Pion production uncertainty in context of Tokai2Kamioka (T2K) experiment

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Abstract

We evaluate uncertainty of the neutral current π^0 production coming from limited knowledge of axial form-factor. The uncertainties of the form-factor parameters are obtained from a self-consistent fit to the results of ANL and BNL experiments measuring pion production free of significant nuclear effects. The evaluated uncertainities are important for T2K background estimates.

1 Introduction

Large uncertainties exist in predicting π meson production cross-sections for low neutrino energy range most important for new long baseline experiments, like TokaiToKamioka (T2K). The problem is particularly eminent for single π^0 production. Consequently, there are many different theoretical expectations based on different parametrisations of the resonance model that are used to describe π production in this energy range. The T2K experiment will enable to verify them to greater extent. However, those predictions are valuable also in the preliminary stage of the experiment - differences in the π^0 production affect background predictions in Super-Kamiokande and therefore estimations of the expected precision of electron neutrino appearance measurements in T2K. This study presents a new way of dealing with old bubble chamber neutrino data. This results in a fit in which two parameters are determined: M_A and $C_5^A(0)$. 1σ contours are then used to obtain uncertainty in cross-section for pion production via simulations of neutrino interactions.

2 Theory and fitting procedure

Dominant channels of π production in T2K energy region are usually described by Rein-Sehgal model, which takes into account several resonances. However, in low energy region (around 1 GeV) a different model, taking into account only Δ resonances, can be applied with satisfying results. This approach, called Rarita-Schwinger formalism for the $\Delta(1232)$ excitation, was used in this work. Variants of resonance models are usually different in the way the structure functions are parameterized. The vector part of form factors is well known from electron scattering experiments; axial form factors can only be studied in neutrino interactions and hence their form is much less certain. The main contribution to the axial current comes from the $C_5^A(Q^2)$ form factor and in this analysis it was assumed to have a dipole form $C_5^A(Q^2) = C_5^A(0)/(1+\frac{Q^2}{M_A^2})^2$, where Q^2 is four-momentum transfer and M_A is axial mass. M_A and $C_5^A(0)$ are the parameters that will be fitted. We look for a simultaneous fit to both ANL and BNL experiments' data by applying the χ^2 method. The best fit is obtained by minimizing a function: $\chi^2 = \chi^2_{ANL} + \chi^2_{BNL}$. In both cases the χ^2 is given by the standard formula with the additional quadratic term which comes from the total systematic uncertainty for the flux:

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{\sigma_{th}^{diff}(Q_i^2) - p\sigma_{ex}^{diff}(Q_i^2)}{p\Delta\sigma_i} \right)^2 + \left(\frac{p-1}{r} \right)^2, \qquad p \equiv \frac{\sigma_{tot-th}}{\sigma_{tot-exp}} \frac{N^{exp}}{N^{th}}$$

$\sigma_{ex}^{diff}(Q_i^2)$ and $\sigma_{th}^{diff}(Q_i^2)$ are experimental results and theoretical predictions for the differential cross-section, $\Delta\sigma_i$ is the experimental result uncertainty (statistical and uncorrelated systematic), $\sigma_{tot-exp}$ and

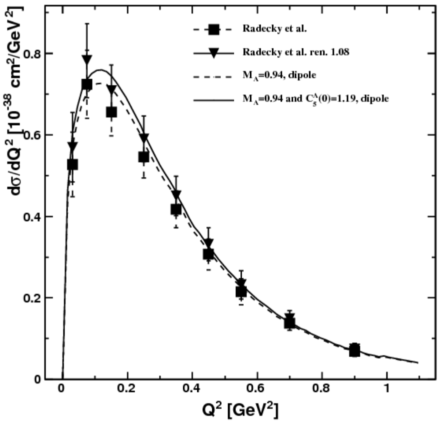

Figure 1: Fit results for ANL data. The solid/dashed lines denote the best fit obtained with $C_5^A(0)$ fitted/fixed (with value 1.15 - the option not discussed here). Black squares - experimental data, black triangles - experimental data multiplied by the fitted re-normalization factor p_{ANL}.

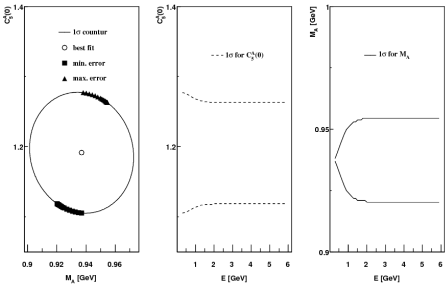

Figure 2: Error ellipse. Black squares and triangles denote the points with maximal and minimal errors for total cross-section for $\nu + p \rightarrow \mu^- + p + \pi^+$ at different ν energies E (left). The obtained points are then mapped in the form of $C_5^A(0)$ and M_A dependence on E (middle and right).

σ_{tot-th} are the experimental and theoretical flux averaged cross-sections measured and calculated with the same cuts.

3 Data and fit results

Two experiments provided data in the energy region of interest - ANL (Argonne National Laboratories) and BNL (Brookhaven National Laboratories). Bubble chambers filled with hydrogen or deuterium were used as detectors. Charged current pion production was studied. Targets used in the above experiments allow to study primary interactions - the impact of reinteractions in target's nucleus is very small. Data that were used in the fit were taken from Refs. [1,2]. Flux uncertainties were assumed as follows: 20% for ANL data ($r_{ANL} = 0.20$) and 10% for BNL data ($r_{BNL} = 0.10$). In the analysis deuteron nuclear effects were taken into account.

The data from ANL and BNL turned out to be consistent. The fit yielded the following parameter values: $M_A = 0.94 \pm 0.03$GeV, $C_5^A(0) = 1.19 \pm 0.08$, $p_{ANL} = 1.08 \pm 0.10$, $p_{BNL} = 0.98 \pm 0.03$. Error ellipse is presented in Fig. 2. The 1σ values for specific energies are points on this ellipse.

4 Cross-section uncertainty

We will now study channels that are most important in modern neutrino experiments, i.e. (i) $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p$, $\nu_\mu + n \rightarrow \mu^- + \pi^+ + n$ (CC π^+ production) and (ii) $\nu_\mu + p \rightarrow \nu_\mu + \pi^0 + p$, $\nu_\mu + n \rightarrow \nu_\mu + \pi^0 + n$ (NC π^0 production). The π^0 production is the main source of background in water Cherenkov far detectors of long baseline neutrino experiments searching for ν_e appearance, like Super-Kamiokande (SK) in T2K. The NC π^0 events are however difficult to study exclusively; one can try to study them by measuring π^+ production and extrapolating the results to π^0 production. We will now use fit results obtained above to estimate cross-section uncertainty for NC π^0 channel. For this purpose two software packages simulating neutrino interactions will be used. The main simulation package used in this analysis was NuWro Monte Carlo generator. It uses Rarita-Schwinger formalism for the $\Delta(1232)$ resonance production model. Nuclear effects in oxygen (NEO) have been recently implemented in NuWro and were used in this study. As a reference, Nuance generator was used. Nuance is a widely used tool, tested in experiments with water Cherenkov detectors like K2K and SK. It appeared to be consistent with the measurements of π^0 production in 1KT near detector of K2K as well as atmospheric neutrinos in SK.

Its implementation of nuclear effects in oxygen can be therefore considered trustworthy. Resonant pion production in this generator is calculated according to Rein-Sehgal model.

The error elipse, presented in Fig. 2 is calculated for Δ^{++}. However, we can scan this elipse, calculating NC π^0 production cross-section for each point on it, and find minimum and maximum value. By doing this for a broad range of incident neutrino energy we can obtain M_A and $C_5^A(0)$ parameters corresponding to lower and upper 1σ bound at each energy and then use them in NuWro simulations, which will allow us to calculate cross-sections for the channels of interest. All simulation samples in this work were created using water as target - the most suitable material when simulating interactions in SK. Simulations utilize T2K beam profile and only ν_μ interactions were taken into account as they dominate the beam. Results are shown in Fig. 3. Relative plots indicate that the differences are most notable in low energy region. In particular at 1 GeV the uncertainty for π^0 production is about $\pm 10\%$.

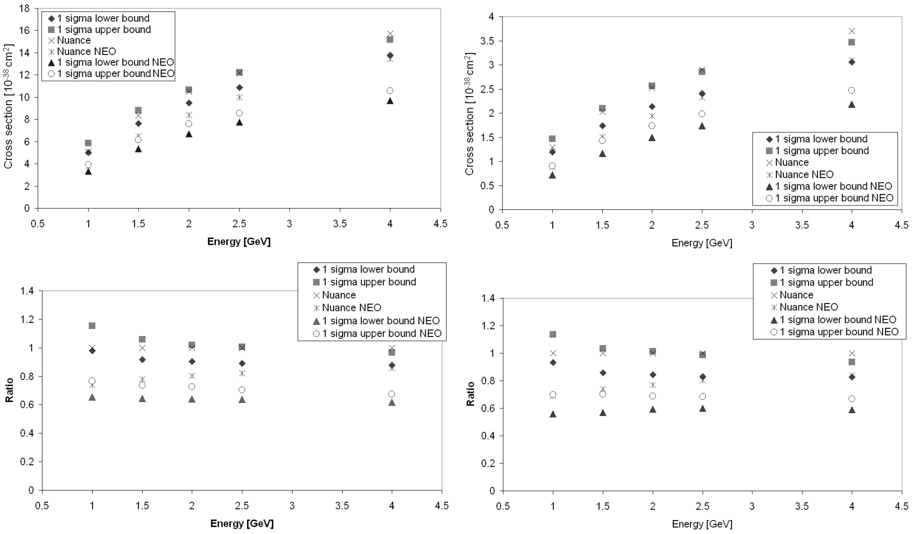

Figure 3: Cross-sections of pion production on water. Left - CC π^+ production, right - NC π^0 production. Top - absolute cross-sections, bottom - cross-sections normalized to Nuance results without NEO. NuWro points show 1σ error contours, Nuance points are shown here for reference.

Typical energies of pions that constitute background are in the range of 1 to 4 GeV, and such energies are the most important as far as the T2K experiment is concerned. Therefore the expected uncertainty varies between 6% and 10%. However, it is important to note that the errors discussed here come only from uncertainties in form factors and do not take into account other model approximations, e.g. nonresonant background in pion production or an influence of matter on the width of Δ resonance.

The results of our work in extended and elaborate form can be found in Ref. [3].

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