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Monitored neutrino beams: NP06/ENUBET

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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. 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. This contribution reports the final design of the horn-less beamline able to deliver a meson yield large enough to perform a ν_e cross section measurement at 1% precision in about 3 years of data taking at CERN-SPS with a ProtoDUNE-like detector. The final configuration of the tunnel instrumentation and its implementation on a large-scale prototype, the Demonstrator, are also described. Finally the particle identification performance is presented together with the first assessment of the lepton monitoring impact in the reduction of the hadroproduction systematics on the neutrino flux.

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1. Introduction

A mitigation of the systematic uncertainties will be fundamental for the full exploitation of data collected by the next generation of neutrino oscillation experiments (DUNE, Hyper-Kamiokande, ESSnuSB). In this context high precision measurements with accelerator-based beams of the poorly known cross section of the electron neutrino, i.e. the appearing species of future oscillation experiments, would be extremely beneficial. ENUBET [1, 2] has been proposed and funded by the ERC to reduce to 1% the uncertainty on the beam flux, that represents the dominant uncertainty for such a measurement, by measuring on the walls of an instrumented decay tunnel the high angle positrons produced in association with the ν_e in the three body decay of kaons (K_{e3}, i.e. $K^+ \to \pi^0 e^+ \nu_e$). In the context of the CERN Neutrino Platform experiment NP06, ENUBET has then extended is 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 instrumenting the forward region of the decay tunnel, thus providing a full constraint also on the ν_μ flux [3]. 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 ENUBET beamline is designed to provide a narrow-band neutrino beam by focusing towards the 40 m long decay tunnel positively charged mesons with a momentum bite of 5-10% centered at 8.5 GeV/c. The magnetic lattice has been optimized with TRANSPORT, while irradiation studies were done with FLUKA, and G4Beamline was used to simulate particle transport and interactions in the shielding elements. The final design [3] is based on a pure static focusing system of secondary mesons composed by three quadrupoles in front of the target, that can be coupled to a slow extraction scheme of protons lasting some seconds and allowing for reduced pile-up effects on the tunnel instrumentation. Charge and momentum selection is accomplished by means of two dipoles for a total banding of ~15°. 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. The layout of the ENUBET beamline is reported in Fig. 1.

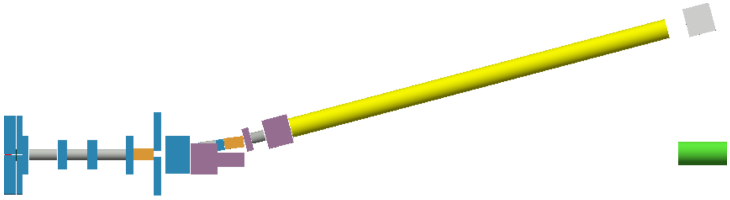

Figure 1: The ENUBET beamline. Focusing quadrupoles and bending dipoles are shown in grey and orange, respectively. Collimators are made of Iron (blue) or Inermet180 (violet). The decay tunnel (yellow), the hadron dump (light grey) and the proton dump (green) are also shown.

This latest implementation improves the kaon and pion yields at the tunnel entrance by a factor ~1.5 with respect to previous results, ensuring a large statistics at the neutrino detector in a reasonable amount of time even with a horn-less setup: assuming the 400 GeV proton beam of the SPS at

CERN with 4.5×10^{19} proton on target per year and a ProtoDUNE-like detector, 500 t mass, placed at 50 m from the end of the decay tunnel, 10^4 ν_e^{CC} interactions can be collected in about 3 years of data taking. A further optimization campaign is on going on the last two collimators, exploiting a fully parametric implementation of the transfer line in Geant4 and a genetic algorithm, with the goal of improving the signal-to-noise ratio at the instrumented decay tunnel. The parameter space is scanned to find the collimators configuration that maximizes the ratio among the number of K^+ reaching the tunnel entrance and the background particles hitting the tunnel walls [4]. Preliminary results show an improvement of 28% in the meson yields complemented by a background reduction.

3. Decay tunnel instrumentation

The lepton tagger is based on a sampling calorimeter as a cost-effective solution to perform $e/\pi/\mu$ separation, placed on the whole surface of the 1 m radius, 40 m long 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 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 shielding against neutron irradiation and ageing of the sensors.

Figure 2: The ENUBET tagger Demonstrator.

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 [5]. This activity culminated in the construction of the Demonstrator (Fig. 2), 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 [6]. The demonstrator has been partially instrumented (half of his 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 data analysis is now on going.

4. 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 [7]. Fig. 3 shows the distributions of the observables measured by the calorimeter for positrons and muons, used to constrain the neutrino flux at detector.

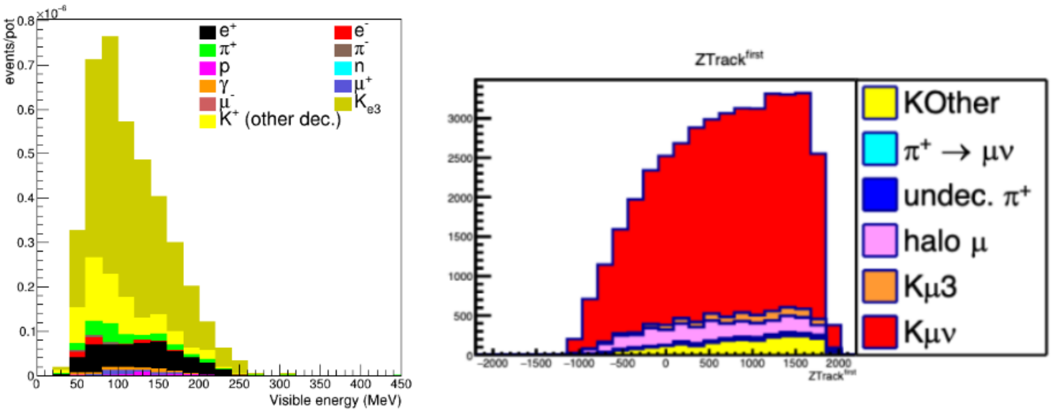

Figure 3: Distribution of observables for selected events. Left: visible energy of positrons from K_{e3} signal (golden) and of background events. Right: impact point along the calorimeter of muons from $K_{\mu2}$ (red) and $K_{\mu3}$ (orange) and of background events.

Using these observables, a signal plus background model for the monitored charged leptons is built in order to constrain the neutrino flux [8]. Hadroproduction (HP) systematics, that represent 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 experiment. 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 [6], thus reaching the goal of ENUBET.

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