PROCEEDINGS OF SCIENCE

Detector R&D for the ENUBET instrumented decay region

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The ENUBET/NP06 project aims at validating, both through simulation and detector prototyping, the possibility of a monitored neutrino beam through lepton tagging in an active decay tunnel. Such a technology would enable a control of the flux at the $O(1\%)$ level, offering the chance to measure neutrino cross sections with unprecedented precision.

The project has undergone various phases of R&D, whose milestones consisted in the construction of different calorimeters and the assessment of their performance. In this contribution the technical details and design solutions regarding the *demonstrator*, which is the final prototype currently under construction, and the *lateral readout calorimeter*, which is its precedessor, are discussed.

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1. Enubet

The ENUBET ERC project is active since 2016, and is recognized as CERN Neutrino Platform experiment NP06 since 2019. In neutrino beam experiments, flux uncertainties constitute a predominant portion of the systematics budget of cross section measurements. The project aims at reducing the uncertainty of ν_e and ν_μ fluxes at the $O(1\%)$ level, enabling better cross section estimates, especially at the energies of interest for DUNE and Hyper-Kamiokande long-baseline experiments [1].

In order to achieve this goal, ENUBET proposes a monitored neutrino beam, consisting of an optimized kaon-enriched beamline and an active decay tunnel able to tag on a particle-by-particle basis the leptons associated with the 2- and 3-bodies semileptonic kaon decays:

$$\begin{aligned} K^+ &\longrightarrow \mu^+ \; \nu_\mu \\ K^+ &\longrightarrow \pi^0 \; e^+ \; \nu_e \\ K^+ &\longrightarrow \pi^0 \; \mu^+ \; \nu_\mu \end{aligned}$$

The active tunnel technology should have good energy and timing resolution, be radiation tolerant, and be sufficiently inexpensive to be scaled up to tens of meters. The active tunnel R&D has been driven by the construction and performance assessment of different prototypes. In 2018 there was a major migration from a *Shashlik calorimeter* [2] to a *lateral readout calorimeter* [3], which was exposed to particle beam at CERN . The analysis of the gathered data suggested the successive improvements to be adopted, and a final optimized design is converging into the construction of the so-called *demonstrator* [4], a 1.65 m $\times$ 90° prototypal portion of the active tunnel.

2. Lateral readout calorimeter

The building block of the lateral readout calorimeter is the lateral compact module (LCM, see left panel of Figure 1). Each LCM is constituted by five 0.5 cm thick scintillating tiles alternated with five 1.5 cm thick iron tiles, for a total length of 10 cm and a section of 3×3 cm^2. The LCM is dimensioned to be sufficient for stopping a 1 - 3 GeV positron in its volume.

The energy deposited by a crossing particle in a scintillating tile is converted into visible photons. These are collected on the sides of the tile by a pair of optical fibers having diameter of 1 mm, and guided to the active surface of a silicon photomultiplier (SiPM). The SiPM converts light into an electrical signal that can be processed and digitized for offline analysis. The fibers run tens of centimeters away from the tiles, in order to protect the SiPMs from the large levels of irradiation which are present in the bulk of the calorimeter and the decay region.

The spectral gap between the scintillator emission peak of 408 nm and the SiPM sensitivity peak of 550 nm is compensated by the wavelenght shift introduced by the fibers. Two types of fibers are mounted for test on the lateral readout calorimeter, the Kuraray Y11 with emission peak at 476 nm, and the Saint-Gobain BCF92 with emission peak at 492 nm. The scintillator of choice is Eljen EJ-204 featuring a scintillating efficiency of 10400 photons / 1 MeV e^-. The 10 fibers coming from the 5 tiles of a LCM are read by a single SiPM, thus it needs to have a sufficiently large active area. The chosen SiPM is AdvanSiD ASD-RGB4S-P, with a 4×4 mm^2 active area.

As shown in the right panel of Figure 1, the lateral readout calorimeter is a prototype composed of 84 LCMs and 4 $\gamma-$veto doublets. It allows particle discrimination through the recognition of the event topology by a neural network.

A $\gamma-$veto doublet is just a pair of 0.5 cm thick scintillator tiles. A $\gamma-$veto doublet produces a 1-MIP-like signal when crossed by a positron, while two, or most likely, zero MIP-like signals for gammas from π^0-decays. Instead the charged pions are recognized in the calorimeter bulk, because they shower and induce a geometrical pattern of energy deposition, while a positron produces signal in just 1 LCM on average.

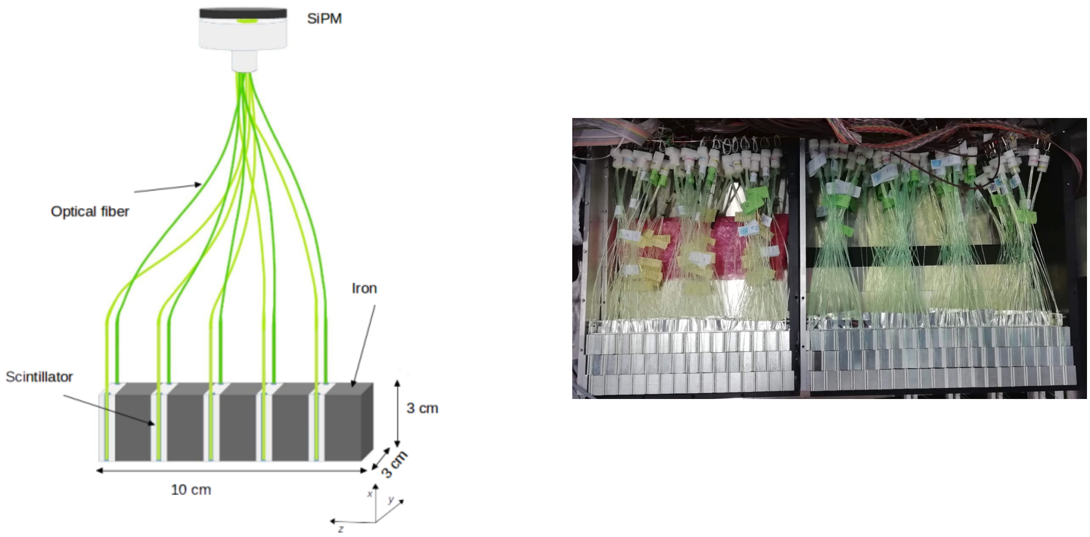

Figure 1: Left: schematic view of a LCM. Right: lateral readout calorimeter.

3. Demonstrator

The demonstrator is a 1.65 m $\times$ 90° portion of active decay tunnel (left panel of Figure 2), whose goal is to establish the feasibility of lepton reconstruction with a technology scalable up to tens of meters.

Its quarter-of-circle design is extendable to cover the 2π angle of a tunnel, even if only 45 degrees will be instrumented with SiPMs and readout electronics. Its calorimetric bulk is made of 75 layers of 15 mm thick iron arches alternated with 75 layers of 7 mm thick scintillators, constituting three coaxial radial shells of 15 LCMs each. In addition to the lateral readout calorimeter, the demonstrator mounts a 30 cm outer cover of 5% borated polyethylene in order to shield the SiPMs from neutrons. According to FLUKA simulations, the shield is able to reduce the neutron flux by a factor of about 20.

The fiber routing scheme has been renewed and improved. Each scintillating tile is frontally coupled to a pair of fibers 1.5 cm apart. Geant4 simulations establish that, with respect to the previous design of laterally coupled fibers, there is an improvement in both light collection and uniformity. The fibers run through grooves in the scintillating tiles, cross the shield, and are bundled in front of SiPMs by 3D-printed routing caps.

The migration from the lateral readout calorimeter to the demonstrator has challenged core aspects of the calorimeter design. An evidence-based transition has been possible by testing the novelties on the small prototype named *Enubino*, displayed in the right panel of Figure 2, which is a single azimuthal unit of the demonstrator (3 LCMs). Both mechanical considerations and light readout performance has been assessed with this prototype, that was exposed to particle beam at CERN in November 2021.

The demonstrator is currently under construction at the INFN laboratories in Legnaro, Italy, and beam exposure is scheduled at CERN in 2022.

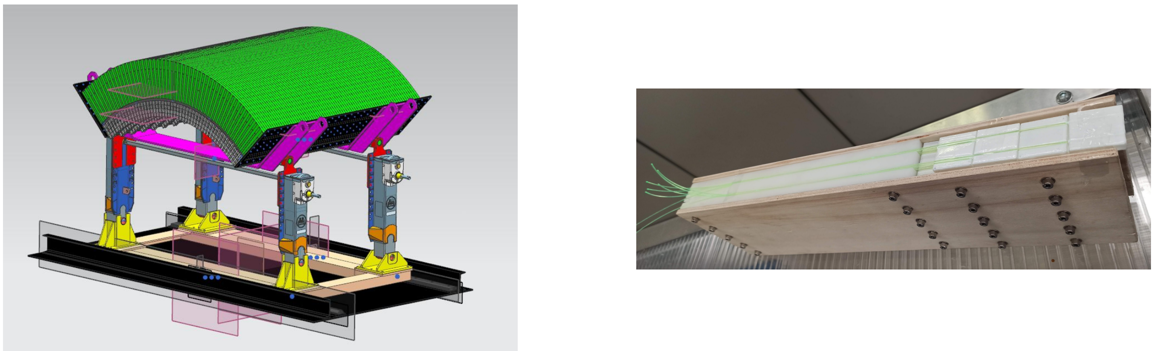

Figure 2: Left: schematic view of the demonstrator. Right: the prototype *Enubino*.

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