As neutrino long baseline experiments enter a new domain of precision, important systematic errors due to poor knowledge of production cross-sections for pions and kaons require more dedicated measurements for precise neutrino flux predictions. The cosmic ray experiments require dedicated hadron production measurements to tune simulation models used to describe air shower profiles. Among other goals, the NA61-SHINE (SPS Heavy Ion and Neutrino Experiment) experiment at the CERN SPS aims at precision measurements (5% and below) for both neutrino and cosmic ray experiments; those will improve the prediction of the neutrino flux for the T2K experiment at J-PARC and the prediction of muon production in the propagation of air showers for the Auger and KASCADE experiments. Motivations for new hadron production measurements are briefly discussed. NA61-SHINE took data during a pilot run in 2007 and in 2009 with different Carbon targets. The NA61-SHINE setup and preliminary spectra for positive and negative pions obtained with the 2007 thin (4% interaction length) Carbon target data are presented. The use of the NA61 data for the T2K neutrino flux predictions is finally discussed in further details.

1 Needs for new hadron production measurements

Many hadron production experiments have been conducted over a range of incident proton momenta from 3 GeV/c to 450 GeV/c. However, most of them cover only limited ranges in momentum $p$ and production angle $\theta$ (or Feynman scaling variable $x_F$ and transverse momentum $p_T$).

Several models of secondary production have been derived by fitting and interpolating experimental data on $p+A \rightarrow \pi^{\pm}X$ or $p+A \rightarrow KX$. Shower cascade models (e.g. MARS, FLUKA) contain a number of physical assumptions and cannot be modified by users. Parametrizations (e.g. Sanford-Wang, Malensek) account for various aspects of production cross-sections such as $p_T$-scale breaking but do depend on the nuclear target properties, re-interactions, etc.

The lack of hadron production data requires reliance on such models to extrapolate from existing data to the conditions of a given experiment. These extrapolations imply large and poorly known systematic uncertainties. Muon and neutrino flux predictions for current and projected cosmic ray and neutrino experiments will require a precision better than that obtained from those extrapolations. New hadron production data at required projectile momentum and with relevant targets are mandatory to reach the goals of those experiments.
The NA61-SHINE measurements

2.1 The NA61-SHINE experimental setup

The NA61-SHINE apparatus (see Fig. 1) is a large acceptance spectrometer which consists in a set of five time projection chambers (TPCs): two TPCs, referred to as vertex TPCs, are embedded in dipole magnets (1 Tm) and provide a high momentum resolution, while two larger TPCs (main TPCs) are placed downstream out of the magnetic field region. A smaller TPC, referred to as GAP TPC, is placed in between the two vertex TPCs. This set of TPCs is complemented by an upgraded time-of-flight (ToF) system with 120 and 70 ps resolution for the forward and left/right walls respectively.

The large acceptance of the NA61-SHINE apparatus covers the relevant phase space of both T2K and Auger experiments. As an example, Fig. 3 compares the absolute (corrected) \(\pi^+\) distribution in the \(\{p, \theta\}\) \(\theta\) is the production angle with respect to the beam direction) phase space measured by NA61 with the thin Carbon target and that of \(\pi^+\)'s from the primary interaction producing neutrinos in the far detector of the T2K experiment obtained from the T2K beam simulation.

The proton on Carbon data at 31 GeV/c from the 2007 pilot run have been used to produce preliminary spectra of both negative (up to 15 GeV/c momentum) and positive (up to 10 GeV/c momentum) pions in angular bins of 60 mrad. Differential cross-sections for different angular bins are shown in Fig. 4 and Fig. 5 respectively. Only statistical errors are shown, while results are still quoted with 20% systematic errors coming from the current level of disagreement obtained.
Figure 2: Energy loss versus momentum (left) and mass squared versus momentum spectra (right) for positive particles. Combined energy loss and time-of-flight measurements for all particles in the momentum range [2.,2.5] GeV/c (bottom).

Figure 3: Absolute $\pi^+$ spectrum in the \{p, $\theta$\} phase space measured in NA61 (left). Distribution of $\pi^+$'s producing neutrinos in the far detector of the T2K experiment.

when comparing results from different analysis procedures in some bins.

Three procedures have been developed for the analysis: the negative hadron analysis, the $dE/dx$ analysis below 1 GeV/c momentum and the combined ToF-$dE/dx$ analysis starting from 0.8 GeV/c, which is necessary for the $\pi^+$ spectra. The three procedures give consistent results within the quoted systematic errors for the negative pion analysis (see Fig. 4) and continuity is observed between the procedures used for the positive pion analysis (see Fig. 5).

The thin Carbon target results also include the determination of the absolute inelastic cross-section (used for normalization) of proton on Carbon at 31 GeV/c, and preliminary comparisons with different models such as GiBUU\cite{7}, Geant4\cite{11} and FLUKA-standalone. Work is currently performed to lower the quoted systematic errors.
3 NA61 data for the T2K neutrino flux predictions

JNUBEAM (release 10a) is the T2K beam simulation program. It has been used to predict fluxes for the four different neutrino species ($\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$ and $\bar{\nu}_e$) at both T2K near and far
detectors. Fig. 6 shows total fluxes for all species at the far detector, as well as contributions from different parent particles for \( \nu_\mu \) and \( \nu_e \) species.

Figure 6: Neutrino fluxes for all species \( (\nu_\mu, \bar{\nu}_\mu, \nu_e \text{ and } \bar{\nu}_e) \) at the far detector (left). Parent contributions to \( \nu_\mu \) (middle) and \( \nu_e \) (right) fluxes at the far detector.

Contributions to the neutrino fluxes have been defined according to the NA61 measurements. In-target and out-of-target contributions refer to the measurements with the full size T2K replica target. Indirect and direct contributions refer to the measurements with the thin target in which only primary interactions are measured.

The in-target contribution comes from neutrino parents produced inside the target (from primary or secondary interactions), as well as from neutrino parents (such as muons) produced in the decay of particles originating from the target (\(~5\text{-}10\%\) of the contribution). Apart from decays out of the target, this contribution corresponds to what is measured with the long target. The out-of-target contribution accounts for neutrino parents produced in re-interactions in the other elements of the beam line (magnetic horns in particular).

The direct contribution comes from neutrino parents produced in the primary interaction, as well as from parents produced in the decay of those secondary particles. Apart from decays, this contributions corresponds to what is measured with the thin target. The indirect contribution accounts for parents produced in secondary interactions in and out of the target.

As shown in Fig. 7, the ratio of the out-of-target contribution to the total contribution is \(~10\%\) at peak energy for both \( \nu_\mu \) and \( \nu_e \) species. The equivalent ratio between indirect and total contributions is \(~40\%\) at peak energy for both \( \nu_\mu \) and \( \nu_e \). This conclusion stresses the importance of the replica target measurements: providing tracks with momentum and angle (with respect to the beam direction) at exit point on the target surface will allow to predict directly a fraction of the neutrino flux at both near and far detectors as high as \(~90\%\) for both \( \nu_\mu \) and \( \nu_e \) components.

Studies showed variations (both in shape and normalization) of the absolute neutrino fluxes as a function of the neutrino parent exiting point position on the target surface, as well as of the beam profile used in the simulation. Those considerations lead to a binning of the replica target data consisting in six equidistant longitudinal bins and three to four radial bins.

The NA61-SHINE thin target measurements can provide pion and kaon production cross-sections as direct input to the T2K beam simulation. In this case, still \(~40\%\) of the neutrino fluxes would require using models for secondary interactions. Due to the limited azimuthal acceptance of NA61-SHINE, the replica target data cannot be used as a direct input to the simulation on an event-by-event basis. However, they can be used to re-weight the beam Monte-Carlo using the event generators of the T2K beam simulation within the NA61-SHINE simulation chain. In this case, \(10\%\) of the neutrino fluxes would still require using models to predict secondary interactions outside the target. A method has been developed to propagate those re-
Figure 7: Ratio of the out-of-target contribution to the total contribution for $\nu_\mu$ (left) and $\nu_e$ (right) components at the far detector.

weighting factors (and associated statistical and systematic errors) from the $\{p, \theta\}$ phase space (in longitudinal and radial bins) of relevance in T2K, to the neutrino flux predictions.

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