High precision flux measurements with ENUBET

M. Pozzato on behalf of the ENUBET collaboration
INFN – Sez. Bologna, V.le Berti Pichat 6/2 - Bologna
michele.pozzato@bo.infn.it

Abstract. The challenges of precision neutrino physics (i.e the study of CP violation) require measurements of absolute $\nu$ cross sections at the GeV scale with exquisite ($O(1\%)$) precision. Such precision is presently limited to about 10% by the uncertainties on neutrino flux at the source. A reduction of this uncertainty by one order of magnitude can be achieved monitoring the positron production in the decay tunnel originating from the $K_{e3}$ decays of charged kaons in a sign and momentum selected narrow band beam. This novel technique enables the measurement of the most relevant cross-sections for CP violation ($\nu_e$ and $\bar{\nu}_e$) with a precision of 1% and requires a special instrumented beam-line. Such non-conventional beam-line will be developed in the framework of the ENUBET Horizon-2020 Consolidator Grant (PI A. Longhin), recently approved by the European Research Council (grant agreement No 681647).
In this poster, we will present the Project and the early experimental results on ultra-compact calorimeters that can be embedded in the instrumented decay tunnel.

1. Introduction

Since the first proposal by Pauli in 1930 to explain an apparent energy non conservation in $\beta$-decay, neutrinos played a fundamental role in the study of weak interactions and, after the observation of the oscillation phenomenon, they opened a window on physics beyond the standard model. Data on neutrino oscillations can be described as the mixing of the three neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$) which are a superimposition of three light mass states with unequal masses. The matrix governing the mixing is parametrized by 3 Euler angles and by a phase potentially leading to a CP violation in the leptonic sector in neutrino oscillations. The precise measurement of neutrino interaction cross sections will play a key role in the next generation of oscillation physics experiments with a significant impact on the study of CP violation and mass hierarchy problems.

Neutrino experiments are affected by an intrinsic limitation given by a large uncertainty of the overall neutrino flux ($\sim 10\%$) directly reflecting on the cross section measurements. A change in the method used to determine the neutrino flux is needed: a technique specifically focused on $\nu_e$ cross sections has been proposed in [1] and is here presented together with first results coming from test beam data.

This new method has the dual advantage of providing a source of $\nu_e$ from $K^+ \rightarrow e^+\nu_e\pi^0$ allowing to study directly their interactions (without relying on extrapolations from $\nu_\mu$) by using an observable (the positron rates) which is directly linked to the $\nu_e$ rate at far detector. The direct monitoring of the neutrino rate at the source is expected to be capable to provide a flux measurement error of $\sim 1\%$. This will be tested in depth by within the project "Enhanced NeUtrino BEams from kaon Tagging" (ENUBET).
2. Beamline
In the proposed setup primary protons are impinging on a target to produce secondary hadrons which are charge and momentum selected and transported to a secondary instrumented beam line (Fig.1).

Figure 1: Facility layout.

Secondary meson yields for this facility were evaluated with FLUKA 2011 [2]; the estimated maximum rate that the detector can deal with is about 500 kHz/cm² leading to \(~1.5\times10^{12}\) PoT/spill assuming a 10 ms spill length and a 450 GeV proton energy. This is unconventional for high energy accelerators where the number of proton in the lattice typically exceeds \(10^{13}\) with a repetition rate of \(~0.1\) Hz. Two possible solutions are under investigation:
- multi-turn resonant extraction lasting 10 ms with \(~10\) Hz repetition and horn-based focusing;
- slow extraction of the order of 1s with DC operated focusing magnets.

3. Instrumented decay tunnel
A cost-effective solution capable of working in the harsh environment of a decay tunnel, with rates up to 500 kHz/cm² and a radiation exposure of about 1.3 kGy [1], comes from employing compact shashlik calorimeters read out with fast wavelength shifting fibers each coupled with its own silicon photomultiplier (SiPM). This detector, effective in e/\(\pi\) separation, is coupled to a plastic scintillator tracker acting as a photon veto (\(t_{0}\)-layer). The use of SiPM embedded inside the module allows to achieve the desired longitudinal segmentation without dead zones in the longitudinal sampling thus achieving a remarkable compactness.

Figure 2: Supermodule schecht

Figure 2 shows a Super Module characterized by a photon veto (\(t_{0}\)-layer), 2 innermost layers (electromagnetic calorimeter) readout every \(~10\) cm \((~5\ X_{0})\) and 6 outer layers (hadronic calorimeter) readout every 60 cm. Positrons produced by the \(K_{e3}\) decays are emitted with a mean angle of 88 mrad. They thus cross on average five \(t_{0}\)-layer doublets. Undecayed pions, together with transported protons and muons from pion decay will not intercept the outer walls of the decay tunnel and will not contribute to the rates, provided that the entrance window and the spread in polar angle of secondaries are small enough \((\pm 5\ cm, \sim 3\ mrad)\). Pile up can be limited at the level of a few percent with a 10 cm² segmentation granularity and a recovery time of \(~10\) ns.
4. Background
The main background sources to the $K_{e3}$ signal come from $K_{\mu2}$, $K_{\mu3}$, $K^+ \rightarrow \pi^+\pi^0$. The first two sources are well under control since the $\mu^+/e^+$ misidentification is at the level of $10^{-3}$ thanks to the longitudinal electromagnetic sampling and the distinct signature of minimum ionizing particles inside the calorimeter. The main source of background for the $e^+$ raises from the $\pi^-$ interactions due to fluctuation in the electromagnetic component in hadronic showers which can mimic a positron signal. Another background source is $K^+ \rightarrow \pi^+\pi^-\pi^0$: even if the branching ratio is quite low ($\sim 6\%$) the higher charge multiplicity leads to higher misidentification. It must be noted that also hadronic $K$ decays (despite producing a contamination in the $e^+$ sample) are a useful sample to constraint the $\nu_e$ flux since the ratio of leptonic to hadronic $K$ decays is precisely measured.

5. Test on compact calorimeters (SCENTT)
A first prototype of the compact calorimeter has been developed and tested at PS beamline at CERN [3]. Fig. 3 (left) shows a picture of the test beam setup.

![Figure 3: Apparatus for the test beam at CERN-PS (left), efficiency and purity $e/\pi$ separation (right)](image)

The challenge of separating electrons from hadrons with high efficiency and high purity is achievable as it is shown in the right panel of Fig 3: the electron sample (electron efficiency $>98\%$) was selected with the Cherenkov counter, operated with CO$_2$ at a pressure of 1.25 bar.

6. Conclusion
The uncertainty in neutrino cross section is dominated by the knowledge of the flux at source in conventional neutrino beams: this is a key point to establish CP violation in the leptonic sector for the next generation neutrino experiment. A novel approach to the $\nu_e$ cross section measurement is based on the monitoring of large angle positrons coming from $K^+ \rightarrow e^+\nu_e\pi^0$ decay. We discussed the most relevant technical challenges and ongoing R&D both for the design of the beamline and for the instrumentation of the decay tunnel. The current design foresees a detector based on compact shashlik calorimeters, suitable for the instrumentation of the decay tunnel and fulfilling the requirements in terms of of PID capability, pile-up and radiation hardness. First tests on a small prototype at the PS beamline at CERN have been shown. ENUBET aims to demonstrate the feasibility of monitoring neutrino rate at the source with high-angle lepton tagging. This technique is expected to improve the flux measurement by a factor ten allowing the measurement of $\sigma(\nu_e)$ with a moderate mass (~500 t) detector (LAr or W-Cherenkov) over a running time of a few years at present accelerators.

References
[1] A. Longhin, L. Ludovici, and F. Terranova, Eur. Phys. J. C75, 155 (2015), arXiv:1412.5987.
[2] G. Battistoni, S. Muraro, P. R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso, and J. Ranft, AIP Conf. Proc. 896, 31 (2007).
[3] A. Berra, et al. N.I.M. A, 2016.05.123, arXiv:1605:09630