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ENUBET: a monitored neutrino beam for high precision cross section measurements

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Abstract. The main source of systematic uncertainty on neutrino cross section measurements at the GeV scale is represented by the poor knowledge of the initial flux. The goal of cutting down this uncertainty to 1% can be achieved through the monitoring of charged leptons produced in association with neutrinos, by properly instrumenting the decay region of a conventional narrow-band neutrino beam. Large angle muons and positrons from kaons are measured by a sampling calorimeter on the decay tunnel walls (tagger), while muon stations after the hadron dump can be used to monitor the neutrino component from pion decays. This instrumentation can provide a full control on both the muon and electron neutrino fluxes at all energies. Furthermore, the narrow momentum width (<10%) of the beam provides a O(10%) measurement of the neutrino energy on an event by event basis, thanks to its correlation with the radial position of the interaction at the neutrino detector. The ENUBET project has been funded by the ERC in 2016 to prove the feasibility of such a monitored neutrino beam and is cast in the framework of the CERN neutrino platform (NP06) and the Physics Beyond Colliders initiative. In our contribution, we summarize the ENUBET design, physics performance and opportunities for its implementation in a timescale comparable with next long baseline neutrino experiments.

1 The ENUBET monitored neutrino beam

The main source of systematic uncertainty on the neutrino cross-section comes from the knowledge of the initial flux in conventional neutrino beams. The ENUBET idea is to develop the concept of monitored neutrino beams [1], where a controlled neutrino flux can be obtained by measuring the charged leptons from mesons along the decay tunnel.

The physics goal of ENUBET is to use the monitoring technique to reduce the uncertainty on the flux of ν_e and ν_μ below 1%, allowing a high-precision determination of neutrino cross sections at the energy of interest for DUNE and HyperK. It will, therefore, reduce the systematics of long-baseline experiments increasing the sensitivity to oscillation parameters and to CP violating phase.

ENUBET started as an ERC project in June 2016 with with the purpose of developing a facility for the measurement of large angle positrons from the $K^+ \rightarrow e^+ \pi^0 \nu_e$ decay, which is directly linked to the flux of ν_e. Furthermore, in March 2019, it was approved as a CERN Neutrino Platform experiment (NP06), in which it also considers the possibility of measuring muons both from the two body large angle decay of the kaons ($K^+ \rightarrow \mu^+ \nu_\mu$) and, after the hadron dump, from the pion decays ($\pi^+ \rightarrow \mu^+ \nu_\mu$) [2].

2 The ENUBET beamline and performance

ENUBET is a conventional neutrino beam where the pions and kaons are produced by protons impinging on a fixed target. They are focused and momentum selected with a momentum bite of O(5 - 10%), by a short transfer line (TL) of about $\sim$ 20 m. The TL is designed for a 8.5 GeV/c particle beam, an optimal choice for the e^+/π^+ separation and to span the region of interest for future neutrino oscillation experiments (DUNE and HyperK). A complete G4beamline[3] simulation is performed and permits to evaluate the beam composition, while the shielding of the components has been optimized with FLUKA and GEANT4. The latest versions of the TL implement a double dipole configuration, that allows to reduce backgrounds from stray particles and the ν_e component at the neutrino detector from early decays in the first part of the TL. The selected particles are then transported to the decay tunnel that is located off the axis of the proton beam. Non-interacting protons are stopped in a proton

dump. The 40 m long decay tunnel is instrumented along its walls to monitor the leptons. Not decayed particles (mostly pions) and leptons produced along the axis (mostly muons from pion decay) are stopped by a hadron dump at the end of the tunnel.
Assuming $\sim 10^{20}$ proton on target, ENUBET is able to provide a sample of about 10^4 ν_e CC (Figure 1 left) and 10^6 ν_μ CC in a 500 t detector located 50 m after the hadron dump monitored with an expected precision of 1%.
The other source of systematic uncertainty is the reconstruction of the ν energy, which is biased by the inaccurate reconstruction of the final state particles. ENUBET is a narrow band beam and using the off-axis narrow band technique [4]. It can provide a measurement of the neutrino energy at 10-20% level, just by locating the radial position of the interaction vertex and without relying on accurate final state particle reconstruction (Figure 1 right).

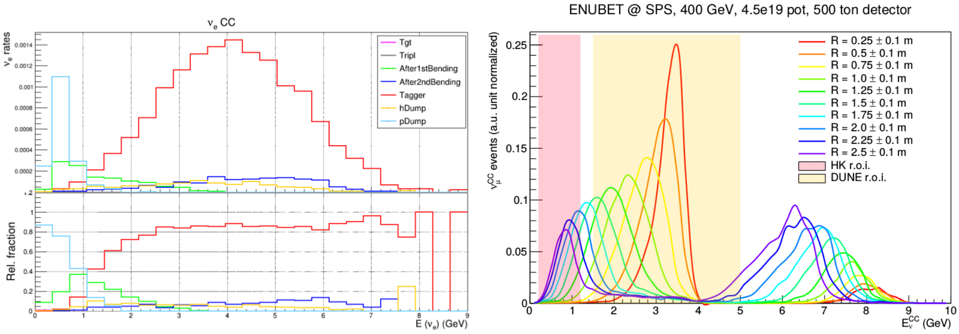

Figure 1. Left top: energy spectrum for ν_e CC interactions in a detector of 500 ton mass and 6×6 m^2 transverse size placed 50 m from the decay tunnel end. Each color corresponds to a neutrino contribution produced within a region of the beamline. Left bottom: relative fraction of each category with respect to the total ν_e CC rate. Right: ν_μ CC energy spectra for different values of distance (R) between the neutrino interaction vertex and the beam axis .

3 Tunnel instrumentation

The ENUBET tunnel instrumentation (see Figure 2) is based on a calorimeter for e^+ / π^+ separation and on an inner light-weight photon veto for e^+ / π^0 separation. This last detector also provides the absolute timing of the events and is thus called the "t_0-layer". Between 2016 and 2018 several prototypes have been built and tested at the CERN East Experimental Area [5–8] to validate the physics performance.
The final choice is an iron-scintillator sampling calorimeter divided into modules (Lateral readout Compact Module, LCM) of 10 cm length that samples the showers every 4.3 radiation lengths. The light is collected by WLS fibers running along the lateral edges of the five scintillator tiles of each module and bundled in groups of ten, and read out by SiPMs.
The photon veto is based on plastic scintillators, whose light is transported by WLS fibers toward the upper part, beyond a 40 cm thick borated polyethylene shielding, where all the SiPMs are located. A detailed description of the performance of a small scale prototype based on this concept is given in [9].
In order to prove the effectiveness of the technique and validate the detector performance, a large scale prototype (the ENUBET "demonstrator" [10]) of 1.65 m length and 3.5 ton mass has been built. It was exposed to the T9 particle beam at CERN PS in Fall 2022.

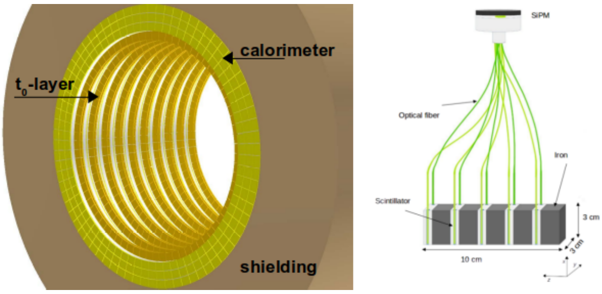

Figure 2. Left: scheme of the ENUBET decay tunnel, instrumented with three layers of calorimetric modules (green), an inner t_0-layer of scintillator tile doublets (yellow) and an outer shielding of Borated Polyethylene (brown). Right: layout of a single Lateral readout Compact Module (LCM).

4 Particle identification and assessment of systematics

A full GEANT4 simulation of the ENUBET facility has been implemented and it includes particle propagation and decay from the transfer line to the detector. The simulation has been validated with data from the prototype tests.

Positrons and muons in the calorimeter are identified with dedicated algorithms [11]. The event reconstruction starts with the identification of a seed, that corresponds to a hit in a LCM of the innermost layer. All LCM and t_0-layer energy deposits compatible in space and time with the seed are clustered together and constitute the candidate event. A set of variables describing the energy deposition in the calorimeter and the event topology are used as input for a Neural Network, based on the Root TMVA package [12], that identifies and classifies positrons and muons.

The preliminary performance (Figure 3) obtained for e^+ from K_{e3} show a selection efficiency of about 22% dominated by the geometrical efficiency (~ 50%), and a S/N of ~2.1, while μ from K^+ are reconstructed with an efficiency of about 34%, and a S/N of ~6.0 .

The relation between leptons measured in the calorimeter and neutrino flux at the detector is used to evaluate neutrino flux systematics. A signal plus background model is built, including a priori hadroproduction and TL related systematic uncertainties. Toy-MC experiments are produced and fitted to study the a posteriori systematic uncertainty and assess the corresponding uncertainty reduction.

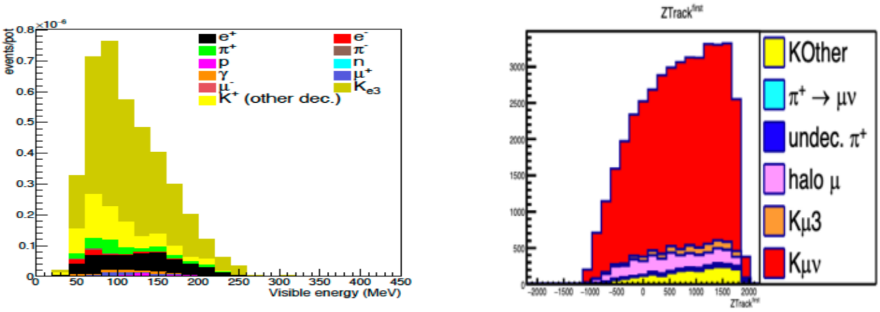

Figure 3. Reconstructed visible energy of K_{e3} positron events (left) and reconstructed impact point along decay tunnel calorimeter wall (Z) of $K_{\mu\nu}$ (right) after the application of the Neural Network.

5 Conclusions

The ENUBET main idea is to prove the feasibility of a monitored neutrino beam, where charged leptons, produced in association with neutrinos, are monitored in order to estimate the neutrino flux. This goal can be achieved by properly instrumenting the decay region of a conventional narrow-band neutrino beam, using a sampling calorimeter. The ENUBET Collaboration proved the feasibility and cost-effectiveness of this technology whose complexity does not exceed significantly the one of a conventional short baseline beam. It was also devised the first end-to-end simulation of a monitored beam and a full Geant4 simulation of the facility is employed to assess the final systematics budget on the neutrino fluxes. The ENUBET results will play an important role in the systematic reduction programme of future long baseline experiments, thus enhancing the physics reach of DUNE and HyperKamiokande.

References

[1] A. Longhin, L. Ludovici and F. Terranova, Eur. Phys. J. **C 75** 155 (2015);
A. Berra et al., CERN-SPSC-2016-036, SPSC-EOI-014, Geneva (2016).
[2] F. Acerbi et al., CERN-SPSC-2020-009, SPSC-SR-268, Geneva (2020).
[3] T. J. Roberts et al., Proc. EPAC'08 2776-2779 (2008).
[4] F. Acerbi et al., CERN-SPSC-2018-034, SPSC-I-248, Geneva (2018).
[5] A. Berra et al., Nucl. Instrum. Meth. **A 830** 345 (2016).
[6] A. Berra et al., IEEE Trans. Nucl. Sci. **64** 1056 (2017).
[7] G. Ballerini et al., JINST **13** P01028 (2018).
[8] F. Acerbi et al., JINST **14** P02029 (2019).
[9] F. Acerbi, et al. JINST **15** P08001 (2020).
[10] F. Acerbi et al., CERN-SPSC-2021-013, Geneva (2021).
[11] F. Pupilli et al., PoS NuFact2021 027 (2022).
[12] A. Hoecker et al., *TMVA-Toolkit for Multivariate Data Analysis* arXiv:physics/0703039