The NA61/SHINE hadron production measurements for T2K: update and recent results.

Sebastien Murphy
on behalf of the NA61/SHINE collaboration
Département de Physique Nucléaire et Corpusculaire (DPNC), University of Geneva, 24 quai Ernest Ansermet, 1205, Geneva, Switzerland
E-mail: sebastien.murphy@cern.ch

Abstract. The NA61/SHINE (SHINE ≡ SPS Heavy Ion and Neutrino Experiment) detector at CERN SPS experiment provides the hadron production cross sections of 30 GeV protons on carbon to characterise the neutrino beam of the T2K experiment at J-PARC. The NA61/SHINE detector and its particle identification capabilities are described and the analysis techniques are briefly discussed. Several new results are presented: recently published pion cross-sections with 2007 data on a thin (4% λt) target; preliminary positively charged kaon cross-sections; new results and new methodology for the extraction of production results from a 90 cm long target (replica of T2K).

1. Physics motivation
In order to generate the T2K neutrino beam a high intensity 30 GeV (kinetic energy) proton beam impinging on a 90 cm long graphite target is used, where π and K mesons decaying into (anti)neutrinos are produced. The un-oscillated neutrino beam is measured by a set of near detectors, and is aimed at the Super-Kamiokande water Cerenkov detector (SK) located 295 km away in Kamioka. The experimental strategy of T2K relies on comparing the neutrino event rates measured in SK to the predictions of a Monte-Carlo simulation based on flux calculations and near detector measurements. Before the NA61/SHINE data were available, the prediction of the flux was based on hadron production models tuned to sparse available data, resulting in systematic uncertainties which are large and difficult to evaluate. Direct measurements allow more precise and reliable estimates. Presently, the T2K neutrino beam-line is set up to focus positively charged hadrons, to produce a $\nu_\mu$ beam. While charged pions generate most of the low energy neutrinos, positively charged kaons generate the high energy tail of the T2K beam, and contribute substantially to the intrinsic $\nu_e$ component of the beam.

2. The NA61/SHINE detector and combined particle identification techniques
The NA61/SHINE experiment is a large acceptance hadron spectrometer in the North Area using the H2 beam-line of the CERN SPS (for details see [1]). The main tracking devices are 4 large volume Time Projection Chambers (TPCs). Two of them, the vertex TPCs, are located in the magnetic field of two superconducting dipole magnets and two larger TPCs are positioned downstream of the magnets, symmetrically on the left and right of the beam line. The TPCs provide a measurement of charged particle momenta $p$ with a high resolution.
Figure 1. Scatter plots of $m^2$ versus $dE/dx$ for positively charged particles in three momentum intervals indicated in the panels. $2\sigma$ contours around fitted pion peaks are shown.

In the forward region, the setup is complemented by a time of-flight (ToF-F) detector array horizontally segmented into 64 scintillator bars read out at both ends by photo-multipliers. The time resolution of each scintillator is about 115 ps [2]. The spectrometer equipped with the TPCs + ToF-F system provide full acceptance coverage of the T2K phase-space (parent particles generating a neutrino which hit the near and far detectors).

The method of particle identification (PID), relies on combining the mass-squared measurements from the ToF-F and energy loss per unit length, $dE/dx$, from the TPCs to achieve a high purity particle separation that covers a large momentum range. While the ToF-F allows good particle separation at lower momenta, $dE/dx$ information is needed at higher momenta. The combination of both measurements enables to select particle yields with a very high efficiency over the whole momentum range relevant for the T2K measurements (see Fig. 1).

3. Thin target measurements

Interaction cross sections and charged pion spectra in $p+C$ interactions at 31 GeV/c have been measured and published [1]. The results of three independent analysis were compared: one based on particle identification with only $dE/dx$ measurements below 800 MeV/c [3]; another which consisted in selecting all negative tracks and extracting $\pi^-$ spectra from a global Monte Carlo correction [4]; an analysis in which the $\pi^+$ and $\pi^-$ yields were retrieved from the combined $tof-dE/dx$ PID [2]. The inverse corrections applied to the spectra and associated systematic error in the $tof-dE/dx$ analysis are shown for one angular bin in Fig. 2. In addition to several track quality cuts, maximum acceptance regions were selected by applying a cut on the azimuthal angle, thereby assuring tracks have a large number of measured points, and a very high reconstruction efficiency. This minimizes the systematical errors arising from possible differences in geometry between data and Monte-Carlo. The obtained $\pi^+$ spectra are shown in Fig. 3.

Using the combined $tof-dE/dx$ method, preliminary $K^+$ production cross sections have also been extracted. Final results will soon be published. The low statistic of the 2007 data set and the small kaon production rate imposes a rather coarse $\{p, \theta\}$ binning limited to only the most populated region of phase space relevant for T2K. An order of magnitude larger data set was recorded in 2009, and, when analyzed, will lead to essentially full coverage. The results are shown in Fig. 4 along with the ratio of $K^+$ to $\pi^+$ production cross sections. The central values and errors of the $\pi^+$ spectra were recalculated to match the $K^+$ binning. The achieved systematic uncertainty on the $K^+$ cross sections are similar to those of the pions (of the order
Figure 2. Example of momentum dependence of the inverse correction factor (left) and systematic errors (right) for the \(\text{tof} - \frac{dE}{dx}\) analysis for positively charged pions in the polar angle interval \([40, 60]\) mrad. \(\epsilon_{\text{rec}}\) and \(\epsilon_{\text{tof}}\) are the efficiencies of the reconstruction and of the ToF-F, respectively. The feed-down correction accounts for pions from weak decays which are reconstructed as primary particles, while the pion loss accounts for pions lost due to decays or secondary interactions.

Figure 3. Laboratory momentum distributions of \(\pi^+\) mesons produced in production \(p + C\) interactions at 31 GeV/c in different intervals of polar angle (\(\theta\)). The spectra are normalized to the mean \(\pi^+\) multiplicity in all production \(p + C\) interactions. Error bars indicate statistical and systematic uncertainties added in quadrature. The overall uncertainty (2.3\%) due to the normalization procedure is not shown. Predictions of hadron production models, FLUKA2008 [5] (solid line), and Venus4.12 [6] (dotted line) are also indicated.

of 5\%). The \(K^+\) spectra are dominated by statistical errors which are around 12\%.

4. Measurements with the T2K replica target
T2K replica target measurements are of primary importance since hadrons from target re-
interactions account for about 40\% of the \(\nu_\mu\) flux at peak energy [7]. Unlike the thin target measurements the primary vertex is not fitted and all hadrons exiting the target are measured. To do so, the tracks reconstructed in the TPCs are extrapolated back through the magnetic field
from their first measured point to the surface of the target. The combined \( \text{tof} - \frac{dE}{dx} \) PID is applied to extract \( \pi^+ \) yields exiting the target in bins of \( \{p, \theta, z\} \) (where \( z \) is the longitudinal coordinate of the target). The FLUKA simulation package [5] used in the T2K beam simulation has been interfaced to the NA61/SHINE simulation chain. The PID based on parameterization of the data has also been implemented in the simulation. This allows for both data and Monte-Carlo samples to be processed with the same reconstruction chain and to compute re-weighting factors for FLUKA. The re-weighting factors extracted from 2007 long target data can be found in [7]. Current uncertainties are dominated by the statistical error which is typically around 10%. Systematic uncertainties are within 5-7%.

5. Conclusion
The importance of the NA61/SHINE measurements for T2K has been widely recognised. The thin target \( \pi^+ \) results were included in the T2K beam simulation for the \( \nu_e \) appearance results [8] and have helped to significantly reduce the errors on the flux prediction and thus the final systematic uncertainty on \( \sin^2 2\theta_{13} \). The \( K^+ \) data have recently been provided to T2K and will help reduce the errors on future results. NA61/SHINE is also the first experiment to successfully extract hadron production data from a replica target. The extra constraint on the production of secondary hadrons is expected to be of great benefit for T2K. Meanwhile, a much larger data set with both the thin and the replica target was recorded in 2009 and 2010 and is presently being analyzed.

6. References
[1] Abgrall N et al. (NA61/SHINE Collaboration) 2011 Phys. Rev. C84 034604
[2] Murphy S 2012 Ph.D. Thesis in preparation, University of Geneva, Geneva Switzerland
[3] Posiadala M 2012 Ph.D. Thesis in preparation, University of Warsaw, Warsaw Poland
[4] Palczewski T 2012 Ph.D. Thesis in preparation, National Center for Nuclear Research, Warsaw Poland
[5] Battistoni G et al. 2007 AIP Conf. Proc. 896 31–49
[6] Werner K 1993 Phys.Rept. 232 87–299
[7] Abgrall N 2011 Ph.D. Thesis, University of Geneva CERN-THESIS-2011-165
[8] Abe K et al. (T2K Collaboration) 2011 Phys. Rev. Lett. 107 041801

Figure 4. Left: Differential cross sections for \( K^+ \) production in \( p + C \) interactions at 31 GeV/c. The spectra are presented as a function of laboratory momentum, \( p \), in two different intervals of polar angle, \( \theta \). Error bars indicate statistical and systematic uncertainties added in quadrature. The 2.5% uncertainty due to the normalization procedure is not included. Right: Ratio of \( K^+ \) over \( \pi^+ \) production. Errors are calculated taking into account only statistical uncertainties.