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ENUBET: a monitored neutrino beam for the precision era of neutrino physics

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Abstract. The ENUBET ERC project, also included in the CERN Neutrino Platform as NP06/ENUBET, is developing a new neutrino beam based on conventional techniques in which the flux and the flavor composition are known with unprecedented precision ($\mathcal{O}(1\%)$). Such a goal is accomplished monitoring the associated charged leptons produced in the decay region of the ENUBET facility. Positrons and muons from kaon decays are measured by a segmented calorimeter instrumenting the walls of the decay tunnel, while muon stations after the hadron dump can be used to monitor the neutrino component from pion decays. Furthermore, the narrow momentum width (<10%) of the beam provides a precise measurement ($\mathcal{O}(10\%)$) 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. ENUBET is therefore an ideal facility for a high precision neutrino cross-section measurement at the GeV scale, that could enhance the discovery potential of the next-generation of long baseline experiments. It is also a powerful tool for testing the sterile neutrino hypothesis and to investigate possible non-standard interactions.

1. ENUBET monitored neutrino beam

The precise measurement of ν_e and ν_μ cross sections in the GeV scale will benefit the long baseline experiments DUNE and HyperKamiokande, by enhancing their sensitivity to oscillation parameters, included the CP violating phase δ [1].

Neutrino cross-section measurements traditionally suffer from flux systematics uncertainty and ν energy systematic uncertainty. ENUBET aims at addressing these limitations, enabling a *monitored neutrino beam* [2] capable of controlling ν flux and flavor at 1 % level, and the ν energy at source at $\sim$ 10 % level.

The basic idea of ENUBET is to reduce the cross-section systematics arising from the final state reconstruction biases, by directly tagging large angle positrons and muons arising from kaon decays in an instrumented decay tunnel.

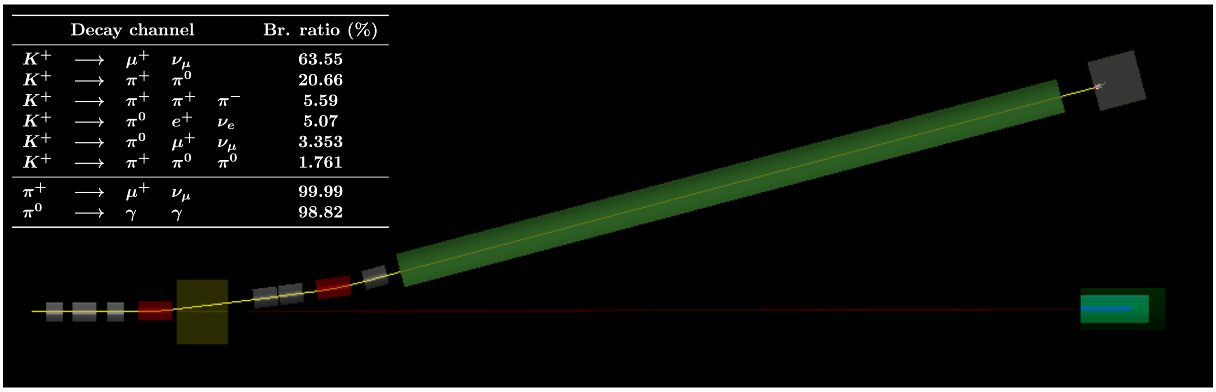
The collaboration, active since 2016, elaborated and evaluated the *monitored neutrino beam* concept, focusing the efforts on beam-line simulation, systematics budget estimate, and active tunnel technology development.

2. Beamline

The success of ENUBET in monitoring the leptons from kaon decays clearly depends on the amount of delivered kaons with respect to the background fluxes, among which the π^+ one dominates. The whole beam-line has been extensively studied through simulations in order to optimize the kaon acceptance while reducing the contaminations, considering a beam of 400 GeV/c momentum.

The target is a graphite cylinder (2.2 g/cm^3) having 3 cm for the radius and 70 cm for the length. The choice of the material and the dimensions have been optimized through FLUKA and G4beamline simulations. Materials such as graphite, beryllium, Inconel, gold, and tungsten have been considered in the evaluation, as well as dimensions ranging in [10, 30] cm for radius and [5, 140] cm for length. The chosen target offers an optimal trade-off between the competing requests of heat dissipation and re-interaction of secondaries.

In order to suppress the positrons produced in the target, a 10 mm thick tungsten foil is placed right after it. It defines the beginning of the transfer line, shown in Figure 1, which provides a 14.8° bending with respect to the proton direction through an optical stage made of 1.8 T field bending dipoles and 15 cm aperture radius focusing quadrupoles. The optical stage is followed by the active decay tunnel, where the leptons from kaon decays are tagged, and the hadron dump. The transfer line is able to select a K^+ flux of $0.4\times\ 10^{-3}$/POT (POT=proton on target) limiting the π^+ flux down to $4.2\times\ 10^{-3}$/POT in the momentum range $8.5\pm5\%$ GeV/c.



Decay channel					Br. ratio (%)
K^+	$\longrightarrow$	μ^+	ν_μ		63.55
K^+	$\longrightarrow$	π^+	π^0		20.66
K^+	$\longrightarrow$	π^+	π^+	π^-	5.59
K^+	$\longrightarrow$	π^0	e^+	ν_e	5.07
K^+	$\longrightarrow$	π^0	μ^+	ν_μ	3.353
K^+	$\longrightarrow$	π^+	π^0	π^0	1.761
π^+	$\longrightarrow$	μ^+	ν_μ		99.99
π^0	$\longrightarrow$	γ	γ		98.82

Figure 1. Schematic top view of the transfer line: the target is not depicted, in the optical section the dipoles are red and the quadrupoles are grey, then the green active decay tunnel is followed by the grey hadron dump. Along the primary proton direction is found the green proton dump. The table shows the kaon and pion decays of interest for ENUBET.

3. Active decay tunnel and demonstrator

The ENUBET project proposes the possibility of a tagged neutrino beam by implementing an active decay tunnel, also denominated as tagger, where the leptons of kaon decays are recognized on an event-by-event basis.

A significant fraction of kaon decays produces a background composed of a mixture of charged and neutral pions. The Table on the top-left of Figure 1 shows the detail of the possible decays occurring in the tagger. The physics of kaon decays dictates that the active decay tunnel must be able to discriminate among positrons, muons and pions, otherwise the decays of interest (i.e. mainly the semileptonic 2 and 3-body decays) would not be recognized.

The chosen tagger technology is a sampling calorimeter constituted by three radial rings plus one innermost γ-veto ring, as shown on the left of Figure 2. The functional block of the 3 rings is the Lateral Compact Module (LCM), which is an array of 5+5 alternate layers of iron and scintillator, for a total dimension of $3 \times\ 3 \times\ 10$ cm^3, corresponding to 4.3 X_0. Instead the γ-veto rings are composed of scintillator doublets, each scintillator being $3 \times 3 \times 0.7$ cm^3 (0.012 X_0).

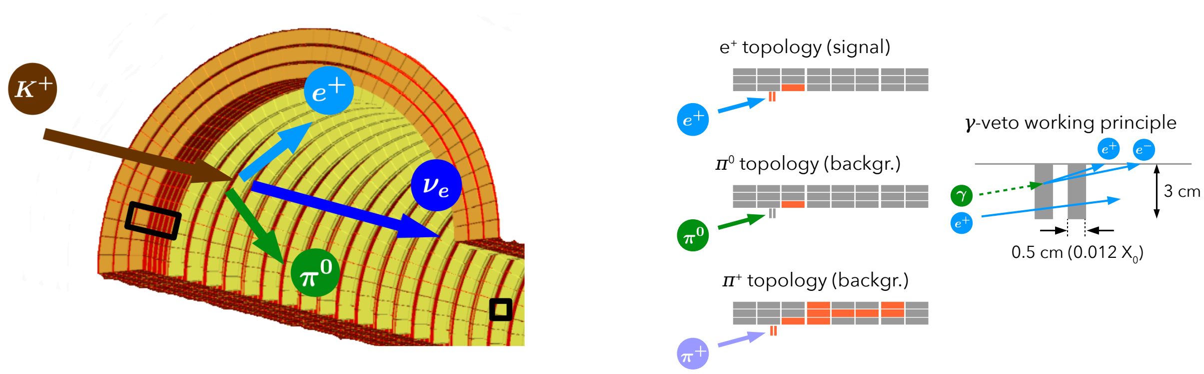


Figure 2. Left: schematic view of a portion of the active decay tunnel. Right: event topology for signal and background. The rectangles represent the LCMs, they are either grey (not crossed) or orange (crossed). The γ-veto doublet is represented in grey (e^-e^+ pair signal) or in orange (single e^+ signal).

A single LCM extends for the typical extension of a positron shower at the energies of interest of a few GeV, while the γ-veto scintillator doublet is able to convert a γ into a e^-e^+ pair and to distinguish between single e^+ signal and e^-e^+ pair signal. These two facts define the event topology, shown on the right of Figure 2, through which the signal-background discrimination can be performed with a multi-variate analysis.

In the last generation of neutrino beam experiments, the decay tunnels were *passive* elements: radiation tolerance of the electronics and the number of channels makes the design of an active decay tunnel very arduous, considering that any applied technology needs complexity and cost sufficiently manageable to be scaled up to few tens of meters.

The ENUBET collaboration has embraced such challenges, and is trying to overcome them by delivering its main hardware output: the *demonstrator* (Figure 3 left). It is a 1.65 m $\times$ 90° prototypal portion of the tagger, which is now under construction and will be exposed to particle beam at CERN in 2022. Its bulk is composed of 75 arches of 15 mm thick iron alternated with 75 layers of 7 mm thick scintillator, for a total of 15 $\times$ 3 LCMs. The calorimetric portion is coated with a 30 cm neutron shield of borated polyethylene which reduces the neutron flux by about a factor 20. The SiPMs are shielded in order to prevent radiation damage, and they receive the light from scintillators via wavelength-shifting optical fibers.

The necessity for a neutron shield was established with a SiPM irradiation campaign [3], while the scheme for optical fiber light readout has beed tested exposing the prototype known as *lateral readout calorimeter* to particle beam at CERN in 2018 [4]. A newly developed light readout scheme has driven the construction of the *Enubino* prototype (Figure 3 right), which is being tested on particle beam at CERN in November 2021.

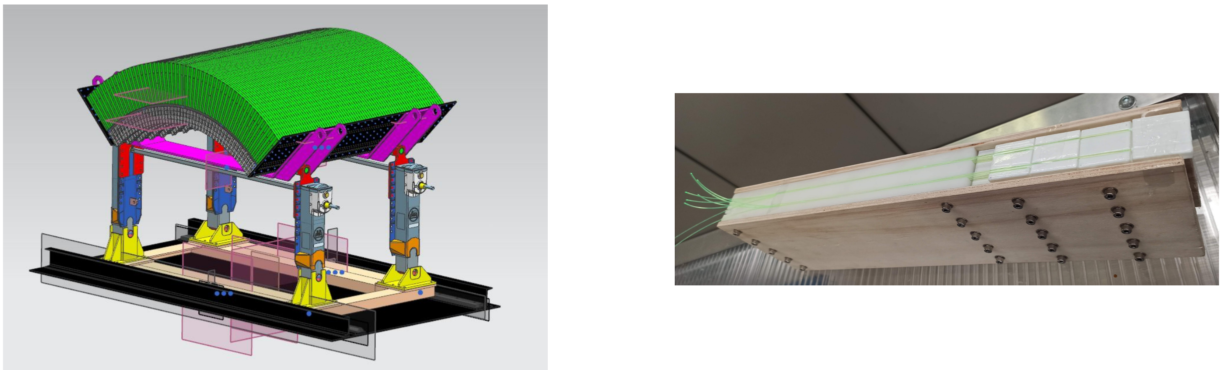


Figure 3. Left: schematic view of the demonstrator. Right: the prototype *Enubino*.

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