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The ENUBET monitored neutrino beam: moving towards the implementation of a high precision cross section experiment at CERN

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Monitored neutrino beams represent a powerful and cost effective tool to suppress cross section related systematics for the full exploitation of data collected in long baseline oscillation projects like DUNE and Hyper-Kamiokande. In the last years the NP06/ENUBET project has demonstrated that the systematic uncertainties on the neutrino flux can be suppressed to 1% in an accelerator based facility where charged leptons produced in kaon and pion decays are monitored in an instrumented decay tunnel. This contribution will present the final design of the ENUBET beamline, the experimental setup for high purity identification of charged leptons in the tunnel instrumentation and the framework for the assessment of the final systematics budget on the neutrino fluxes. We will also present the results of a test beam exposure at CERN-PS of the Demonstrator: a fully instrumented 1.65 m long section of the ENUBET instrumented decay tunnel. Finally the physics potential of the ENUBET beam with ProtoDUNEs as neutrino detectors and plans for its implementation in the CERN North Area will be discussed.

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1. Introduction

Thanks to unprecedented beam powers and detector masses, the next generation of neutrino oscillation experiments (DUNE, Hyper-Kamiokande, ESSnuSB) will not be limited by statistical uncertainties, but a superior mastering of systematic uncertainties will be required in order to fully exploit the collected data for the precise measurement of oscillation parameters and the determination of a possible CP violation in the leptonic sector. In this context a prominent role is played by neutrino cross sections at the GeV scale, in particular the one of the electron neutrino (the appearing flavour in future experiments), that are known with a precision (10-30%) inappropriate for the need of these facilities [1]. As outlined by the European Strategy for Particle Physics deliberation document [2], an experimental program to measure neutrino cross sections at the percent level is highly desirable.

ENUBET [3, 4] has been proposed and funded by the ERC to reduce to 1% the uncertainty on the beam flux, that represent the dominant uncertainty for a high precision neutrino cross section measurement. This goal is achieved in a conventional beamline by measuring on the walls of an instrumented decay tunnel (tagger) the charged leptons produced in association to neutrinos in meson decays, thus bypassing in a direct way uncertainties on the beamline geometry and focusing and on the hadroproduction that usually limit the precision on the flux at the level of 5-10%. In particular, the ν_e flux at the detector can be inferred by monitoring the rate of the large angle positrons emitted in the three body decay of kaons (K_{e3}, i.e. $K^+ \to \pi^0 e^+ \nu_e$), that represent their main source if the decay tunnel is kept short enough to suppress decays in flight of muons. In the context of the CERN Neutrino Platform experiment NP06, ENUBET has then extended its scope to the monitoring of large angle muons from $K_{\mu\nu}$ decays ($K^+ \to \mu^+ \nu_\mu$, $K^+ \to \pi^0 \mu^+ \nu_\mu$), while low angle muons from pions can be measured by instrumenting the forward region of the decay tunnel after the hadron dump, thus providing a full constraint also on the ν_μ flux [5]. The main challenges for the success of the project are the definition of a cost-effective technology to instrument the harsh environment of the entire decay tunnel and the design of a meson transfer line able to deliver a clean and well collimated beam in order not to swamp the instrumentation.

2. The meson transfer line

The final design of the ENUBET beamline [6] is shown in Fig. 1. It is designed to provide a narrow-band neutrino beam by focusing towards the 40 m long decay tunnel (1 m radius) positively charged mesons with a momentum bite of 5-10% centered at 8.5 GeV/c, coming from the interaction of 400 GeV/c protons on a graphite target, whose dimensions (70 cm long, 3 cm radius) have been optimized with a FLUKA simulation to maximize the kaon yield. The total length of the line (26.7 m) is optimized to reduce early kaon decays before the tunnel entrance. The magnetic lattice has been designed in TRANSPORT and is based on a purely static focusing system of the secondary mesons implemented with a quadrupole triplet in front of the proton target. Contrary to a horn-based focusing, that requires a fast extraction of protons in pulses of $\mathcal{O}(10\ \mu s)$ due to constraints posed by the Joule heating of the conductors, DC operated magnets can be coupled to a slow extraction scheme of protons lasting some seconds. Such a design represented one of the major breakthrough in the ENUBET project, because it allows for a large enough neutrino yield to accomplish the envisaged physics program, while implying a significant reduction of pile-up effects on the tunnel instrumentation and ensuring an event-by-event monitoring of charged leptons.

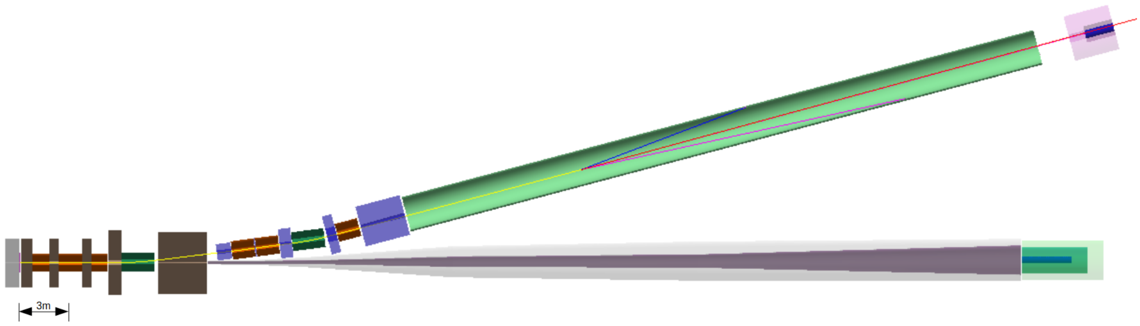

Figure 1: The final design of the ENUBET beamline. Quadrupoles are shown in orange, while bending dipoles are depicted in green. Copper collimators are reported in brown, while the elements in violet are Inermet-180 collimators. The 40 m decay tunnel is also shown, together with the pipe for non interacting protons and the proton and hadron dumps.

Charge and momentum selection of secondary mesons is accomplished by means of two normal-conducting dipoles providing a total bending with respect to the proton beam direction of 14.8°. The background at the neutrino detector composed by untagged ν_e from early kaon decays in the first half of the transfer line is reduced thanks to the large bending angle.

Studies on the irradiation of the beamline elements and of the tunnel instrumentation have been conducted with FLUKA, while G4Beamline has been used to simulate particle transport and interactions in the shielding elements. The entire beamline has been implemented in a Geant4 simulation, that enabled to access the full history of particles to ease the systematics assessment on the neutrino flux (Sec. 5). This fully parametric simulation was pivotal for the implementation of a framework based on a genetic algorithm employed to fine tune the apertures and dimensions of the last two collimators before the tunnel entrance, allowing for a significant reduction of the background from the beam halo on the tagger and for a slight increase in the meson yields.

3. The neutrino beam

The ENUBET beamline is able to provide 10^4 ν_e^{CC} interactions on a ProtoDUNE-like detector, 500 t mass and 6×6 m^2 transverse size, placed at a distance of 50 m from the end of the decay tunnel in about 2.3 years of data taking, assuming 4.5×10^{19} protons on target per year. The energy spectrum, shown in Fig. 2, has a mean energy of about 4 GeV that is well suited for the study of neutrino cross section in the DUNE energy region.

Neutrinos produced from K_{e3} decays in the tagger volume (in red), that can be directly monitored by the tunnel instrumentation, represent ∼68% of the total sample above 1.5 GeV, with additional contributions coming from the the straight part of the beamline after the second bending and the hadron dump that can be accounted for by the simulation. Neutrinos below this threshold, mostly produced by interactions in the proton dump and in the focusing quadrupole triplet, can be efficiently discarded by a coarse energy cut.

The ENUBET beamline also ensures ∼6×10^5 ν_μ^{CC} interactions at the detector, under the same assumptions previously reported. The energy spectrum exhibits a double peak structure typical of

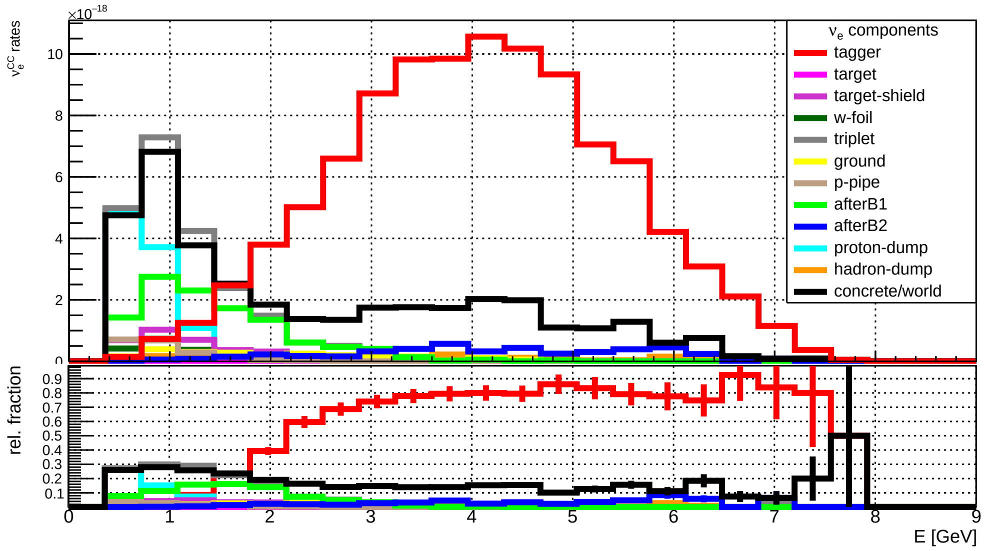

Figure 2: Energy spectrum of ν_e^{CC} interactions, with a breakdown of the neutrino components according to their production point within the ENUBET beamline. The bottom plot reports the fraction of each spectrum relative to the total sample.

narrow-band neutrino beams, in which the sample below 4 GeV is originated from pion decays, while the higher energy one is produced by kaon decays. The narrow momentum bandwidth and the short baseline of ENUBET allow for an a-priori determination of the neutrino energy that is based on its strong correlation with the radial distance of the interaction vertex from the beam axis induced by the 2-body decay kinematics ("narrow band off-axis" technique). By selecting interactions in radial windows, the incoming neutrino energy can be determined with a precision given by the width of the pion peaks ranging from 10 to 25% in the DUNE energy domain [6]. Such a precise determination at source of the neutrino energy allows to mitigate the uncertainties affecting its measurement through the reconstruction of the interaction final state.

4. The instrumented decay tunnel and its Demonstrator

The lepton tagger (Fig. 3, left) is based on a sampling calorimeter as a cost-effective solution to perform $e/\pi/\mu$ separation, placed on the whole surface of decay tunnel. The calorimeter is segmented in the longitudinal, radial and azimuthal coordinates and its basic unit, called LCM (Lateral Compact Module), has a 3×3 cm^2 transverse size and is composed by a stack of five 0.7 cm thick scintillator tiles interleaved with five 1.5 cm thick iron tiles, for a total of 4.3 X_0. Three radial layers of LCM are foreseen. The dimension of the LCM is a compromise between the need for high-granularity modules for pile-up reduction and particle identification and the total cost of the tunnel instrumentation (< 10% of the cost of the facility). The instrumentation is complemented by rings of plastic scintillator doublet tiles (3×3 cm^2, 0.7 cm thick) below the calorimeter (t0-layer), acting as a photon veto to suppress the π^0 background and providing timing information. Both the detectors are read out by WLS fibers placed on the frontal faces of the tiles and coupled to SiPMs placed above a 30 cm borated polyethylene (BPE) shielding against neutron irradiation and ageing of the sensors: indeed, FLUKA simulations have shown that a neutron reduction by a factor ∼18 is induced by the BPE layer.

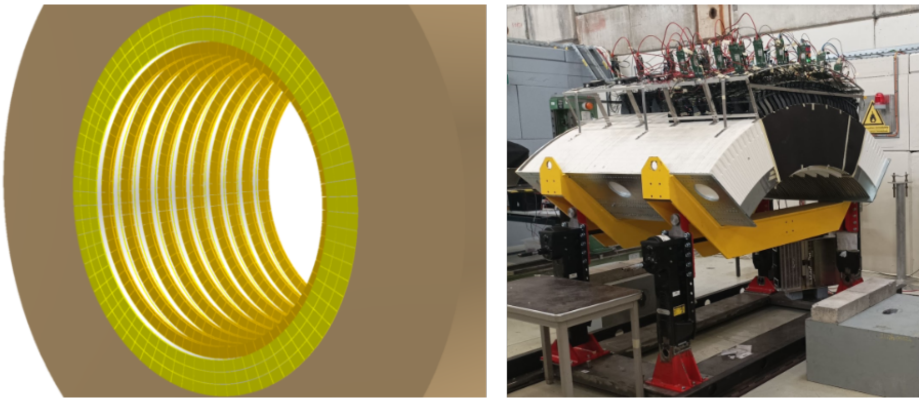

Figure 3: Left: scheme of the decay tunnel instrumentation: the three layers of calorimetric modules are shown in yellow, while the t0-layer is depicted in orange. The BPE shielding is also shown in brown. Right: The ENUBET tagger Demonstrator during the 2023 testbeam at CERN-PS.

An intense prototyping and test beam activity allowed to define the final layout of the instrumentation and to verify that it meets the requirements of the project in terms of efficiency, time and energy resolution [7]. This activity culminated in the construction of the Demonstrator, a large scale prototype (1.65 m in length, 3.5 t mass) with the goal to prove the performance, scalability and cost-effectiveness of the chosen technology [8]. The demonstrator has been partially instrumented (half of its length, 18° coverage in ϕ) for a total of 400 active channels and has been exposed to the T9 particle beam at CERN-PS in October 2022. The instrumentation on the Demonstrator was then extended to fully cover its length, with a coverage in ϕ of 45° in the newly equipped part and an increase of a factor ∼3 in the total number of readout channels (Fig. 3, right). This extended version of the Demonstrator has been tested again at CERN-PS in summer 2023. The data analysis is now on going and preliminary results show a good energy linearity and a resolution of $\sim 17/\sqrt{E}\%$, that is appropriate for e/π separation in the 1-3 GeV range.

5. Particle identification and flux systematics assessment

The full instrumentation of the ENUBET tagger has been implemented in a GEANT4 simulation that has been validated with data from prototypes tested at CERN and that is used to evaluate the particle identification performance. Detector response is treated at hit-level with the inclusion of pile-up effects. An event building algorithm cluster energy deposits correlated in space and time within predefined cuts and a Neural Network is employed to discriminate the signal from the background exploiting differences in the energy deposition pattern. Positrons from K_{e3} are reconstructed with an efficiency of 22% and a S/N∼2, whereas muons from $K_{\mu\nu}$ are identified with an efficiency of 34% and a S/N∼6 [6]. Fig. 4 shows the distributions of the observables measured by the calorimeter for positrons and muons, used to constrain the neutrino flux at detector.
Using these observables, a signal plus background model for the monitored charged leptons is built in order to constrain the neutrino flux. Hadroproduction (HP) systematics, that represent

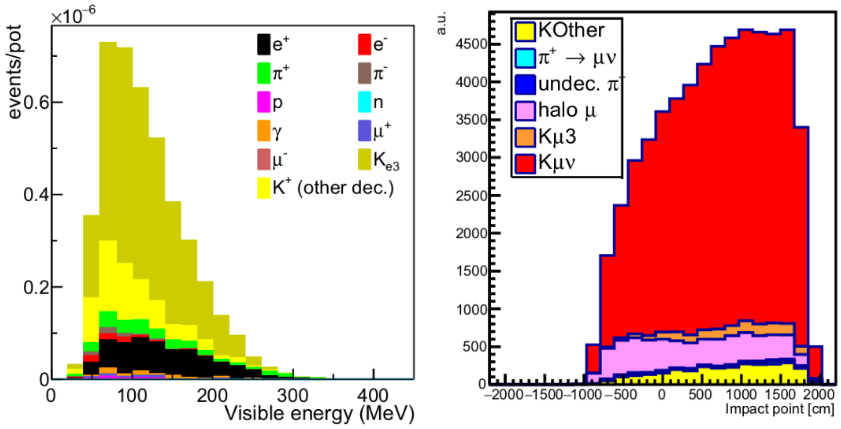

Figure 4: Distribution of observables for selected events. Left: visible energy of positrons from K_{e3} signal (golden) and of background events. Right: impact point along the calorimeter of muons from $K_{\mu 2}$ (red) and $K_{\mu 3}$ (orange) and of background events.

the dominant contribution on the neutrino flux uncertainty, are included in the model as nuisance parameters and are derived from a parametrization of data from the NA56/SPY [9] and NA20 [10] experiments that used 450 and 400 GeV/c protons on target respectively. The model is used to produce and fit a set of toy-MC experiments, from which a posteriori values for the HP parameters are determined. The new parameters are used to reweight the MC and get the a posteriori neutrino flux at detector. The 6% systematic uncertainty on the neutrino flux due to the original HP data uncertainties is reduced to 1% with the constraint from the monitoring of leptons, thus reaching the goal of ENUBET.

6. The NP06/ENUBET implementation at CERN North Area

After the successful R&D program of the ERC project that demonstrated the feasibility of a monitored neutrino beam, the NP06/ENUBET collaboration is focusing its efforts to propose a short-baseline experiment at the CERN North Experimental Area to be run in parallel with Hyper-Kamiokande and DUNE, in order to provide a neutrino cross section measurement with a ~1% precision. Such a proposal leverages on the SPS accelerator as proton driver and on both ProtoDUNE-HD and ProtoDUNE-VD as neutrino detectors, and the details of a site-dependent implementation will be addressed in the next couple of years. A dedicated beamline extracted at the North Area and pointing towards the ProtoDUNEs would be the most convenient and cost-effective option, able to maximize the use of already existing facilities and to ensure the implementation of a slow extraction scheme of protons. However the interference with other experiments and potential radiation issues should be carefully evaluated. An alternative solution to mitigate these drawbacks, at the expense of an higher cost of the facility, could be represented by a new dedicated extraction line near the North Area to feed the ENUBET beamline towards the ProtoDUNEs.

In addition to the engineering and technical aspects of the implementation at CERN, a careful assessment of the physics performance and an in-depth knowledge of the assets and limitations for the use of ProtoDUNE (e.g. cosmics rejection in a slow extraction, kinematic reconstruction of final states, etc.) will complement this study.

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