Neutrino - nucleus cross sections in T2K

from Martini et al model implementation into GENIE MC generator to the performances of the HA-TPCs

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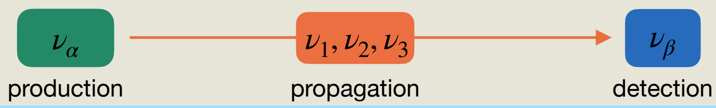
NEUTRINO OSCILLATIONS

The 3 neutrino flavour eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$ are superposition of the 3 mass eigenstates (ν_1, ν_2, ν_3) via the PMNS matrix:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

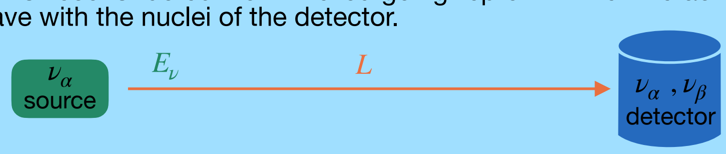
flavour eigenstates — PMNS matrix — mass eigenstates

Due to the non-diagonal nature of the PMNS matrix, a neutrino initially created with flavour α, through a weak interaction, can be detected having a different flavour β. This phenomenon is called "neutrino oscillation".



NEUTRINO OSCILLATION EXPERIMENTS

Neutrino oscillation experiments observe neutrinos of a particular flavour α with energy E_ν and track their transformation into a flavour β over a distance L. The type of the neutrino is reconstructed from the outgoing lepton in the interactions that the neutrinos have with the nuclei of the detector.



The observable of these experiments is the number of neutrinos that went through an oscillation:

$$N_{\nu_\beta}(E_\nu^{rec}) \sim \int \Phi_{\nu_\alpha}(E_\nu^{true})\, P_{\nu_\alpha\to\nu_\beta}(E_\nu^{true}, L, \Theta)\, \sigma_{\nu_\beta}(E_\nu^{true})\, \epsilon_{det}\, d(E_\nu^{true}, E_\nu^{rec})\, dE_\nu$$

reconstructed energy; true energy; baseline length; oscillation parameters

number of ν_β detected events; ν_α flux; $\nu_\alpha \to \nu_\beta$ oscillation probability; ν_β cross section; detector efficiency; migration matrix

From the formula above, it is possible to estimate the oscillation parameters that appear into the oscillation probability. The ν_β cross section appears both explicitly and implicitly into the detector efficiency and the migration matrix that connects true and reconstructed neutrino energy. For this reason the knowledge and the modelling of the neutrino - nucleus cross section is crucial.

ENERGY RECONSTRUCTION IN T2K

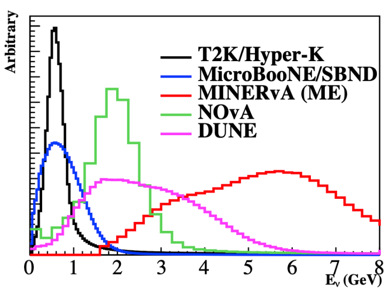


Figure 1: neutrino beams energy distribution in accelerator based experiments.

Neutrino beams in accelerator based experiments are not monochromatic, therefore the neutrino energy E_ν^{true} cannot be known, but just reconstructed (E_ν^{rec}). Fig 1 shows that the neutrino produced by T2K have $E_\nu \sim 1$ GeV. The channels of neutrino - nucleus interaction at this energy are depicted in Fig 2.

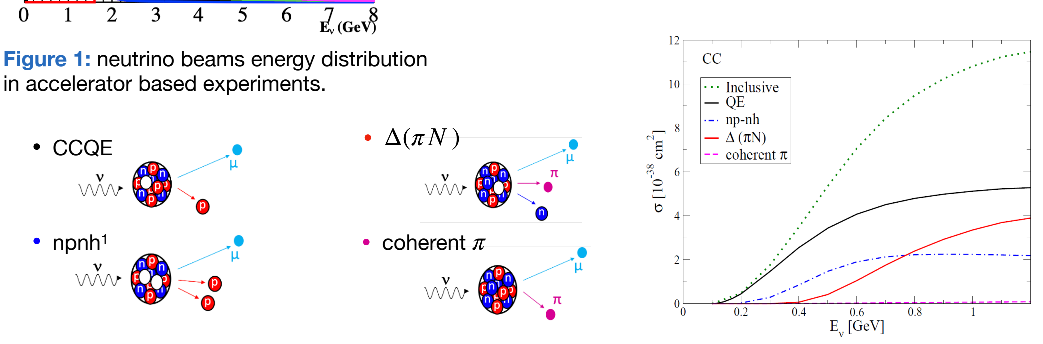


Figure 2: neutrino - nucleus channels of interaction at $E_\nu \sim \mathcal{O}(1\text{GeV})$

In T2K, E_ν is reconstructed assuming the interaction is CCQE (see Fig 2) on a stationary nucleon with fixed nuclear binding energy. It is therefore used only the lepton kinematics to get E_ν^{rec}:

$$E_\nu^{rec} \equiv E_\nu^{CCQE} = \frac{2\,(m_n - E_B)\,E_l - (E_B^2 - 2m_nE_B^2 + m_l^2 + \Delta M)}{2\left[(m_n - E_B) - E_l + p_l\cos\theta_l\right]}$$

Due to this approach, non CCQE interactions lead to a bias in the distribution represented in Fig 3 that would propagate in the evaluation of the oscillation parameters.

Having a correct model that describes the neutrino - nucleus interaction is therefore needed to adjust the mapping between E_ν^{rec} and E_ν^{true}.

[1]npnh represents the case where n ≥ 1 nucleons are knocked out from the nucleus. The 2p2h and 3p3h are both possible. With this nomenclature the CCQE is also called 1p1h.

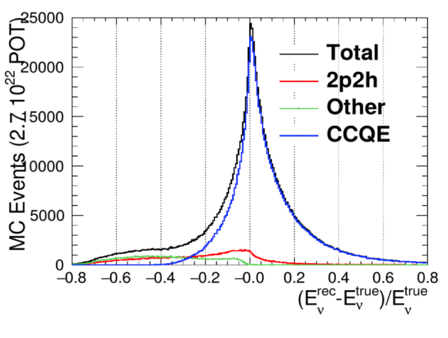


Figure 3: distribution of $(E_\nu^{rec} - E_\nu^{true})$ / E_ν^{true}.

MARTINI et al MODEL

Martini, Ericson, Chanfray and Marteau gave the explanation to the MiniBooNE CCQE-like cross section [1]. As illustrated in Fig 4 the predictions for genuine CCQE cross section did not match the data. To reconstruct the neutrino - nucleus interaction, MiniBooNE looked at the muon in the final state, without reconstructing the hadronic part. Martini et al proposed to include the npnh interactions in the cross section predictions. In fact, these interactions have the same final state as the genuine CCQE If one looks at the leptonic part only (Fig 5).

As shown in Fig 4, thanks to the inclusion of the npnh channel, the Martini et al cross section predictions matched MiniBooNE data.

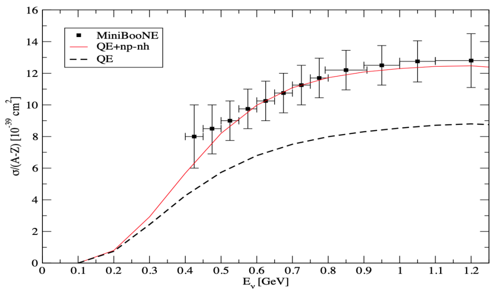


Figure 4: quasi-elastic like ν_μ - [12]C cross section as a function of neutrino energy. Predictions for both genuine CCQE events and the inclusion of the npnh component are shown.

CCQE-like = genuine CCQE + npnh

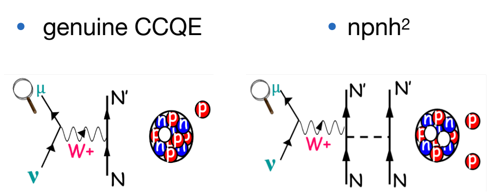


Figure 5: MiniBooNE CCQE-like events include both genuine CCQE and npnh interactions.

[2]The picture shows just the 2p2h case, but, as seen in [3], npnh includes the 3p3h as well.

MARTINI npnh IMPLEMENTATION INTO GENIE

Monte Carlo generators are needed to simulate neutrino - nucleus interactions and to extrapolate the corresponding cross sections (total or for a given channel of interaction). GENIE [2] is one of the main MC event generators. Martini et al model was not yet implemented into it.

My result of the implementation of the Martini et al npnh cross sections predictions into GENIE is shown in Fig 6. It is evident that the npnh Martini et al model implementation into GENIE is successful since the cross section generated in GENIE (blue line) is superimposed to the one generated outside GENIE (red line).

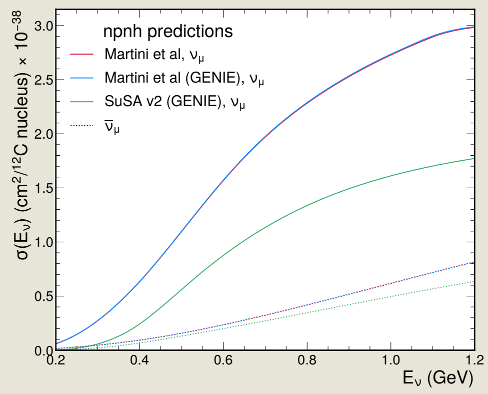


Figure 6: Predictions for ν_μ - [12]C npnh cross sections as a function of neutrino energy (solid line); the $\bar{\nu}_\mu$ case is also shown (dotted line). The npnh Martini et al model cross section generated with GENIE are shown in blue, while red line shows the predictions generated without GENIE. SuSA v2 predictions generated with GENIE are shown for comparison.

DEPOSITED ENERGY MEASUREMENTS IN THE HA-TPC

Beyond MC modelling, in my thesis I am also involved in experimental activities with the final aim of measuring the CCQE-like cross section in the upgrade of the near detector ND280 in the T2K experiment[3].

In order to evaluate the performances of the HA-TPC of ND280, I analysed a run of cosmic. Fig 7 shows the result of the analysis. The mean deposited energy follows the Bethe-Bloch predictions for muons. The deposited energy resolution, used for the particle identification, is below the required 10% value.

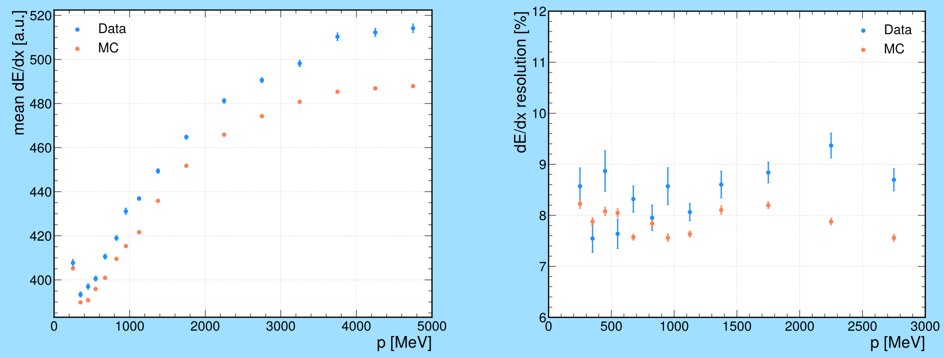


Figure 7: Mean deposited energy (left) and deposited energy resolution (right) as a function of the reconstructed momentum. In both plots data are compared with a MC simulation.

[3]For details about the upgrade of T2K see poster of U. Virginet and A. Chalumeau.

REFERENCES

[1] M. Martini, M. Ericson, G. Chanfray, J. Marteau "Unified approach for nucleon knock-out and coherent and incoherent pion production in neutrino interactions with nuclei" In: Physical Review C 80.6 (Dec. 2009)

[2] C. Andreopoulos et al. "The GENIE Neutrino Monte Carlo Generator: Physics and User Manual" arXiv: 1510.5494 [hep-ph] (2015)