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Hadroproduction experiments to constrain accelerator-based neutrino fluxes

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Abstract. The precise knowledge of (anti-)neutrino fluxes is one of the largest limitation in accelerator-based neutrino experiments. The main limitations arise from the poorly known production properties of neutrino parents in hadron-nucleus interactions. Strategies used by neutrino experiment to constrain their fluxes using external hadroproduction data will be described and illustrated with an example of a tight collaboration between T2K and NA61/SHINE experiments. This enabled a reduction of the T2K neutrino flux uncertainty from $\sim 25\%$ (without external constraints) down to $\sim 10\%$. On-going developments to further constrain the T2K (anti-)neutrino flux are discussed and recent results from NA61/SHINE are reviewed. As the next-generation long baseline experiments aim for a neutrino flux uncertainty at a level of a few percent, the future data-taking plans of NA61/SHINE are discussed.

1. Introduction
1.1. Standard neutrino beamline
Long baseline experiments use a $\nu_\mu$ ($\bar{\nu}_\mu$) flux to probe the (anti-)neutrino mixing parameters. The flux is produced with the help of a beamline made of a set of standard elements, as sketched in figure 1:

A high intensity proton beam fast extracted from an accelerator. The proton momentum spans from tens to hundreds of GeV/$c$. Current and future experiments aim to achieve a beam power at the MW scale, and a total statistic of at least $10^{21}$ protons on target (POT).

Figure 1: Schematic view of a standard neutrino beamline. Here, the focusing horns are set in positive polarity selecting positively charged hadrons.
A long target made of light material such as carbon or beryllium (to handle the heat from radiation) and usually as long as a few interaction lengths. Neutrino ancestors are created during the beam inelastic collisions in the target. The geometry of the target is of great importance as the re-interactions will produce low energy hadrons. To limit this effect, some experiments use a segmented target enabling small-angle high-momentum secondaries to escape.

A set of focusing horns following Van der Meer idea [1] consisting of two axially-symmetric conductors with a pulsed current running from the inner to the outer conductor. Typically, a 2 to 3 horn system is placed around (or just downstream of) the target. Focusing horns select the secondary particles according to their electric charge while defocusing the opposite ones. When horns are running with in positive (negative) polarity, positively (negatively) charged secondaries are selected, leading to a neutrino (anti-neutrino) enhanced flux. Selected hadron beam is then focused towards the decay pipe.

A decay pipe allowing the neutrino ancestors to decay. The design of the pipe should be carefully chosen in order to maximise the number of hadron decays, while minimising the lepton (muons) decay contribution to the neutrino flux.

A dump to absorb remaining charged particles at the end of the decay pipe. A muon monitor detector can be placed after the dump to survey the secondary beam direction using high momentum muons passing through the dump.

More details on neutrino beamlines can be found in [2].

1.2. Need for hadroproduction experiments

Mostly $\pi^+ [\pi^-]$ are produced leading to the $\nu_\mu, [\bar{\nu}_\mu]$ flux components. But other hadrons ($K^\pm$, $K^0_L$) and muons (created together with the neutrino) can decay in the decay pipe, which lead to an electron and wrong-sign neutrino flux component : $\nu_e, \bar{\nu}_e, [\bar{\nu}_\mu, \nu_\mu, \nu_e]$. In figure 2, the predicted neutrino flux by species at MiniBooNE and T2K far detector are presented (both for running in positive focusing mode).

The kaon decays contribute to the high energy tail of the spectrum, while pions and muons decays populate the peak region. In order to have an accurate prediction of the neutrino flux composition, energy spectrum and intensity at the detectors, the secondary hadron production cross section and kinematics from the proton–target interactions has to be known. Due to the high intensity, limited space and risks of secondary beam destruction, this measurement cannot
be performed directly in the neutrino beamline. Therefore, long baseline neutrino experiments cooperate with external hadroproduction experiments where the beam features are reproduced (beam energy, target material) and the secondary hadrons directly measured.

2. Hadroproduction experiments

2.1. Introduction

Data taken in hadroproduction experiments can be sub-divided into two categories:

Thin target where the primary p-A interaction can be studied. In particular the total p-A inelastic (or production) cross section can be measured as well as the differential multiplicity of various secondary particles ($\pi^\pm$, $K^\pm$, neutral strange particles, protons). As for T2K, at the peak energy, it has been shown that 60% of the $\nu_\mu$ and $\nu_e$ neutrinos originate from the decay of hadrons produced in the primary interaction [5] (in positive focusing mode).

Replica target of the corresponding neutrino experiment is used. The differential yield per incoming beam proton of charged pions escaping the target is measured. At T2K, at the peak energy, 90% of the $\nu_\mu$ and $\nu_e$ neutrinos originate from hadrons produced in the target [5] (in positive focusing mode).

Below are briefly described selected hadroproduction experiments. More details can be found in the references.

2.2. HARP

The HARP experiment was located at the CERN PS and took data in 2001 and 2002. Its apparatus consisted of a large-acceptance spectrometer with a forward and a large-angle detection system [6]. The main elements of the detector are drift chambers, a dipole magnet and time of flight detectors. The data were taken in roughly 300 different settings: p and $\pi^\pm$ beam with momentum from 1.5 to 15 GeV/c and with a large range of target materials in thin and thick configurations. The phase-space covered for the measurement of secondaries ($\pi^\pm$, $K^\pm$, p) ranges from 0.5–8.0 GeV/c in momentum and 25–250 mrad in polar angle in the forward configuration, and from 0.1–0.8 GeV/c in momentum and 350–2150 mrad in polar angle in the large angle configuration. The hadroproduction data measurements have been used by the K2K [8], Mini-, Sci- and Micro-BooNE experiments [7, 3] for direct constrains. Also, many other experiments have used HARP data to constrain their re-interactions in the long target.

2.3. MIPP

The MIPP experiment, located in the NuMI facility at FERMILAB, is a spectrometer with a TPC just downstream of the target, 2 dipole magnets, a time of flight detector and a gas ring imaging Cherenkov detectors [9]. The beam conditions of the NuMI-based experiments (MINOS, MINERvA, NOvA) are reproduced: 120 GeV/c protons on a 90 cm long aluminium tube encompassing 47.2 cm graphite slabs. The hadroproduction yields ($\pi^\pm$) off the target has been measured in a phase-space of 0.3–80 GeV/c for the total momentum and 0–2 GeV/c in transverse momentum $p_T$.

2.4. NA61/SHINE

The NA61/SHINE experiment (successor of the NA49 experiment) is located at the H2 beamline of the CERN SPS. It is a large acceptance spectrometer with 5 TPCs – two of them are inside a superconducting magnet – and a time of flight detector [11]. NA61/SHINE has taken data for the T2K experiment (31 GeV/c proton on a graphite target) between 2007 and 2010 with two graphite target configurations: thin (up to 5.4 M triggers) and a T2K replica (up to 10 M triggers), and is now conducting measurements for the NuMI-based experiments [12].
The charged particle identification is performed through a combined ToF-dE/dx (dE/dx only) analysis for particle with momentum above (below) 1 GeV/c. Neutral strange particles are selected using a standard invariant mass fit criteria. Using the thin target data, the differential multiplicity of $\pi^\pm$, $K^\pm$, p, $K^0_S$ and $\Lambda$ production has been measured \cite{13, 14, 15, 16} in bins of secondary particle momentum and polar angle. The measured phase-space is 0.2~22 GeV/c in momentum and 0~420 mrad in polar angle which is highly relevant for the T2K experiment. The total uncertainties are around 5% for charged pions, around 10% for protons and around 15% for charged kaons, $K^0_S$ and $\Lambda$.

Using the replica target data, the differential yield of $\pi^\pm$ per incoming beam proton in bins of pion momentum and polar angle has been measured. The measurements are presented in bins of longitudinal position along the target \cite{5, 17, 18}. The total uncertainty of the measurements ranges between 4% and 14%, the backward tracking of pions from the detector to the surface of the target being the main source.

3. Neutrino flux tuning using thin target dataset : Strategies and results

\begin{equation}
\frac{dN}{dp}(p, \theta)_{data} = \frac{\frac{dN}{dp}(p, \theta)_{MC}}{\sigma_{data} \sigma_{MC}} \times \exp[-\rho d (\sigma_{data} - \sigma_{MC})]
\end{equation}

\begin{equation}
w_{\text{int.}} = \frac{\sigma_{data}}{\sigma_{MC}}
\end{equation}

The data from the hadroproduction experiments (total cross section and differential multiplicity of hadron production) are used to constrain the p-target interactions in the neutrino flux simulation as follows:

- The amount of hadrons produced per interactions predicted by the hadronic model is corrected following equation 1. These weights, computed from a separate high statistic Monte Carlo sample, are applied to the parents of neutrinos when corresponding measurements are available.

- The amount of interactions in materials are corrected following equation 2 where the thickness of material crossed is taken into account.

This is illustrated in figure 3 for the charged kaons (case a). If there is no direct data available to constrain the neutrino parent, due for example to in-target re-interactions (case c in figure 3) or out-of-target interactions (case b in figure 3) the following methods can be used:

- In order to increase the kinematical coverage of the measured hadron production, the differential multiplicity are often parametrised and can therefore be extended to a wider space-phase \cite{19, 20}. The multiplicity correction is computed with respect to the data parametrisation.

- If the interaction occurs at a momentum different from available measurements, one can apply a momentum scaling using the Feynman hypothesis \cite{22}. When expressed in $x_F - p_T$ kinematics (where $x_F = p_{L}^* / p_{L,\text{max}}^*$ is the fraction of longitudinal momentum taken), differential hadroproduction cross section can be considered as invariant.

- If the interaction occurs on a different nucleus, target dependency of the hadroproduction cross section can be parametrised in $x_F - p_T$ kinematics following the prescription of \cite{19}.

- One can make educated guesses, for example the yield of $K^0_L$ can be expressed as a mixture of $K^+$ and $K^-$ yields.
• Trust the hadronic model predictions.

This is the method followed by T2K to constrain their neutrino flux predictions [21] and, to some extent by MINERvA [10]. T2K uses the data from NA61/SHINE while MINERvA utilises the data of NA49. In figure 4, the $\nu_\mu$ flux uncertainties from hadronic interactions of MINERvA and T2K far detector are presented (both running in neutrino mode). At their peak energies, MINERvA reports 7% error (around 3 GeV) and T2K 9% (around 650 MeV). MINERvA hadronic uncertainties are driven by nucleon interactions on targets other than carbon in most of the spectrum, and by $\pi^\pm$ multiplicity from p–C interactions around the peak energy. For T2K, the interaction length is the dominant source in the whole energy range.

4. Neutrino flux tuning using replica target dataset: Strategies and results

If charged pion yields off a replica target have been measured, these data can be used in the neutrino flux tuning procedure as follows:

• The yields of pions escaping the target are corrected according to equation 3. This weight is applied to $\pi^\pm$ neutrino parents produced in the target. Therefore, in-target re-interactions leading to pion production and interaction cross sections are not directly constrained anymore. This is illustrated in figure 5 for the escaping pion (case c).

• For any other hadrons escaping the target (case a in figure 5) or for out-of-target interactions (case b in figure 5), the thin target tuning procedure shall be used as described in the previous section.

This is the method currently being developed by the T2K collaboration to incorporate the $\pi^\pm$ yields off the replica target data measured in NA61/SHINE. The MINERvA experiment followed a similar approach with the MIPP data. In figure 6 are presented the $\nu_\mu$ flux hadronic uncertainties when the replica target tuning is used for MINERvA and T2K far detector (both...
running in neutrino mode). At its peak energy, MINERvA reports 5% error. At T2K peak energy, the error is 4%. As only the NA61/SHINE $\pi^\pm$ uncertainties have been propagated in this $\nu_\mu$ flux prediction, this should be considered as a low limit until the analysis is completed.

5. Conclusions and prospects

The tight collaborations between hadroproduction and long baseline neutrino experiments lead to precise knowledge of the neutrino flux. Without hadroproduction data, the neutrino flux error would amount to about 25%. Using thin-target tuning, the flux uncertainty down to about 10% and the replica-target tuning can push the uncertainty down to about 5%. Future long baseline experiments (DUNE, Hyper-Kamiokande) are computing their sensitivities with the assumption that the flux error will be known at a level below 5%. Therefore, new sets of data taking are scheduled, in particular at NA61/SHINE [12], with various targets and beam energies to better understand and constrain the primary and secondaries interactions in and out of the target.

References