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# Monitored beams for high-precision neutrino flux determination: The ENUBET project

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**Summary.** — The knowledge of initial flux, energy and flavour of current neutrino beams is currently the main limitation for a precise measurement of neutrino cross-sections. The ENUBET ERC project (2016–2021) is studying a facility based on a narrow-band neutrino beam capable of constraining the neutrino flux normalization through the monitoring of the associated charged leptons in an instrumented decay tunnel. In particular, the identification of large-angle positrons from $K_{e3}$ decays at single-particle level can reduce the $\nu_e$ flux uncertainty at the level of 1%. This setup would allow for an unprecedented measurement of the $\nu_e$ cross-section at the GeV scale. Such an experimental input would be highly beneficial to reduce the budget of systematic uncertainties in the next long baseline oscillation projects (*i.e.*, HyperK-DUNE). Furthermore, in narrow-band beams, the transverse position of the neutrino interaction at the detector can be exploited to determine *a priori* with significant precision the neutrino energy spectrum without relying on the final-state reconstruction.

## 1. – ENUBET (Enhanced NeUtrino BEams from kaon Tagging)

Despite the remarkable improvement achieved in the last 10 years due to the contribution of experiments such as MiniBooNE, SCIBooNE, T2K, MINER$\nu$A and NO$\nu$A, the cross-section of the muon neutrino is still known with a precision of 7–10%; as far as the electron neutrino is concerned, this precision is even worse, mainly because there is no available intense and pure source of electron neutrinos in the GeV energy range. The poor knowledge of the $\sigma(\nu_e)$ can jeopardize the CPV discovery potential and the insight on the underlying physics (standard *vs.* exotic, matter *vs.* antimatter) in next-generation experiments.

The main limiting factor for the precise measurement of the neutrino cross-section at these energies are the systematic uncertainties in the initial flux determination.

The solution proposed by the ENUBET Collaboration [1-3] is to monitor the neutrino flux inside the decay tunnel with conventional technologies and to aim for a pure and precise (1%) source of $\nu_e$ from a kaon-based beam, in which the only source of $\nu_e$ is the three body semileptonic decay $K_{e3}$ ($K^+ \rightarrow \pi^0 e^+ \nu_e$). This decay is also the only source of positrons inside the tunnel. By counting the positrons in a fully instrumented decay region, it is possible to evaluate the $\nu_e$ flux, bypassing the uncertainties from POT monitoring, hadro-production and beamline efficiency. This technique aims to determine the absolute $\nu_e$ flux at the neutrino detector with a precision of $\mathcal{O}(1\%)$, improving of one order of magnitude the cross-section measurement at the GeV scale.

## 2. – The ENUBET beamline

The ENUBET beamline [4] collects, focuses and transports the kaons to the decay tunnel entrance, while keeping the level of background under control. The number of $K^+$ and $\pi^+$ is maximized with the use of conventional magnets and by minimizing the total length of the transfer line, in order to reduce kaon decay losses. The beam must also be collimated enough so as to prevent any undecayed meson to hit the inner surface of the instrumented decay tunnel. Given these constraints, the current simulated ENUBET beamline is comprised of a short (~20 m) transfer line and a 40 m long decay tunnel; the hadron beam has a reference momentum of 8.5 GeV/$c$ with a momentum bite of 10%. The target is in beryllium, 110 cm long and 3 mm diameter, and is simulated with FLUKA along with the proton interactions with it. The proton drivers considered are CERN SPS (400 GeV), Fermilab Main Ring (120 GeV) and JPARC (30 GeV). As far as the proton dump is concerned, its position and size are still under optimization.

Two possible beamline designs have been considered, with two different focusing systems: one "horn-based", with a magnetic horn placed between the ENUBET target and the transfer line, and a "static" one, with the transfer line quadrupoles placed directly downstream the target.

In the horn-based transfer line, the horn is pulsed for 2–10 ms and cycled at ~10 Hz during the accelerator flat-top. Studies to combine the proton extraction from the accelerator, typically of few ms, with the the horn pulses are ongoing at CERN. This option is efficient in terms of meson yields (4–5 times the static option), with rates of $77 \times 10^{-3}\pi^{+}$/POT and $7.9 \times 10^{-3}K^{+}$/POT in the 6.5–10.5 GeV/$c$ momentum range expected at the SPS. On the other hand, the static option employs second-long slow extraction schemes already well proven in most accelerators. This configuration has yields four times larger with respect to preliminary estimates [1], transporting at the tunnel entrance $19 \times 10^{-}3\pi^{+}$/POT and $1.4 \times 10^{-}3K^{+}$/POT in the 6.5–10.5 GeV/$c$ momentum range. Figure 1 shows the static beamline, composed by a quadrupole followed by a dipole and another quadrupole triplet after the resulting bending of 7.4°. This configuration is particularly interesting because it reduces significantly (by two orders of magnitude) the particle rate in the instrumented decay tunnel, allowing to associate in time the $\nu$ at the far detector with the observation of the associated lepton from the parent hadron in the decay tunnel and hence paving the way for a "tagged neutrino beam".

**2**˙1. *The ENUBET narrow-band beam.* – The narrow momentum width ensures that the neutrino energy is known at the 10% level on event by event basis with no need to rely on the reconstruction of the final-state particles; the differential cross-section is determined without biases due to energy reconstruction, providing the ideal tool to study neutrino interactions with nuclei. Moreover, it is possible to know the flavour composition at the 1% level: the slow extraction scheme reduces by more than an order of magnitude the muon rate after the beam dump, allowing for a precise measurement of the $\nu_{\mu}$ flux from pion decays, in addition to the $\nu_{e}$ and $\nu_{\mu}$ from kaon decay. Such precision is suitable to study NSI and sterile neutrinos at the GeV scale.

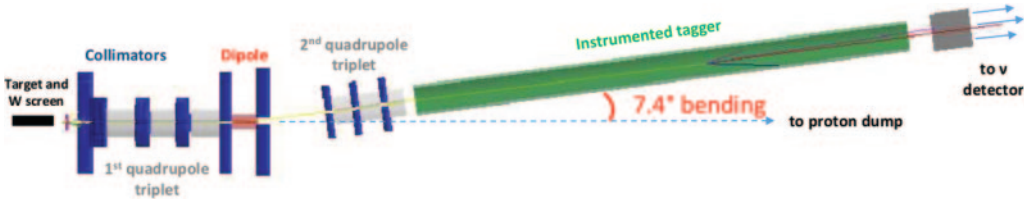

Fig. 1. – Schematics of the ENUBET beam in the static focusing option.

## 3. – The tagger

The ENUBET decay tunnel is fully instrumented and performs the identification of $K_{e3}$ events and their separation from the background. A calorimeter, built as a hollow cilinder inside the beampipe, performs the $e^+/\pi^+$ separation, while an inner light-weight detector is used for timing and $e^+/\pi^0$ separation.

The calorimeters are sampling calorimeters with longitudinal segmentation, instrumented with plastic scintillators. This option guarantees an energy resolution in line with the ENUBET requirements ($<25\%/\sqrt{E}$), a short recovery time ($\sim$10 ns) and is cost-effective.

The calorimeters have a longitudinal granularity of $4.3X_0$ (10 cm) and are built of iron tiles (1.5 cm thick) and plastic scintillator tiles (0.5 cm thick) with a transversal dimension of $3 \times 3\,\mathrm{cm}^2$. The $e^+/\pi^+$ separation is performed by observing the energy pattern deposition from the particle showers: the shower generated by a positron is fully contained in about $2 \times 4.3X_0$, while a pion-induced shower develops further. The light readout has been tested with two different readout schemes: a "compact" shashlik one and a "lateral" one. In the "compact" shashlik readout the tiles of absorbing and scintillating material are crossed perpendicularly by the WLS fibres, with a fibre density of $1/\mathrm{cm}^2$, nine for every tile. After $4.3X_0$ each fibre is coupled with a SiPM mouted on a custom PCB. The PCB is embedded in the calorimeter structure, ensuring a uniform light collection, with no dead areas due to fibre bundling. This type of readout is very compact and is easily scalable; however, it exposes the SiPMs directly to a large flux ($10^{11}$ 1 MeV-eq n/cm$^2$) of fast neutrons originated by the hadronic showers.

In the "lateral" readout two fibres are glued at two opposite sides of each scintillator tile and bundled in groups of ten at larger radii of the decay tunnel. In this scheme the light collection is less uniform, but the photosensors are located far from the high radiation area and are accessible for maintenance. Moreover, this type of calorimeter is easier and cheaper to assemble.

**3·1.** *Tagger prototypes performances.* – Prototypes of both types of light readout have been tested at CERN-PS T9 beamline, with a mixed beam of $e^-$, $\mu^-$ and $\pi^-$, with beam momentum from 0.5 to 5 GeV/$c$. Both the shashlik (fig. 2 [5]) and the

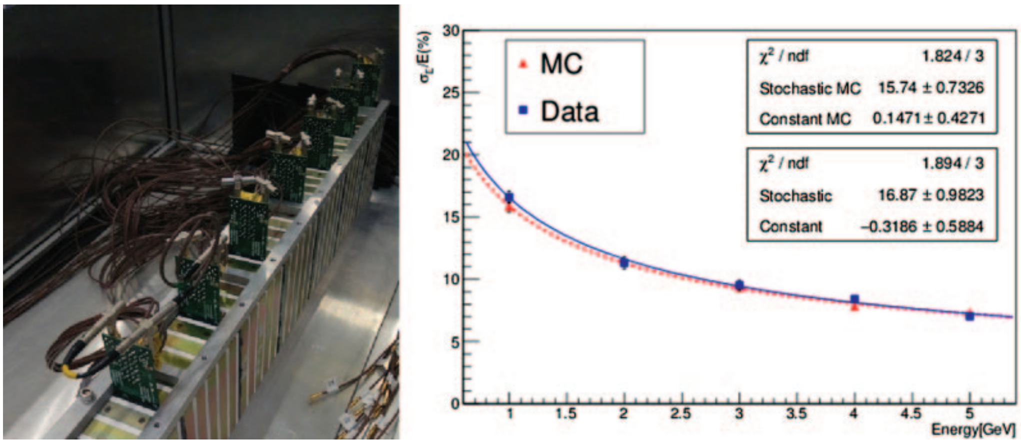

Fig. 2. – Left: the shashlik prototype tested at CERN; right: its energy resolution [5].

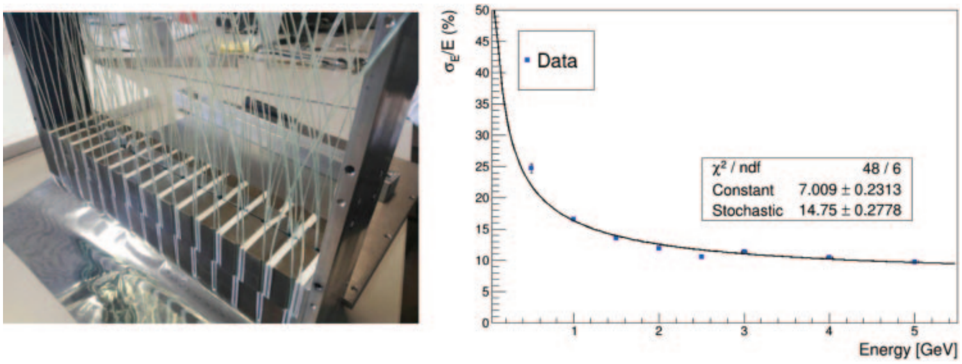

Fig. 3. – Left: the lateral readout prototype tested at CERN; right: its energy resolution (preliminary results).

lateral readout prototype (fig. 3) provide an energy resolution of $\sim 17\%/\sqrt{E}$, within the ENUBET constraints. The energy resolution of the lateral readout displays a bigger constant term, probably due to the non-uniform light collection.

Irradiation tests on the SiPMs have been performed in order to assess the radiation damage on the photosensors in the shashlik scheme at the LNL-INFN. SiPMs with cell size of 12, 15 and 20 $\mu$m have been irradiated with neutron fluences up to $1.2\times10^{11}$ n/cm$^2$ 1 MeV-eq. As fig. 4 shows, the electron peak is still well distinguishable from the noise pedestal after irradiation [6]. The MIP peak is separated from the noise too, provided that the number of photoelectrons per MIP is $\gtrsim$50, condition achievable by doubling the scintillator thickness (from 0.5 to 1 cm).

**3**˙2. $K_{e3}$ *positron reconstruction.* – A full GEANT4 simulation of the detector, validated by the prototype tests perfomed at CERN in the years 2016–2018, is under optimization. The simulation includes the propagation and decay of particles from the transfer line to the detector, the hit-level detector response and accounts for pile-up effects [7]. The analysis chain for each event starts with the event builder, in which the seed of the event is identified along with the cluster of neighbour modules. A TMVA multivariate analysis performs the $e/\pi/\mu$ separation with 6 variables that de-

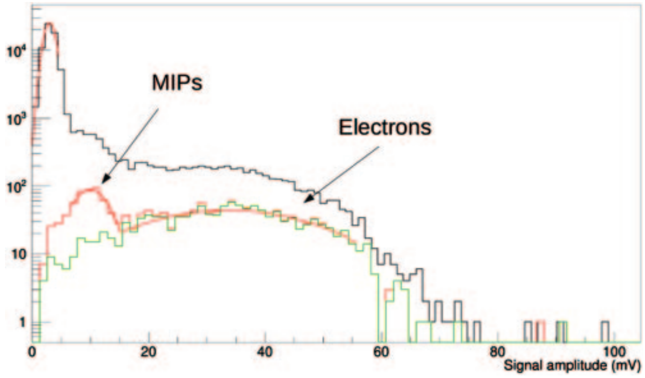

Fig. 4. – Energy deposit in a shashlik calorimeter with compact readout prototype equipped with irradiated SiPMs and with scintillator tile thickess of 1 cm.

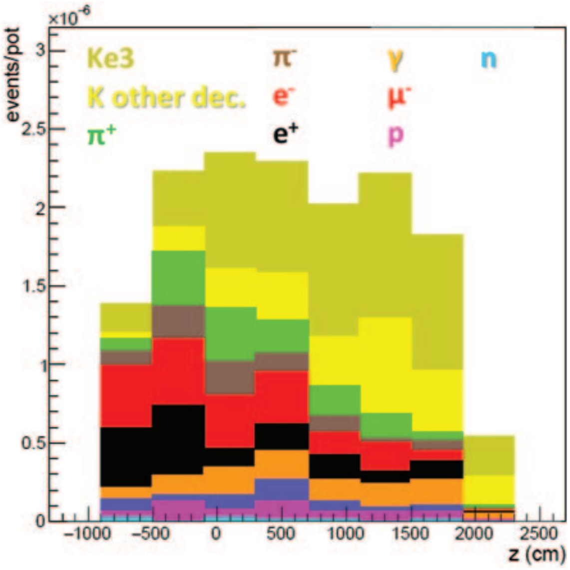

Fig. 5. – All the events selected as $K_{e3}$ by the algorithm.

scribe the pattern of the energy deposition in the calorimeter. The analysis of the signal on the tiles of the photon veto provides the information for the $e/\gamma$ separation. In fig. 5 is shown the contribution of different $K$ decay modes and background particles to all the events reconstructed as $K_{e3}$. By instrumenting half (180°) of the decay tunnel it is possible to identify positrons from $K_{e3}$ events at single particle level with a $S/N = 0.46$.

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## REFERENCES

[1] Longhin A., Ludovici L. and Terranova F., *Eur. Phys. J. C*, **75** (2015) 155.
[2] Berra A. *et al.*, CERN-SPSC-2016-036, SPSC-EOI-014.
[3] Acerbi F. *et al.*, CERN-SPSC-2018-034, SPSC-EOI-248.
[4] Brunetti G. *et al.*, arXiv:1903.09044 [physics.acc-ph].
[5] Ballerini G. *et al.*, *JINST*, **13** (2018) P01028.
[6] Acerbi F. *et al.*, *JINST*, **14** (2019) P02029.
[7] Pupilli F. *et al.*, talk at *the 2019 Neutrino Telescopes Conference*, `https://zenodo.org/record/2712637`.