Predicting neutrino flux for the T2K experiment

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Abstract. The T2K experiment is a long-baseline neutrino oscillation experiment. One of its main goals is the discovery of the ν_μ to ν_e oscillations governed by the last unknown mixing angle θ_{13}. Additionally T2K aims to make precision measurements of Δm^2_{23} and θ_{23} oscillation parameters. The experiment uses the two detector approach where a near detector measures the neutrino flux close to the ν source, while a far detector measures the oscillated flux. To determine the oscillation parameters the extrapolation of the measurements at the near detector to the far detector has to be done. Such extrapolation relies on the predictions of the neutrino fluxes for the two detectors. In this paper the estimation of the neutrino flux predictions for the T2K experiment is briefly described.

1. Introduction

The T2K (Tokai to Kamioka) experiment [1] utilizes a 30 GeV proton beam from the Japan Proton Accelerator Research Complex (J-PARC) to conventionally produce an intense muon neutrino beam to study the neutrino oscillation phenomenon. One of its main goals is to discover the ν_μ to ν_e oscillations governed by the yet unknown θ_{13} mixing angle. The possibility that this parameter has a non-zero value has been suggested by the recent T2K result [2]. In addition, the experiment aims to make precise measurements of Δm^2_{23} and θ_{23} oscillation parameters. T2K is the first experiment to use an off-axis configuration [3] to get a narrow band ν_μ beam. The unoscillated neutrino flux is measured by a near detector, ND280, which intercepts neutrinos at $2 - 2.5^\circ$ relative to the beam axis (off-axis angle) and is located approximately 280 m away from the production site. The ν beam direction is measured by the INGRID detector placed on the beam axis at the same distance from the target as ND280. The T2K far detector, Super-Kamiokande (SK), located 295 km away from J-PARC and 2.5° off-axis, measures the flux after a significant fraction of ν_μ have undergone oscillations.

To ensure the stability of the off-axis neutrino beam, the proton beam position and angle at the target are controlled to better than 1 mm and 0.5 mrad, respectively. This translates to approximately 1 mrad uncertainty on the neutrino beam direction where a 1 mrad shift results in a 2% shift in the peak energy of the off-axis beam. The stability of the beam direction is further monitored by a muon monitor and the INGRID detector. The measurements of both detectors are consistent and indicate the stability of the ν beam direction is better than 1 mrad.

The analysis strategy of the T2K experiment is to determine the oscillation parameters by comparing the flux measurements at ND280 to the observations at SK. Due to its proximity to the neutrino source the energy distribution of neutrinos seen at the ND280 detector is not exactly the same as the one at SK. Flux predictions derived from beam Monte Carlo simulation are used to relate the two measurements to each other.

2. T2K neutrino beam Monte Carlo and flux predictions

The primary interactions of the proton beam in the graphite T2K target are treated by FLUKA 2008 (latest version at the time of the analysis) [4, 5]. The particles generated in these interactions are then exported for the subsequent transport through the beam-line to a GEANT3 [6] based simulation which uses GCALOR model [7] for hadronic interactions.

The expected fluxes from different parent types are shown in figure 1 for ν_μ at ND280 and SK as well as ν_e at SK. The ν_μ flux sharply peaks in the region 0.5 – 0.7 GeV, where the first oscillation maximum is located. As can be seen from figure 1 the majority of ν_μ come from pion parents. The same pions are responsible for production of muons that in turn produce a significant fraction of low energy ν_e, which are one of the most important backgrounds for the ν_e appearance signal. Understanding the pion production is therefore an essential first step for both the good sensitivity for the ν_e appearance searches and the precision measurement of the ν_μ disappearance signal.

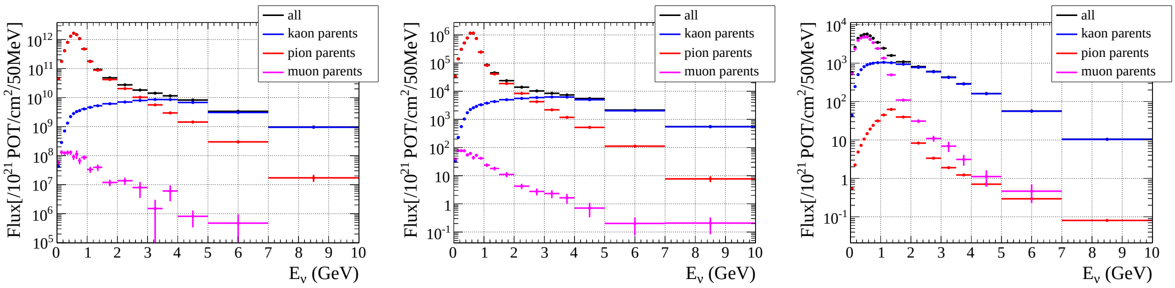

Figure 1. The contributions to the neutrino fluxes and near and far detectors from different neutrino parents. From left to right: ND280 ν_μ, SK ν_μ, and SK ν_e. The fluxes for SK are without the oscillation effects

One of the physics goals of the NA61/SHINE experiment is to provide precise measurements of the hadron production from a graphite target at the T2K beam energy. The experiment has collected data in 2007 and 2009-2010 running with a thin target (0.04 interaction lengths) as well as a replica of the T2K target (1.9 interaction lengths long target). The NA61 pion production results from the analysis of the 2007 run with the thin target [8] have been included in the analysis of the T2K data.

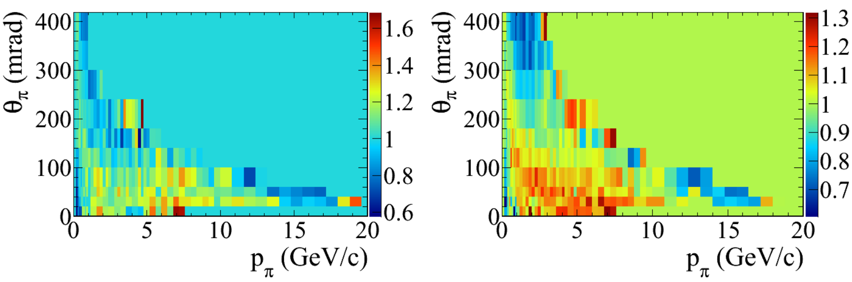

Figure 2. Data/FLUKA ratios of the production multiplicity for π^+ on the left and π^- on the right. Nominal FLUKA values are used outside of the data phase-space coverage

The T2K flux predictions are tuned using the NA61 thin target data by weighting the production of secondary pions—pions produced in the interactions of beam protons—inside the graphite target according to the ratio of the measured to FLUKA predicted multiplicity. Figure 2 shows such multiplicity ratios for π^+ and π^- for different values of pion momenta and production angles. The NA61 pion data is also used to tune the production multiplicity of tertiary pions. Since these pions are produced by protons of lower momentum, momentum scaling is needed. This is done by converting the multiplicity ratios in figure 2 from $p - \theta$ to $x_F - p_T$ phase-space and then determining appropriate weights according to the pion's x_F and p_T rather than p and θ.

In addition to tuning the pion phase-space distribution, the interaction rates of particles in a given material are also corrected. The particles produced in the forward direction may undergo absorption inside the long target. Escaping particles can also be absorbed in the interactions with the surrounding material which mostly consist of horn aluminum. The rate of these interactions is determined by the magnitude of the production cross-section for a given particle in a given material. While the agreement between FLUKA and existing production cross-section data was found to be adequate, significant discrepancy was observed between GCALOR and data. The particle interaction rates with aluminum outside of the target are therefore corrected.

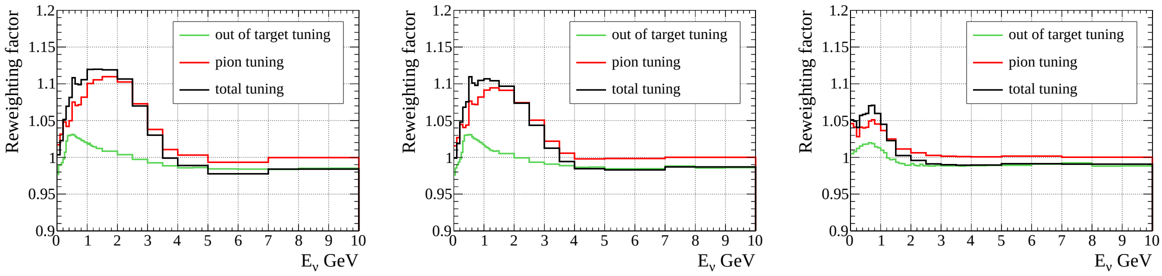

Figure 3. Re-weighting factors for tuning the beam MC as a function of the true neutrino energy. From left to right: ND280 ν_μ, SK ν_μ, and SK ν_e

The weights applied to different neutrino energy bins for ND280 ν_μ, SK ν_μ, and SK ν_e fluxes as a result of tuning the flux predictions based on the NA61 pion measurement and production cross-section data are displayed in figure 3.

3. Systematic uncertainties

Hadron production related uncertainties are the largest contribution to the overall systematic uncertainty on the flux predictions. The experimental errors on the NA61 measurement determines the uncertainty on the pion production in most of the T2K relevant pion phase-space. The uncertainties on kaon and secondary nucleon multiplicities are evaluated from comparison of FLUKA to the measurements with 24 GeV/c protons on beryllium target [9].

In addition to the hadron production uncertainties, other dominant sources of uncertainty are the off-axis angle uncertainty estimated from the INGRID measurement of the neutrino beam direction, proton beam parameters evaluated from the proton monitor measurements, uncertainty in the absolute value of the horn currents, and uncertainty in the alignment of the target and the horns. The fractional error envelopes for each error source are shown in figure 4 as a function of the neutrino energy.

The flux uncertainty on the predicted rate of ν_μ charged current events at ND280, R^{MC}_{ND280}, is 15.4%. The flux uncertainty on the predicted number of electron like events for SK, N^{MC}_{SK}, under $\theta_{13} = 0$ hypothesis (background only) is 16.1%. Given R^{Data}_{ND280}, the measured event rate at ND280, the flux uncertainty on the expected number of e-like events at SK

$$N^{exp}_{SK} = (N^{MC}_{SK}/R^{\mu,MC}_{ND280}) \times R^{Data}_{ND280}$$

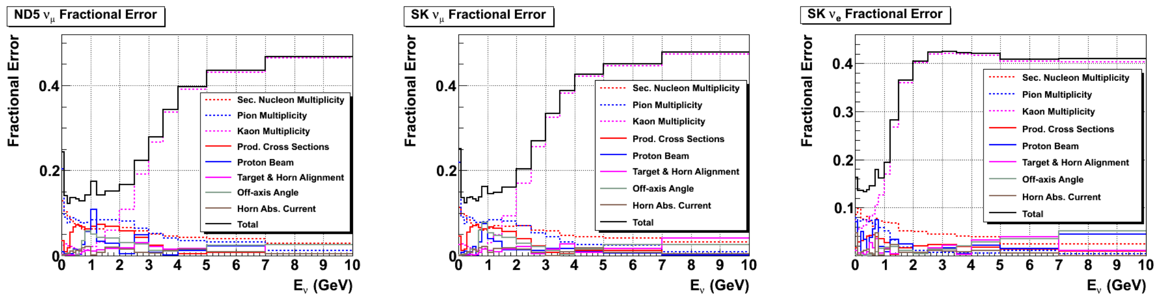

Figure 4. Fractional error as a function of the true neutrino energy. From left to right: ND280 ν_μ, SK ν_μ, and SK ν_e

is the uncertainty on the $N^{MC}_{SK}/R^{MC}_{ND280}$ ratio which leads to a cancellation of some of the flux systematic uncertainties between the two detectors. This results in a smaller flux related uncertainty on N^{exp}_{SK} of only 8.5%.

4. Consistency with ND280 and INGRID measurements

The ratio of the measured to the predicted charged current ν_μ event rate for ND280 is

$$R^{Data}_{ND280}/R^{MC}_{ND280} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$

The ratio of the event rates for INGRID detector is

$$R^{Data}_{INGRID}/R^{MC}_{INGRID} = 1.057 \pm 0.001(\text{stat.}) \pm 0.040(\text{syst.})$$

where the systematic uncertainties quoted do not include the flux and neutrino cross-section uncertainties. Both near detectors show a good agreement with the expectations from the tuned flux.

5. Conclusions

The T2K flux predictions are based on and validated by external hadron production data. As the majority of the neutrinos come from pion parents, the pion production measurements from the NA61 experiment are of particular importance for the reliable flux calculations. The current T2K flux estimations make use of these measurements as well as and existing cross-section data to tune model predictions. A good agreement is found between the event rates predicted from the tuned flux and the measurements performed at the ND280 and INGRID detectors. The uncertainties on the predicted flux are evaluated resulting in an 8.5% uncertainty on the number of the expected ν_e events at SK from background sources. The kaon production results and the measurements of the particle yields from the T2K replica target by the NA61 experiment are expected to further reduce the flux uncertainties.

References

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