Constraints on T2K Neutrino Flux Predictions with NA61/SHINE Experimental Data

L Zambelli
On behalf of the NA61/SHINE collaboration
LPNHE, UPMC, 4 place Jussieu
75005 Paris, France

New NA61/SHINE measurements performed with a thin target (2 cm carbon) are presented. Inelastic and production cross section of p+C interactions at 31 GeV/c are released, as well as the spectra of \( \pi^\pm, K^\pm, p, K_L^0 \) and \( \Lambda \). All spectra are compared to chosen hadronic models from GEANT4 physics lists. The relation between these data and the improvement of the T2K neutrino flux is presented, leading to the world-leading measurement of the \( \theta_{13} \) mixing angle in an accelerator-based experiment.

1 The T2K Experiment

The Tokai-To-Kamioka (T2K) accelerator-based experiment in Japan has been designed for the study of the neutrino oscillation phenomena. The latter can be described with the 3 × 3 PMNS mixing matrix which depends on 6 parameters (2 mass splittings, 3 mixing angles and one complex phase) and is a function of the neutrino traveling distance (L) and neutrino energy (E). The precise measurement of the \( \theta_{13} \) is of high interest for neutrino physics as a non-vanishing value can open the door to the CP violation in the leptonic sector. One method (chosen by T2K) to probe this mixing angle is to observe an appearance of electron neutrinos in a nearly pure muon neutrino beam at the atmospheric \( L/E \). With a 295 km baseline between J-PARC complex at Tokai (primary and secondary beamline, near detector) and Kamioka (far detector SuperKamiokande) and an off-axis angle of 2.5°, the \( \nu_\mu \) energy spectrum is peaked at 650 MeV.

As \( \theta_{13} \) is known to be small, the \( \nu_e \) appearance signal is expected to be rare. Hence, a good knowledge of the neutrino flux (one of the main sources of uncertainty) is mandatory.

The \( \nu_\mu \) beam is made by the in-flight decay of focused hadrons – mainly pions – created by the inelastic interactions occurring between 31 GeV/c protons and a long carbon target (1.9 \( \lambda_f \)). Other species are also produced in these interactions: neutral and charged kaons, protons and lambda-hyperons. When pions and kaons decay, so as the muons produced together with the \( \nu_\mu \), electronic-flavored neutrinos will also be made, leading to a source of irreducible background for an accurate measurement of the \( \theta_{13} \) angle. The precise knowledge of the T2K flux – spectra and composition – is hence mandatory. This is hampered by our poor understanding of the hadron production in p-C interactions. Therefore, a direct measurement of the hadronic production in a parallel experiment is conducted with NA61/SHINE at CERN.


Figure 1 – The $p-\theta$ phase space of $\pi^+, \pi^-, K^+, K^-, K^0_S$ and protons (from left to right, top to bottom) contributing to the flux expected at the T2K far detector SuperKamiokande. The region covered by the NA61/SHINE measurement is overlaid for the 2009 (solid line) and 2007 (dashed line) measurement.

2 NA61/SHINE measurements

The T2K beam conditions are reproduced (same proton energy, same target material) with two targets configuration. A thin graphite target ($0.04 \lambda_f$) is used to study primary interactions of protons with carbon, and leads to the production and inelastic cross section measurement. A T2K replica target is also used for the measurement of the spectra of identified hadrons. In 2007, a pilot run has been conducted with the thin 3 and the replica 6 target, with 671k and 230k triggers recorded, respectively. Although the $p-\theta$ phase space of interest was widely covered, see figure 1, the results were statistically limited. During 2008, the detector undergone various updates: new trigger logics, DAQ upgrade and new TPC readout. The wall of the Time of Flight detector has been extended, improving the $\theta$ coverage. The data taken in summer 2009, with both targets, has a statistics increased by an order of magnitude: 5.6M (thin) and 4M (replica) triggers. The use of the GAP TPC detector for the reconstruction of this dataset also improved the kinematic coverage in the forward region.

The measurement performed with the thin target data is presented in the next subsections.

2.1 Inelastic and production cross section

The computation of the inelastic and production cross sections in $p$–$C$ interactions at 31 GeV/c are relevant not only for comparisons with Monte Carlo predictions, but also for spectra normalization. The minimum-biased analysis principle for the inelastic cross section is based on the computation of the trigger cross section, by measuring the interaction probability when the target is inserted and removed. This value is then corrected for trigger biases thanks to a simulation based on the FTF_BIC physics list of Geant4. In order to compute the production cross section, one has to remove the contribution from quasi-elastic processes. This is also estimated with a Monte-Carlo: $\sigma_{QE} = 27.8 \pm 2.2$ mb. The final results are:

$$\sigma_{inel}(p-C \text{ at } 31 \text{ GeV/c}) = 261.3 \pm 2.8(\text{stat.}) \pm 2.2(\text{model}) \pm 1.0(\text{detector}) \text{ mb}$$
The charged hadron (π^±, K^± and p) spectra are extracted simultaneously using combined information on masses, derived from ToF measurements, and energy loss (dE/dx) measured in TPC. Hence, one can have a clear separation of the different species for all momentum and polar angle ranges. Raw yields are fitted using a maximum likelihood method and the spectra are corrected for acceptance, trigger bias, and efficiencies. Since the 2009 dataset has a high statistics, the results are presented in several angular bins. Positively charged pions spectra is presented in figure 2. The systematic uncertainties have been finalized, and the biggest source for protons and pions arises from the feed-down contamination due to decays of neutral strange particles: $\Lambda^0 \rightarrow p + \pi^-$ and $K_S^0 \rightarrow \pi^+ + \pi^-$. 

2.3 Neutral strange particle spectra

The measurement of the $K_S^0$ yield is also relevant for a better prediction of the high energy tail of the $\nu_e$ beam in T2K coming from the 3-body decay of neutral kaons: $K_S^0 \rightarrow \pi^0 \pi^0 \nu_e$. The measurement of the production of the neutral strange particles requires a different analysis strategy in order to increase the acceptance. Tracks fulfilling a $V^0$-like topology are selected, and raw yields are extracted from invariant mass fits in selected bins in the $p - \theta$ phase space. In order to account for acceptance, trigger bias, efficiencies and visible branching ratio, a correction factor is computed with a Monte-Carlo simulation. The influence of short tracking due to a strong electronic noise in this dataset tends to increase the statistical error. The systematical uncertainty is estimated to be about 16 to 25%. 

The measurement within the same dataset of $K^+$, $K^-$ and $K_S^0$ can provide a test for various hypotheses in the predictions of relative yields of the charged and neutral kaons. One can either use the isospin symmetry or basic assumptions on parton distributions in nucleons. As seen in figure 2, a reasonable agreement is observed for both hypotheses, and higher statistics would be needed for a clear discrimination.

3 Constraining the neutrino flux: A quick recipe

The prediction of the T2K neutrino flux consists of several steps. First, a prediction is made by Monte Carlo. All interactions happening in the target are simulated by the Fluka software. Escaping particles are then propagated through the secondary beamline (horns, decay tunnel, beam dump) via Geant3, where the physics model used is GCALOR. For every neutrino produced, we store all the interactions leading to its production. From various hadroproduction data – where those taken at NA61/SHINE are used in priority – weights are computed with respect to the predictions of the Monte Carlo. For each species $i$ produced with momentum $p_i$ and polar angle $\theta_i$ made by the interaction with momentum $p_0$ on nucleus $A$, a weight is computed by:

$$W(p_i, \theta_i, p_0, A) = \frac{\left| \frac{dN}{dp_i}(p_i, \theta_i, p_0, A) \right|_{\text{data}}}{\left| \frac{dN}{dp_i}(p_i, \theta_i, p_0, A) \right|_{\text{MC}}}$$

Where the subscript $MC$ stands for Fluka or GCALOR. For interactions not covered directly by external data, we use scaling hypothesis in momentum and/or in target. Every interaction in the chain of the neutrino production is then re-weighted accordingly. This allows us to get the tuned flux predictions, used in all T2K analysis. The main sources of errors for the neutrino flux arises from the hadronic production, but also from the proton beam profile and our knowledge of the secondary beamline geometry. Currently, 12% error is estimated for $\nu_\mu$ and $\nu_e$ flux at the peak energy (~650 MeV), as well as NA61/SHINE thin target measurement based on 2007 data are used for the re-weighting process. More details can be found in the T2K flux paper.
Figure 2 - Laboratory momentum distributions of the π⁺ (left) and K⁰ (right) multiplicities produced in p-C interactions at 31 GeV/c in different intervals of polar angle θ. Error bars indicate statistical uncertainty. Data points are overlapped by the Geant4 physics list FTF_BIC predictions for different releases of the software. From various comparisons with Geant4 physics lists¹⁰, this one is so far the most promising to reproduce our data.

4 Conclusions, Perspectives

Improvements are expected to further decrease the precision of the neutrino flux predictions. The inclusion of the 2009 thin target data, with wider coverage and new spectra (see figure 1), in the re-weighting process is expected soon. Thin target data helps to constrain directly up to 60% of the flux. Data from the replica target, more difficult to analyze, will be soon released and will constrain up to 90% of the flux⁶. Together with the development of new beamline detectors, as well as a close collaboration with Geant4 developers could allow us to reach the goal of a 5% precision on the T2K neutrino flux.

References

5. N. Abgrall et al, CERN-SPSC-2013-028