PROCEEDINGS OF SCIENCE

Expanding T2K near detector fit by adding proton information

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T2K (Tokai to Kamioka) is a long-baseline neutrino oscillation experiment located in Japan. One of the most challenging tasks of T2K is to determine whether CP is violated in the lepton sector, which is suggested by recent T2K results. By utilizing the near detector (ND280) data, T2K can constrain neutrino interaction and flux uncertainties by fitting a parameterized model to data. This allows for a significant reduction of the systematic uncertainties in neutrino oscillation analyses. The fit to ND280 data currently uses several samples which are based on muon kinematics and pion multiplicity. There is ongoing work to expand these samples by incorporating the reconstructed proton multiplicity in order to enhance ND280 sensitivity to neutrino cross-section modelling that drive current systematic uncertainties. The poster presents the properties of new ND280 samples and how they enhance the sensitivities to nuclear effects that are dominant at the energy range relevant for T2K. The addition of the proton multiplicity information will also help to reduce systematic uncertainties that affect neutrino oscillation measurements at T2K.

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1. T2K Experiment and ND280

T2K is a long baseline experiment studying neutrino oscillations in the appearance and disappearance channels [1]. Muon neutrino or antineutrino beam is produced at J-PARC, where also Near Detector station is located. It consists of ND280, INGRID, WAGASCI, but only ND280 is directly used in the T2K oscillation analysis. ND280 is also used in standalone cross section measurements. T2K Far Detector is famous 50 kt water Cherenkov detector Super-Kamiokande.

The ND280 data is crucial for the oscillation analysis. By fitting unoscillated MC predictions to ND280 data it is possible to constrain the cross section and flux models. Those constraints are passed to the T2K Far Detector predictions, where fit with Super Kamiokande samples takes place. Two separate methods are used for ND280 fit: frequentist Gradient Descent and Bayesian Markov Chain Monte Carlo (MCMC). In both methods the Poissonian Log Likelihood, with Barlow Beeston correction [2] and penalty term coming from systematic parameters, is minimized. The Likelihood considers muon kinematics (momentum and emission angle) for each of 18 ND280 event samples used in 2020 analysis [3]. Adding new samples allows to better probe interesting muon kinematic regions and gives sensitivity to new effects. As a result it improves T2K sensitivity however it requires also reassessment of the systematic errors.

2. Proton Tagged Samples

T2K has been using ND280 event samples based on pion tagging in 2020 analysis. Since samples using proton multiplicity have shown interesting sensitivities in the recent T2K cross section measurements [4, 5] there is ongoing work on adding new samples with proton tagging to the ND280 fit. Proton tagged samples: CC0π-0p and CC0π-Np originate from split of CC0π (events without reconstructed pions) based on proton multiplicity reconstructed in TPC and FGD (ND280 sub-detectors). Moreover CC0π-0p has greater purity of CCQE with respect to CC0π (58% with respect to 51%). For more details on proton selection, efficiencies and purities see [4, 5].

Both samples occupy different phase space of muon kinematics as it can be seen in Fig. 1. In case of CC0π-0p most of neutrino momentum is taken by the muon, which is going forward. CC0π-Np events contain a high momentum proton, so to conserve momentum the muon has to travel at a higher angle. Having this distribution separated gives additional freedom and sensitivity to the fitter.

3. Enhanced ability to constrain CCQE interaction model

Proton tagged samples have different distributions of Q^2 and can help to better probe effects at lower and higher regions of Q^2. Low Q^2 events can be suppressed by Pauli Blocking [6] or other nuclear effects. Pauli Blocking and binding energy are related to the releasing of a nucleon with a certain momentum, leading to suppression of low Q^2 events by Pauli Blocking. Most of the protons reconstructed in ND280 have high momentum, so they aren't affected by nucleon correlations. Events without visible proton will often have a true proton of relatively low momentum due to low Q^2 transferred to hadron system. Therefore, CC0π-0p has lower Q^2 as it is presented in the Fig. 2 (left), which translates to CC0π-0p being more affected by the Pauli Blocking as can be seen in Fig. 2 (right).

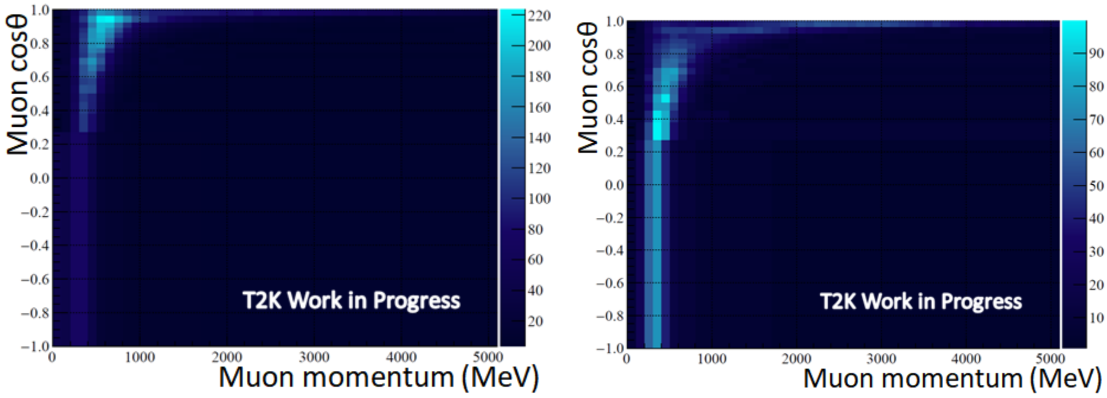

Figure 1: Muon momentum and $\cos\theta$ distribution for CC0π-0p (left) and CC0π-Np (right).

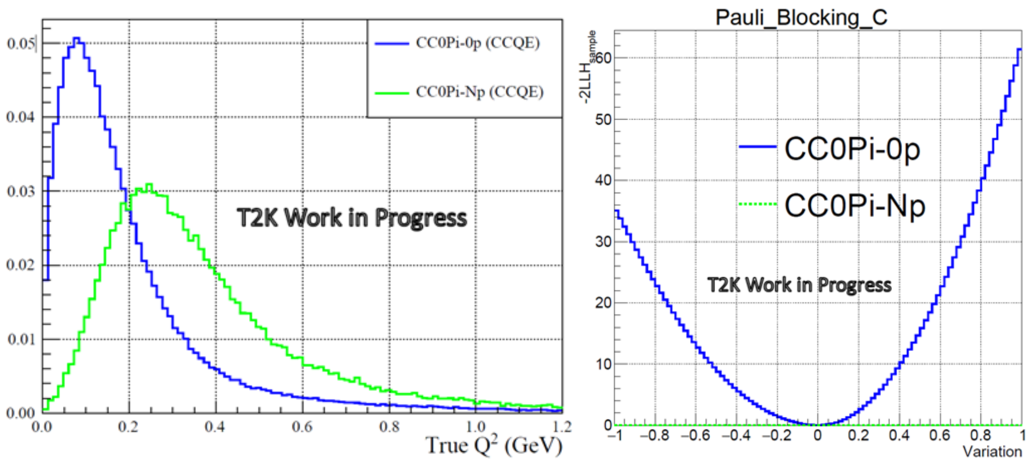

Figure 2: Left: true Q^2 distribution. Right: Log Likelihood scan as function of Pauli Blocking parameter to show impact of low Q^2 effects for each sample. ±1 variation of parameter correspond to 30 MeV shift to Fermi Surface.

4. Ability to constrain 2p2h models and 2p2h Interactions: Nucleon Pairs

Nieves et. al. model [7] describing 2p2h interactions has very characteristic two peak structure in phase space of energy and momentum transfer (q_0/q_3, see Eq. 1 for definition). Proton tagged events have different distributions: CC0π-0p occupy mostly lower q_0/q_3 region, while CC0π-Np higher q_0/q_3 region as it is shown in Fig. 3. Since in CC0π-Np there is reconstructed high energy proton hence q_0/q_3 must be higher than in CC0π-0p. There are several 2p2h models but each predicts different q_0/q_3 distribution. It means that with proton tagged samples we can better probe 2p2h interactions.

$$q_0 = E_\nu - E_\mu, \qquad |\vec{q}_3| = |\vec{p}_\nu| - |\vec{p}_\mu| \tag{1}$$

2p2h interactions of neutrinos can happen on proton-neutron (pn) or neutron-neutron (nn) pair. Both Nieves [7] and SUSAv2 [8, 9] models predict different kinematic properties of a proton coming from pn or nn pair. New systematic parameter describing uncertainty of the pn/nn ratio was introduced in the cross section model. It was checked that both proton tagged samples have

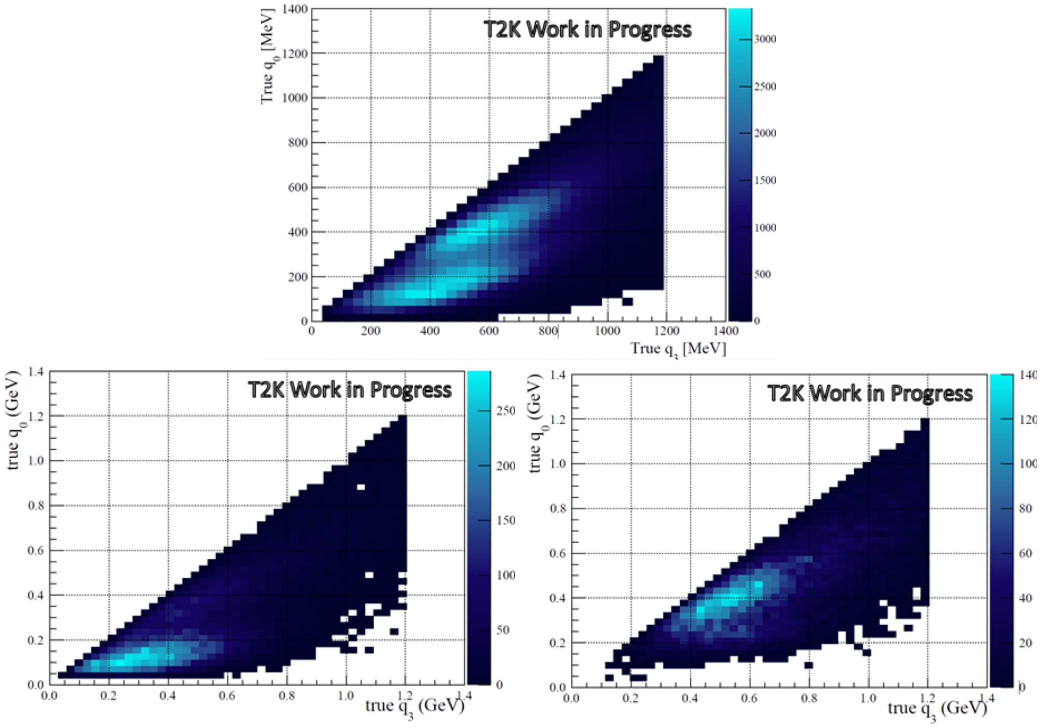

Figure 3: True q_0/q_3 distribution for CC0Pi (top), CC0π-0p (left) and CC0π-Np (right), using Nieves model.

similar sensitivity to this parameter, although rather small as changes to proton kinematic via this effect is subtle.

5. Summary

Proton tagged samples are going to be used in the newest T2K oscillation analysis. Separation of the CC0π-0p sample allowed to increase purity of CCQE with respect to old CC0π sample. Furthermore, it is sensitive to low Q^2 effects like Pauli Blocking. Both samples can help to better understand 2p2h via probing q_0/q_3 phase space. With inclusion of the new samples T2K will then gain new information which might enhance sensitivity to the oscillation parameters.

Acknowledgments

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