A non-conventional neutrino beamline for the measurement of the electron neutrino cross section*

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Abstract

Absolute neutrino cross section measurements at the GeV scale are ultimately limited by the knowledge of the initial ν flux. In order to evade such limitation and reach the accuracy that is needed for precision oscillation physics ($\sim 1\%$), substantial advances in flux measurement techniques are requested. We discuss here the possibility of instrumenting the decay tunnel to identify large-angle positrons and monitor ν_e production from $K^+ \to e^+ \nu_e \pi^0$ decays. This non conventional technique opens up opportunities to measure the ν_e CC cross section at the per cent level in the energy range of interest for DUNE/HK. We discuss the progress in the simulation of the facility (beamline and instrumentation) and the ongoing R&D.

INTRODUCTION

A precise measurement of neutrino interaction cross sections will play a key role in the next generation of oscillation physics experiments and will impact significantly on the CPV and mass hierarchy (MH) reach of long baseline facilities (see e.g. [1]). This is particularly evident for ν_e cross sections since $\nu_\mu \to \nu_e$ transitions (and their CP conjugate) represent the main observable to measure the CP phase and determine the sign of Δm^2_{31} (MH).

In the last ten years, an intense experimental programme has been pursued, employing both the near detectors of running long-baseline experiments and dedicated cross section experiments [1]. This programme already provided a wealth of new data on absolute and differential cross section both with inclusive (CC and NC) and exclusive final states identification. These data challenge current theoretical interpretations of neutrino interaction on nuclei at the GeV scale and boosted the development of several new models and a systematic comparison of existing approaches [2].

Modern cross section experiments are swiftly reaching the intrinsic limitations of conventional neutrino beams. In these beamlines, both the ν_e and ν_μ flux is inferred by a full simulation of meson production and transport from the target down to the beam dump and is validated by external data (hadro-production data, online monitoring of the protons on target and muon current after the beam dump). Employing dedicated hadro-production experiments (replica targets) the uncertainty on the neutrino flux can be reduced to $\sim$10% and additional improvements in the 5-10% scale are still possible [3].

On the other hand, reaching the per cent scale requires a change of paradigm in the techniques employed to determine the neutrino flux similar to the one recently proposed by the nuSTORM Collaboration [4].

A technique with a similar aim as nuSTORM and specifically focused on ν_e cross sections has been considered in [5]: a beamline with focused and sign-selected secondaries at 8.5 GeV that are transported down to an instrumented decay tunnel where electron neutrinos are produced by the three body decay of K^+ (K_{e3}, i.e. $K^+ \to e^+ \nu_e \pi^0$). Inside this non conventional decay tunnel, large angle positrons are identified by purely calorimetric techniques. The mean energy and momentum bite (±20%) of the transfer line is optimized to enhance the ν_e components from K_{e3} and suppress to a negligible level the ν_e contamination from muon decays. This beamline provides an intense source of electron neutrinos for the study of ν_e CC interactions. It exploits an observable (the positron rate) that can be directly linked to the rate of ν_e at the far detector through the three body kinematics of K_{e3}. The positron rate in the decay tunnel allows for the *direct* monitoring of the ν rate at source and provides a per cent measurement of the flux.

The proposal put forward in [5] must be validated through a dedicated R&D. The most relevant items are the design and optimization of the beamline, the choice of the technology for the positron monitoring and the evaluation of the systematic budget. In this talk, we report on the progress of such R&D, the results achieved in the last few months and the plans for the future.

YIELD AT THE TARGET AND TRANSFER LINE

High precision ν_e cross section measurements based on K_{e3} decays can be performed employing conventional beamlines with primary protons impinging on a target, producing secondary hadrons which are captured, sign selected and transported further down to the instrumented decay tunnel (see Fig. 1).

Secondary meson yields for this facility were evaluated with FLUKA 2011 [6] to simulate primary proton interactions on a 110 cm long (about 2.6 interaction lengths) cylindrical beryllium target of 3 mm diameter. Graphite and INCONEL targets are being simulated, too. For the momentum range and transfer line acceptance of interest for this study, the secondary yields at the target grow linearly with the primary proton energy. The yields have been computed simulating proton energies of relevance for the J-PARC Proton Synchrotron

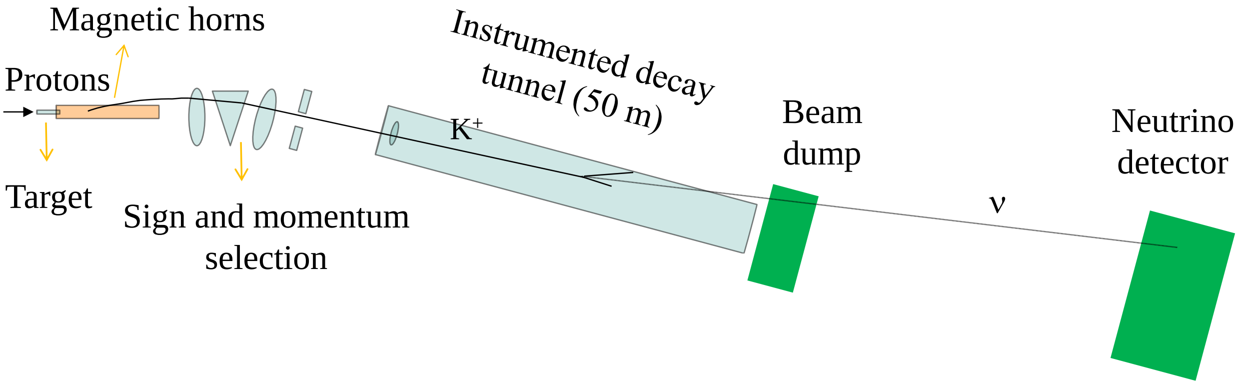

FIG. 1: Layout of the facility (not to scale).

(30 GeV), the Fermilab Main Injector (120 GeV) and the CERN SPS (450 GeV).

An end-to-end simulation of the focusing and transfer line is not available yet and will be the subject of upcoming R&D work. Following [5], fluxes at the entrance of the decay tunnel are estimated considering the phase space xx', yy' of pions and kaons in a momentum bite of 8.5 GeV/c ± 20% at 5 cm downstream the 110 cm long target. All secondaries within an emittance $\epsilon_{xx'} = \epsilon_{yy'} = 0.15$ mm rad are focused assuming a typical horn focusing efficiency of 85% [4].

Table I summarizes the results. The second and third columns show the pions and kaons per proton-on-target (PoT) transported at the entrance of the decay tunnel. The fourth column shows the number of PoT in a single extraction spill to obtain 10^{10} pions per spill. The last column shows the number of integrated protons on target that are needed to collect 10^4 ν_e charged current events on a 500 tons neutrino detector. These proton fluxes are well within the reach of the above-mentioned accelerators both in terms of integrated PoT (from 5×10^{20} at 30 GeV to 5×10^{19} at 450 GeV) and protons per spill (2.5×10^{12} to 3×10^{11}).

E_p (GeV)	π^+/PoT (10^{-3})	K^+/PoT (10^{-3})	PoT for a 10^{10} π^+ spill (10^{12})	PoT for 10^4 ν_e CC (10^{20})
30 [J-PARC]	4.0	0.39	2.5	5.0
120 [Fermilab]	16.6	1.69	0.60	1.16
450 [CERN]	33.5	3.73	0.30	0.52

TABLE I: Pion and kaon yields at (8.5±1.7) GeV/c. The rightmost column is evaluated assuming a 500 ton neutrino detector located 50 m after the beam dump.

PROTON EXTRACTION SCHEME

The results of the previous Section combined with the maximum particle rate sustainable by the instrumentation of the decay tunnel (see below) fix the main constraint on the length of the proton spill extracted from the accelerator. For a maximum particle rate of 500 kHz/cm^2, this constraint corresponds to an upper limit to the average number of PoT per second:

$$\text{PoT/s} \ < \ 1.5 \times 10^{14} \tag{1}$$

For instance, assuming 450 GeV protons extracted from the SPS (third line of Table I), a 2 ms (10 ms) spill requires less than 3×10^{11} PoT/spill (1.5×10^{12} PoT/spill). This operation mode is unpractical for high energy machines (e.g. the SPS) where the number of protons circulating in the lattice exceeds 10^{13} but the repetition rate is O(0.1) Hz. These machines must hence resort to (resonant) slow extraction modes. Two options are currently under investigation:

- **Slow extraction modes**: a 1 s slow extraction mode similar to the one devised for SHiP at the CERN-SPS [7]. It is the classical solution envisaged for the "tagged neutrino beams" [8, 9] and it fulfills the constraint of Eq. (1) even in the occurrence of complete depletion of the protons accumulated in the lattice (4.5×10^{13} for the CERN-SPS). It comes with two significant drawbacks: it prevents the use of magnetic horns and challenges the cosmic background reduction of the neutrino detector. Still, due to the relatively low flux needed for cross section measurements compared with standard oscillation experiments, static focusing systems based on FODO/FFAG [10] represent a viable option for this facility.

- **Multiple slow resonant extractions**: Slow extractions of limited duration (10 ms, a few thousands turns) repeated frequently ($\sim$ 10 Hz) can be envisaged to deplete the lattice at the end of the acceleration phase. For instance, in the standard operation mode of the CERN-SPS [7], particles are extracted during a flat top of 4.8 s inside the 15 s full acceleration cycle (super-cycle). This mode corresponds to a 30% duty cycle. Assuming 4.5×10^{13} accumulated protons in the lattice, full depletion is achieved with 30 extractions of 10 ms (1.5×10^{12} PoT per extraction) repeated every 160 ms. The feasibility of this kind of schemes for the particular case of the CERN-SPS is under investigation.

In both cases, assuming full depletion mode (i.e. the accelerator running in dedicated mode for the neutrino experiment) the integrated exposure requested in Table I to perform the cross section measurement is reached in $\sim$200 days ($\sim$ 1 year considering a standard 200 days/y effective livetime).

INSTRUMENTED DECAY TUNNEL

In conventional low energy neutrino beams, the decay tunnel is located just after the horn and therefore accepts neutral and wrong sign particles, together with high energy protons. Doses and rates are therefore not suitable for additional instrumentation. In the facility considered here (Fig. 1) the decay tunnel is located at the end of the transfer line, while neutrals and protons are dumped before the bending dipoles. In addition, the positrons produced by kaon decays have a polar angle that is much larger than muons from $\pi^+ \to \mu^+ \nu_\mu$ decays. Additional instrumentation can hence be located just in the outer radius of the tunnel. Undecayed pions, transported protons and muons from pion decay will reach the beam dump without intercepting the outer walls of the decay tunnel and, hence, will not contribute to the rates. This is assured by the above constraint on the emittance: if the entrance windows of the secondaries in the tunnel and the spread in polar angle is smaller than the muon production angle from pion decay (4 mrad for 8.5 GeV pions), all particles (but decayed kaons) will reach the beam dump without additional focusing units inside the tunnel. In [5], a 50 m long tunnel with 40 cm inner radius and a ±5 cm entrance windows with polar angles smaller than 3 mrad has been considered. The precise values are under evaluation in the framework of the end-to-end simulation of the transfer line.

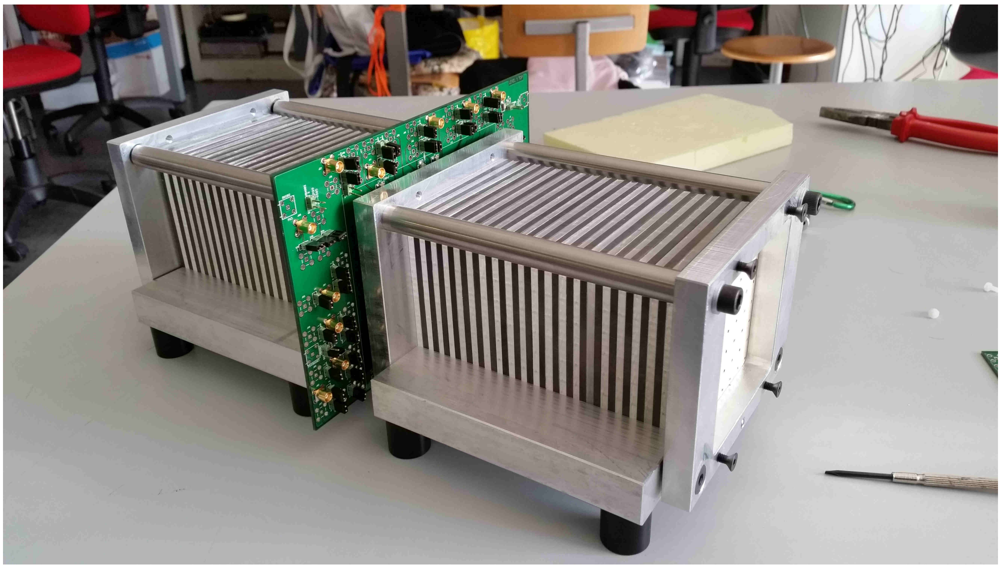

FIG. 2: Test prototype for the light readout system of the calorimeter based on SiPM embedded in the shashlik module.

The most critical issue is the identification of the detector technology that can be used to instrument (a fraction of) the evacuated (<1 mbar) decay tunnel. As for the general study performed in [5], the detector must be able to stand a maximum rate of 500 $\mathrm{kHz/cm^2}$ and provide charged pions/positron misidentification and photon veto at few percent level. Radiation hardness must be assured at the level of > 1.3 kGy. Shashlik calorimeters with fast fiber readout and longitudinal segmentation (sampling every 4 X_0) complemented by a plastic scintillator photon veto offer a compact and cost effective solution, which has already been proved to be radiation hard at the >5 kGy level [11]. Both ionizing and non ionizing (neutron) doses are low enough to allow for the use of solid state photosensors (SiPM) embedded inside the module of the calorimeters. Each SiPM reads separately a WLS fiber of the module and the outputs of multiple SiPM's are summed up. Full simulation of this setup is in progress and, for modules of $3 \times 3 \times 10$ $\mathrm{cm^2}$ size (sum of 9 SiPM), preliminary results confirm the positron identification capability estimated for a generic calorimeter in [5]. The embedding of the SiPM inside the modules to achieve longitudinal segmentation without loss of compactness and with negligible dead zones has been tested in summer 2015 with an early prototype (Fig. 2) at CERN PS. The test demonstrated that nuclear counter effects are negligible and the embedding does not introduce significant deterioration of the energy response with respect to standard fiber bundling [12].

EVENT RATES AND SYSTEMATICS CONTRIBUTIONS

The high momentum (8.5 GeV) secondaries selected in the transfer line produce a neutrino beam at the end of the decay tunnel that is enriched in ν_e from kaon decays and depleted in ν_e from muon decay in flight (DIF). For the parameters of [5], the ν_e/ν_μ flux ratio at the neutrino detector is independent of the proton energy and it is:

$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 1.8\ \%\ (\nu_e \text{ from } K_{e3})\ \ ;\ \ \frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 0.06\ \%\ (\nu_e \text{ from DIF}).$$

The mean energy of the neutrinos interacting at the far detector (ν_e CC events) is 3 GeV with a FWHM of ~3.5 GeV. This region covers the entire range of interest for the next generation long baseline experiments. Unlike conventional neutrino beams, a facility that is able to monitor the positron production at the decay tunnel can provide a flux estimate that does not depend on prior information on the proton intensity and secondary yields. A summary of the most relevant contributions is given in Tab. II. Current activities focus on the evaluation of the sub-dominant contributions due to the instrumentation response in the decay tunnel.

CONCLUSIONS

The knowledge of the flux at source in conventional neutrino beams dominates the precision of neutrino cross section measurements in short baseline experiments. In order to reach a per cent accuracy, a breakthrough in the experimental techniques employed to estimate the flux is needed. The technique we are investigating is particularly well suited for the measurement of the ν_e cross section - a key ingredient to establish CP violation in the leptonic sector - and it is based on the monitoring of large angle positrons originating from $K^+ \rightarrow e^+\nu_e\pi^0$. 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. In particular, we identified a specific detector option based on shashlik calorimetry that is suitable for the instrumentation of the decay tunnel and fulfills the requirements of PID capability, pile-up mitigation and radiation hardness.

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Uncertainty	Conv.	This	
kaon (pion) production yield	X		
kaon/pion ratio	X		
protons-on-target	X		
statistical error on monitored e^+		X	<0.1%
geometrical efficiency	X	X	survey (<0.5%)
3 body kinem. and K^+ mass	X	X	< 0.1%
phase space at tunnel entrance		X	measured on-site
BR of K_{e3}	X		
e/π/γ separation		X	measured with test beams and on-site with control samples
calorimeter response stability		X	on-site monitoring and calibration
residual gas in beampipe		X	negligible at 0.1 mbar

TABLE II: Main contributions to flux uncertainty for conventional ("Conv.") neutrino beams and for this facility ("This"). "X" indicates whether the contribution is relevant or is by-passed by the monitoring of the positrons.

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