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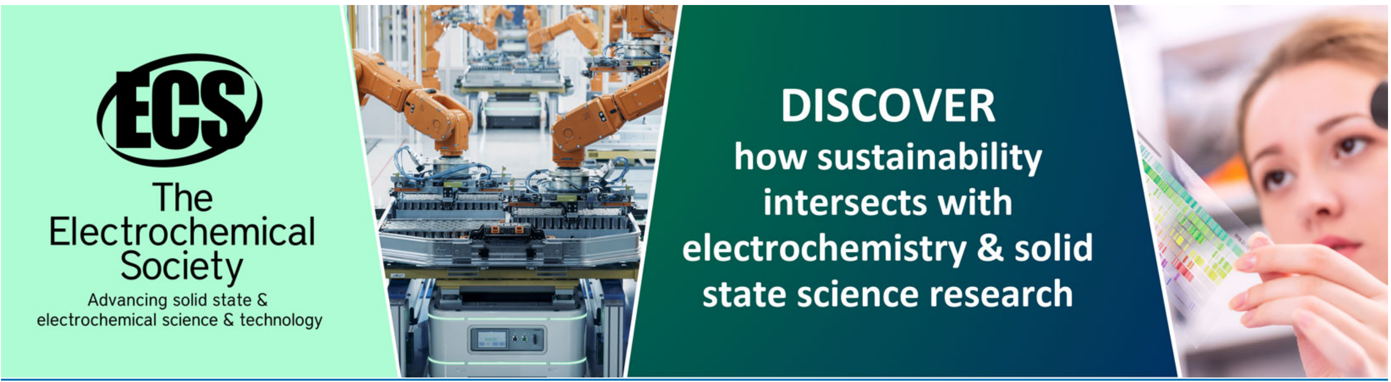

Towards T2K neutrino flux predictions using the replica target measurements by NA61/SHINE

L Zambelli[1], A Fiorentini[2], T Vladisavljevic[3] for the T2K and NA61/SHINE collaborations

[1] Laboratoire d'Annecy-le-Vieux de Physique des Particules, France
[2] York University, Canada
[3] Oxford University, UK and Kavli IPMU, University of Tokyo, Japan

E-mail: `laura.zambelli@lapp.in2p3.fr`

Abstract. The precise knowledge of the neutrino flux composition and kinematics is one of the biggest challenges of long-baseline experiments such as T2K. Neutrinos are made by the in-flight decay of unstable hadrons produced by the interactions of 31GeV/c protons in a long graphite target. Mostly π^+ (π^-) are created, leading to the ν_μ ($\bar{\nu}_\mu$) enhanced flux. As kaons and muons are also produced, an irreducible background of electron (anti-)neutrino is also present. The main source of uncertainty in the flux prediction is driven by the lack of data on the proton-carbon interaction in this energy range. The measurements performed by the NA61/SHINE large-acceptance experiment at CERN are used by the T2K collaboration to improve the flux predictions. Two datasets have been taken: using a thin target to study the primary interaction, and a replica of the T2K target to account for the re-interactions. The recently released differential multiplicity distributions of $\pi^\pm$ along the replica target measured in NA61/SHINE will be presented. This dataset is now in the process of being used by T2K to further tune the flux prediction as 90% of the neutrinos will be directly constrained.

1. The T2K experiment and its neutrino flux

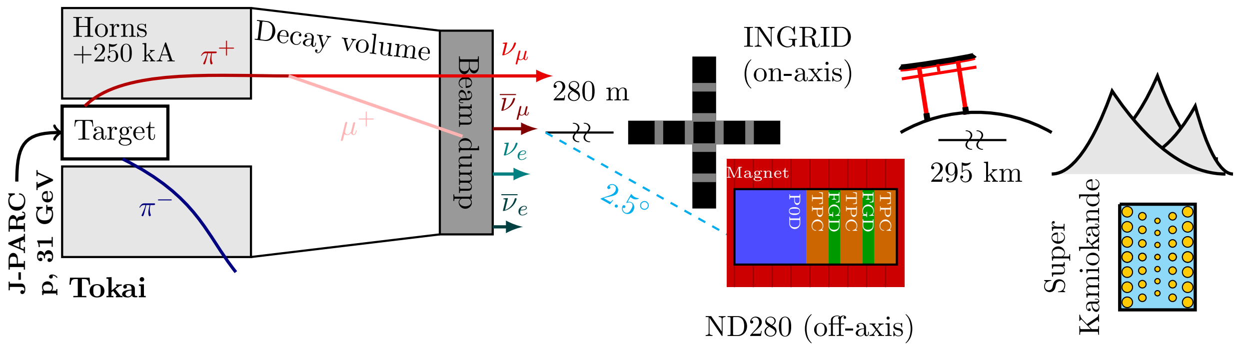

Figure 1. The T2K experiment main components when running in neutrino mode

T2K (Tokai to Kamiokande) is a long baseline neutrino oscillation experiment located in Japan [1] probing (anti-)neutrino mixing parameters using accelerator made (anti-)neutrinos [2]. The main features of the experiment are drawn in figure 1. The J-PARC accelerator delivers a

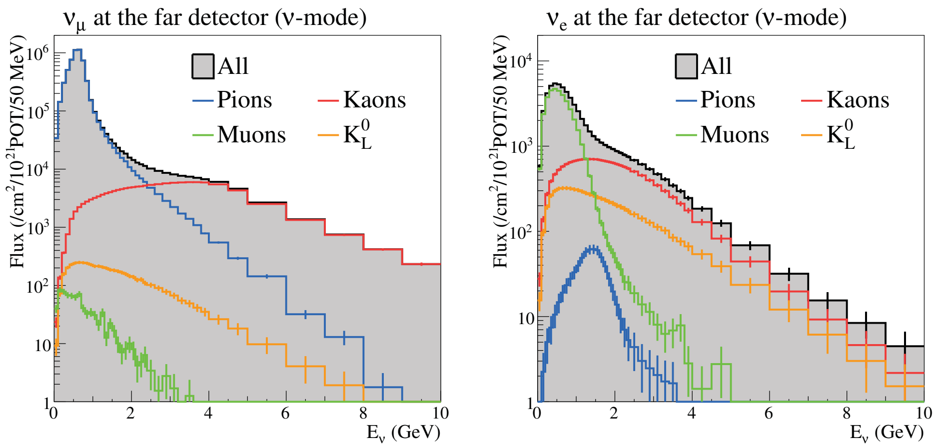

Figure 2. Prediction of the ν_μ (left) and ν_e (right) flux at the T2K far detector when running in neutrino mode. Parents contributions are highlighted.

high intensity proton beam (up to 450 kW as of today) at 31 GeV/c directed onto a long target of carbon (90 cm, $1.9\lambda_{int}$). Hadrons produced in the collisions are focused to the decay volume by a set of three horns. A positive (negative) horn current polarity leads to a ν_μ ($\bar{\nu}_\mu$) enhanced flux. At the end of the decay tunnel, a beam dump absorbs everything other than neutrinos.

Pions are the main hadrons produced, driving the muonic neutrino component through well know 2-body decay channel. As charged and neutral kaons can also be created in the target, electronic and wrong sign neutrinos contaminate the flux. The T2K near (ND280) and far (Super-Kamiokande) detectors are placed off-axis with respect to the beamline leading to a neutrino flux peaked at 650 MeV. In figure 2 the ν_μ and ν_e flux predictions at the far detector are presented, together with their corresponding parent contribution. The knowledge of the neutrino flux composition, direction, intensity and energy spectrum at each detectors is one of the main uncertainty of the oscillation analysis. Understanding the neutrino parent kinematics is the key problem for a precise neutrino flux prediction. In this energy range, the p–C interaction data is relatively poor.

2. NA61/SHINE replica target data

In order to better understand the interaction occurring in the target, the T2K beam features (proton beam, target material) are reproduced at an auxiliary hadroproduction experiment. This enables the measurement of outgoing produced secondary particles which is impossible to carry out in the neutrino beamline. For T2K, the fixed target large acceptance experiment NA61/SHINE [3] at CERN is used with two different targets. A thin target (2 cm) is used to study the primary p–C interactions and to measure the differential production cross section of $\pi^\pm$, $K^\pm$, p, K_S^0 and Λ [4]. These data are currently implemented in the T2K neutrino flux prediction re-weighting procedure [5] directly constraining 60% of the neutrino at the peak energy. The second target is the replica of the T2K target and the outgoing charged pions are measured [6, 7]. At the peak energy, 90% of the neutrino originates from hadrons produced by re-interactions in the target.

For the analysis of NA61/SHINE data, the target is divided in 6 longitudinal bins along the Z-axis. Using a ToF-dE/dx combined analysis, the corrected differential yield per incoming beam proton of escaping $\pi^\pm$ are measured in bins of momentum and polar angle for each Z-bins [6, 7]. The total uncertainty of the measurement ranges between 4 and 14% – the main one being the backward extrapolation from the detector to the target surface. Selected results are presented

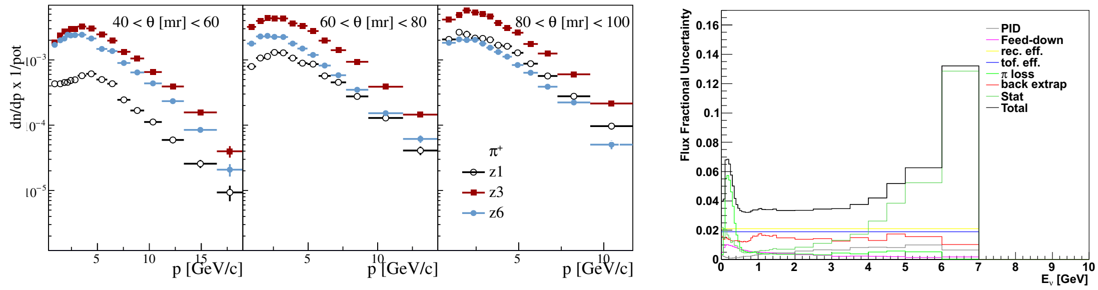

Figure 3. Left: π^+ Differential yield per incoming beam proton escaping the target in the first, third and last Z-bin as a function of the pion kinematics in momentum and polar angle. Right: An example of NA61/SHINE error propagated to the ν_μ flux prediction at the far detector (in neutrino mode). More details in [6, 7].

in figure 3 (left).

3. Tuning T2K flux with the NA61/SHINE replica target data

In the T2K flux simulation, instead of tuning each interaction leading to the neutrino production [5, 8], a weight is only applied to the charged pions when they escape the target:

$$w(\pi^\pm, z, p, \theta) = [dn(\pi^\pm)/dp]^{\mathrm{NA61/SHINE}}_{replica\ data} / [dn(\pi^\pm)/dp]^{\mathrm{T2K}}_{simu}$$

If the outgoing particle is not a pion, or if an out-of-target interaction occurs in the beamline, the thin-target tuning is still applied.

Currently, at the peak energy, the total systematic flux uncertainty amounts to 9%, driven by the uncertainties related to the p–C interaction and cross section and differential hadroproduction cross section. Also, many re-interactions occur in the target, which are difficult to re-weight in the thin-target tuning procedure. All those issues are avoided using this new technique, therefore a reduction of the overall flux uncertainty is foreseen.
A preliminary replica-target tuning have been implemented in the simulation. In figure 3 (right), one can see the ν_μ flux uncertainty at the far detector (in neutrino mode) only due to the π contributions. At the peak energy, the error is 4%, but one should keep in mind that this is a low limit as other sources are not yet included. Finally, when one compares the replica-target tuning to the thin-target one, a 10% disagreement is apparent [6, 7]. This preliminary result needs to be further cross-checked and better understood.

Physicists from the current and future neutrino experiments at Fermilab are now also taking data with NA61/SHINE and plan to apply similar techniques for the precise flux predictions.

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