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Status of the ENUBET project

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Abstract. The next generation of neutrino experiments requires measurements of absolute neutrino cross sections at the GeV scale with high precision (~1%) presently limited by the uncertainties on neutrino flux. Monitoring the lepton production in the decay tunnel of neutrino beams is the most straightforward way to measure the neutrino flux at source. The ENUBET Collaboration develops novel technologies to monitor positrons from $K^+ \to \nu_e e^+ \pi^0$ decays on an event by event basis. This technique can achieve a precision in the ν_e flux below 1% and enable a new generation of cross section and short baseline experiments. In this paper, we present the achievements of the first year of the Project on beamline simulation, rate and dose assessment, detector prototyping and evaluation of the physics reach.

1. The ENUBET project

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. The next generation of oscillation physics experiments aiming at the study of CP violation and mass hierarchy problems will rely on precise measurements of neutrino interaction cross sections.

The prediction of the neutrino flux in conventional beam is a challenging task which relies on the detailed simulation of the beamline (constrained by data from beam monitoring devices and measurements such as proton intensity, horn currents,...) and on the hadro-production data coming from experiments which provide the particle yields from the target. Neutrino experiments are affected by an intrinsic limitation given by a large uncertainty of the overall neutrino flux (~10%) directly reflecting on the cross section measurements. Moreover the ν_e and $\overline{\nu_e}$ cross sections are poorly known despite of their relevance in the next generation long-baseline experiments.

A change in the method used to determine the neutrino flux is needed: the direct monitoring of leptons produced in the decay tunnel together with neutrinos can overcome these limitations reducing the flux-related systematics: a technique specifically focused on ν_e cross sections has been proposed in [1]. This new method has the advantage of providing a source of ν_e from $K^+ \rightarrow e^+ \nu_e \pi^0$ allowing to study directly their interactions (without relying on extrapolations from ν_μ) by using an observable (the positron rates) directly linked to the ν_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 ~ 1%. The ENUBET project (*"Enhanced NeUtrino BEams from kaon Tagging"*) [2] aims at demonstrating the technical feasibility of monitored neutrino beams. The project is funded by the European Research Council (ERC Consolidator Grant, PI A. Longhin, host institution INFN) from June 2016 to May 2021. ENUBET is also framed in the CERN Neutrino Platform under the NP3-Plafond R&D programme since December 2016.

2. Design of the hadronic 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. Two possible solutions are under study by the ENUBET collaboration in designing the focusing system for incoming proton momentum of 30, 120, 400 GeV/c: a conventional pulsed horn and a static system. The optimization of the focusing system and the design of the transfer line confirm (or even improve) the collection efficiency assumed in [1]: the optimization of the line (dipoles and quadrupoles) is performed with TRANSPORT [3]. G4Beamline is used for the implementation and full simulation of particle transport, collimation and re-interaction. The dose assessment is addressed by using FLUKA [4,5]. The positron tagger can operate safely in terms of pile-up if the local particle rate is below 500 kHz/cm^2. This can be achieved with two possible solutions under study:

- multi-Hz slow extraction lasting O(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/cm^2 comes from employing compact shashlik calorimeters read out with fast wavelenght shifting fibers each coupled with its own silicon photomultiplier (SiPM). This detector, effective in e/π separation, will be used together with 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.

A GEANT4 simulation of the decay tunnel and instrumentation has been performed in parallel with the simulation of the transfer line: a reconstruction algorithm for particle identification has been developed to cope with pile-up in realistic conditions and it is based on the energy deposit pattern in the calorimeter modules to discriminate electromagnetic from hadronic showers. Timing

information coming both from shashlik calorimeter and the photon veto is exploited to clusters modules belonging to the same event ("event building") and to reject electromagnetic shower generated from π^0 decays. The ENUBET instrumentation provides positron identification with 25% of efficiency while keeping signal-to-noise ratio near to 1: these performances are estimated by taking into account beam related background profiting of the input from the transfer line simulation. The assessment of systematics in the neutrino flux due to the detector response is ongoing.

Ionizing and non-ionizing doses (from neutrons) have been evaluated with FLUKA 2011 at the inner surface of the target for different choices of its radius (40, 80, 100 cm) as shown in figure 1 (left). For 1 m radius the integrated doses (correspond to $10^4\ \nu_e^{CC}$ events at the detector) amounts to < 0.05 kGy and 1.9×10^{11} n/cm^2 (1 MeV equivalent): an additional mitigation can be achieved by placing the photosensors outside the calorimeter with a non-shashlik solution.
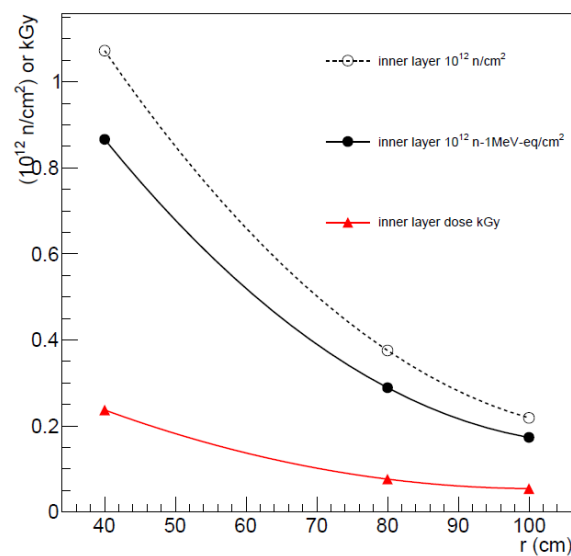
Figure 1. (Left): Ionizing dose (red line, kGy), neutron fluence (black dashed line, in n/cm^2) and 1 MeV equivalent neutron fluence (black continuous line) in the innermost modules of the calorimeter as a function of the tagger radius.

Different scenarios corresponding to 2-3 months of data taking at the present running performance of major accelerating facilities have been considered: a 500 t neutrino detector (transverse size of 6×6 m^2) placed 50 m downstream of the tagger is able to record $10^4\ \nu_e^{CC}$ events with 1.0×10^{20} proton on target (pot) at J-PARC synchrotron (30 GeV). Same results can be obtained at Fermilab Main Ring (120 GeV) with 2.4×10^{19} pot and at CERN SPS (400 GeV) with 1.1×10^{19} pot.

4. Prototypes tests at test beams

The basic calorimetric unit (Ultra-Compact Module - UCM) is made of five, 15-mm thick, iron layers interleaved by 5-mm thick plastic scintillator tiles. The transverse dimension is 3×3 cm^2 for a 10 cm length (4.3 X_0). Nine wavelength shifting (WLS) fibers crossing the UCM are connected directly to 1 mm^2 SiPM produced by the Fondazione Bruno Kesserl (FBK) avoiding the occurrence of large passive regions usually needed to bundle the fibers to a common photo-sensor. UCM prototypes and photon-veto prototypes have been characterized with cosmic rays and charged particles (1-5 MeV range) at CENR-PS East Area facility (T9) in several exposure 2016 (July-November) and 2017 (August-October)[6, 7, 8].

4.1. UCMs

Test beams aim to characterize UCMs in terms of energy resolution, response linearity for electromagnetic showers, modules uniformity and the effectiveness of minimum ionizing particles for self-calibration for different setup. Moreover a comparison between data a GEANT4 simulation has been deeply investigated to check the capability to reproduce data distributions. Different technological solutions have been studied: the choice of plastic scintillators (EJ200, EJ204, Uniplast) and thickness (5 - 10 mm) as well as different WLS fibers (Kuraray Y11-MC, St. Gobain BCF-92-MC). Injection molded scintillators (suitable for large scale production) have been successfully produced by Uniplast (Russia) and tested at CERN in July 2017.

During the November 2016 CERN test beam a module composed of 56 UCM in 7 longitudinal layers (~30 X_0, figure 2) and of an outer module acting as an energy catcher, were exposed to e^-/π^- with grazing incidence at various incidence angles from 0 to 200 mrad.
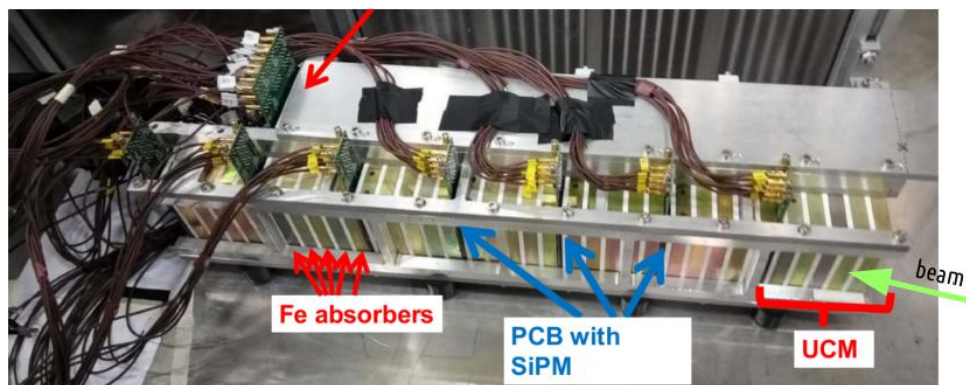
Figure 2. The calorimeter exposed at the CERN-PS T9 particle beams. The prototype is composed of an inner part (bottom in the picture) seven calorimetric blocks and a 60 cm long "hadronic" block for the outer part (up in the picture). The compact layout of the light readout is visible through the cabled PCBs.
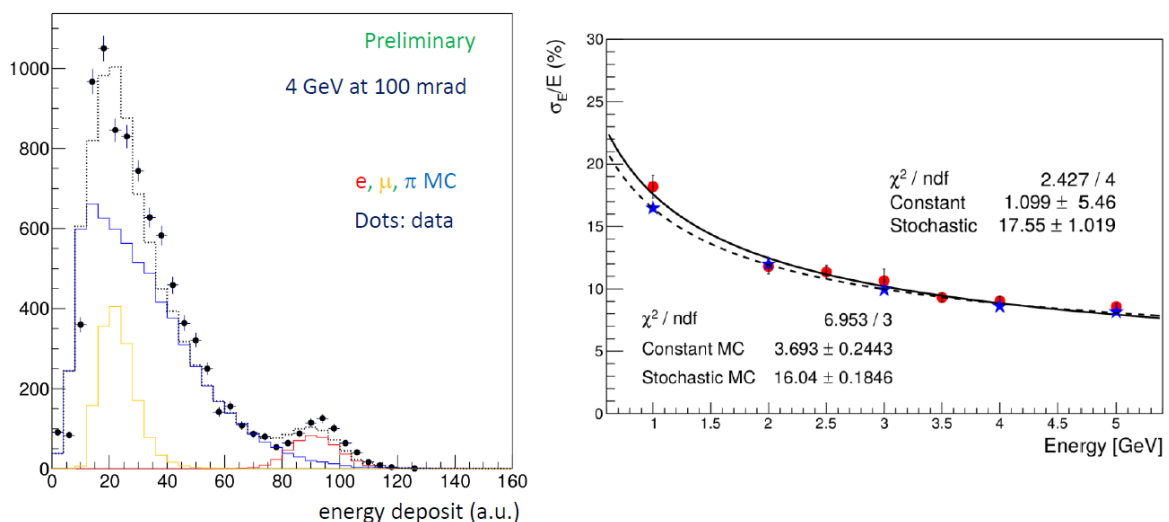
Figure 3. Data and Monte Carlo distributions of the total visible energy for a 100 mrad tilt of the calorimeter and a 4 GeV beam of negative pions, muons and electrons in the CERN-PS T9 beamline. (Right): Energy resolution for electrons in data (red point) and Monte Carlo (blue). The fitted parametrization follows the standard form: $\frac{\sigma(E)}{E} = \frac{\sigma}{\sqrt{E}} + c$.

The electron/pion separation capabilities in data and Monte Carlo have been determined at various incident angles. In figure 3 (left) the distribution of the total visible energy for a 100 mrad tilt of the calorimeter and a 4 GeV beam of negative pions, muons and electrons is shown for data (bullets) and Monte Carlo (histograms, broken down by particles). Figure 3 (right) shows the energy resolution for electrons in data and Monte Carlo. Non conventional options based on polysiloxane scintillators [9] to avoid drilling or injection molding and allowing an improved radiation hardness are also being scrutinized: a prototype polysiloxane shashlik calorimeter composed of three modules (13 X_0 in total) consisting of 12 UCM units and a 15 mm scintillator thickness was built at INFN-LNL and exposed to particle beams at the CERN East area. The absolute light yield and uniformity are very promising.

4.2. Photon Veto

The baseline option for the photon-veto (plastic scintillator doublets) has also been tested with several layouts for light collection. The requirements for this detector are the precise timing and the 1 mip/2mip separation. A custom 2 stages wideband amplifier based on HMC58-2 and Gali TB0447-05 chips has been tested to readout a SiPM SenSL-30020J (3x3 mm^2). First measurements performed on this SiPM with a PiLas laser (407 nm) showed that the time resolution is below 100 ps (matching the requirements).

During test beam at CERN in 2017 with pions, several light collection configurations have been checked as well as different scintillators/WLS fibers (EJ200 coupled with Kuraray-Y11 MC and EJ204 coupled to St. Gobain BCF92MC): all configurations have a good response in terms of efficiency (> 95%) and uniformity. In order to perform a first test on 1 particle /2 particles separation we have enhanced the π^0 production with a Delrin cylinder and let them decay through an iron slab: in figure 4 it is clearly visible the separation provided by a single t_0-layer. A first timing measurement has been performed on a single tile with EJ-204 coupled with BCF92: the results are really promising (~400 ps).
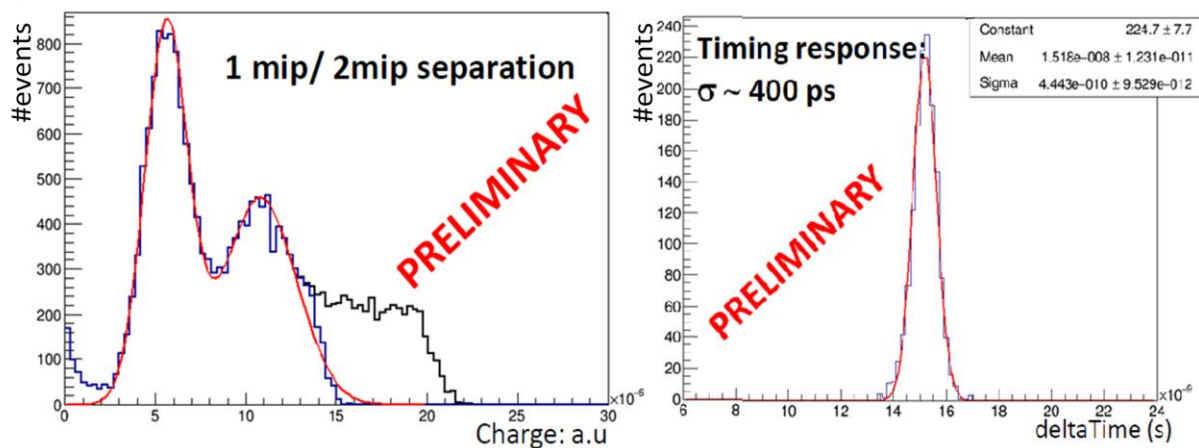

Figure 4. (left) e$^+$e$^-$ couples produced from the π^0 decay: it's visible the separation between 1 particle and 2 particles. (right) timing measurements performed with a fast scintillator used as trigger, the resolution of ~400 ps.

5. SiPM neutron irradiation at INFN-LNL

In the ENUBET reference design the SiPMs will be exposed to radiation. Since such devices are sensitive in particular to neutron damages, we have performed iraadiation test in June 2007 at the CN facility at INFN-LNL (Legnaro).

Neutron fluences up to 10^{12} n/cm^2 were achieved by sending 5 MeV protons on a Beryllium target. The target area with concrete shielding is shown in figure 5, left. SiPM of different pixel sizes (12, 15, 20 μm) produced by FBK were exposed and characterized in terms of I vs V curves at

increasing irradiation (figure 5, right). Noise waveforms were also sampled before and at intermediate irradiation levels. Data are under analysis and will be presented in a full paper.
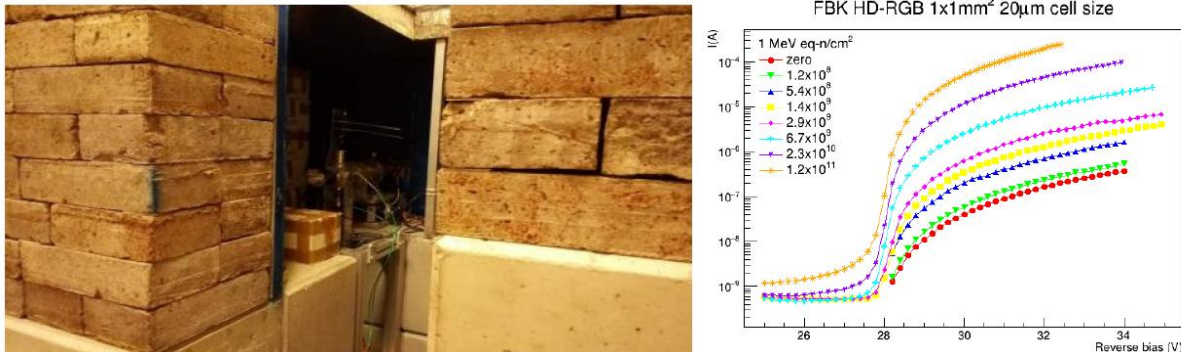
Figure 5. (Left) The target region at INFN-LNL used to produce large neutron fluxes for SiPM irradiation: the Be target is visible at the center of the picture. (Right) IV curves for a 20 μm cell SiPM from FBK for various values of the estimated neutron irradiation (neutrons 1 MeV-eq/cm^2).

6. Conclusions

The final goal of ENUBET (2016-2021) is to demonstrate that e$^+$-monitored ν_e beams can be built using existing technologies and hosted at CERN, Fermilab or J-PARC for a new generation of experiments on neutrino cross sections. The results obtained in the preparatory and initial phase of the project are very encouraging. The design and simulation of the hadronic beamline has started and the preliminary results support or improve the initial estimates of the achievable event rates. Full simulations support the viability and effectiveness of the calorimetric approach whereas prototypes tests demonstrate that shashlik calorimeters with longitudinal segmentation can fulfill the requests for e$^+$ monitoring in the relevant energy region of few GeV.

7. Acknowledgment

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