ENUBET: Enhanced NeUtrino BEams from kaon Tagging

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Abstract: A reduction of the neutrino flux uncertainty by one order of magnitude in conventional neutrino beams can be achieved monitoring the positron production in the decay tunnel originating from the $K_{e3}$ decays of charged kaons. This novel approach will be developed in the framework of the ERC ENUBET Project. In this talk we present the aims of the project and the ongoing R&D for the instrumentation of the decay tunnel. In particular, we describe a specialized shashlik calorimeter (iron-scintillator) with a compact readout based on small-area silicon photomultipliers that allows for a very effective longitudinal segmentation of the detector to enhance electron/hadron separation. The expected performance of the detector estimated from a full GEANT4 simulation of the neutrino decay tunnel are presented. We also discuss preliminary results on a prototype composed by 12 ultra compact modules exposed to pions and electrons at CERN-PS.

Keywords: Calorimeters; Particle identification methods; Neutrino detectors

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1 Introduction

Neutrino oscillation physics has moved from discovery to precision era. The neutrino oscillation phenomenon is nowadays well established and it was awarded the Nobel prize in 2015. Nonetheless some parameters of the mixing matrix have still to be measured with higher precision and some unknowns such as the mass hierarchy or the value of the CP violating phase have to be unveiled.

In the last 40 years, detectors have grown in terms of size, resolution and complexity, however on the beam side there has been no major conceptual breakthrough since the 70’s although beam intensities have grown by several orders of magnitude.

The limit for next generation experiments in neutrino physics is given by the rough (> 5%) knowledge of initial fluxes and beam contamination. As a consequence, the physics reach of precision physics experiments is strongly linked to the systematic reduction program currently underway, where the key element to reduce the flux uncertainty is a better knowledge of the neutrino interaction cross section.

The ENUBET (i.e. Enhanced NeUtrino BEams from kaon Tagging) project fits very well this roadmap being a development on the beam side for a major reduction of the systematics related to the flux and cross section knowledge.

2 The ENUBET approach

In conventional neutrino beams the neutrino production chain is the following: protons collide on a target (typically made of carbon) producing secondary mesons (π and K) which are selected in momentum and focused to a decay tunnel where in turn they decay producing neutrinos.
Most of the $\nu_\mu$ are produced by the pion decay i.e. $\pi^+ \rightarrow \mu^+ \nu_\mu$. The electron neutrinos are instead produced mostly by two processes i.e. the so called muon decay in flight (DIF) $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$, and the three-body decay of the kaon ($K_{e3}$) $K^+ \rightarrow \pi^0 e^+ \nu_e$.

The positron emitted in the $K_{e3}$ process has a much larger angle with respect to the one produced in the DIF one: for a parent meson of about 8.5 GeV the mean angles are 88 mrad and 28 mrad respectively.

In a conventional neutrino beam the decay tunnel is a passive region and the knowledge on the neutrino flux relies on the simulation of the full chain. The simulation has large intrinsic uncertainties related in particular to the hadron production: to reduce such uncertainty down to 5–10%, dedicated hadroproduction experiments with replica target of the neutrino beams are performed (e.g. NA61 [1] for the T2K experiment [2] at JPARC).

ENUBET follows a different approach i.e. the development of a monitored beam [3]. In this case the decay tunnel is a fully instrumented region and counting the large angle positrons gives directly the electron neutrino flux without any assumption on the hadron production in the target, the number of protons-on-target or the elements along the neutrino beamline.

To have a well controlled source of $\nu_e$ the idea is to monitor the positrons emitted in the $K_{e3}$ decay which have indeed a large angle. To increase the ratio of $\nu_e$ from $K_{e3}$ with respect to the one issued by muon DIF high energy secondaries and short decay tunnels should be selected (see figure 1). With mesons of about 8 GeV and a decay tunnel of 50 m the contribution of positrons from $\mu$ DIF is below 3%.

A cartoon showing the beamline and the ENUBET approach can be seen in figure 2. The instrumented area, made of 2 layers of electromagnetic calorimeter and 6 layers of hadronic calorimeter (as explained in section 4), is attached to the inner wall of the decay tunnel at a distance of 40 cm from the beam axis. Kaon decay products cross the instrumented walls and are detected, whereas $\pi^+$ and $\mu$ decay at small angles and the decay products reach the beam dump without hitting the wall of the decay tunnel.

![Figure 1](image_url)  
**Figure 1.** $\nu_e$ issued by $\mu$ DIF (red) and $K_{e3}$ (black) as a function of the parent meson momentum and for two possible decay tunnel lengths.
Figure 2. Cartoon showing the beamline and the ENUBET approach.

Figure 3. Impact of ENUBET measurement of the $\nu_e$ charge current cross section with respect to present experimental results. The ENUBET points correspond to the measurement which could be achieved with $10^4$ charged current events in a possible 500 ton neutrino detector with the energy spectrum corresponding to the thin grey line. The energy spectrum corresponds to the $\nu_e$ flux multiplied by the charged current cross section and does not include any possible acceptance efficiency of the 500 ton detector.

3 Goals and project status

The ENUBET approach is well suited for short baseline experiments where the intensity requirements are less stringent. We considered three possible main applications.

- The most important application, and the main goal of ENUBET as funded by the ERC, is related to the electron neutrino cross section measurement. We aim at an electron neutrino source whose flux is known with a precision better than 1% which is a unique tool for the next generation of neutrino experiment in the precision era. In figure 3 the impact of the ENUBET measurement on the $\nu_e$ charged current cross section is shown compared to present experimental results. Such a precision on the differential neutrino cross section can be reached
if we collect a statistics of $10^4$ events in a possible 500 ton detector located 100 m from the entrance of the decay tunnel and if the flux of electron neutrinos is known with 1% precision, as ti can be attained with the instrumentation of the decay tunnel proposed in ENUBET.

- The ENUBET technique could be exploited in a next generation experiment on sterile neutrino search, especially in case of positive signal from the Fermilab SBL program [4].
- The proof of principle of ENUBET could also be considered as a first step towards a real tagged neutrino beam i.e. where the $\nu_e$ charged current interaction in the detector is time correlated with the observation of the positron in the decay tunnel.

The ENUBET project was approved by the European Research Council (ERC) for a 5 year duration (June 2016 – May 2021) with an overall budget of 2 million euro. The project was awarded the ERC Consolidator Grant, 2015 (PE2) with A.Longhin as principal investigator and Italian Institute for Nuclear Research (INFN) as host institution. The collaboration as of August 2016 consists of about 40 physicists from 9 institutions (INFN, CERN, IN2P3, University of Bologna, Insubria, Milano-Bicocca, Napoli, Padova and Roma) [5].

Many activities are ongoing in parallel mostly consisting in beamline design, preparation of test beams at CERN T9 and INFN-LNF beams, design and construction of 3 m section of the instrumented decay tunnel and design of the proton extraction scheme considering the CERN-SPS.

## 4 Detector concept

To instrument the decay tunnel and measure the electron neutrino flux by counting the positrons from $K_{e3}$ decays we have to consider several constraints. The geometrical acceptance should be large at angles larger than the decay cone of $\pi^+ \rightarrow \mu^+ \nu_\mu$ (i.e. about 4 mrad): this sets the geometry of the positron tagger all around the decay tunnel. In addition the photon conversion from $\pi^0$ issued by kaon decays (i.e. $K^+ \rightarrow \pi^0 \pi^+$) must be suppressed: for this reason we envisage a photon veto inside the decay tunnel which also determine the $t_0$ of the event.

Calorimetric techniques offer the cheapest and safest mean to distinguish between positrons and charged pions exploiting the longitudinal development of the shower, and the proposed shashlik calorimeter (iron/scintillator) coupled to a silicon photomultiplier (SiPM) readout solves the problem of longitudinal segmentation. We designed a basic unit called ultra compact module (UCM) which is a module made of 5 layers of iron 15 mm thick interleaved by plastic scintillator tiles of 5 mm thickness. The front dimensions are $3 \times 3 \text{ cm}^2$ and the total length of 10 cm corresponds to $4 \text{ X}_0$. The 9 wavelength shifting fibers crossing the UCM are connected directly to $1 \text{ mm}^2$ SiPM in a plastic holder. A picture of an UCM can be seen in figure 4.

A full module (see figure 5) is made of 2 electromagnetic layers and 6 hadronic ones. Each layer is made of 6 UCM in a row and the difference between electromagnetic and hadronic layer is in their readout. The electromagnetic layer is readout after each UCM (6 times per layer) whereas the hadronic one is readout at the end of the full module i.e. after 60 cm which corresponds to about 2.6 interaction lengths.

The photon veto, also called “$t_0$ layer” since it is used as time reference of the event, is made of a doublet made of two plastic scintillators with a surface of $3 \times 3 \text{ cm}^2$ and a thickness of 5 mm.
each separated by a distance of 5 mm. The implementation of a doublet comes from the need of discriminating positrons from gammas converting in the first layer looking at the energy deposited (i.e. 1 m.i.p. against 2 m.i.p.). If the energy deposited in the $t_0$ doublet corresponds to a m.i.p. the electromagnetic signal in the calorimeter is considered as given by an electron. Conversely, if there is no energy deposited in the $t_0$ doublet, or the deposited energy corresponds to the signal given by 2 m.i.p., the electromagnetic signal in the calorimeter is considered as given by a gamma. Rings of “$t_0$ layer” will be installed in the inner radius of the calorimeter at a distance of 37 cm from the beam axis. The distance of about 7 cm between consecutive rings along the beamline is computed in order to have particles emitted at large angles (all particles emitted by kaons will have an angle smaller than about 400 mrad) crossing at least one doublet. Positrons with a mean angle of 88 mrad will cross on average 5 doublets before reaching the calorimeter.

![Figure 4. Picture of an UCM.](image1)

![Figure 5. Picture of a full module.](image2)
5 Results

In the preparatory phase of ENUBET, the possibility to measure neutrino cross section with a statistical error below 1% (i.e. dominated by the systematics) was investigated using a preliminary simulation of the beamline. Results were published in ref. [3] and the reference parameters corresponding to the beamline and to the neutrino detector are shown in table 1.

Using the selected reference parameters the rate in the calorimeter was computed finding a maximum of 500 kHz/cm$^2$ summing all particles. The number of protons on target was computed and it is well within reach of present accelerator complexes i.e. CERN-SPS, Fermilab or JPARC. In addition the energy spectrum of neutrino was computed showing a good coverage of the region of interest of future experiments such as DUNE [6].

| Table 1. Reference parameters in the physics reach studies. |
|----------------------------------------------------------|
| $10^{10}$π per spill                                    |
| 2 ms spill                                               |
| 500 ton ν detector @ 100 m from the entrance of the decay tunnel |
| $10^4$ν$\text{e}$ CC in the detector                     |

In the last year several results were obtained both on the simulation and on the prototyping of the detector.

The software framework was set up at the computing cluster of IN2P3 at Lyon and a full Geant4 [7] simulation of the instrumented tunnel is available and used to study particle identification. In addition a preliminary event builder was developed in order to consider only neighbouring sectors of the calorimeter and avoid pile up, and identification algorithms were developed in order to discriminate positron from charged and neutral pions.

The full chain is divided into two steps: first a neural network based on TMVA [8] uses five variables related to the pattern of the energy deposition in the calorimeter to discriminate between charged pions and positrons (see figure 6). These variables are:

- The total deposited energy.
- The maximal energy deposited in one UCM.
- The fraction of energy in the first electromagnetic layer.
- The fraction of energy in the second electromagnetic layer.
- The fraction of energy deposited in 1 Moliere Radius along the reconstructed shower direction.

As a second step, sequential cuts based on the information from the photon veto are applied to reject $\pi^0$ events. The obtained selection efficiencies for the different event samples, quoted in table 2, confirm the early results obtained from fast simulations and published in ref. [3].

On the prototyping side for shashlik calorimeter with longitudinal segmentation an effort is ongoing since 2015 thanks to the SCENTT R&D [9] funded by INFN.

A test beam was carried out at the CERN-PS T9 line in July 2016 where 12 UCM were tested with pions and electrons in an energy range of 1–5 GeV. Several important requirements
Figure 6. Results of the TMVA neural network (using the option MLPBNN which stands for Multi Layer Perceptrons Bayesian Neural Network) on Monte Carlo simulation to discriminate charged pions from positrons.

Table 2. Selection efficiencies.

| Sample | Intrinsic efficiency (events not in beam dump) | Global efficiency |
|--------|-------------------------------------------------|-------------------|
| $e^+$  | 90.7%                                           | 49.0%             |
| $\pi^+$| 85.7%                                           | 2.9%              |
| $\pi^0$| 95.1%                                           | 1.2%              |

for the ENUBET project were tested in particular the m.i.p. sensitivity without any saturation for electromagnetic showers up to 4 GeV. In addition the energy resolution was evaluated to 19% at 1 GeV (see figure 7, well within the requirements of $25\%/\sqrt{E}$ set by the need of a good separation between charged pions and positrons.

Additional requirements such as the fast recovery time, at the level of 10 ns, and the validation of the Monte Carlo results on $\pi/e$ separation, will be addressed with a dedicated test beam in November 2016.

6 The beamline

Claiming an overall systematic budget < 1% requires an end-to-end simulation of the neutrino beamline. Such simulation work (currently based on CERN-SPS) has just started. Two options are currently under investigation both needing R&D: a horn based option and a static focusing. In the horn option, several few millisecond extraction are foreseen during the 2 s flat top. Such an operation of the horns is unconventional for what concerns proton extraction and focusing of the secondaries, however a large acceptance and therefore a large flux could be obtained.
Figure 7. Energy resolution of the UCM measured in the CERN-PS T9 test beam.

A static focusing system with a 2 s slow extraction similar to the one envisaged for the SHiP experiment [10, 11] is also under consideration.

7 Conclusions

The precise knowledge of neutrino cross section is a key element for the next generation of neutrino oscillation experiments aiming at the CP violation measurements. Exploiting the positron tagging in the $K_{e3}$ decay ($K^+ \to \pi^0 e^+ \nu_e$) could reduce the current uncertainty on flux prediction, and therefore on the neutrino cross section, by about one order of magnitude. The ENUBET project, will investigate this approach in the next five years.

The results obtained in the preparatory phase of the project were presented. A full simulation of the decay tunnel supports the effectiveness of the calorimetric approach for large angle lepton identification whereas first prototypes demonstrate that shashlik calorimeters with longitudinal segmentation can be built without compromising energy resolution (19% at 1 GeV) and provide the performance requested by the ENUBET technology.

The final goal of the project is to demonstrate that a “positron monitored” $\nu_e$ source based on $K_{e3}$ can be constructed using existing beam technologies and neutrino detectors of moderate mass (500 tons), and can be implemented at CERN, Fermilab or JPARC.

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