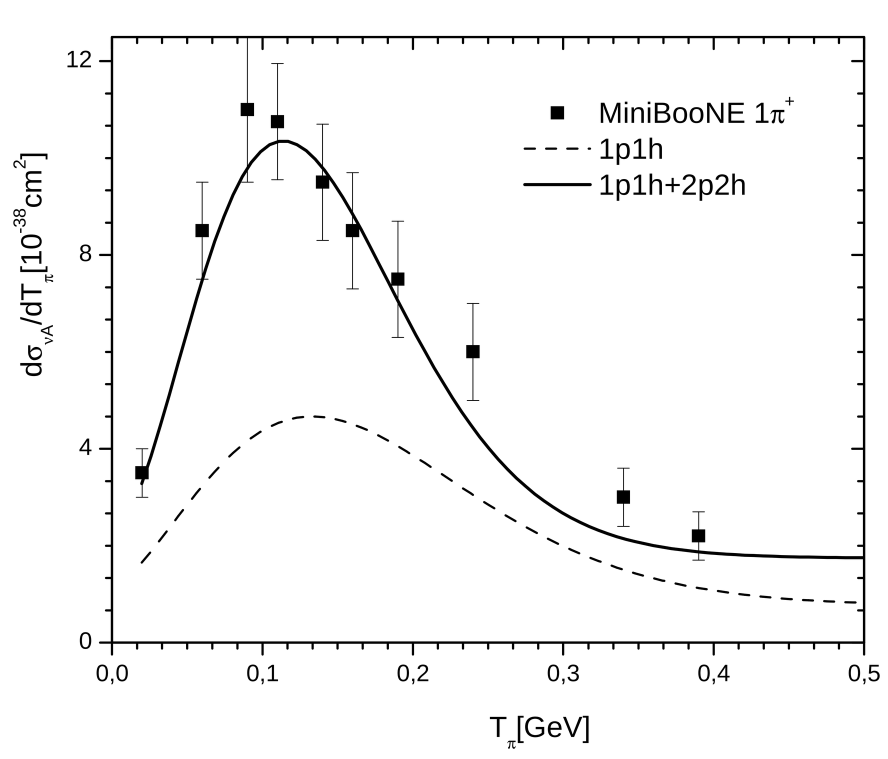

FIGURE 5: $1\pi^+$ production differential cross section.

3 2p2h+1π Contribution

The amplitude corresponding to this contribution is

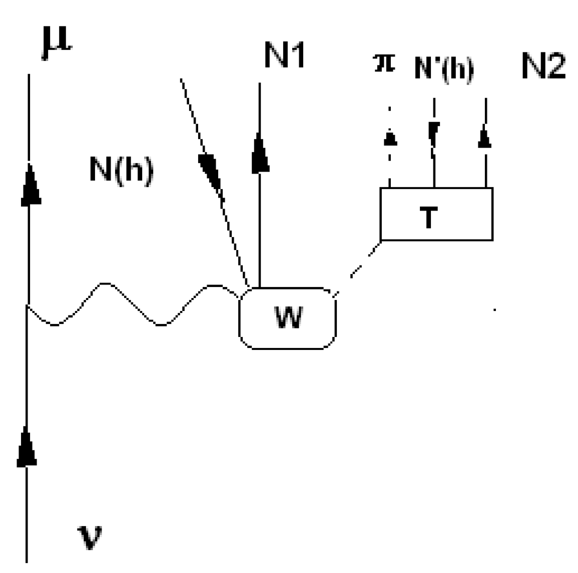

FIGURE 2: Amplitude for the $\nu N \to l N' N_1 N_2 \pi$ $(2p2h + 1\pi)$ process.

and the corresponding section can be resumed as

$$d\sigma^{2p2h+1\pi}_{\nu A} = \frac{n_A(\boldsymbol{k})(1 - n_A(\boldsymbol{N}_1))}{|\mathbf{v}_\nu - \mathbf{v}_A|2E(\boldsymbol{\nu})}\frac{1}{2}\sum_{m_\nu,m,m_l,m_1}\int\frac{d^4\pi'}{(2\pi)^4}$$
$$\times\; S\sum_{m_2m'}|T(N2m_2,\pi,k'm',\pi')|^2\frac{n_A(\boldsymbol{k}')(1 - n_A(\boldsymbol{N}_2))}{(\pi'^2 - m_\pi^2)^2}$$
$$\times\; (2\pi)^4\delta^4(N_2 + \pi - \pi' - k')d^3N(\boldsymbol{N}_2)d^3k'N(\boldsymbol{k}')N^2(\boldsymbol{\pi})d^3\pi$$
$$\times\; |W^\mu(N_1m_1, lm_l, \pi', km, \nu m_\nu)J^l_\mu(lm_l, \nu m_\nu)|^2$$
$$\times\; (2\pi)^4\delta^4(N_1 + \pi' + l - \nu - k)\; N^2(\boldsymbol{l})d^3l\; d^3N_1(\boldsymbol{N}_1)d^3kN(\mathbf{k}),$$

where the involved calculation to introduced the rescattering $\pi' N'$ contribution indicated in red, is simplified making the replacement

$$[\cdots] \Rightarrow \frac{1}{(\pi'^2 - m_\pi^2 - \Pi(\pi'))} \Rightarrow 2\pi\delta(\pi'^2 - m_\pi^2 - \Re(\Pi(\pi'))),$$

since the final pion should be on-shell and where for $\Pi(\pi')$ we only consider the $\Delta(1232MeV)$ resonant contribution dropping the another non-resonant terms since this is the most important one. We work out this self-energy in the $\Delta - h$ approach, taking into account that the Δ width will account the final pion-nucleon additional state through the absorptive evaluation of the pion-nucleon Δ-self energy. All this is depicted in the next figure as $\Rightarrow$

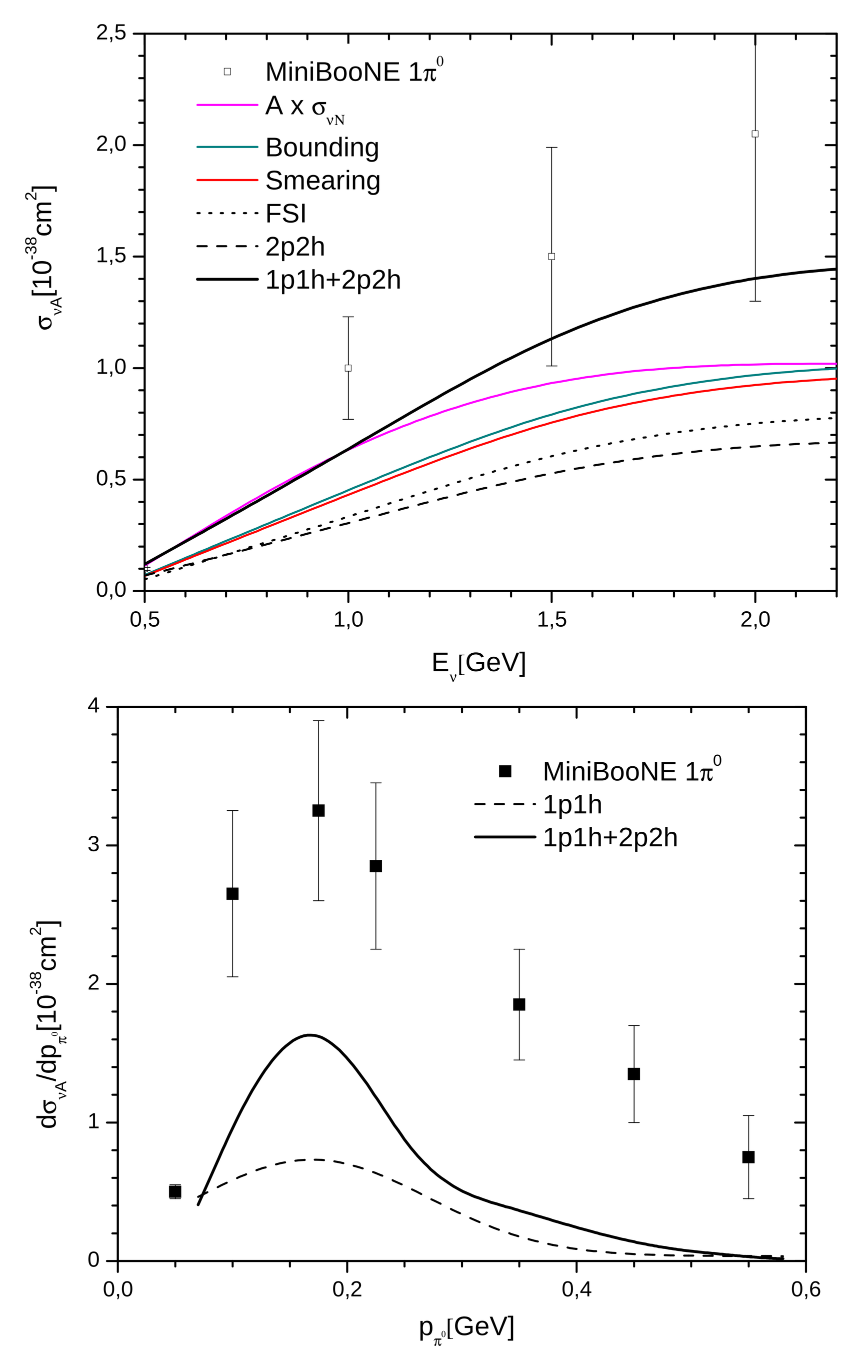

FIGURE 6: Idem for $1\pi^0$.

6 Conclusions

- 2p2h contribution is important and comparable to the 1p1h one
- In the π^0 channel nonresonant contributions and charge exchange terms should be included
- MEC should be included at the same time that 2p2h contributions.