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Future sensitivity of upgraded T2K near detector to (anti-)neutrino-nucleus charged current interaction with no mesons in the final state

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Neutrino oscillation physics has now entered the precision era. In parallel with needing more giant detectors to collect more data with, future experiments further require a significant reduction of systematic uncertainties with respect to what is currently available. In the neutrino oscillation measurements from the T2K experiment, the systematic uncertainties related to neutrino interaction cross-sections are currently the most dominant. To reduce this uncertainty a much-improved understanding of neutrino-nucleus interactions is required. In particular, it is crucial to better understand the nuclear effects which can alter the final state topology and kinematics of neutrino interactions in such a way which can bias neutrino energy reconstruction and therefore bias measurements of neutrino oscillations.

The upgraded ND280 near detector of T2K will directly confront our naivety of neutrino interactions using a new detector configuration with full polar angle acceptance and a much lower proton tracking threshold. Furthermore, neutron tagging capabilities in addition to precision timing information will allow the upgraded detector to estimate neutron kinematics from neutrino interactions. Such improvements permit access to a much larger kinematic phase space which correspondingly allows techniques such as the analysis of transverse kinematic imbalances (TKI) to offer remarkable constraints of the pertinent nuclear physics for T2K analyses.

In this talk we quantitatively demonstrate ND280's upgraded sensitivity to key nuclear effects such as removal energy and 2p2h. To this end, we present a fit of a parameterised interaction and flux model to simulated measurements of TKI and neutrino energy from the upgraded ND280.

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1. Introduction

The T2K (Tokai to Kamioka) experiment [1], located in Japan, is a long-baseline neutrino oscillation experiment. T2K aims to measure electron neutrino appearance and to increase the precision of ν_μ disappearance parameters. The goal of T2K is searching for the CP violation in the lepton sector.

The T2K near detector ND280 constrains the neutrino flux and neutrino interaction cross sections for oscillation analysis. The upgraded ND280 detector [2] ("ND280 Upgrade") is an improvement of the existing near detector of the T2K experiment ("ND280"). In the upgraded ND280 configuration, there is a new type of active target for neutrino interactions, made of more than 2 million 1 cm^3 optically isolated scintillating cubes which is super-FGD. The 3D readout and fine segmentation of the super-FGD allow for an excellent hadron reconstruction with very low thresholds in a hydrocarbon material (300 MeV/c). This lower threshold tracking allows a significantly improved characterisation of the nuclear effects that can bias neutrino energy reconstruction which is responsible for some of the largest uncertainties in T2K's latest neutrino oscillation analysis. In addition, the Super-FGD's neutron detection capabilities both extend its sensitivity to anti-neutrino interactions and allow a potential isolation of an almost nuclear-effect free sample of neutrino interactions on hydrogen [3]. Since neutron detection does not rely on particle tracking, but instead on the identification of neutron-nucleus secondary interactions displaced from the neutrino interaction vertex, and there exists an abundance of hydrogen within the Super-FGD to facilitate detection of low energy elastic scatters, there is no important hard neutron detection threshold.
The following sections provide a quantitative estimate of ND280 Upgrade's sensitivity to the most important sources of systematic uncertainty through measurements of the lepton and nucleon in charged-current interactions with no mesons in the final state. These sensitivities are presented as a function of accumulated statistics, covering both the T2K and Hyper-Kamiokande ("Hyper-K") [4] eras and given by the number of protons impinging on the target (POT) in the neutrino beamline.

2. Methodology

2.1 Simulation

The subdetectors for the upgraded ND280, such as HA-TPC and Super-FGD, are under testing and development. Hence the complete simulation of the ND280 upgrade is in active development at the present time based on the estimated detector performances coming from many test-beams. This data has allowed the development of a preliminary Super-FGD detector simulation and reconstruction framework. From this early simulation, the leading detector effects (smearing and resolution) have been parameterised and applied to a sample of neutrino interactions generated with version 5.4.0 of the NEUT simulation [5, 6] on a hydrocarbon scintillator (CH) target using the T2K flux prediction [7]. Notice that the Omar Benhar Spectral Function (SF) model for the nucleus was used. The modelled detector performance is summarised in Fig. 1

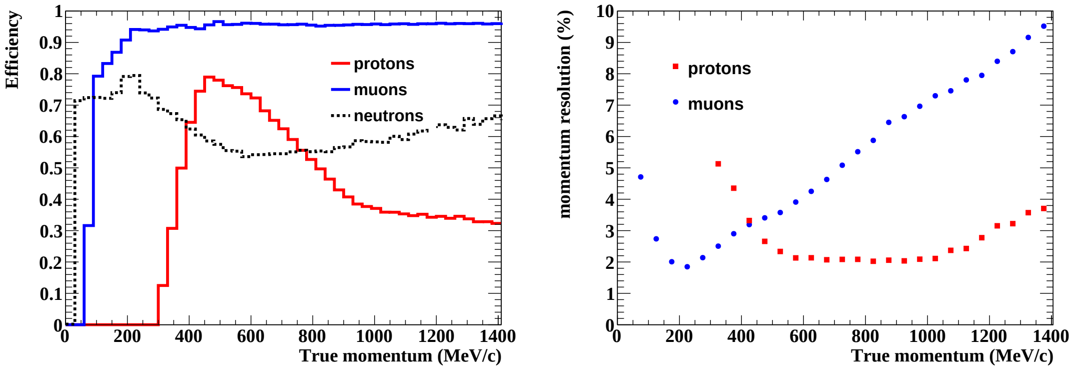

Figure 1: Left: The efficiency to detect protons, muons and neutrons. **Right**: The momentum resolution of muons and protons as a function of their respective momenta. The neutron momentum resolution ranges from15% to 30%

2.2 Analysis strategy

The T2K oscillation analysis relies on a fit of ND280 data to constrain a parameterised model of the neutrino flux and interaction cross-sections. The primary ND280 samples are split depending on whether zero, one or more charged pions are reconstructed in the final state. This analysis uses the CC0π channel only with one nucleon in the final state, but now fitting data presented as a function of hadronic kinematics and its correlations with lepton kinematics, which better exploits the performance assets of the Super-FGD.

A binned likelihood fitter is built in two-dimensions to evaluate the sensitivity of the ND280 upgrade to flux and cross-section model by exploiting Single Traverse Variables (STVs) [8]. This fitter does Asimov fit using the Minuit, including statistical and systematic uncertainties. The statistical uncertainty is implemented as a Poisson term in the likelihood whilst the systematic uncertainties are parametrized as a function of the fit variables and implemented as nuisances with priors included mostly as Gaussian penalty terms in the likelihood.

2.3 Fit variables

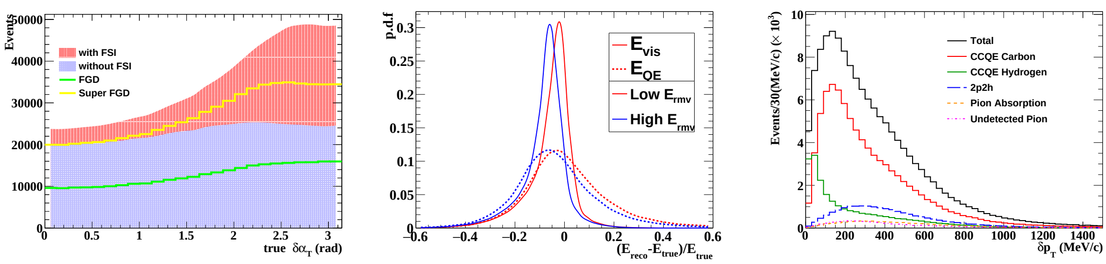

Figure 2: Left: The shaded regions show the $\delta\alpha_T$ distribution. The overlaid solid lines indicate how the total $\delta\alpha_T$ distribution changes from current ND280 FGD to the Super-FGD. **Middle**: The neutrino energy reconstruction resolution and bias is shown for the two estimators E_{vis} and E_{QE}. **Right**: The reconstructed δp_T distribution for selected CC0π anti-neutrino interaction. All three plots are shown for 1×10^{22} POT.

The choice of fit variables really depends on the parameters to be constrained. For instance, to keep the nucleon Final State Interaction (FSI) under control, $\delta\alpha_T$ is a suitable variable to use since its shape has been shown to be sensitive to nucleon FSI. The left plot of Fig. 2 shows the $\delta\alpha_T$ distribution for all CC0π interactions and how sensitive of the Super-FGD to the FSI. The other variable is also a good estimator of neutrino energy. E_{vis} is the total visible energy of all outgoing particles of selected events. The middle plot of Fig. 2 compares the neutrino energy resolution for the two estimators alongside the impact of a possible bias due to removal energy (E_{rmv}). It shows that E_{vis} has better resolution than reconstructed neutrino energy for CCQE events E_{QE} and it is sensitive to E_{rmv}. The last variable is transverse momentum imbalance δp_T. It is known to well separate CCQE from CC-non-QE in CC0π samples whilst also well characterising the Fermi motion. Its distribution is shown in the right plot of Fig. 2.

2.4 Systemactic included in the fitter

CCQE parameter: These parameters are modelled in SF, including P shell, S shell and Short Range Correlation (SRC) parameters. The **2p2h** uncertainties are provided through two normalisation factors, one for $E_{vis} < 600$ MeV and one for the remaining phase space.

Pion production: Pion production is divided into two parameters. The first one alters the normalisation of the pion absorption FSI contribution (**Pion FSI**). The second one controls the normalisation of the Pion production background (**Undetected Pion**).

Nucleon FSI: The outgoing nucleons must go through the nucleus medium before being detected. This parameter is used to quantify this FSI process. **Removal energy** (E_{rmv}): This parameter is used to constrain how much the removal energy shift from its nominal value.

Hydrogen interaction normalisation: This parameter is valid only in the case of anti-neutrino interaction since neutrino can not interact with proton. **Flux covariance uncertainty**: The flux uncertainties are handled using the T2K flux covariance matrix shown in Ref [7], which provides correlated uncertainties on the flux between ranges of neutrino energy.

We also consider a ‘ bin-to-bin uncorrelated uncertainty” which accounts for systematic uncertainties in detector response modelling and small shape freedoms not included via the other parameters.

3. Results and discussion

It is expected that the Super-FGD should allow a particularly strong constraint on nucleon FSI via a measurement of $\delta\alpha_T$. To evaluate this, the left plot of Fig. 3 shows only the nucleon FSI strength uncertainty as a function of the number of POT following fits using either $\delta\alpha_T$ or δp_T alongside E_{vis}. We have shown quantitatively, for the first time, that nucleon FSI can also be very well constrained thanks to the use of $\delta\alpha_T$. The precision of the constraint is enabled by the low proton (and neutron) tracking threshold in ND280 Upgrade and the absence of degeneracy (correlation) with other nuclear-model uncertainties in $\delta\alpha_T$. The right plot of Fig. 3 shows the constraint on the removal energy parameter from a fit to E_{vis} and δp_T for neutrino and anti-neutrino interactions. In the neutrino case the removal energy shift can be measured at 2 MeV at relatively low statistics and better than 1 MeV with ultimate statistics. The corresponding anti-neutrino constraint is 3 to 4 times worse. The constraints on 2p2h give 5.0% (ν) and 8.0% ($\bar{\nu}$) uncertainty at ultimate POT. In

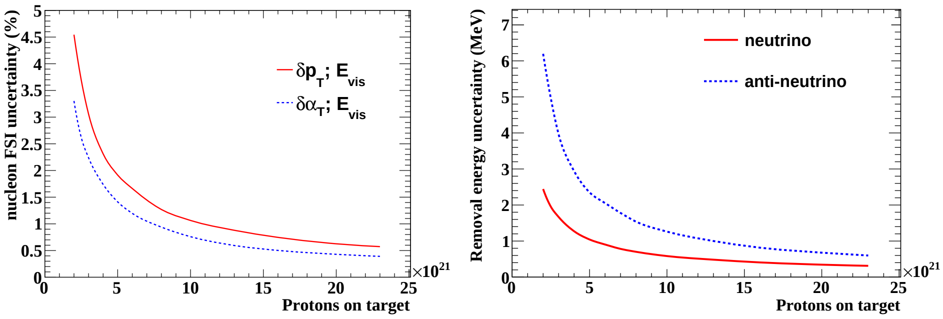

Figure 3: Left:The 1σ sensitivity to the nucleon FSI parameter as a function of POT for neutrino interactions when fitting the reconstructed CC0π data binned in δp_T and E_{vis} or in $\delta\alpha_T$ and E_{vis}. **Right**: The 1σ sensitivity to the nuclear removal energy shift parameter as a function of POT for neutrino and anti-neutrino interactions when fitting the reconstructed CC0π data binned in δp_T and E_{vis}

general, Fig. 4 illustrate that the uncertainties of all systematic parameters at ultimate statistics are below 7% and below 20% in neutrino and anti-neutrino case, respectively [9].
It has been demonstrated that the upgraded ND280 detector will allow increasing sensitivity to nuclear-model uncertainties, enabled by the use of observables formed from both lepton and nucleon kinematics, which can complement the usual T2K analysis of only muon kinematics. Importantly, the use of nucleon kinematics also allows less room for incorrect models to describe ND280 Upgrade data and facilitates more robust constraints.

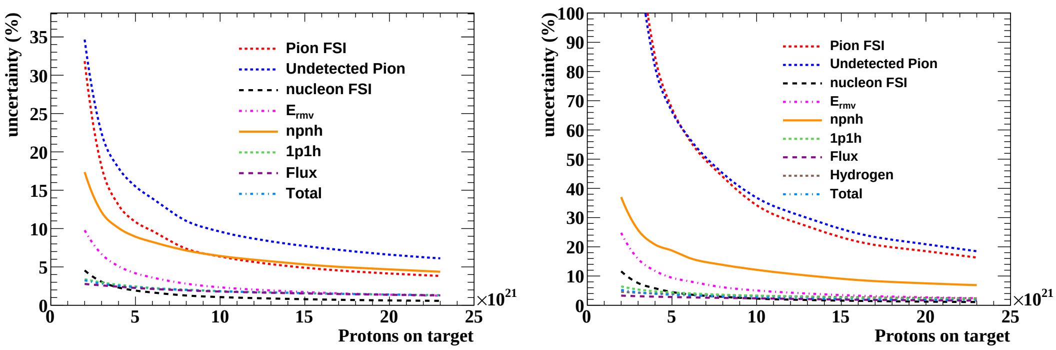

Figure 4: The 1σ sensitivity to systematic parameters as function of POT in neutrino case (left) and anti-neutrino case (right) when fitting the reconstructed CC0π data binned in δp_T and E_{vis}. The values in the plot are the ratio of the parameter uncertainty to the parameter nominal value expressed as a percentage.

Whilst it is shown that most parameter constraints plateau at an acceptable level for Hyper-K era statistics, some show scope for improvement even beyond this limit. This is particularly true for those relating to the flux constraint from the hydrogen enhanced region of δp_T. At very high statistics, improved (and more robust) sensitivities may also be gained by using finer binning or adding additional dimensions to the fit. This could be realised by either additional beam exposure for ND280 Upgrade and/or future further upgrades to increase the target mass (e.g. using the methods suggested in Refs. [10, 11]).

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